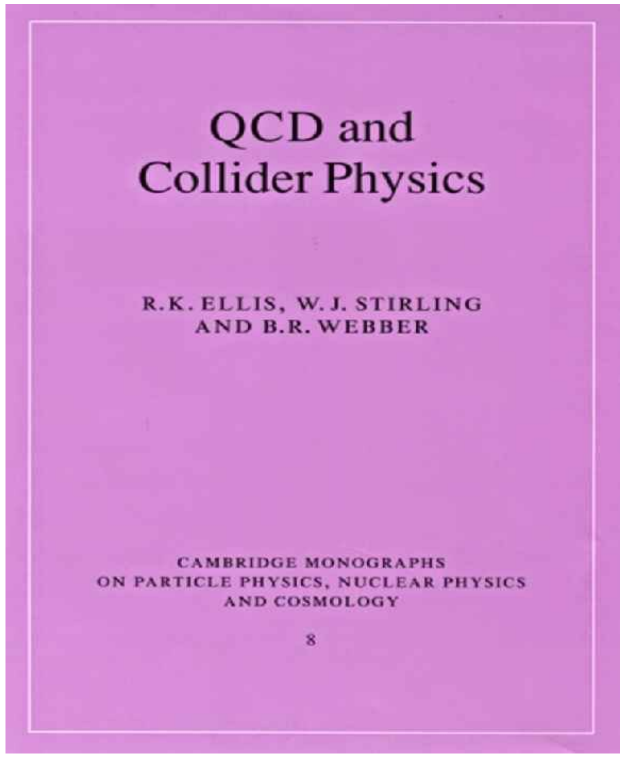
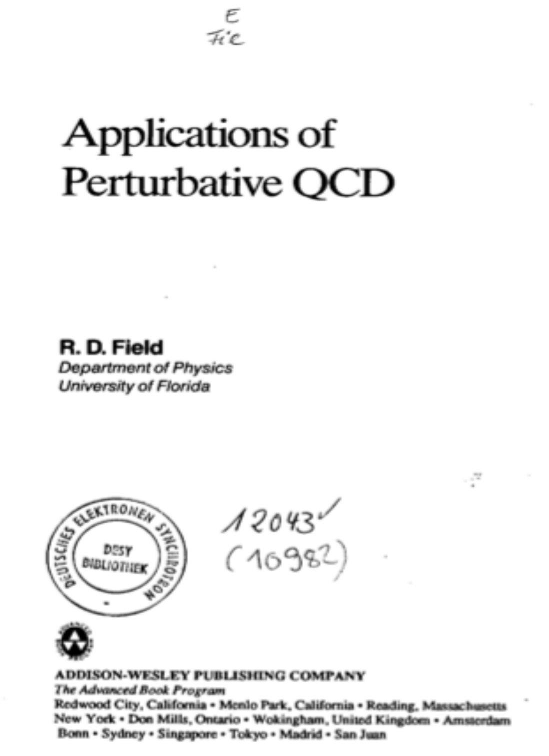
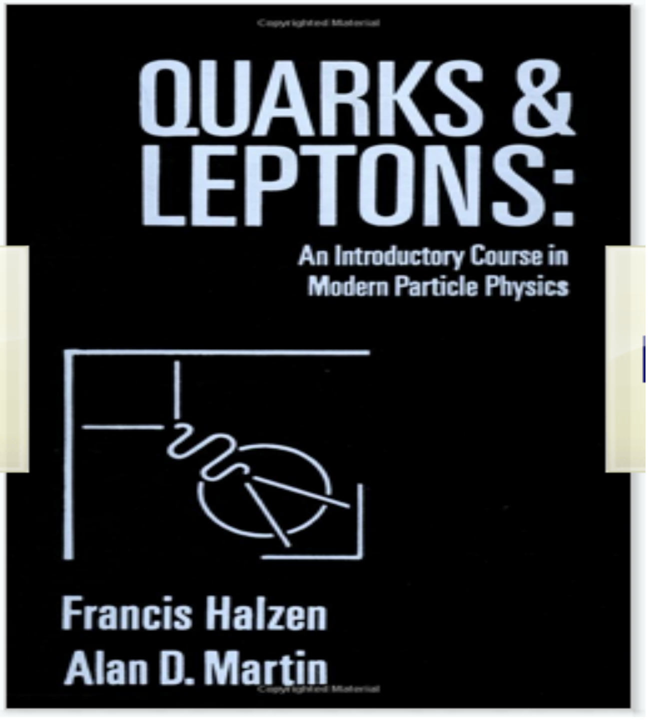
QCD parton dynamics, hadronic final states, MCs

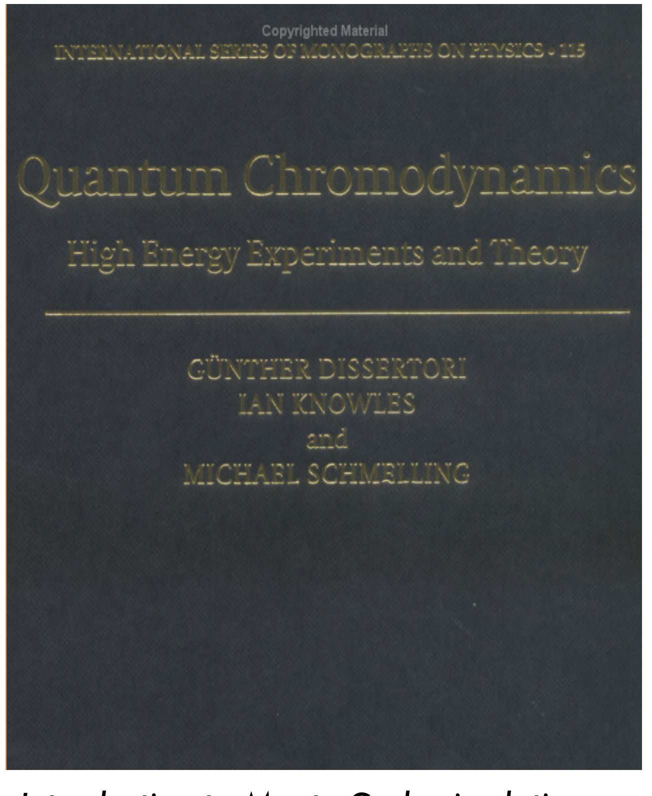
H. Jung (DESY)
hannes.jung@desy.de

Literature

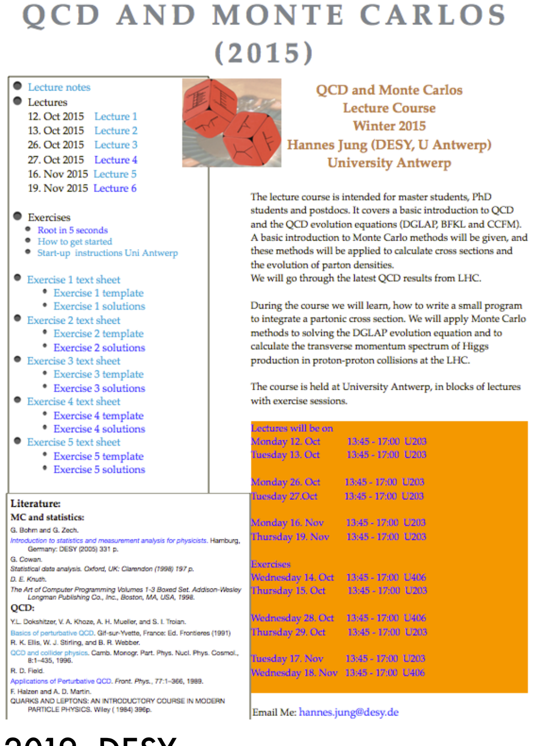








http://www.desy.de/~jung/qcd_and_mc_2015


QCD AND MONTE CARLOS (2015)

- Lecture notes
- Lectures
  - 12. Oct 2015 Lecture 1
  - 13. Oct 2015 Lecture 2
  - 26. Oct 2015 Lecture 3
  - 27. Oct 2015 Lecture 4
  - 16. Nov 2015 Lecture 5
  - 19. Nov 2015 Lecture 6
- Exercises
  - Root in 5 seconds
  - How to get started
  - Start-up instructions Uni Antwerp
- Exercise 1 text sheet
  - Exercise 1 template
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  - Exercise 2 template
  - Exercise 2 solutions
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- Exercise 5 text sheet
  - Exercise 5 template
  - Exercise 5 solutions

QCD and Monte Carlos
Lecture Course
Winter 2015
Hannes Jung (DESY, U Antwerp)
University Antwerp

The lecture course is intended for master students, PhD students and postdocs. It covers a basic introduction to QCD and the QCD evolution equations (DGLAP, BFKL and CCFM). A basic introduction to Monte Carlo methods will be given, and these methods will be applied to calculate cross sections and the evolution of parton densities.
We will go through the latest QCD results from LHC.

During the course we will learn, how to write a small program to integrate a partonic cross section. We will apply Monte Carlo methods to solving the DGLAP evolution equation and to calculate the transverse momentum spectrum of Higgs production in proton-proton collisions at the LHC.

The course is held at University Antwerp, in blocks of lectures with exercise sessions.

Lectures will be on
Monday 12. Oct 13:45 - 17:00 U203
Tuesday 13. Oct 13:45 - 17:00 U203

Monday 26. Oct 13:45 - 17:00 U203
Tuesday 27.Oct 13:45 - 17:00 U203

Monday 16. Nov 13:45 - 17:00 U203
Thursday 19. Nov 13:45 - 17:00 U203

Exercises
Wednesday 14. Oct 13:45 - 17:00 U406
Thursday 15. Oct 13:45 - 17:00 U203

Wednesday 28. Oct 13:45 - 17:00 U406
Thursday 29. Oct 13:45 - 17:00 U203

Tuesday 17. Nov 13:45 - 17:00 U203
Wednesday 18. Nov 13:45 - 17:00 U406

Literature:

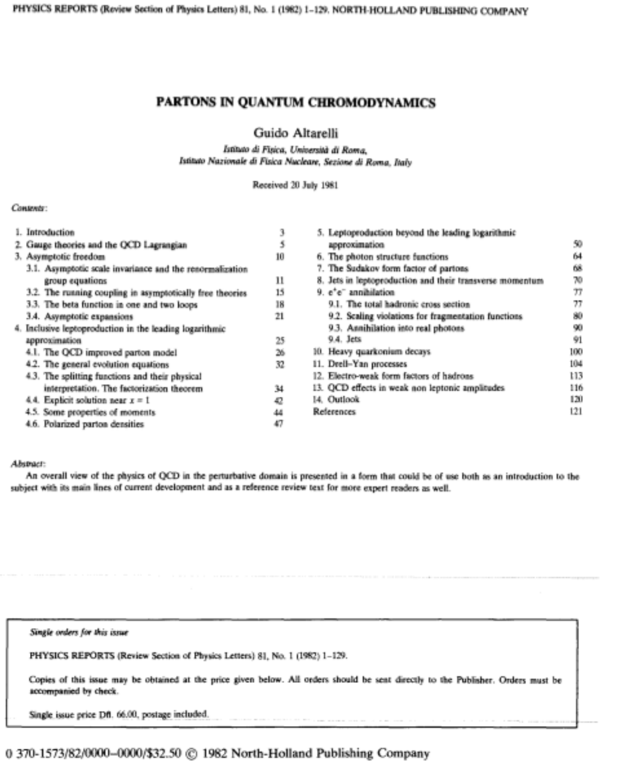
MC and statistics:

G. Bohm and G. Zech.
Introduction to statistics and measurement analysis for physicists. Hamburg, Germany: DESY (2005) 331 p.
G. Cowan.
Statistical data analysis. Oxford, UK: Clarendon (1998) 197 p.
D. E. Knuth.
The Art of Computer Programming Volumes 1-3 Boxed Set. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1998.

QCD:

Y.L. Dokshitzer, V. A. Khoze, A. H. Mueller, and S. I. Troian.
Basics of perturbative QCD. Gif-sur-Yvette, France: Ed. Frontieres (1991)
R. K. Ellis, W. J. Stirling, and B. R. Webber.
QCD and collider physics. Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 8:1–435, 1996.
R. D. Field.
Applications of Perturbative QCD. *Front. Phys.*, 77:1–366, 1989.
F. Halzen and A. D. Martin.
QUARKS AND LEPTONS: AN INTRODUCTORY COURSE IN MODERN PARTICLE PHYSICS. Wiley (1984) 396p.

Email Me: hannes.jung@desy.de


PHYSICS REPORTS (Review Section of Physics Letters) 81, No. 1 (1982) 1–129. NORTH-HOLLAND PUBLISHING COMPANY

PARTONS IN QUANTUM CHROMODYNAMICS

Guido Altarelli
Istituto di Fisica, Università di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy

Received 20 July 1981

Contents:

Abstract:
An overall view of the physics of QCD in the perturbative domain is presented in a form that could be of use both as an introduction to the subject with its main lines of current development and as a reference review text for more expert readers as well.

Single orders for this issue

PHYSICS REPORTS (Review Section of Physics Letters) 81, No. 1 (1982) 1–129.

Copies of this issue may be obtained at the price given below. All orders should be sent directly to the Publisher. Orders must be accompanied by check.

Single issue price Dfl. 66.00, postage included.

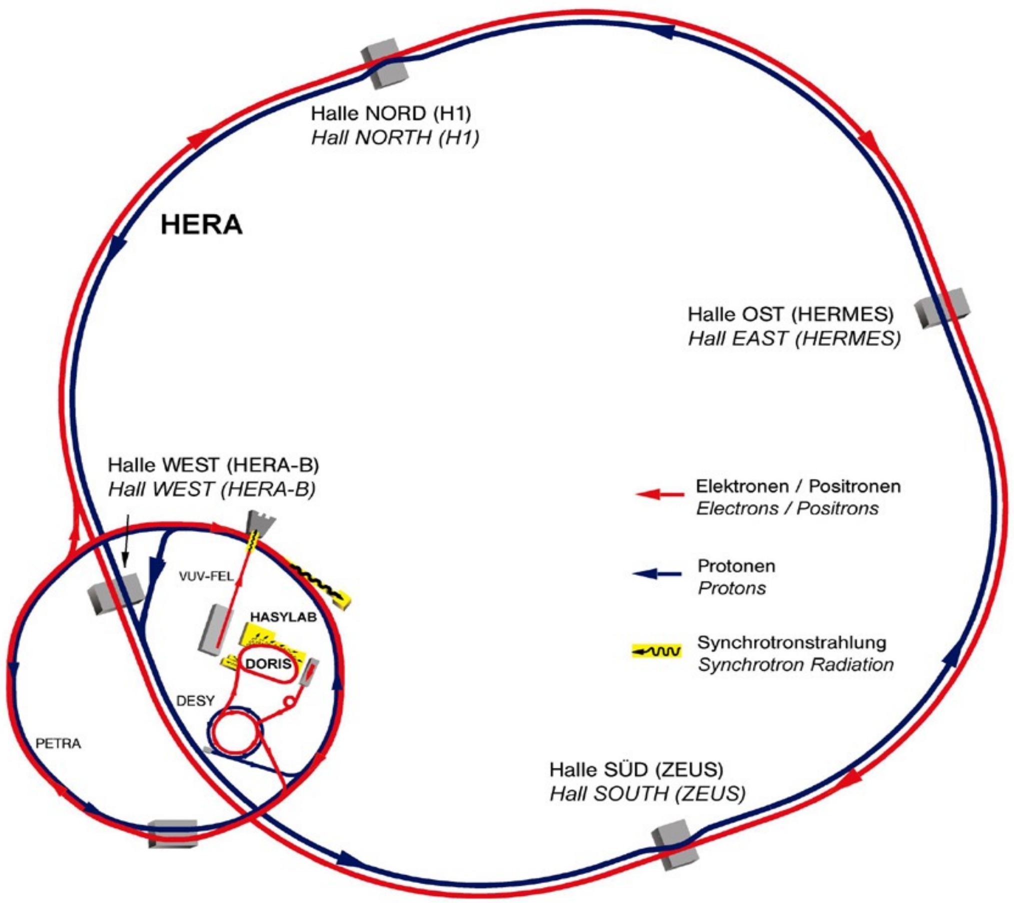
What is QCD ?

