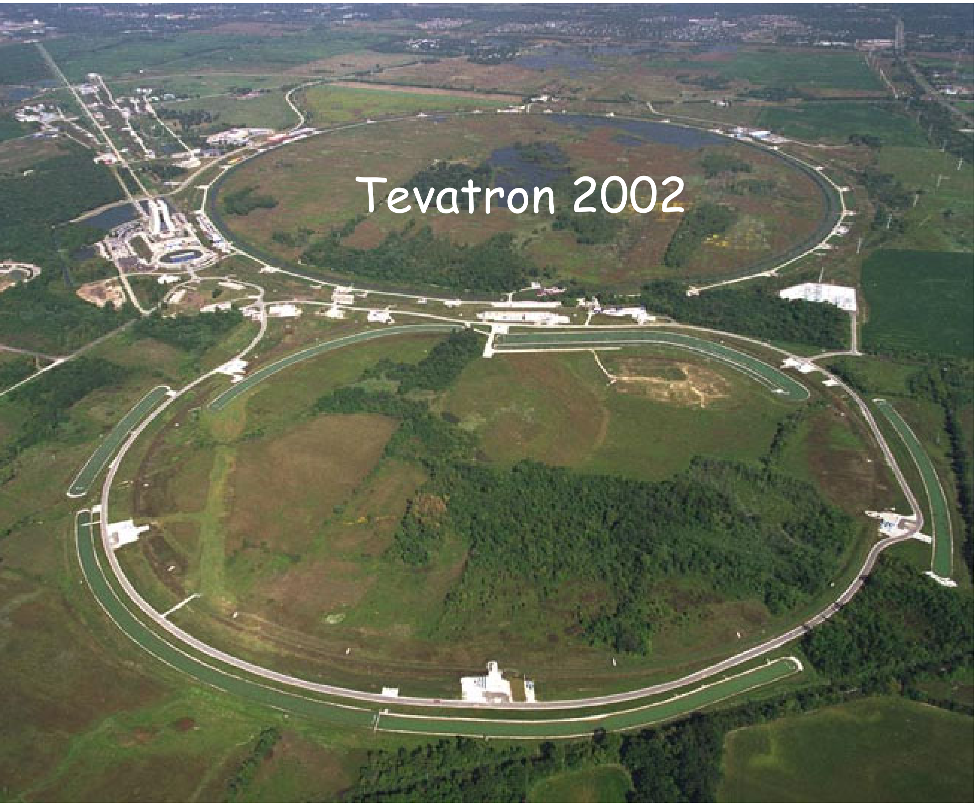
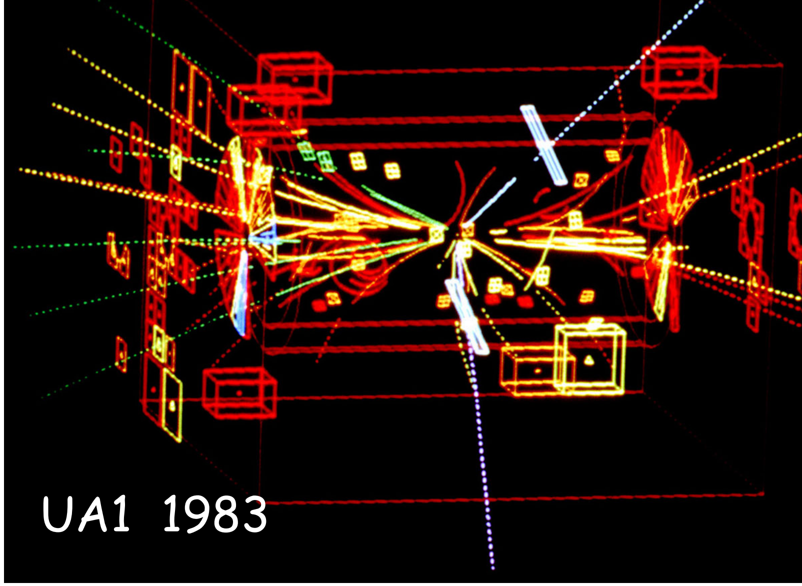
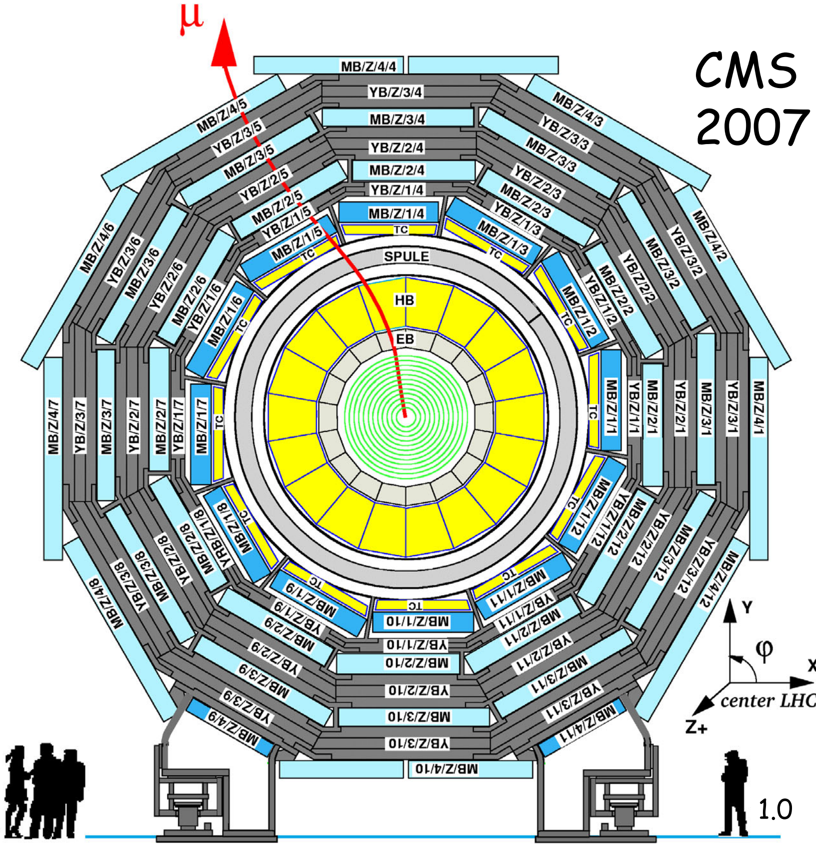
Thomas Hebbeker, RWTH Aachen
Belgian-Dutch-German school
September 2003

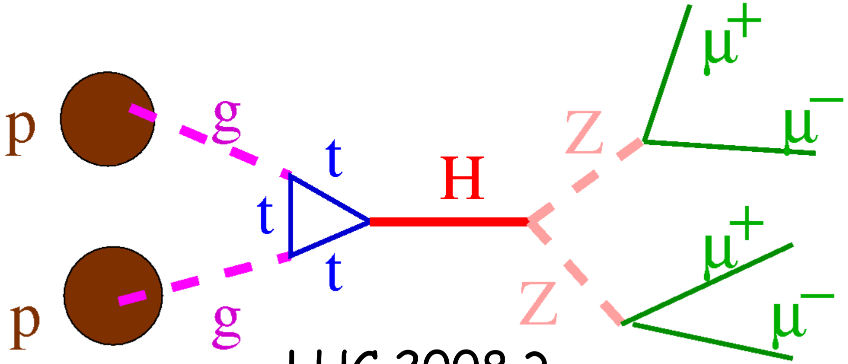
part I

pp physics









LHC 2008 ?

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

<u>Not</u> 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

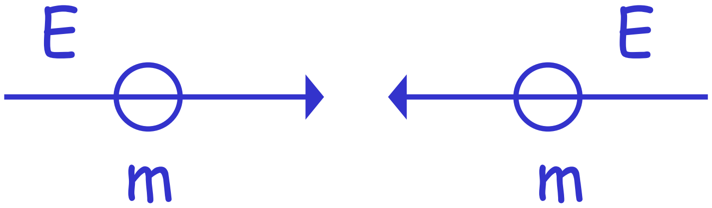
Part IV New Phenomena

References

T.Hebbeker

Collider versus Fixed Target

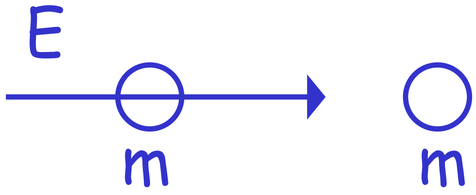
$E \gg m$



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

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

$$\boxed{= 4E^2}$$



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

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

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

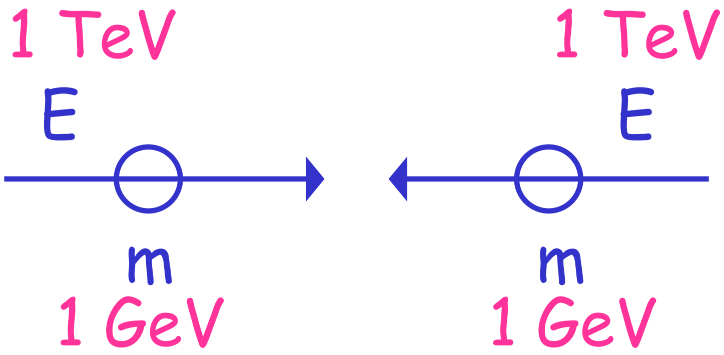
$$= E^2 + 2mE + m^2 - (E^2 - m^2)$$

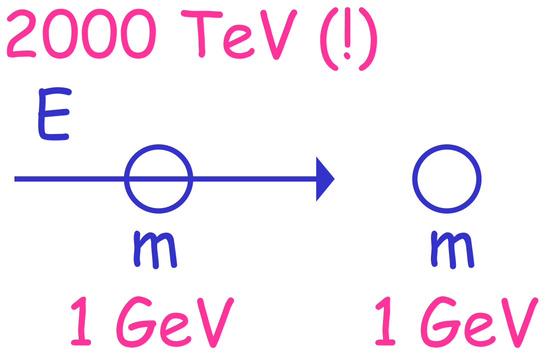
$$= 2mE + 2m^2$$

$$\boxed{\approx 2mE}$$

Collider versus Fixed Target

$E \gg m$





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

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

$$\boxed{= 4E^2}$$

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

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

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

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

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

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

$$\boxed{\approx 2mE}$$

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

DONUT: fixed target experiment

T.Hebbeker

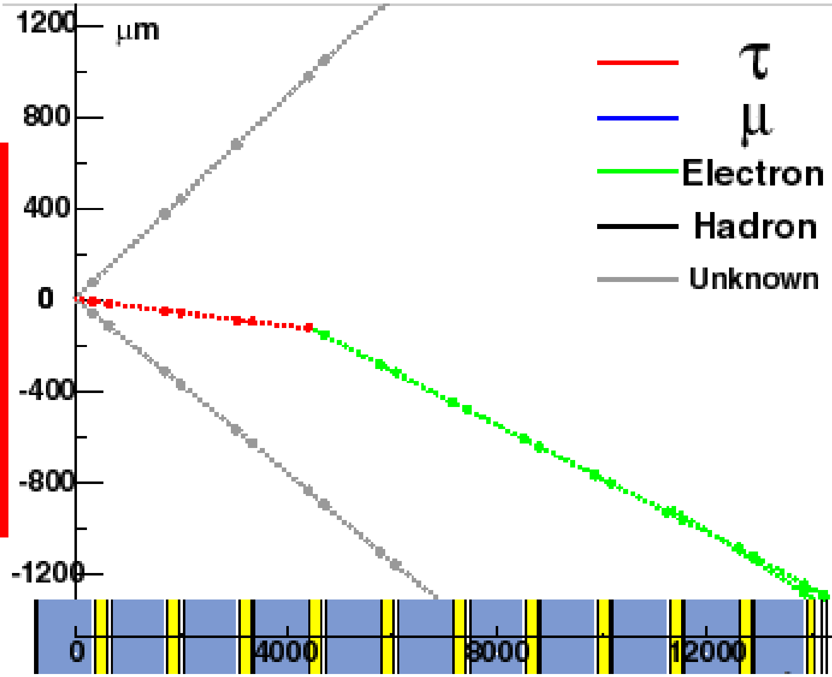
Machine: p (800 GeV) + A

DONUT =

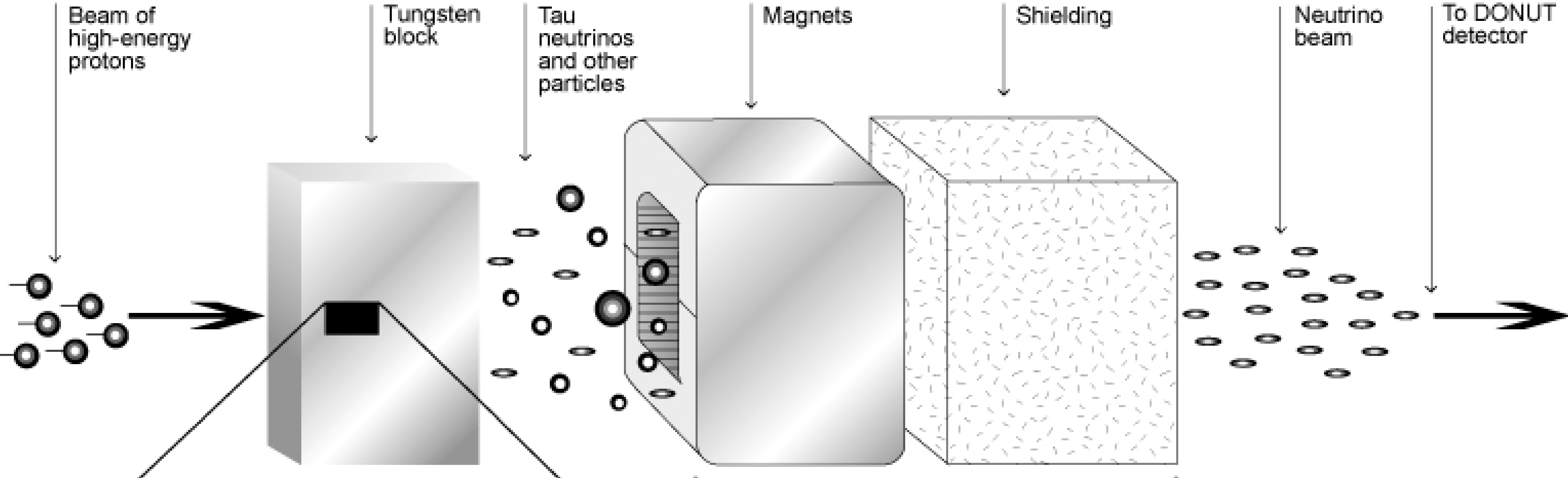
Direct Observation

of the Nu Tau

LHC =
Neutrino
Source !



Creating a Tau Neutrino Beam



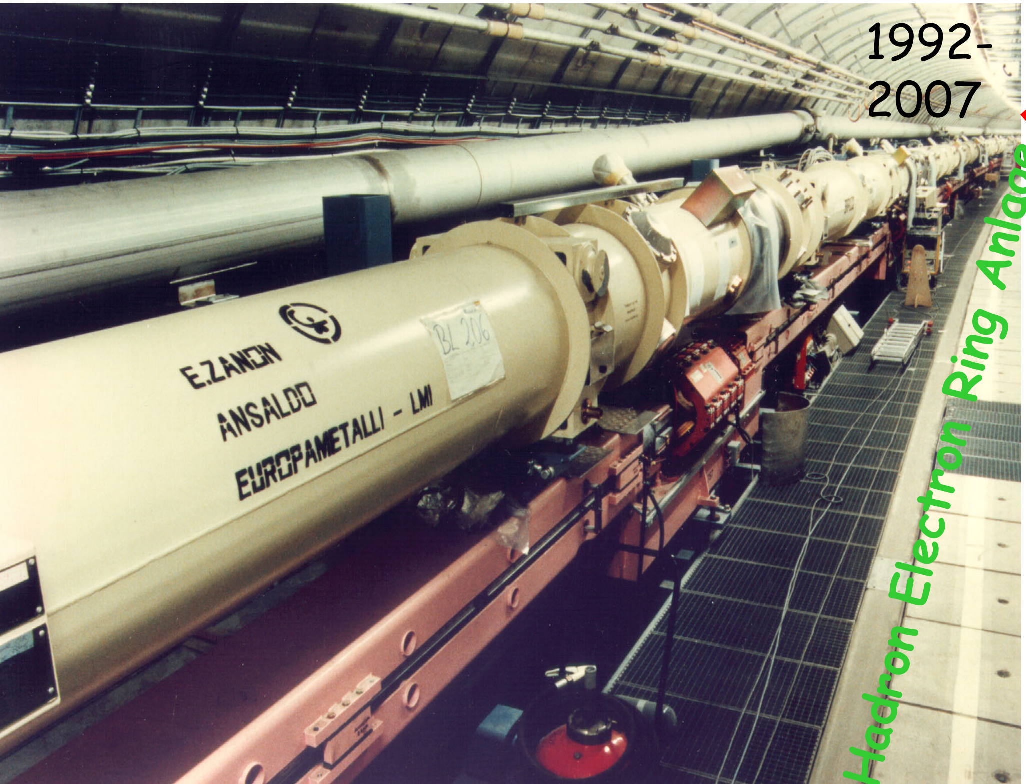
HERA electron microscope

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

Detectors: H1, Zeus

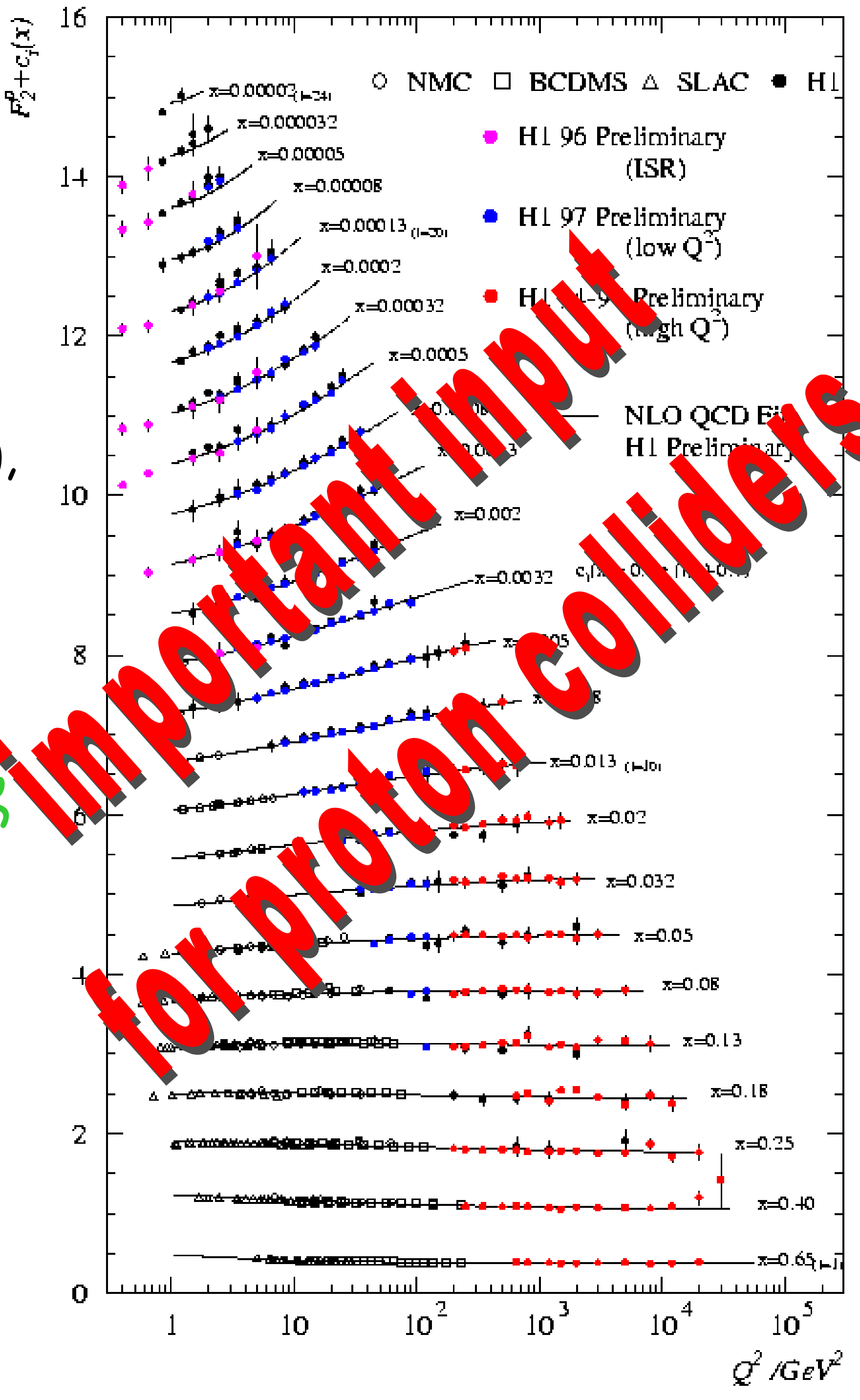
Physics: structure proton (0.001 fm),

...



