Diffractive PDF determination from HERA incl. and jet data at NNLO

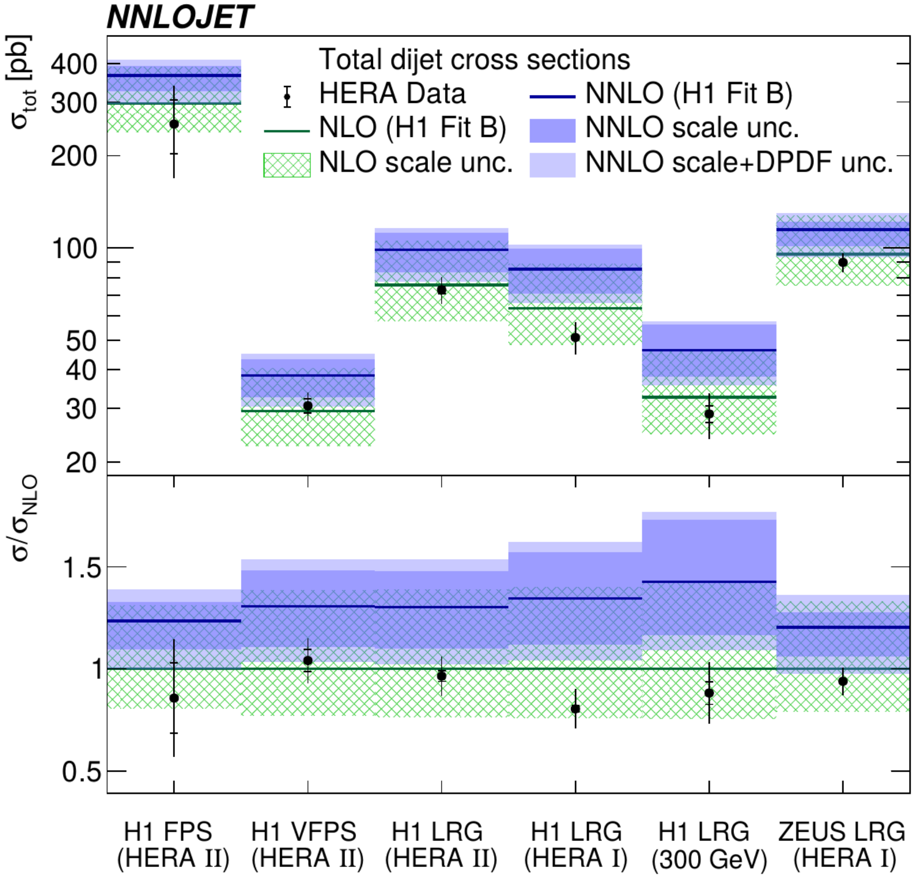
Radek Žlebčík
on behalf of the H1 Collaboration
Nicosia, **Low-x 2019, August 29**

Troodos mountains, Cyprus

Why new DPDFs?

Motivation 1:
Progress in theory

- Compared to 2006 or 2007 the NNLO predictions are currently available for both, the inclusive production and jet production
- Large NNLO/NLO k-factors observed for dijet production



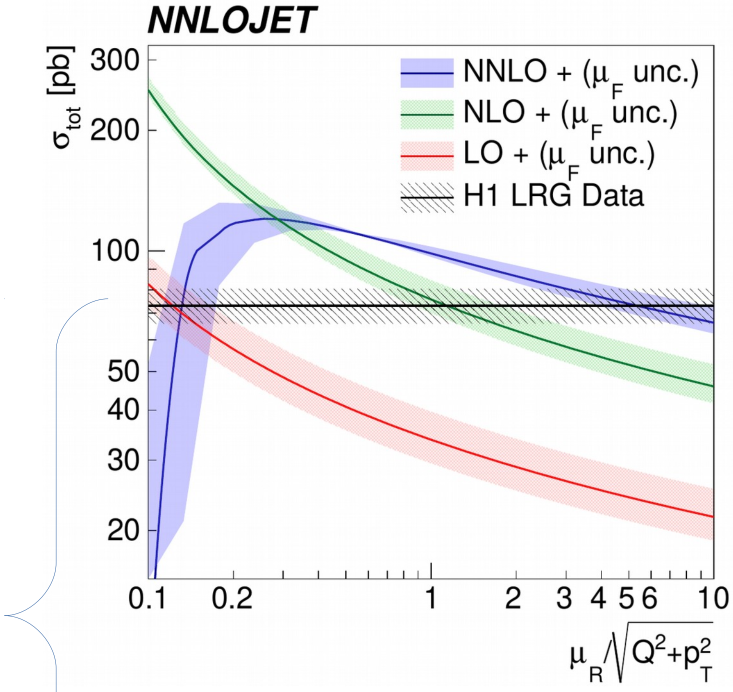
The NNLO prediction based on H1 Fit2006B NLO DPDF overestimates the data **by ~30%** With much lower scale unc. for NNLO

Eur.Phys.J. C78 (2018) no.7, 538 [arXiv:1804.05663]

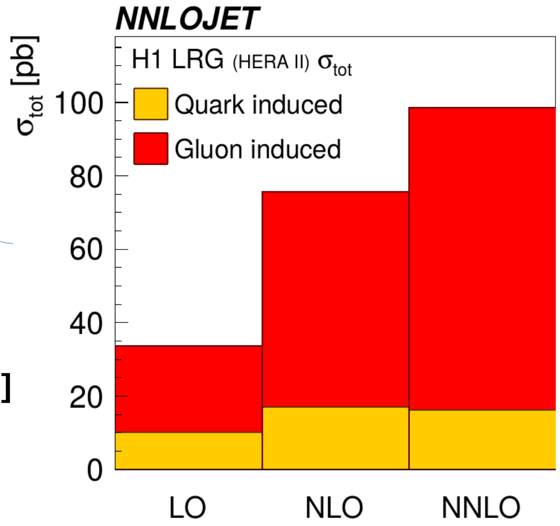
Are inclusive and jet data compatible at NNLO?

Scale dependence of dijet cross section

Jets in DDIS ($\sqrt{s}$ = 319 GeV)



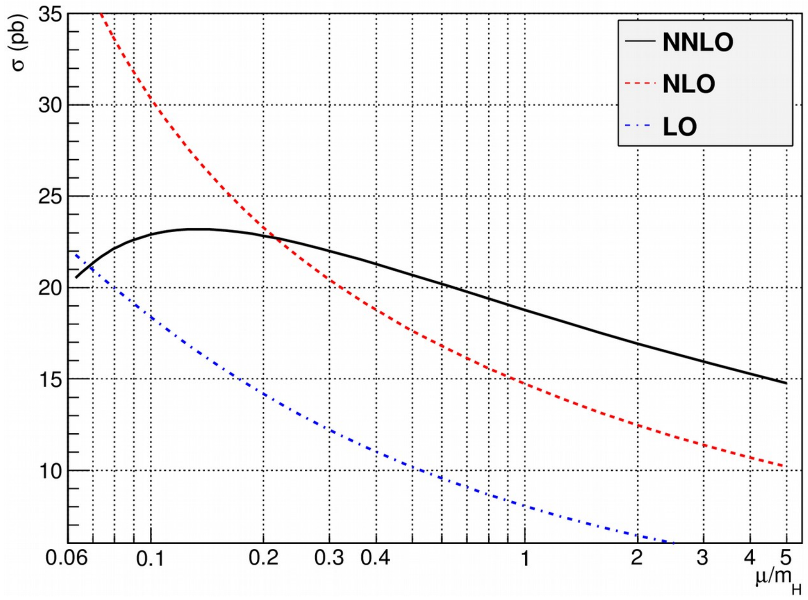
Based on
H1 2006B
DPDF



Eur.Phys.J. C78
(2018) no.7, 538
[arXiv:1804.05663]

Higgs production in pp ($\sqrt{s}$ = 8 TeV)

JHEP 1204 (2012) 004

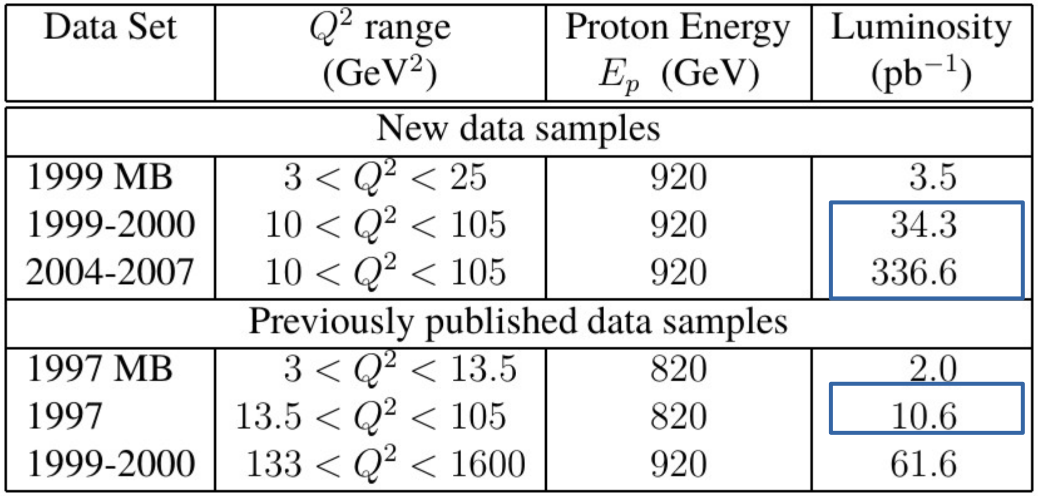


- The gluon-DPDF induced cross section rises gradually with order
- The quark-Induced cross section stagnates at NLO
- At NNLO 84% of the cross section is from gluon DPDF

Motivation 2:
Progress in data

- Compared to last diffractive fits from 2006 or 2007 the HERA II data of much higher luminosity available

Inclusive DDIS data:



Data Set	Q^2 range (GeV^2)	Proton Energy E_p (GeV)	Luminosity (pb^{-1})
New data samples			
1999 MB	$3 < Q^2 < 25$	920	3.5
1999-2000	$10 < Q^2 < 105$	920	34.3
2004-2007	$10 < Q^2 < 105$	920	336.6
Previously published data samples			
1997 MB	$3 < Q^2 < 13.5$	820	2.0
1997	$13.5 < Q^2 < 105$	820	10.6
1999-2000	$133 < Q^2 < 1600$	920	61.6

~40 times higher luminosity

Eur.Phys.J. C72 (2012) 2074 [arXiv:1203.4495]
+ data at lower energies 225, 252 GeV

The jet data:

