Let's design an experiment from the beginning

A couple of simple and completely "invented" examples

Let's design an experiment - I

- Suppose we want to observe a "new" particle (the J/ψ) by doing photo-production experiment:

$$\gamma + p \rightarrow J/\psi + X$$

- (this is an experiment already done…) We want to measure the cross-section for photoproduction of meson vectors.
- Design:
  1. γ beam properties
  2. Target properties and expected flux
  3. Muon detection and momentum measurement
  4. Detector lay-out

γ beam properties

→ Center of mass energy ? $\sqrt{s} > M(J/\psi) + M_p = 4.034$ GeV
→ Natural option: photons on a hydrogen target: photon momentum ? $P_\gamma > 8.2$ GeV
→ How can we produce a photon beam ?
1 - bremsstralung but wide spectrum, need of tagging
2 - Compton back-scattering

Let me choose option 2 with $P_\gamma = 10 - 15$ GeV

Table 1
Parameters of the Compton backscattering facilities for nuclear physics. γ-ray maximum energies and intensities are given for various existing electron accelerators, where a Compton beam has been installed or it is planned to work in the near future

Project name	Electron energy (GeV)	Laser energy (eV)	Photon energy (MeV)	Energy resolut. (MeV)	Electron current (A)	Beam intensity ($\frac{\gamma}{s}$)	Operat. date
LADON [7–10]	1.5	2.45	5–80	2–4	0.05	5×10^5	1978–93
LEGS [11]	2.5–2.8	2.41–4.68	110–450	5	0.2	5×10^6	1987
GRAAL [14,15]	6	2.41–3.53	550–1500	16	0.15	3×10^6	1995
ROKK-1	2	2.34–2.41	100–960	2	0.01	2×10^5	1982
ROKK-2 [12]	2	2.41–3.53	140–220	4	0.2	2×10^6	1987
ROKK-1M [13]	2	1.17–4.68	100–1600	10–20	0.1	3×10^6	1993
HIGS [16,17]	1	2–12.5	≤ 220	0.8	0.1	2×10^8	1997
LEPS [18]	8	2.41–4.68	1500–2400	15	0.1–0.2	5×10^6	1998
TJNAF [19]	6	2.41–3.53	≤ 1500	1–2	1.6×10^{-6}	10^6	2000
ELFE	15–30	2.41–3.52	$3 - 20 \times 10^3$	≥ 16	0.05–0.15	10^7	

Target, flux, MC simulation

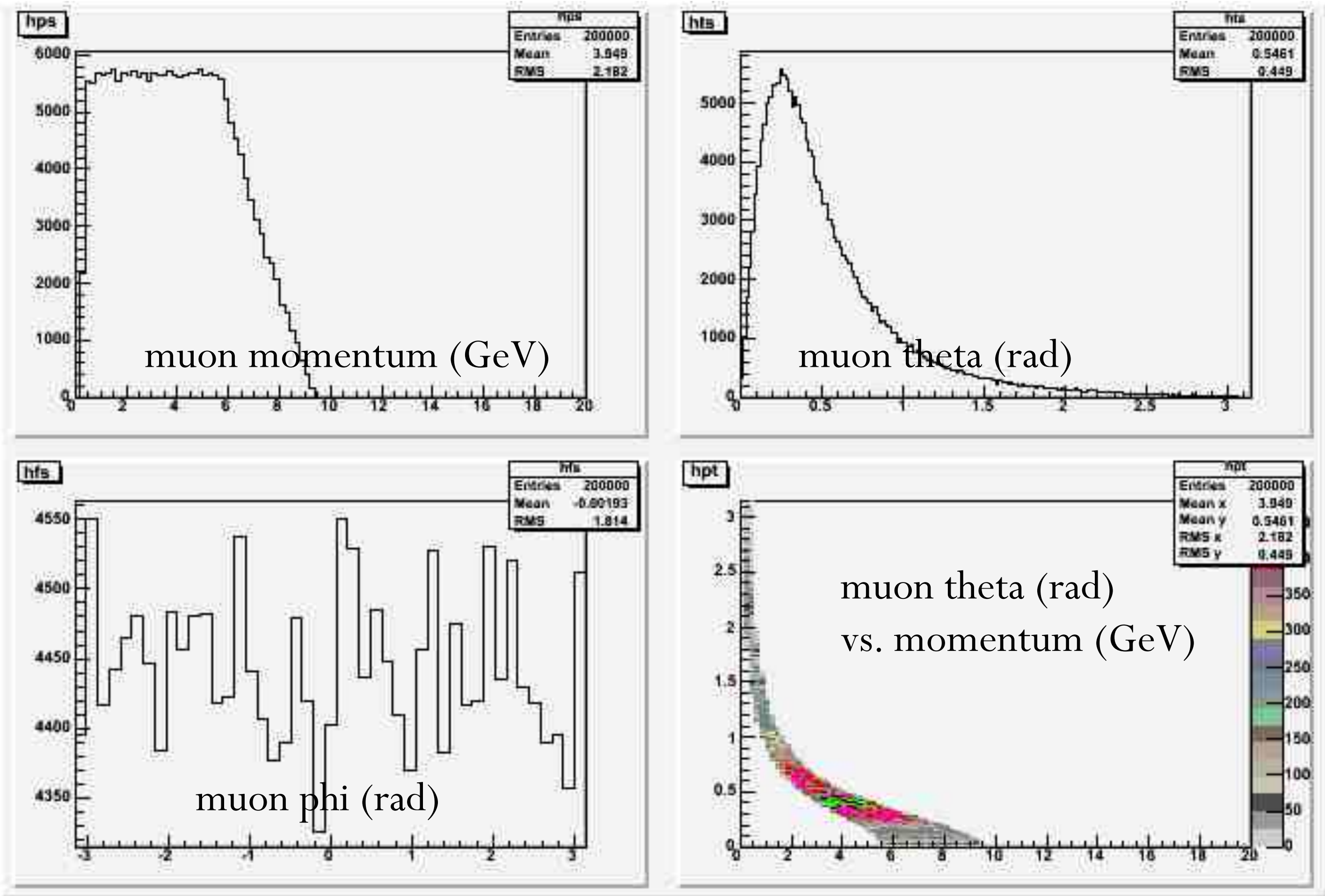
- The beam: ELFE could be good from the point of view of the beam momentum, but what about the flux ? Assume a LH target 1/2 m long:
  - Nproj = 10^7 s^{-1}
  - LH target (50 cm long): $\rho = 0.07$ gcm^{-3}, A = 1 ➔ $\phi = 2.1 \times 10^{31}$ $cm^{-2}s^{-1}$
- Is the flux sufficient ? From previous measurements/estimates one expects a total cross-section of ≈ 1 nbarn.
  - Which rate of events do we expect ? $N = \sigma \times \phi = 2 \times 10^{-2}$ s^{-1} ➔ ≈ 1500 evts/day (if efficiency equal to 1)
- The detector: we want to measure a pair of muons or a pair of electrons with invariant mass equal to the J/ψ mass. It is an inclusive measurement.
- Muon pair: which momentum I expect ?
  - Simple simulation:
    - In the center of mass frame 0<E(J/ψ)< (case of X = p, a recoiling proton);
    - J/ψ 2-body decay isotropic in J/ψ ref.frame
    - boost from J/ψ ref.frame to center of mass ref.frame
    - boost from center of mass ref.frame to lab frame
    - muon spectra
- Electron pair: same, replacing muon with electron masses.