1992-2007

Hadron Electron Ring Anlage



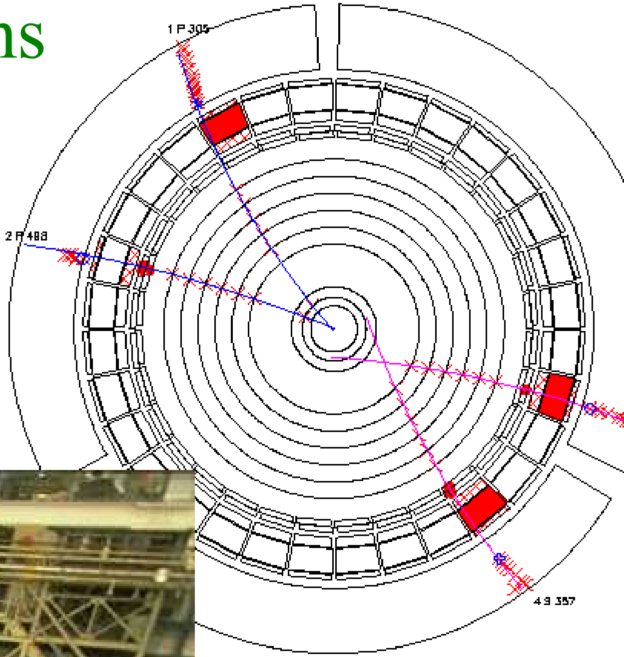
important input for proton colliders

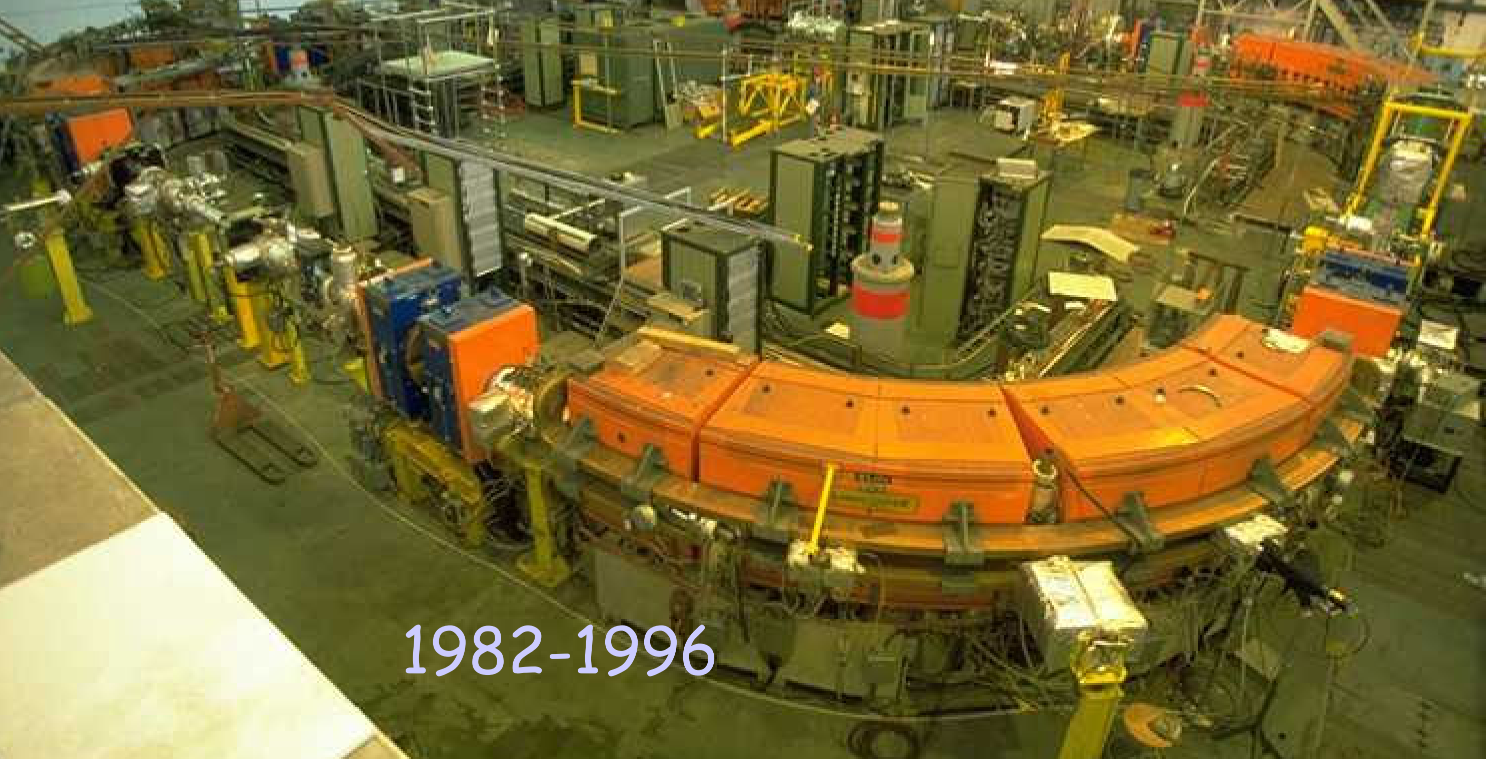
LEAR: Low energy hadron collisions

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

Experiments: CPLEAR, Crystal Barrel ...

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





1982-1996

CPLEAR

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

complete annihilation

$p+\bar{p}$

RHIC: Heavy ion collisions

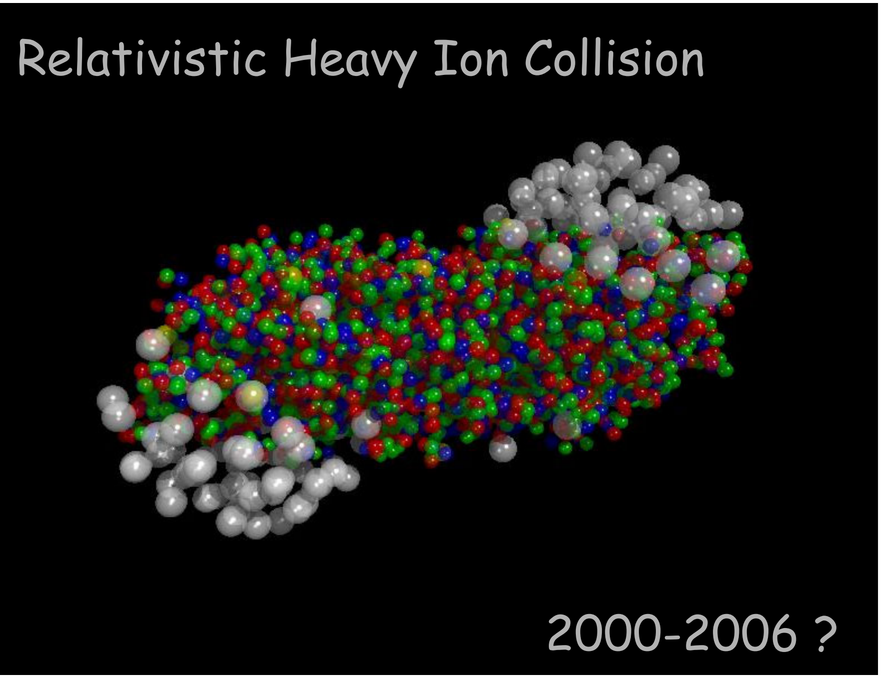
multi quark physics

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

Detectors: Phobos, Star, ...

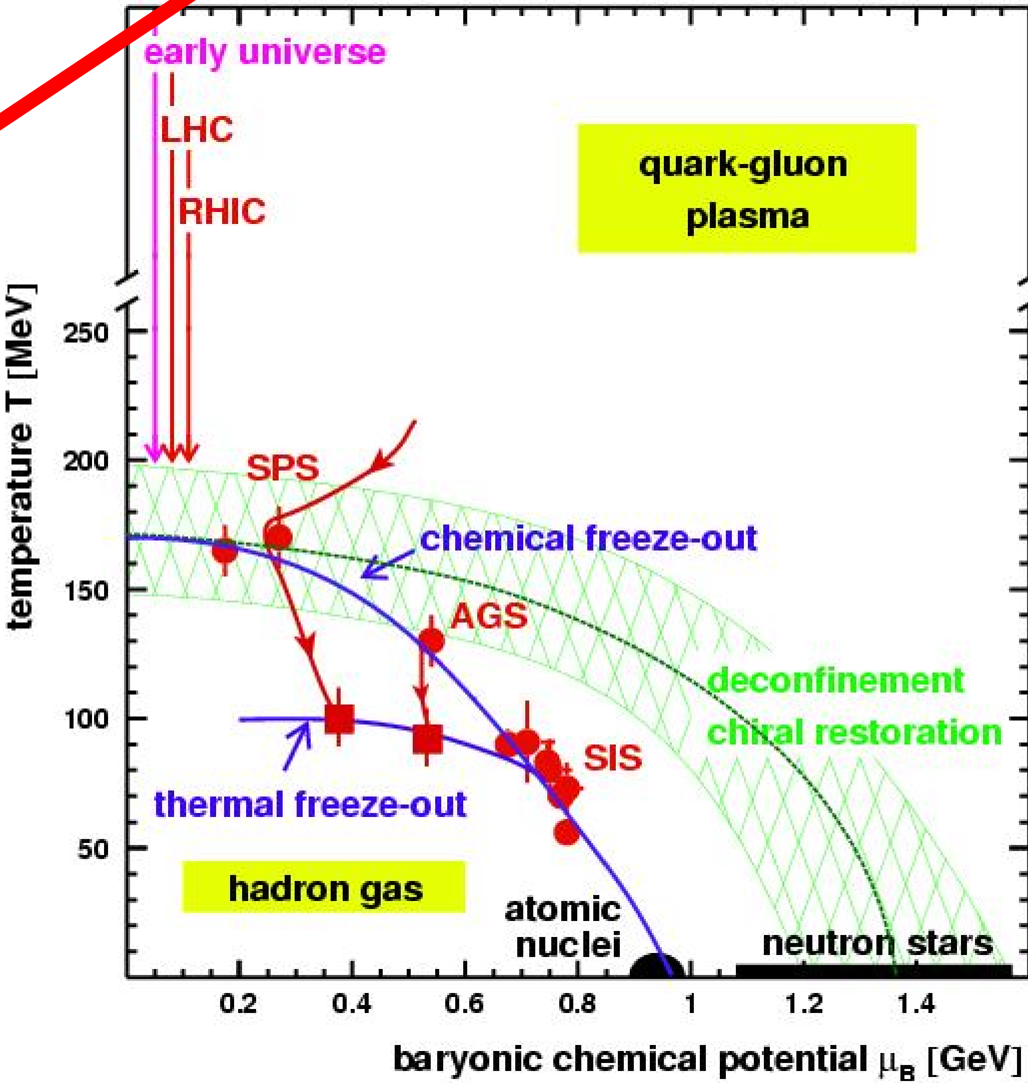
Physics: quark gluon plasma

proton spin **(pol. p)**



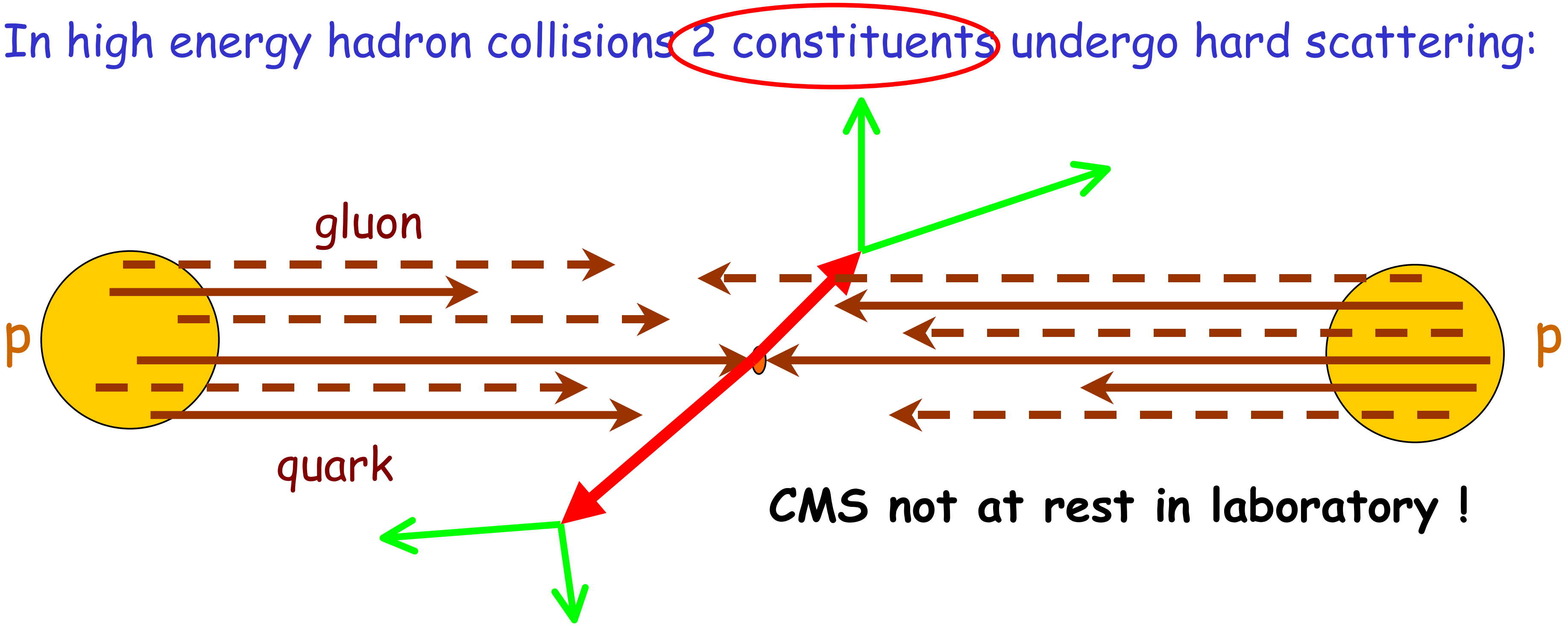
Relativistic Heavy Ion Collision

2000-2006 ?



Effective Center of Mass Energy

In high energy hadron collisions 2 constituents undergo hard scattering:



CMS not at rest in laboratory !

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

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

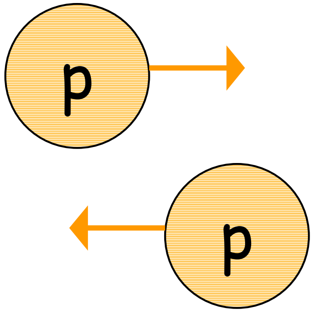
Examples: $q\overline{q} \rightarrow W$ $gg \rightarrow h\,(!)$ $qg \rightarrow qg$

T.Hebbeker

Cross Section

Elastic cross section

LUMINOSITY



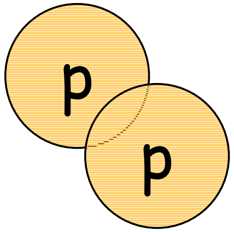
strong,
electromagnetic

scattering angle tiny

Total inelastic cross section

BACKGROUND

LUMINOSITY

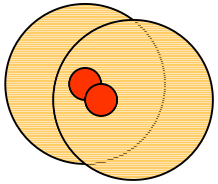


strong

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

Pointlike cross section

SIGNAL



electroweak

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

LHC

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

$e^+ e^-$ 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

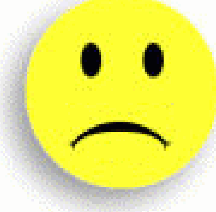
- hadrons = (anti)protons
  - storage ring

magnetic field

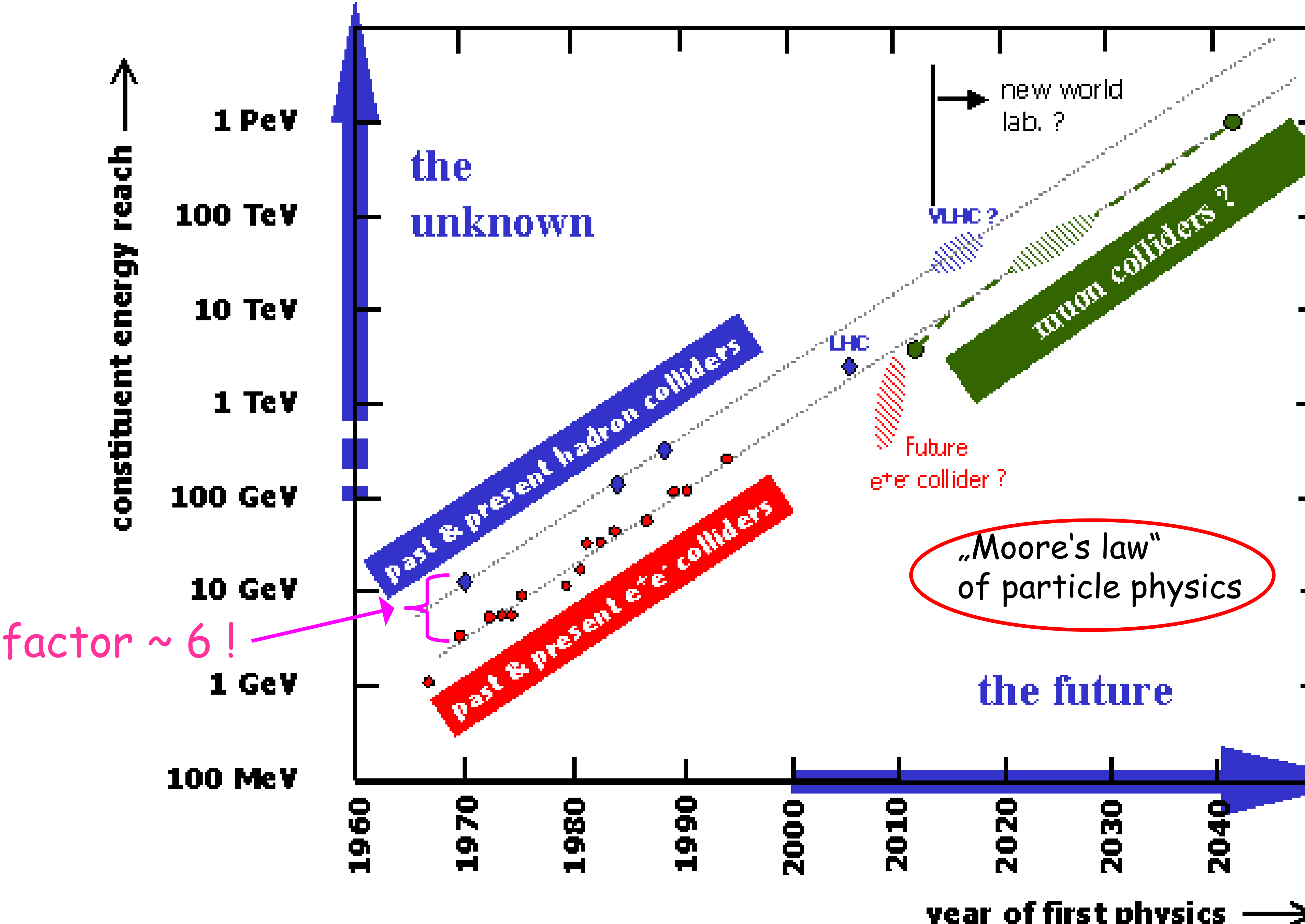
14 TeV

Composite

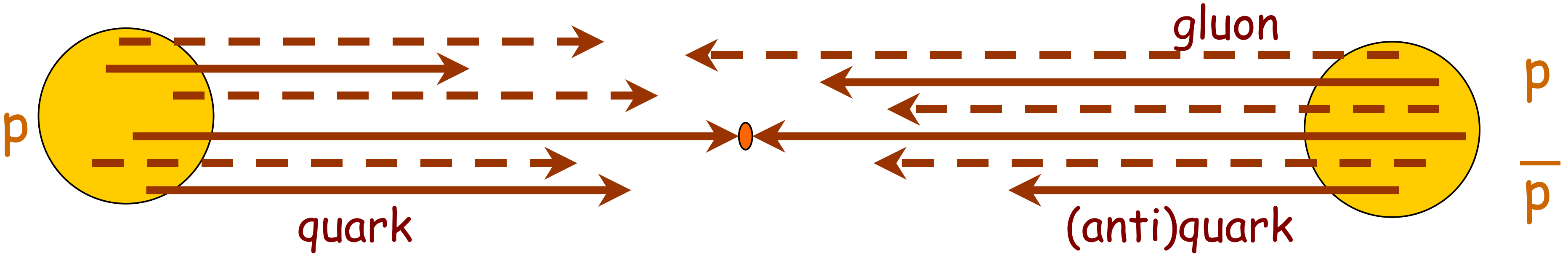
strong



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



Proton or Antiproton ? Physics:

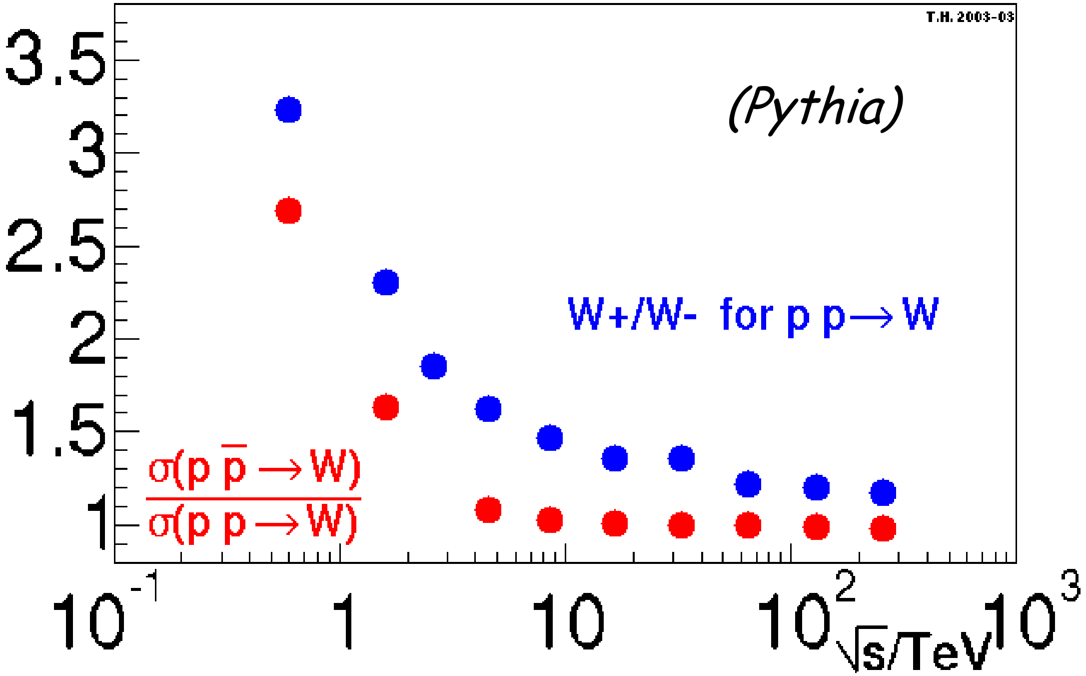


At low energy: valence quarks dominate hard scattering: $p\,p \neq p\,\bar{p}$

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

Example:

inclusive W production



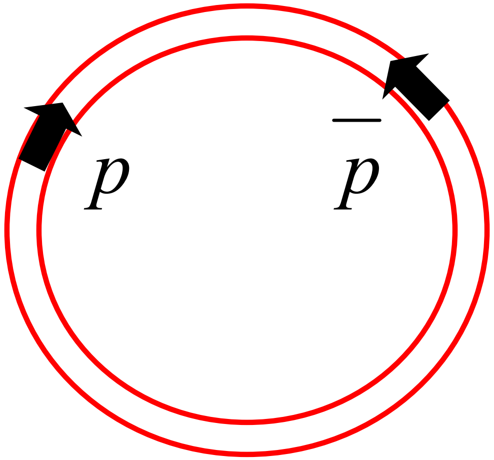
Proton or Antiproton ?

$p\,\bar{p}$

- one accelerator ☺
- antiproton production:

$1\,\bar{p}$ per $3\cdot10^5\,p$

☹



SPS $5\cdot10^{11}\,\bar{p}$

Tevatron

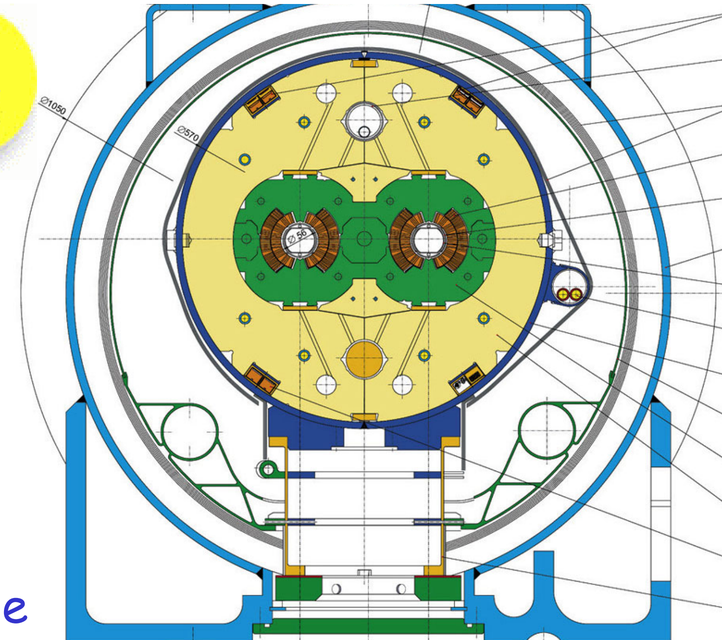
$1\cdot10^{12}\,\bar{p}$

$p\,p$

- two accelerators ! ☹
- no antiprotons ! ☺

LHC

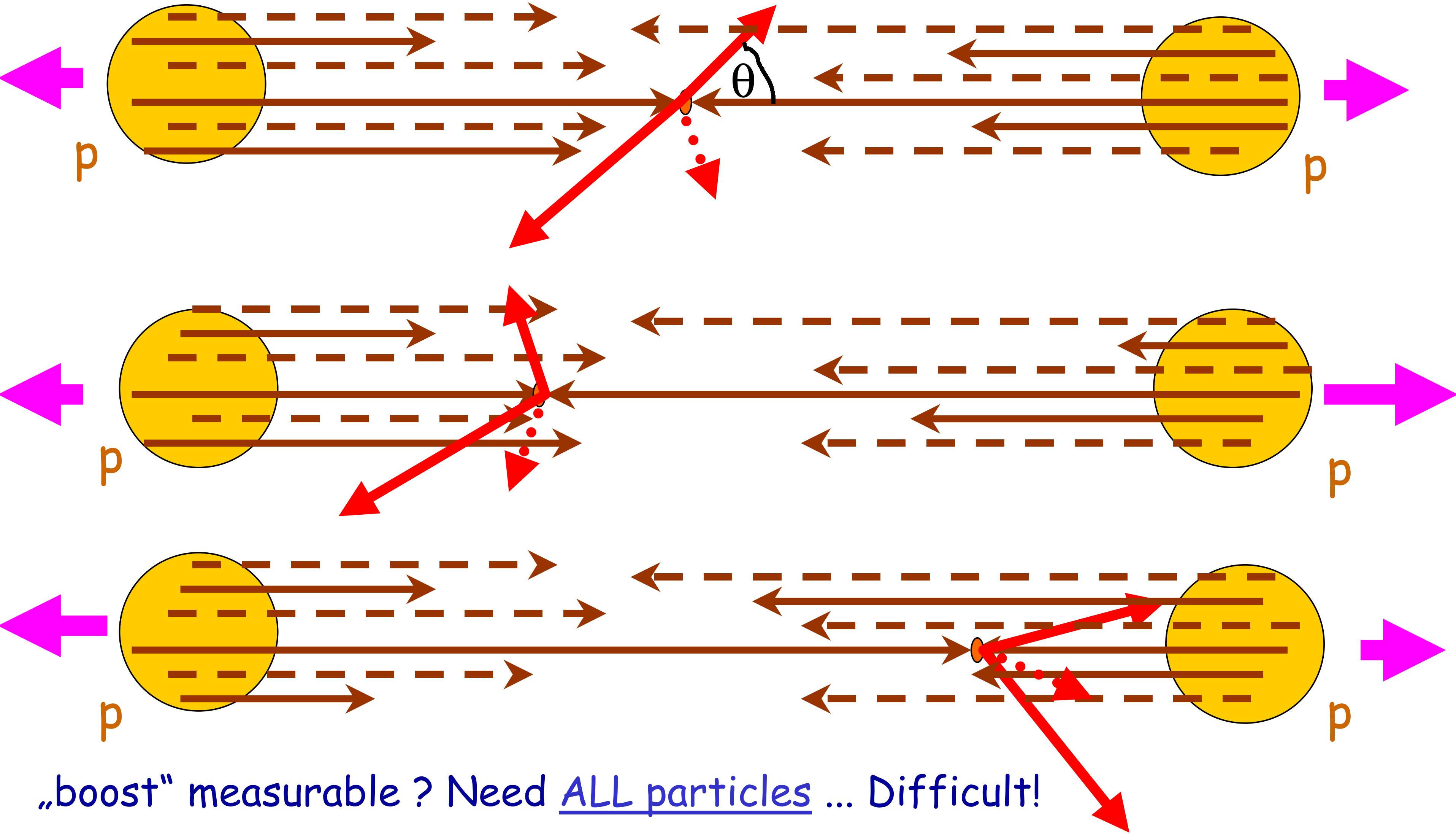
$3\cdot10^{14}\,p$



LHC dipole

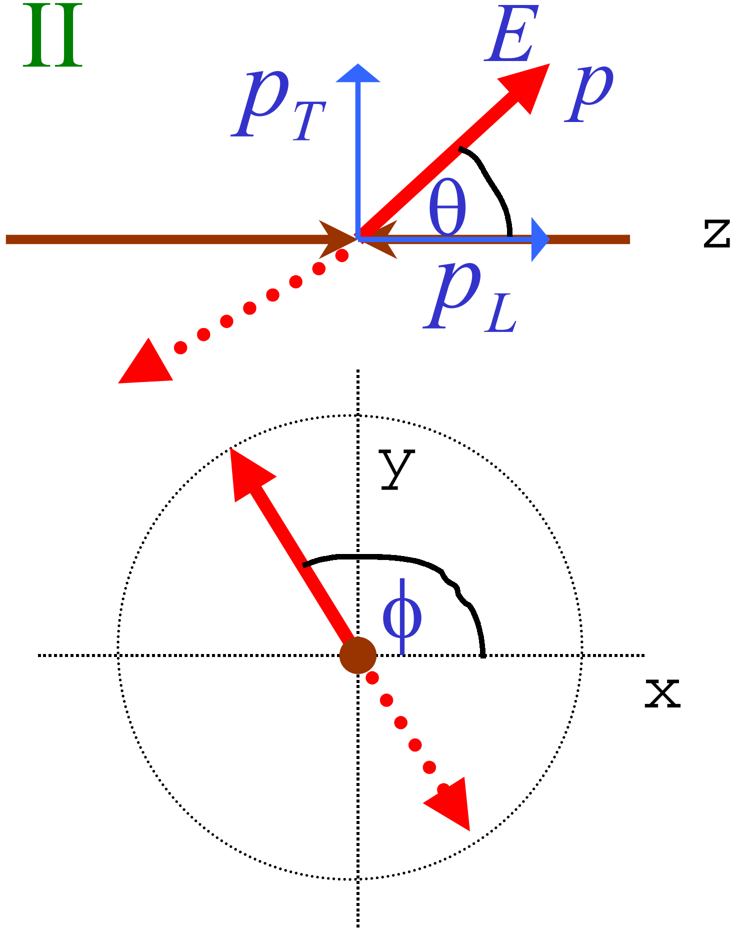
Kinematics I

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



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

Kinematics II



Kinematical variables:

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

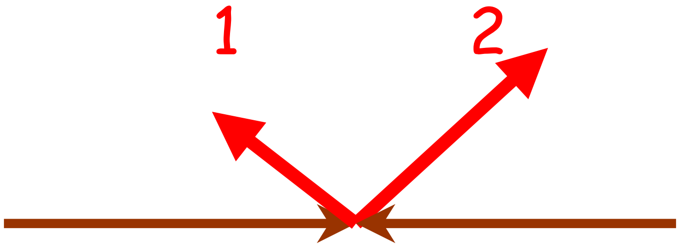
- rapidity $y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L}$

$m << E, p_L$

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

Kinematics III

Boost invariance ?



Kinematical variables:

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

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

$$\left. \begin{array}{l} y_1 - y_2 \\ \eta_1 - \eta_2 \end{array} \right\}$$ ☺

Rapidity I

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

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

Boost along z:

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

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

$$\boxed{y_1' - y_2' = y_1 - y_2}$$

Rapidity II

T.Hebbeker

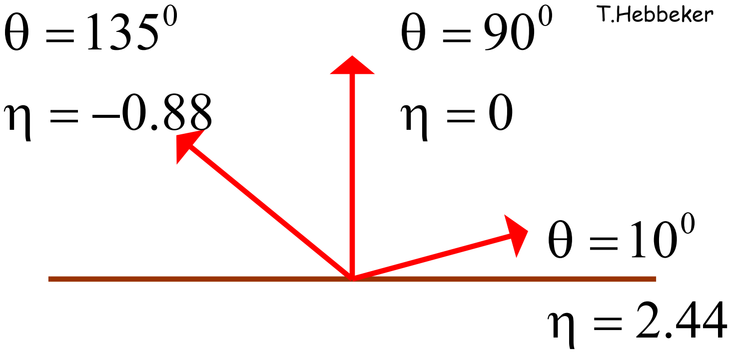
$$\boxed{y} = \ln \frac{E + p_L}{\sqrt{p_T^2 + m^2}}$$

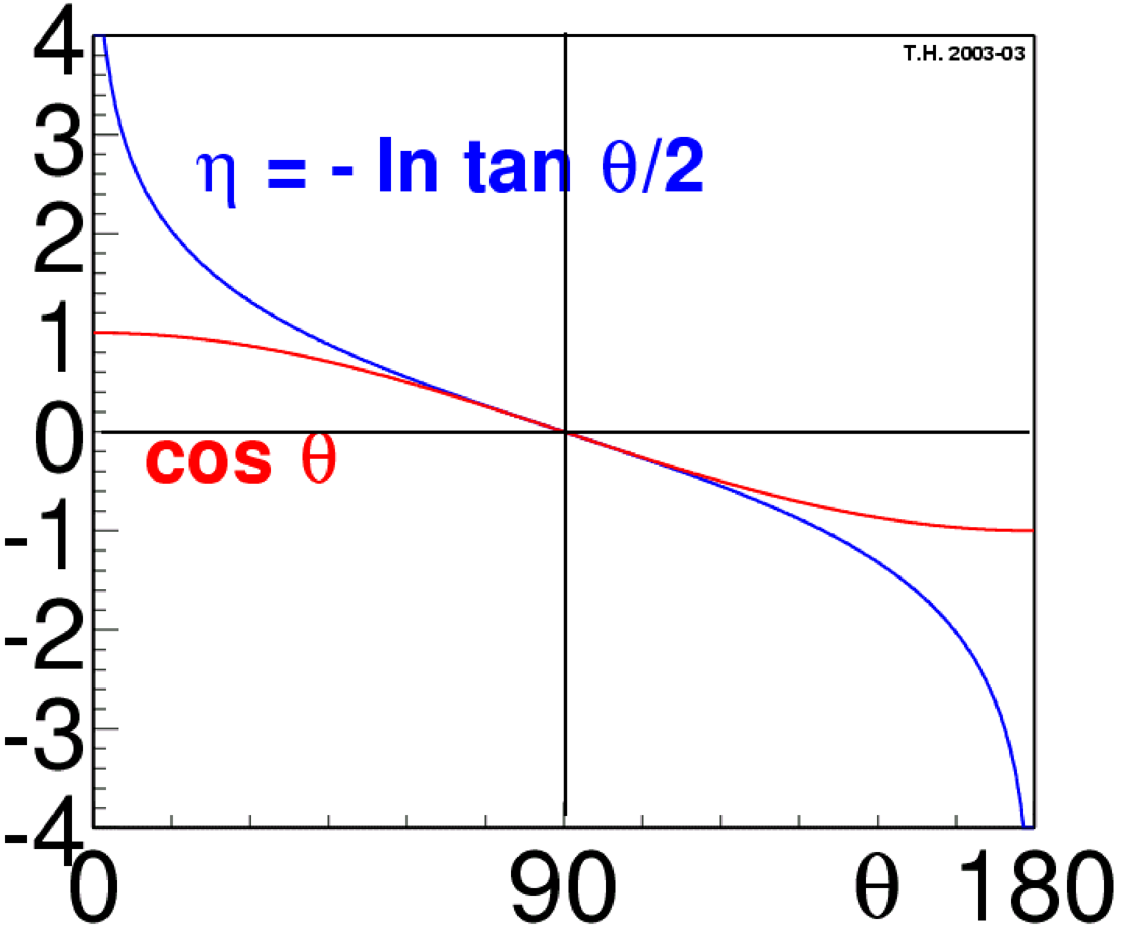
$m << E, p_L$

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

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

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





Rapidity III

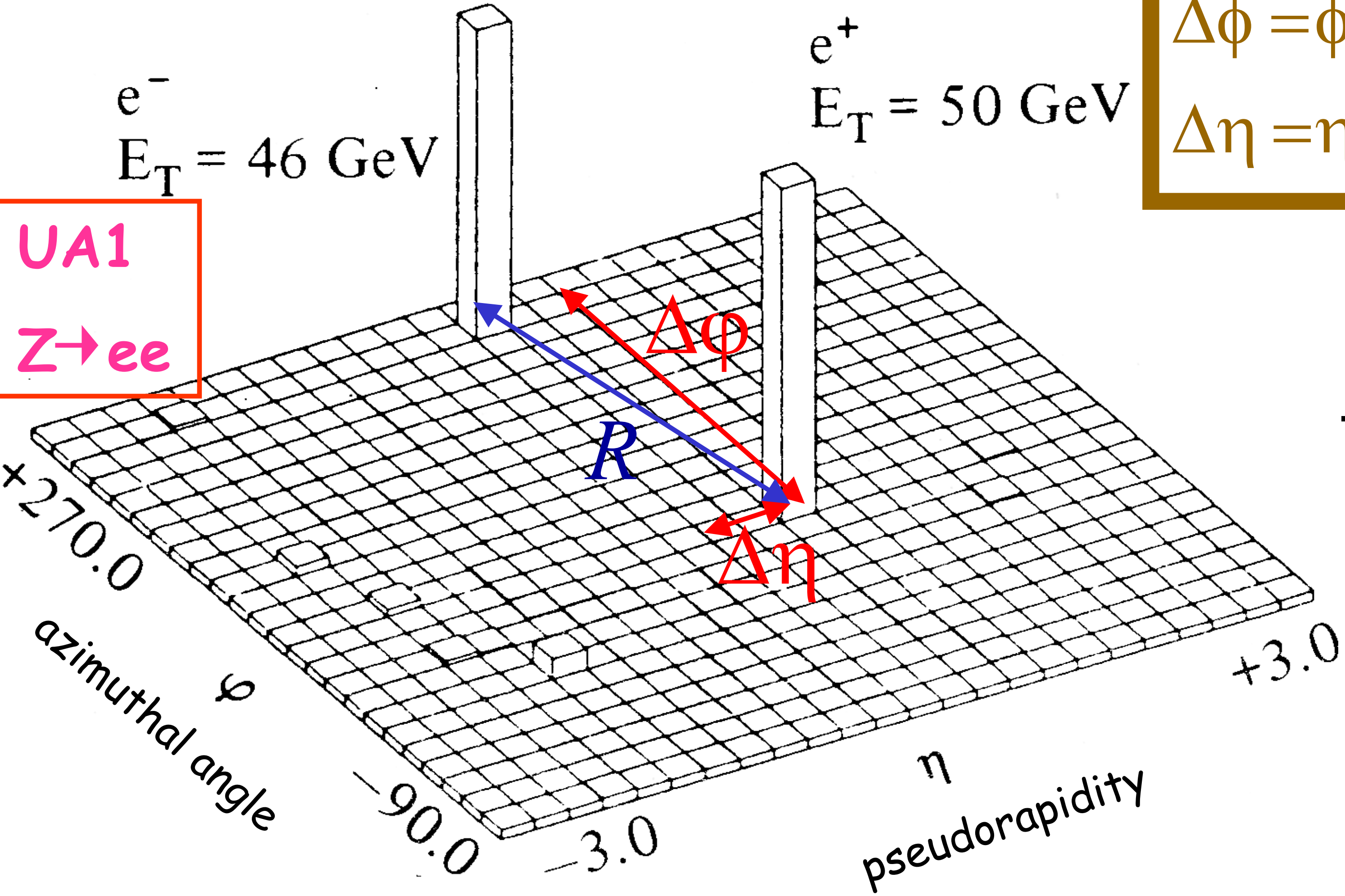
Particle directions ⟷ ϕ,η

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

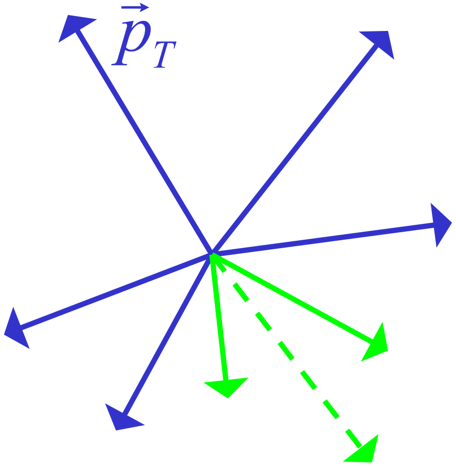
c) „invisible particles“ (neutrinos, gravitons, ...):