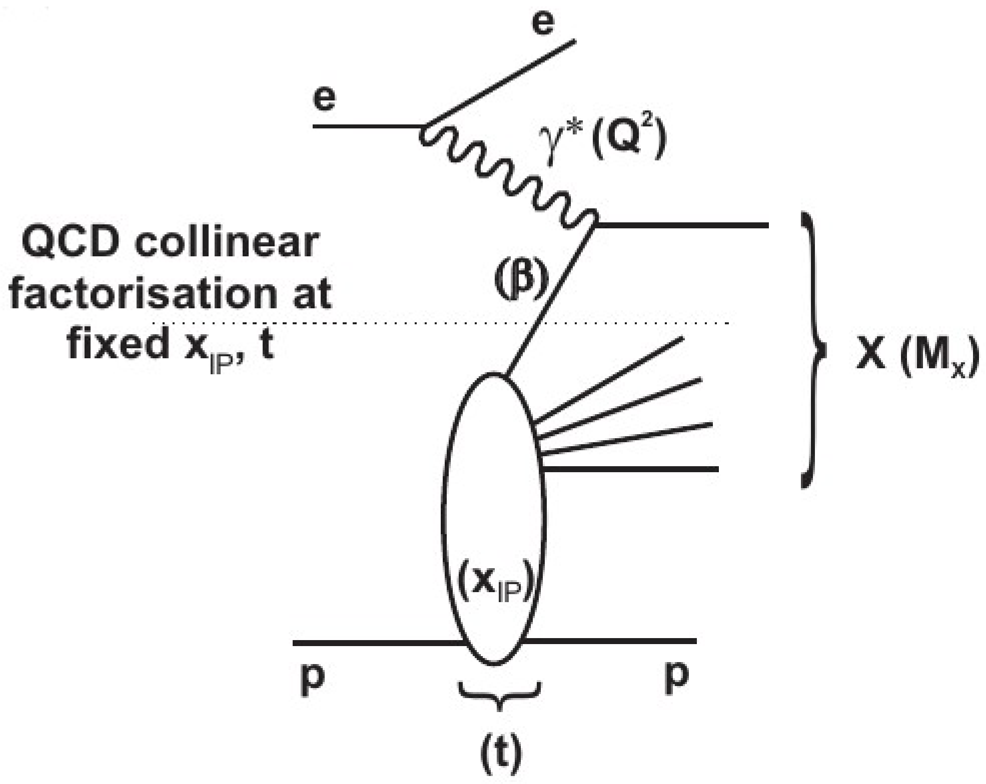
New data sample		
2005-2007	920 + 27.6	290 pb^{-1}
Previously published		
1999-2000	920 + 27.5	51.5 pb^{-1}

~6 times higher luminosity

JHEP 1503 (2015) 092 [arXiv:1412.0928]:
With proper treatment of correlations between bins

Diffractive Production in ep

In diffractive events the beam proton stays intact or dissociates into low mass hadronic system Y



At HERA about 10% of low-x events are diffractive

DIS variables:

$$Q^2 = -(k - k')^2 \qquad y = \frac{p \cdot q}{p \cdot k}$$

Diffractive variables:

$$x_{I\!P} = 1 - \frac{E'_p}{E_p} \qquad t = (p - p')^2$$

Mass: $M_X^2 = Q^2 \left(\frac{1}{\beta} - 1 \right)$

At LO: The momentum fraction entering the hard subprocess with respect to the diffractive exchange

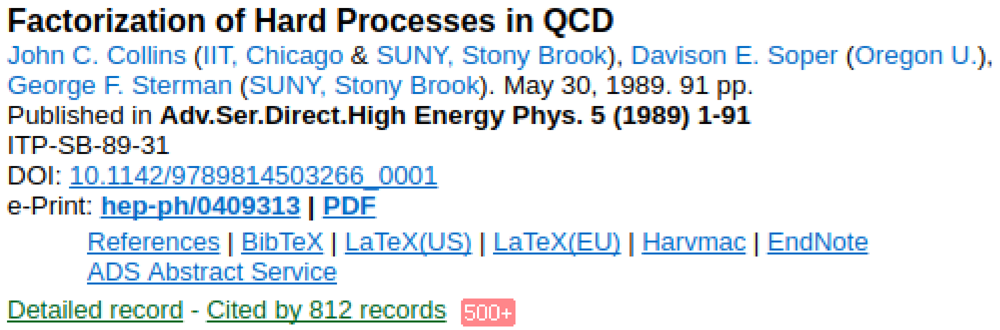
$$\beta = \frac{x_{Bj}}{x_{I\!P}} = \frac{Q^2}{s y x_{I\!P}}$$

Collinear QCD factorization theorem in hard diffraction

- For diffractive events with a **hard scale** (e.g Q^2 or jets p_T)
- Factorization of the diffractive cross section into process independent DPDFs and partonic cross sections

$$\mathrm{d}\sigma(ep \to epX) = \sum_i f_i^D(x, Q^2, x_{IP}, t) \otimes \mathrm{d}\sigma^{ie}(x, Q^2)$$

- For diffractive processes (including dijets) with high enough Q^2 factorization proven by Collins within perturbative QCD, for low Q^2 factorization breaking suggested



Factorization of Hard Processes in QCD
John C. Collins (IIT, Chicago & SUNY, Stony Brook), Davison E. Soper (Oregon U.), George F. Sterman (SUNY, Stony Brook). May 30, 1989. 91 pp.
Published in **Adv.Ser.Direct.High Energy Phys. 5 (1989) 1-91**
ITP-SB-89-31
DOI: 10.1142/9789814503266_0001
e-Print: **hep-ph/0409313 | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 812 records 500+

Proof of factorization for diffractive hard scattering
John C. Collins (Penn State U.). Sep 1997. 12 pp.
Published in **Phys.Rev. D57 (1998) 3051-3056**, Erratum: **Phys.Rev. D61 (2000) 019902**
PSU-TH-189
DOI: 10.1103/PhysRevD.57.3051, 10.1103/PhysRevD.61.019902
e-Print: **hep-ph/9709499 | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 404 records 250+

NLO DPDFs

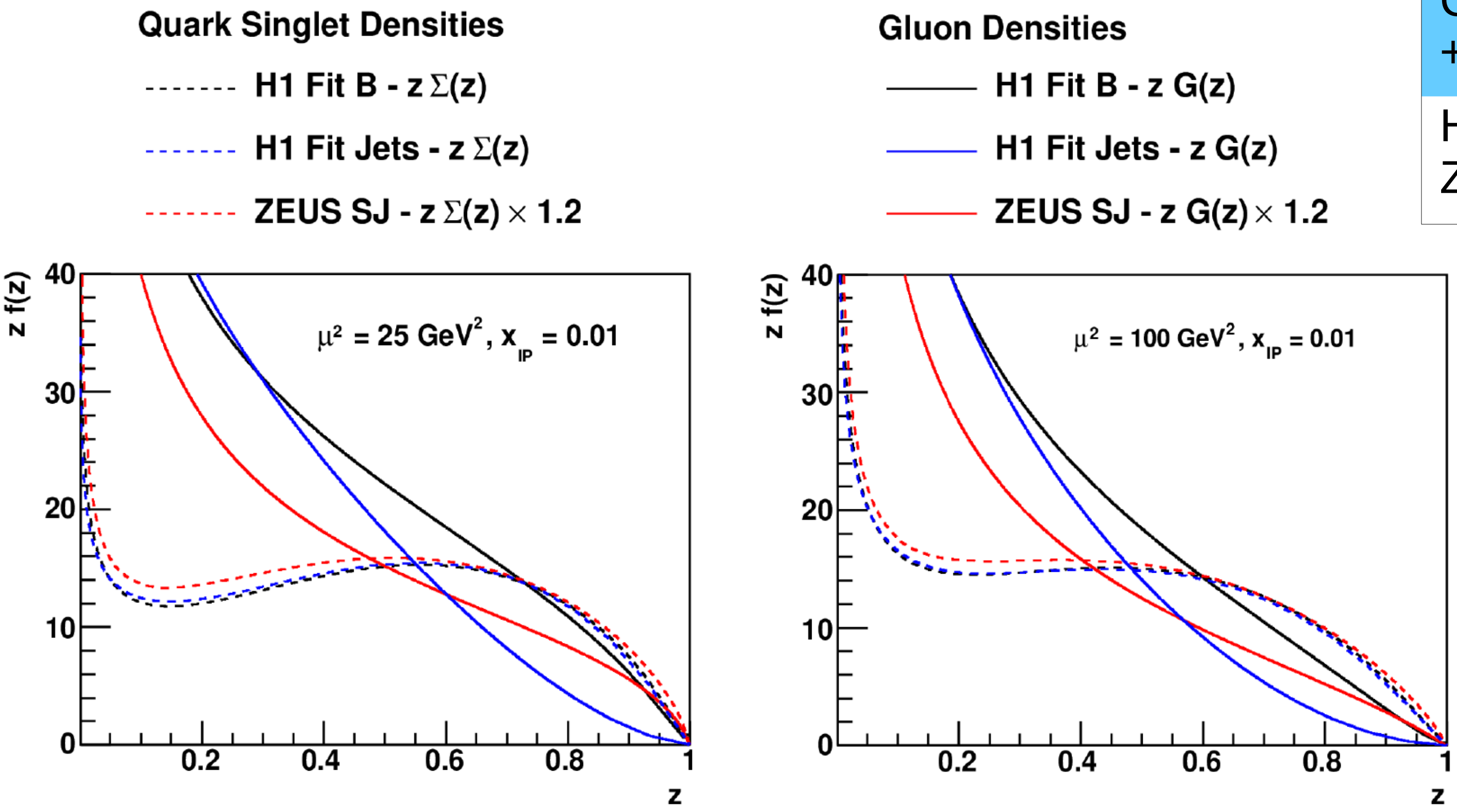
- DPDF sets differ mainly in gluon component which is weekly constrain from inclusive diffractive data
- For gluon dominated diffractive dijet production we have sizable DPDF uncertainty
- DPDFs obey standard DGLAP evolution equation

Fits of **inclusive** data

~~H1 2006 Fit A~~
H1 2006 Fit B
MRW DPDF
GKG18

Combined **inclusive** + **dijets** data fits

H1 2007 Fit Jets
ZEUS 2009 Fit SJ



70% of diffractive exchange momentum carried by gluons

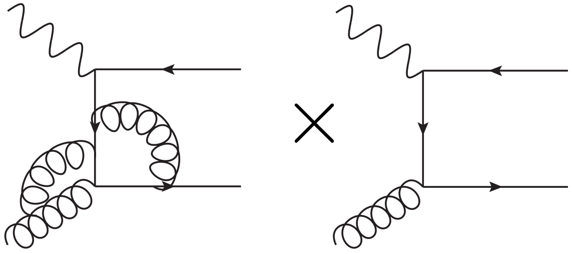
Overview of the new fit

Theory

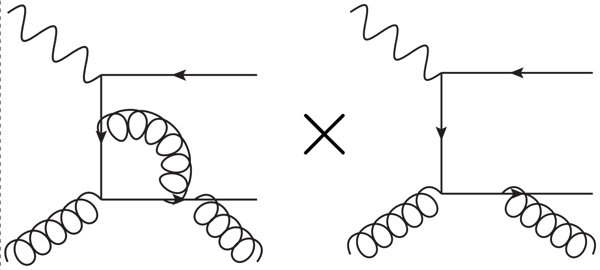
- NNLO accuracy for both inclusive and jet production
- Using FONLL-C GM-VFNS (by APFEL) for inclusive production,
  $\longrightarrow$ default QCD scale for inc. production: $\mu_R^2 = \mu_F^2 = Q^2$
- Using NNLOJET (massles quarks) + fastNLO for dijets,
  $\longrightarrow$ default QCD scale for dijets: $\mu_R^2 = \mu_F^2 = Q^2 + \langle p_T^{*\mathrm{jets}} \rangle^2$
- Scale unc. by simultaneous (for all processes)
  $\mu_F = \mu_R$ x2, x0.5 variation

Examples of α_S^3 diagrams contributing to dijet production

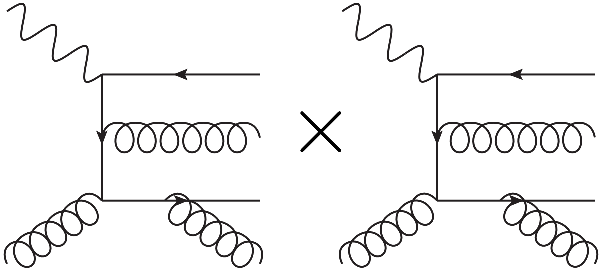
virtual-virtual



real-virtual



real-real



Fit performed using **Alpos** framework https://indico.desy.de/indico/event/22011/session/7/contribution/23

DPDF Parametrization

- Regge factorisation ansatz

$$f_i^D(z,\mu^2,x_{I\!P},t) = f_{I\!P/p}(x_{I\!P},t)\,f_{i/I\!P}(z,\mu^2) + n_{I\!R}\,f_{I\!R/p}(x_{I\!P},t)\,f_{i/I\!R}(z,\mu^2)$$

