QCD
al tempo di
LHC

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Strong interactions

- ## High-energy collisions

  Fixed-target experiments (pN, πN, γN)
  DIS (HERA)
  Hadron colliders (Tevatron, LHC)

- ## Hadron properties

  Hadron masses
  Hadron decays

- ## High-density media

  Heavy-ion collisions (RHIC, LHC)
  Star formation and evolution

QCD

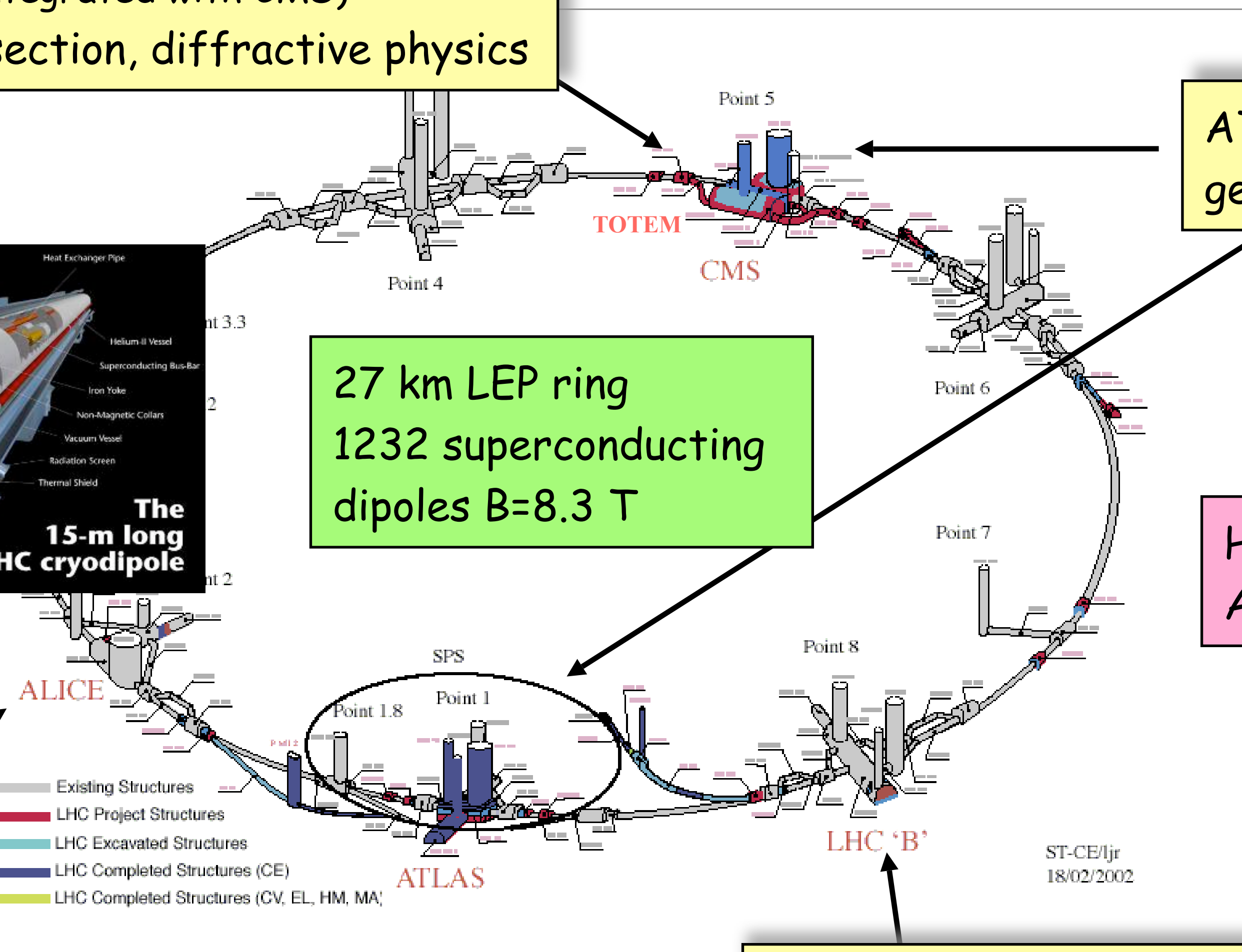
- an unbroken Yang-Mills gauge field theory featuring asymptotic freedom and confinement
- in non-perturbative regime (low Q^2) many approaches: lattice, Regge theory, χ PT, large N_c, HQET
- in perturbative regime (high Q^2) QCD is a precision toolkit for exploring Higgs & BSM physics
- LEP was an electroweak machine
- Tevatron & LHC are QCD machines

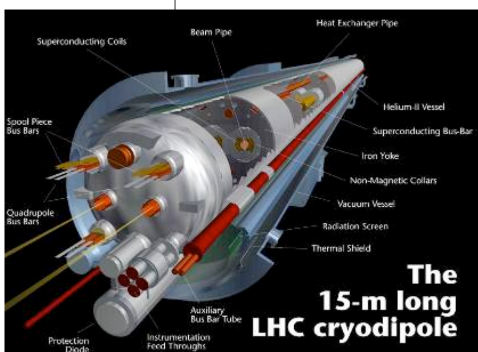
LHC

- pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2009)
  $L_{initial} \leq$ few x $10^{33}\ cm^{-2}\ s^{-1}$ (until 2009)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

TOTEM (integrated with CMS):
pp, cross-section, diffractive physics

ATLAS and CMS :
general purpose





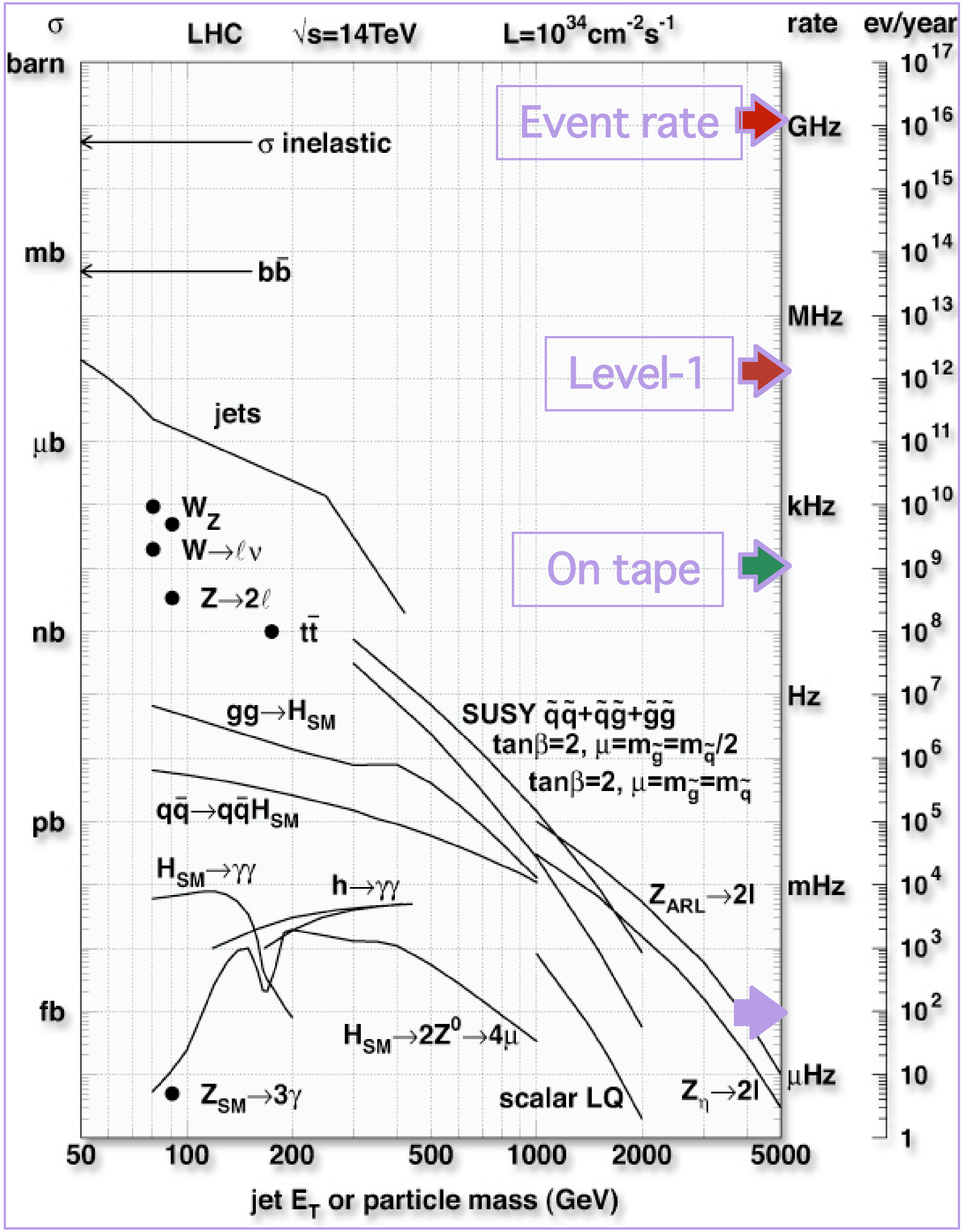
27 km LEP ring
1232 superconducting
dipoles B=8.3 T

Here:
ATLAS and CMS

ALICE :
ion-ion,
p-ion

LHCb :
pp, B-physics, CP-violation

LHC is a QCD machine



SM processes are backgrounds to New Physics signals

design luminosity

$L = 10^{34}\ cm^{-2}\ s^{-1} = 10^{-5}\ fb^{-1}\ s^{-1}$

integrated luminosity (per year)

$L \approx 100\ fb^{-1}\ yr^{-1}$

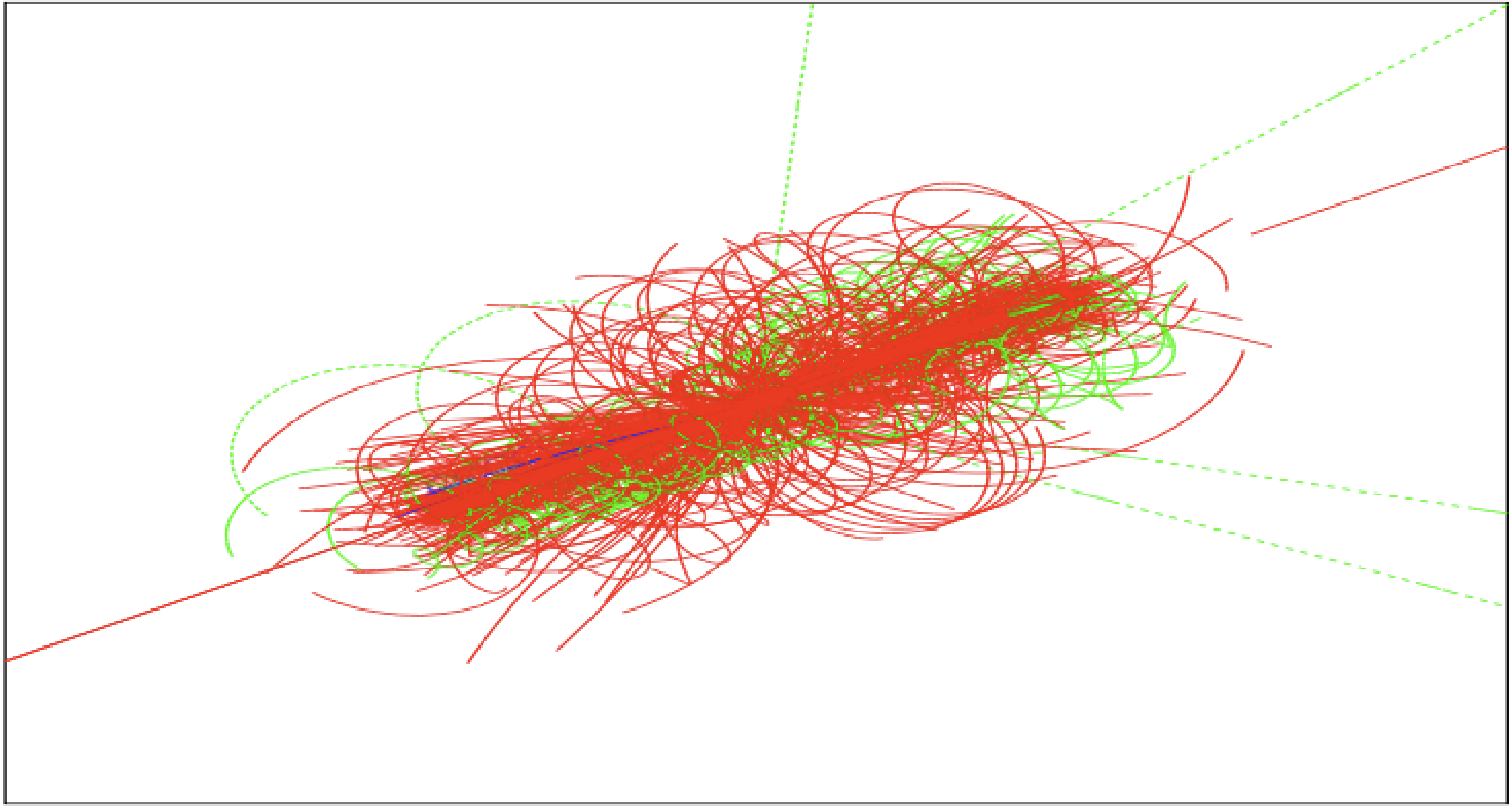
With 1 fb^{-1} we shall get ...

