



# DIS2022

XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects

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Xacobeo 21-22



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Fondo Europeo de Desenvolvemento Rexional "Unha maneira de facer Europa"

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## Towards mini-global parton-branching TMD fits

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# Motivation

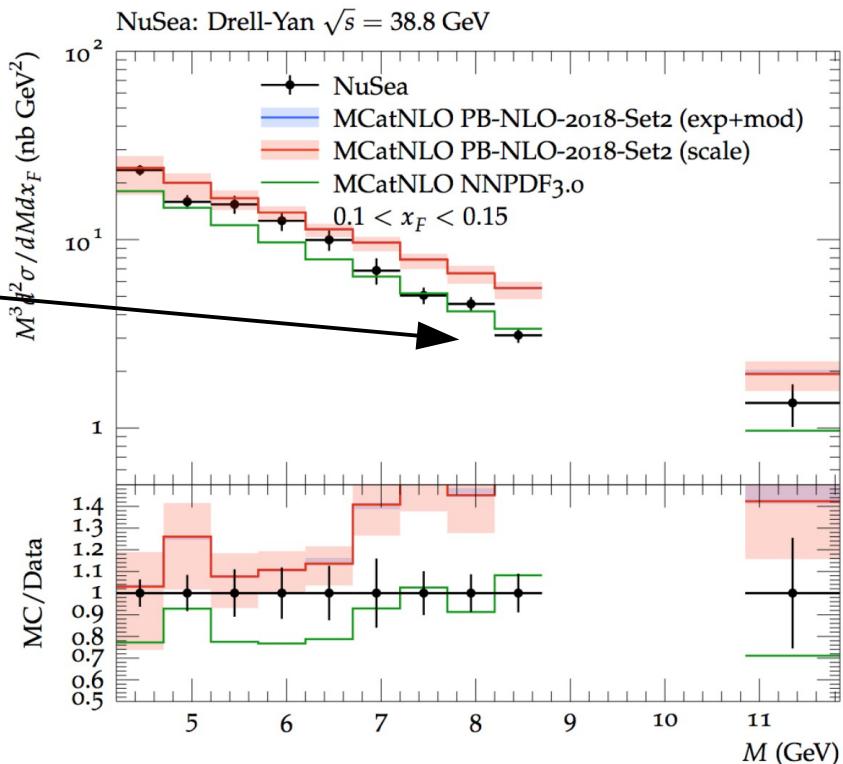
- PB TMDs together with PB TMD parton shower allow very good description of measurements over wide kinematic range
  - excellent description of the DY spectrum in a wide range of  $p_T$
  - also for jet multiplicity even much beyond reach of corresponding fixed-order calculation

**Is there still any room for improvement? YES!**

- PB-TMD NLO fits use HERA DIS data
  - can be improved by including different data sets in fits

arXiv:2001.06488

- NuSea data studied in arXiv:2001.06488
  - generally well described by PB-TMD + NLO
  - this deteriorates for region of highest masses
    - large- $x$  region - parton densities used in calculation poorly constrained
    - NNPDF3.0 set fits better - more data used
  - can be improved in global fits
  - jet data constrain gluon at high  $x$



# What data can help constraining quarks and gluons?

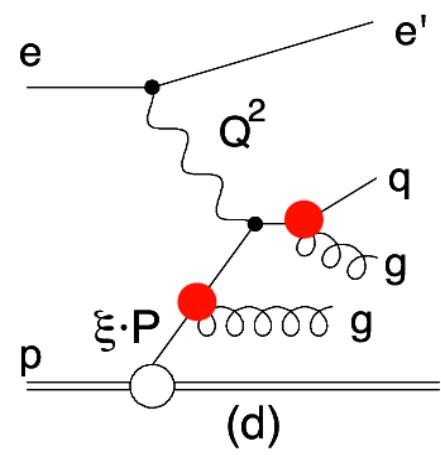
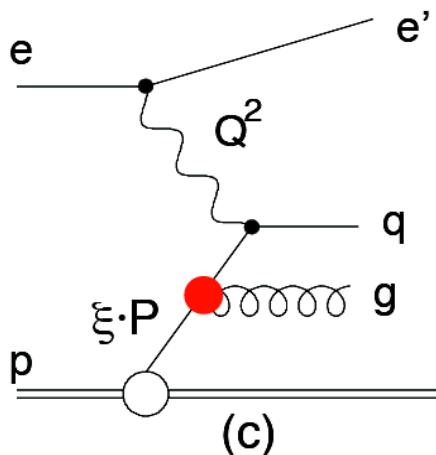
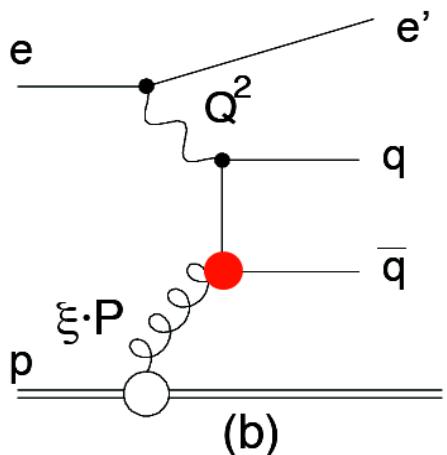
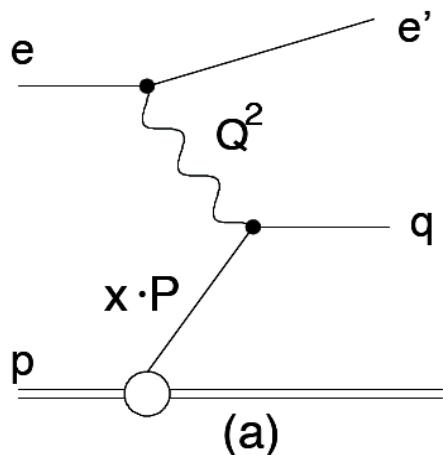
- Looking at various global fits lots of data can be added
- We start small
  - adding slowly additional data sets from HERA and CMS
  - for data sets and bins to use we take recommendation from NNPDF3
  - **Aiming for mini-global parton-branching TMD fits**

# Jets @ HERA

At HERA direct information on  
gluon distribution and  $\alpha_s$  comes  
from jet production