- **Pomeron PDF** $f_{i/I\!P}(z,\mu^2)$

times z=1 regulator: $\exp\left(-\frac{0.01}{1-z}\right)$

	Gluon	Singlet $(u=d=s=\bar{u}=\bar{d}=\bar{s})$
H1 Fit2006A	$A_g \quad (1-z)^{C_g}$	$A_q\, z^{B_q}(1-z)^{C_q}$
H1 Fit2006B	A_g	
H1 Fit2007Jets ZEUS SJ **H1 Fit2019 NNLO**	$A_g\, z^{B_g}(1-z)^{C_g}$	

- **Reggeon PDF** $f_{i/I\!R}(z,\mu^2)$

⟶ only few % at $x_{IP} = 0.03$

⟶ Fixed to the pion PDF (GRV NLO as default)

⟶ The overall normalization $n_{I\!R}$ taken as free parameter

Collinear QCD factorization in inclusive DDIS

$$\alpha_{em} \overset{\text{def}}{=} \frac{1}{137}$$

- The reduced diffractive cross section:

$$\frac{\mathrm{d}^3\sigma^{ep\to eXY}}{\mathrm{d}Q^2\mathrm{d}\beta\mathrm{d}x_{I\!P}} = \frac{4\pi\alpha_{em}^2}{\beta Q^4}\left(1-y+\frac{y^2}{2}\right)\underbrace{\left(F_2-\frac{y^2}{1+(1-y)^2}F_L\right)}_{\sigma_r^{D(3)}(\beta,Q^2,x_{I\!P})}$$

- Regge factorization ansatz

Fitted

Fixed

$$F_{2/L}^{D(3)}(\beta,Q^2,x_{I\!P}) = f_{I\!P/p}(x_{I\!P})F_{2/L}^{I\!P}(\beta,Q^2) + n_{I\!R}\,f_{I\!R/p}(x_{I\!P})F_{2/L}^{I\!R}(\beta,Q^2)$$

$$F_{2/L}^{I\!P}(\beta,Q^2) = C_{2/L}^{i}(\beta/z,Q^2,\mu^2)\otimes f_{i/I\!P}(z,\mu^2)$$

Up to NNLO

Standard DIS coef. functions

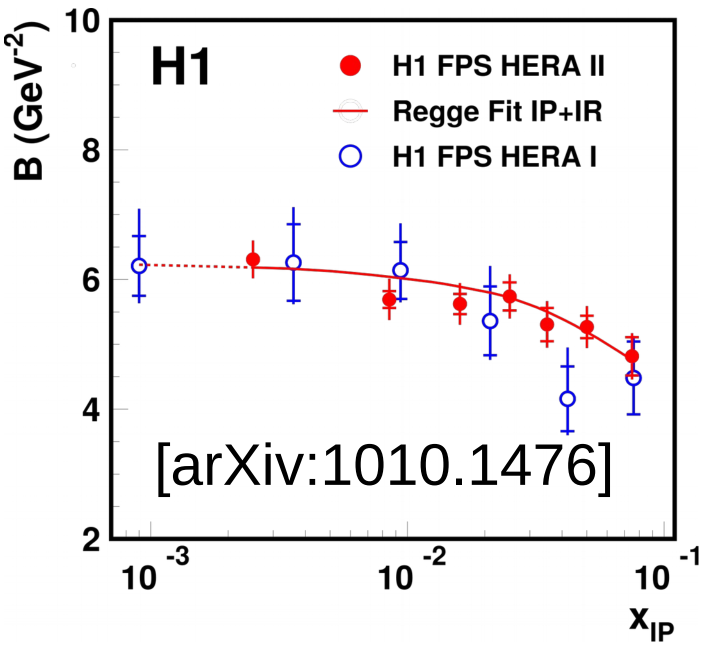
Obeys DGLAP

Both coef. functions and DGLAP evolution depend on α_s and m_c, m_b

Flux Parametrization

- Param. inspired by Regge theory (Streng and Berger):

$$f_{I\!P/p}(x_{I\!P},t) \propto \left(\frac{1}{x_{I\!P}}\right)^{2[\alpha_{I\!P}(0)+\alpha'_{I\!P}t]-1} \mathrm{e}^{B^0_{I\!P}t} \quad \Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}t} \propto \mathrm{e}^{-B|t|}$$



[arXiv:1010.1476]

B-slope dependence:

$$B = B^0_{I\!P} + 2\alpha'_{I\!P}\left(\log\frac{1}{x_{I\!P}}\right)$$

$$\Rightarrow \quad \begin{aligned} \alpha'_{I\!P} &= 0.04^{+0.08}_{-0.06}\ \mathrm{GeV}^{-2} \\ B^0_{I\!P} &= 5.73^{+0.84}_{-0.93}\ \mathrm{GeV}^{-2} \end{aligned}$$

Uncertainties anti-correlated

- t-integrated version:

Fitted

Fixed

~1.2

~0.01

$$f_{I\!P/p}(x_{I\!P}) \propto \left(\frac{1}{x_{I\!P}}\right)^{\boxed{2\alpha_{I\!P}(0)-1}} \frac{1}{1+\boxed{2\frac{\alpha'_{I\!P}}{B^0_{I\!P}}}\log\frac{1}{x_{I\!P}}} \doteq \left(\frac{1}{x_{I\!P}}\right)^{2\alpha_{I\!P}(0)-1-2\frac{\alpha'_{I\!P}}{B^0_{I\!P}}}$$

Parameters & Model Unc.

- Fixed params. mostly identical with H1 2006 & 2007 fits

	Parameter	Value	Source
Pomeron slope	$\alpha'_{\mathbb{P}}$	$0.04^{+0.08}_{-0.06}$ GeV^{-2}	H1 FPS HII [arXiv:1010.1476]
Pomeron B-slope	$B^0_{\mathbb{P}}$	$5.73^{+0.84}_{-0.93}$ GeV^{-2}	H1 FPS HII [arXiv:1010.1476]
Reggeon intercept	$\alpha_{\mathbb{R}}(0)$	0.5 ± 0.1	H1 LRG HI [hep-ex/9708016]
Reggeon slope	$\alpha'_{\mathbb{R}}$	$0.3^{+0.6}_{-0.3}$ GeV^{-2}	H1 FPS HI [hep-ex/0606003]
Reggeon B-slope	$B^0_{\mathbb{R}}$	$1.6^{+0.4}_{-1.6}$ GeV^{-2}	H1 FPS HI [hep-ex/0606003]
charm mass	m_c	1.4 ± 0.2 GeV	PDG2004
bottom mass	m_b	4.5 ± 0.5 GeV	PDG2004
strong coupling	$\alpha_S(M_Z^2)$	0.118 ± 0.002	PDG2004
staring scale of ev.	μ_0	$1.15^{+0.24}_{-0.15}$ GeV	

- Parameters $\alpha'_{\mathbb{P}}, B_{\mathbb{P}}$ ($\alpha'_{\mathbb{P}}, B_{\mathbb{P}}$) strongly anti-correlated
  $\longrightarrow$ Varied simultaneously as (up,down) & (down,up)

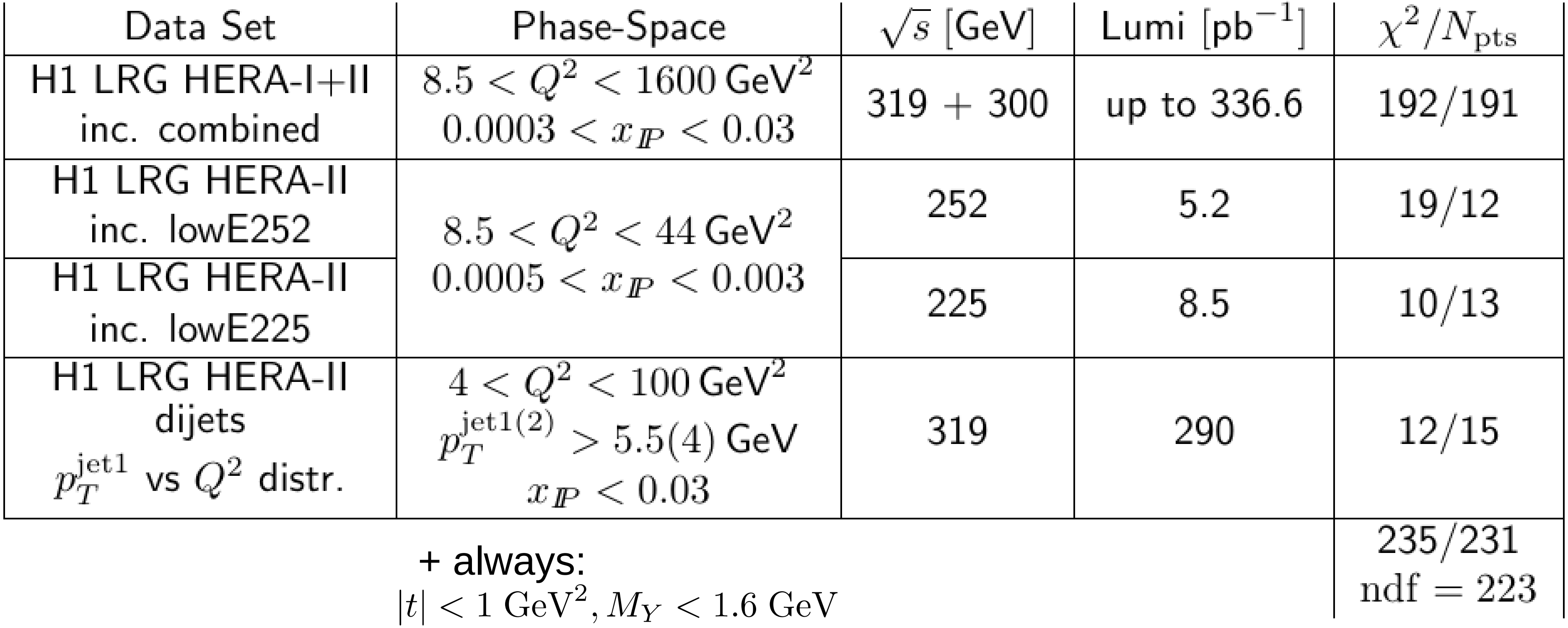
- The QCD scale varied by a factor of 2
  (dominant unc. together with μ_0 variation)

- **8 parameters fitted:** 6 of pomeron PDF + $\alpha_{\mathbb{P}}(0)$ & $n_{\mathbb{R}}$

Fitted data sets

Data

- Combined H1 HERA-I + HERA-II LRG inc. data [arXiv:1203.4495]
- H1 LowE HERA-II LRG inc. data $\sqrt{s} = 225$ GeV, $\sqrt{s} = 252$ GeV [arXiv:1107.3420]
- H1 HERA-II dijets LRG data, p_T^{jet1} vs Q^2 dist. [arXiv:1412.0928]

