Perturbative QCD at HERA

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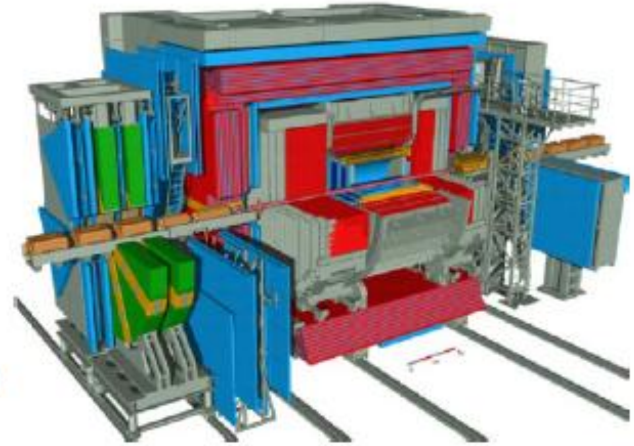
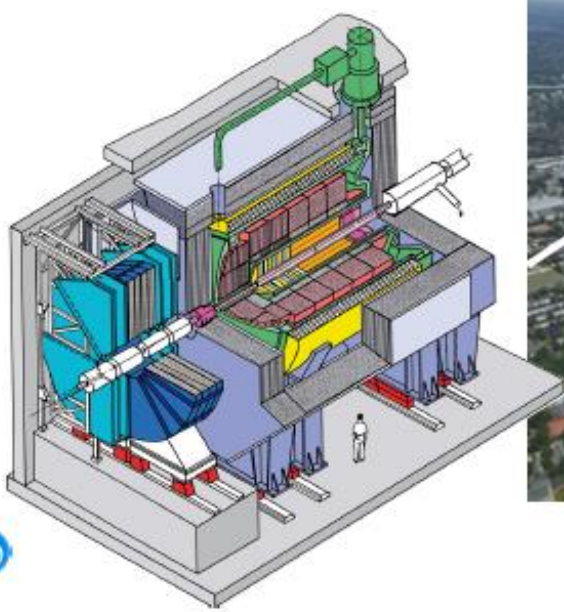
Outline : **QCD explorer HERA**
Proton structure
Jets and α_s
Prompt photons
Heavy quark production and masses
Summary & Prospects

Back-up : **some details on above**
ratio of $D^{*\pm}$ PhP x-sections at different $\sqrt{s}$
charged particle spectra in DIS

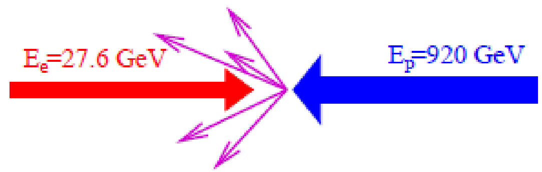
The HERA ep collider (1992 - 2007)

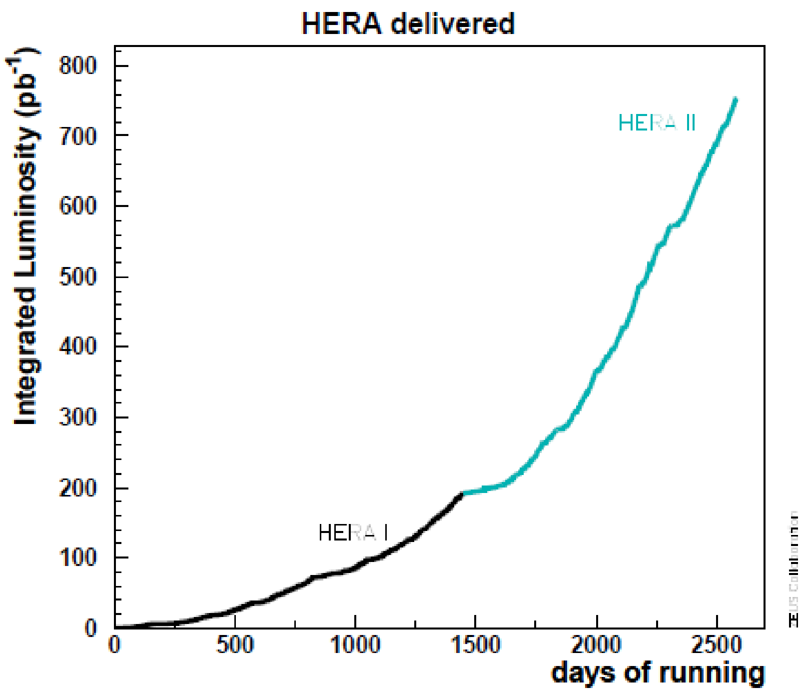
- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Center of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 fb^{-1} (per experiment)





QCD explorer HERA





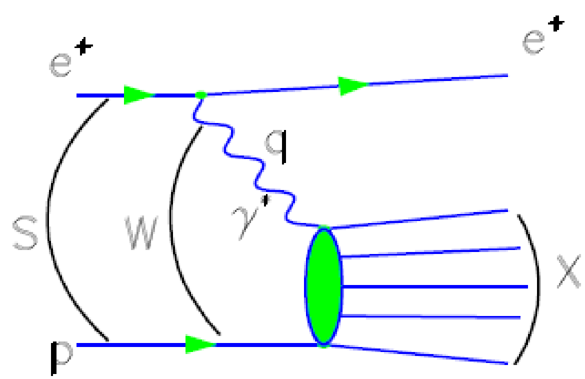
	HERA	HERA II
	1992-2000	2003-2007
$\sqrt{s}$	320 (300)	320 GeV
$\mathcal{L}$	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31}\, cm^{-2}\, s^{-1}$
$\mathcal{L}_{int}$	0.13	$0.37\, fb^{-1}$

$$e(k) + p(P) \to e(k') + X \qquad s = (P+k)^2$$

$$Q^2 = -q^2 = -(k-k')^2$$

Photoproduction $Q^2 \simeq 0\, GeV^2$

DIS $Q^2 > 1\, GeV^2$



$$W^2 = (P+q)^2$$

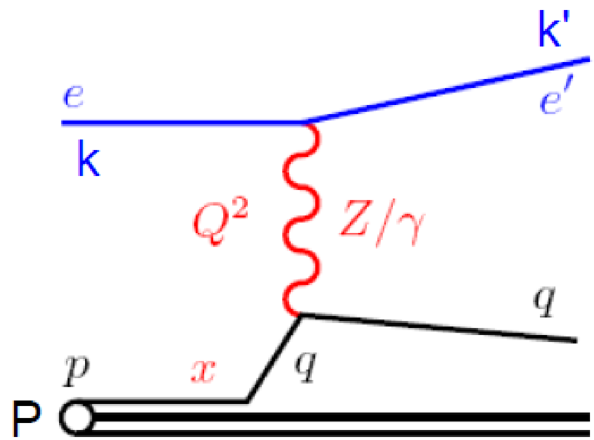
$$y = \frac{qP}{kP} \cong \frac{W^2+Q^2}{s}$$

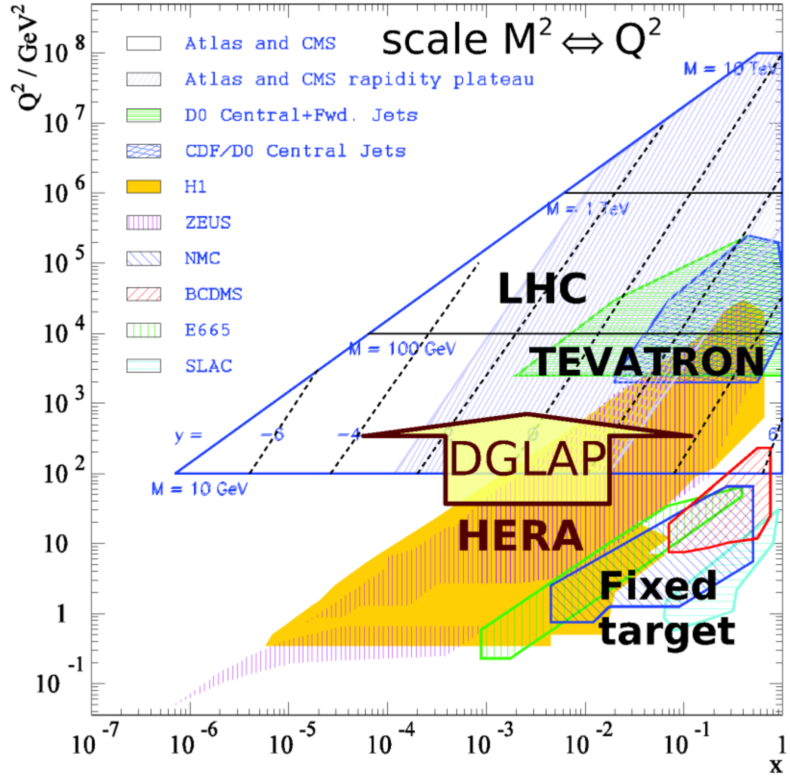
$$x = \frac{Q^2}{2qP} \cong \frac{Q^2}{sy}$$

$\sigma_{c\bar{c}} \approx\ 1\,\mu\text{b} \Longrightarrow 10^9$ events $(\mathcal{L}_{int} = 1\, fb^{-1})$

$\sigma_{b\bar{b}} \approx 10\,\text{nb} \Longrightarrow 10^7$ events $(\mathcal{L}_{int} = 1\, fb^{-1})$

Proton Structure





At moderate Q^2

reduced cross section	cross section measurement	structure functions

$$\tilde{\sigma}_{NC}(x, Q^2, y) = \frac{d^2\sigma^{ep}_{NC}}{dx dQ^2} \cdot \frac{xQ^4}{2\pi\alpha Y_+} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

$$Y_+ = 1 + (1-y)^2$$

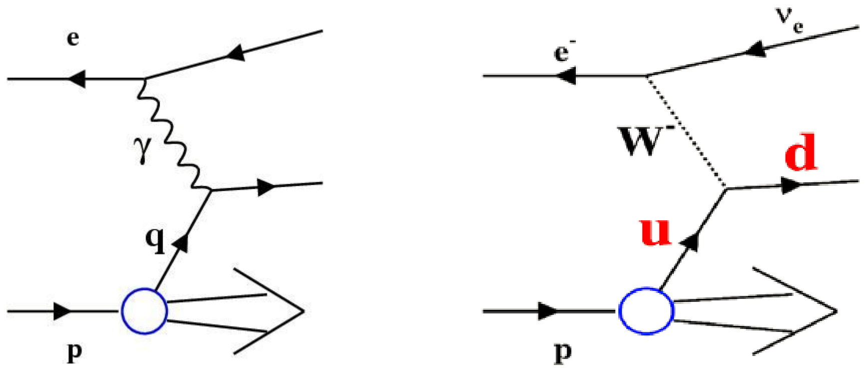
In QPM: $F_2(x, Q^2) = \sum e^2_{q_i} x(q_i + \bar{q}_i)$ Total quark content

$F_L(x, Q^2) = F_2 - 2xF_1 = 0$ Callan-Gross relation

In QCD: add particle to carry angular momentum, gluon is needed

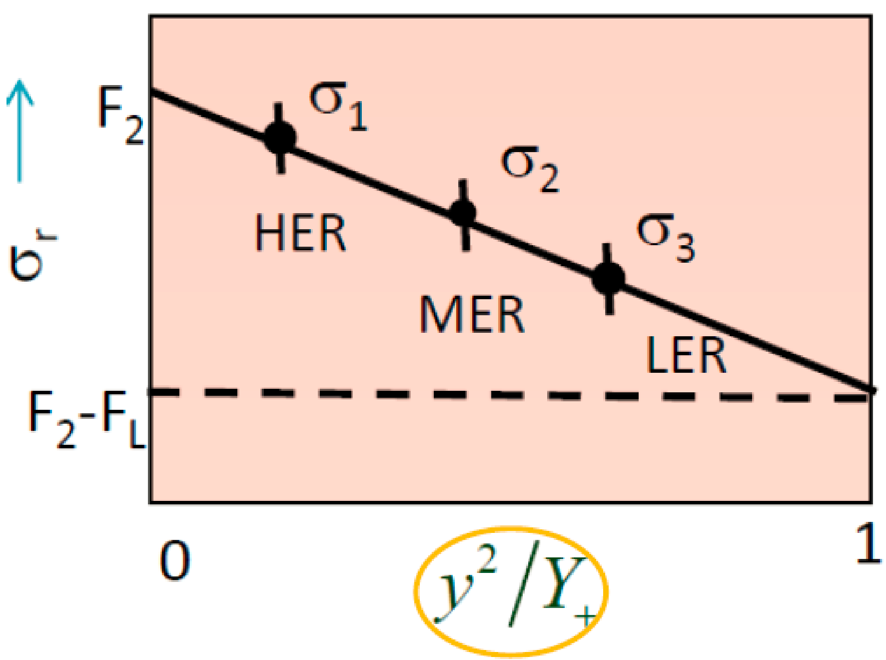
$$F_L(x, Q^2) = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum_q e_q^2 (1 - \frac{x}{z}) \cdot xg \right]$$

Proton Structure



- 21 HERA I data samples
- 20 HERA II data samples, including:
  - 8 inclusive HERA II E_p = 920 GeV
  - 4 FL data E_p = 920 GeV
  - 4 FL data E_p = 575 GeV
  - 4 FL data E_p = 460 GeV

- Bulk of HERA data: Ep=920 GeV (HER)
- Ep=460 GeV (LER) and Ep=575 (MER) data taken in 2007



$$\sigma_{r,NC} = F_2 - \frac{y^2}{Y_+} F_L$$

Straight line fit:

F_2 = Intercept

F_L = Negative slope

HERAPDF 1.0, 1.5, 2.0

HERAPDF1.0

HERAPDF1.5

HERAPDF2.0 (prel.)