A simple root code

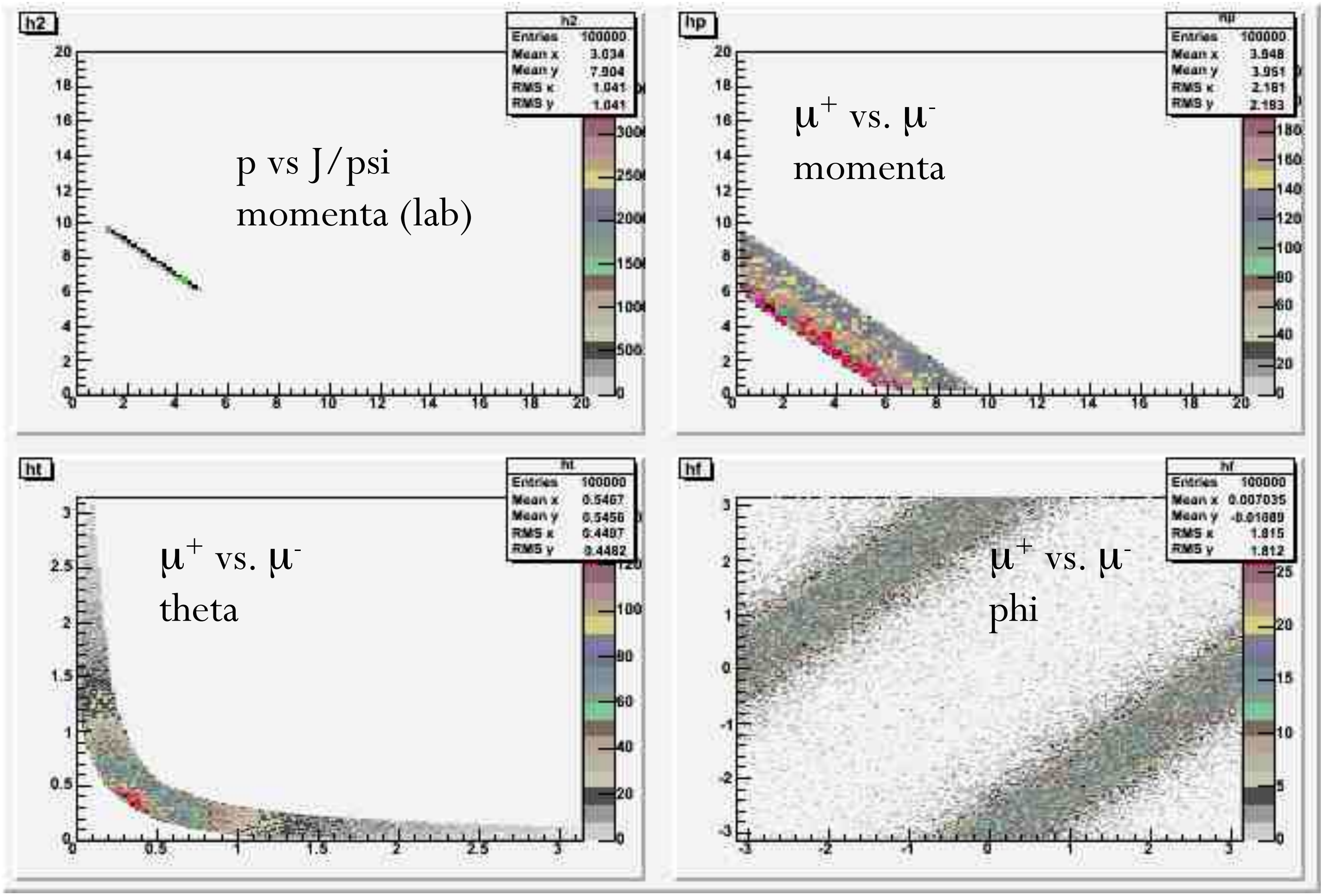
```
void PhaseSpaceI() {
// example of use of TGenPhaseSpace
//Author: Cesare Bini
  if (!gROOT->GetClass("TGenPhaseSpace")) gSystem.Load("libPhysics");
  TLorentzVector target(0.0, 0.0, 0.0, 0.938);
  TLorentzVector beam(0.0, 0.0, 10., 10.);
  TLorentzVector W = beam + target;
  TLorentzVector Psi;
  //(Momentum, Energy units are Gev/C, GeV)
  Double_t masses[2] = { 0.938, 3.097} ;
  Double_t mmasses[2] = { 0.104, 0.104} ;
  TGenPhaseSpace event;
  TGenPhaseSpace jpsi;
  event.SetDecay(W, 2, masses);

  TH2F *h2 = new TH2F("h2","h2", 100,0.,20., 100,0.,20.);
  TH2F *hp = new TH2F("hp","hp", 100,0.,20., 100,0.,20.);
  TH2F *ht = new TH2F("ht","ht", 180,0,3.1415,180,0,3.1415);
  TH2F *hf = new TH2F("hf","hf", 180,-3.1415,3.1415,180,-3.1415,3.1415);
  TH1F *hts = new TH1F("hts","hts", 180,0,3.1415);
  TH1F *hfs = new TH1F("hfs","hfs", 45,-3.1415,3.1415);
  TH1F *hps = new TH1F("hps","hps", 100,0.,20.);
  TH2F *hpt = new TH2F("hpt","hpt",100,0.,20.,180,0.,3.1415);
for (Int_t n=0;n<100000;n++) {
   Double_t weight1 = event.Generate();
   TLorentzVector *pProton = event.GetDecay(0);
   TLorentzVector *pPsi    = event.GetDecay(1);
   TLorentzVector Proton = *pProton;
   TLorentzVector Psi = *pPsi;
   jpsi.SetDecay(Psi,2,mmasses);
   Double_t weight2 = jpsi.Generate();
   TLorentzVector *mup = jpsi.GetDecay(0);
   TLorentzVector *mum = jpsi.GetDecay(1);
   TLorentzVector mmp = *mup;
