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Belgian-Dutch-German school
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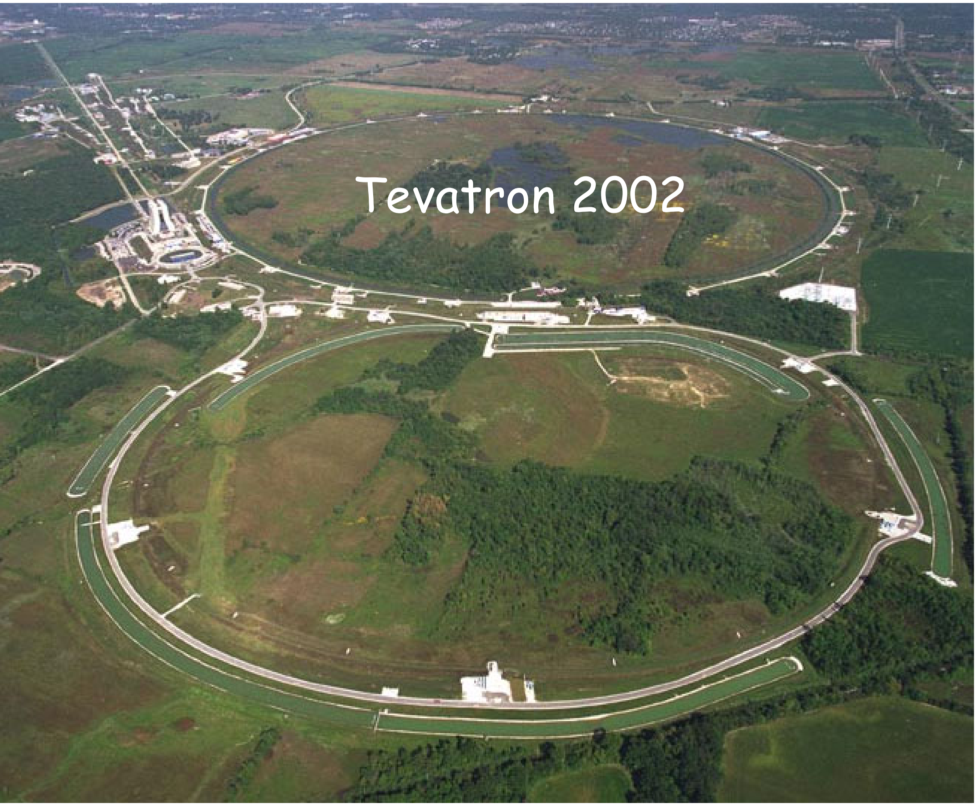
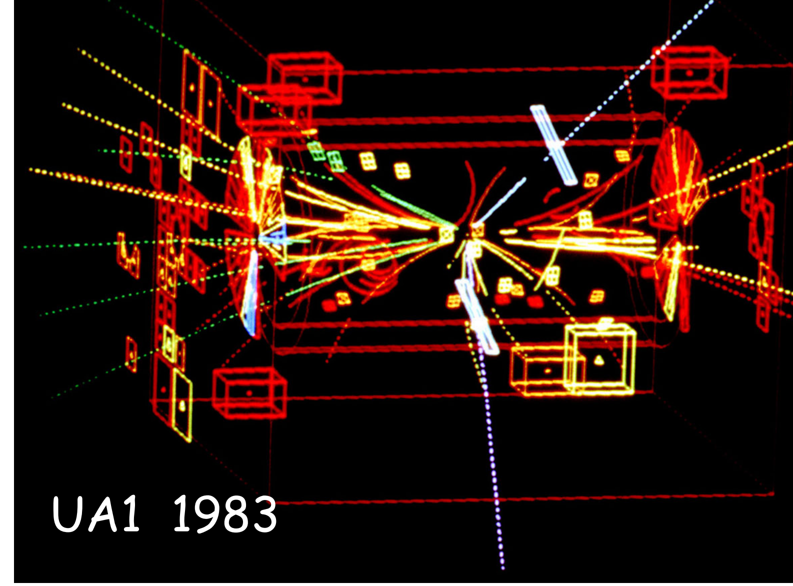
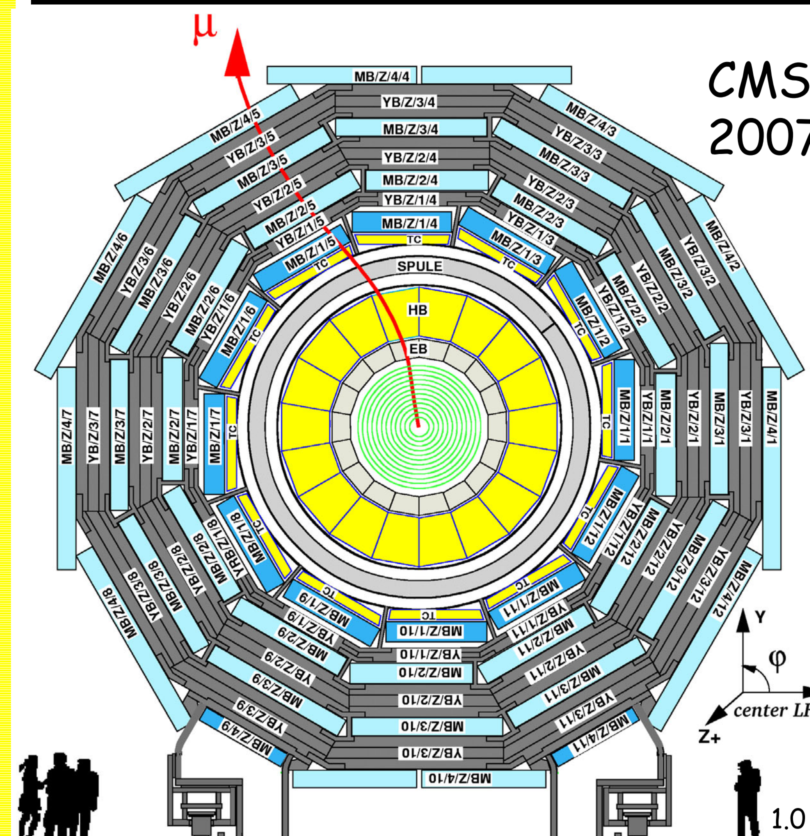
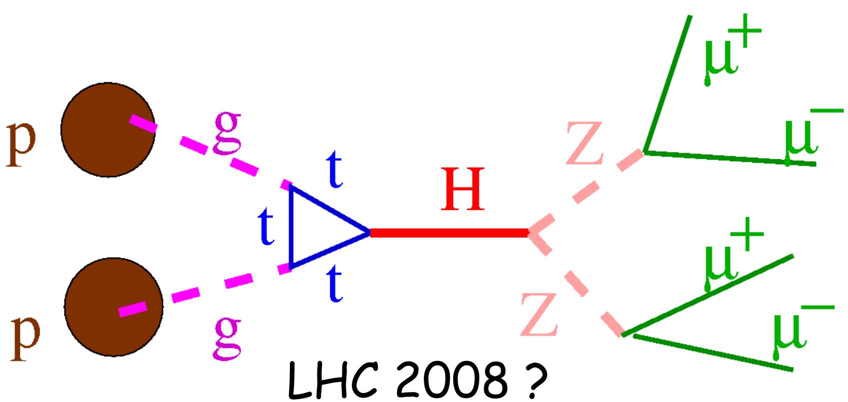
part I

pp physics









p p physics ?

Here: center of mass collisions of

- proton + proton $(p + p)$ ISR, RHIC, LHC
- proton + antiproton $(p + \bar{p})$ SPS, TEVATRON

} hadron colliders

at high energy ($\sqrt{s} = E_1 + E_2 >> m_p$)

Wanted:
high energy

Not in focus:

- one nucleon at rest (fixed target) DONUT ....
- electron/positron + proton HERA
- low energy collisions CPLEAR ...
- heavy ion collisions RHIC ...

pp physics

Part I Introduction

- p p collisions
- accelerators and detectors
- kinematical variables
- structure functions
- cross sections
- challenges
- luminosity determination

Part II Standard Model Physics

Part III Higgs

Part IV New Phenomena

References

Collider versus Fixed Target

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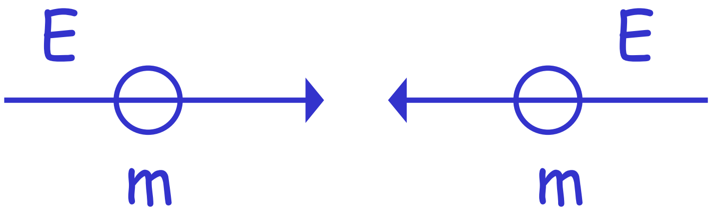
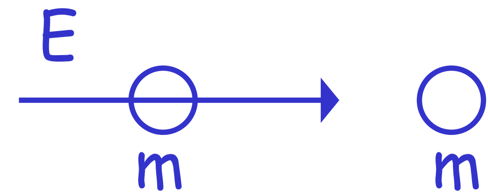
E >> m





$$s = [(E_1, \vec{p_1}) + (E_2, \vec{p_2})]^2$$

$$= [(2E, \vec{0})]^2$$

$$= 4E^2$$

$$s = [(E_1, \vec{p_1}) + (E_2, \vec{p_2})]^2$$

$$= [(E, \vec{p}) + (m, \vec{0})]^2$$

$$= (E+m)^2 - \vec{p}^{\,2}$$

$$= E^2 + 2mE + m^2 - (E^2 - m^2)$$

$$= 2mE + 2m^2$$

$$\approx 2mE$$

Collider versus Fixed Target

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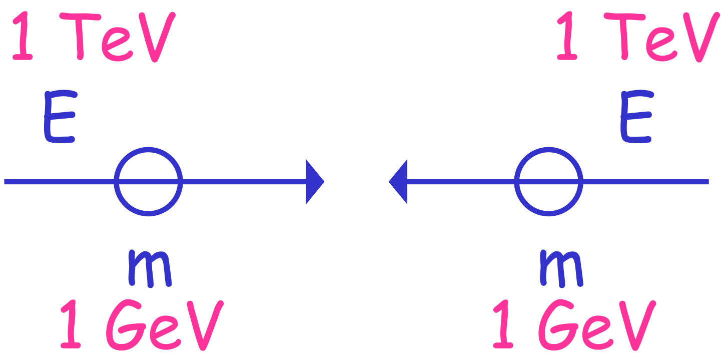
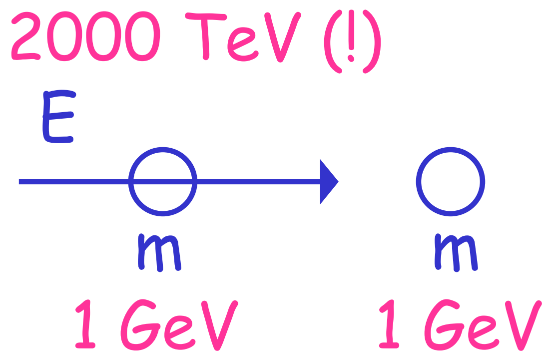
$E \gg m$





$$s = [(E_1, \overrightarrow{p_1}) + (E_2, \overrightarrow{p_2})]^2$$

$$= [(2E, \vec{0})]^2$$

$$= 4E^2$$

$$\sqrt{s} = 2\,TeV$$

$$s = [(E_1, \overrightarrow{p_1}) + (E_2, \overrightarrow{p_2})]^2$$

$$= [(E, \vec{p}) + (m, \vec{0})]^2$$

$$= (E+m)^2 - \vec{p}^{\,2}$$

$$= E^2 + 2mE + m^2 - (E^2 - m^2)$$

$$= 2mE + 2m^2$$

$$\approx 2mE$$

$$\sqrt{s} = 2\,TeV$$

DONUT: fixed target experiment

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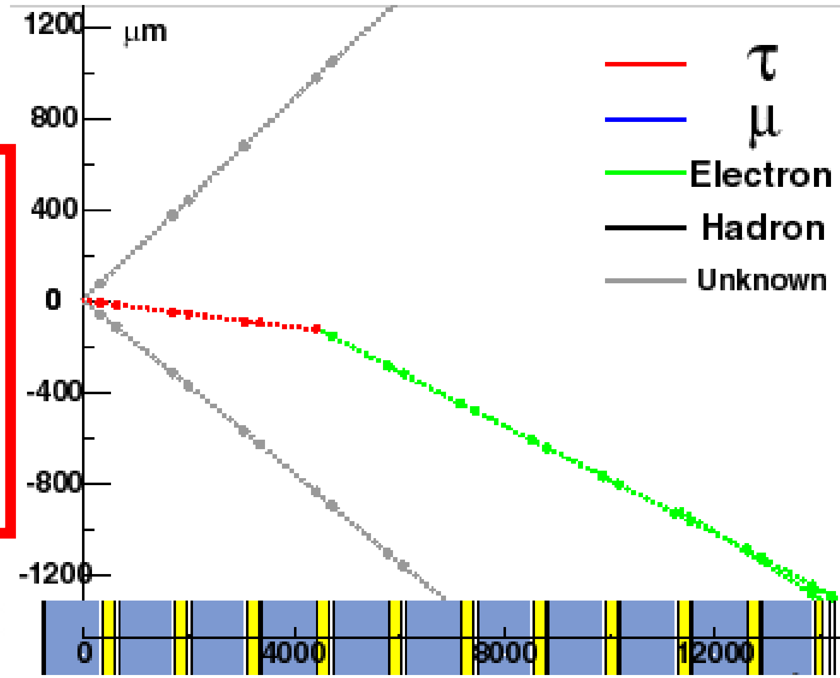
Machine: p (800 GeV) + A

DONUT =

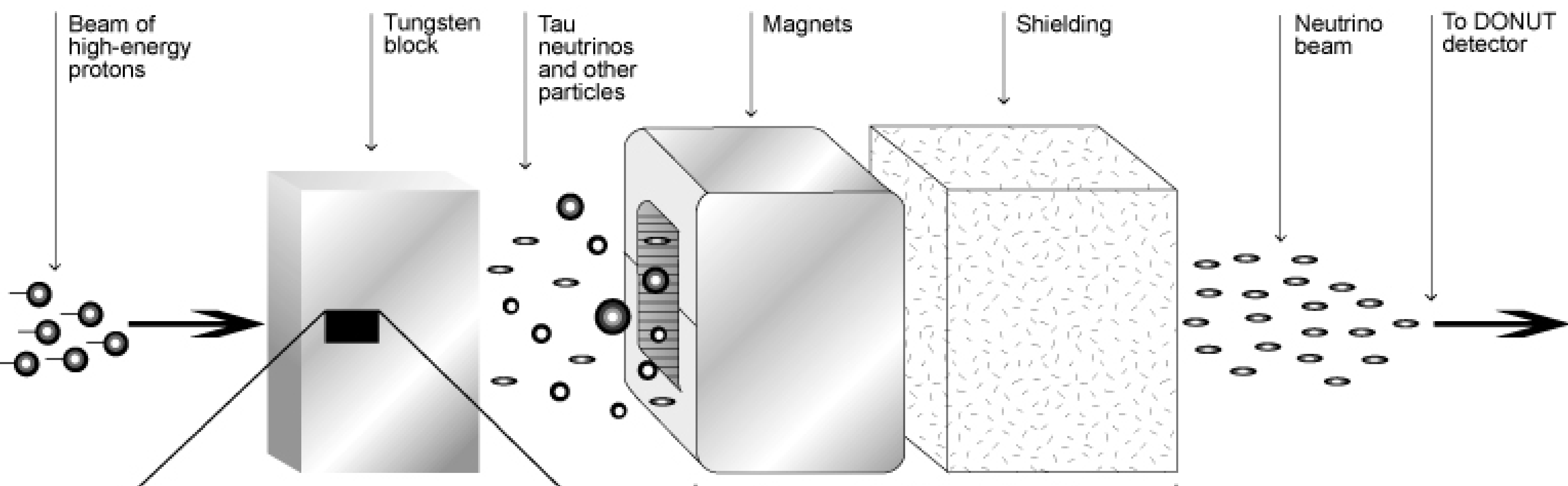
Direct Observation

of the Nu Tau

LHC =
Neutrino
Source !



