Physics at the LHC

Motivation, Machine, Experiments, Physics

Thomas Schörner-Sadenius

DESY Summer Student Programme
Hamburg, August 2010

OUTLINE

- Part 1 – Motivation: Why the LHC?
- Part 2 – Realisation: How the LHC?
  - The accelerator.
  - The experiments ALICE, LHCb, TOTEM and LHCf.
  - ATLAS and CMS.
- Intermezzo: Basics of pp physics
- Part 3 – Results: What at the LHC?
  - Commissioning and performance
  - The rediscovery of the Standard Model.
  - Higgs boson searches.
  - Searches for Supersymmetry and other BSM physics.

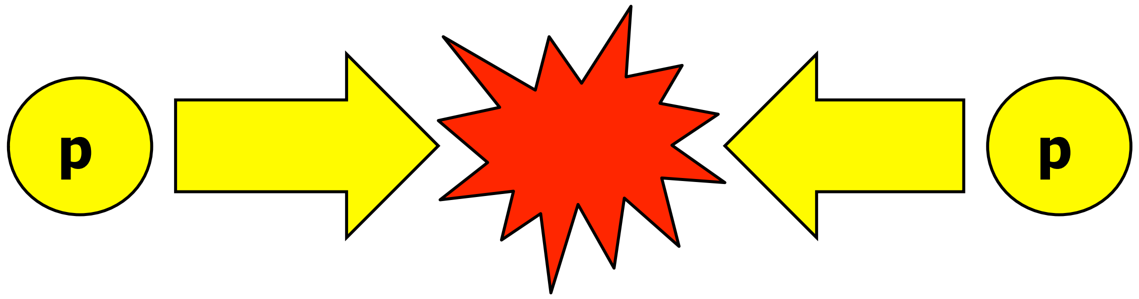
INTERMEZZO

Basics of pp physics

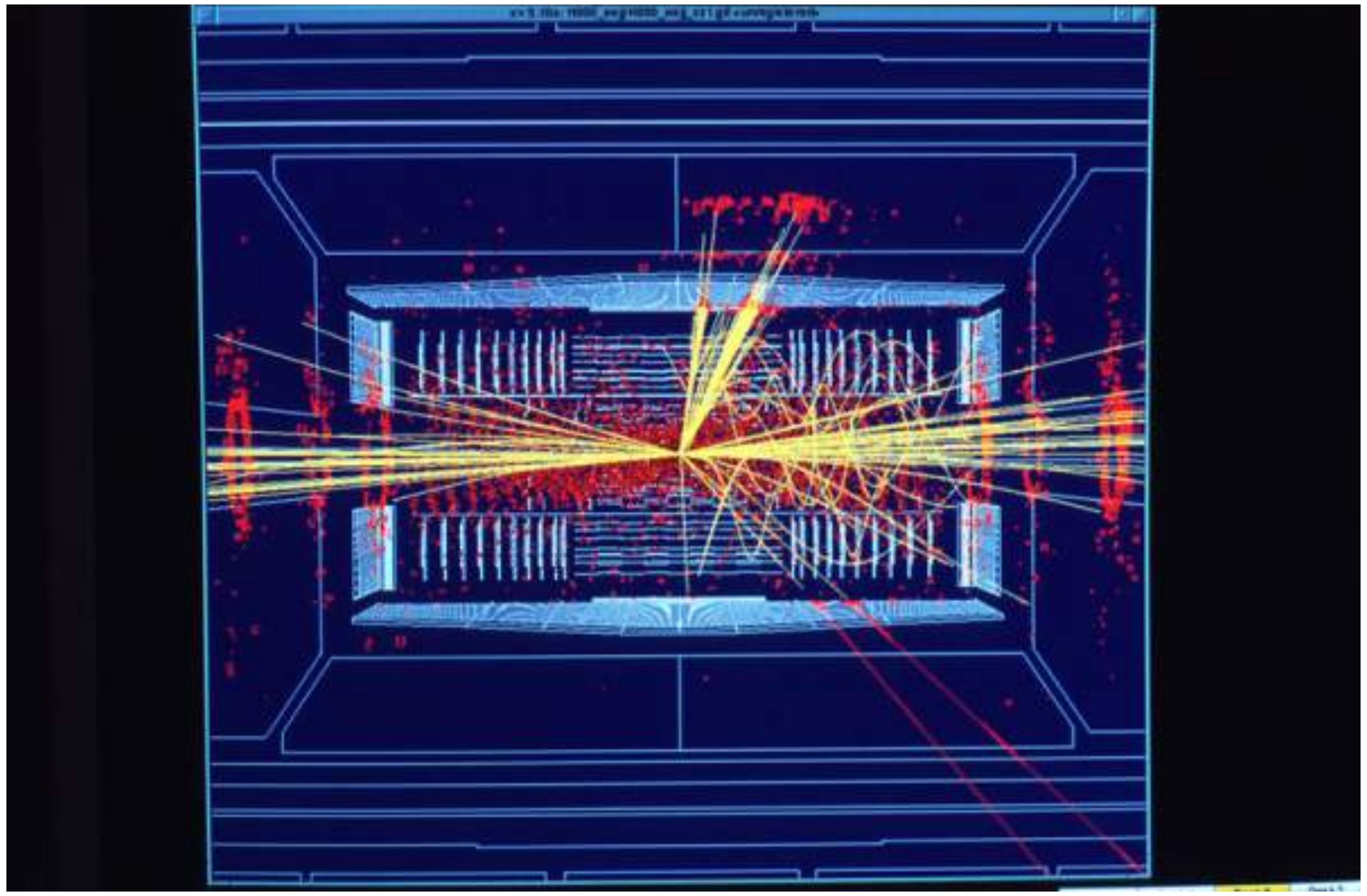
OVERVIEW OF pp REACTIONS (1)

pp reactions:

… from a simple (but potentially coloured!) initial state:



… to a very complicated final state on "hadron level" and in the detector:

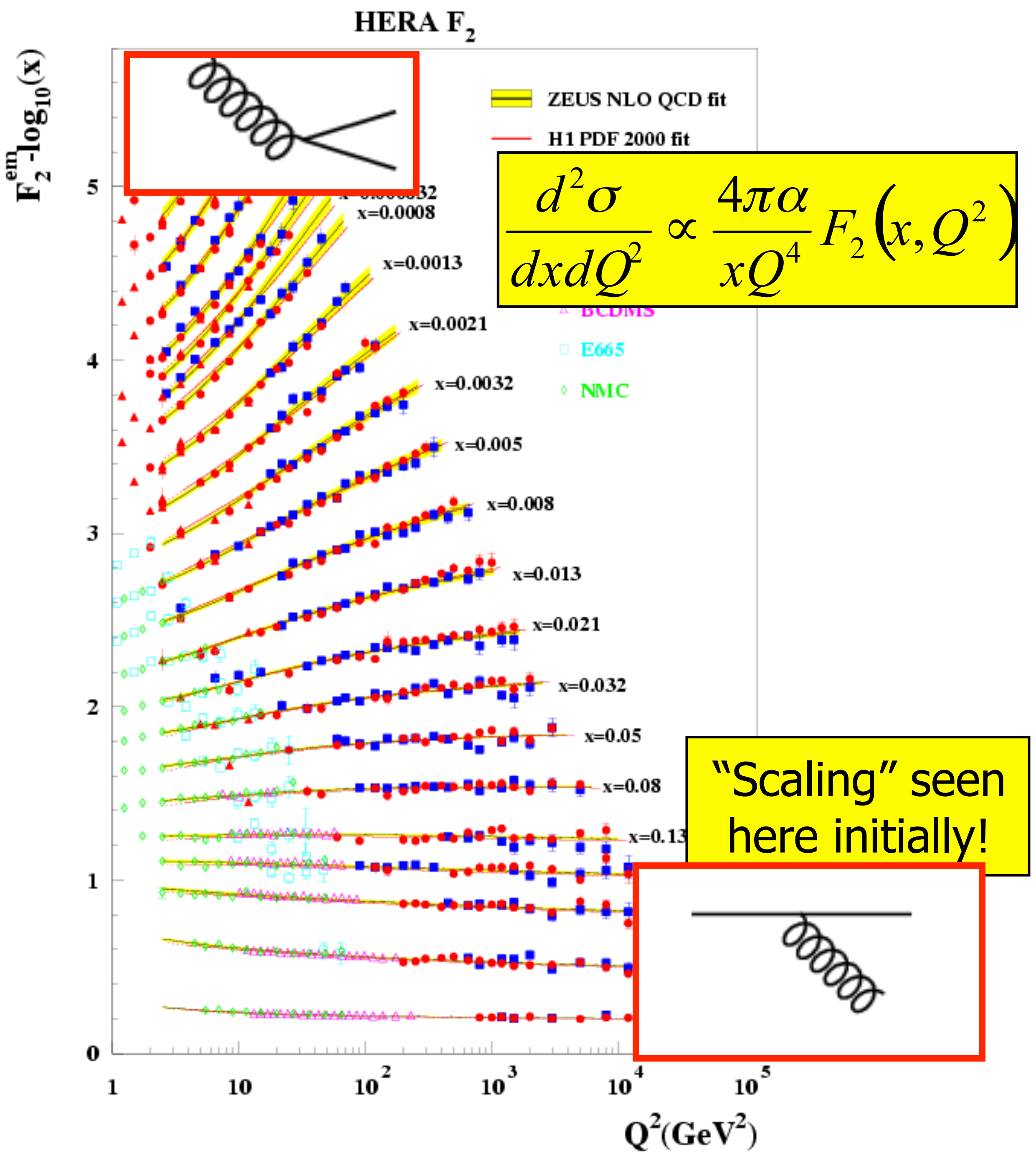


To be understood:

- The complex protons.
  → proton structure
  → HERA physics and deep inelastic scattering
- The reaction between (constituents of) the protons.
  → (hard) QCD, using perturbation theory and Feynman rules
  → models for things that cannot be treated using pQCD.
- The transformation to signals in the detector.
  → detector simulations, detector understanding

