Lecture:

Standard Model of Particle Physics

Heidelberg SS 2016

Experimental Tests of QED
Part 2

Overview

PART I

- Cross Sections and QED tests
- Accelerator Facilities + Experimental Results and Tests

PART II

- Tests of QED in Particle Decays
- QED Radiative Effects (Bremsstrahlung, Higher Order Processes)

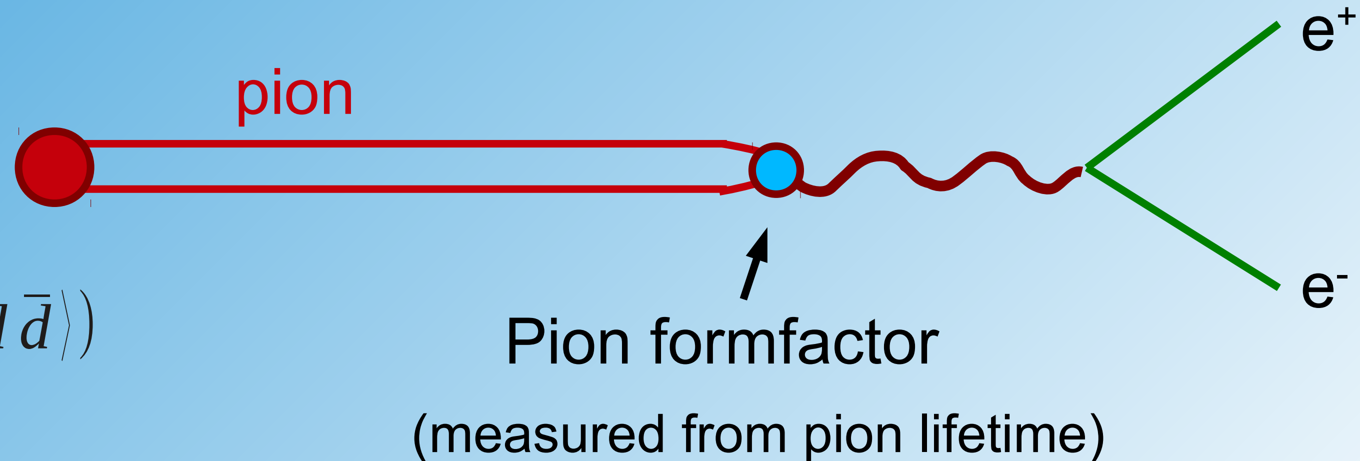
Electromagnetic Decay of Pion

- Pion is the lightest hadron (meson)
- consists of *u* and *d* quarks (isospin triplet)
- No strong or weak decay

Can the electromagnetic decay of the pion be described by QED?

Complication: quarks are involve large QCD corrections!

Solution: introduce pion form factor



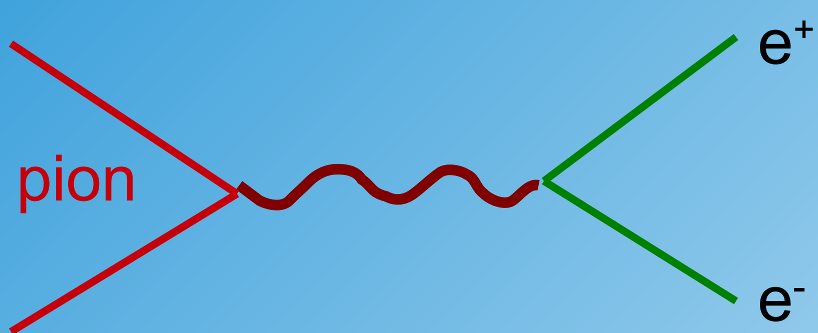
$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$$

Test Pion Branching Ratios

- dominant decay: $B(\pi^0 \rightarrow \gamma\gamma) = 98.823\ \%$
- radiative decay: $B(\pi^0 \rightarrow e^+e^-\gamma) = 1.174\ \%$
- 2-prong decay: $B(\pi^0 \rightarrow e^+e^-) = 6.46 \times 10^{-8}$

Can QED describe this surprisingly small branching ratio?

<u>Vector Currents</u>: $j^{\mu}_{elm} = \bar{v}(x)\gamma^{\mu}u(x)$ per photon/fermion vertex



- Vector currents conserve helicity.
- Resulting spin should be $J(\pi^0)=1$
- But pion is a Pseudo-scalar $J(\pi^0)=0$
  - ➜ contradiction → helicity suppression

Polarisation of helicity state is given by fermion velocity:

$\langle\lambda\rangle = \pm\beta$ for right/left chiralities

<u>Resulting suppression factor:</u>

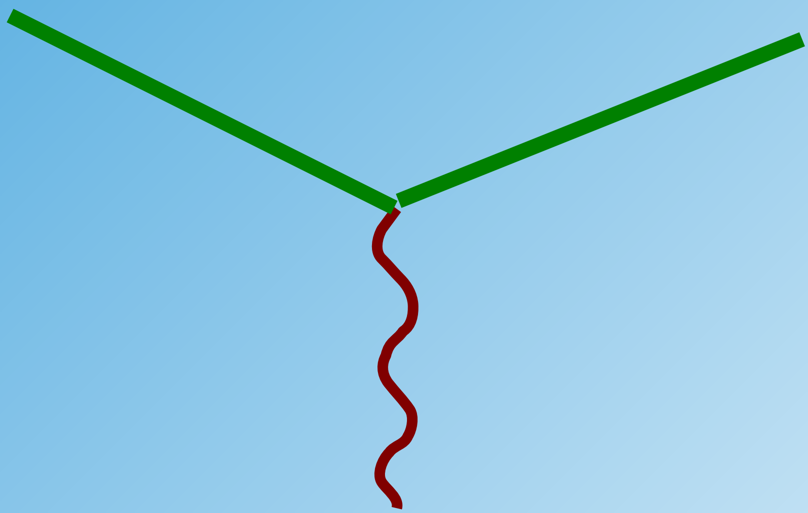
$$\frac{1}{16}\left(1-\beta_q^2\right)\left(1-\beta_e^2\right) = \frac{1}{16\,\gamma_q^2\gamma_q^2} = \frac{m_q^2 m_e^2}{m_\pi^4}$$

no scalar couplings!

$\sim 3 \cdot 10^{-8}$

QED Radiative Effects

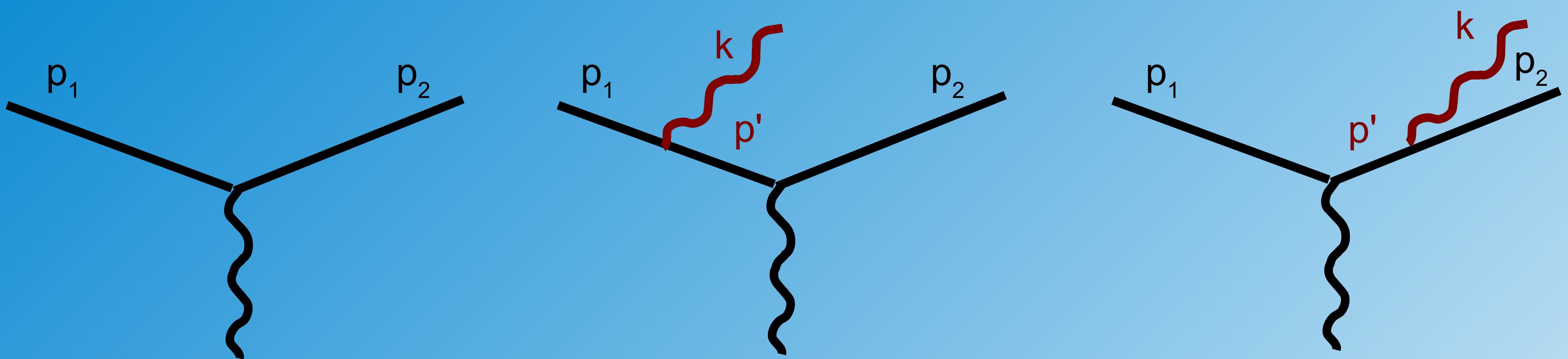
- **Bremsstrahlung**
- **Higher Order Processes**



Experimentally very important:

- can be exploited for measurements (luminosity, radiative returns)
- but can also disturb measurements!

QED First Order Corrections



initial state radiation (ISR) final state radiation (FSR)

Fermion propagator:

$$\frac{1}{p'^2-m^2}=\frac{1}{(p_1-k)^2-m^2} \qquad \frac{1}{p'^2-m^2}=\frac{1}{(p_2+k)^2-m^2}$$

ISR:

$$\frac{1}{(p_1-k)^2-m^2}=\frac{1}{p_1^2+k^2-2p_1k-m^2}=\frac{1}{-2p_1k}\approx\frac{1}{-2E_eE_\gamma(1-\cos\theta)}$$

(if mass small)

Singularities:

- photon emission under zero degrees $\theta\rightarrow 0$
- soft photon $E_\gamma\rightarrow 0$

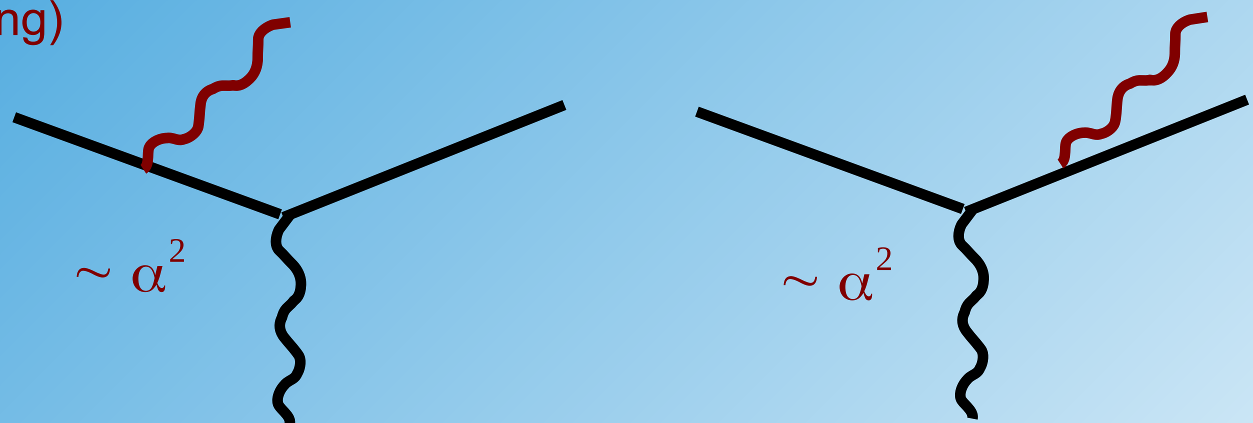
FSR: similar

ISR + FSR: interference term shows no singularity (wide angle scattering)

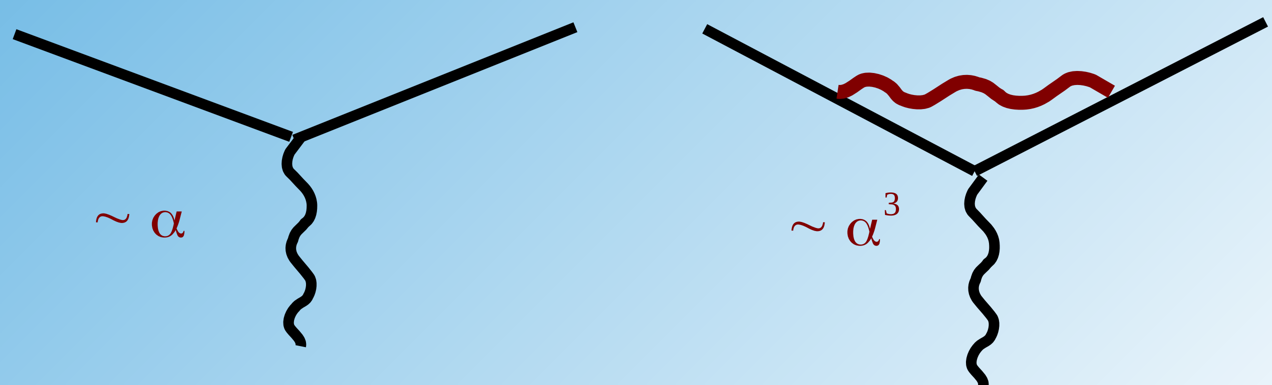
QED First Order Corrections

- Singularities are not allowed in (renormalisable) gauge theories and have to cancel
- Singularity from “soft” and collinear Bremsstrahlung cancel with virtual vertex corrections in QED

“real corrections” (Bremsstrahlung)



virtual correction:

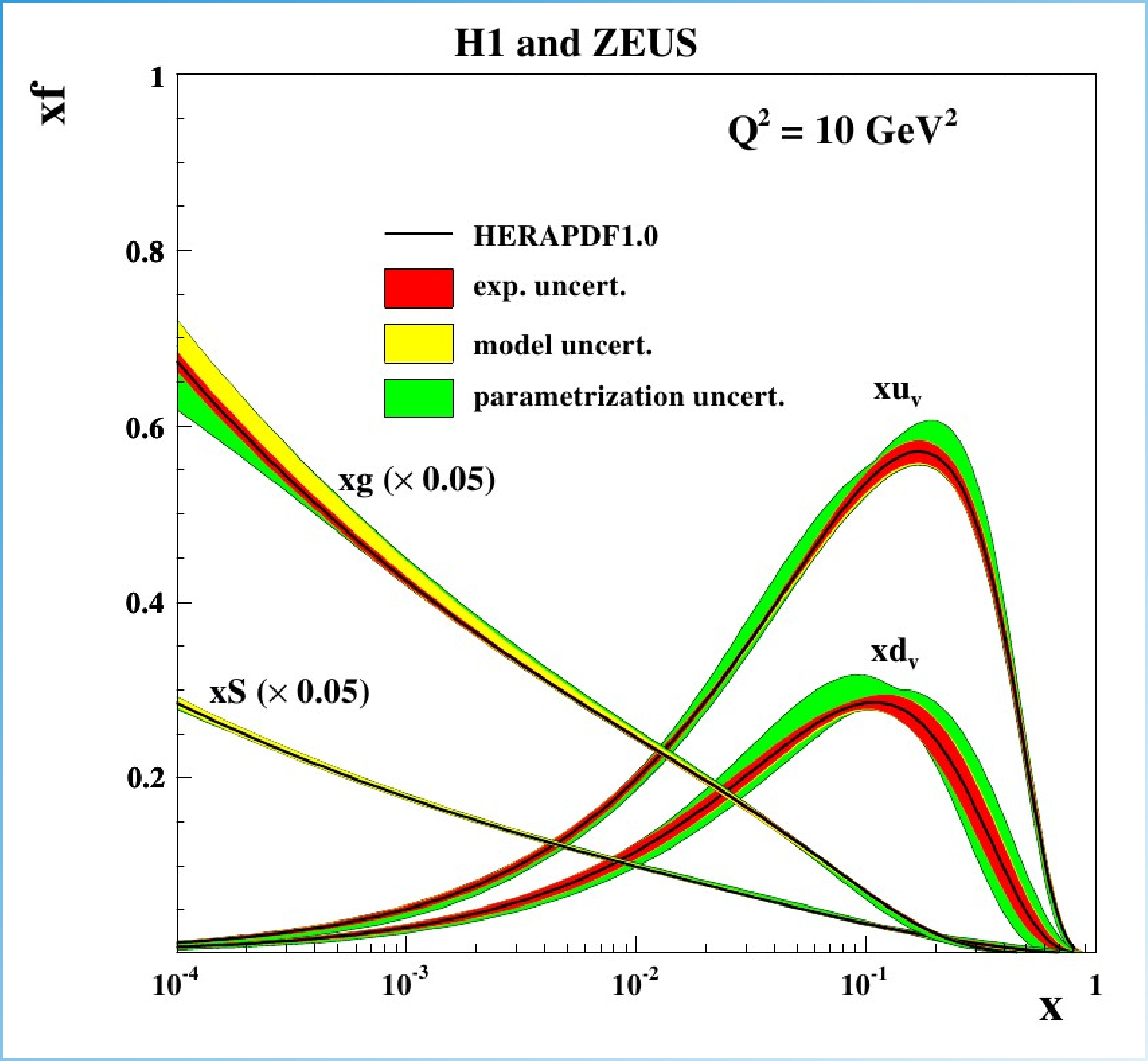


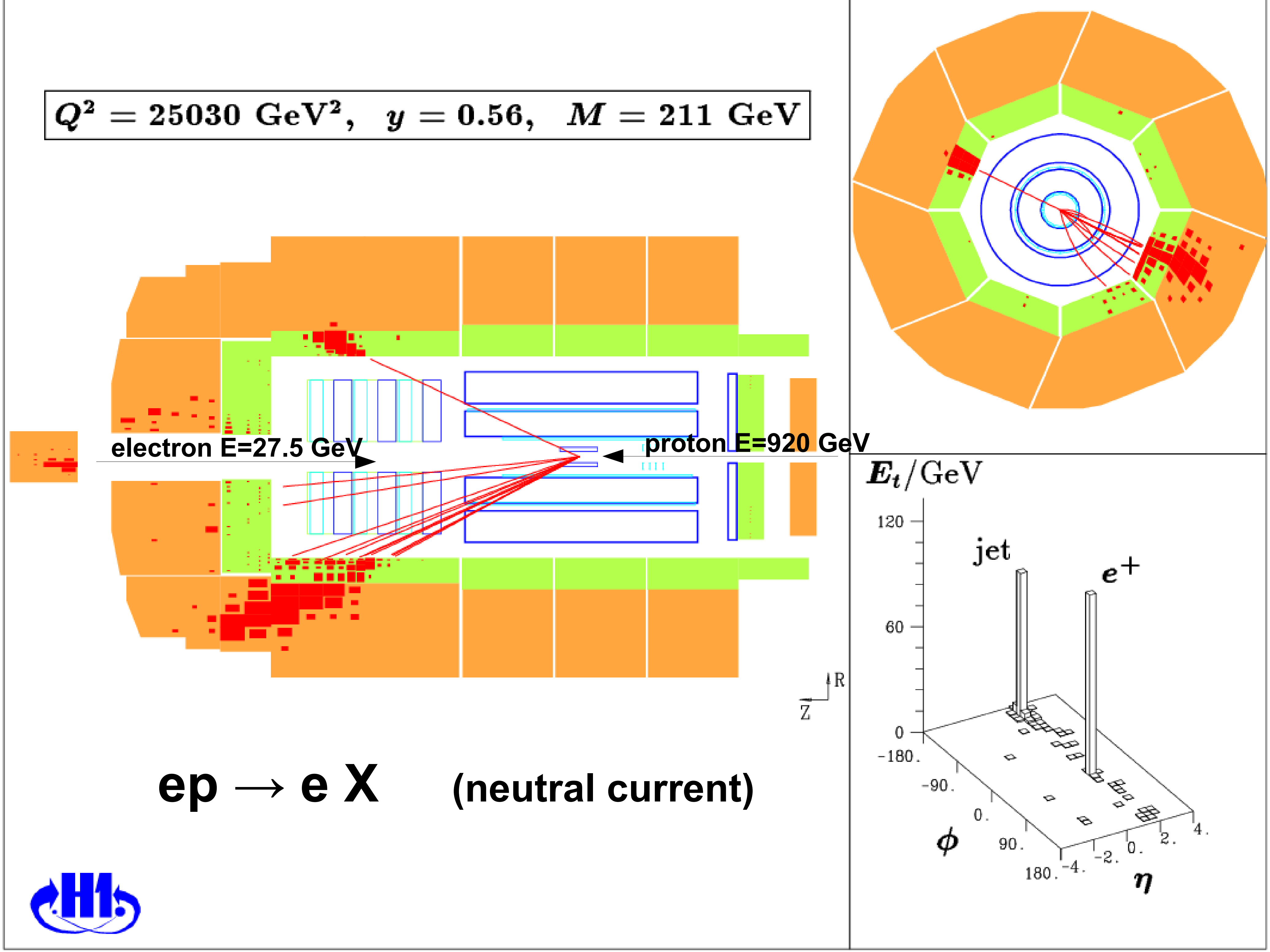
interference of LO diagram and vertex correction $\sim \alpha^2$ compensates singularities from Bremsstrahlung

Electron-Proton Collider HERA

E_e = 26.7 GeV E_p = 920 GeV

Proton Parton Densities



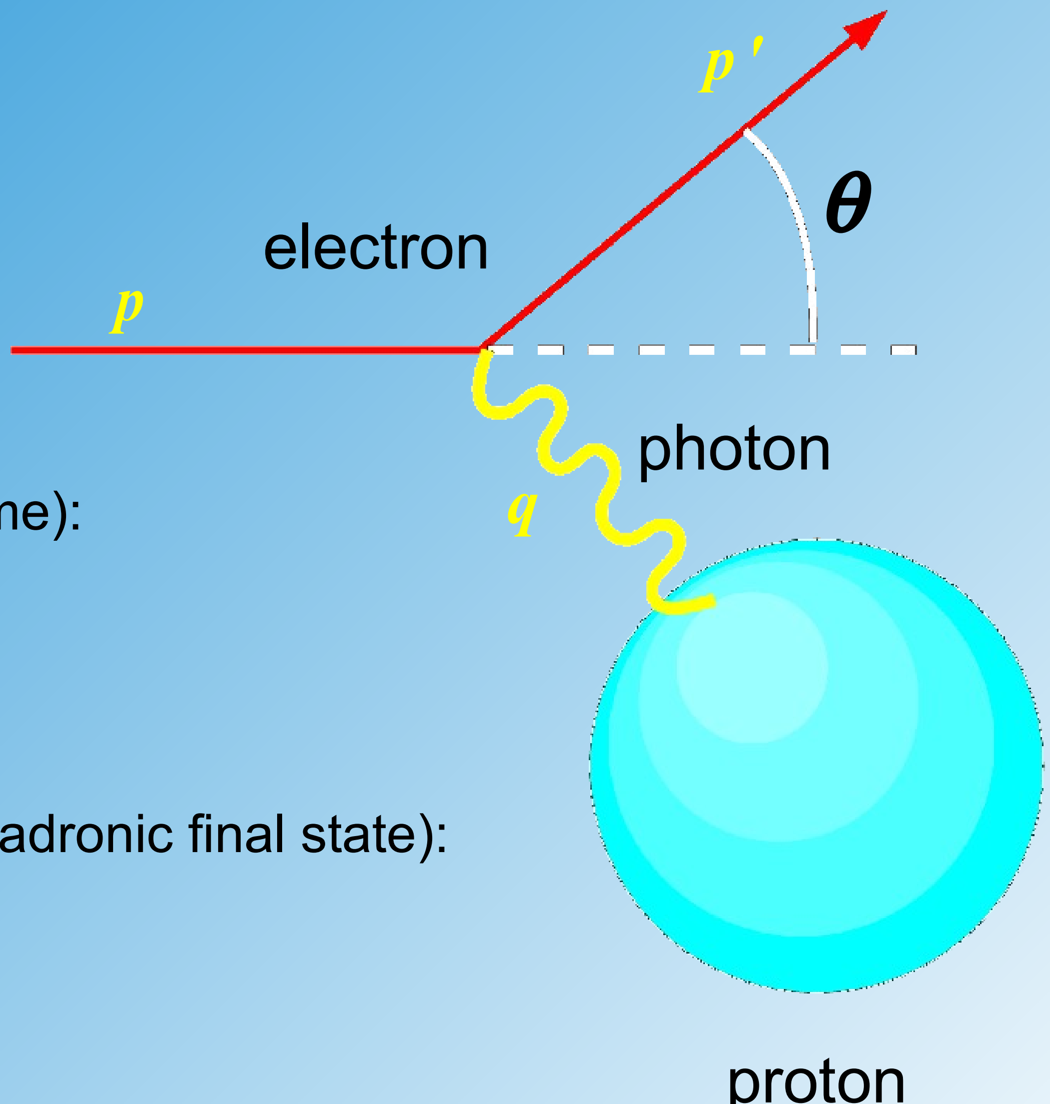


$Q^2 = 25030\ \mathrm{GeV}^2,\quad y = 0.56,\quad M = 211\ \mathrm{GeV}$
electron E=27.5 GeV
proton E=920 GeV
R
Z
E_t/GeV
120
60
0
jet
e^+
-180.
-90.
0.
90.
180.
ϕ
-4.
-2.
0.
2.
4.
η
ep → e X (neutral current)