Creating a Tau Neutrino Beam



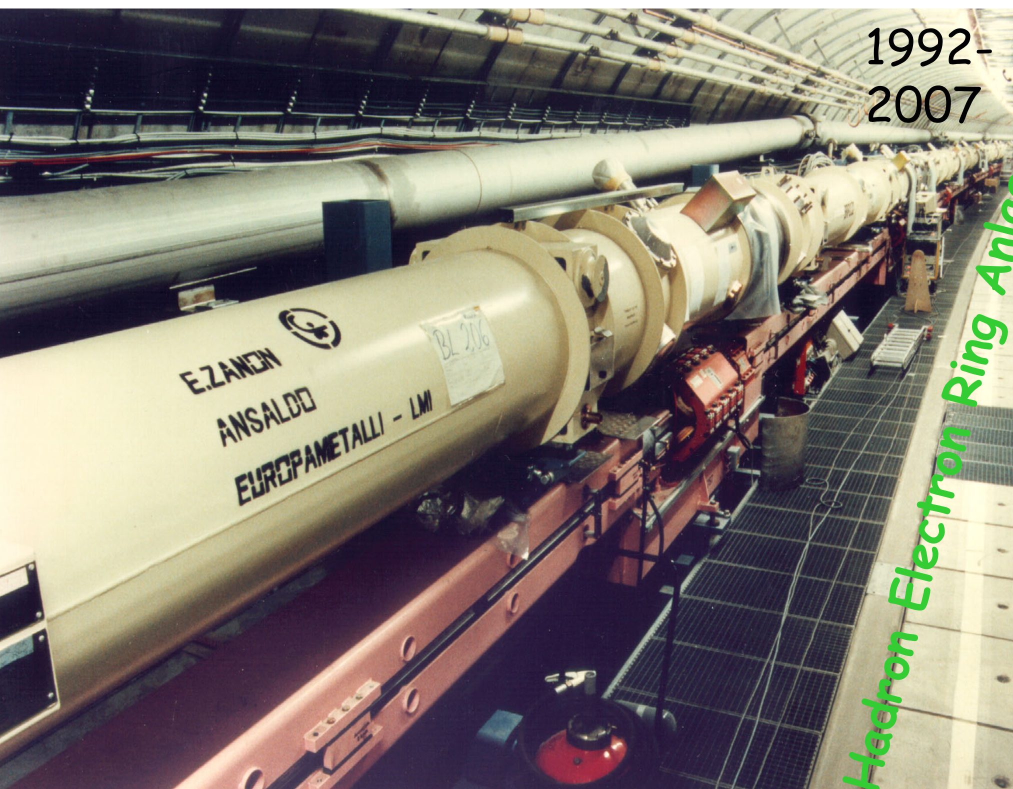
HERA electron microscope

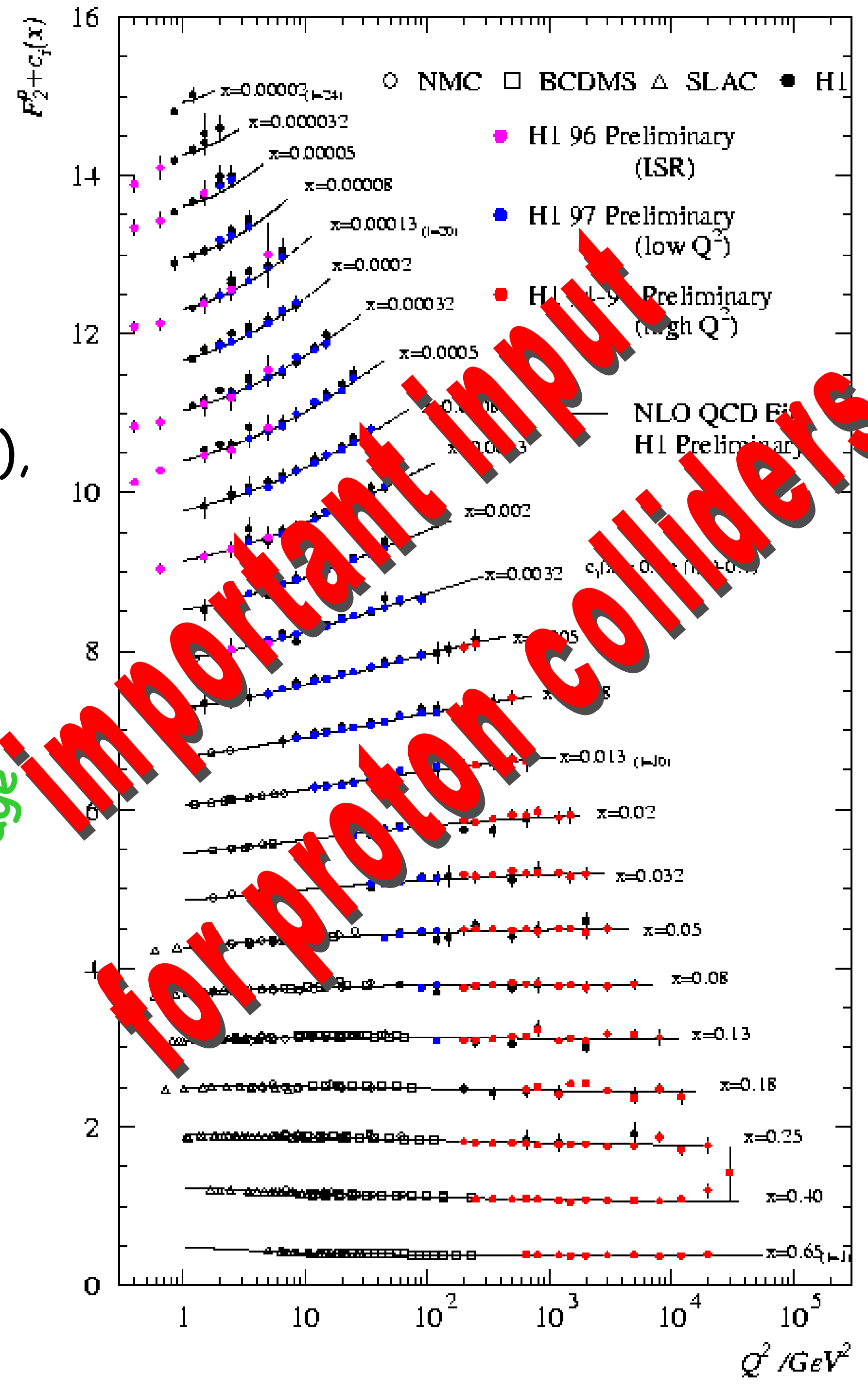
Machine: e (30 GeV) + p (900 GeV)

Detectors: H1, Zeus

Physics: structure proton (0.001 fm),

...





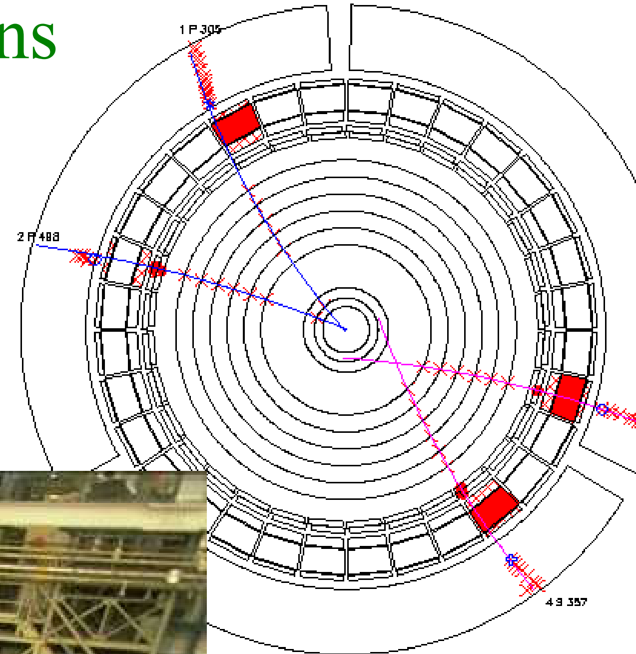
important input for proton colliders

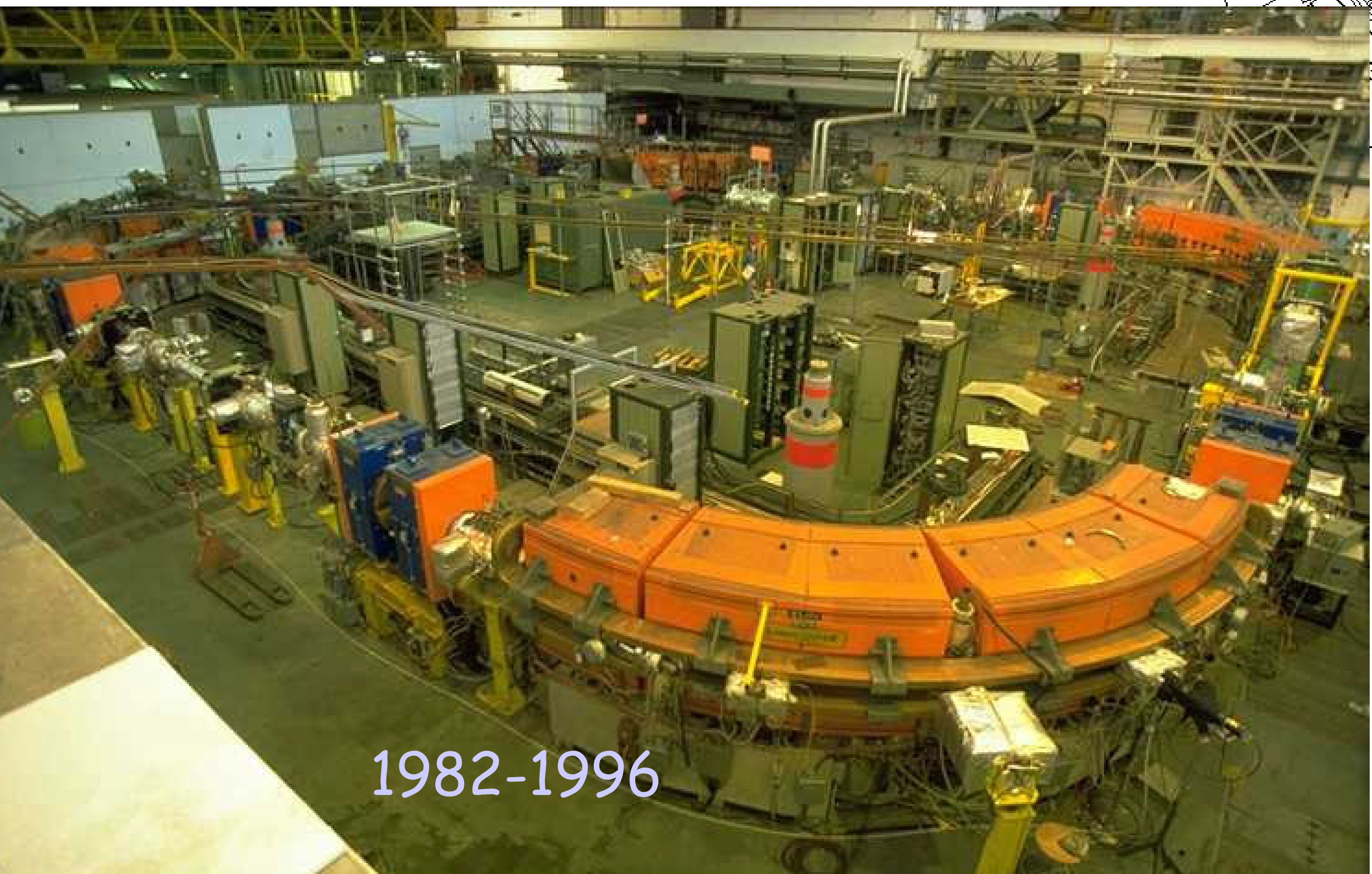
LEAR: Low energy hadron collisions

Machine: $\bar{p}$ (100 MeV – 2 GeV) + H_2 ... (gas)

Experiments: CPLEAR, Crystal Barrel ...

Physics: CP violation, exotic mesons, $\overline{H}$ ...





CPLEAR

$$K^0 \rightarrow \pi^+ \pi^-$$

complete annihilation

$$p + \bar{p}$$

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RHIC: Heavy ion collisions

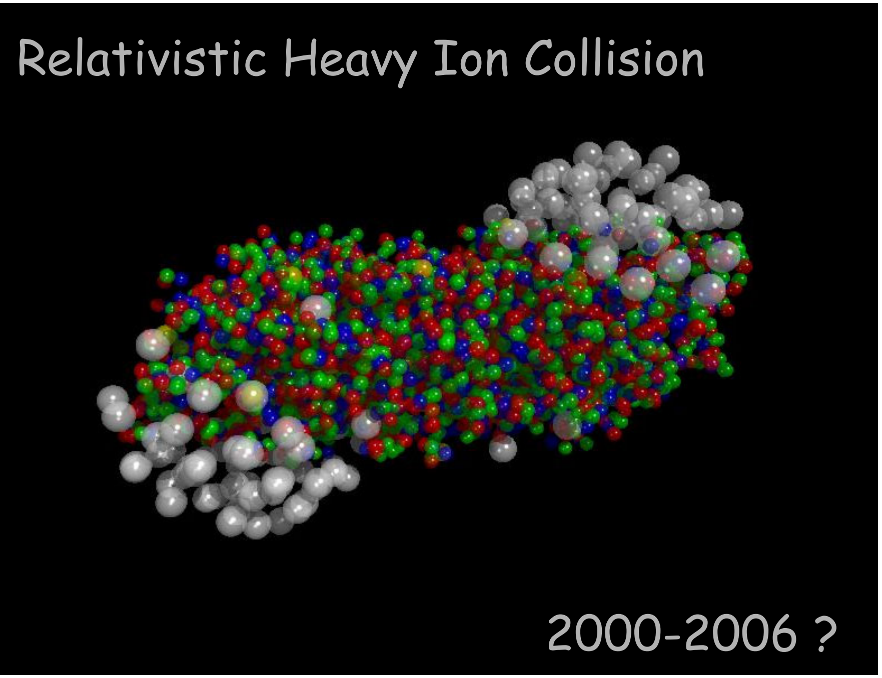
Machine: A (200 GeV*Z) + A (200 GeV*Z)

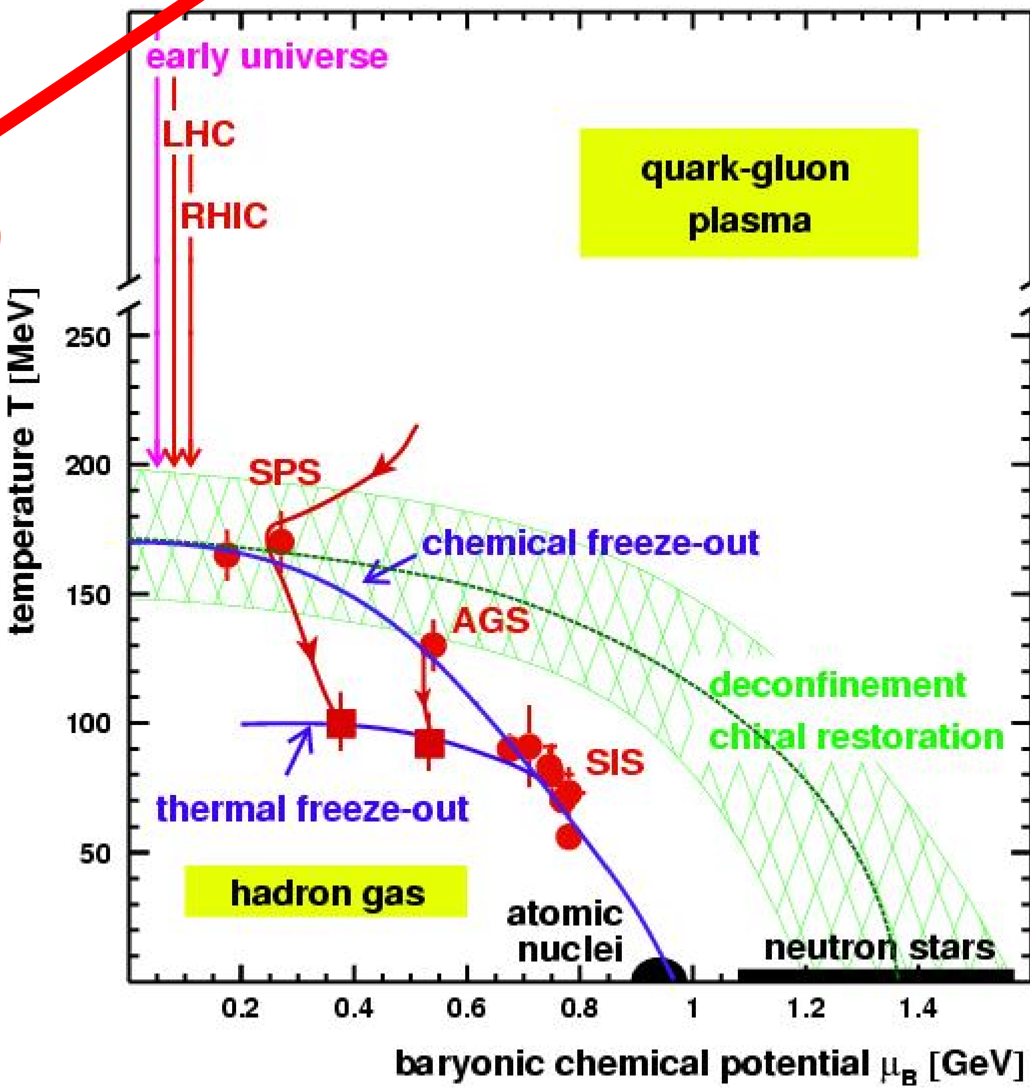
multi quark physics

Detectors: Phobos, Star, ...

