Phenomenology at colliders (3)

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Plan

I. INTRODUCTION AND MOTIVATION

II. STRUCTURE FUNCTIONS AND PARTON DISTRIBUTION FUNCTIONS

1. Deep inelastic scattering and structure functions
2. Quark parton model
3. Scaling violation
4. QCD evolution and DGLAP equations

IiI. FACTORISATION THEOREMS; PDF PARAMETERISATIONS

1. Factorisation theorems
2. Drell-Yan production with CMS
3. Parton distribution function parameterisations
4. Parton distribution uncertainties
5. Some (of many) uncovered topics

DIS cross section

$$F_1(x,Q^2) = MW_1 \qquad F_2(x,Q^2) = \nu W_2$$

$$\frac{d^2\sigma}{dxdy} = \frac{d^2\sigma}{dxdQ^2} xs = \frac{4\pi\alpha^2}{Q^4} s \left[(1-y) F_2(x,Q^2) + \frac{y^2}{2} 2xF_1(x,Q^2) \right]$$ em interaction : NC γ exchange

$$= \ldots \left[\ldots \pm \frac{G_F^2}{8\pi^2} \frac{Q^4}{(1+Q^2/M^2)} y(1-y/2)\, xF_3(x,Q^2) \right]$$ weak interaction : CC W exchange

F_1, F_2, $F_3(x,Q^2)$ = structure functions – physical observables (measured quantities)

Scaling

Incoherent **scattering** on free partons

$$\left.\begin{array}{l} \rightarrow F_2(x) = \sum_i e_i^2 \, x \, f_i(x) \\ \rightarrow F_1(x) = \frac{1}{2x} F_2(x) \end{array}\right\} \text{QPM}$$

Structure functions depend only on x; cross section given by quark distributions f(x)

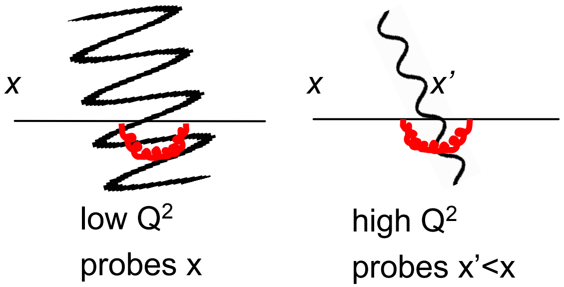
$$\frac{d^2\sigma}{dxdy} = \frac{2\pi\alpha^2}{Q^4} s \left[1 + (1-y)^2 \right] \sum_i e_i^2 \, x \, f_i(x) \qquad \text{QPM}$$

Scaling violations

Q^2 evolution of structure functions

photon resolution improves with Q^2

→ disentangles virtual gluon emission



As Q^2 increases,

quark content decreases at large x (valence)

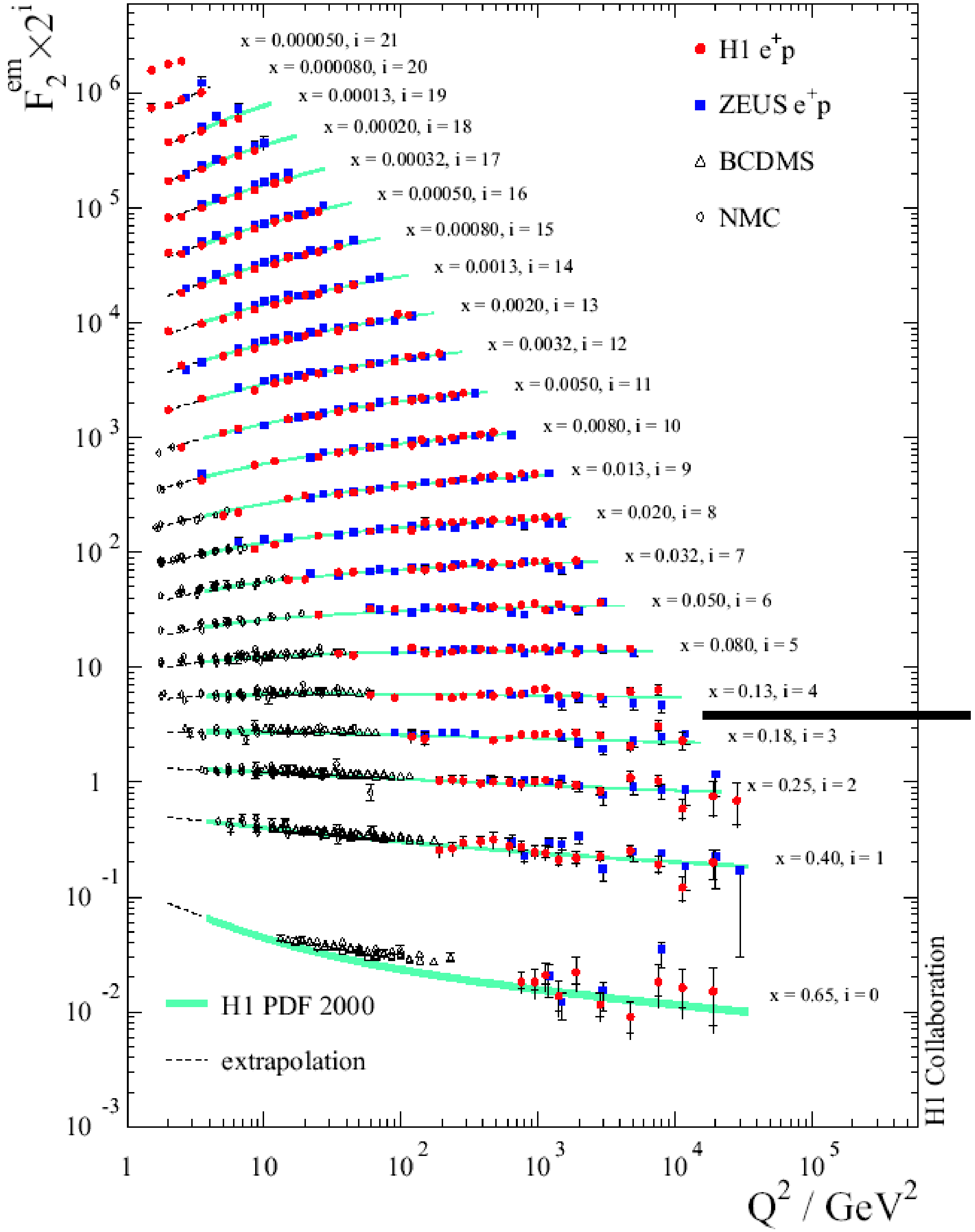
and increases at low x

also : at low x, the gluon content and the sea

increase

(low x since due to bremsstrahlung → soft)

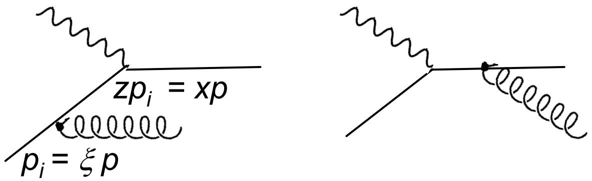
parton distribution function evolutions

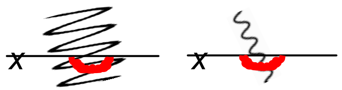


« structure of the quark »

Gluon emission by the quark :

a quark « structure » shows up





Take over the SF formalism, with proton → quark

	proton	quark
	p	$p_i = \xi p$
	$x = Q^2/2p.q$	$z = Q^2/2p_i.q = x/\xi$

Hence $$2F_1(x,Q^2) = \left.\frac{\sigma_T(x,Q^2)}{\sigma_0}\right|_{\gamma^* p} = \sum_i \int_0^1 dz \int_0^1 d\xi \, f_i(\xi)\, \delta(x-\xi z)\, \left.\frac{\hat\sigma_T(z,Q^2)}{\hat\sigma_0}\right|_{\gamma^* quark}$$

where $\sigma_0 = \dfrac{4\pi\,\alpha_s^2(Q^2)}{s}$ and similarly for $\hat\sigma_0$ with $\hat s = \xi s$

$f_i(\xi)$ is the probability to find in the proton a (« **primary** ») quark with momentum fraction ξ,

$\hat\sigma_T(z,Q^2)$ is the photon-quark transverse cross section,

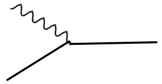
for a (« **secondary** ») quark of momentum fraction $\boldsymbol{z}$;

ξ and z can vary from 0 to 1, but **$x = \xi z$ is fixed** (hence the δ function)

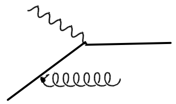
After integration on z :

$$2F_1(x,Q^2) = \sum_i \int_0^1 \frac{d\xi}{\xi}\, f_i(\xi)\, \frac{\hat\sigma_T(x/\xi,Q^2)}{\hat\sigma_0}$$

quark evolution equation

At first order : $\gamma^* q \to q$  where $z = x / \xi = 1$

At next order, the photon quark cross section contains a $\gamma^* q \to q\, g$ contribution

with for 

$$\frac{d\hat{\sigma}}{dp_T^2} \simeq e_q^2\, \hat{\sigma}_0\, \frac{1}{p_T^2} \frac{\alpha_s(Q^2)}{2\pi} P_{qq}(z)$$

where $P_{qq}(z) = \frac{4}{3}\left(\frac{1+z^2}{1-z}\right)$

$P_{qq}(z)$ is the probability of a quark emitting a gluon and reducing the quark momentum by the factor z :

« <u>splitting function</u> »

$$\hat{\sigma}(\gamma^* q \to qg) = \int_{\mu_F^2}^{s^2/4} dp_T^2 \frac{d\hat{\sigma}}{dp_T^2} \simeq e_q^2\, \hat{\sigma}_0\, \frac{\alpha_s(Q^2)}{2\pi} P_{qq}(z)\, \log\frac{Q^2}{\mu_F^2}$$

log. scaling violation

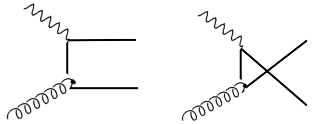
Keeping the relation between F_2 and quarks $\frac{1}{x} F_2(x,Q^2) = \sum_q e_q^2 \left[q(x) + \Delta q(x,Q^2) \right]$

=> quark density evolution

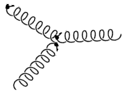
$$\frac{dq(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi}\, q(\xi,Q^2)\, P_{qq}\left(\frac{x}{\xi}\right)$$

DGLAP equations

Similarly : quark in gluon $P_{q\,g}$



gluon in gluon $P_{q\,g}$



Notation $P_{ij} \otimes f_i(x,Q^2) = \int_x^1 \frac{d\xi}{\xi} P_{ij}(\frac{x}{\xi})\, f_i(\xi,Q^2)$

$$\frac{dq(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[P_{qq} \otimes q(x,Q^2) + P_{qg} \otimes g(x,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[P_{gq} \otimes q(x,Q^2) + P_{gg} \otimes g(x,Q^2)\right]$$

Remarks

1. DGLAP equations = Renormalisation group equations (RGE)

$$q(x,Q^2;\mu_F^2) = q(x) + \frac{\alpha_S(Q^2)}{2\pi} \log\frac{Q^2}{\mu_F^2} \int_x^1 \frac{d\xi}{\xi} P_{qq}(\frac{x}{\xi})\ q(\xi)$$

Choice of factorisation scale μ_F is arbitrary → *q(x,Q²)* should not depend on μ_F :

$$\frac{dq(x,Q^2;\mu_F^2)}{d\log\mu_F} = 0 \quad \rightarrow \text{ the DGLAP equations}$$

2. Higher orders

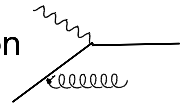
NLO and NNLO splitting functions have been calculated. Very complicated !