Kinematics Scattering Process

The virtuality of the exchanged photon is given by:

$$Q^2 = -q^2 = -(p - p')^2 \propto \frac{1}{\sin^4 \theta/2}$$



Energy transfer (in Proton-rest frame):

$$\nu = E_{Elektron} - E_{Elektron}'$$

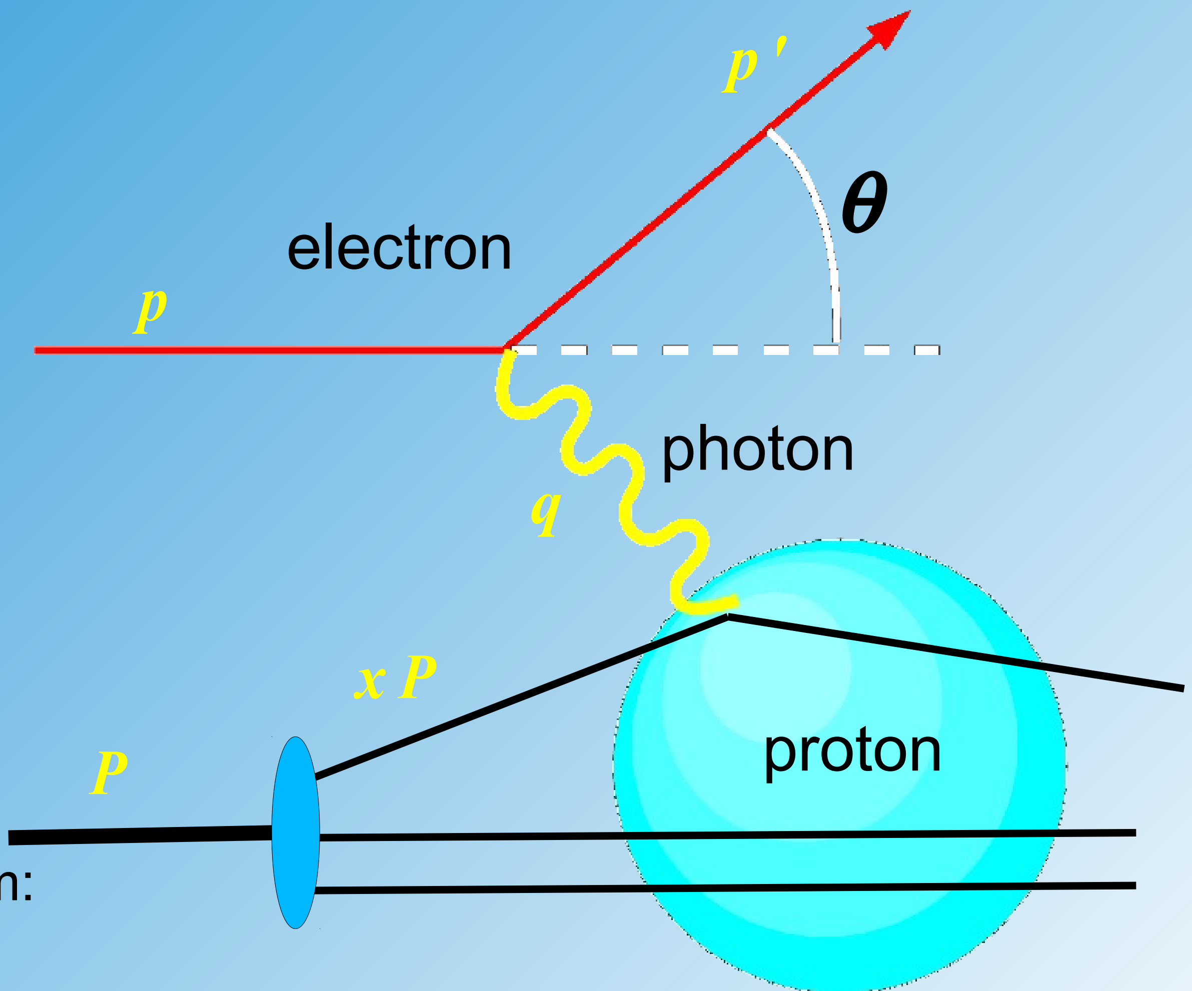
Energy of photon-proton system (hadronic final state):

$$W = m_p + \nu$$

Lorentz Invariant Kinematics of Deep Inelastic Scattering Process

The virtuality of the exchanged photon is given by:

$$Q^2 = -q^2 = -(p - p')^2 \propto \frac{1}{\sin^4 \theta/2}$$



Relative energy loss (inelasticity):

$$y = \frac{\nu}{E_{Elektron}} = \frac{q\,P}{p\,P}$$

relative fraction of parton momentum:

$$x = \frac{q^2}{2\,q\,P} = \frac{Q^2}{s\,y}$$

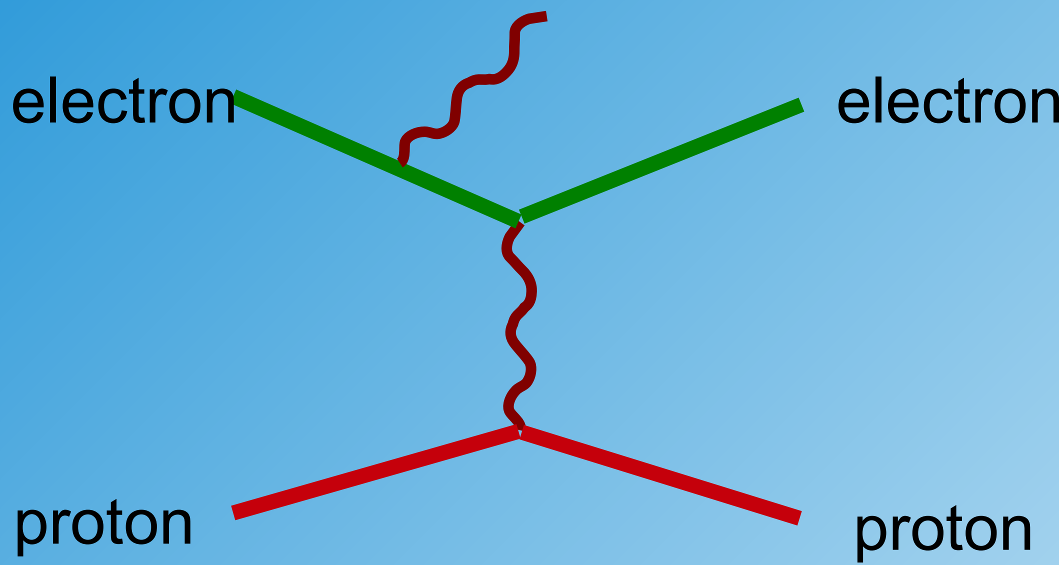
with cms energy: $s = 2\,p\,P$

Determination of Luminosity?

Reference Process

Need process with large cross section

- Bethe Heitler Process: e p → ep γ
- Bremsstrahlung-Process with large cross section (~ 1 barn)!



Note,

- the proton stays intact (elastic)!
- the cross section can only be measured with a minimum photon energy cut! → infrared singularity

Radiative Effects in Electon-Proton Scattering

Bremsstrahlung effects are large for particles with low mass

Electron mass: m_e = 0.511 MeV → heavy radiation!

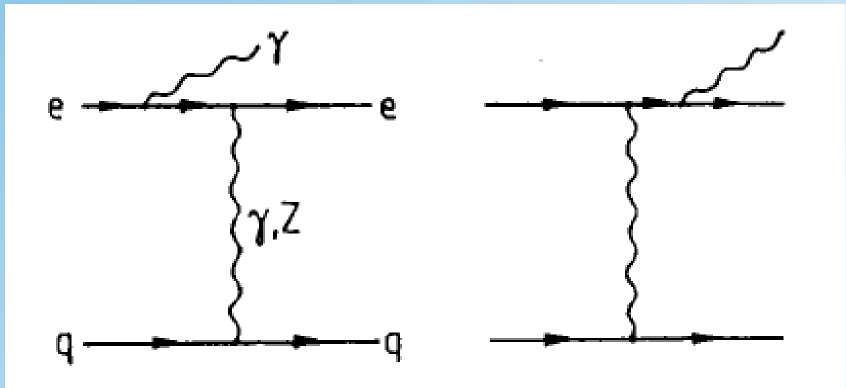
Proton mass: m_p = 938 GeV

Radiation is large if

1. photon is **soft**
2. photon is emitted **collinear**

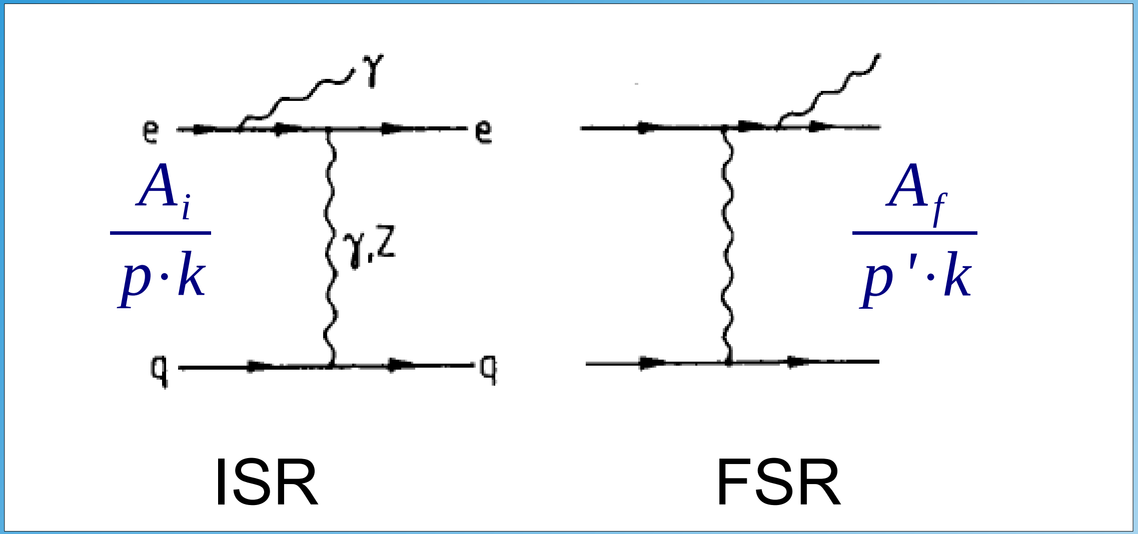
Photons can be emitted from

1. incoming electron (initial state radiation, **ISR**)
2. outgoing electron (final state radiation, **FSR**)

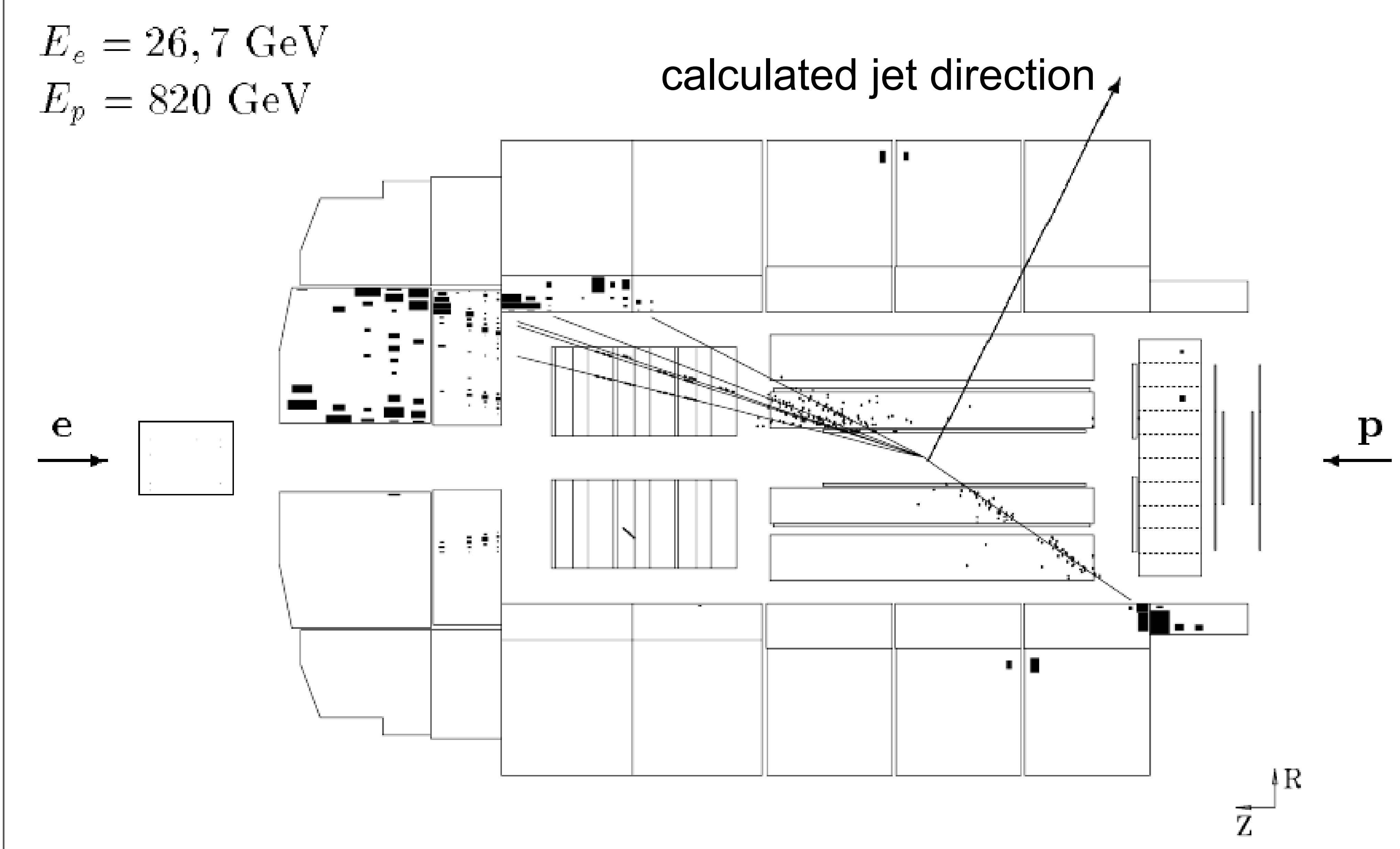


Radiative Poles

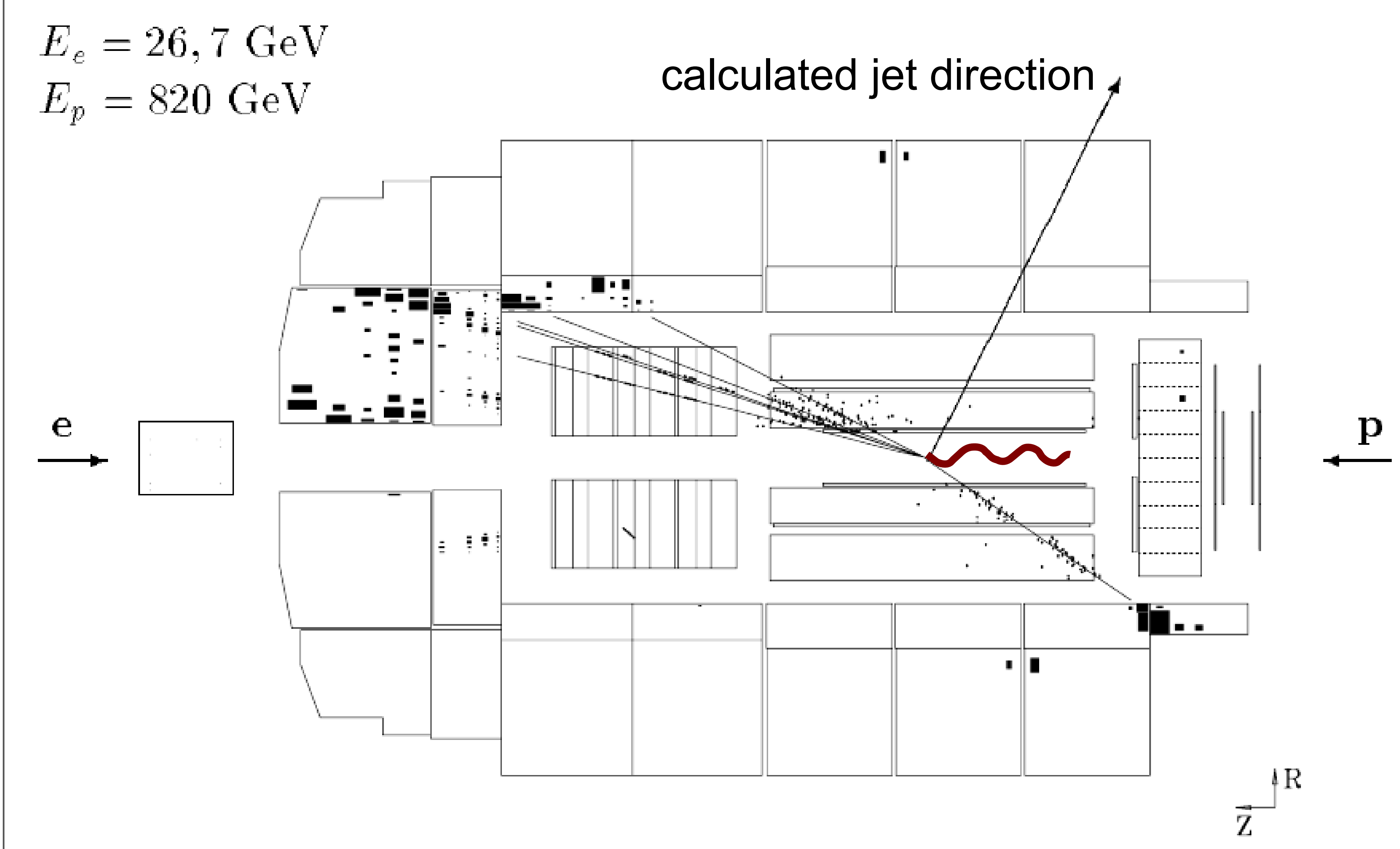
Neglecting the small electron mass, the poles become:



Note ISR reduces the available center of mass energy $s^{1/2}$



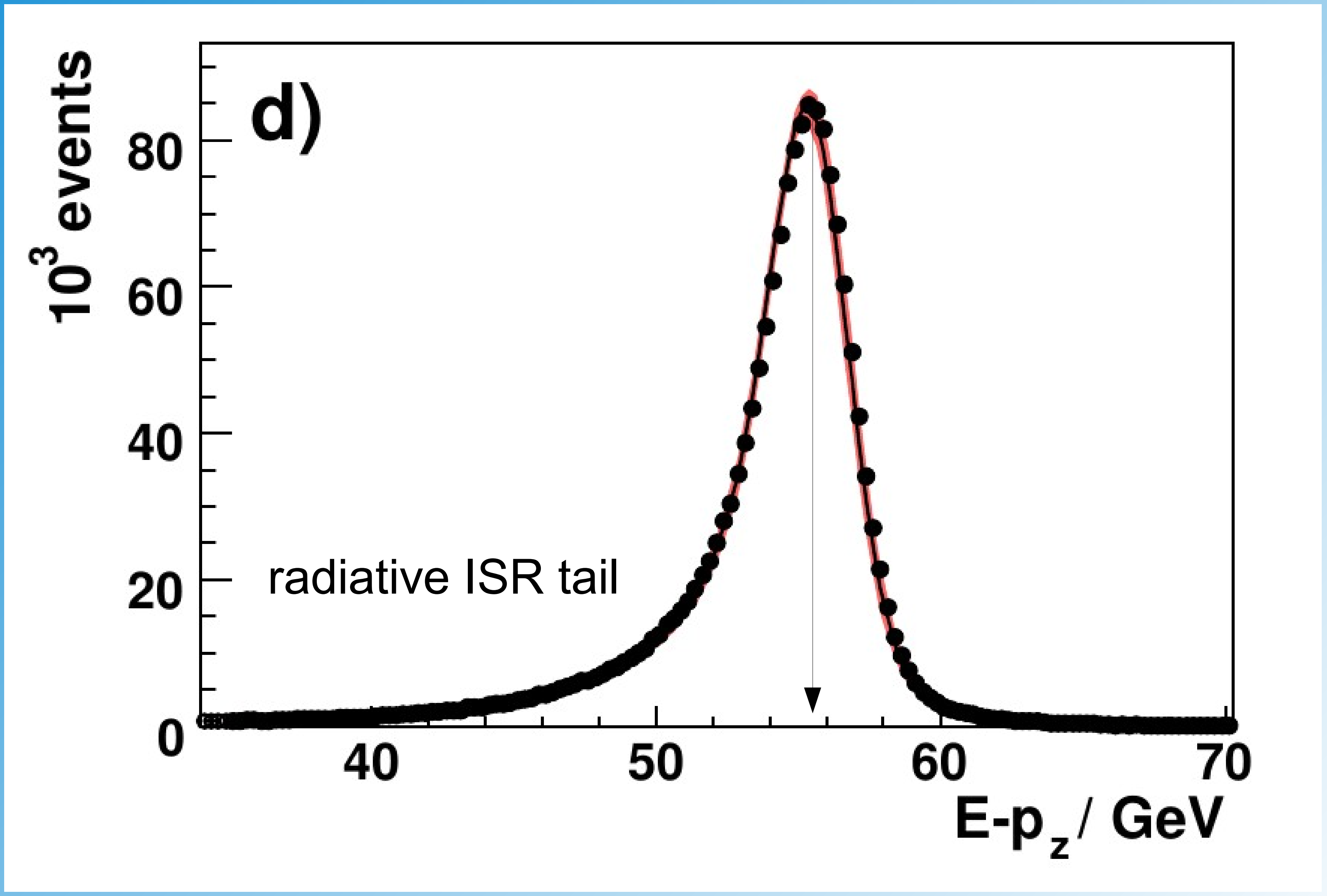
Initial State Radiation?