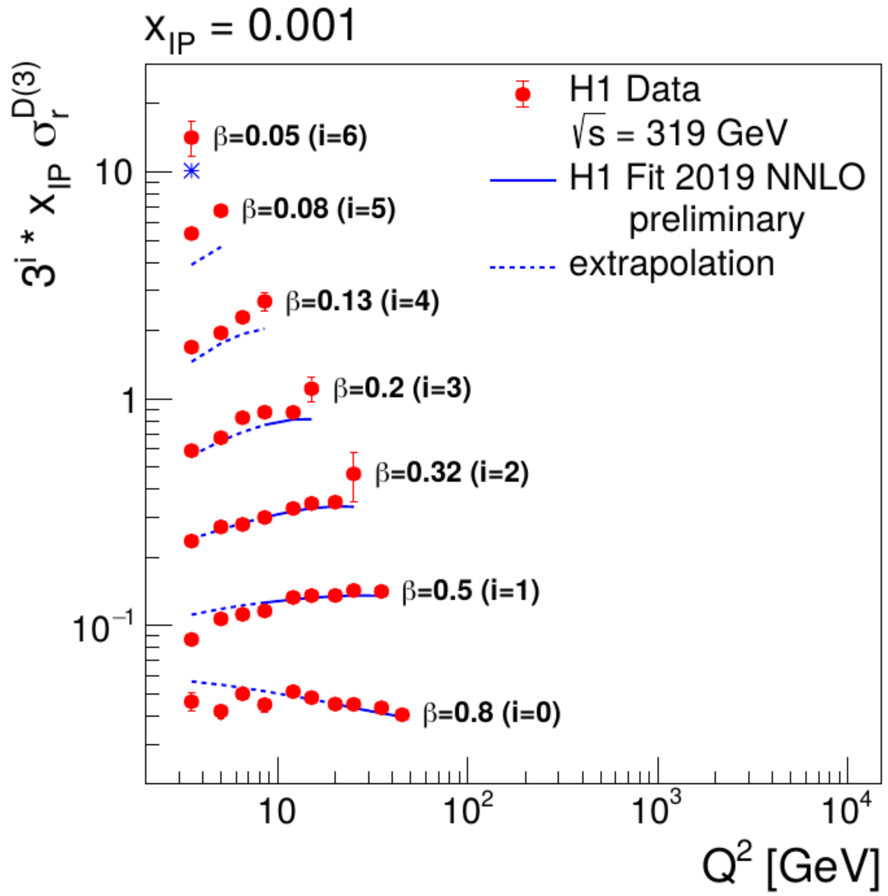


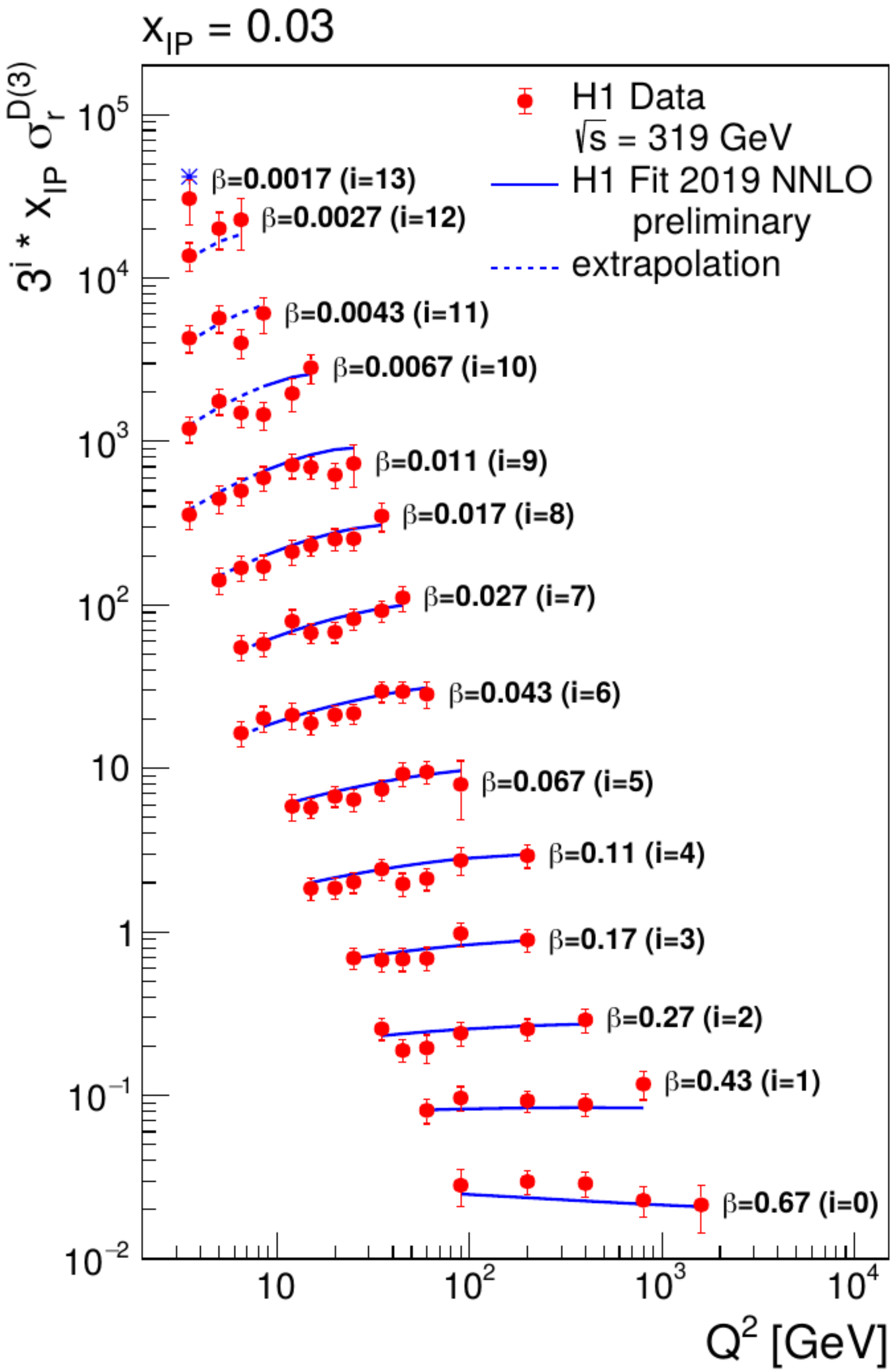
Data Set	Phase-Space	$\sqrt{s}$ [GeV]	Lumi [pb^{-1}]	χ^2/N_{pts}
H1 LRG HERA-I+II inc. combined	$8.5 < Q^2 < 1600$ GeV^2 $0.0003 < x_{I\!P} < 0.03$	319 + 300	up to 336.6	192/191
H1 LRG HERA-II inc. lowE252	$8.5 < Q^2 < 44$ GeV^2 $0.0005 < x_{I\!P} < 0.003$	252	5.2	19/12
H1 LRG HERA-II inc. lowE225		225	8.5	10/13
H1 LRG HERA-II dijets p_T^{jet1} vs Q^2 distr.	$4 < Q^2 < 100$ GeV^2 $p_T^{jet1(2)} > 5.5(4)$ GeV $x_{I\!P} < 0.03$	319	290	12/15
	+ always: $\vert t\vert < 1$ GeV^2, $M_Y < 1.6$ GeV			235/231 ndf = 223

Fit gives reasonable chi2/ndf, both the "total" and partial data set

Fitted data – Inclusive Sample (Q^2 dep.)

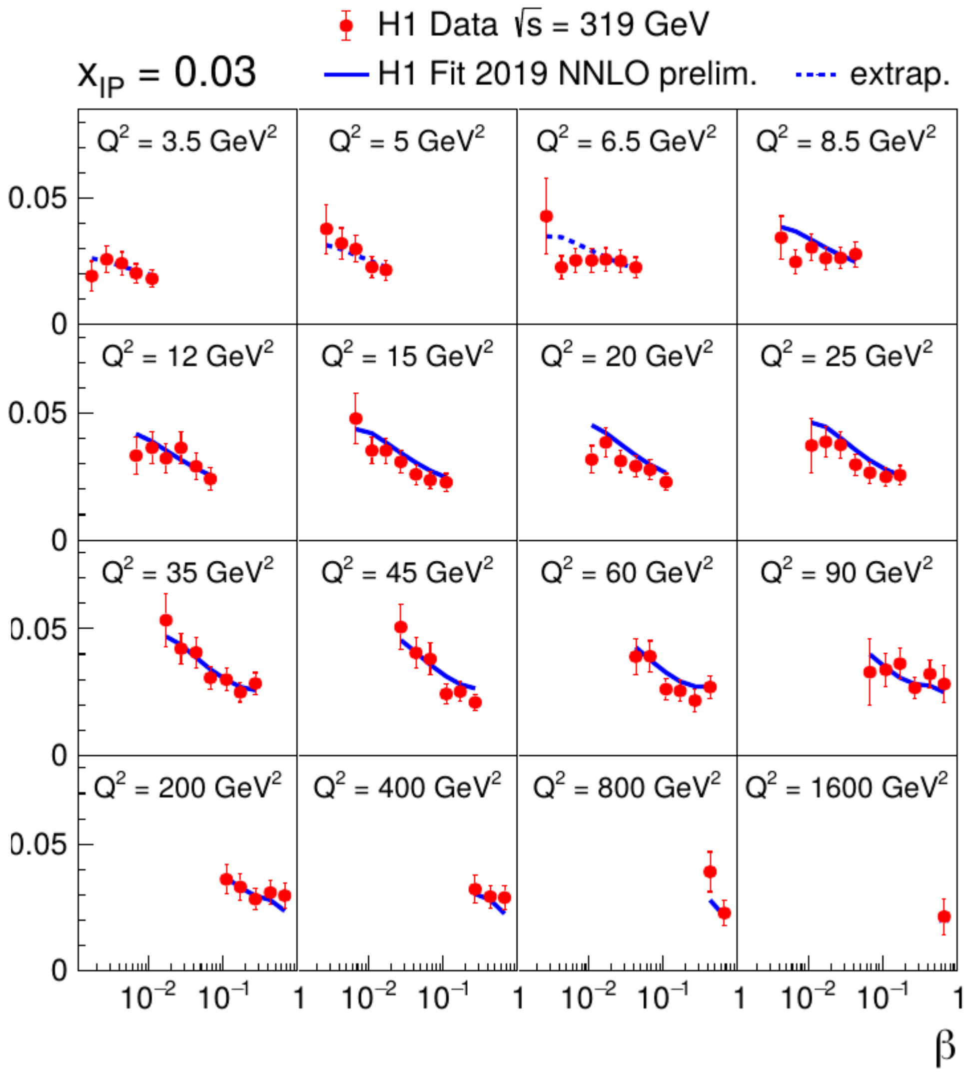
- At the nominal HERA energy ($\sqrt{s}$=319GeV) fitted combined H1 HERA I+HERA-II data x_{IP}=0.0003, 0.001, 0.003, 0.01, 0.03
- Description in "extrapolated" region Q^2 < 8.5 sometimes worse

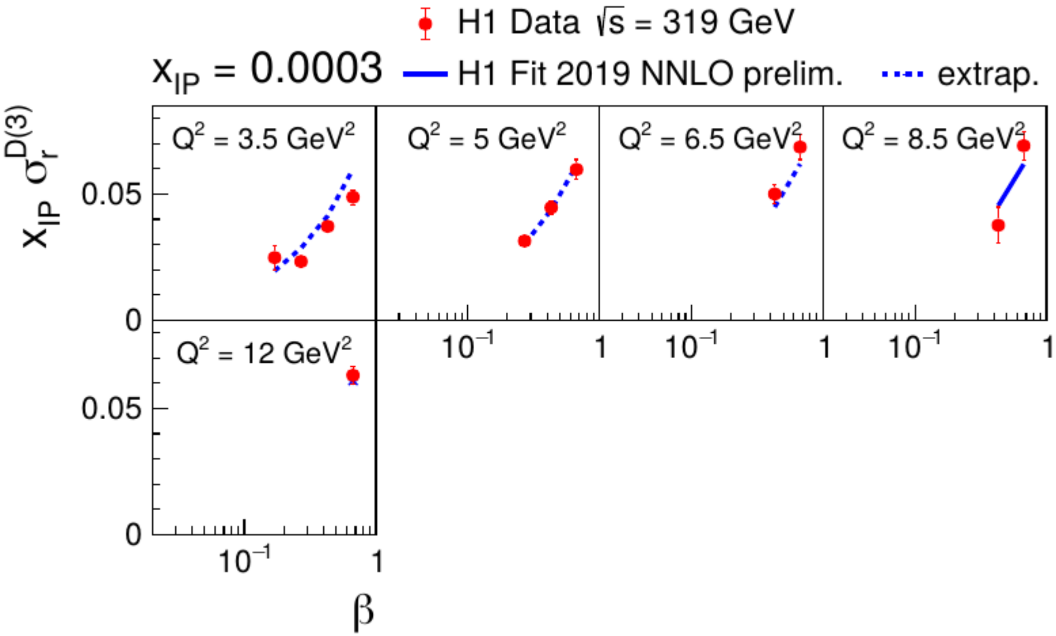




Fitted data – Inclusive Sample (β dep.)