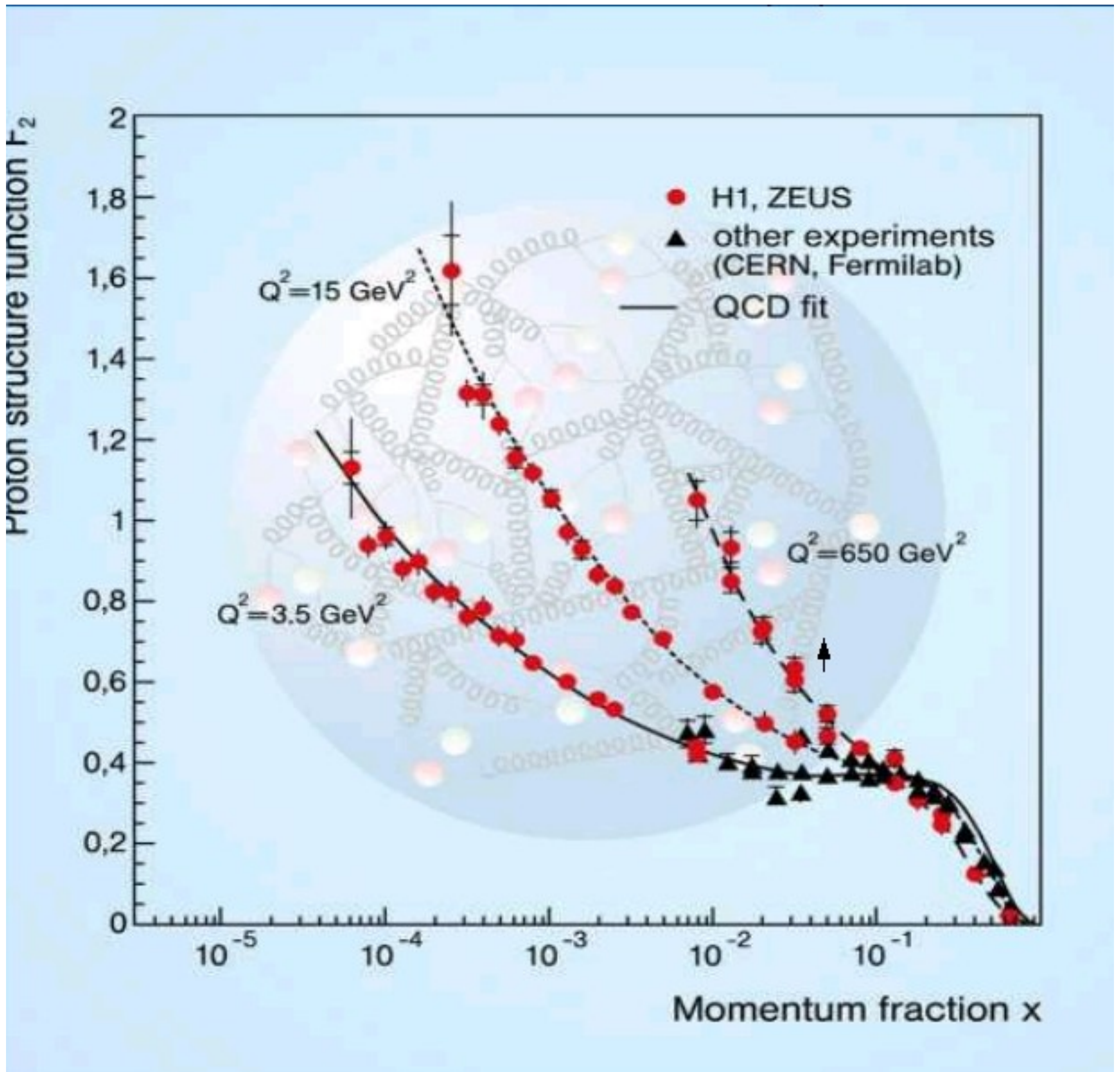
HERA: STRUCTURE FUNCTIONS

Low x: With increasing Q^2, more and more radiated gluons and quark pairs from g→ qq are seen!



High x: With increasing Q^2, less and less un-radiated partons are left here!

Increasing Q^2 → low x populates, high x depopulates!



HERA: STRUCTURE FUNCTIONS

Connection between structure function F_2 and PDFs

→ extraction of PDFs from F_2 data!

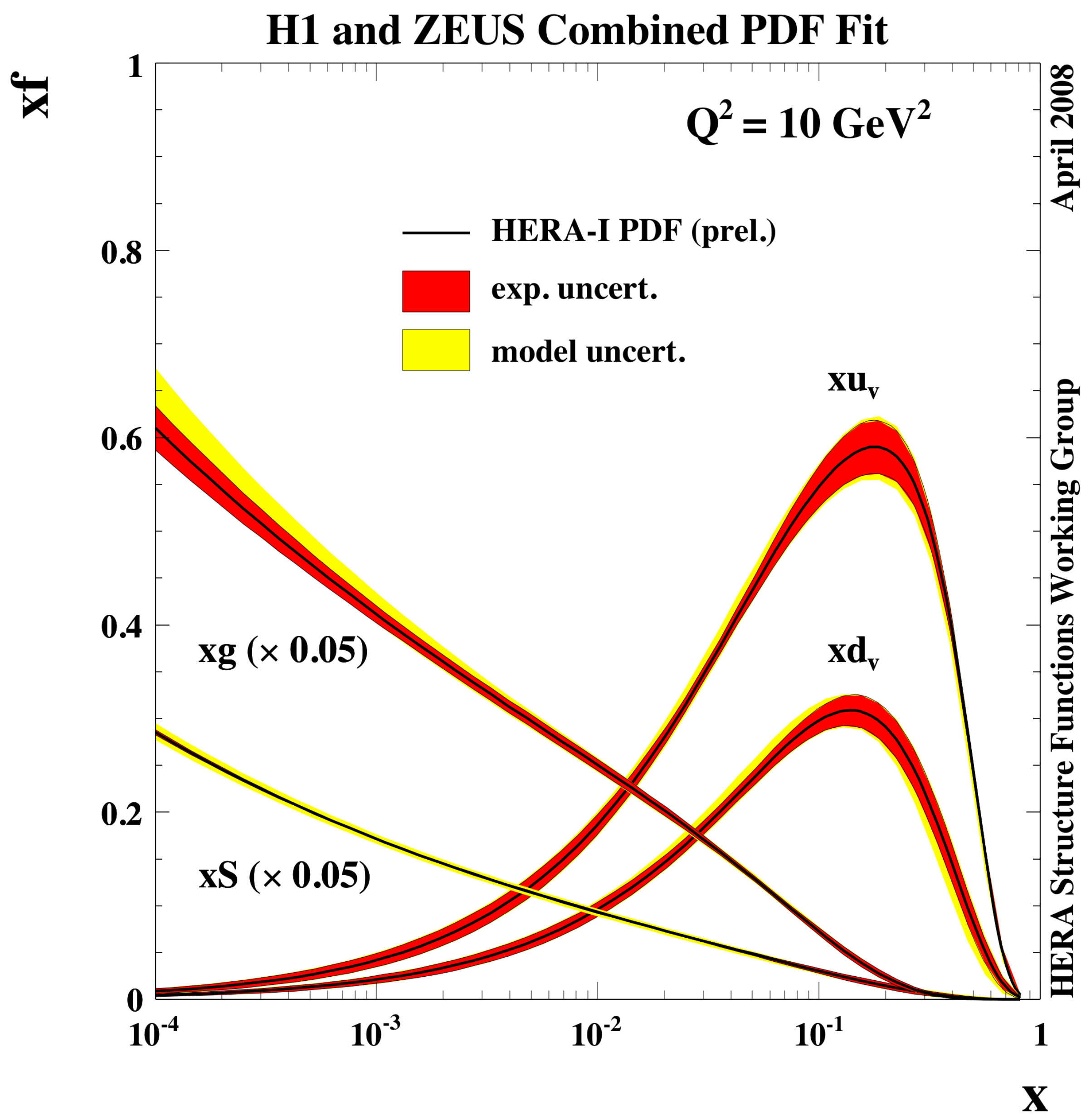
– Remember definition of F_2:

$$F_2 = F_2(x,Q^2) = \sum_i e_i^2 x q_i(x,Q^2)$$

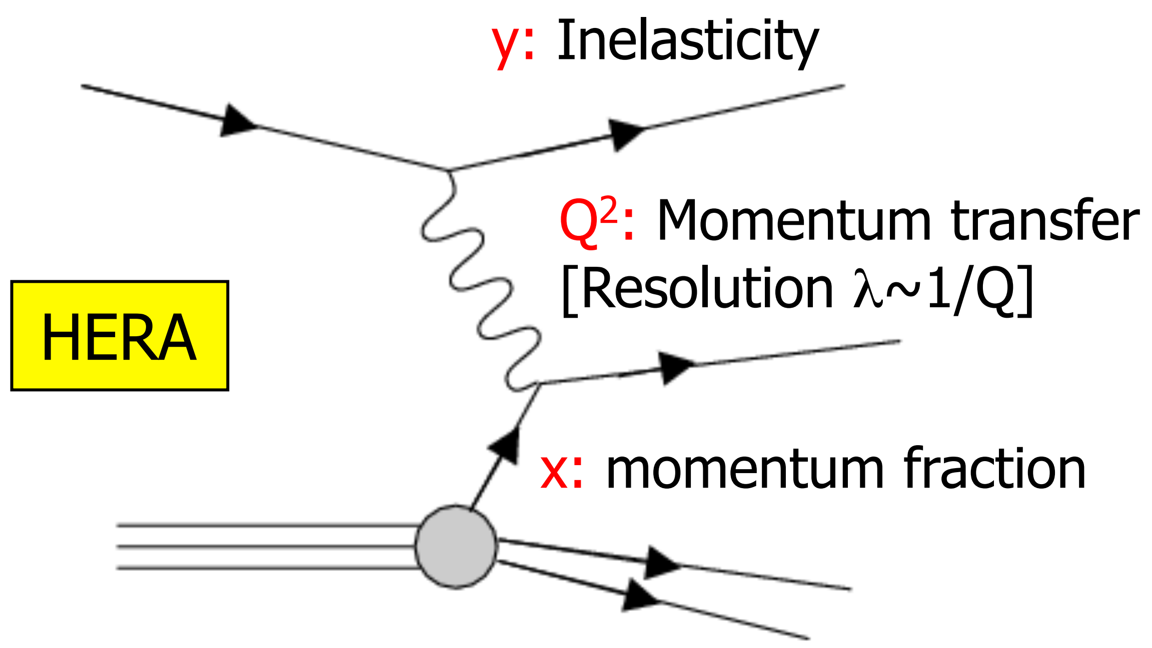
– Consider “DGLAP” evolution of structure function with Q^2:

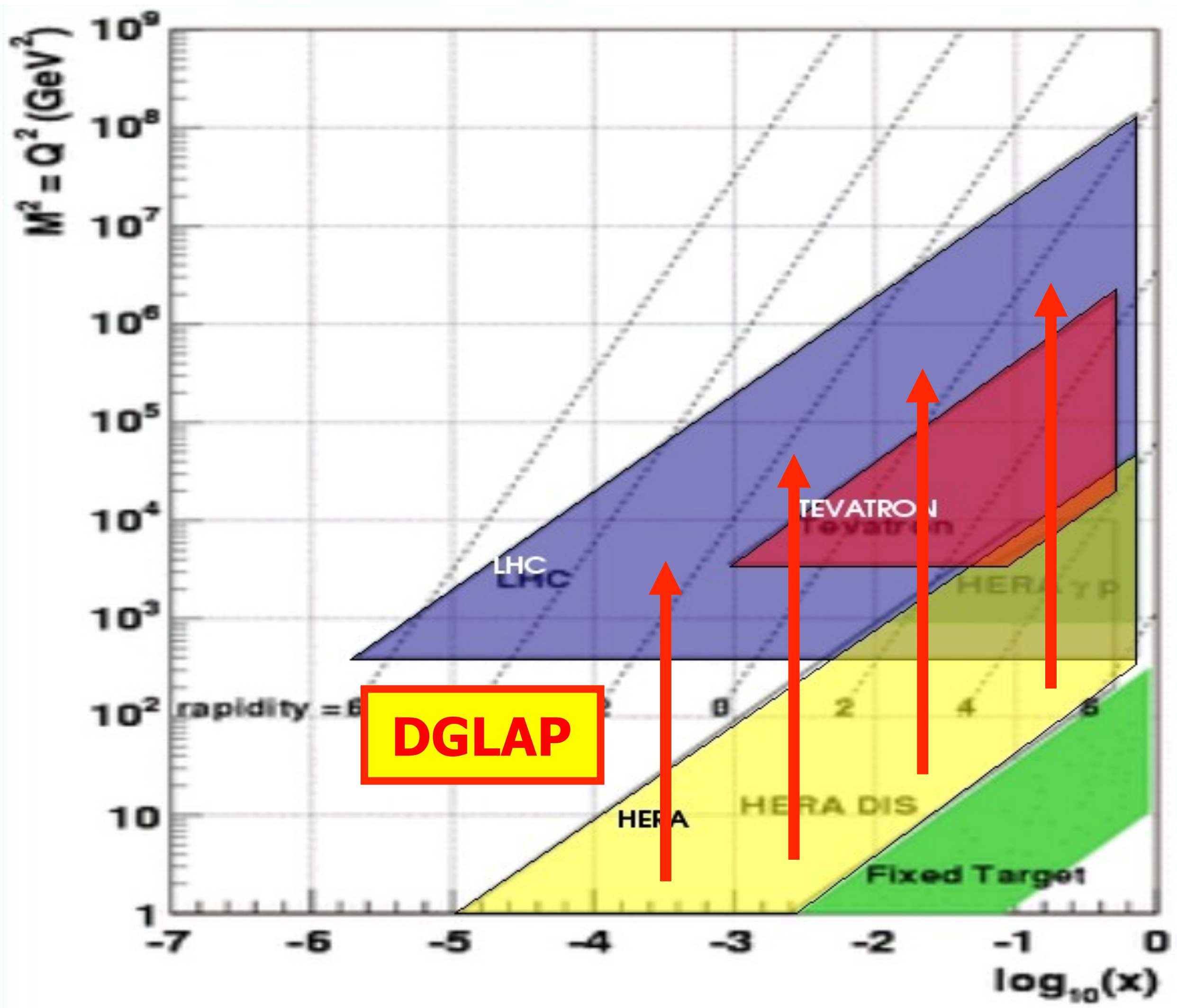
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} \cdot \int_x^1 \frac{dz}{z}\frac{x}{z}\left[P_{qq}\left(\frac{x}{z}\right)F_2(z,Q^2) + 2zP_{qg}\left(\frac{x}{z}\right)g(z,Q^2)\sum_i Q_i^2\right]$$

→ Sufficient information to extract PDFs from behaviour of F_2 with x and Q^2!



x AND Q^2 AT HERA AND THE LHC





LHC covers different (and much wider) range in x and Q^2 as compared to HERA:

– Options for determining the PDFs in an extended region? Probably very difficult!