Physics: quark gluon plasma

proton spin (pol. p)





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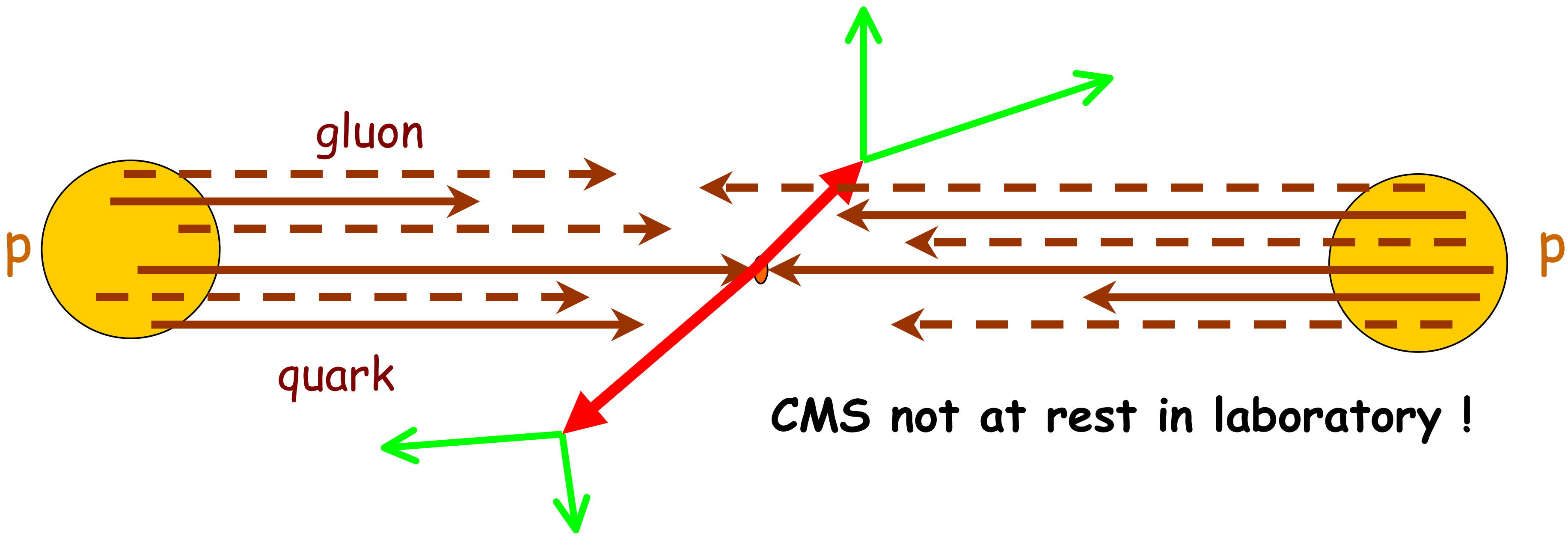
Effective Center of Mass Energy

In high energy hadron collisions 2 constituents undergo hard scattering:



center of mass energy $\sqrt{s'}$ of colliding partons (q, g):

Rough estimate: $\sqrt{s'} \approx \frac{1}{6} \bullet \sqrt{s}$ Calculation: structure functions!

Examples: $q\bar{q} \to W$ $gg \to h(!)$ $qg \to qg$

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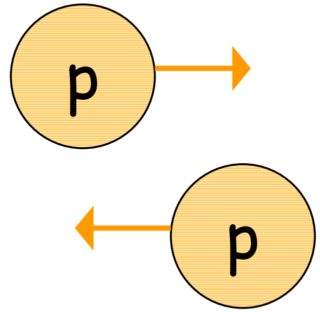
Cross Section

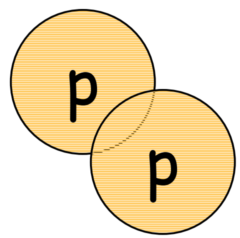
Elastic cross section — LUMINOSITY



strong, electromagnetic

scattering angle tiny

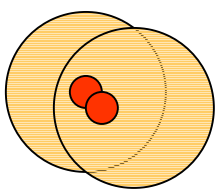
Total inelastic cross section — BACKGROUND, LUMINOSITY



strong

$$\sigma \approx 10\, fm^2 \approx 10^{-25}\, cm^2$$

Pointlike cross section — SIGNAL



electroweak

$$\sigma \leq \frac{\alpha^2}{s} \approx 10^{-36}\, cm^2$$

LHC (→ s)

Signal / Background $< 10^{-11}$

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$e^+ e^-$ or $\mu^+ \mu^-$ or Hadron Collider ?

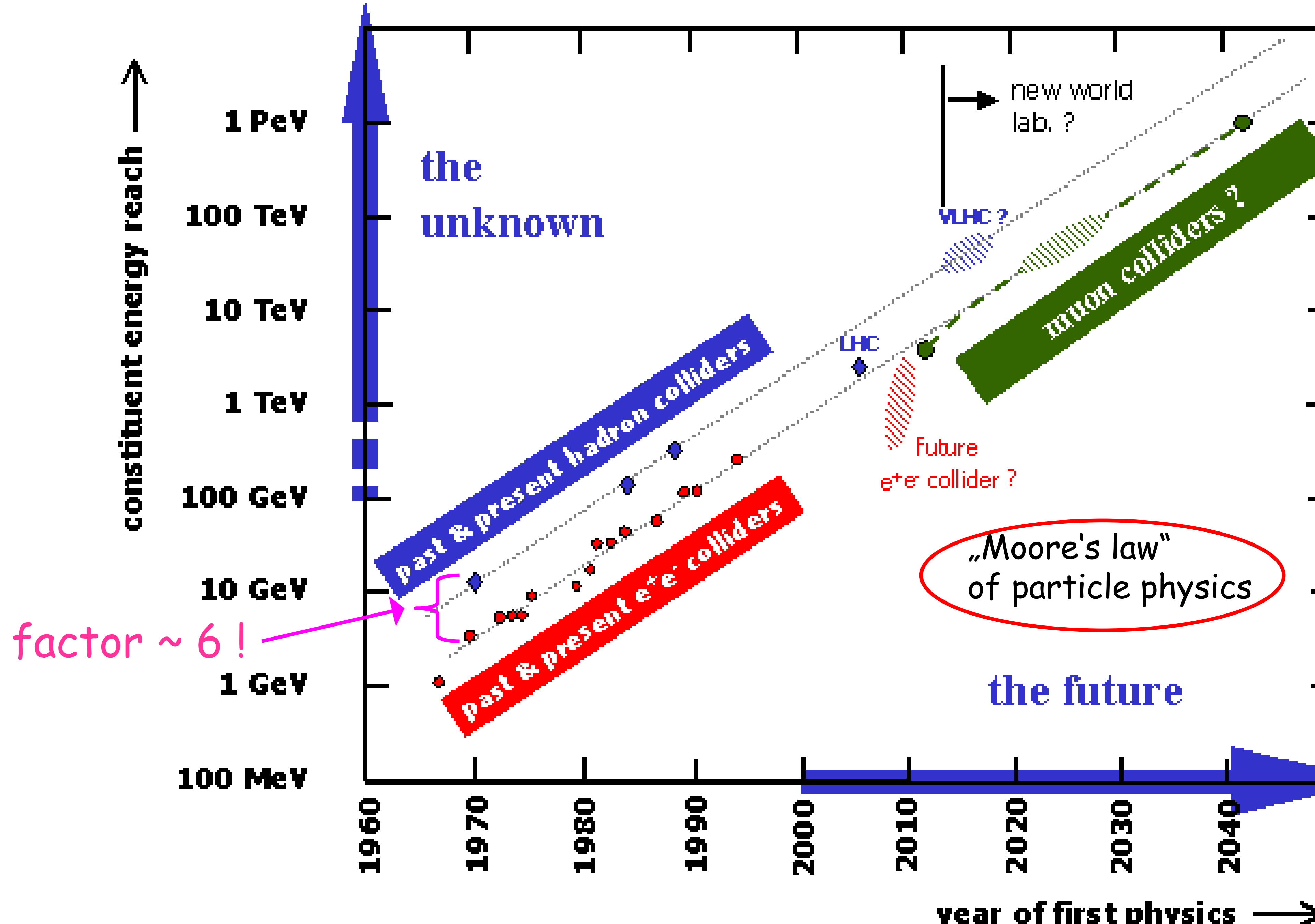
- leptons
  - electrons — $\sqrt{s}$ ~ 200 GeV
    - storage ring — synchrotron radiation
    - linear accelerator — gradient, length — 800 GeV ?
  - muons
    - storage ring — NOT YET

} Pointlike, electroweak

- hadrons = (anti)protons
  - storage ring — magnetic field — 14 TeV

} Composite, strong

The Livingston Plot: Past, Present & Future(?)



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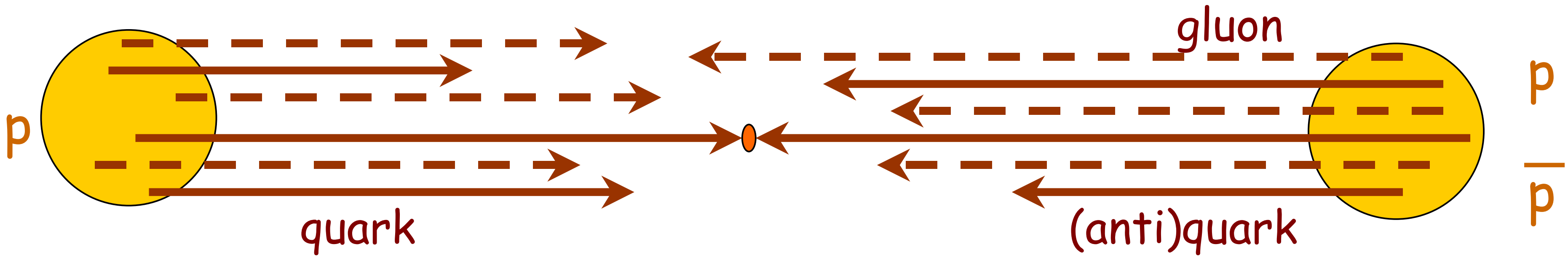
Proton or Antiproton ? Physics:

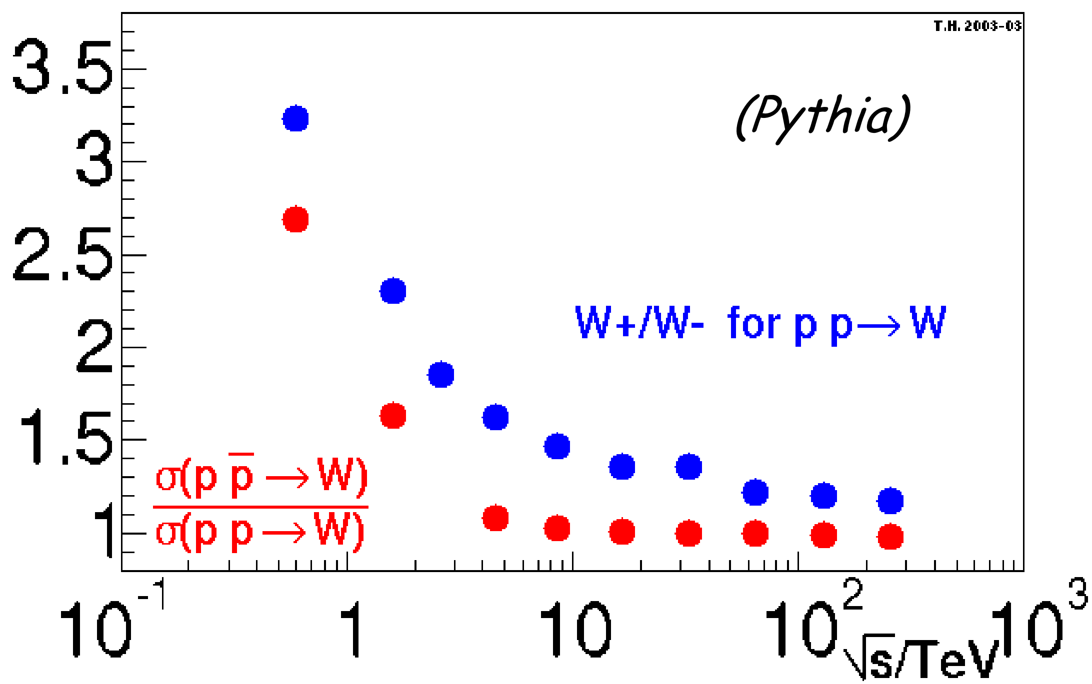


At low energy: valence quarks dominate hard scattering: $p\,p \neq p\,\bar{p}$

At high energy: sea quarks and gluons dominate hard scattering: $p\,p \approx p\,\bar{p}$

Example:

inclusive W production



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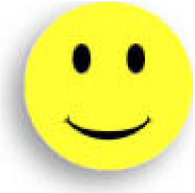
Proton or Antiproton ?