→ Possible simultaneous determination  
of parton densities and  $\alpha_s$

## Jets at HERA

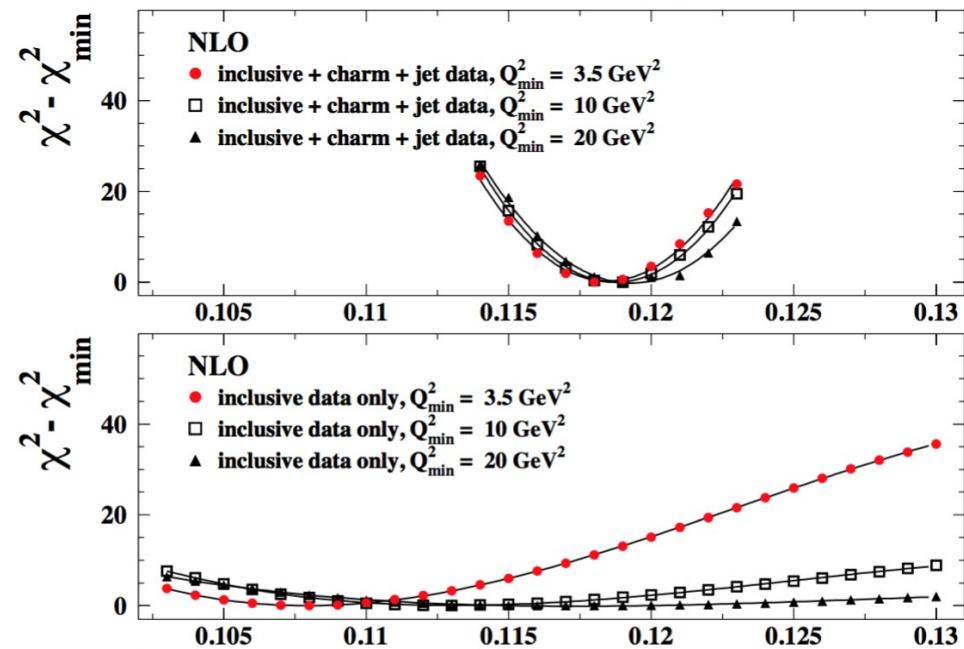


elweak coupling

$\propto \alpha_s$

dijets

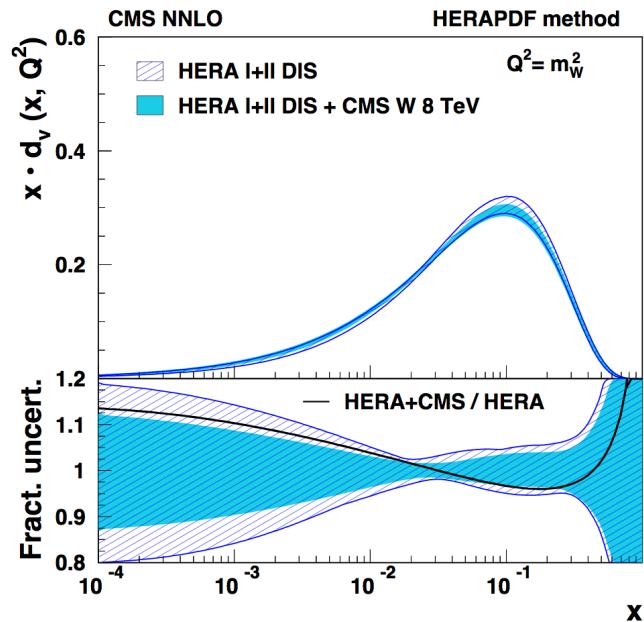
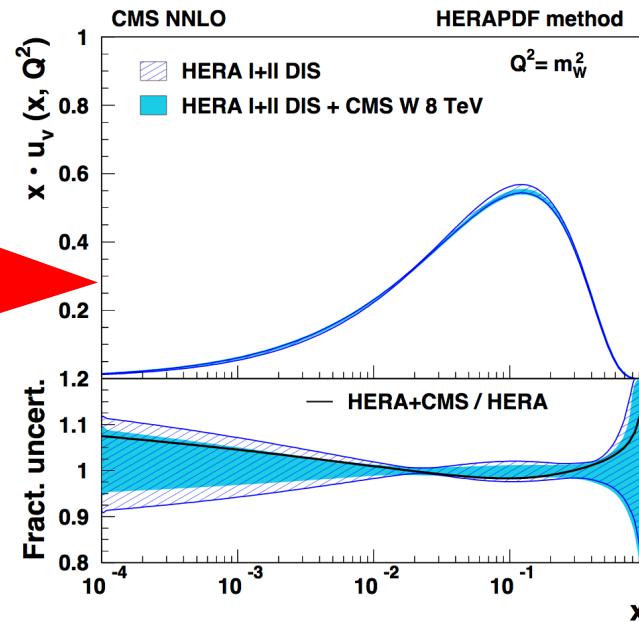
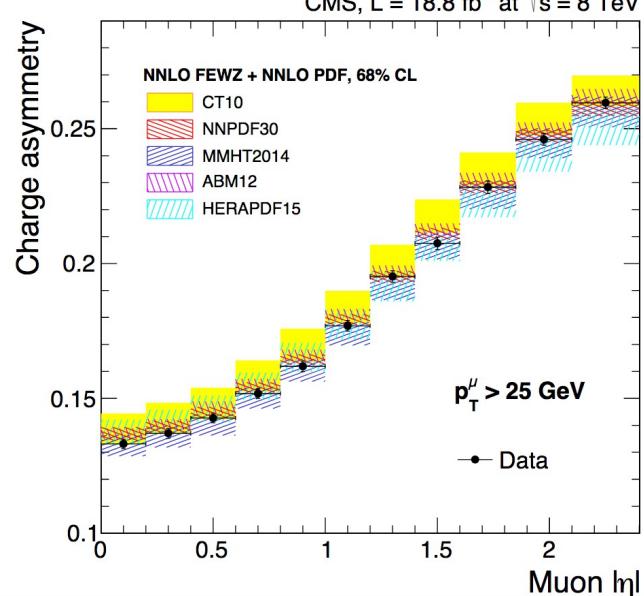
$\propto \alpha_s^2$   
trijets



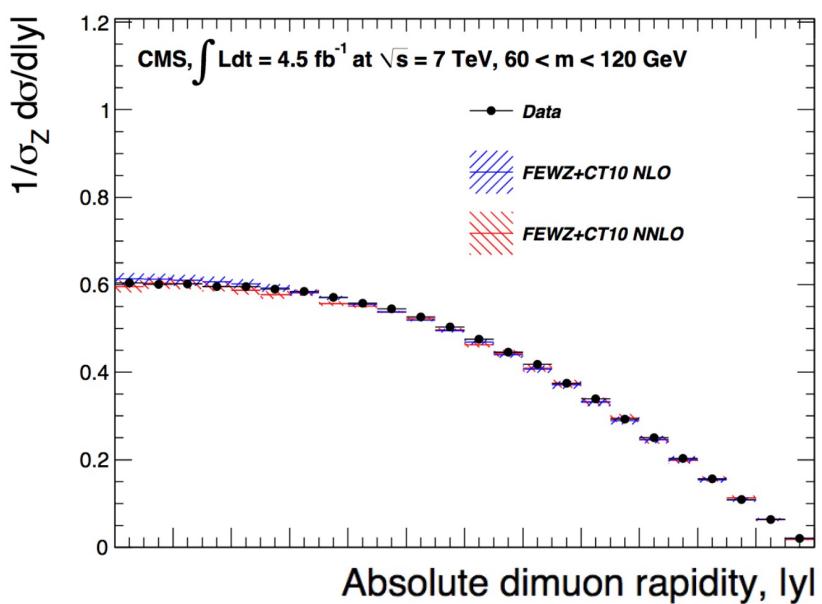
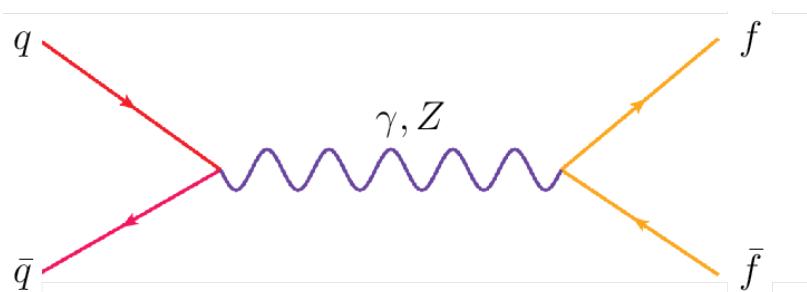
# CMS W/Z production