- Good description by NNLO QCD predictions over wide range of x_{IP} and β
- At LO β is the momentum fraction parton entering hard process wrt pomeron
(argument of DPDF)





Fitted data – LowE Inclusive Sample

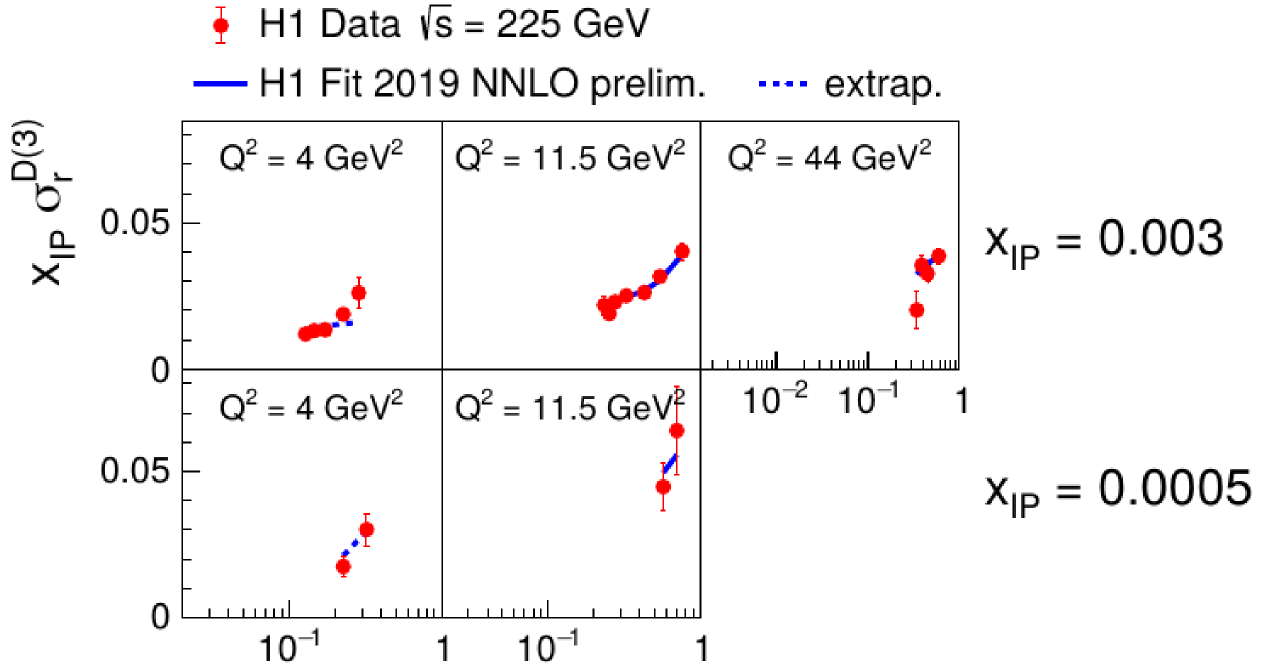
- The F_2 & F_L beam energy independent
- The reduced cross section predicted to be energy dependent:

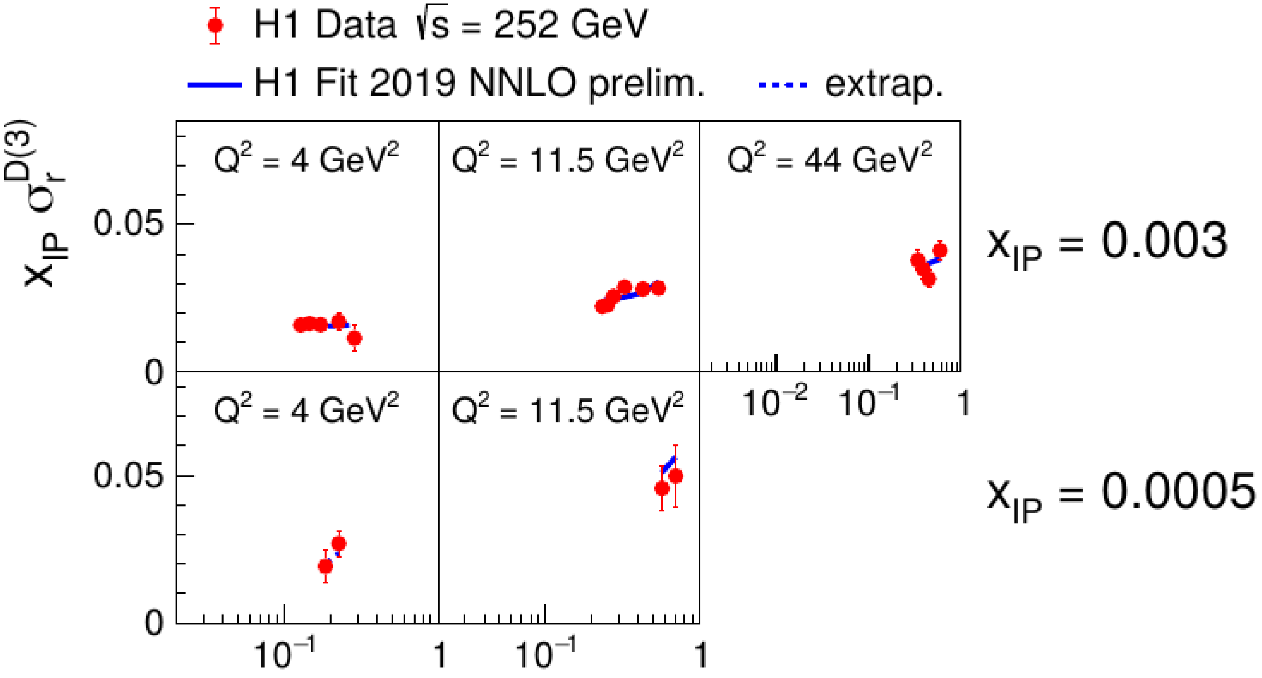
$$\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P}) =$$

$$F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

since: $$y = \frac{Q^2}{\beta x_{I\!P} s}$$

To disentangle F_2 & F_L the σ_r must be measured for several beam energies

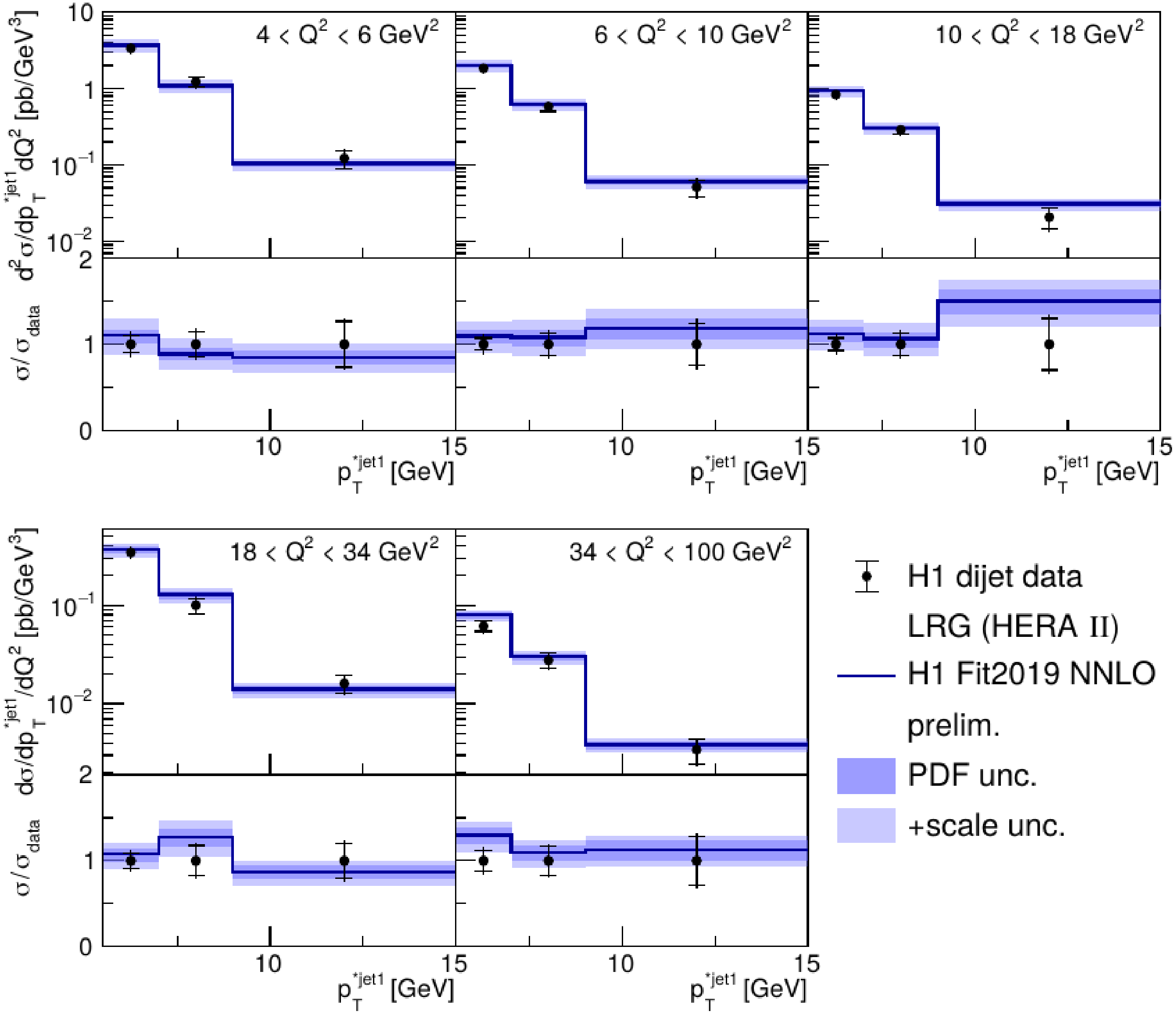




Fitted data – Jet Data

- Currently only the 2D p_T^{jet1} vs Q^2 H1 HERA-II cross sections fitted
- Shown PDF & scale uncertainty of the fit
- Good fit quality