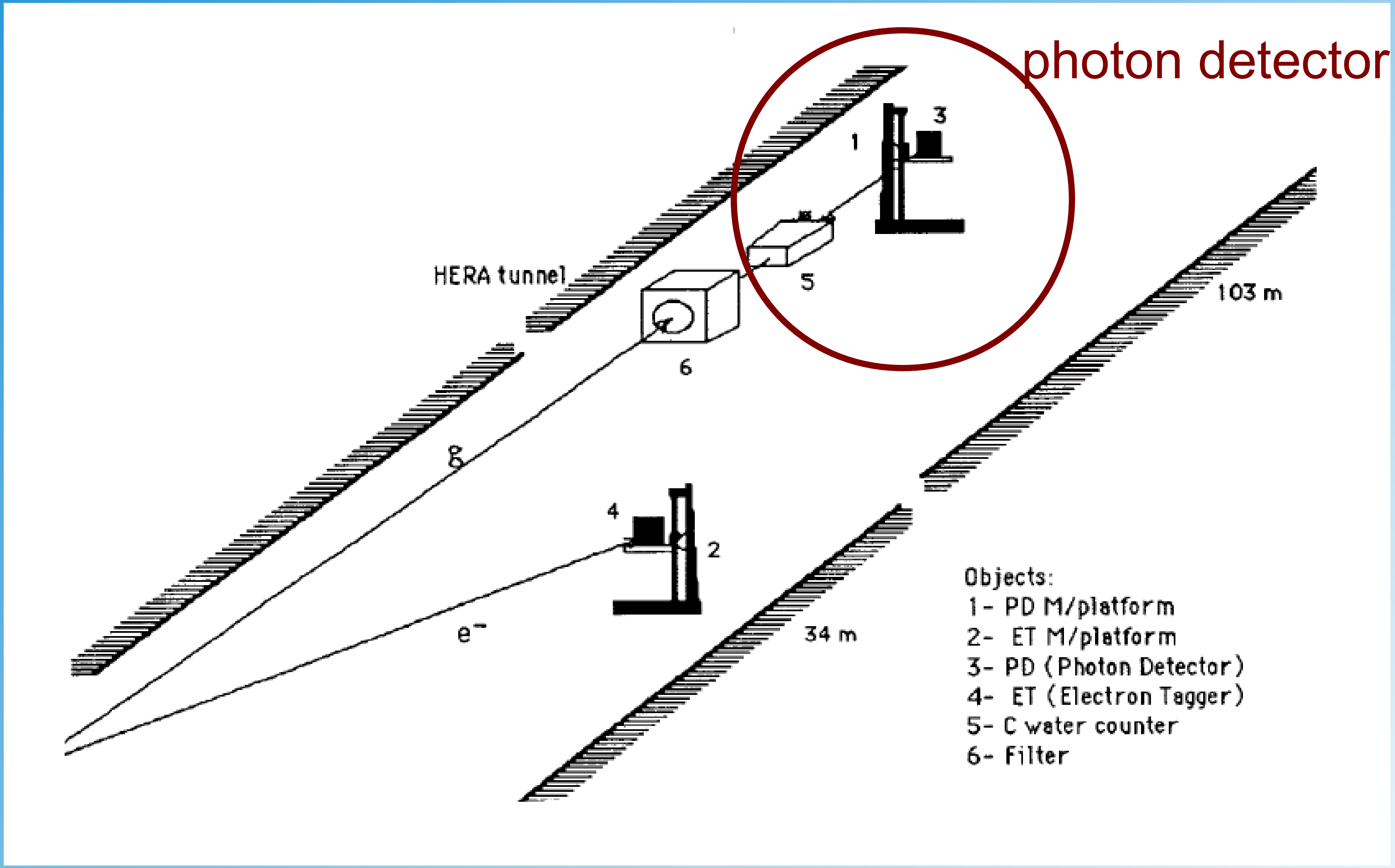
Energy *E* conserved and momentum *p* conserved *E-p_z* conserved

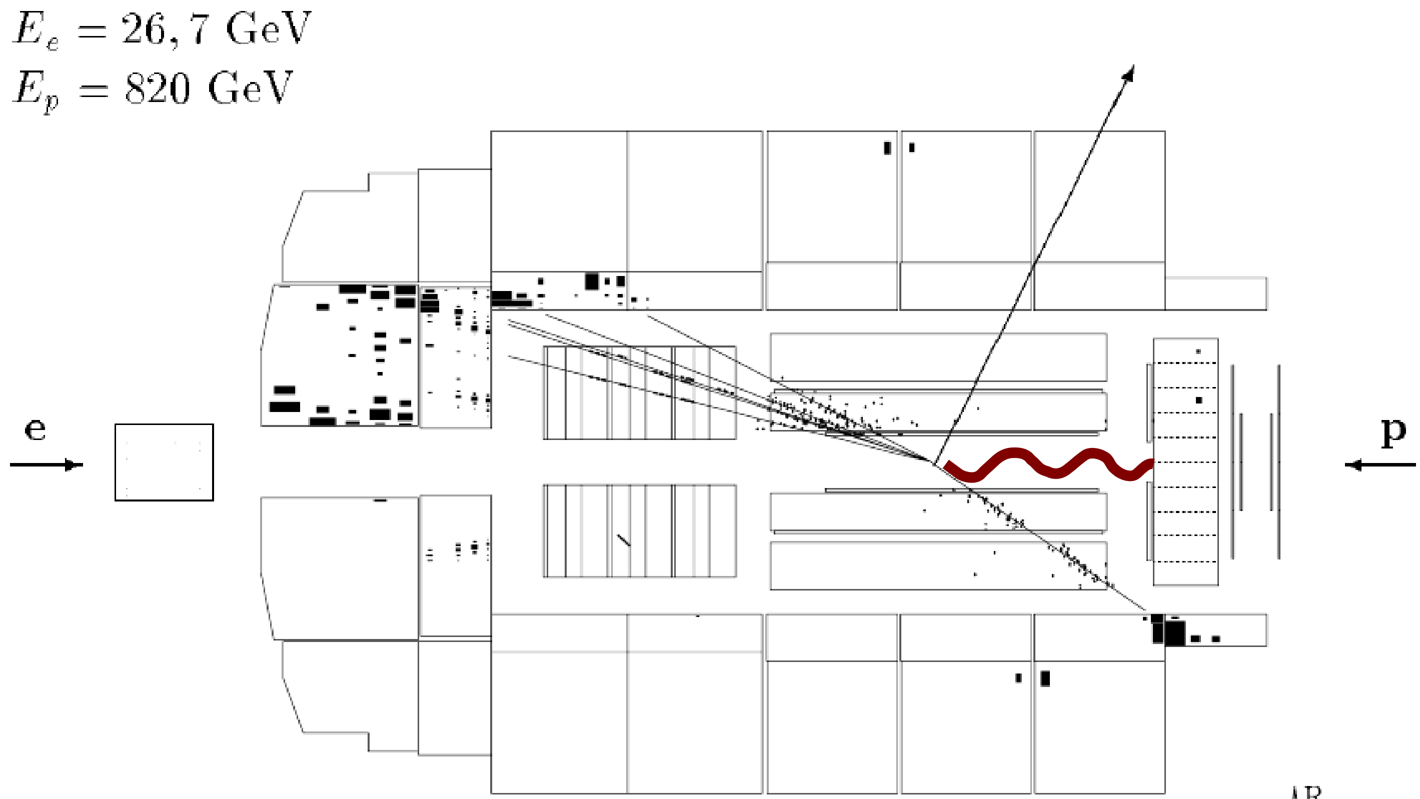
E-p_z (proton)=0 E-p_z (electron) = 2 x 26.7 GeV

Kinematic Reconstruction of ISR

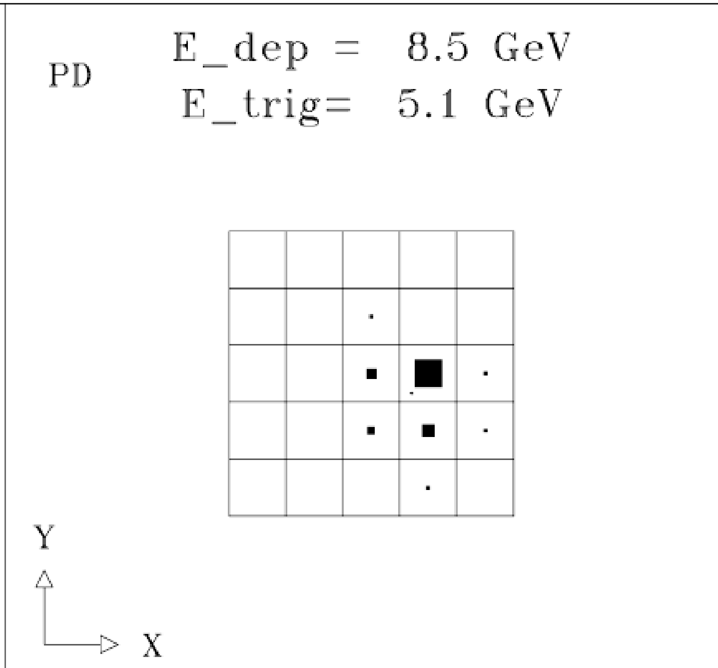


Photondetector at H1

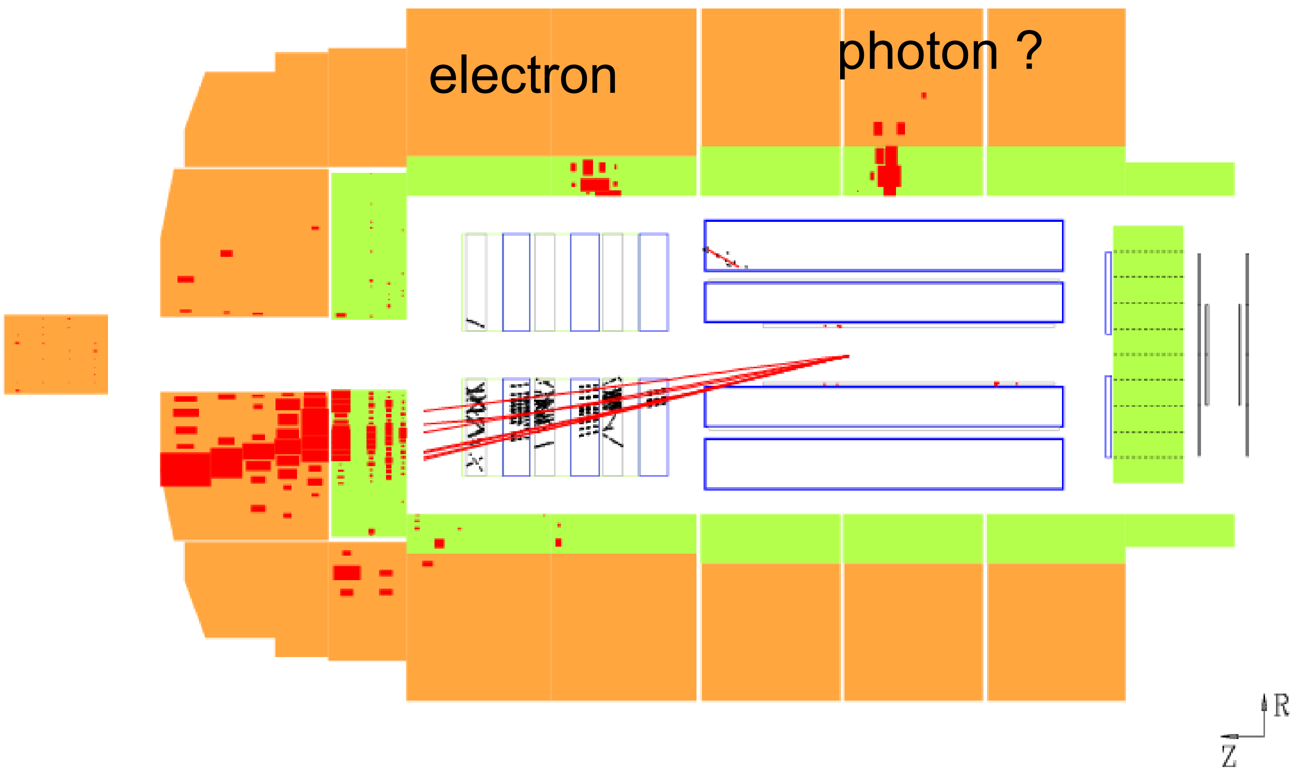


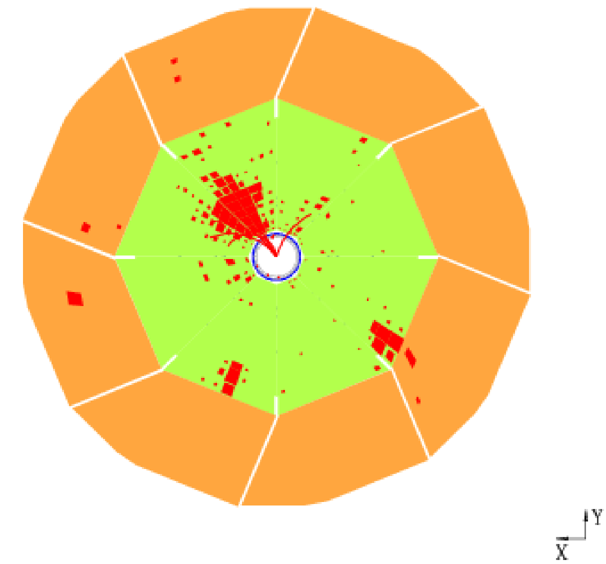


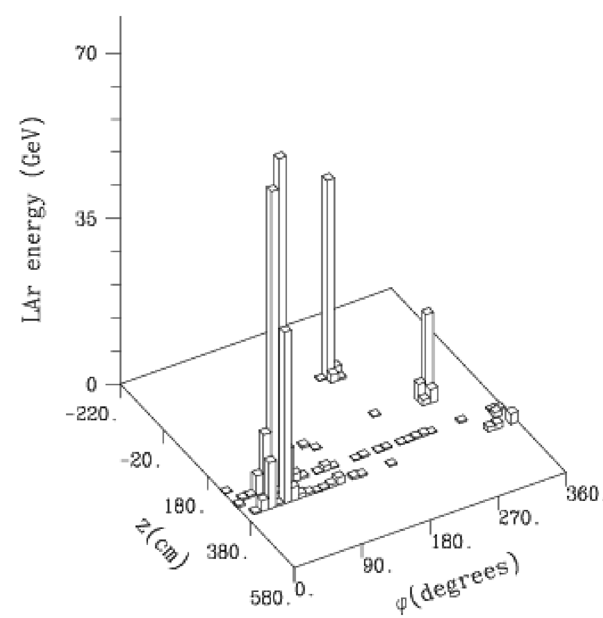
Initial State Radiation?



NC - DIS with hard Photon



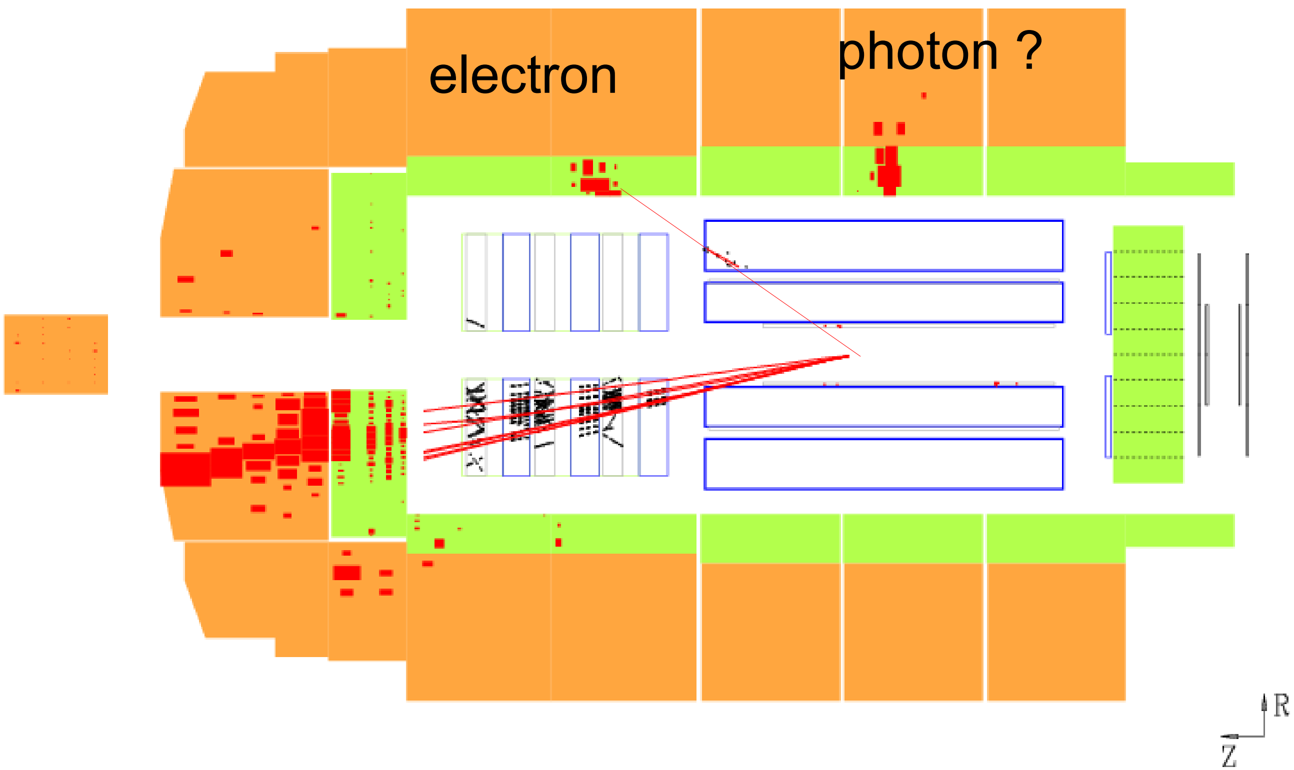


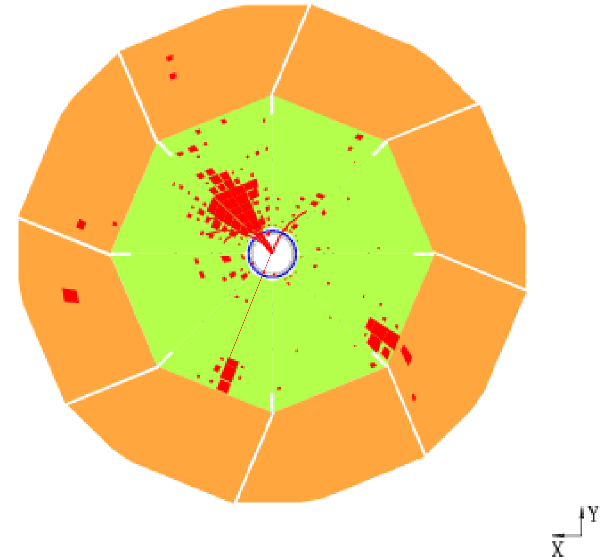


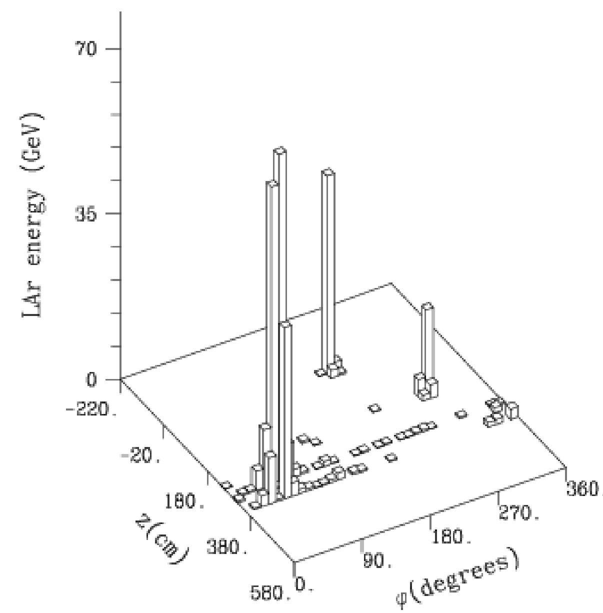
Inner Drift Chamber operational?

Final State Radiation?

