Topics on QCD and Spin Physics

(third lecture)

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Lecture 1: Introduction.

1.1 The origins of QCD: the quark model, Bjorken scaling and the parton model.

1.2 From QED to QCD: the QCD lagrangian and its Feynman diagrams.

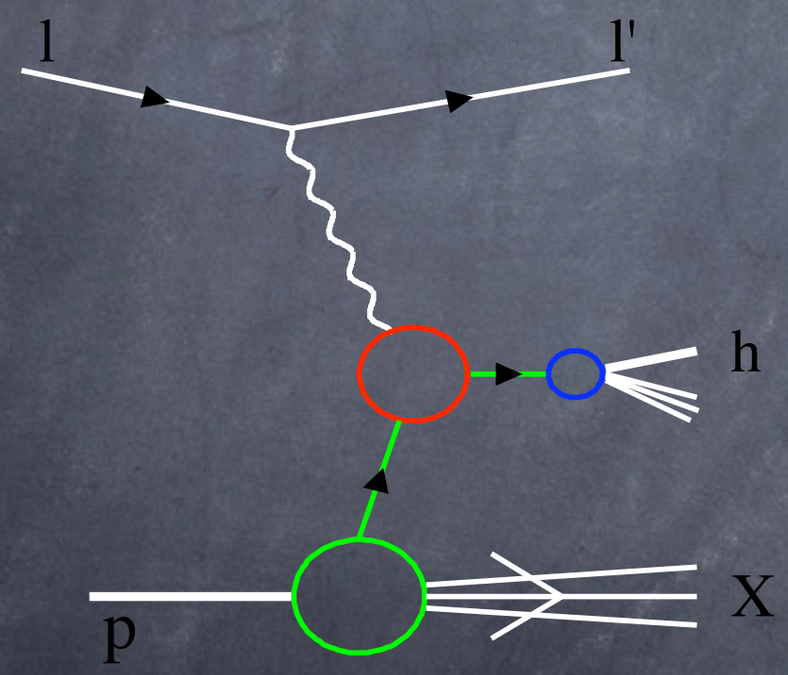
1.3 The running coupling constant: renormalization and asymptotic freedom.

Lecture 2: DIS and PDFs.

2.1 DIS kinematics and cross sections.

2.2 Defining PDFs, evolution equations, LO, NLO and beyond.

2.3 PDFs extraction from data.



hadronization: a path to confinement

accessed by "jets"

fragmentation functions "FFs"

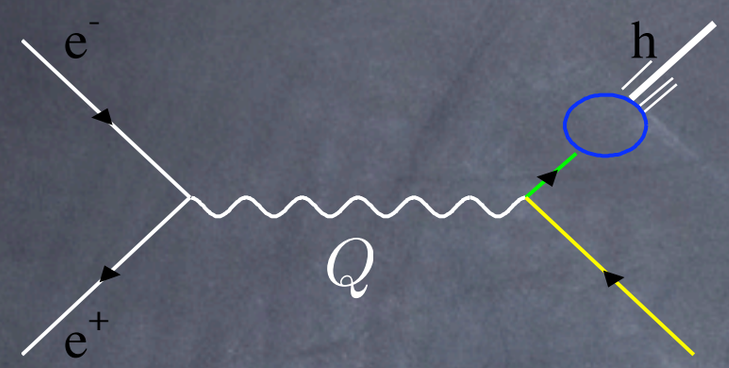
Lecture 3: Final states in QCD.

3.1 Factorization beyond DIS: fragmentation functions and jets.

3.2 SIDIS, e+e- -> hadrons, pp -> hadrons.

3.3 Combined global fits of fragmentation functions.

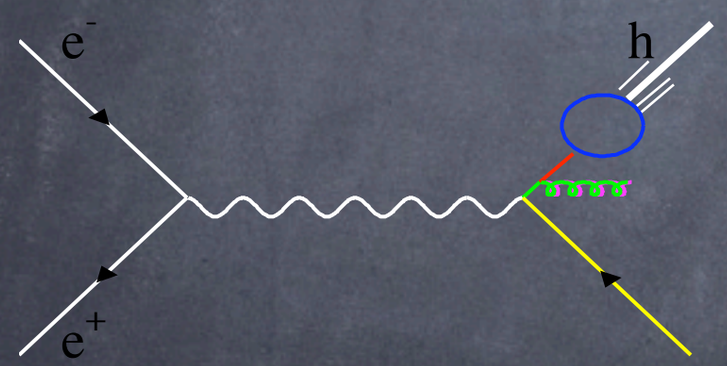
Looking for FFs:



$$z \equiv \frac{E_h}{E_q} = \frac{2E_h}{Q}$$

$$\frac{d\sigma}{dz}(e^+e^- \to h\,X) = \sum_q \sigma(e^+e^- \to q\bar{q})\left[D_q^h(z) + D_{\bar{q}}^h(z)\right]$$

$$\sum_h \int_0^1 z\,D_q^h(z)\,dz = 1 \qquad \sum_q \int_0^1 \left[D_q^h(z) + D_{\bar{q}}^h(z)\right]\,dz = n_h$$



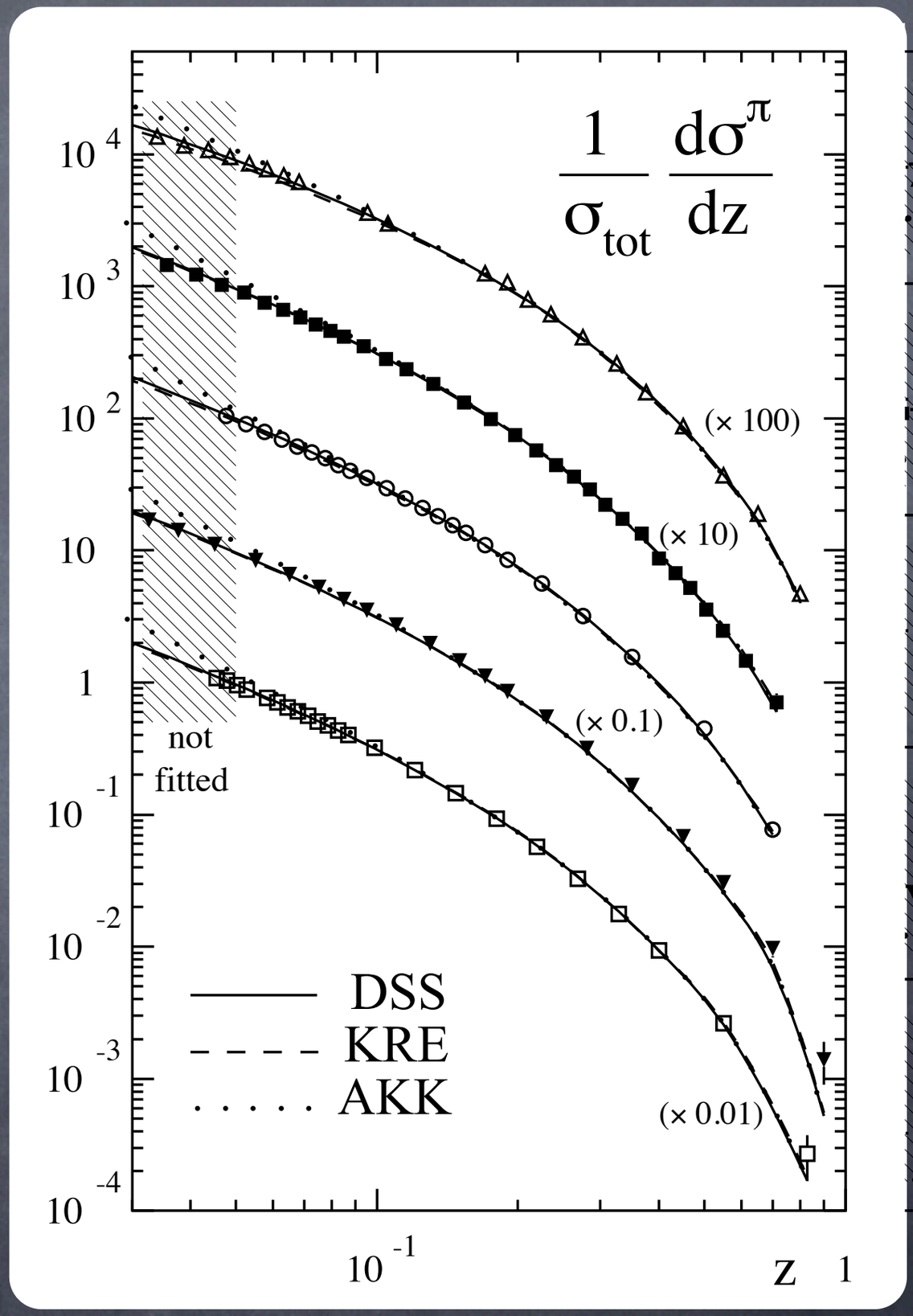
$$D_q^h(z) \longrightarrow D_q^h(z, Q^2)$$

$$\frac{dD_q^h(z,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dy}{y}\left[D_q^h(y,Q^2)\,P_{qq}\left(\frac{x}{y}\right) + D_g^h(y,Q^2)\,P_{qg}\left(\frac{x}{y}\right)\right]$$

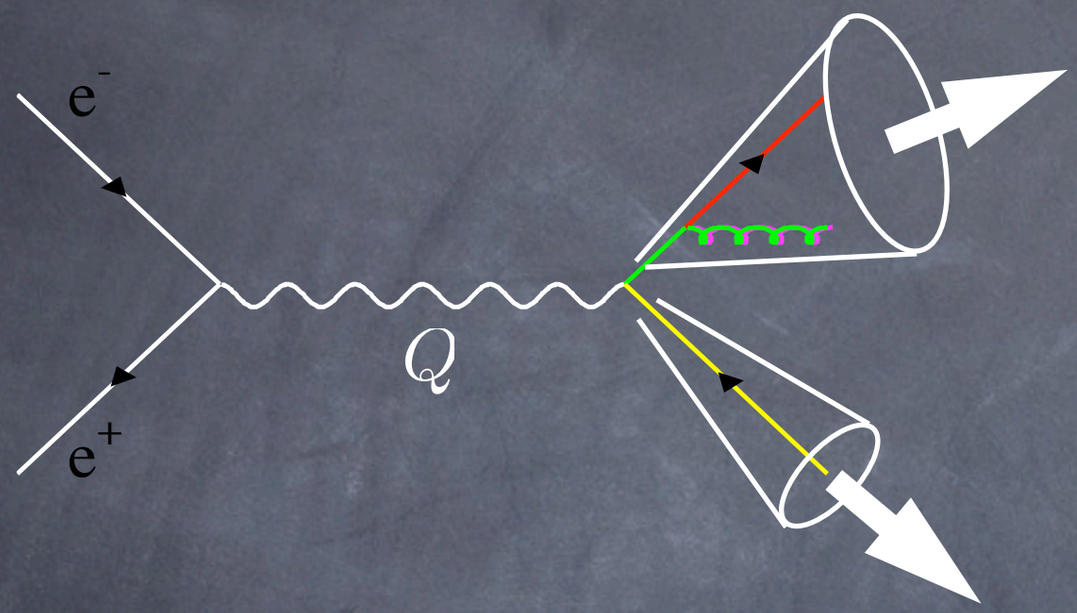
$$\frac{dD_g^h(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_q D_q^h(y,Q^2)\,P_{gq}\left(\frac{x}{y}\right) + D_g^h(y,Q^2)\,P_{gg}\left(\frac{x}{y}\right)\right].$$

why does it work?

collinear emission?