   TLorentzVector mmm = *mum;
   hp->Fill(mmp.P(),mmm.P(),weight1*weight2);
   h2->Fill(Proton.E() ,Psi.E() ,weight1);
   ht->Fill(mmp.Theta(),mmm.Theta(),weight1*weight2);
   hf->Fill(mmp.Phi(),mmm.Phi(),weight1*weight2);
   hps->Fill(mmp.P(),weight1*weight2);
   hps->Fill(mmm.P(),weight1*weight2);
   hts->Fill(mmp.Theta(),weight1*weight2);
   hts->Fill(mmm.Theta(),weight1*weight2);
   hfs->Fill(mmp.Phi(),weight1*weight2);
   hfs->Fill(mmm.Phi(),weight1*weight2);
   hpt->Fill(mmp.P(),mmp.Theta(),weight1*weight2);
   hpt->Fill(mmm.P(),mmm.Theta(),weight1*weight2);
  }
}
```

Muon momenta and angular spectra (E_γ = 10 GeV) - I



Muon momenta and angular spectra (E_γ = 10 GeV) - II



Muon detection and momentum measurement

1. Muon pairs: Muons are produced mostly in the forward region with momenta between hundreds MeV and 10 GeV. I need to identify muons, and measure their momenta: how to detect and measure GeV momenta muons ?
   1. I need a "forward detector" with an acceptable acceptance;
   2. I need a low momentum threshold (correlated with angular acceptance);
   3. I need to identify muons rejecting electrons, pions, protons or other charged particles;
2. Possible recipe:
   - Muons are penetrating particles: ➔ filter with material (for instance other detectors) upstream; this defines the momentum threshold.
   - Measure curvature in magnetic field. Need of tracking chambers in a magnet with sufficient angular and momentum resolution.