- Quantum Chromo Dynamics = quantum field theory of strong interactions
- Basic elements;
  - quarks: u,d,s,c,b,t
  - fractional charges 1/3 or 2/3
  - carry color: $r, g, b = white$
  - anti-quarks carry anti-color: $r\bar{r} = white, g\bar{g} = white, b\bar{b} = white$
  - exchange bosons are gluons
  - gluons couple to quarks, anti-quarks and gluons
  - gluons carry color+anti-color (but not in a color singlet):

$$r\bar{g}, r\bar{b}, g\bar{r}, g\bar{b}, \sqrt{\frac{1}{2}}(r\bar{r} - g\bar{g}), \sqrt{\frac{1}{2}}(r\bar{r} + g\bar{g} - 2b\bar{b})$$

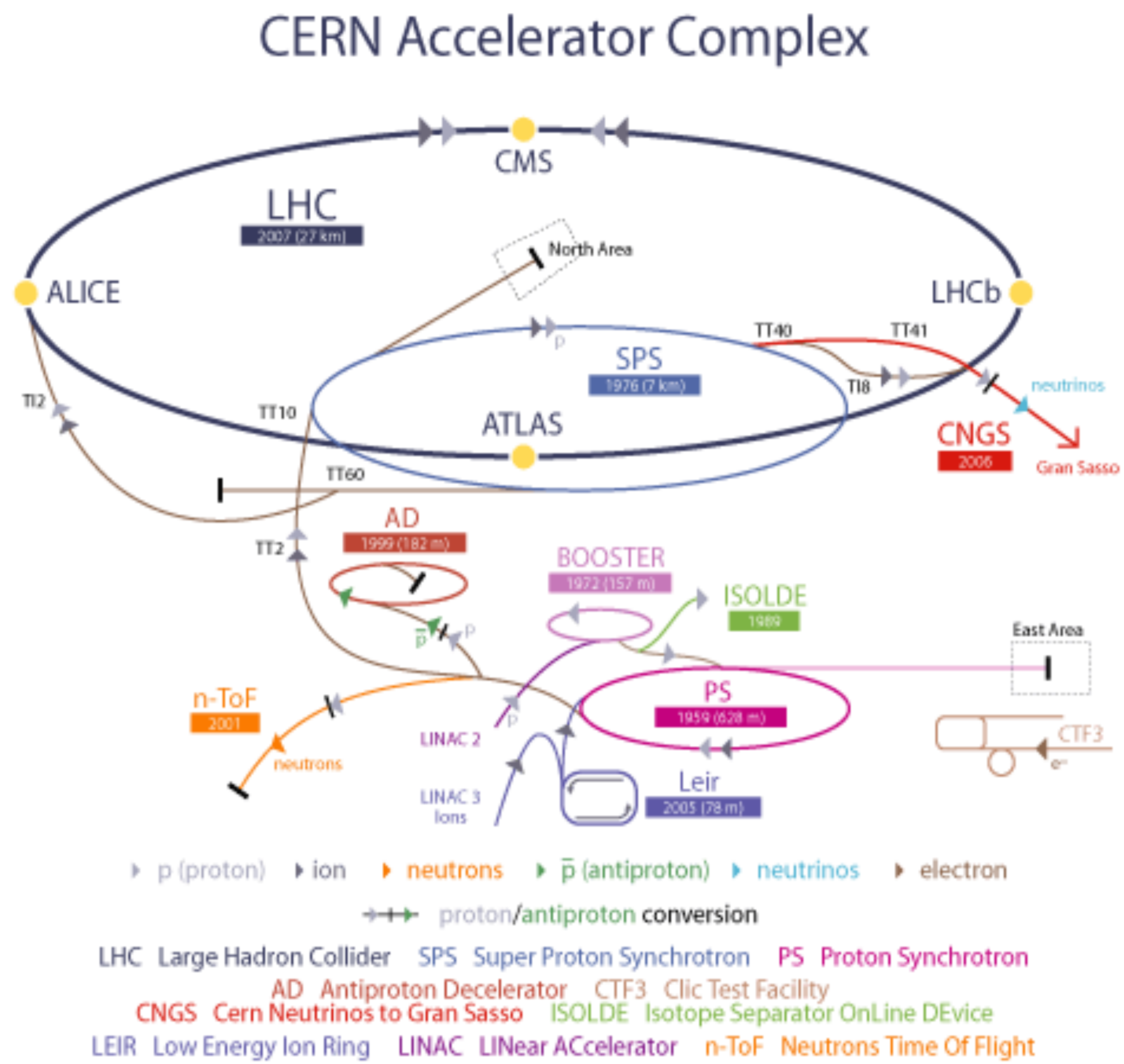
Fixed Target, HERA & LHC

- HERA at DESY



$$\sqrt{s}_{HERA} = 300 GeV$$

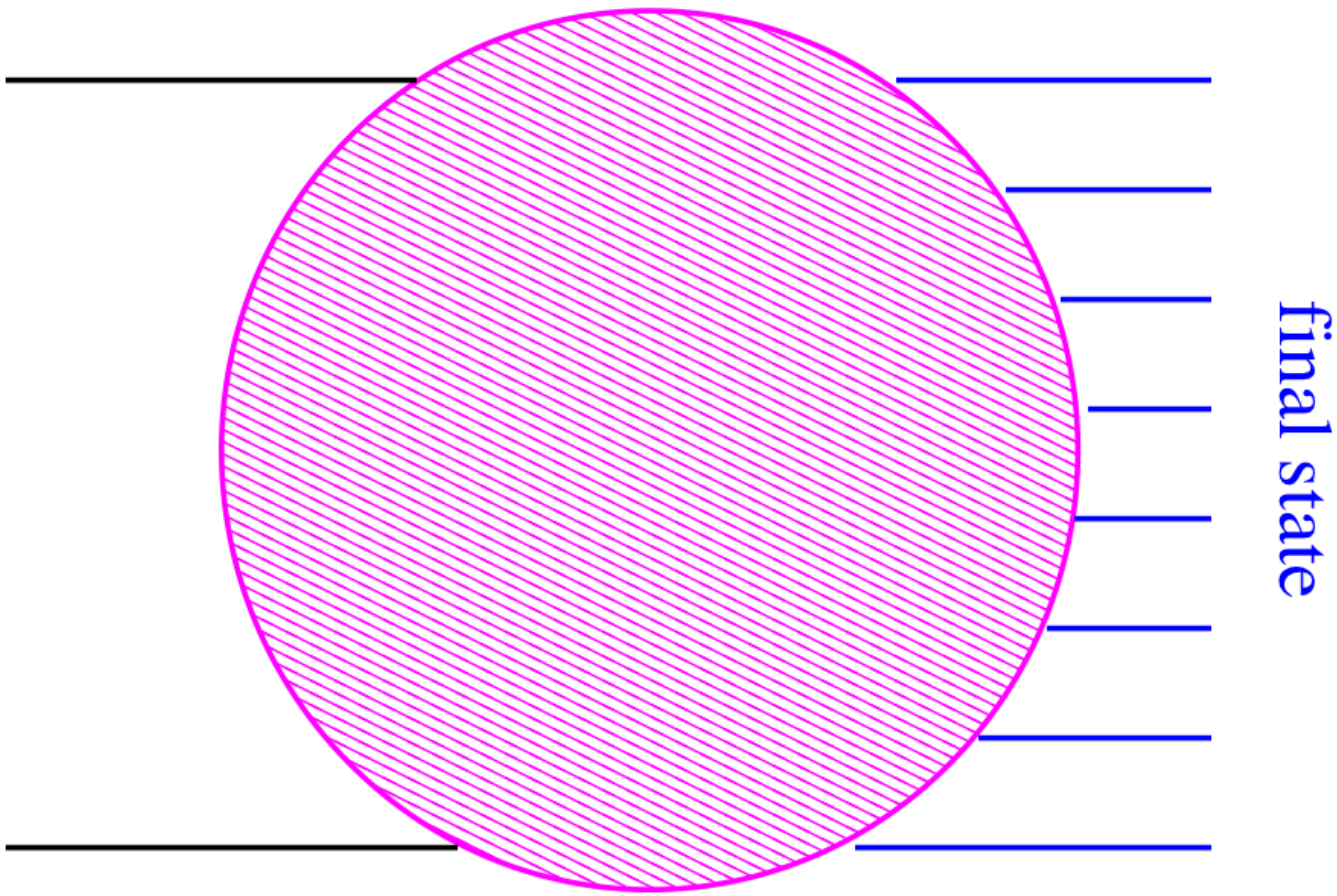
- SPS & LHC at CERN



$$\sqrt{s}_{LHC} = 7 - 14 TeV$$

The general case

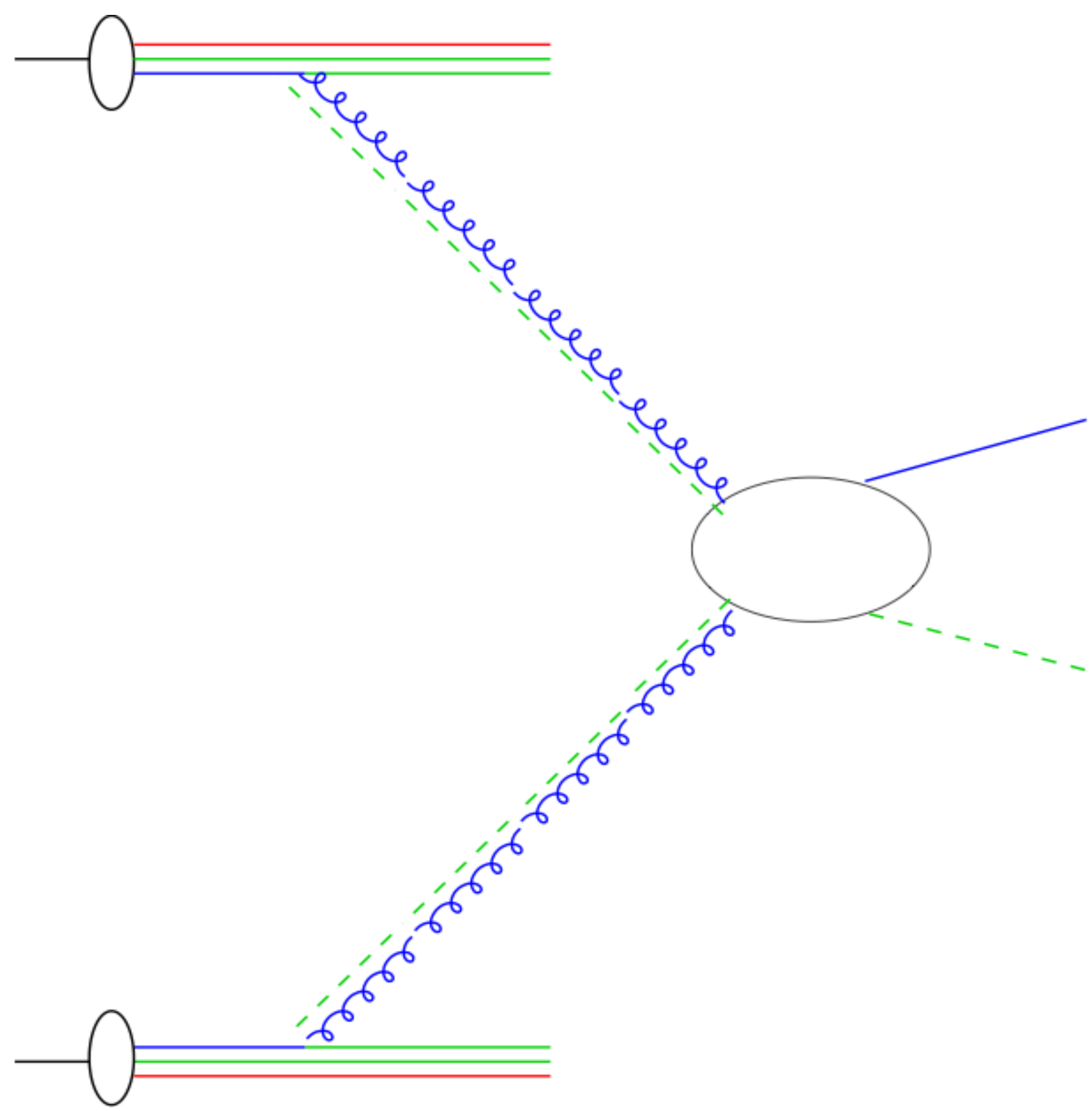
- Calculation of cross section of $A + B \rightarrow anything$



➔ Start with jet production ....

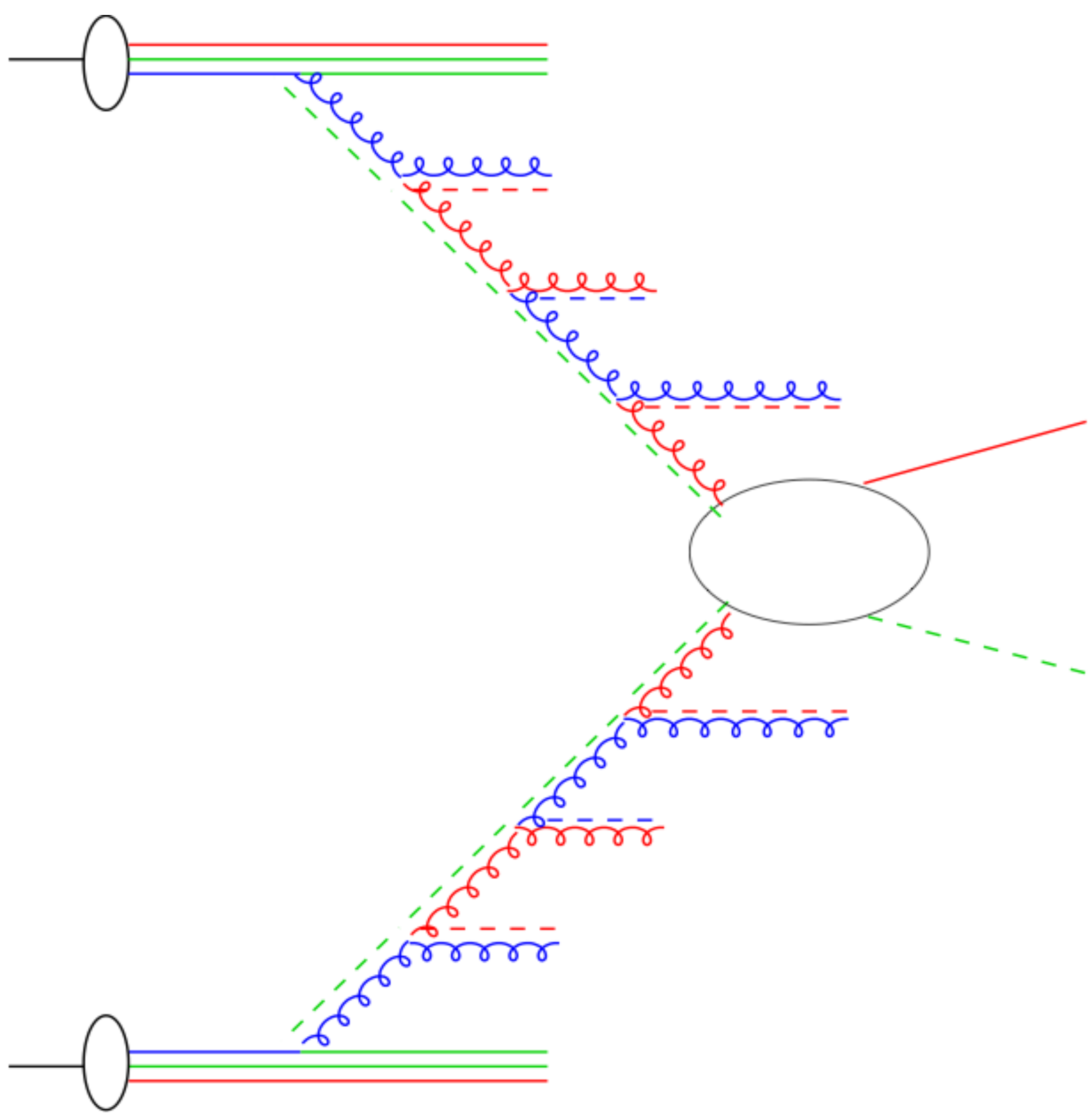
Picture of jet production

- General approach to hard scattering processes



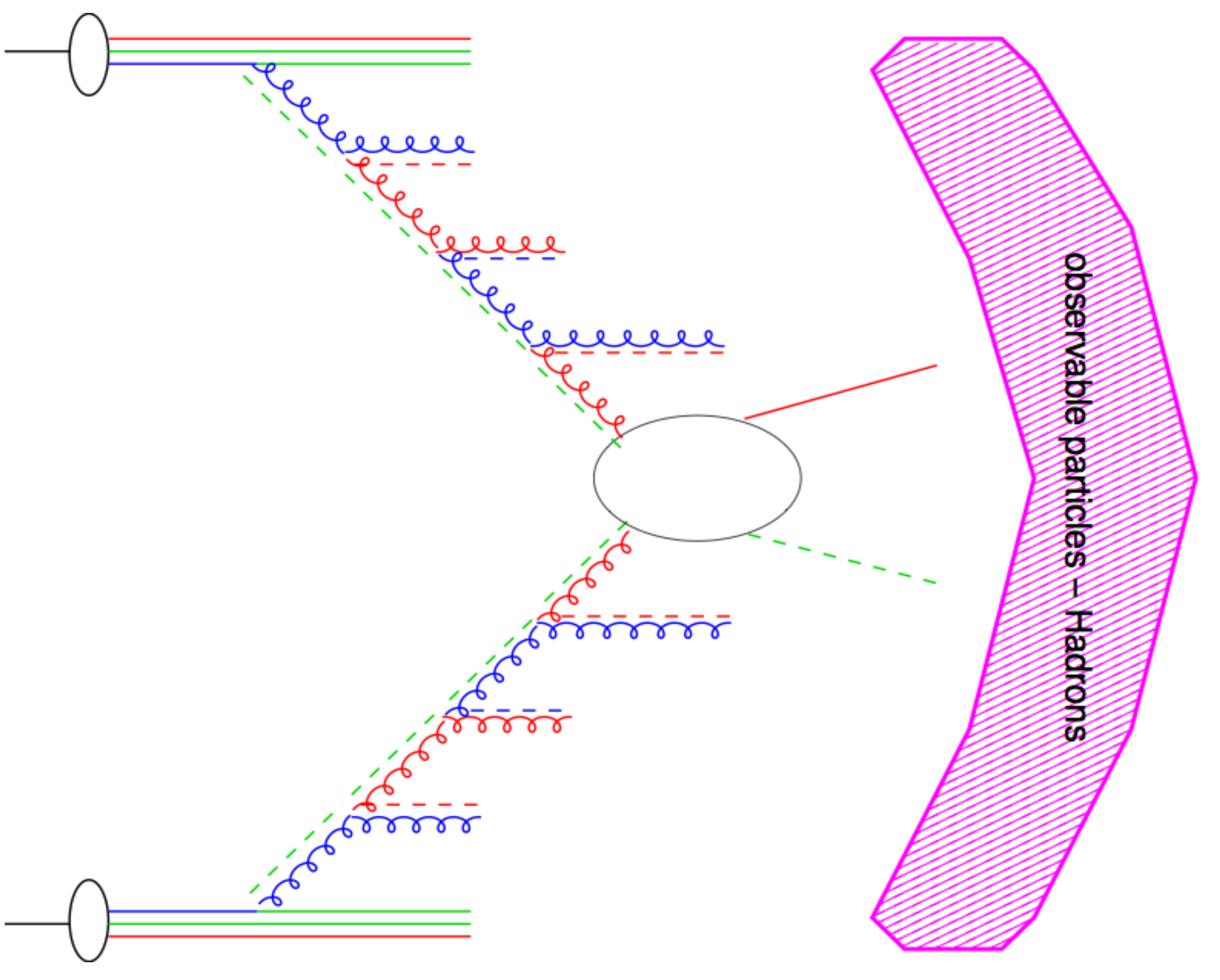
Picture of jet production

- General approach to hard scattering processes
  - including higher order parton radiation



