FYSH560, spring 2011

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Office: FL249. No fixed reception hours.

kl 2011

Dates, times

- Lectures: Mon, Wed at 12h15, FYS2
- Excercises: Wed at 10h15, FL140 (downstairs)
  - Questions handed out Wed, **Return Tuesday by 14 o'clock to T.L.'s mailbox (next to copy machine on 2nd floor corridor)**

Changes to previously announced

- No lecture Wed March 2nd (T.L. at workshop) — replacement ?

Passing the course:

- Exercises: 40% of grade
- Exam: 60% of grade

Change in exercise time?

Suggestions?

	ma	ti	ke	to	pe
8 – 10					
10 – 12	astro	ydin	astro, harj?	ydin	
12 – 14	luento	suht. t.	luento	suht. t.	
14 – 16	materiaali	qft/QMII	materiaali	qft/QMII	

Literature, main sources

These slides and handwritten, scanned, lecture notes will be available on the course web page (link from Korppi)

Especially beginning of the course will loosely follow the books:

- V. Barone and E. Predazzi, High-Energy Particle Diffraction (Springer 2002) **should become available in FYS4, otherwise will have scans/copies**
- J. R. Forshaw and D. A. Ross, Quantum Chromodynamics and the Pomeron (Cambridge 1997) **available in FYS4**

Literature, review articles

- E. Iancu and R. Venugopalan, "The color glass condensate and high energy scattering in QCD," arXiv:hep-ph/0303204.
- F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, "The Color Glass Condensate," arXiv:1002.0333 [hep-ph].
- F. Gelis, T. Lappi and R. Venugopalan, "High energy scattering in Quantum Chromodynamics," Int. J. Mod. Phys. E **16** (2007) 2595 [arXiv:0708.0047 [hep-ph]].
- S. J. Brodsky, H. C. Pauli and S. S. Pinsky, "Quantum Chromodynamics and Other Field Theories on the Light Cone," Phys. Rept. **301** (1998) 299 [arXiv:hep-ph/9705477].
- C. Marquet, "Chromodynamique quantique à haute énergie, théorie et phénoménologie appliqué aux collisions de hadrons," PhD thesis, in French, http://tel.archives-ouvertes.fr/tel-00096416/fr/

Contents

This course has never been lectured before, no canonical content.
Will hopefully **not** be calculationally intensive.

Contents, outline

Tentative schedule, will be updated as we go along.

1. **Preliminaries** Collider experiments — partons, hadrons — cross section and scattering amplitude — chromodynamics — Feynman rules (L1)
2. **High energy kinematics** classical optics — eikonal scattering — eikonal vertex — the relativistic S-matrix — optical theorem (L2-3), [BP chap 2]
3. **Pre-QCD models** (L4) [FR chap. 1]
4. **The QCD pomeron** (L5-6), [BP chap 8, FR chap 3& 4]
5. **DIS at low *x*** (L7), [BP chap 9, FR chap 6]
6. **Light front quantization** (L8) [Brodsky review]
7. **Diffraction** (L9), [BP chap 10]
8. **Gluon radiation** (L10-11)
9. **Color Glass Condensate** (L12-13)

Detailed contents, present plan

1. **Preliminaries** Collider experiments — partons, hadrons — cross section — Feynman rules — chromodynamics (L1)
2. **High energy kinematics** classical optics — eikonal scattering — eikonal vertex — the relativistic S-matrix — optical theorem (L2-3), [BP chap 2]
3. **Pre-QCD models** analyticity, unitarity — Regge trajectories — the pomeron (L4), [FR chap. 1]
4. **The QCD pomeron** scattering via 2-gluon exchange — the Lipatov vertex — ladder diagrams (L5-6), [BP chap 8]
5. **DIS at low** $\boldsymbol{x}$ Infinite momentum frame vs. dipole frame — dipole scattering (L7), [BP chap 9]
6. **Light front** coordinates — quantization — virtual photon wave function (L8)
7. **Diffraction** Diffractive DIS — diffraction in pp — DDIS as elastic dipole scattering — Good-Walker (L9), [BP chap 10]
8. **Gluon radiation** idea of RGE — DGLAP — BK (L10-11)
9. **Color Glass Condensate** Timescales — effective theory — DIS on classical color field — gluon production in AA, glasma (L12-13)