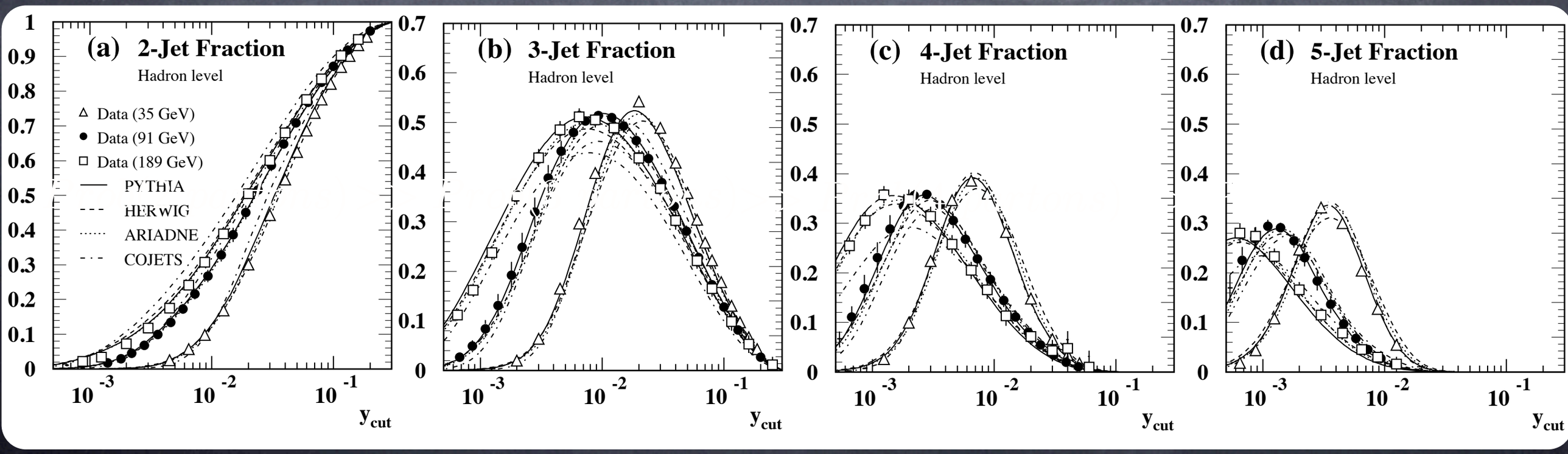
A good example: $\hat{\sigma}(e^+e^- \to q\bar{q}g)$



$$z_q \equiv \frac{2E_q}{Q} \qquad z_{\bar{q}} \equiv \frac{2E_{\bar{q}}}{Q} \qquad z_g \equiv \frac{2E_g}{Q}$$

$$z_q + z_{\bar{q}} + z_g = 2$$

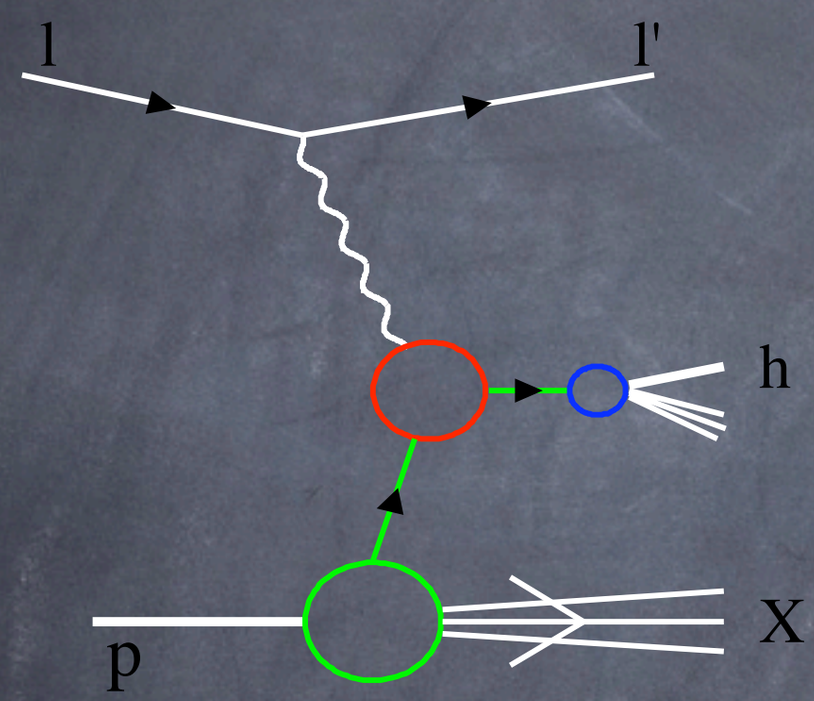
$$\frac{d\hat{\sigma}}{dz_q dz_{\bar{q}}} = \sigma_0 \frac{2\alpha_s}{3\pi} \frac{z_q^2 + z_{\bar{q}}^2}{(1-z_q)(1-z_{\bar{q}})}$$



SIDIS: semi-inclusive deep inelastic scattering

"one-particle-inclusive"

$$l + p \to l' + h + X$$



current fragmentation

$$d\sigma = f_i \otimes \hat{\sigma}_{ij} \otimes D_j^h$$

f_i parton density

$\hat{\sigma}_{ij}$ partonic cross section

D_j^h fragmentation function

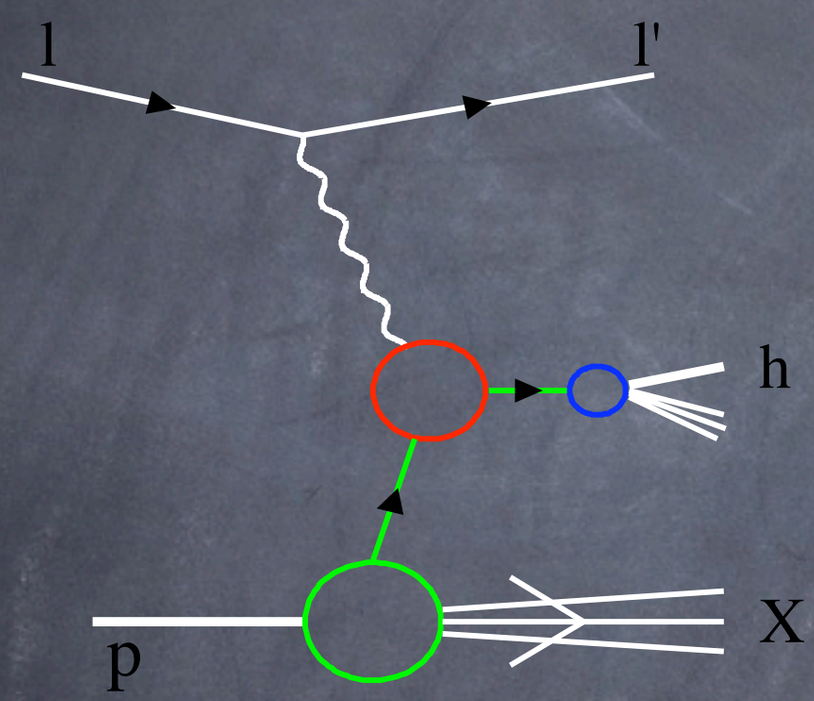
$$2F_1^h(x, z, Q^2) = \sum_{q,\bar{q}} e_q^2 \, f_q(x, Q^2) D_q^h(z, Q^2)$$

LO

SIDIS: semi-inclusive deep inelastic scattering

"one-particle-inclusive"

$$l + p \to l' + h + X$$



current fragmentation

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D_j^h fragmentation function

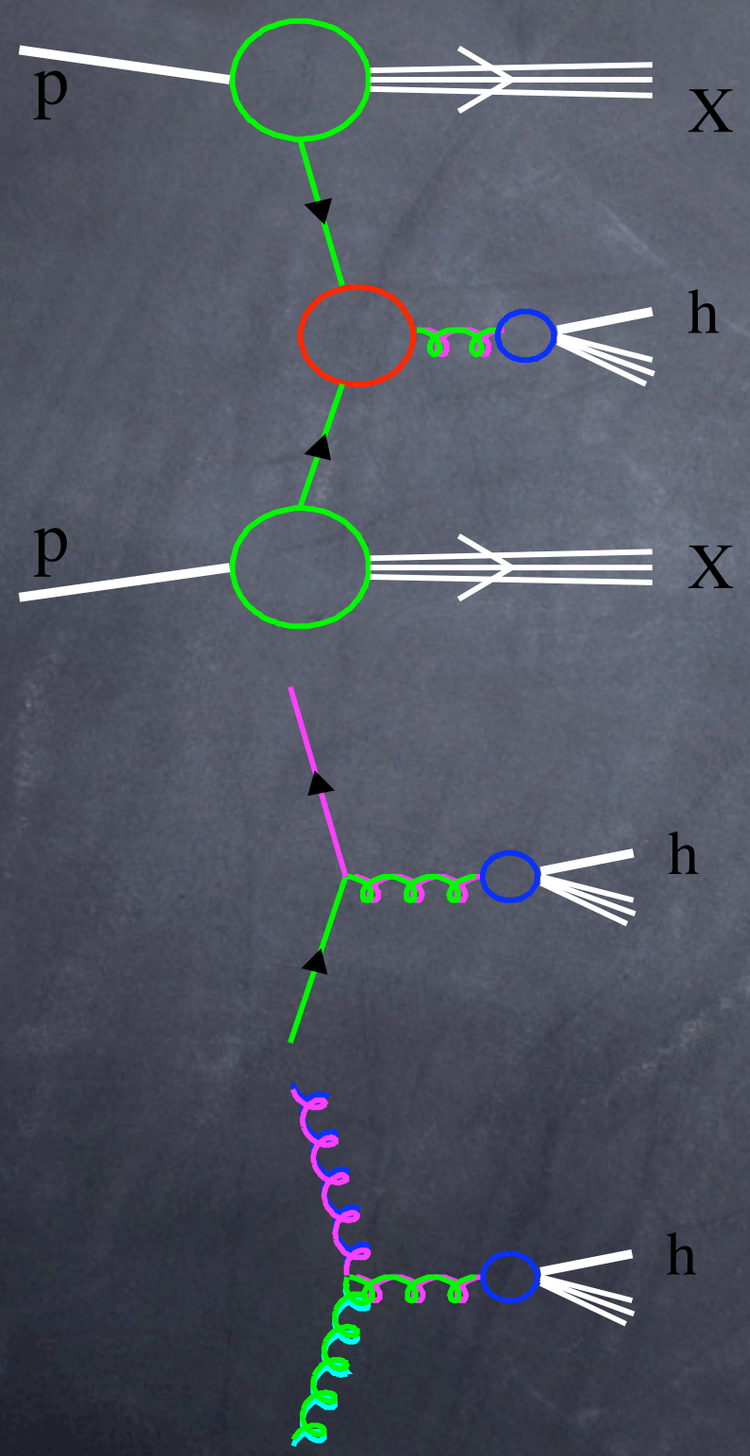
$$2F_1^h(x,z,Q^2) = \sum_{q,\bar{q}} e_q^2 f_q(x,Q^2) D_q^h(z,Q^2)$$

NLO

$$+\frac{\alpha_s}{2\pi}\sum_{q,\bar{q}} e_q^2 \left[f_q \otimes C_{qq} \otimes D_q^h + f_q \otimes C_{gq} \otimes D_g^h + f_g \otimes C_{qg} \otimes D_q^h \right]$$

Single-inclusive h production in p-p (p-pbar) collisions

$$p + p \to h + X$$



$$d\sigma = f_i \otimes f_j \otimes \hat{\sigma}_{ijk} \otimes D_k^h$$

$$\sim f_q \otimes f_{\overline{q}} \otimes \hat{\sigma}_{q\overline{q}g} \otimes D_g^h$$

gluon fragmentation at lowest order

$$\sim f_g \otimes f_g \otimes \hat{\sigma}_{ggg} \otimes D_g^h$$

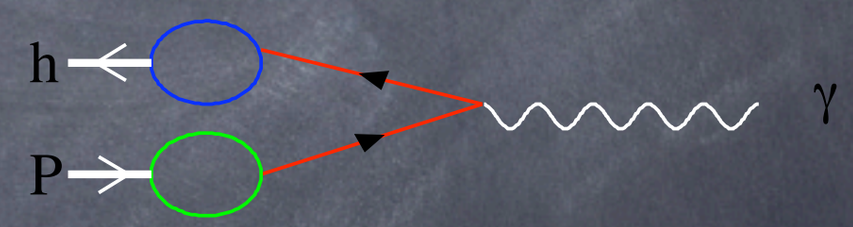
Target fragmentation: fracture functions

initial state partons carry no p_T $\quad f_i(x, Q^2)$

final state hadrons produced collinearly $\quad D_i^h(z, Q^2)$

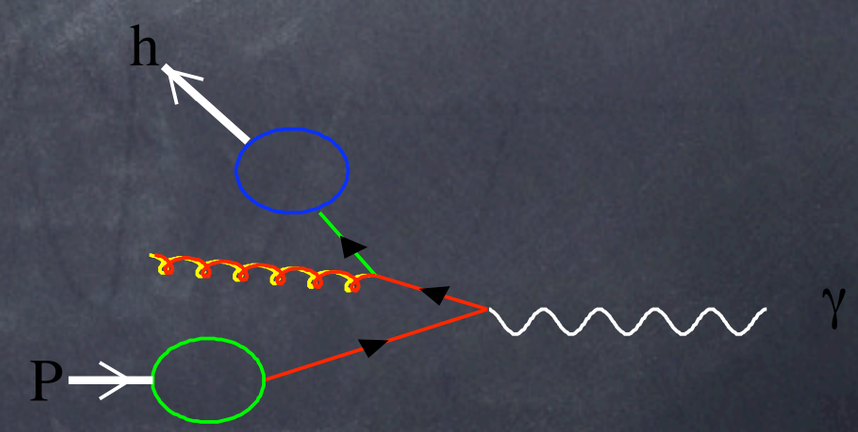
in $\gamma - p$ c.m. frame (lowest order)

(only "backward" hadrons in a collider)



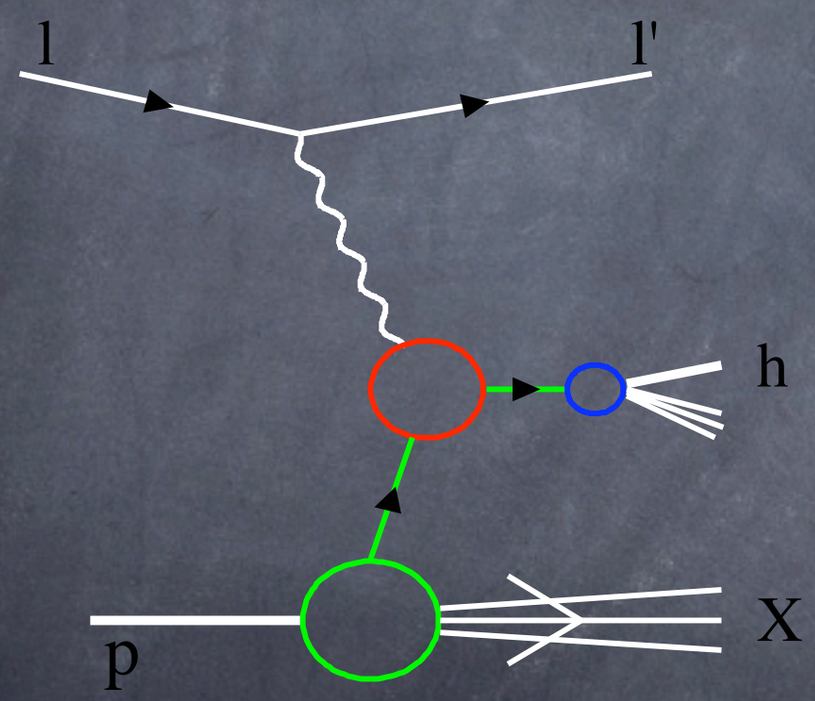
(order α_s)