– Necessity to use HERA PDFs for LHC predictions. DGALP formalism:

1. Determine $F_2(x,Q_0^2)$ at low start scale Q_0^2.
2. Evolve F_2 to higher Q^2 using DGLAP equation:

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto -\alpha_S P_{qq} F_2 + \alpha_S P_{qg} g$$

BUT:

– Is DGLAP reliable?

– Are other effects relevant?

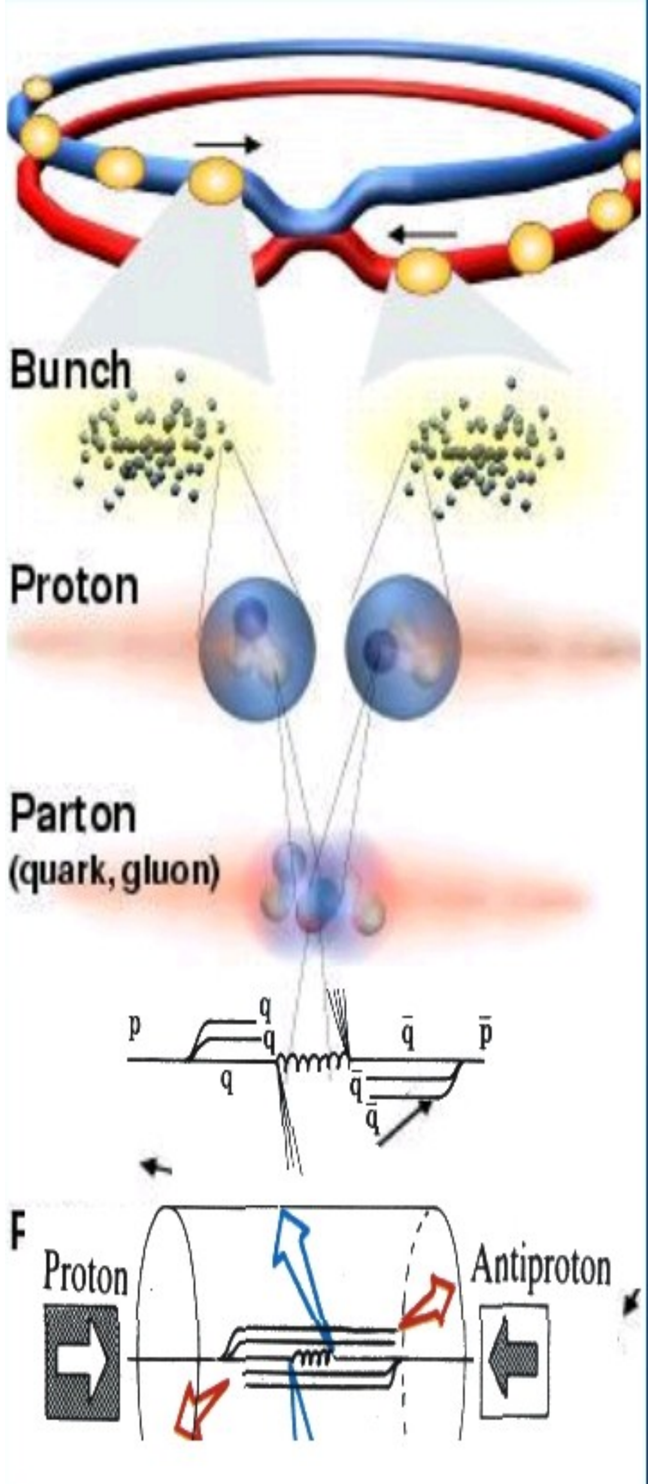
– Do new dynamics (low x) play a role for the PDFs at LHC?

➔ Need effort to control/test/improve PDFs at the LHC! Specific processes needed for that! (like W, t or Z production).

OVERVIEW OF pp REACTIONS (2)

pp reactions:

… the global picture:



2835×2835 bunches in the LHC ring.

10^9 protons / bunch

≤30 pp collisions per bunch crossing

N parton-parton collisions / pp collision

Complex final-states in every parton-parton collision.

Description/understanding of the different stages:

The rate of proton-proton interactions is connected to the (proton-proton) cross-section σ_{pp} via the luminosity:

$$\dot{N} = \sigma_{pp} \cdot L$$

Luminosity L is machine parameter; related to the bunch-crossing frequency f, the number of particles per bunch, and the cross-sections of the bunches:

$$L = f \frac{N_1 \cdot N_2}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

The proton-proton cross-section σ_{pp} is connected to the parton-parton cross-section σ_{ij} (for partons i,j) via the parton distribution functions $f_{i/p}$ (probability to find parton of type i in proton p):

$$\sigma_{pp} \propto \sum_{ij} f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p}$$

The parton-parton cross-sections σ_{ij} can (in principle) be calculated using perturbative methods.

$$\hat{\sigma}_{ij} = \sum_n c_{ij}^{(n)} \alpha_S^n$$

Need to disentangle multi-proton (overlay) and multi-parton collisions experimentally.

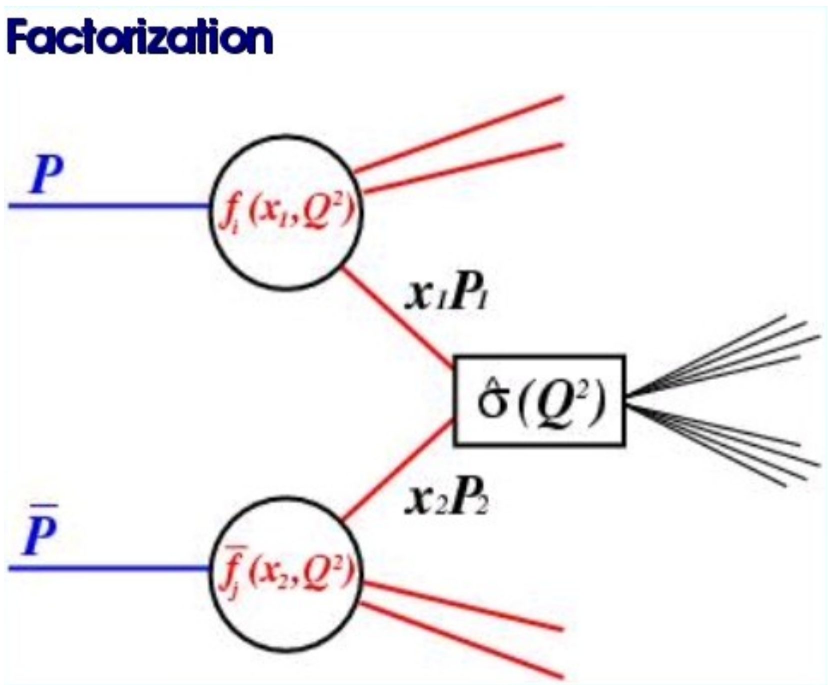
PRINCIPLE OF FACTORISATION, σ_{ij}

Remember the formula for the pp cross-section:

$$\sigma_{pp} \propto \sum_{ij} f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p}$$

– The “hard scattering matrix element” σ_{ij} (or parton-parton cross-section) can be calculated perturbatively starting from (simple) Feynman diagrams. It contains processes at large (energy/momentum/mass) scales / small distances.

– The PDFs f_i must be determined experimentally from data (HERA!). They resum soft / long-range contributions to the cross-section.



“Factorisation”: It is possible to disentangle effects that play at very different scales!

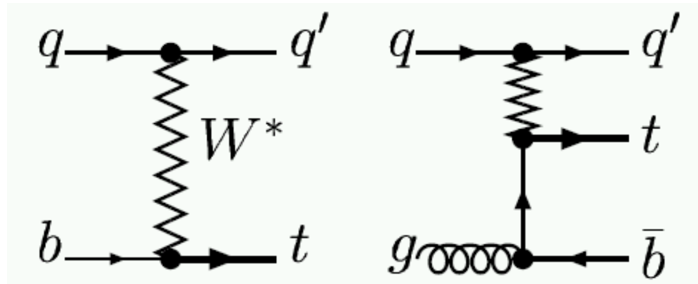
– We have already discussed the PDFs f_i.

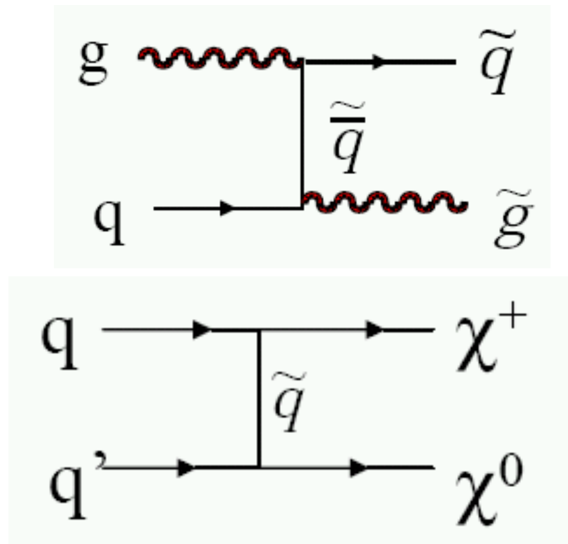
– Now discuss the hard scattering matrix element σ_{ij}.