High energy collider experiments

$\sqrt{s}$

Total collision energy s

- Fixed target $s = ((m, \mathbf{0}) + (|\mathbf{k}|, \mathbf{k}))^2 \approx 2m|\mathbf{k}|$
- Collider $s = ((|\mathbf{k_1}|, \mathbf{k_1}) + (|\mathbf{k_2}|, \mathbf{k_2}))^2 \approx 4|\mathbf{k_1}||\mathbf{k_2}|$

(We assume $m = 0$ whenever possible)

Assuming $|\mathbf{k}| \sim \$$ this means $\$ \sim s$ (fixed target), $\$ \sim \sqrt{s}$ (collider)

This is a course on **high** s. What are the experiments?

Hadronic

- CERN SPS (Super Proton Synchrotron), 1976 –
  - $p\bar{p}$ collider $\sqrt{s} = 630\text{GeV} \Longrightarrow 900\text{GeV}$
  - p, A-fixed target
  - p injector for LHC at 450GeV
  - Experiments: **UA1, UA2**, ... UA9, NAxx, WAxx
- Tevatron: 1983-2010 (?) $p\bar{p}$ @ $\sqrt{s} \approx 1000\text{GeV} \Longrightarrow 1960\text{GeV}$
- RHIC:
  - pp @ $\sqrt{s} = 500\text{GeV}$ (even more, not politically correct)
  - $AuAu$ @ $\sqrt{s} = 200A\text{GeV}$
- LHC: 2010 —
  - pp @ $\sqrt{s} = 7\text{TeV} \Longrightarrow 14\text{TeV}$
  - $AuAu$ @ $\sqrt{s} = 2.76A\text{TeV} \Longrightarrow 5.5\text{TeV}$

With leptons

Lepton-lepton (less important for this course)

- SLAC SLD: e^+e^- @ $\sqrt{s} = 90\text{GeV}$
- LEP: 1989-2000: e^+e^- @ $\sqrt{s} = 91\text{GeV} \Longrightarrow 209\text{GeV}$
- ILC $\sqrt{s} \sim$ TeV?

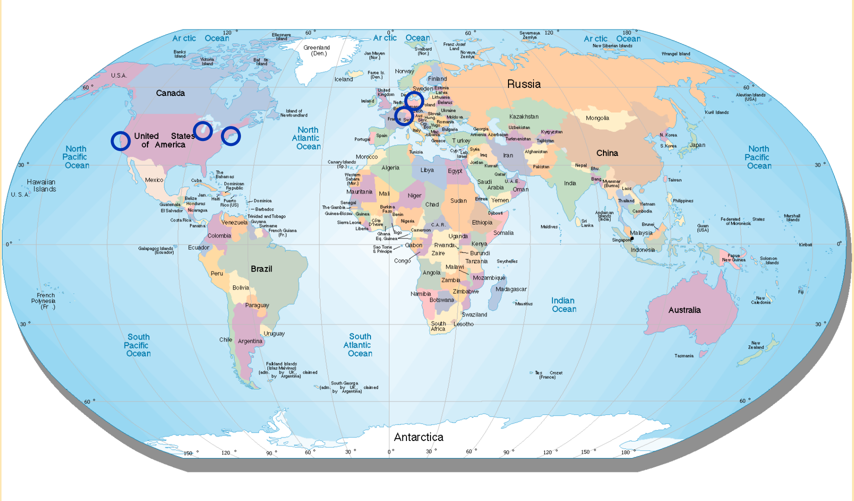
Lepton-proton/hadron **DIS**

- Fixed target, highest energy $2\sqrt{1\text{GeV} \times 465\text{GeV}} = 30\text{GeV}$ at Fermilab muon beam.
- HERA, final $\sim 30\text{GeV}$ on $\sim 900\text{GeV} \Longrightarrow \sqrt{s} \sim 320\text{GeV}$

Future:

- EIC
  - Electron to collide with RHIC p/A beam 30GeV on 100AGeV / 250GeV $\Longrightarrow \sqrt{s} \approx 100A\text{GeV}/\ 170\text{GeV}$
  - p/A beam to collide with JLab 12GeV e^- beam.
- LHeC
  - electron 80GeV? to collide with LHC. $\sqrt{s_{pe}} = 1.5\text{TeV}$

Is there a next one?



