Full acceptance physics at the LHC

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- Motivation
- Detector Considerations
- FELIX at the LHC
- Primary Physics Menu

Invited talk, presented by Karsten Eggert, at
DIS98
Brussels, April 4-8, 1998

Motivation for a full acceptance detector

- Complete studies of forward physics at hadron colliders have never been done, neither the ISR, nor the SPS, nor the Tevatron have been instrumented with a real full acceptance detector.
- A full acceptance (neutrals and charged) detector at a hadron collider (e.g. LHC) must be optimized for both, hard and soft QCD processes, in pp, pA and AA collisions.
- Such an ultimate QCD detector has to focus on QCD phenomena which are hard/impossible to study with the other LHC experiments

  Hadron structure (longitudinal and transverse) down to very low x-values ($x \sim 10^{-6} - 10^{-7}$)

  QCD in the perturbative and <u>non - perturbative</u> region.

  Breakdown of the evolution-equation formalism and significant nonlinear effects are expected.

  Observation of a broad range od QCD phenomena: multiple sources for hadron collisions.

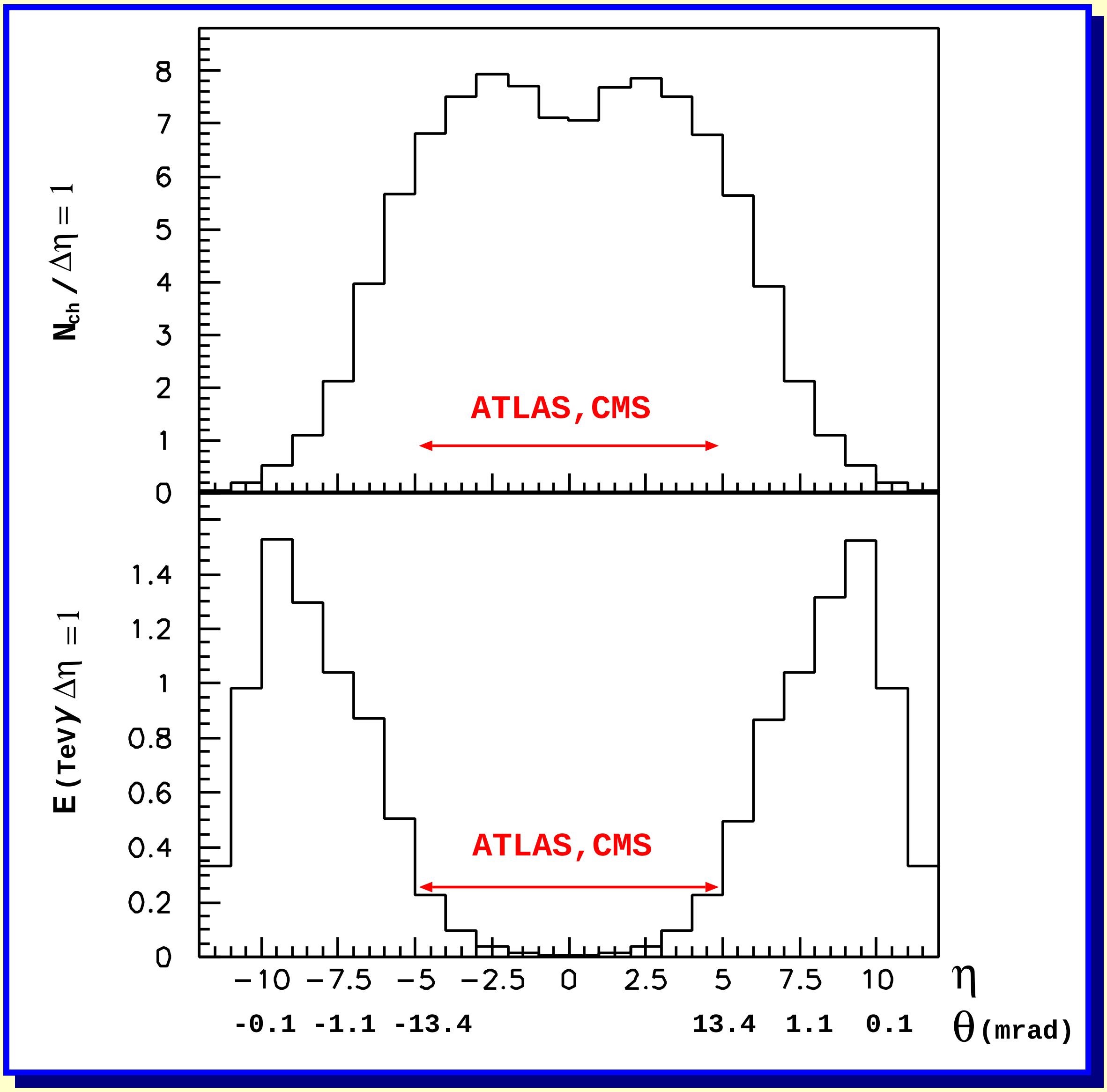
  No collider data in the forward regions, where cosmic ray experiments claim the existence of anomalies.

QCD detector program

- Strong interactions in a new domain of large parton densities due to fast growing $q(x, Q^2)$,$g(x, Q^2)$
- Large cross-sections for minijets
  sensitivity to correlations in nuclear wave functions
- Soft pp QCD: screening effects, possibility of a new phase, DCC? ...
- Hard diffraction, multijet production
  rapidity gaps in hard processes ("BFKL Pomeron")
- Elastic scattering
- pA program
  nuclear shadowing
  QCD effects for parton propagation in nuclei
  color transparency
- $\gamma\gamma$ collisions, using Ca-Ca and Pb-Pb collisions
  e.g. interations of two small objects
  onium-onium scattering
  ? ? ?

Particle- and Energy- Flow at the LHC ($\sqrt{s}$=14 TeV)

Inelastic and diffractive events



$$\eta = -\ln \mathrm{tg}\Theta/2 \qquad y = \tanh^{-1} p_L/E$$

$$E = m_\perp \cosh y \sim \frac{m_\perp}{2} e^y \ \text{ for } \ y \gg 1 \qquad m_\perp^2 = p_t^2 + m^2$$

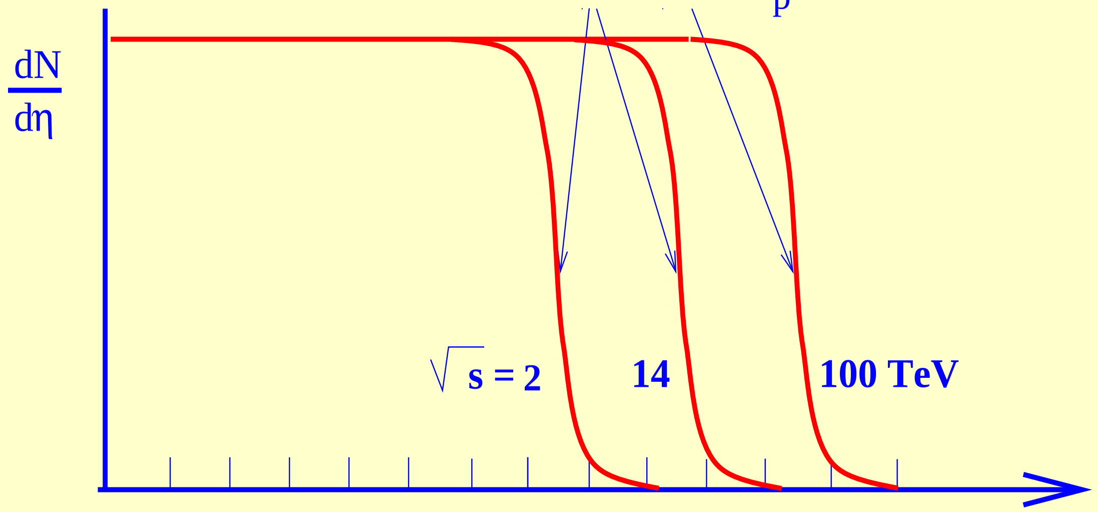
Fraction of total energy flow seen by:

- ATLAS, CMS $\sim$ 10%
- FELIX $\sim$ 100%

Principle forward detector considerations

Particle production

$$\eta_{max} \sim \ln \sqrt{s} / m_p$$



$\eta = -\ln \mathrm{tg}\, \theta/2$ 3 5 7 8 9 10 11 12 13 η

θ	100	10	1	0.1	0.01	0.001	mrad
$\langle p \rangle = \frac{0.5}{\theta}$ GeV	0.005	0.05	0.5	5	50		TeV
$L = \frac{r\ (=3\ \mathrm{cm})}{\theta}$	0.3	3	30	300	3000		m

Long straight sections ($\pm$ 100 m for LHC) with strong magnetic fields:

- to separate the beams for neutral detection
- to sweep forward particle out of the beam

$\Rightarrow$ machine QUADS far upstream

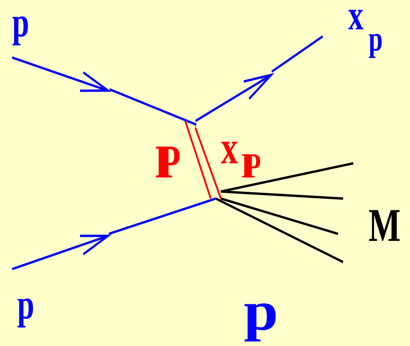
$\Rightarrow$ larger β-values, lower luminosity

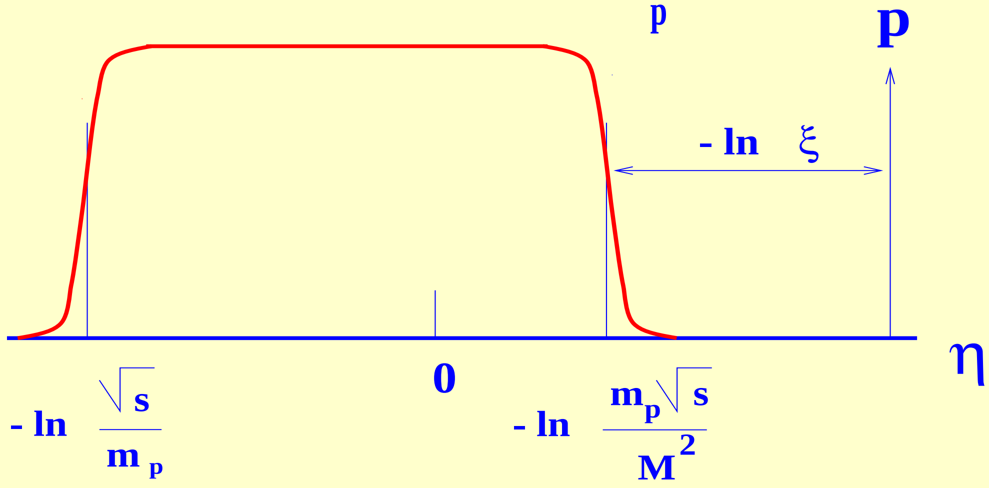
Incompatible with high luminosity-low β experiments

Principle forward detector considerations

Diffraction:

$$x_{I\!P} = 1 - x_p = \xi = \frac{M^2}{s}$$





$$\frac{d^2\sigma_{sd}}{d\xi dt} = \frac{A}{\xi} b e^{-bt}$$

$b \sim 10$ GeV^{-2}
$t \sim \theta^2 p^2$

(LHC) $\boxed{10^{-8} < \xi < 0.1}$ $\boxed{t > 0.1 \text{ GeV}^2}$

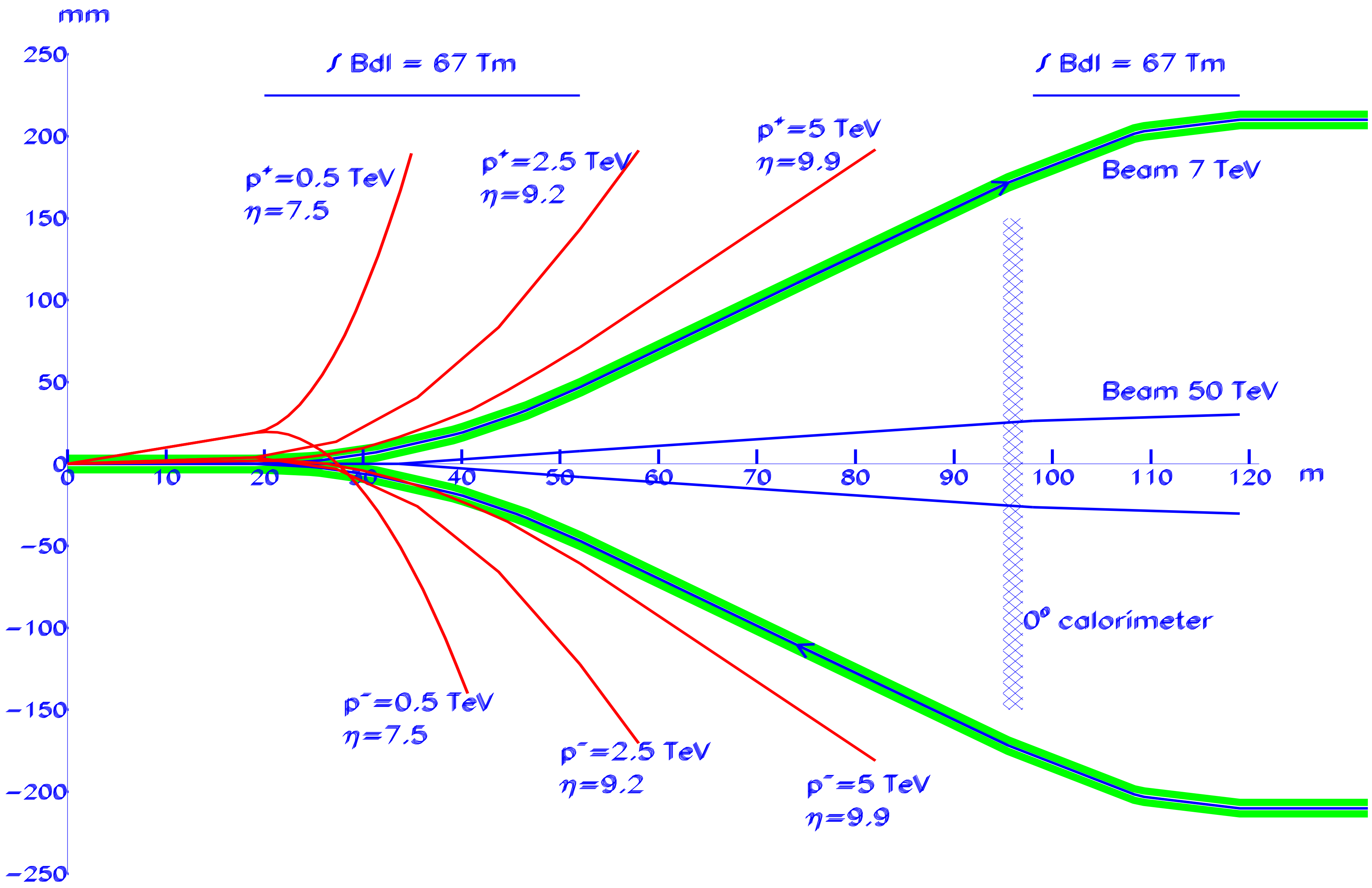
Elastic scattering: $$\frac{d\sigma}{dt} \sim e^{-2bt}$$

(LHC) $\boxed{10^{-2} < t < 10 - 20 \text{ GeV}^2}$

Detection of protons, close to beam momentum, with "Roman pots" far upstream (200-400 m).