("forward" hadrons suppressed)

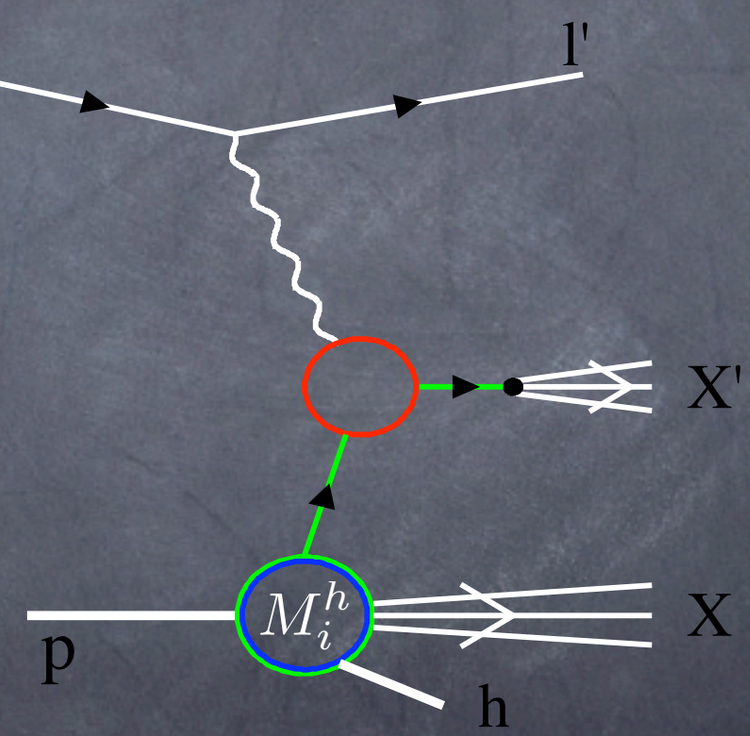


no $\mathcal{O}(\alpha_s^0)$ contribution for "forward" processes

no consistent factorization of (forward) divergencies



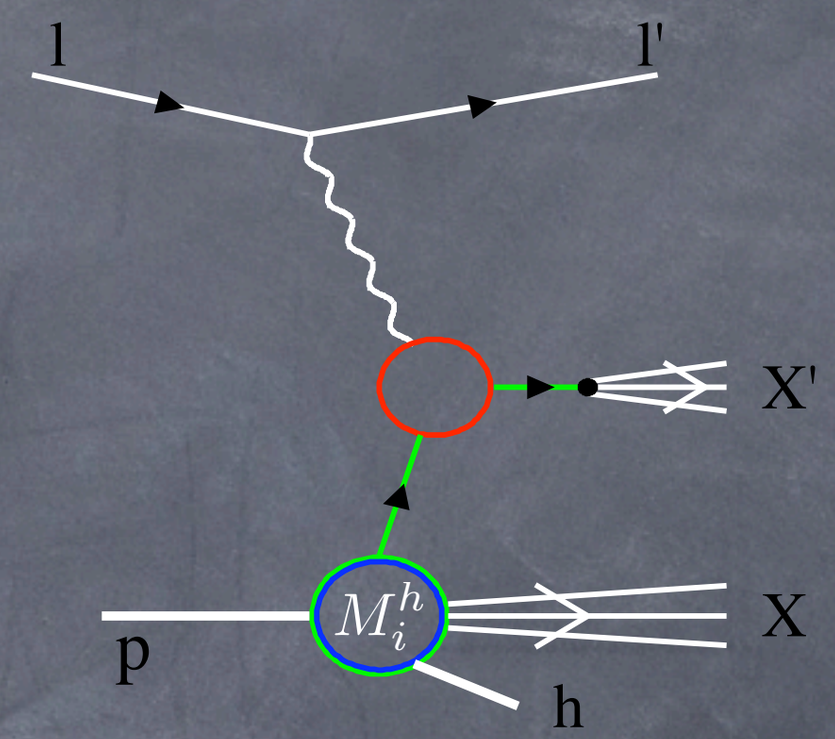
current fragmentation



target fragmentation

$M_i^h(x,z,Q^2)$ fracture functions

$D_i^h(z,Q^2)$ $f_i(x,Q^2)$



$$\frac{\partial\, M_i^h(x,z,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_{\frac{x}{1-z}}^{1} \frac{du}{u}\, P_{i\leftarrow j}(u)\, M_j^h\left(\frac{x}{u}, z, Q^2\right)$$

$$+ \frac{\alpha_s(Q^2)}{2\pi}\, \frac{1}{x} \int_{x}^{\frac{x}{x+z}} \frac{du}{u} \int_{\frac{z}{x}}^{\frac{1-u}{u}} \frac{dv}{v}\, P_{ki\leftarrow j}(u,v)\, f_j\left(\frac{x}{u}, Q^2\right)\, D_k\left(\frac{z}{x\,v}, Q^2\right)$$

"non-homogeneous evolution"

Global fits FFs:

increasing interest in accurate FFs:

precise one particle inclusive measurements

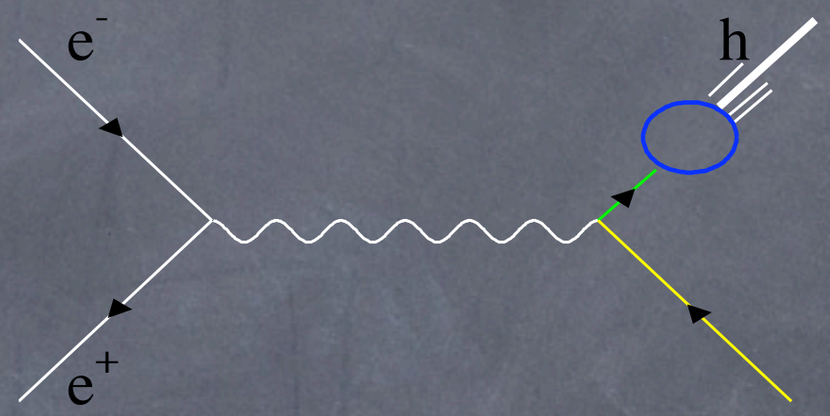
full NLO framework available

recent NLO analyses:

CGGRW(1994), BFGW(2000)	$D_q^{h^\pm}$	L. Bourhis et al., Eur.Phys.J C19 (2001) 89
BKK(1995), KKP(2000), AKK(2005), AKK(2008)	$D_q^{\pi^\pm}$ $D_q^{K^\pm}$ $D_q^{p^\pm}$	S. Albino et al., Nuc.Phys. B725 (2005) 206
KRE(2000)	$D_q^{\pi^+}$ $D_q^{\pi^-}$ $D_q^{K^+}$ $D_q^{K^-}$ $\ldots$	S. Kretzer et al., Phys.Rev. D62 (2000) 0540001
HKNS(2007)	uncertainies	M. Hirai et al., Phys.Rev. D75 (2007) 094009

Standard FFs analyses:

$$e^+e^- \to (\gamma,\, Z) \to H$$



$$\frac{1}{\sigma_{tot}}\frac{d\sigma^H}{dz} = \frac{\sigma_0}{\sum_q \hat{e}_q^2}\left[2\,F_1^H(z,Q^2) + F_L^H(z,Q^2)\right]$$

$$2F_1^H(z,Q^2) \;=\; \sum_q \hat{e}_q^2 \left\{ \left[D_q^H(z,Q^2) + D_{\bar{q}}^H(z,Q^2)\right] + \frac{\alpha_s(Q^2)}{2\pi}\left[C_q^1 \otimes \left(D_q^H + D_{\bar{q}}^H\right) + C_g^1 \otimes D_g^H\right](z,Q^2) \right\}$$

SIA can only give information on the sum $D_q^H(z,Q^2) + D_{\bar{q}}^H(z,Q^2)$!

gluon fragmentation strongly suppressed $\sim \frac{\alpha_s(M_Z^2)}{2\pi}$

ansatz needed if only SIA or charge averaged data used,

"linear suppression"

$$D_{\bar{q}}^{h^+}(z,Q^2) \overset{??}{=} (1-z)\, D_q^{h^+}(z,Q^2)$$

Further disadvantages:

SIA data dominated by precise LEP/SLD measurements at M_Z

mostly determine "singlet" distribution:

$$\Sigma = D_u + D_{\bar{u}} + D_d + D_{\bar{d}} + D_s + D_{\bar{s}} + D_c + D_{\bar{c}} + D_b + D_{\bar{b}}$$

bad resolution for g fragmentation

not precise at large z (relevant for pp collisions)

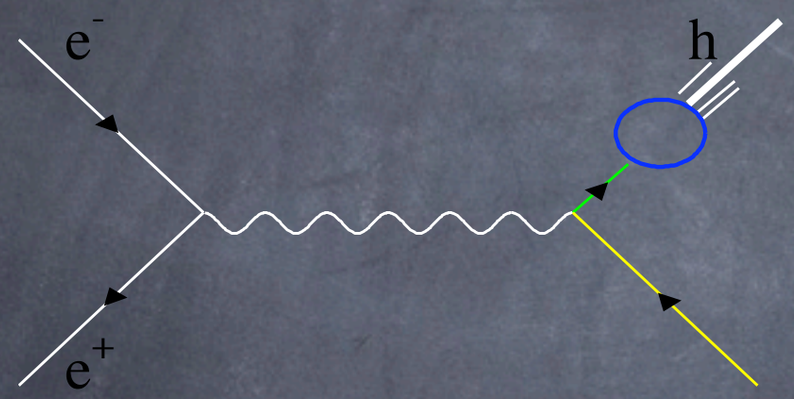
DSS set of FFs:

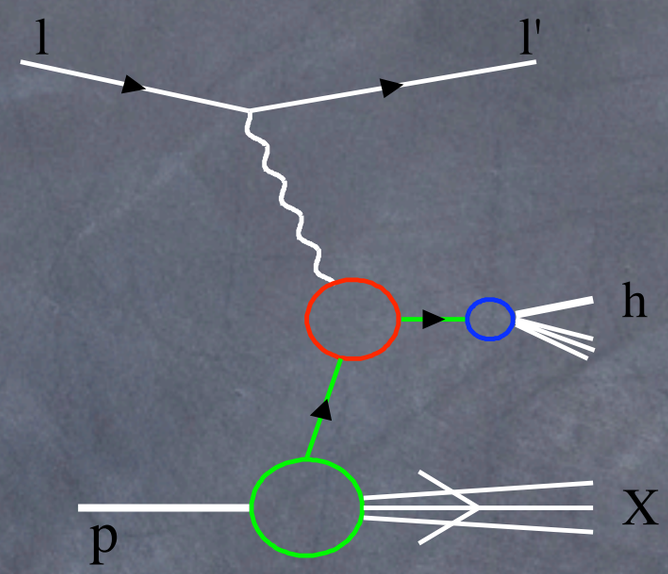
D.de Florian, R.S., M. Stratmann 2007

$D^H_{q+\overline{q}}(z, Q^2)$

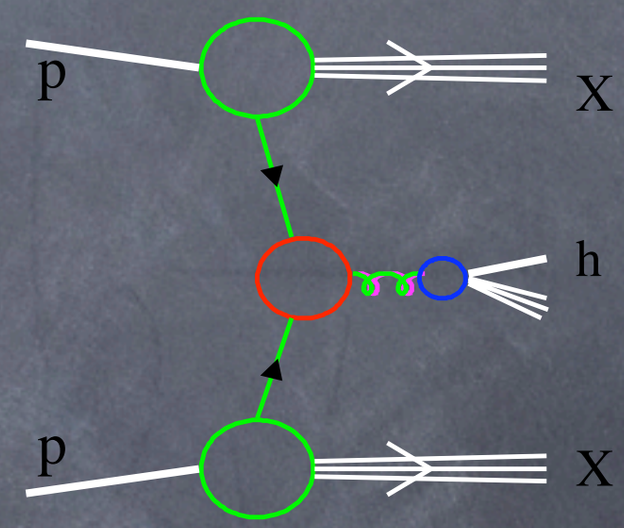
$D^H_q(z, Q^2)\, D^H_{\overline{q}}(z, Q^2)$

$D^H_g(z, Q^2)$





charge & flavor separation



gluon fragmentation

DSS set of FFs:

Flexible parametrization:

$$D_i^H(z, Q_0^2) = N_i\, z^{\alpha_i} (1-z)^{\beta_i} \left[1 + \gamma_i (1-z)^{\delta_i}\right]$$

at initial scale

$$\begin{aligned} Q_0^2 &= 1\,\mathrm{GeV}^2 \quad u, d, s, g \\ Q_0^2 &= m_Q^2 \quad c, b \end{aligned}$$

with α_s and Λ_{QCD} from MRST

Try to avoid Isospin symmetry assumptions:

breaking of SU(3) in the sea and SU(2) in "favored" FFs (unless data can not discriminate)

$$D_{d+\bar{d}}^{\pi^+} = N D_{u+\bar{u}}^{\pi^+}$$

$$D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = N' D_{\bar{u}}^{\pi^+}$$

for "unfavored" fragmentations

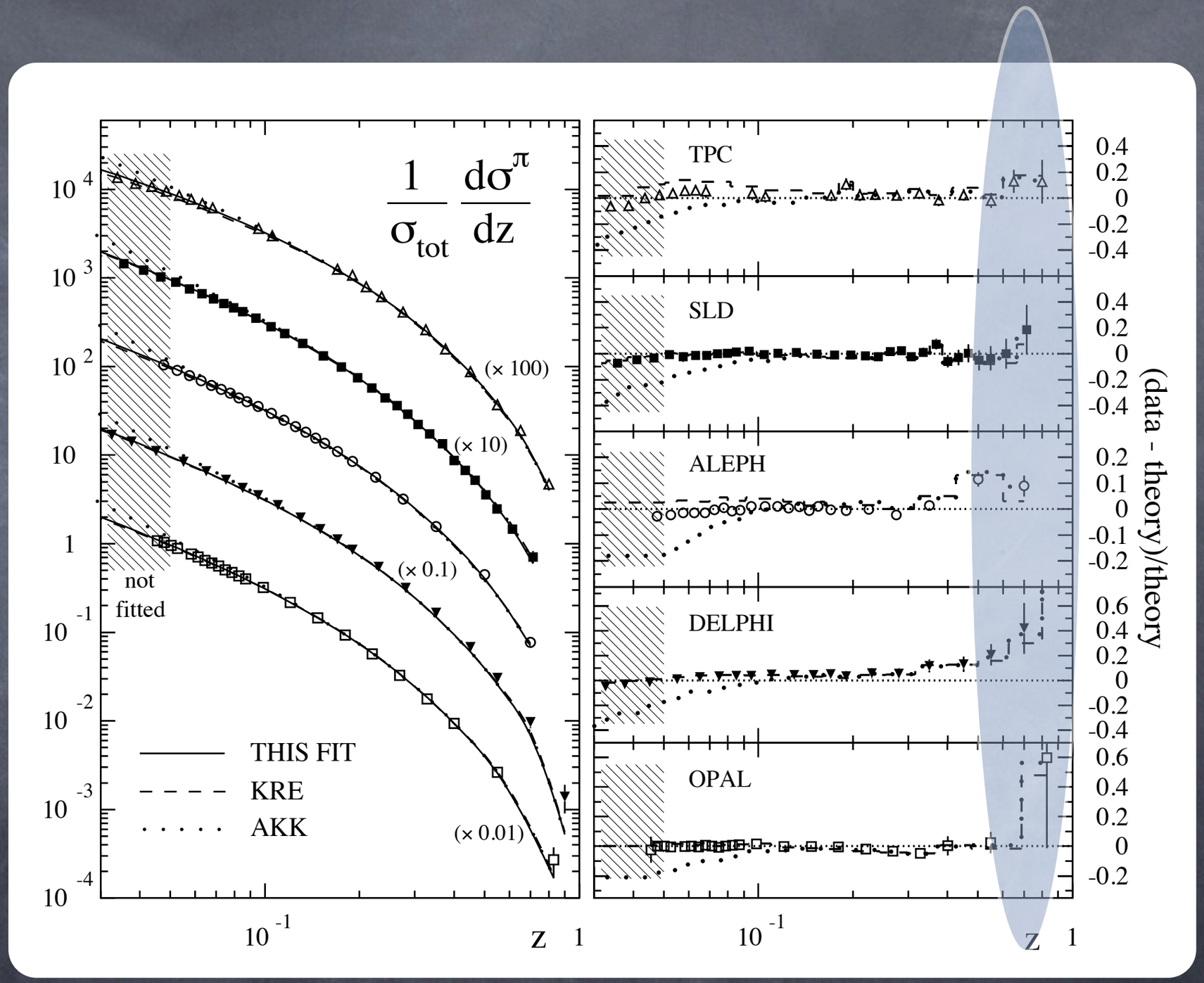
$$D_{\bar{u}}^{\pi^+} = D_d^{\pi^+}$$

$$D_{\bar{u}}^{K^+} = D_s^{K^+} = D_d^{K^+} = D_{\bar{d}}^{K^+}$$

Is it possible to still have a good fit to SIA data?