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

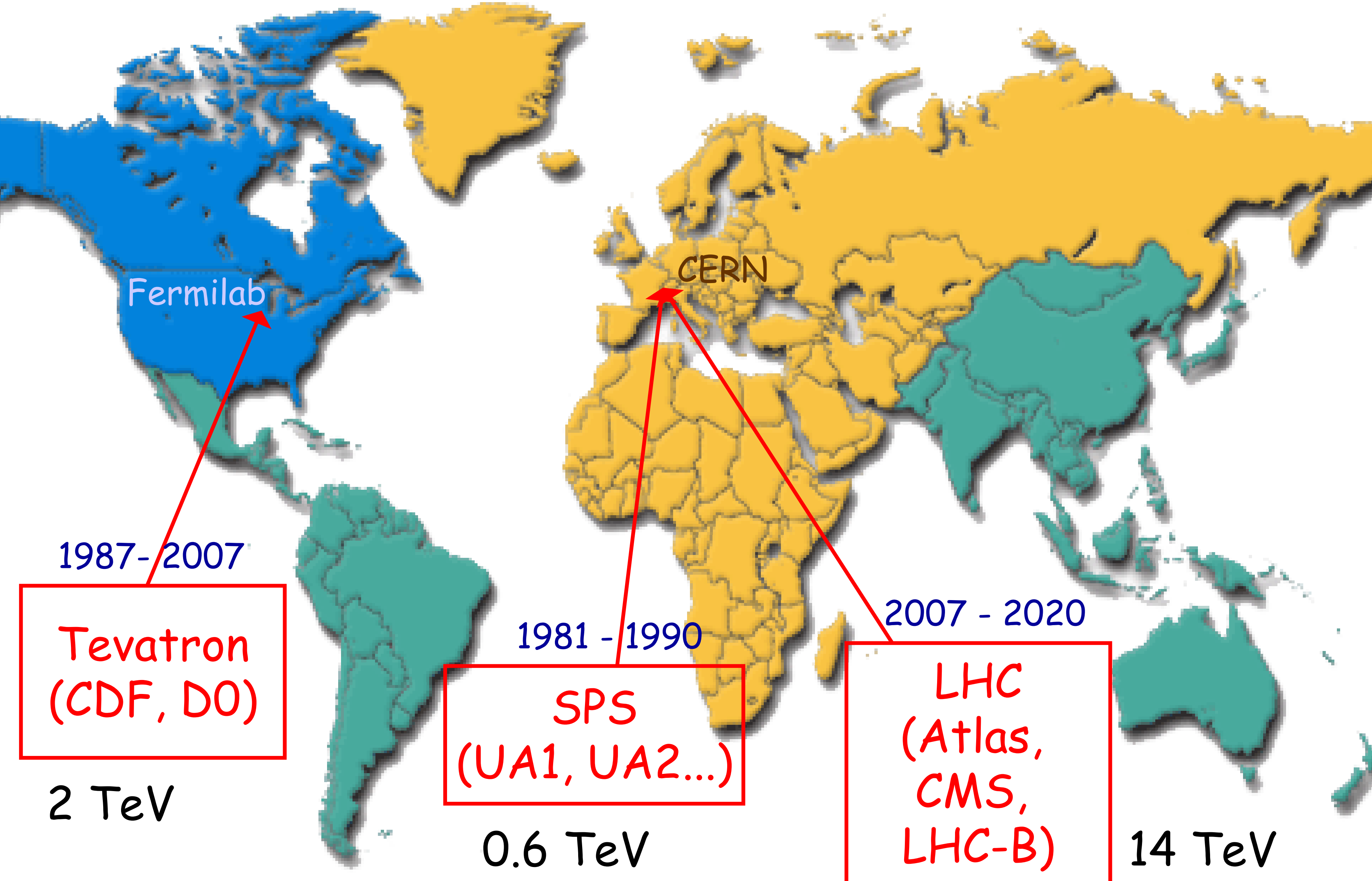
$$MET = |\sum_{invis} \vec{p}_T|$$

Example: $W \rightarrow \mu \, \nu$

plane perpendicular to beam:



Hadron colliders and detectors



1987- 2007

Tevatron
(CDF, D0)

2 TeV

1981 - 1990

SPS
(UA1, UA2...)

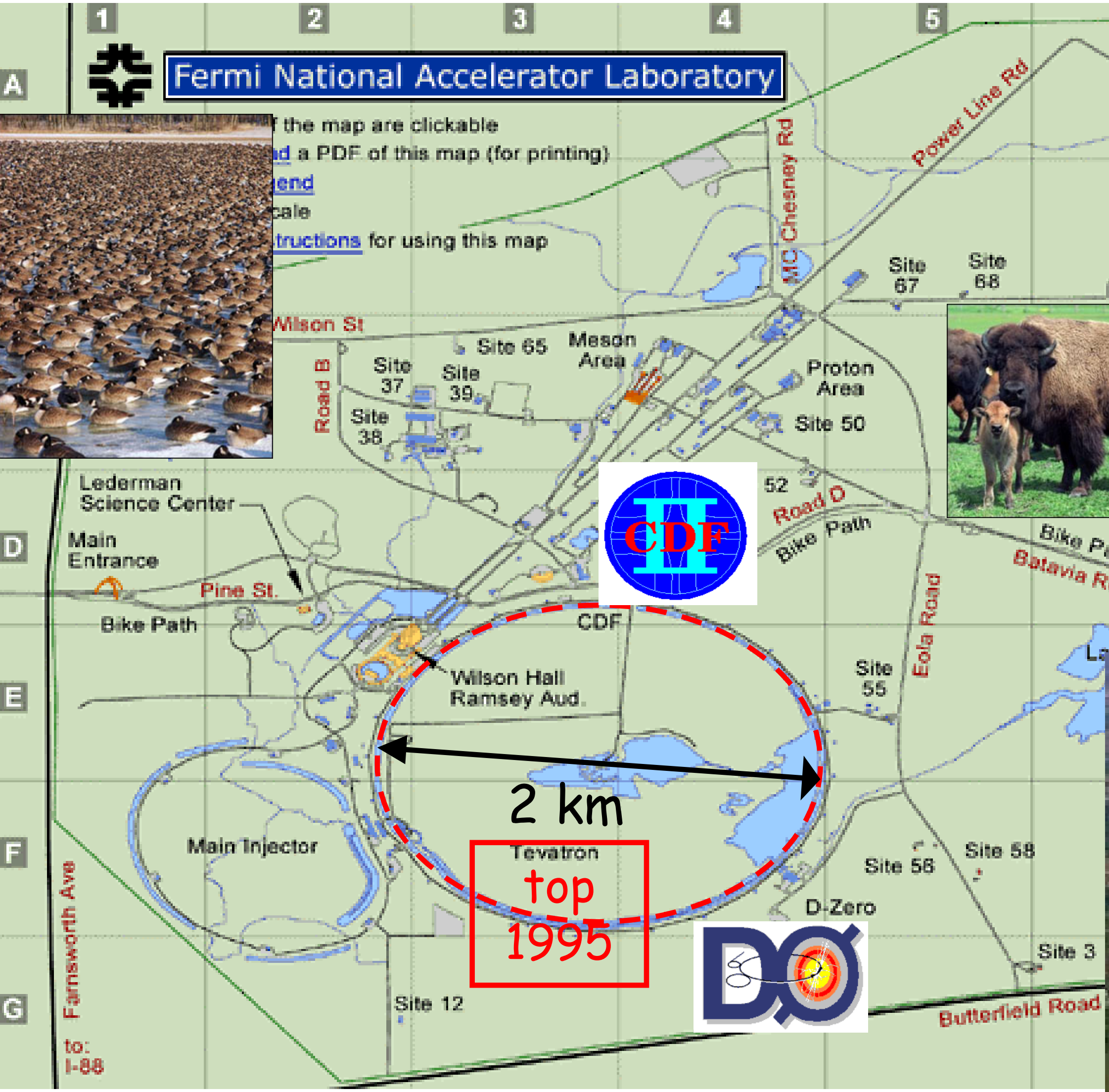
0.6 TeV

2007 - 2020

LHC
(Atlas,
CMS,
LHC-B)

14 TeV

Fermilab/Tevatron



FNAL =

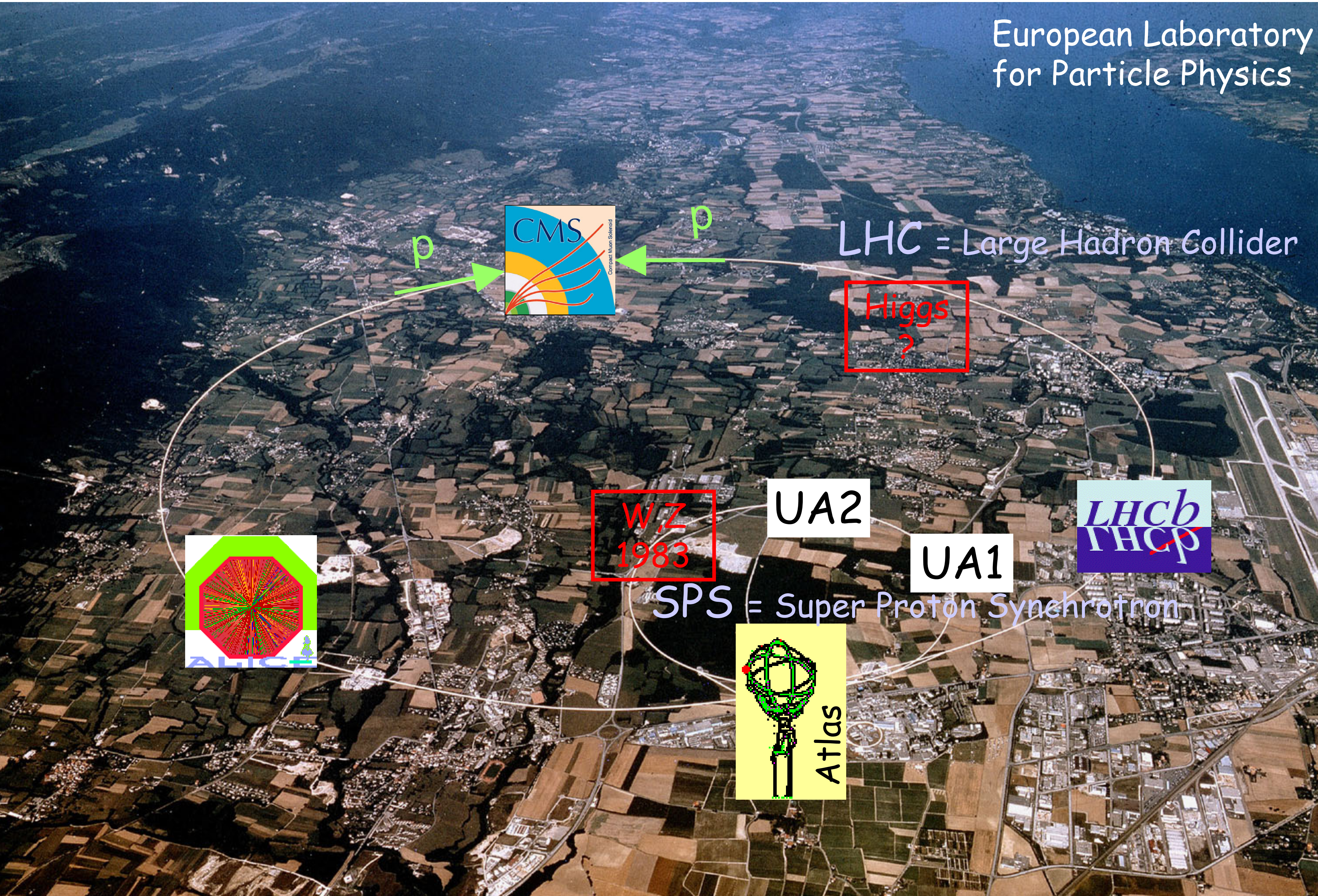
Fermilab

(Enrico Fermi)

1967

Tevatron = TEV machine

SPS, LHC / CERN

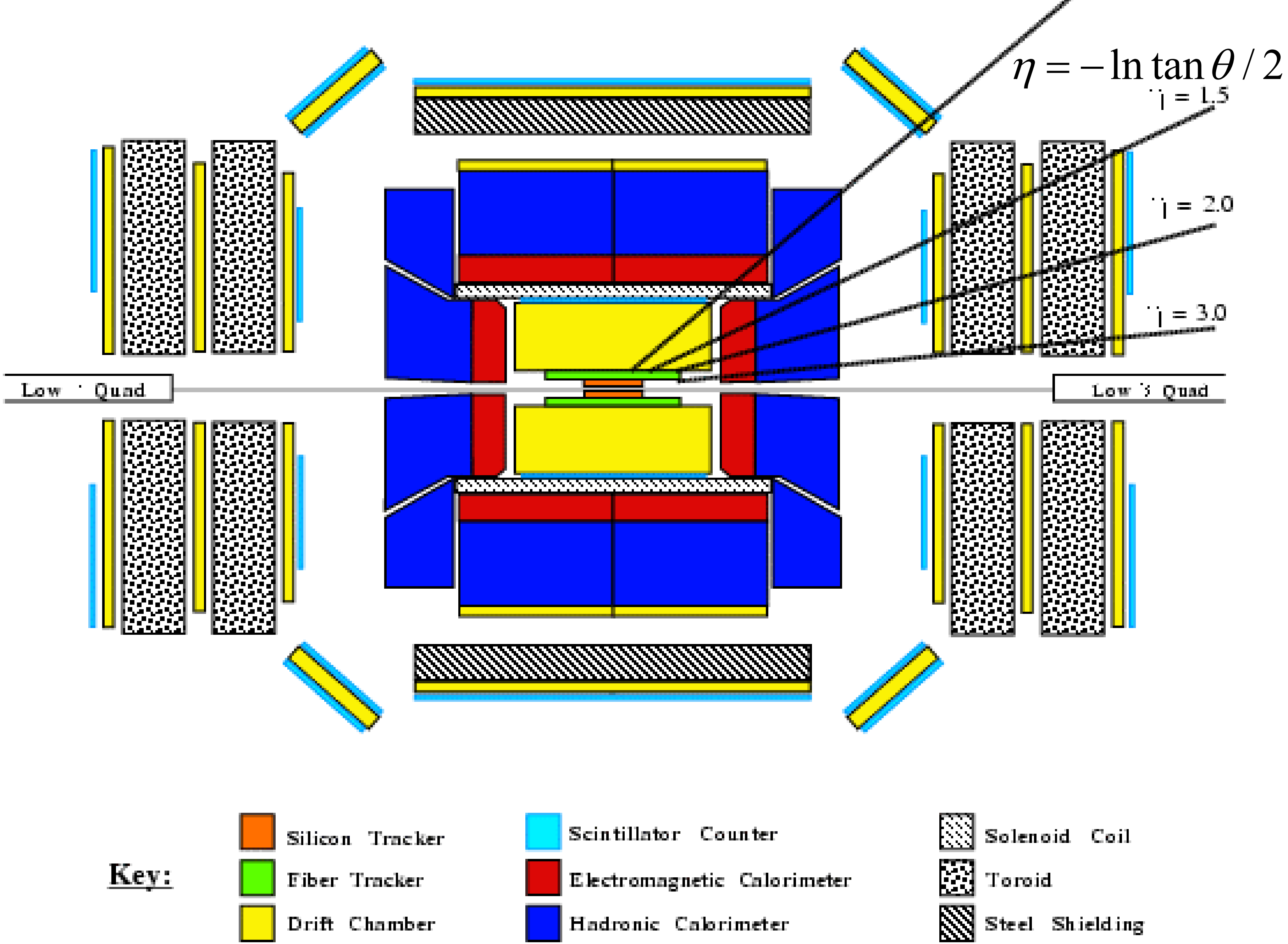

European Laboratory
for Particle Physics
LHC = Large Hadron Collider
SPS = Super Proton Synchrotron
p
p
CMS
Higgs
?
W,Z
1983
UA2
UA1
LHCb
ALICE
Atlas

SPS, Tevatron, LHC

2003

	SPS	Tevatron	LHC
Particles	$p+\overline{p}$	$p+\overline{p}$	$p+p$
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

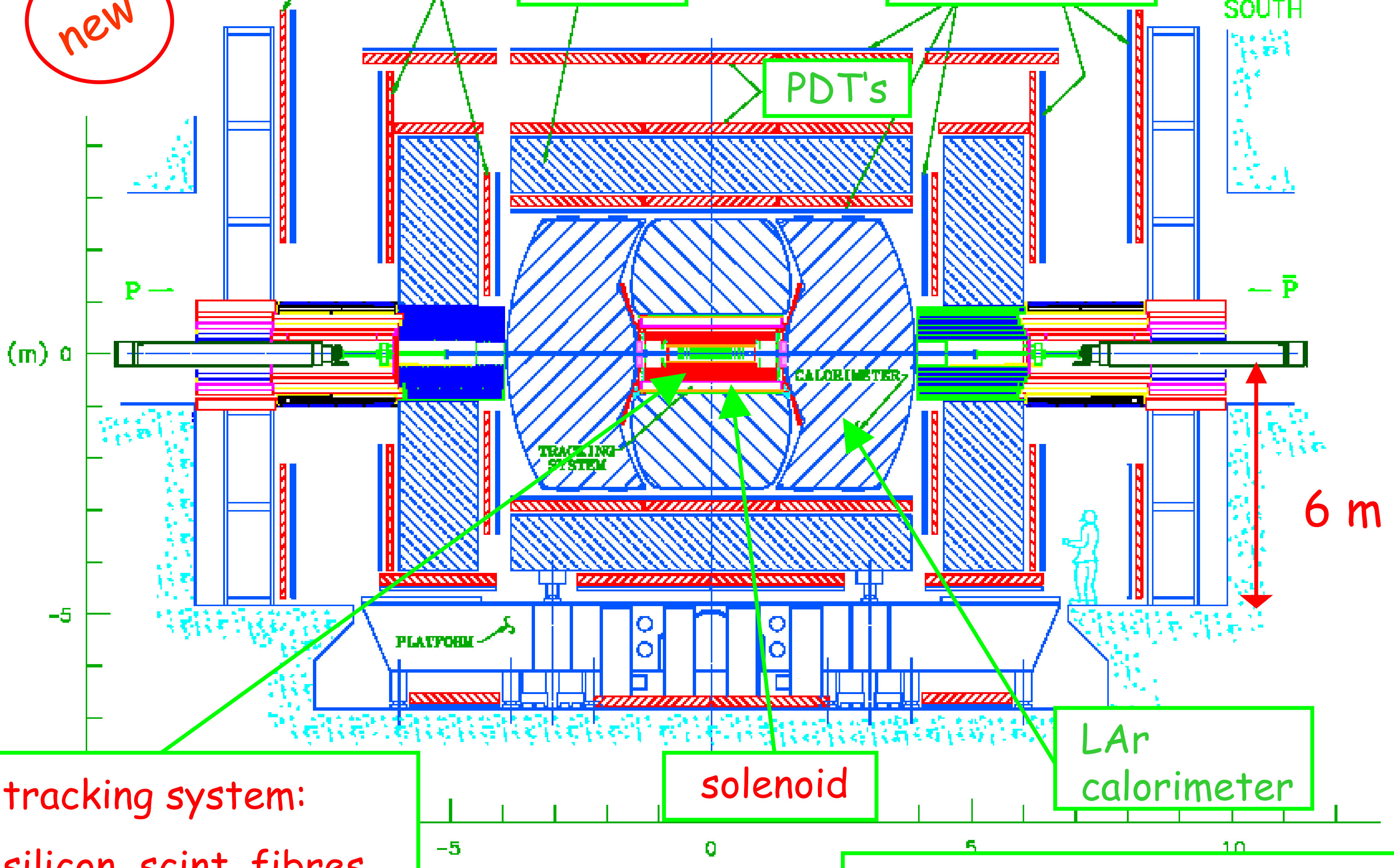


$$\eta = -\ln \tan \theta / 2$$

D0

T.Hebbeker

new



mini drift tubes

muon toroid

scintillators

PDT's

tracking system:

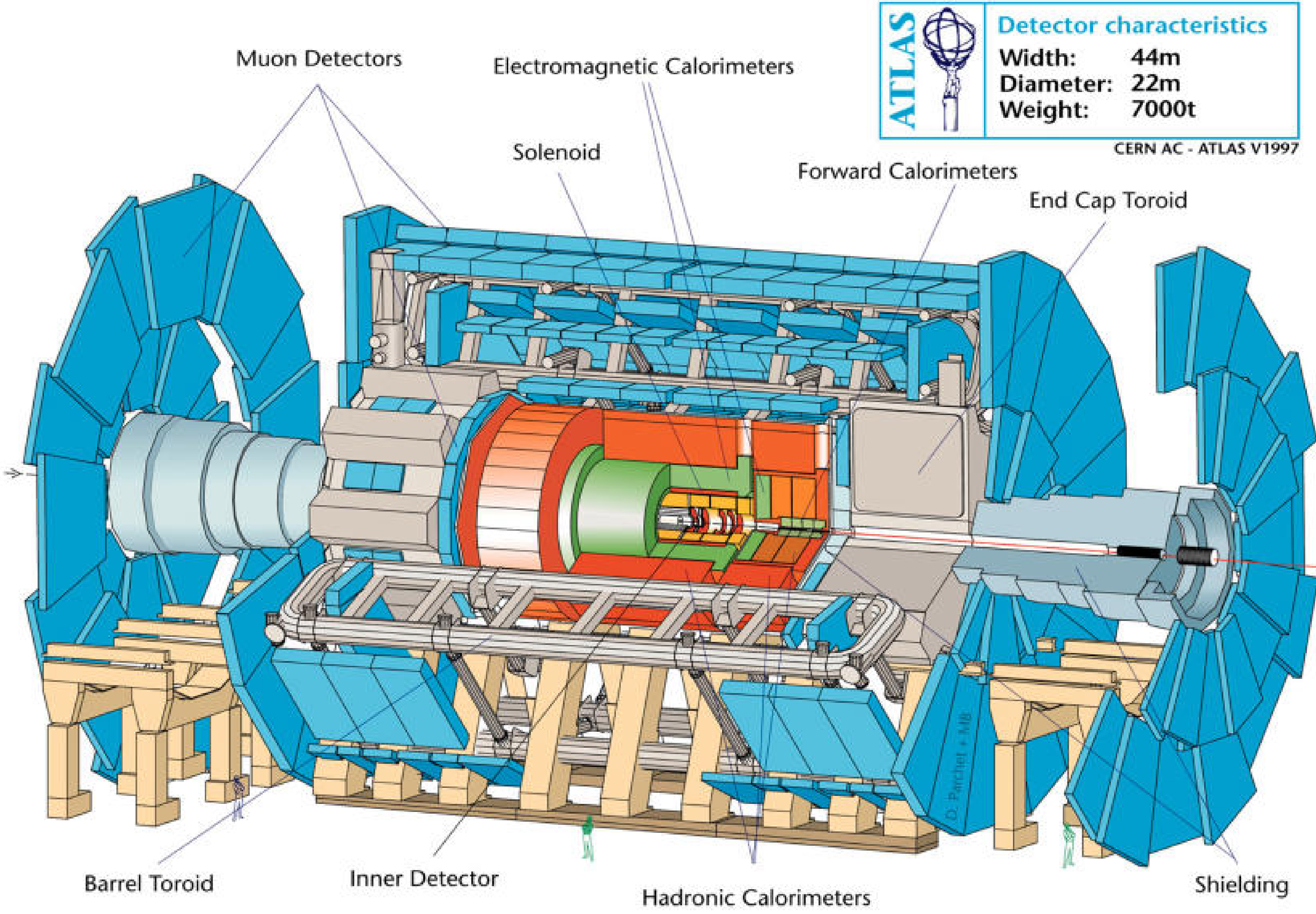
silicon, scint. fibres

solenoid

LAr calorimeter

electronics, trigger, DAQ

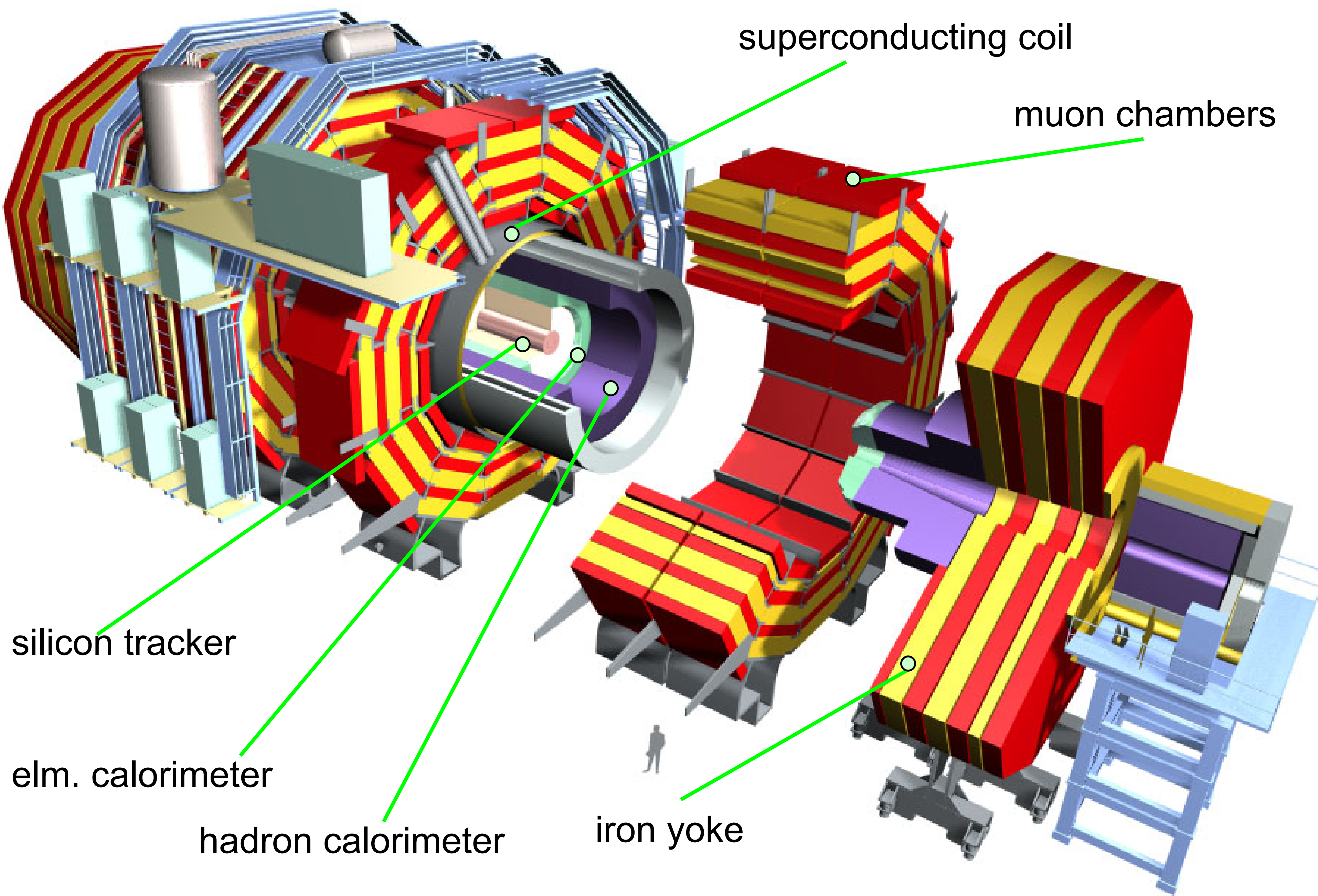
ATLAS = A Toroidal LHC ApparatuS



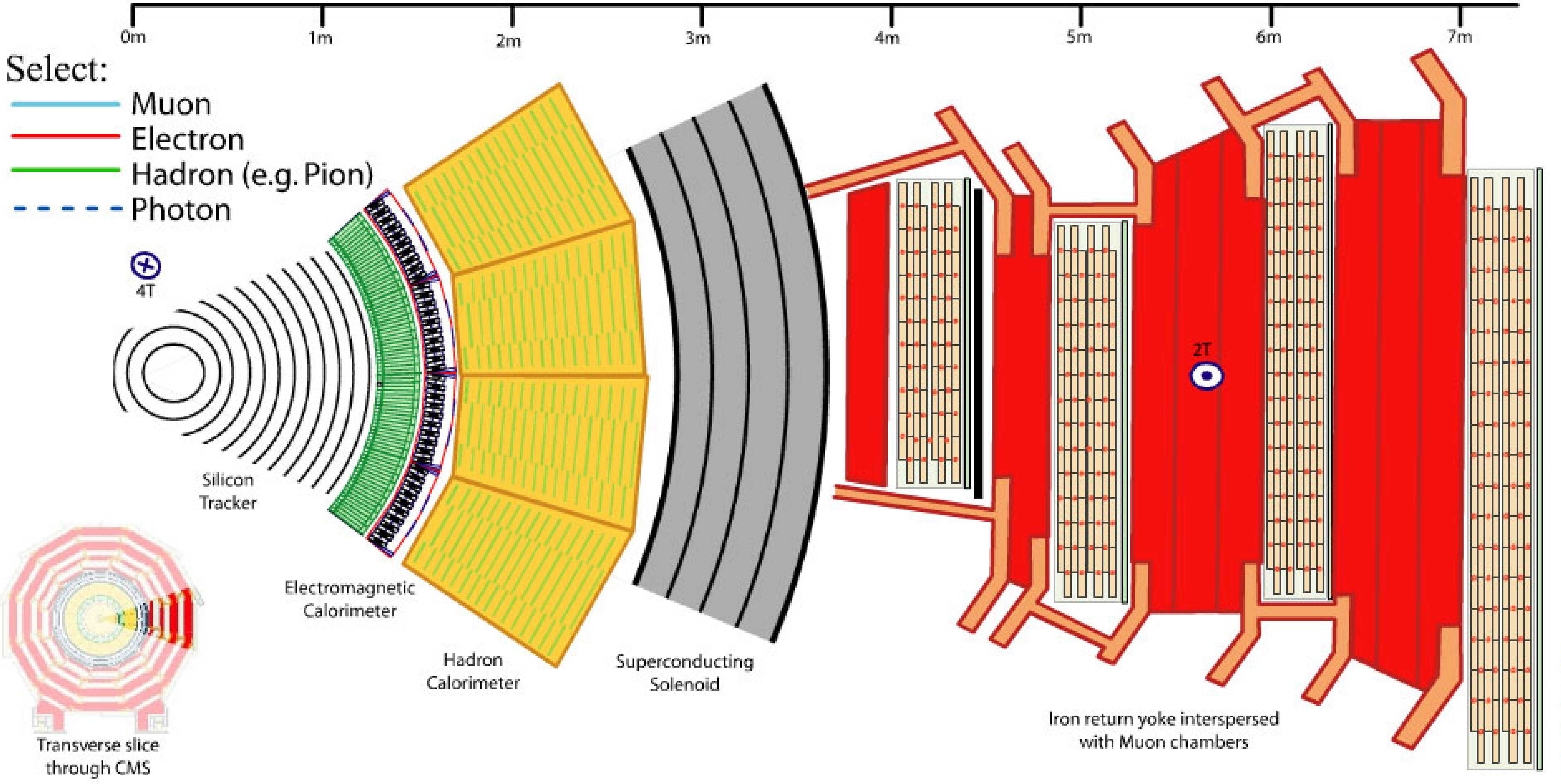
Detector characteristics

Width:	44m
Diameter:	22m
Weight:	7000t

CMS = Compact Muon Solenoid

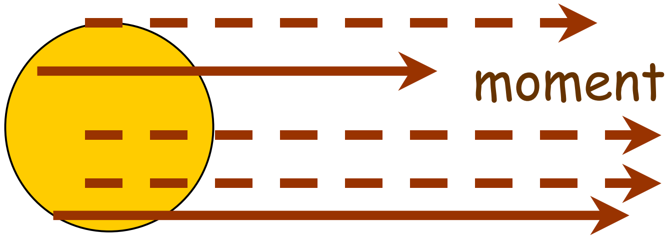


CMS response to particles



D. Barney, CERN, 2002

Structure functions



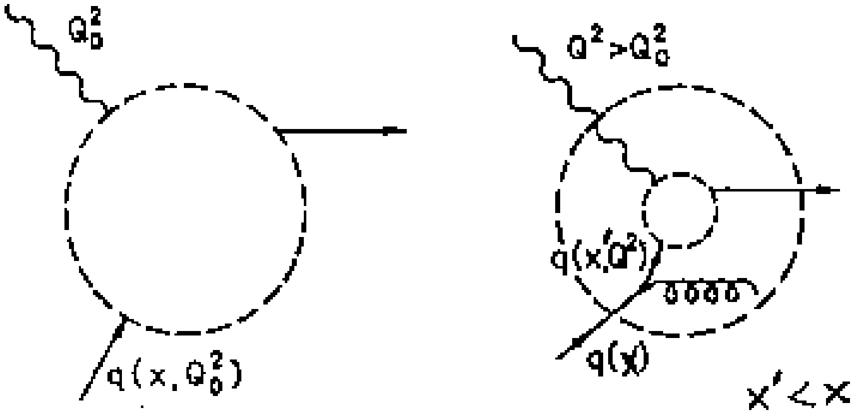
momentum $x \cdot p$

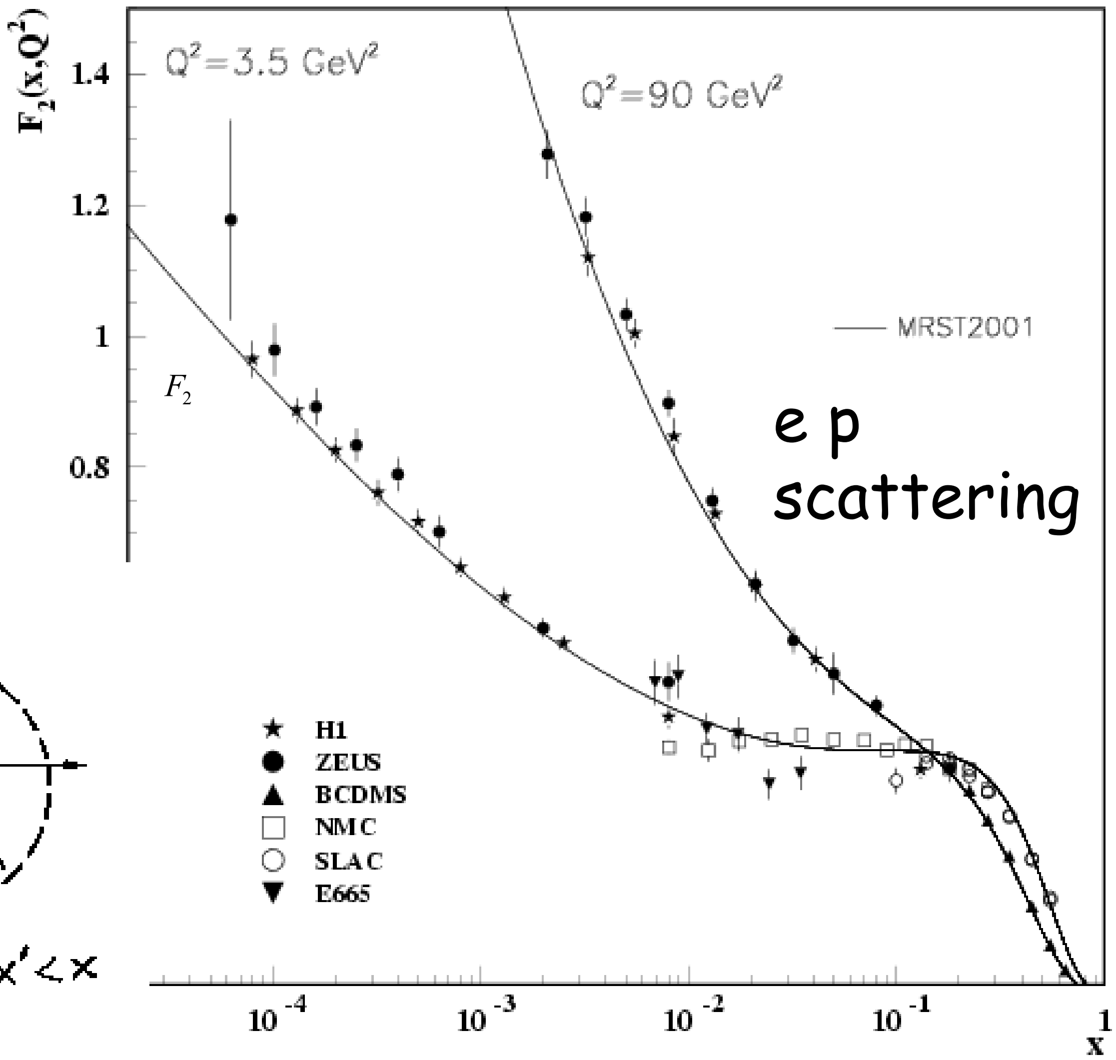
momentum p

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

„Bjorken x“

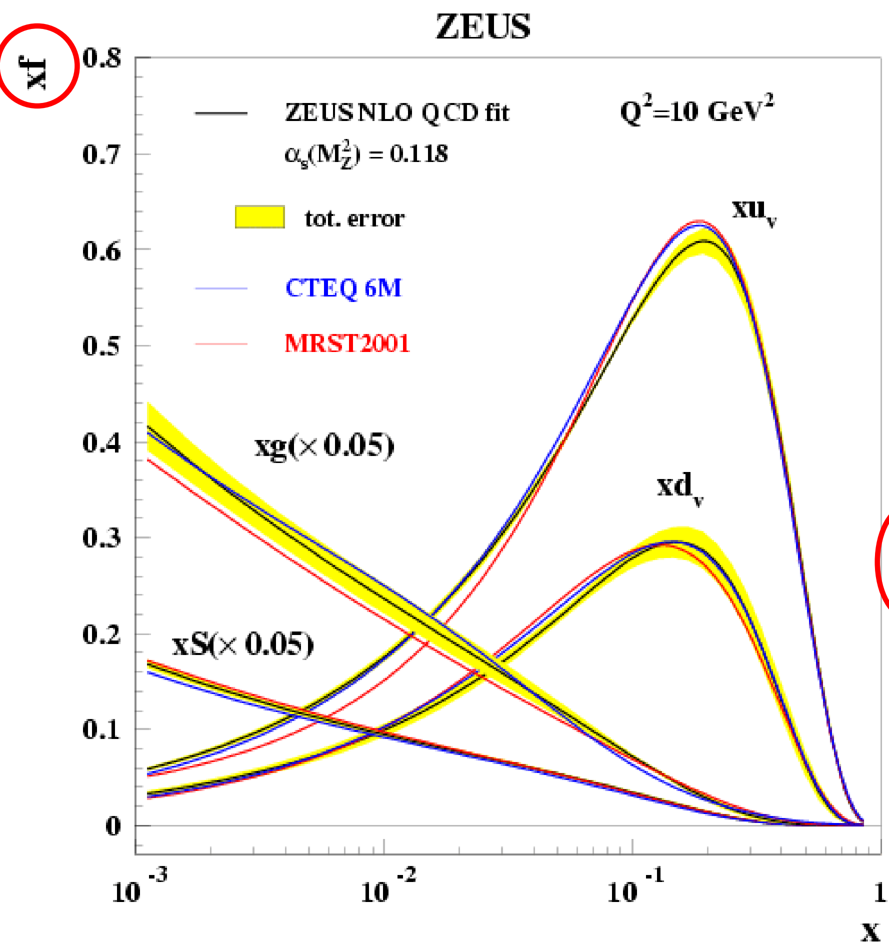
depends on resolution,
given by Q^2:





e p
scattering

Structure functions

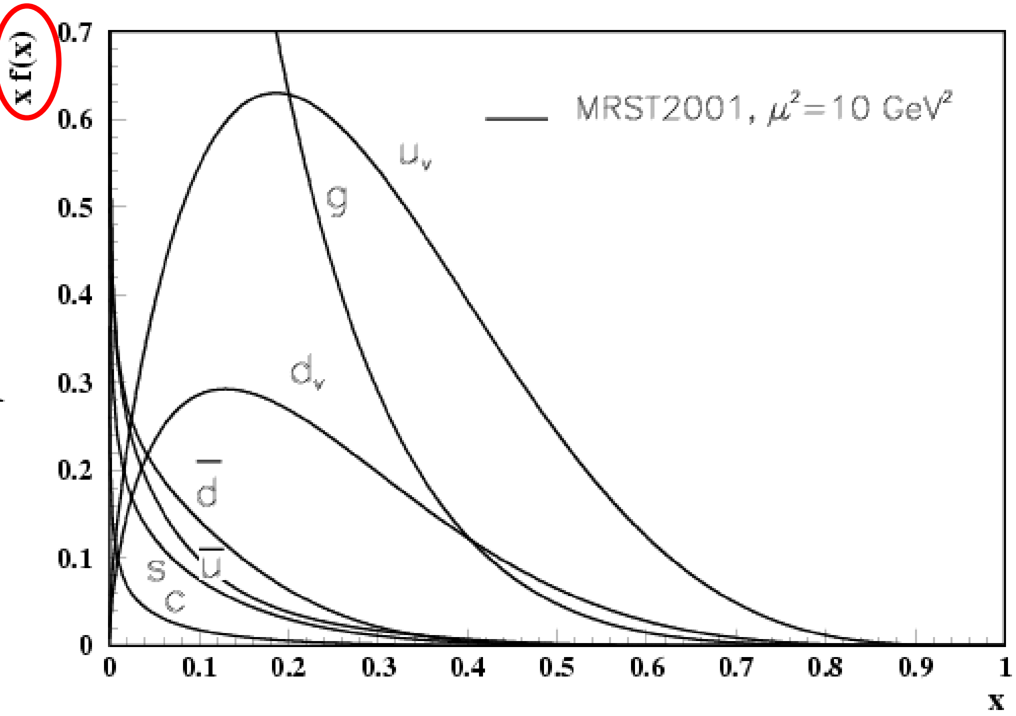


Measurements:

F_2 , F_3 ... in DIS

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

⇨ valence, sea, gluons...