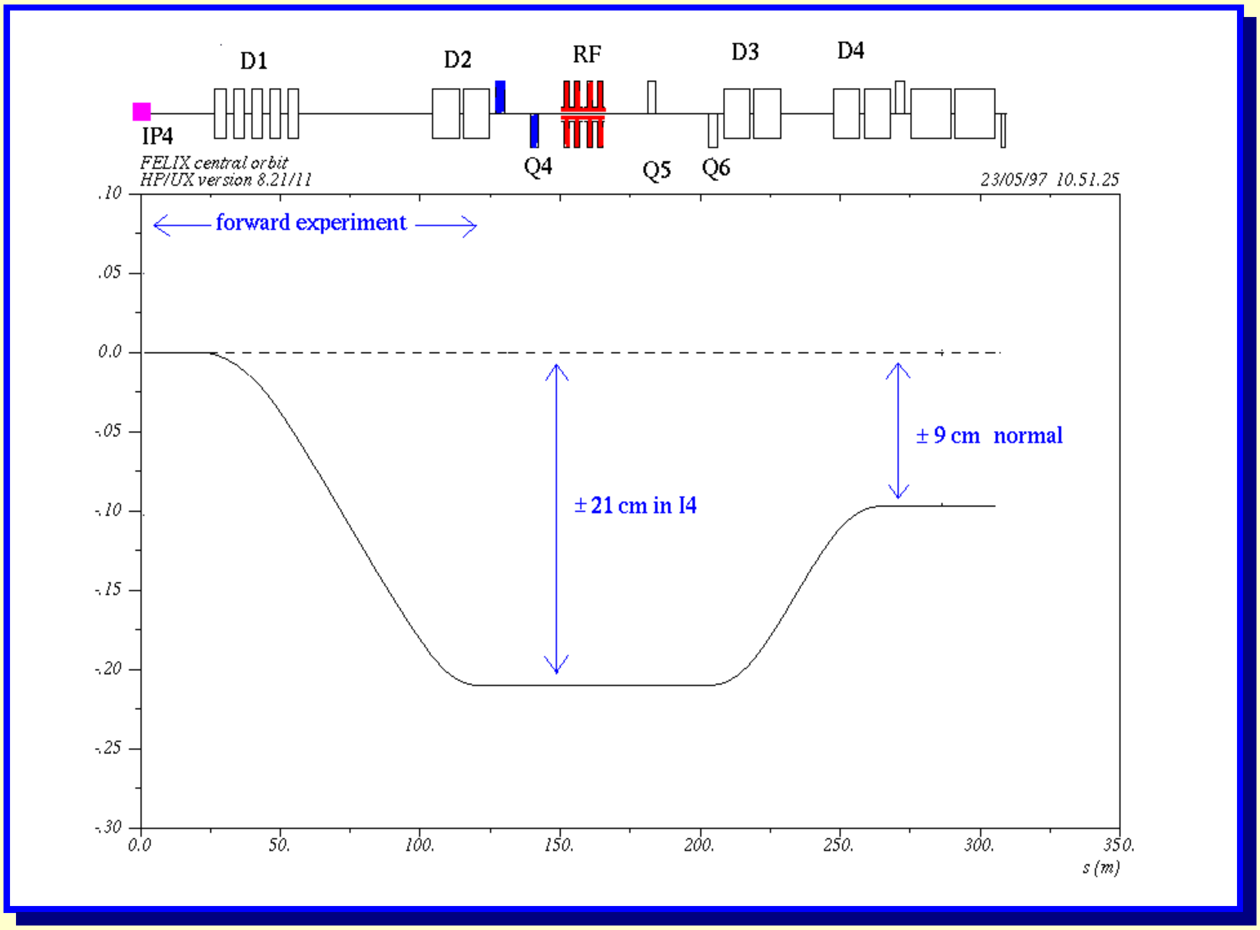
Compatible with high luminosity experiments

Principle forward detector considerations



Beam optics in I4 at the LHC

Integration of FELIX into the LHC lattice



- ✥ Low β QUADS are far away from the IP
- ⇒ Free space of 120 m to separate the beams and to install forward detectors
- ✥ Radiofrequency cavities for acceleration of each beam individually allow collisions of various ion species: p-Pb, p-Ca, Ca-Pb......

Luminosity for various particle beams

beam particles	$\sqrt{s}$/nucleon (TeV)	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2} sec^{-1})	β^* (m)	bunchstruct (nsec)	Run time (s/year)
$p\,p$	14	14	10^{29}	900	25	10^7
			10^{29-30}	110, 900	25	
			10^{31-32}	23, 110	25	
$Pb\,Pb$	5.5	1148	10^{26}	23	25, 125	10^6
$Ca\,Ca$	7	280	$4 \cdot 10^{30}$	23	25	10^5-10^6
$p\,Pb$	8.8	126	10^{30}	23	25, 125	10^5
$p\,Ca$	9.9	88	10^{31}	23	25	10^5

- LHC starts in 2005 : $\beta^* = 0.5$ m $\quad \mathcal{L} = 10^{30} - 10^{33}$ cm^{-2} sec^{-1}

  $I = \frac{1}{10} I_0,\ \varepsilon = \frac{1}{4}\varepsilon_0$

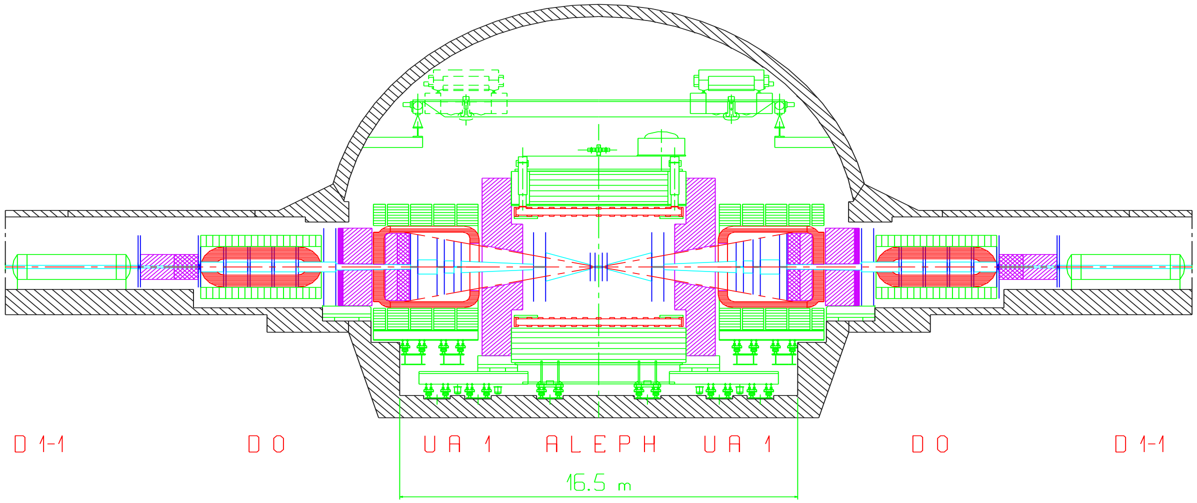
- β^*=900 m $\quad \mathcal{L} = 10^{27} - 10^{30}$ cm^{-2}sec^{-1}

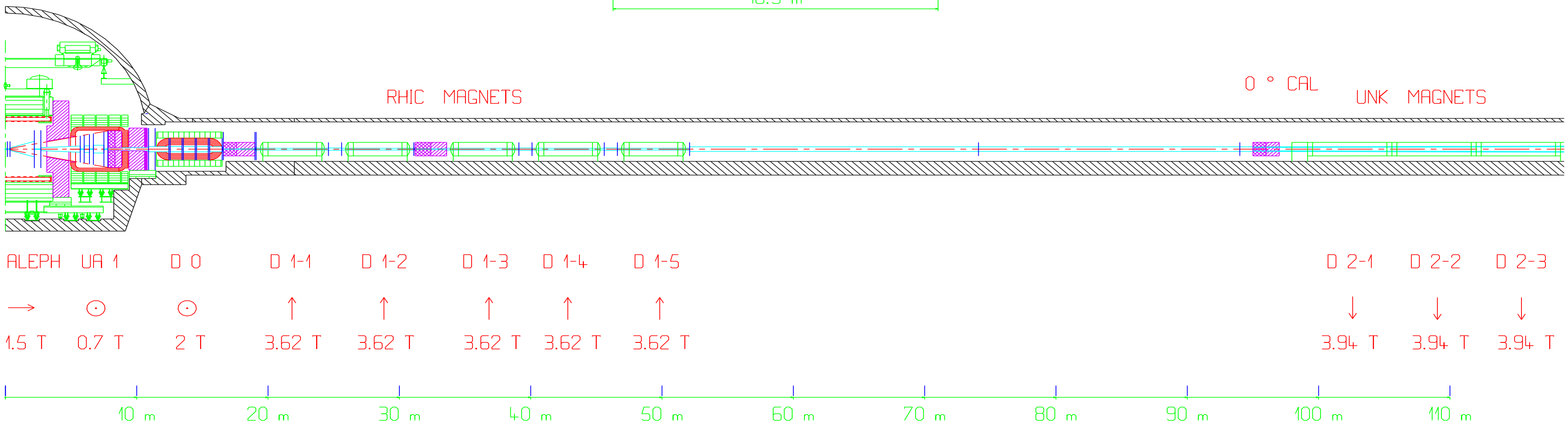
  elastic scattering, σ_{tot}, min. bias