Let's design an experiment - IV

Filtering:

thickness in g/cm^2 (t) ➔ cut due to range (ionisation loss)

interaction length (λ_I)➔ typical penetration of hadrons (p, π)

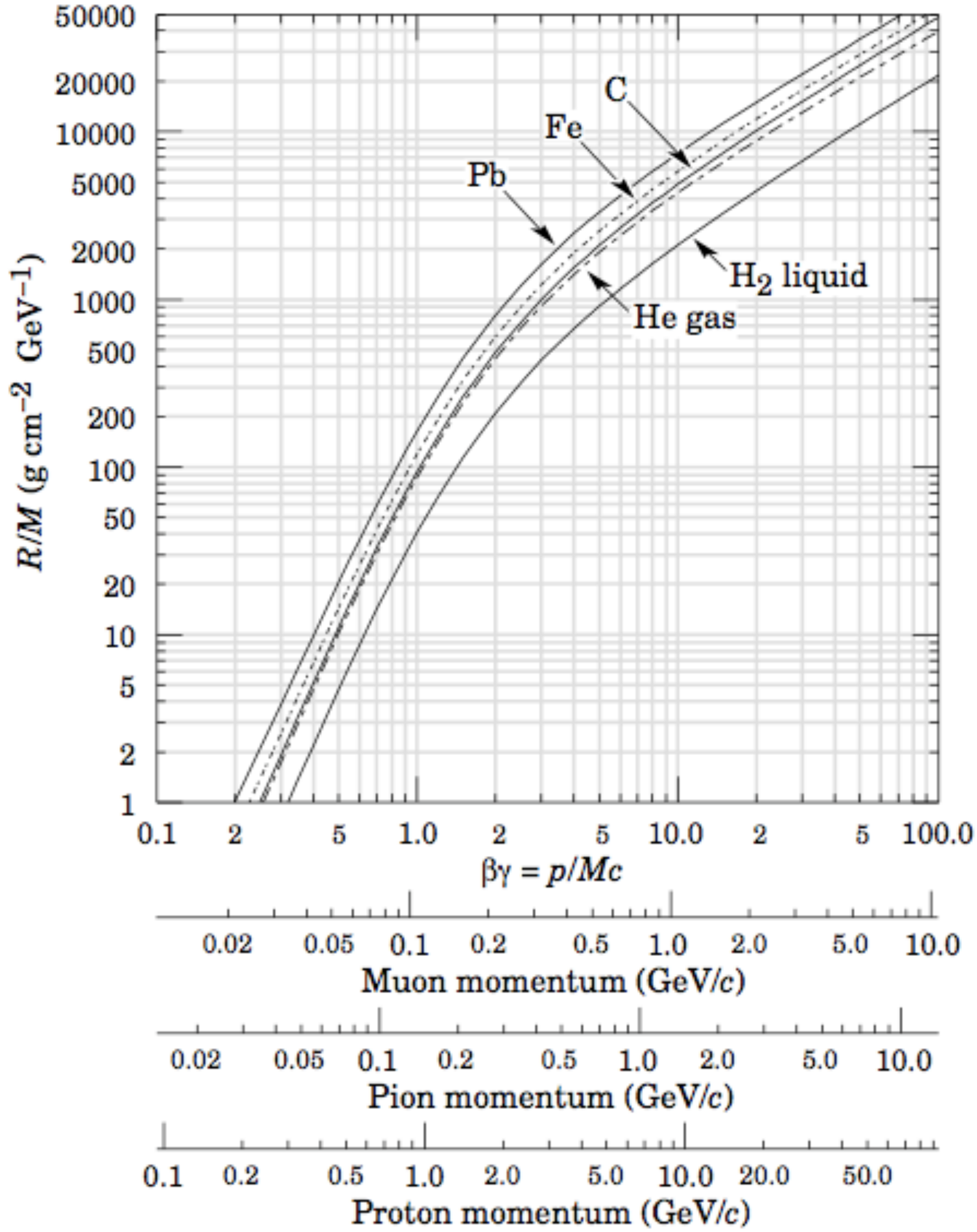
radiation length (X_0)➔ typical penetration of e and γ

Hypotheys: 0.5 m Pb: t = 565 g/cm^2 ➔ $p_\mu > 0.8$ GeV; nX_0 = 88 (!); $n\lambda_I = 3$ is a good compromise: we loose muons below 1 GeV but have a good rejections vs. electrons and an acceptable rejection vs. pions ($e^{-3} \approx 5\%$ remaining)

Better if W is available: with 25 cm the same momentum cut and the same rejection

Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter. length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\|_{min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({gℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815386(8)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.64(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	

NB: Different dependence on Z of λ_I and X_0:
em processes go as ≈Z^2, hadronic processes go as ≈A or even slowlier



50000
20000
10000
5000
2000
1000
500
200
100
50
20
10
5
2
1
R/M (g cm−2 GeV−1)
C
Fe
Pb
H2 liquid
He gas
0.1
2
5
1.0
2
5
10.0
2
5
100.0
βγ = p/Mc
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10.0
Muon momentum (GeV/c)
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10.0
Pion momentum (GeV/c)
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
Proton momentum (GeV/c)