Most important insight:

This is the process-dependent part! Examples:

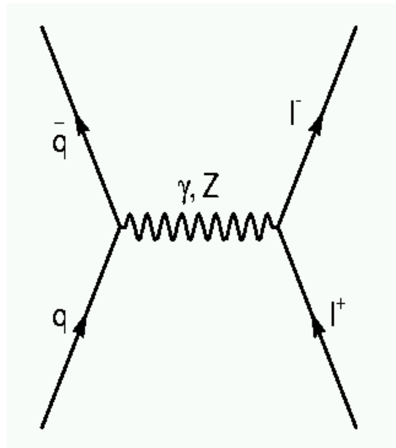
Top production





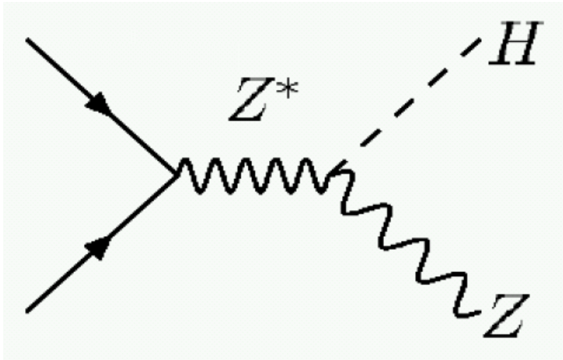
SUSY particle production

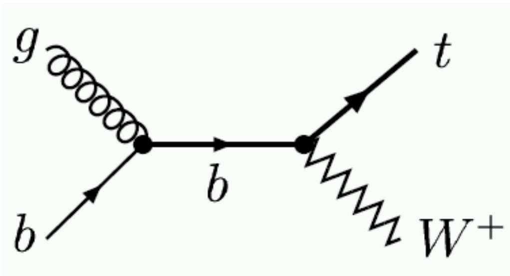
Drell-Yan fermion pair production



THE HARD SCATTERING CROSS-SECTION σ_{ij}

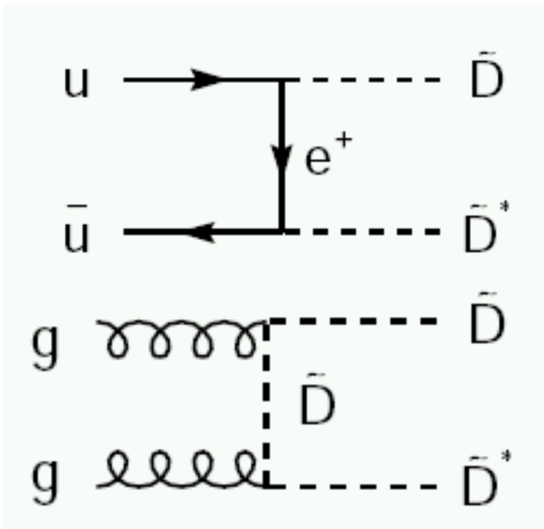
Higgs production





W+t production

Leptoquark production



For all processes: if you want to calculate a cross section then

– use (universal) PDFs $f_{i/p}$.

– calculate, using Feynman rules, the hard cross-sections.

-- put things together ("convlolute"), assuming factorisation to be valid.

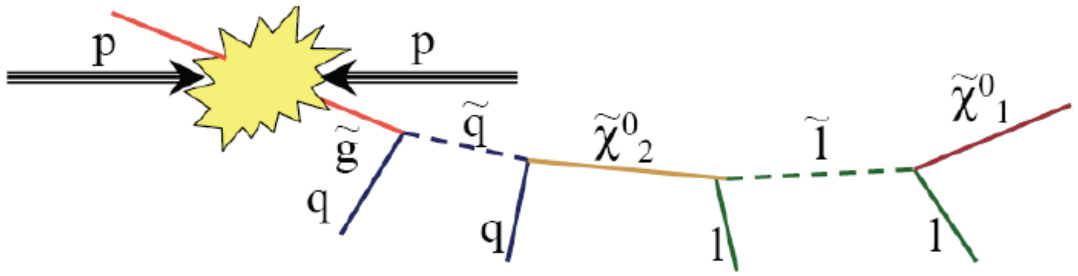
Missing in this picture:

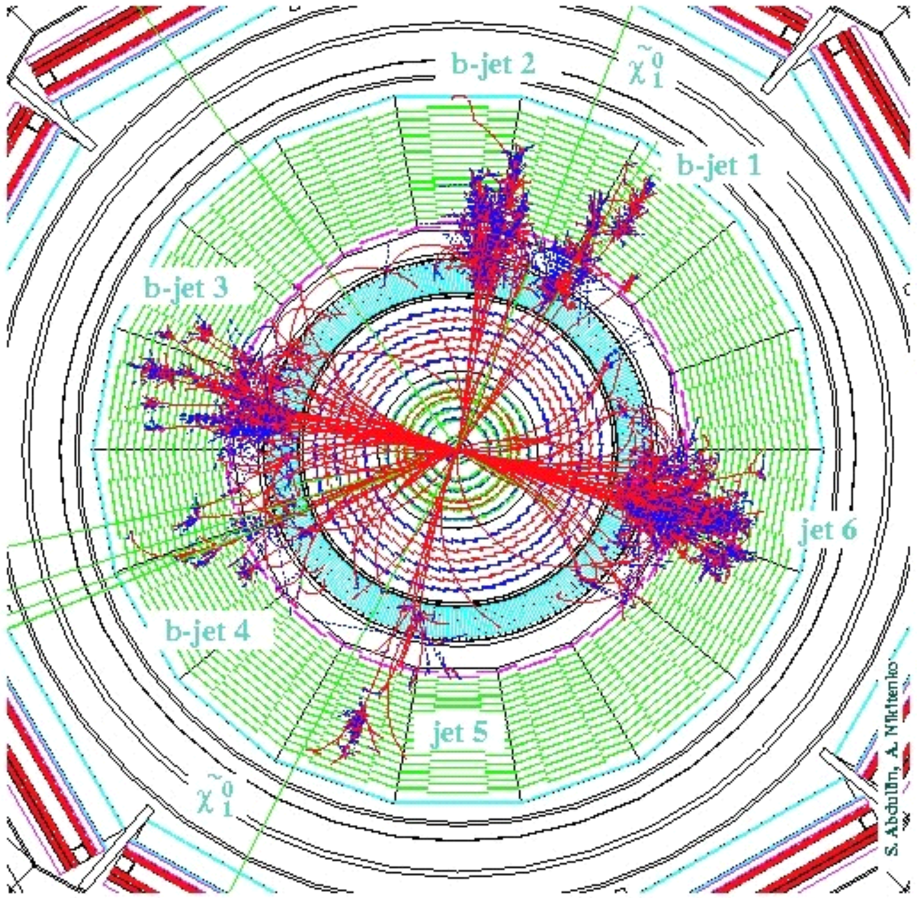
– Initial and final state radiation.
– Hadronisation and decay.
– Higher orders.
– Parton showers.
– Loads of subtleties …

THE LHC CROSS-SECTIONS

Many interesting (specific, easy-to-identify) processes are very complicated even at lowest order:

– SUSY cascade decays:

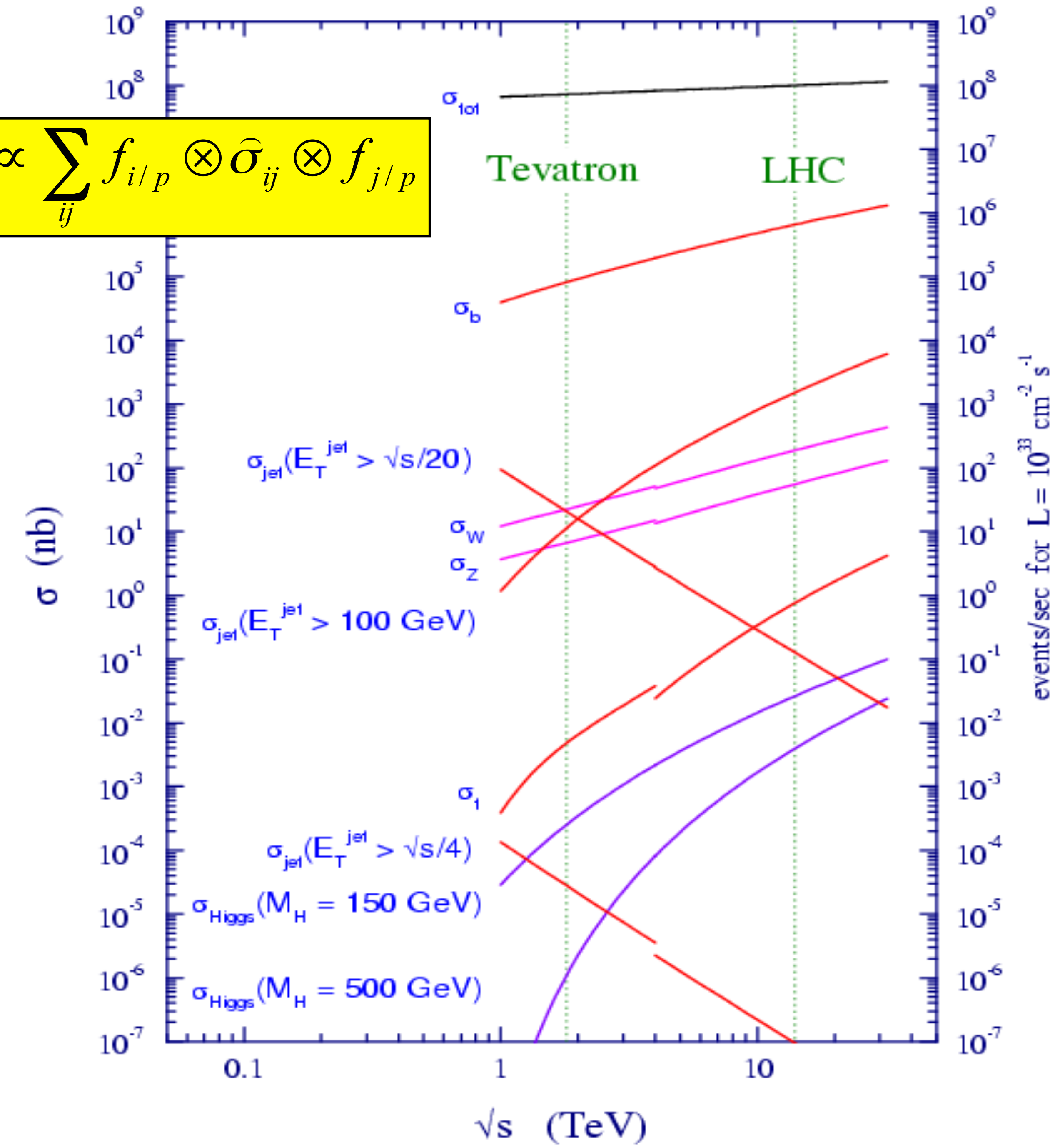




There are tools that calculate the LO cross-section given any PDF and any given σ_{ij}. And a few full-size event generators (HERWIG, PYTHIA, …)

Putting all ingredients together and calculating:

$$\sigma_{pp} \propto \sum_{ij} f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p}$$



Note that cross-sections for known SM processes is huge – and small for Higgs, SUSY → necessity for trigger, later!