- β^*=110 m, 23 m $\quad \mathcal{L} = 10^{31} - 10^{32}$ cm^{-2} sec^{-1}

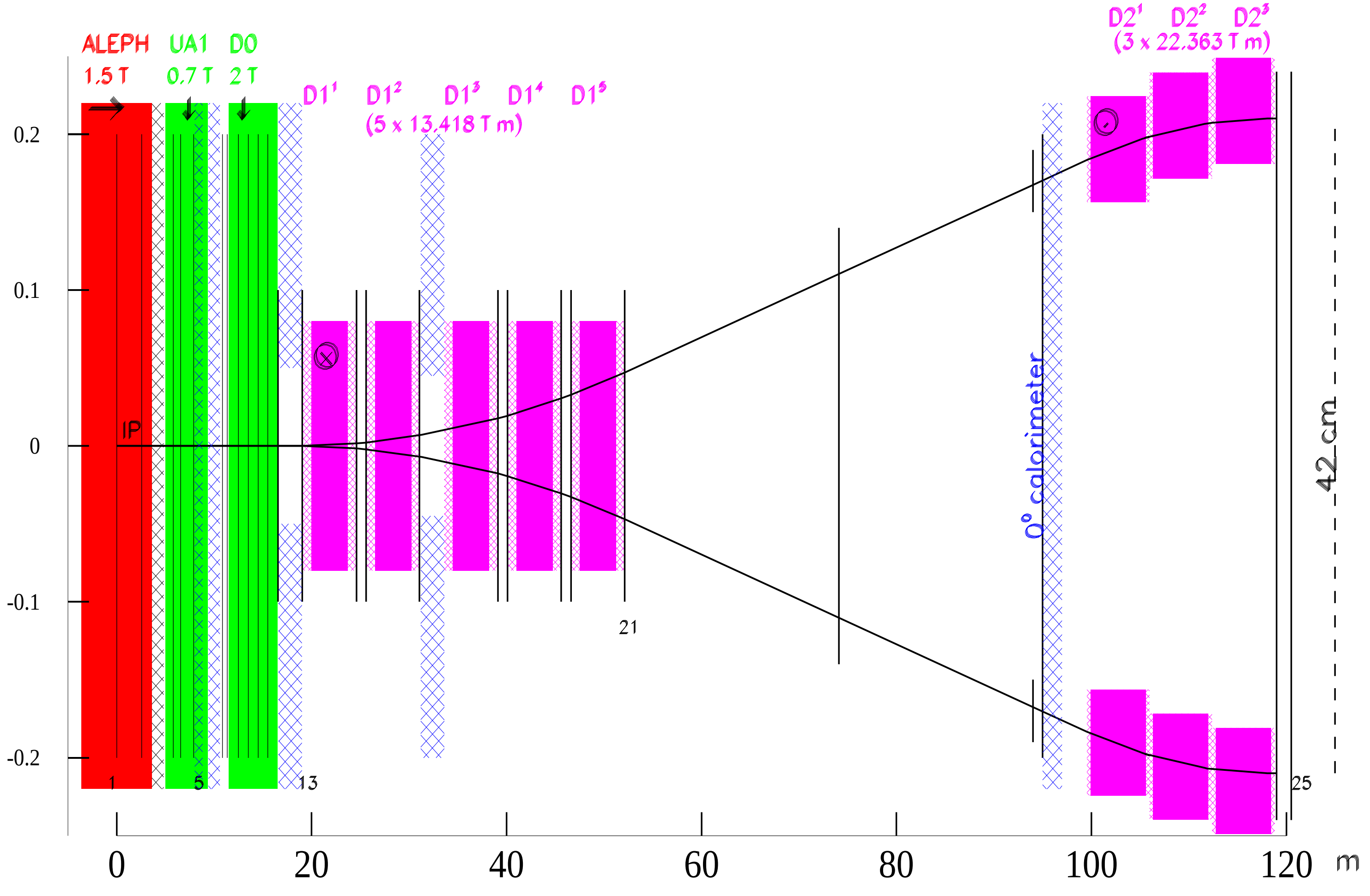
  full program of FELIX

FELIX, CENTRAL & FORWARD





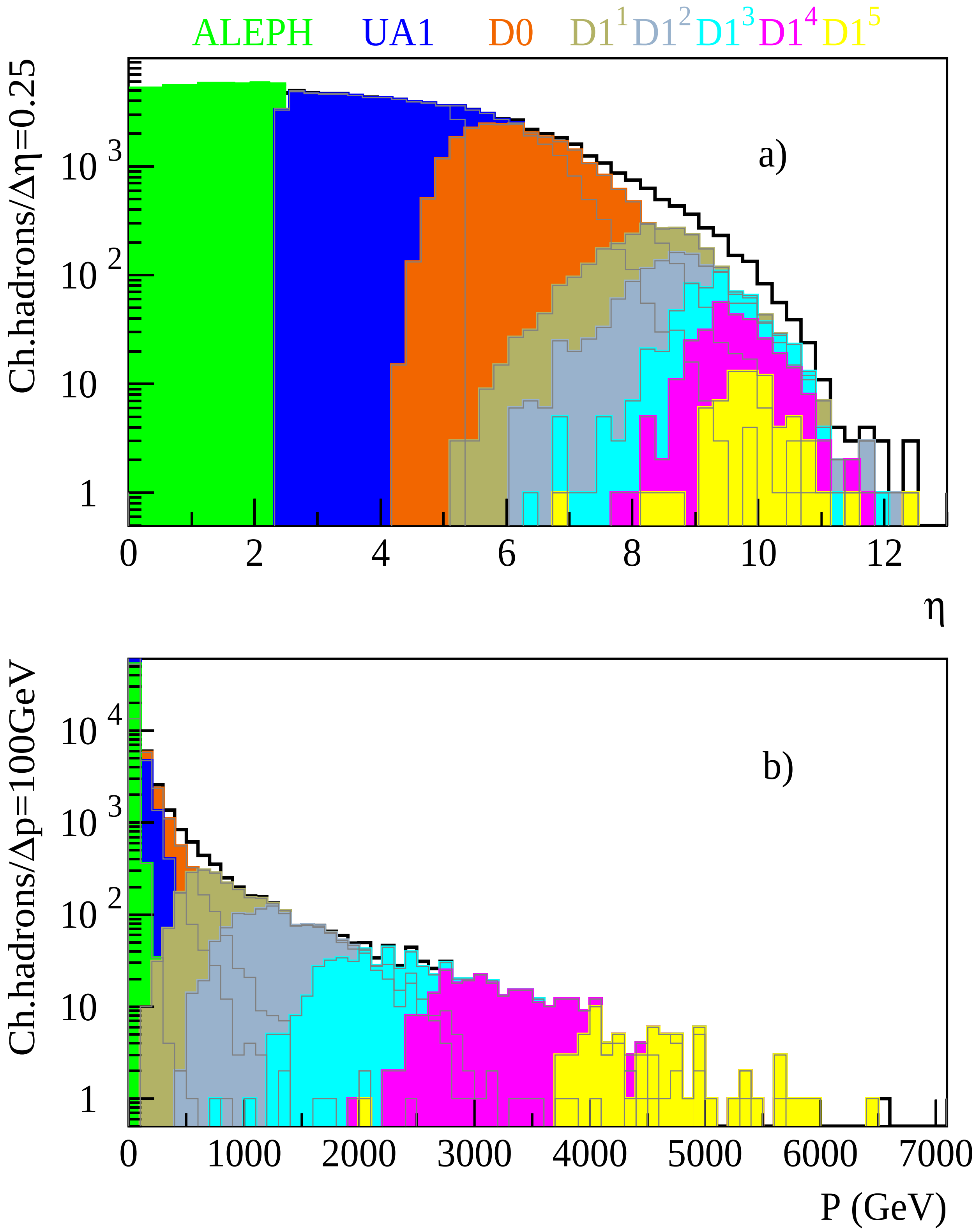
FELIX set-up



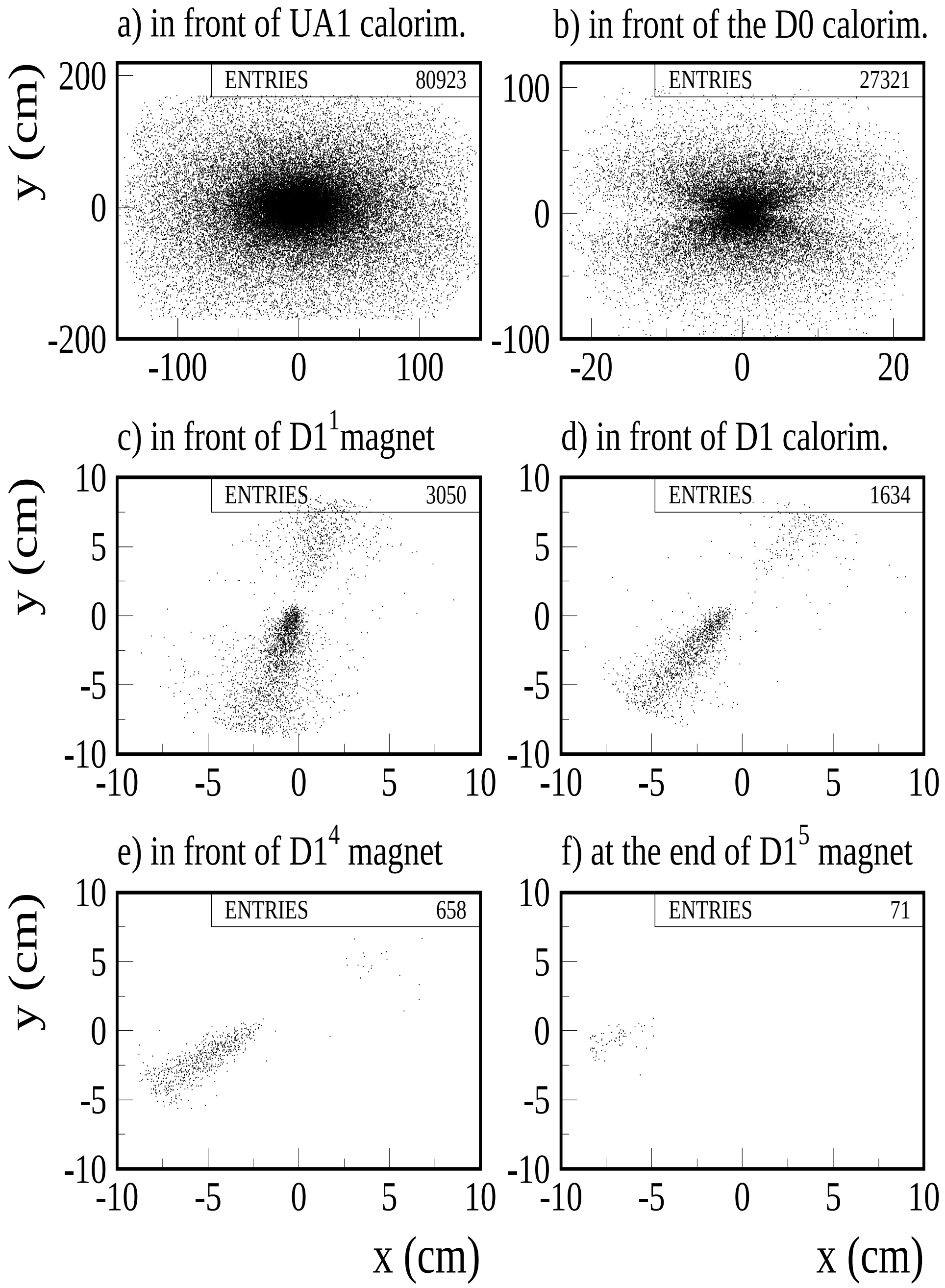
ALEPH
1.5 T
UA1
0.7 T
D0
2 T
D1¹ D1² D1³ D1⁴ D1⁵
(5 x 13.418 T m)
D2¹ D2² D2³
(3 x 22.363 T m)
0° calorimeter
42 cm
IP
0.2
0.1
0
-0.1
-0.2
1
5
13
21
25
0
20
40
60
80
100
120
m

Charged Particle Distribution

Acceptances of the various spectrometers

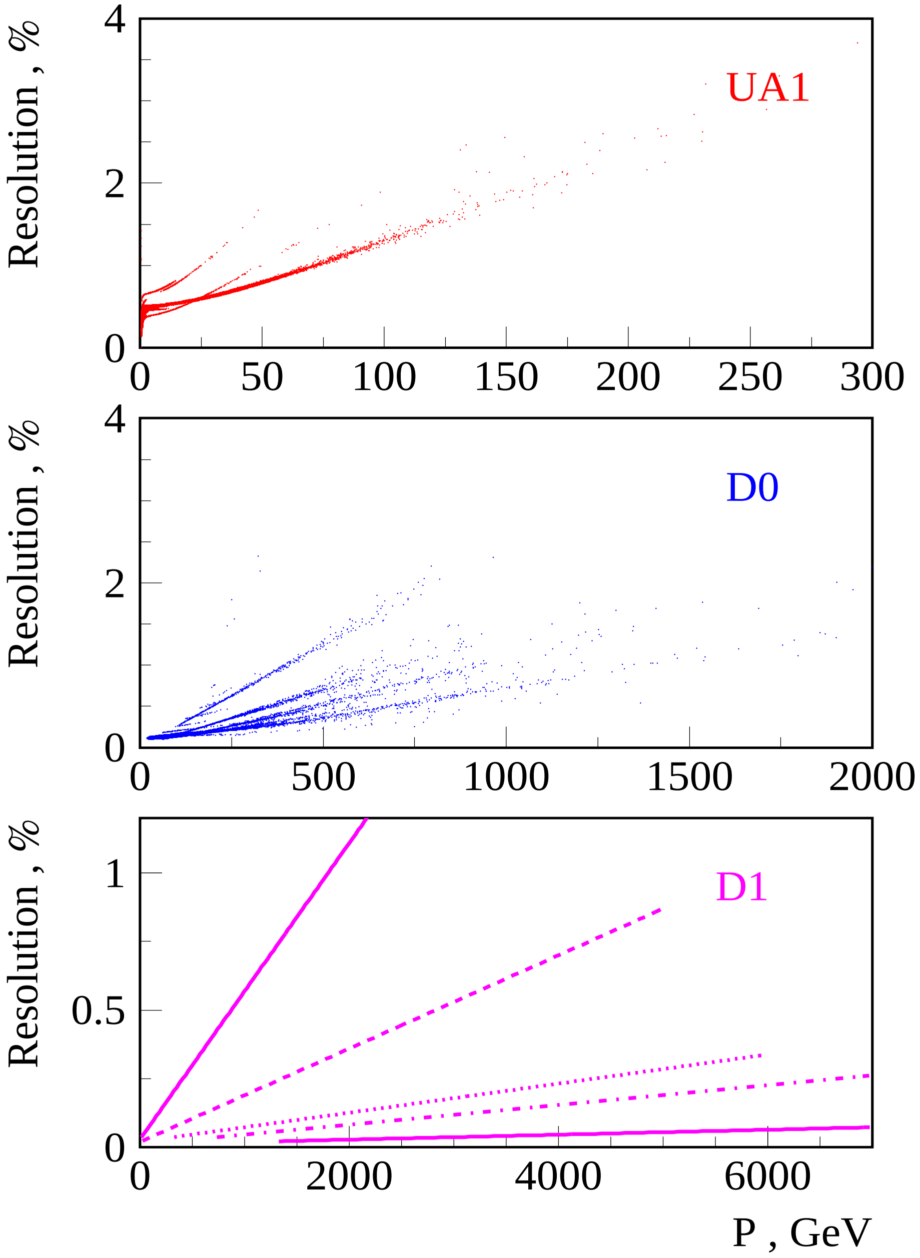


Particle Density



The x-y position scatter plots of charged particles at various detector positions in z. (2000 minimum bias events from PYTHIA)

Momentum Resolution



Main Tasks for the Calorimetry

- **Measurement of total energy**
  (as hermetic as possible)

- **Measurement of energy and position of:**
  - **single particles**
  - **jets**

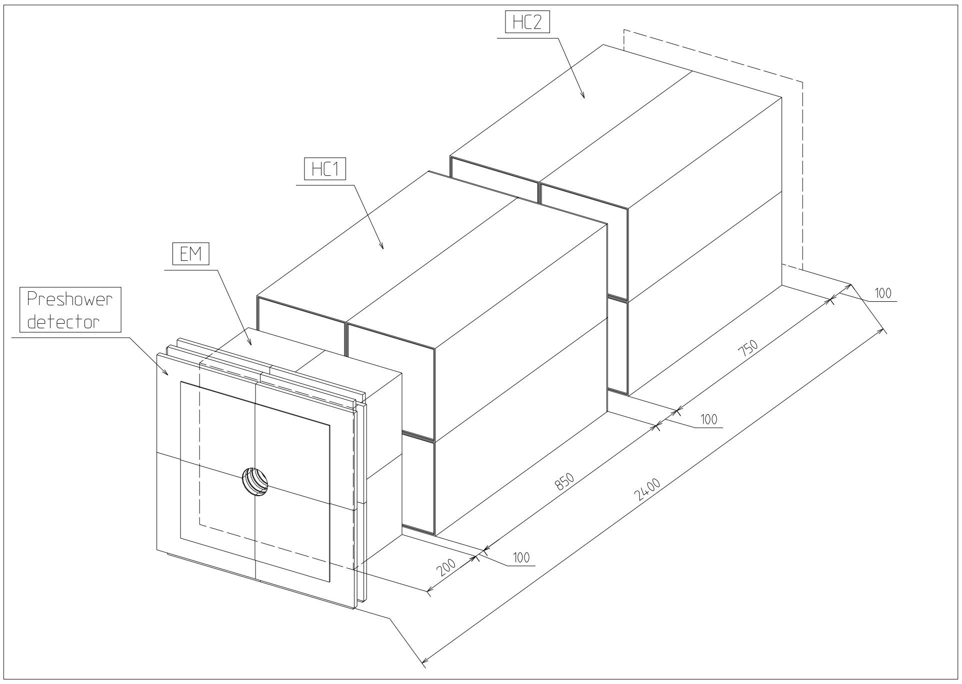
- **Particle identification:**
  (electrons, photons, neutrons, muons)

- **Measurement of event topology**

- **Aperture limitations for tracking**

Forward Calorimeters

Principal Structure



Expected calorimeter performance

	Electromagnetic	Hadronic
Granularity		
$\Delta\eta \times \Delta\phi$	0.2×0.2	0.5×0.5
Space resolution	2 mm/$\sqrt{E}$	15 mm/$\sqrt{E}$
Energy resolution	$12\%/\sqrt{E} \bigoplus 0.5\ \%$	$50\%/\sqrt{E} \bigoplus 2\ \%$

Preshower detector

Electron-photon identification

Improved angular resolution

Photons	0.3 mm/$\sqrt{E}$
Hadrons	0.3 mm

Primary Physics Menu

- Strong interactions in a new domain of large parton densities due to fast growing $q(x, Q^2)$ and $g(x, Q^2)$
  parton densities $x \lesssim 10^{-6}$
- Transverse structure of the proton is studied by the observation of multi-parton interactions
- Very high parton densities can create, at a perturbative distance scale, "hot spots" in the space-time evolution of the collision process
- Particle production from deep within the light cone may exist, possibility of a new phase, DCC...
- Qualitative changes are expected even in the structure of generic events
- Diffractive final states ($1/2\ \sigma_{tot}$) are endemic, many are important, and some are spectacular
  - elastic scattering
  - single diffraction
  - multigap diffraction
  - diffractive dissociation

Primary Physics Menu

- Connection to cosmic ray physics
- Forward heavy flavour production
- New opportunities for tagging event classes (particle beams) via leading particle studies

– $I\!P$-$I\!P$, $I\!P$-p	forward proton
– π p, π π, K p, K K	forward n, Λ^0
– γ p , γ γ	intact forward A

- p A collisions (even larger parton densities) nuclear shadowing, QCD effects for parton propagation, color transparency
- $\gamma\gamma$ collisions up to $\sqrt{\hat{s}} \sim 500$ - 1000 GeV using p-p,Ca-Ca and Pb-Pb collisions e.g.: interations of two small objects, new particle production

Parton densities

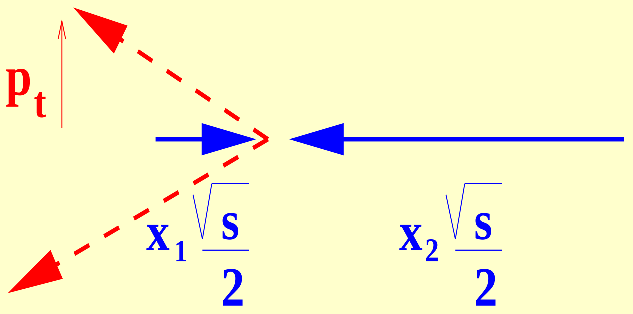
HERA has provided data down to x values of:

$$x \sim 10^{-4} \text{ at } Q^2 \sim \text{several GeV}^2$$

FELIX will extend these measurements to

$$x \sim 10^{-6} - 10^{-7} \text{ via}$$

- di-leptons from Drell-Yan (quark)
- low-mass jets (gluons)
- low-mass jet-photon systems (gluons)



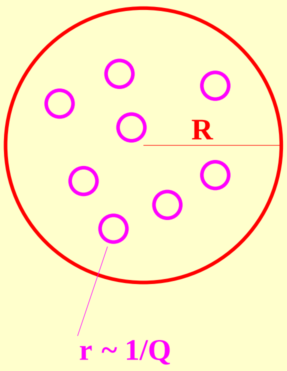
$$x_1 > \frac{4p_t^2}{x_s \cdot s}$$

$$p_t = 10\,\mathrm{GeV} \rightarrow \Theta < 10^{-3}$$

$$\eta \sim 7 - 8$$

saturation:

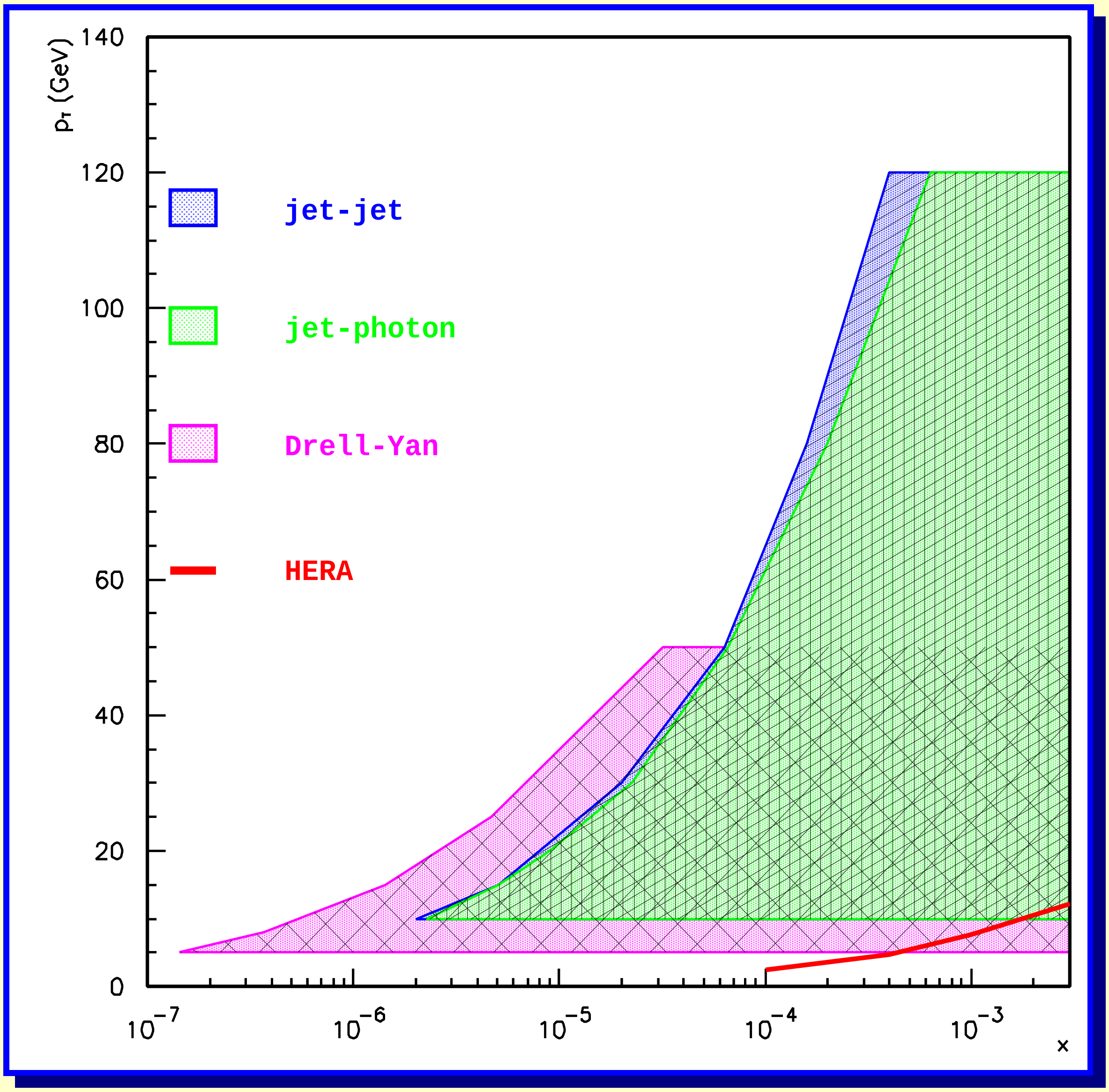
$$\frac{\alpha_2}{Q^2} xg(x, Q^2) > \pi R^2$$