final state	events	overall # of events (2008)
jets (p_T > 100 GeV)	10^9	
jets (p_T > 1 TeV)	10^4	
$W \to e\nu$	$2 \cdot 10^7$	10^7 (Tevatron)
$Z \to e^+e^-$	$2 \cdot 10^6$	10^6 (LEP)
$b\bar{b}$	$5 \cdot 10^{11}$	10^9 (BaBar, Belle)
$t\bar{t}$	$8 \cdot 10^5$	10^4 (Tevatron)

even at very low luminosity, LHC beats all the other accelerators

$H \to ZZ \to 4\mu$

ATLAS simulation



4 dashed straight lines are the μ's
... the remainder are by-product of hadron interactions
but this is a *golden mode*:
if the background is overwhelming it is much worse than that

LHC: the next future

- calibrate the detectors, and re-discover the SM
  i.e. measure known cross sections: jets, $W, Z, t\bar{t}$

- understand the EWSB/find New-Physics signals (ranging from Z' to leptons, to gluinos in SUSY decay chains, to finding the Higgs boson)

- constrain and model the New-Physics theories

in all the steps above (except probably Z' to leptons)

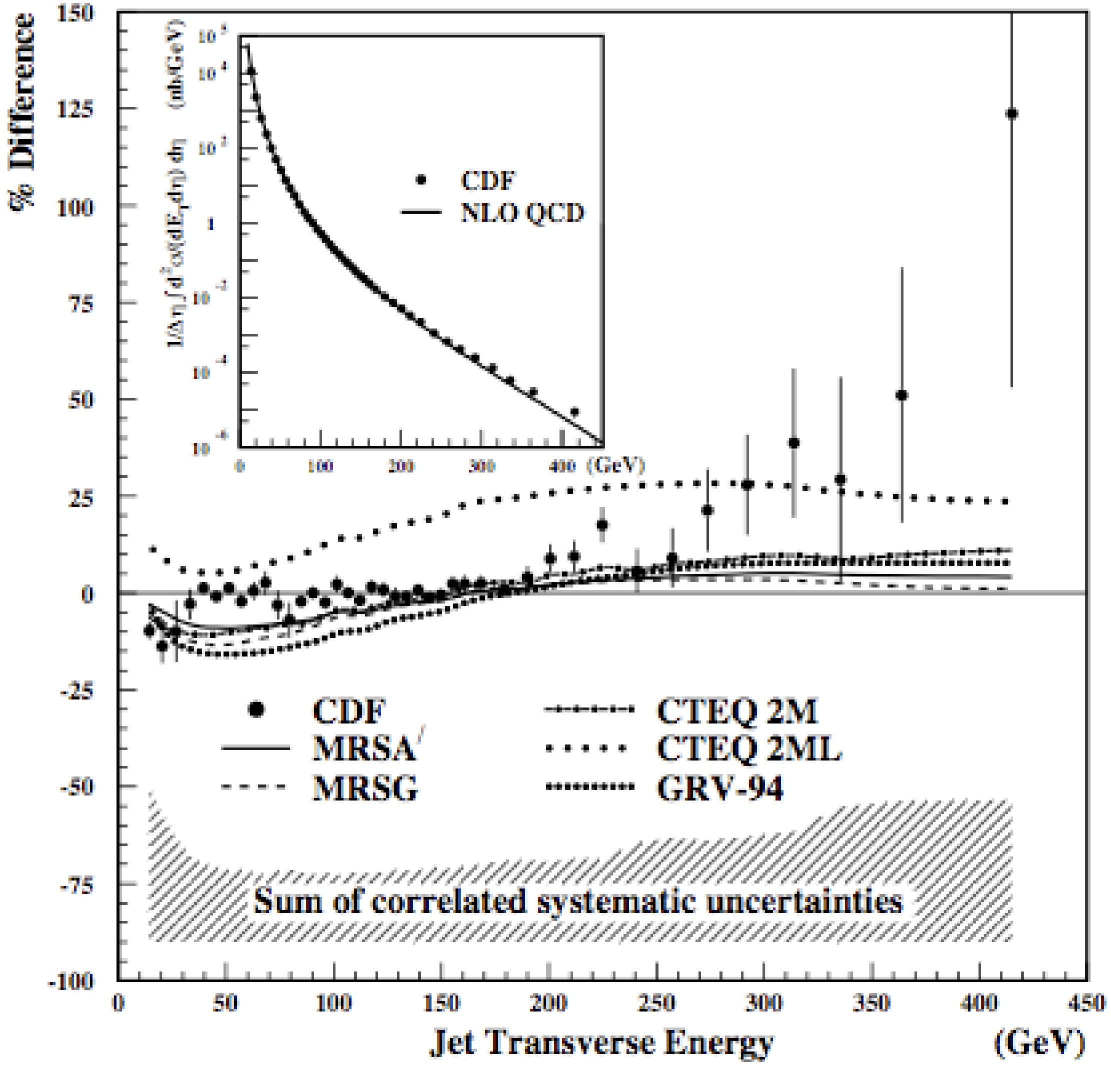
precise QCD predictions play a crucial role

Tales from the past - 1

Jets at high transverse energy

inclusive 1-jet spectrum

CDF Collab. PRL 77 (1996) 438



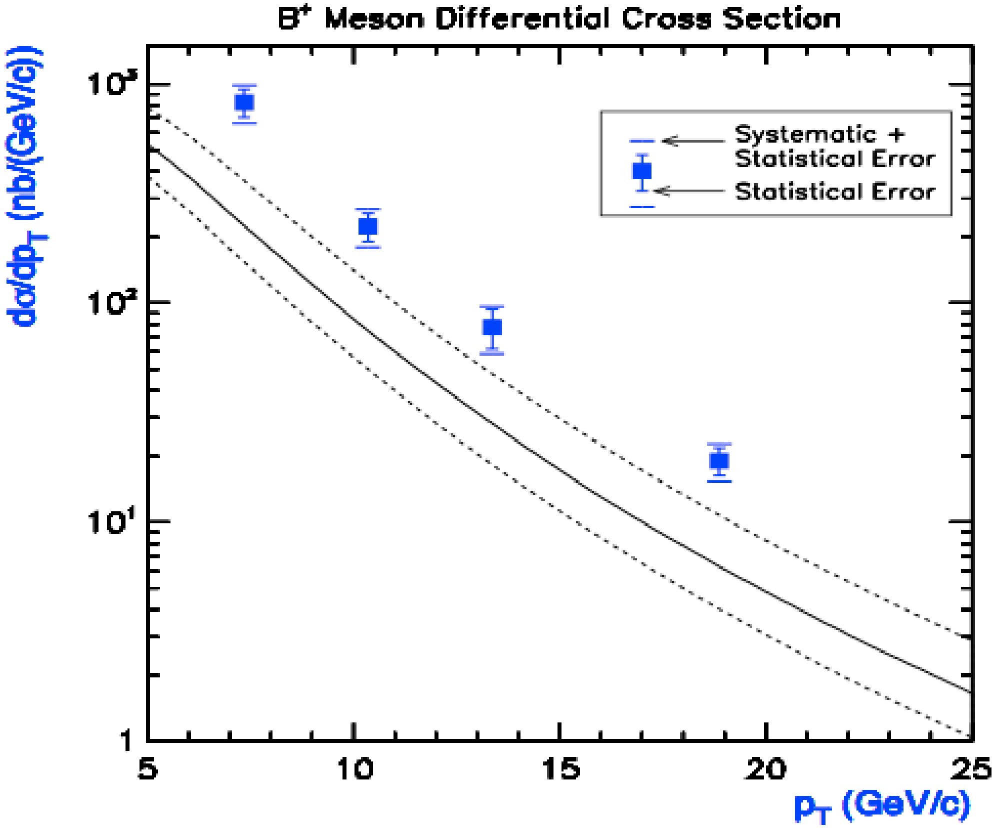
excess of data over theory

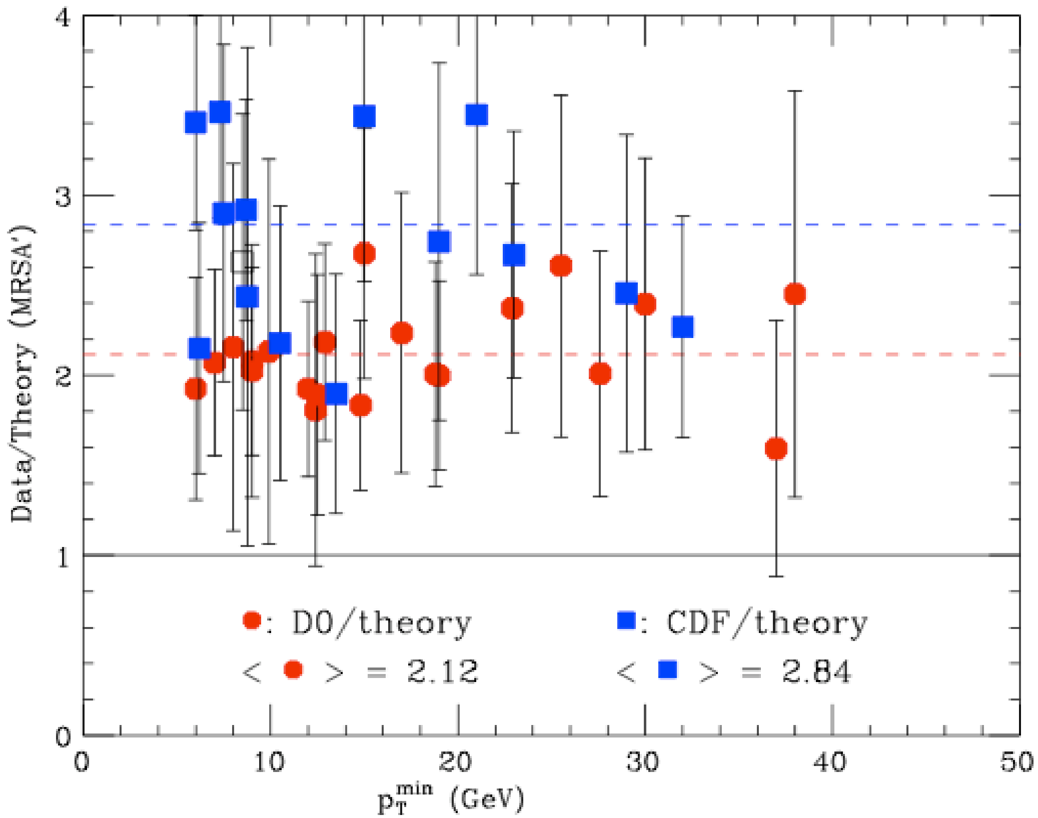
Could it be contact interactions ?
⇒ New Physics ?

more prosaic explanation:
gluon density at high *x*
was largely unknown;
use Tevatron 2-jet data
to measure it:
no more excess

Tales from the past - 2

B production: the 90's

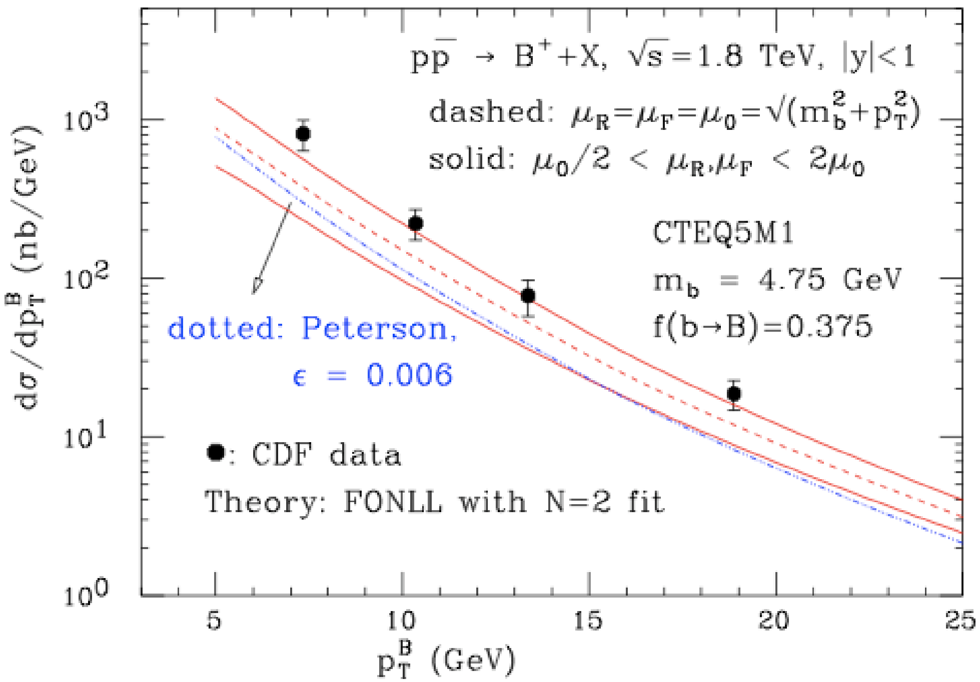


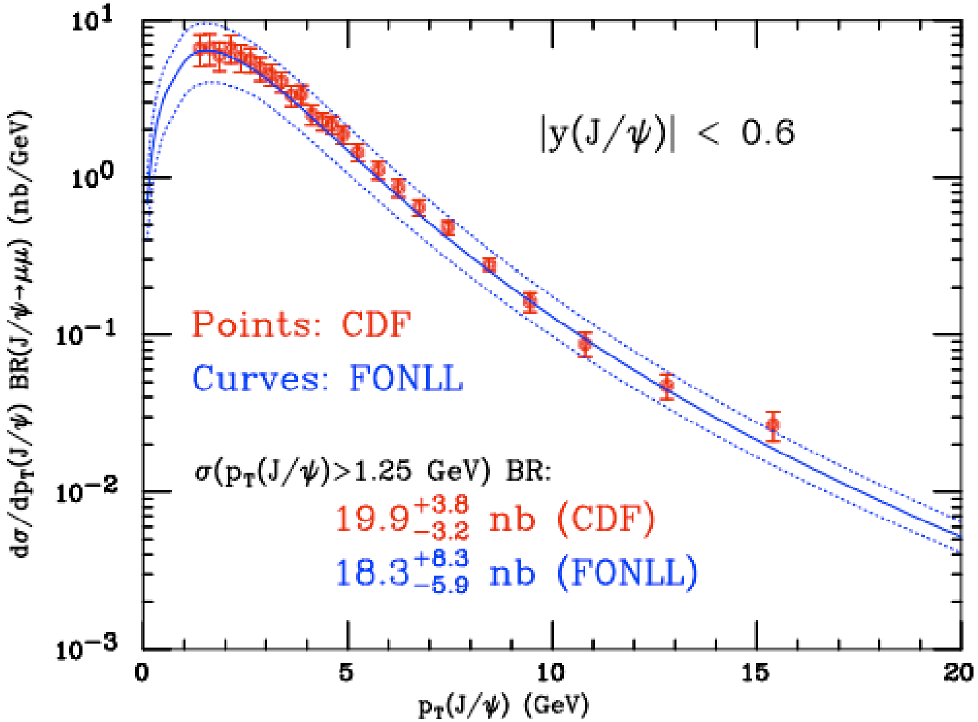


discrepancy between Tevatron data and NLO prediction

B cross section in $p\bar{p}$ collisions at 1.96 TeV

$d\sigma(p\bar{p} \to H_b X, H_b \to J/\psi\ X)/dp_T(J/\psi)$





FONLL = NLO + NLL

total x-sect is $19.4 \pm 0.3(stat)^{+2.1}_{-1.9}(syst)$ nb

Cacciari, Frixione, Mangano, Nason, Ridolfi 2003

CDF hep-ex/0412071

use of updated fragmentation functions by (Cacciari & Nason)