III. Factorisation theorems; pdf parameterisations

III.1 Factorisation theorems

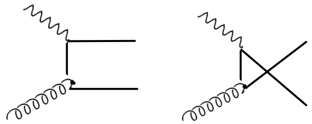
Infrared singularities

Remember logarithmic singularity for quark structure, due to collinear gluon emission



$$\hat{\sigma}(\gamma^* q \to qg) = e_q^2\, \hat{\sigma}_0\, \frac{\alpha_s}{2\pi} P_{qq}(z)\ \log\frac{Q^2}{\mu_F^2} + \int_0^{\mu_F^2} dp_T^2\, \frac{d\hat{\sigma}}{dp_T^2}$$

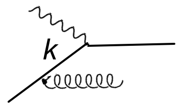
For gluon structure, log *(Q / m)* singularity due to γg fusion diagrams



Generally speaking, *infrared* singularities due to *soft and collinear* configurations

(degenerate kinematic situations)

they correspond to *on mass shell* intermediate parton, with $k^2 = m^2 \approx 0$



They correspond to *long distances*

QCD factorisation theorems

(to be demonstrated : DIS, jet production, Drell-Yan, prompt photon emission, fragmentation in e^+e^-) :

Infrared (long distance) singularities (due to nearly on mass shell partons)

can be separated from hard (short distance) partonic process (with large off mass shellness)

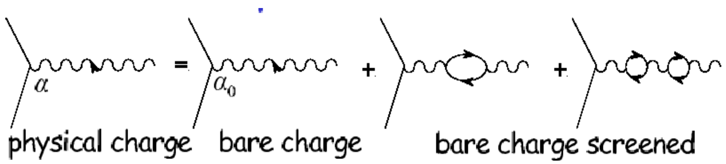
i.e. infrared singularities can be « factorised out »

order by order in pQCD (or useless !)

into ***universal*** **parton density functions**

- which must be ***measured*** (cannot be calculated !)
- at some factorisation ***scale*** μ_F
- of which the ***evolution*** from μ_F can be calculated using the P_{ij} coefficient kernels (DGLAP equations)

Very much like charge and mass are redefined to dispose of familiar *UV* singularities due to loop corrections



« *renormalisation* » is factorisation of UV divergences

« *factorisation* » is renormalisation of soft / collinear divergences

Master formula

$$\sigma^h(x,Q^2) = \sum_{i=q\,\bar{q}\,g} \int_0^1 \frac{d\xi}{\xi} \underbrace{C^i\left(\frac{x}{\xi},\frac{Q^2}{\mu^2},\frac{\mu_F^2}{\mu^2},\alpha_S(\mu^2)\right)}_{coefficient\ \ function} \underbrace{\phi_{i/h}(\xi,\mu_F,\mu^2)}_{pdf}$$

μ renormalisation scale (fixes $\alpha_s(\mu^2)$)

μ_F factorisation scale

ones often takes $\mu_F = \mu$ - can be Q^2 or E_T (jet) etc.

NB complicated cases where 2 scales (e.g. Q^2 and jet E_T ; also when large *log 1/x*)

- the factorisation scale μ_F can be seen as where hard and soft processes separate,

  i.e. maximum off-shelness of partons grouped into pdf $\phi_{i/h}$

- as μ is present in both coeff. fct. and in pdf's,

  a « factorisation scheme » (*MS-bar*, *DIS*) must define (for higher orders) the attribution of the short distance finite contributions (i.e. to coeff. fct. or to pdf's)

  (remember : pdf's are « theoretical » objects)

Parton distribution functions

$$\sigma^h(x,Q^2) = \sum_{i=q\,\bar{q}\,g} \int_0^1 \frac{d\xi}{\xi} \; C^i\left(\frac{x}{\xi},\frac{Q^2}{\mu^2},\frac{\mu_F^2}{\mu^2},\alpha_S(\mu^2)\right) \; \phi_{i/h}(\xi,\mu_F,\mu^2)$$

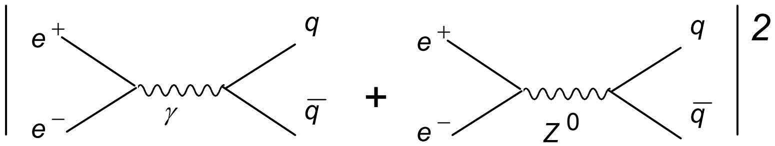
- coeff. functions are QCD calculable as power series in α_s,
  infrared safe
  process dependent (NC DIS, CC DIS, jet, etc.)
  independent of initial hadron *h*
- pdf's are specific to *h*
  but process independent (including independent of Q^2)
- pdf evolution kernels (e.g. DGLAP) are
  QCD calculable as power series in α_s
  infrared safe

- compute the process ($e^+ e^-$, DIS, …) cross section at parton level, at a given order of perturbation theory
- compute the « parton structures » $\phi_{i/q}$ $\phi_{i/g}$ at the same order (in a given factorisation scheme)
- thus derive the coefficient functions C^i (at same order, in the same scheme)
- combine the C^i with the experimental cross section σ^h to derive the non perturbative parton distributions in the hadron $\phi_{i/h}$ (at same order, in the chosen scheme) (i.e. inverse master formula)
- use the evolution kernels to extract the pdf's for a given μ factorisation scale value

III.2 Drell-Yan production with CMS

Drell-Yan production

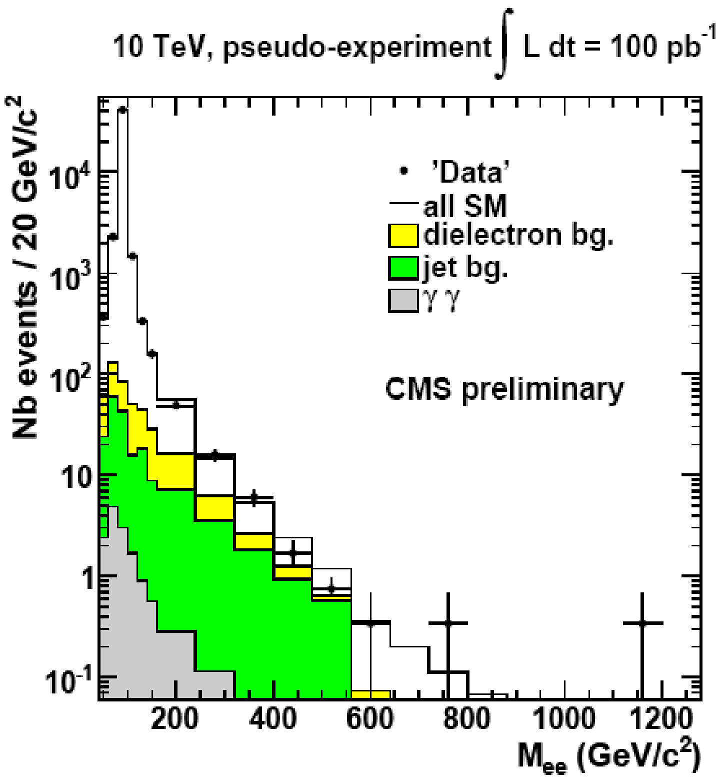
LEP $e^+e^- \to \gamma / Z \to q\bar{q}$

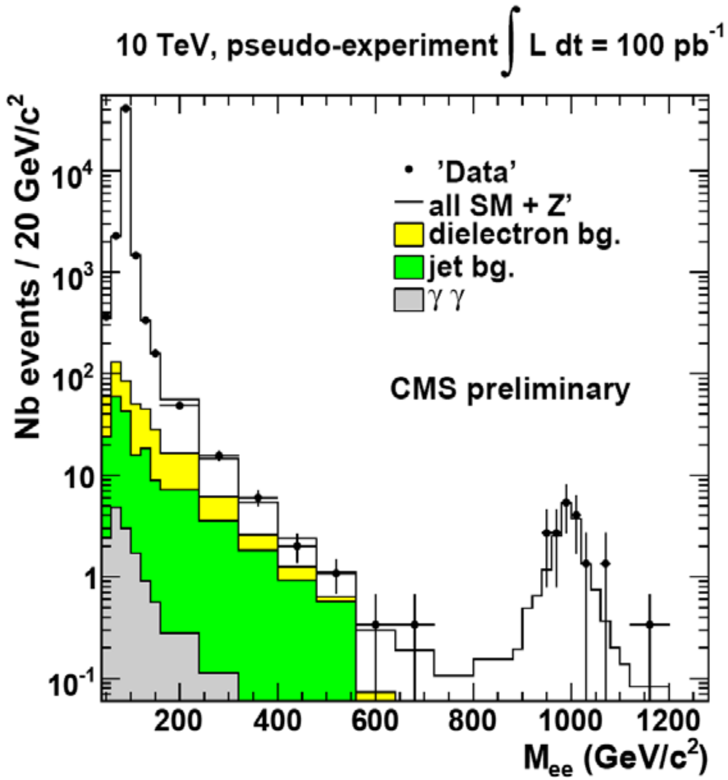


LHC $q\bar{q} \to \gamma / Z \to e^+e^-$

+ Z' ???

(GUT, extradimensions)





Kinematics

quark with proton energy fraction x_1 antiquark with x_2

Let us compute

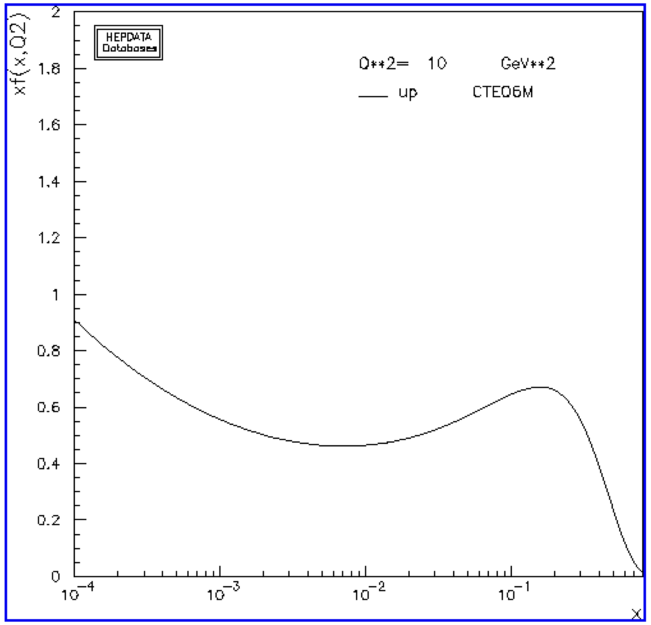
$M = \sqrt{(x_1 x_2)}\ \sqrt{s}$ ($\sqrt{s} = 2E_b$)