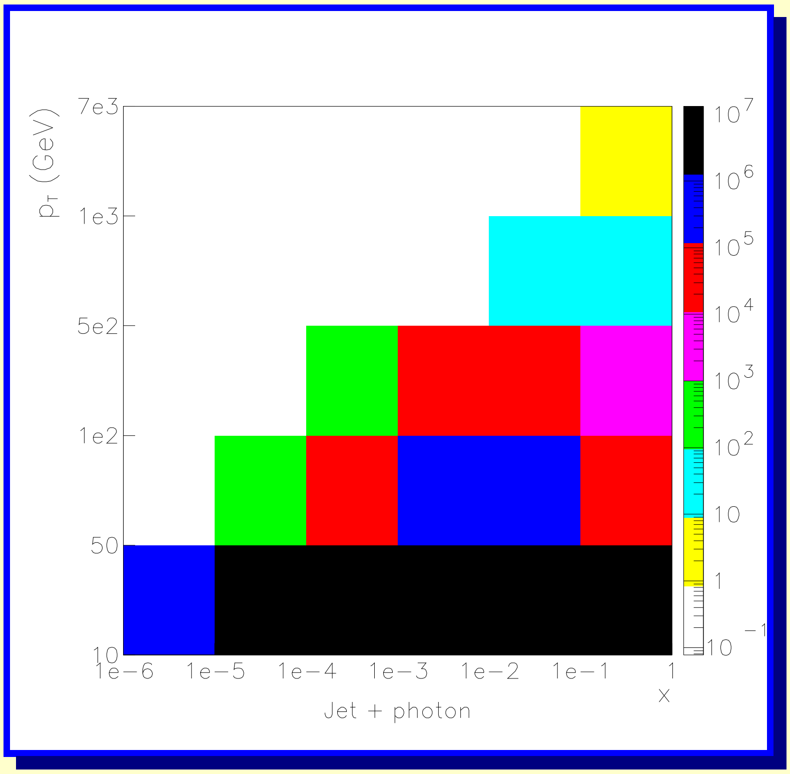


saturation?? or growing proton ??

Small-x Parton Measurements (structure functions)

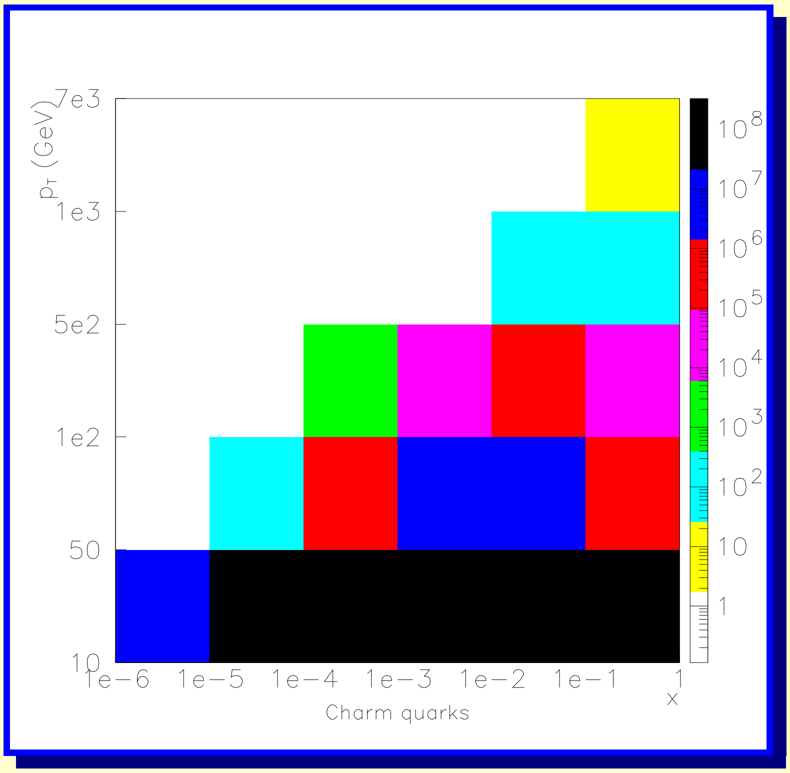
excellent jet, γ, μ, measurements in forward cones are needed





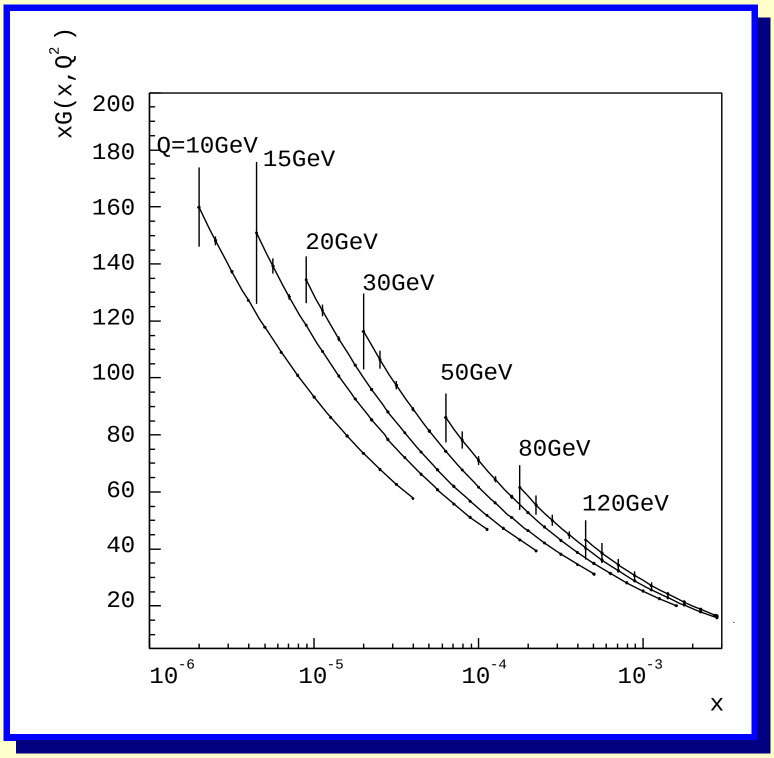
Number of events in (p_T, x) bins for jet $+\ \gamma$ production for an integrated luminosity of 100 pb^{-1}

Number of events in (p_T, x) bins for charm quark production for an integrated luminosity of 100 pb^{-1}



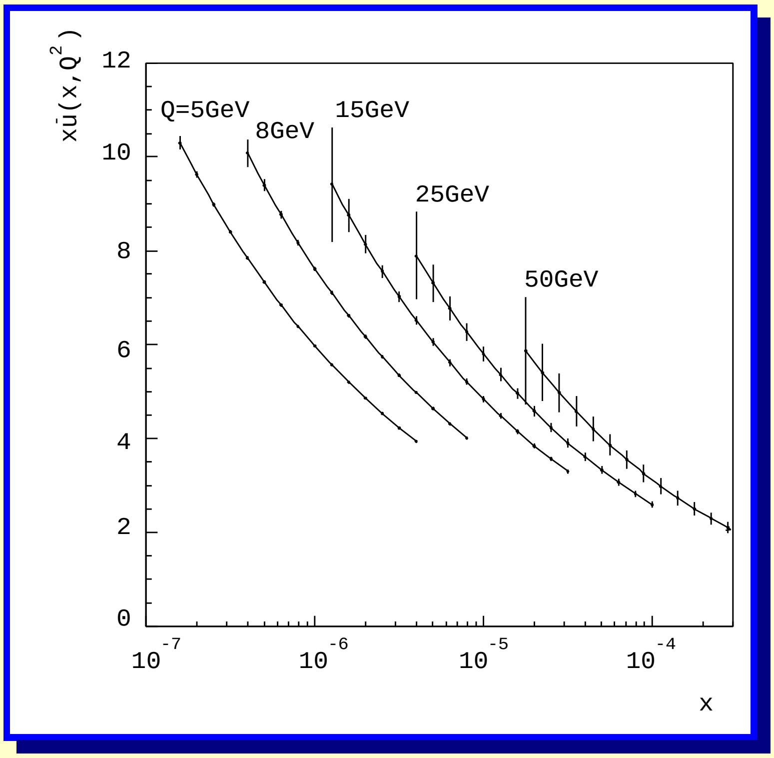
Qualitative changes are expected ...

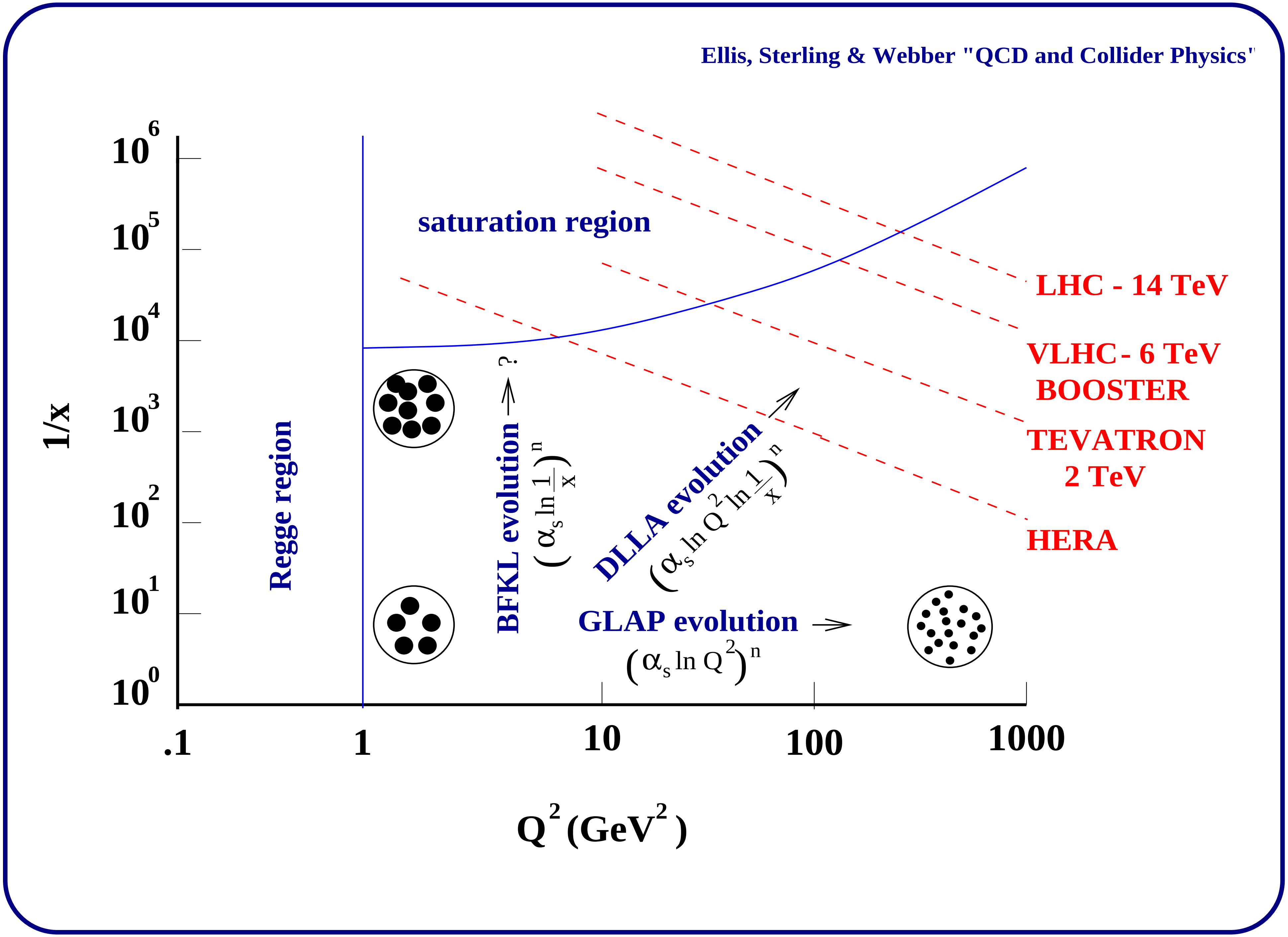
Parton densities become large...



Gluon momentum distribution, as determined from the jet+γ cross-section.

The antiquark momentum distribution, as calculated from the Drell-Yan cross-section

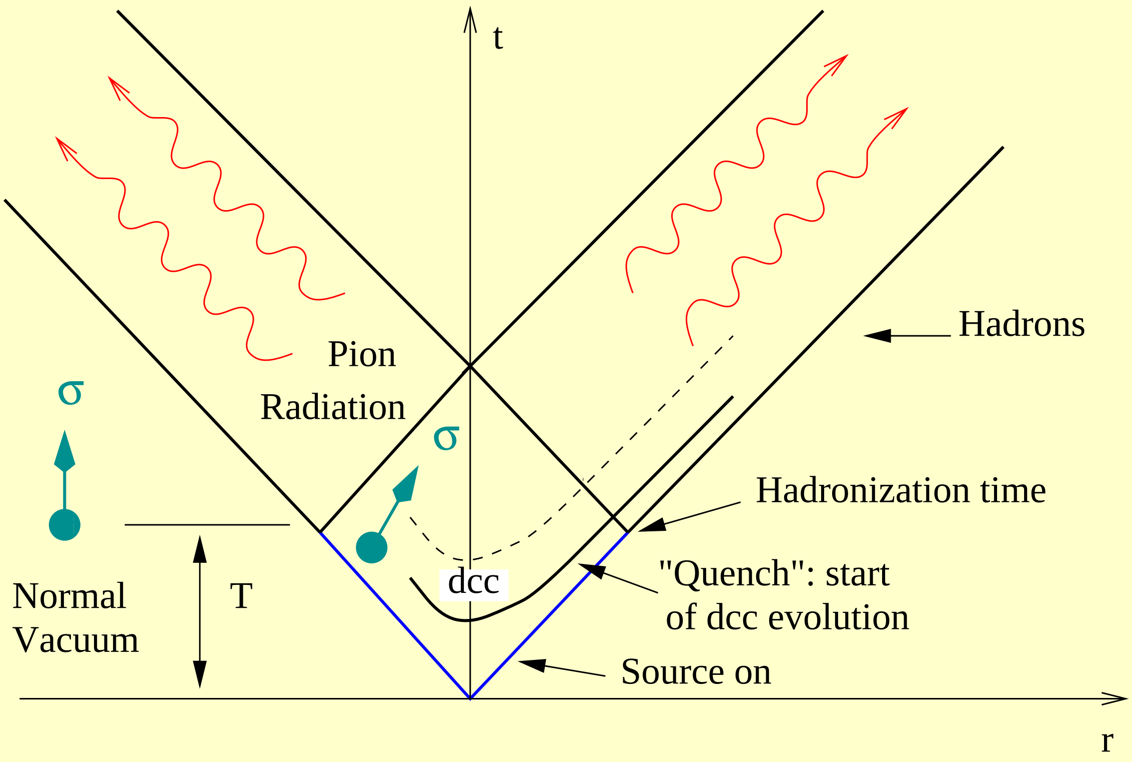



Ellis, Sterling & Webber "QCD and Collider Physics"
1/x
10^6
10^5
10^4
10^3
10^2
10^1
10^0
saturation region
Regge region
BFKL evolution → ?
$\left(\alpha_s \ln \frac{1}{x}\right)^n$
DLLA evolution
$\left(\alpha_s \ln Q^2 \ln \frac{1}{x}\right)^n$
GLAP evolution →
$\left(\alpha_s \ln Q^2\right)^n$
LHC - 14 TeV
VLHC - 6 TeV
BOOSTER
TEVATRON
2 TeV
HERA
.1
1
10
100
1000
$Q^2\,(GeV^2)$