Picture of jet production

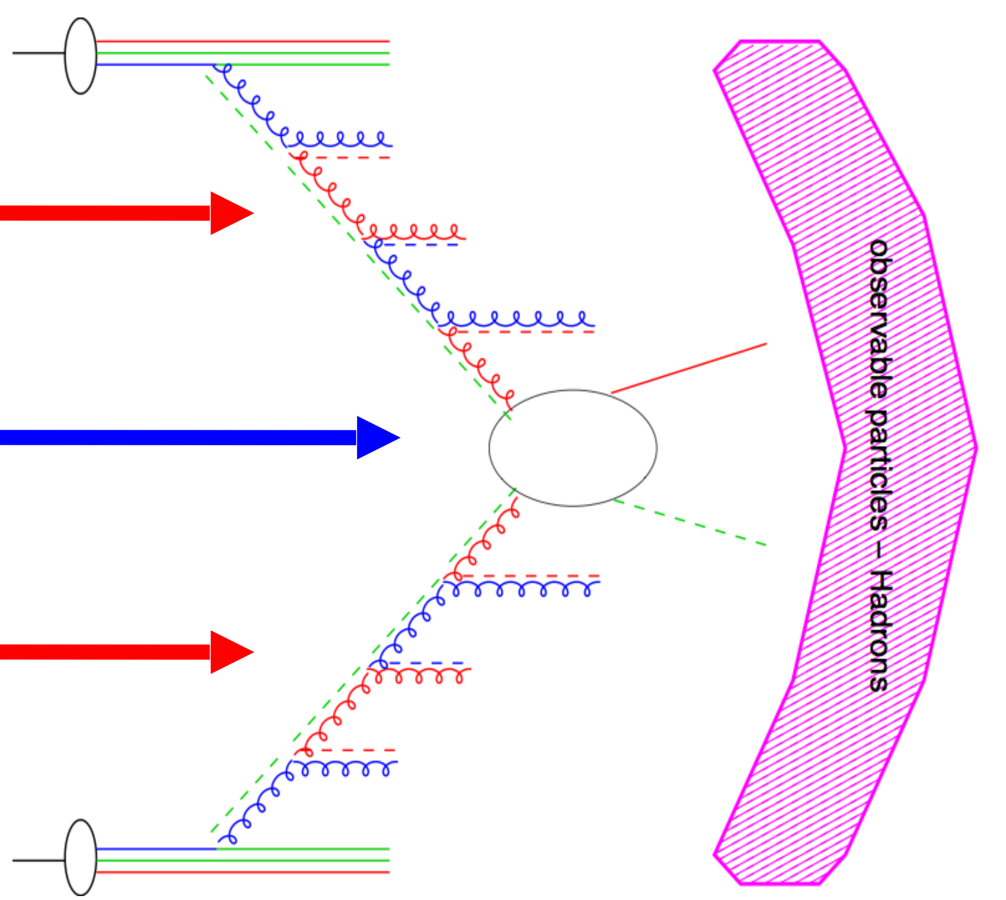
- General approach to hard scattering processes
  - including higher order parton radiation
  - adding hadronization and fragmentation



Picture of jet production

- General approach to hard scattering processes
  - including higher order parton radiation
  - adding hadronization and fragmentation
  - ➔ leads to the concept of factorization:

$$\sigma = f(x_1, \mu^2) \otimes \hat{\sigma}(x_1, x_2, \mu^2) \otimes f(x_2, \mu^2)$$



➔ factorization ansatz is used in

any calculation (LO,NLO, MC event generators ...)

How can processes be calculated ?

- Monte Carlo method
  - refers to any procedure that makes use of random numbers
  - uses probability statistics to solve the problem
- Monte Carlo methods are used in:
  - Simulation of natural phenomena
  - Simulation of experimental apparatus
  - Numerical analysis

Monte Carlo method

- Monte Carlo method
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- Monte Carlo methods are used in:
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  - Numerical analysis
- Random Numbers
  - one of them is 3
  - No such thing as a single random number
  - A sequence of random numbers is a set of numbers that have nothing to do with the other numbers in a sequence

Random Numbers

- In a uniform distribution of random numbers in [0,1] every number has the same chance of showing up
- Note that 0.000000001 is just as likely as 0.5

To obtain random numbers:

- Use some chaotic system like roulette, lotto, 6-49, ...
- Use a process, inherently random, like radioactive decay
- Tables of a few million truly random numbers exist .....

(.....until a few years ago.....)

BUT not enough for most applications

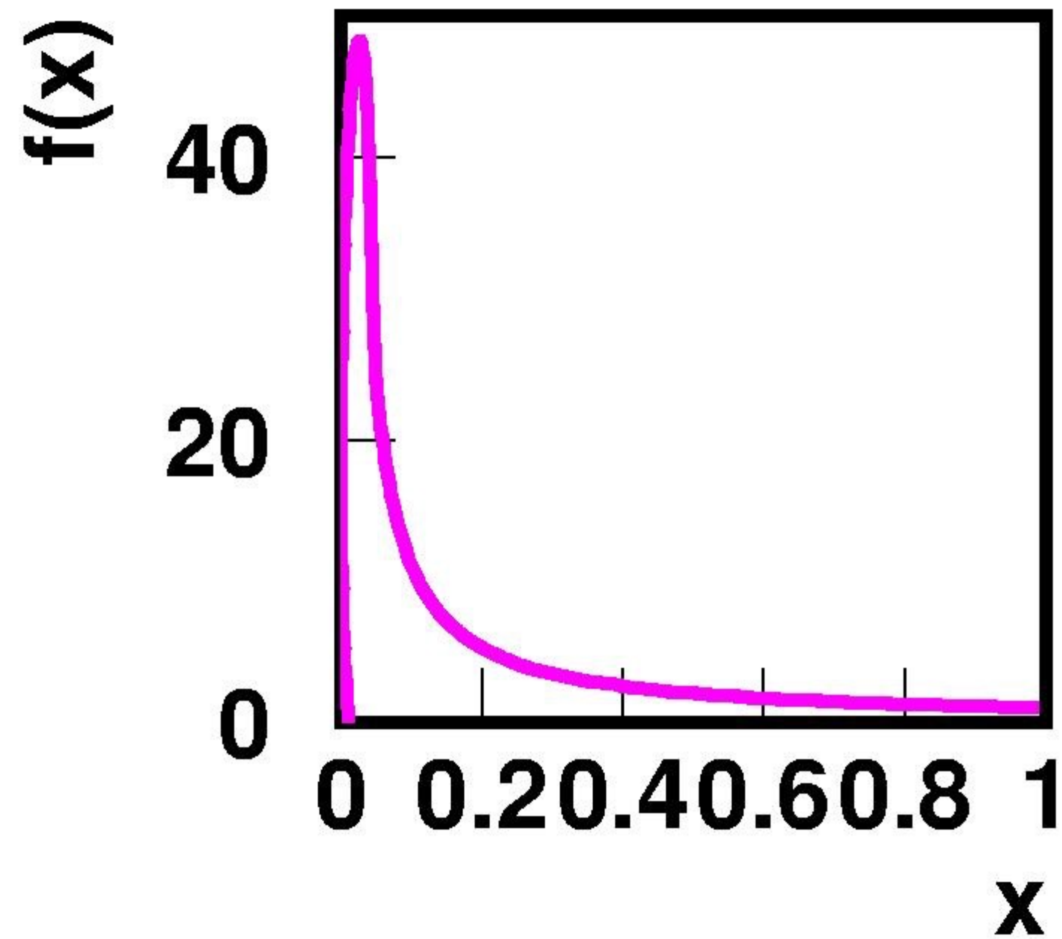
➔.... we have true random number generators ...

Generating distributions

- Brute Force or Hit & Miss method
  - use this if there is no easy way to find a analytic integrable function
  - find $c \leq \max f(x)$
  - reject if $f(x_i) \leq u_j \cdot c$
  - accept if $f(x_i) \geq u_j \cdot c$

Generating distributions: Hit & Miss

MC for function f(x):
get random number:
R1 in (0,1) and R2 in (0,1)
calculate x = R1
reject event if: $f_x < f_{max}$ R2



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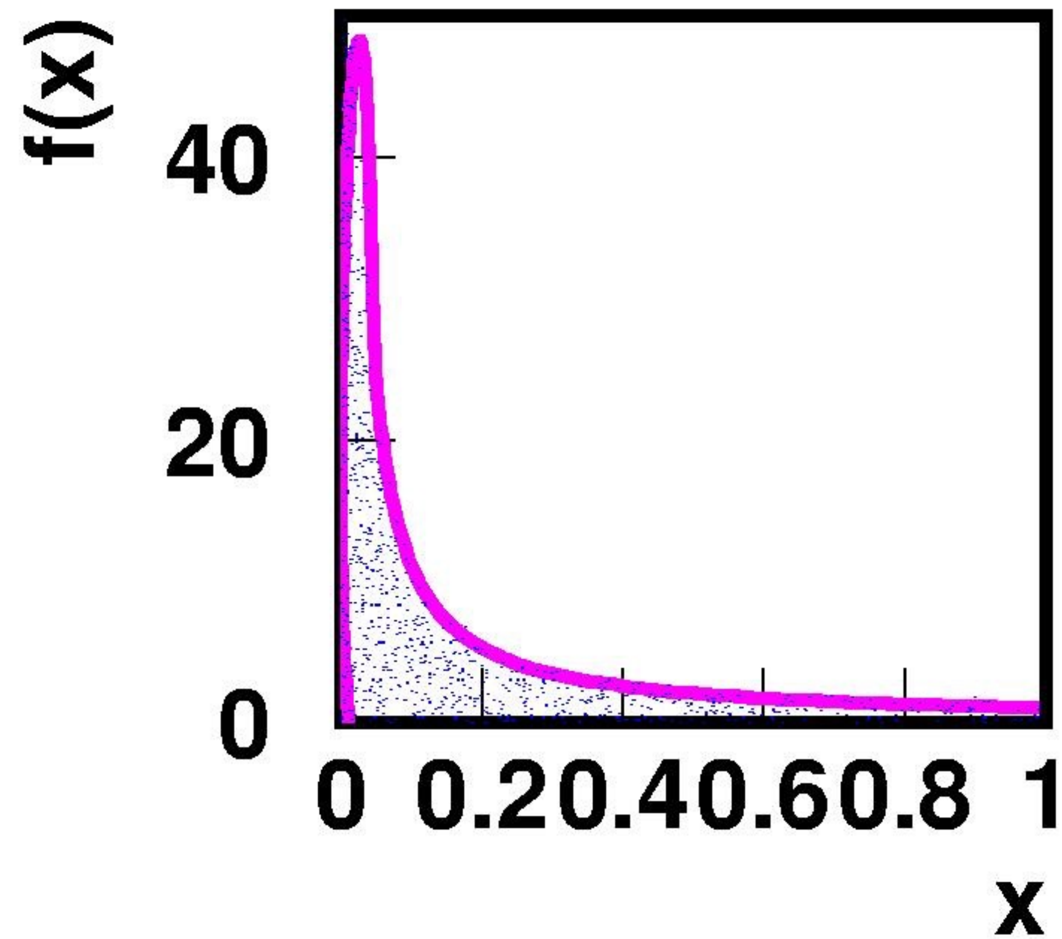

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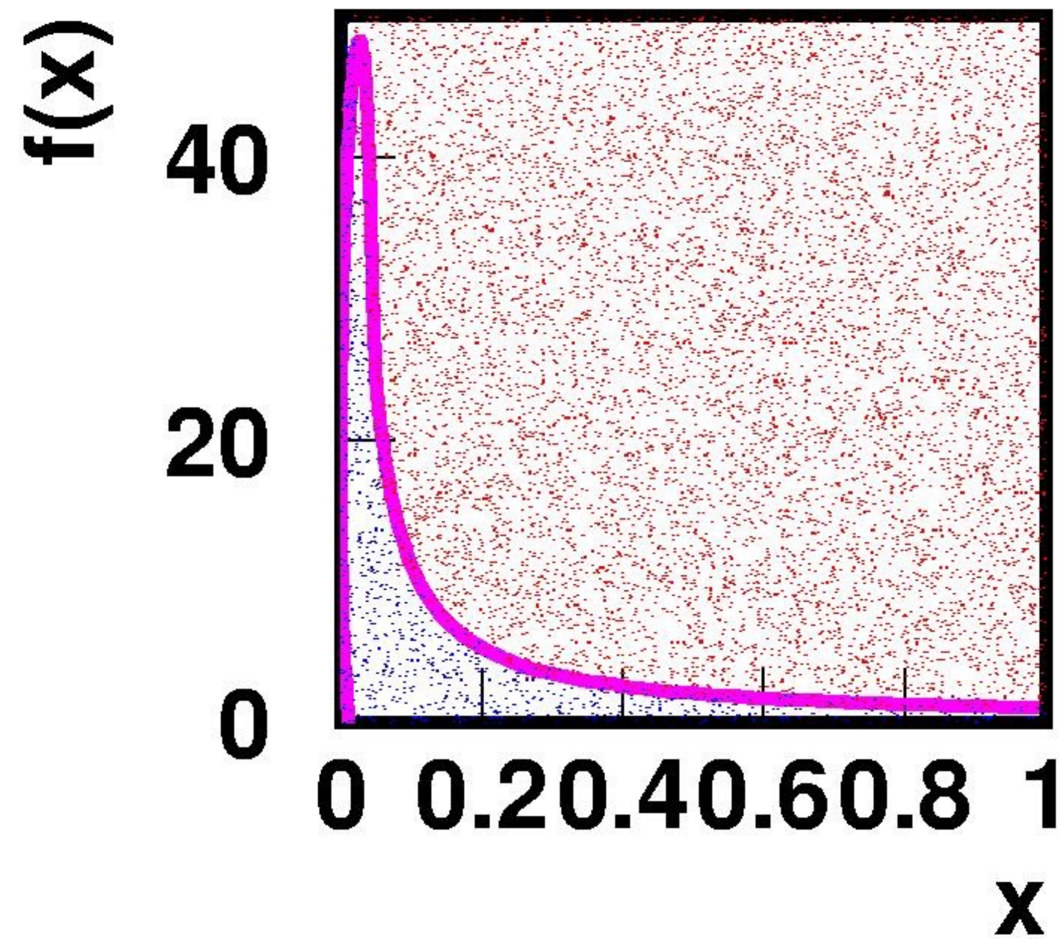
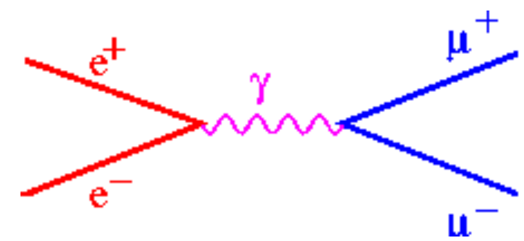


Works always:
→ but can be very inefficient

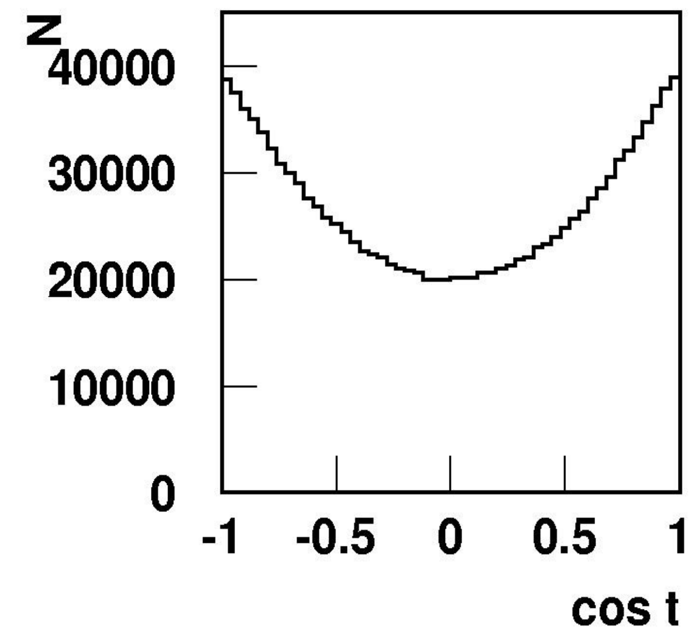
Constructing a MC for e+ e{ → X



- process: $e^+e^- \to \mu^+\mu^-$

$$\frac{d\sigma}{d\cos\theta d\phi} = \frac{\alpha_{em}^2}{4s}\left(1+\cos^2\theta\right)$$