Let's design an experiment - V

Momentum measurement

Assume a uniform magnetic field ***B*** in a region of dimension ***L*** and a particle of trasverse momentum $\boldsymbol{p_T}$ entering the region

$$p_T(GeV) = 0.3\rho(m)B(T)$$

We define the "sagitta" ***s*** and suppose to measure it through 3 points x_1, x_2 and x_3: $\boldsymbol{s} = x_2-(x_1+x_3)/2$

$$s = \frac{0.3BL^2}{8p_T}$$

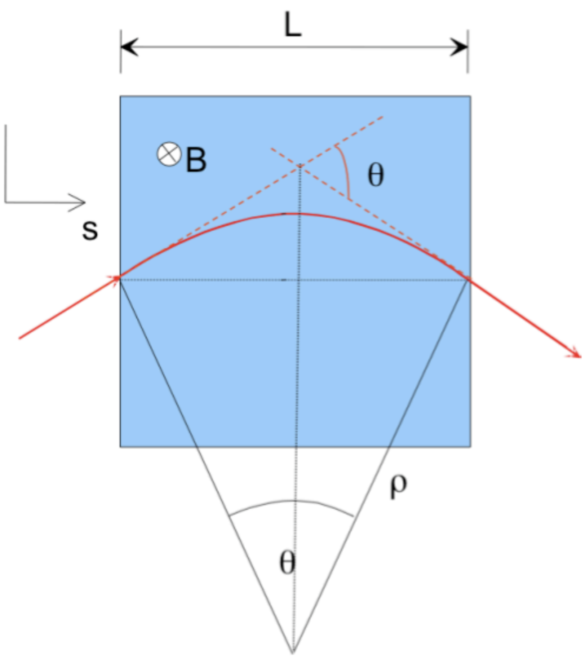
From ***s*** we get the transverse momentum, given the field ***B*** and the distance ***L*** between detectors 1 and 3

The resolution on $\boldsymbol{p_T}$ is:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{3}{2}}\sigma_X \frac{8p_T}{0.3BL^2}$$

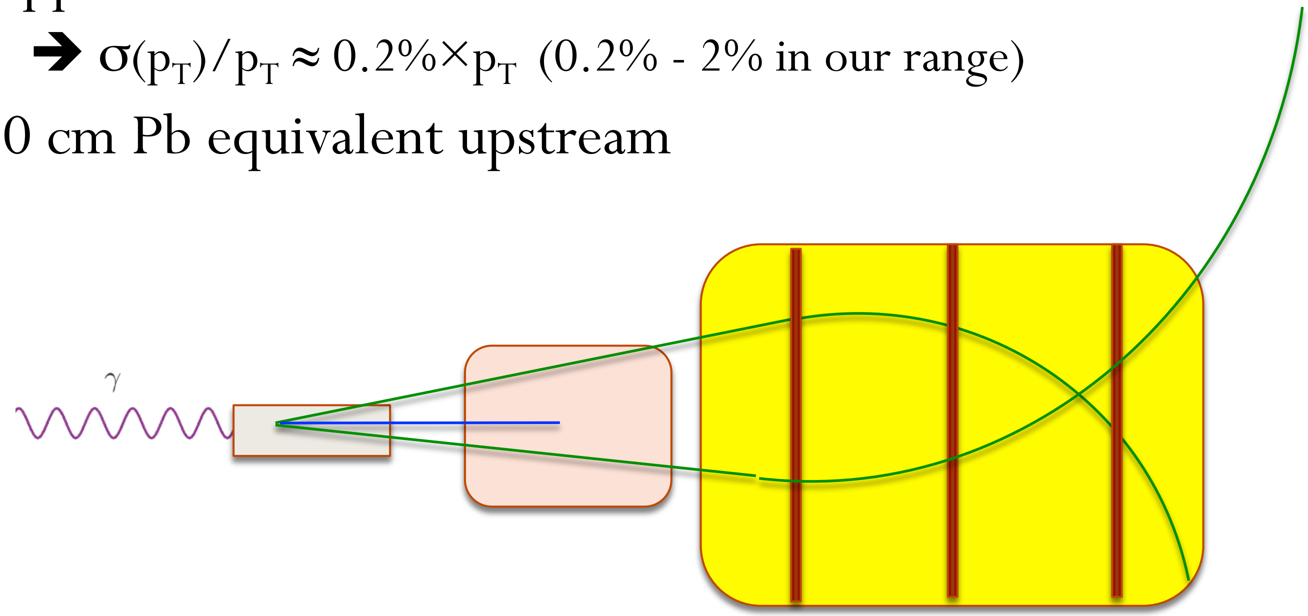
In case of N points rather than 3, the resolution is:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{720}{N+4}}\sigma_X \frac{p_T}{0.3BL^2}$$