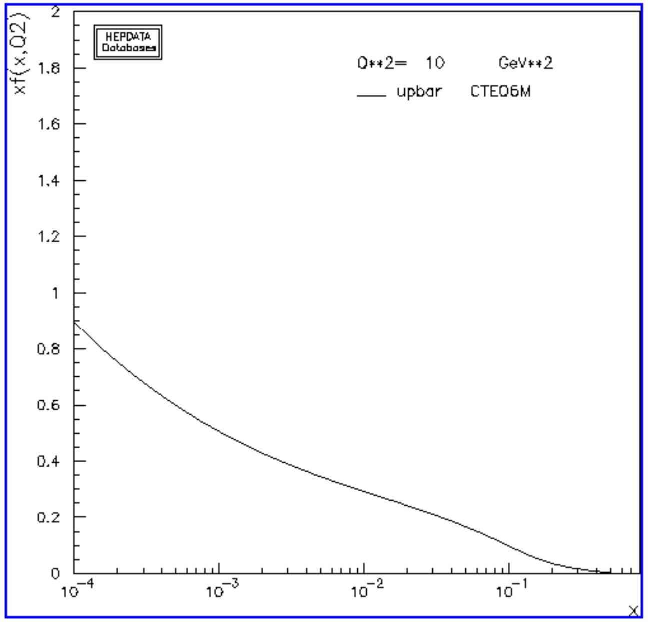
$x_1\ x_2$ not fixed   and no reason that $x_1 = x_2$

i.e. two interacting particles (quarks) have different energies ≠ e^+e^-

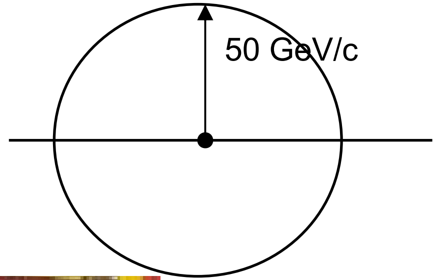
M = 100 GeV → <*x*> = *?*

but mass distribution depends on quark distribution in proton – pdf's

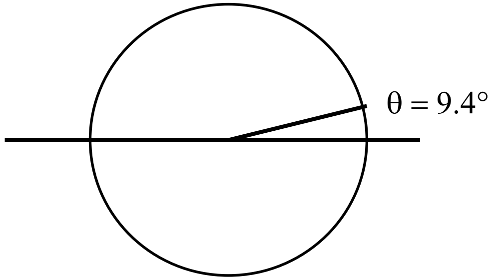


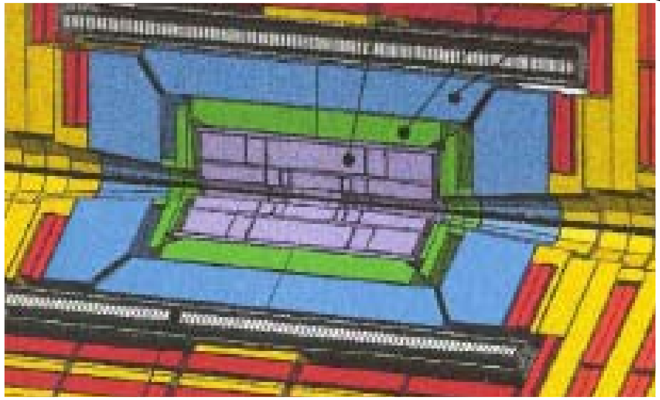


What is Z p_t distribution for Z at rest ?



mostly « central » in detector acceptance



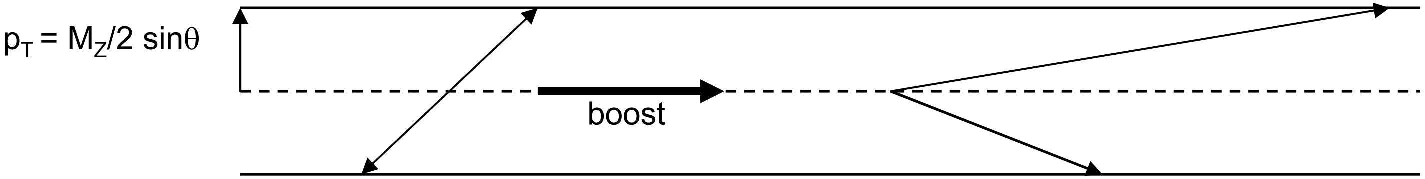


but is Z at rest ?

$M = \sqrt{(x_1 x_2)} \sqrt{s}$

=> *p_z = ?*

=> Z boosted – decay out of acceptance



loss of acceptance depends of pdf's !

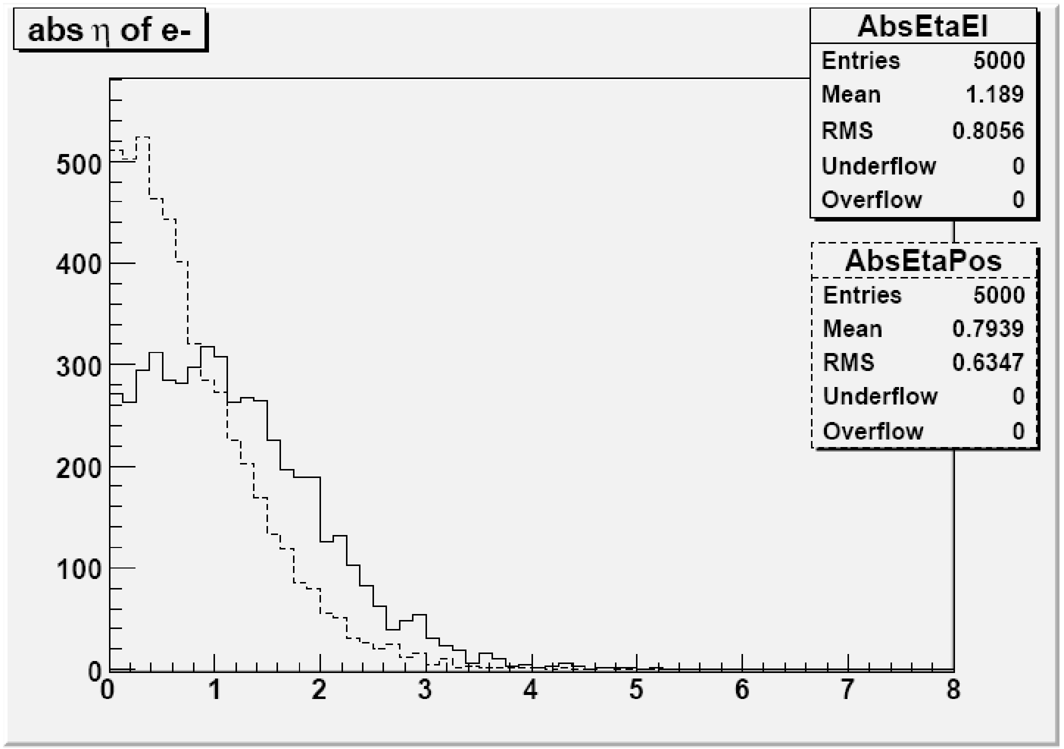
NB different acceptance for e+ and e-

Different acceptance for electrons (solid) and positrons (dashed)

In SM, e^- is preferentially emitted in direction of quark

x(quark) is generally larger than x (antiquark)

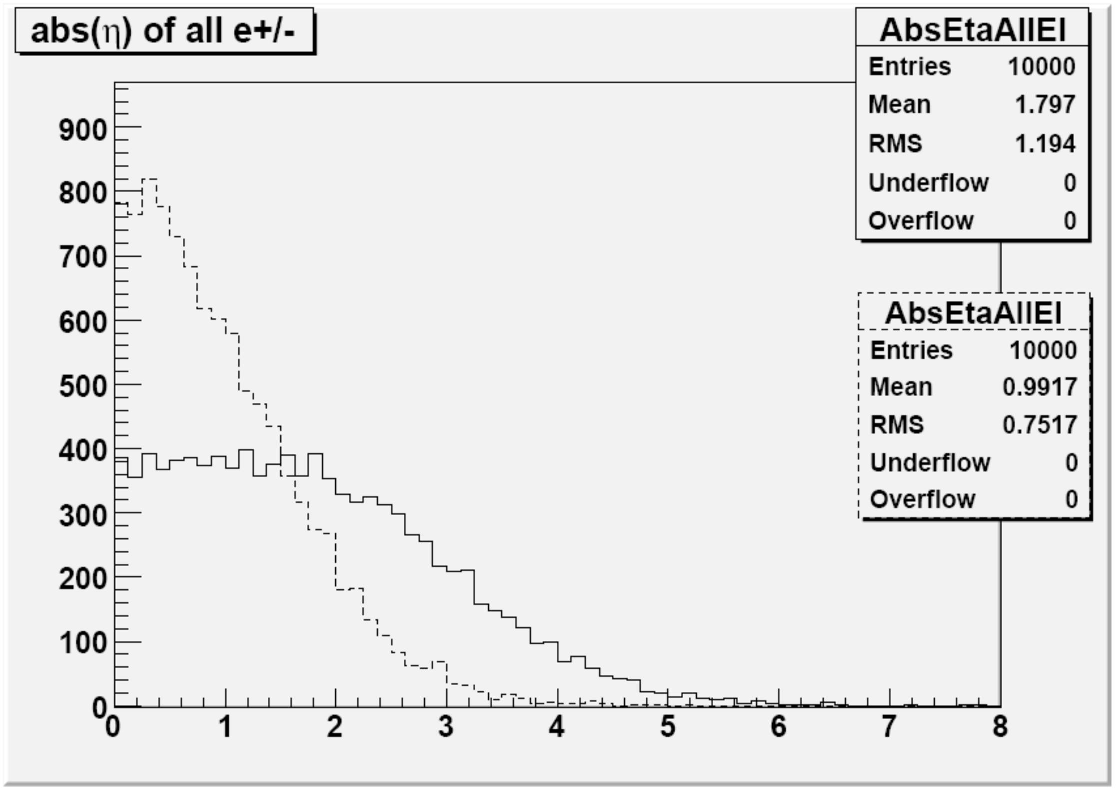
=> e^- is statistically more boosted than e^+



(Master thesis V. Dero, ULB)

Different acceptance for low (200 GeV - solid) and large mass (2000 GeV - dashed)

2000 GeV => $\sqrt{(x_1 x_2)}$ = 0.2 => both quark at relatively large x => Z not much boosted
200 GeV => $\sqrt{(x_1 x_2)}$ = 0.02 => x (quark) can be large (0.1), x (antiquark) small 0.004
=> very different => Z boosted



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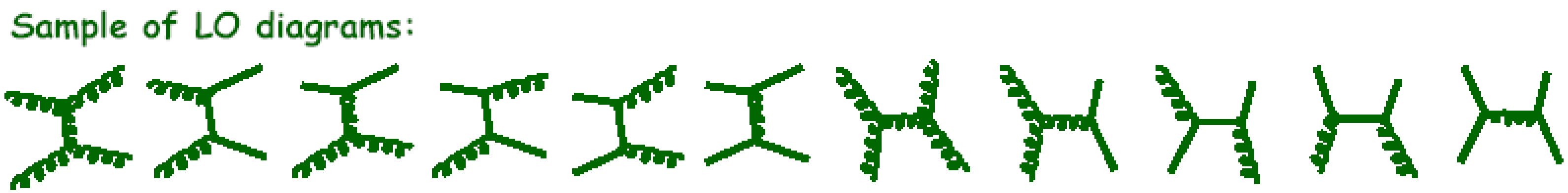
jet production