NC - DIS with hard Photon



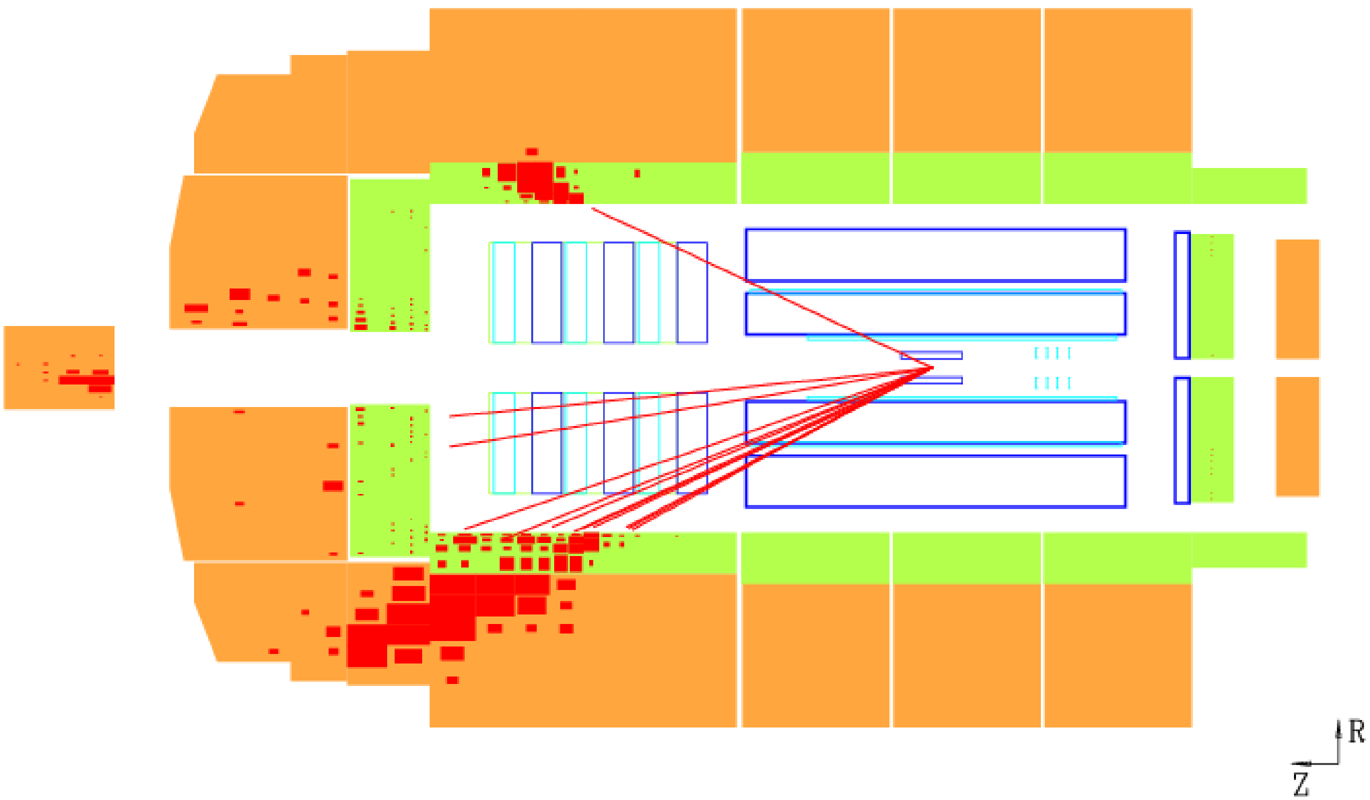


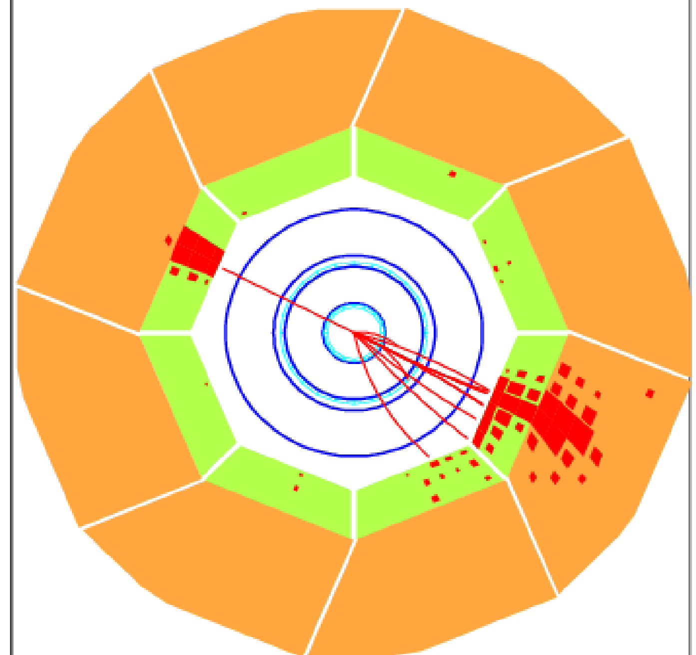


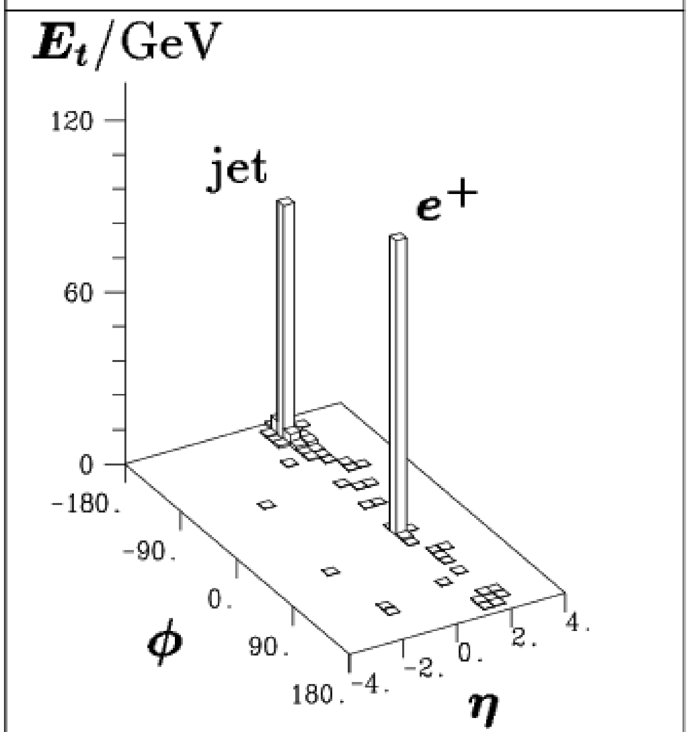
Inner Drift Chamber operational?

Final State Radiation?

$$Q^2 = 25030\ \mathrm{GeV}^2, \quad y = 0.56, \quad M = 211\ \mathrm{GeV}$$





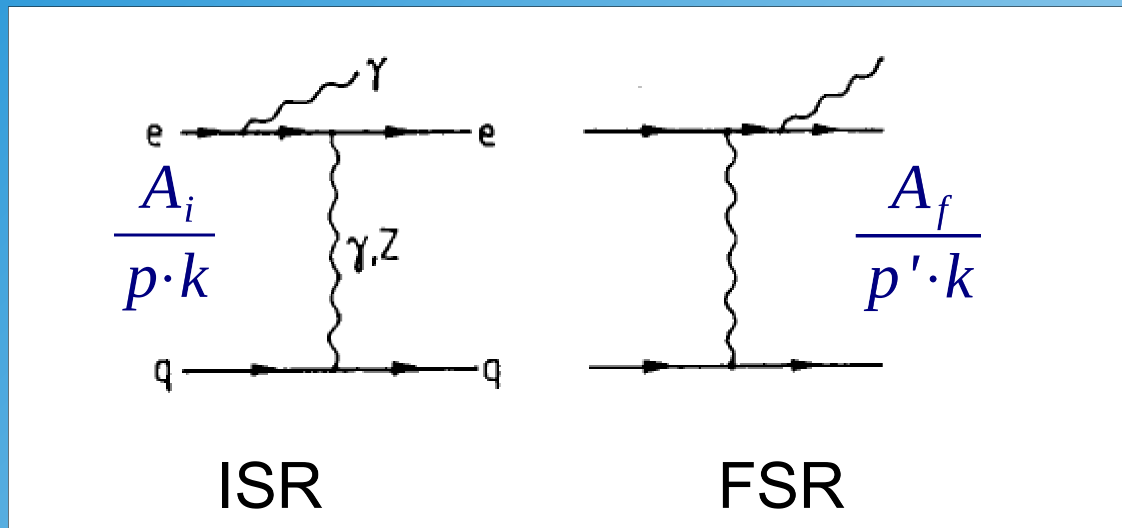


Question: Final State Radiation?

collinear photon can not be resolved!

Radiative Poles II

Neglecting the small electron mass, the poles become:



$$\frac{A_i}{p \cdot k} \qquad \frac{A_f}{p' \cdot k}$$

Note ISR reduces the available center of mass energy $s^{1/2}$

- There is a third pole ("Compton" events / Wide Angle Bremsstrahlung):

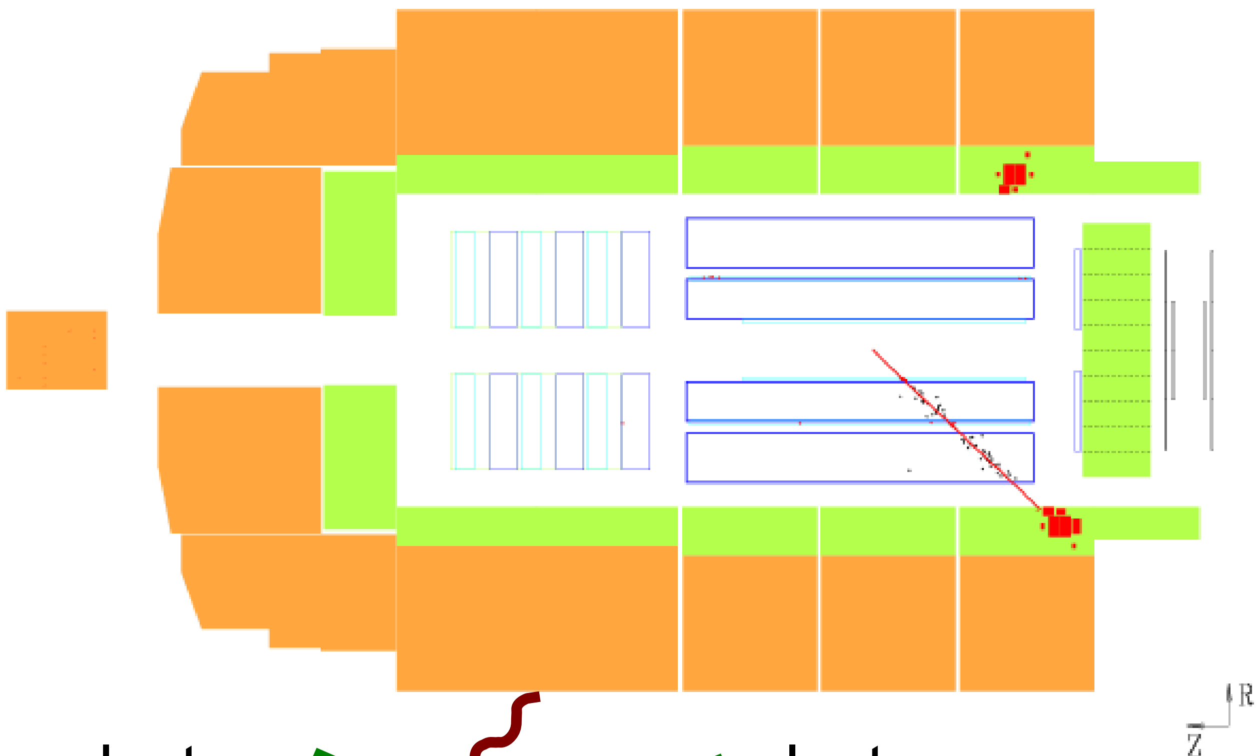
$$\frac{A_c}{(p - p' - k)^2} = \frac{1}{q^2}$$

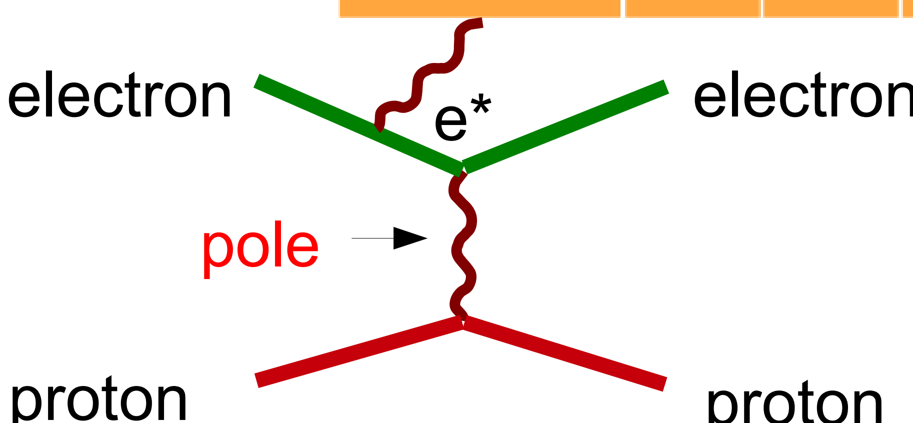
(energy is transferred from the proton to the electron line)

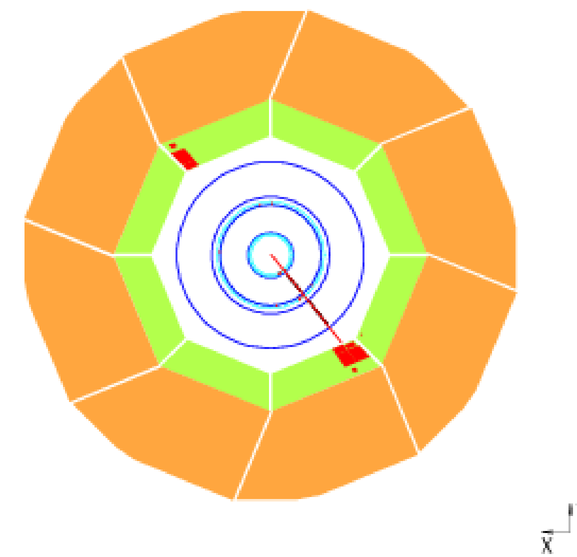
Final state electron and photon have large opening angles and are p_T balanced

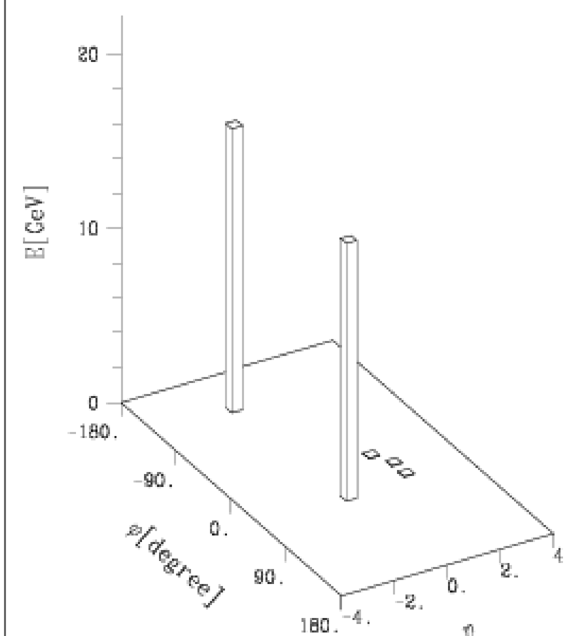
QED Compton

ep → ep γ



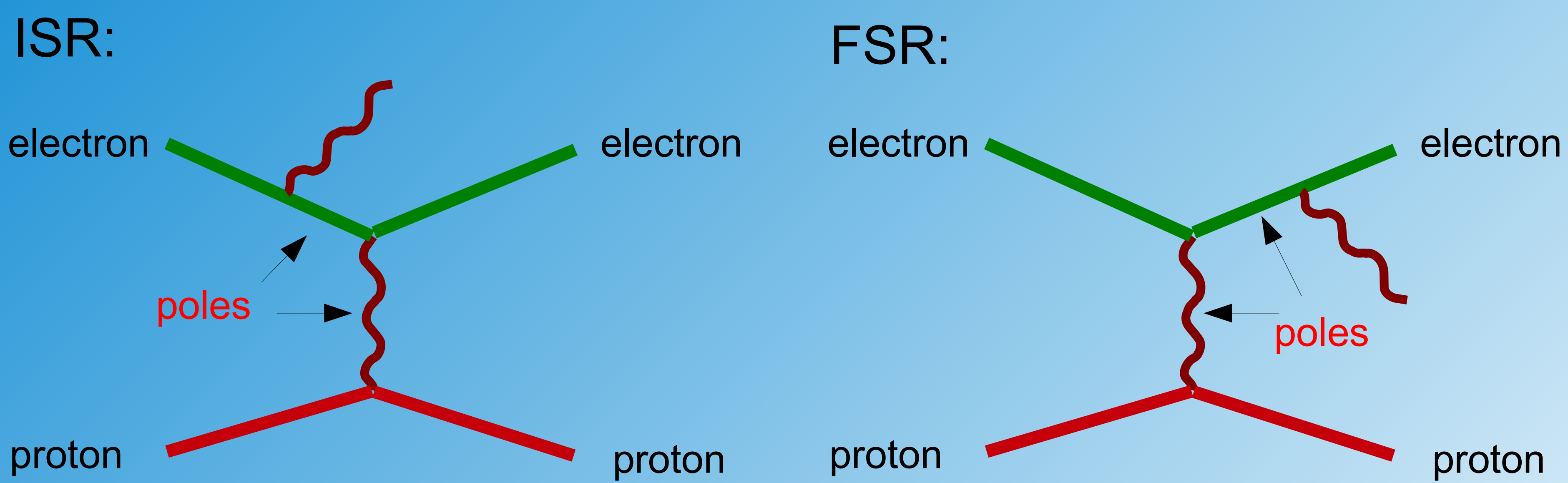






Bethe-Heitler Process

process: ep → ep γ



Cross section is largest if electron and photon are scattered (emitted) at small angle (Compton and ISR/FSR poles combined)

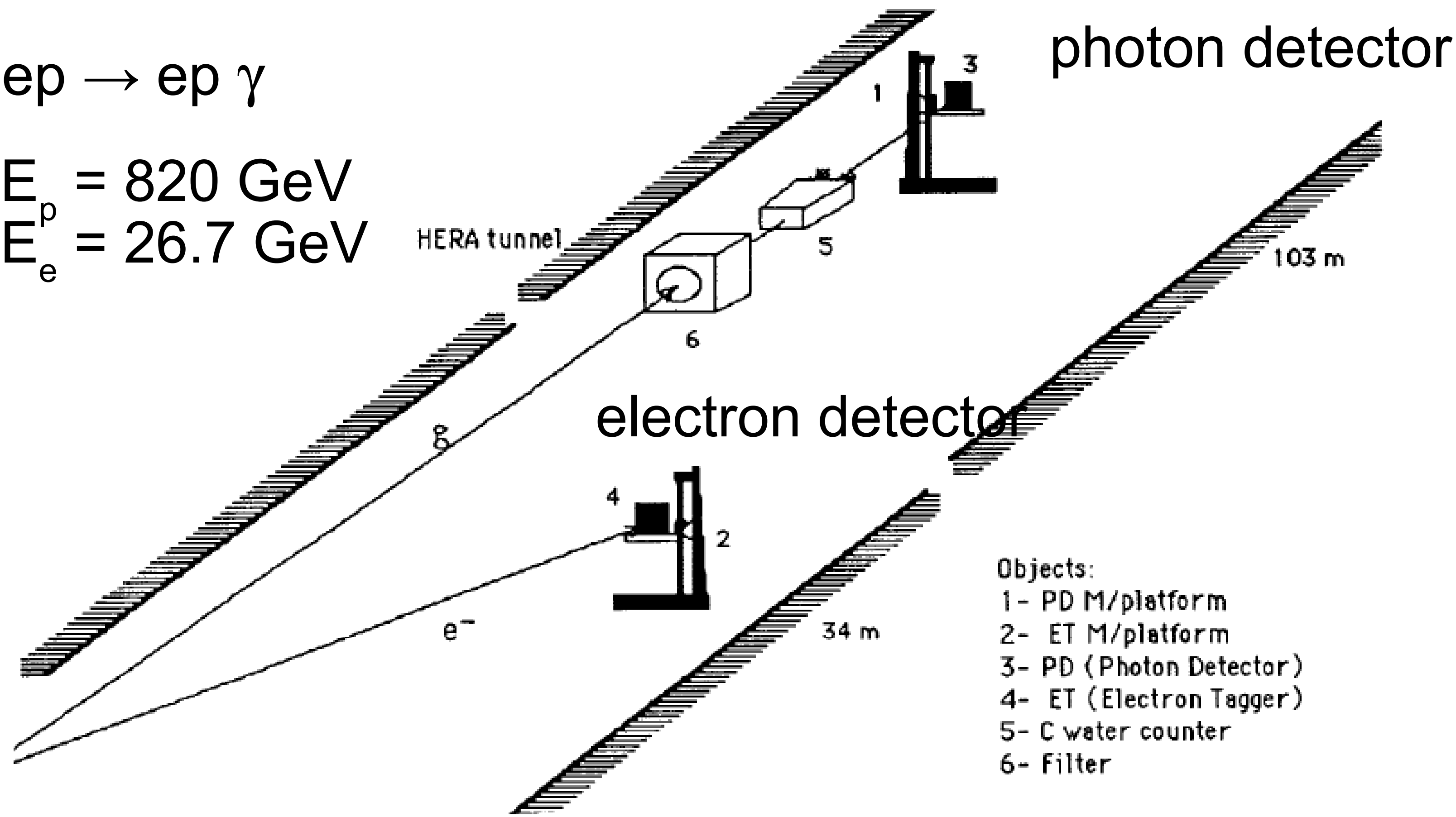
Electron and photon go down the beampipe and are not registered in the central detector