Lay-out

- Experiment parameters
  - At least three tracking stations of resolution $\sigma_X \approx 100\ \mu m$
  - Dipole magnet. Typical B values in the range of 0.5 – 1 T: suppose to have B = 0.5 T and L = 2 m
    - ➔ $\sigma(p_T)/p_T \approx 0.2\% \times p_T$ (0.2% - 2% in our range)
  - 50 cm Pb equivalent upstream



Other points - miscellanea

- Momentum resolution: include multiple scattering effect and longitudinal component effect (through measurement of the y coordinate) $$\left(\frac{\sigma(p)}{p}\right)^2 = \left[\sqrt{\frac{3}{2}}\sigma_X \frac{8p\sin\vartheta}{0.3BL^2}\right]^2 + \left[\frac{0.2}{\beta B\sqrt{LX_0\sin\vartheta}}\right]^2 + \cot^2\vartheta\,\sigma^2(\vartheta)$$
- Energy loss in the filter is not negligible: 2 MeV/g/cm^2 $\times$ 560 g/cm^2 $\approx$ 1 GeV with wide fluctuations: probably it could be possible to investigate lower material upstream (low momenta hadrons have higher cross-section)
- Determination of the interaction vertex is also an issue (not point-like target)
- Invariant mass measurement resolution

A low energy collider experiment - I

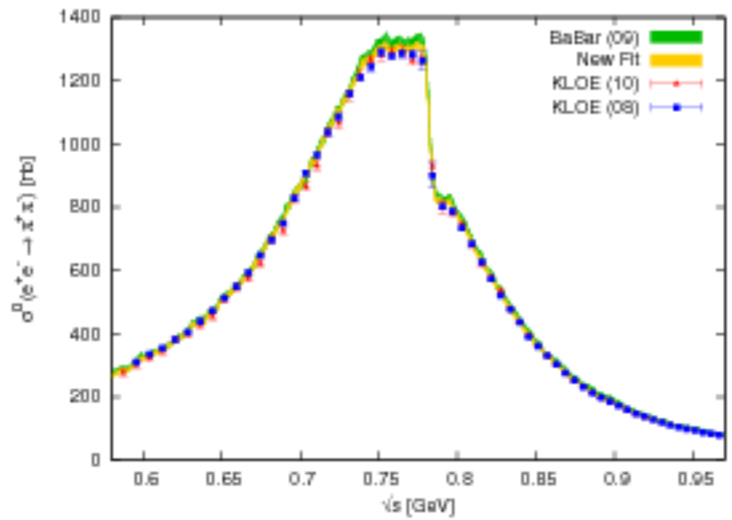
- Process $e^+e^- \rightarrow \pi^+\pi^-$ in the center of mass energy between 500 MeV and 1000 MeV
- I want to measure precisely the ρ lineshape and the $\rho-\omega$ interference.
- Required luminosity:
  - 50 points with uncert.< 1%

  ➔ $>10^4$ evts / point

  Since $\sigma \approx 200 \div 1000$ nb /point

  ➔ $L_{int} > 50$ nb^{-1} /point,

  total 2.5 pb^{-1};



If L $\approx 10^{31}$cm^{-2}s^{-1} few days running time is enough. "Energy scan"

A low energy collider experiment - II

- Simple final state: two pions back-to-back with fixed (low) momentum at any given value of s.

$$p = \sqrt{\frac{s}{4} - m^2} = 210 \div 480\, MeV$$

- Possible backgrounds ?
  - At these c.o.M. energies few processes are below threshold:

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

  $e^+e^- \rightarrow e^+e^-$ (Bhabha scattering)

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

  $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ (threshold $\approx 3 \times m_\pi \approx 400$ MeV)

  $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ (threshold $\approx 4 \times m_\pi \approx 540$ MeV)

  $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ ("")

  $e^+e^- \rightarrow K^+K^-$ (threshold $\approx 2 \times m_K \approx 980$ MeV)