→ good agreement with data → no New Physics

QCD

- is a 1-parameter theory: one just needs $\alpha_s(M_Z)$, which we know at $O(1\%)$
- is formulated in terms of quarks and gluons, which we cannot observe (confinement) although we cannot prove it
- we cannot compute hadron wavefunctions
- we cannot compute (yet) mass spectra, but lattice computations improve
- we cannot compute (yet) nucleon-nucleon forces, but lattice ...

to summarise: we can make
- not-so-accurate statements about the matter content, characterised by low Q^2 and motivated by the hadron spectroscopy
- much more accurate statements about the gauge content at high Q^2 which probes the dynamics and is motivated by the scattering experiments

QCD at the LHC

Precise determination of

- strong coupling constant α_s
- parton distributions
- electroweak parameters
- LHC parton luminosity

Precise prediction for

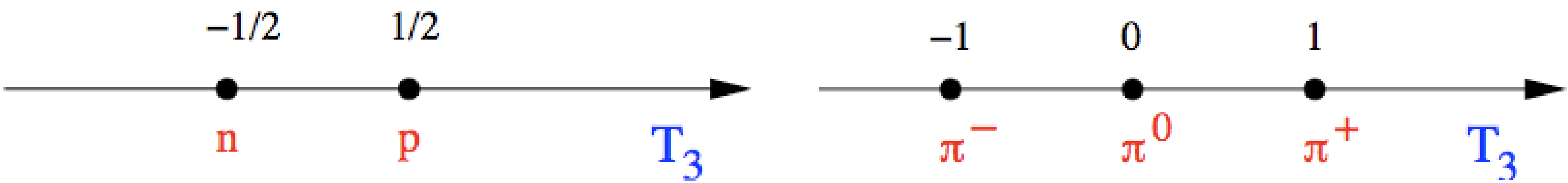
- Higgs production
- new physics processes
- their backgrounds

Goal: to make theoretical predictions of signals and backgrounds as accurate as the LHC data

History of QCD

Hadron spectroscopy

After WWII, few hadrons known. Fit Heisenberg's pre-war SU(2) isospin symmetry



$$\mathcal{L} = g_{\pi N N} \bar{N} \gamma_5 \vec{\tau} \cdot \vec{\pi} N$$

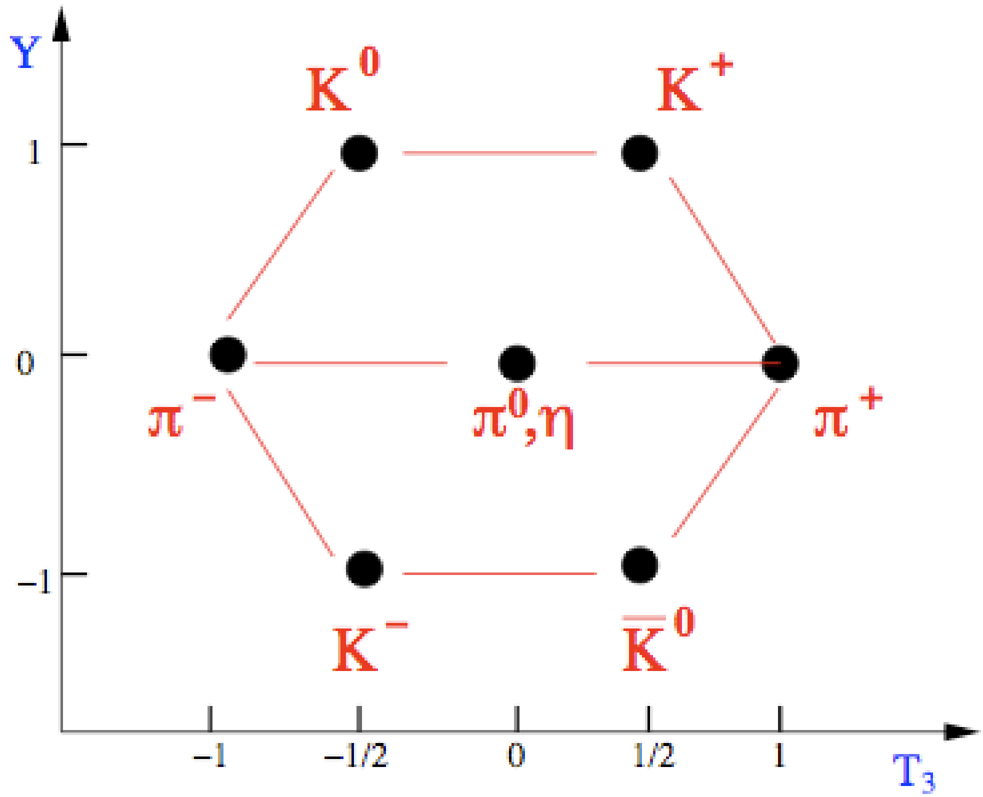
Hadron spectroscopy - eightfold way

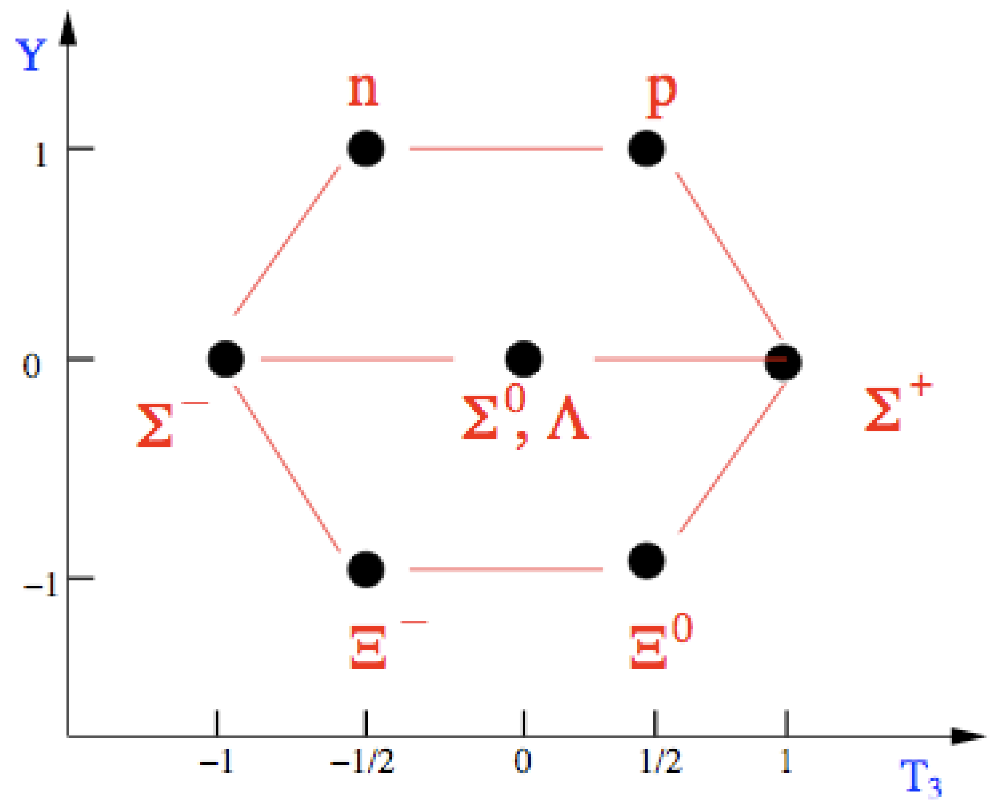
In the 50's, more hadrons are discovered, some with a long lifetime, which requires to introduce a new quantum #, the strangeness

Breakthrough:

Gell-Mann Ne'eman 1961

fit hadrons into the irreducible representations of an SU(3) isospin symmetry



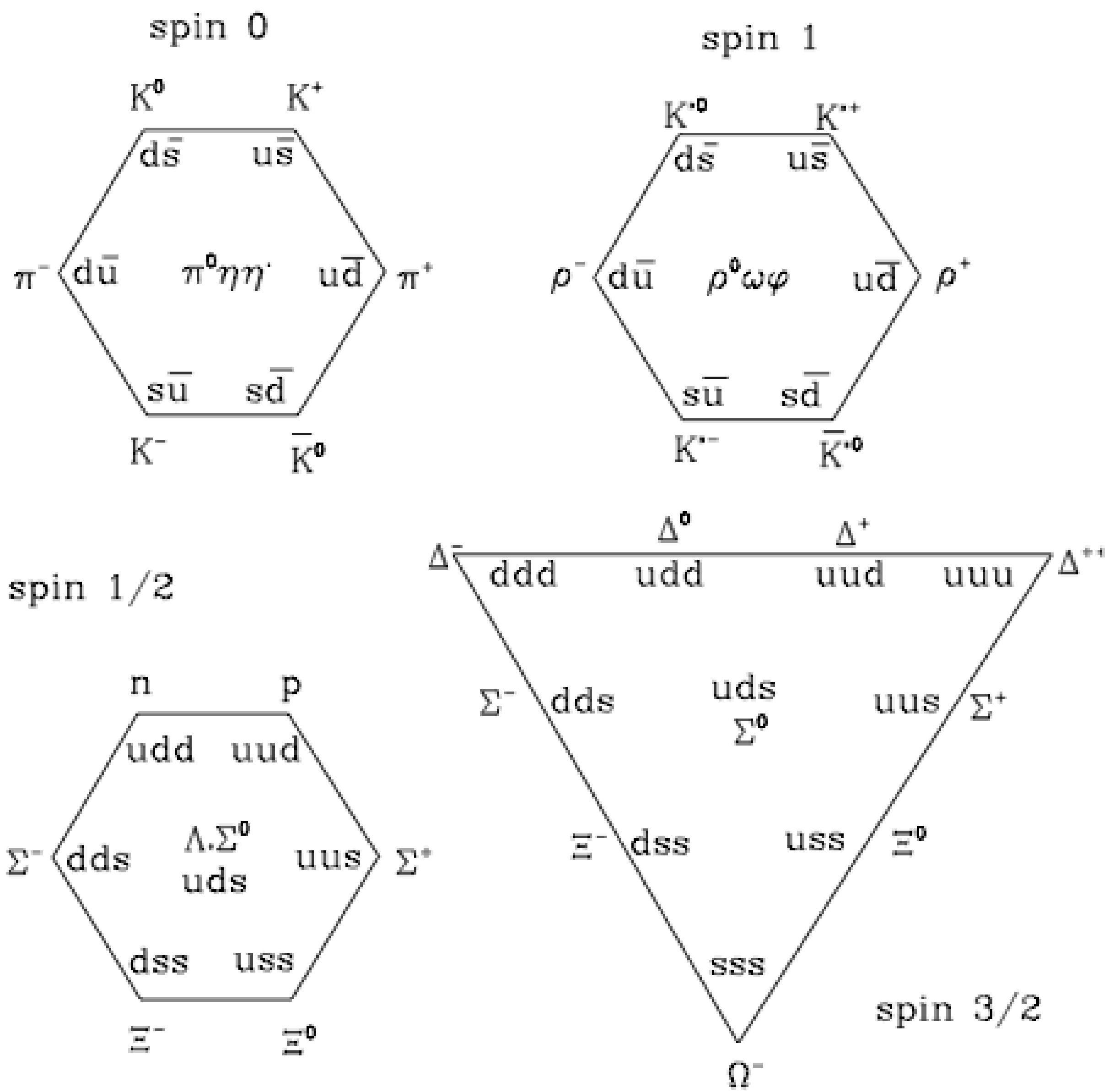


hypercharge $Y = N + S$ charge $Q = T_3 + Y/2$ Gell-Mann Nishima

Hadron spectroscopy

Bigger breakthrough:

Gell-Mann, Zweig (1964) propose to interpret the eight-fold way through objects (quarks) associated to the fundamental representation of SU(3)



quark model

Quark	Charge	Mass	Baryon Number	Isospin
u	$+\frac{2}{3}$	~ 4 MeV	$\frac{1}{3}$	$+\frac{1}{2}$
d	$-\frac{1}{3}$	~ 7 MeV	$\frac{1}{3}$	$-\frac{1}{2}$
c	$+\frac{2}{3}$	$\sim 1.5\ \mathrm{GeV}$	$\frac{1}{3}$	0
s	$-\frac{1}{3}$	~ 135 MeV	$\frac{1}{3}$	0
t	$+\frac{2}{3}$	$\sim 172\ \mathrm{GeV}$	$\frac{1}{3}$	0
b	$-\frac{1}{3}$	$\sim 5\ \mathrm{GeV}$	$\frac{1}{3}$	0