# Wasymmetry



# Drell-Yan Z production



# Data samples used in mini-global fit

HERA1+2 CCep

HERA1+2 CCem

HERA1+2 NCem

HERA1+2 NCep 820

HERA1+2 NCep 920

HERA1+2 NCep 460

HERA1+2 NCep 575

ZEUS inclusive dijet 98-00/04-07 data

H1 low Q<sub>2</sub> inclusive jet 99-00 data

ZEUS inclusive jet 96-97 data

H1 normalised inclusive jets with unfolding

H1 normalised dijets with unfolding

H1 normalised trijets with unfolding

CMS W muon asymmetry

CMS W muon asymmetry 8 TeV

CMS 7 TeV Z Boson rapidity 2

CMS 7 TeV Z Boson rapidity 3

CMS 7 TeV Z Boson rapidity 4

CMS 7 TeV Z Boson rapidity 5

We use HERAPDF2 approach for QCD fits  
(also model parameter values)  
+ xFitter

xFitter  
PDF Fitting package



# HERAPDF2.0-like parameterisation

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

- → **Parameters obtained by parameterisation scan**
- **additional parameters**

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g},$$

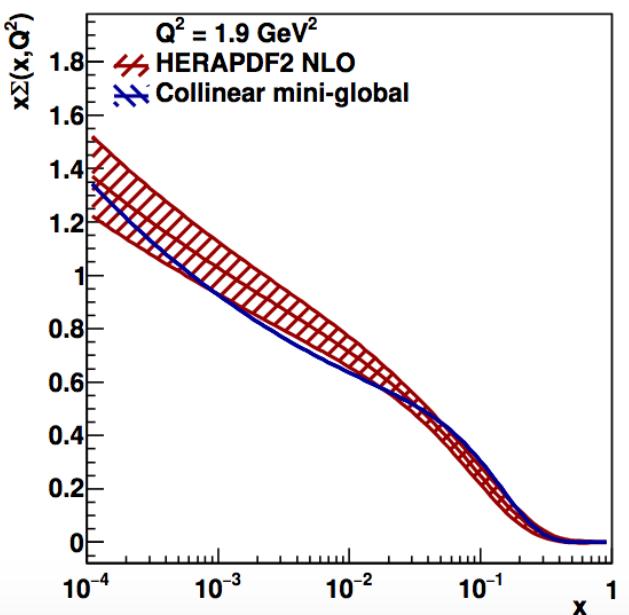
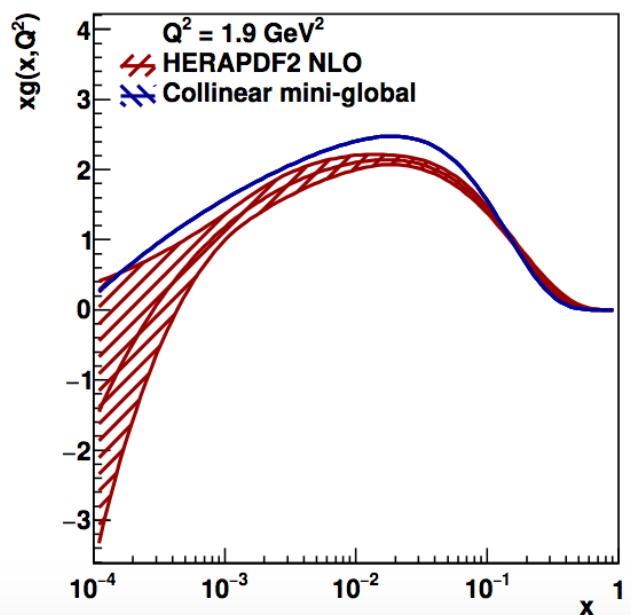
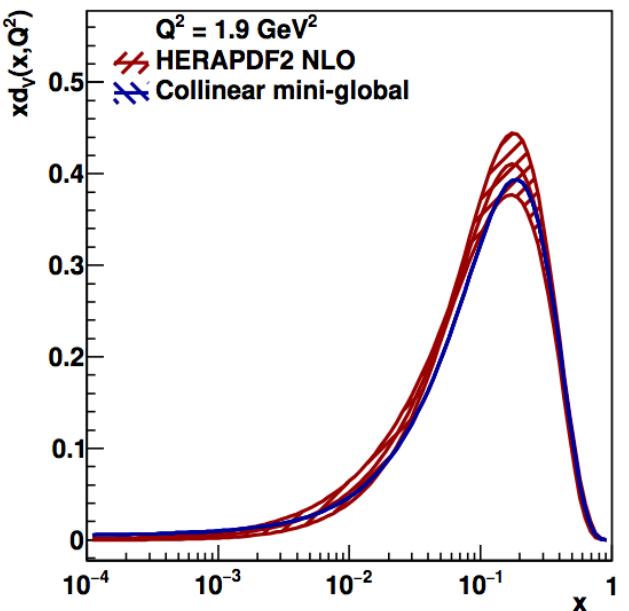
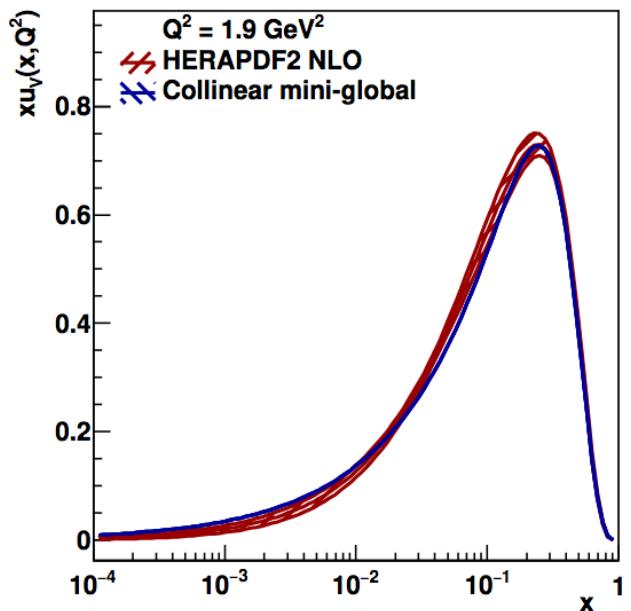
$$xu_v(x) = A_{uv} x^{B_{uv}} (1-x)^{C_{uv}} \left(1 + E_{uv} x^2\right), \quad \textcolor{magenta}{+ D_{uv} x}$$

$$xd_v(x) = A_{dv} x^{B_{dv}} (1-x)^{C_{dv}} \textcolor{magenta}{(1 + D_{dv} x)}$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x),$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}} \textcolor{magenta}{(1 + D_{db} x)}$$

# Comparison to HERAPDF2 NLO



Can we get PB PDFs & TMDs with new data?