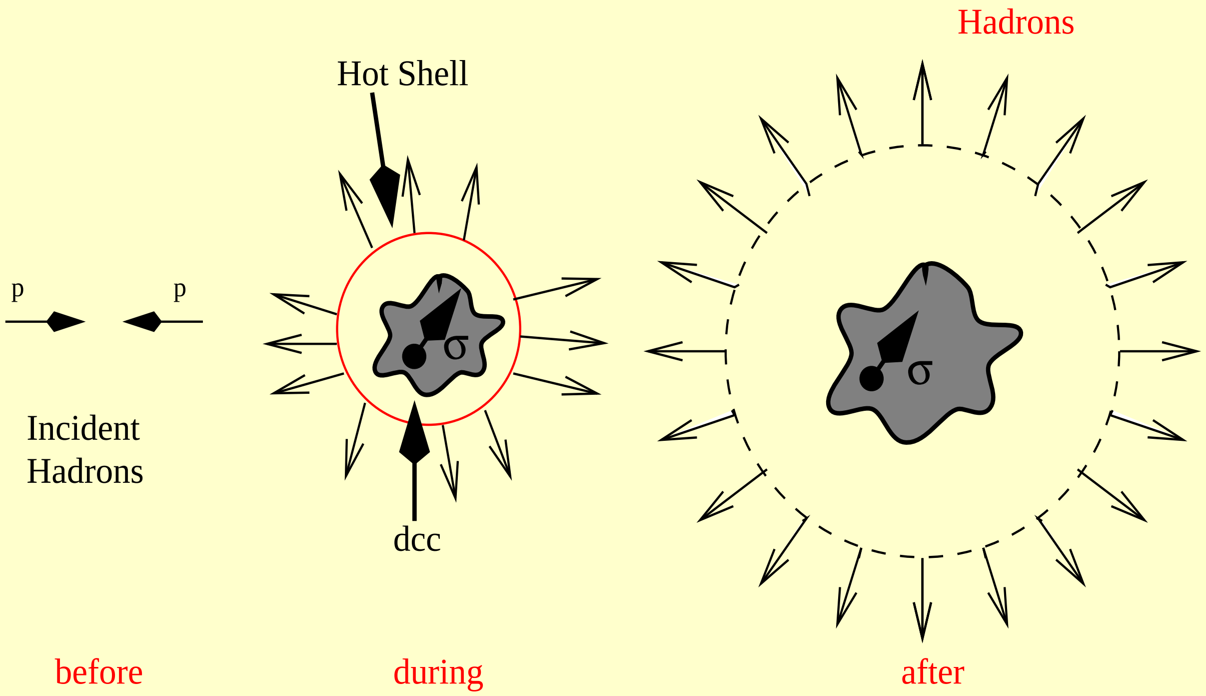
Disoriented Chiral Condensate (dcc)

J.D. Bjorken, C. Taylor

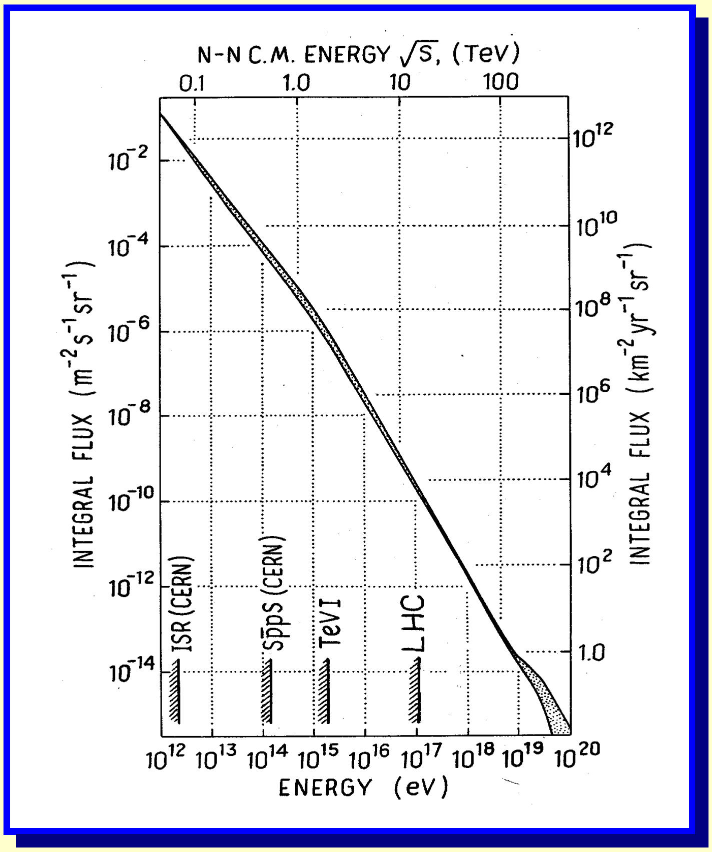
Hot spots



Evolution of a high multiplicity, high energy collision:



The astroparticle connection



Integral flux of high energy cosmic rays

- Change of slope at $\sqrt{s} \sim 5$ TeV
- Measurements of the very forward energy flux (including diffraction) are essential for the understanding of cosmic ray events
- Anomalies in cosmic rays:
  - Centauros and Anticentauros
  - Multimuon bundles
  - Long flying component
  - Abundant heavy flavour production
  - • • •

Transverse structure of the proton

Extrapolations to LHC energies lead to a

LARGE NUMBER OF MULTIPLE PARTON COLLISIONS

- Multiple parton collisions carry informations about the distribution of partons in transverse space, which can be obtained directly from the multiplicity distribution in the number of parton collisions

NEW INFORMATION ON THE HADRON STRUCTURE

- The parton distributions measured in deep inelastic scattering are averaged over the transverse parton coordinates

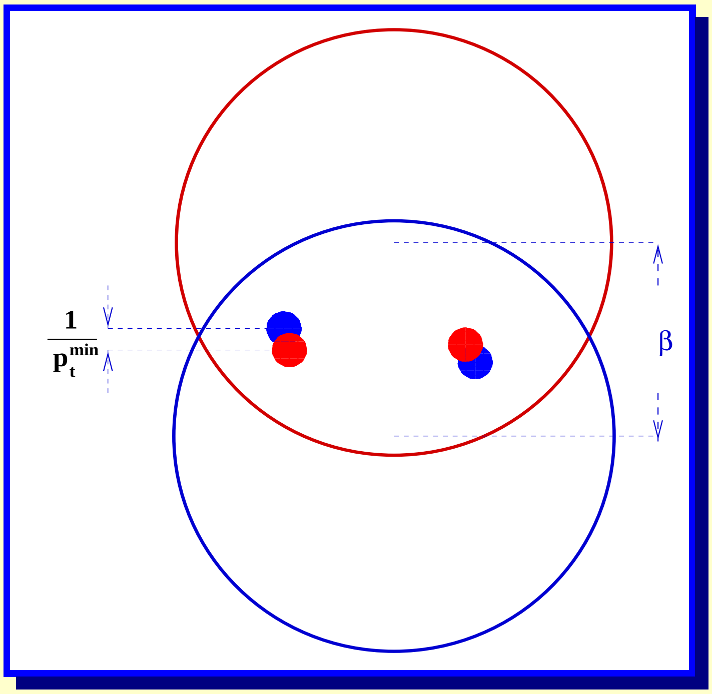
Multi-parton interactions

- large flux of partons at small x
  $\Longrightarrow$ increasing number of parton collisions at large energies

- large cross section for production of minijets observed by UA1

  $\Longrightarrow$ possibility of having several partonic collisions in the same inelastic event

- double parton collisions have been observed by CDF



A view of double scattering in the transverse plane.

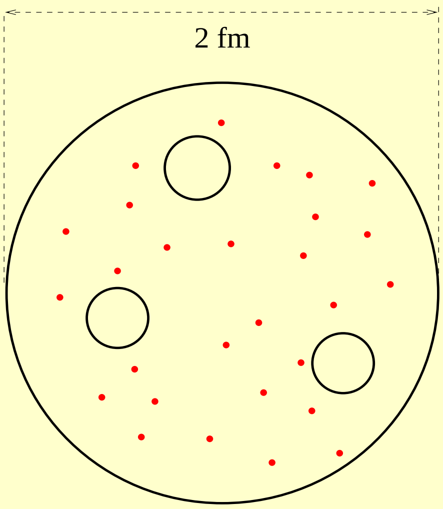
Minijet production in central collisions may become common place

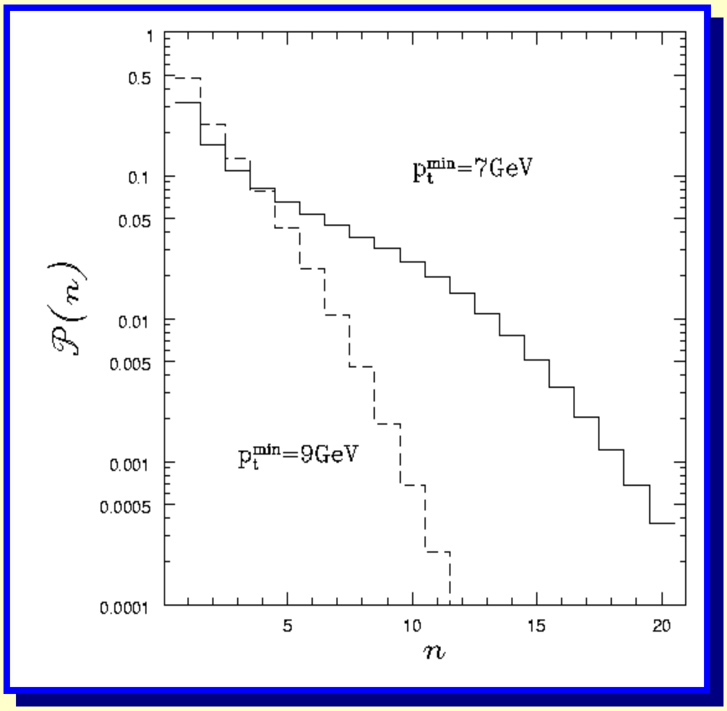
Transverse structure of the proton

Model 1:

- All partons are distributed with gaussian shape around the hadron centre (r= 1 fm).
- The number of partons is Poisson distributed.

  $\Longrightarrow$ The number of parton collisions in a single hadronic event is Poisson distributed with an average number proportional to the overlap of the matter distribution of the two hadrons





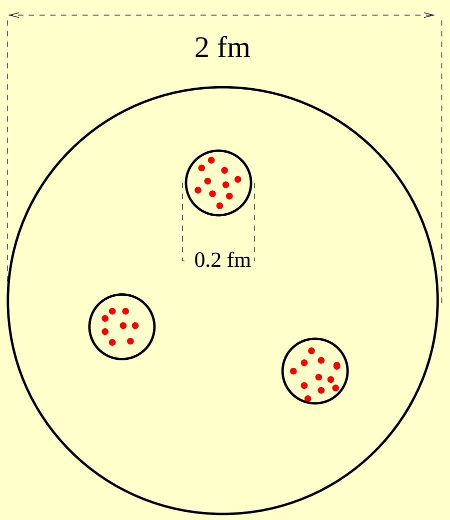
Normalized distribution of the number of partonic collisions per hadronic pp interaction at the LHC for two different p_T^{min} thresholds.

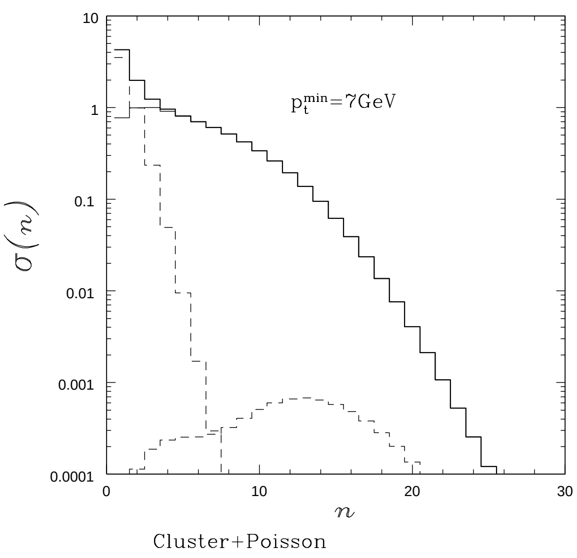
Transverse structure of the proton

Model 2:

- Valence quarks are distributed with gaussian shape around the hadron centre (r= 1 fm).
- All other partons cluster around the position of the valence quarks (r=0.1 fm).
- The number distribution of partons is a poissonian.

$\Longrightarrow$ The average number of parton collisions in a single hadronic event is still Poisson distributed, with an average number proportional to the overlap of the matter distribution of the two hadrons





- notice the change in shape of $\sigma(n)$ due to the large increase of the multiplicity of parton collisions when two clusters overlap

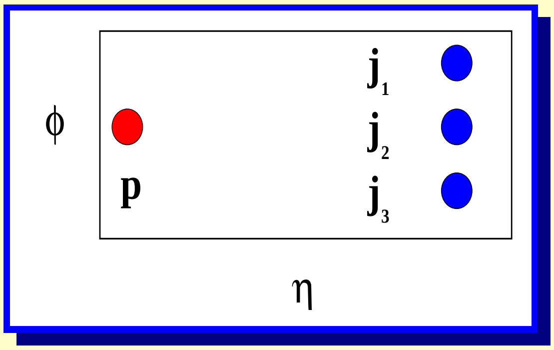
Diffraction into forward jets

Stan Brodsky

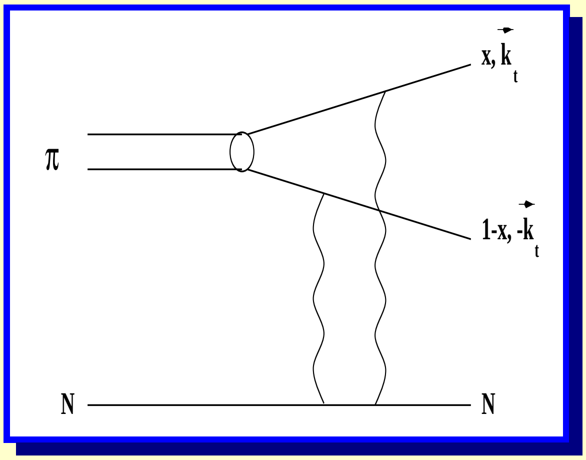
Proton diffraction into three jets

$$\sigma^{pp}_{3jets} \sim 10^{-4}\text{–}10^{-5}\left(\frac{5\mathrm{GeV}}{p_{tjet}}\right)^{8}\ \mathrm{mb}$$