- goal: generate 4-momenta of μ 's, need *cm* energy s, $\cos\theta$, ϕ



random number R1(0,1): ϕ = 2 π R1
random number R2(0,1): cos θ = -1 + 2 R2

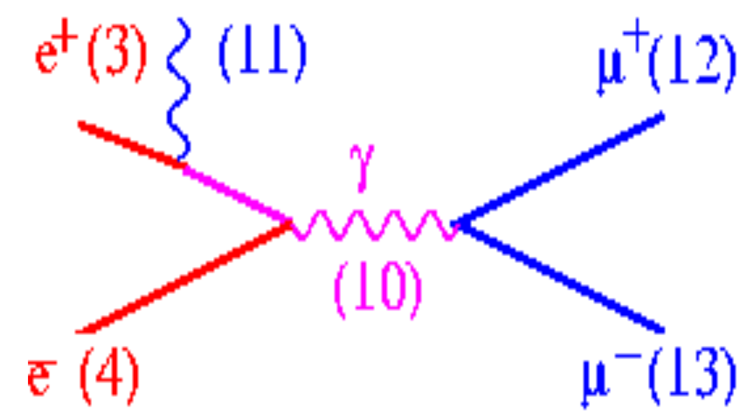
for every R1, R2 use weight with $\frac{d\sigma}{d\cos\theta d\phi}$
repeat many times

Example event for $e^+e^- \rightarrow X$

- example from PYTHIA: Event listing

```
  I particle/jet KS     KF  orig    p_x      p_y      p_z       E        m

  1 !e+!         21    -11    0    0.000    0.000   30.000   30.000    0.001
  2 !e-!         21     11    0    0.000    0.000  -30.000   30.000    0.001
==============================================================================
  3 !e+!         21    -11    1    0.000    0.000   30.000   30.000    0.000
  4 !e-!         21     11    2    0.000    0.000  -30.000   30.000    0.000
  5 !e+!         21    -11    3    0.143    0.040   26.460   26.460    0.000
  6 !e-!         21     11    4    0.000    0.000  -29.998   29.998    0.000
  7 !Z0!         21     23    0    0.143    0.040   -3.539   56.458   56.347
  8 !mu-!        21     13    7   -9.510    1.741   24.722   26.546    0.106
  9 !mu+!        21    -13    7    9.653   -1.700  -28.261   29.913    0.106
==============================================================================
 10 (Z0)         11     23    7    0.143    0.040   -3.539   56.458   56.347
 11 gamma         1     22    3   -0.143   -0.040    3.539    3.542    0.000
 12 mu-           1     13    8   -9.510    1.741   24.722   26.546    0.106
 13 mu+           1    -13    9    9.653   -1.700  -28.261   29.913    0.106
==============================================================================
               sum:  0.00          0.000    0.000    0.000   60.000   60.000
```



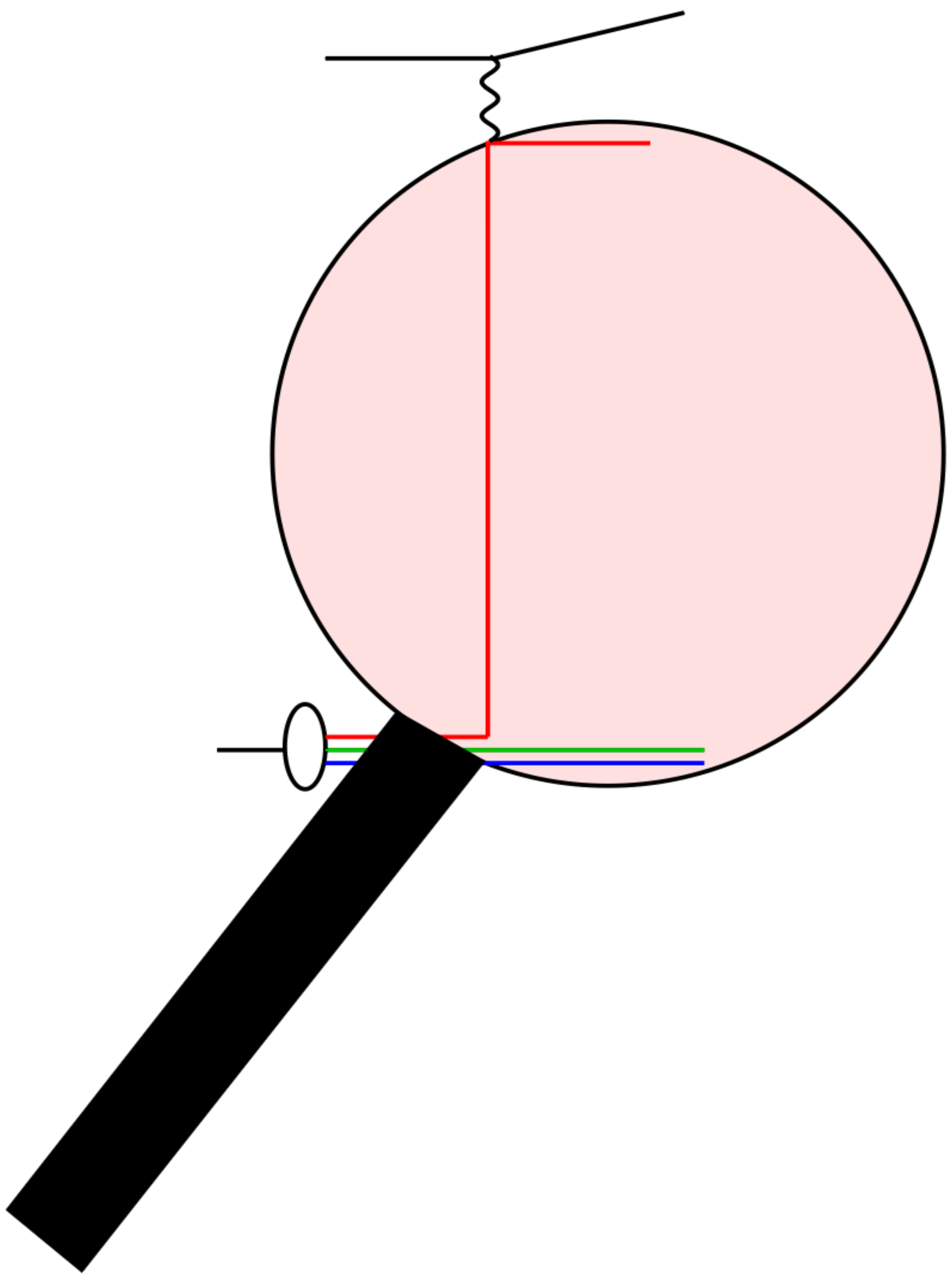
- technicalities/advantages
- can work in any frame
- Lorentz-boost 4-vectors back and forth
- can calculate any kinematic variable
- x-section:
  - fill histogram in any variable, no Jacobeans !

From e^+e^- to hadron scattering …

… add a hadron in the initial state:

ep scattering

A proton in the initial state



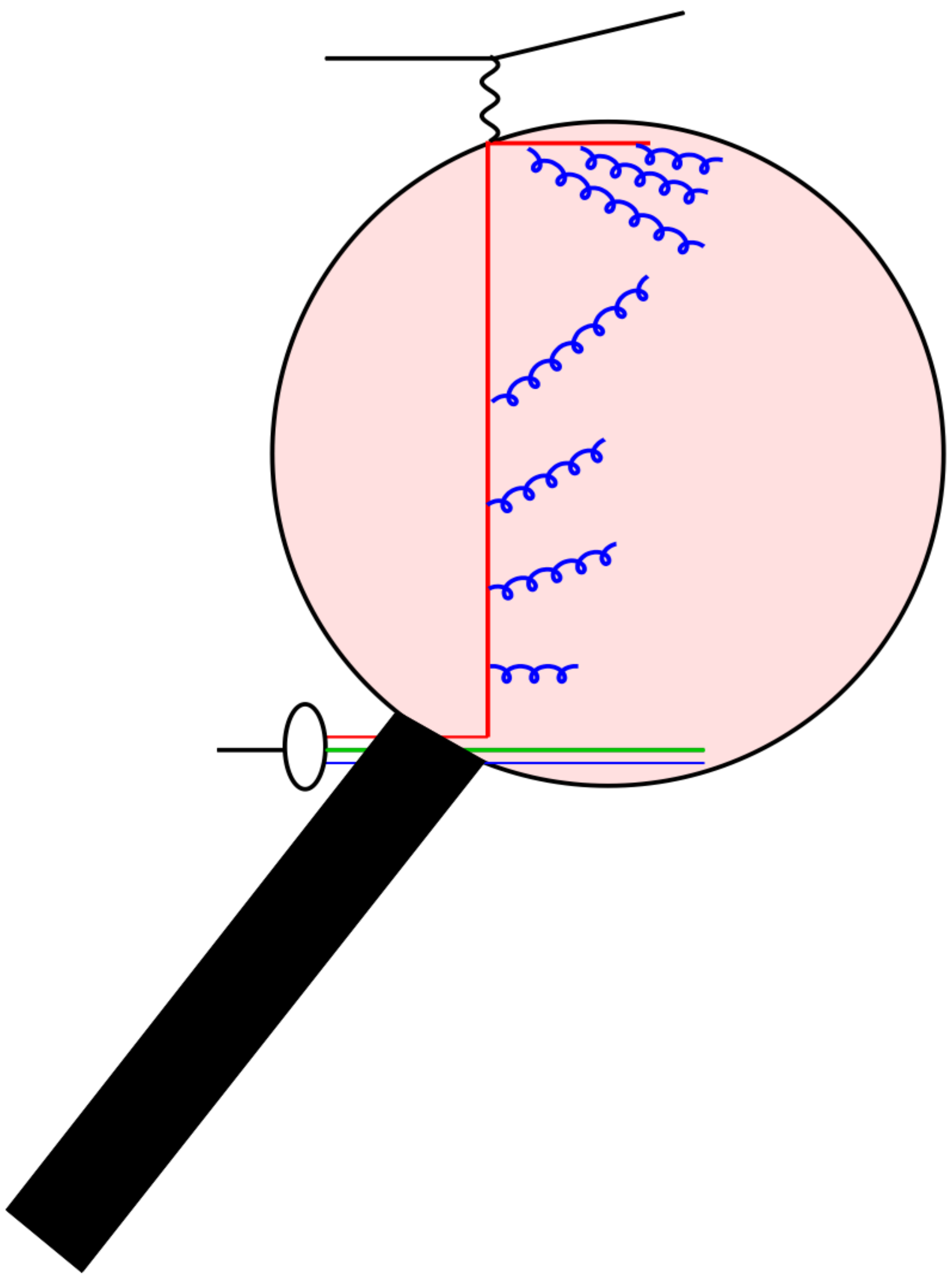
- Deep Inelastic Scattering is a incoherent sum of

$$e^+ q \rightarrow e + q$$

- only 50 % of p momentum carried by quarks
- need a large gluon component
- partonic part convoluted with parton density function $f_i(x)$

$$\sigma(e^+ p \rightarrow e^+ X) = \sum_i f_i(x, \quad) \sigma(e^+ q_i \rightarrow e^+ q_i)$$

A proton in the initial state



- Deep Inelastic Scattering is a incoherent sum of

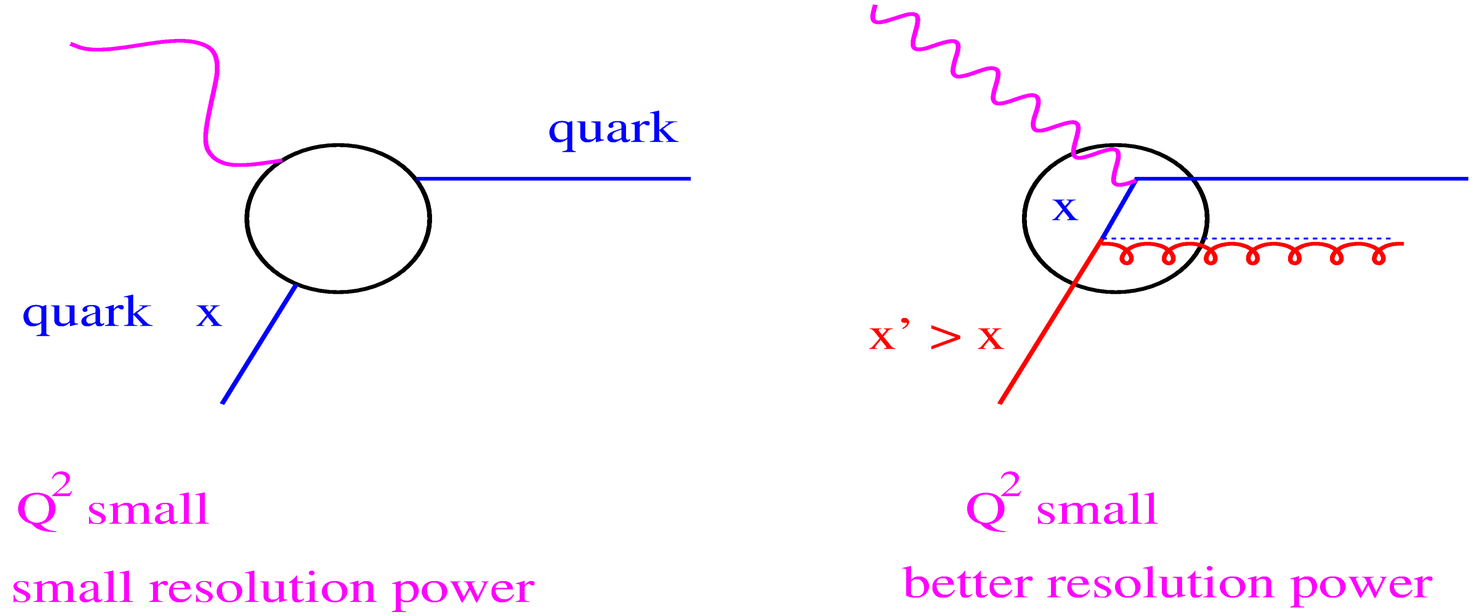
  $$e^+ q \to e + q$$

- only 50 % of p momentum carried by quarks
- need a large gluon component
- partonic part convoluted with parton density function $f_i(x)$
- BUT we know, PDF depends on resolution scale Q^2

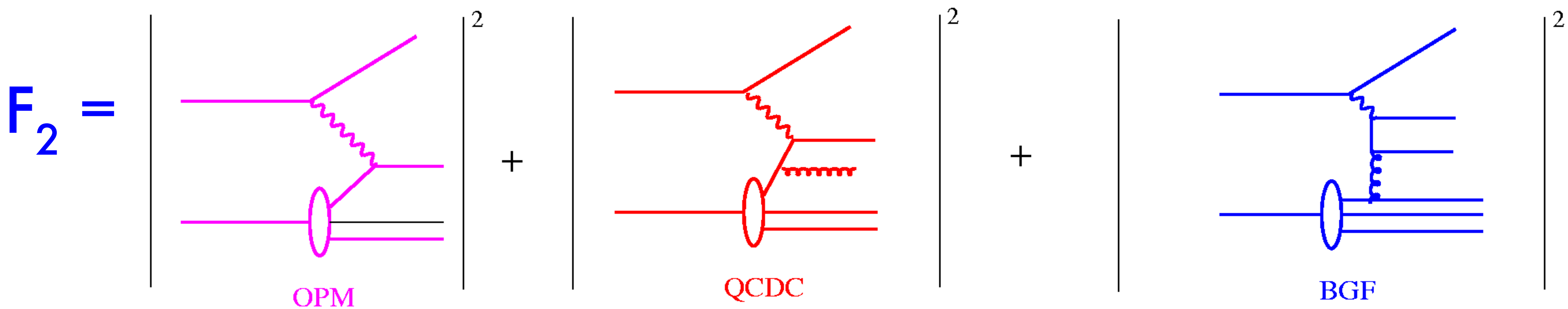
$$\sigma(e^+ p \to e^+ X) = \sum_i f_i(x, Q^2) \sigma(e^+ q_i \to e^+ q_i)$$

$F_2(x,Q^2)$: DGLAP evolution equation

- QPM: F_2 is independent of Q^2
- Q^2 dependence of structure function: Dokshitzer Gribov Lipatov Altarelli Parisi



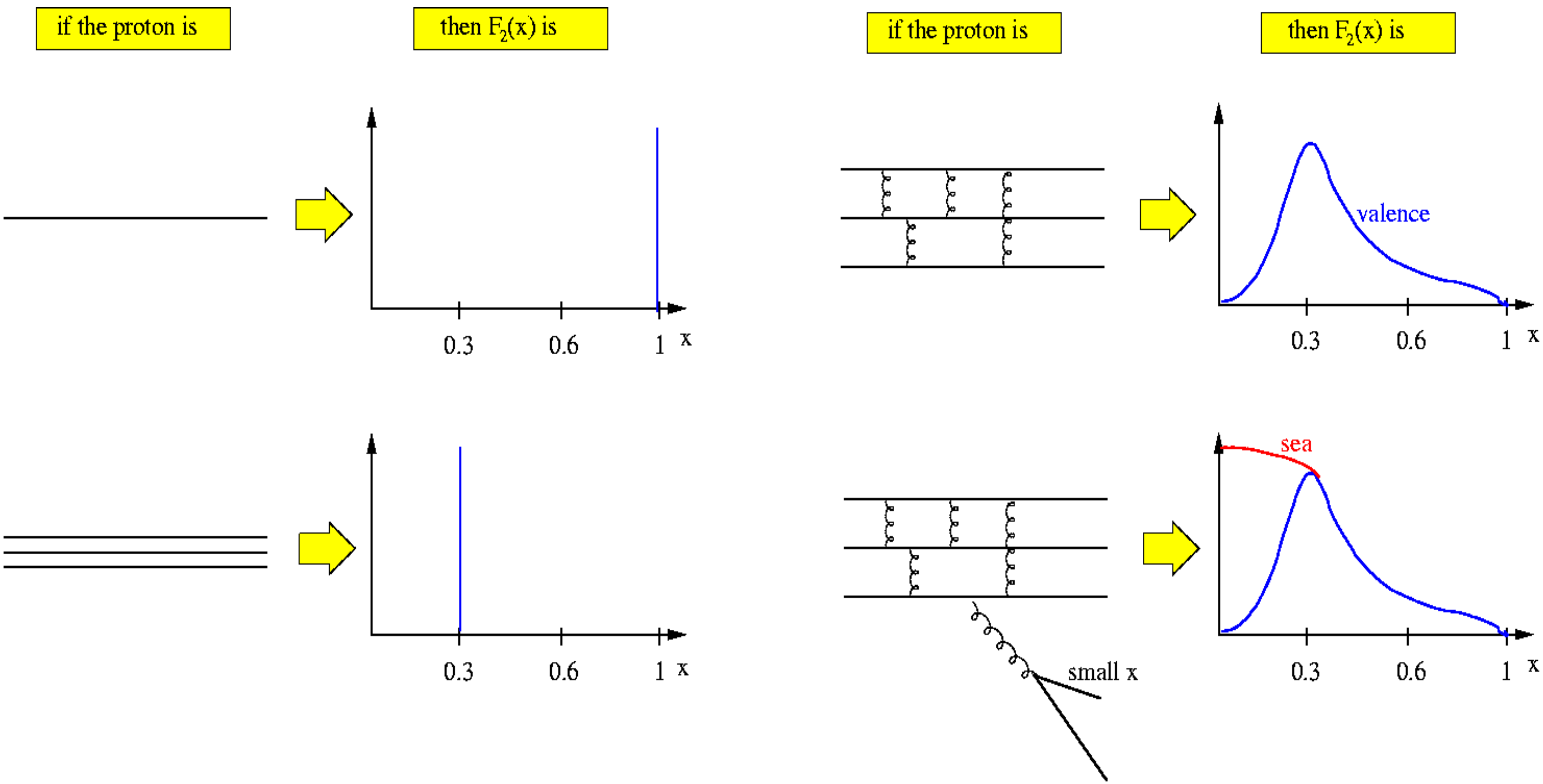
➔ Probability to find parton at small x increases with Q^2



➔ Test of theory: Q^2 evolution of $F_2(x,Q^2)$!!!!!