→ start with few discussed new data sets

TMDs-what is it? [Phys. Lett. B 772 (2017), 446-451], [JHEP 01 (2018), 070]

- TMDs : Transverse Momentum Dependent parton distributions
- extended collinear PDFs : transverse momentum effects from intrinsic  $k_t$  + evolution

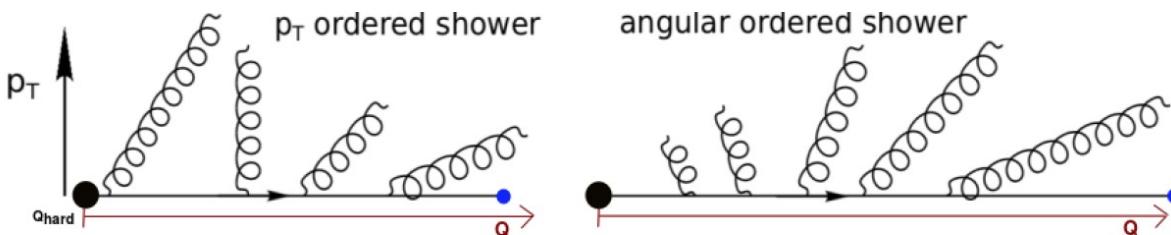
Why TMD?

- fixed order calculations are limited in application
- small transverse momentum & small-x phenomena need TMDs

New approach: Parton Branching (PB) method

- evolution of TMDs and collinear PDFs at LO, NLO & NNLO
- automatically contain soft gluon resummation (at NLL identical to CSS approach)
- unique feature: backward evolution fully determines the TMD shower
- very successful for description of inclusive processes

[Phys. Rev. D 100 (2019) no.7, 074027], [Eur. Phys. J. C 80 (2020) no.7, 598 ]



- Two angular ordered sets with different choice of scale in  $\alpha_s$ :
  - set1:  $\alpha_s$ (evolution scale)
  - set2:  $\alpha_s$ (transverse momentum): similar quality as the NLO + NNLL prediction in  $p_t(z)$  description



Fitting procedure in a nutshell:

- parameterize collinear PDF at  $\mu_0^2$
- produce PB kernels for collinear & TMD distributions to evolve them to  $\mu^2 > \mu_0^2$   
[Eur. Phys. J. C **74**, 3082 (2014)]
- perform fits to measurements using xFitter frame to extract the initial parametrization  
(with collinear coefficient functions at NLO)
- store the TMDs in a grid for later use in CASCADE3 [Eur. Phys. J. C **81**, no.5, 425 (2021)]
- plot collinear and TMD pdfs within TMDPLOTTER [[arXiv:2103.09741](https://arxiv.org/abs/2103.09741)]

## 5 FLNS:

- full coupled evolution with all flavors &  
 $\alpha_s(M_Z^{n_f=5}) = 0.118$
- HERAPDF parametrization form
- using full HERAI+II inclusive DIS data  
( $3.5 < Q^2 < 50000 \text{ GeV}^2$  &  $4 \cdot 10^{-5} < x < 0.65$ )
- $\chi^2/dof = 1.21$

[Phys. Rev. D **99** (2019) no. 7, 074008]

## 4 FLNS:

- the same functional form & data as 5FL - parameters are re-fitted
- $m_b \rightarrow \infty$  &  $\alpha_s(M_Z^{n_f=4}) = 0.1128$
- $\chi^2/dof = 1.25$

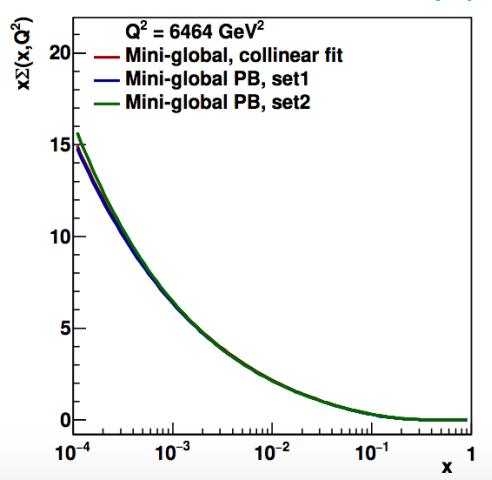
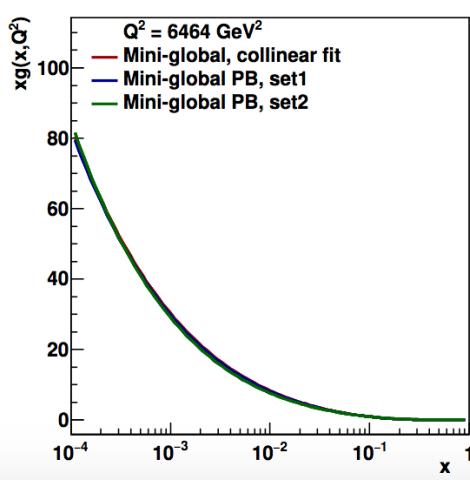
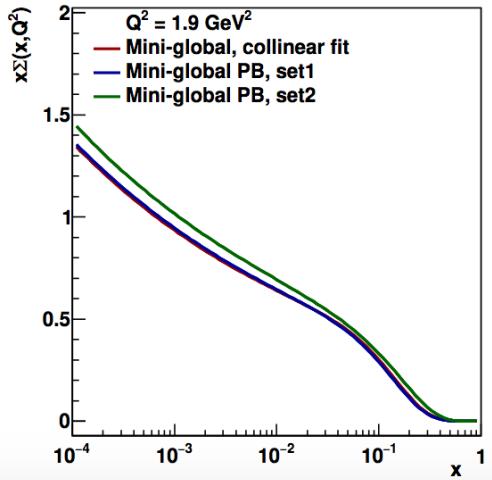
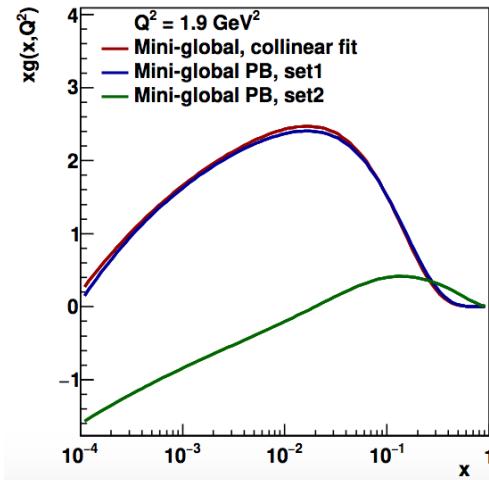
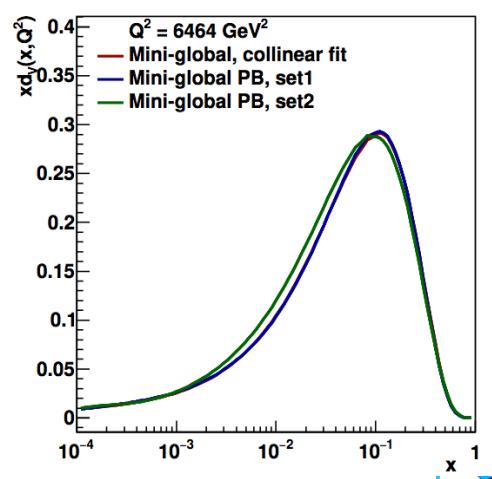
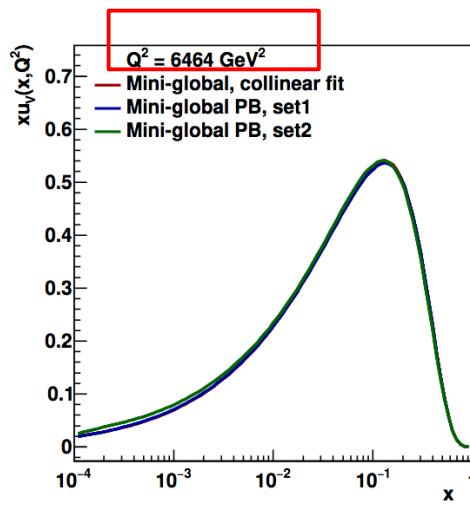
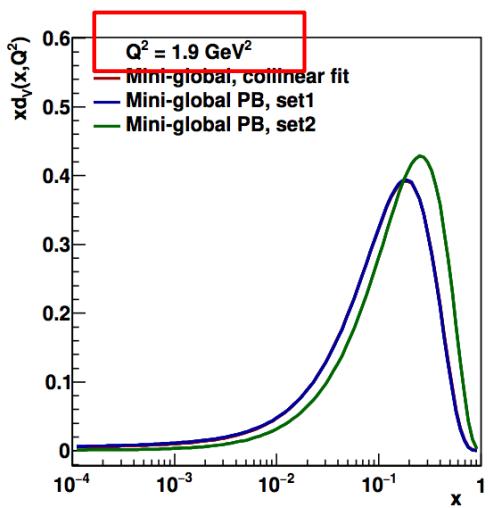
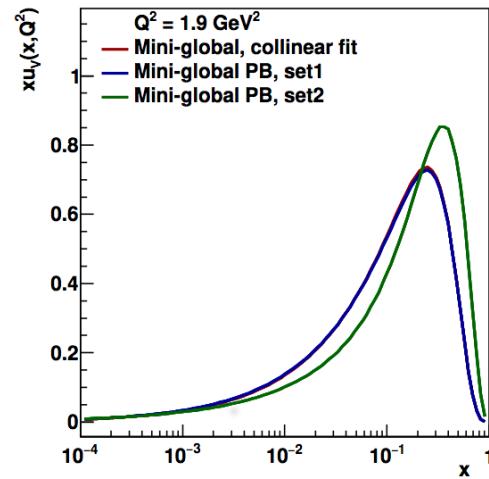
[[arXiv:2106.09791](https://arxiv.org/abs/2106.09791)]