Luminosity Measurement at HERA

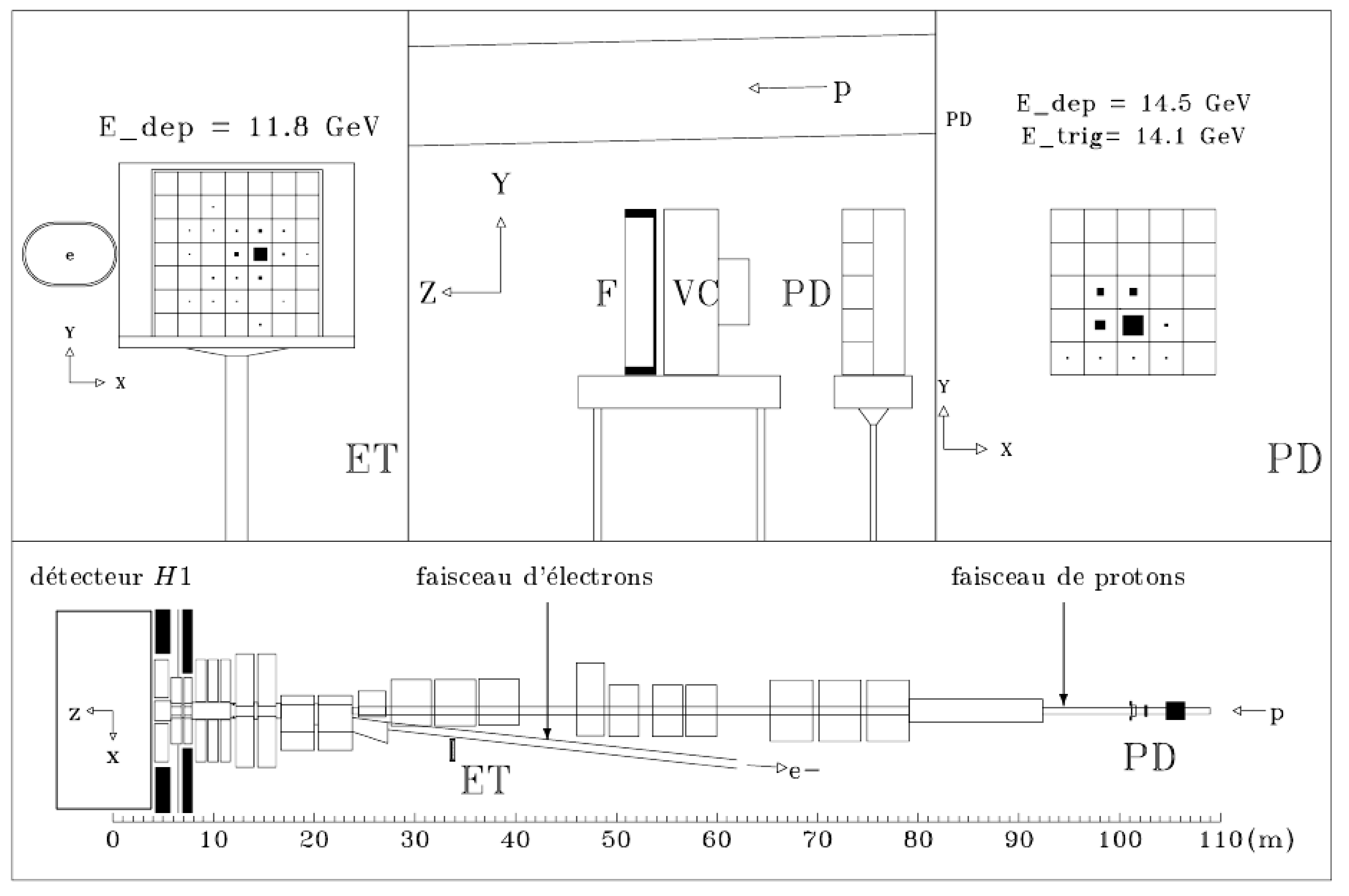
dedicated electron and photon detectors

$ep \rightarrow ep\,\gamma$

$E_p = 820$ GeV
$E_e = 26.7$ GeV



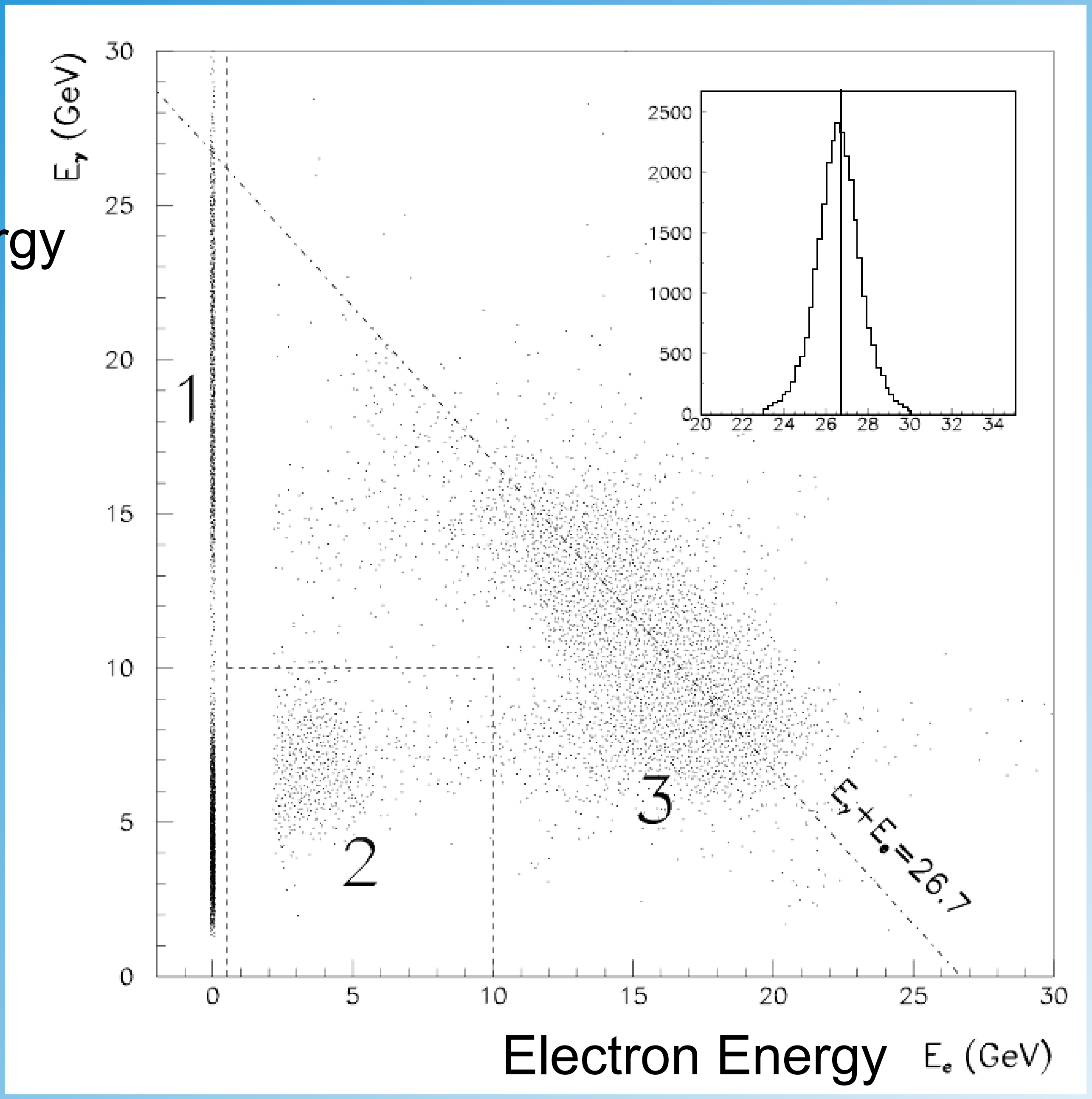
H1 Luminosity Detectors



Method: measure coincidence signal

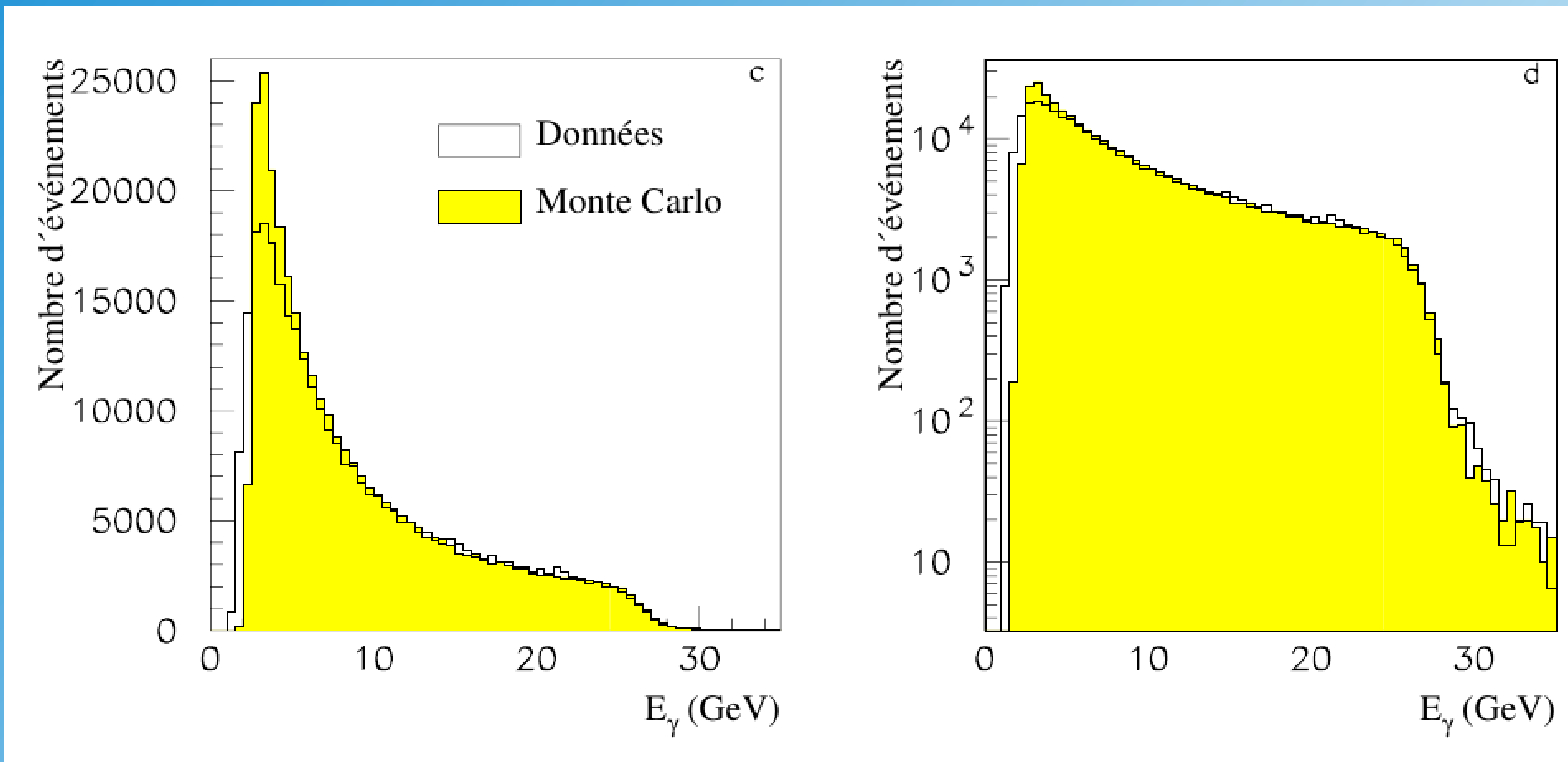
Coincidence Technique

Photon Energy



Data Monte Carlo Comparison

Photon Detector Energy



Principle of Luminosity Measurement

Time integration of the instantaneous luminosity:

$$\mathcal{L}_{\mathrm{b}} = \int_0^{\Delta T} L_{\mathrm{b}}(t)\mathrm{d}t$$

Relation between photon counts, Bethe-Heitler cross section and integrated Luminosity

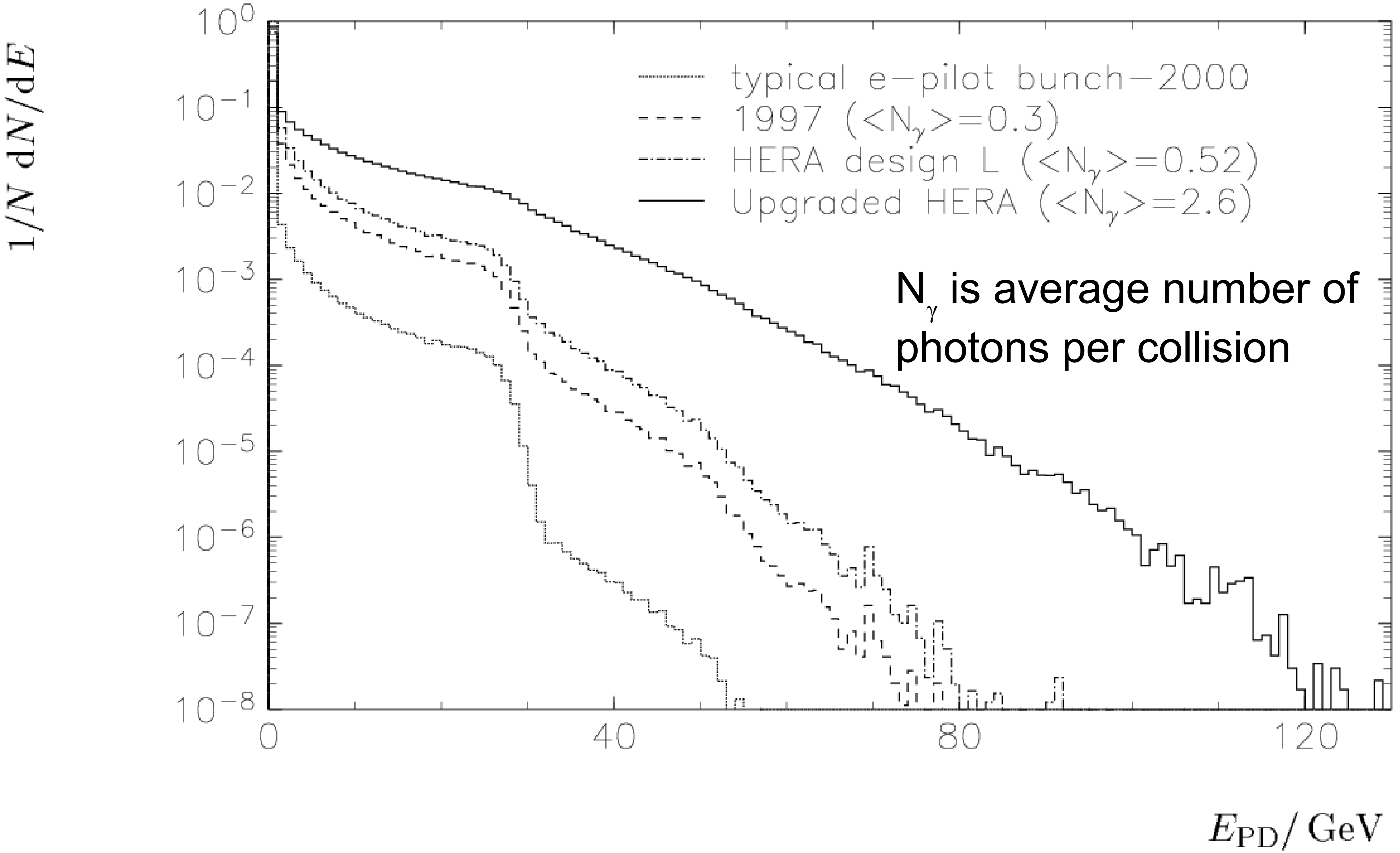
$$N_\gamma(E > \epsilon) = \mathcal{L}_{\mathrm{b}} A \int_\epsilon^\infty \frac{\mathrm{d}\sigma_{\mathrm{BH}}}{\mathrm{d}E}\mathrm{d}E$$

Breakdown of Systematic Errors

Item	Online Actual	Offline Actual	Online Upgrade
Theoretical uncertainty	0.5	0.5	0.5
Trigger efficiency	0.1	0.1	–
Background subtraction	0.3	0.2	0.2
Pile up corrections	0.3	0.2	–
Photon detector acceptance	1.0	0.6	0.5
E-scale, resolution	2.0	0.7 – 1.2	0.6
p-bunch satellites	2.0	0.5 – 1.0	

Pileup Correction →

Effect of Pileup

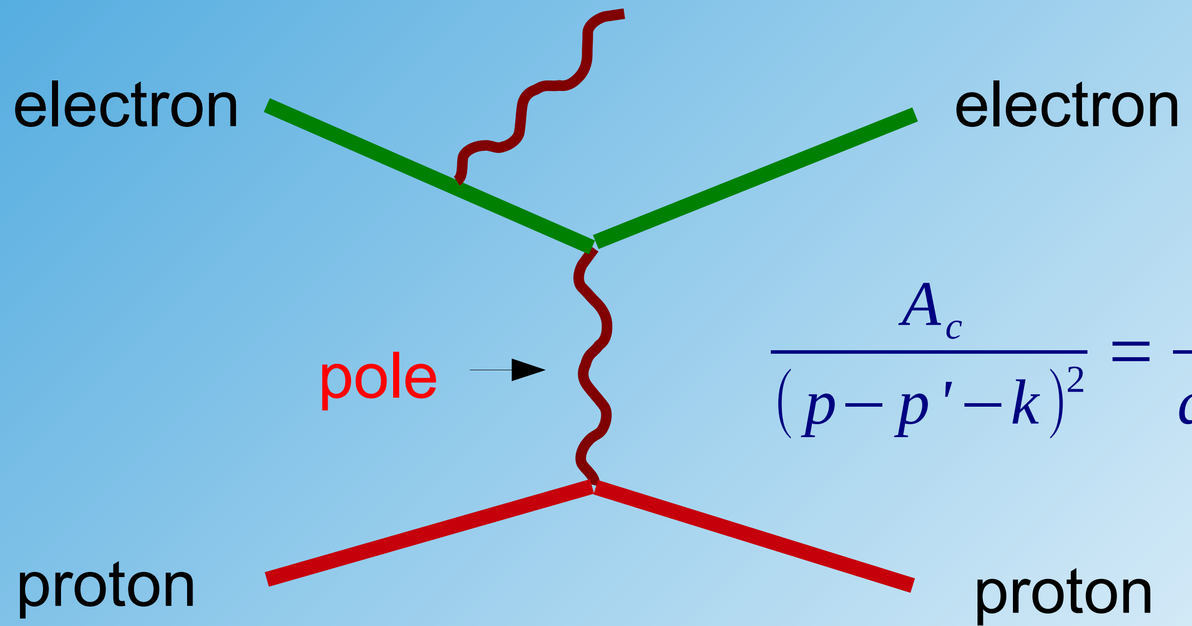


N_γ is average number of photons per collision

QED Compton Analysis

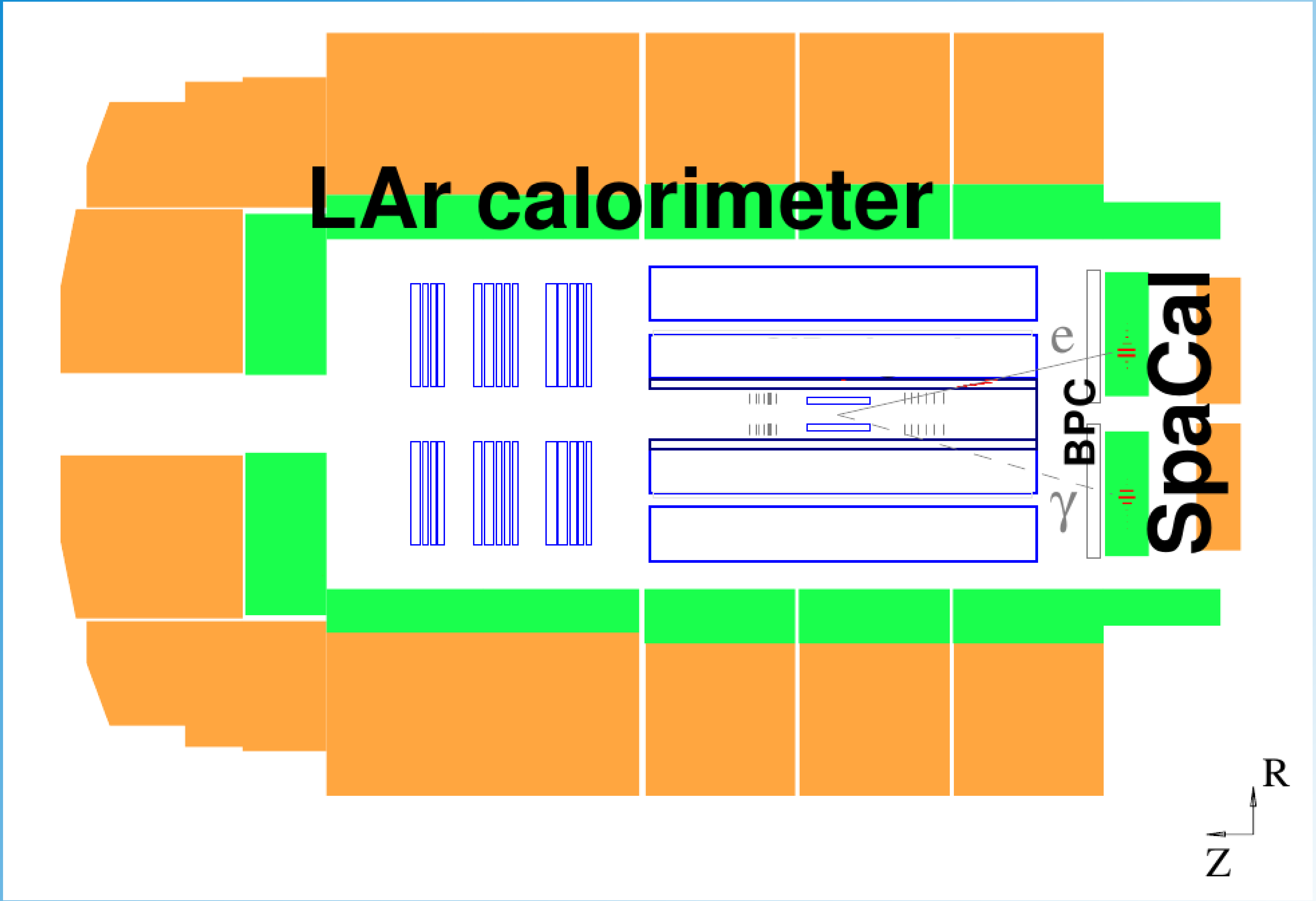
2nd method:

Determination of the Integrated Luminosity in the H1 Experiment at HERA using Elastic QED Compton Events



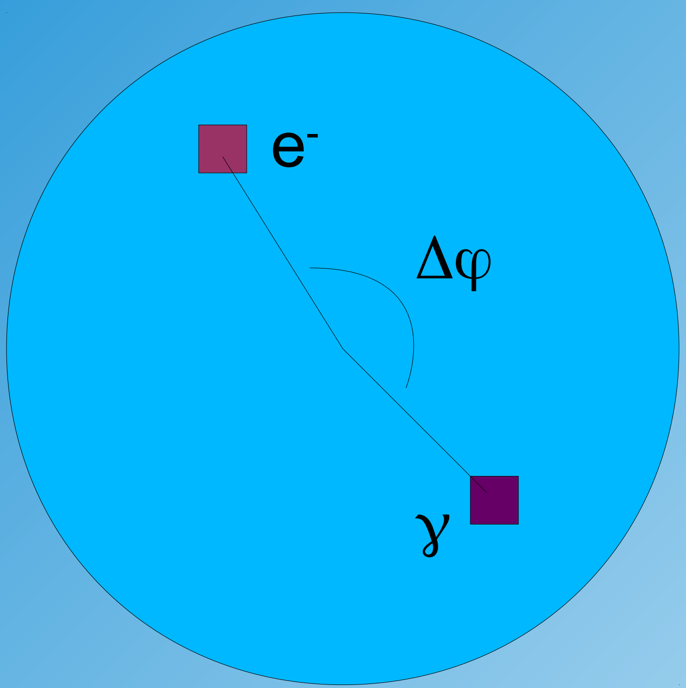
$$\frac{A_c}{(p-p'-k)^2} = \frac{1}{q^2}$$