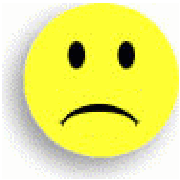
$p\,\bar{p}$

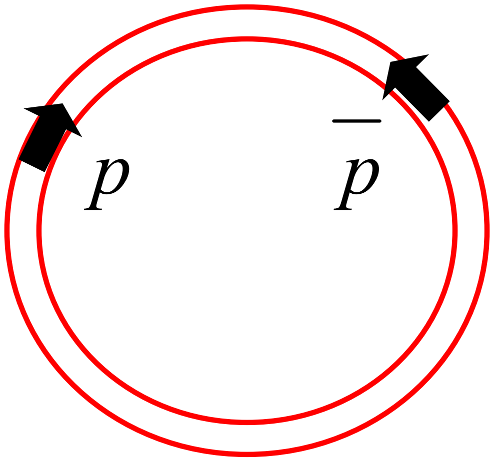
- <u>one</u> accelerator



- antiproton production:

$$1\,\bar{p} \;\; per \;\; 3\cdot 10^{5} \; p$$





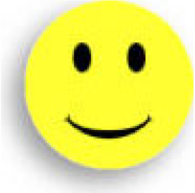
SPS $5\cdot 10^{11}\,\bar{p}$

Tevatron $1\cdot 10^{12}\,\bar{p}$

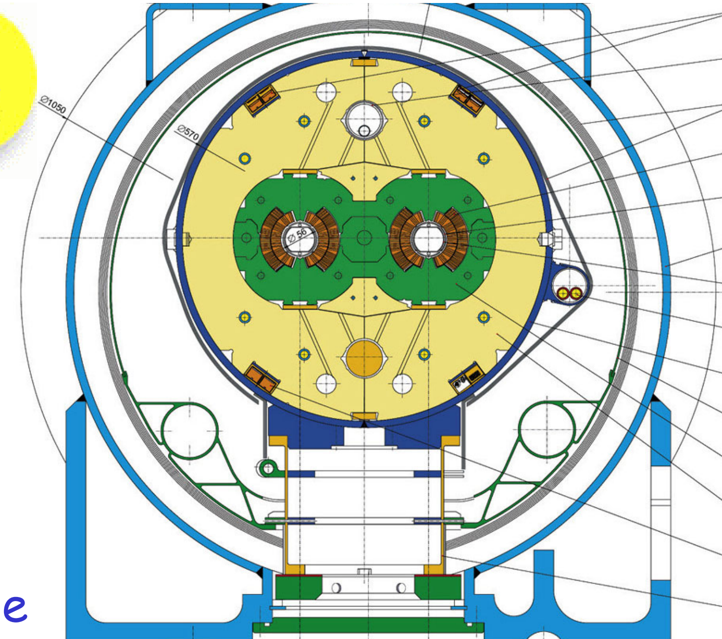
$p\,p$

- <u>two</u> accelerators !

- no antiprotons !



LHC $3\cdot 10^{14}\,p$



LHC dipole

Kinematics I

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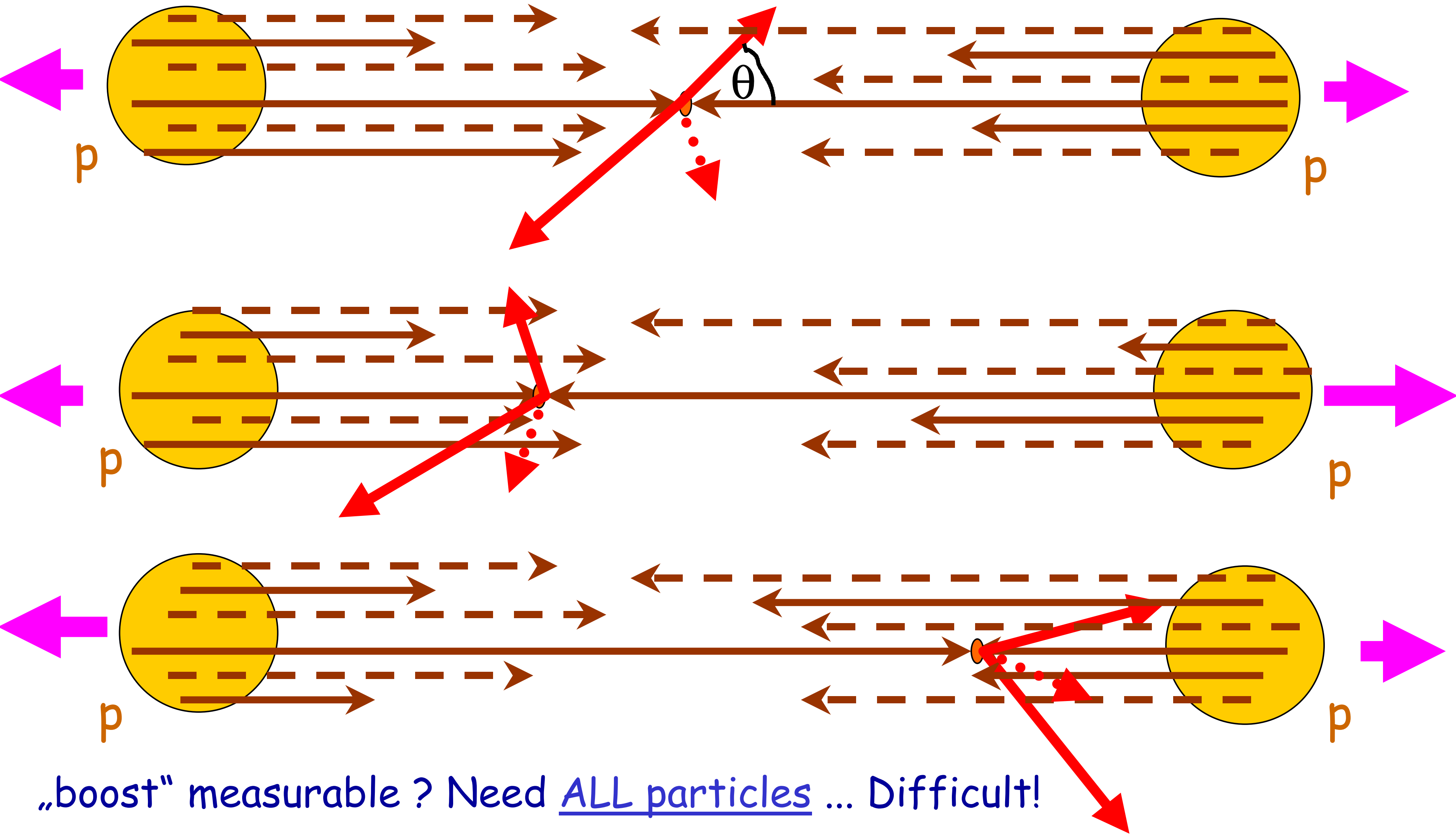
„boost" of center of mass system along beam axis = a priori unknown !



„boost" measurable ? Need ALL particles ... Difficult!

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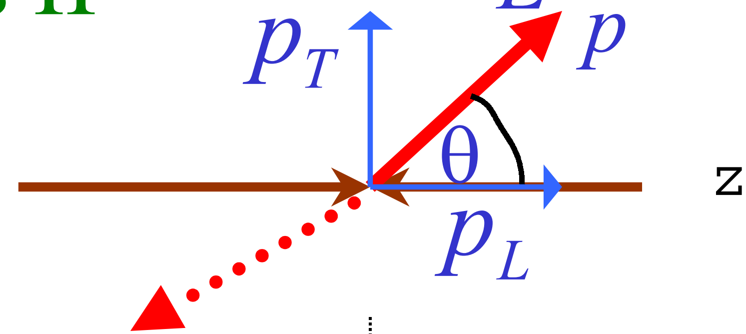
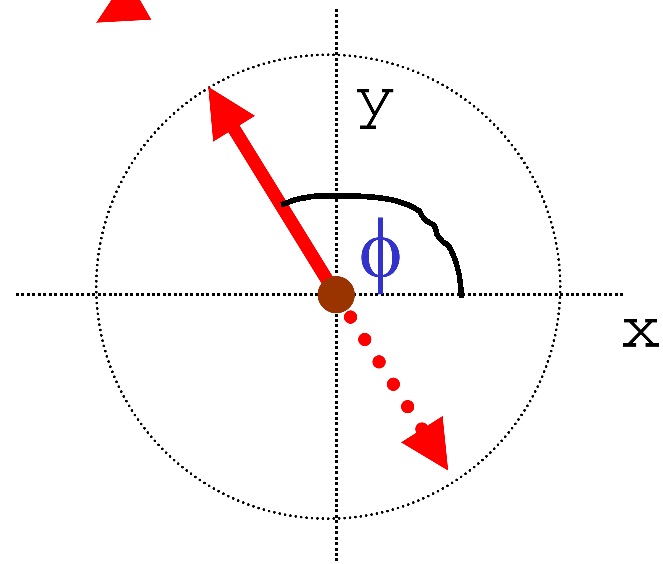
Kinematics II



Kinematical variables:

- azimuthal angle ϕ
- polar angle θ
- energy E
- momentum p
- transverse momentum p_T
- longitudinal momentum p_L



- rapidity $$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$

$m << E, p_L$

- pseudorapidity $$\eta = -\ln \tan \frac{\theta}{2}$$

Kinematics III

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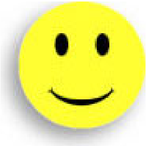
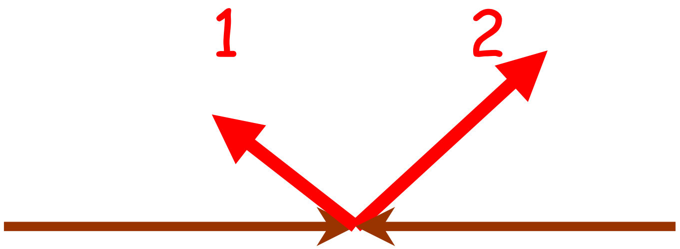
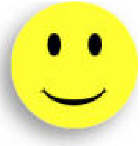
Boost invariance ?

<u>Kinematical variables:</u>

- azimuthal angle ϕ 
- polar angle θ
- energy E
- momentum p
- transverse momentum p_T 
- longitudinal momentum p_L



- rapidity $$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$ $$y_1 - y_2$$
- pseudorapidity $$\eta = -\ln \tan \frac{\theta}{2}$$ $$\eta_1 - \eta_2$$



Rapidity I

$$y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L} = \ln\frac{\sqrt{E+p_L}}{\sqrt{E-p_L}}\cdot\frac{\sqrt{E+p_L}}{\sqrt{E+p_L}} = \ln\frac{E+p_L}{\sqrt{E^2-p_L^2}}$$

$$= \ln\frac{E+p_L}{\sqrt{p_T^2+m^2}}$$

Boost along z:

$$y' = \ln\frac{E'+p'_L}{\sqrt{p_T^2+m^2}} = \ln\frac{\gamma\,(E+\beta\,p_L)+\gamma\,(p_L+\beta\,E)}{\sqrt{p_T^2+m^2}}$$

$$= \ln[\gamma\,(1+\beta)\frac{E+p_L}{\sqrt{p_T^2+m^2}}] = y + \ln\gamma\,(1+\beta)$$

$$y_1' - y_2' = y_1 - y_2$$

Rapidity II

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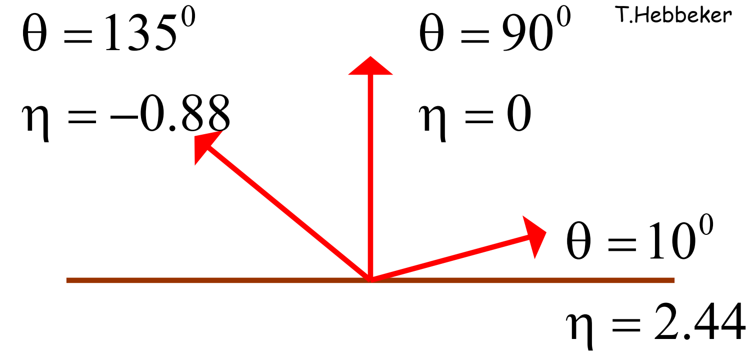
$$y = \ln \frac{E + p_L}{\sqrt{p_T^2 + m^2}}$$

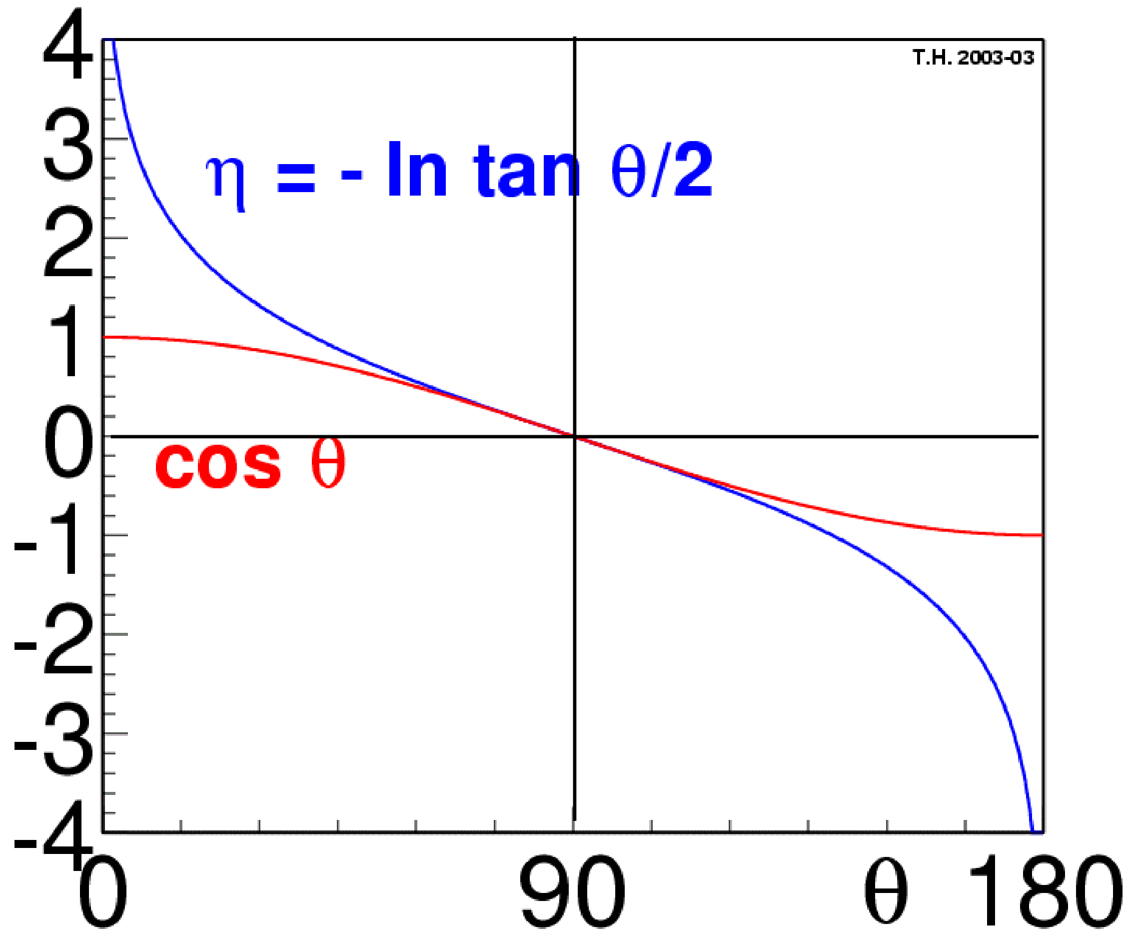
$m << E, p_L$

$$\to \ln \frac{E + E\cos\theta}{E\sin\theta}$$

$$= \ln \frac{2\cos^2\frac{\theta}{2}}{2\sin\frac{\theta}{2}\cos\frac{\theta}{2}}$$