# TMDs with jets

now we do PB QCD analysis with new data sets:

- PB method implemented in xFitter:  
Eur. Phys. J. C75 (2015), no. 7, 304
- kernels for PB fit with HERA DIS:  
Eur. Phys. J. C 74, 3082 (2014)

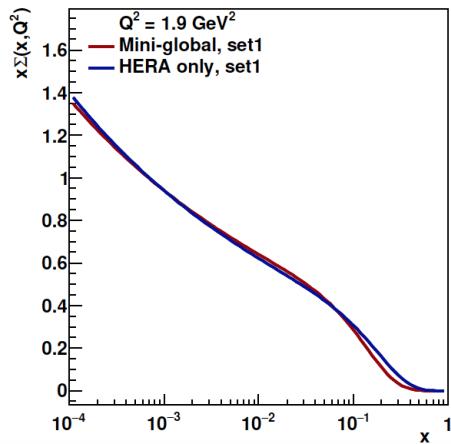
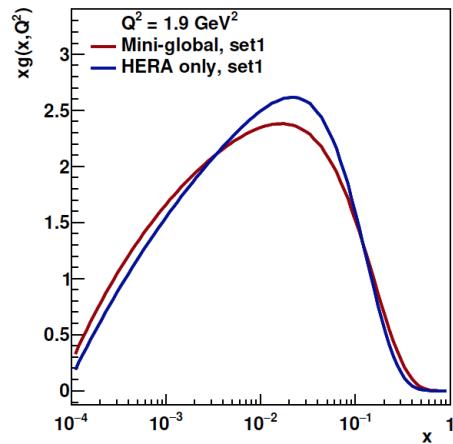
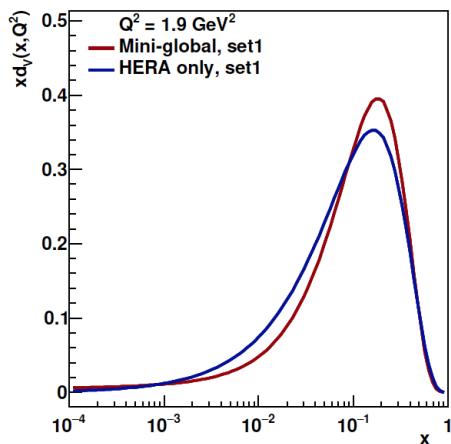
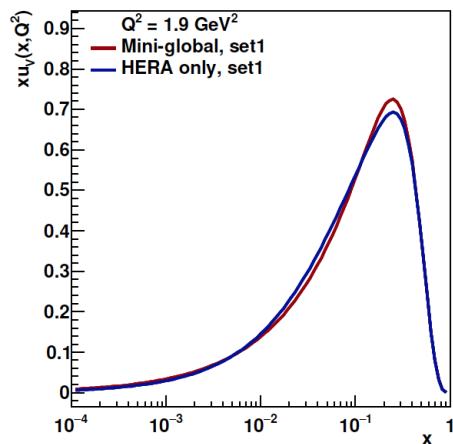
# Comparison of collinear and PB PDFs