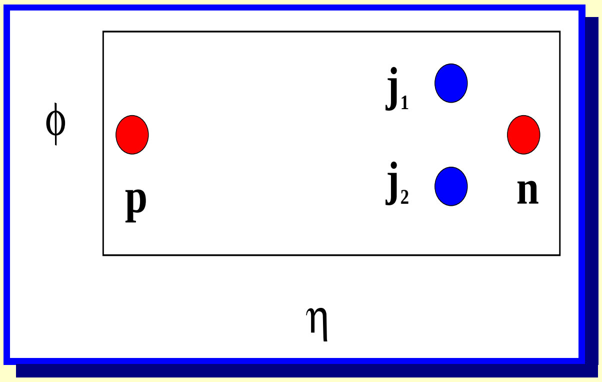
$$\sigma^{pA}_{3jets} \sim A^{4/3}$$

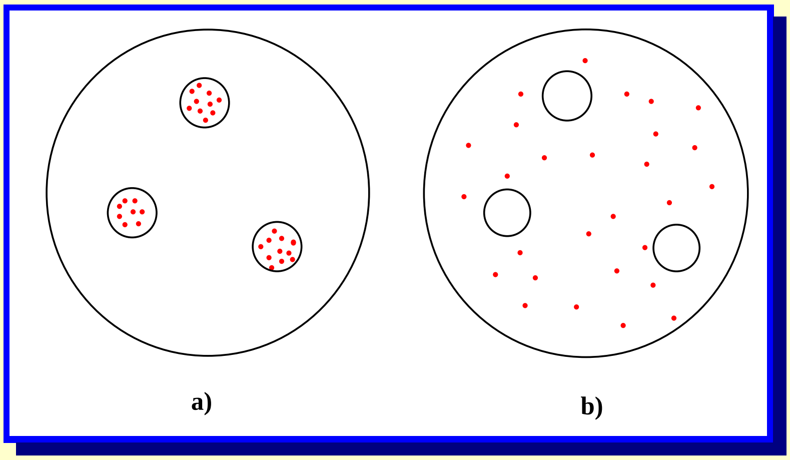


Pion diffraction into two jets



E791

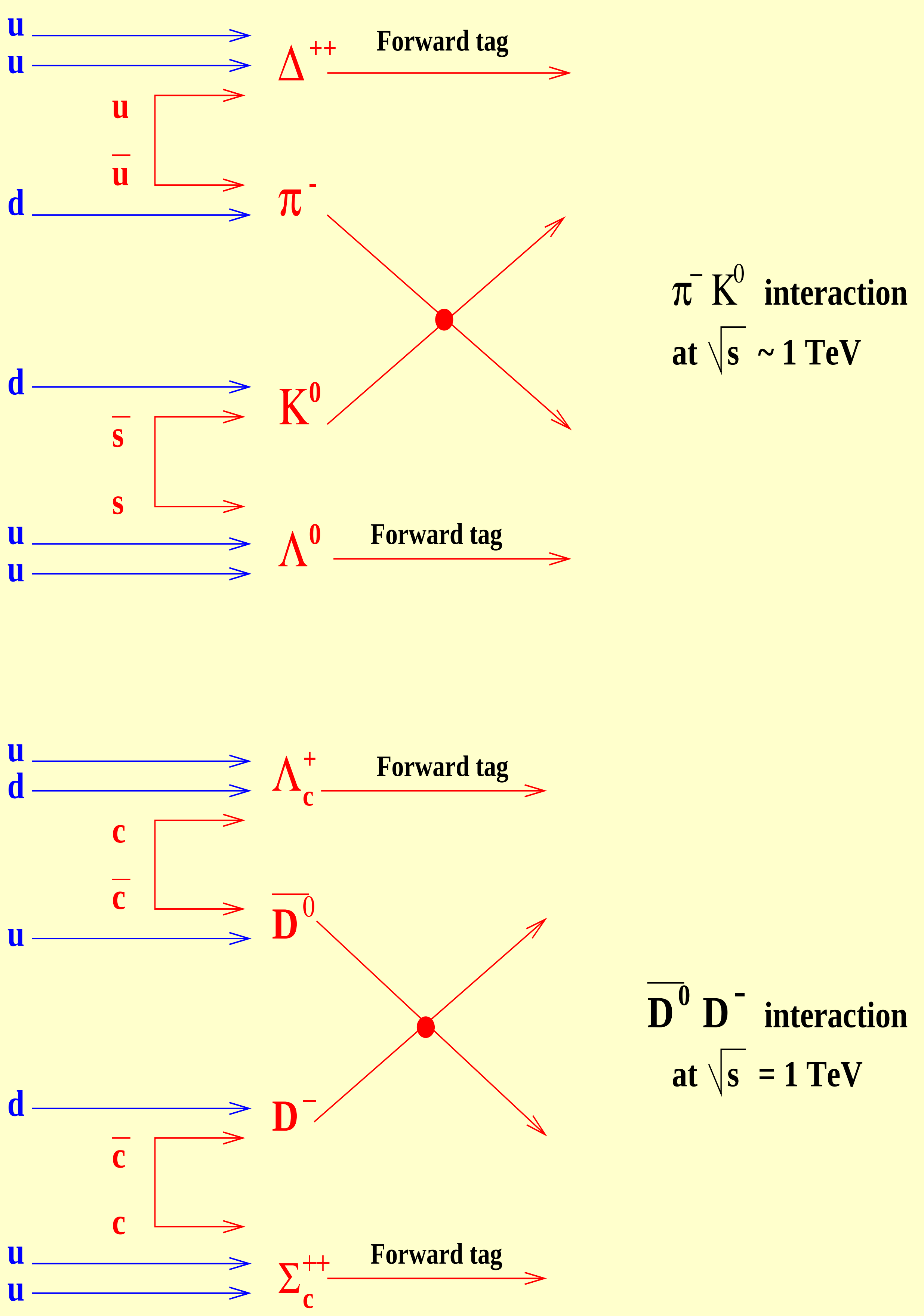




“Sea” partons in the infinite - momentum state of the proton: inside the constituent quarks (a)
or outside (b)

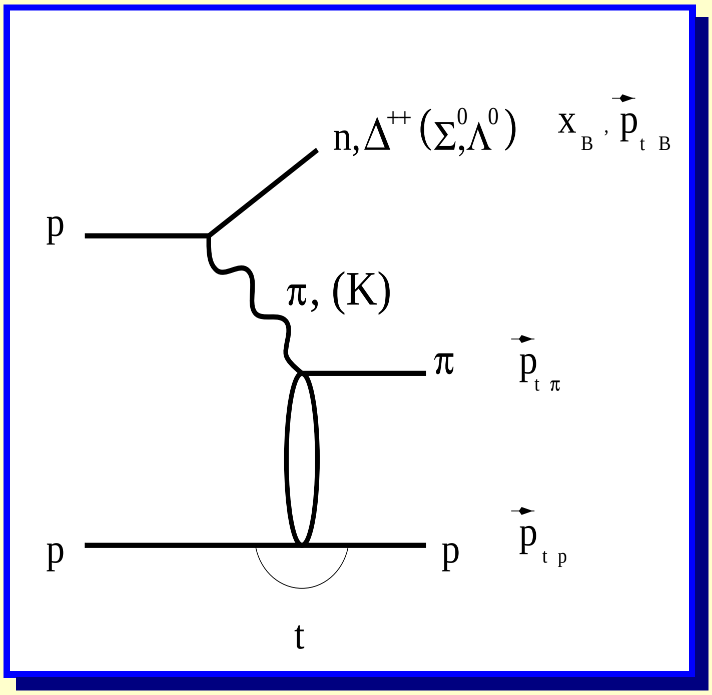
small colour singlet passes through nucleus (color transparency)

Particle beams via forward tags



Leading baryons

Tagged particle beams



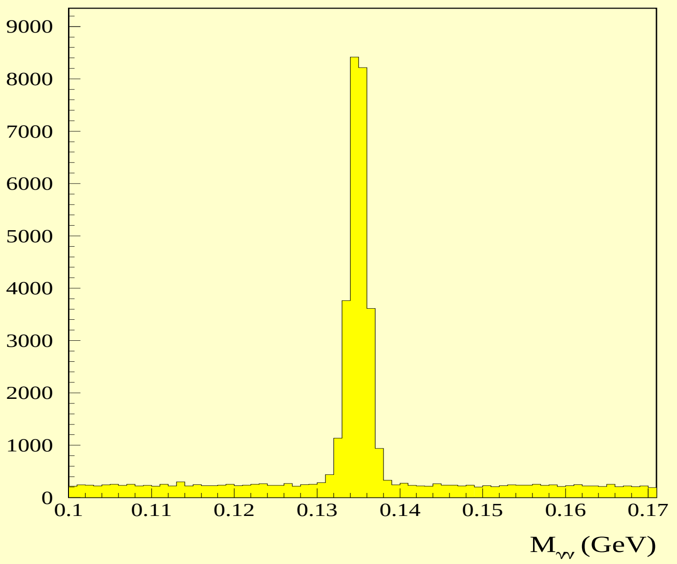
Elastic πp- or Kp- scattering

$$\frac{(d\sigma/dt)\pi p \rightarrow \pi p}{(d\sigma/dt)pp \rightarrow pp} \sim \frac{t}{6\mathrm{GeV}^2}$$

$$\frac{(d\sigma/dt)Kp \rightarrow Kp}{(d\sigma/dt)\pi p \rightarrow \pi p} \sim 3$$

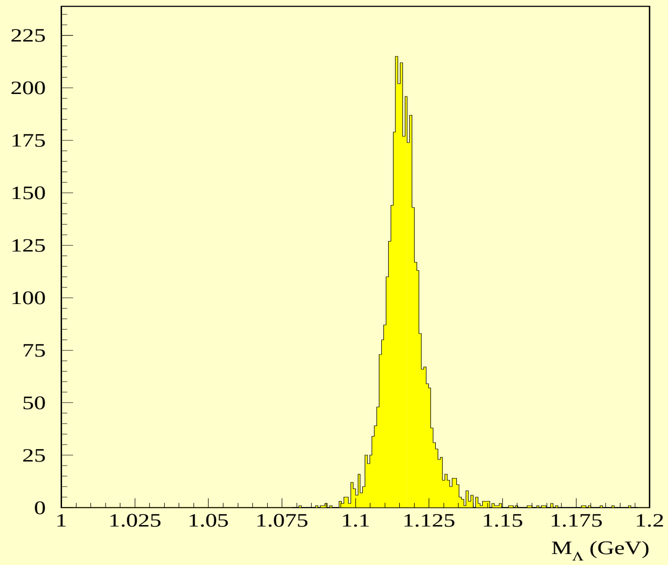
Flux of pions in proton of $\sim 1\%$ is compensated by larger πp scattering cross-section at large t.

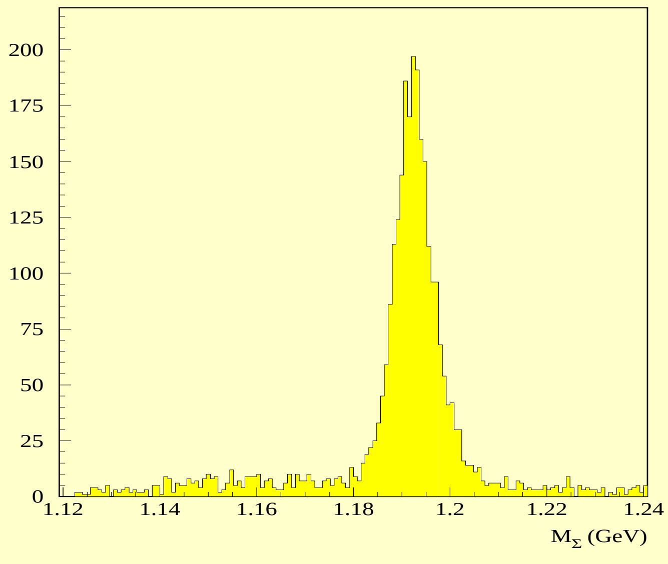
Mass reconstruction



$\gamma\gamma$ mass spectrum in the π^0 region

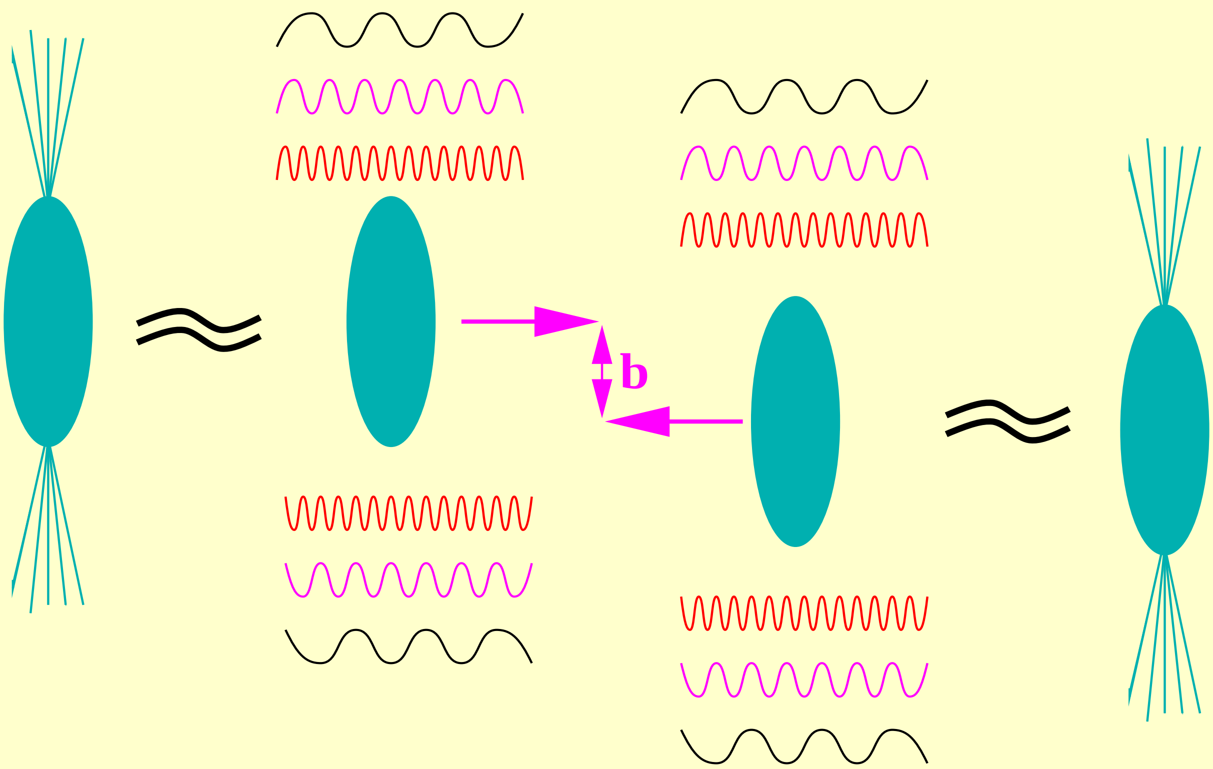
$\Lambda \to n\pi^0$





$\Sigma^0 \to n\pi^0\gamma$

Quasireal photons



Quasireal Photons (Weizsäcker-Williams approximation)

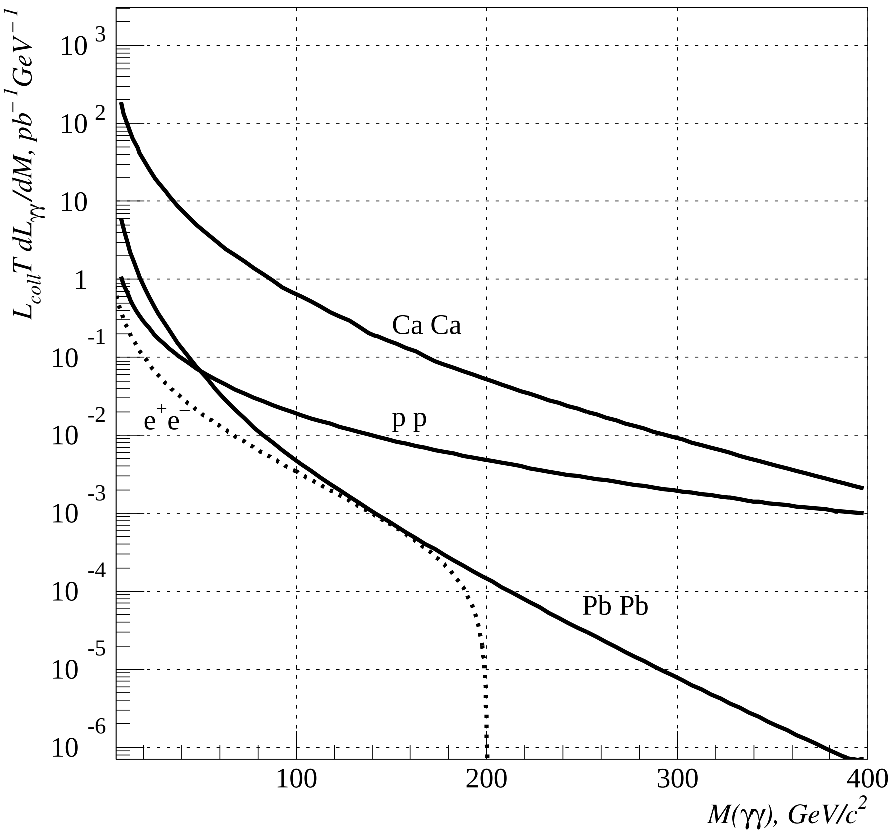
max. photon energy:

$$\hbar\omega_0 \sim \frac{\hbar c\gamma}{R_{ion}} \qquad \gamma = \frac{Z}{A}\gamma^{pp}$$

LHC	$E_{\gamma max}$	$\sim 0.17\ A^{-1/3}(E/A)$	$R_{ion} = 1.2$ fm $A^{1/3}$
Pb		$\sim$ 80 Gev	7 fm
Ca		$\sim$ 170 GeV	4 fm
p		$\sim$ 1000 GeV	1.2 fm

High flux of photons with energies well above HERA.