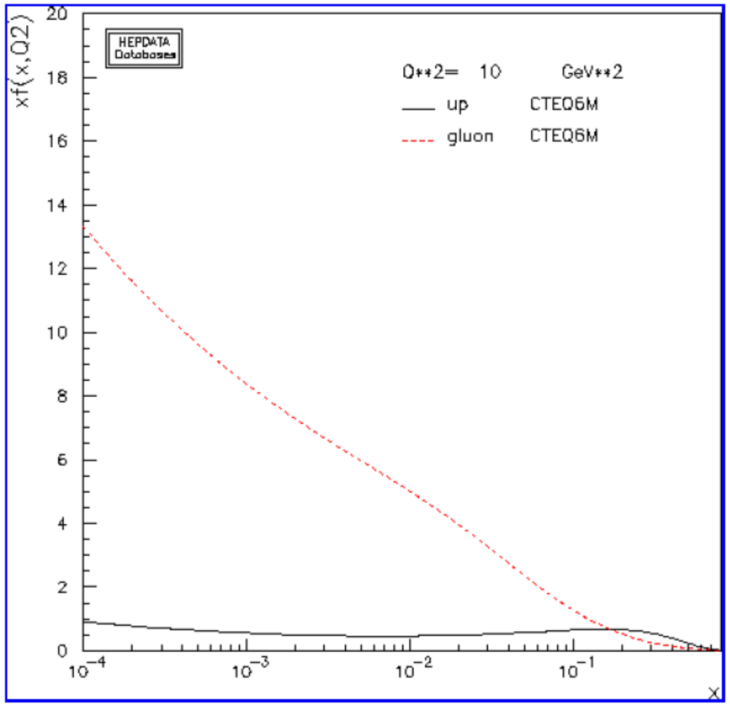
Jets LO diagrams



different diagram contributions (gg, gq, qq) depend on pdf's

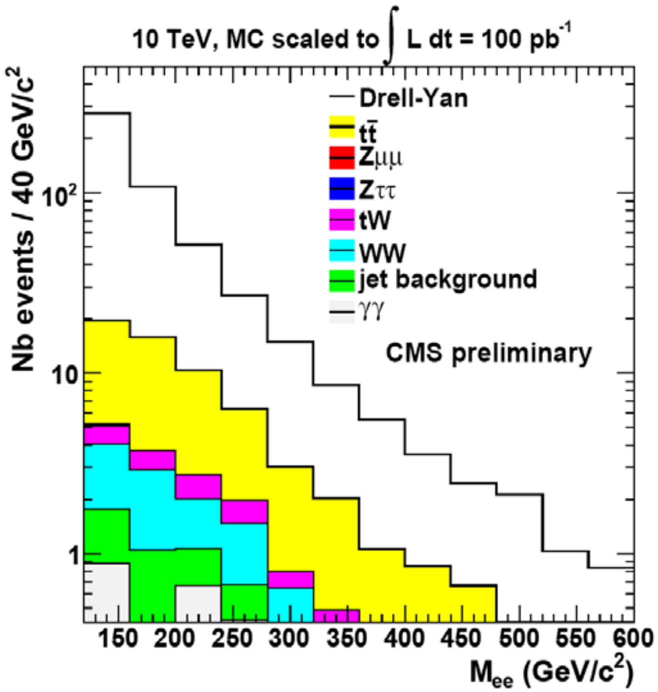
Tevatron qq dominate

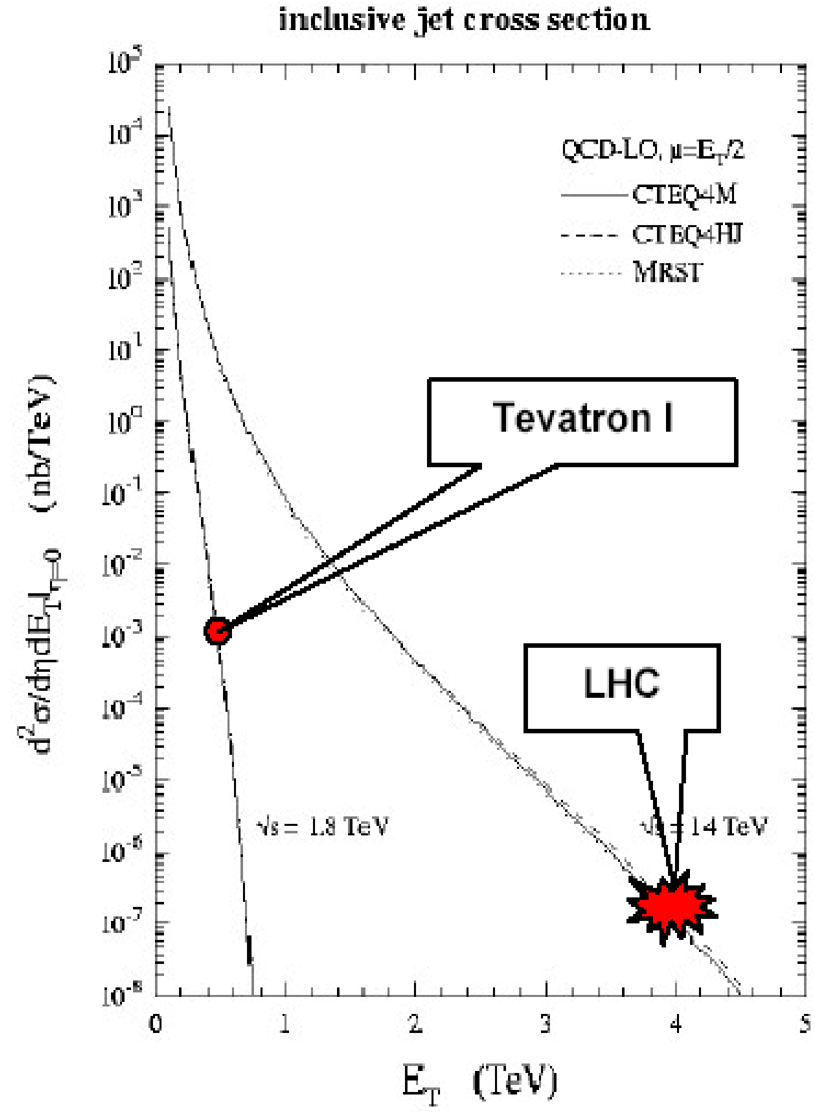
LHC gg dominate



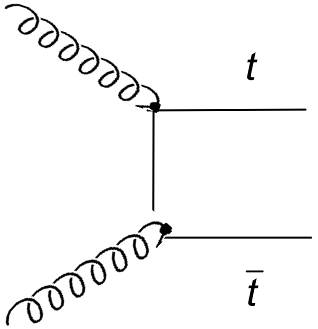
dijet production = important background to large mass Z production

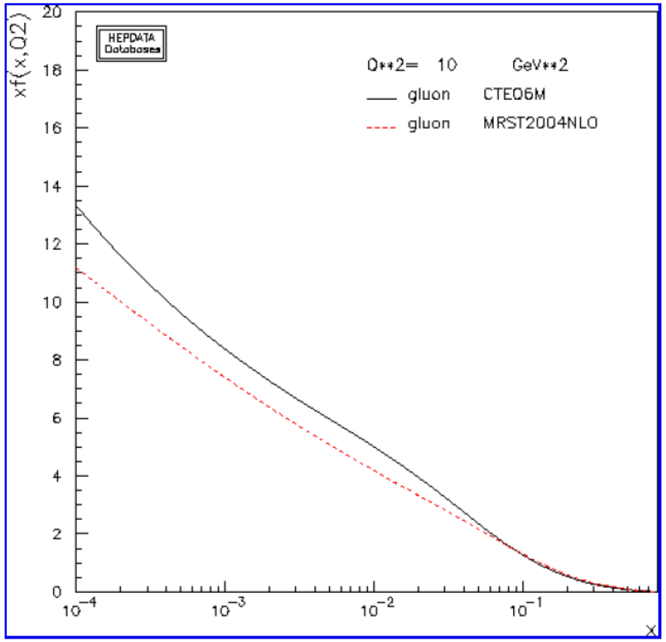
2 jets mistaken as electron : rare, but enormous jet cross section



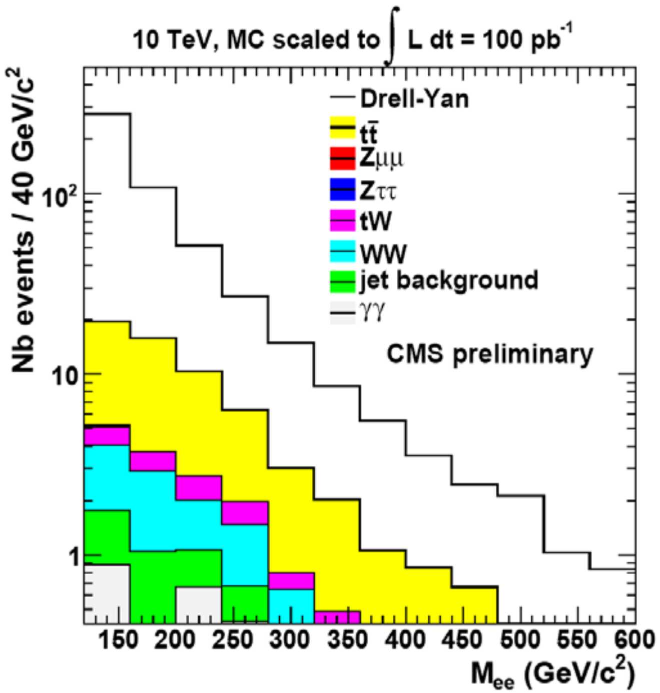


top pair production





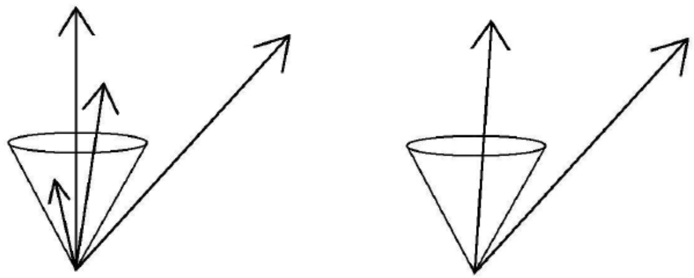
Depends on gluon pdf's



[dominant background to large mass Z production
$t \rightarrow W^+ b$ and $W^+ \rightarrow e^+ \nu_e$ and similar for tbar
=> true $e^+ e^-$ pair]

underlying event (soft physics)

Electron identification against jet background : isolation criteria

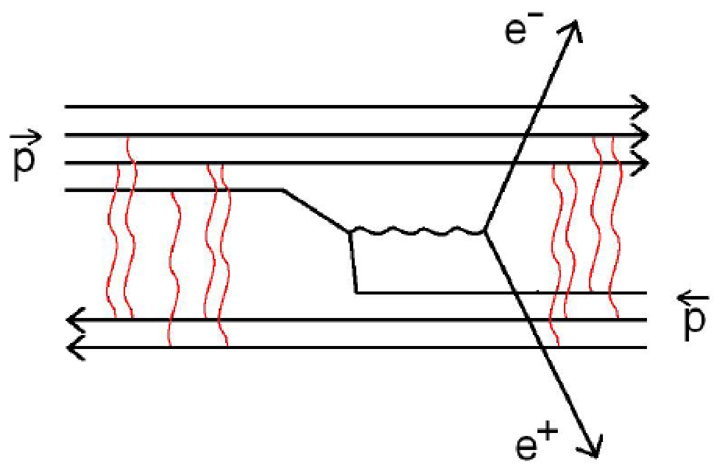


« Hard » $q\bar{q} \rightarrow \gamma / Z \rightarrow e^{+}e^{-}$ interaction

+ proton remnant jets

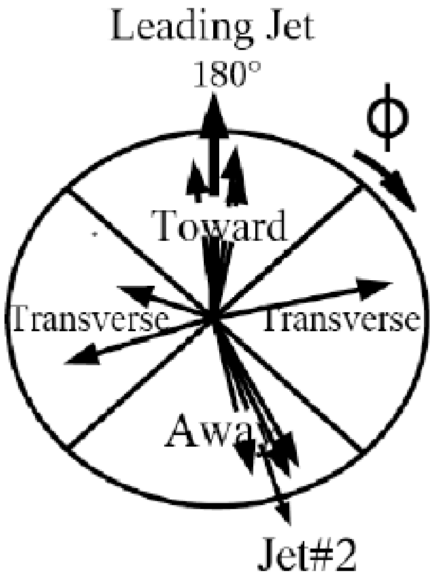
+« soft » interactions between proton remnants = high density colour fields