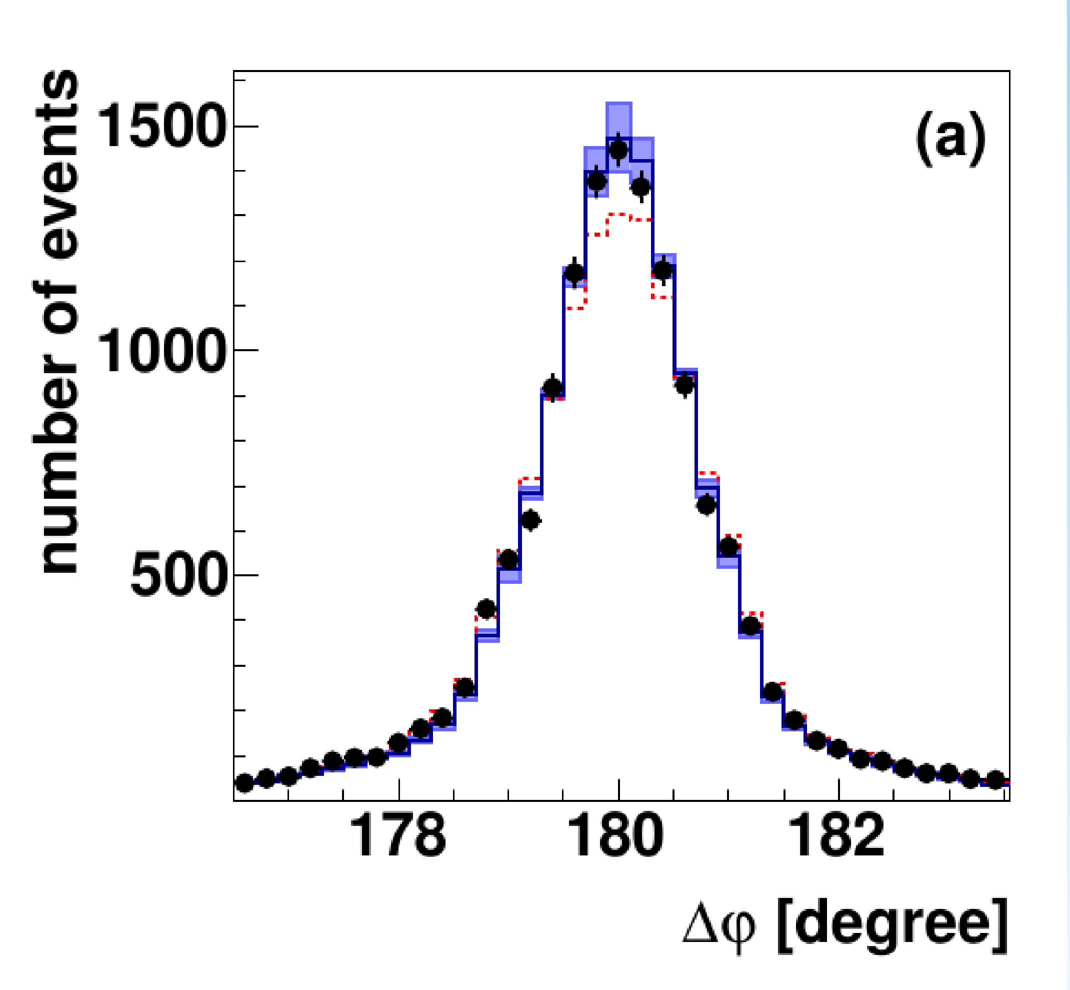
QED Compton Event



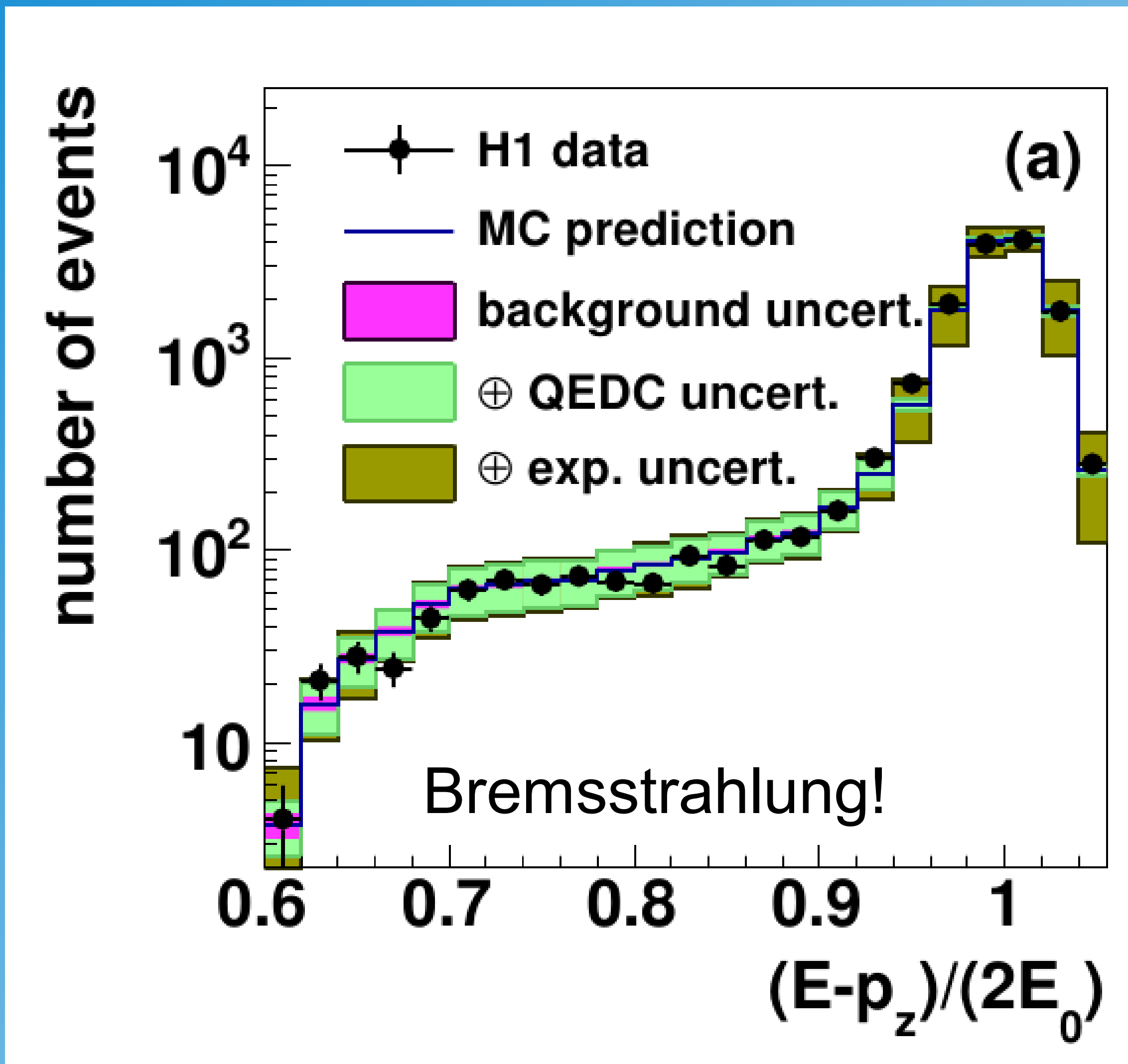
QED Compton Events

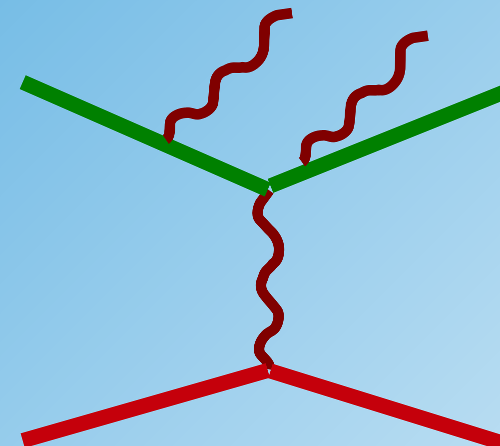
Back-to-Back Topology:





Radiative Corrections to Compton Events!





before interaction:

$E = E_e + E_\gamma$	26.7 GeV
$p_z = p_{z,e}$	-26.7 GeV
$E\text{-}p_z = E_e - p_z$	53.4 GeV

after interaction:

$E = E_e + E_\gamma$	<= 26.7 GeV
$p_z = p_{z,e} + p_{z,\gamma}$	>= -26.7 GeV

Uncertainties to Compton Analysis

Trigger uncertainties	
Trigger efficiency	0.02%
Veto inefficiency	0.22%
	0.22%

Reconstruction uncertainties	
SpaCal energy scale	0.56%
SpaCal energy resolution	1.10%
SpaCal position resolution	0.34%
CIP efficiency	0.18%
CIP resolution	$< 0.01\%$
Conversion probability	0.33%
Alignment	0.39%
z-vertex distribution	0.24%
SpaCal cluster finder	0.04%
CTD efficiency	0.03%
LAr energy veto	0.05%
	1.41%

Background uncertainties	
non-elastic QEDC	1.11%
elastic DVCS	0.25%
p-dissociative DVCS	0.08%
diffractive ρ	0.03%
diffractive ϕ	$< 0.01\%$
diffractive ω	0.03%
diffractive J/ψ	0.03%
diffractive ψ'	0.08%
diffractive Υ	0.01%
non-resonant diffractive DIS	0.16%
$ep \rightarrow epe^+e^-$	0.13%
	1.17%

QEDC theory uncertainties	
Higher order corrections	0.99%
Proton form factor	0.35%
	1.05%

total systematic error [in percent]: $0.22^2 + 1.41^2 + 1.17^2 + 1.05^2 = \mathbf{2.12}^2$

Bremsstrahlung in Charged Currents

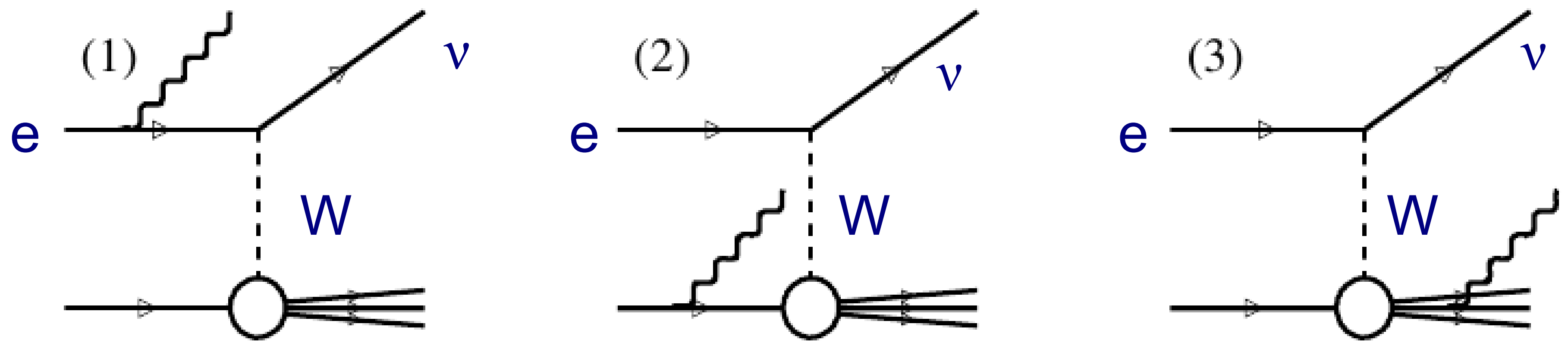
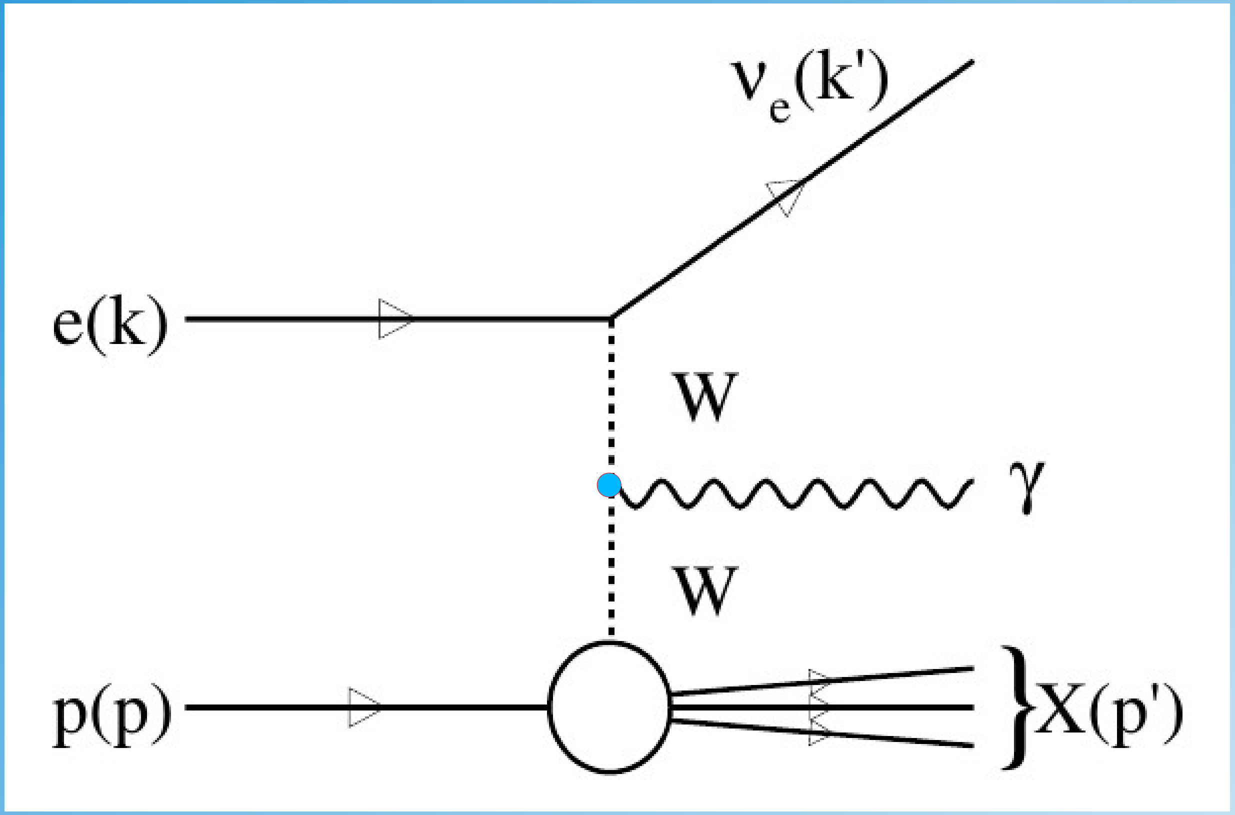


Figure 1.7: Feynman diagrams for scattering with radiation.

Neutrinos are note seen in detector and create missing p_T

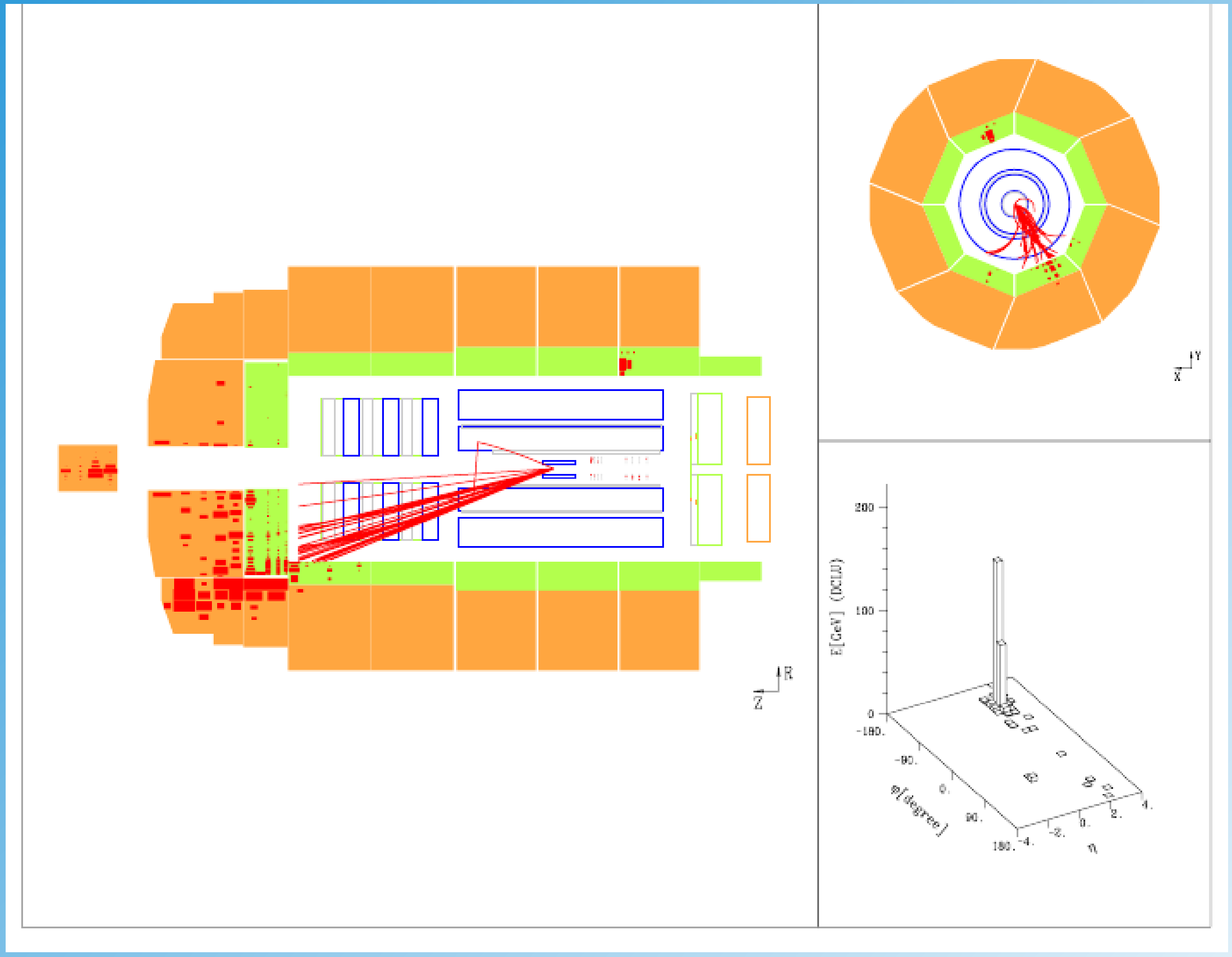
Radiative Charged Current Events and W-W-γ Coupling



The W-boson is electrically charged and can also radiate photons!

It is possible to test anomalous couplings

Charged Current Event with Bremsstrahlung

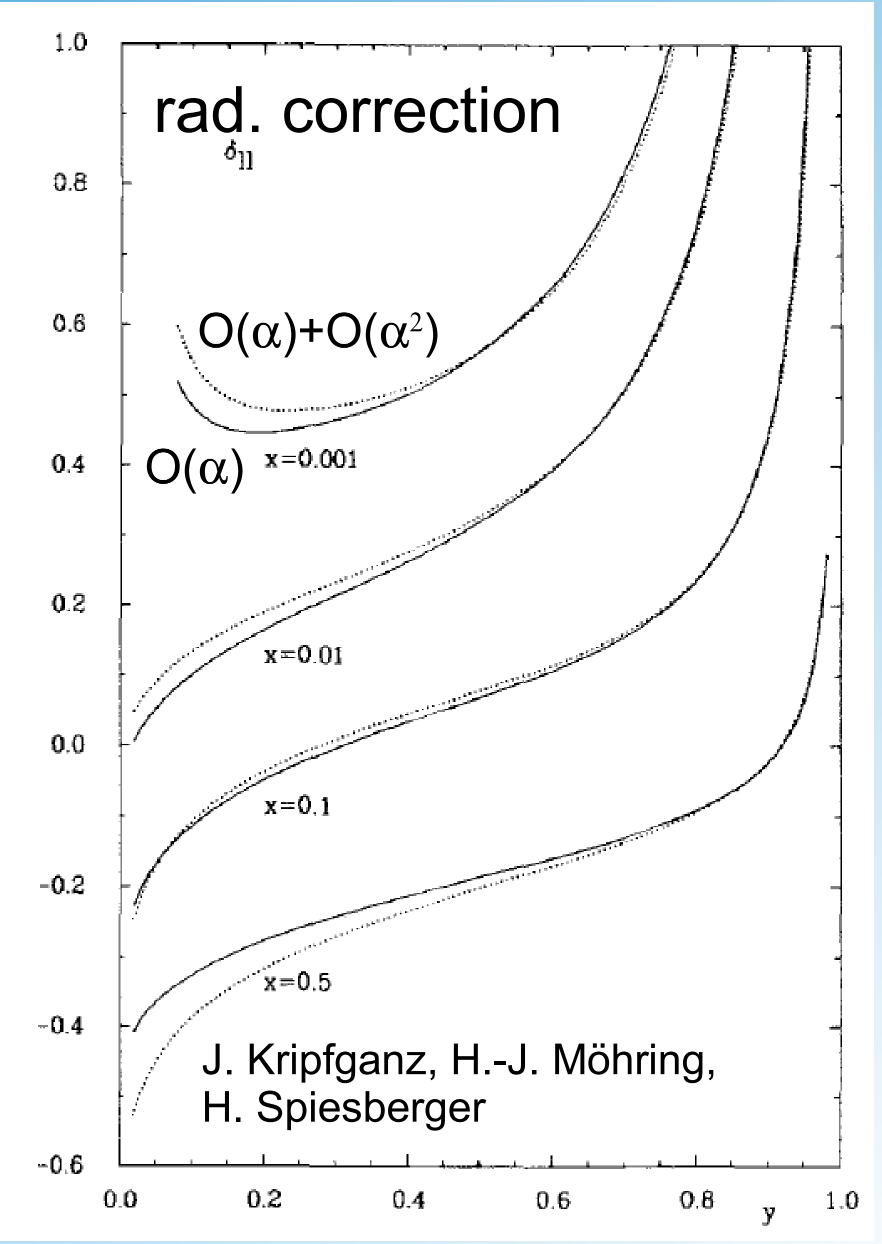


Radiative Corrections in CC events

Higher order leading logarithmic QED corrections to deep inelastic ep scattering at very high energies have significant impact on the kinematic reconstruction