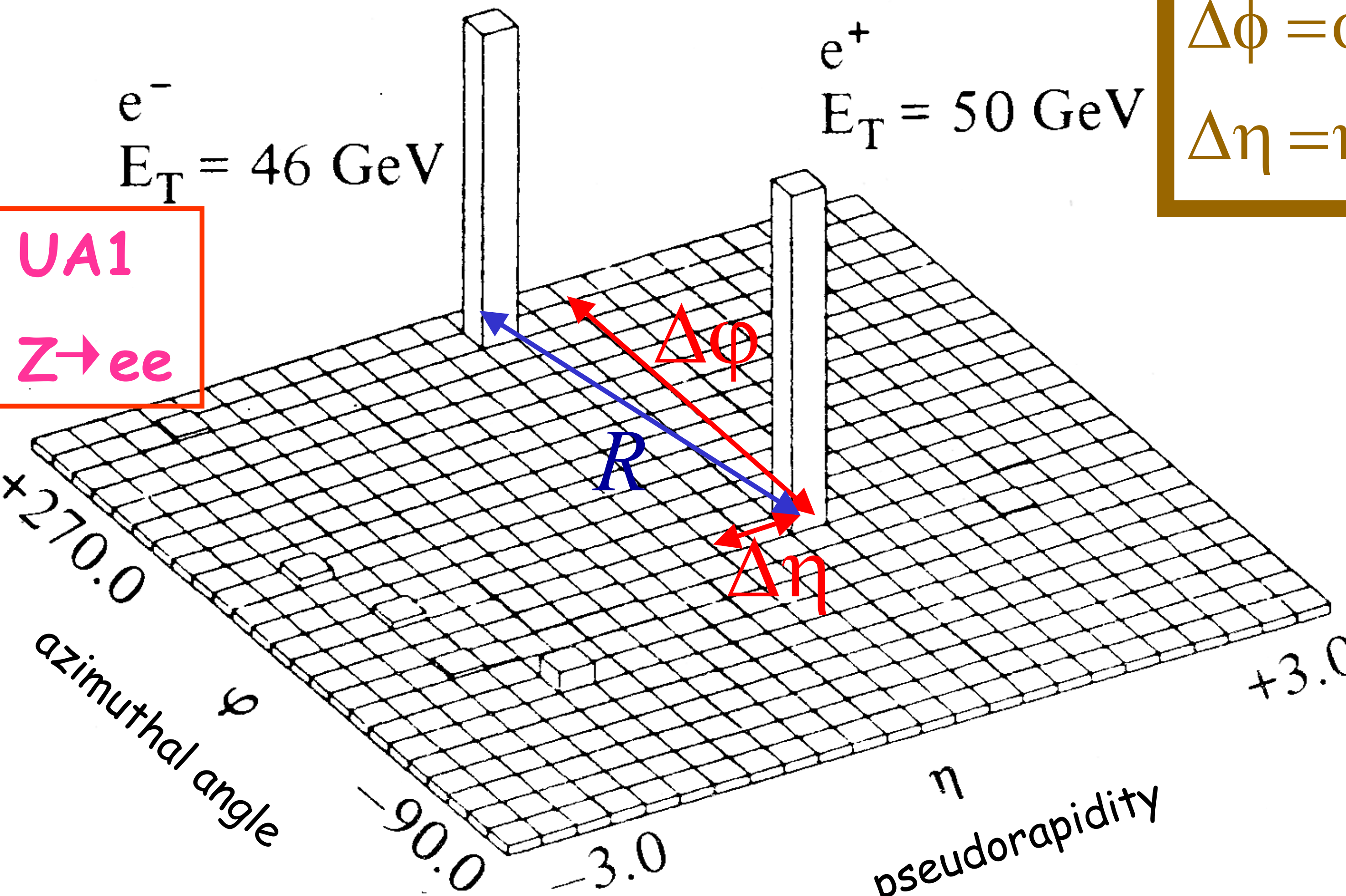
$$= -\ln\tan\frac{\theta}{2} = \eta$$





Rapidity III

Particle directions ↔ ϕ, η



distance measure:

$$R^2 = (\Delta\phi)^2 + (\Delta\eta)^2$$

$$\Delta\phi = \phi_1 - \phi_2$$

$$\Delta\eta = \eta_1 - \eta_2$$

Note:

- rotation:

  $\Delta\phi = const$

- boost:

  $\Delta\eta = const$

Missing transverse energy/momentum

a) energy = momentum (masses small)

b) $\vec{p}_T$ can be measured for all „visible" particles:

i) small angle to beam pipe: escapes but $\vec{p}_T$ small

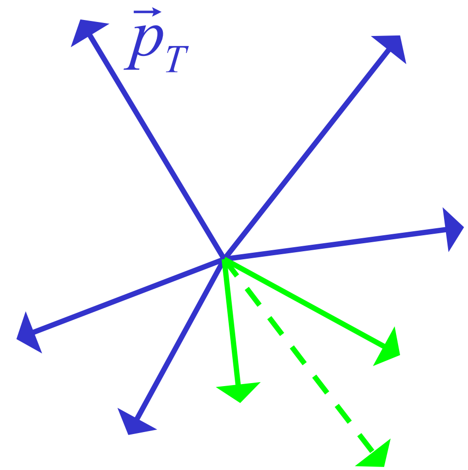
ii) large angle: seen in detector

c) „invisible particles" (neutrinos, gravitons, ...):

$$\sum_{invis} \vec{p}_T = -\sum_{vis} \vec{p}_T$$

$$MET = |\sum_{invis} \vec{p}_T|$$

plane perpendicular to beam:



Example: $W \to \mu\ \nu$

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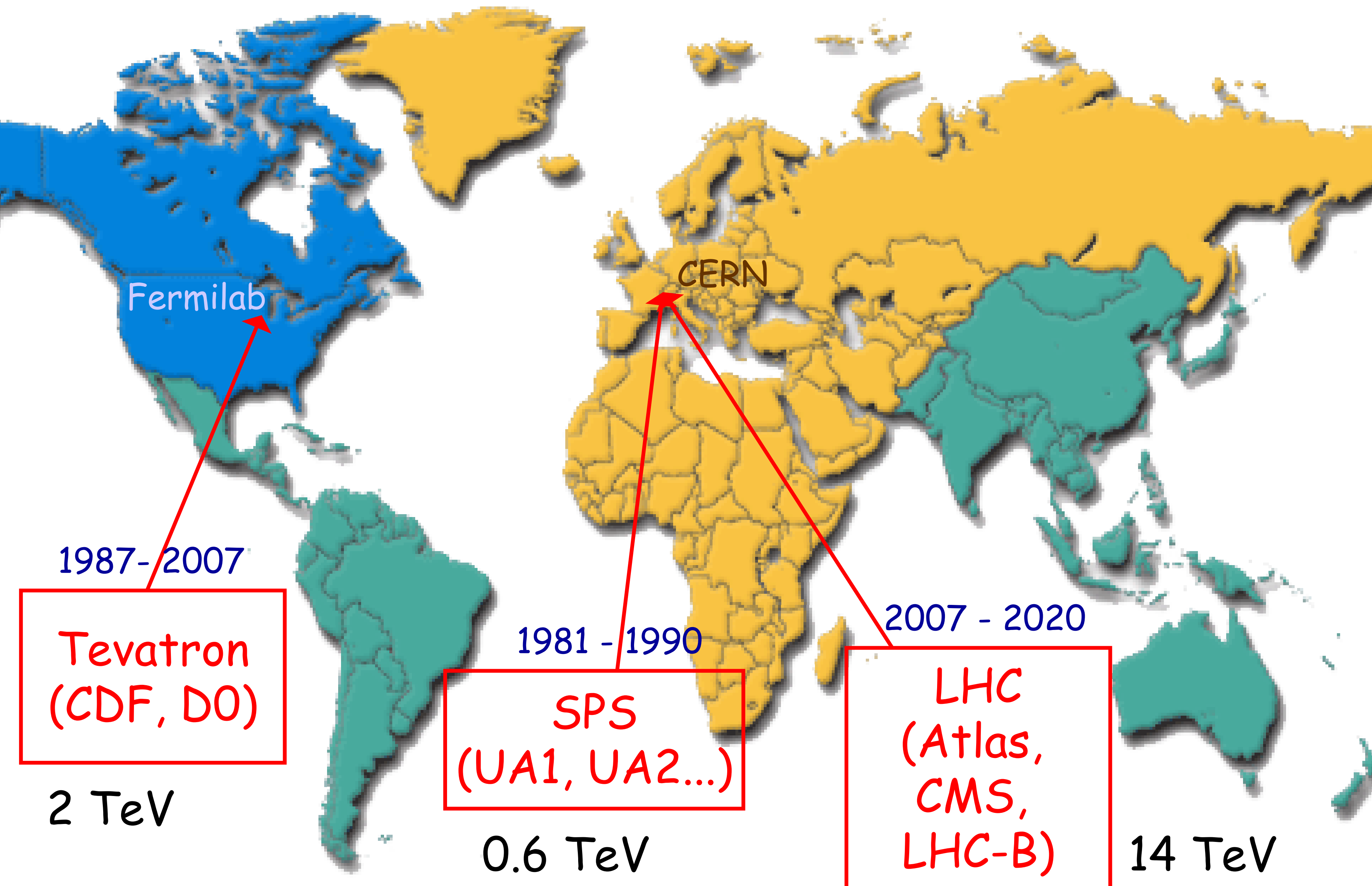
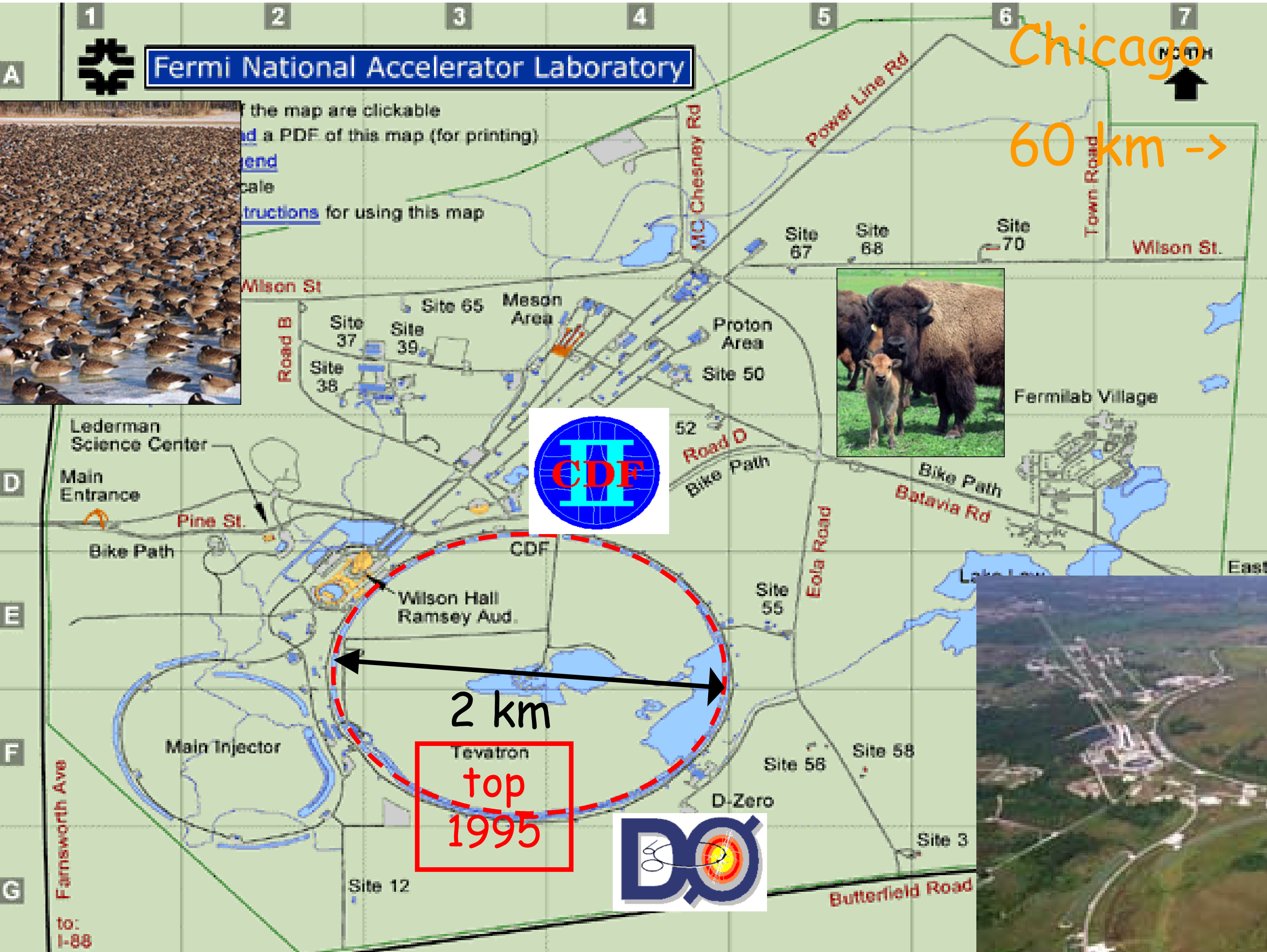
Hadron colliders and detectors



Fermilab/Tevatron



FNAL =

Fermilab

(Enrico Fermi)

1967

Tevatron = TEV machine

SPS, LHC / CERN

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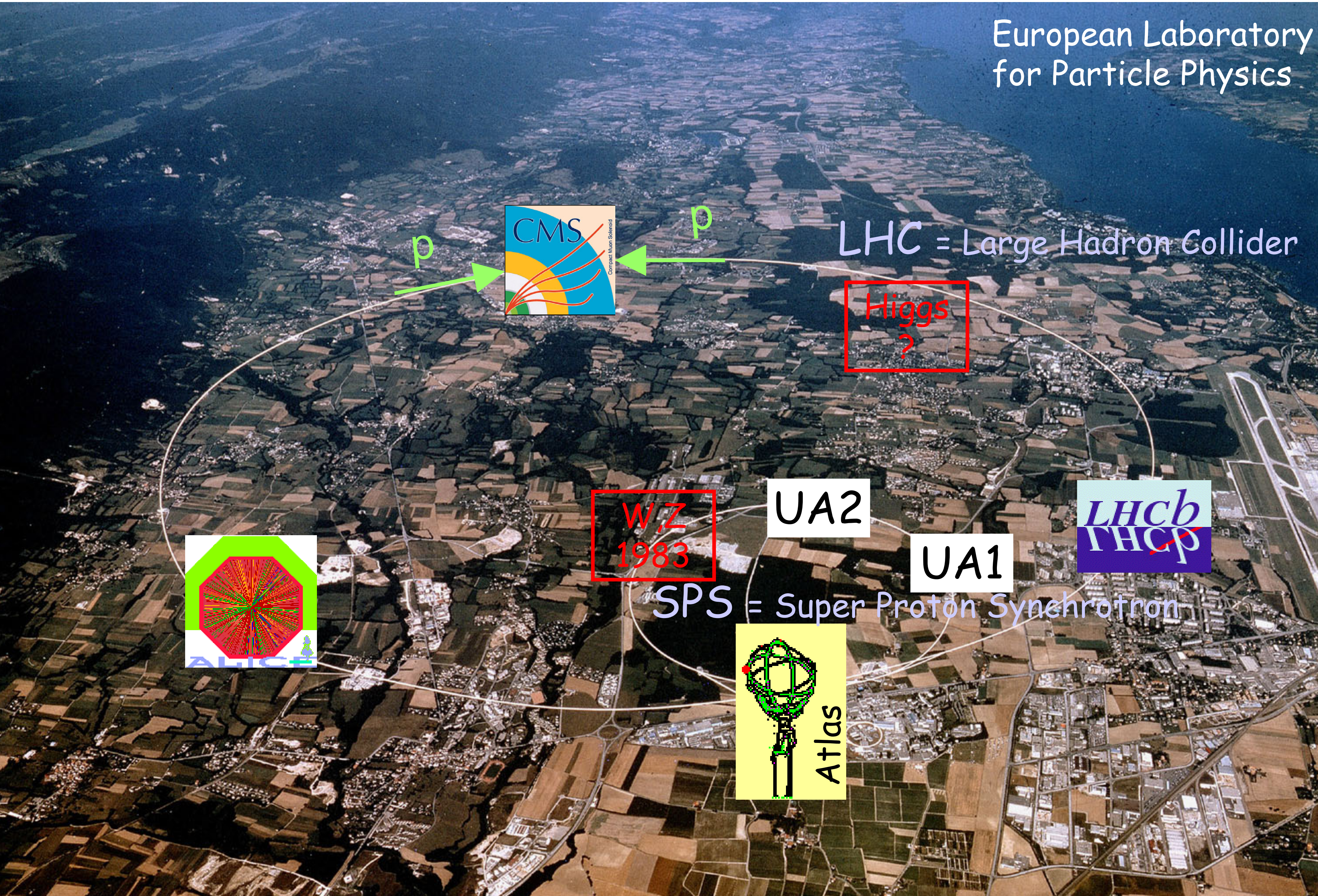