Hadron spectroscopy

- quarks have fractional electric charge & barion #
- Δ^{++} = uuu violates spin-statistics theorem: Δ^{++} puzzle

solution: Han Nambu; Greenberg 1965

introduce new SU(3) global symmetry, with colour as quantum #

colour is not observed ⇒ hadrons must be colour singlets

Indirect evidence for colour:

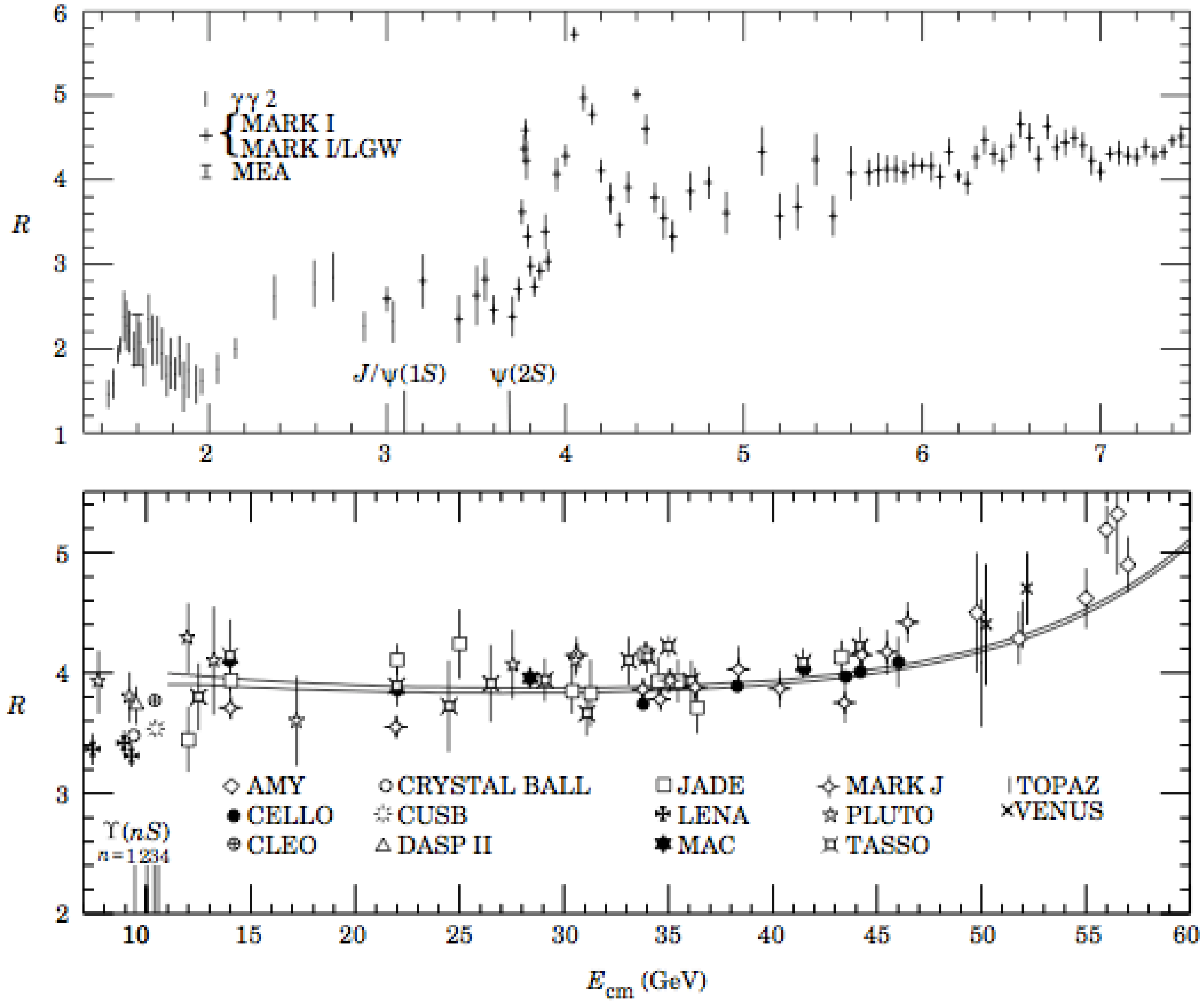
$\pi^0 \to \gamma\gamma$ (Adler-Bell-Jackiw anomaly)

$e^+e^- \to$ hadrons

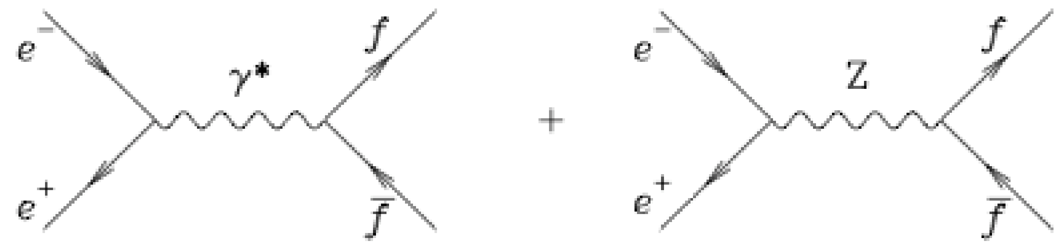
In 1971 Fritsch, Gell-Mann propose to promote colour SU(3) to a local symmetry

$e^+e^- \rightarrow$ hadrons

$$R_{e^+e^-} = \frac{\sigma_{e^+e^- \to \text{hadrons}}}{\sigma_{e^+e^- \to \mu^+\mu^-}}$$



$e^+e^- \rightarrow$ hadrons

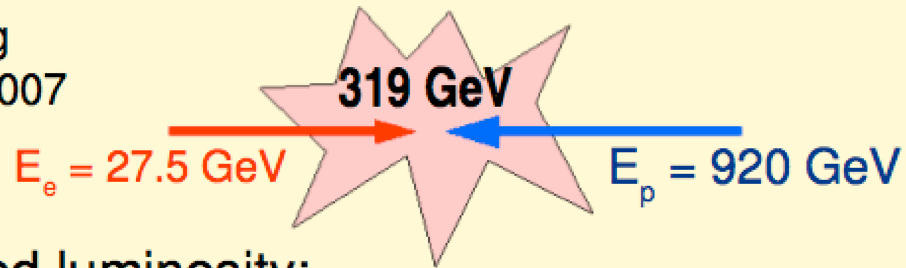


$$
\begin{aligned}
R_{e^+e^-} &= N_c \sum_f Q_f^2 \\
&= 3\left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right]
\end{aligned}
$$

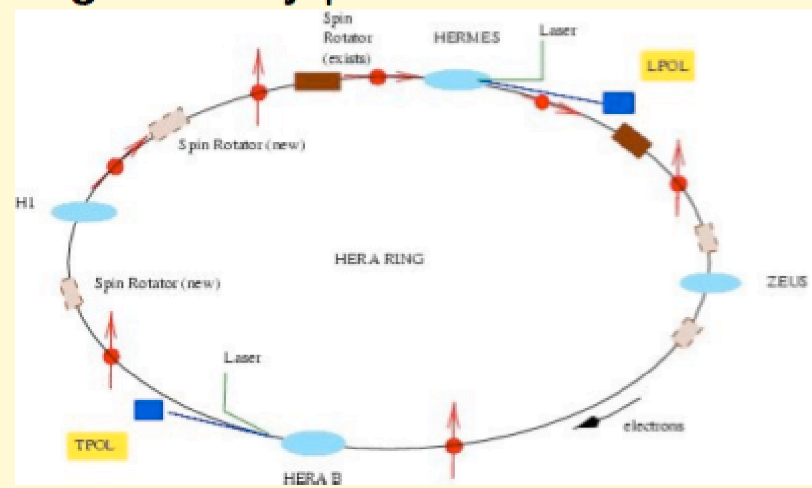
up, down, strange   charm, bottom

from A. Schöning's talk (H1) at DIS 2008

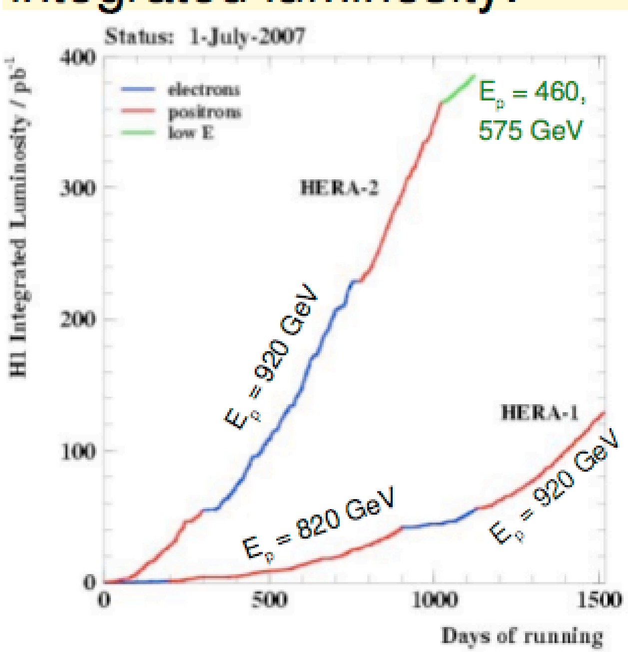
data taking
until mid 2007



longitudinally polarised $e^{\pm}$ beams:

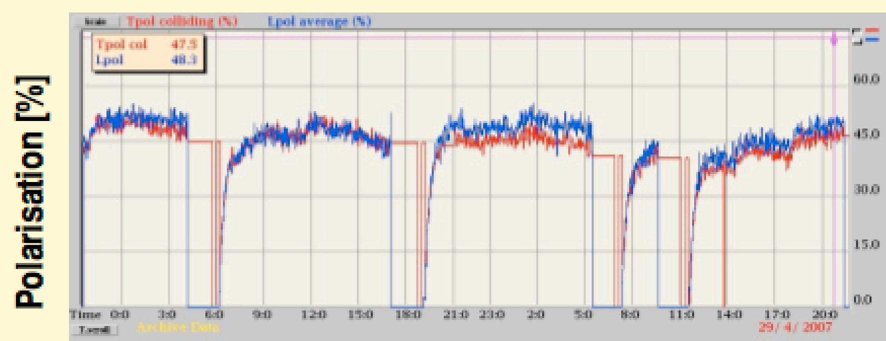


integrated luminosity:



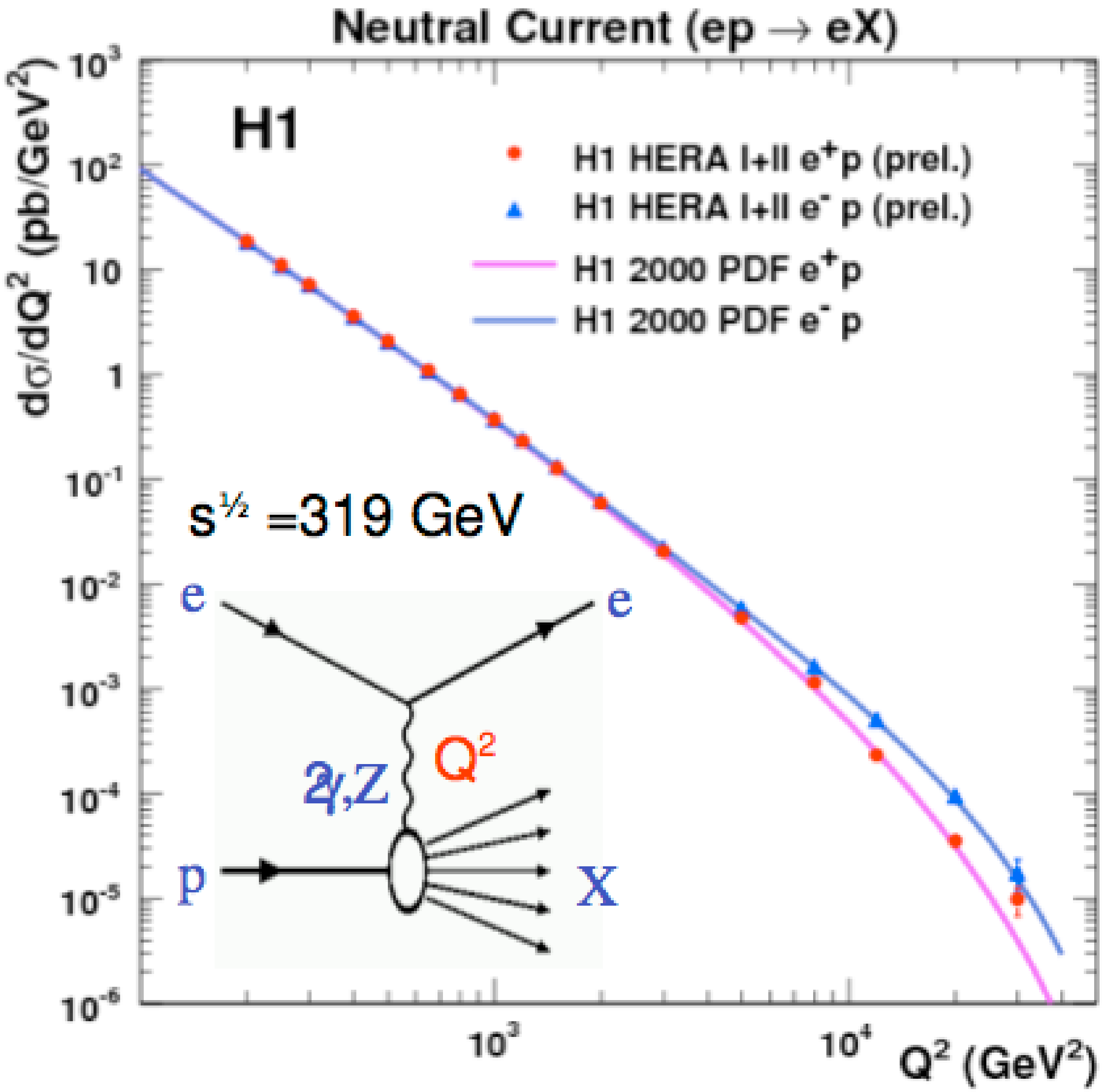
low energy: ~ 20 pb^{-1}

high energy:	
184 pb^{-1}	e^-p
294 pb^{-1}	e^+p
488 pb^{-1}	total



polarisation of more than 45%

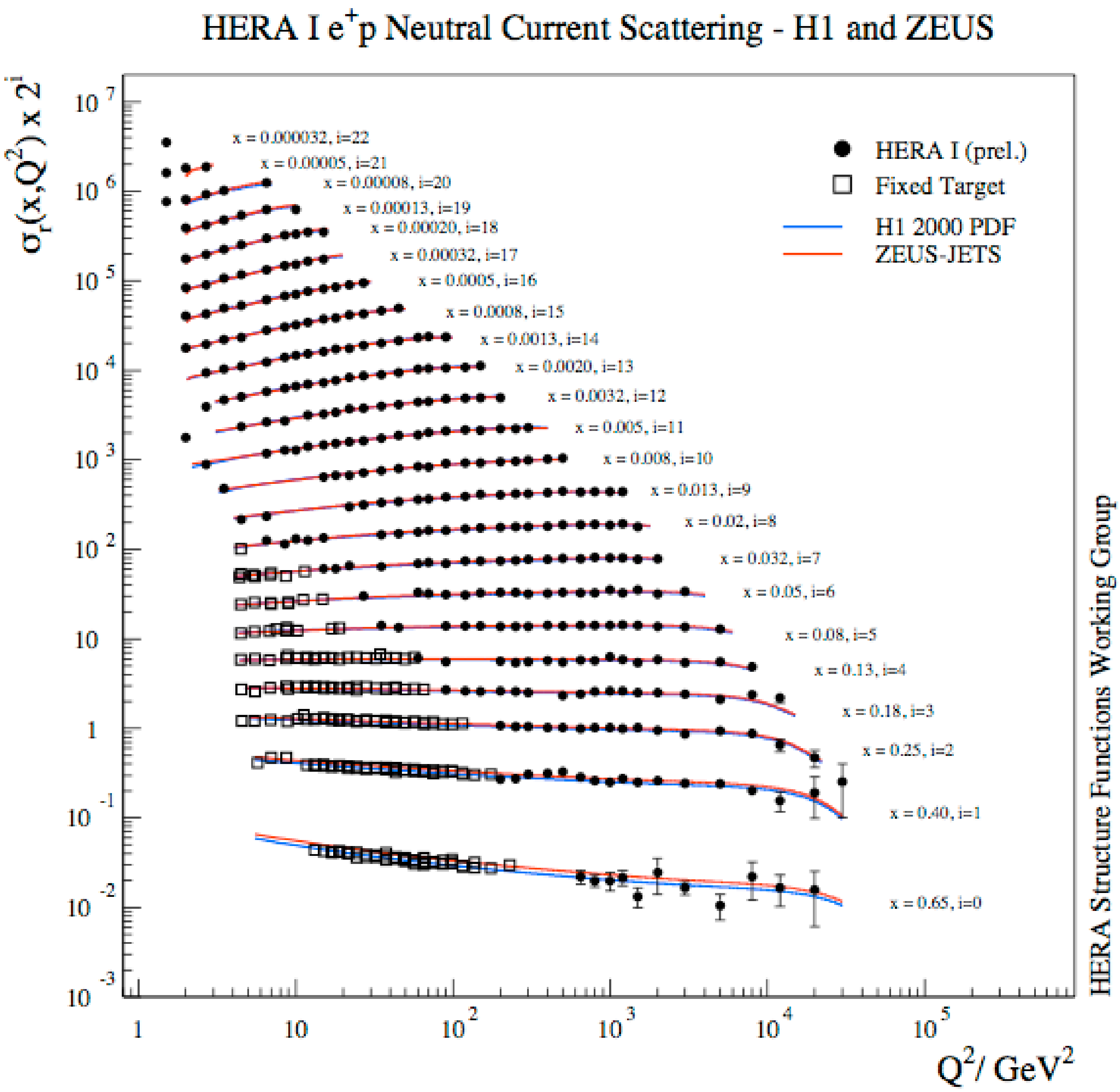
A. Schöning



without γ-Z interference, no difference between e^+ and e^-

HERA F_2

DIS08



DIS08 Joël Feltesse

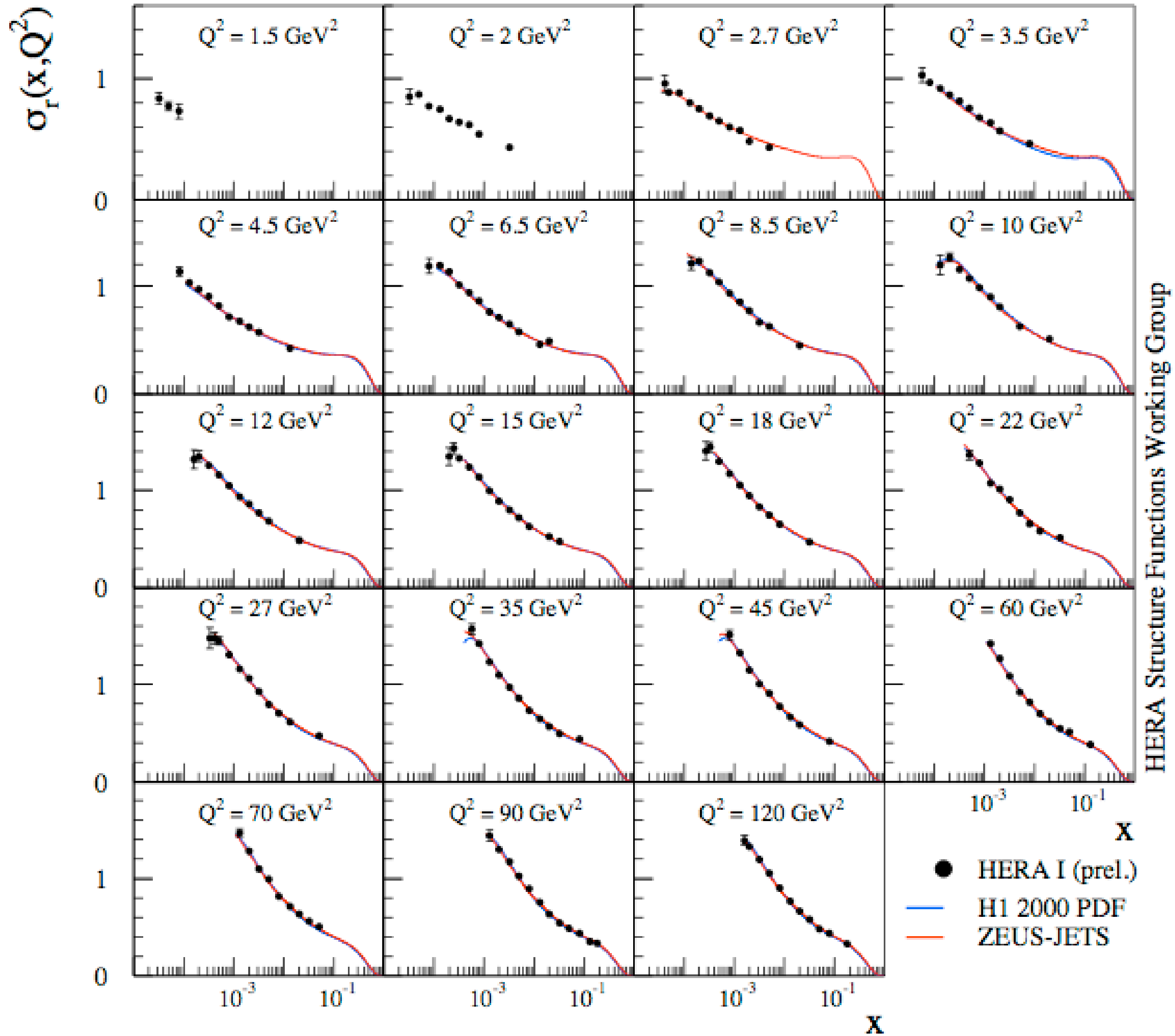
large violations at small x

small violations at large x

horizontal lines ⇒ Bjorken scaling

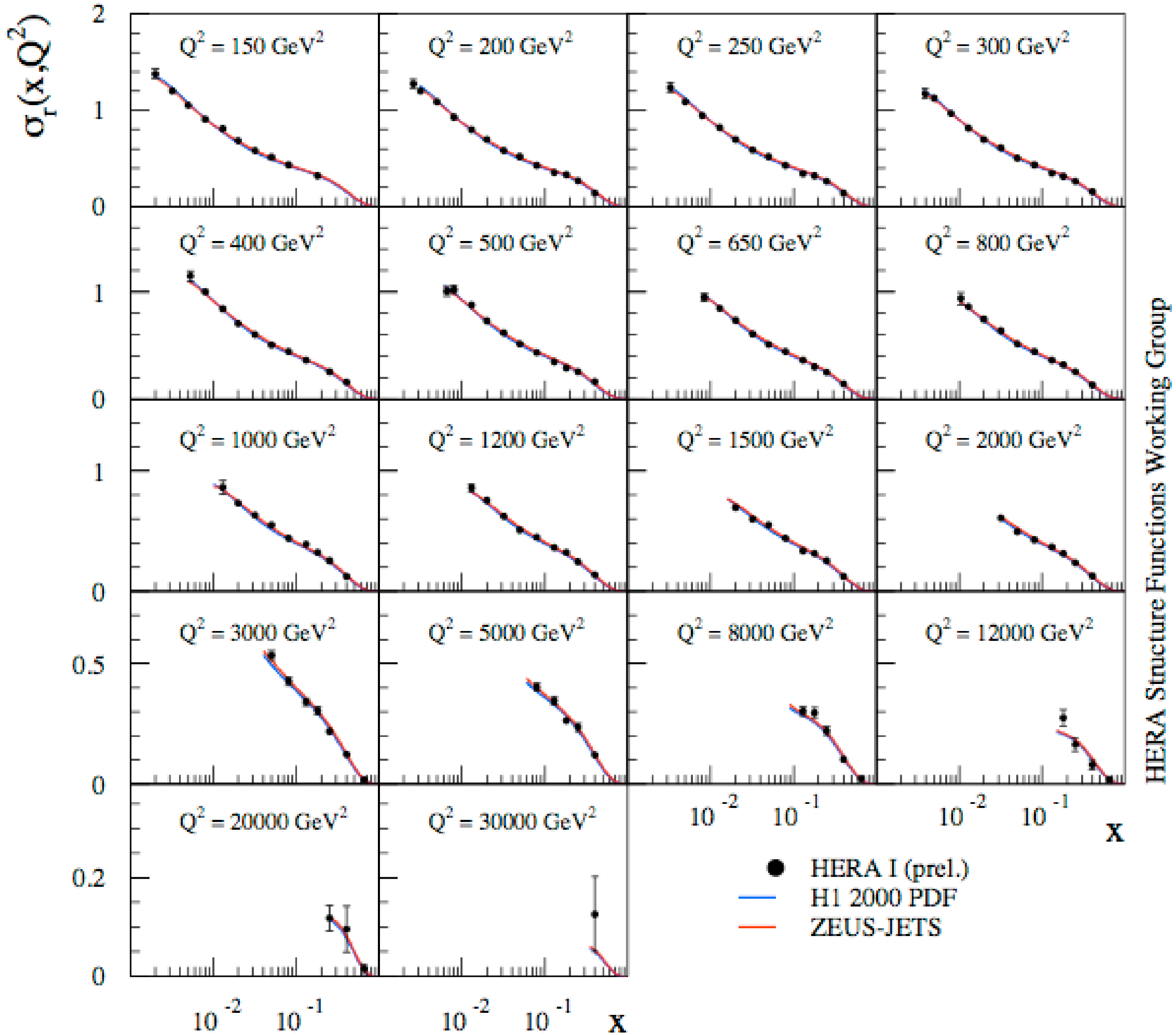
straight (non-horizontal) lines ⇒ scaling violations, logarithmic in Q^2