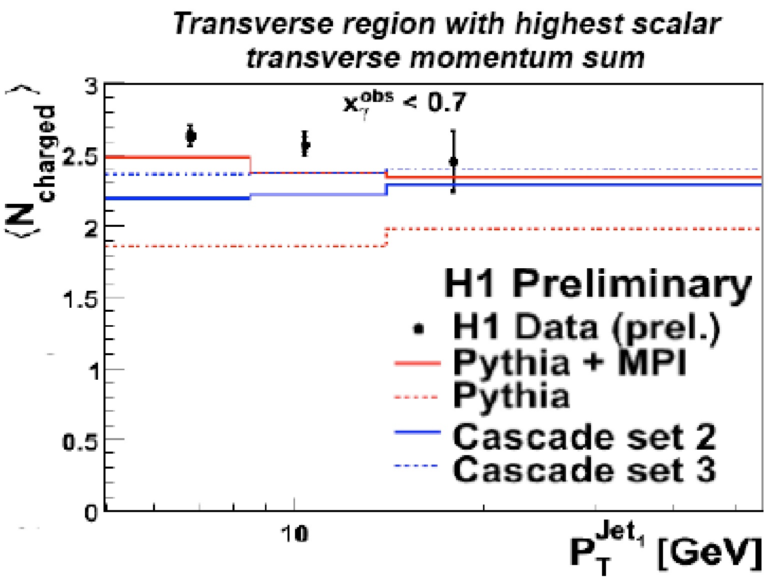
-> additional tracks with limited p_T



(Master thesis V. Dero, ULB)

Coupures	Nombre moyen de particules A une masse de 200 GeV -- A une masse de 2000 GeV	
Pas de coupure	359	351
$\|\eta\| < 2.4$	159	162
$p_t > 1\ GeV$	58	63
$\|\eta\| < 2.4$ et $p_t > 1\ GeV$	35	40





III.3 Parton distribution parameterisations

Parameterising pdf's

- Choose a starting parameterisation for the various parton species (quarks, antiquarks, gluons)

  at a given μ scale (usually $\mu_F = \mu$)

  in a given factorisation scheme (usually *MS-bar*)

  - with a number of parameters sufficiently *large* to describe the data
  - but sufficiently *small* to be really constraint by physics and not artefacts

- Decide upon simplification hypotheses to decrease number of degrees of freedom
  - isospin (*u(x)* in proton = *d(x)* in neutron; *u* sea in proton = *d* sea in neutron, but *u* sea in proton might be different form *u* sea in neutron)
  - x-distributions of quark and antiquark seas : have to be the same in total, but what about *x* dependences ?
  - *s(x)* sea versus *u(x), d(x)* seas

- Choose experimental data
  - theoretically relevant (be sure factorisation applies !)
  - theoretically under control – e.g.

    higher order effects (NLO / LO ; NNLO / NLO)

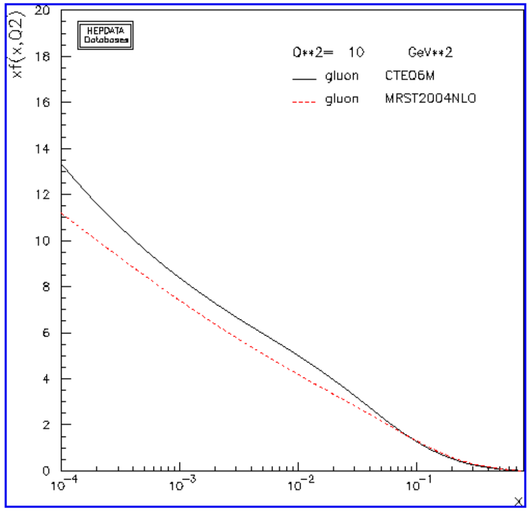
    treatment of nuclear effects (in extracting neutron pdf's from *eA* and μA scattering)

  - experimentally reliable

    (e.g. phase space extrapolations for HERA charmed meson production)

- … and fit
  - (for errors – see below !)

Main parameterisations



- MRST

  starting scale : $\mu^2 = Q_0^2 = 2$ GeV^2

  u quark $$xu(x,Q_0^2) = A_u(1-x)^{\eta_u}(1+\varepsilon_u\sqrt{x}+\gamma_u x)x^{\delta_u}$$

  d quark $$xd(x,Q_0^2) = A_d(1-x)^{\eta_d}(1+\varepsilon_d\sqrt{x}+\gamma_d x)x^{\delta_d}$$

  sea $$xS(x,Q_0^2) = A_s(1-x)^{\eta_s}(1+\varepsilon_s\sqrt{x}+\gamma_s x)x^{\delta_s}$$

  $\Delta q = \bar{u} - \bar{d}$ $$x\Delta(x,Q_0^2) = A_\Delta(1-x)^{\eta_\Delta}(1+ \quad \gamma_\Delta x+\delta_\Delta x^2)x^{\delta_\Delta}$$

  gluons $$xg(x,Q_0^2) = A_g(1-x)^{\eta_g}(1+\varepsilon_g\sqrt{x}+\gamma_g x)x^{\delta_g} \quad \left[-A\_(1-x)^{\eta_-}x^{-\delta_-}\right]$$

  strange sea $$\kappa = \frac{s(x)}{\bar{u}(x)+\bar{d}(x)} \simeq 0.4$$

  sea asymm. $$\Delta s(x) = s(x) - \bar{s}(x)$$

- CTEQ $(1+\varepsilon_i\sqrt{x}+\gamma_i x) \quad \rightarrow \quad (1+\gamma_i x^{\varepsilon_i})$
- DIS (H1, ZEUS)

around 20 free parameters (or even more) for some 2000 data points

(A_u and A_d fixed by valence quark counting, A_g fixed by momentum sum rule)

Parameterisations differ in detailed form of parameterisation at starting scale, data sets included, factorisation / renormalisation scale Q_0^2 and scheme, value of $\alpha_s(Q_0^2)$, assumptions on κ, sea asymmetry, possible negative gluon

Data sets

DIS (1)   fixed target μp, μn BCDMS, NMC, SLAC, E665 $x > 10^{-2}$

$e^+ p$, $e^- p$ (NC and CC) H1, ZEUS $x > 10^{-5}$ quarks, gluons (through evolution)

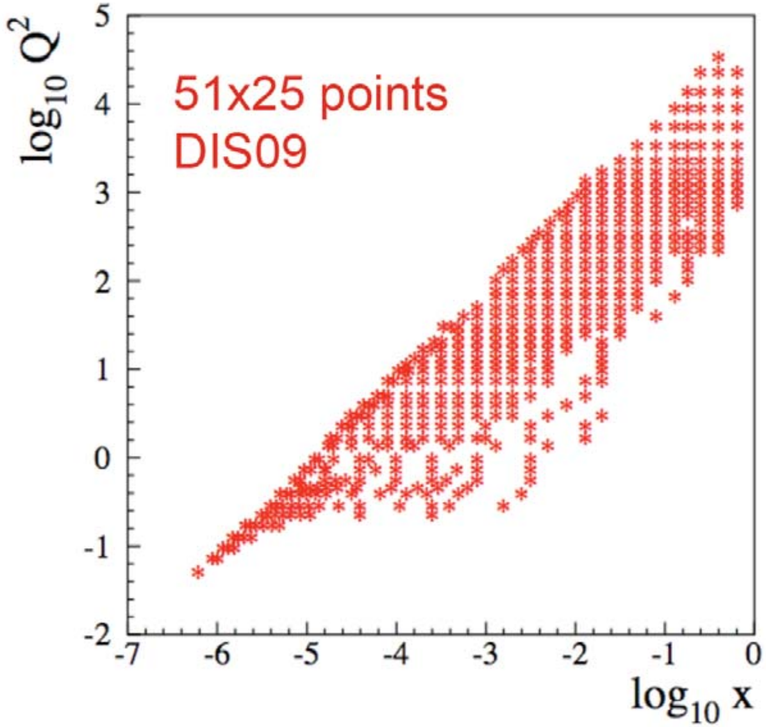
$e^+ p$, $e^- p$ CC → u / d at large x (without nucl. tgt problems)

$F^2_{c\bar{c}}$ $F^2_{b\bar{b}}$ →direct access to gluons (photon gluon fusion)

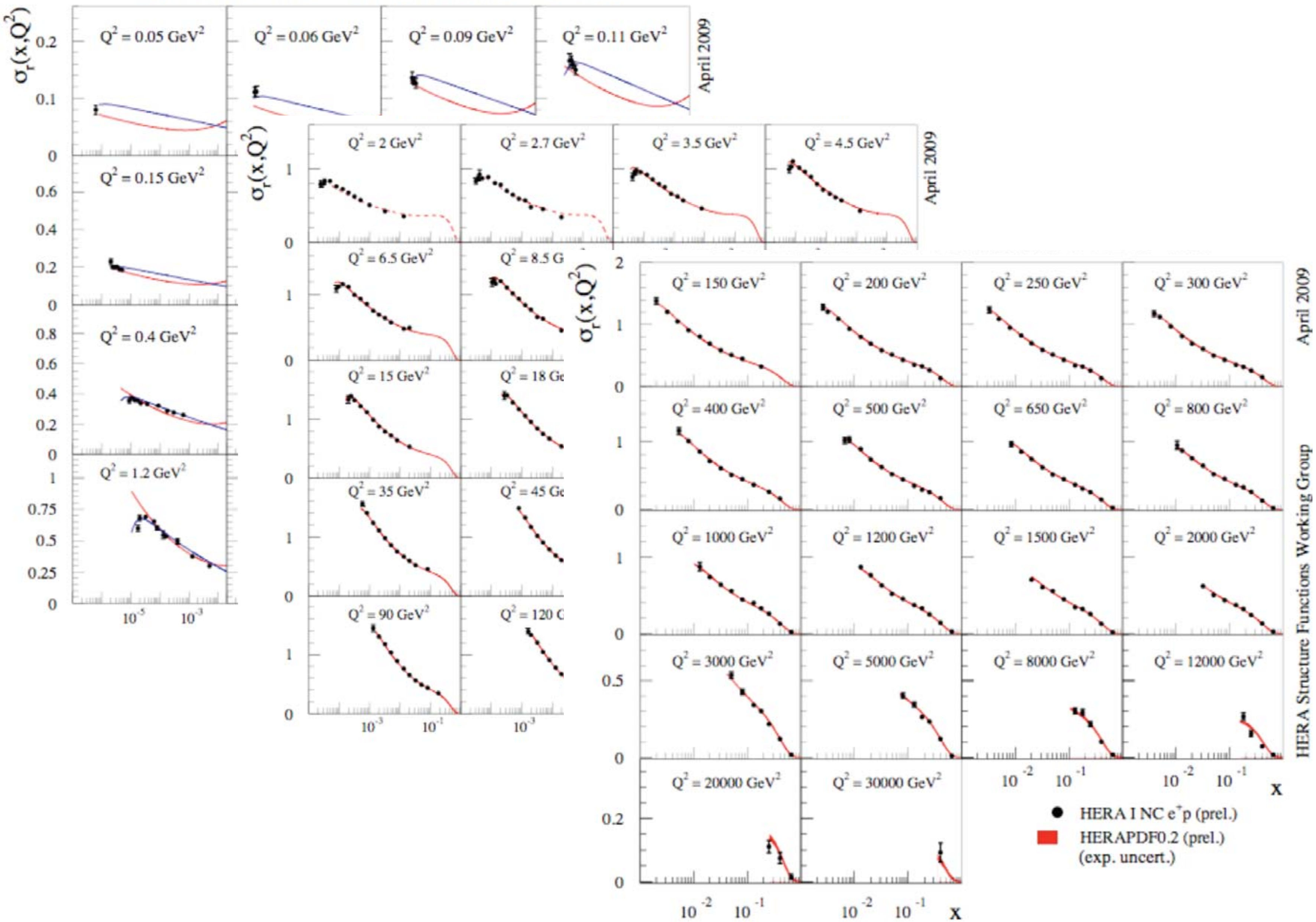
2009 joint analysis by H1 and ZEUS of
1995-2000 data set