$$\chi^2/ndf = 12/15$$

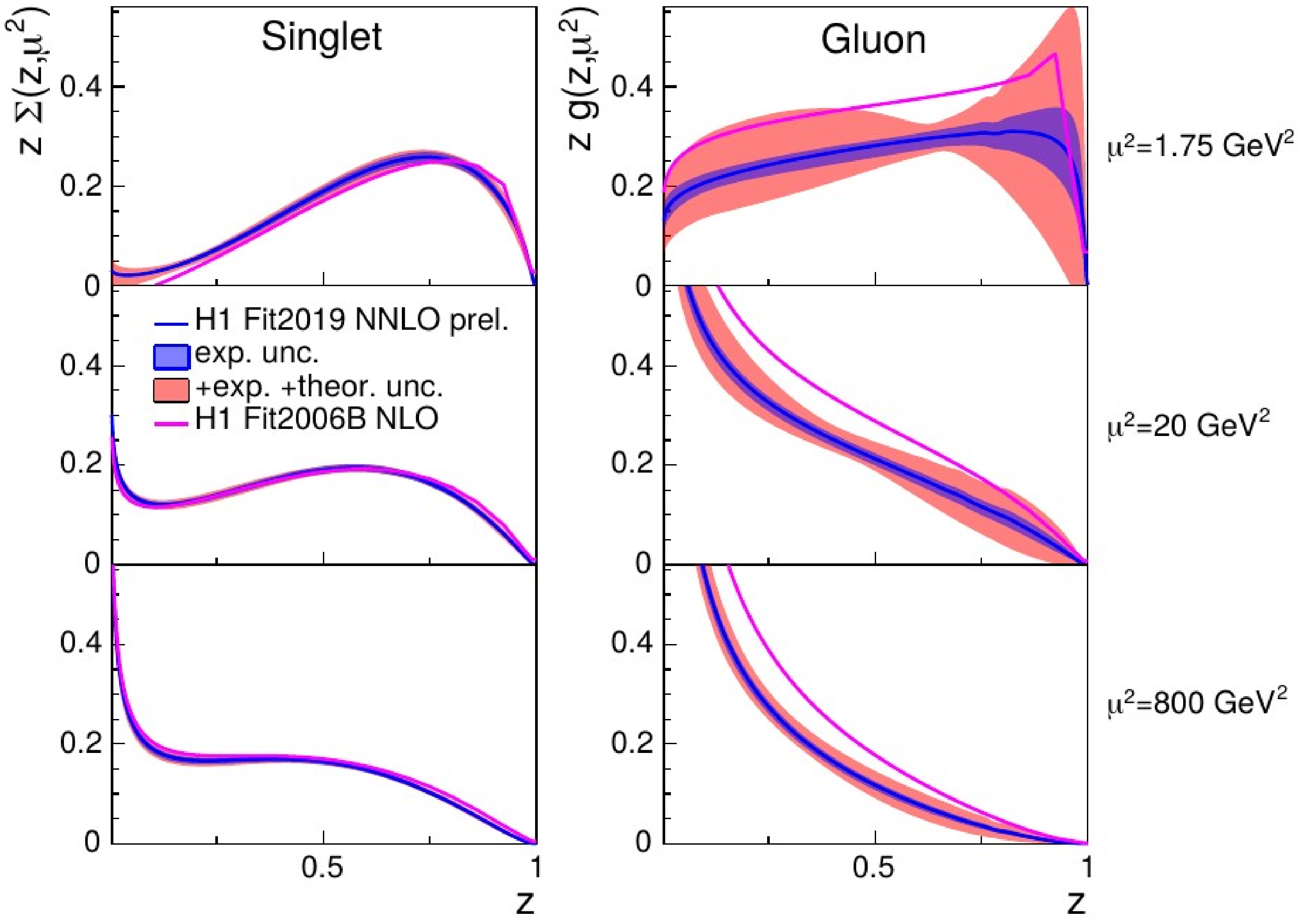


The DPDF Comparison (H1 Fit2019 NNLO vs H1 Fit2006B NLO)

- The old and new DPDFs in different QCD order & flavour scheme → comparison problematic!

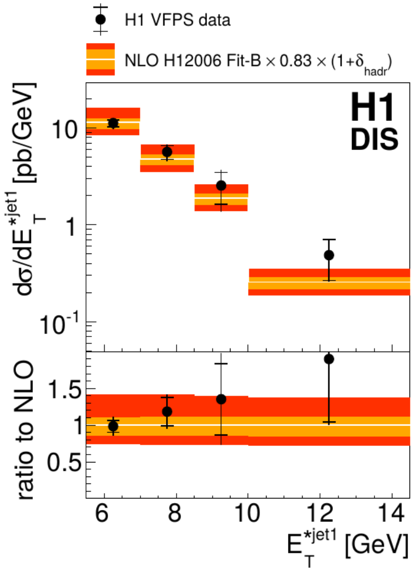
  Singlet = u + d + s (+anti-q)

- The quark single component comparable for both fits
- Gluon component of the newer fit ~25% lower

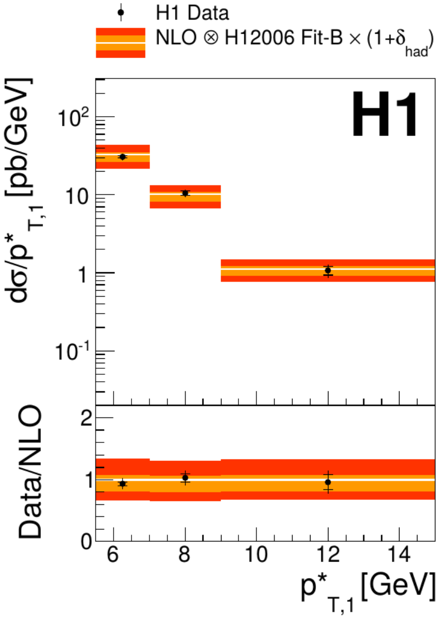


The HERA DDIS jets Legacy

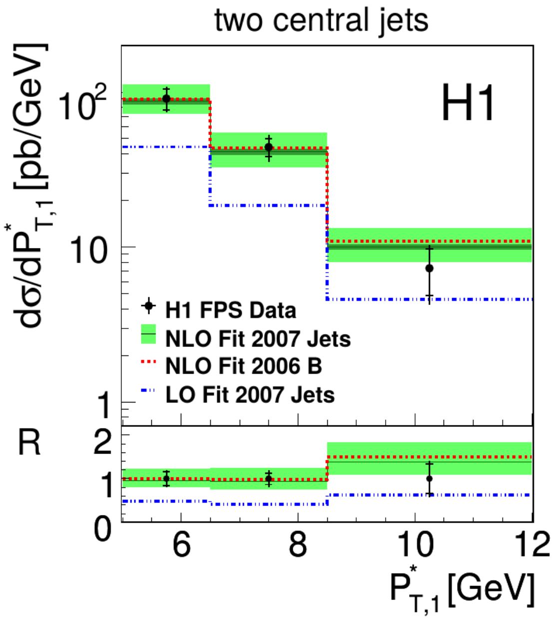
JHEP 1505 (2015) 056



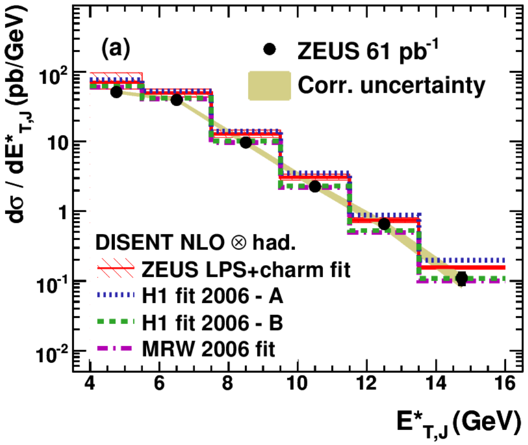
JHEP 1503 (2015) 092



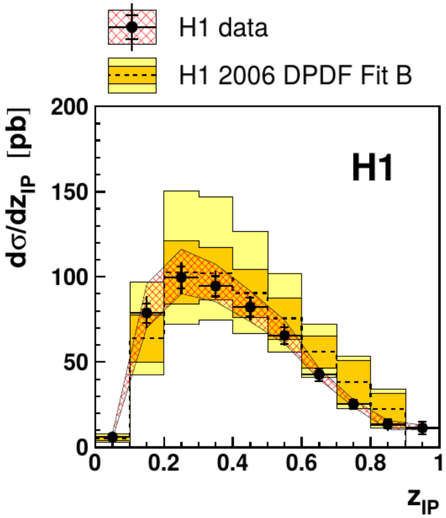
Eur.Phys.J.C72 (2012) 1970



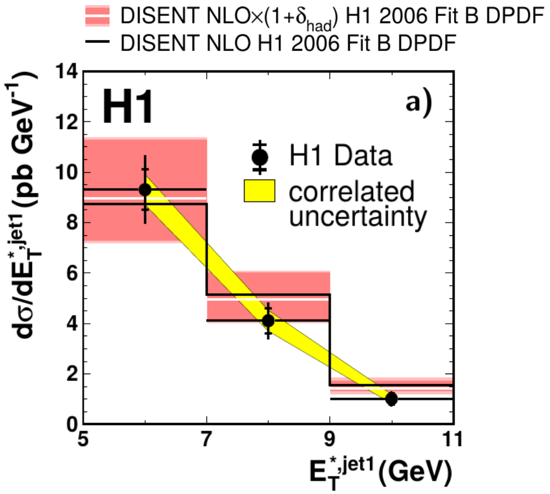
Eur. Phys. J. C 52 (2007) 813-832



JHEP 0710:042,2007



Eur.Phys.J.C 51 (2007) 549



The DDIS HERA dijets measurements

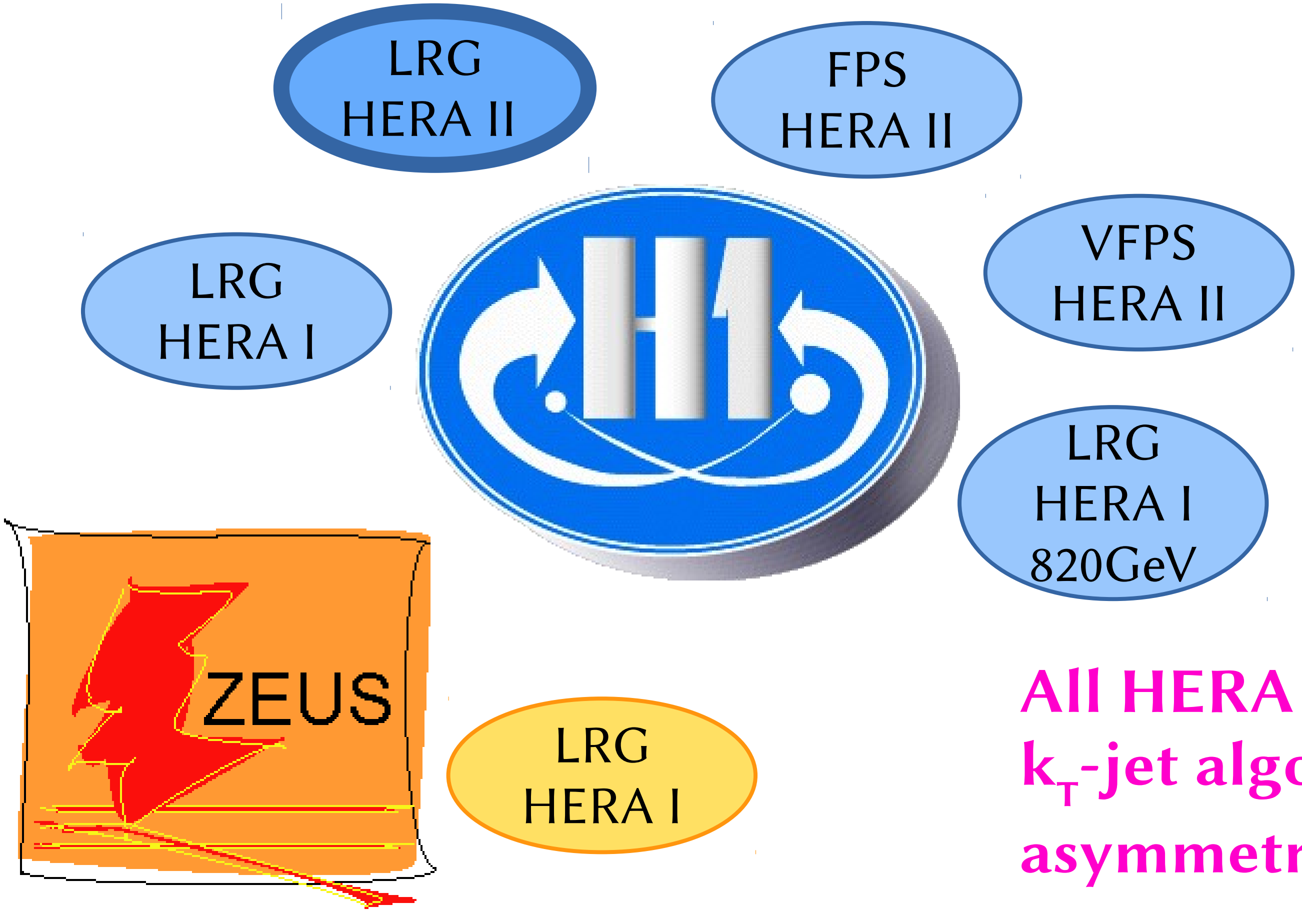
- 5times e+p 27.6 GeV + 920 GeV
  1times e+p 27.5 GeV + 820 GeV
- 4times Large Rapidity Gap selection (LRG)
  2times Proton Spectrometer (FPS, VFPS)