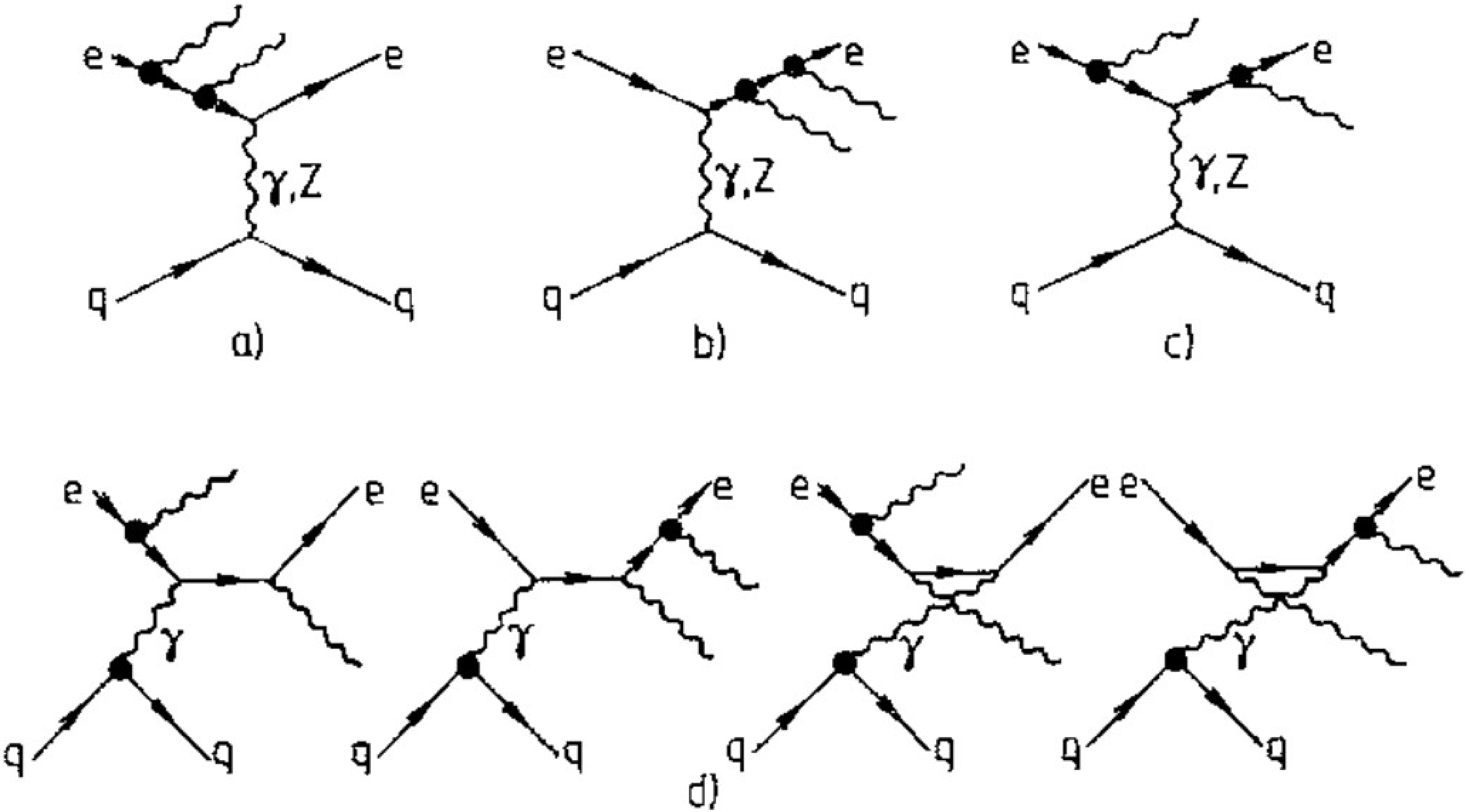
These logarithmic QED corrections come from multiple photon emissions

➜ systematic error of precision measurements

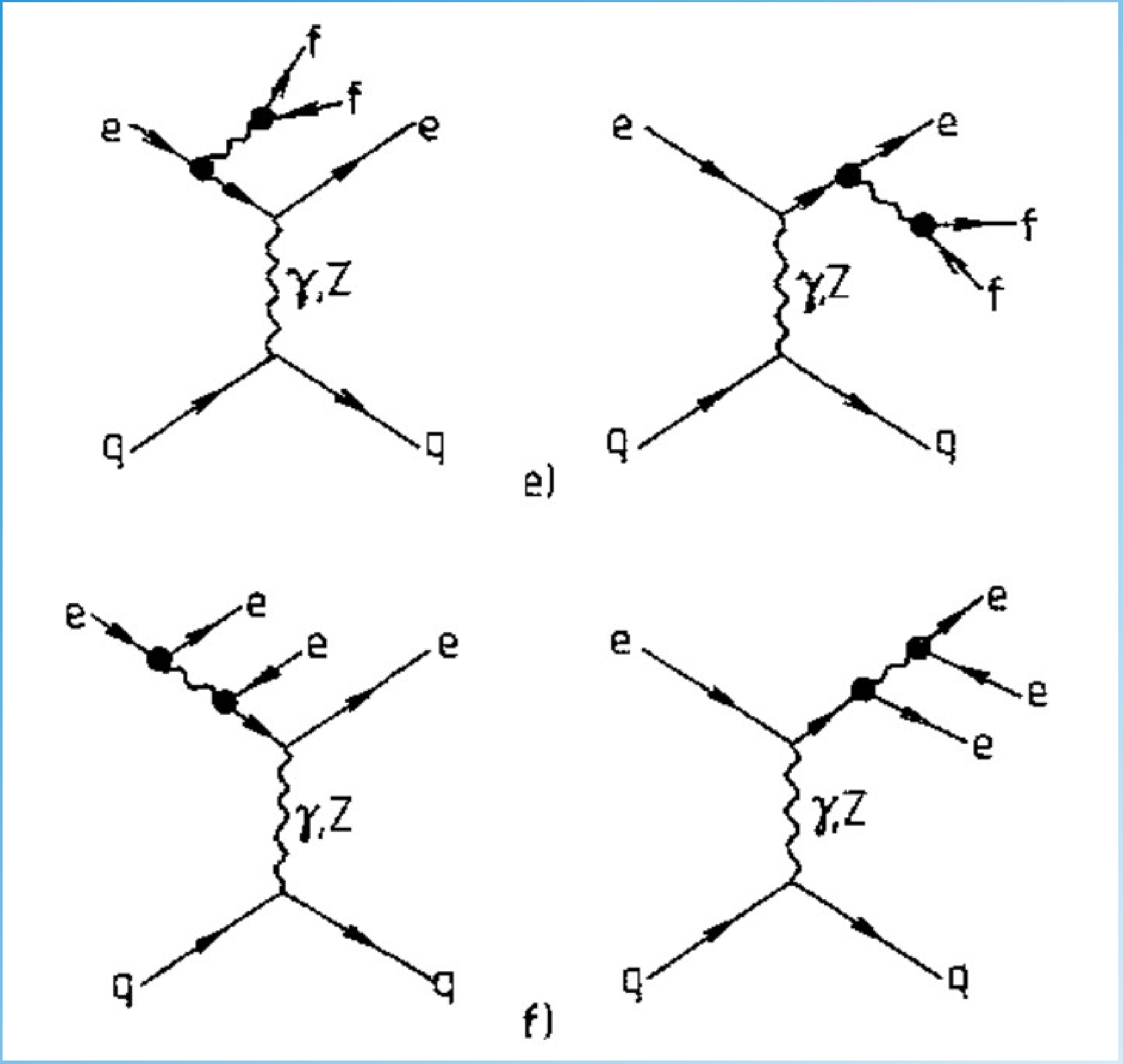


Higher Order Processes at HERA

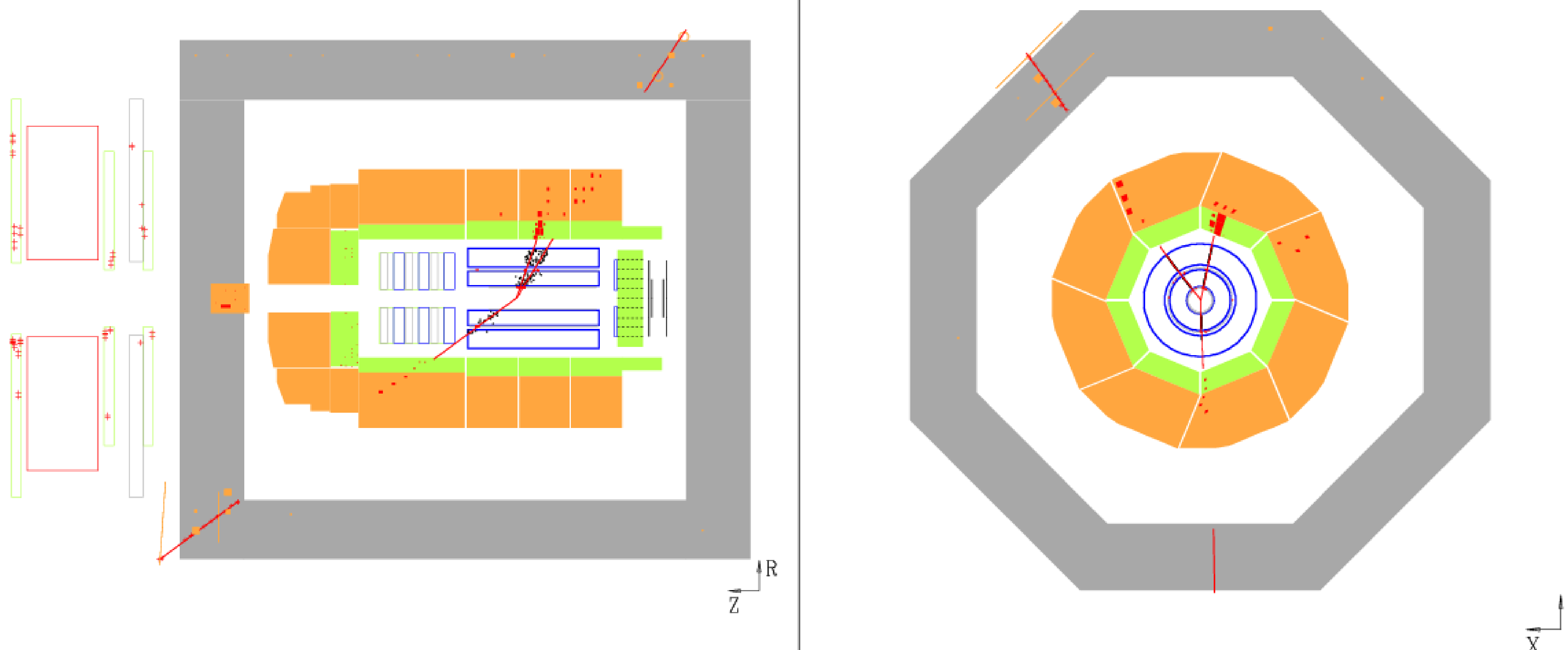
2-Photon Final States in DIS



3-Lepton Final States in DIS



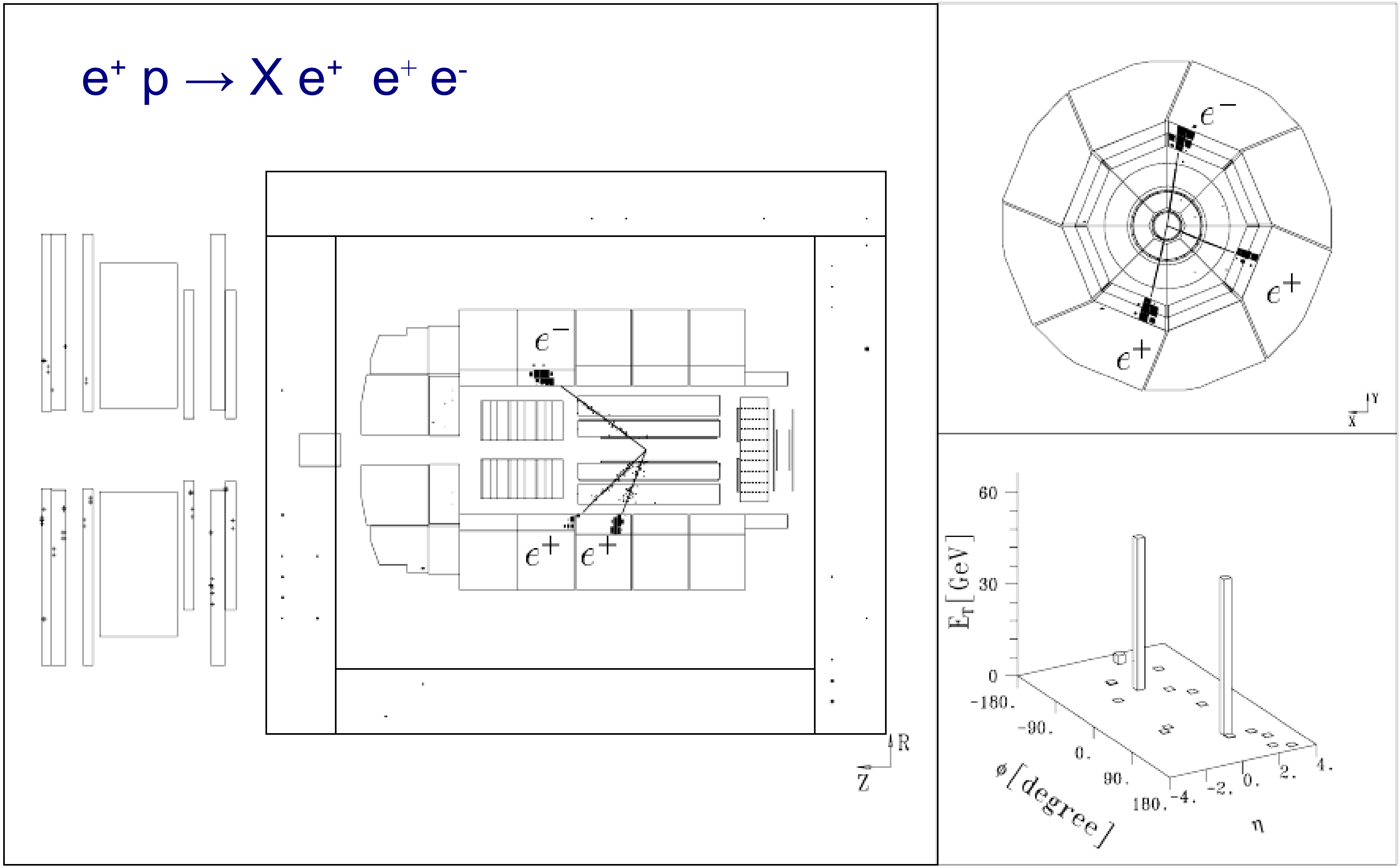
Alpha[4] Processes at HERA



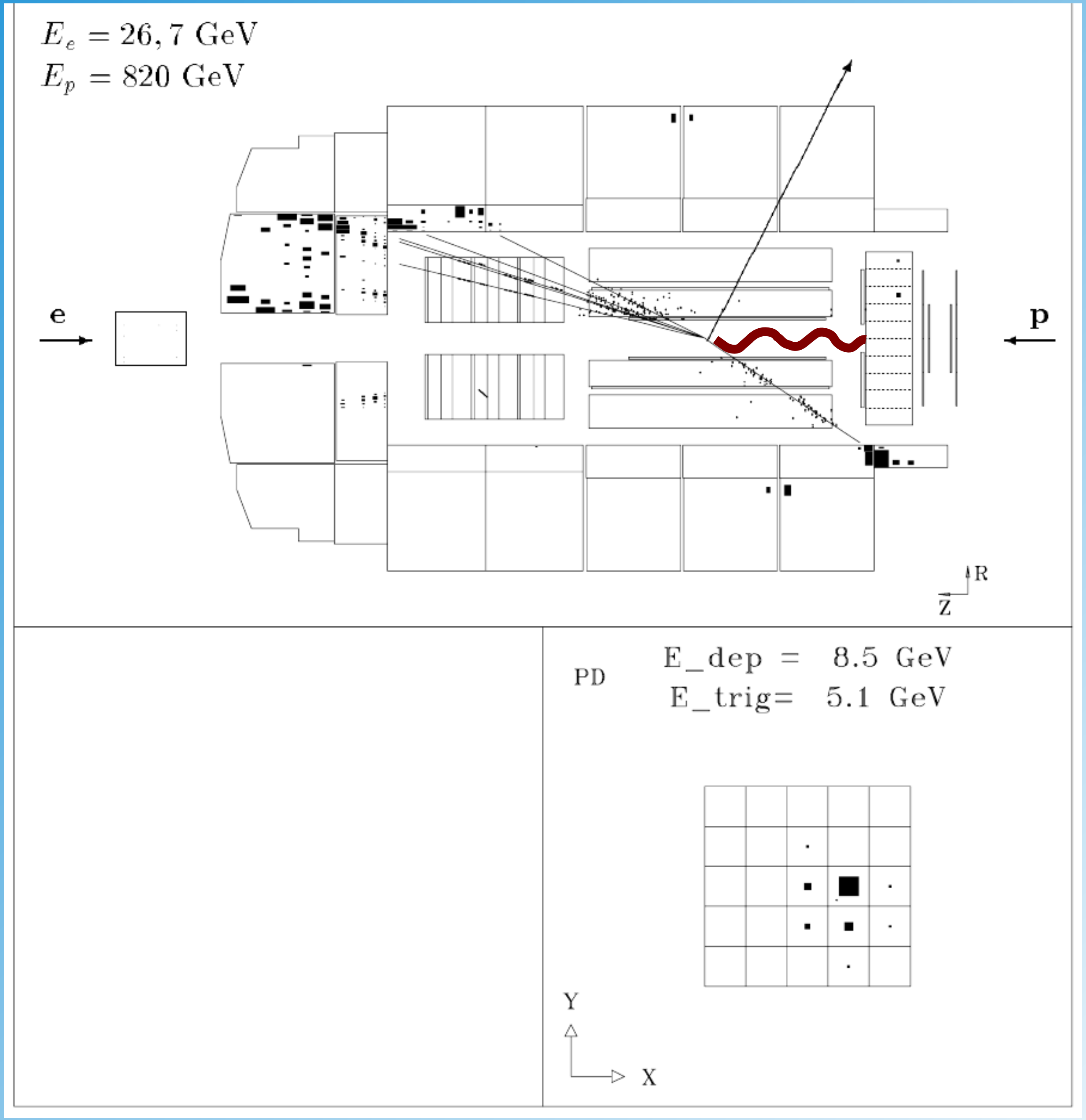
$e^+ p \rightarrow e^+ X \mu^+ \mu^-$

Alpha^4 Processes at HERA

$e^+ p \to X e^+ \; e^+ e^-$

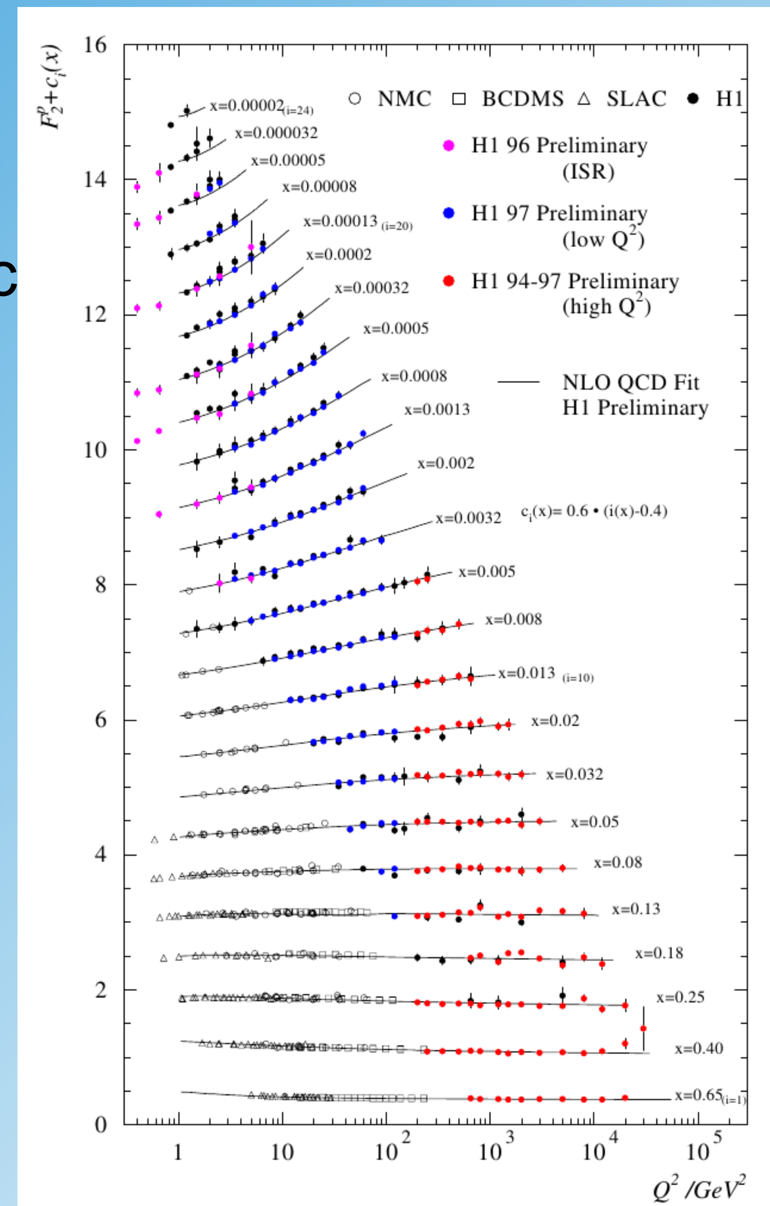


Exploitation of ISR



Exploitation of ISR

- ISR reduces the center of mass energy of the actual hard interaction
- This can be used to extend the kinematic phase space to lower energies



$$Q^2 = -q^2 = -(p - p')^2$$

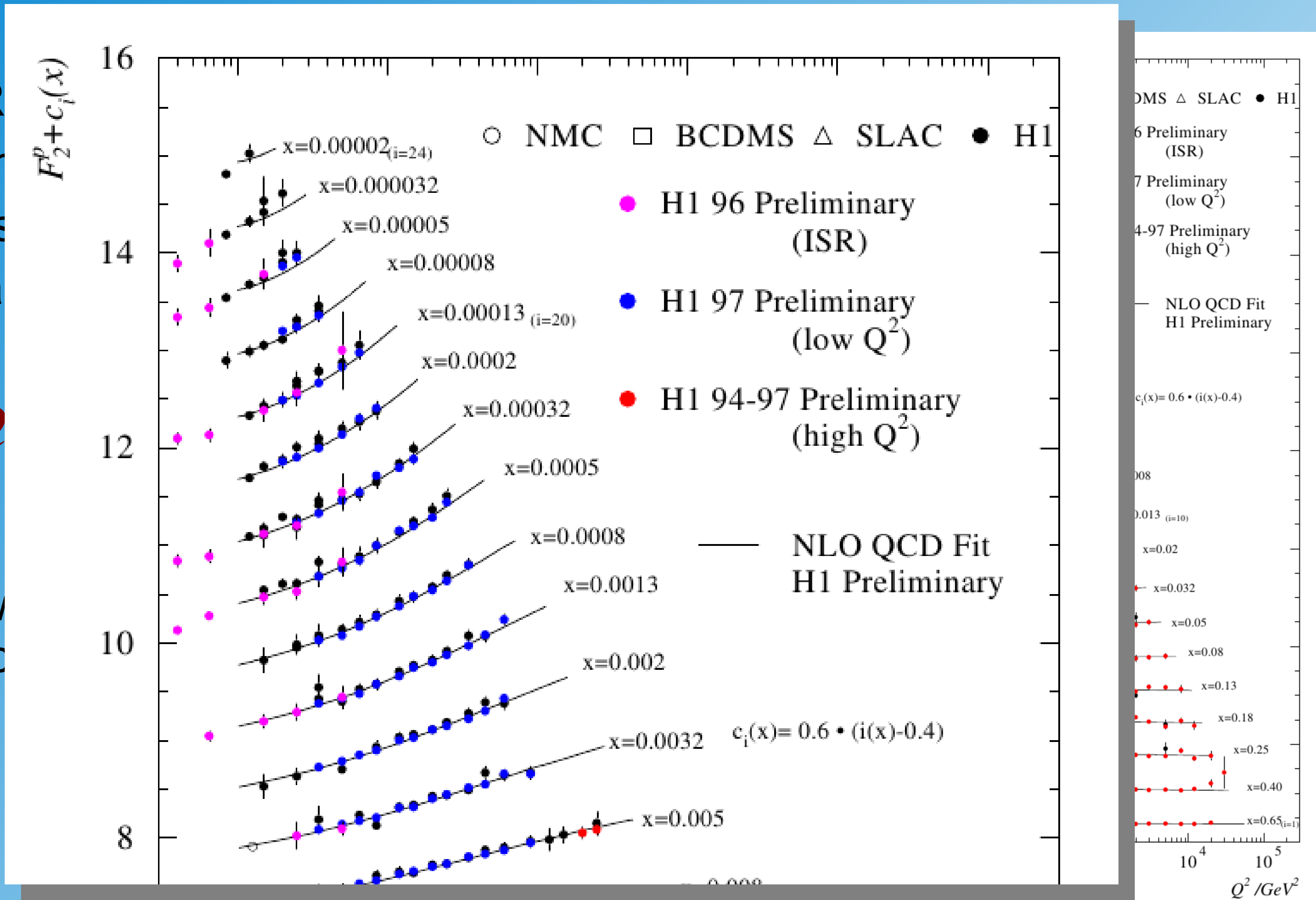
allows to access smaller values of Q^2
which could not be reached otherwise!