KRE: S. Kretzer 2000

AKK: S. Albino 2005

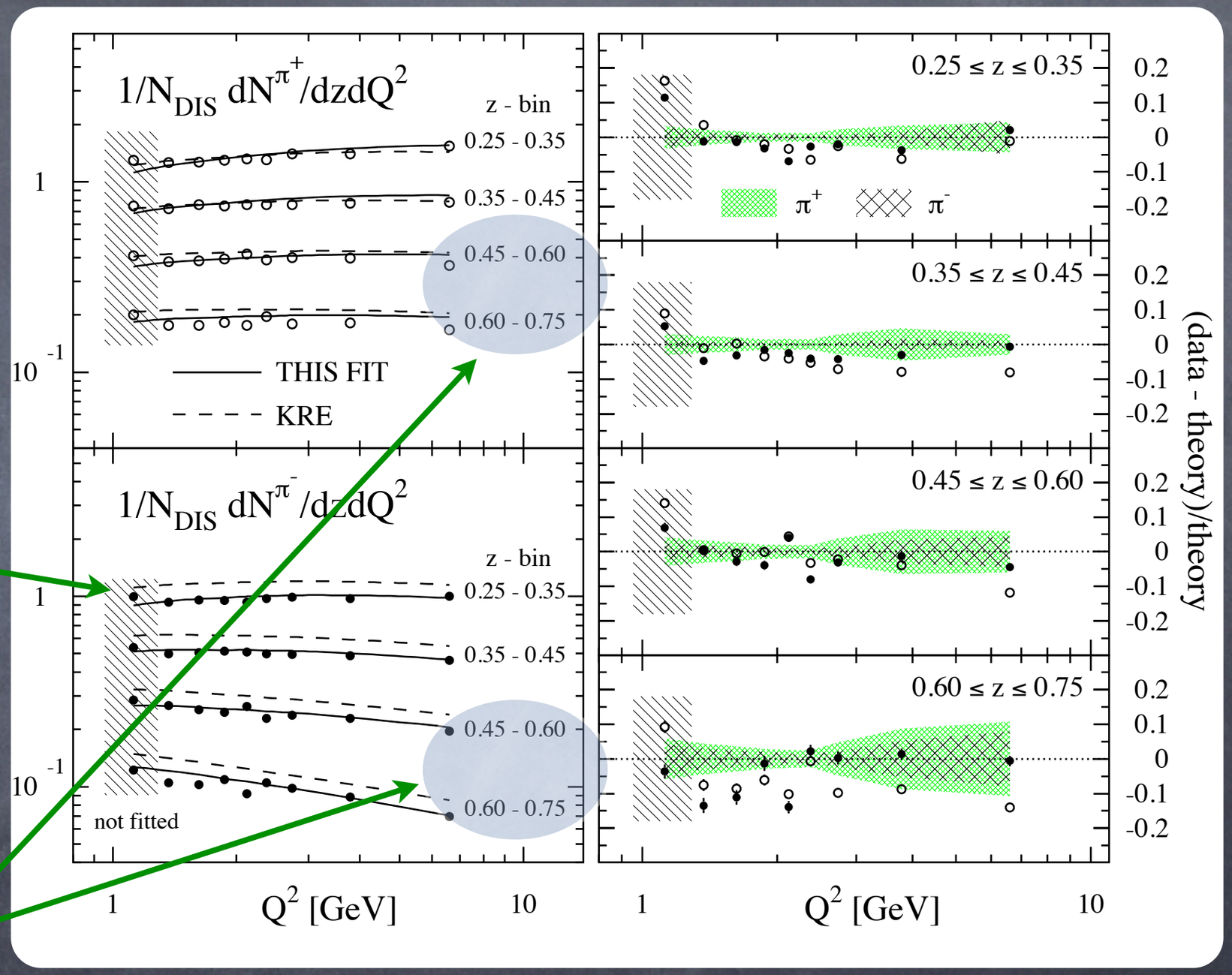


large errors at z > 0.5

Real challenge: SIDIS "charge discriminated" data

ad-hoc charge separation from Kretzer fails

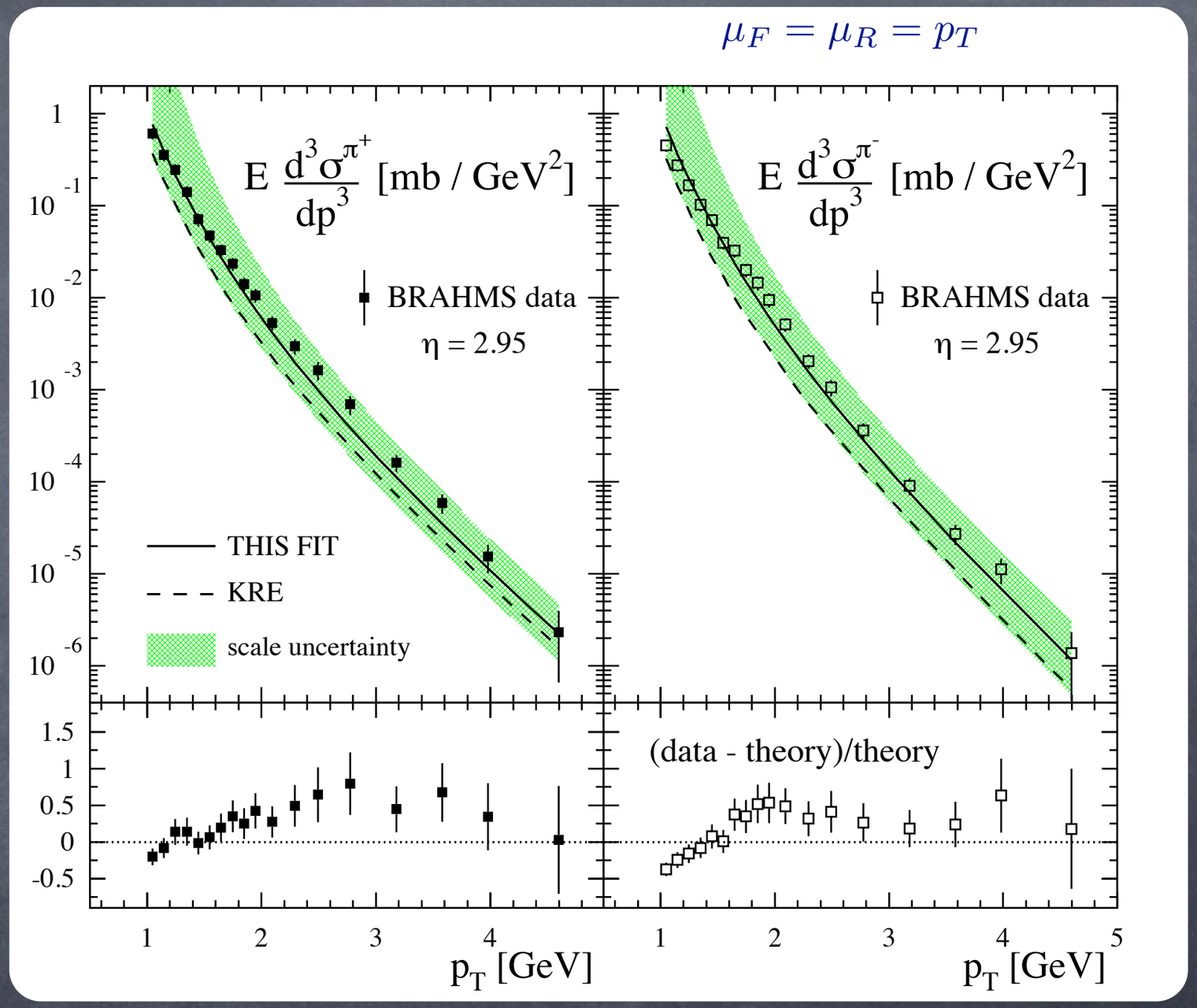
large z covered



HERMES preliminary, A. Hillenbrand PhD Thesis

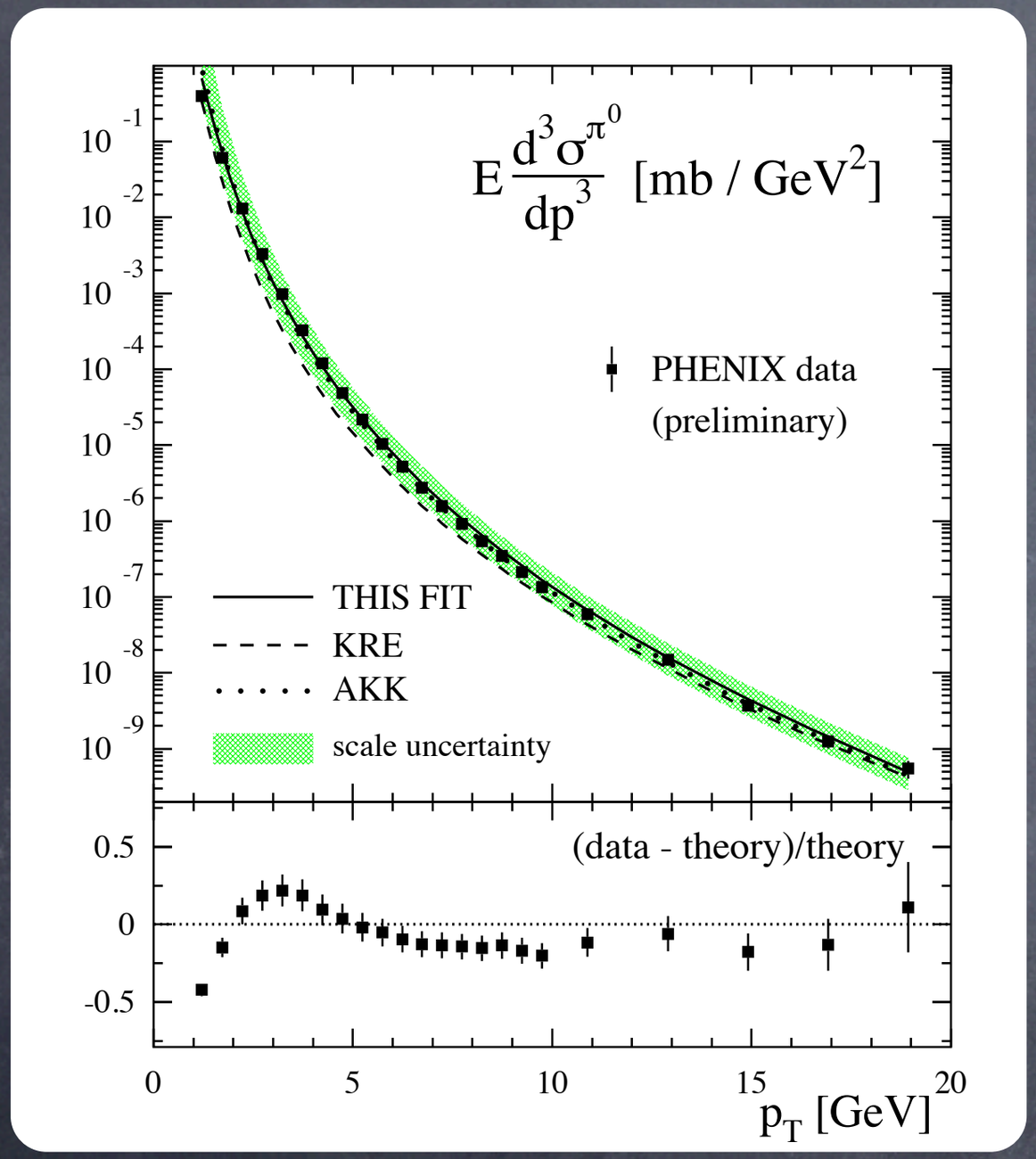
crucial data!

Real challenge: RHIC "charge discriminated" data

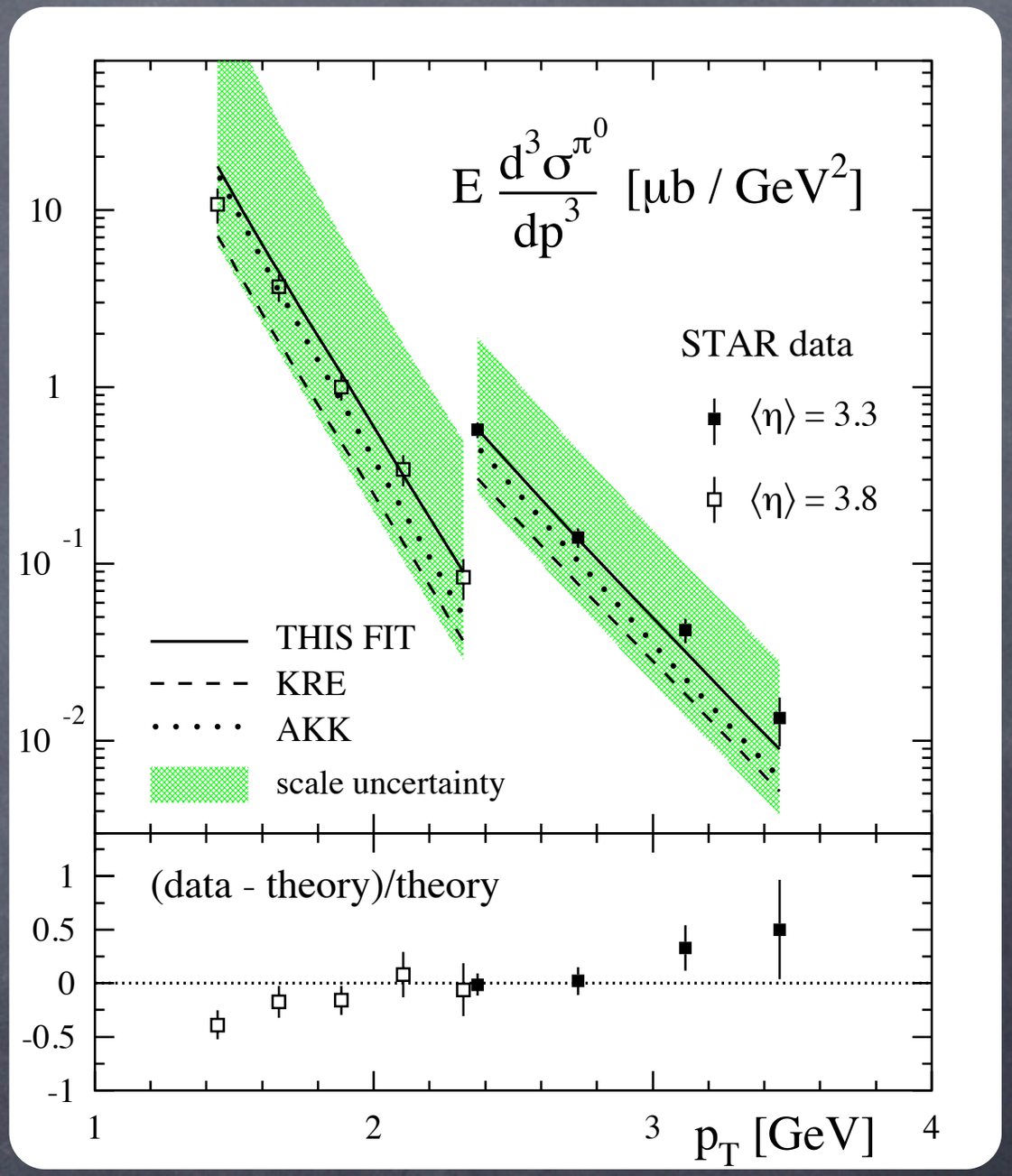


Charged pions (at large z)

$D^h_{q+\bar{q}}(z, Q^2)$ should work for π^0 :



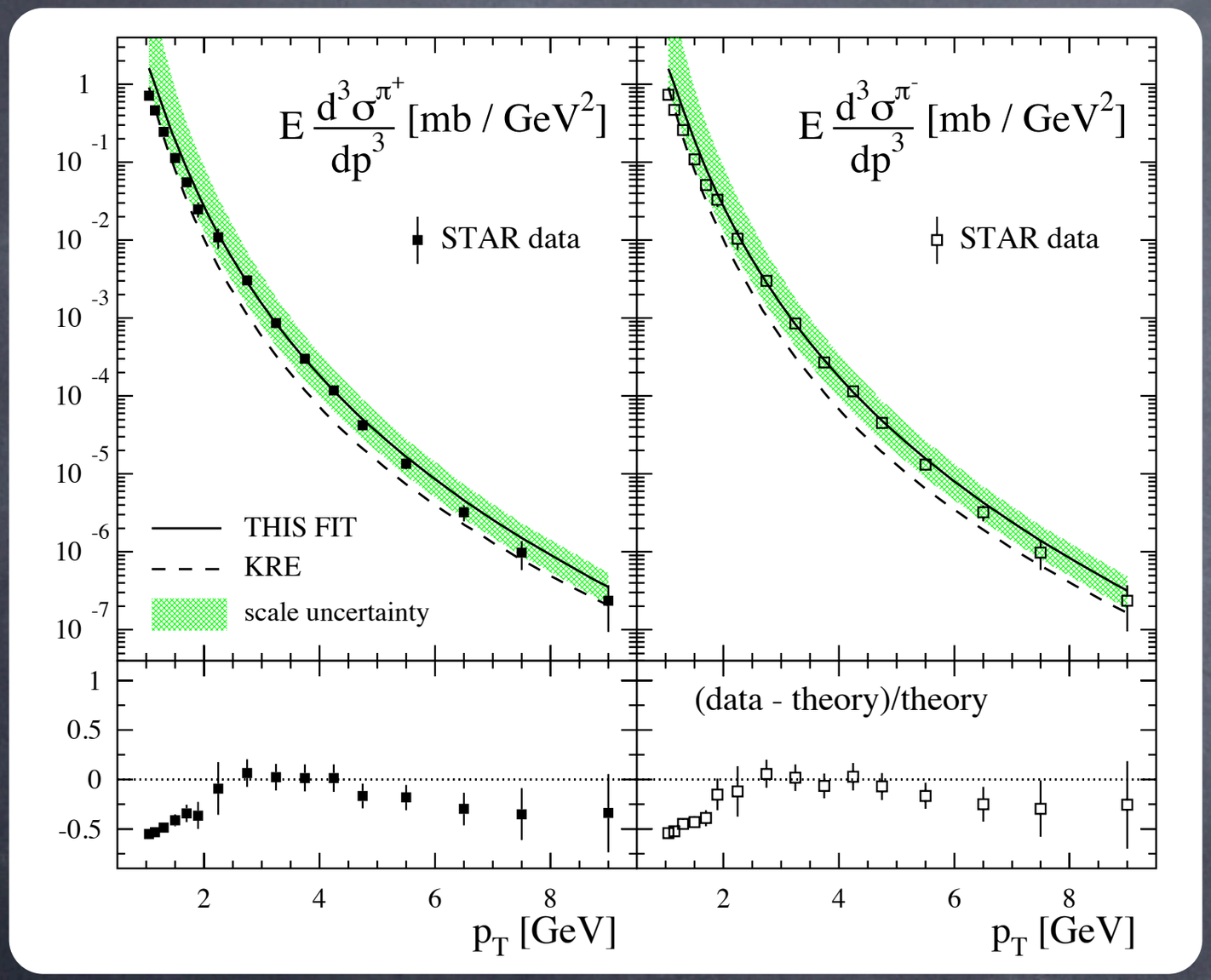
Neutral pions at PHENIX



Neutral pions at STAR

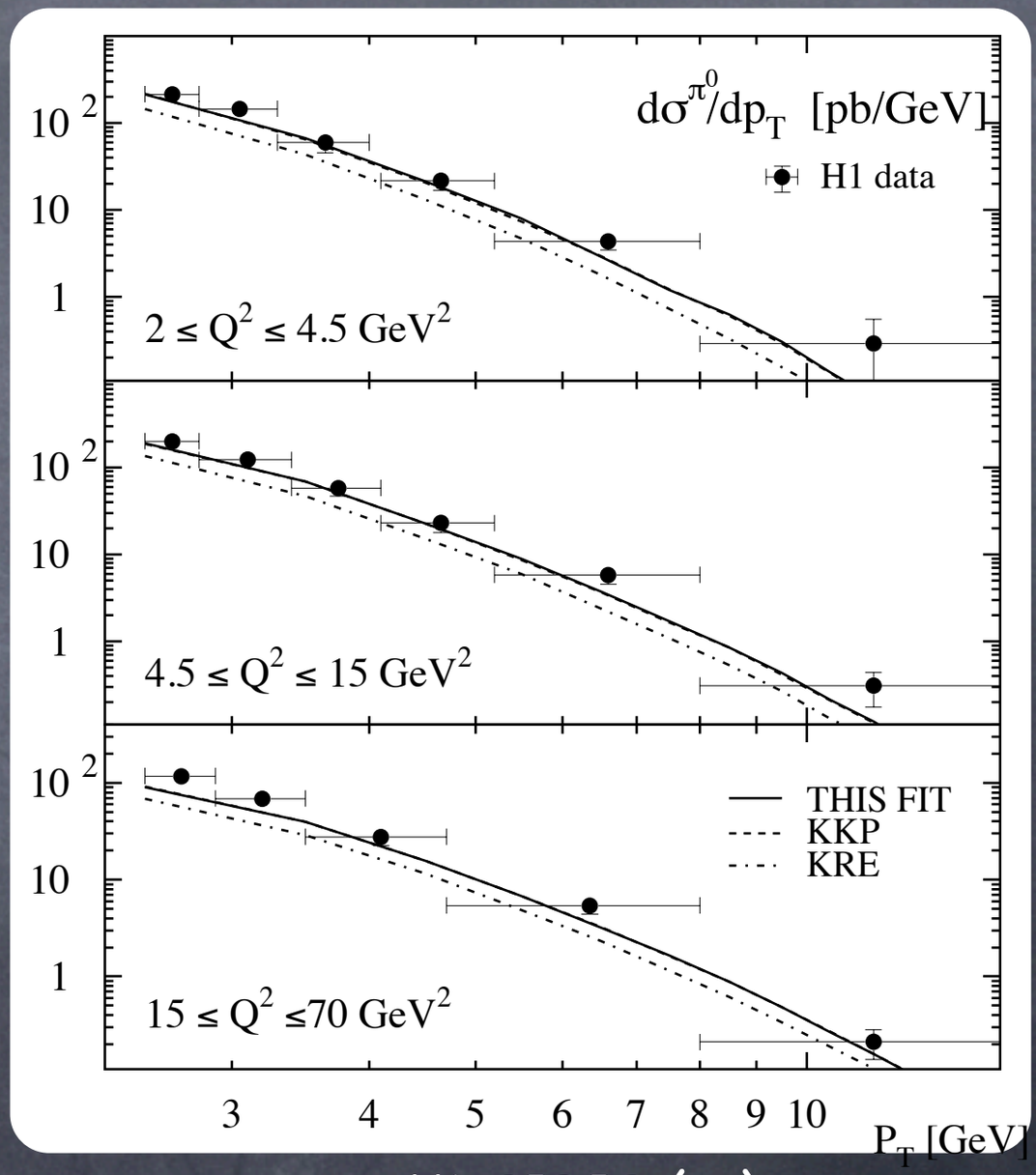
Cross checks:

not included



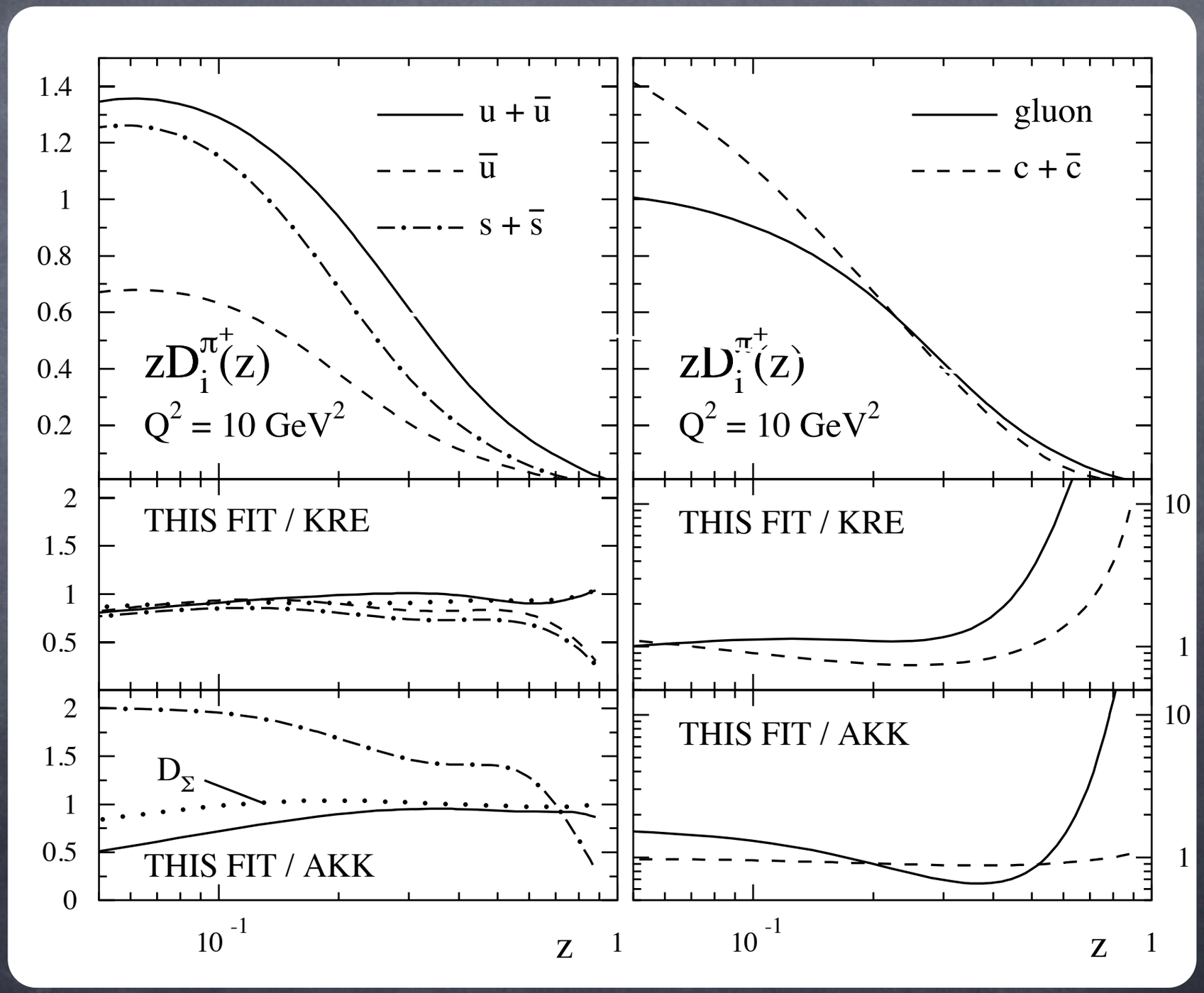
charged pions at STAR

not included

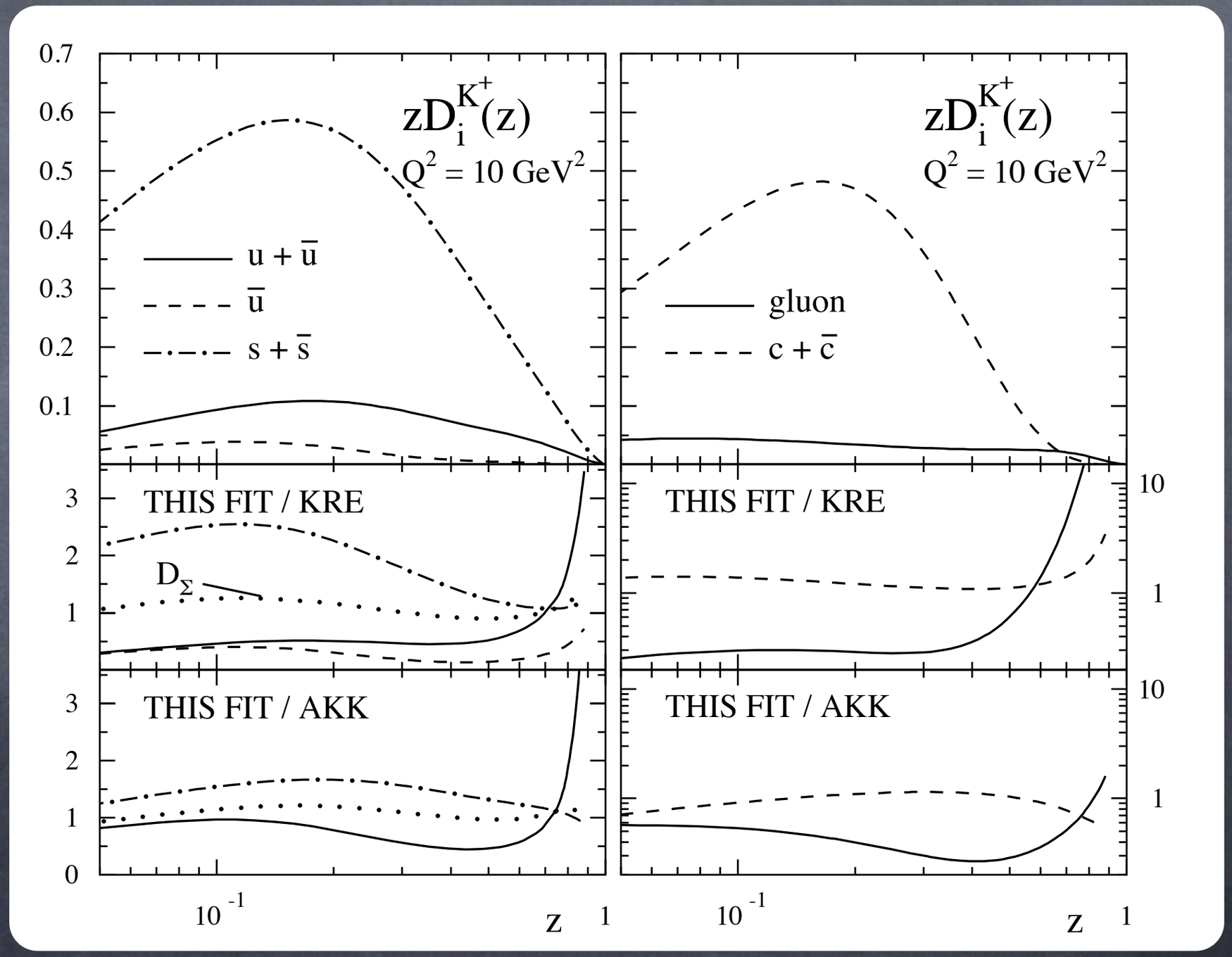


H1 SIDIS (p_T)

FFs (pions)



FFs (Kaons)


$zD_i^{K^+}(z)$
$Q^2 = 10\ GeV^2$
$u + \bar{u}$
$\bar{u}$
$s + \bar{s}$
gluon
$c + \bar{c}$
THIS FIT / KRE
D_Σ
THIS FIT / AKK
z

Uncertainties in PDFs/FFs

How accurate are they?

black box: data → PDFs

data uncertainties → ??

th. uncertainties → ??

fit assumptions → ??

Uncertainties: lagrange multipliers

$$\Delta\mathcal{O}(\{a_j\}) \text{ vs. } \Delta\chi^2$$

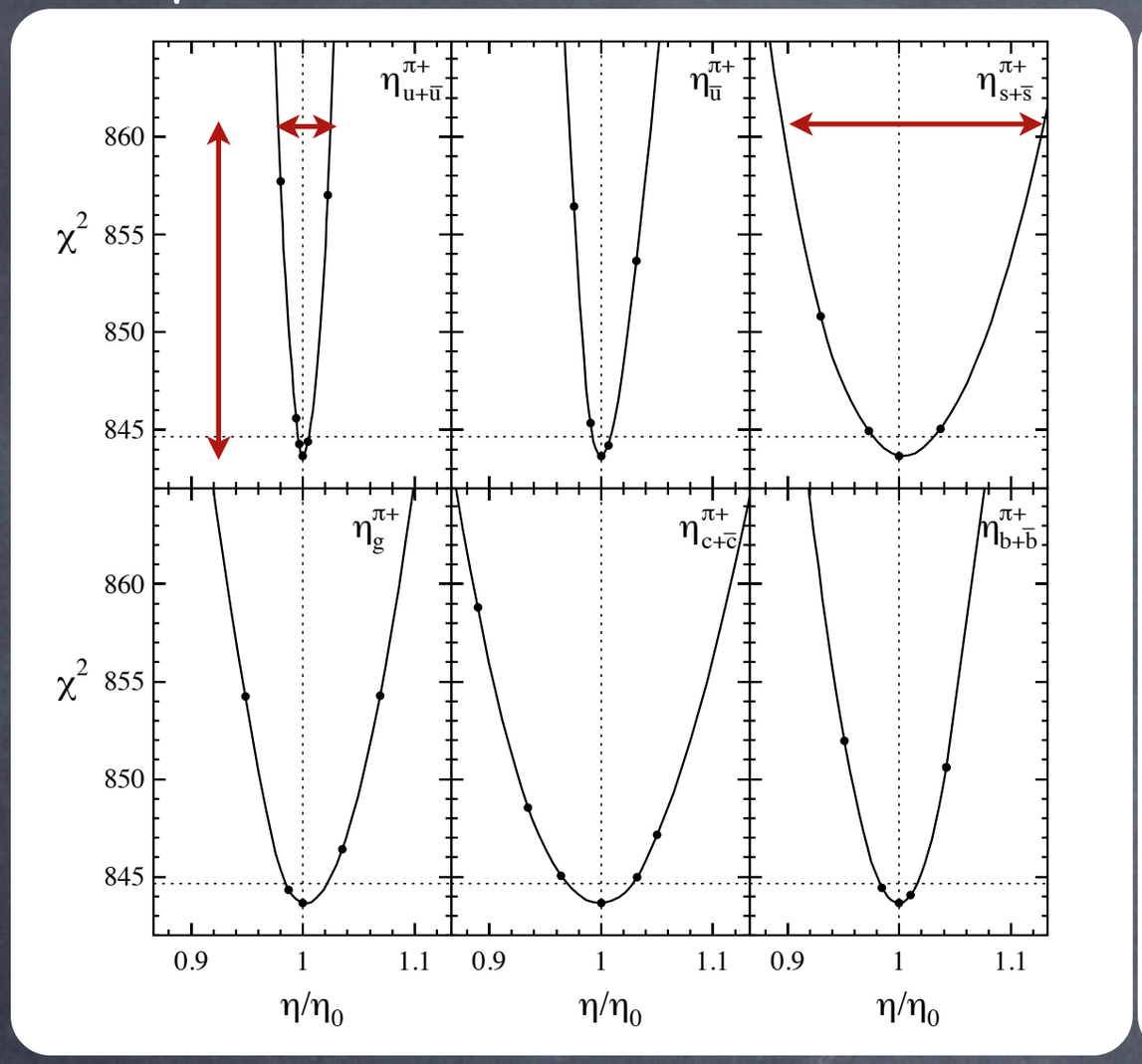
See how fit to data deteriorates when PDFs/FFs forced (artificially) to give different prediction for O({a})

$$\Phi(\lambda_i, \{a_j\}) = \chi^2(\{a_j\}) + \sum_i \lambda_i \, \mathcal{O}_i(\{a_j\})$$