$\gamma\gamma$ physics



TL_{coll}:

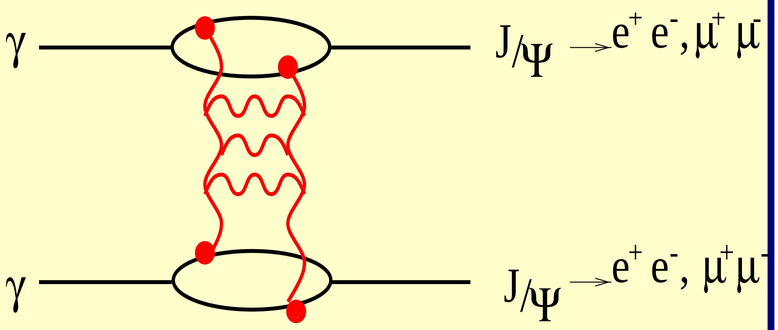
pp $\rightarrow 10^3$ pb^{-1}

CaCa $\rightarrow 4$ pb^{-1}

PbPb $\rightarrow 10^{-4}$ pb^{-1}

e^+e^- $\rightarrow 100$ pb^{-1}

Test of BFKL:



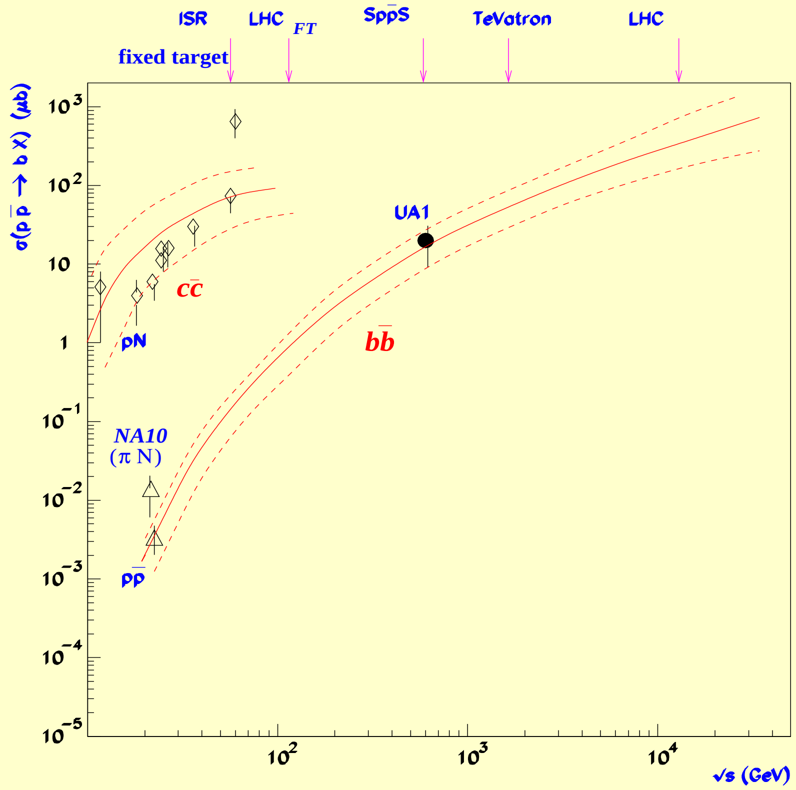
$J/\psi \sim$ pointlike

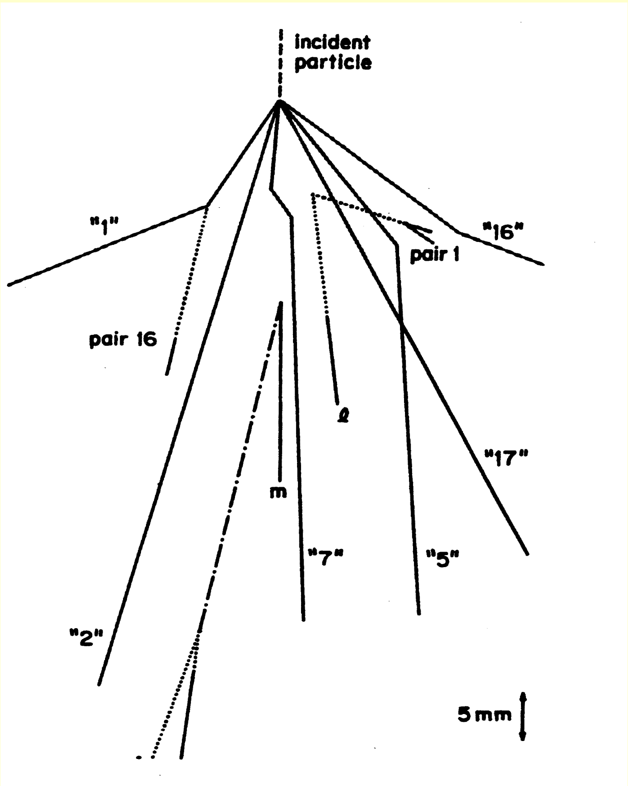
enhancement due to BFKL $\sim$ 100

Bartels, Brodsky

Heavy Flavour Production

Charm
and
Beauty
cross-sections





Emulsion chamber observation of the associated production of five heavy flavour decays in the forward cone of a cosmic ray interaction

Diffractive final states

Many are important, and some are spectacular

Diffraction is the class of phenomena associated with non-exponentially suppressed rapidity gaps.

About half of all hadronic collisions should be diffractive (elastic scattering + inelastic diffractive dissociation).

Diffraction processes represent a primary challenge to theorists: how to understand the phenomena from first principles.

A full acceptance detector must be capable of detecting the

- diffractive protons
- dissociated protons

over a large kinematical range.

Diffractive final states

Soft diffraction

- elastic scattering
- peripheral collisions with large impact parameters
- final states containing leading particles tags

Semihard diffraction

initial-state projectile fluctuates into a transversely compact configuration:

- vector-meson photoproduction at HERA (J/Ψ)
- pion dissociation into dijets (E791 at FNAL)

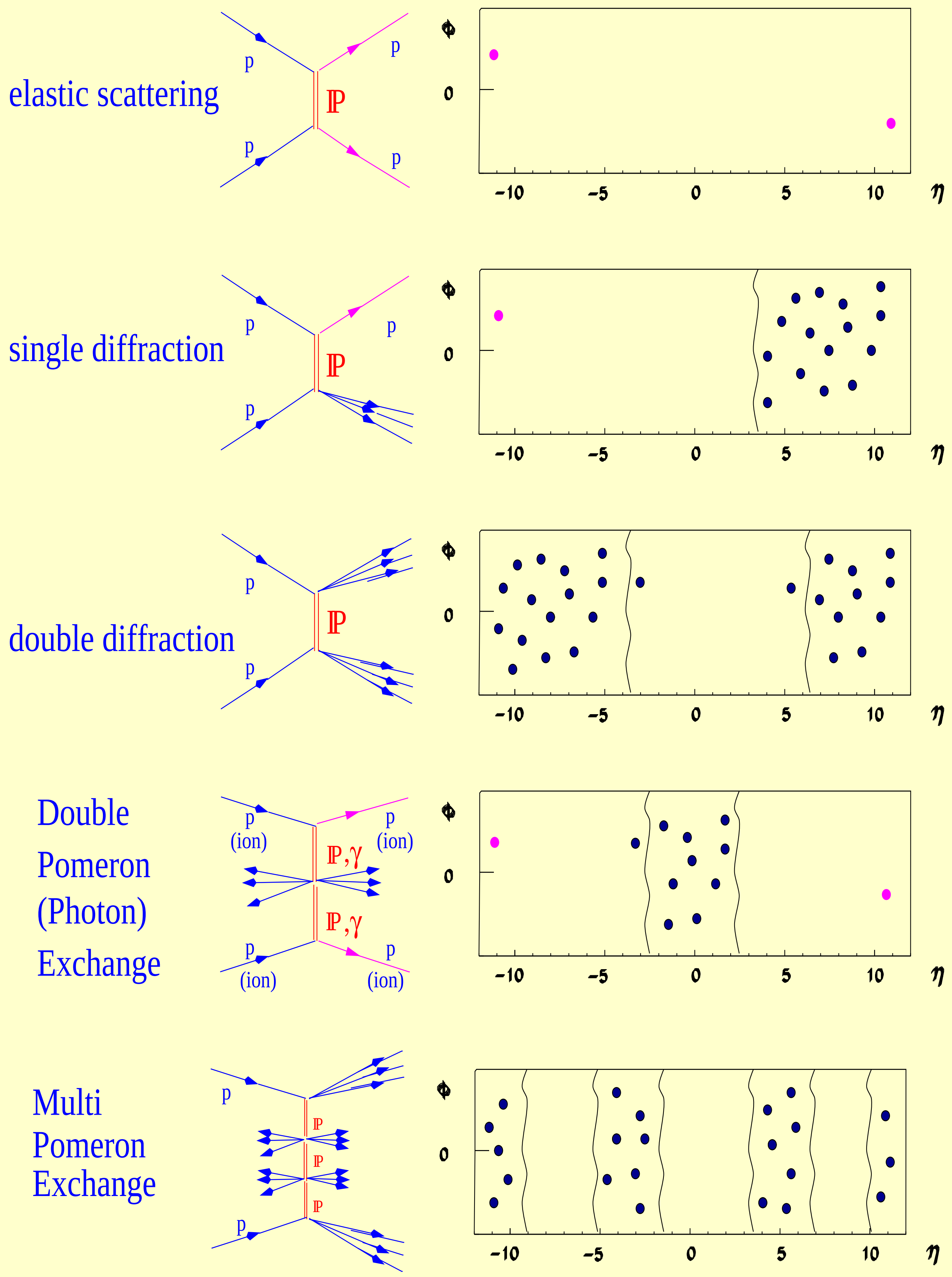
Hard diffraction

multitude of basic event classes

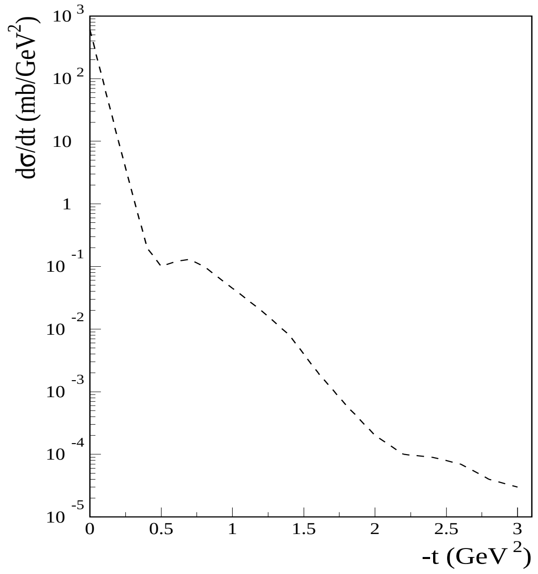
hard (short distance) collisions with coplanar dijets and rapidity gaps (even multi rapidity gaps)

- single diffraction (Pomeron-proton interaction)
- double Pomeron exchange (hard Pomeron)
- multiple Pomeron exchange

Diffractive Processes



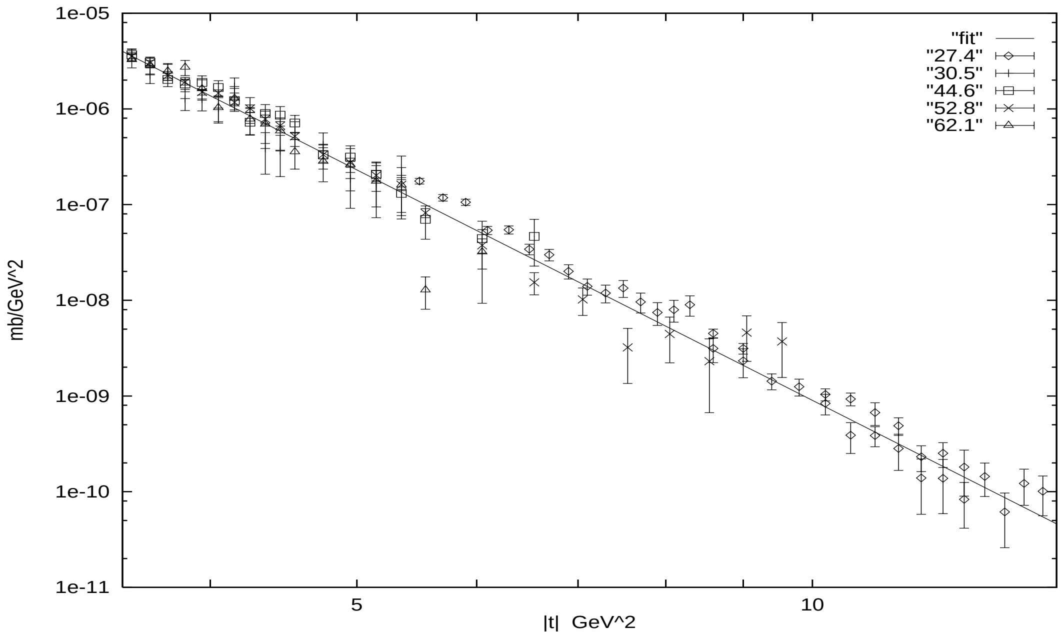
Elastic Scattering



Exchange of a soft Pomeron,
measurement
of the slope $B(s,t)$
Determination of
optical point $(t=0)$
$\Longrightarrow \sigma_{tot}$

$$\sigma^2_{tot} = \frac{16\pi(dN/dt)_{t=0}}{(1+\rho^2)(N_{el}+N_{inel})}$$

$$5 \cdot 10^{-3}\ \mathrm{GeV}^2 < t < 10 - 20\ \mathrm{GeV}^2$$

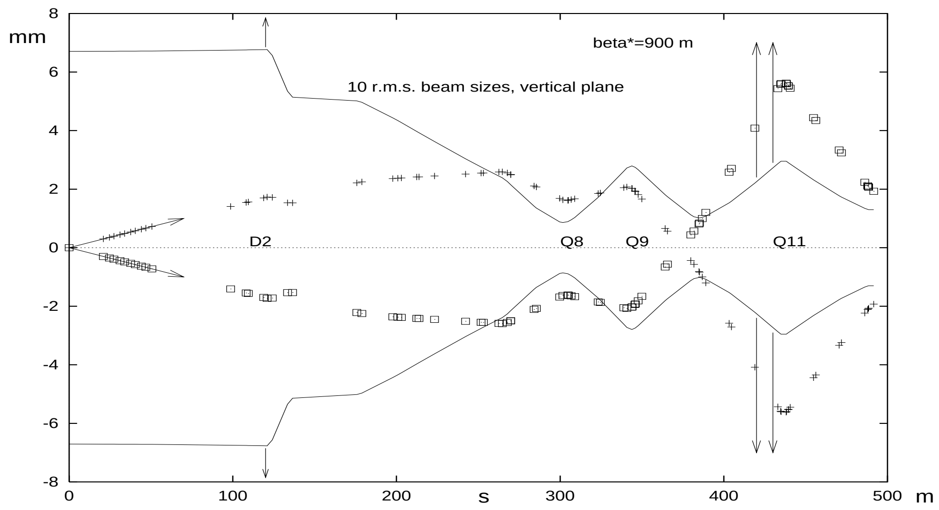


t^{-8} behaviour at large t (ISR)
three valence quarks scatter independently
link to perturbative QCD, hard Pomeron