H1prelim-14-041(2)
ZEUS-prel-14-005(7)

Data Set		x Grid from	x Grid to	Q^2/GeV^2 Grid from	Q^2/GeV^2 Grid to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
HERA I E_p = 820 GeV and E_p = 920 GeV data sets								
H1 svx-mb	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319
H1 low Q^2	96-00	0.0002	0.1	12	150	22	e^+p	301, 319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300
ZEUS NC	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318
HERA II E_p = 920 GeV data sets								
H1 NC	03-07	0.0008	0.65	60	30000	182	e^+p	319
H1 CC	03-07	0.008	0.40	300	15000	182	e^+p	319
H1 NC	03-07	0.0008	0.65	60	50000	151.7	e^-p	319
H1 CC	03-07	0.008	0.40	300	30000	151.7	e^-p	319
H1 NC med Q^2	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319
H1 NC low Q^2	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318
ZEUS CC	06-07	0.0078	0.42	280	30000	132	e^+p	318
ZEUS NC	05-06	0.005	0.65	200	30000	169.9	e^-p	318
ZEUS CC	04-06	0.015	0.65	280	30000	175	e^-p	318
ZEUS NC nominal	06-07	0.000092	0.008343	7	110	44.5	e^+p	318
ZEUS NC satellite	06-07	0.000071	0.008343	5	110	44.5	e^+p	318
HERA II E_p = 575 GeV data sets								
H1 NC high Q^2	07	0.00065	0.65	35	800	5.4	e^+p	252
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251
HERA II E_p = 460 GeV data sets								
H1 NC high Q^2	07	0.00081	0.65	35	800	11.8	e^+p	225
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225

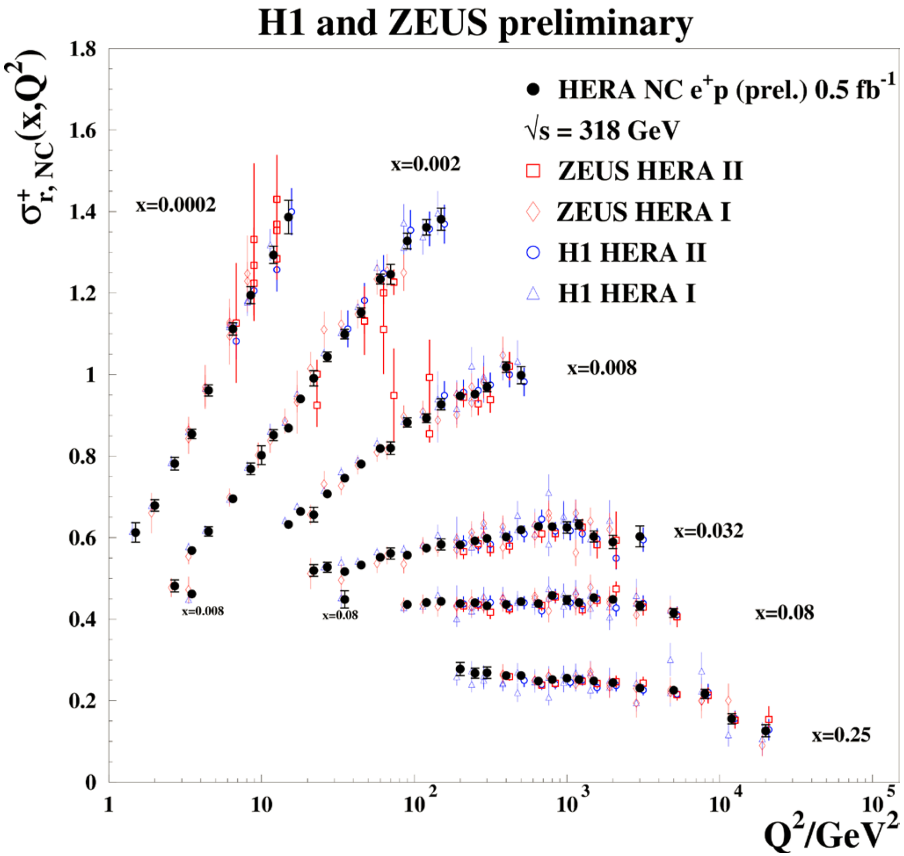
Full HERA I data

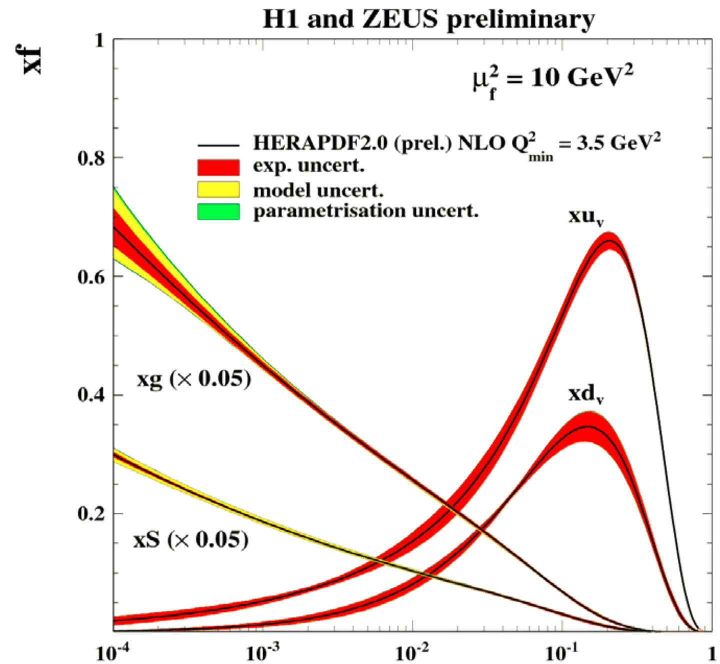
HERA II data HER

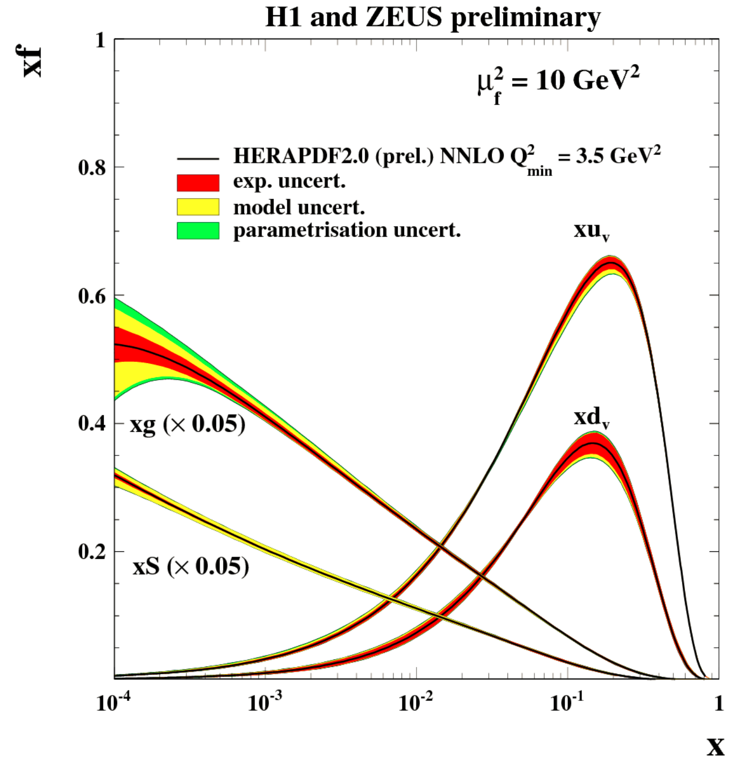
HERA II data LER

- All results are final and published!