From Naïve F_2 picture to QCD ...

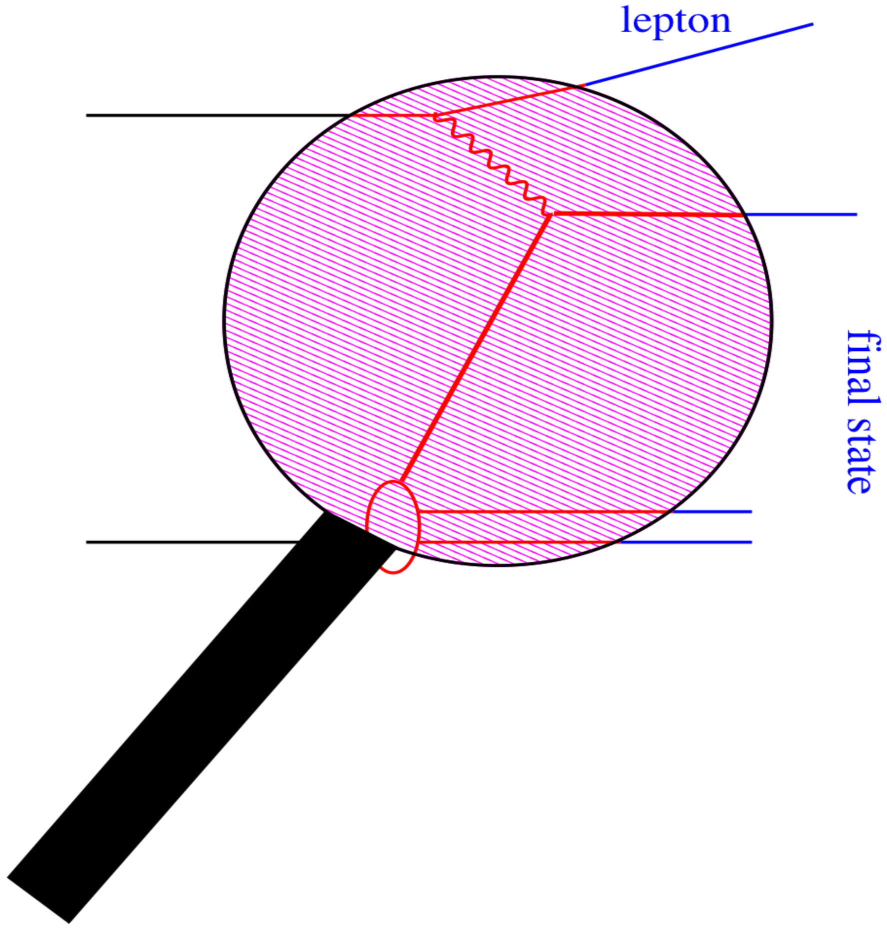
From Halzen & Martin: Quarks & Leptons, p201

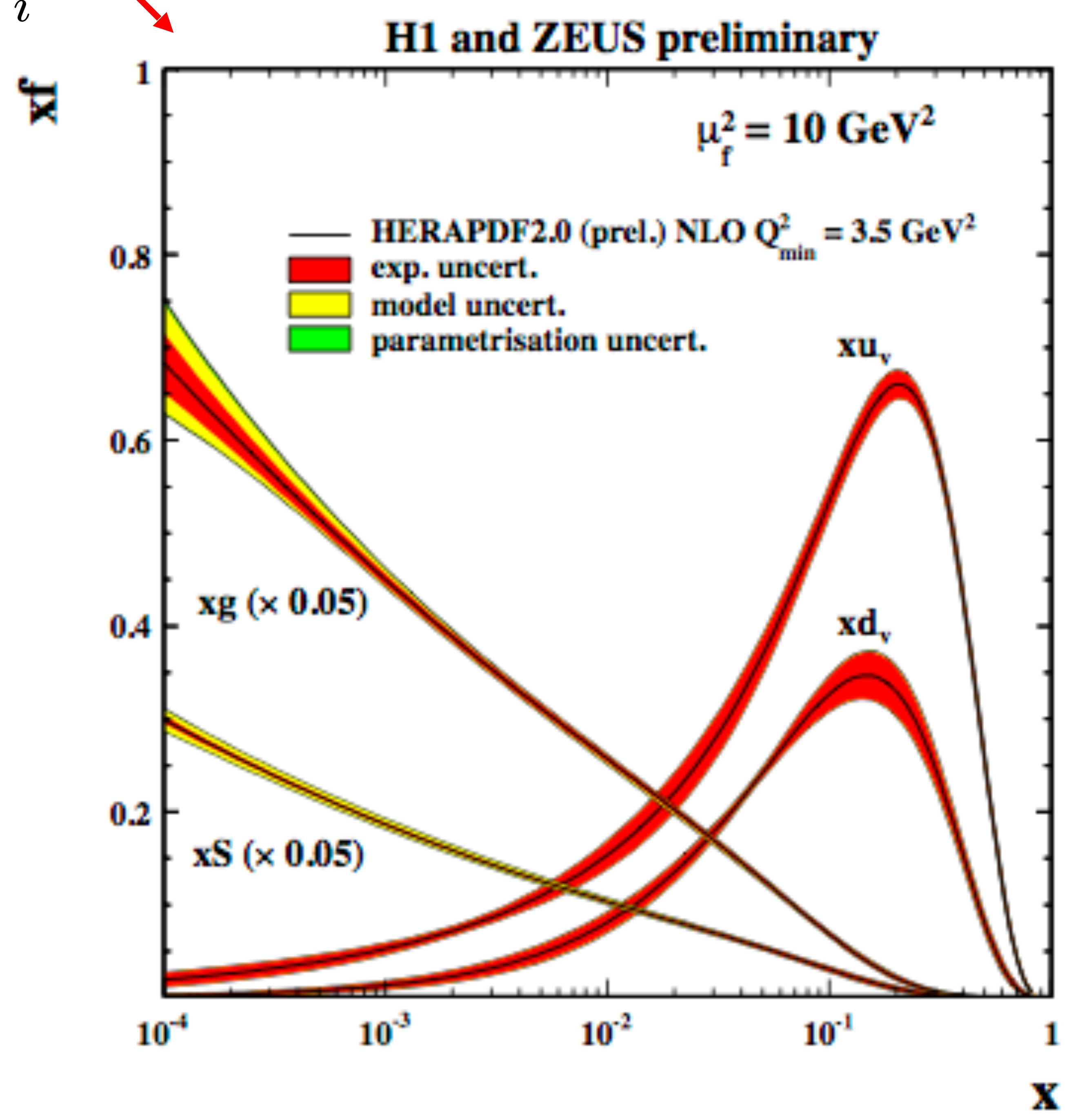


Lepton Hadron scattering

- Deep Inelastic Scattering is a incoherent sum of $e^+ q \to e + q$

$$\sigma(e^+ p \to e^+ X) = \sum_i f_i(x, Q^2) \sigma(e^+ q_i \to e^+ q_i)$$





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- need a large gluon component

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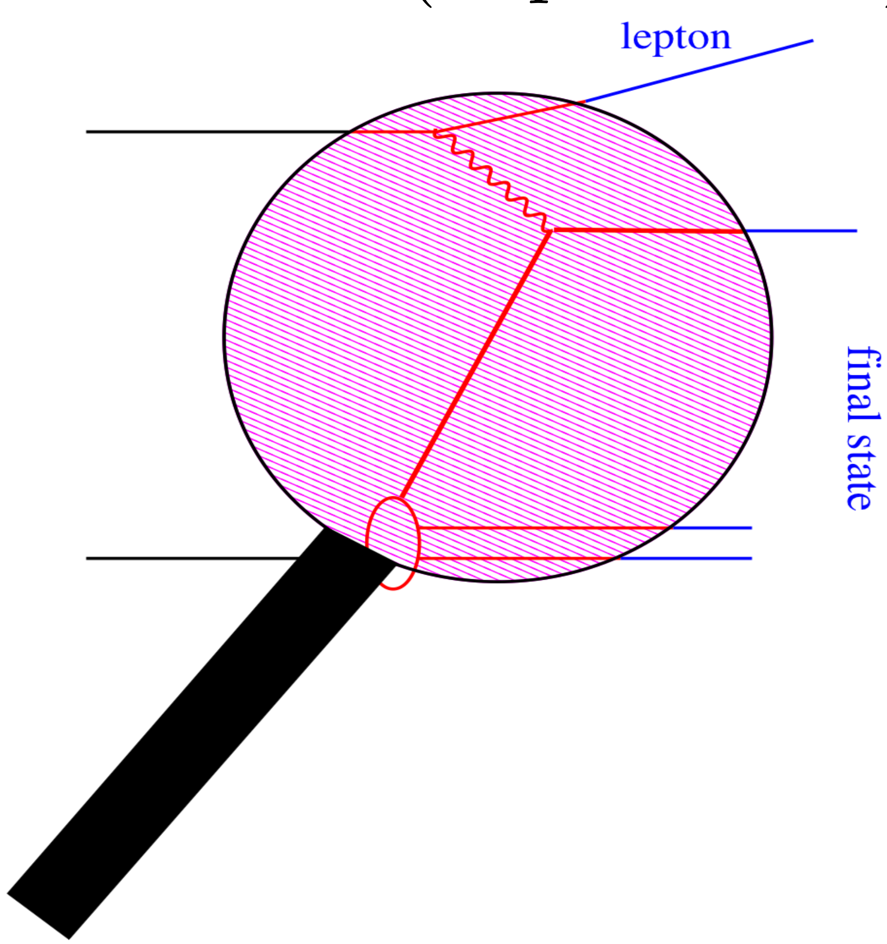
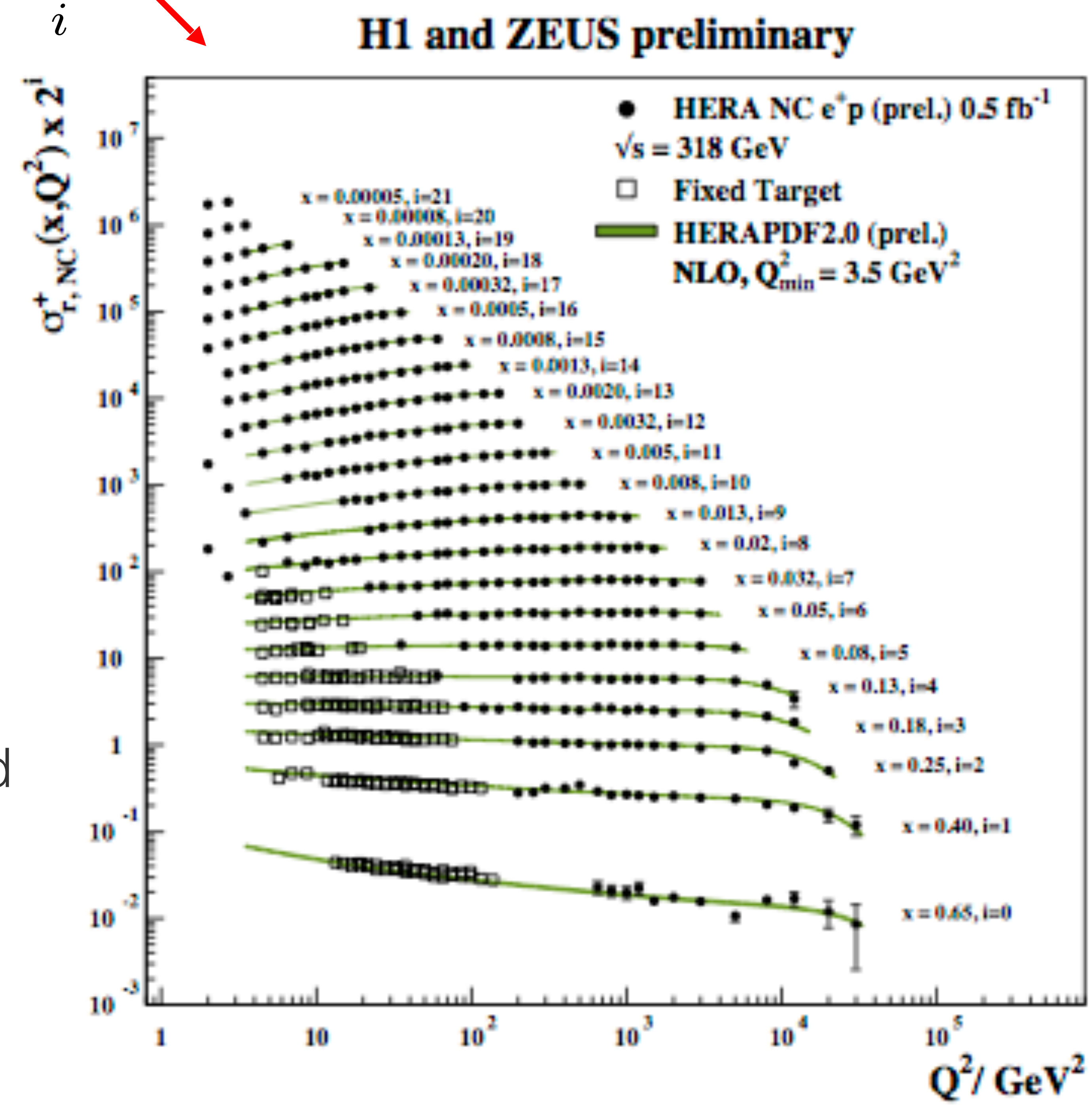
- Deep Inelastic Scattering is a incoherent sum of $e^+ q \to e + q$