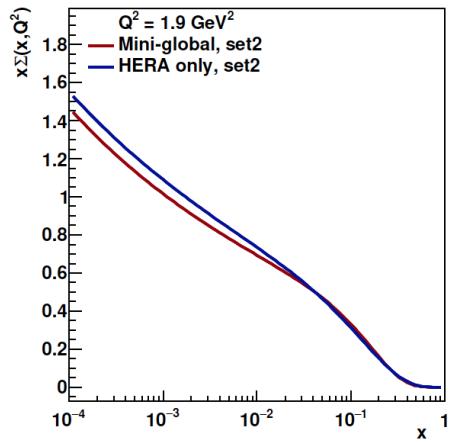
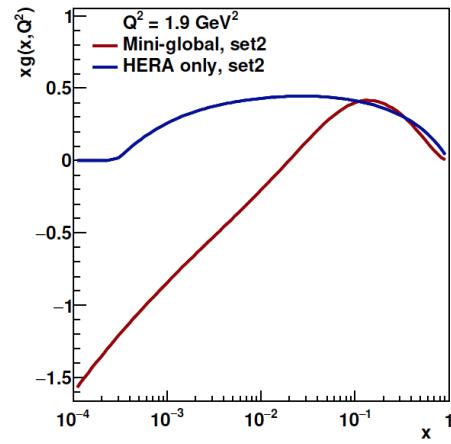
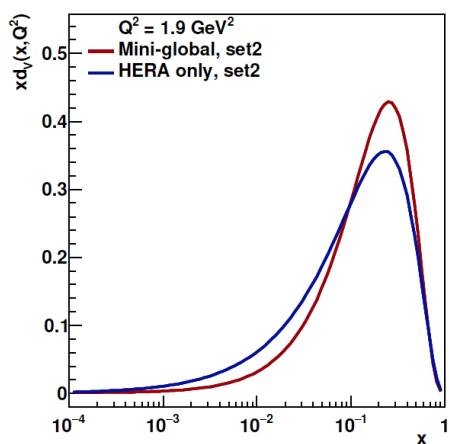
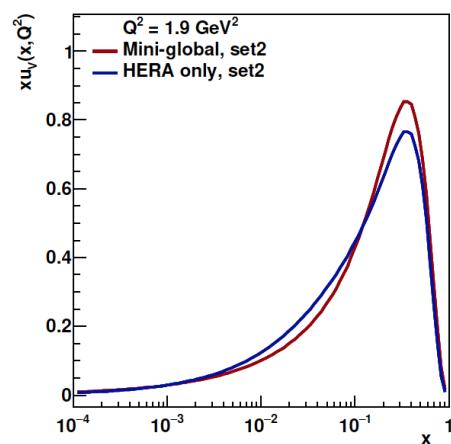
- Collinear and PB set1 very similar → fixed  $\alpha_s$
- $\chi^2$  also good for jet data after the fit
- At large scale set1 gets similar o set2

# Comparison of PB mini-global and HERA-only

set1



set2



- Difference between PB mini-global and HERA-only larger for set2  
→ especially for gluon

# Comparison to data (examples)

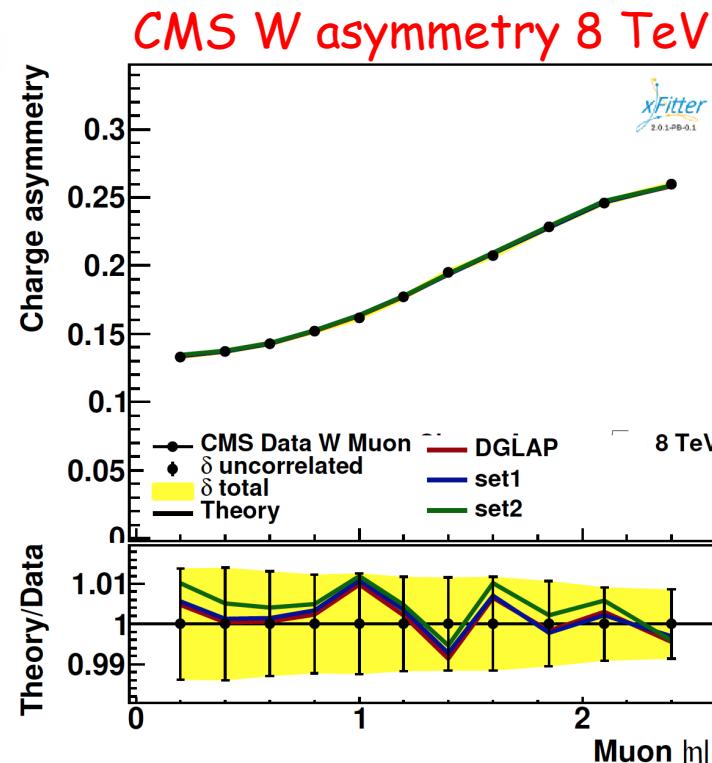
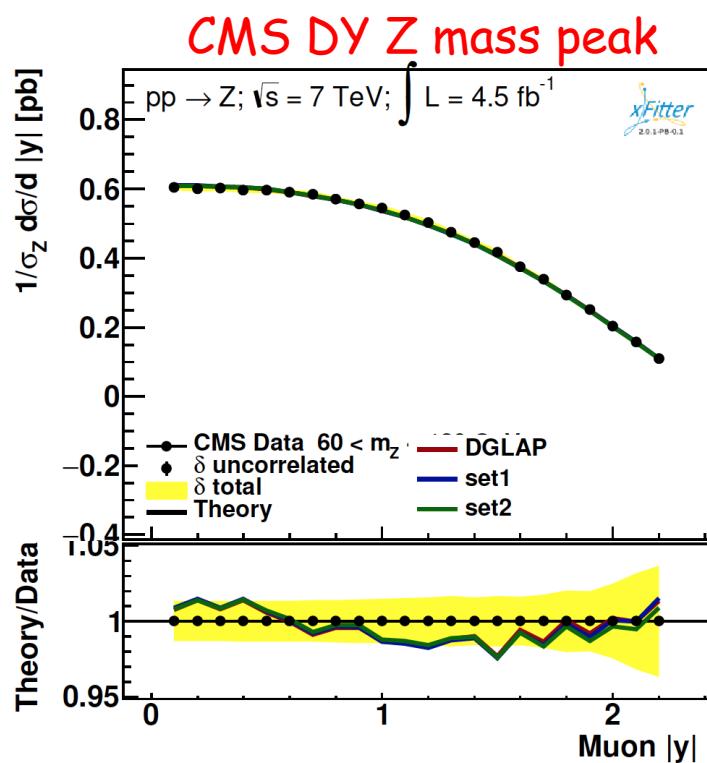
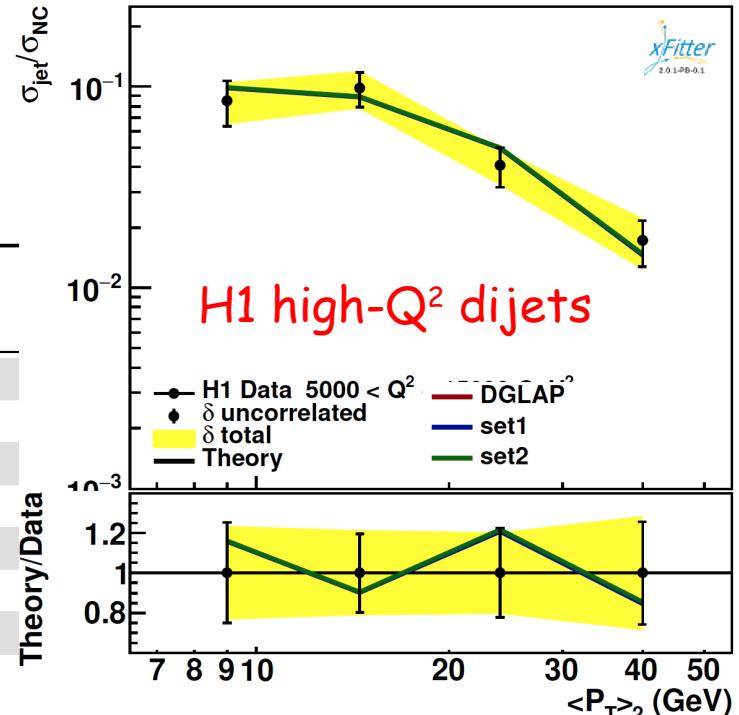
Dataset