HERAPDF 2.0



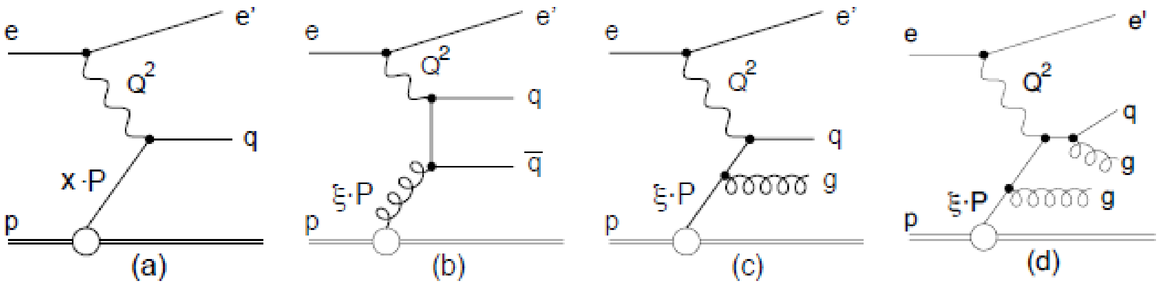




~1% for 20 < Q^2 < 100 GeV^2

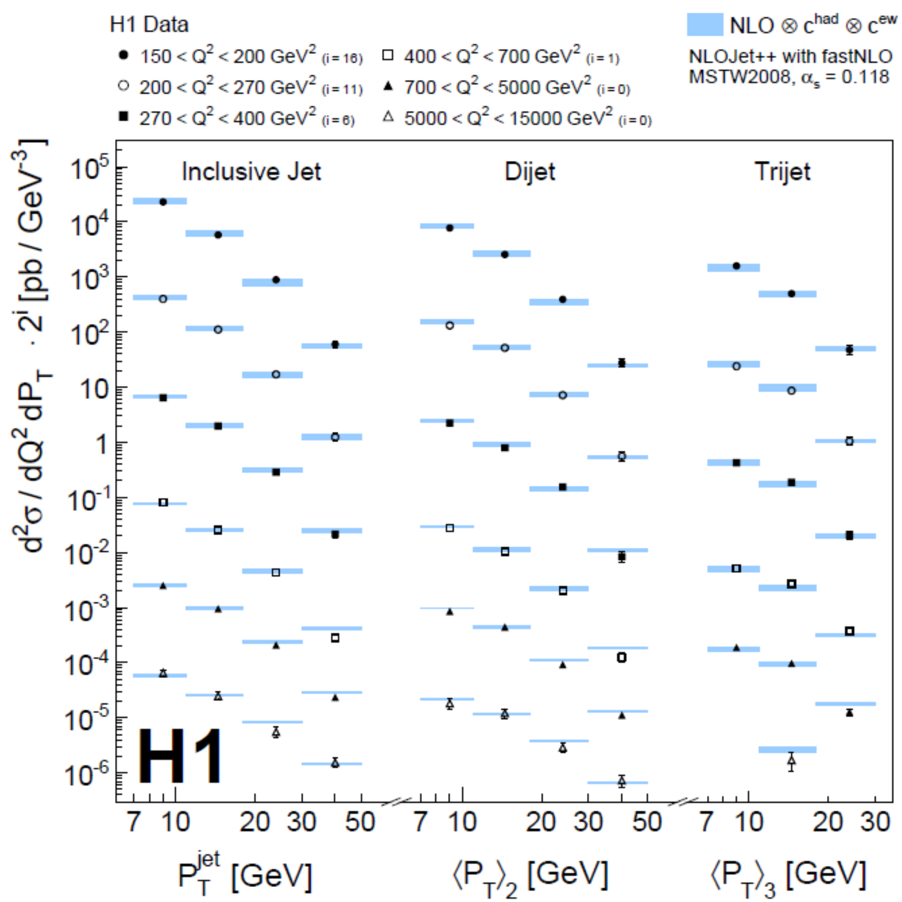
Multijet Production and α_s extraction

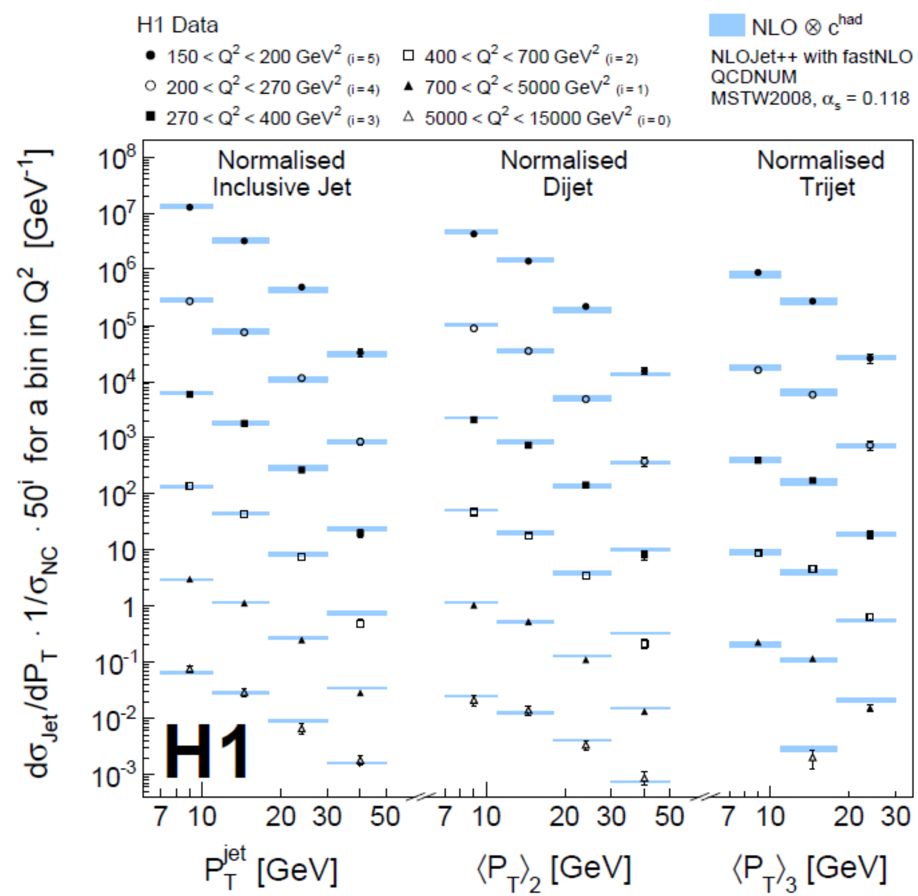
DESY 14-089
June 2014



$150 < Q^2 < 15\,000$ GeV²
$0.2 < y < 0.7$

$$\mu_r^2 = (Q^2 + P_T^2)/2 \text{ and } \mu_f^2 = Q^2$$





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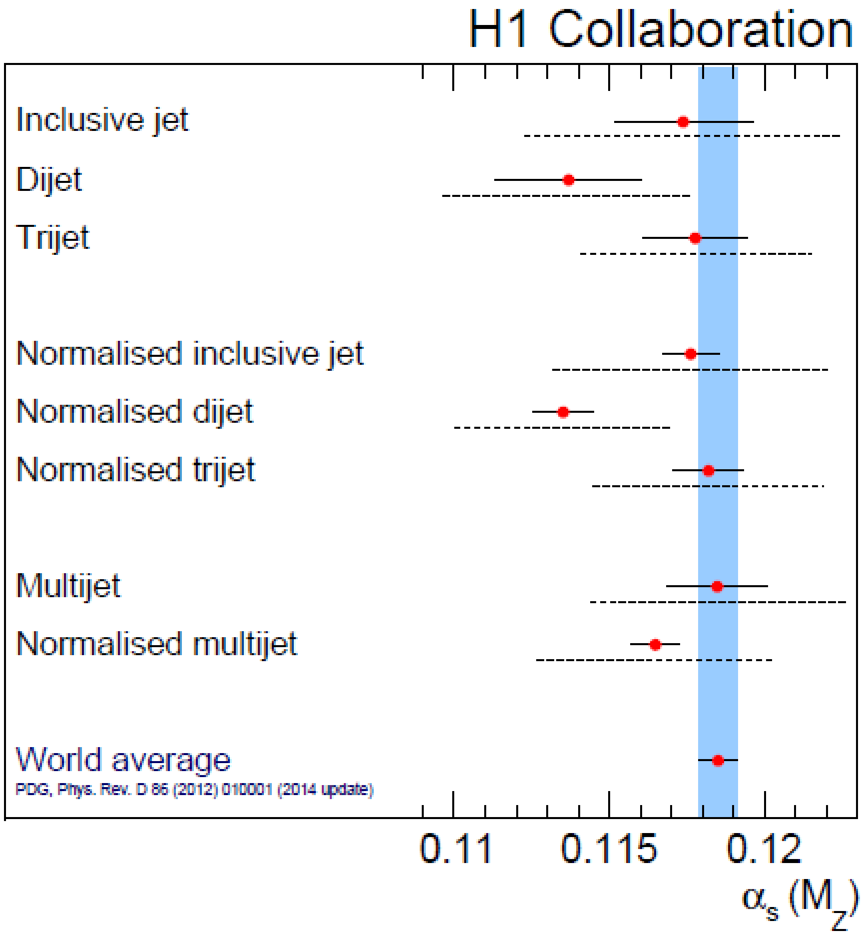
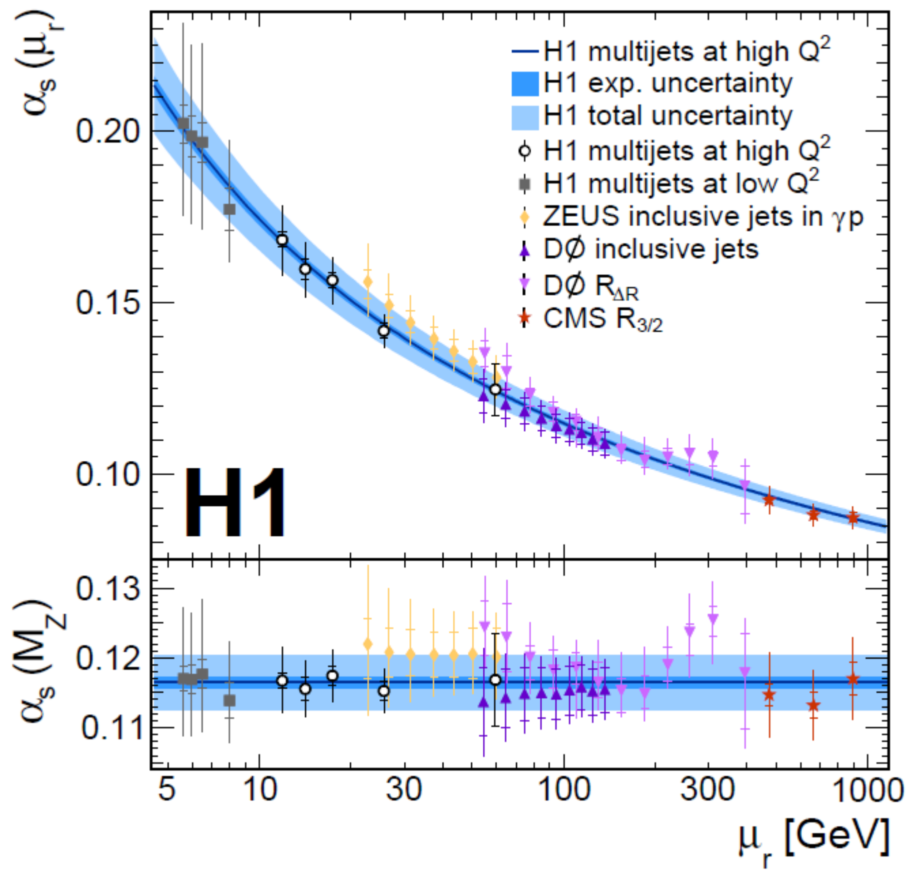




$\alpha_s = 0.1165 \pm 0.0008_{exp} \pm 0.0038_{theo}$

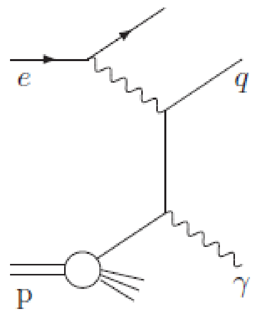
For $Q^2 > 400$ GeV^2 :

$$\alpha_s(M_Z)|_{k_T} = 0.1165\ (8)_{\rm exp}\ (5)_{\rm PDF}\ (7)_{\rm PDFset}\ (3)_{\rm PDF(\alpha_s)}\ (8)_{\rm had}\ (36)_{\mu_r}\ (5)_{\mu_f}$$
$$= 0.1165\ (8)_{\rm exp}\ (38)_{\rm pdf,theo}\ .$$

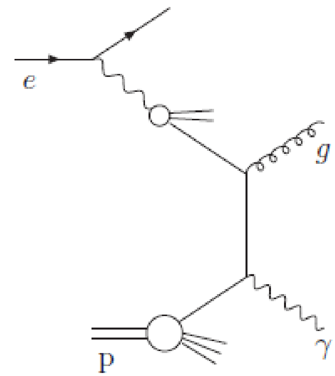
$$\alpha_s(M_Z)|_{k_T} = 0.1160\ (11)_{\rm exp}\ (32)_{\rm pdf,theo}$$

Prompt photons in photoproduction

direct



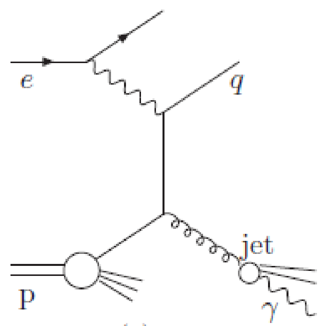
(a)



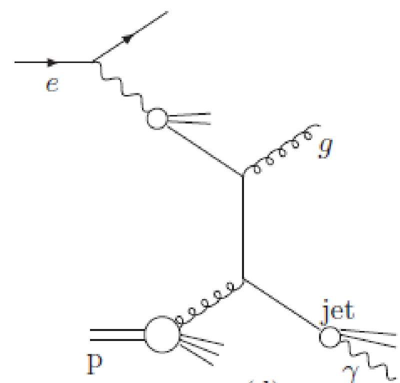
(b)

resolved

direct,
fragmentation

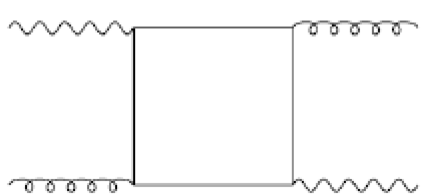


(c)



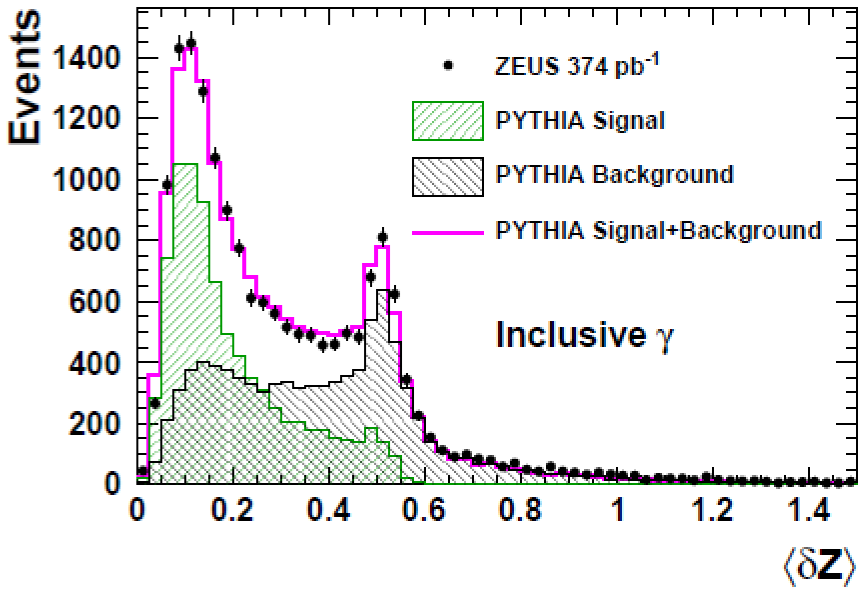
(d)

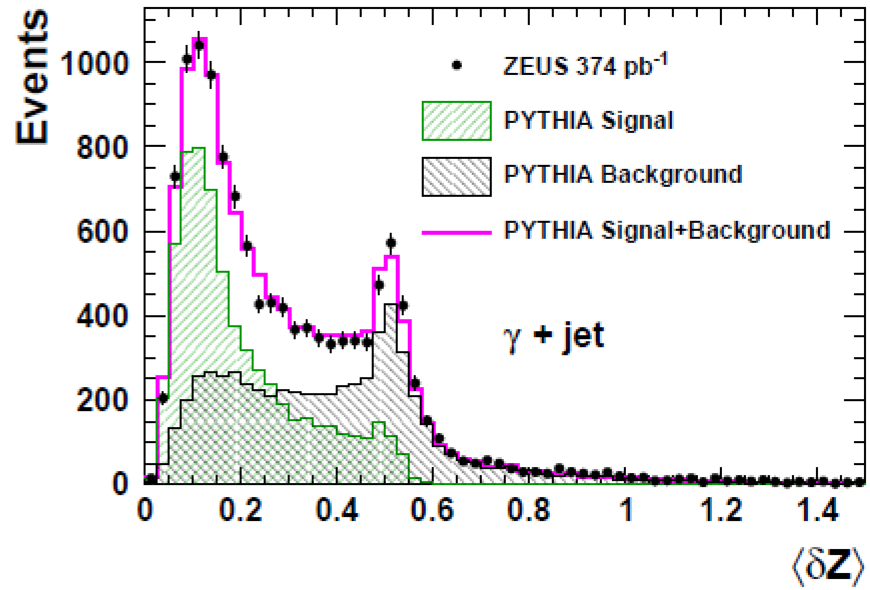
resolved,
fragmentation



box diagram

Extraction of Photon Signals



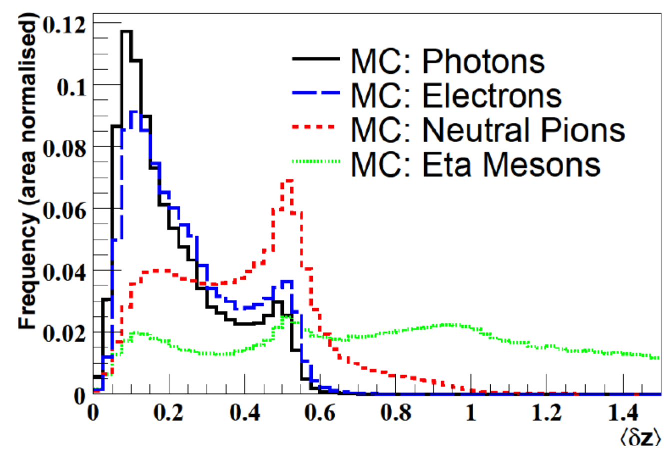


$$< \delta Z > = \frac{\sum_i E_i |Z_i - Z_{cluster}|}{w_{cell} \sum_i E_i}$$

E_T-weighted mean of $|Z_{CELL} - Z_{Mean}|$

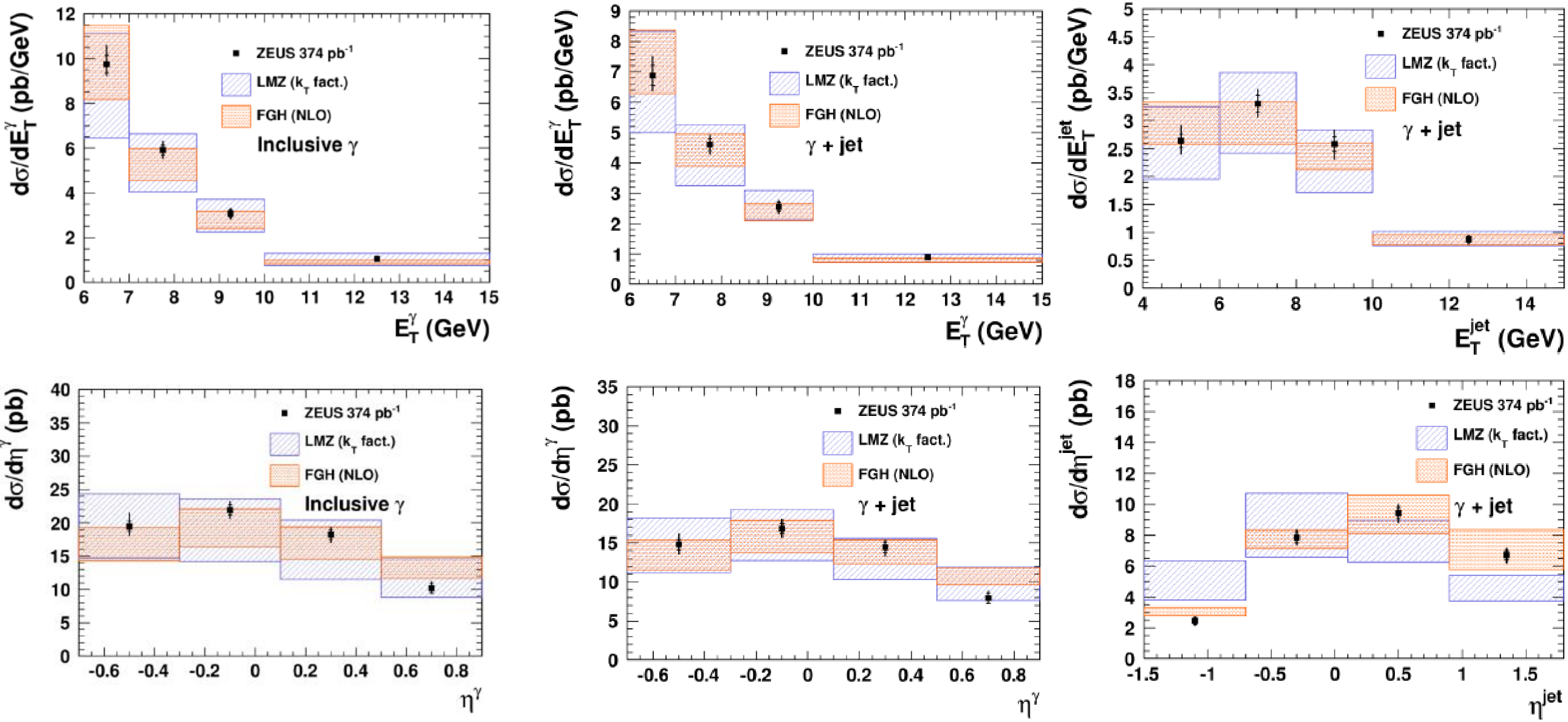
Phys. Lett. B730 (2014) 293

ArXiv 1405.7127



$\pi_0 \to \gamma\gamma$ (98.8 %)
$\eta \to \gamma\gamma$ (39.3 %)
$\eta \to \pi_0\pi_0\pi_0$ (32.6 %)