SPS, Tevatron, LHC

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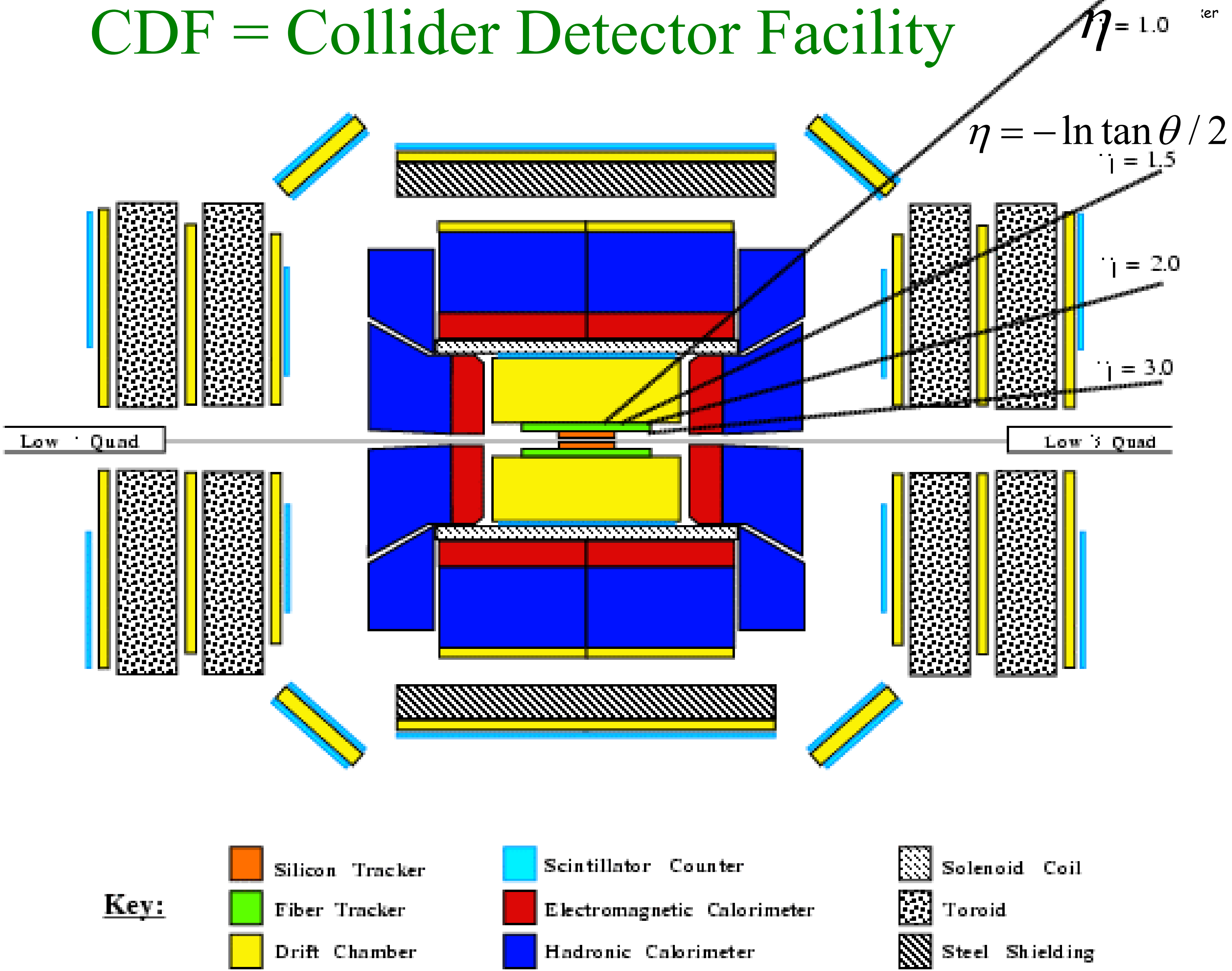
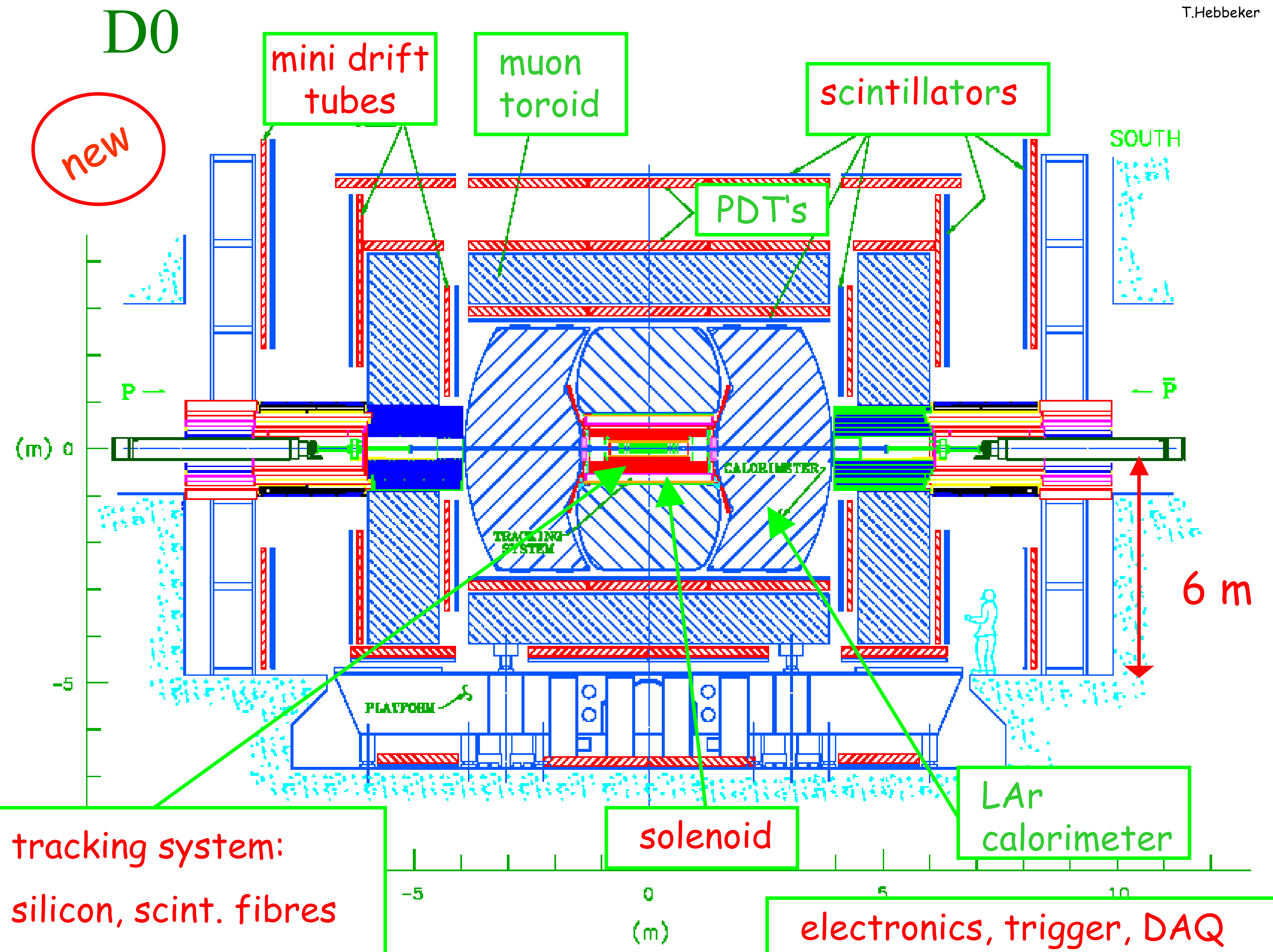
2003

	SPS	Tevatron	LHC
Particles	$p+\bar{p}$	$p+\bar{p}$	$p+p$
c.m. energy TeV	0.6	2.0	14
luminosity 10^{30} /cm^2/s 1/fb / year	6 0.05	50 0.5	10000 100
Bunches	6 + 6	36 + 36	2835 + 2835
Bunch separation ns	3800	396	25

CDF = Collider Detector Facility



D0



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new
mini drift tubes
muon toroid
scintillators
SOUTH
PDT's
P
P̄
(m) 0
-5
CALORIMETER
TRACKING SYSTEM
PLATFORM
6 m
-5
0
5
10
(m)
tracking system:
silicon, scint. fibres
solenoid
LAr calorimeter
electronics, trigger, DAQ

ATLAS = A Toroidal LHC ApparatuS

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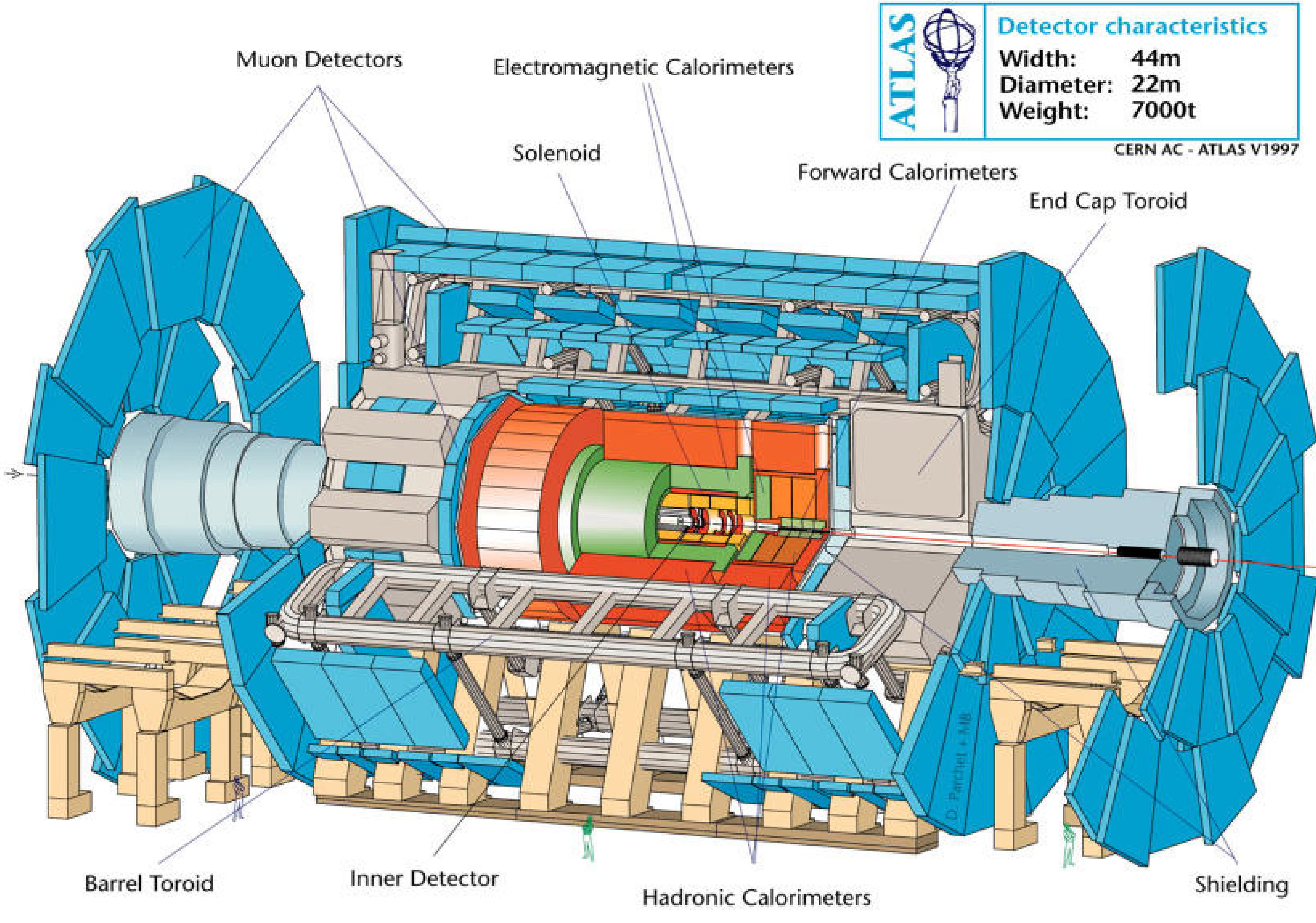