LUMINOSITY DETERMINATION (AT LHC)

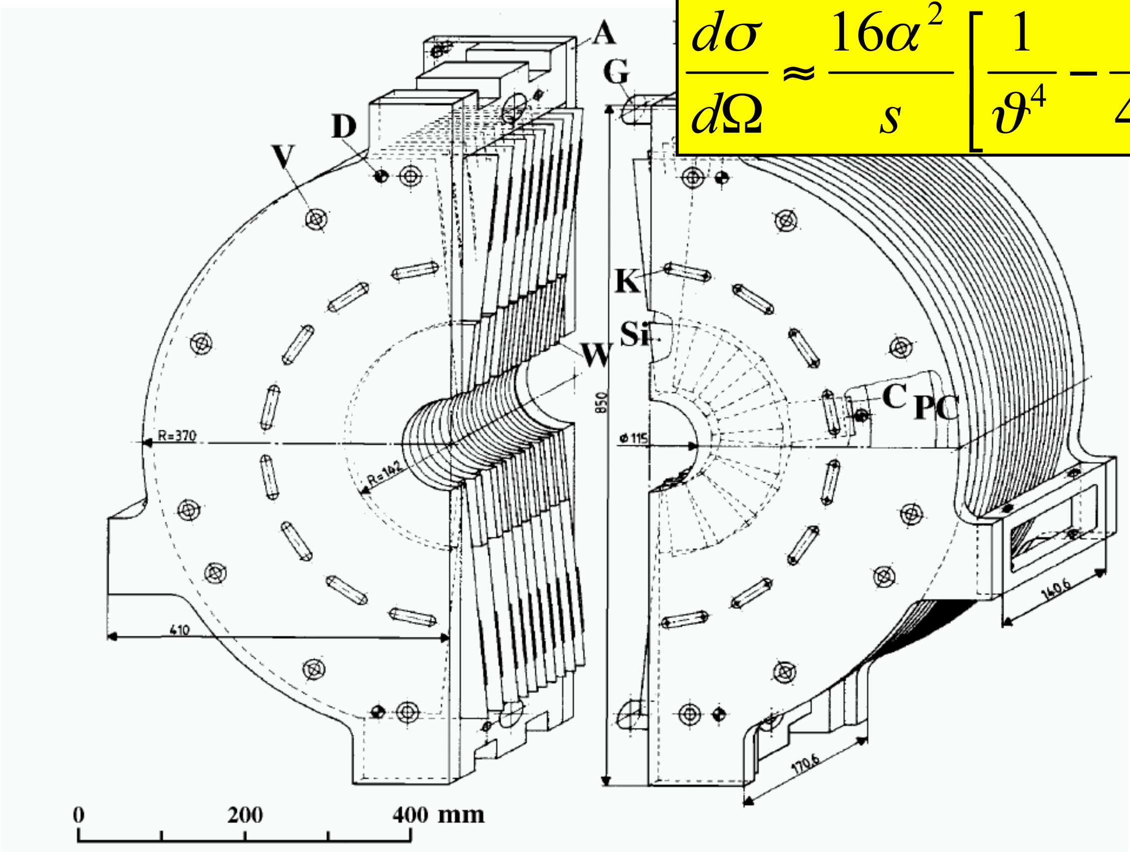
Remember: $\dot{N}_i = \sigma_{pp}^{(i)} \cdot L$

– For each process i
  we measure the rate (or number) of events.
– But we are truly interested in the pp cross-section
  σ_{pp} (for process i) → we need luminosity L.

Simplest approach:

– Define 'test' process with very precisely calculable cross-section. Then use above equation to get L.
– LEP: Small-angle Bhabha ee→ee scattering.
➔ Experimentally challenging (acceptance!). Typical uncertainties 1%.

$$\frac{d\sigma}{d\Omega} \approx \frac{16\alpha^2}{s}\left[\frac{1}{\vartheta^4} - \frac{1}{4\vartheta^2}\right]$$



– HERA: Bremsstrahlungs process ep→ep γ .

For pp collisions:

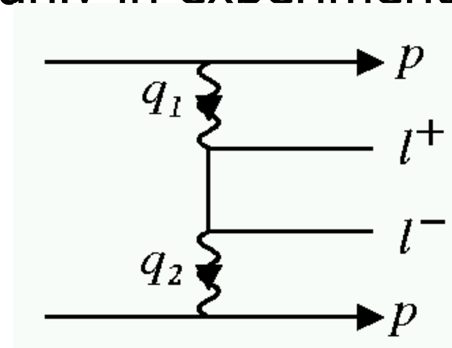
– Precise lumi determination (5%) important, for example, for Higgs mass determination.
– No clear 'candle' to normalise to; various ideas on the market.

1. method: Optical theorem:

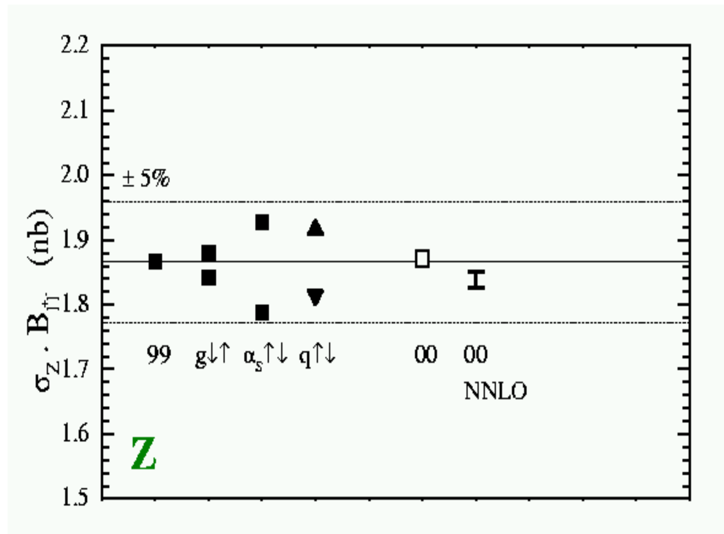
$$\left.\frac{dN_{el}}{dt}\right|_{t=0} = \frac{(N_{el} + N_{inel})^2}{16\pi L}\left(1+\rho^2\right)$$

2. Photon-photon production of lepton pairs
   (leptons measured cleanly in experiments!).

$$pp \rightarrow p + \gamma\gamma + p \rightarrow p + l^+ l^- + p$$



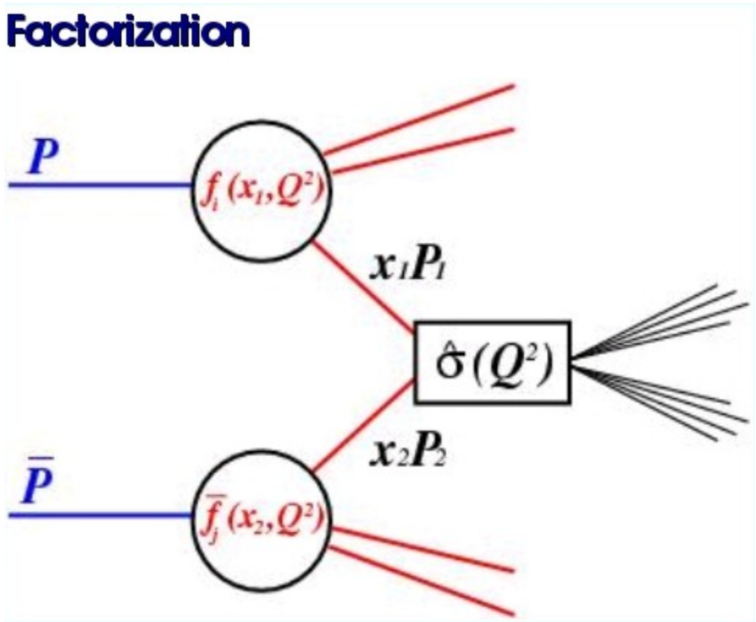
3. W and Z production (clean signatures via leptonic decay modes).
→ cross-sections known to about 4%.



CROSS-SECTIONS, PARTON LUMINOSITIES (1)

At hadron colliders, not the full CMS energy is ready for collision – only a fraction τ :

$$\hat{s} = x_1 x_2 s = \tau s$$



→ Might be useful to specify how many collisions are available at which s-hat

→ parton luminosities!

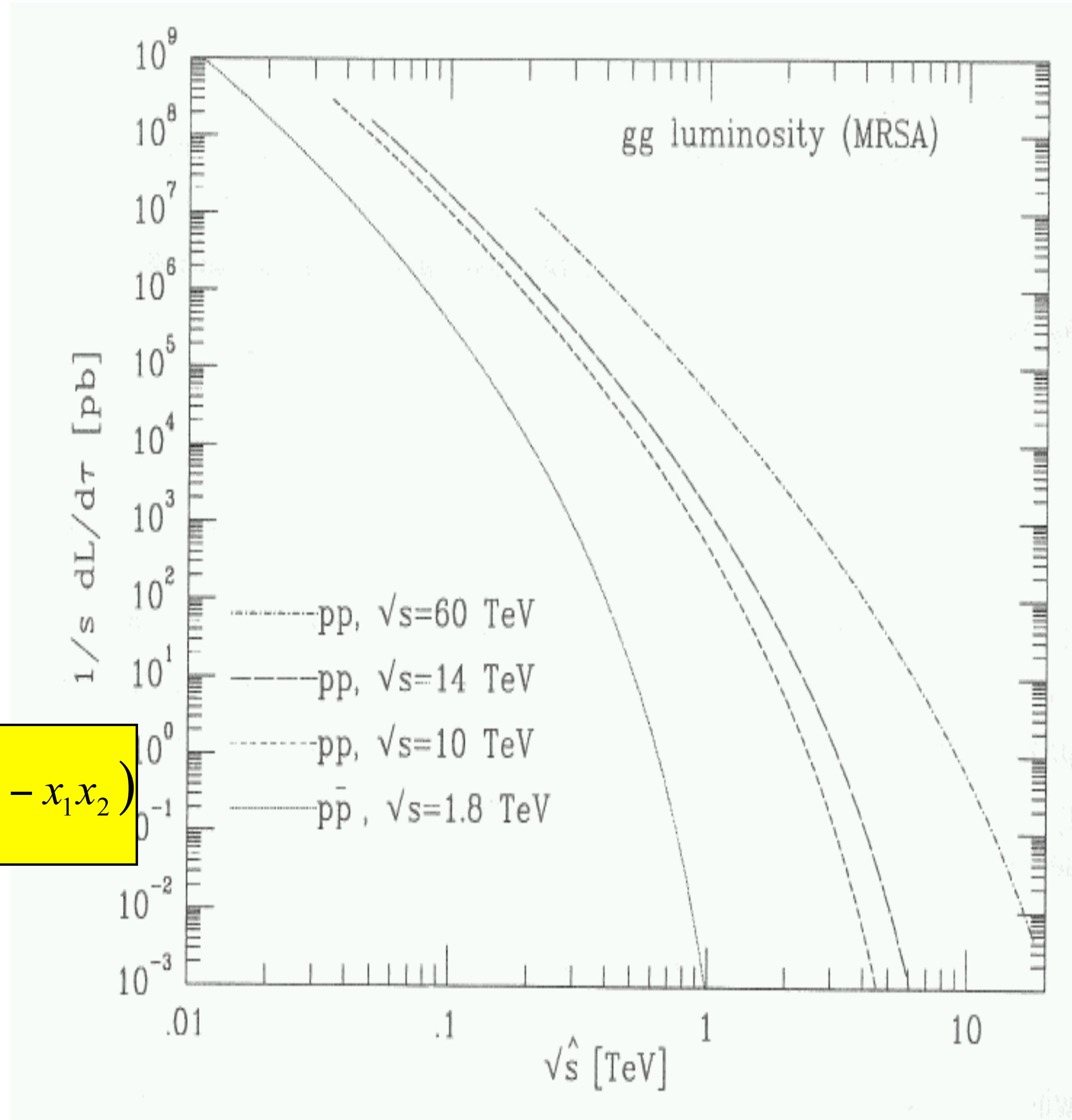
$$\tau \frac{dL_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_0^1 dx_1 dx_2 \left[x_1 f_{i/p}(x_1,\mu) x_2 f_{j/p}(x_2,\mu) + (1 \leftrightarrow 2) \right] \delta(\tau - x_1 x_2)$$

Then rewrite cross-section:

$$\sigma(s) = \sum_{ij} \int\int dx_1 dx_2 f_{i/p}(x_1,\mu) f_{j/p}(x_2,\mu) \hat{\sigma}_{ij}$$

$$= \sum_{ij} \int_{\tau_0}^1 \frac{d\tau}{\tau} \left(\frac{1}{s} \frac{dL_{ij}}{d\tau} \right) \left(\hat{s} \hat{\sigma}_{ij} \right)$$

Now study parton luminosity for various processes and CMS energies. For example gg:

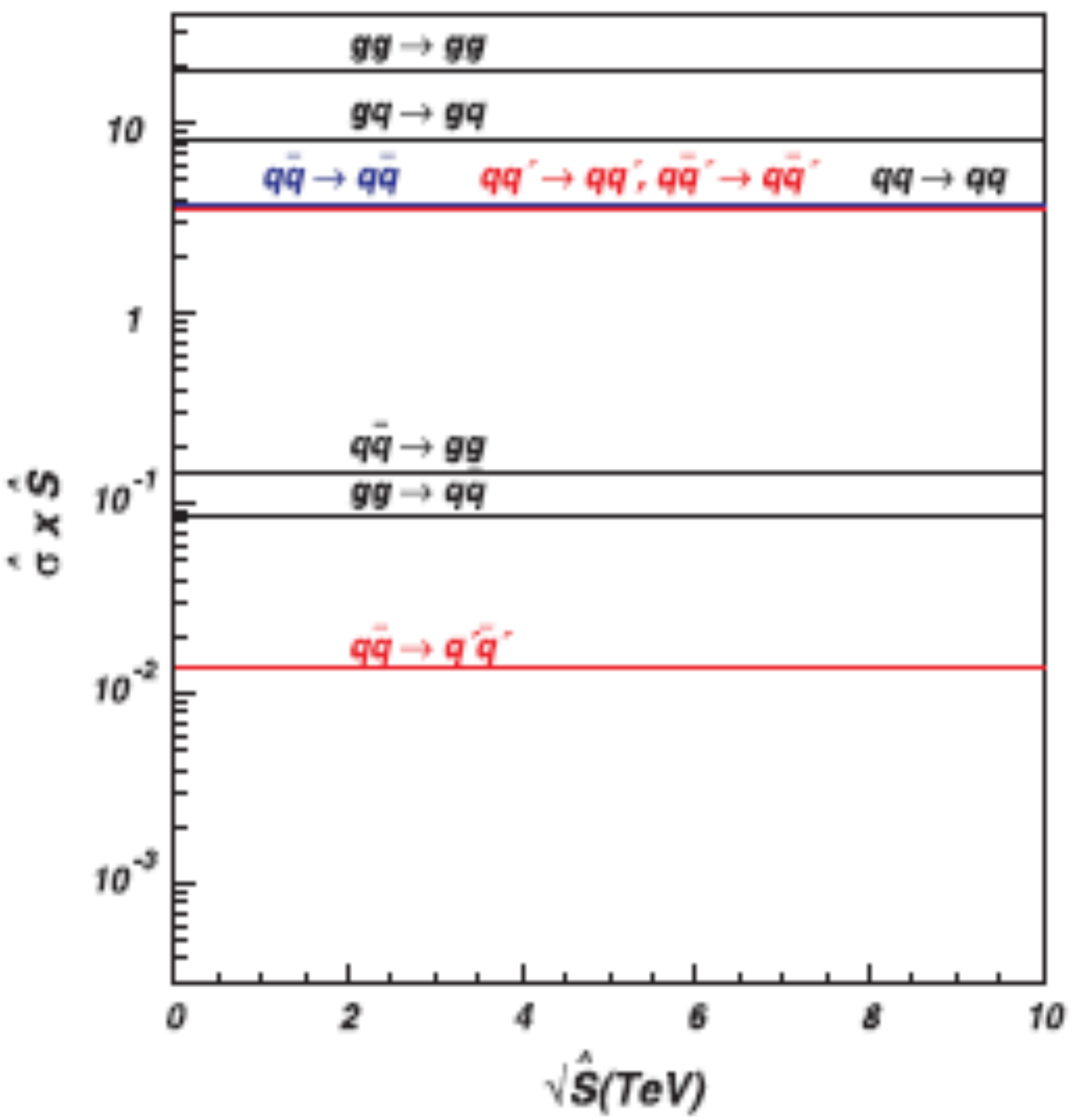


→ Much higher parton lumis at LHC than at Tevatron. High s-hat reached!

CROSS-SECTIONS, PARTON LUMINOSITIES (2)

.. with the "partonic cross-section" (at LHC):

$$\hat{s}\,\hat{\sigma}_{ij} \approx 10^{-3} \ldots 20$$



LHC / Tevatron:

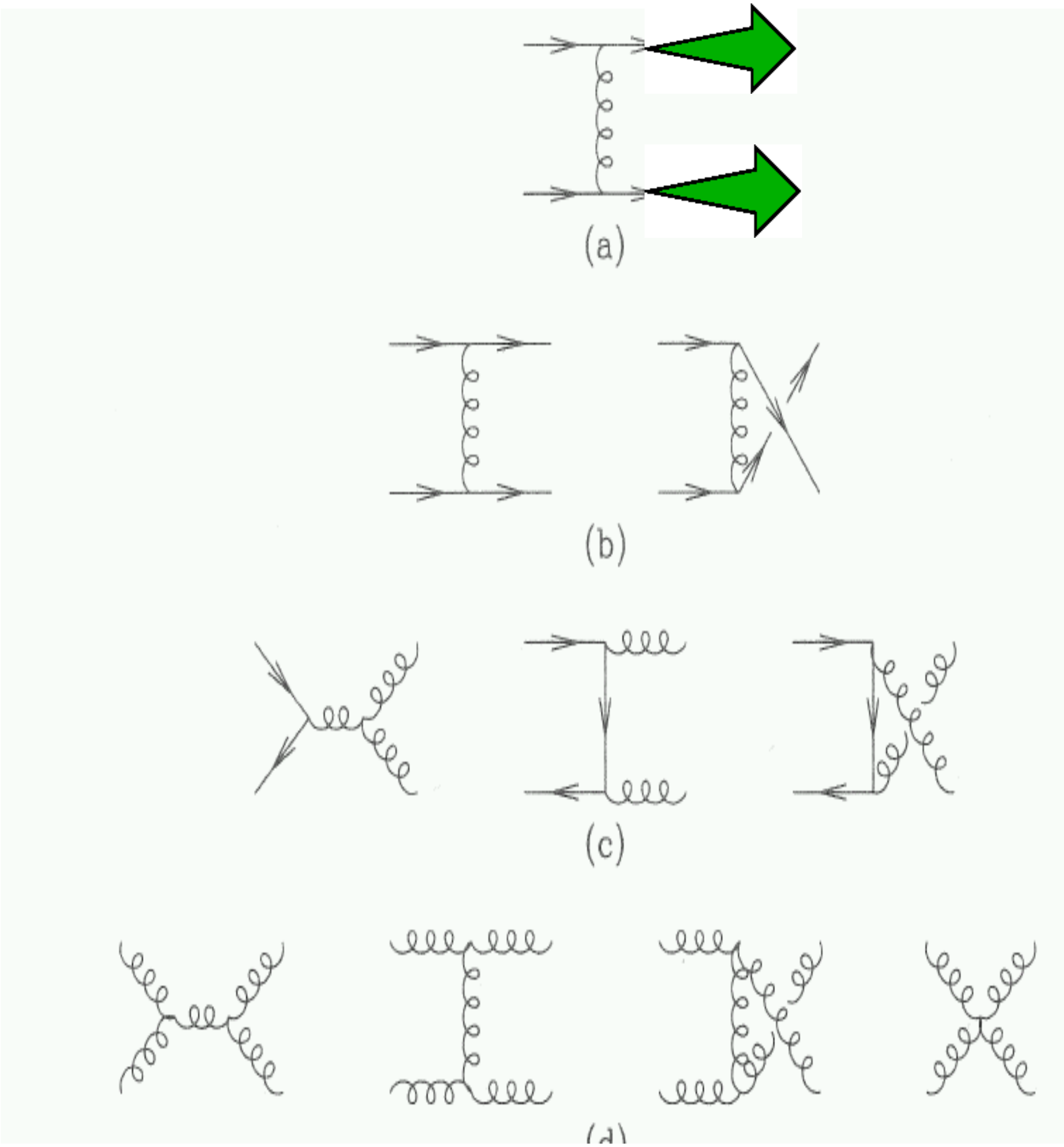
– factor 40 for gg→ H @ M_H= 120 GeV

– factor 10000 for gg→ XX @ M_X= 0.5 TeV

TWO-JET PRODUCTION (1)

The most intuitive process in pp collisions: two jet production: pp→ jet+jet.

Can proceed from the following diagrams in LO:

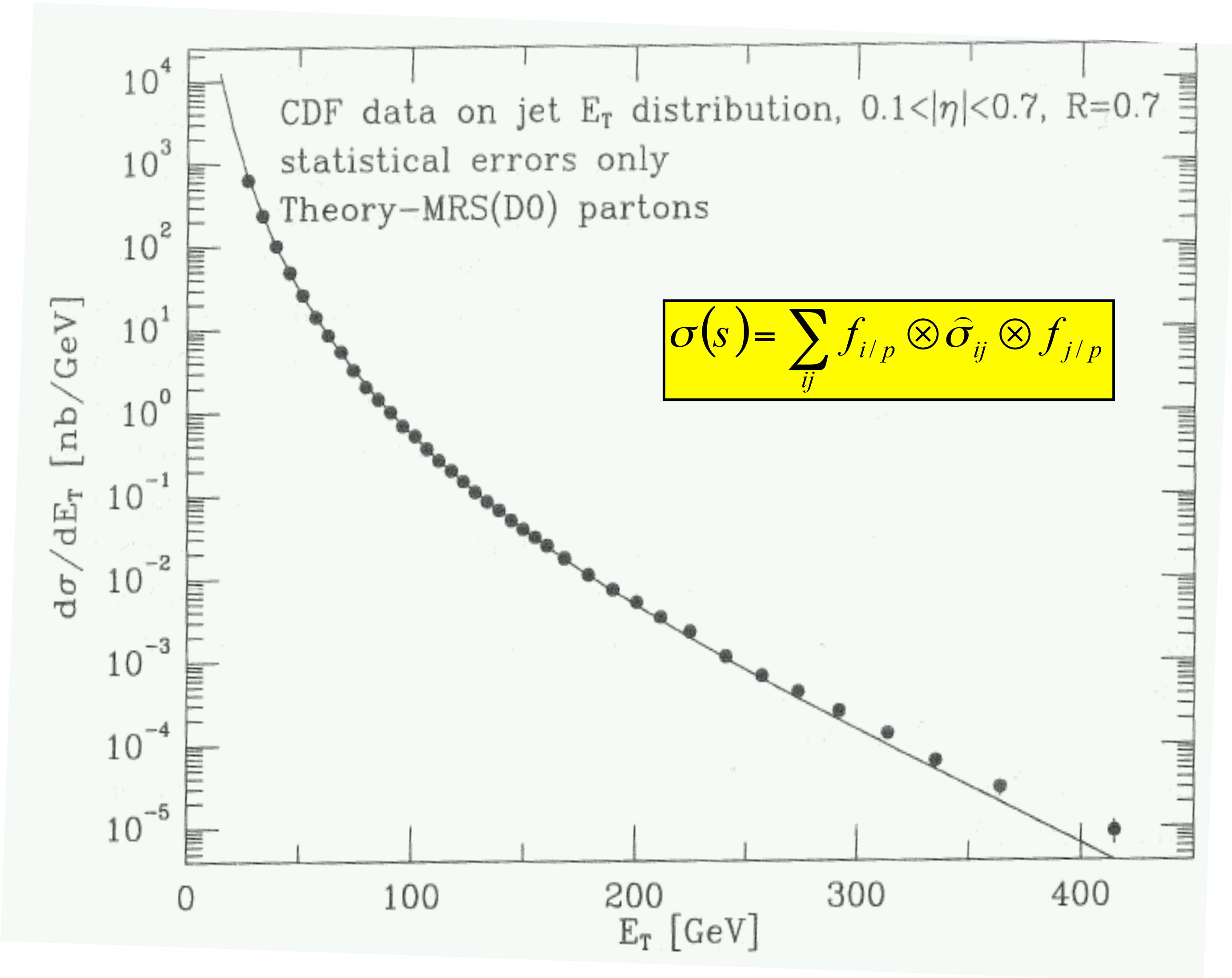


… with the following matrix elements and their values at 90 deg CMS scattering angle:

Process	$\overline{\sum}\lvert\mathcal{M}\rvert^2/g^4$	$\theta^* = \pi/2$
$q\,q' \to q\,q'$	$\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\,\overline{q'} \to q\,\overline{q'}$	$\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\,q \to q\,q$	$\frac{4}{9}\,(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}) - \frac{8}{27}\,\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.26
$q\,\overline{q} \to q'\,\overline{q'}$	$\frac{4}{9}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.22
$q\,\overline{q} \to q\,\overline{q}$	$\frac{4}{9}\,(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}) - \frac{8}{27}\,\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.59
$q\,\overline{q} \to g\,g$	$\frac{32}{27}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{8}{3}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	1.04
$g\,g \to q\,\overline{q}$	$\frac{1}{6}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{3}{8}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.15
$g\,q \to g\,q$	$-\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}} + \frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$	6.11
$g\,g \to g\,g$	$\frac{9}{2}\,(3 - \frac{\hat{t}\hat{u}}{\hat{s}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2})$	30.4

TWO-JET PRODUCTION (2)

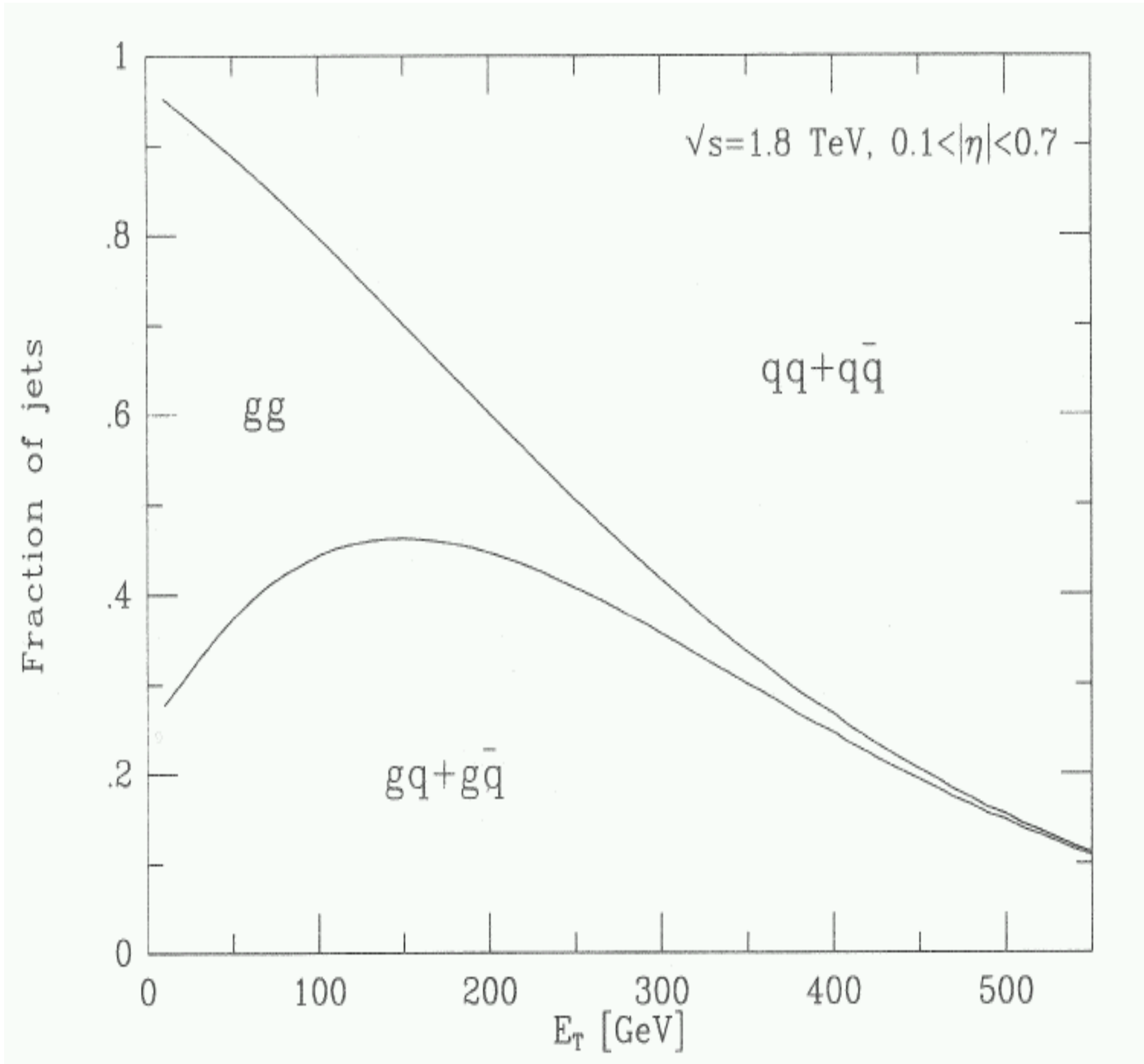
One can measure and calculate the two-jet cross-section (for a given pseudorapidity):



Factorised QCD can well describe these complicated measurements:

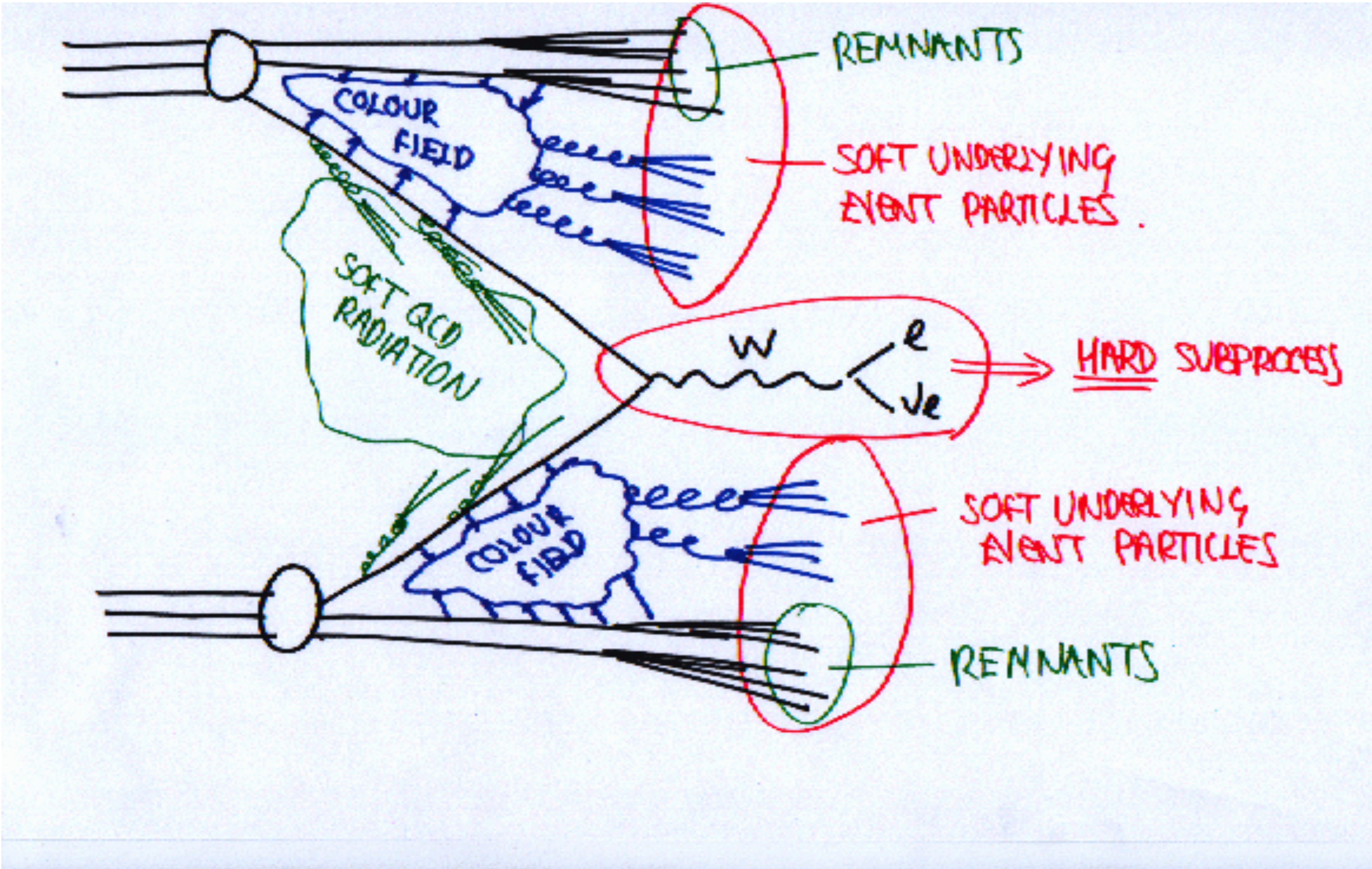
$$\frac{1}{2\pi E_T}\frac{d^2\sigma}{dE_T d\eta}=\frac{1}{16\pi s}\sum_{i,j,k,l=q,\bar{q},g}\int_0^1 dx_1 dx_2 f_i(x_1,\mu) f_j(x_2,\mu)\times$$
$$\times\sum\left|M(ij\to kl)\right|^2\delta(\hat{s}+\hat{t}+\hat{u})$$

Note the composition of the sample as a function of the jet transverse energy (relative to the beam axis):



→ qq interactions reach larger E_T values than gg interactions do, mainly because of the different PDF distributions – quarks reach higher x values!

OVERVIEW

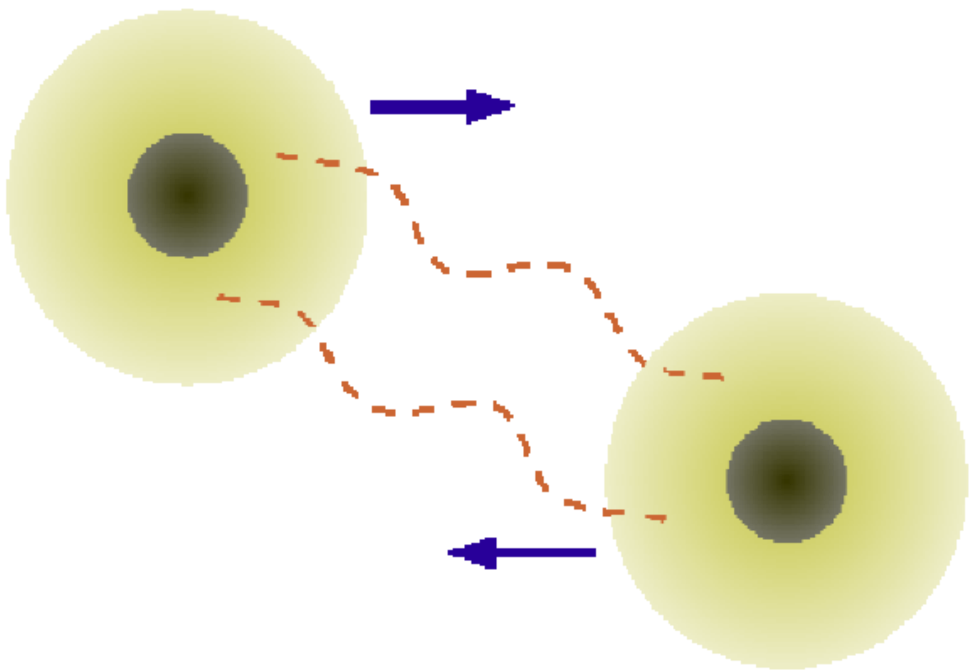


REMNANTS
COLOUR FIELD
SOFT UNDERLYING EVENT PARTICLES.
SOFT QCD RADIATION
W
l
νe
HARD SUBPROCESS
COLOUR FIELD
SOFT UNDERLYING EVENT PARTICLES
REMNANTS

MINIMUM BIAS, PILE-UP, UNDERLYING EVENTS, AND MULTI-PARTON INTERACTIONS

Most of the pp reactions:

- "minimum bias" (MB) events: In most cases the protons will more or less "fly through" and undergo only very peripheral or soft interactions: elastic or single/double diffractive.