Exploitation of ISR

- ISR
  of th
- This
  pha

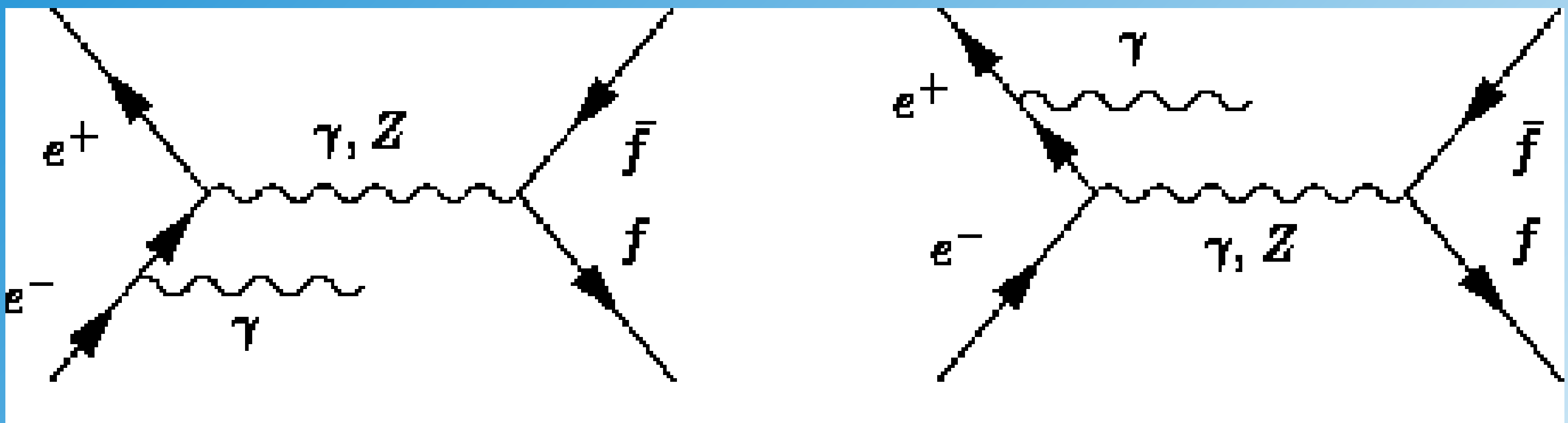
Q

allow
whic



Radiative Returns

Z-boson are resonantly produced in $e^+ e^-$ collisions at resonance (m_Z ~91 GeV)



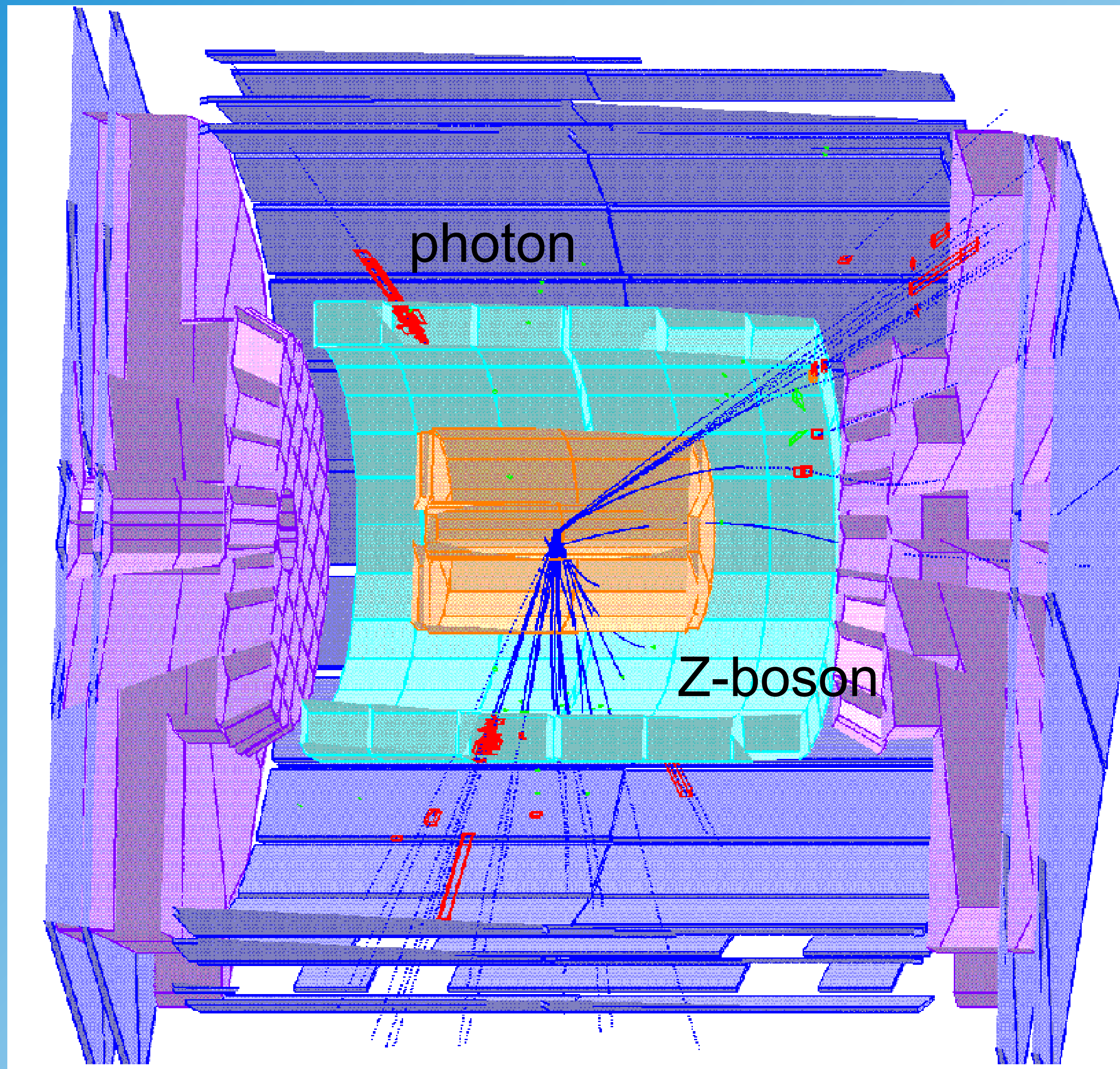
For $s^{1/2} > m_Z$ the radiative return allows a return to the resonance:

$$e^+ e^- \rightarrow Z \gamma$$

This effect can be large, e.g. at LEP

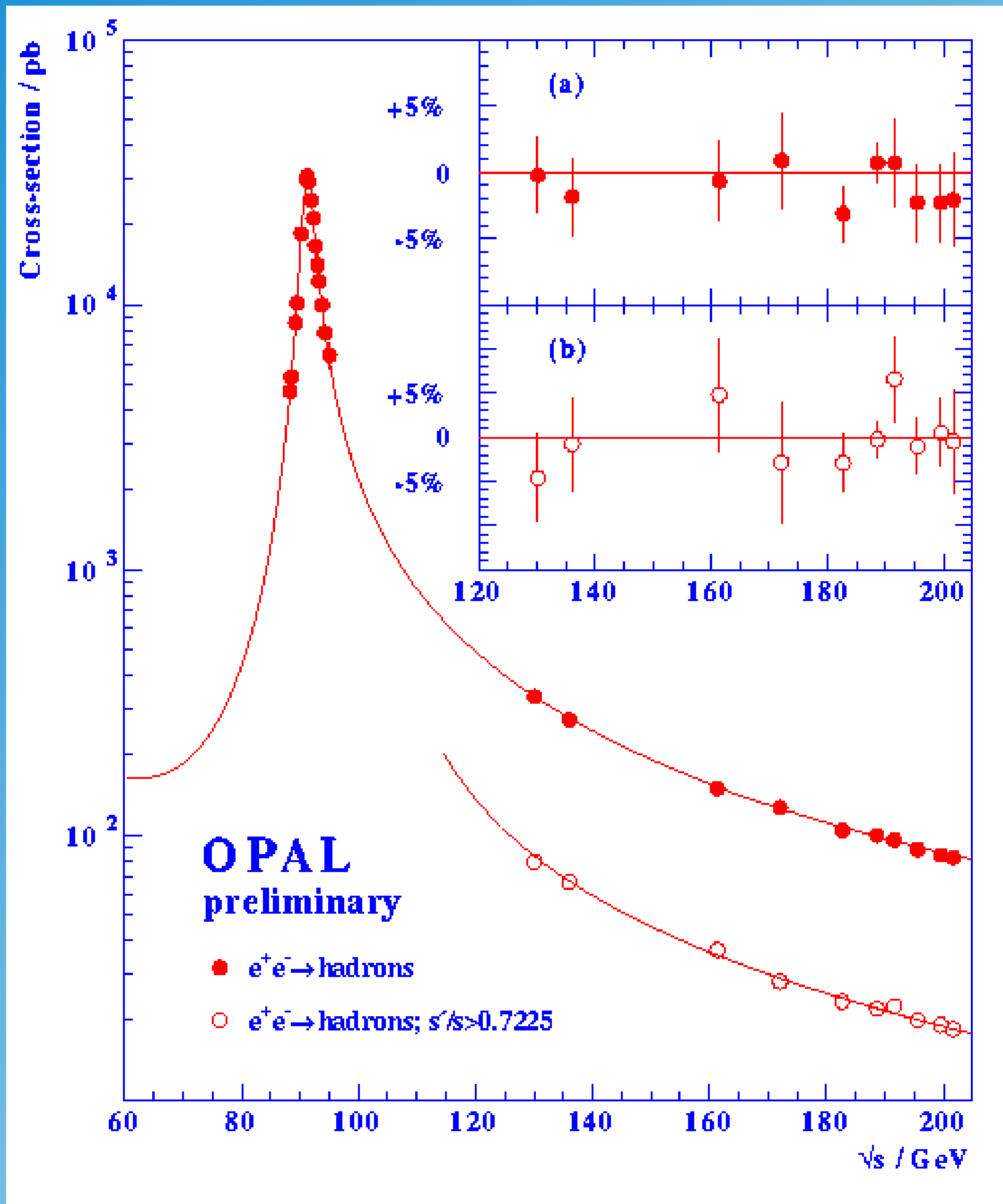
DELPHI Radiative Return Event at LEP 2
$s^{1/2} \sim 160$ GeV

e^+ →



← e^-

Measurement of Radiative Return

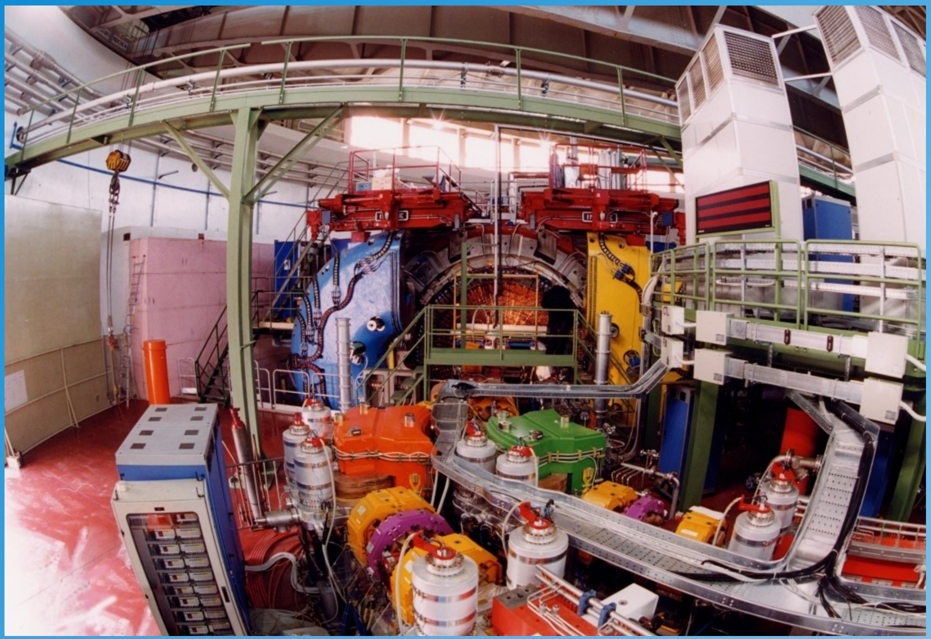


radiative returns
are extemely important!

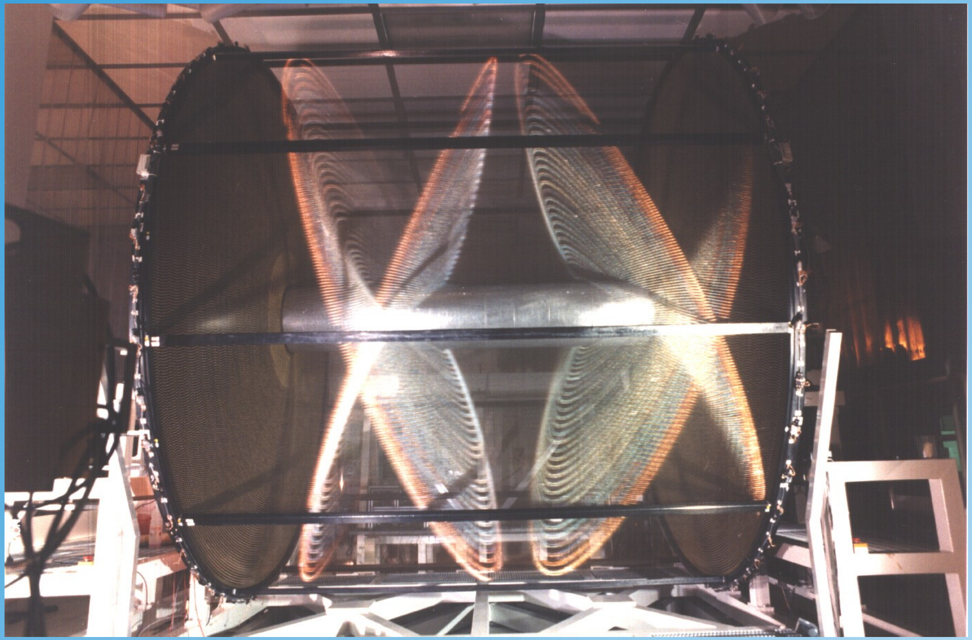
incl. radiative return

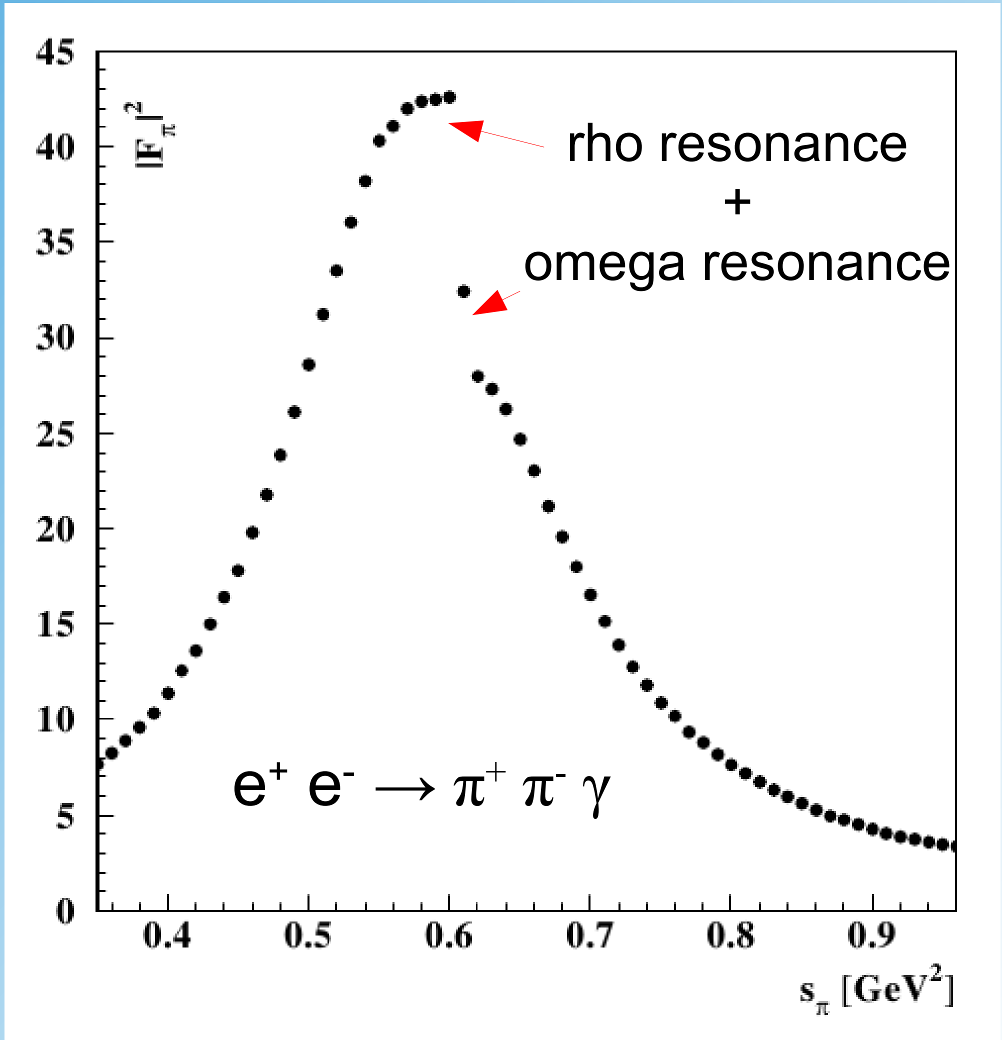
no radiative return

Radiative Return at KLEO (Daphne)

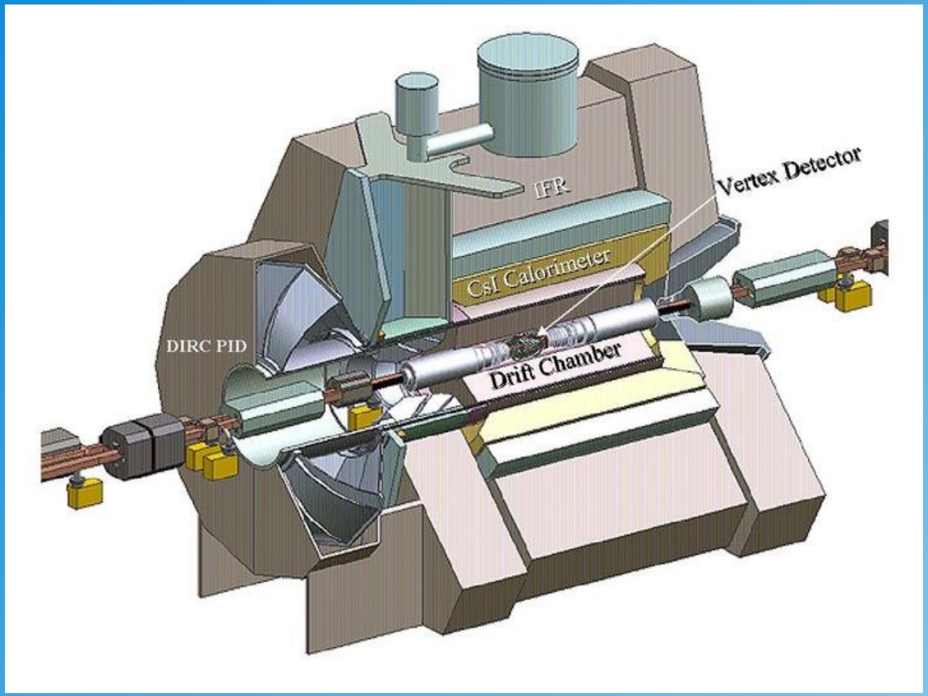


$e^+ e^-$ collider at $s^{1/2}$ = 1 GeV





Radiative Returns at Babar



$e^+ e^-$ collider at $s^{1/2} = 10$ GeV

$e^+ e^- \rightarrow p \bar{p} \gamma$