- Main job: separate pion pairs from muon, electron and photon pairs

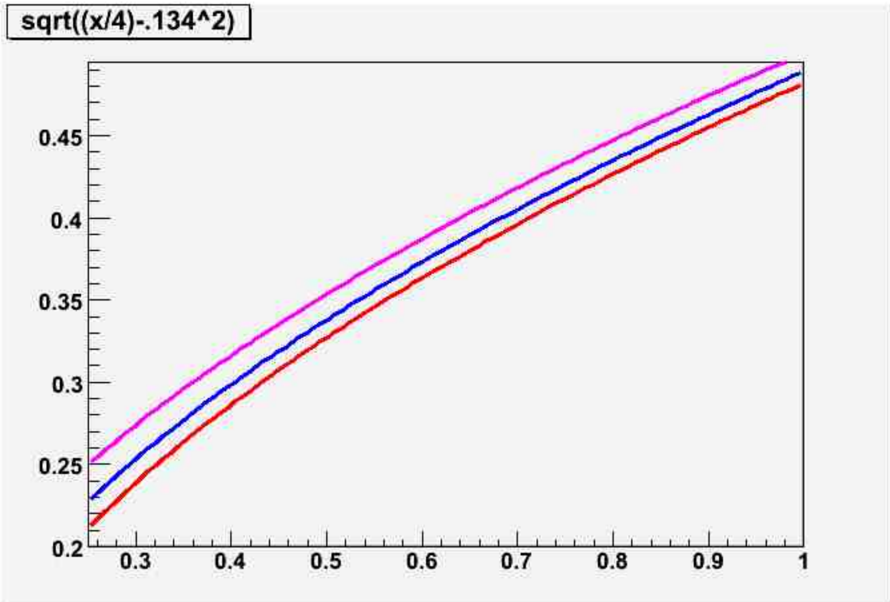
A low energy collider experiment - III

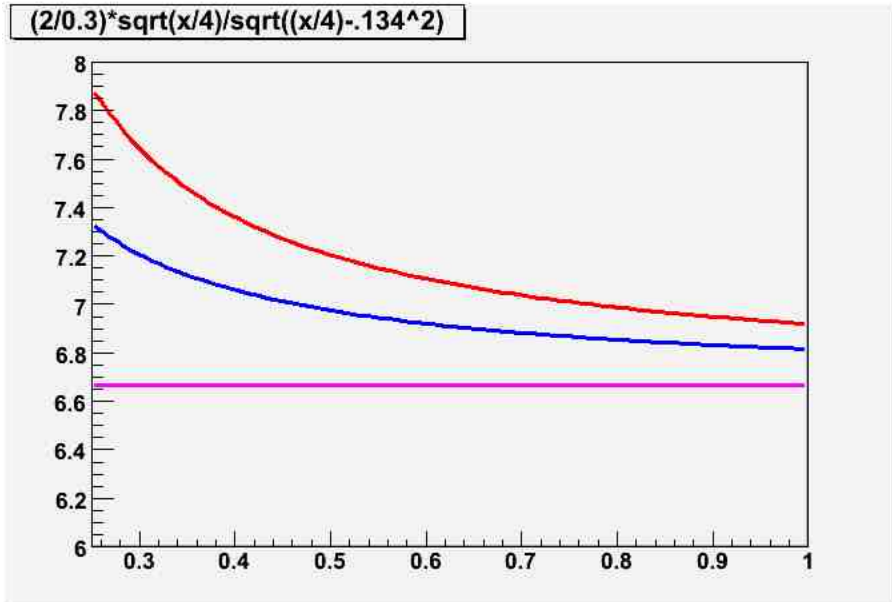
- Low momenta particles with small range ➔light materials
- Difficult to use the filtering method
- First method: Try to discriminate by a precision measurement of the momenta: at each value of s you select all collinear track pairs coming from the IP and measure the momentum. You will find 3 peaks: pions, muons and electrons.
- Second method: Try to discriminate by a precision measurement of the Time-Of-Flight.
- One can use both methods to be "redundant"

Momentum and Time separations

Momentum separation:
momentum difference btw π and μ
between 5 and 10%
➔momentum measurement better than 1%
on the full range

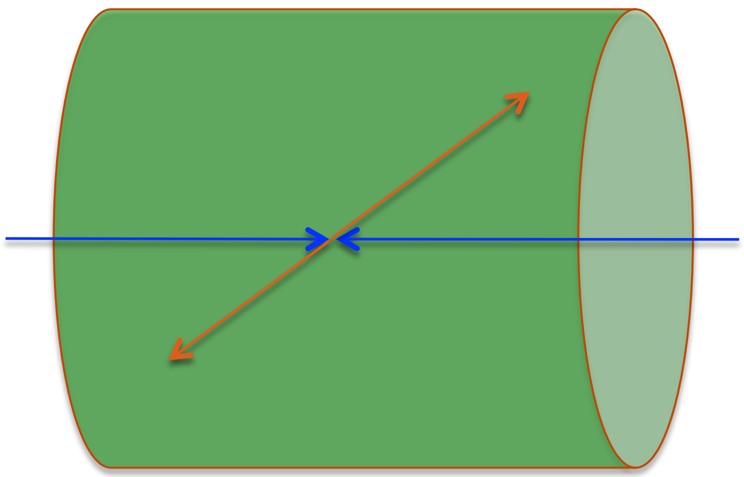
time-Of-Flight separation (on 2 m lever arm):
time difference btw π and μ
between 100 and 600 ps
➔time measurement better than 30 ps
on the full range (very difficult…)