H1 LRG HERA II Phase Space

$$4 < Q^2 < 100 \text{ GeV}^2$$
$$0.1 < y < 0.7$$

$$x_{\mathbb{P}} < 0.03$$
$$|t| < 1 \text{ GeV}^2$$
$$M_Y < 1.6 \text{ GeV}$$

$$p^*_{T,1} > 5.5 \text{ GeV}$$
$$p^*_{T,2} > 4.0 \text{ GeV}$$
$$-1 < \eta^{lab}_{1,2} < 2$$

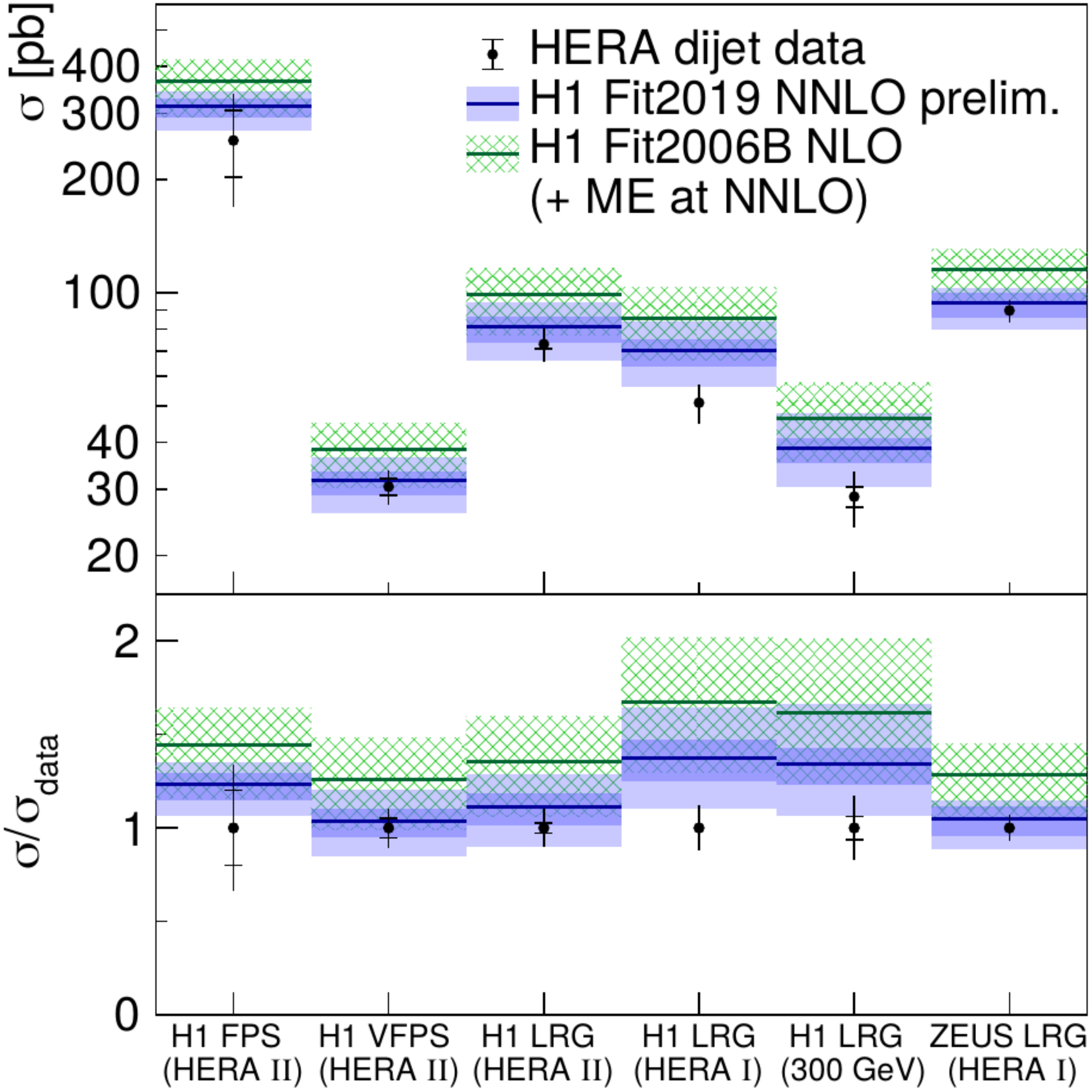


All HERA analyses are using k_T-jet algorithm (R=1) and asymmetric jet p_T cuts

Total Dijet Cross Sections

- **H1 Fit2019 NNLO** ⟶ describes well the H1 HERA-II data + ZEUS HERA-I ⟶ H1 HERA-I data slightly below
- **H1 Fit2006B NLO** with NNLO ME overestimates all the cross sections

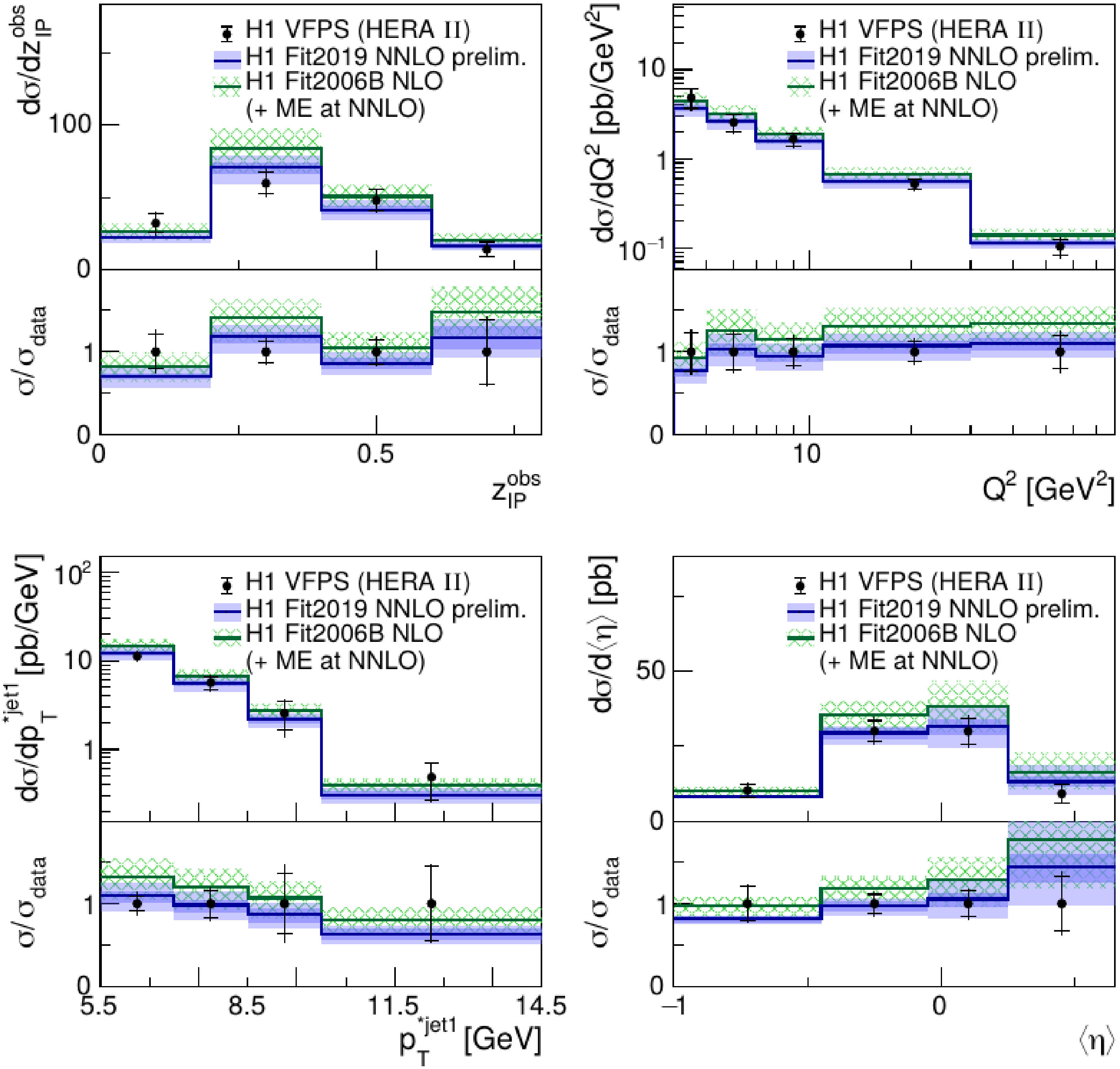
In addition to the total cross sections we analyzed
39 single-differential and
4 double-differential distributions



Dijet cross sections (H1 VFPS)

- The data based on Very Forward Proton Spectrometer (VFPS) do not contain any proton dissociation and are in many ways systematically independent to the LRG-based data

- Good description of the kinematic variables z_{IP}, Q^2, p_T^{jet1}, $<\eta>$

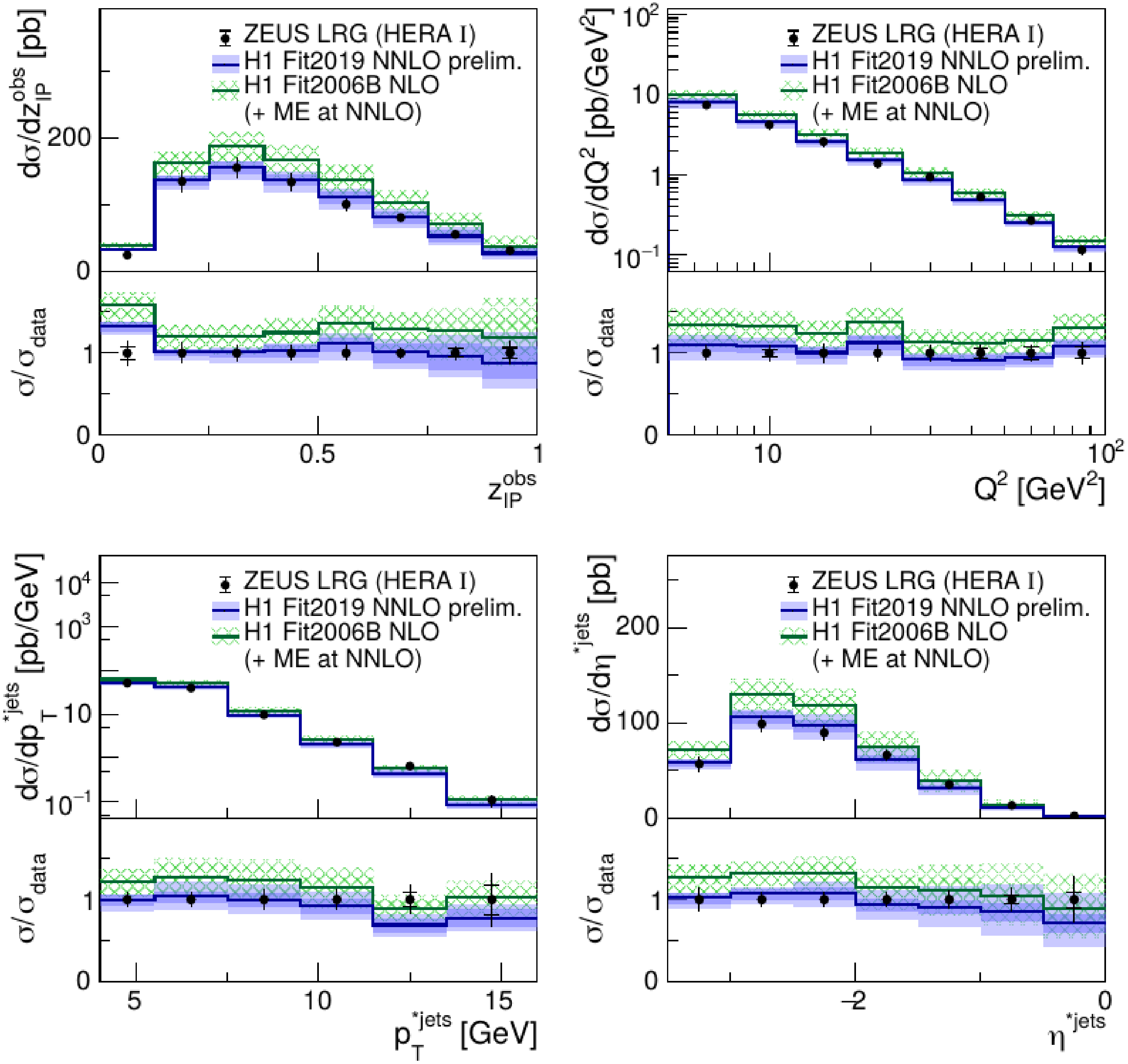


Dijet cross sections (ZEUS LRG)