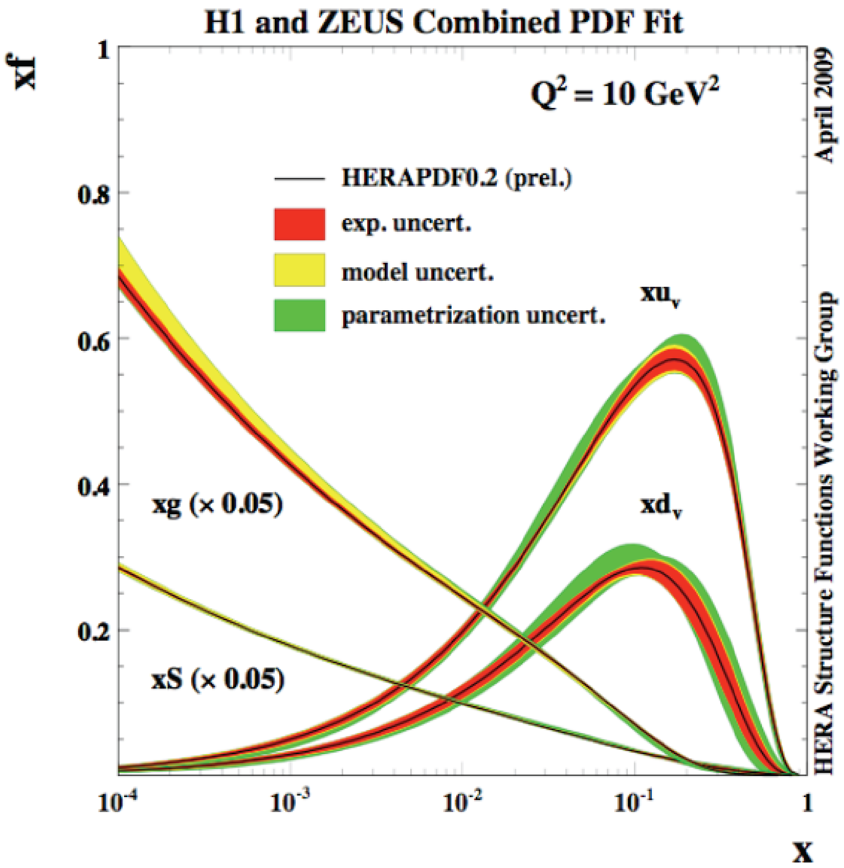
110 point-to-point correlated error sources

χ^2 / dof = 576 / 592

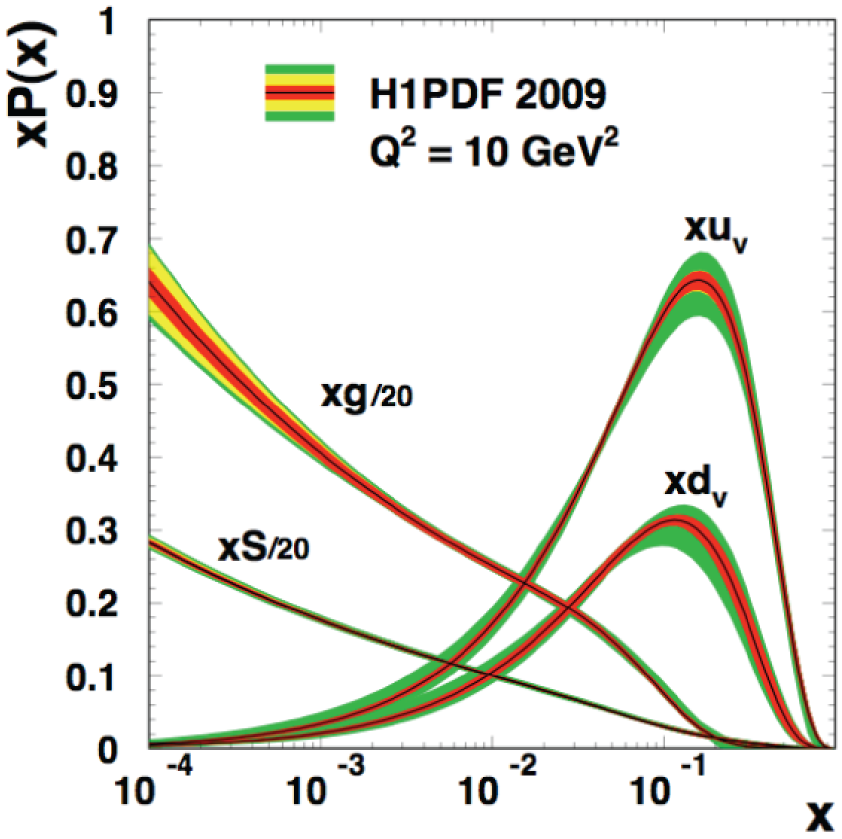


H1 and ZEUS Combined PDF Fit





H1 and ZEUS Combined PDF Fit
xf
Q² = 10 GeV²
HERAPDF0.2 (prel.)
exp. uncert.
model uncert.
parametrization uncert.
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
April 2009
HERA Structure Functions Working Group
x

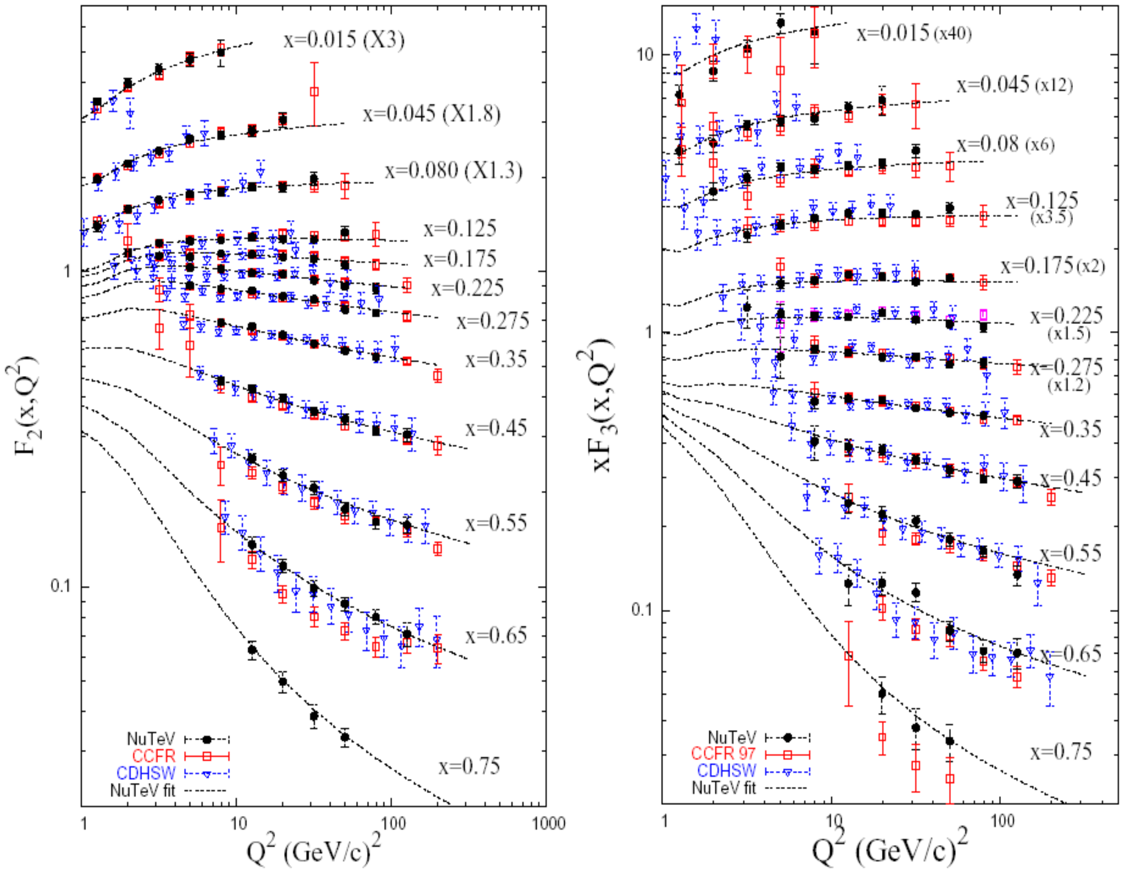


xP(x)
H1PDF 2009
Q² = 10 GeV²
xu_v
xd_v
xg/20
xS/20
x

Data sets (2)

DIS (2) νp νn $\bar{\nu} p$ $\bar{\nu} n$ CCFR $x > 10^{-2}$: total quarks, valence

NuTeV + strange sea (dimuon events from CC charm prod.)