HERA I e⁺p Neutral Current Scattering - H1 and ZEUS



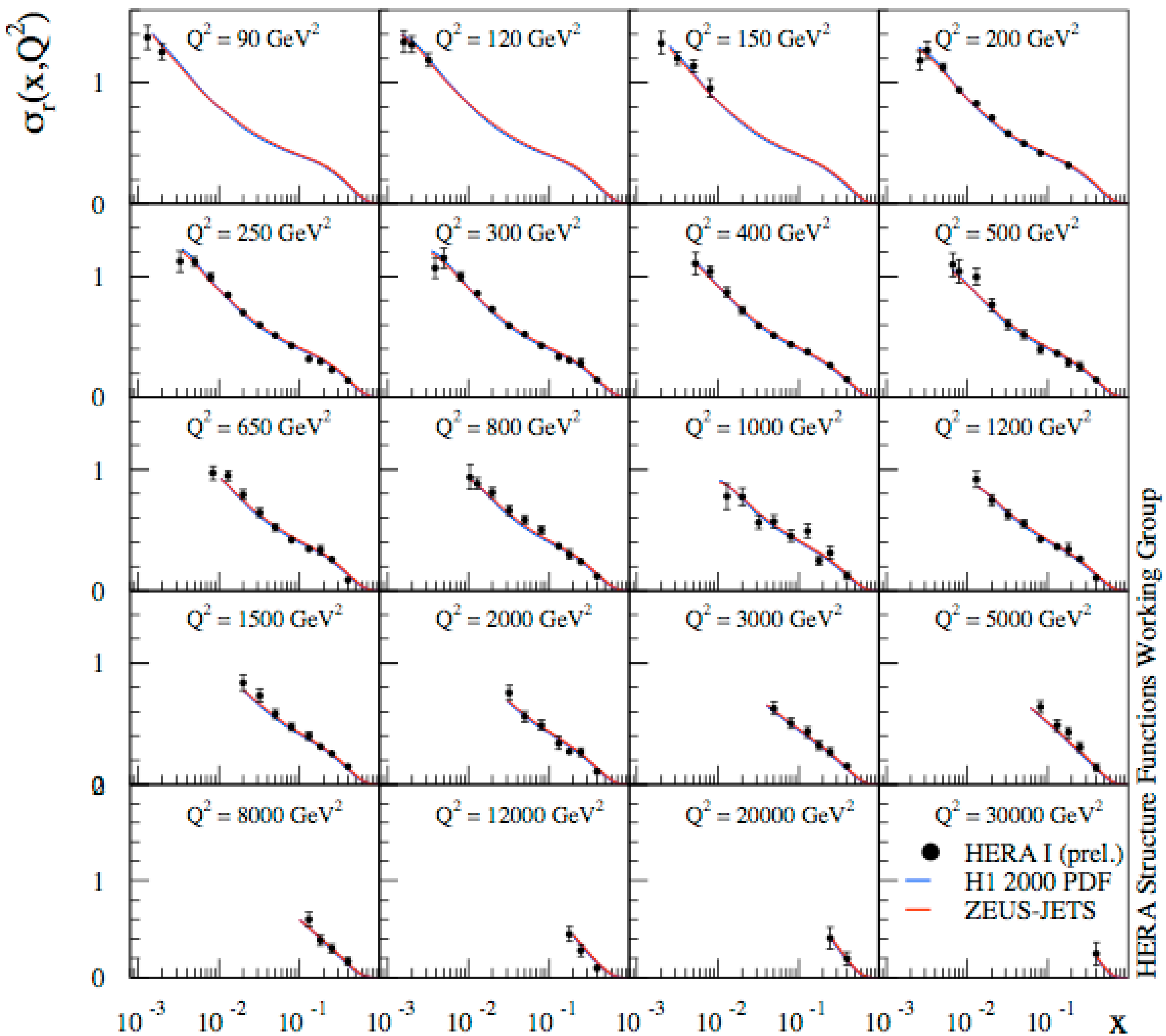
DIS08 Joël Feltesse

HERA I e^+p Neutral Current Scattering - H1 and ZEUS



DIS08 Joël Feltesse

HERA I e⁻p Neutral Current Scattering - H1 and ZEUS



DIS08 Joël Feltesse

Measurement of F_L

NC cross section:

$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

$F_2 \sim \sigma_T + \sigma_L$

$F_L \sim \sigma_L$

(F_L term contributes only at high y!)

QCD: $$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum_q w_q^2 (1-\frac{x}{z})\, zg(z)\right]$$

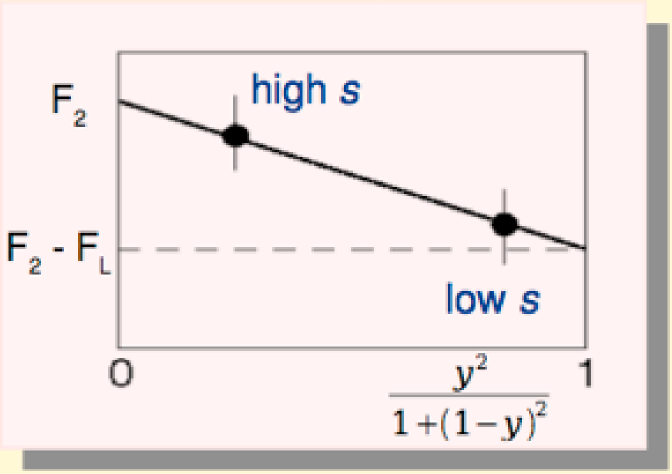
- indirect method:
  - F_2 extrapolation method (Phys.Lett.B393:452,1997)
- direct method:
  - measure σ_r for same (Q^2,x) at different y:

$s = \frac{Q^2}{x\,y}$ → measure at different beam energies

E_p= 920 GeV → lower y

E_p= 460 GeV → high y (high BG!)

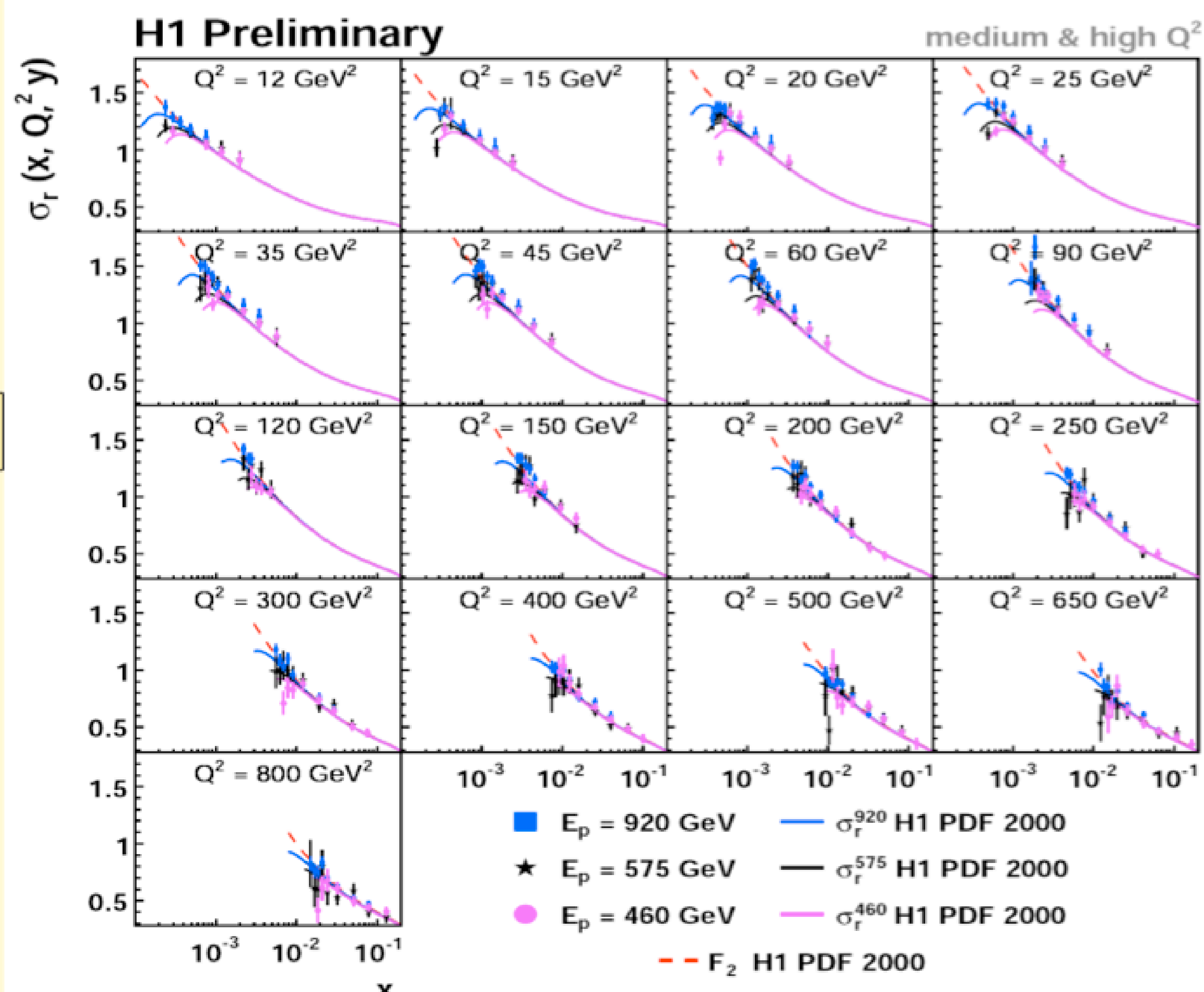
Rosenbluth plot:



A. Schöning

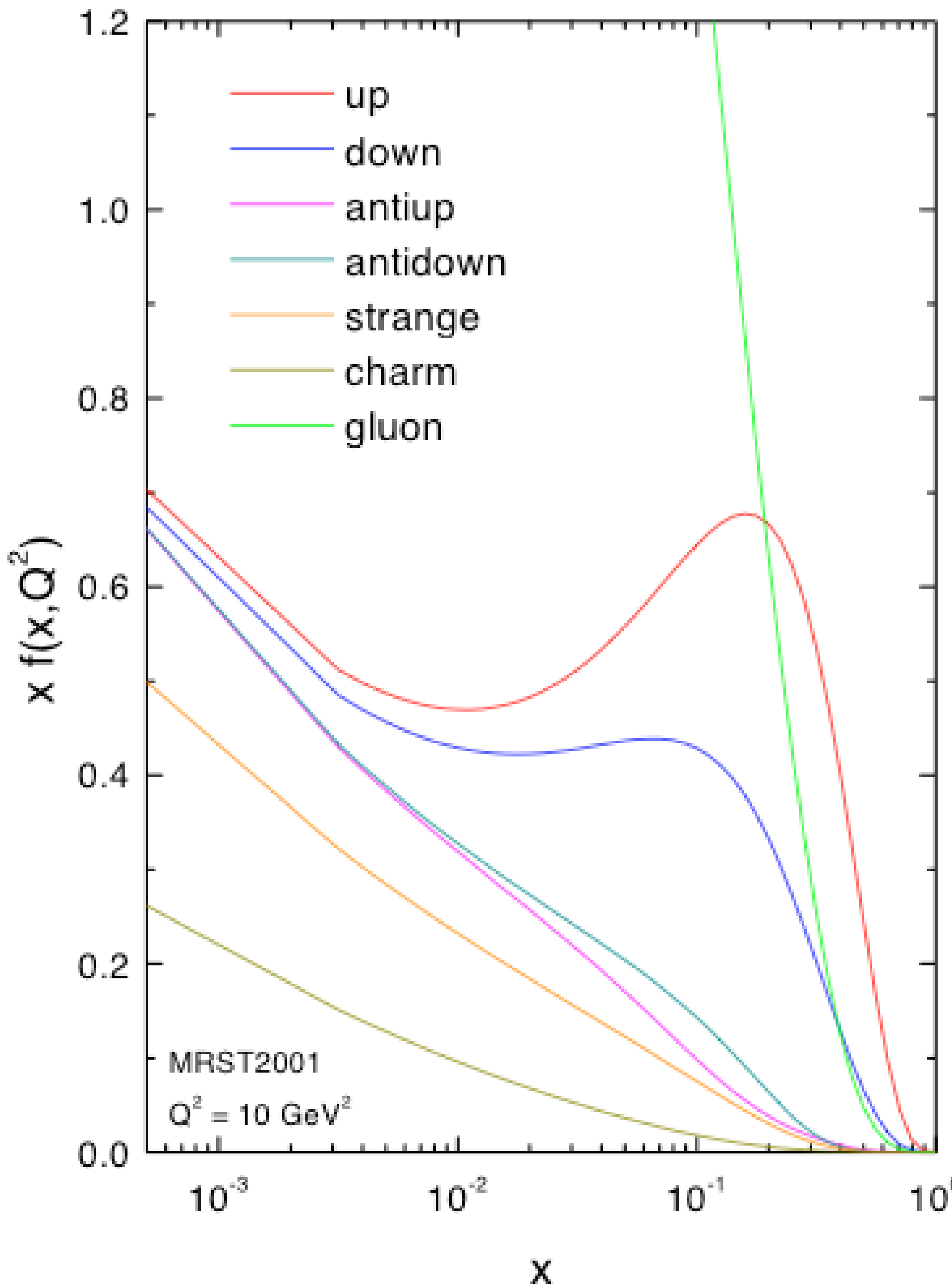
Cross Sections for F_L

y ~ 1/x



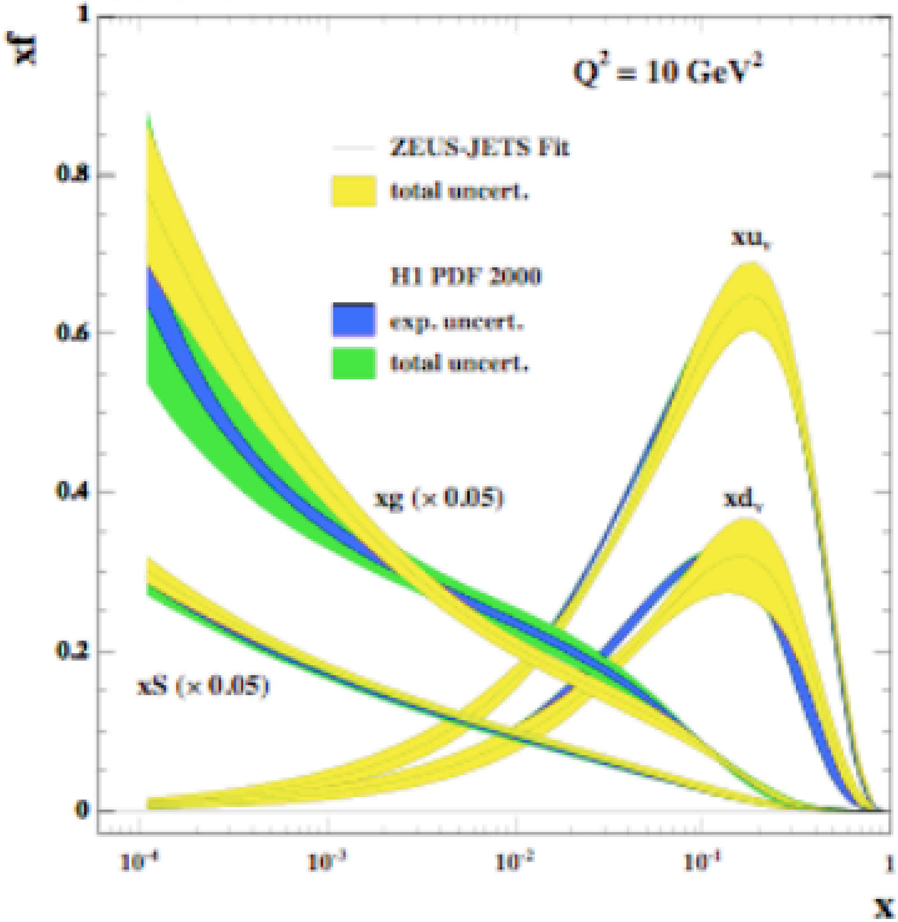
Parton distribution functions (PDF)