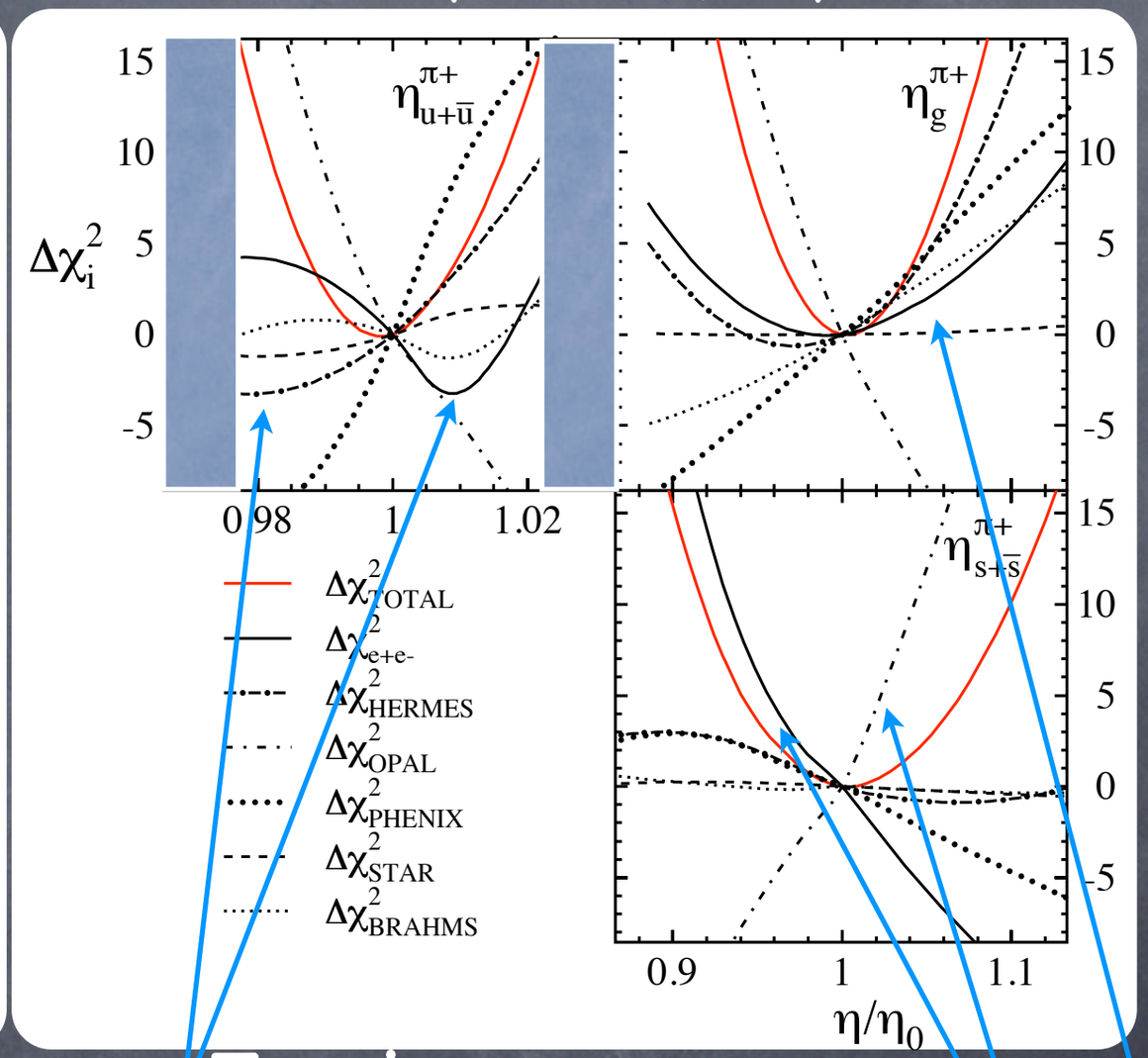
We study truncated moments: $\int_{0.2}^{1} z \, D_i^H(z, Q = 5\,\text{GeV}) \, dz$

Uncertainties: pions as an example

χ^2 profiles for the different flavors



Individual profiles by experiment



Tension

Complementarity

Precision

$u \sim 2\,\%$

$s \sim 10\,\%$

$\Delta\chi^2 = 15 (\simeq 2\%)$

Not so nice:

NLO

experiment	data type	rel. norm. in fit	data points fitted	χ^2
TPC [15]	incl.	0.94	17	18.5
	"*uds* tag"	0.94	9	1.9
	"*c* tag"	0.94	9	5.7
	"*b* tag"	0.94	9	7.4
TASSO [17]	incl. (34 GeV)	0.94	11	30.1
	incl. (44 GeV)	0.94	7	20.5
SLD [16]	incl.	1.008	28	14.0
	"*uds* tag"	1.008	17	11.6
	"*c* tag"	1.008	17	11.1
	"*b* tag"	1.008	17	33.2
ALEPH [11]	incl.	0.97	22	38.3
DELPHI [12]	incl.	1.0	17	42.3
	"*uds* tag"	1.0	17	26.4
	"*b* tag"	1.0	17	42.8
OPAL [13, 14]	incl.	1.0	21	9.2
	"*u* tag"	1.10	5	11.8
	"*d* tag"	1.10	5	9.0
	"*s* tag"	1.10	5	49.8
	"*c* tag"	1.10	5	38.3
	"*b* tag"	1.10	5	73.0
HERMES [18]	π^+	1.03	32	67.4
	π^-	1.03	32	120.8
PHENIX [19]	π^0	1.09	23	76.4
STAR [23]	π^0, $\langle\eta\rangle = 3.3$	1.05	4	3.4
	π^0, $\langle\eta\rangle = 3.7$	1.05	5	9.8
BRAHMS [22]	π^+, $\langle\eta\rangle = 2.95$	1.0	18	28.2
	π^-, $\langle\eta\rangle = 2.95$	1.0	18	43.0
TOTAL:			392	843.7

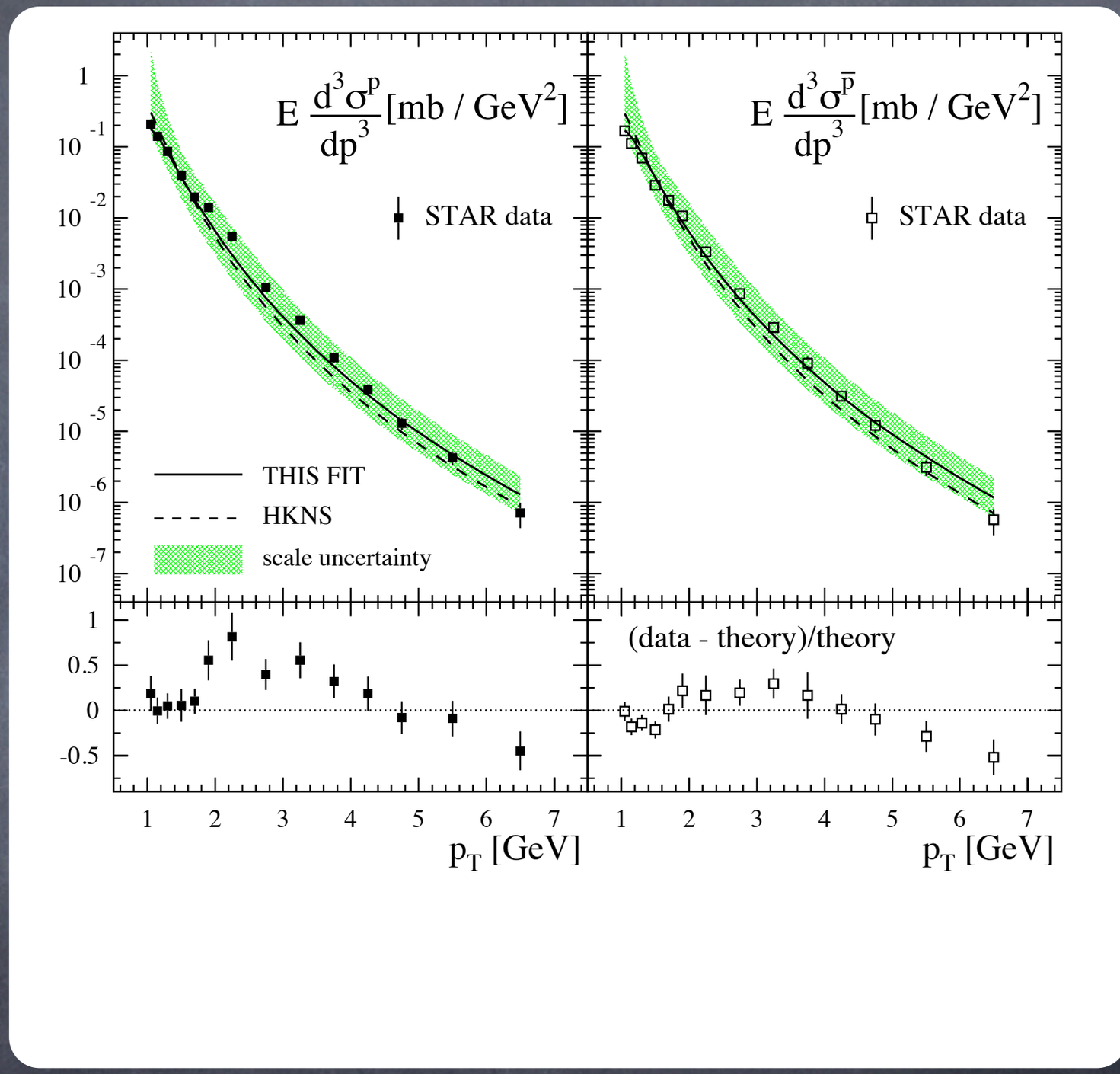
LO

experiment	data type	rel. norm. in fit	data points fitted	χ^2
TPC [15]	incl.	0.94	17	22.7
	"*uds* tag"	0.94	9	1.9
	"*c* tag"	0.94	9	5.6
	"*b* tag"	0.94	9	7.3
TASSO [17]	incl. (34 GeV)	0.94	11	48.1
	incl. (44 GeV)	0.94	7	21.5
SLD [16]	incl.	1.007	28	20.9
	"*uds* tag"	1.007	17	21.3
	"*c* tag"	1.007	17	9.3
	"*b* tag"	1.007	17	34.5
ALEPH [11]	incl.	0.97	22	64.4
DELPHI [12]	incl.	1.0	17	45.9
	"*uds* tag"	1.0	17	30.6
	"*b* tag"	1.0	17	51.9
OPAL [13, 14]	incl.	1.0	21	20.7
	"*u* tag"	1.10	5	9.3
	"*d* tag"	1.10	5	7.5
	"*s* tag"	1.10	5	66.7
	"*c* tag"	1.10	5	36.9
	"*b* tag"	1.10	5	88.8
HERMES [18]	π^+	1.03	32	53.6
	π^-	1.03	32	153.9
PHENIX [19]	π^0	1.09	23	82.2
STAR [23]	π^0, $\langle\eta\rangle = 3.3$	0.95	4	15.5
	π^0, $\langle\eta\rangle = 3.7$	0.95	5	11.7
BRAHMS [22]	π^+, $\langle\eta\rangle = 2.95$	1.0	18	46.3
	π^-, $\langle\eta\rangle = 2.95$	1.0	18	77.7
TOTAL:			392	1056.8

20%!