... in these cases no high-p_T exchange takes place – no particles are scattered under large angles, all reaction products go more or less in the proton flight direction ("diffractive" and "elastic" events).

$$\sigma_{total} = \sigma_{elastic} + \sigma_{s.-diffractive} + \sigma_{double-diffractive} + \sigma_{non-diffractive}$$

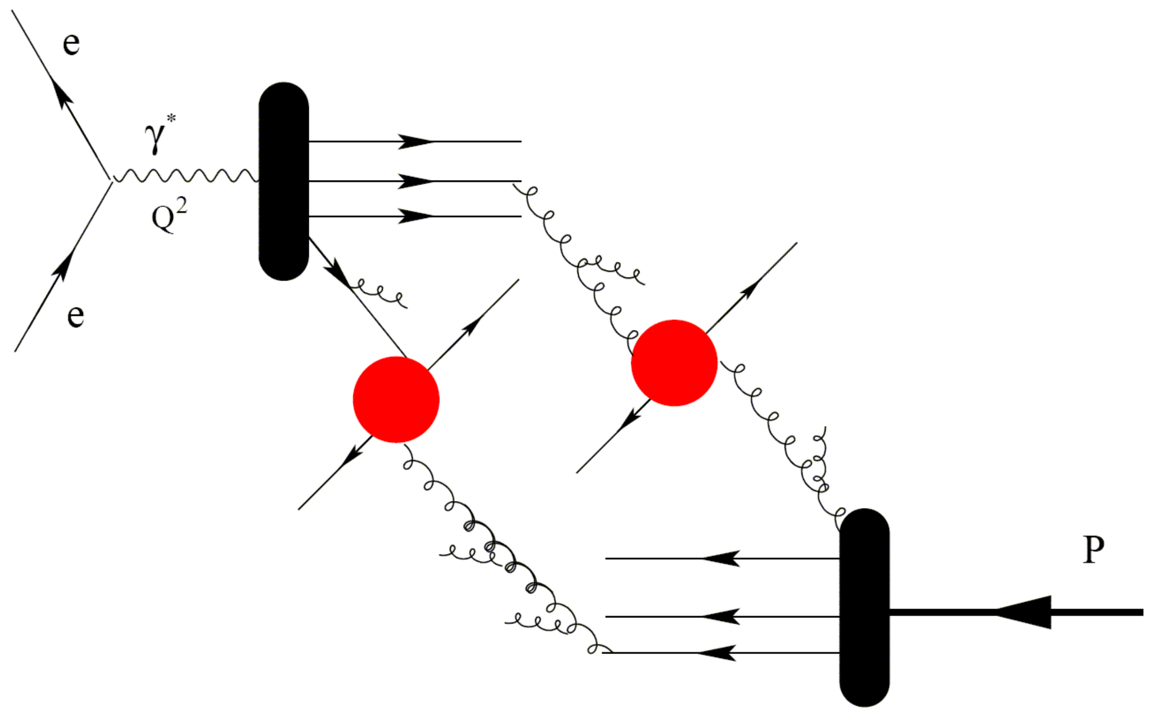
Only the hard, non-diffractive events can be calculated in perturbative QCD:

- Soft events do not have a hard scale → α_S is too large for perturbative calculations!

Nevertheless MB events important – there are so many, and they may help to understand the detector!

More complications:

- Pile-up: More than one pp interaction in one bunch crossing (disentangle using vertex information?)
- Multi-parton interactions: More than one pair of partons may scatter!
- Underlying event: Everything except the hardest scattering (later):



THEORETICAL PREDICTIONS

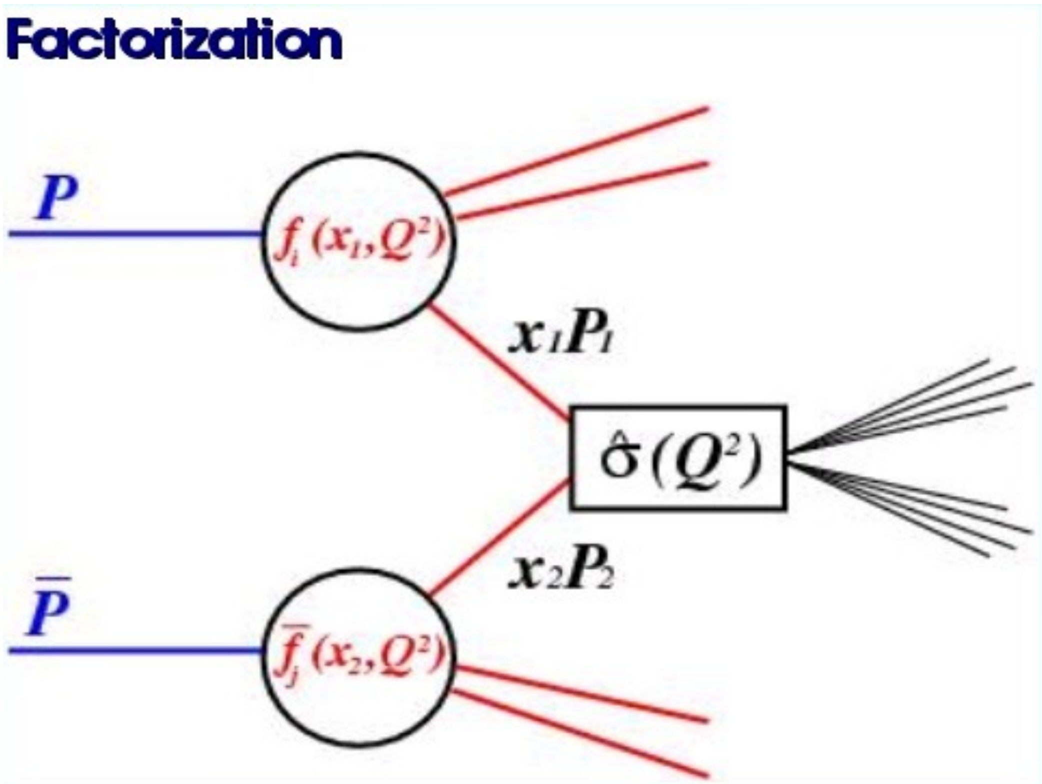
We distinguish:

– Leading-order MC programs with parton-shower formalism.

– Fixed-order calculations without parton showers (typically at NLO for QCD, NNLO for weak processes …)

– "MC@NLO"-type programs that combine the best of all worlds – namely higher orders and details of the final state via parton-shower algorithms!

Distinguish the "hard scattering matrix element" and the "parton shower" (and note the difficulty in combining them!):



Hard matrix element:

– correct treatment of large-angle, hard phenomena.

– correct normalisation of cross sections via inclusion of real and virtual corrections.

– Corrections lead to events with negative weights → inherent problems for combination with parton showers?

Parton showers:

– Summation of all (?) soft and collinear effects in the final state → correct description of soft behaviour.

– Summation of "leading logarithms".

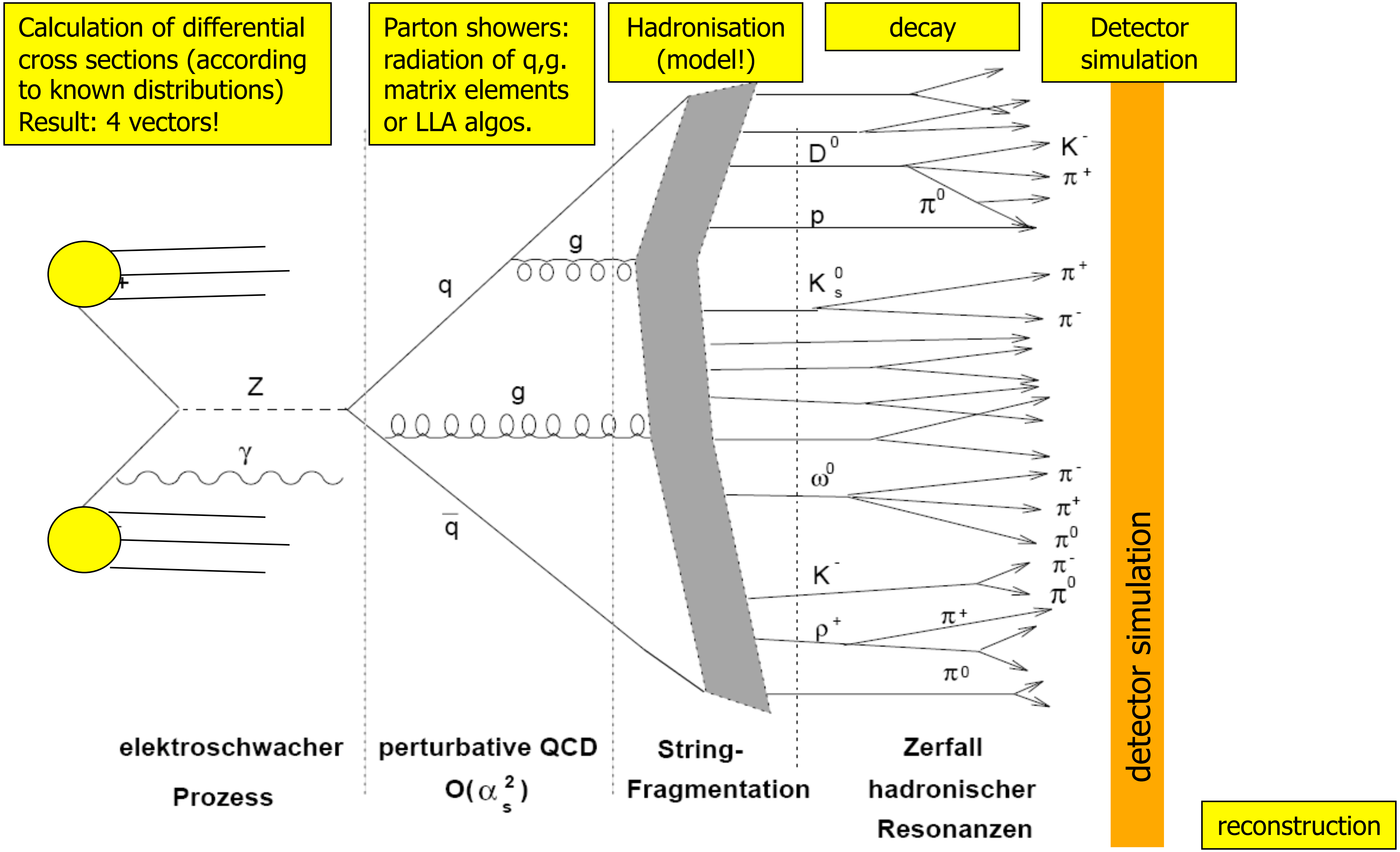
– Radiation in initial and final state and their interference can change kinematics of an event
  → cancellation of real and virtual divergencies not guaranteed anymore!
  → combination with NLO difficult!!!!

Only lately:

– Concepts for combination of next-to-leading order calculations and parton showers (key words MC@NLO, CKKW, …).

– Far too deep to be discussed here today ;-) ..

SIMULATION


Calculation of differential cross sections (according to known distributions) Result: 4 vectors!
Parton showers: radiation of q,g. matrix elements or LLA algos.
Hadronisation (model!)
decay
Detector simulation
Z
γ
q
g
g
q̄
D0
p
K0s
ω0
K-
ρ+
K-
π+
π0
π+
π-
π-
π+
π0
π-
π0
π+
π0
detector simulation
elektroschwacher Prozess
perturbative QCD O(αs2)
String-Fragmentation
Zerfall hadronischer Resonanzen
reconstruction

SIMULATION