- The H1 Fit2019 NNLO based predictions agree well with the ZEUS dijet data [arXiv:0708.1415]

- At LO the $z_{I\!P}^{\text{obs}}$ directly related to the pomeron momentum fraction entering ME

$$z_{I\!P}^{\text{obs}} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$



Conclusions

- First combined fit to the inclusive+jet DDIS DATA at NNLO
- The NNLO DPDF has lower gluon contribution compared to NLO version
- The jet data compatible with new inclusive data (at both NNLO and NLO)
  → *Factorization in diffractive DDIS up to NNLO established*

Outlook:

- Release the fit at LO, NLO & NNLO
- Include possible extra jet observables to the fit
- FPS data?

Backup

NNLO QCD Predictions

- **NNLOJET** program based on antenna subtraction
  J. Currie, T. Gehrmann, A. Huss and J. Niehues, JHEP 07 (2017) 018, [1703.05977]

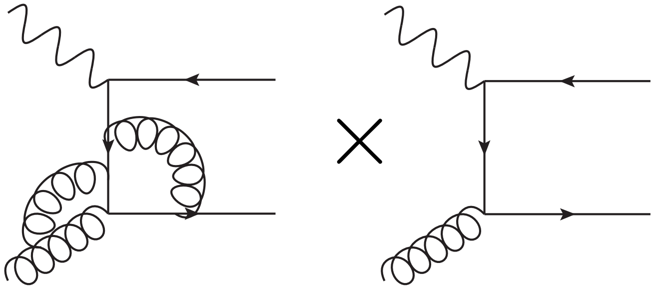
$$\mathrm{d}\sigma(ep \to epX) = \sum_{i,n} \mathrm{d}\sigma^{ie(n)}(x, Q^2) \otimes \alpha_S^n \otimes f_i^D(x, Q^2, x_{IP}, t)$$

Cookbook

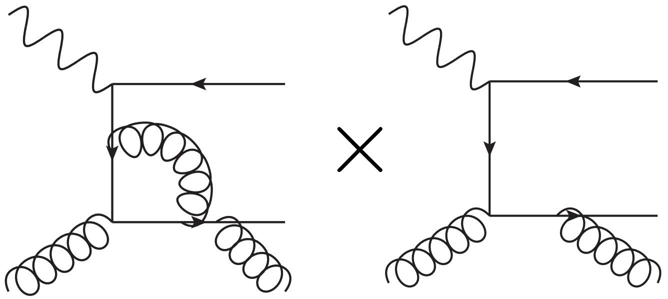
1) The matrix element tables precalculated by **NNLOJET** program (~1M CPU hours)
2) Then convoluted with DPDFs and α_S using **fastNLO** (<1s)

✓ The NLO 2jet and 3jet contributions verified against Sherpa and NLOJET++

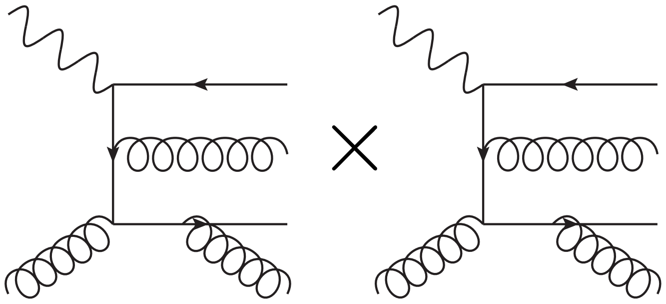
virtual-virtual



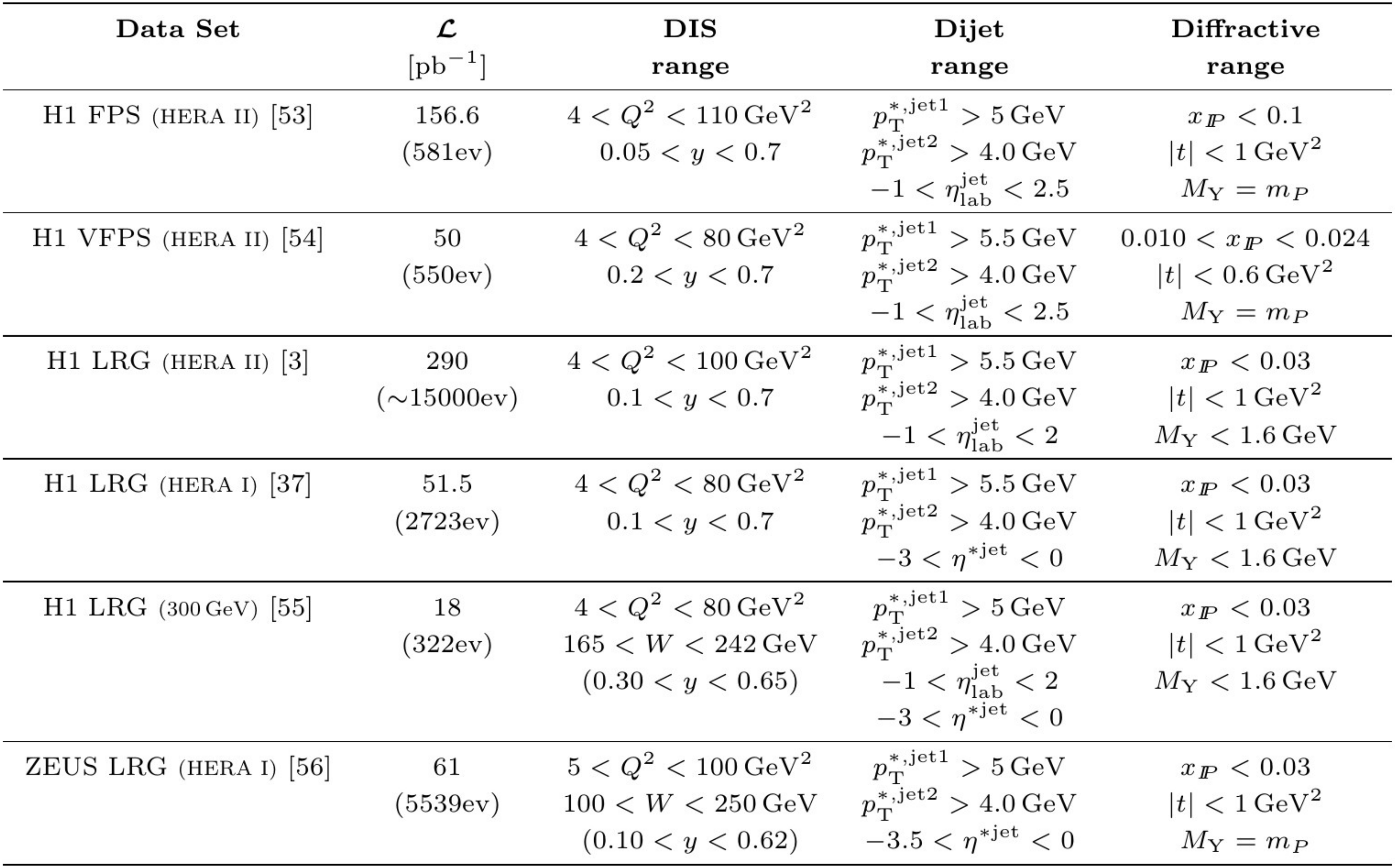
real-virtual



real-real



Backup



Data Set	$\mathcal{L}$ [pb^{-1}]	DIS range	Dijet range	Diffractive range
H1 FPS (HERA II) [53]	156.6 (581ev)	$4 < Q^2 < 110\,\mathrm{GeV}^2$ $0.05 < y < 0.7$	$p_\mathrm{T}^{*,\mathrm{jet1}} > 5\,\mathrm{GeV}$ $p_\mathrm{T}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-1 < \eta_\mathrm{lab}^\mathrm{jet} < 2.5$	$x_{I\!P} < 0.1$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_\mathrm{Y} = m_P$
H1 VFPS (HERA II) [54]	50 (550ev)	$4 < Q^2 < 80\,\mathrm{GeV}^2$ $0.2 < y < 0.7$	$p_\mathrm{T}^{*,\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $p_\mathrm{T}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-1 < \eta_\mathrm{lab}^\mathrm{jet} < 2.5$	$0.010 < x_{I\!P} < 0.024$ $\lvert t\rvert < 0.6\,\mathrm{GeV}^2$ $M_\mathrm{Y} = m_P$
H1 LRG (HERA II) [3]	290 (∼15000ev)	$4 < Q^2 < 100\,\mathrm{GeV}^2$ $0.1 < y < 0.7$	$p_\mathrm{T}^{*,\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $p_\mathrm{T}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-1 < \eta_\mathrm{lab}^\mathrm{jet} < 2$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_\mathrm{Y} < 1.6\,\mathrm{GeV}$
H1 LRG (HERA I) [37]	51.5 (2723ev)	$4 < Q^2 < 80\,\mathrm{GeV}^2$ $0.1 < y < 0.7$	$p_\mathrm{T}^{*,\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $p_\mathrm{T}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-3 < \eta^{*\mathrm{jet}} < 0$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_\mathrm{Y} < 1.6\,\mathrm{GeV}$
H1 LRG (300 GeV) [55]	18 (322ev)	$4 < Q^2 < 80\,\mathrm{GeV}^2$ $165 < W < 242\,\mathrm{GeV}$ $(0.30 < y < 0.65)$	$p_\mathrm{T}^{*,\mathrm{jet1}} > 5\,\mathrm{GeV}$ $p_\mathrm{T}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-1 < \eta_\mathrm{lab}^\mathrm{jet} < 2$ $-3 < \eta^{*\mathrm{jet}} < 0$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_\mathrm{Y} < 1.6\,\mathrm{GeV}$
ZEUS LRG (HERA I) [56]	61 (5539ev)	$5 < Q^2 < 100\,\mathrm{GeV}^2$ $100 < W < 250\,\mathrm{GeV}$ $(0.10 < y < 0.62)$	$p_\mathrm{T}^{*,\mathrm{jet1}} > 5\,\mathrm{GeV}$ $p_\mathrm{T}^{*,\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-3.5 < \eta^{*\mathrm{jet}} < 0$	$x_{I\!P} < 0.03$ $\lvert t\rvert < 1\,\mathrm{GeV}^2$ $M_\mathrm{Y} = m_P$