Protons, anti-protons, and charged hadrons

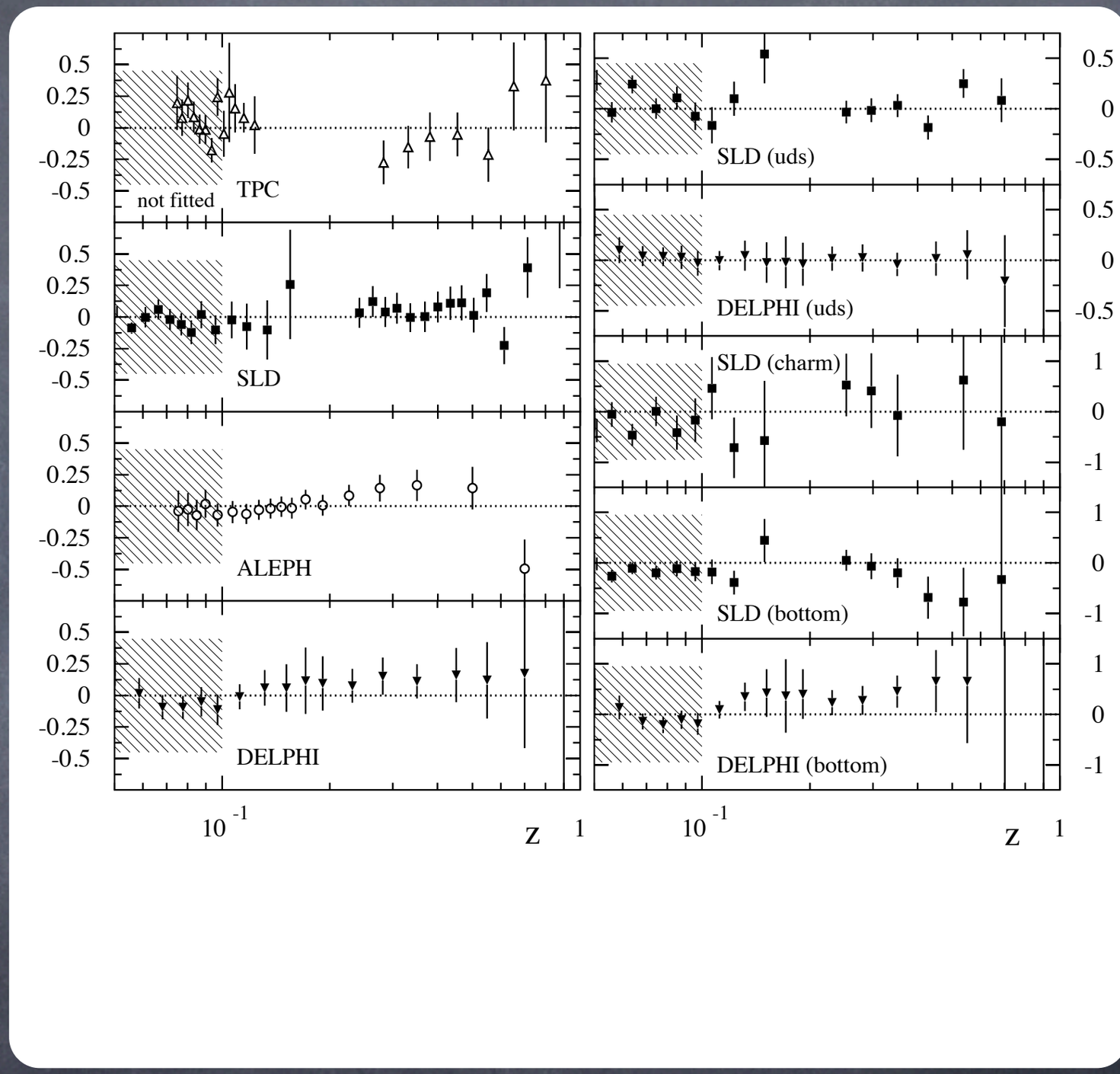
D_i^p $D_i^{\overline{p}}$



Protons, anti-protons, and charged hadrons

D_i^p $D_i^{\overline{p}}$ $D_i^{h^+}$ $D_i^{h^-}$

$$h^\pm \equiv \pi^\pm + K^\pm + p^\pm + res$$



Protons, anti-protons, and charged hadrons

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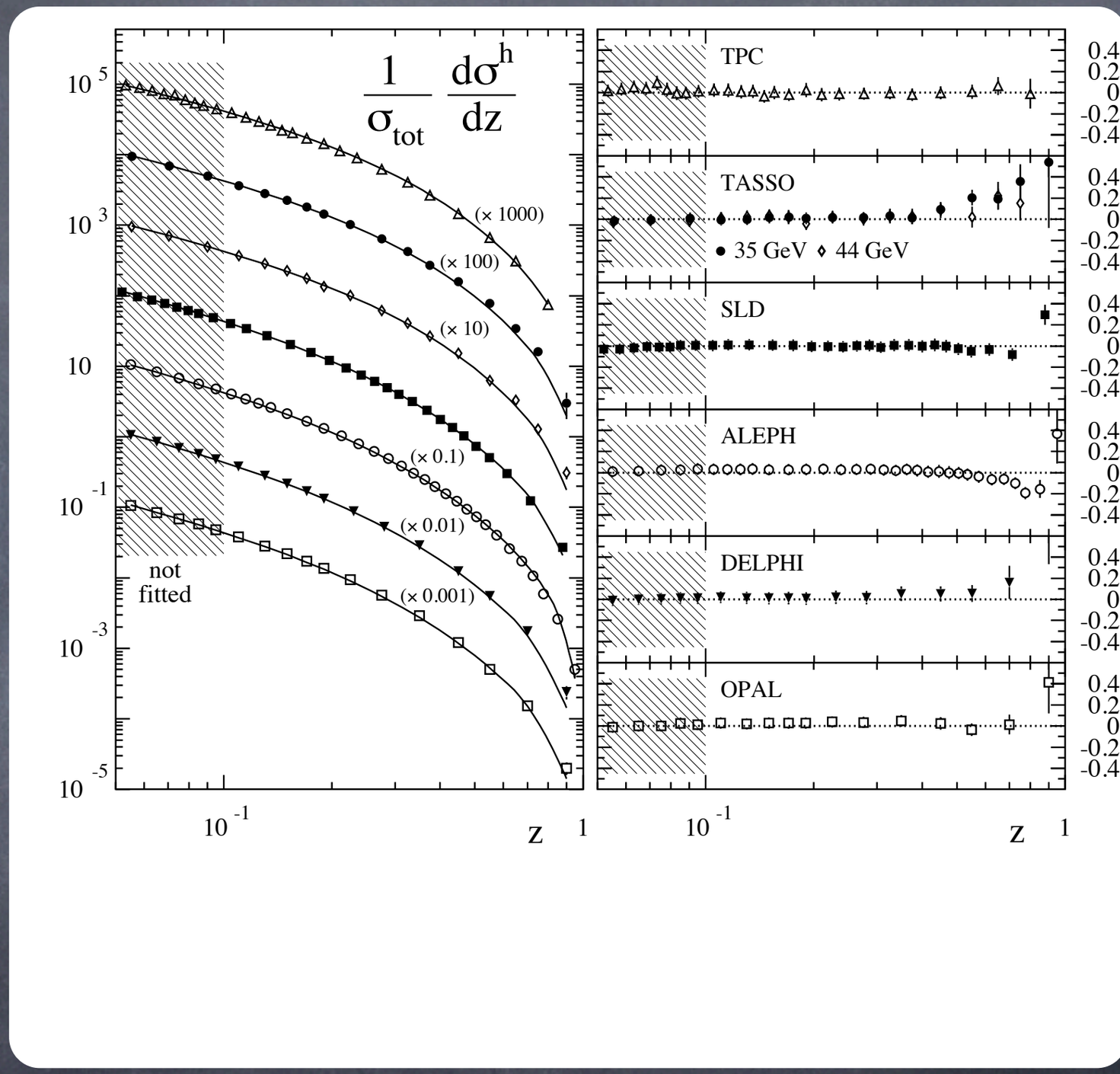

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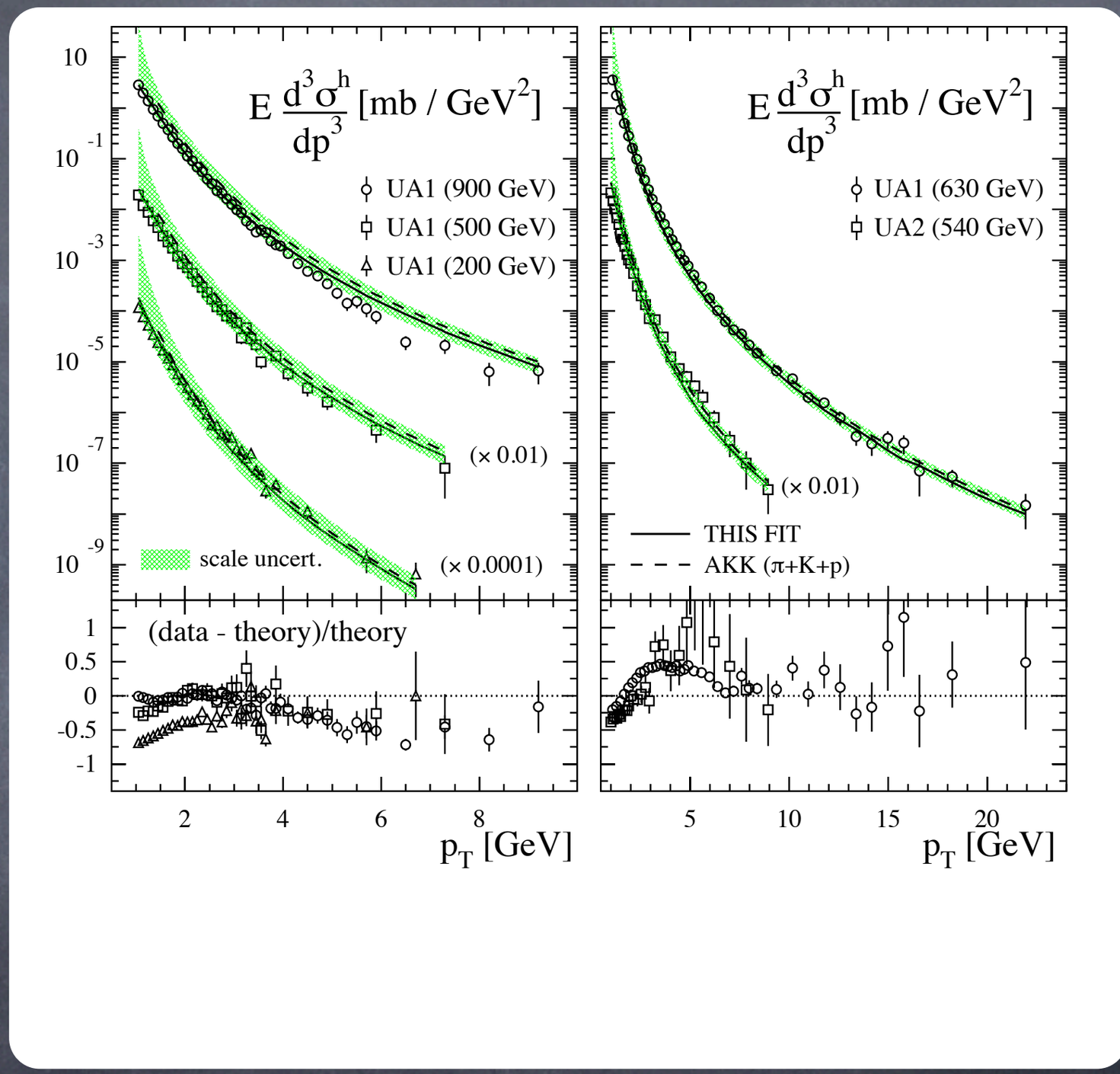

Protons, anti-protons, and charged hadrons

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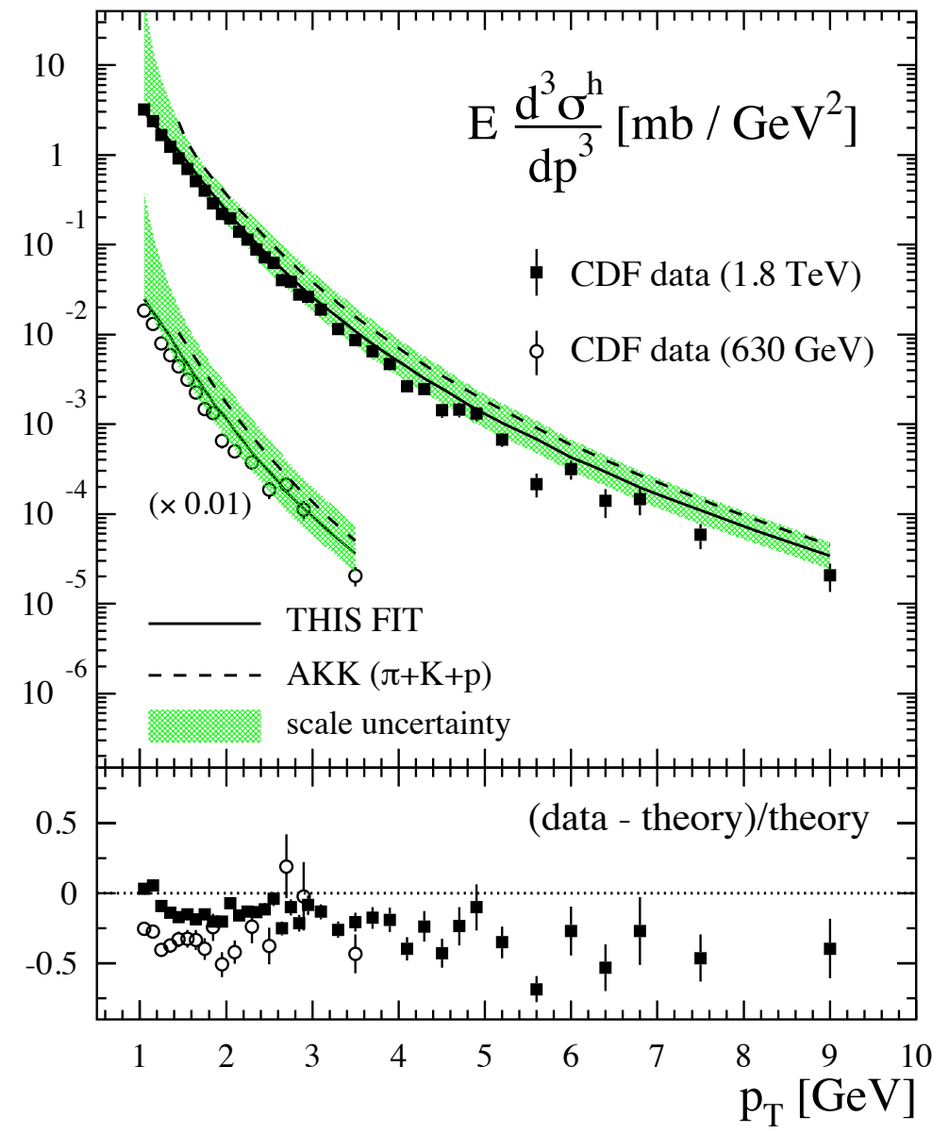

Protons, anti-protons, and charged hadrons

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