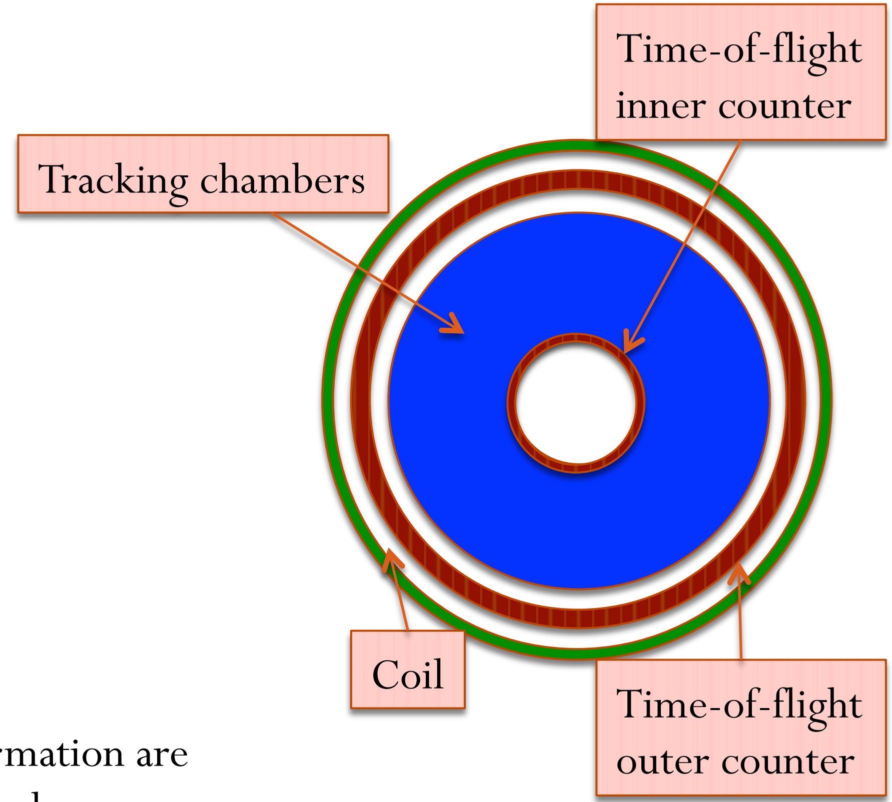




A low energy collider experiment - IV

- Experiment layout





Momentum and Time-Of-Flight information are combined to discriminate π from μ and e.

Magnetic fields - I

Table 31.9: Progress of superconducting magnets for particle physics detectors.

Experiment	Laboratory	B [T]	Radius [m]	Length [m]	Energy [MJ]	X/X_0	E/M [kJ/kg]
TOPAZ*	KEK	1.2	1.45	5.4	20	0.70	4.3
CDF*	Tsukuba/Fermi	1.5	1.5	5.07	30	0.84	5.4
VENUS*	KEK	0.75	1.75	5.64	12	0.52	2.8
AMY*	KEK	3	1.29	3	40	†	
CLEO-II*	Cornell	1.5	1.55	3.8	25	2.5	3.7
ALEPH*	Saclay/CERN	1.5	2.75	7.0	130	2.0	5.5
DELPHI*	RAL/CERN	1.2	2.8	7.4	109	1.7	4.2
ZEUS*	INFN/DESY	1.8	1.5	2.85	11	0.9	5.5
H1*	RAL/DESY	1.2	2.8	5.75	120	1.8	4.8
BaBar*	INFN/SLAC	1.5	1.5	3.46	27	†	3.6
D0*	Fermi	2.0	0.6	2.73	5.6	0.9	3.7
BELLE*	KEK	1.5	1.8	4	42	†	5.3
BES-III	IHEP	1.0	1.475	3.5	9.5	†	2.6
ATLAS-CS	ATLAS/CERN	2.0	1.25	5.3	38	0.66	7.0
ATLAS-BT	ATLAS/CERN	1	4.7–9.75	26	1080	(Toroid)†	
ATLAS-ET	ATLAS/CERN	1	0.825–5.35	5	2×250	(Toroid)†	
CMS	CMS/CERN	4	6	12.5	2600	†	12

* No longer in service

† EM calorimeter is inside solenoid, so small X/X_0 is not a goal

Magnetic fields - II

- Dipoles:
  - Used for fixed target or cosmic ray experiments, not practical for colliders;
- Solenoid
  - Most used in collider experiments:

$$B = \mu_0 nI \rightarrow \mu_0 nI \frac{L}{\sqrt{L^2 + 4R^2}}$$

$$\frac{\sigma(p)}{p} \propto \frac{p_T}{BL^2}$$

  - non-negligible perturbation to beams (coupling)
- Toroid
  - Return iron not needed
  - no perturbation for the beams
  - better for forward tracks

$$B = \frac{\mu_0 NI}{2\pi r}$$

$$\frac{\sigma(p)}{p} \propto \frac{p_T}{BR}$$

Position-sensitive detectors

Table 31.1: Typical resolutions and deadtimes of common charged particle detectors. Revised November 2011.

Detector Type	Intrinsinc Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	$\lesssim 10$ mm	1–2 ns	—
Streamer chamber	300 μm[a]	2 μs	100 ms
Liquid argon drift [7]	~175–450 μm	~ 200 ns	~ 2 μs
Scintillation tracker	~100 μm	100 ps/n[b]	10 ns
Bubble chamber	10–150 μm	1 ms	50 ms[c]
Proportional chamber	50–100 μm[d]	2 ns	20-200 ns
Drift chamber	50–100 μm	2 ns[e]	20-100 ns
Micro-pattern gas detectors	30–40 μm	$<$ 10 ns	10-100 ns
Silicon strip	pitch/(3 to 7)[f]	few ns[g]	$\lesssim 50$ ns[g]
Silicon pixel	$\lesssim 10$ μm	few ns[g]	$\lesssim 50$ ns[g]
Emulsion	1 μm	—	—