Prompt photon Cross Sections



fixed order calculations

- by M. Fontannaz, J.Ph. Guillet and G. Heinrich Eur. Phys. J. C 21 (2001) 303, Eur. Phys. J. C 34 (2004) 191 (FGH)

- components:

▷ direct direct, ▷ direct fragmentation

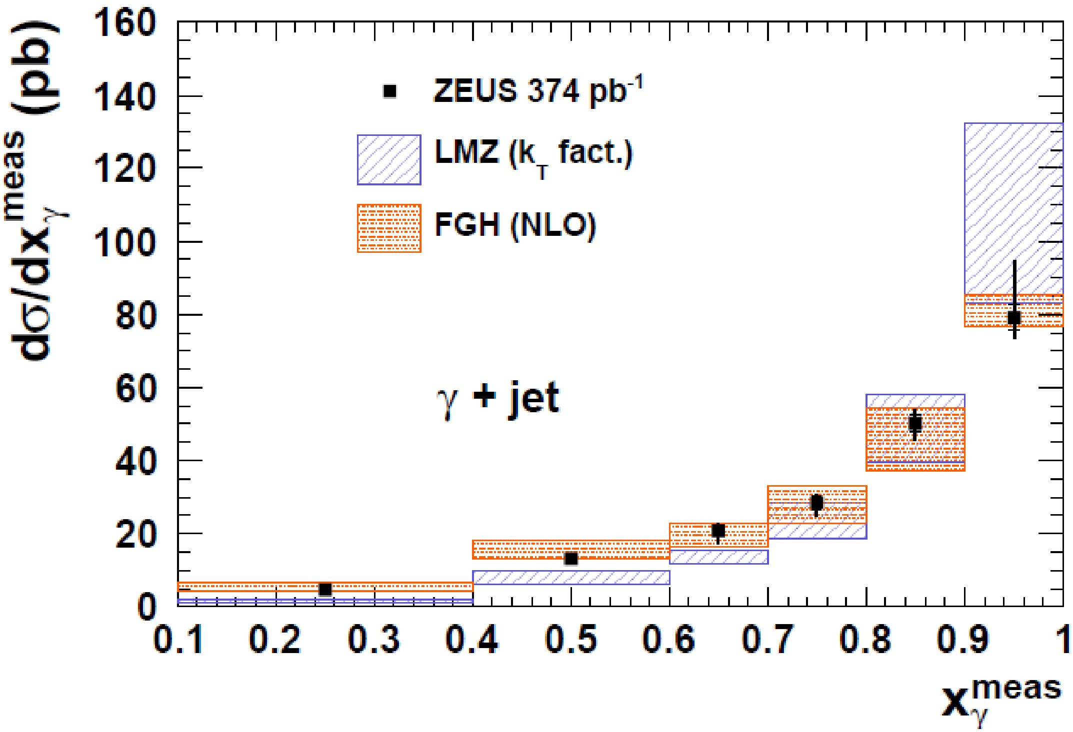
▷ resolved direct, ▷ resolved fragmentation

▷ box diagram (direct direct)

k_T-factorisation approach

- calculated by A.V.Lipatov, M.A. Malyshev, N.P.Zotov, Phys. Rev. D 72 (2005) 054002, Phys. Rev. D 81 (2010) 094027, Phys. Rev. D 88 (2013) 074001 (LMZ):
- investigation of the photoproduction of the isolated photon at HERA in the framework of kt-factorisation QCD approach
- both direct and resolved processes are considered
- the box contribution was included
- fragmentation contribution is neglected

Direct/Resolved Contributions to γ + jet



Direct LO process final state:
- jet
- photon
- scattered electron (escape undetected)
- proton remnant (escape undetected)

$\Rightarrow \; x_\gamma^{\rm meas} = 1$ (**LO** direct)

Resolved LO process final state:
- all mentioned above

+ resolved photon remnant

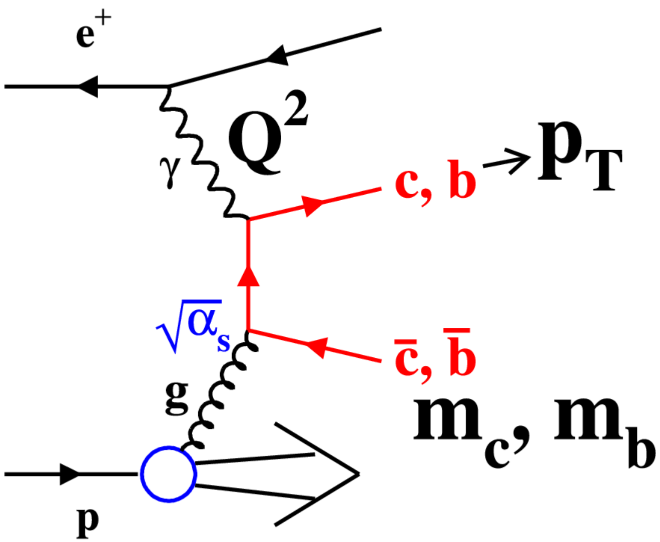
$\Rightarrow \; x_\gamma^{\rm meas} < 1$

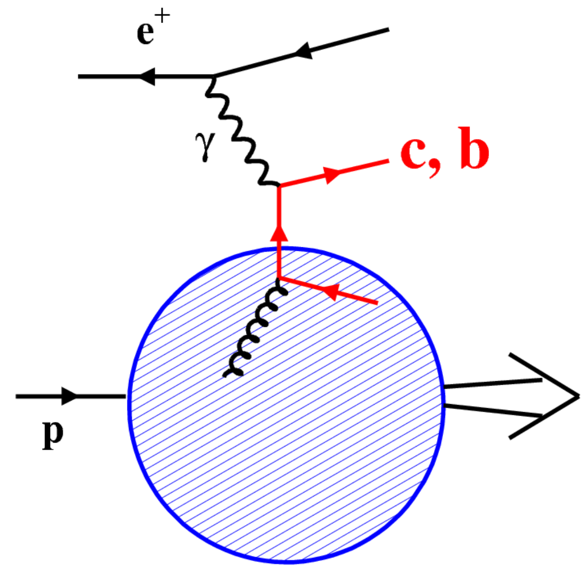
$$x_\gamma^{\rm meas} = \frac{E^\gamma - p_Z^\gamma + E^{\rm jet} - p_Z^{\rm jet}}{E^{\rm all} - p_Z^{\rm all}}$$

very good description of the $x_\gamma^{\rm meas}$ by FGH
reasonable description by LMZ (typically theory within 1-2 sigma from data)

LMZ is somewhat too “direct”

Heavy Quark Production and Masses





Massive scheme (FFNS)

Expected to be valid at scales ~ $m_{b,c}$

Programs exist to calculate fully differential cross sections (HVQDIS, FMNR)

Massless scheme (ZM-VFNS)

Allows resummation of terms proportional to $\log(Q^2/m_{b,c}^{\;2})$

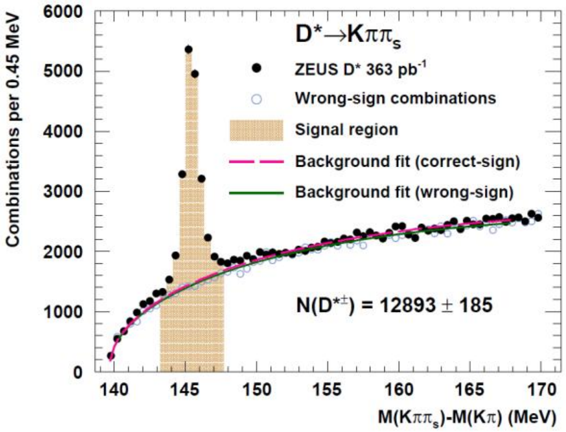
Expected to be valid at scales $\gg m_{b,c}$

Mixed schemes (GM-VFNS)

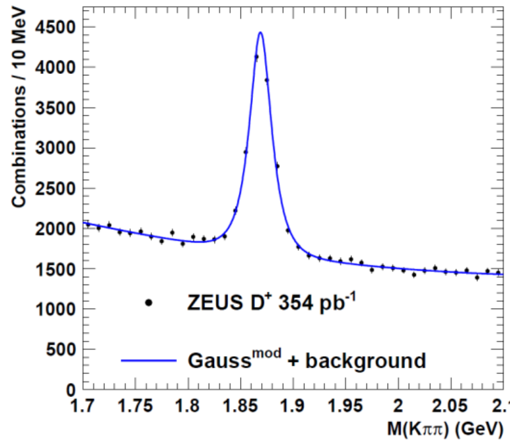
Employ both FFNS and ZM-VFNS

Interpolation is ambiguous → various approaches (RT, ACOT etc.) exist

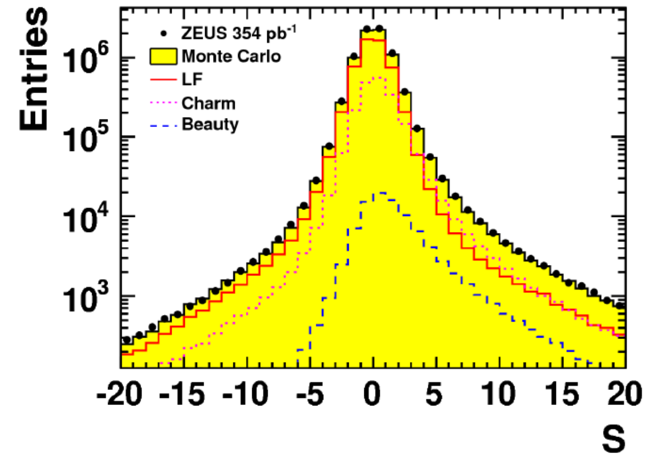
HQ signals and Cross Sections in DIS



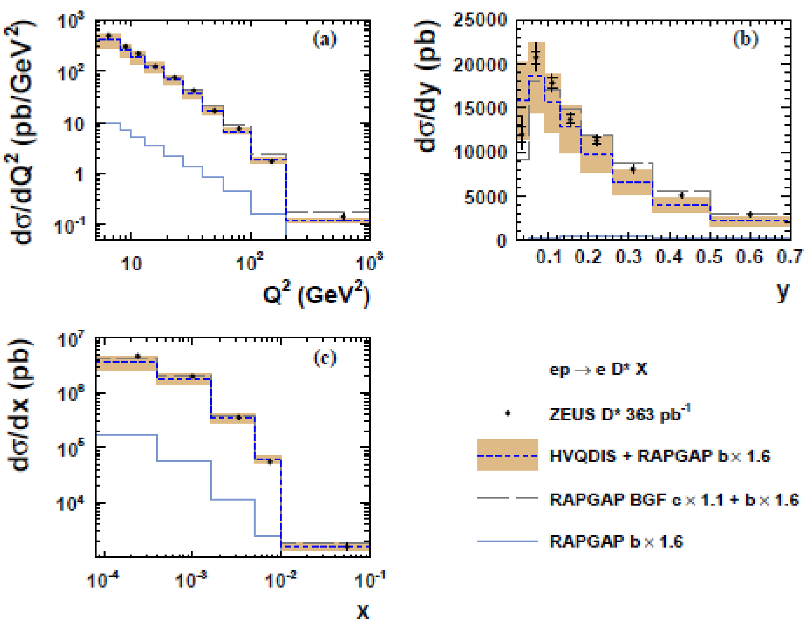
$D^{*\pm} \rightarrow D^0(\rightarrow K^{\mp}\pi^{\pm})\pi_s^{\pm}$