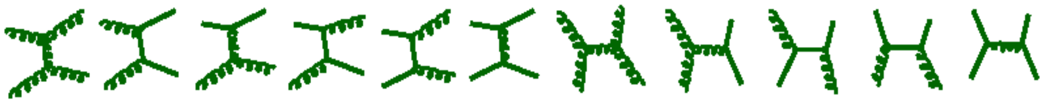


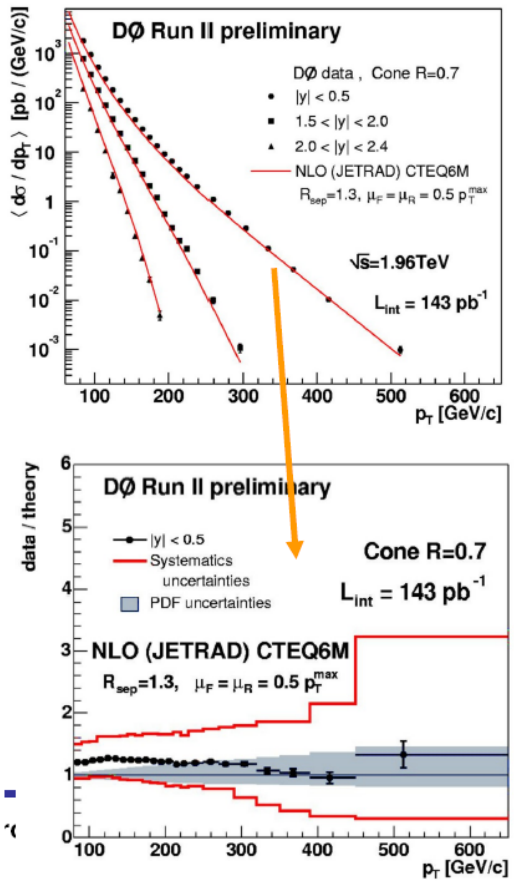
Data sets (3)

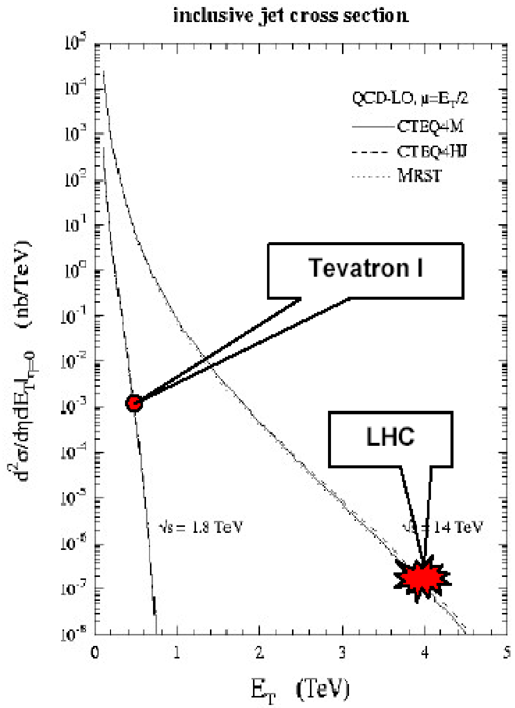
Jets Tevatron collider CDF, D0 → constraints on high *x* gluon

Jets in DIS at HERA ZEUS

Sample of LO diagrams:

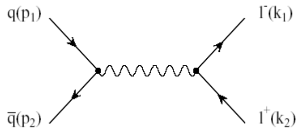


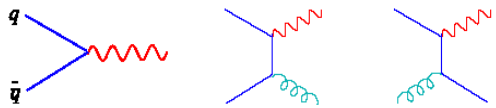




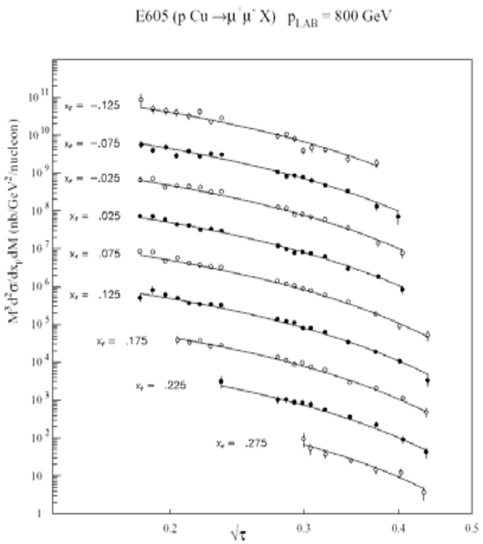
Data sets (4)

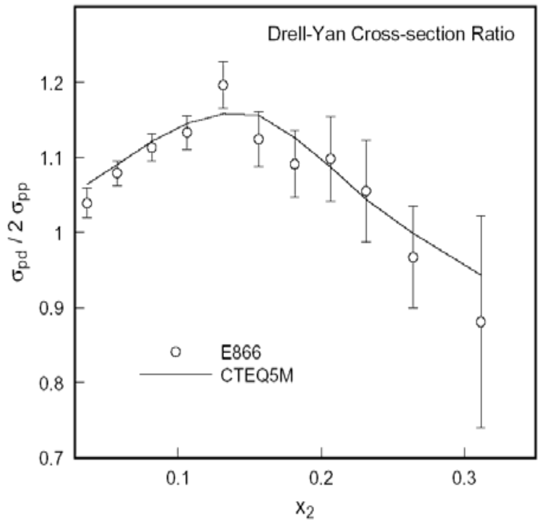
Drell-Yan (muon pair production) : Fermilab, *p* and *n* → *u*, *d* valence; $\bar{u}$, $\bar{d}$





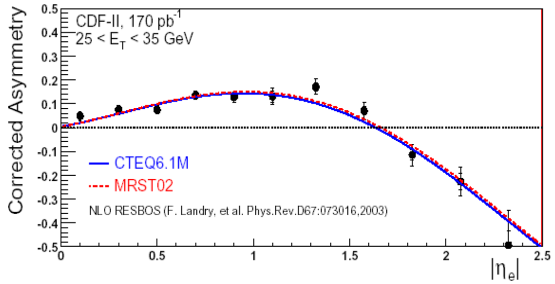
Large *K*-factor (= NLO / LO) → convergence ? factorisation true ? now understood : $\alpha(\mu\mu)$ not small

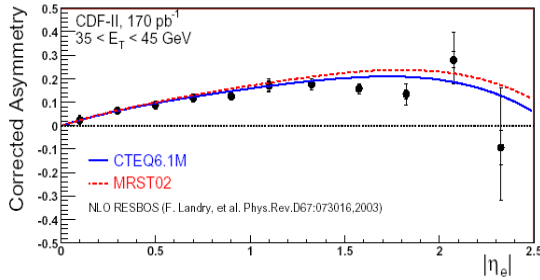




W asymmetry (CDF)

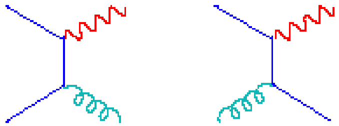
u/d ratio at high x



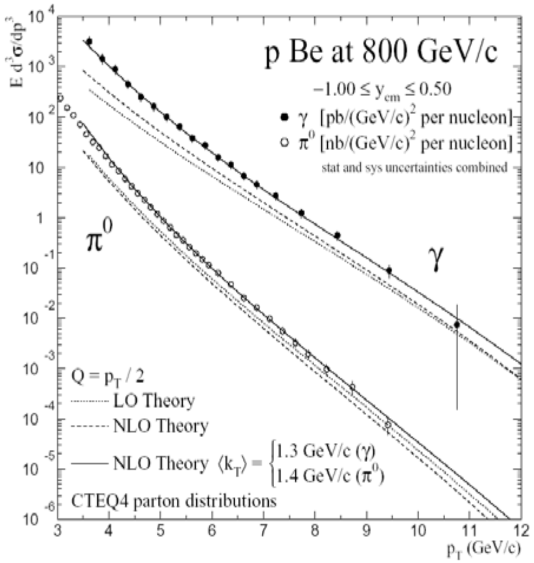


Data sets (5)

Prompt photon production



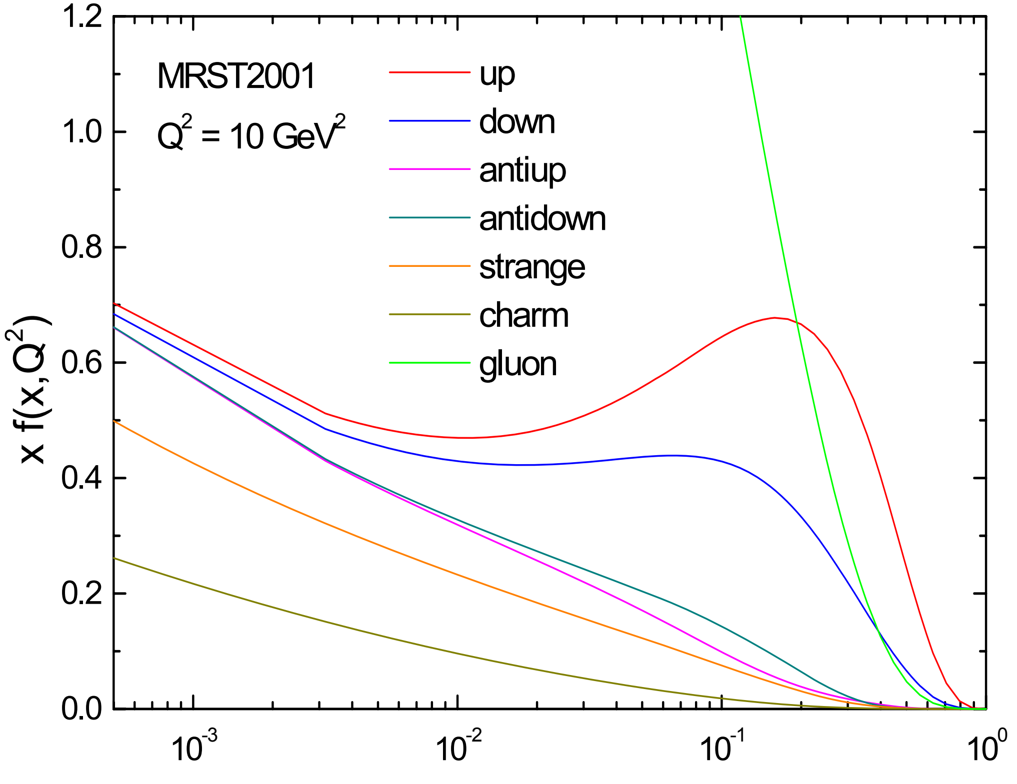
Sensitive to primordial k_T of quarks inside nucleon (i.e. higher orders



Results…

$$\frac{dq(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[P_{qq}\otimes q(x,Q^2) + P_{qg}\otimes g(x,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[P_{gq}\otimes q(x,Q^2) + P_{gg}\otimes g(x,Q^2)\right]$$



III.4 Parton distribution uncertainties

Experimental uncertainties

- selection of data

  choice of accepted Q^2, W domain

- effect of experimental errors ?

  correlated / uncorrelated systematics

- how to combine « poorely compatible » experiments ?

- Hessian estimate of errors (correlation matrix)

  deviation in χ^2 of the global fit from the minimum χ^2 value is assumed to be quadratic in the deviation of the fitted parameters errors from their best value → errors obtained from the covariance matrix, with $\Delta\chi^2 = 1$

  BUT - hypothesis on the quadratic behaviour of uncertainties : (very) questionable

  - (there may exist) strong correlations between parameters (if larger number than necessary)

  - inconsistencies between experiments

  → which tolerance to define errors on pdf's ? $\Delta\chi^2$ = 100 (CTEQ), 50 (MRST), 1 (H1 – only DIS) ?