$$\sigma(e^+ p \to e^+ X) = \sum_i f_i(x, Q^2)\sigma(e^+ q_i \to e^+ q_i)$$

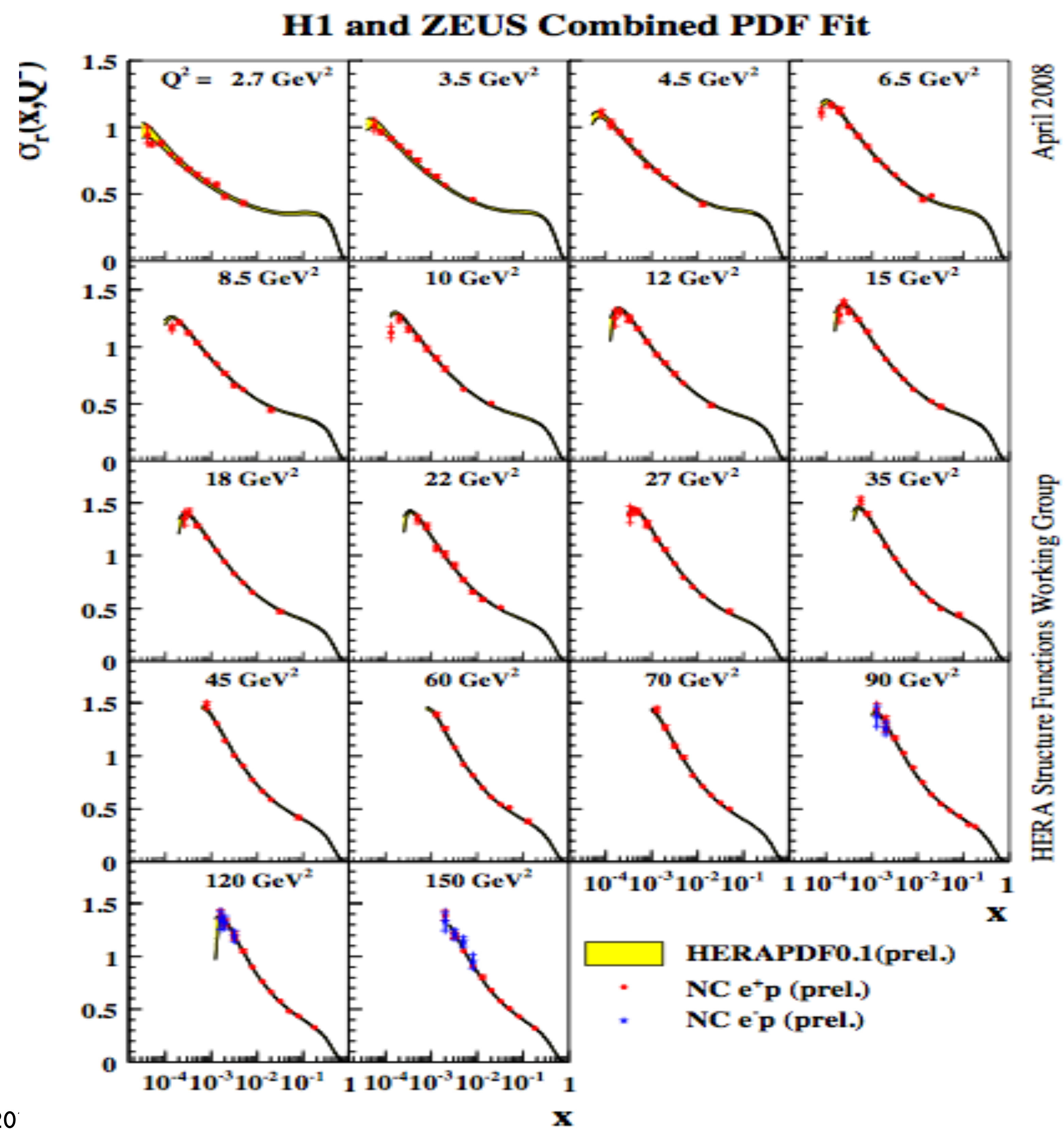




- only 50 % of p momentum carried by quarks
- need a large gluon component

Inelastic Scattering: main results

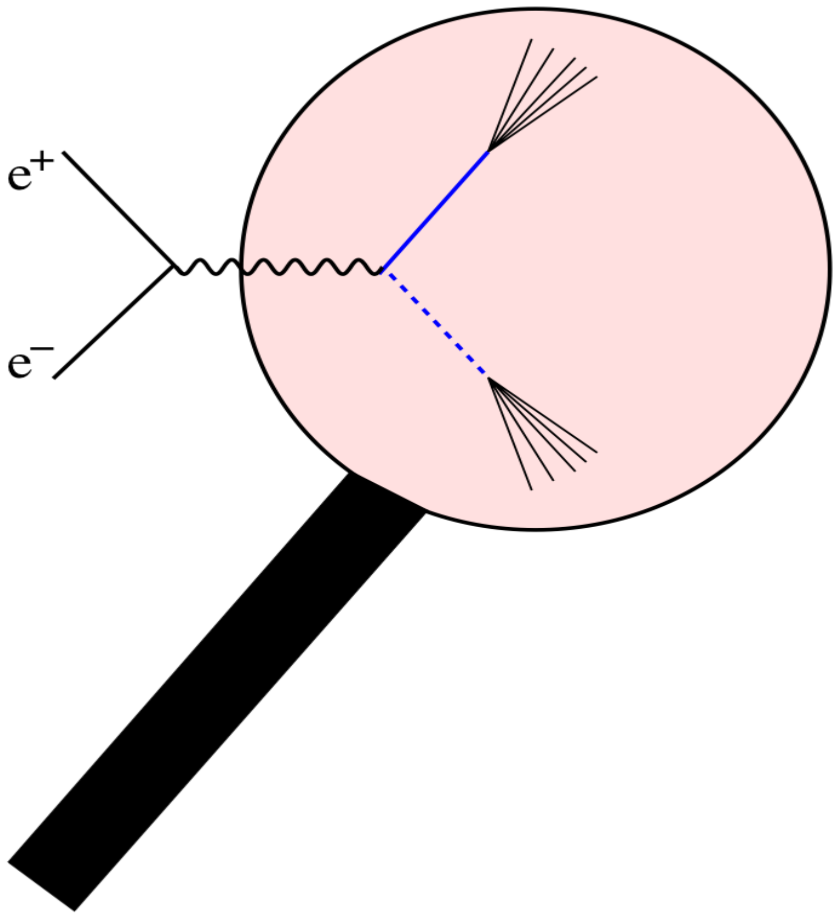
- F_2 scaling at large *x*
- ~ 50 % gluons
- F_2 rise at small x
    - How can rising F_2 be understood ?
    - Does rise continue forever ?
    - What limits F_2 ?

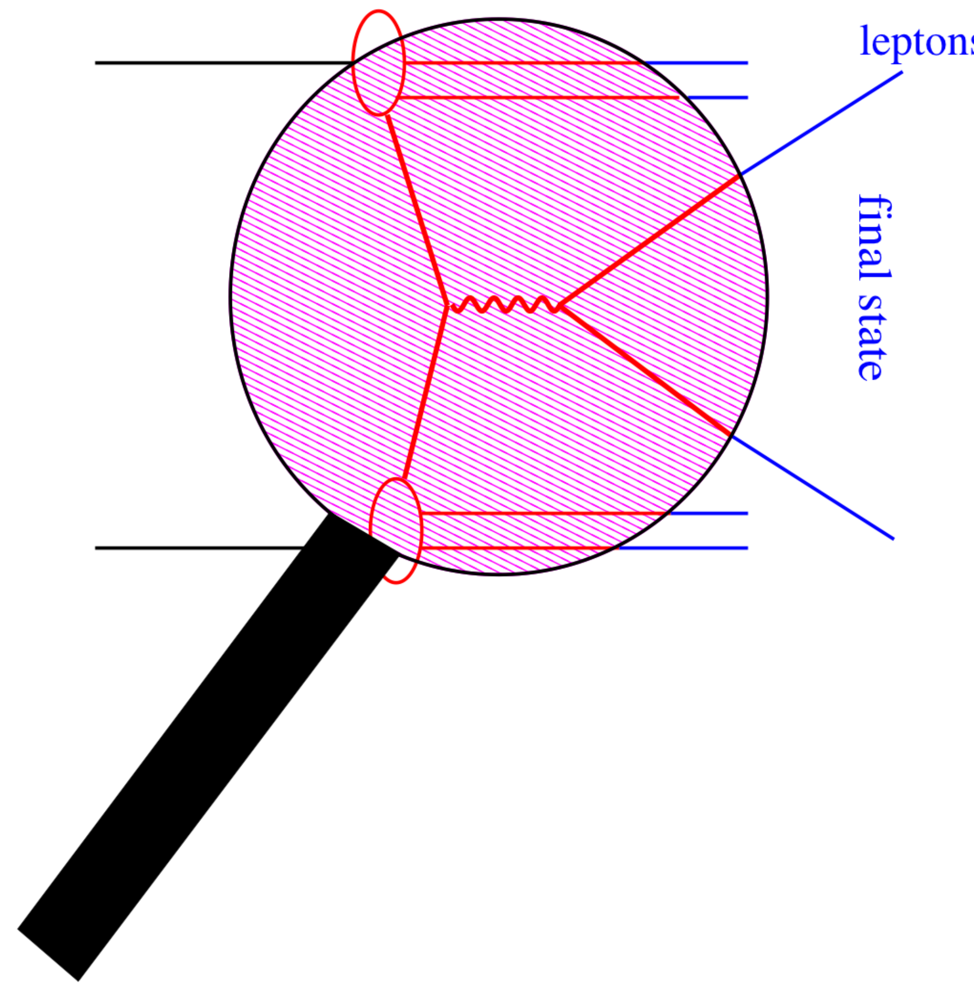


From ep scattering …

… to pp scattering

Rotating the diagrams



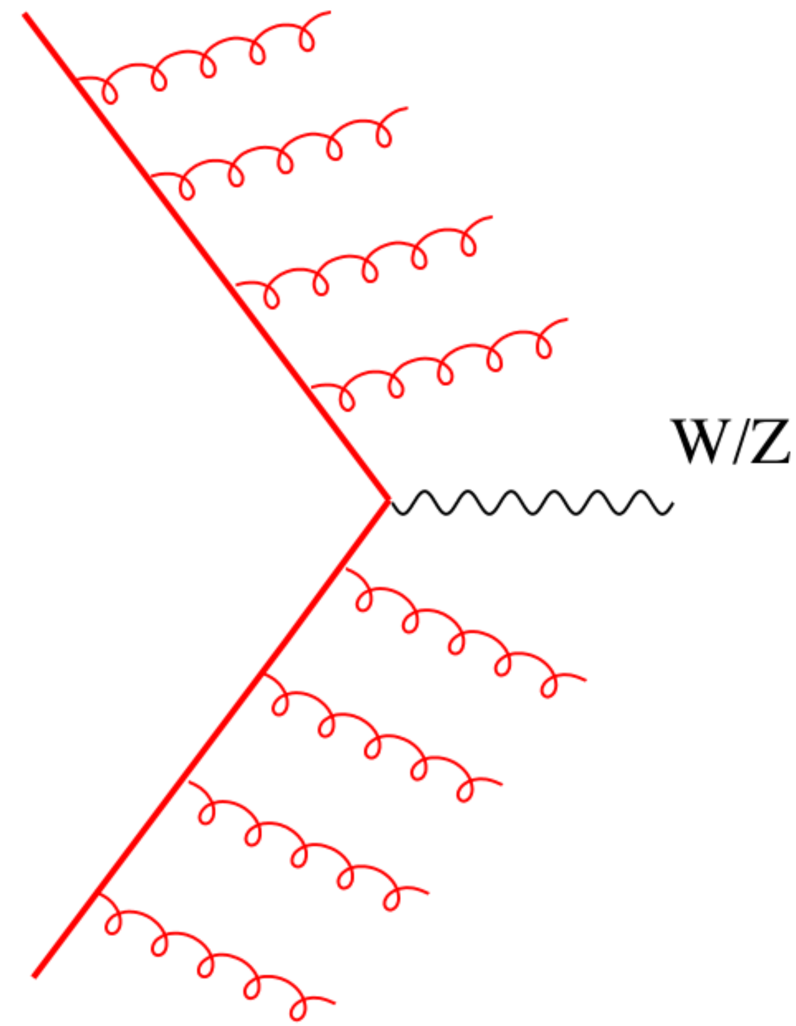


$$\sigma(e^+e^- \to q\bar{q}) = 3\frac{4\pi\alpha^2}{3s}e_q^2$$

$$\sigma(q\bar{q} \to l^+l^-) = \frac{4\pi\alpha^2}{3\times 3s}e_q^2$$

Monte Carlo approach

- simulate explicitly parton radiation with evolution of parton densities
- advantage to include properly energy momentum conservation in each step
- perform resummation numerically



Jet production in pp

- x-section (i.e. for light and heavy quarks ($t\bar{t}$) production)

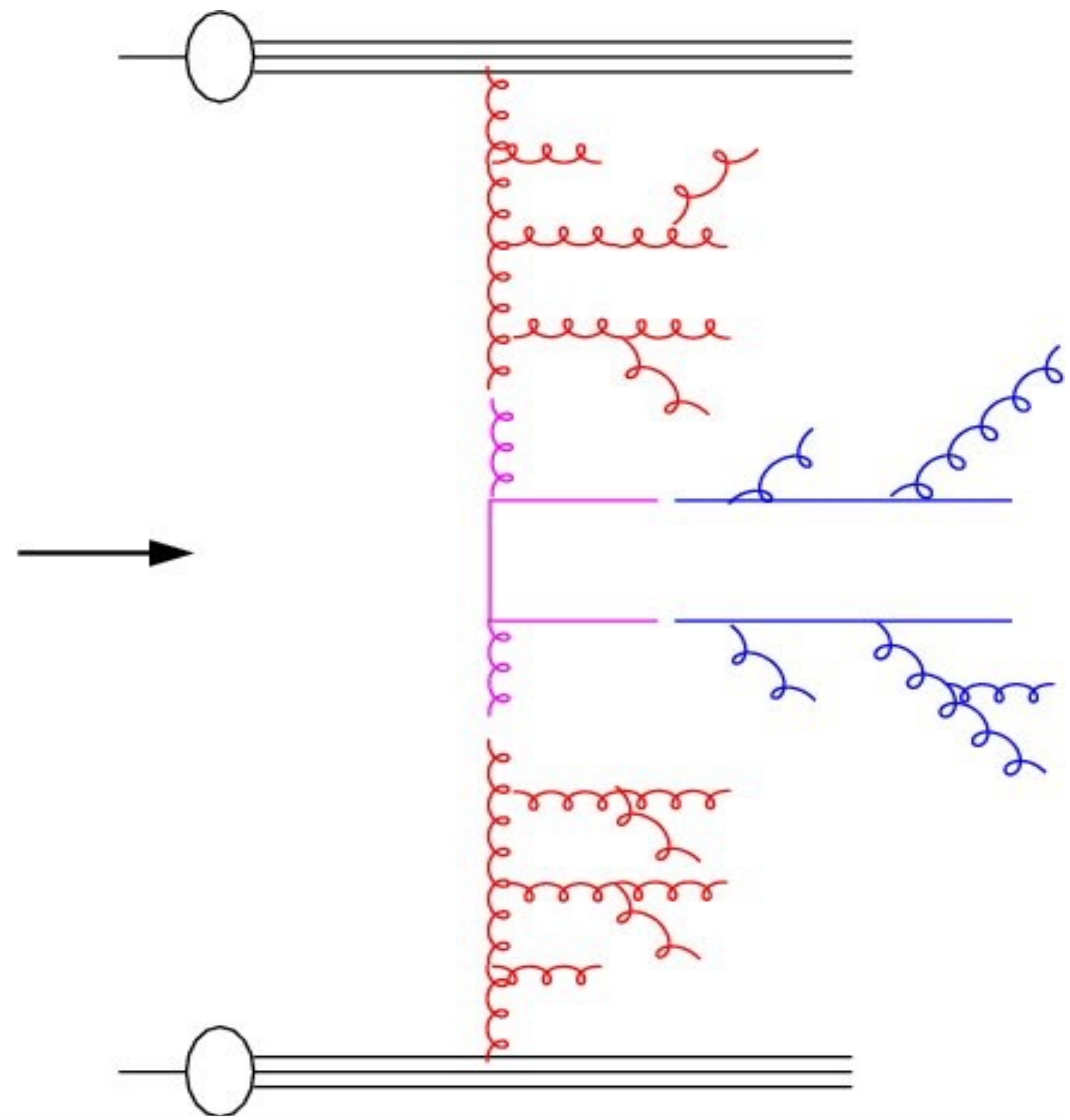
$$\sigma(\mathrm{pp} \to \mathrm{q\bar{q}X}) \quad = \quad \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} x_1 G(x_1,\bar{q}) x_2 G(x_2,\bar{q}) \times \hat{\sigma}(\hat{s},\bar{q})$$

- with gluon densities

$$xG(x,\bar{q})$$

- hard x-section:

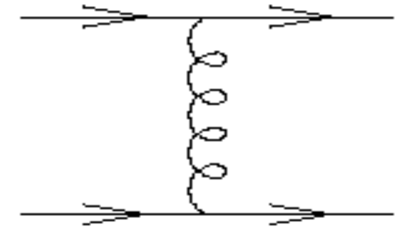
$$\frac{d\sigma}{dt} = \frac{1}{64\hat{s}^2}|M_{ij}|^2$$



Lowest Order Diagrams

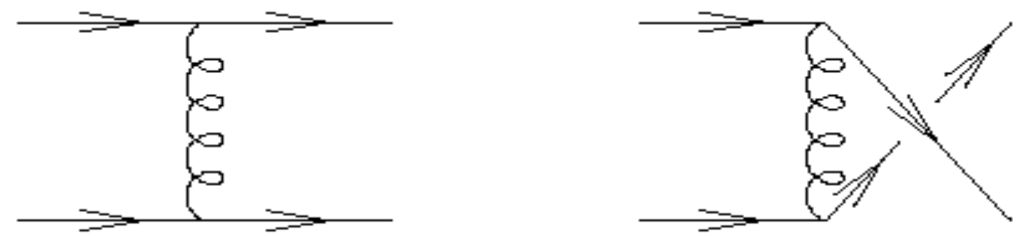
Ellis, Stirling, Webber
QCD & collider physics p248

$qq' \to qq'$



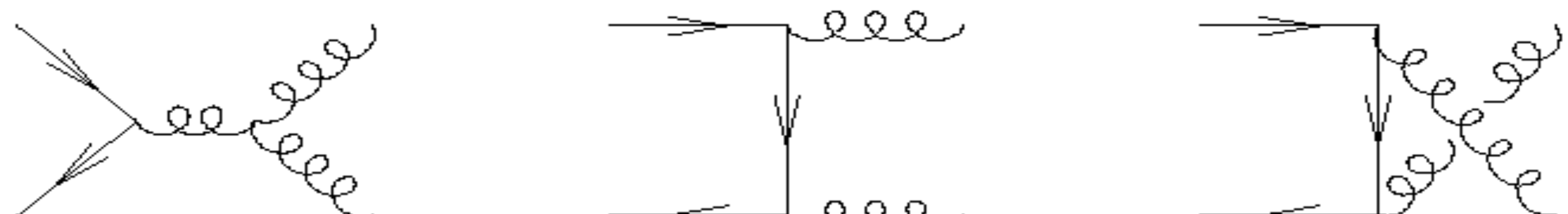
(a)