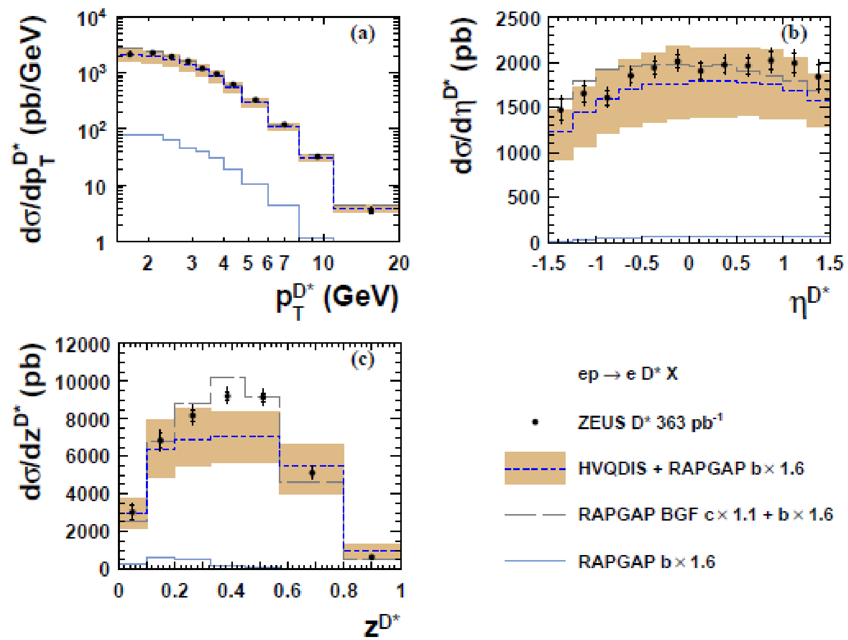


Lifetime tagging of weak decays



Inclusive lifetime tagging





Good agreement with NLO FFNS

$z^{D^*} = E(D^*)/E(\gamma^*)$
in p rest frame

Charm DIS Data Samples

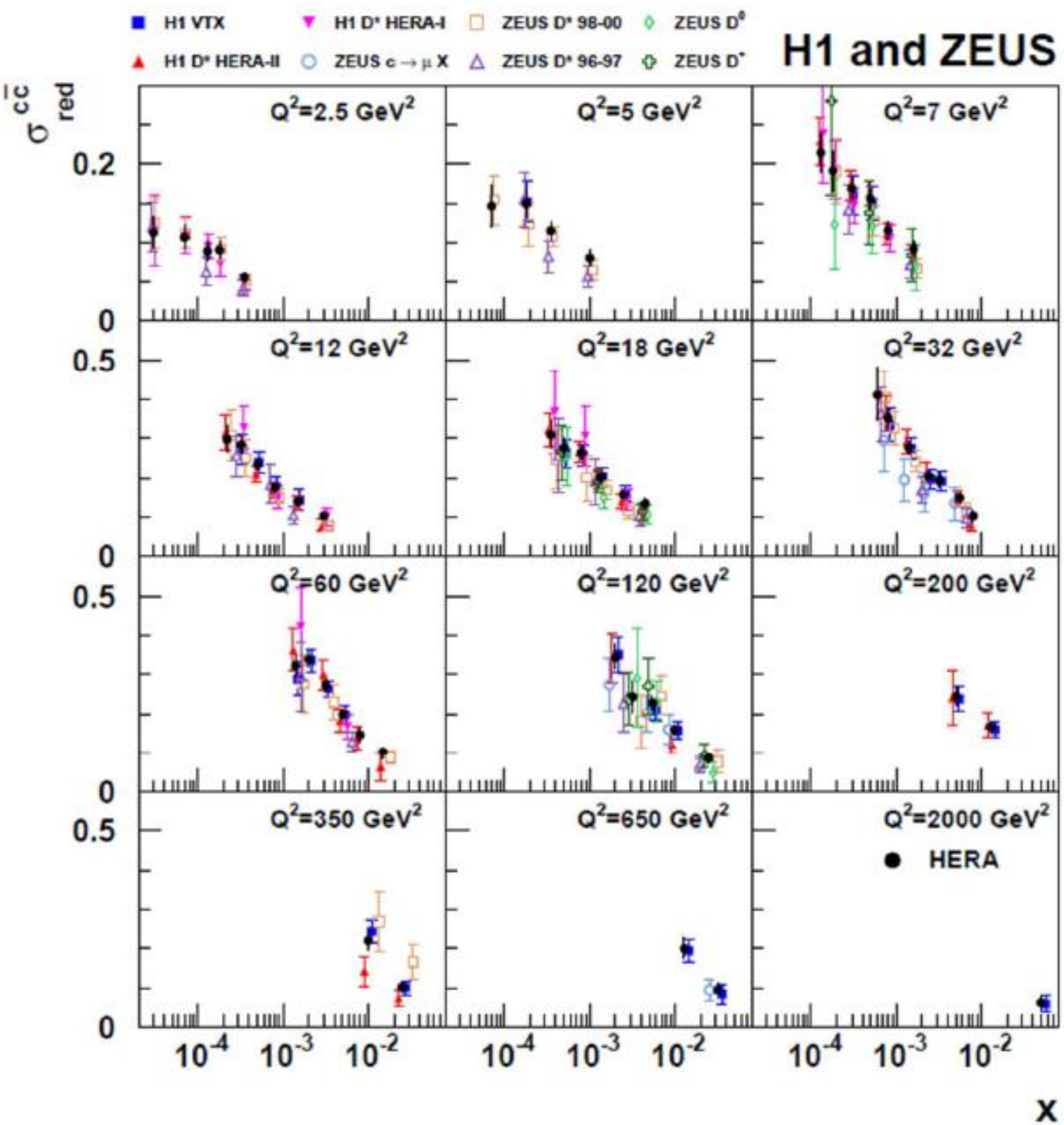
Data set	Tagging method	Q^2 range [GeV^2]	N	$\mathcal{L}$ [pb^{-1}]
1 H1 VTX [14]	Inclusive track lifetime	5 – 2000	29	245
2 H1 D^* HERA-I [10]	D^{*+}	2 – 100	17	47
3 H1 D^* HERA-II [18]	D^{*+}	5 – 100	25	348
4 H1 D^* HERA-II [15]	D^{*+}	100 – 1000	6	351
5 ZEUS D^* (96-97) [4]	D^{*+}	1 – 200	21	37
6 ZEUS D^* (98-00) [6]	D^{*+}	1.5 – 1000	31	82
7 ZEUS D^0 [12]	$D^{0,\mathrm{no}D^{*+}}$	5 – 1000	9	134
8 ZEUS D^+ [12]	D^+	5 – 1000	9	134
9 ZEUS μ [13]	μ	20 – 10000	8	126

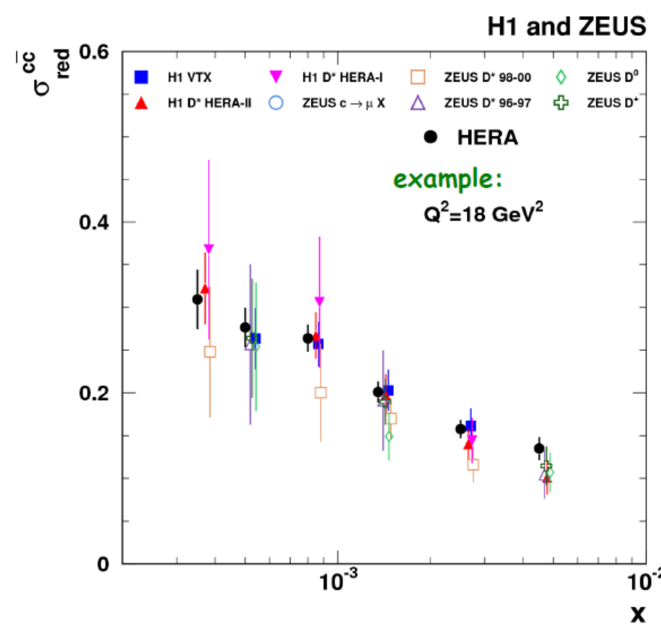
- two independent experiments
- a large variety of tagging techniques: inclusive methods using the large lifetime of charmed hadrons, inclusive track lifetime, complete reconstruction of charmed mesons, D^{*+}, charm semileptonic decay, μ
- a large number of measurements, $\sum N = 155$ data points, in a common grid spanning the x – Q^2 plane (except for [14] where scaling factors, always smaller than 18 %, have been applied to migrate the original measurements to the closest point of the common grid)
- developped a combination method taking into account properly correlated and uncorrelated uncertainties (155 data points in 52 bins)

key observable:

$$\sigma_{\mathrm{red}}^{c\bar{c}} = \frac{\mathrm{d}^2\sigma^{c\bar{c}}}{\mathrm{d}x\mathrm{d}Q^2} \cdot \frac{xQ^4}{2\pi\alpha^2(Q^2)\,(1+(1-y)^2)}$$

Combined Charm Reduced x-sections



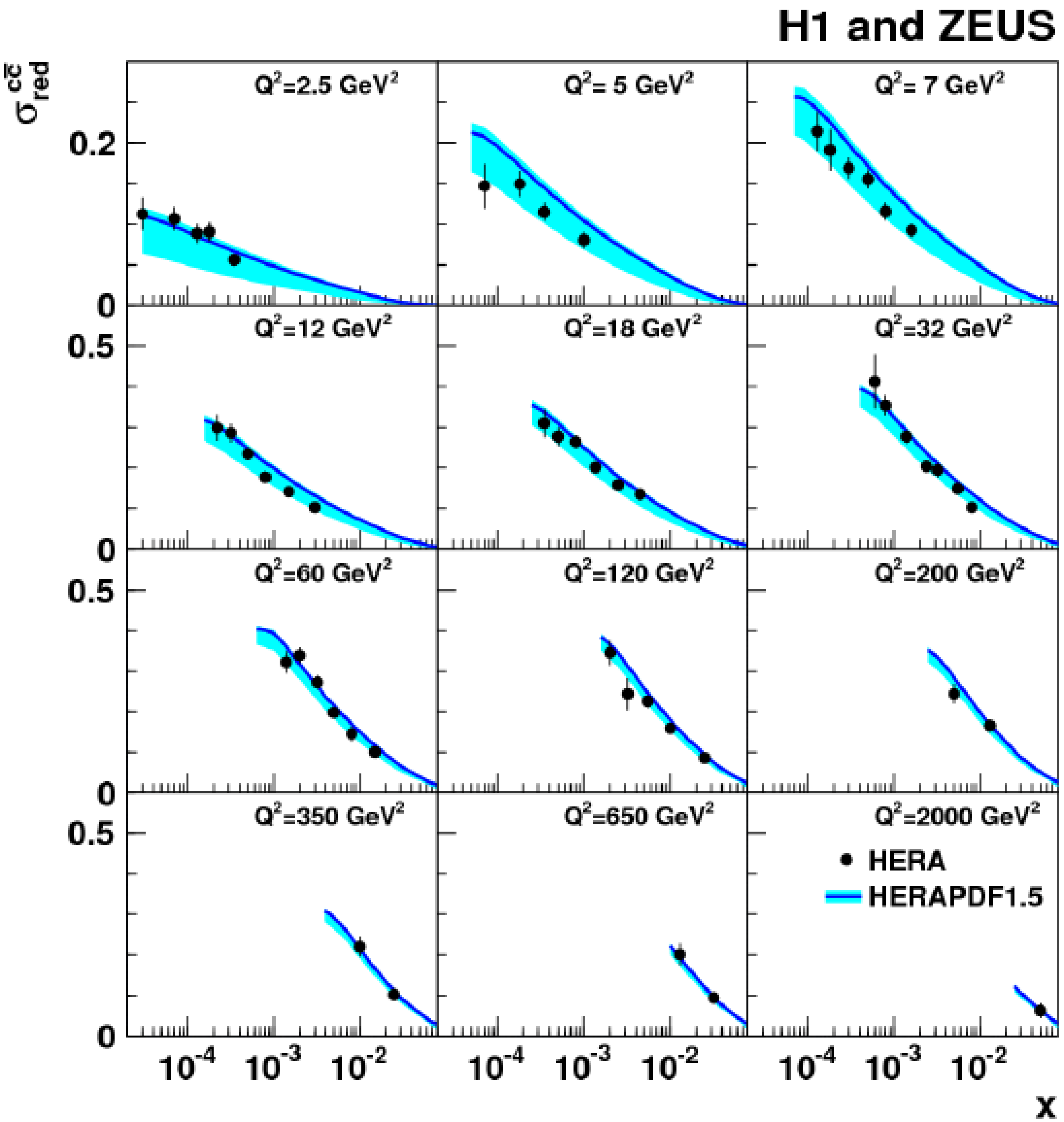


✓ good consistency of data among the several possible tests $\chi^2 / \mathrm{ndf} = 62 / 103$

✓ good complementarity of data

✓ 10 % uncertainty on average, 6 % at small x and medium Q^2

Sensitivity to m_c

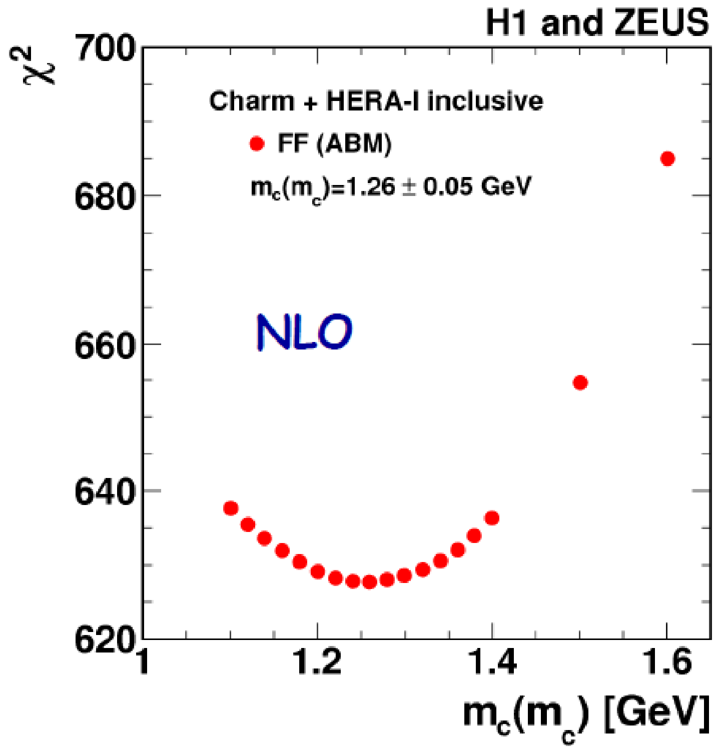


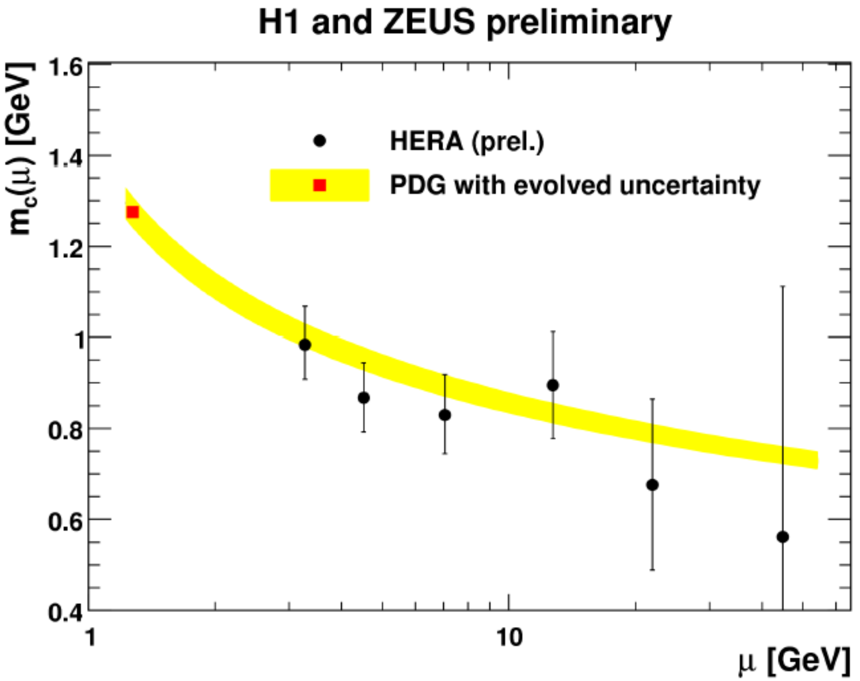
well described using HERAPDF1.5
(fitted from inclusive DIS only)

strong charm mass dependence
(blue band: 1.35->1.6 GeV)

Can be used to constraint m_c

m_c value and running





$$\mu = \sqrt{Q^2 + 4m_c^2}$$

$$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{param} \pm 0.02_{\alpha_s}\ GeV$$