just to get an idea of the PDF size, take some PDF fit

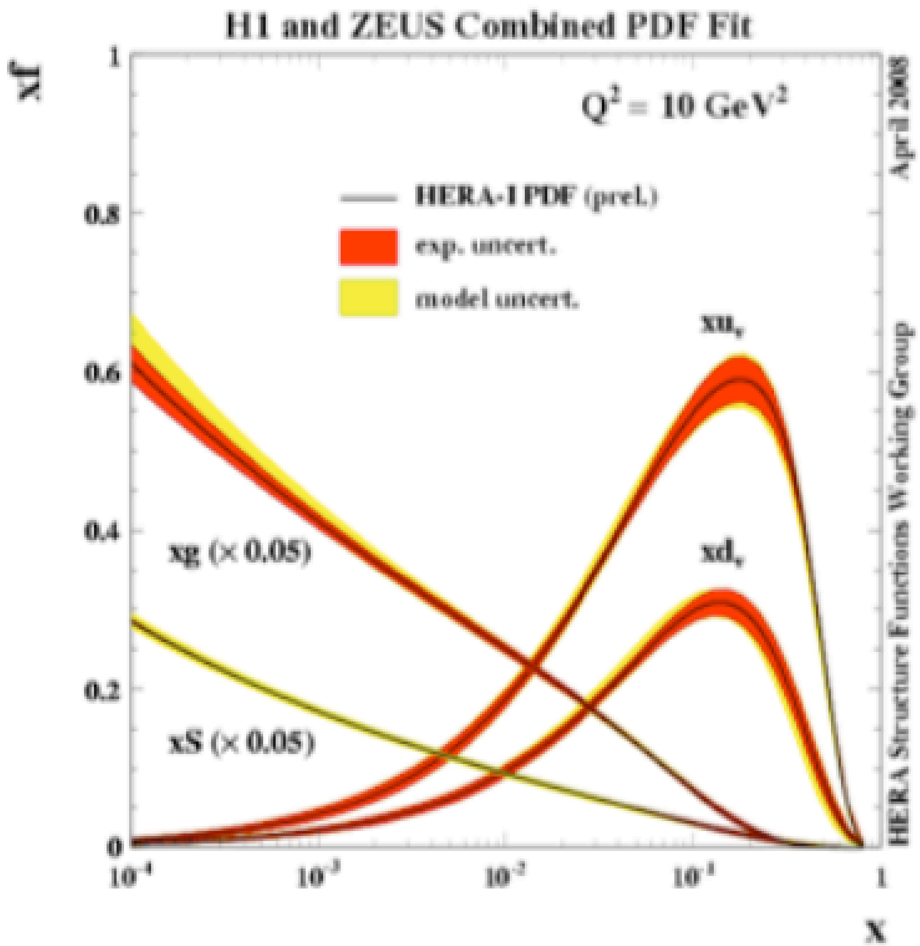


from H. Abramowicz talk (Zeus) at DIS 2008

Note in published PDFs H1 has alphas variation included in model error, ZEUS does not.



Systematic uncertainty greatly reduced when data combined



coefficients of the β function

$$\frac{d\alpha_s}{d\ln(Q^2/\mu^2)} = -\beta_0\alpha_s^2 - \beta_1\alpha_s^3 - \beta_2\alpha_s^4 - \beta_3\alpha_s^5 + \mathcal{O}(\alpha_s^6)$$

$$\beta_0 = \frac{\hat\beta_0}{4\pi} \qquad \beta_1 = \frac{\hat\beta_1}{(4\pi)^2} \qquad \beta_2 = \frac{\hat\beta_2}{(4\pi)^3} \qquad \beta_3 = \frac{\hat\beta_3}{(4\pi)^4}$$

$\hat\beta_0$ Gross Wilczek; Politzer 1973

$\hat\beta_1$ Caswell Jones 1974

$\hat\beta_2$ Tarasov Vladimirov Zharkov 1980

$\hat\beta_3$ van Ritbergen Vermaseren Larin 1997

coefficients of the β function

$$
\begin{aligned}
\hat{\beta}_0 &= \frac{11}{3}C_A - \frac{4}{3}T_F n_f \\
\hat{\beta}_1 &= \frac{34}{3}C_A^2 - 4C_F T_F n_f - \frac{20}{3}C_A T_F n_f \\
\hat{\beta}_2 &= \frac{2857}{54}C_A^3 + 2C_F^2 T_F n_f - \frac{205}{9}C_F C_A T_F n_f \\
&\quad - \frac{1415}{27}C_A^2 T_F n_f + \frac{44}{9}C_F T_F^2 n_f^2 + \frac{158}{27}C_A T_F^2 n_f^2 \\
\hat{\beta}_3 &= C_A^4\left(\frac{150653}{486} - \frac{44}{9}\zeta_3\right) + C_A^3 T_F n_f\left(-\frac{39143}{81} + \frac{136}{3}\zeta_3\right) \\
&\quad + C_A^2 C_F T_F n_f\left(\frac{7073}{243} - \frac{656}{9}\zeta_3\right) + C_A C_F^2 T_F n_f\left(-\frac{4204}{27} + \frac{352}{9}\zeta_3\right) \\
&\quad + 46 C_F^3 T_F n_f + C_A^2 T_F^2 n_f^2\left(\frac{7930}{81} + \frac{224}{9}\zeta_3\right) + C_F^2 T_F^2 n_f^2\left(\frac{1352}{27} - \frac{704}{9}\zeta_3\right) \\
&\quad + C_A C_F T_F^2 n_f^2\left(\frac{17152}{243} + \frac{448}{9}\zeta_3\right) + \frac{424}{243}C_A T_F^3 n_f^3 + \frac{1232}{243}C_F T_F^3 n_f^3 \\
&\quad + \frac{d_A^{abcd} d_A^{abcd}}{N_A}\left(-\frac{80}{9} + \frac{704}{3}\zeta_3\right) + n_f \frac{d_F^{abcd} d_A^{abcd}}{N_A}\left(\frac{512}{9} - \frac{1664}{3}\zeta_3\right) \\
&\quad + n_f^2 \frac{d_F^{abcd} d_F^{abcd}}{N_A}\left(-\frac{704}{9} + \frac{512}{3}\zeta_3\right)
\end{aligned}
$$

Evolution

- factorisation scale μ_F is arbitrary
  - cross section cannot depend on μ_F

$$\mu_F \frac{d\sigma}{d\mu_F} = 0$$

implies DGLAP equations

V. Gribov L. Lipatov; Y. Dokshitzer
G. Altarelli G. Parisi

$$\mu_F \frac{d f_a(x,\mu_F^2)}{d\mu_F} = P_{ab}(x,\alpha_S(\mu_F^2)) \otimes f_b(x,\mu_F^2) + \mathcal{O}(\frac{1}{Q^2})$$

$$\mu_F \frac{d\hat{\sigma}_{ab}(Q^2/\mu_F^2,\alpha_S(\mu_F^2))}{d\mu_F} = -P_{ac}(x,\alpha_S(\mu_F^2)) \otimes \hat{\sigma}_{cb}(Q^2/\mu_F^2,\alpha_S(\mu_F^2)) + \mathcal{O}(\frac{1}{Q^2})$$

  - $P_{ab}(x,\alpha_S(\mu_F^2))$ is calculable in pQCD

Parton distribution functions (PDF)

- factorisation for the structure functions (e.g. $F_2^{ep}, \; F_L^{ep}$)

$$\mathcal{F}_i(x,\mu_F^2) = C_{ij} \otimes q_j + C_{ig} \otimes g$$

with the convolution $\quad [a \otimes b](x) \equiv \int_x^1 \frac{dy}{y}\, a(y)\, b\left(\frac{x}{y}\right)$

$C_{ij}, \; C_{ig}$ coefficient functions

$q_i(x,\mu_F^2) \quad g(x,\mu_F^2)$ PDF's

- DGLAP evolution equations

$$\frac{d}{d\ln\mu_F^2}\begin{pmatrix} q_i \\ g \end{pmatrix} = \begin{pmatrix} P_{\mathrm{q_i q_j}} & P_{\mathrm{q_j g}} \\ P_{\mathrm{g q_j}} & P_{\mathrm{gg}} \end{pmatrix} \otimes \begin{pmatrix} q_j \\ g \end{pmatrix}$$

- perturbative series $\quad P_{ij} \approx \alpha_s P_{ij}^{(0)} + \alpha_s^2 P_{ij}^{(1)} + \alpha_s^3 P_{ij}^{(2)}$

- anomalous dimension $\quad \gamma_{ij}(N) = -\int_0^1 dx\, x^{N-1}\, P_{ij}(x)$

PDF's

- general structure of the quark-quark splitting functions

$$P_{\mathrm{q}_i \mathrm{q}_k} = P_{\bar{\mathrm{q}}_i \bar{\mathrm{q}}_k} = \delta_{ik} P^{\mathrm{v}}_{\mathrm{qq}} + P^{\mathrm{s}}_{\mathrm{qq}}$$

$$P_{\mathrm{q}_i \bar{\mathrm{q}}_k} = P_{\bar{\mathrm{q}}_i \mathrm{q}_k} = \delta_{ik} P^{\mathrm{v}}_{\mathrm{q}\bar{\mathrm{q}}} + P^{\mathrm{s}}_{\mathrm{q}\bar{\mathrm{q}}}$$

- flavour non-singlet
  - flavour asymmetry

$$q^{\pm}_{\mathrm{ns},ik} = q_i \pm \bar{q}_i - (q_k \pm \bar{q}_k) \quad \Longleftarrow \quad P^{\pm}_{\mathrm{ns}} = P^{\mathrm{v}}_{\mathrm{qq}} \pm P^{\mathrm{v}}_{\mathrm{q}\bar{\mathrm{q}}}$$

  - sum of valence distributions of all flavours

$$q^{\mathrm{v}}_{\mathrm{ns}} = \sum_{r=1}^{n_f} (q_r - \bar{q}_r) \quad \Longleftarrow \quad P^{\mathrm{v}}_{\mathrm{ns}} = P^{\mathrm{v}}_{\mathrm{qq}} - P^{\mathrm{v}}_{\mathrm{q}\bar{\mathrm{q}}} + n_f (P^{\mathrm{s}}_{\mathrm{qq}} - P^{\mathrm{s}}_{\mathrm{q}\bar{\mathrm{q}}})$$

- flavour singlet

$$q_{\mathrm{s}} = \sum_{i=1}^{n_f} (q_i + \bar{q}_i) \quad \Longleftarrow \quad \frac{d}{d \ln \mu_F^2} \begin{pmatrix} q_{\mathrm{s}} \\ g \end{pmatrix} = \begin{pmatrix} P_{\mathrm{qq}} & P_{\mathrm{qg}} \\ P_{\mathrm{gq}} & P_{\mathrm{gg}} \end{pmatrix} \otimes \begin{pmatrix} q_{\mathrm{s}} \\ g \end{pmatrix}$$

with

$$P_{\mathrm{qq}} = P^{+}_{\mathrm{ns}} + n_f (P^{\mathrm{s}}_{\mathrm{qq}} + P^{\mathrm{s}}_{\bar{\mathrm{q}}\mathrm{q}})$$

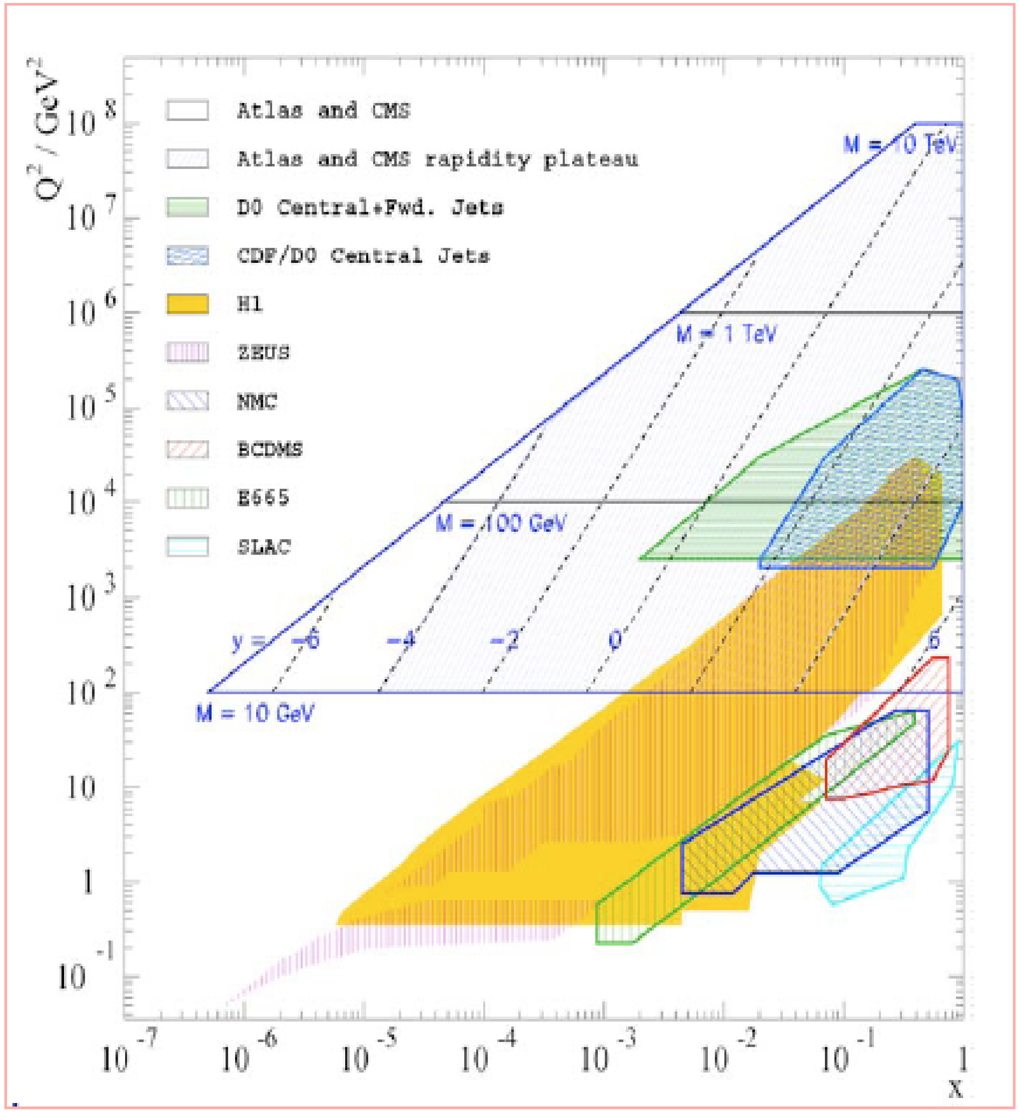
$$P_{\mathrm{qg}} = n_f P_{\mathrm{q}_i \mathrm{g}} \,, \quad P_{\mathrm{gq}} = P_{\mathrm{gq}_i}$$