CMS = Compact Muon Solenoid

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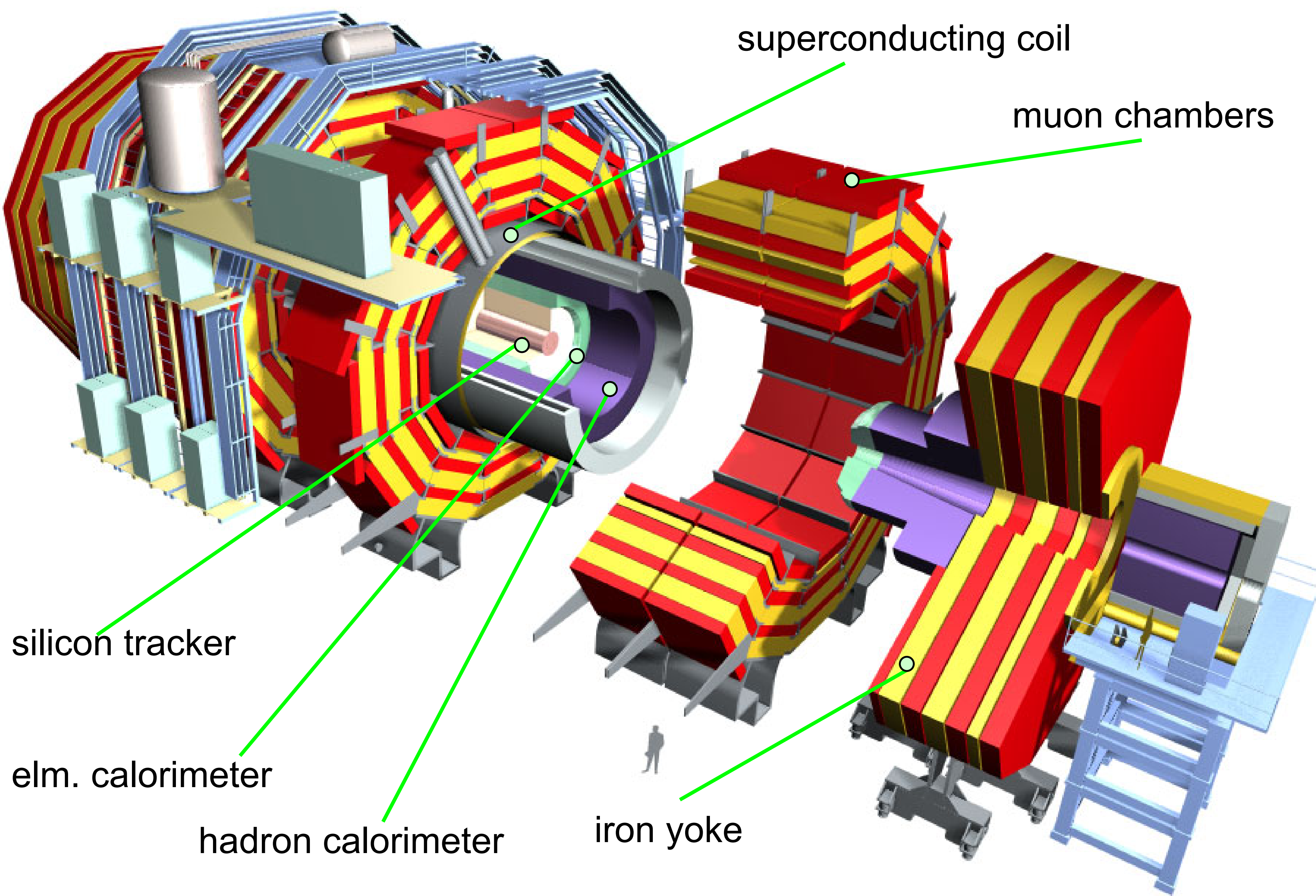
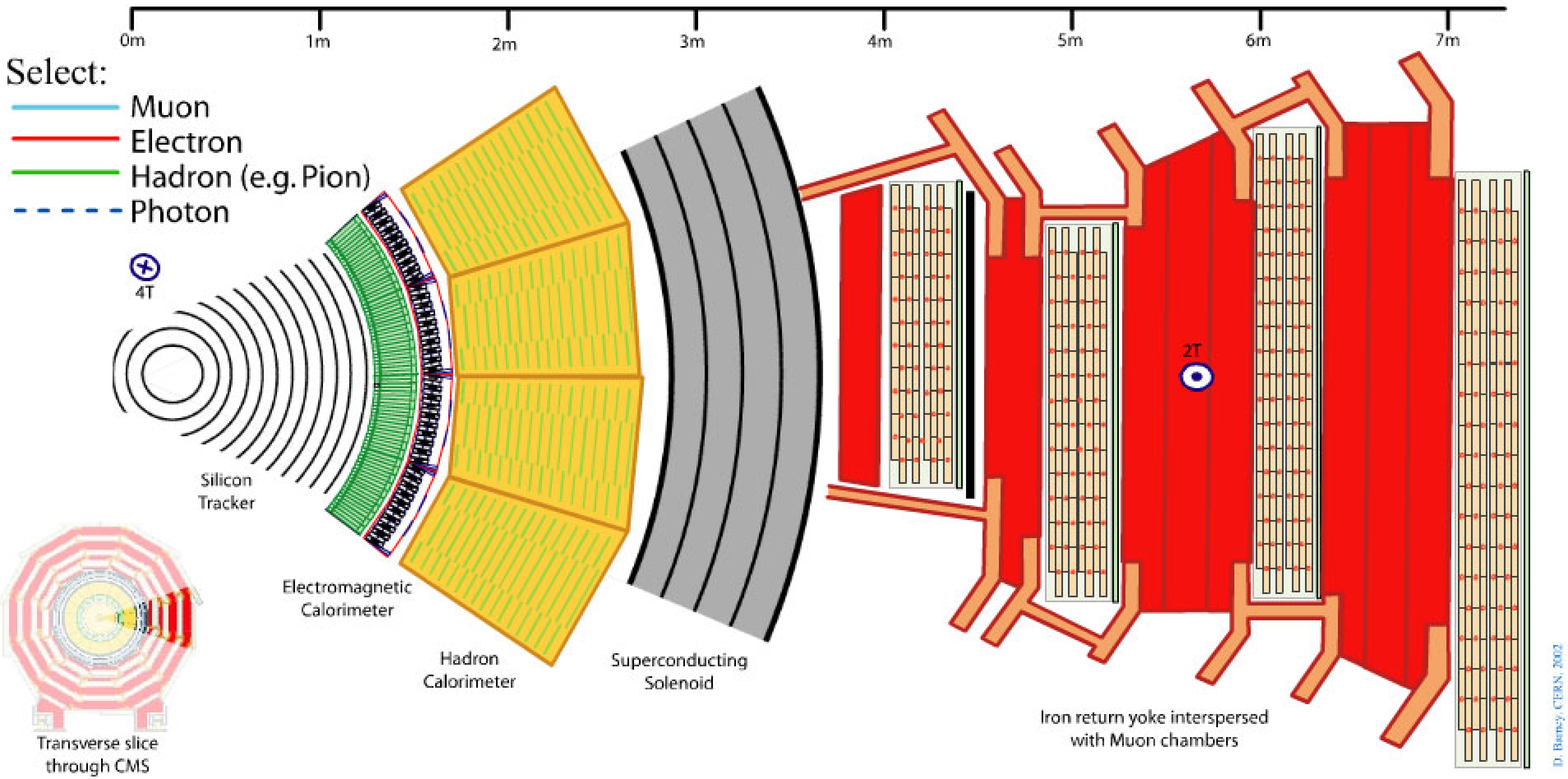
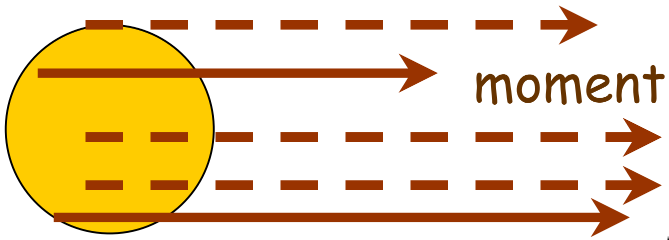


CMS response to particles



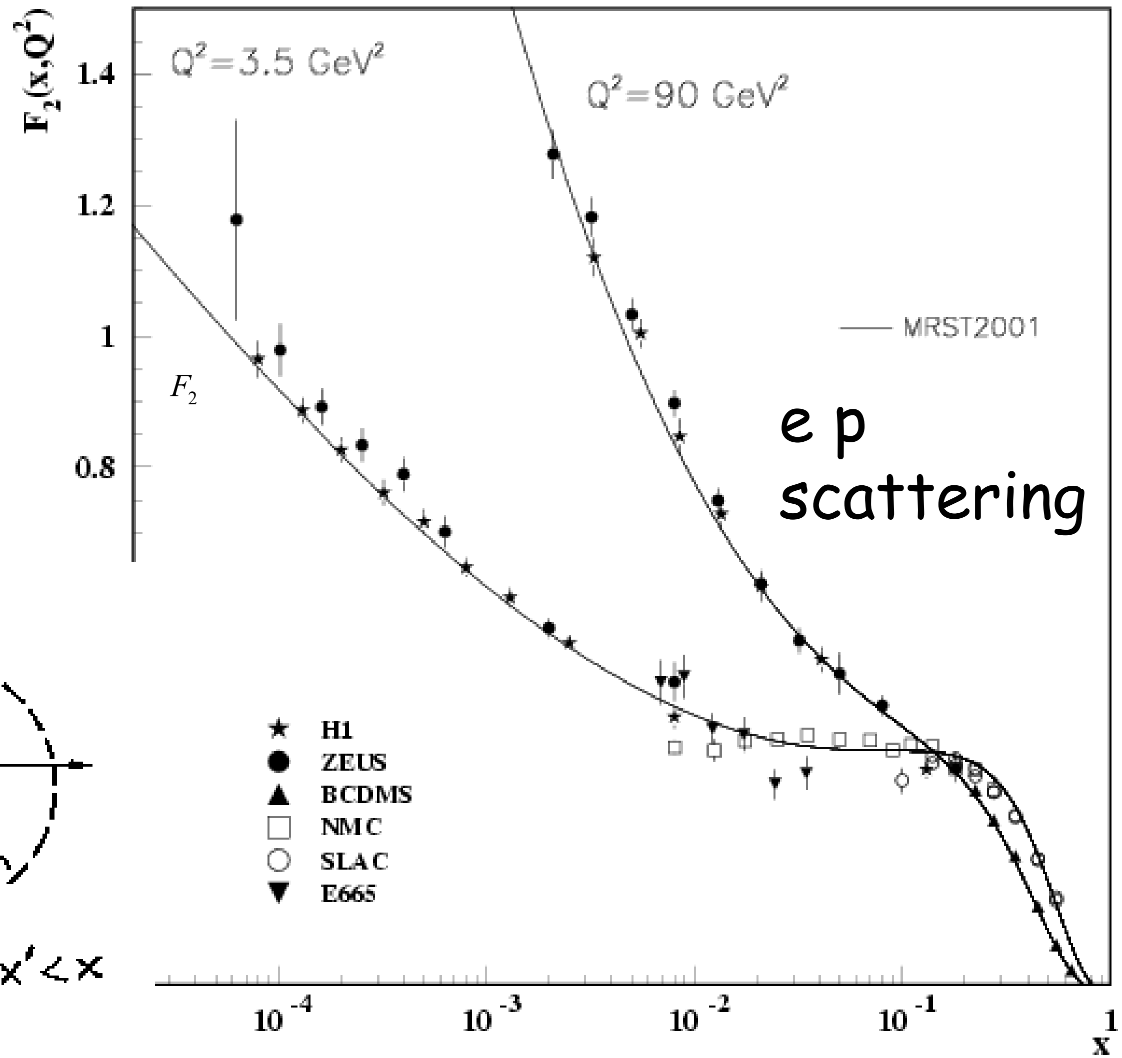
Structure functions



momentum $x \cdot p$

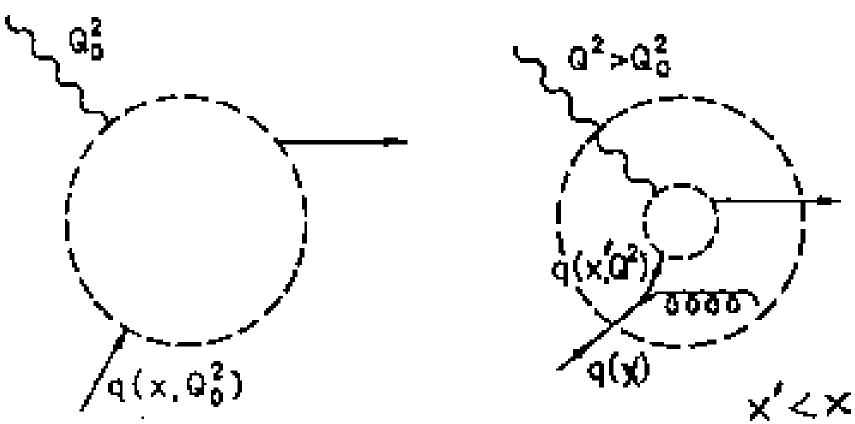
momentum p

$$F_2(x) = x\,[\frac{4}{9}u(x) + \frac{1}{9}d(x) + \ldots]$$

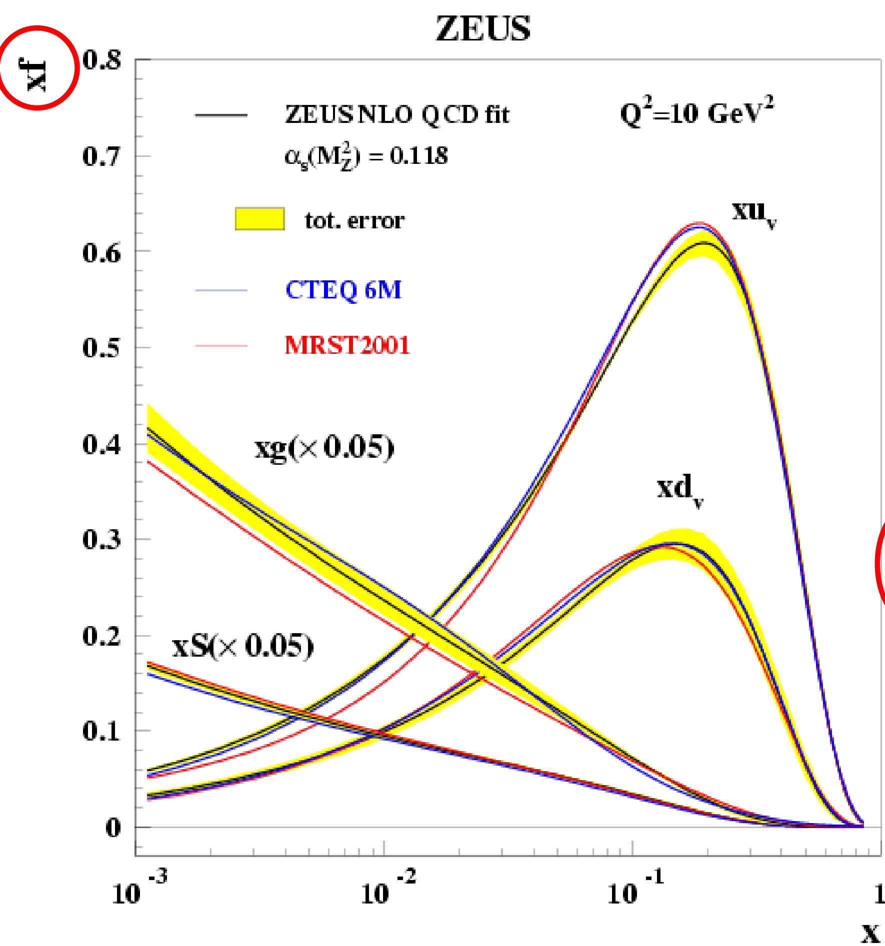


„Bjorken x"

depends on resolution, given by Q^2:



Structure functions



Measurements:

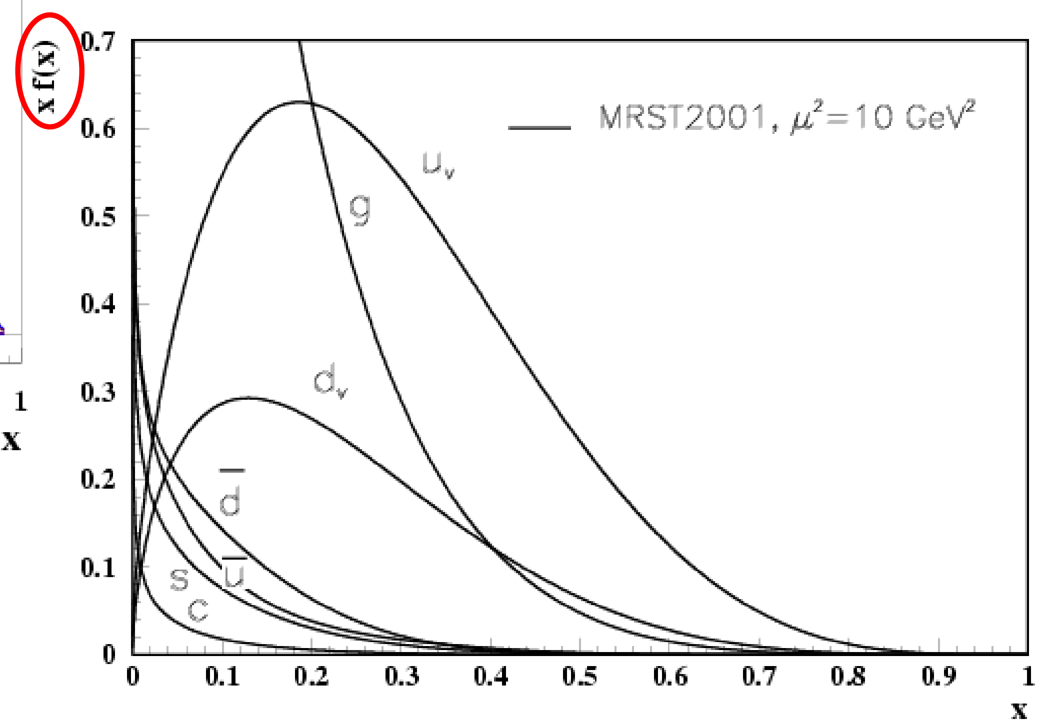
F_2, F_3 ... in DIS

(n,p,elm.,weak, Q^2-depend.)

⇨ valence, sea, gluons...