- Lagrange multipliers : a series of global fits using Lagrange parameters attached to each given measurement, constraining the measured cross sections by the quoted errors → how does the global description deteriorates as one moves away from the unconstrianed best fit – while spanning a range of Lagrange multipliers

  But very heavy procedure

Theoretical uncertainties

- higher QCD orders – in DIS : NNLO
- *log (1/x)* and *log (1-x)* effects
- absorptive corrections – parton recombinations
- other higher twist contributions
- form of the parameterisation at starting scale
- number of parameters ?
- … and relevance of the chosen factorisation scheme for the chosen parameterisation form
- choice of starting scale of evolution
- choice of α_S
- simplification assumptions

  isospin violation

  $s \neq \bar{s}$
- treatment of heavy flavours
- nuclear effects
- inclusion of e-w corrections (significant at NNLO)
- …

Remark : pdf's in Monte Carlos

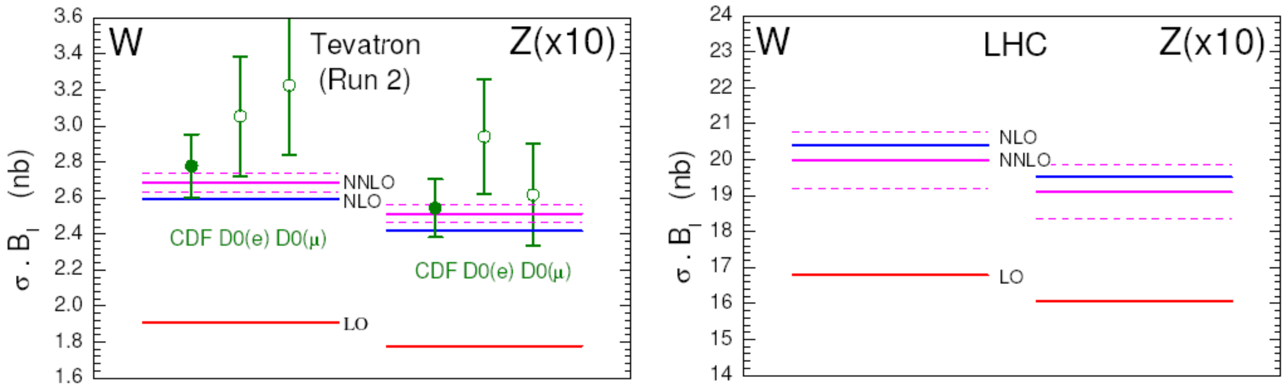
Present Monte Carlos are generally LO + simulation of higher orders through parton shower (JETSET)

JETSET follows DGLAP evolution – HERWIG is believed to be closer to BFKL evolution

Higher orders

All order summation is finite (factorisation theorem) *but* how fast is the convergence ?

- trust convergence if corrections decrease when computing next order



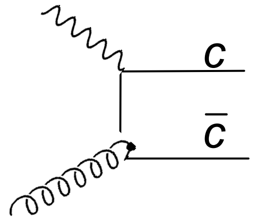
- sensitivity to scale = indication of size of next order contribution

$$\mu \frac{d}{d\mu} C^{(n)}(x, Q^2, \mu) \sim O(\alpha_s^{n+1})$$

small scale sensitivity at NL for DIS and D-Y

large for heavy quarks and prompt photon

Heavy quarks



No HQ in the nucleon at small scale

- dynamically generated (photon gluon fusion)

Works at not too large Q^2 but logarithmic divergence at large Q^2 $\approx \log \frac{Q}{m_q}$

- at large Q^2, treated as massless quarks

→ Fixed / variable flavour number scheme

Jets

full NNLO calculations not available yet

→ estimated through scale dependence :

μ often varied from 0.5 E_T to 2 E_T

Resummations

- Fixed order calculations ←→ resummation of all order contributions : *leading logarithms*

  Necessary when 2 scales, e.g. Q^2 and jet E_T

  ! double counting !

- DGLAP evolution : hard scale given by Q^2

  resums $\alpha_s^n \log^n Q^2$ terms (+ NLO etc.),

  corresponds to strong ordering in k_T of (virtual) partons

- BFKL evolution : in DIS domain (sufficiently large Q^2), very high energy

  resums $\alpha_s^n \log^n \frac{1}{x}$ terms

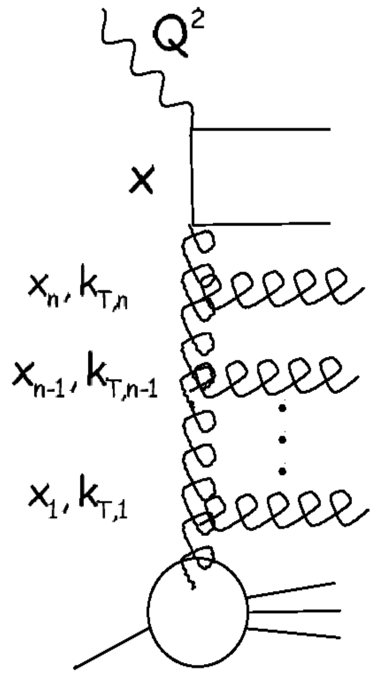
  corresponds to strong parton ordering in x (long. momentum)

  but not necessarily in k_T

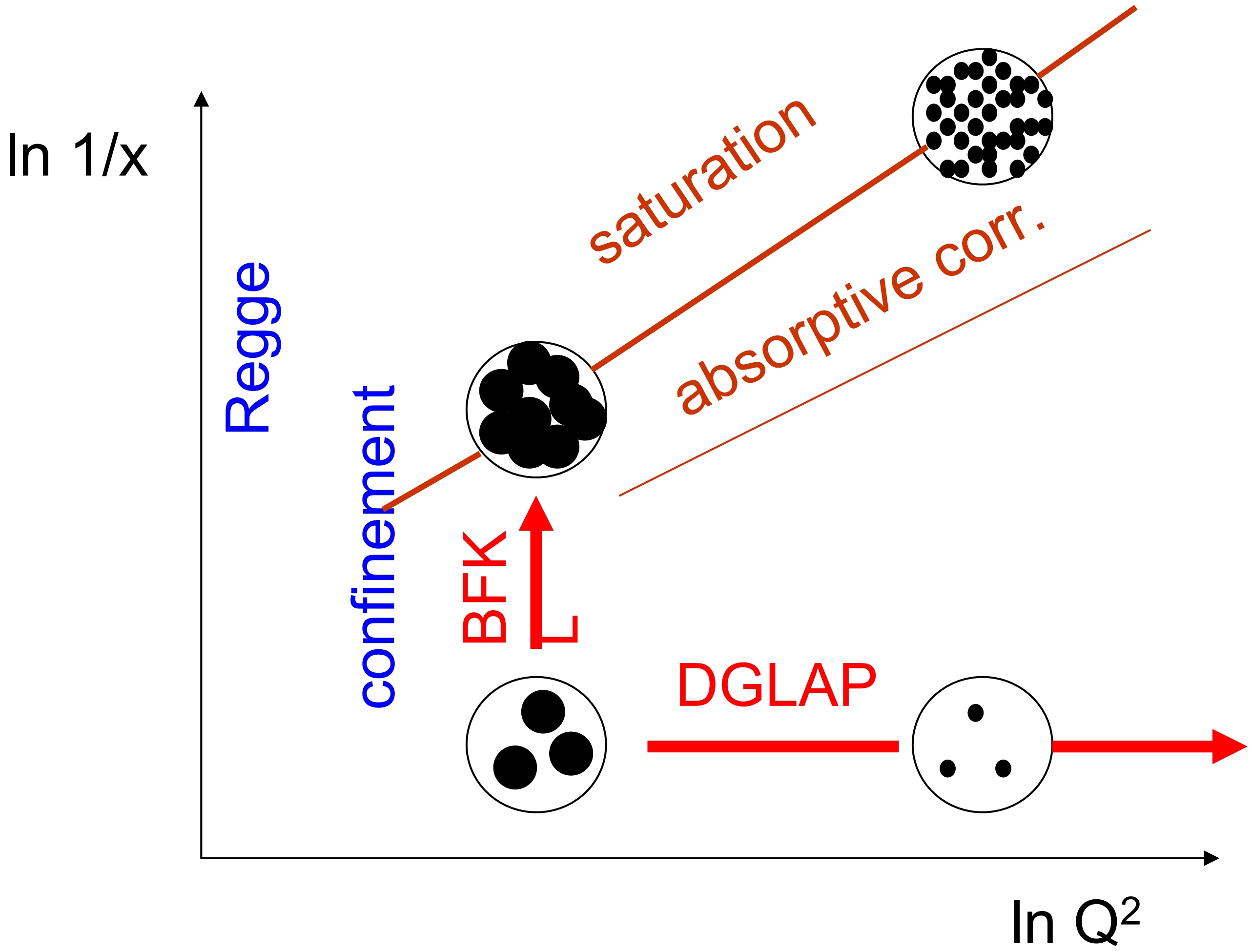
  Predicts fast increase

- CCFM evolution : connexion between DGLAP and BFKL

  angular ordering : $\theta = \frac{k_T}{xp}$

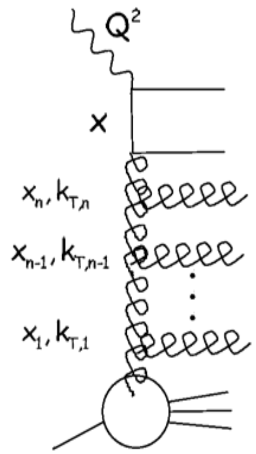


At very high parton density : saturation – parton recombination - non linear evolutions


ln 1/x
Regge
confinement
saturation
absorptive corr.
BFK
L
DGLAP
ln Q2

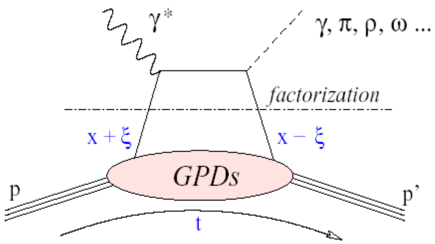
III.5 (Some of many) uncovered topics

Other parton distributions



- unintegrated k_T distributions
  relevant at very high energy, and when no strong k_T ordering
    (BFKL domain)
    e.g. large k_T jet or particle at large x

- generalised parton distributions
  correlations between partons



    vector meson and real photon production (DVCS)
    most relevant for large mass difference between initial and final state

- spin parton distributions
  dedicated experiments (HERMES, COMPAS, etc.)

Other hadrons or hadronic objects

- photon

  $\gamma\,\gamma$ scattering at LEP, hard photoproduction at HERA

  i.e. measurement of the hadronic structure of the photon

  (« resolved » photon ←→ « direct » photon = pointlike)

  $\gamma \to q\bar{q}$ + evolution, including gluon content of the photon

  NB in DGLAP evolution, inhomogeneous component (cf. NS SF)

- pion

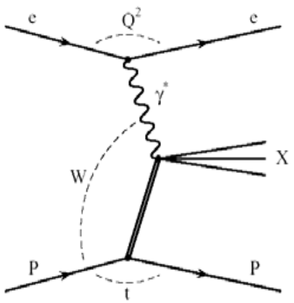
  Drell-Yan, leading neutron final states at HERA (interactions on the pion virtual cloud around the proton)

- pomeron : hadronic structure of diffractive exchange

  HERA (total diffractive production, vector mesons, charm, jets, etc.

  Tevatron (diffractive jet and W production)

  LHC : diffractive Higgs production



  Factorisation theorem proved

  but strong higher twist contributions

  + effects on evolution equations

  + underlying interaction → breaks simple application of of pdf transportation from HERA to Tevatron (« survival probability »)

Some references

- Introduction on DIS, SF, etc.
  F. Halzen, A.D. Martin, *Quarks and Leptons*, Wiley

- Introduction to pdf's and QCD
  CTEQ site http://www.phys.psu.edu/~cteq/ in particular
  QCD Handbook http://www.phys.psu.edu/~cteq/#Handbook
  W.K. Tung, Perturbative QCD and the parton structure of the nucleon
  see also : J.C. Collins, What exactly is a parton density? arXiv:hep-ph/0304122

- Present status of pdf's - draw your favourite pdf's
  MRST site http://durpdg.dur.ac.uk/hepdata/

- Pdf uncertainties : see e.g. (+ ref. therein)
  A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne
  Uncertainties of predictions from parton distributions
  I. Experimental errors arXiv:hep-ph/0211080
  II. Theoretical errors arXiv:hep-ph/0308087

- CERN PDFLIB manual http://consult.cern.ch/writeup/pdflib/