$qq \to qq$



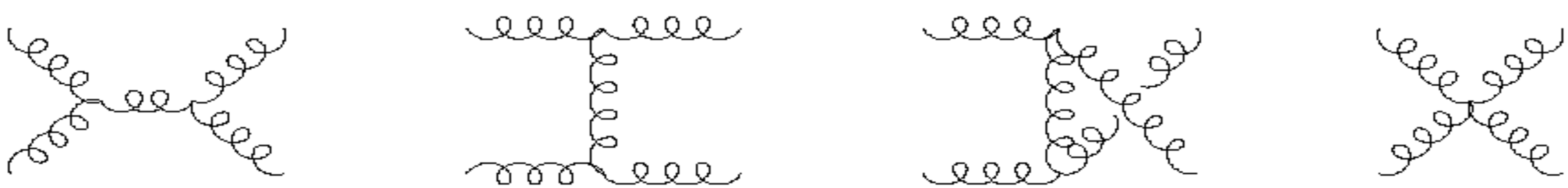
(b)

$q\bar{q} \to gg$



(c)

$gg \to gg$

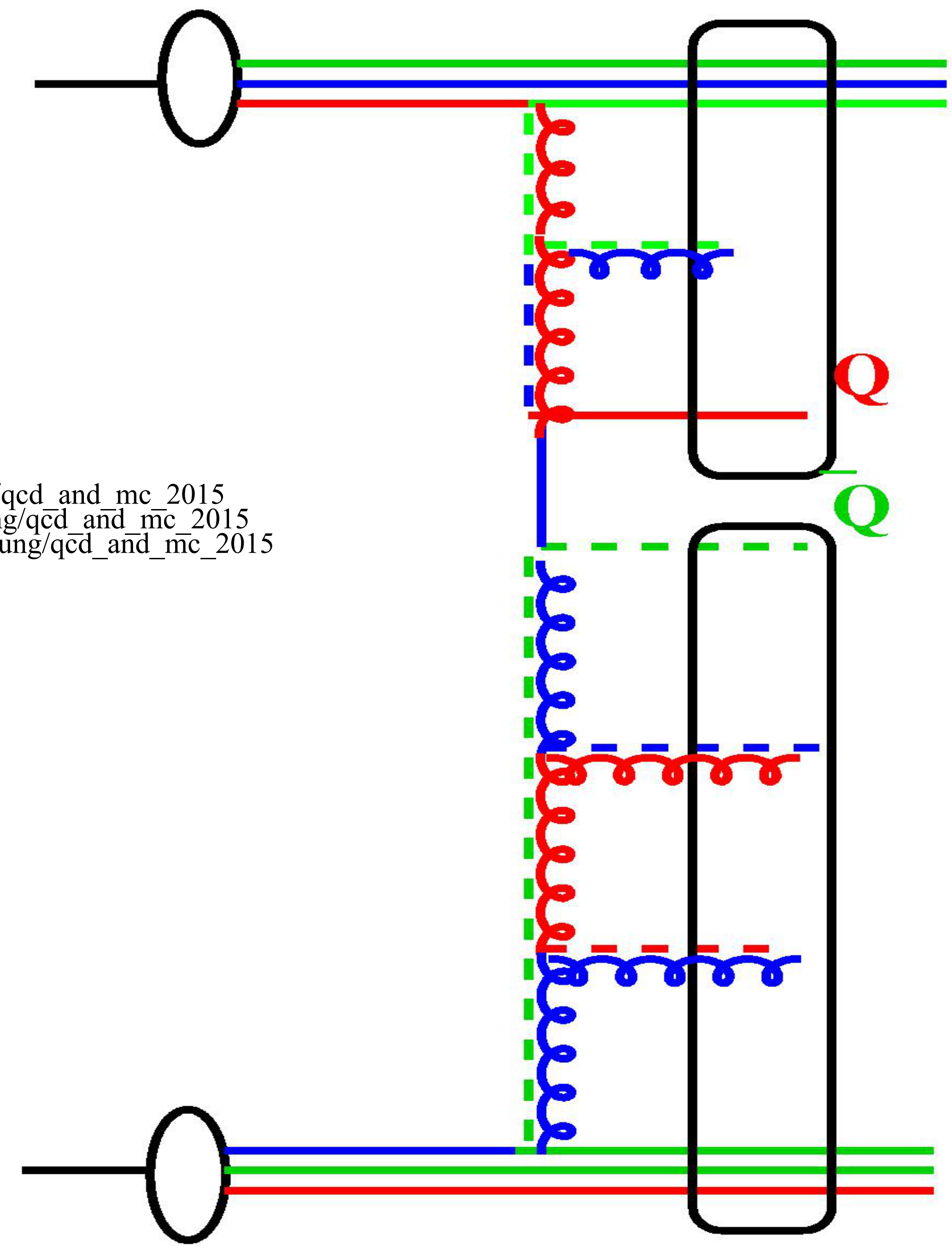


(d)

Color Flow in pp

- quarks carry color
- anti-quarks carry anti-color
- gluons carry color – anti-color
    - connect to color singlet systems
    - watch out pp or $p\bar{p}$

$$pp \to q\bar{q} + X$$



http://www.desy.de/~jung/qcd_and_mc_2015
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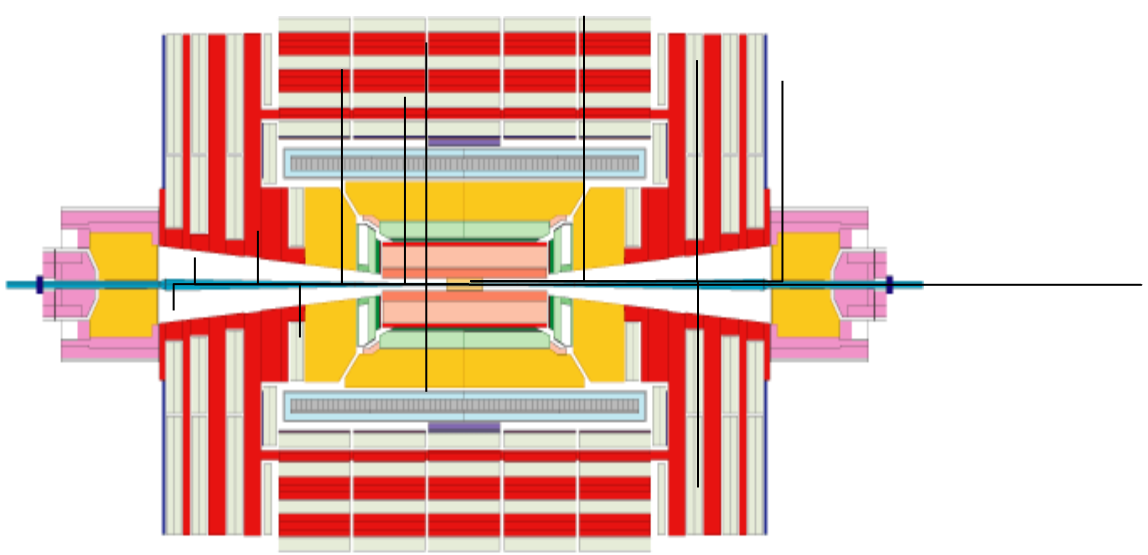
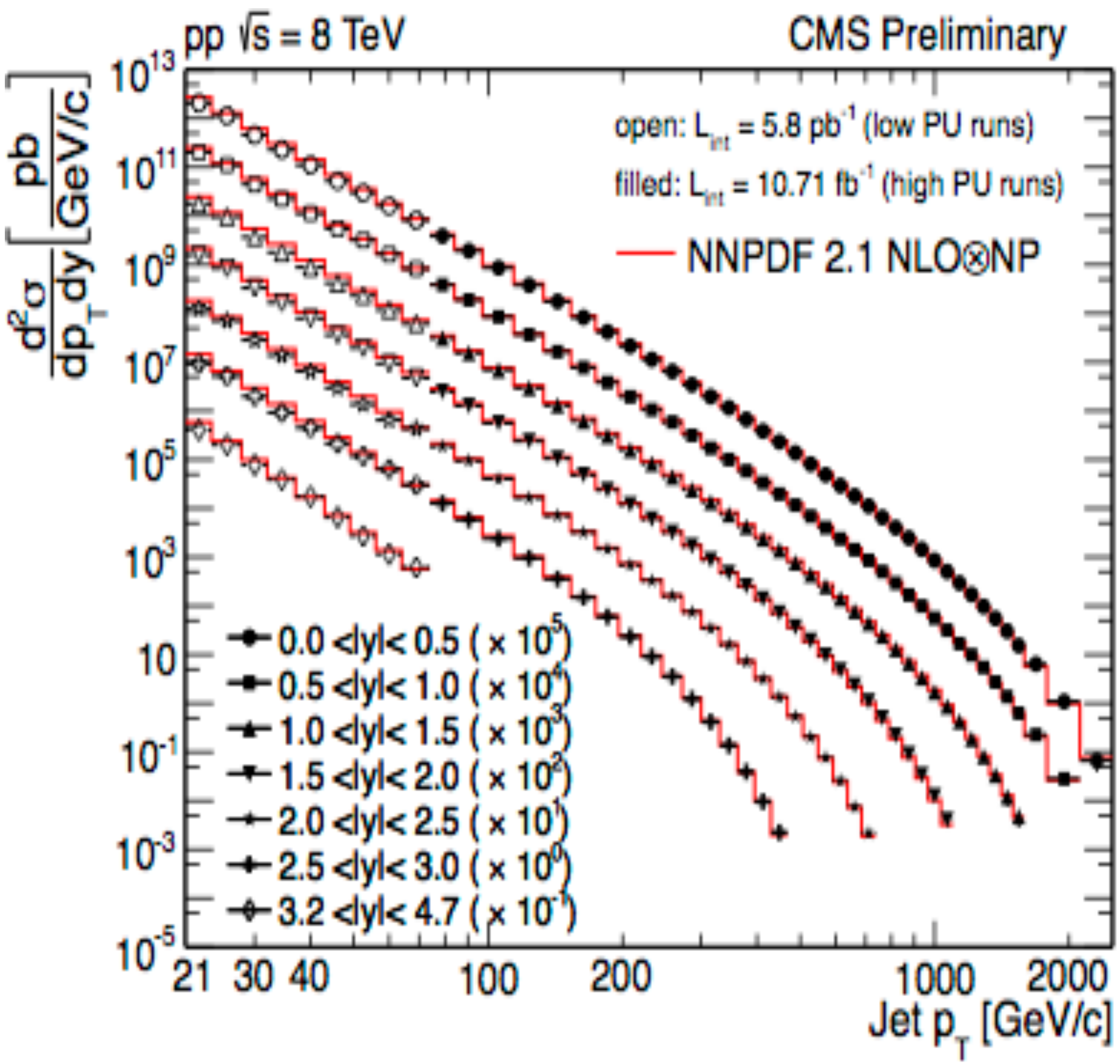
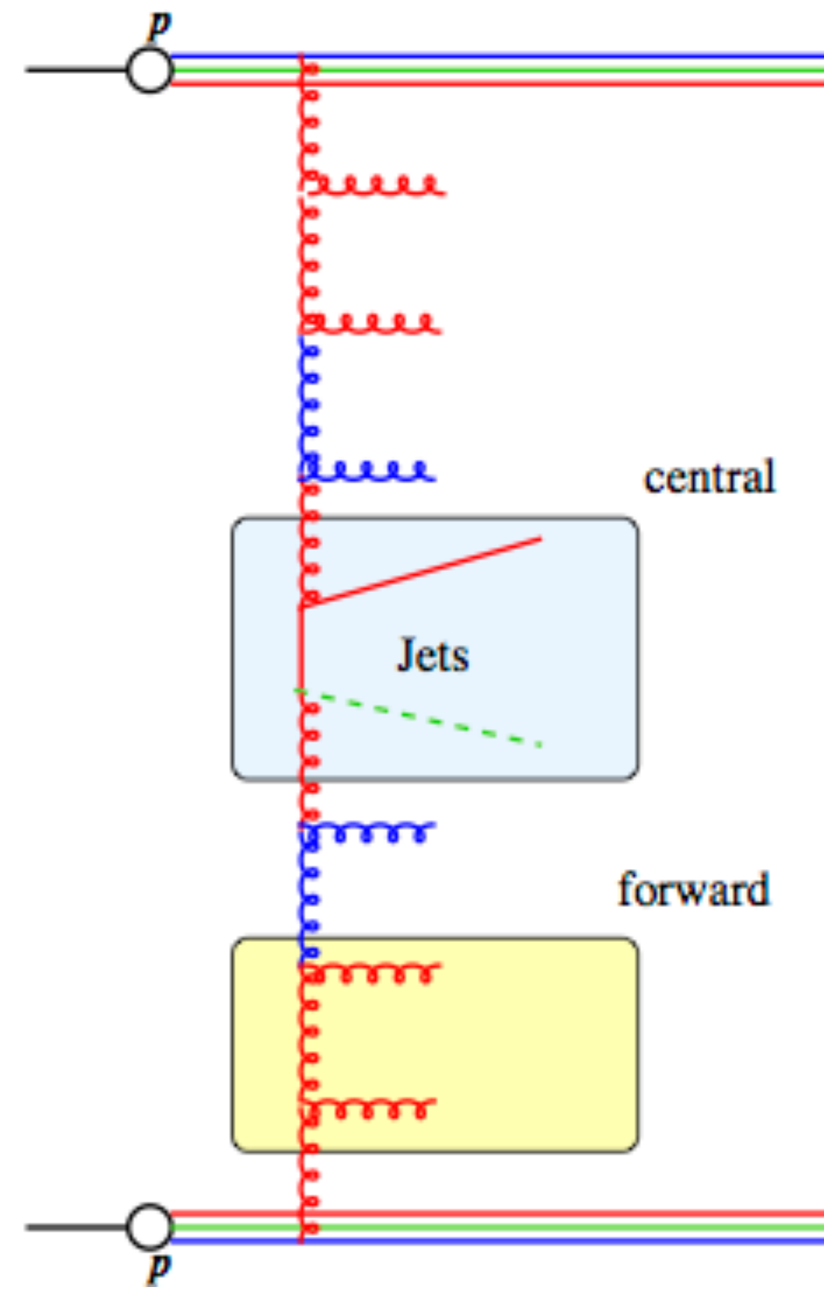


Jet production at the LHC



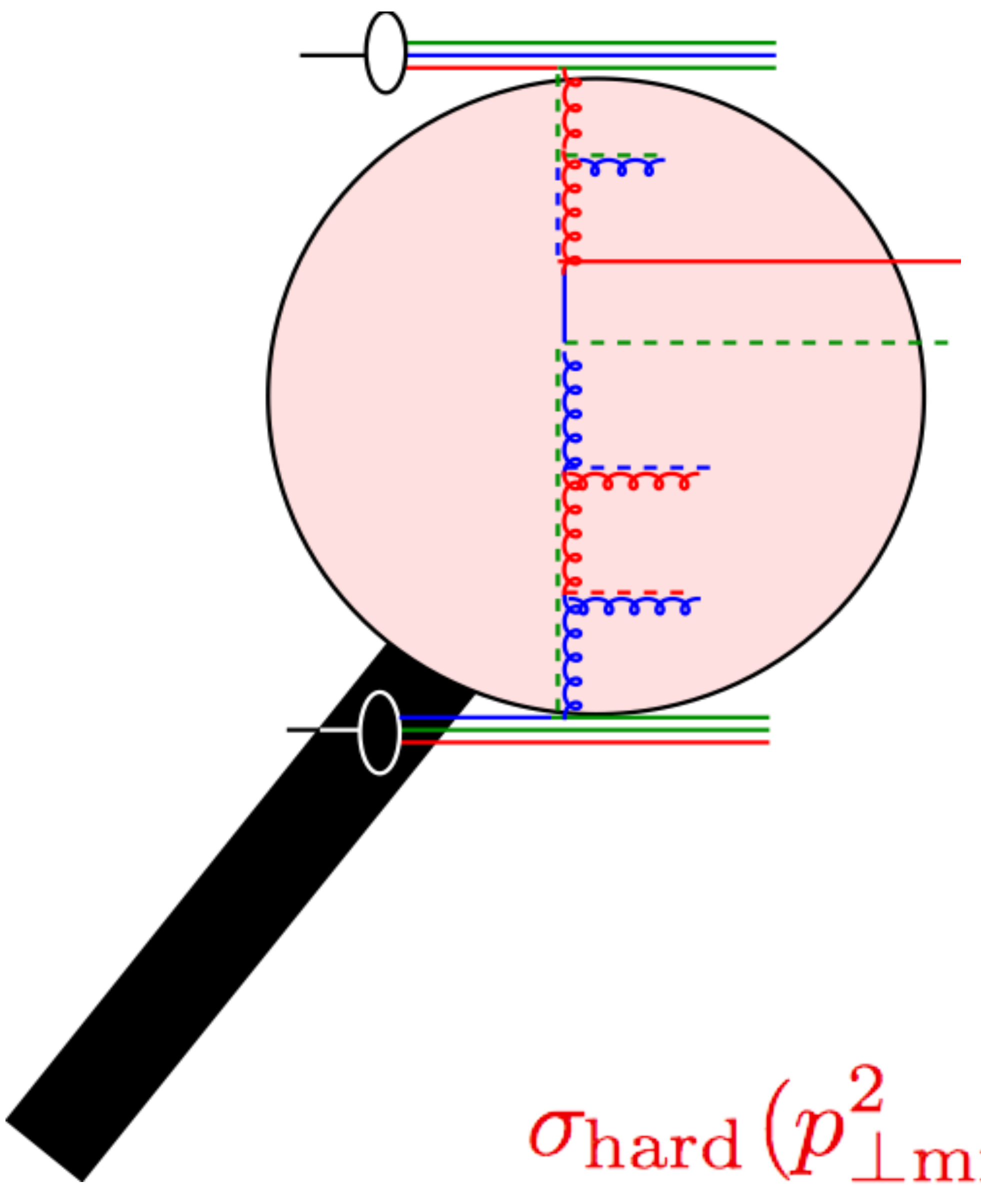


What happens at highest energies ?