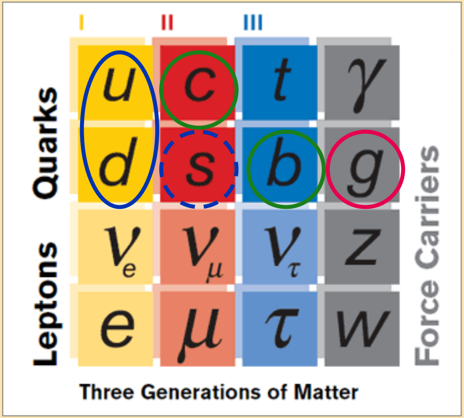
$\sqrt{s} > 50$GeV colliders

Is there a next one?

Still doing HE physics

Partons and hadrons

Elementary particles



In this course

- Light quarks
- Heavy quarks
- gluons

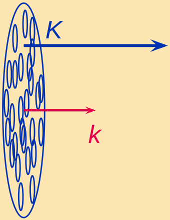
Other hadrons

Mesons $q\bar{q}$ Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

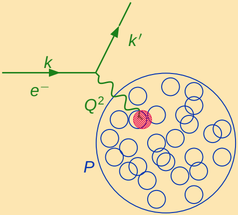
Partons, IMF

Inifinite **M**omentum **F**rame:



J.D. Bjorken: Hadrons consist of pointlike constituents: “partons”.

- Longit. momentum fraction x: $k = xK$
- Transverse momentum p_T or Q



Seen in **D**eep **I**nelastic **S**cattering

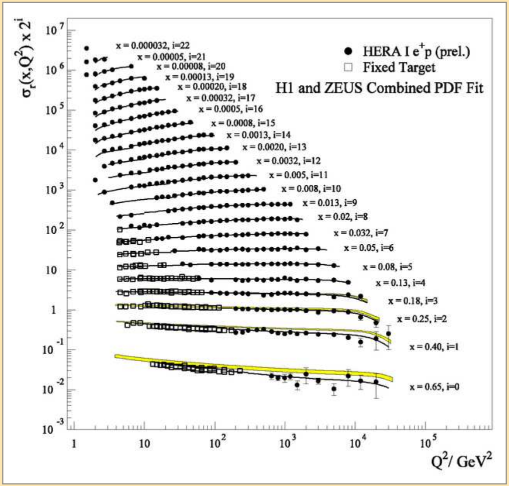
$$Q^2 = -(k-k')^2 = -q^2$$
$$x = \frac{Q^2}{2P\cdot(k-k')}$$

Bj scaling:

Q^2-dependence is just like for a point-like particle.
Later: partons are quarks and gluons; small deviations from scaling.

Success of partonic picture

Bjorken scaling in inclusive (*ep* →anything) DIS cross section:



- Lines horizontal: free partons.
- Small deviations: understood in pQCD (perturbative QCD)

Not everything is so simple

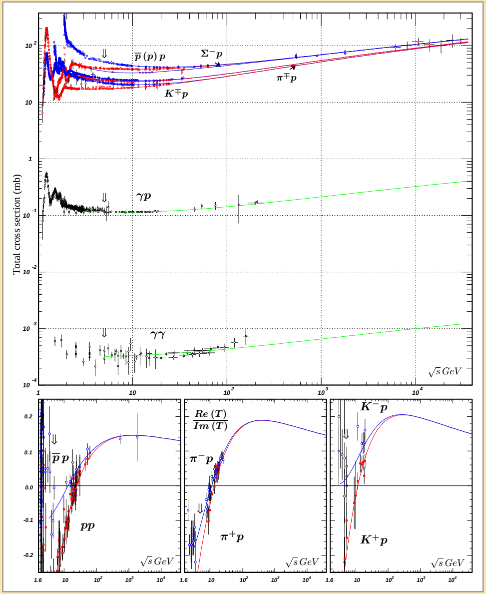
Total cross section not calculated from QCD!

(Why is $\gamma\gamma$ on same plot? We will learn that γ is a hadron ...)

$$\frac{\mathrm{Re}(T)}{\mathrm{Im}(T)}$$

matters in this course.

(T = scattering amplitude.)



Next

Review basic contents from particle physics course:

- Cross section and scattering amplitude
- Feynman rules and diagrams
- QCD Lagrangian, color
- Light cone, rapidity variables