PDF history

- leading order (or one-loop) anomalous dim/splitting functions — Gross Wilczek 1973; Altarelli Parisi 1977
- NLO (or two-loop)
  - F_2, F_L — Bardeen Buras Duke Muta 1978
  - anomalous dim/splitting functions — Curci Furmanski Petronzio 1980
- NNLO (or three-loop)
  - F_2, F_L — Zijlstra van Neerven 1992; Moch Vermaseren 1999
  - anomalous dim/splitting functions — Moch Vermaseren Vogt 2004
  - the calculation of the three-loop anomalous dimension is the toughest calculation ever performed in perturbative QCD!
    - one-loop $\gamma_{ij}^{(0)}/P_{ij}^{(0)}$ ⇒ 18 Feynman diagrams
    - two-loop $\gamma_{ij}^{(1)}/P_{ij}^{(1)}$ ⇒ 350 Feynman diagrams
    - three-loop $\gamma_{ij}^{(2)}/P_{ij}^{(2)}$ ⇒ 9607 Feynman diagrams

    20 man-year-equivalents, 10^6 lines of dedicated algebra code

LHC kinematic reach



LHC opens up a new kinematic range

x range covered by HERA but Q^2 range must be provided by DGLAP evolution

100-200 GeV physics is large x physics (valence quarks) at Tevatron, but smaller x physics (gluons & sea quarks) at the LHC

rapidity distributions span widest x range

Feynman x's for the production of a particle of mass M $x_{1,2} = \frac{M}{14\,\mathrm{TeV}}\, e^{\pm y}$

QCD at high Q^2

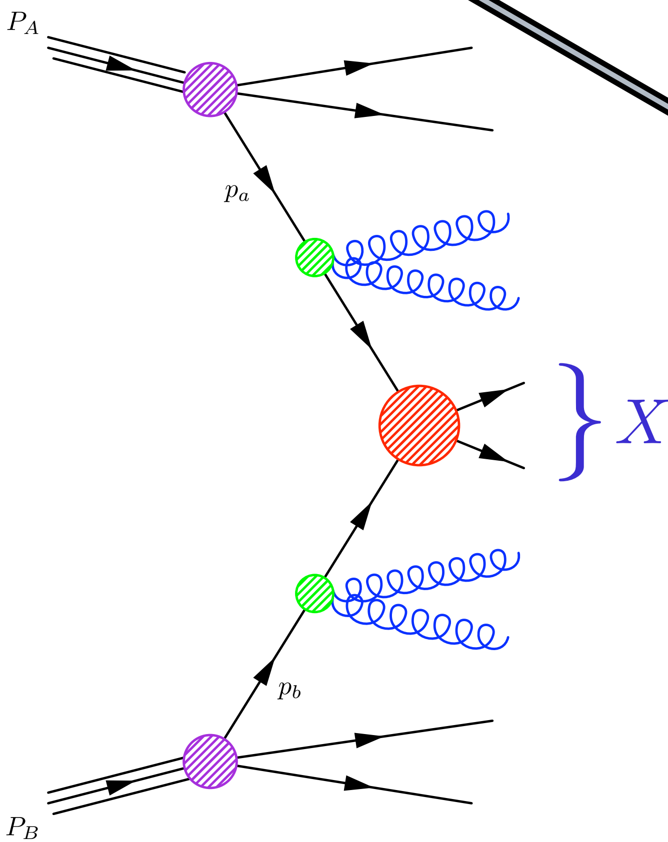
- Parton model
- Perturbative QCD
  - factorisation
  - universality of IR behaviour
  - cancellation of IR singularities
  - IR safe observables: inclusive rates
    - jets
    - event shapes

Factorisation

computed in pQCD

extracted from data
evolved through DGLAP

is the separation between
the short- and the long-range interactions



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_{a/A}(x_1,\mu_F^2)\, f_{b/B}(x_2,\mu_F^2)$$
$$\times \; \hat\sigma_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

$$X = W, Z, H, Q\bar{Q}, \text{high-}E_T\text{jets}, \ldots$$

$\hat\sigma$ is known as a fixed-order expansion in α_S

$$\hat\sigma = C\alpha_S^n(1 + c_1\alpha_S + c_2\alpha_S^2 + \ldots)$$

$c_1 =$ NLO $\qquad c_2 =$ NNLO

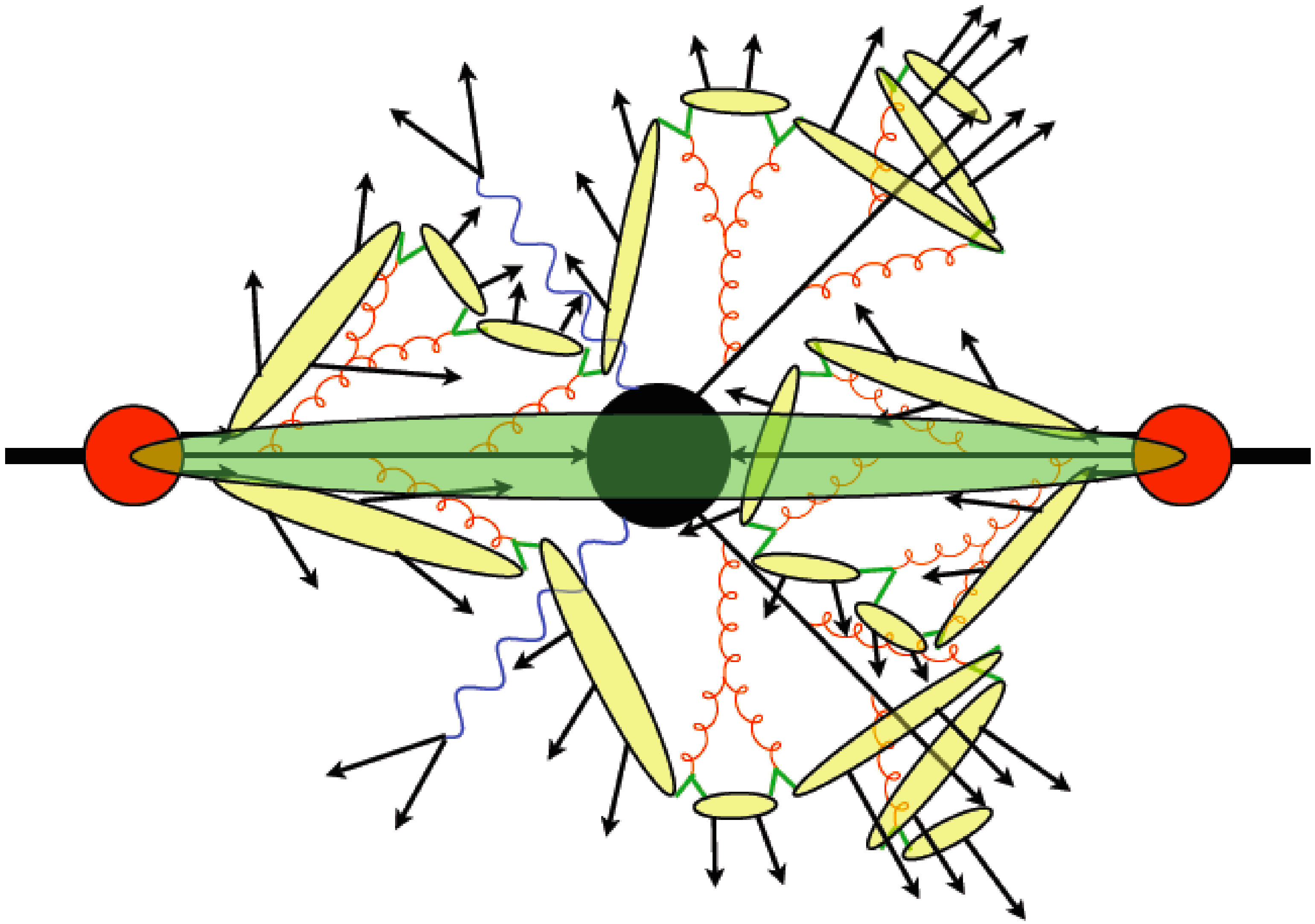
or as an all-order resummation

$$\hat\sigma = C\alpha_S^n[1 + (c_{11}L + c_{10})\alpha_S + (c_{22}L^2 + c_{21}L + c_{20})\alpha_S^2 + \ldots]$$

where $L = \ln(M/q_T), \ln(1-x), \ln(1/x), \ln(1-T), \ldots$

$c_{11}, c_{22} =$ LL $\qquad c_{10}, c_{21} =$ NLL $\qquad c_{20} =$ NNLL

LHC Event Simulation

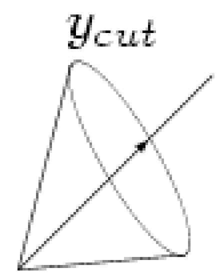


Parton showering and hadronisation are modelled through shower Monte Carlos (HERWIG o PYTHIA)

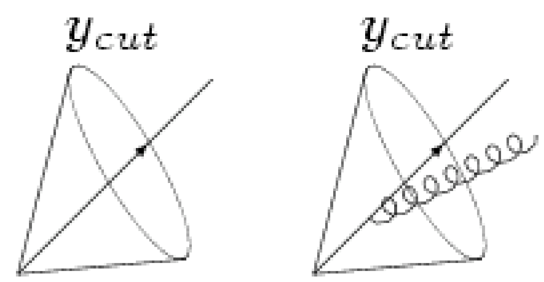
Jet structure

the jet non-trivial structure shows up first at NLO

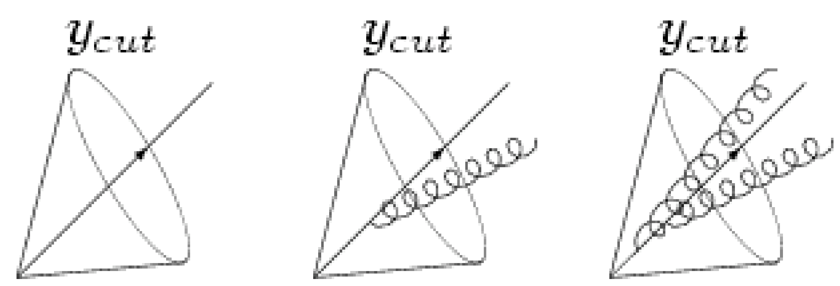
leading order



NLO



NNLO



World average of $\alpha_S(M_Z)$

$$\alpha_S(M_Z) = 0.1189 \pm 0.0010$$

S. Bethke hep-ex/0606035

Process	Q [GeV]	$\alpha_s(M_{Z^0})$	excl. mean $\alpha_s(M_{Z^0})$	std. dev.
DIS [Bj-SR]	1.58	$0.121\ ^{+\ 0.005}_{-\ 0.009}$	0.1189 ± 0.0008	0.3
τ-decays	1.78	0.1215 ± 0.0012	0.1176 ± 0.0018	1.8
DIS [ν; xF_3]	2.8 - 11	$0.119\ ^{+\ 0.007}_{-\ 0.006}$	0.1189 ± 0.0008	0.0
DIS [e/μ; F_2]	2 - 15	0.1166 ± 0.0022	0.1192 ± 0.0008	1.1
DIS [e-p $\rightarrow$ jets]	6 - 100	0.1186 ± 0.0051	0.1190 ± 0.0008	0.1
Υ decays	4.75	0.118 ± 0.006	0.1190 ± 0.0008	0.2
$Q\overline{Q}$ states	7.5	0.1170 ± 0.0012	0.1200 ± 0.0014	1.6
e^+e^- [$\Gamma(Z \rightarrow had)$]	91.2	$0.1226^{+\ 0.0058}_{-\ 0.0038}$	0.1189 ± 0.0008	0.9
e^+e^- 4-jet rate	91.2	0.1176 ± 0.0022	0.1191 ± 0.0008	0.6
e^+e^- [jets & shps]	189	0.121 ± 0.005	0.1188 ± 0.0008	0.4

Rightmost 2 columns give the exclusive mean value of $\alpha_S(M_Z)$ calculated without that measurement, and the number of std. dev. between this measurement and the respective excl. mean