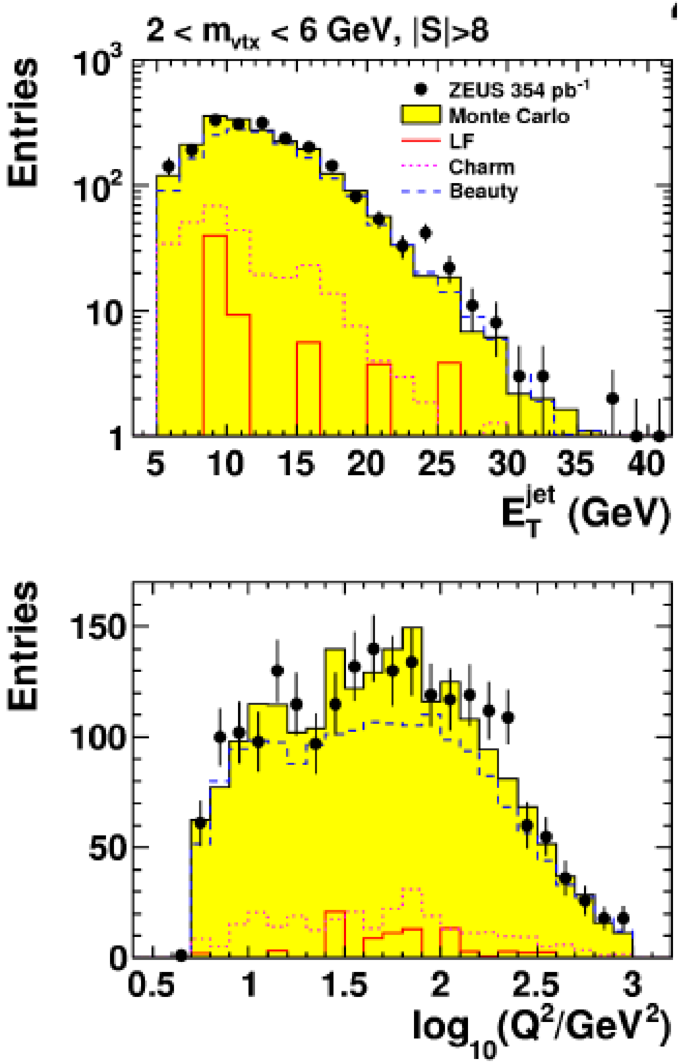
Errors are experimental, model, parametrisation and α_s

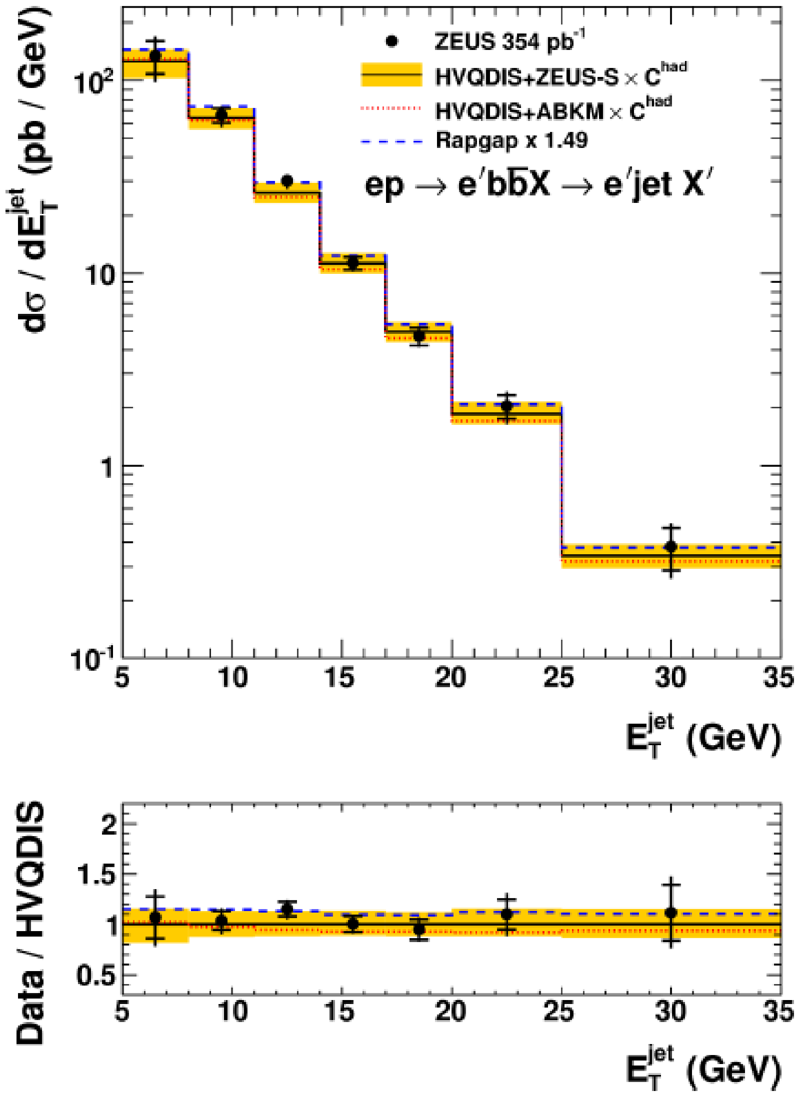
Consistent with PDG: $m_c(m_c) = 1.275 \pm 0.025$ GeV

$$m_c(\mu) = m_c(m_c)\frac{\left(\frac{\alpha_s(\mu)}{\pi}\right)^{\frac{1}{\beta_0}}}{\left(\frac{\alpha_s(m_c)}{\pi}\right)^{\frac{1}{\beta_0}}}$$

β_0 for N_f=3 is $\frac{9}{4}$

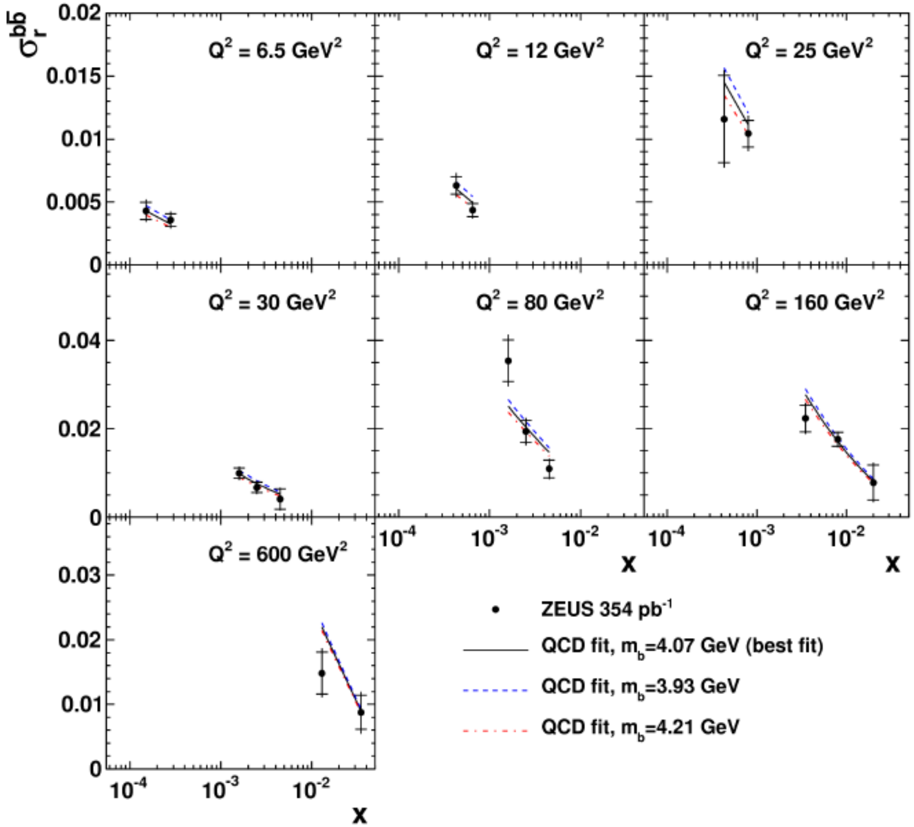
Beauty signals and x-sections in DIS

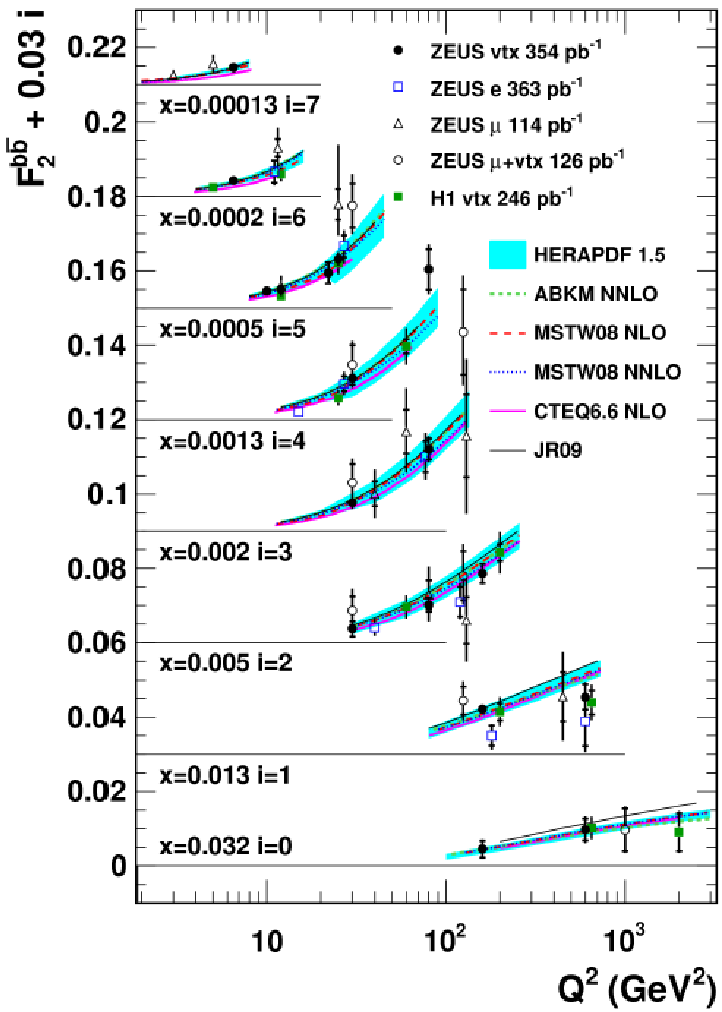




Reasonable description by HVQDIS NLO QCD

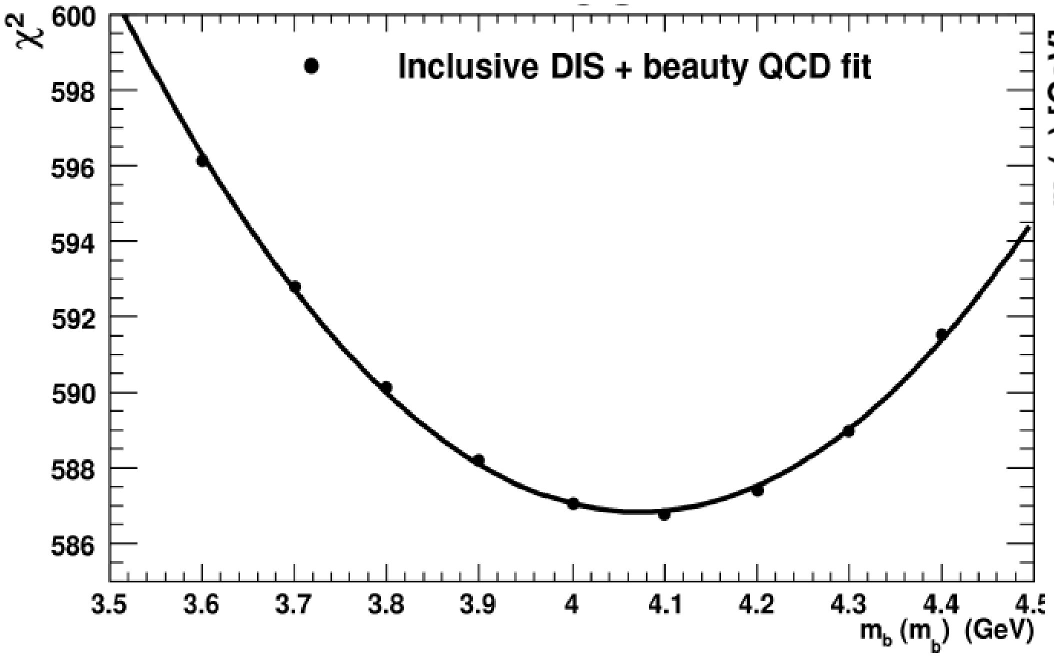
Beauty Reduced x-sections and F_2

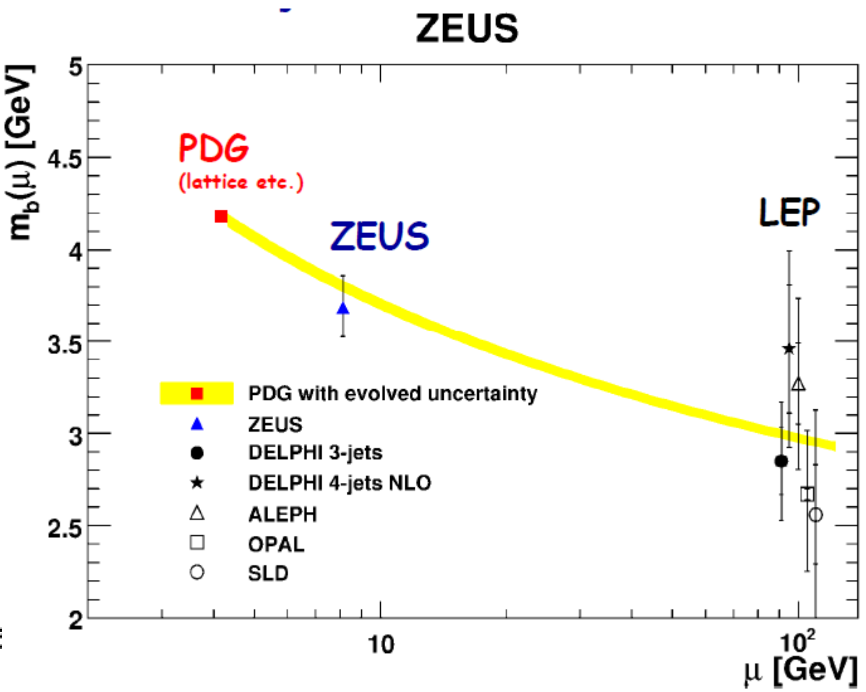




Sensitivity to m_b comes mostly from low Q^2

m_b value and running





$m_b(m_b)$ = 4.07 $\pm 0.14_{fit}$ $^{+0.01}_{-0.07}$ $_{mod}$ $^{+0.05}_{-0.00}$ $_{par}$ $^{+0.08}_{-0.05}$ $_{th}$ GeV

PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

translate back to $2m_b$

mass running consistent with QCD

Summary & Prospects

No new data but a lot of new results

- Proton Structure studied in almost full range of LHC sensitivity
  HERAPDF 2.0 is available and widely used

- Extensive results on jet production
  Precise α_s measurements

- New precise measurements of prompt photon production
  Verification of collinear and k_t predictions

- Charm and beauty contributions to proton structure
  Extraction of m_c and m_b values

- More final and combined H1+ZEUS results
  HERA legacy forever

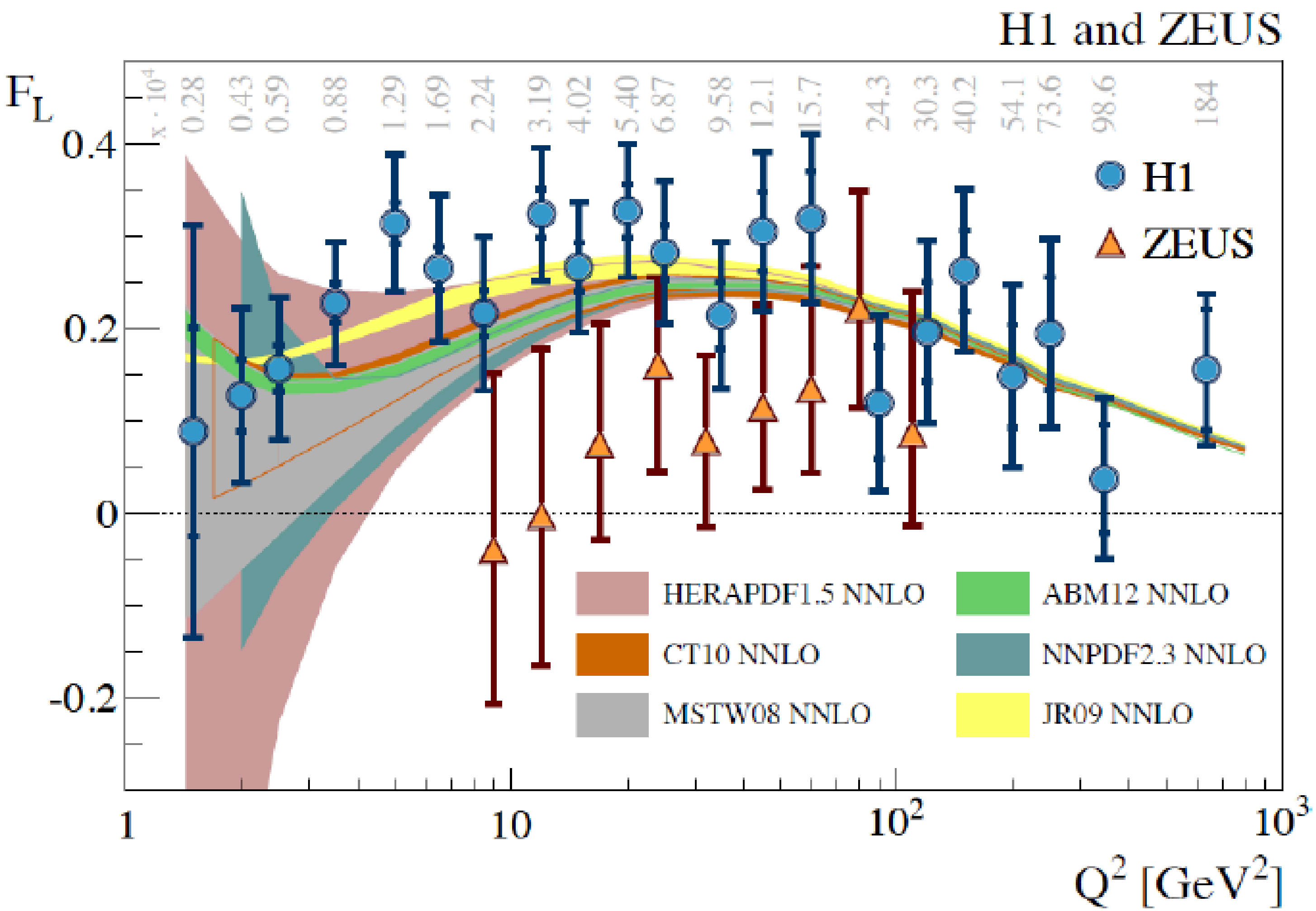
Back-up Slides

Data Samples

H1					ZEUS				
Data set		$\mathcal{L}$ [pb^{-1}]	e^+ / e^-	$\sqrt{s}$ [GeV]	Data set		$\mathcal{L}$ [pb^{-1}]	e^+ / e^-	$\sqrt{s}$ [GeV]
HERA I E_p = 820 GeV and E_p = 920 GeV data sets									
H1 svx-mb	95-00	2.1	e^+p	301, 319	ZEUS BPC	95	1.65	e^+p	300
H1 low Q^2	96-00	22	e^+p	301,319	ZEUS BPT	97	3.9	e^+p	300
H1 NC	94-97	35.6	e^+p	301	ZEUS SVX	95	0.2	e^+p	300
H1 CC	94-97	35.6	e^+p	301	ZEUS NC	96-97	30.0	e^+p	300
H1 NC	98-99	16.4	e^-p	319	ZEUS CC	94-97	47.7	e^+p	300
H1 CC	98-99	16.4	e^-p	319	ZEUS NC	98-99	15.9	e^-p	318
H1 NC HY	98-99	16.4	e^-p	319	ZEUS CC	98-99	16.4	e^-p	318
H1 NC	99-00	65.2	e^+p	319	ZEUS NC	99-00	63.2	e^+p	318
H1 CC	99-00	65.2	e^+p	319	ZEUS CC	99-00	60.9	e^+p	318
HERA II E_p = 920 GeV data sets									
H1 NC	03-07	182.0	e^+p	319	ZEUS NC	06-07	135.5	e^+p	318
H1 CC	03-07	182.0	e^+p	319	ZEUS CC	06-07	132.0	e^+p	318
H1 NC	03-07	151.7	e^-p	319	ZEUS NC	05-06	169.9	e^-p	318
H1 CC	03-07	151.7	e^-p	319	ZEUS CC	04-06	175.0	e^-p	318
H1 NC med Q^2	03-07	182.0	e^+p	319	ZEUS NC nominal	06-07	44.5	e^+p	318
H1 NC low Q^2	03-07	182.0	e^+p	319	ZEUS NC satellite	06-07	44.5	e^+p	318
HERA II E_p = 575 GeV data sets									
H1 NC high Q^2	07	17.2	e^+p	252	ZEUS NC nominal	07	7.1	e^+p	251
H1 NC low Q^2	07	5.9	e^+p	252	ZEUS NC satellite	07	7.1	e^+p	251
HERA II E_p = 460 GeV data sets									
H1 NC high Q^2	07	17.2	e^+p	225	ZEUS NC nominal	07	13.9	e^+p	225
H1 NC low Q^2	07	12.2	e^+p	225	ZEUS NC satellite	07	13.9	e^+p	225

The Longitudinal Structure Function $F_L(Q^2)$

Average F_L measurement over x at each Q^2 to reduce statistical uncertainty



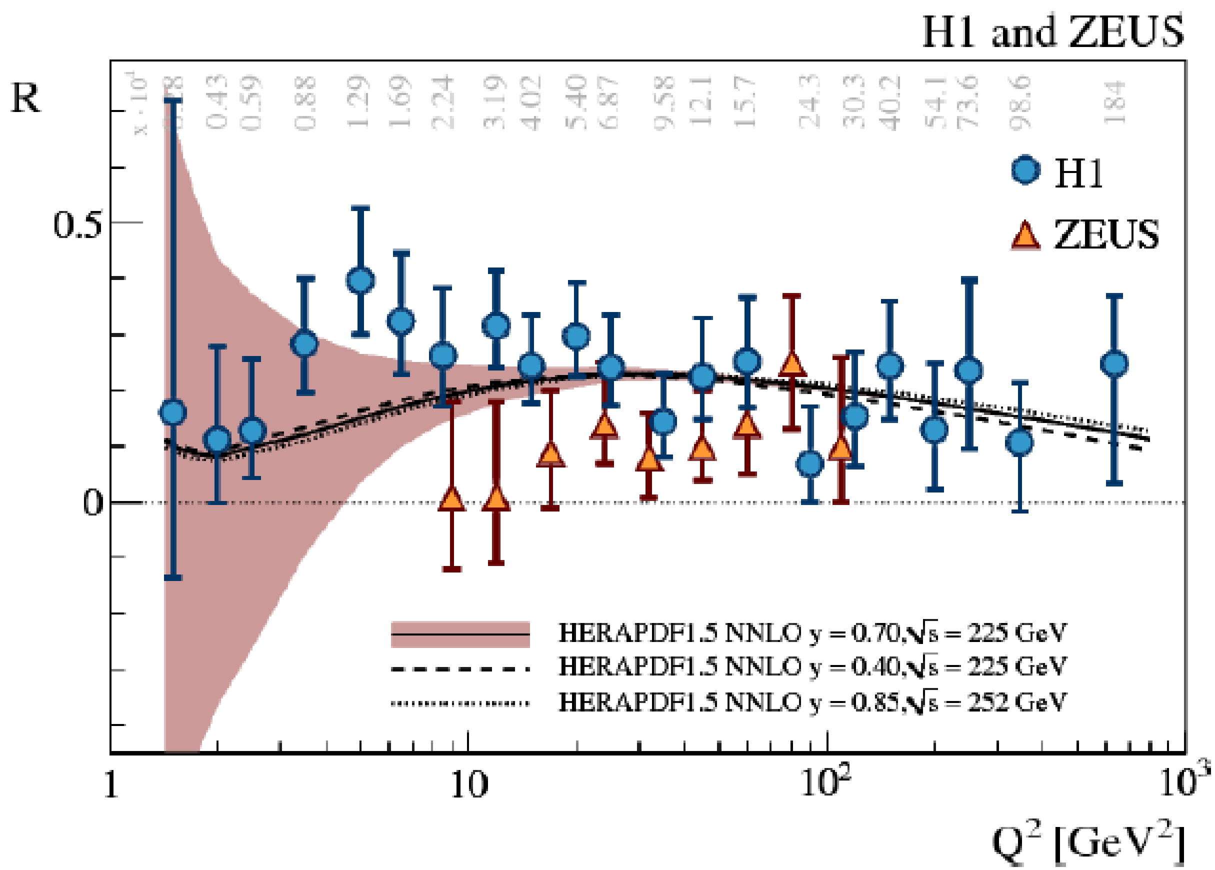
Good agreement between the NNLO predictions and the measurement

Additional constraints to PDF's at low Q^2

Agreement between H1 and ZEUS is within one sigma

The Ratio $R = \sigma_L / \sigma_T$ Extraction

For γ^*p R measures interaction with longitudinally polarized virtual photon.
Relation between F_L and R: $F_L = F_2 * R/(R+1)$.