DGLAP

set1

set2

Dataset	DGLAP	set1	set2
HERA1+2 CCep	40 / 39	41 / 39	42 / 39
HERA1+2 CCem	64 / 42	63 / 42	58 / 42
HERA1+2 NCem	215 / 159	218 / 159	226 / 159
HERA1+2 NCep 820	70 / 70	72 / 70	71 / 70
HERA1+2 NCep 920	450 / 377	457 / 377	438 / 377
HERA1+2 NCep 460	218 / 204	223 / 204	233 / 204
HERA1+2 NCep 575	222 / 254	223 / 254	217 / 254



# Caveat ...

- For jet data we need to "choose" scale for PDF fits
  - set2 sensitive to chosen factorisation scale
  - it needs to be sufficiently large
    - We chose  $\mu_r = \mu_f = (Q^2 + p_T^2)/2$
    - Works well for all included HERA jet data sets except for H1 HERAI low  $Q^2$  jets

After minimisation						
	2105.26	1383	1.522		1916.23	1383
<b>Partial chi2s</b>						
Dataset 1	428.82(+13.01)	377	HERA1+2 NCep 920		429.94(+10.85)	377
Dataset 2	69.96(+0.67)	70	HERA1+2 NCep 820		69.99(+0.48)	70
Dataset 3	214.90(+5.05)	254	HERA1+2 NCep 575		218.22(+3.51)	254
Dataset 4	235.33(+2.82)	204	HERA1+2 NCep 460		237.38(+1.52)	204
Dataset 5	238.18(+1.74)	159	HERA1+2 NCem		229.56(+1.80)	159
Dataset 6	42.20(+0.83)	39	HERA1+2 CCep		41.37(+1.31)	39
Dataset 7	59.10(-2.52)	42	HERA1+2 CCem		60.65(-2.39)	42
Dataset 8	0.00(+0.00)	11	CMS W muon asymmetry			
Dataset 9	0.00(-0.00)	11	CMS W muon asymmetry 8 TeV			
Dataset 10	50.93(-3.91)	30	ZEUS inclusive jet 96-97 data		50.87(-4.05)	30
Dataset 11	0.00(-1.01)	24	H1 normalised inclusive jets with unfolding		0.00(-1.06)	24
Dataset 12	0.00(-0.54)	24	H1 normalised dijets with unfolding		0.00(-0.60)	24
Dataset 13	0.00(-0.92)	16	H1 normalised trijets with unfolding		0.00(-0.94)	16
Dataset 14	223.66(-12.36)	28	H1 low Q2 inclusive jet 99-00 data		50.55(-10.07)	28
Dataset 15	27.08(-0.21)	22	ZEUS inclusive dijet 98-00/04-07 data		29.30(-0.26)	22
Dataset 16	0.00(+0.00)	27	CMS Z TAU Z PDF uncertainty		0.00(+0.00)	27

$$(Q^2 + p_T^2)/2$$

$$(Q^2 + p_T^2)$$

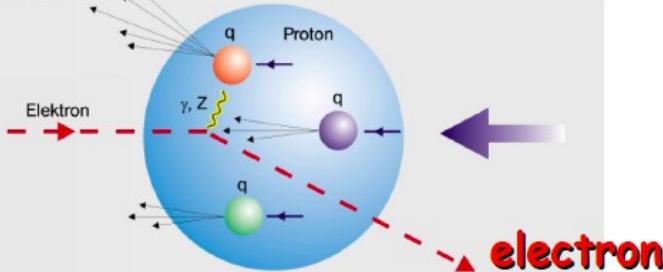
- We observe huge partial chi2 for H1 HERAI low  $Q^2$  jets
  - situation dramatically improves when we use  $\mu_f = (Q^2 + p_T^2)$  → maybe  $\mu_f = (Q^2 + p_T^2)/2$  not large enough for low  $Q^2$  jets?
  - for presented here fit we use this scale only for this data
- However does it actually make sense?? → we need to understand that!

# Summary & outlook

- PB fits so far include only HERA inclusive data
  - Studies of other processes at HERA and LHC gives more information on TMD PDFs and better uncertainty constrains
  - Ultimate goal: global PB TMDs - why not start small, with mini-global?
    - HERA jets
    - CMS DY data + W asymmetries
- PB method implemented in xFitter → so far fits with HERA DIS
  - Preliminary results with HERA jets and CMS data added → good agreement with collinear PDFs
  - New precise PB-sets from mini-global fit will be used to repeat our previous studies on the inclusive jet, Z+b, ... where our predictions were in general 10-20% below measurements
  - Work ongoing to add more LHC and fixed target data