Fits/parametrisations:

- CTEQ
- MRST

Cross section calculation in pp

final state

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

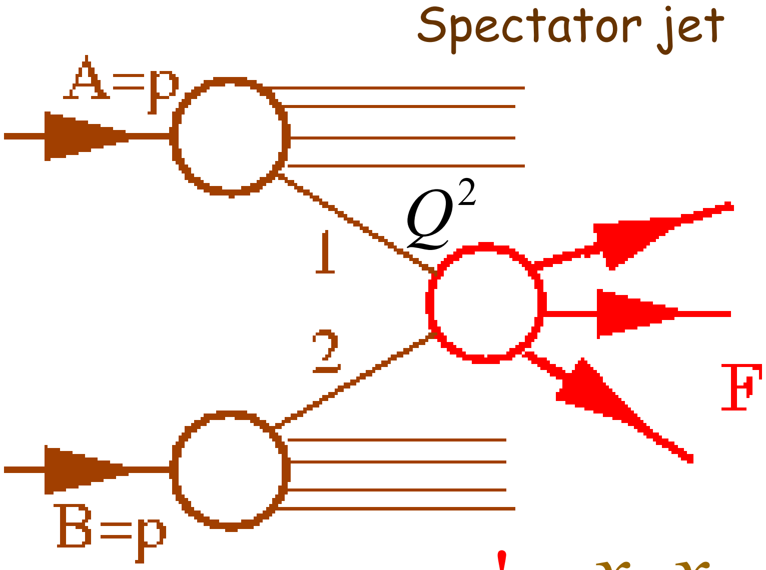
kinematical variable

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

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

Q² = („momentum transfer")²

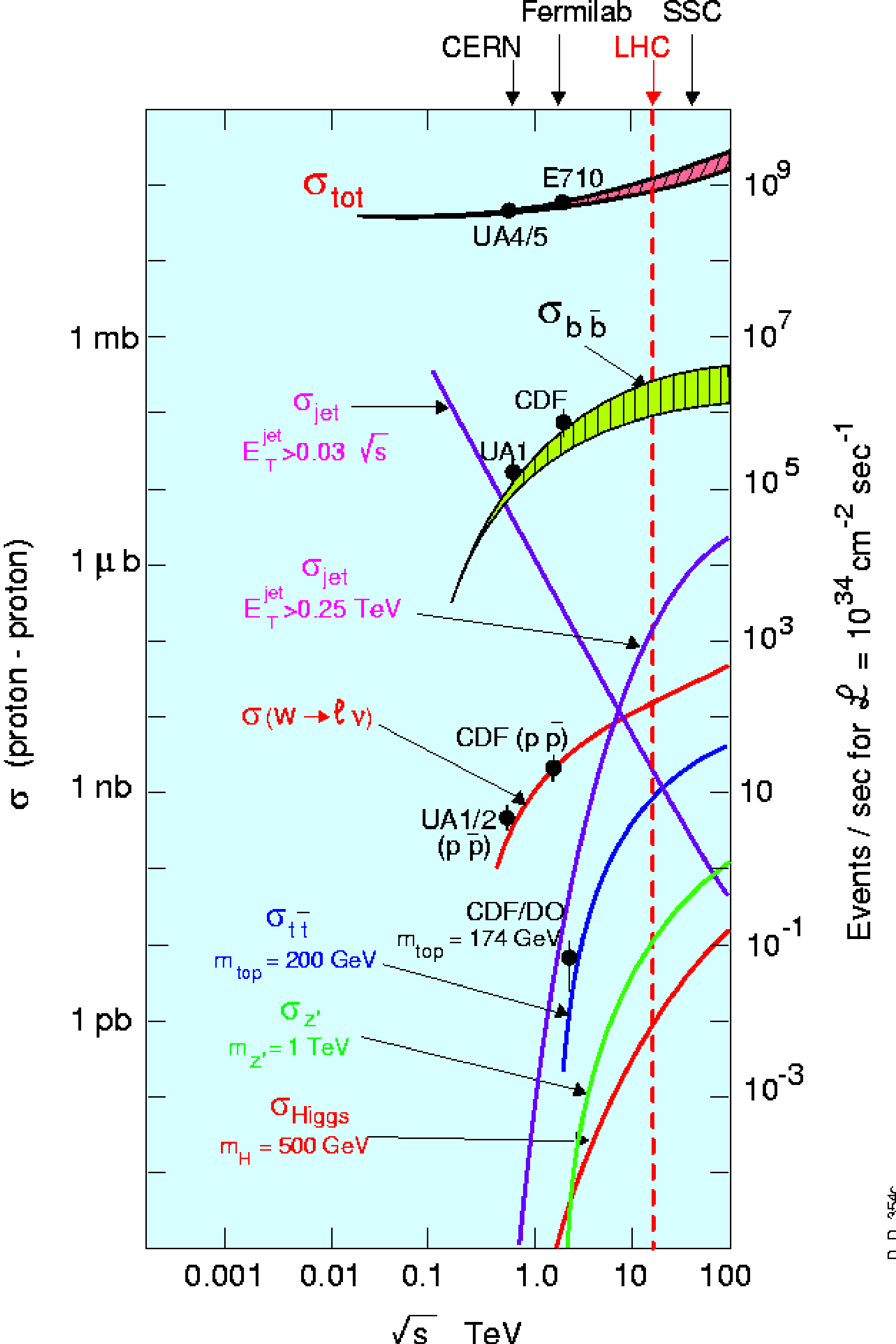
depends on final state



$$s' = x_1\, x_2\, s$$

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

Cross Sections at Hadron Colliders



Note:

may trade:

energy ↔ luminosity

Example:

In principle top discovery at SPS !

Challenges

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 $|\eta| < 2.5$

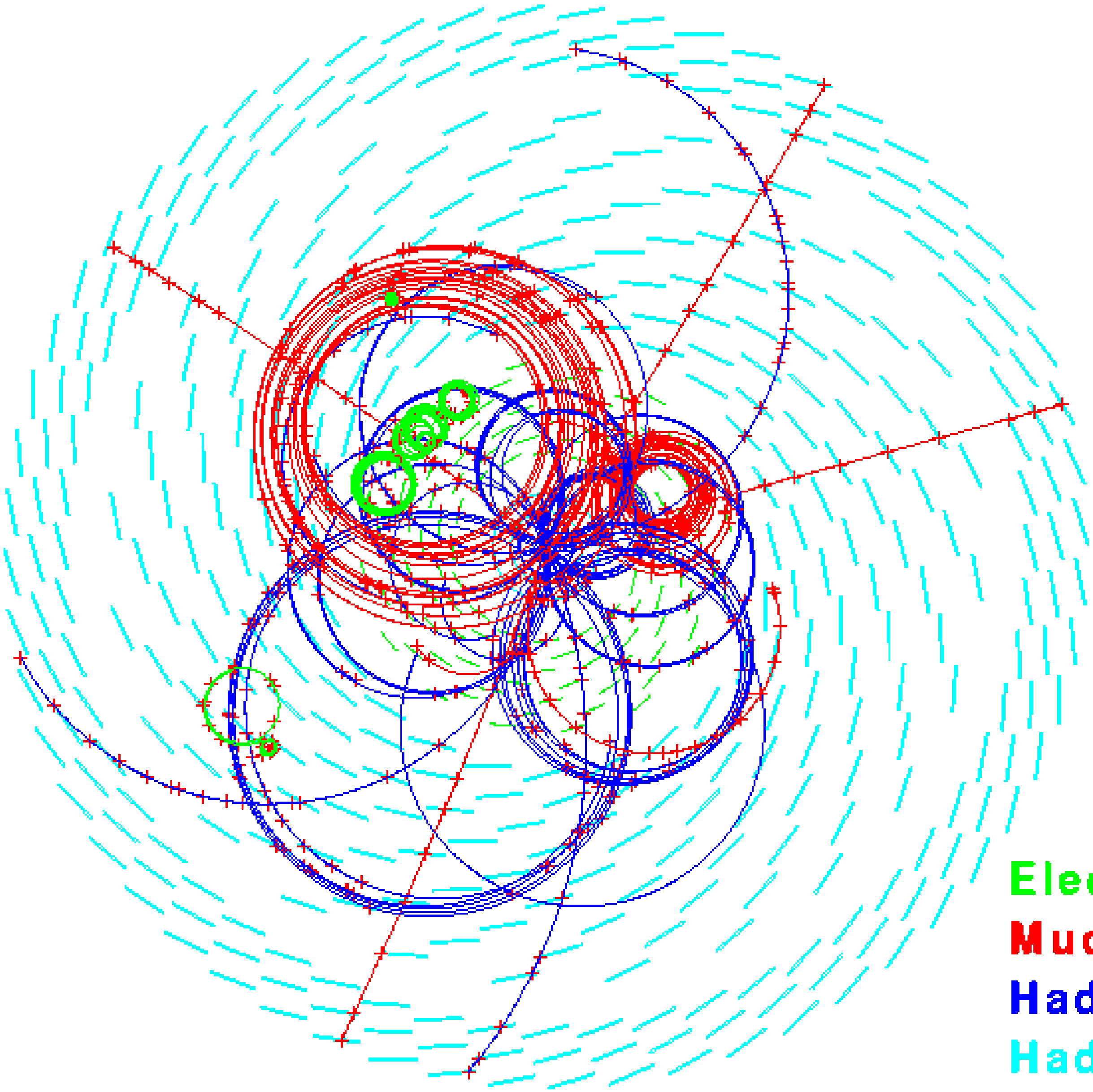
10^{11} particles /s

radiation damage detectors (~ 10 Mrad)

many bunches to limit #interactions/Xing

(25 ns bunch distance => 20/Xing)

Example: Higgs event in CMS tracker

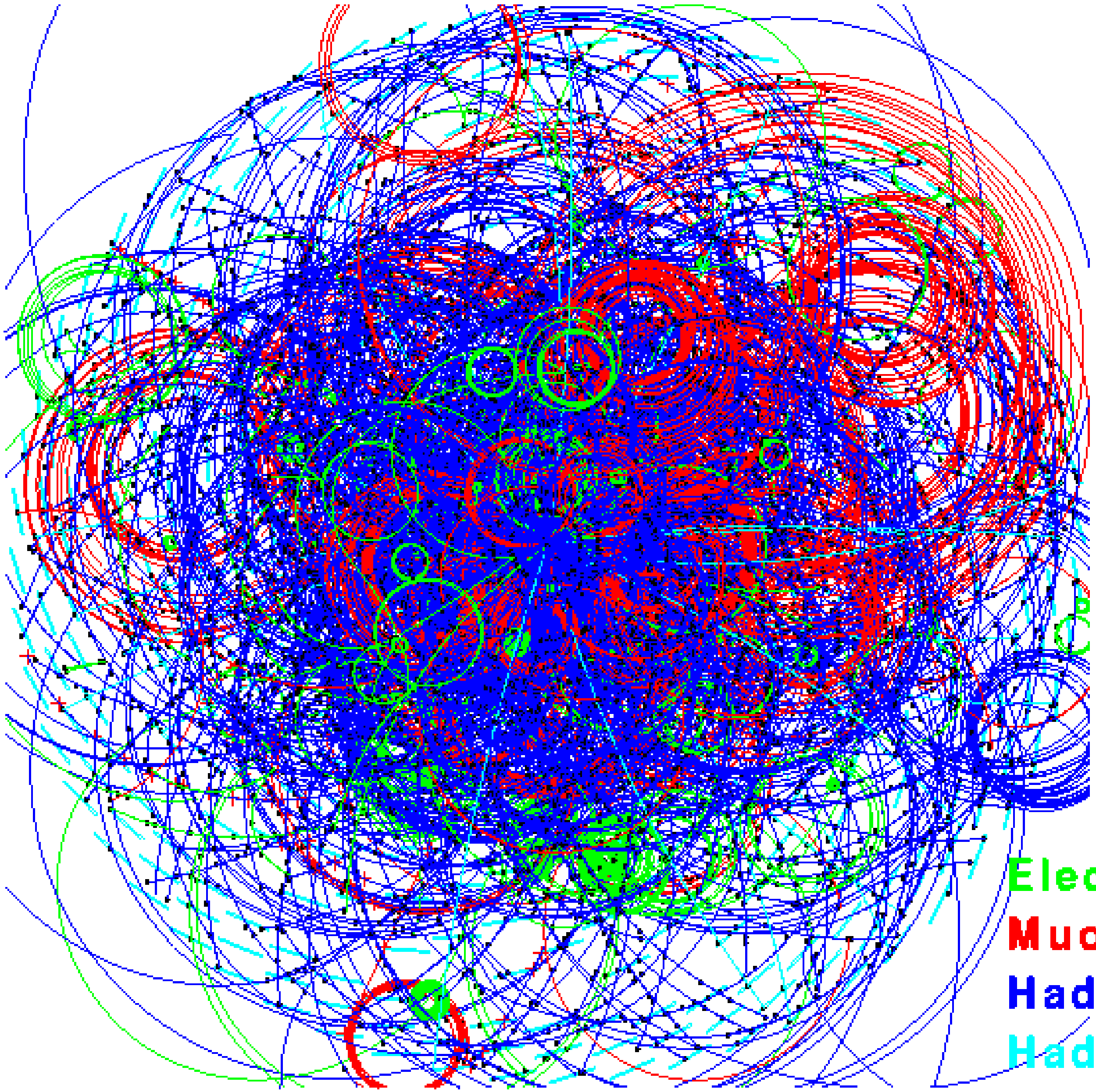


CMS

H -> μμμμ
m(H)=150GeV

Electrons
Muons
Hadrons pt<2GeV
Hadrons pt>2GeV

Example: Higgs event in CMS tracker



CMS

H -> μμμμ

m(H)=150GeV

+ 20 Min bias

Luminosity determination in pp

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

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 ($2 \to 2$):

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

Rapidity range:

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

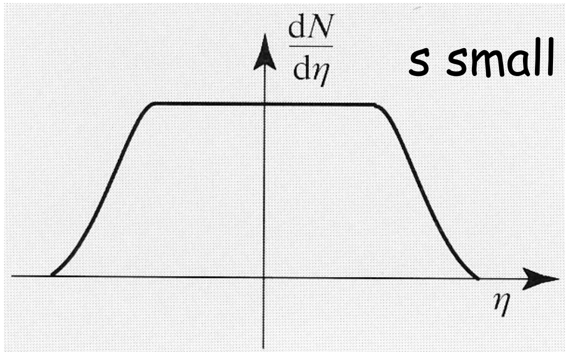
Empirical in pp collisions:

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

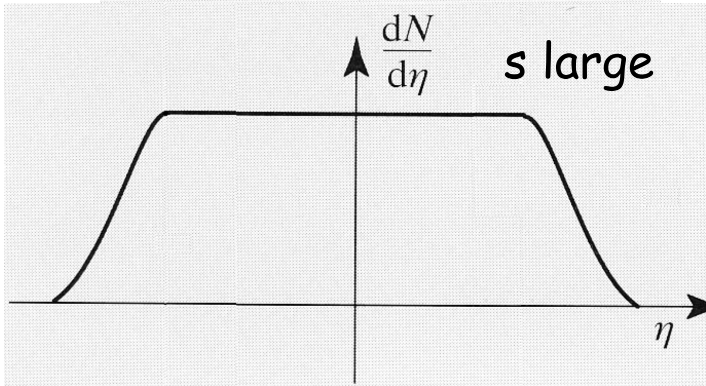
$$\frac{d\,N}{d\,\eta} \sim const$$

...

„plateau"



s small

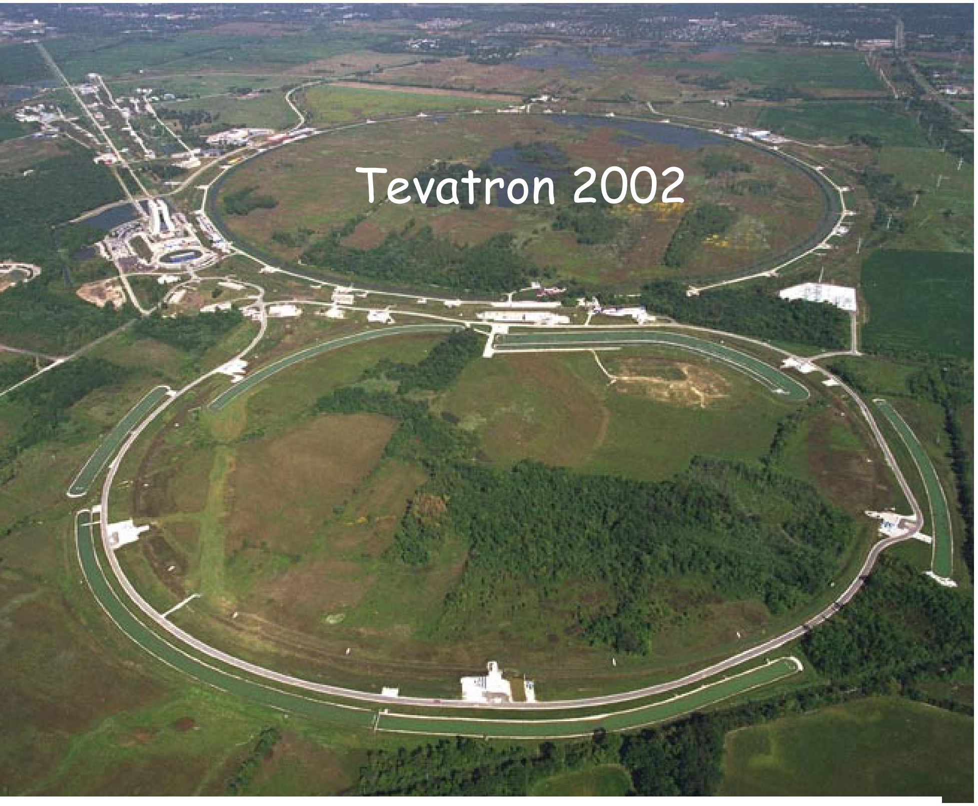


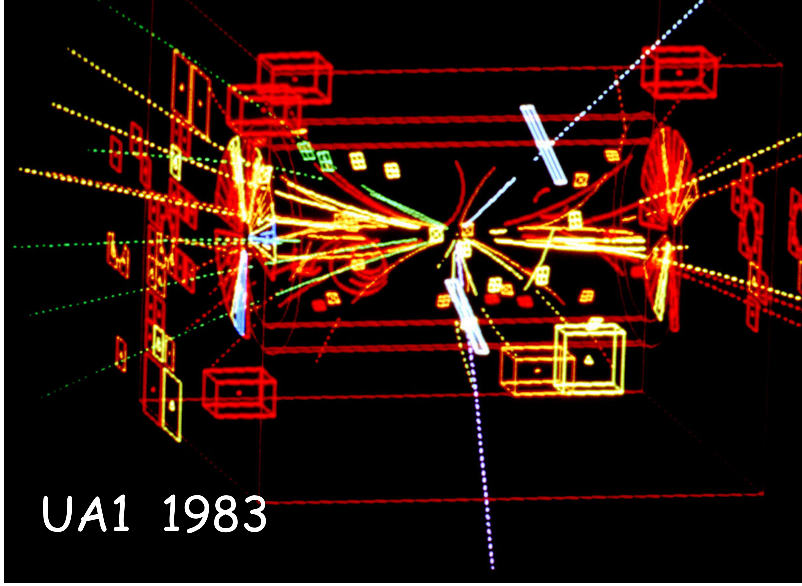
s large

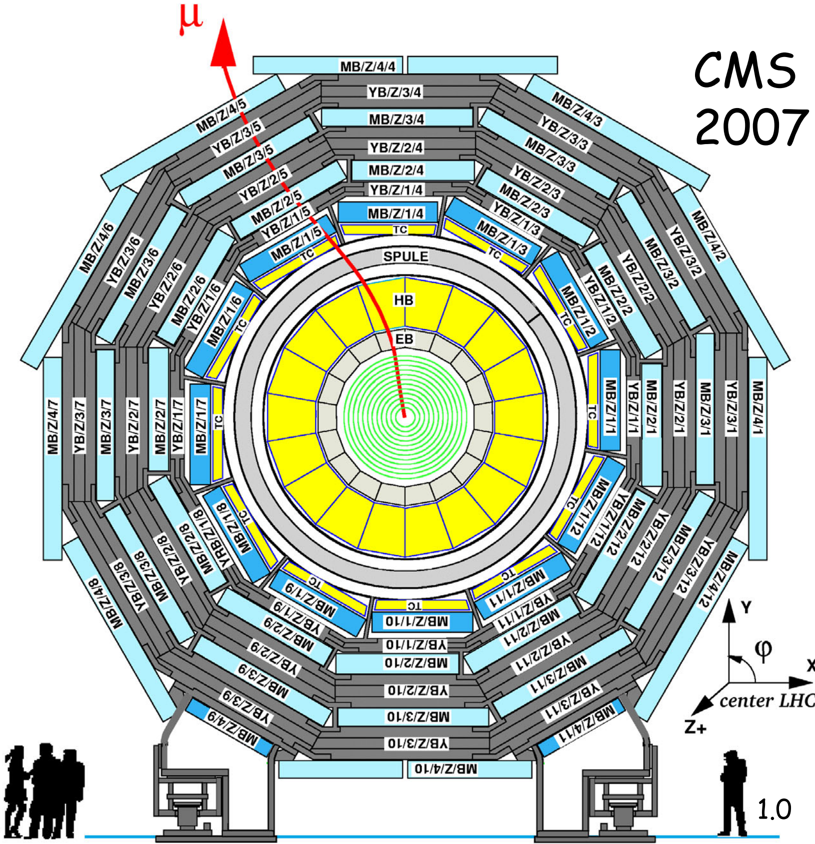
Thomas Hebbeker, RWTH Aachen
Belgian-Dutch-German school
September 2003

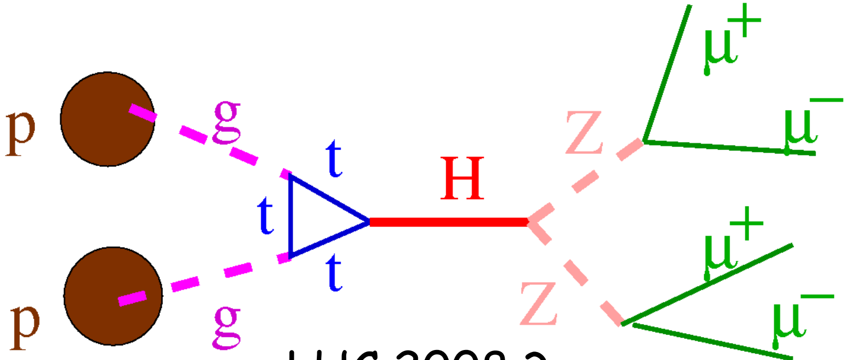
part **II**

p p physics









LHC 2008 ?