Fits/parametrisations:

- CTEQ
- MRST



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Cross section calculation in pp

final state

Wanted: $$\frac{d\sigma_F(\sqrt{s},Q^2)}{dV}$$

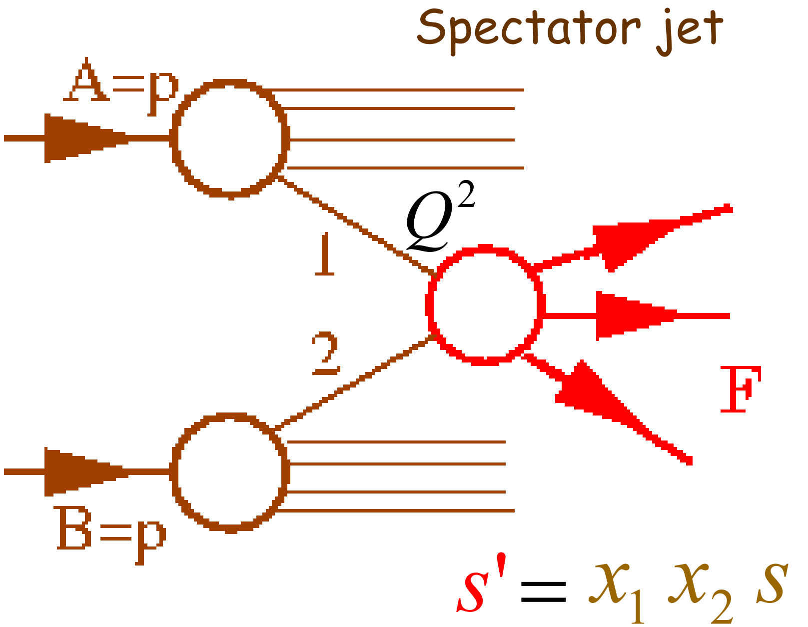
kinematical variable

Calculable: $$\frac{d\sigma_F^{ij}(x_i,x_j,Q^2)}{dV}$$

Known: $$f_i(x_i,Q^2)$$

Q^2 = („momentum transfer")^2

depends on final state



$$\frac{d\sigma_F(\sqrt{s},Q^2)}{dV} = \sum_{i,j}\int dx_i\, dx_j\, f_i(x_i,Q^2)\, f_j(x_j,Q^2)\frac{d\sigma_F^{ij}(x_i,x_j,Q^2)}{dV}$$

Cross Sections at Hadron Colliders

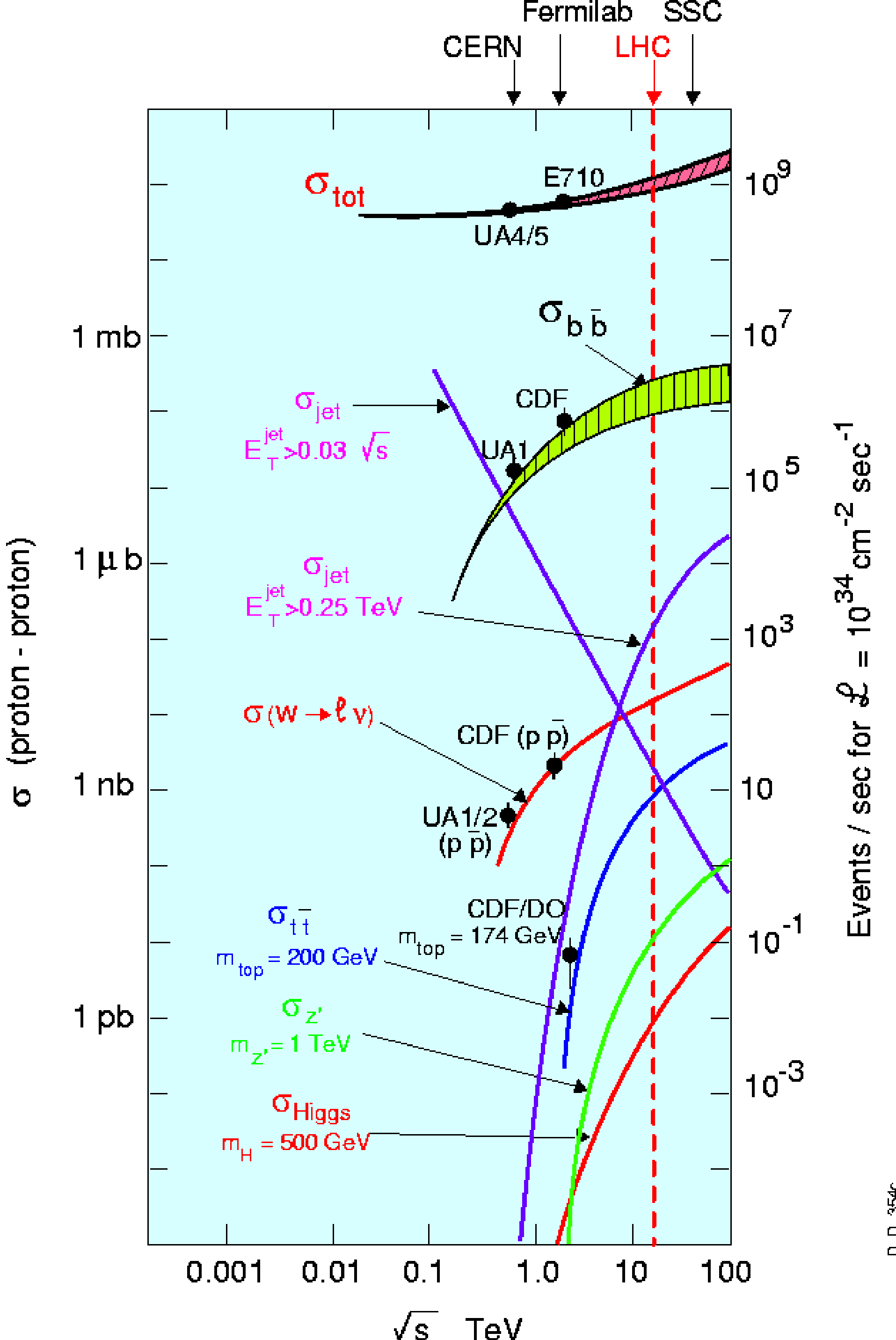
Note:

may trade:

energy ↔ luminosity

Example:

In principle top discovery at SPS !



Challenges

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Require: Event rate (Higgs...) $\dot{N} = \sigma \cdot L$ > **1/hour**

⇒ high luminosity $L = 10^{34} / cm^2 / s$

⇒ huge background $\dot{N}_{tot} = 10^{9} / s$

100 particles /collision $|\eta| < 2.5$

10^{11} particles /s

⇒ radiation damage detectors (~ 10 Mrad)

many bunches to limit #interactions/Xing

(25 ns bunch distance => 20/Xing)

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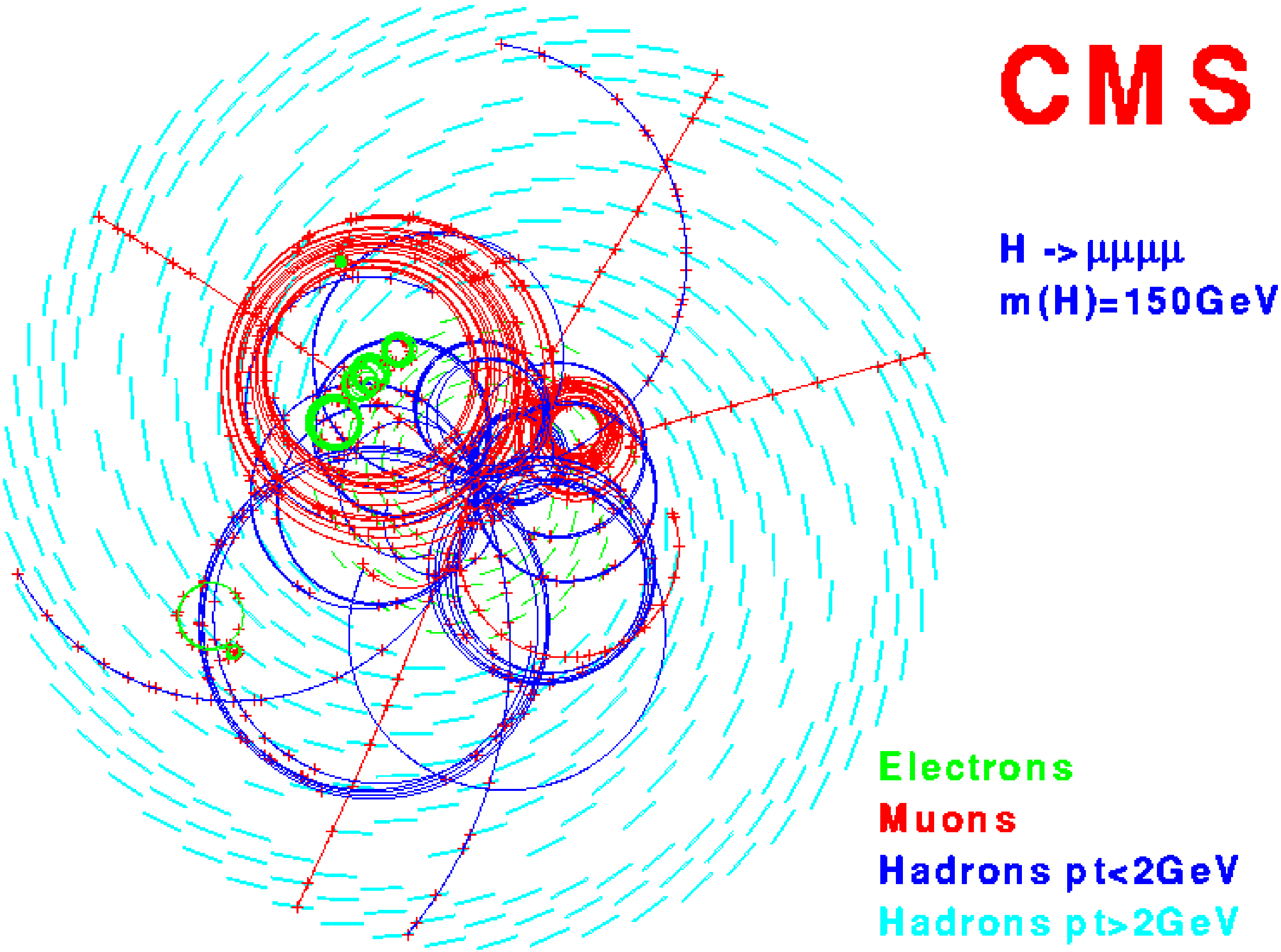
Example: Higgs event in CMS tracker



Example: Higgs event in CMS tracker

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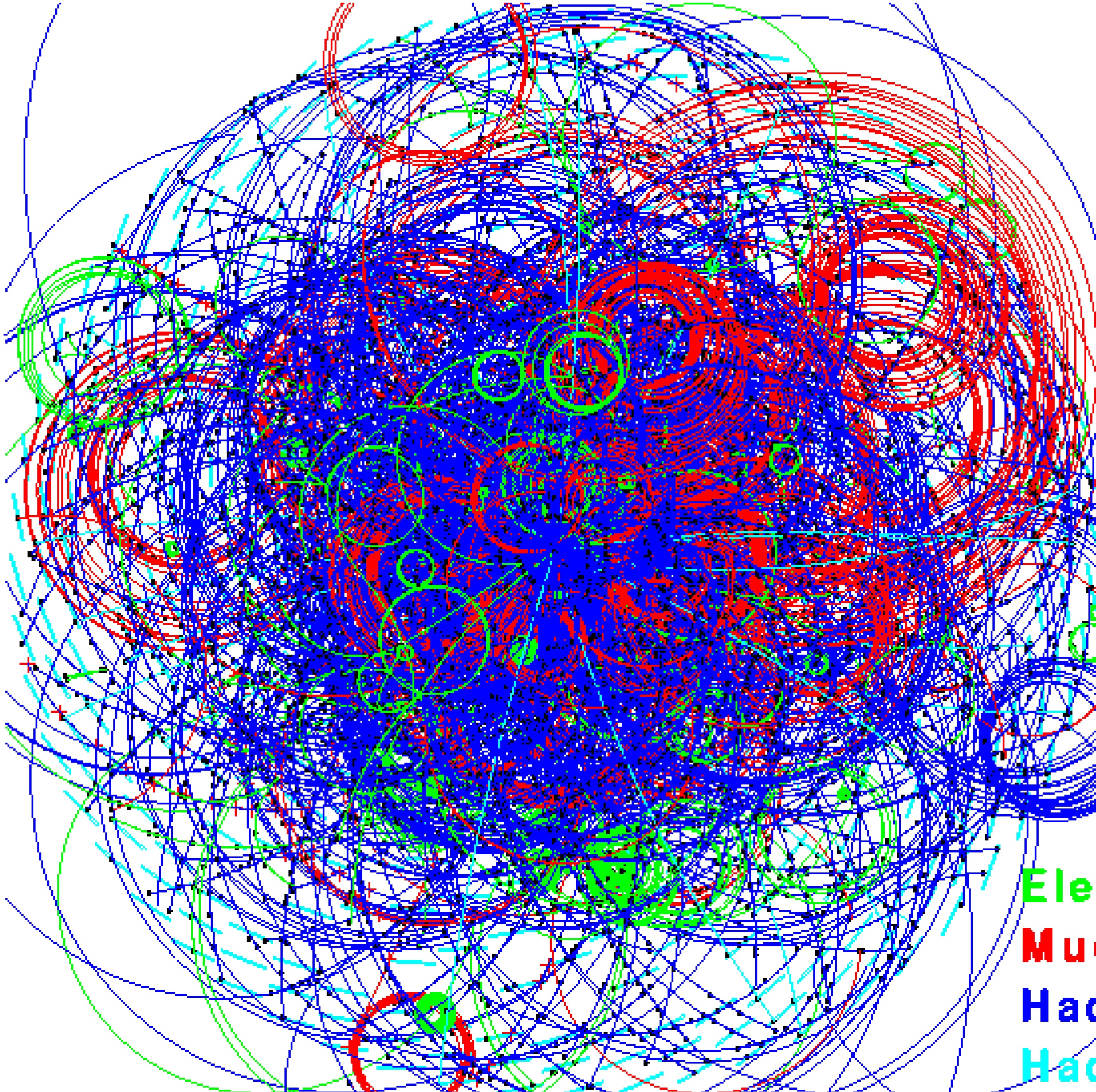

CMS

H -> μμμμ

m(H)=150GeV

+ 20 Min bias

Electrons

Muons

Hadrons pt<2GeV

Hadrons pt>2GeV

Luminosity determination in pp

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Remember: $10^{34}/cm^2/s \approx 100/fb$ per „year" !

a) from collider parameters:

$$L \sim \frac{f \cdot N_p \cdot N_{\bar{p}}}{\sigma_x \cdot \sigma_y}$$

...not very precise (10%)...

b) via reference process:

$$L = \frac{\dot{N}_{ref}}{\sigma_{ref}}$$

...to be measured by detector(5%)...

known, large

(in)elastic forward scattering

p
p

p
h
y
s
i
c
s

Part I Introduction

- p p collisions
- accelerators and detectors
- kinematical variables
- structure functions
- cross sections
- challenges
- luminosity determination

Part II Standard Model Physics

Part III Higgs

Part IV New Phenomena

References

Appendices

Rapidity IV

Distribution of particles $dN/d\eta$ (form invariant !) in p p collisions ?

In **center of mass system** of hard collision ($2 \to 2$):

$$y = \ln \frac{E + p_L}{\sqrt{p_T^2 + m^2}} \le \ln \frac{2E}{m} = \ln \frac{\sqrt{s'}}{m}$$

Rapidity range:

$$-\ln \frac{\sqrt{s'}}{m} \le y \le \ln \frac{\sqrt{s'}}{m}$$

Empirical in pp collisions:

$$N_{tot} \sim \ln \sqrt{s}$$

$$\frac{d\,N}{d\,\eta} \sim const$$

... „plateau"