# Additional slides

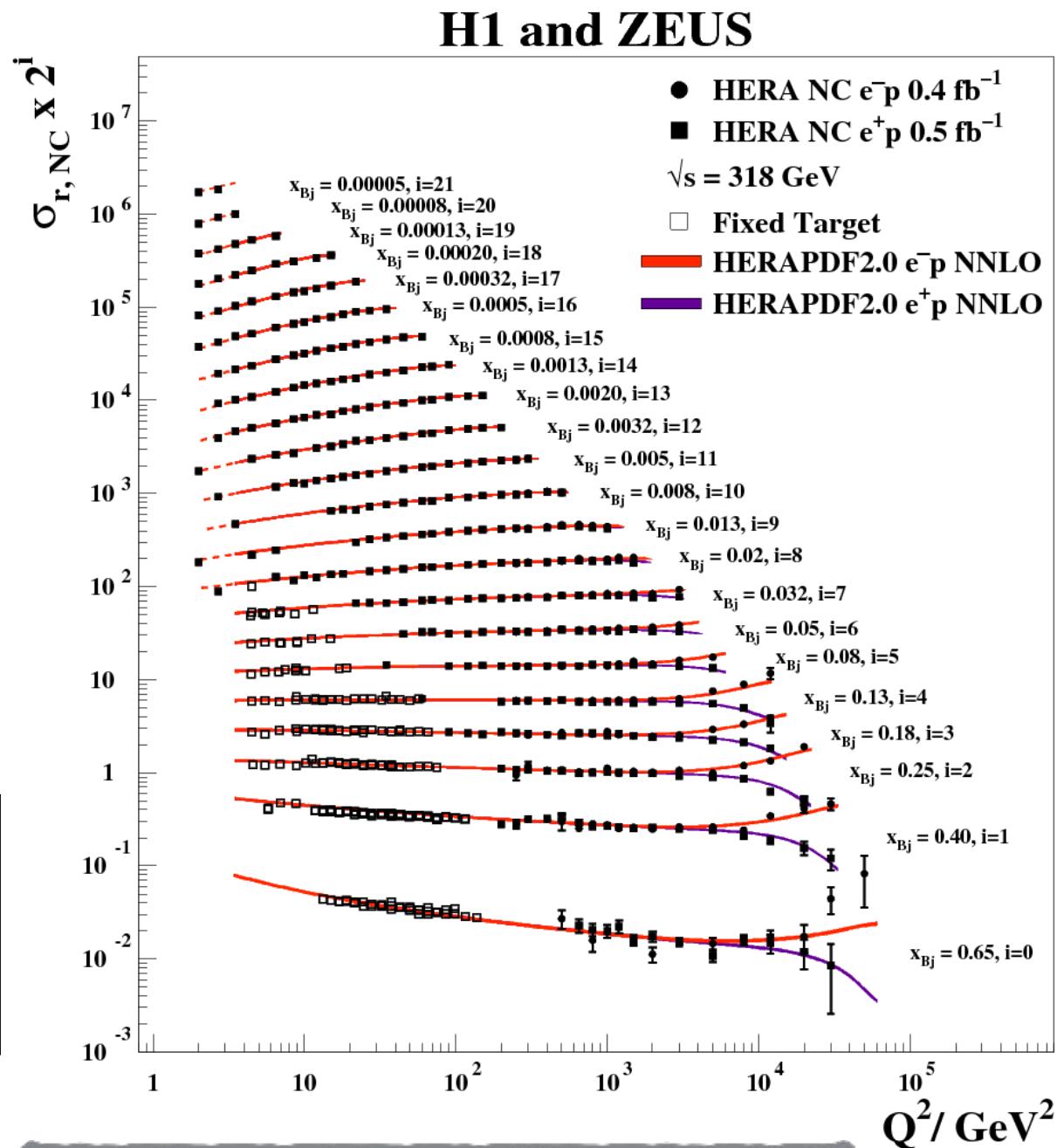
# HERA combined inclusive DIS



HERA combined DIS data are  
core of every modern PDF  
extraction

- 2927 data points combined to 1307
- impressive precision

HERAPDF approach uses  
ONLY HERA data in  
global QCD fit



- PB evolution equation for collinear and TMD PDFs:

$$f_a(x, \mu^2) = f_a(x, \mu_0^2) \Delta_s(\mu^2, \mu_0^2) + \sum_b \int_x^{z_M} \frac{dz}{z} \int_{\mu_0}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \cdot \frac{\Delta_s(\mu^2, \mu_0^2)}{\Delta_s(\mu'^2, \mu_0^2)} P^{(R)}(z) f_b\left(\frac{x}{z}, \mu'^2\right)$$

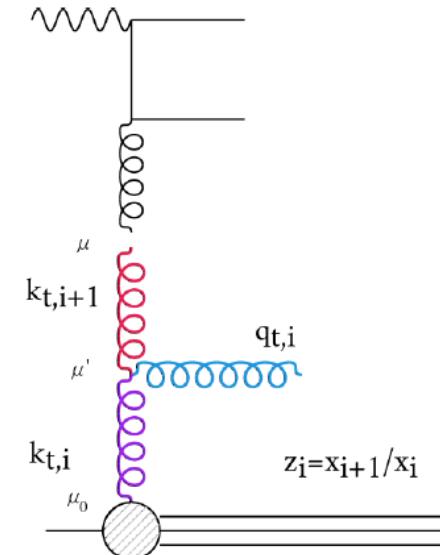
$$\begin{aligned} \tilde{\mathcal{A}}_a(x, \mathbf{k}, \mu^2) &= \Delta_a(\mu^2, \mu_0^2) \tilde{\mathcal{A}}_a(x, \mathbf{k}, \mu_0^2) + \sum_b \int \frac{d^2 \mu'}{\pi \mu'^2} \frac{\Delta_a(\mu^2, \mu_0^2)}{\Delta_a(\mu'^2, \mu_0^2)} \Theta(\mu^2 - \mu'^2) \Theta(\mu'^2 - \mu_0^2) \\ &\times \int_x^{z_M} dz P_{ab}^{(R)}(\text{as}(\mu'^2), z) \tilde{\mathcal{A}}_b(x/z, \mathbf{k} + (1-z)\mu', \mu'^2) , \end{aligned}$$

- iterative solution:

$$f_0(x, \mu^2) = f(x, \mu_0^2) \Delta_s(\mu^2, \mu_0^2)$$

$$f_1(x, \mu^2) = f(x, \mu_0^2) \Delta_s(\mu^2, \mu_0^2)$$

$$+ \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_s(\mu^2, \mu_0^2)}{\Delta_s(\mu'^2, \mu_0^2)} \int \frac{dz}{z} P^R(z) f(x/z, \mu_0^2) \Delta(\mu'^2, \mu_0^2)$$



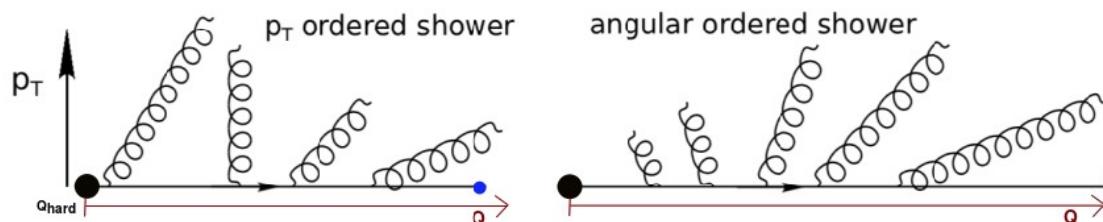
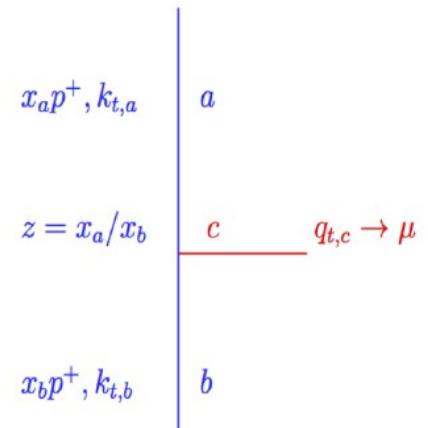
[Phys. Rev. D 99 (2019) no. 7, 074008]

- kinematics governed by momentum conservation ( $\mathbf{k}_{t,b} = \mathbf{k}_{t,a} + \mathbf{q}_{t,c}$ ) [JHEP 01 (2018), 070]

- gives physics interpretation of evolution

scale:

- $p_t$ -ordering:  $\mu^2 = q_t^2$
- angular ordering:  $\mu^2 = q_t^2/(1-z)^2$



- Two angular ordered sets with different choice of scale in  $\alpha_s$ :
  - set1:  $\alpha_s$  (evolution scale)
  - set2:  $\alpha_s$  (transverse momentum): similar quality as the NLO + NNLL prediction in  $p_t(z)$  description
- TMD parametrization:

$$f_{0,b}(x, \mathbf{k}_{t,0}^2, \mu_0^2) = f_{0,b}(x, \mu_0^2) \cdot \exp(-|k_{T,0}^2|/2\sigma^2) \quad \sigma^2 = q_s^2/2 \quad \& \quad q_s = 0.5 \text{ GeV}$$