High energy behavior of xsections

Partonic Cross sections

- Cross section $\sigma(p_1 + p_2 \to j_1 + j_2 + X) = f(x_1, \mu^2) \otimes \hat{\sigma}(x_1 p_1 + x_2 p_2 \to j_1 + j_2) \otimes f(x_2, \mu^2)$



- partonic cross section diverges with $p_\perp$
- calculate x-section as function of $p_{\perp,\min}$

$$\sigma_{\rm hard}(p^2_{\perp\min}) = \int_{p^2_{\perp\min}} \frac{d\sigma_{\rm hard}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

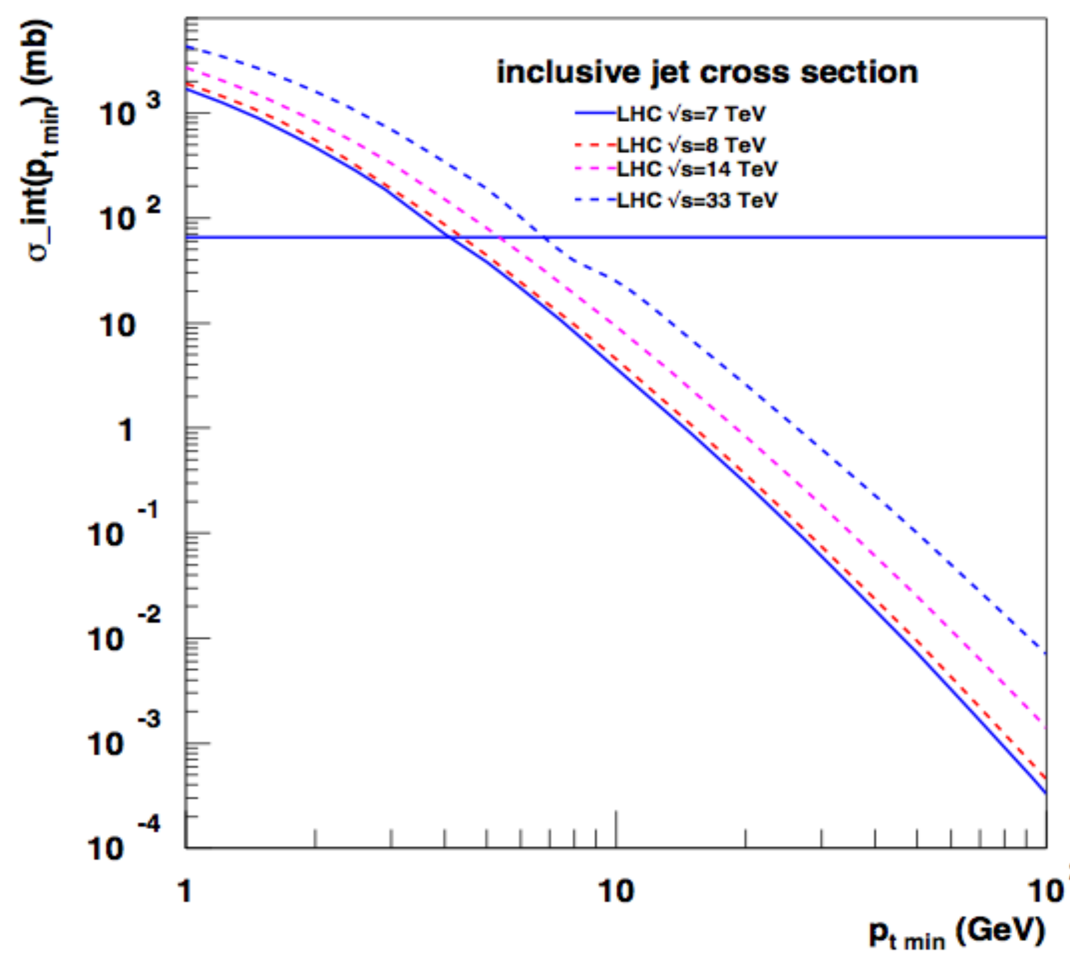
Partonic Cross Section

- Basic partonic perturbative cross section

$$\sigma_{\text{hard}}(p^2_{\perp\text{min}}) = \int_{p^2_{\perp\text{min}}} \frac{d\sigma_{\text{hard}}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

diverges faster than $1/p^2_{\perp,min}$ as $p_{\perp,min}$ and exceeds eventually total inelastic (non-diffractive) cross section

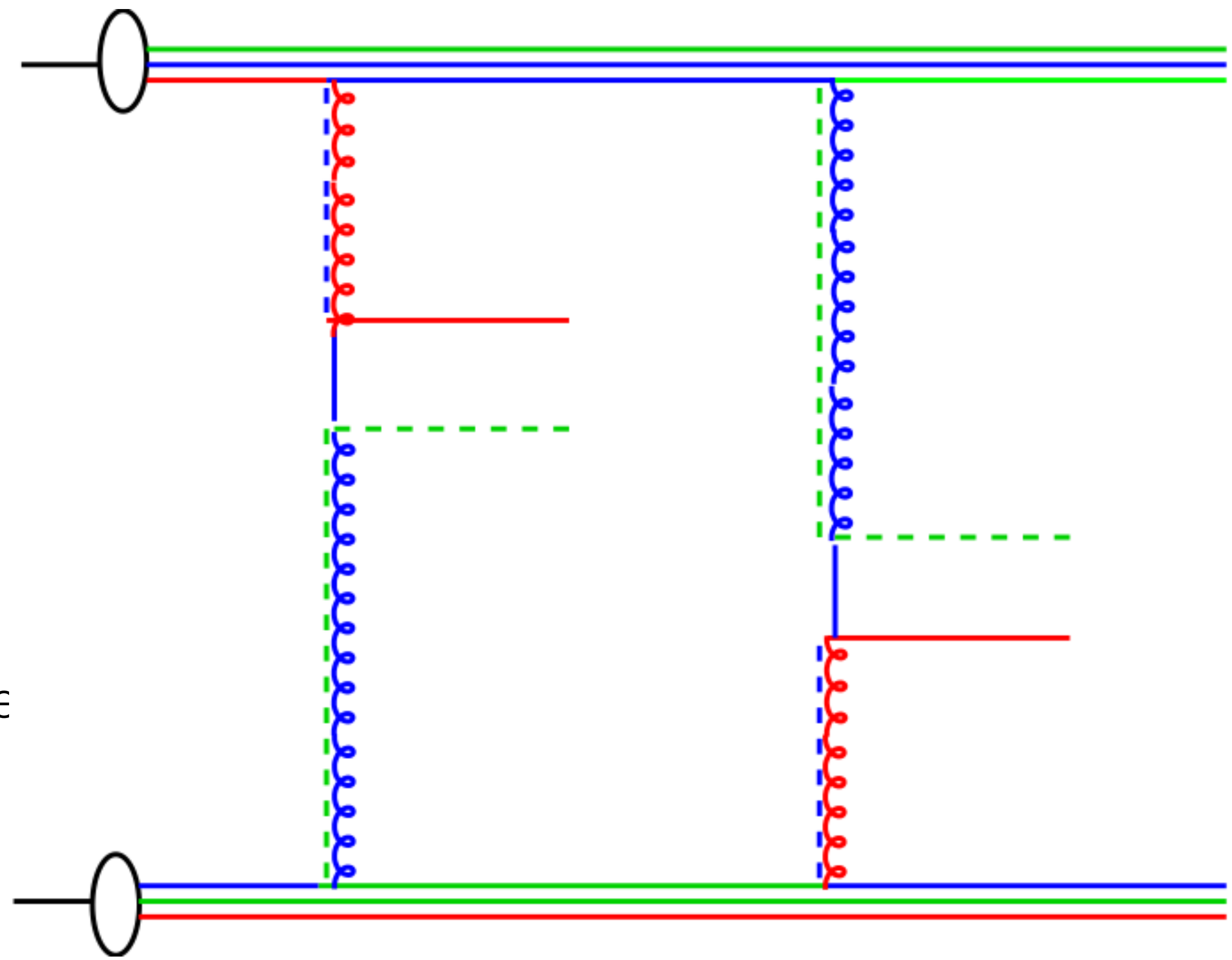
- Interaction x-section exceeds total xsection
- happens well above λ_{QCD}
- in perturbative region



Models for Multi-Parton Interaction

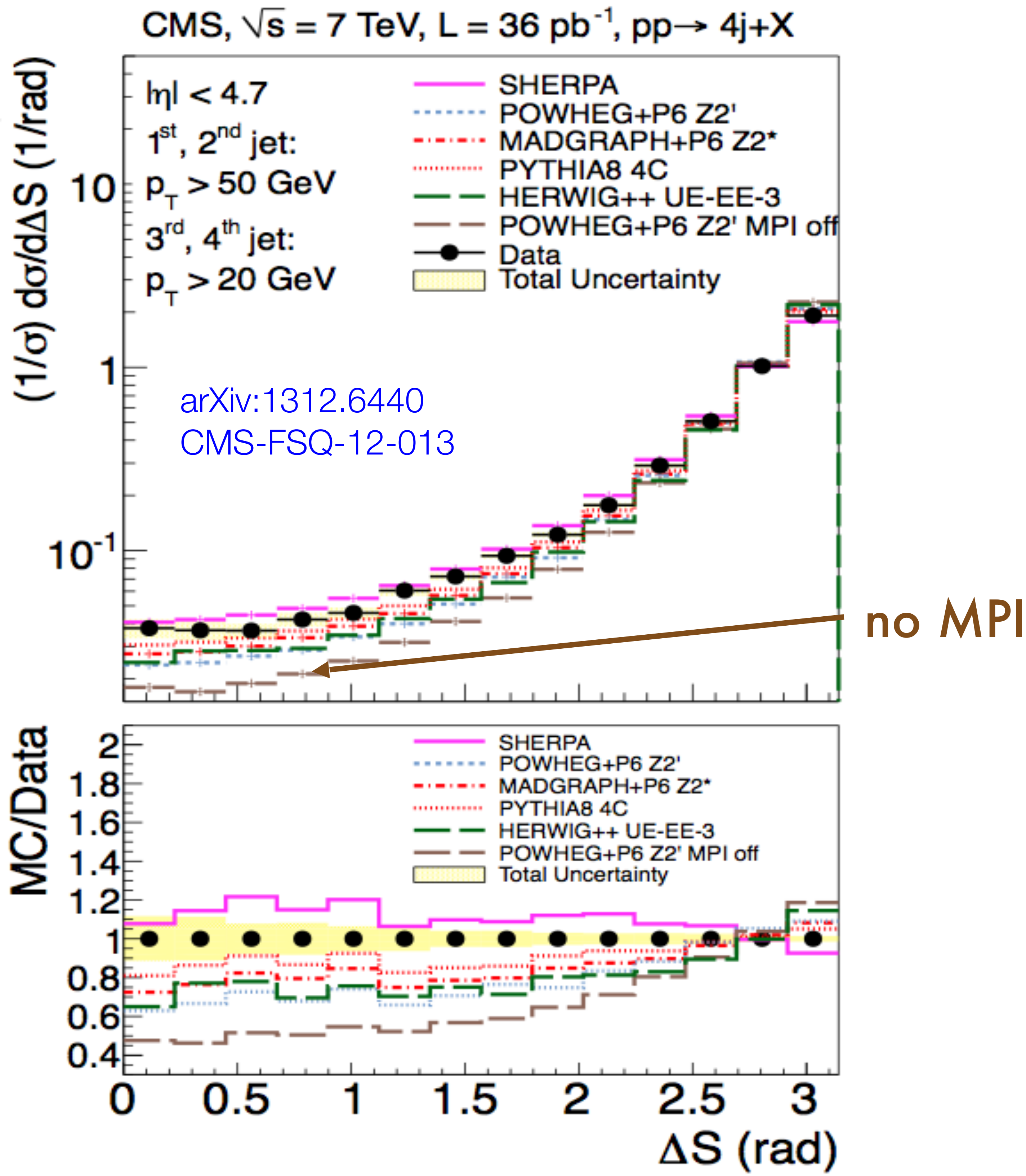
- The very simple model
  - ➔ add secondary interactions
  - ➔ first model by: T. Sjostrand, M. Zijl PRD (1987) 2019
- order scatterings in p_t
  - ➔ use of sudakov form factor
  - ➔ result in Poisson distribution of numbe of scatterings:

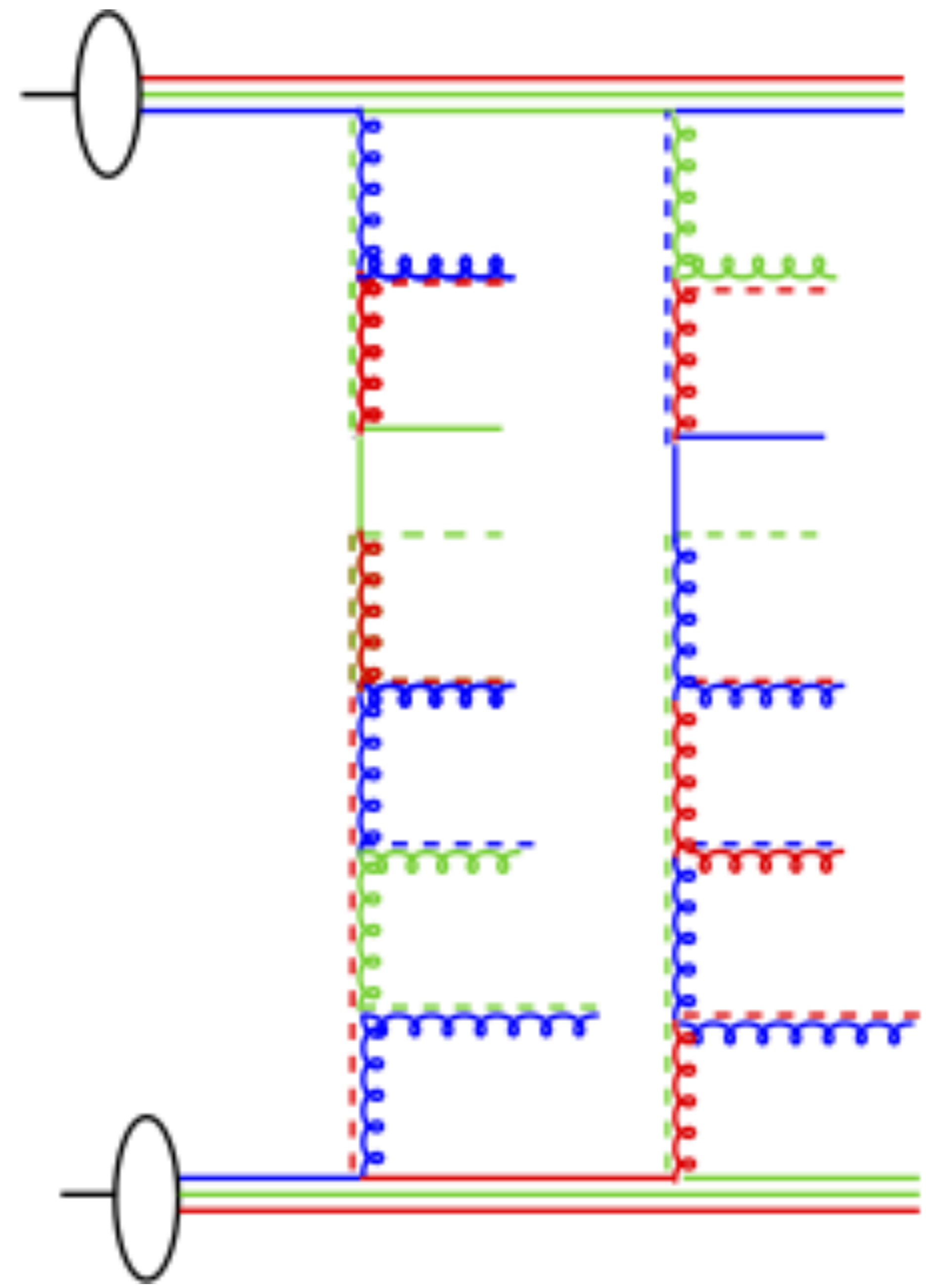
with $$p_r = \frac{\mu^r}{r!} \exp\left(-\mu\right)$$



$$\mu = \langle n \rangle = \frac{1}{\sigma_{nd}} \int_{p_{\perp \min}}^{p_{\perp \max}} \frac{d\sigma_{\text{hard}}}{dp'_{\perp}} dp'_{\perp}$$

Multiparton interaction at the LHC





Partonic Cross Section

- Basic partonic perturbative cross section

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diverges faster than $1/p^2_{\perp,\text{min}}$ as $p_{\perp,\text{min}}$ and exceeds eventually total inelastic (non-diffractive) cross section

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