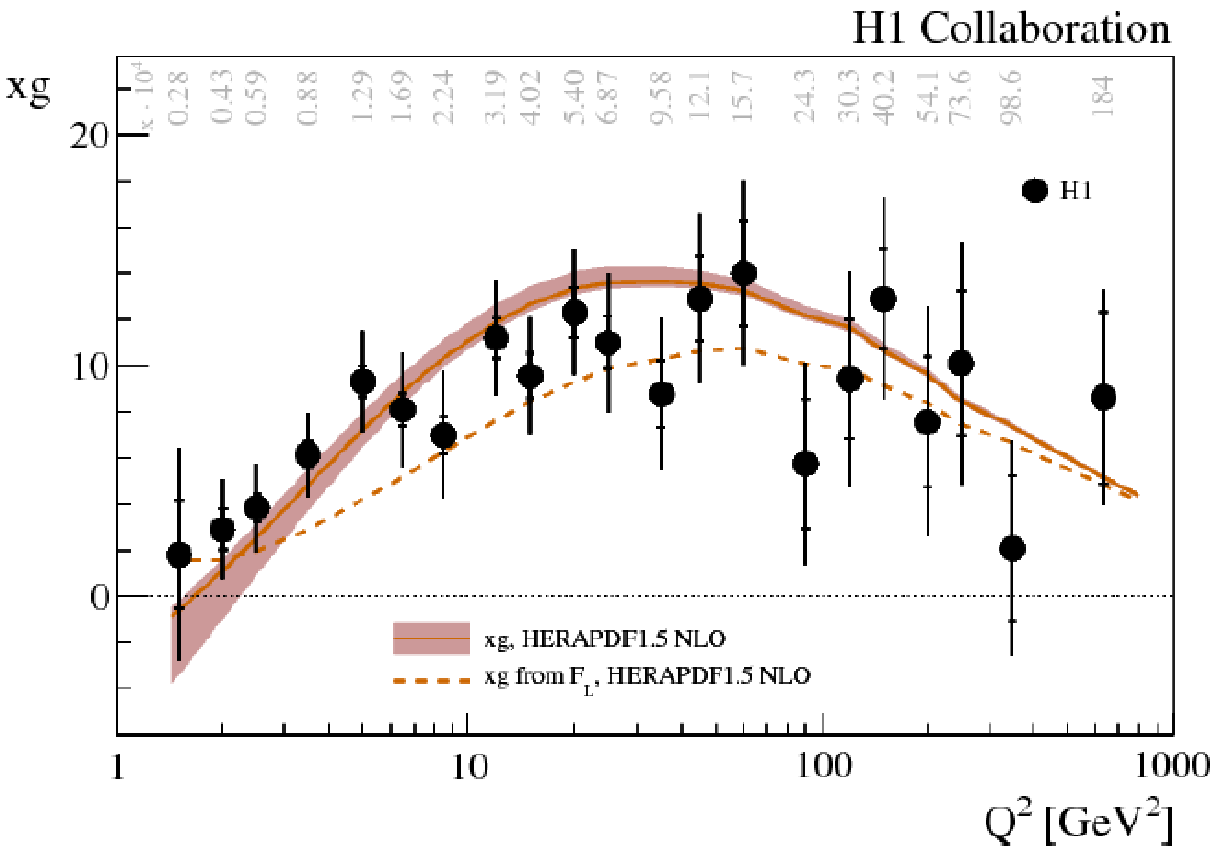


R is approximately constant. Constant value fit gives

H1 0.23 ± 0.04

ZEUS $0.105 + 0.055 - 0.037$

The Gluon Density Extraction



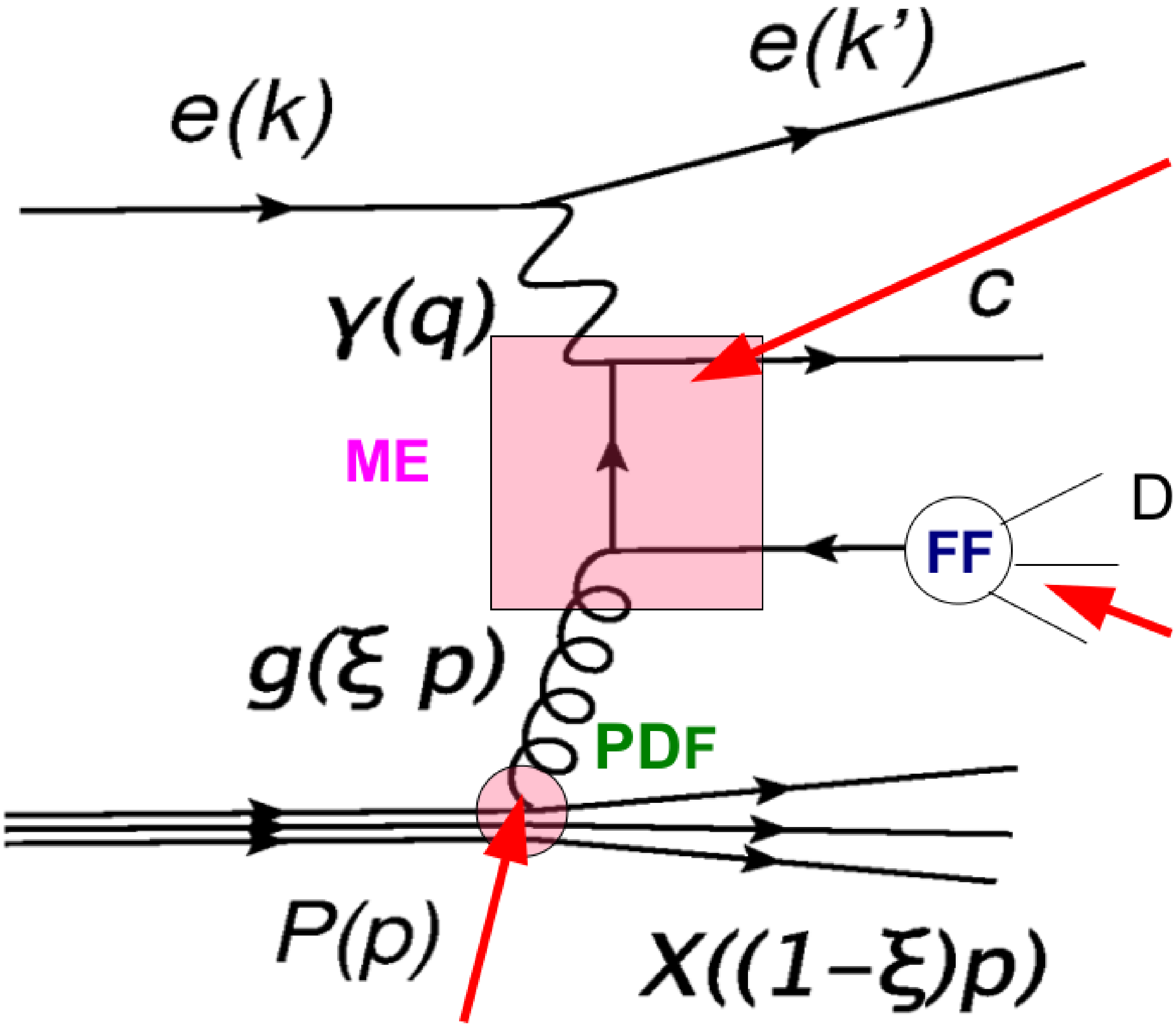
- Shaded area
  prediction from the QCD fit
- Data and dashed line
  extraction at order α_s from the F_L measurement and prediction

$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax, Q^2)$$

A. M. Cooper-Sarkar *et al.*, Z. Phys. C **39** (1988)
E. B. Zijlstra and W. L. van Neerven, Nucl. Phys. **B 383** (1992)
G. R. Boroun, B. Rezaei, Eur. Phys. J. **C72** (2012) 2221
G. R. Boroun, B. Rezaei, arXiv:1401.7804.

Reasonable agreement between direct gluon density (approximate) extraction and indirect measurement from scaling violation

Heavy Quark Production



Secondary vertex method

Tag: jet + secondary vertex

Phase space of the measurement:

$5 < Q^2 < 1000\ \mathrm{GeV}^2$

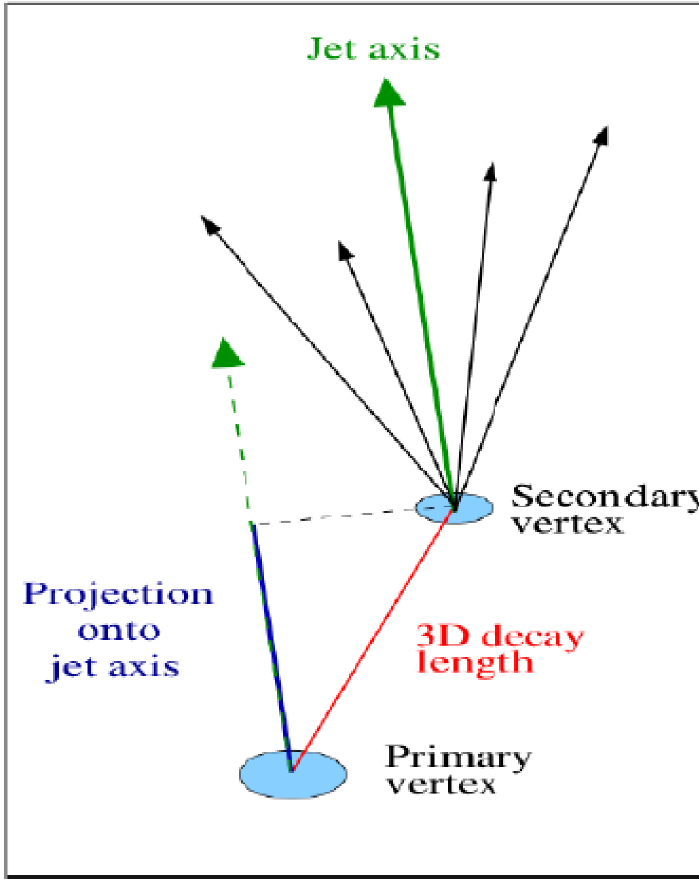
$0.02 < y < 0.7$

$E_T^{jet} > 5(4.2)\ \mathrm{GeV}$

$-1.6 < \eta^{jet} < 2.2$

- Employs long lifetime of ground state hadrons containing charm or beauty quarks
- No specific decay mode requirement → increase in statistics

- Select tracks belonging to a jet
  - p_T(track)>500 MeV
- Fit a secondary vertex
- Project decay length onto a jet axis
- Calculate decay length significance



Quark mass definitions

Pole quark mass

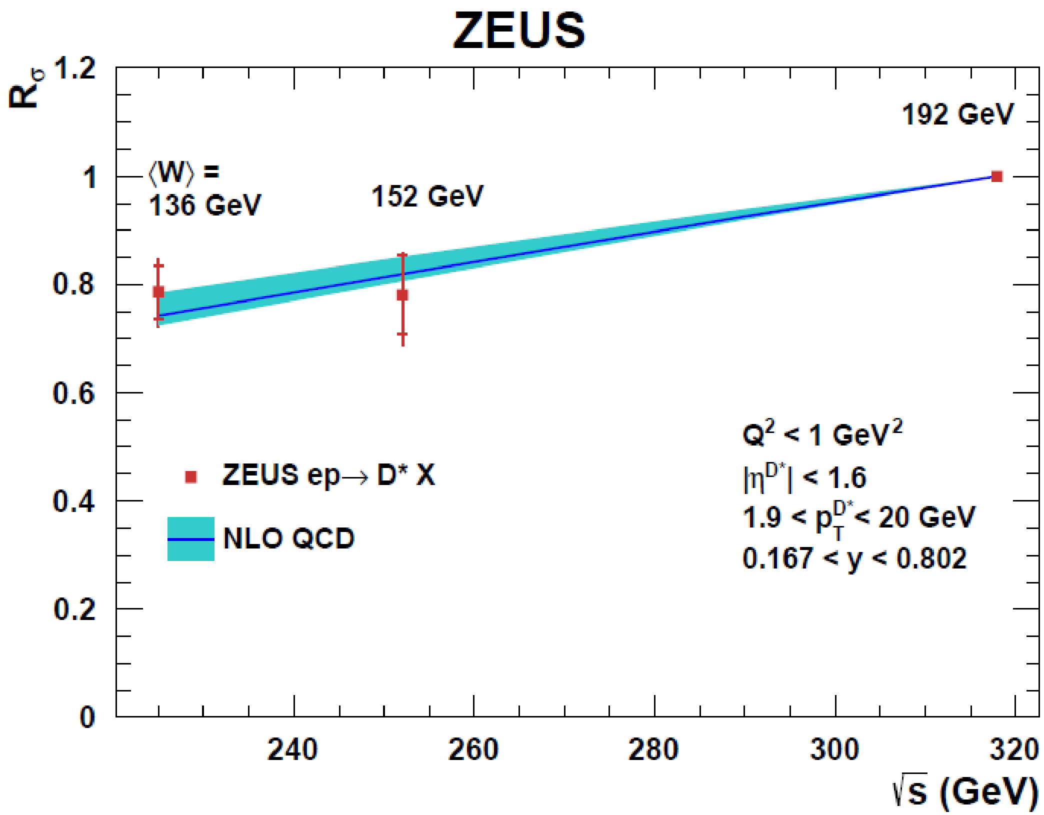
- Based on (unphysical) concept of quark being a free parton
- Pole mass is ambiguous up to corrections of O(λ_{QCD})

Running quark mass ($\bar{M}S$)

- $\bar{M}S$ (minimal substraction scheme) mass definition m(μ_R) realizes running mass (scale dependence)
- renormalization group equation (mass anomalous dimenstion γ)

$$\left(\mu_R^2 \frac{\delta}{\delta \mu_R^2} + \beta(\alpha_s) \frac{\delta}{\delta \alpha_s}\right) m(\mu_R) = \gamma(\alpha_s) m(\mu_R)$$

Ratio of D*± PhP x-sections at different √s



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May 2014

Parameters for NLO QCD calculation:

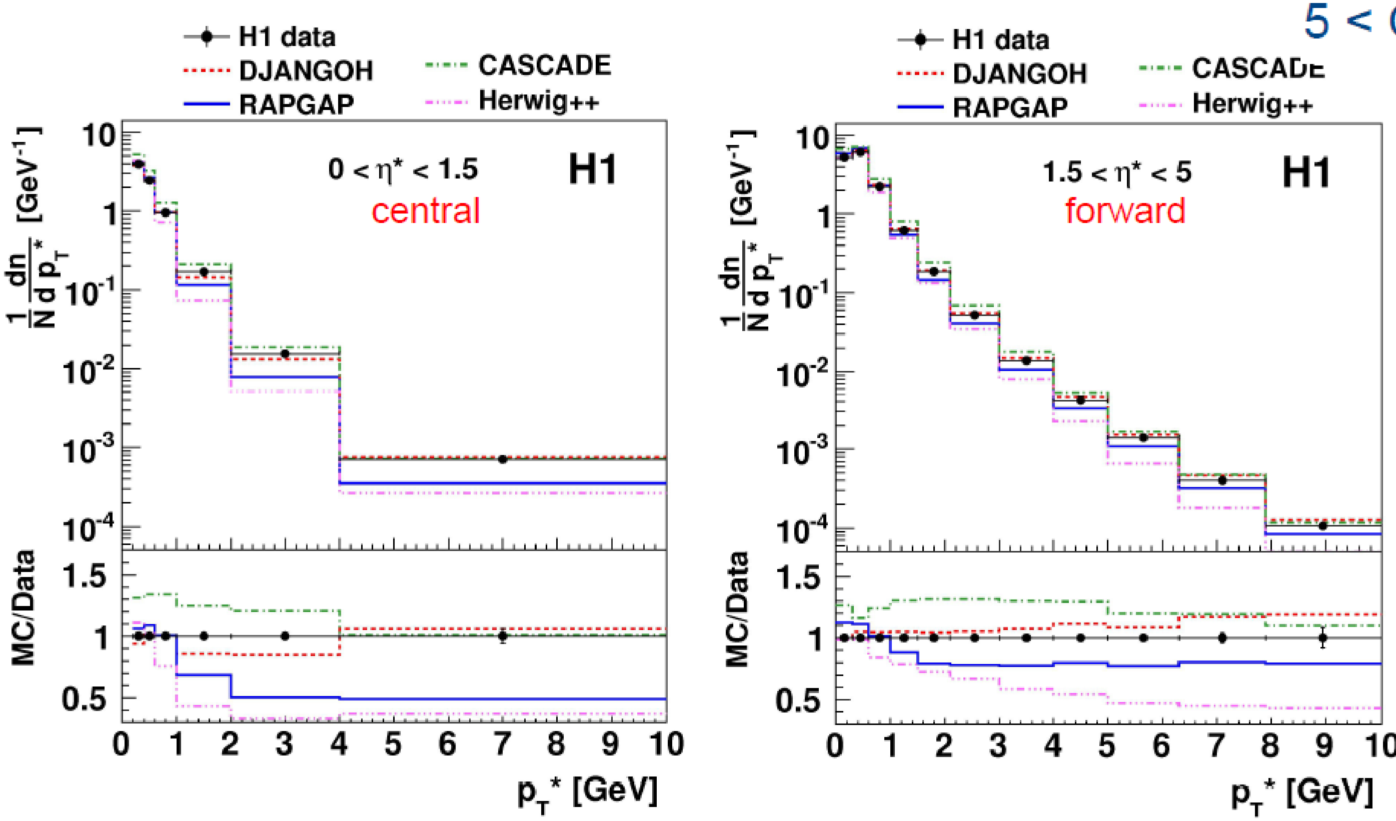
Fixed-flavor-number scheme (FFNS):

Strong coupling constant : $\alpha_s(M_Z) = 0.118$,
mass of c quarks: m =1.50 GeV
Fragmentation fraction f(c->D*)=0.237
PDFs : proton - ZEUS-S FFNS
photon - GRV-G HO
Peterson fragmentation function: = 0.079

Scales were set to $\mu = \sqrt{m_c^2 + \hat{p}_T^2}$

Charged Particle Spectra in DIS

5 < Q² < 100 GeV²



DJANGOH does best, RAPGAP is also satisfactory at low p_T but not at high p_T.

CASCADE (based on CCFM) is the least successful model.

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