Elastic Scattering

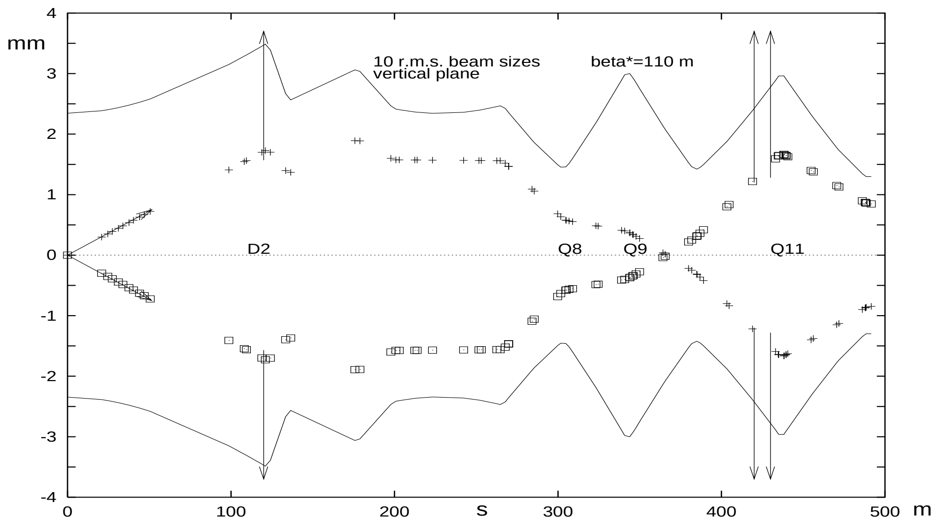
10σ beam profile in the vertical plane, trajectory of a scattered proton ($\Theta = 14\mu rad$; $t = 10^{-2} GeV^{-2}$)

β^*=900 m



The optical functions are optimized at s=430 m to reach the smallest t-value $t = 3 \cdot 10^{-3}$ GeV^2

β^*=110 m

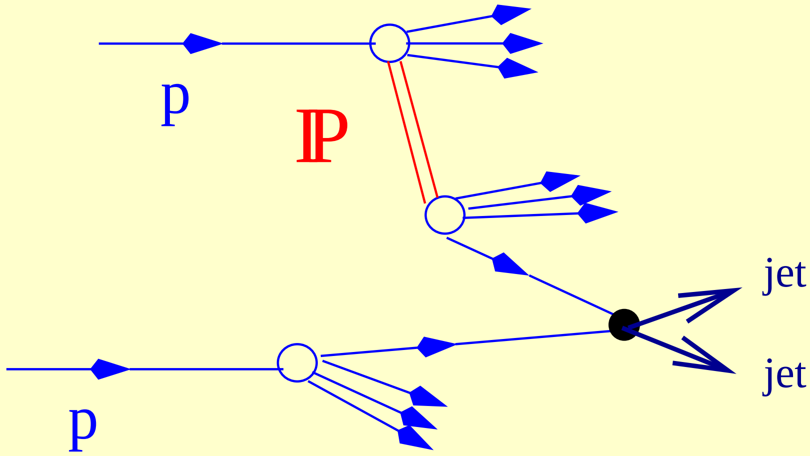


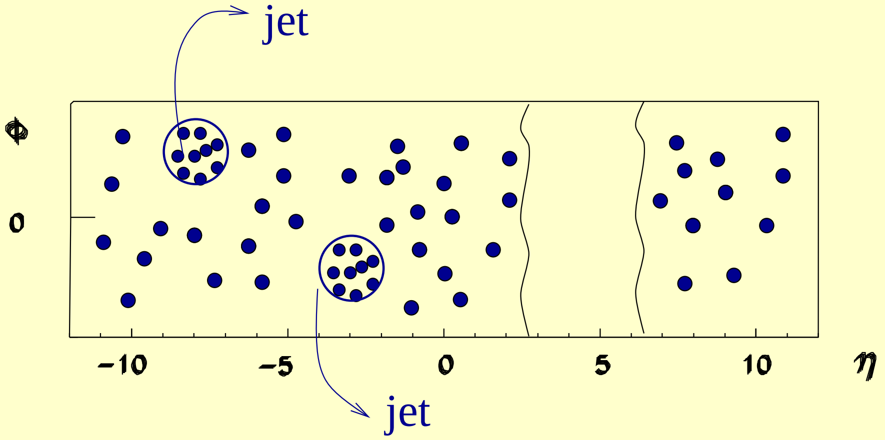
The near stations ($s < 120m$) accept all elastic scattered protons with $t > 4 \cdot 10^{-2}$ GeV^2

Pomeron in hard collisions

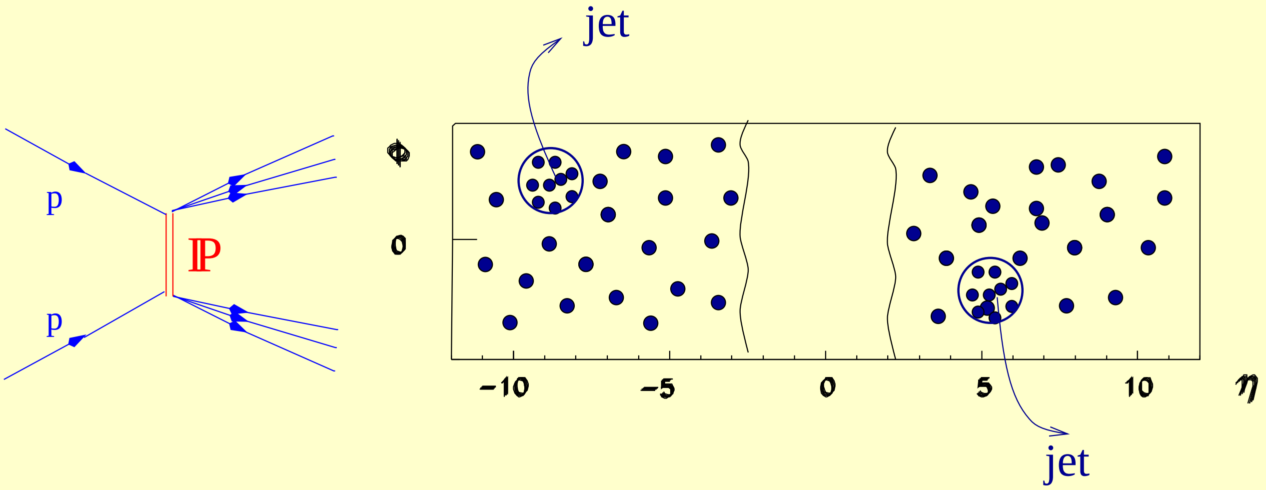
Ingelman - Schlein

process



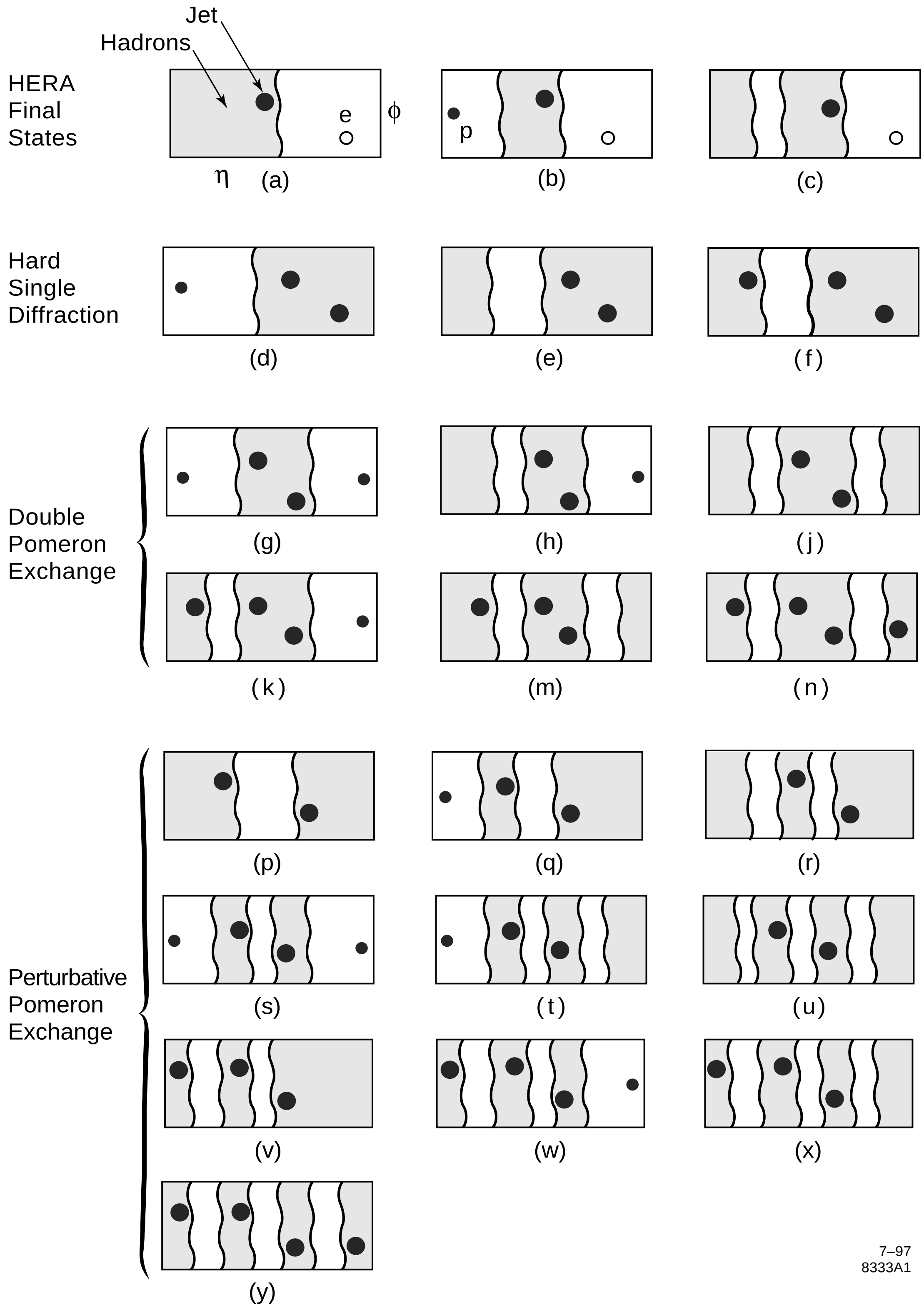


Event structure for a hard collision of a pomeron with a proton: the produced jets are coplanar



Coplanar jets which span a rapidity gap. How pointlike is the Pomeron? Can large p_t be exchanged in diffractive processes?

Basic hard diffraction



Diffraction

characterized by two variables:

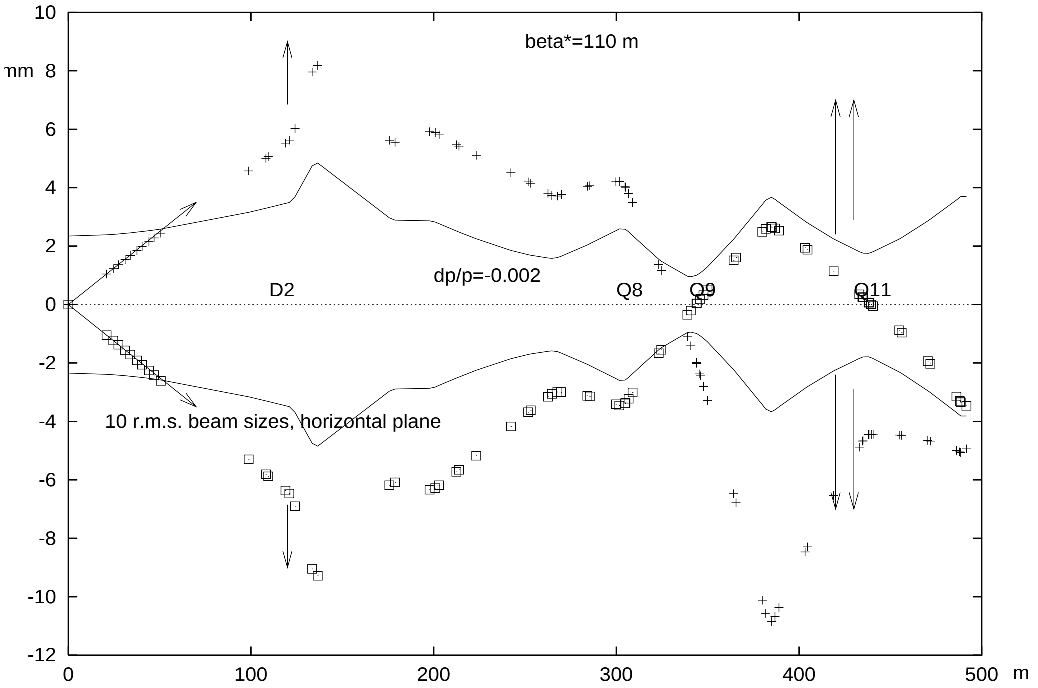
$$t = -p_0 p_{rec} \Theta^2, \;\; \xi = \frac{\Delta p}{p} = \frac{M_X^2}{4 p_0^2}$$

Elongation of a diffractive proton in horizontal plane:

$$x(s) = v_x(s) \cdot x^* + L_x^{eff} \cdot \Theta_x^* + \xi D(s)$$

$$D(s = 430m) \sim 1.3m$$

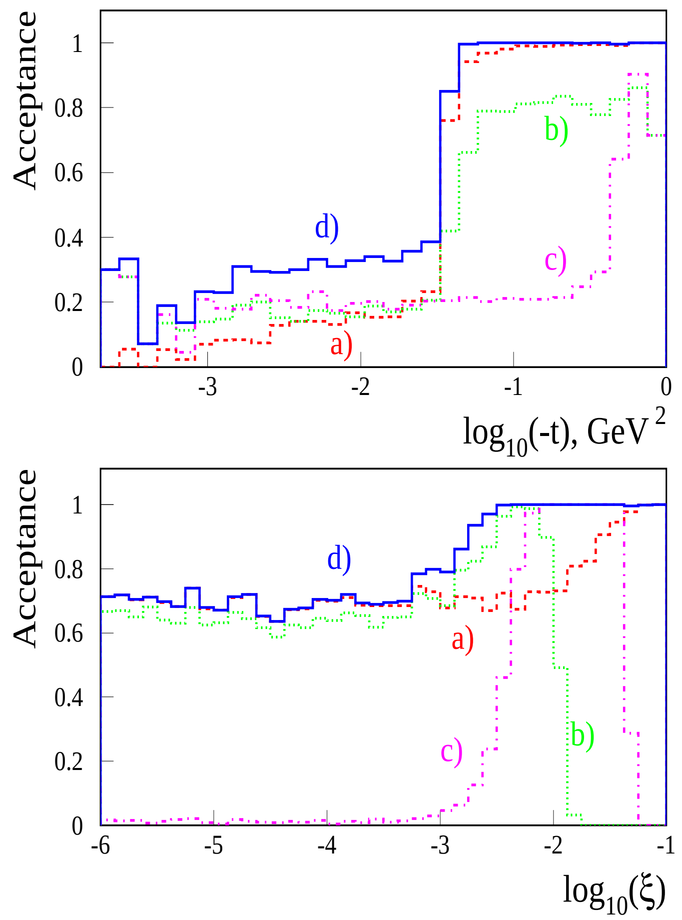
β^*=110 m, horizontal plane



10σ profile and trajectory of a proton with
Θ =50 μrad and $\xi = 2 \cdot 10^{-3}$

Diffraction

Proton acceptance as a function of t and ξ



a) near station

far stations

b) at Q11

c) at Q9

d) all stations

- $\sim$ 80% of all diffractive protons are detected
- protons are momentum analyzed for $\xi >$ few $\cdot\ 10^{-3}$ with a resolution of $\sigma(p)/p \sim$ few $\cdot\ 10^{-4}$

FELIX:

Detector costs (total):	$\sim$ 50 MCHF
Stageable (needed at start):	$\sim$ 35 MCHF
Integration into the LHC:	$\sim$ 24 MCHF
(beam line, magnets, infrastructure)	

$\Longrightarrow$ To get FELIX started
we need more collaborators

A strong community has to actively support NOW a "FELIX" - like experiment. Otherwise there is no chance for a full acceptance detector at the LHC

Is the HERA community interested?