Part I Introduction

Part II Standard Model Physics

- cross section calculation
- QCD and jets
- W and Z
- charm and bottom
- top

Part III Higgs

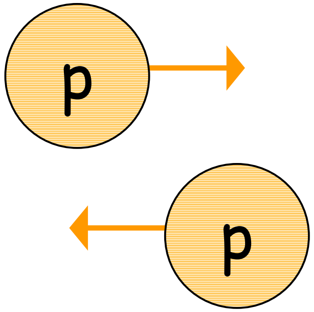
Part IV New Phenomena

References

Cross Section

Elastic cross section

LUMINOSITY



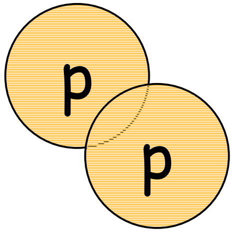
strong,
electromagnetic

Xsection relatively small
scattering angle tiny

Total inelastic cross section

BACKGROUND

LUMINOSITY

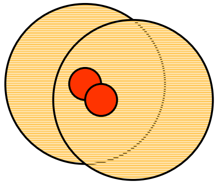


strong

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

Pointlike cross section

SIGNAL



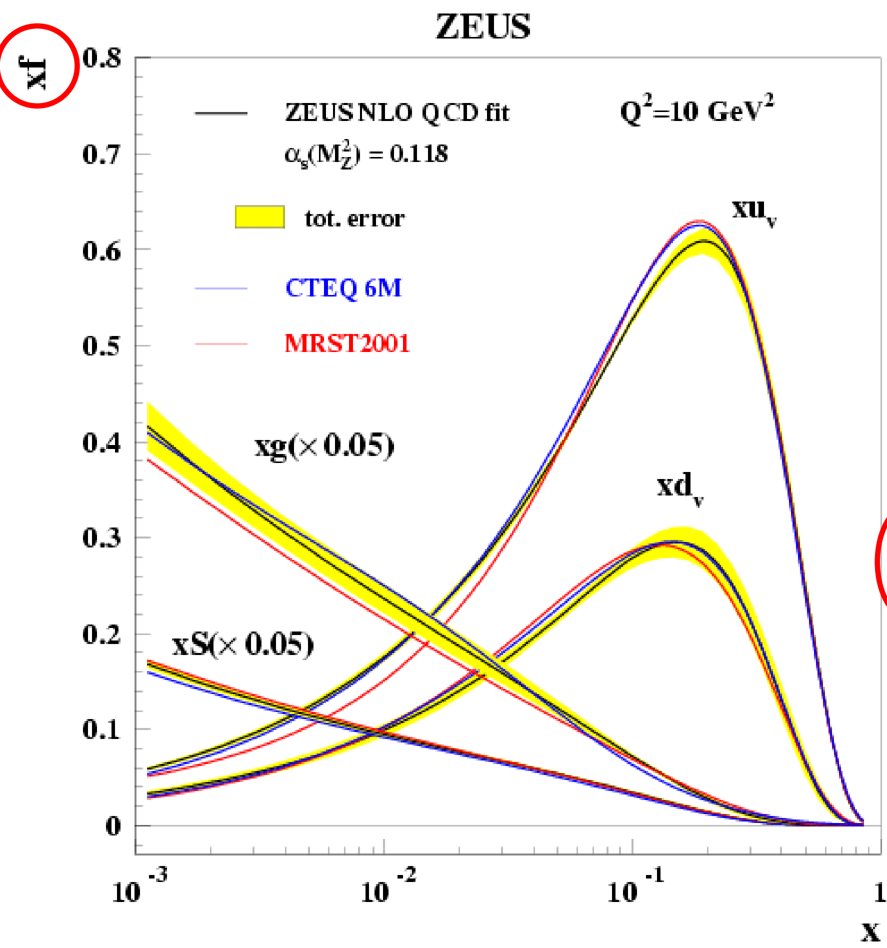
electroweak

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

LHC

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

Structure Functions

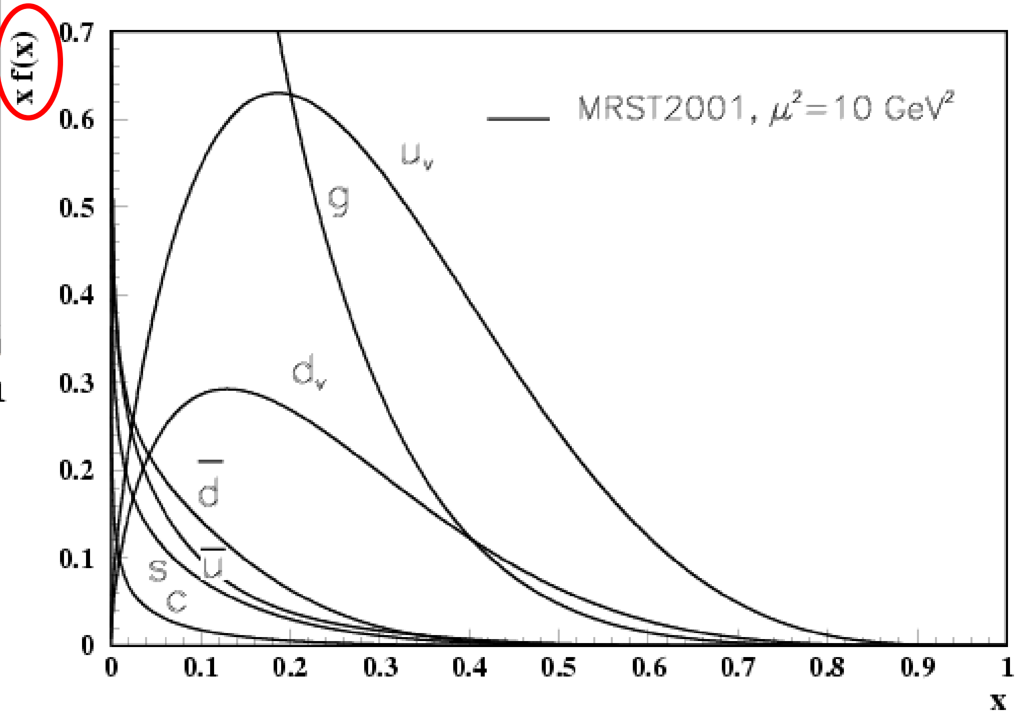


Measurements:

F_2 , F_3 ... in DIS

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

⇨ valence, sea, gluons...



Fits/parametrisations:

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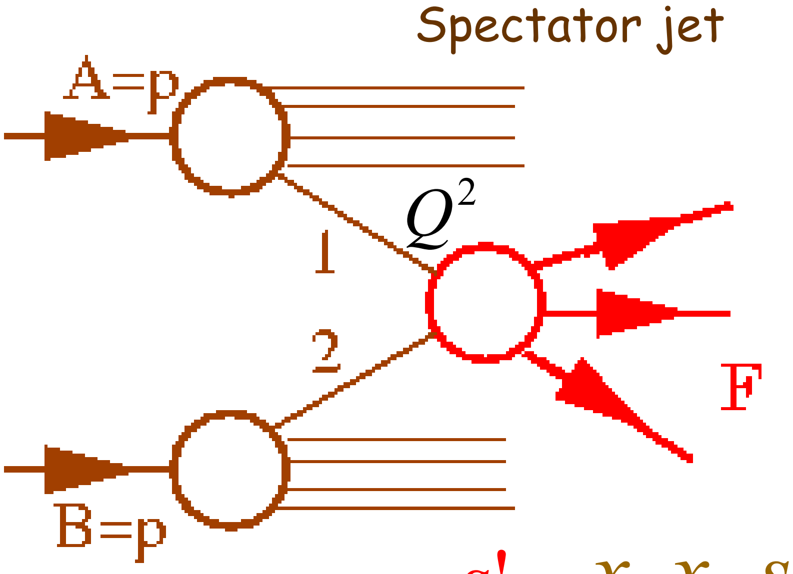
Cross section calculation in pp

final state

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

kinematical variable



$$s' = x_1\, x_2\, s$$

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

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

Cross Sections at Hadron Colliders

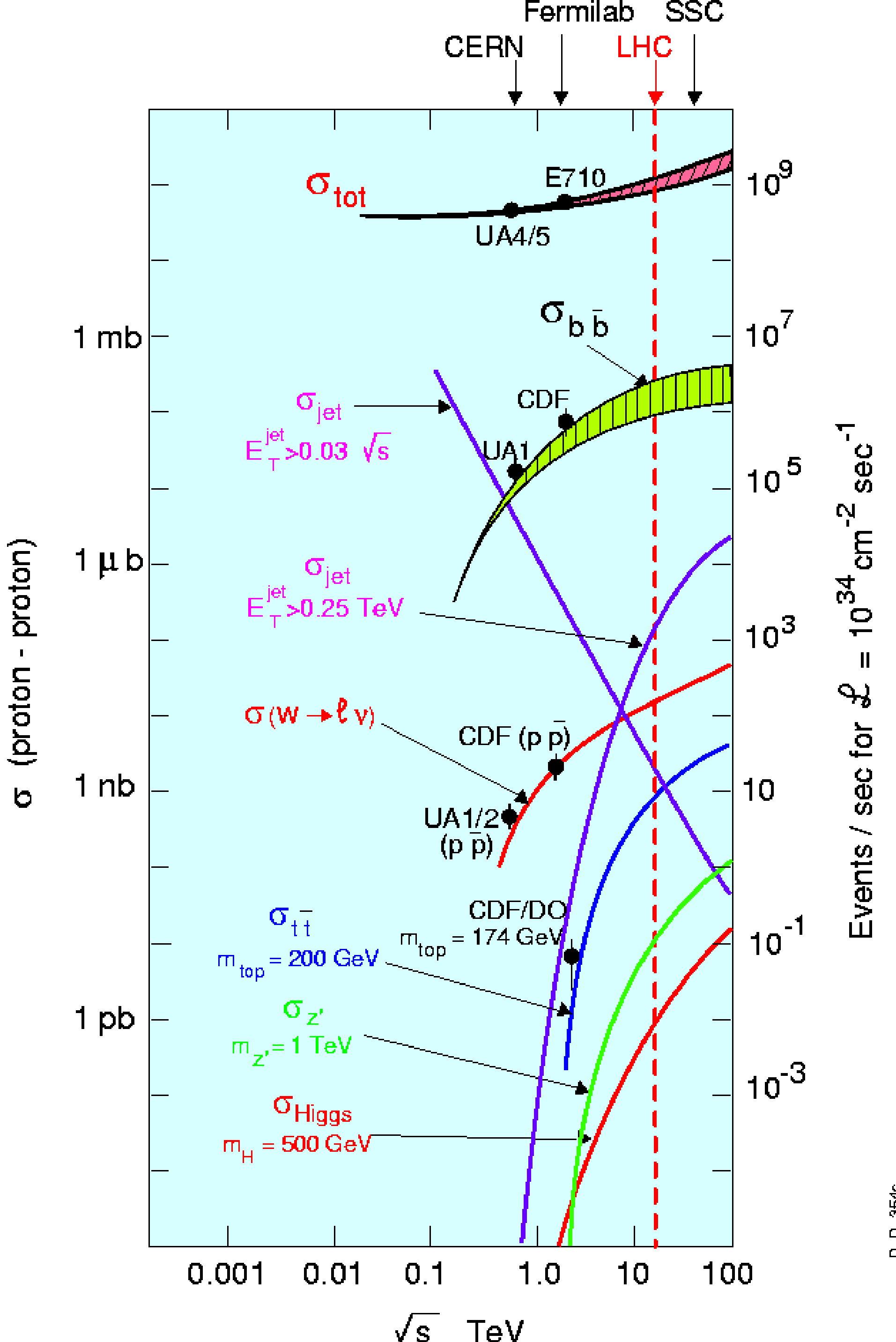
<u>Note:</u>

may trade:

energy ↔ luminosity

Example:

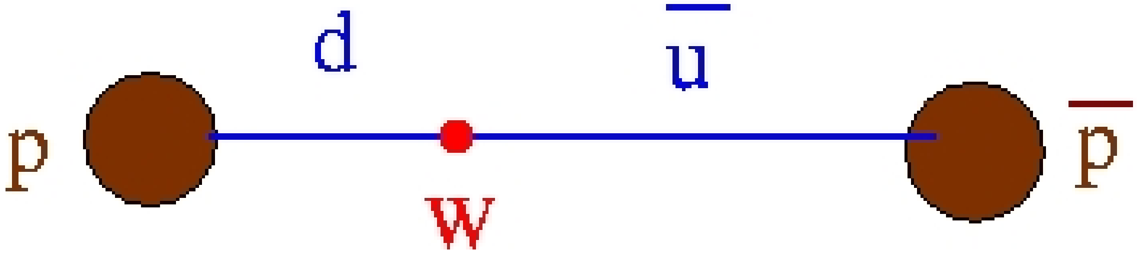
In principle top discovery at SPS !



Estimate of Xsection $p\,\bar{p} \to W^-X$

Ansatz:

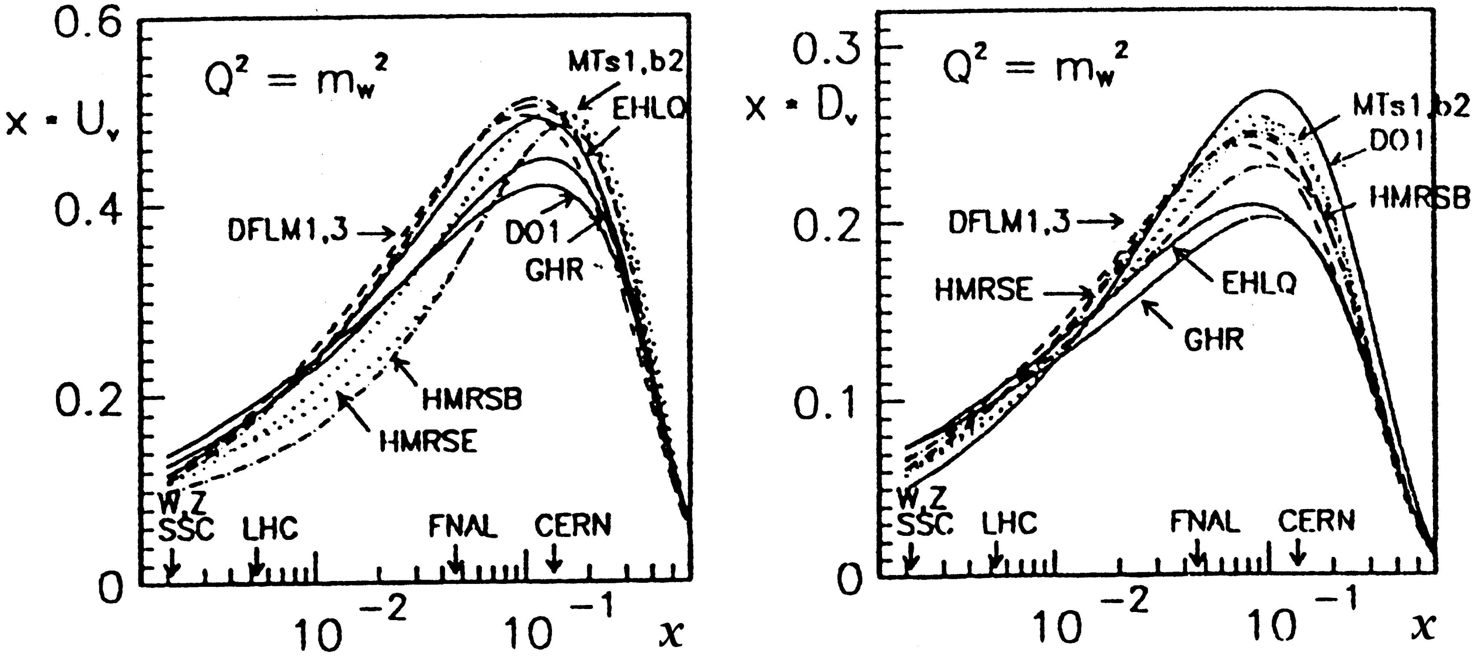
$$d\,\bar{u} \;\to\; W^- \qquad (valence \;\; quarks)$$



$$\sigma_W(\sqrt{s}) = \int\int f^d(x_1)\, f^{\bar{u}}(x_2)\, \sigma^{d\bar{u}}(\sqrt{s'})\, dx_1\, dx_2$$

$$s' = x_1\, x_2\, s$$

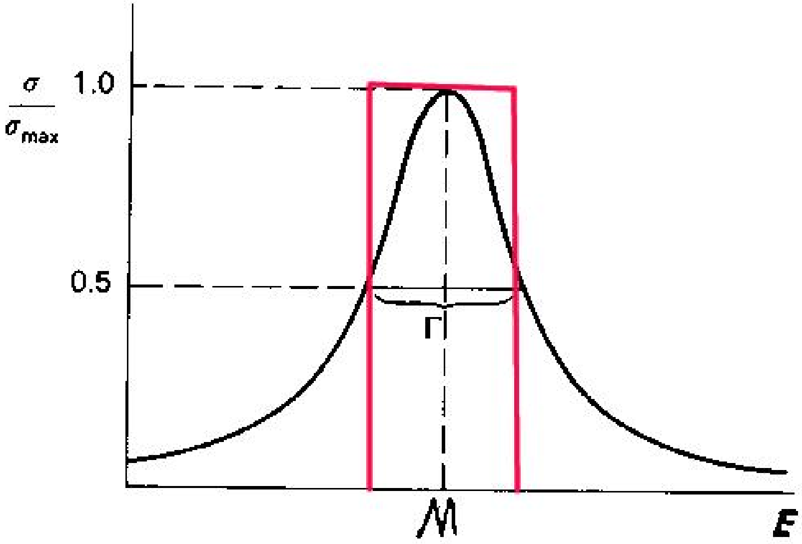
Structure Functions:



Rough parametrisation:

$$f_d(x) = \frac{0.2}{x} \qquad\qquad f_{\bar{u}}(x) = 2\, f_d(x)$$

Cross section (quark level):



$$\sigma^{d\bar{u}}(\sqrt{s}') = \sigma_0 \cdot \frac{s\,\Gamma_W^2}{(s' - m_W^2)^2 + m_W^2 \Gamma_W^2}$$

$$\sigma_0 = \frac{12\pi}{m_W^2} \cdot \frac{\Gamma_{qq}}{\Gamma_W} \approx \frac{12\pi}{m_W^2} \cdot \frac{6}{9} \approx \frac{25}{m_W^2}$$

$$\sigma^{d\bar{u}}(\sqrt{s}') \approx \frac{25}{m_W^2} \cdot \begin{cases} 1 & m_W - \Gamma_W/2 < \sqrt{s'} < m_W + \Gamma_W/2 \\ 0 & \text{else} \end{cases}$$

Calculate:

$$\sigma_W(\sqrt{s}) = 25 \cdot 0.2 \cdot 0.4 \cdot \frac{1}{m_W^2} \cdot \int_{x_2^{min}}^{1} \frac{1}{x_2} \left[\int_{x_1^{min}}^{x_1^{max}} \frac{1}{x_1} \, dx_1 \right] \, dx_2$$

$$x_2^{min} \approx \frac{m_W^2}{s}$$

$$x_1^{min} = \frac{(m_W - \Gamma_W/2)^2}{x_2 \, s} \qquad x_1^{max} = \frac{(m_W + \Gamma_W/2)^2}{x_2 \, s}$$

$$\sigma_W(\sqrt{s}) \approx 25 \cdot 0.2 \cdot 0.4 \cdot \frac{1}{m_W^2} \cdot \int_{x_2^{min}}^{1} \frac{1}{x_2} \left[2 \frac{\Gamma_W}{m_W} \right] \, dx_2$$

$$\sigma_W(\sqrt{s}) = -4 \cdot \frac{1}{m_W^2} \cdot \frac{\Gamma_W}{m_W} \cdot \ln \frac{m_W^2}{s}$$

Results:

$$1/\mathrm{GeV} = 2 \cdot 10^{-16}\,\mathrm{m}^2$$

$$m_W = 80\,\mathrm{GeV}$$

$$\Gamma_W = 2\,\mathrm{GeV}$$

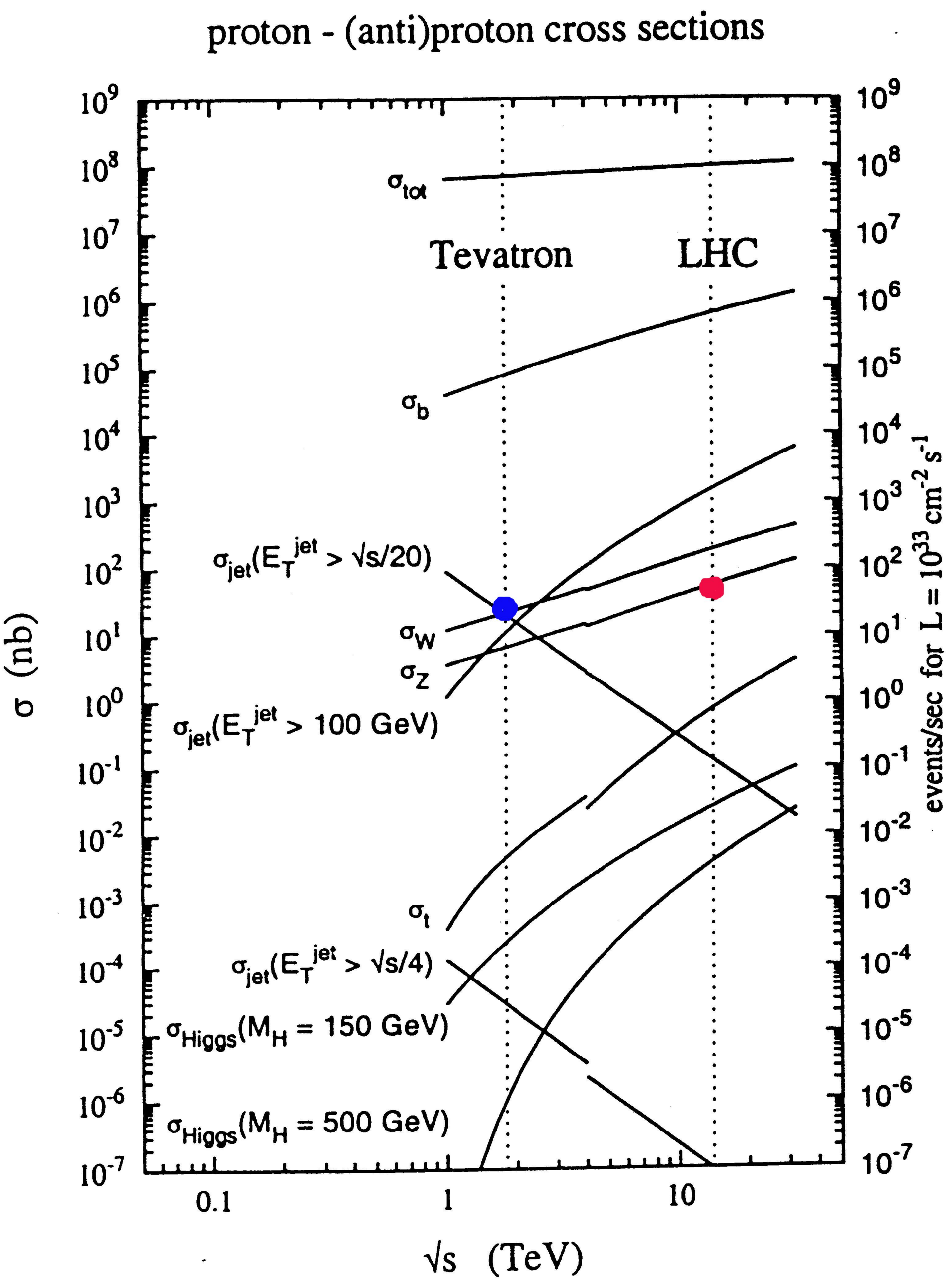
$$\sigma_W(\sqrt{s}) \approx 4\,\mathrm{nb} \cdot \ln \frac{s}{m_W^2}$$

FERMILAB :

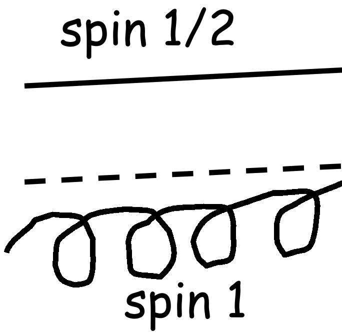
$$\sigma_p(\sqrt{s}) \approx 25\,\mathrm{nb}$$

LHC(pp!) :

$$\sigma_p(\sqrt{s}) \approx 40\,\mathrm{nb}$$

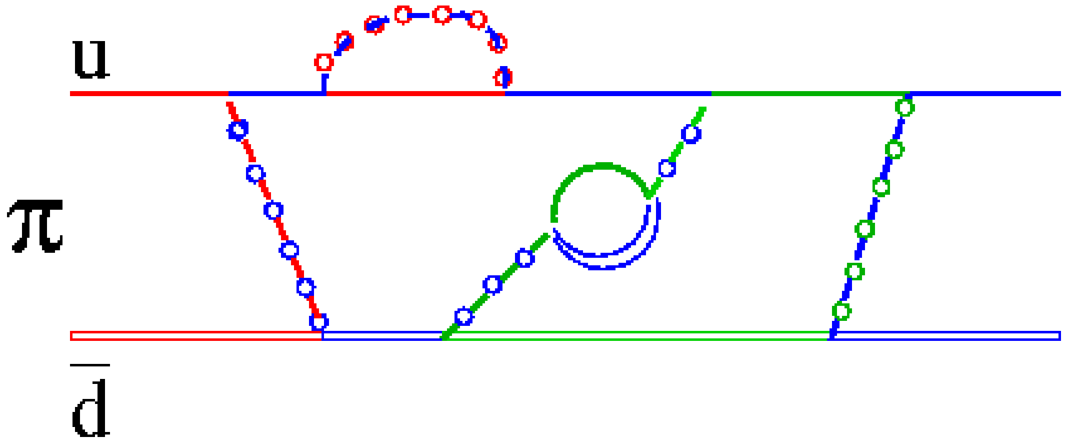


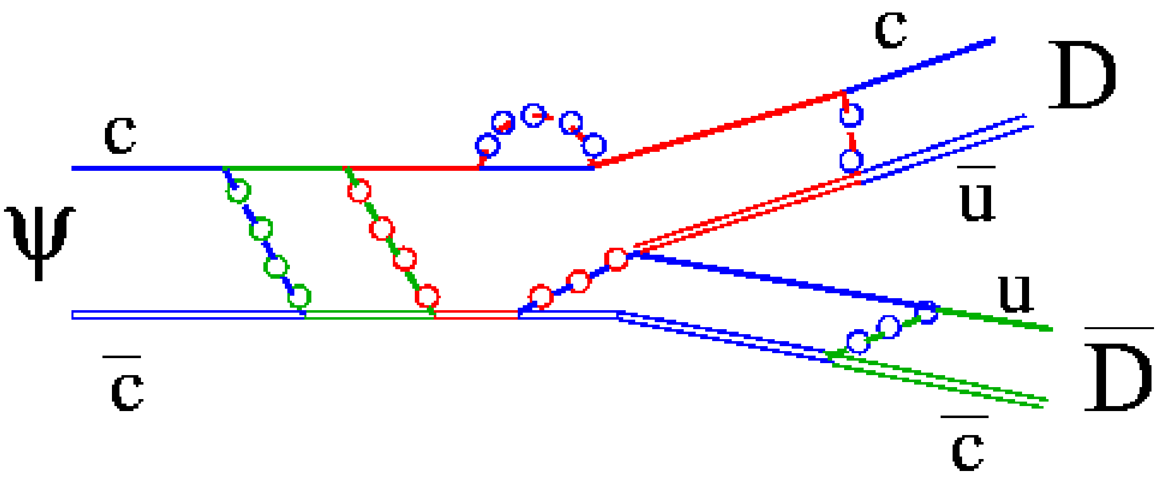
QCD = Quantum Chromodynamics



Gauge theory: • quarks with 3 colors (r,g,b)

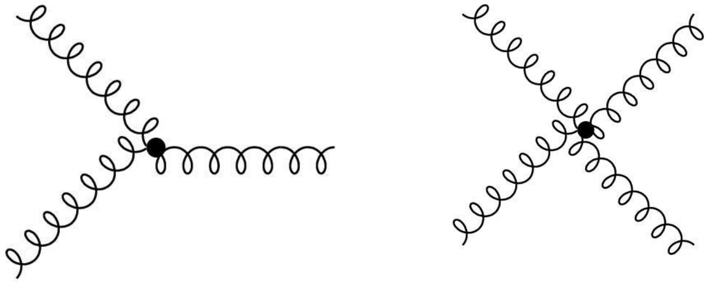
SU(3) • 8 gluons (color + anticolor $\bar{r}$,$\bar{g}$,$\bar{b}$)





self coupling, running, confinement

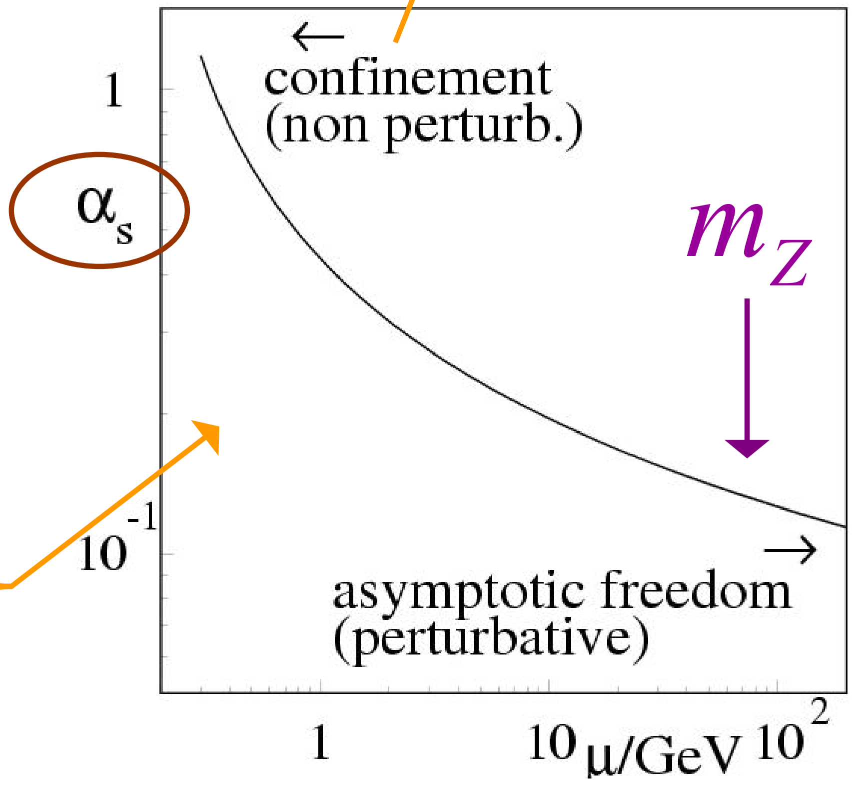
nonabelian:



mesons and baryons „white“:

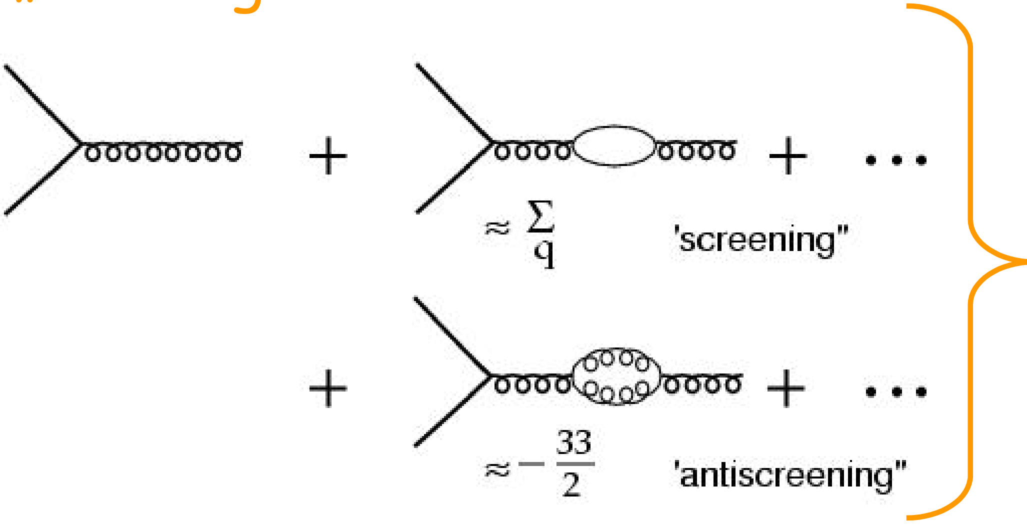
$q\bar{q}$ qqq

strong coupling „constant“



~ 1/distance

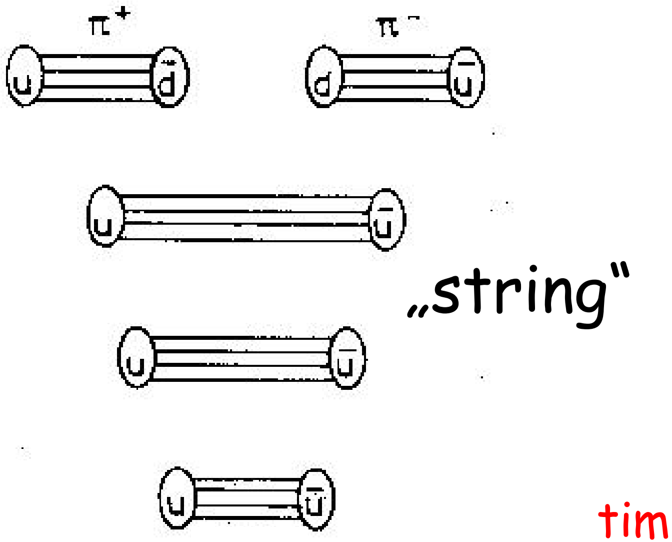
„Running“:



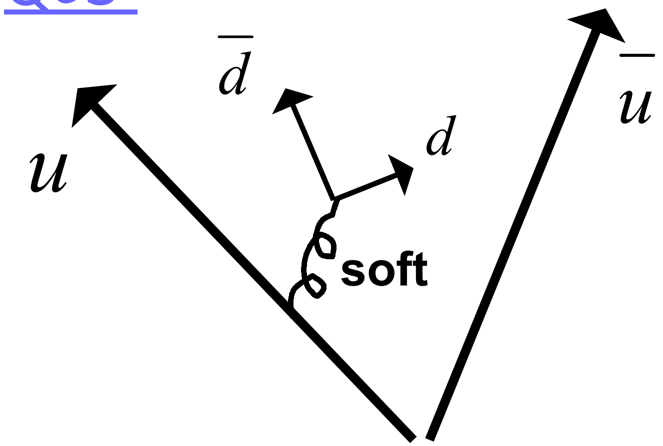
Hadronization = Fragmentation

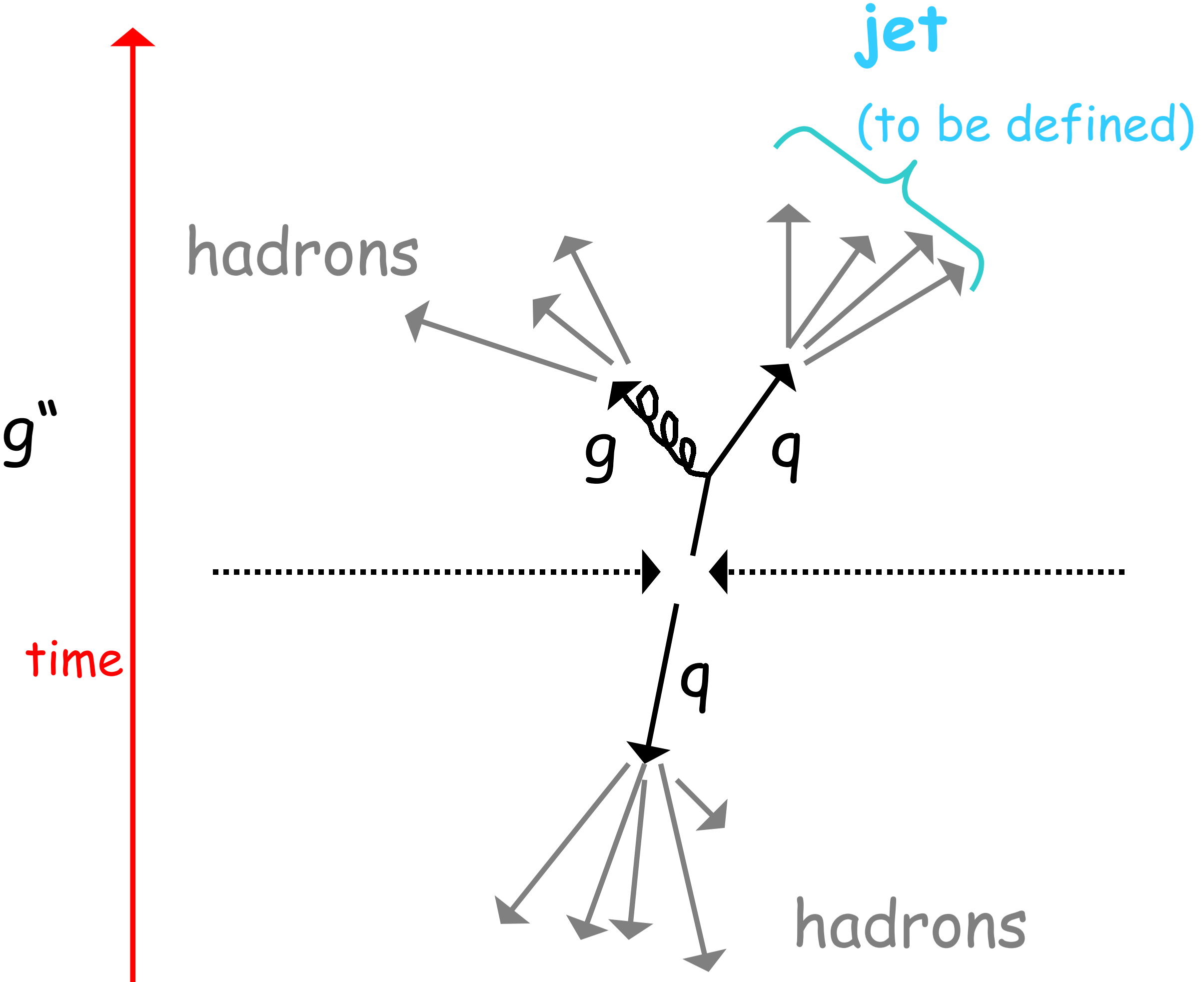
T.Hebbeker

String model:



QCD:

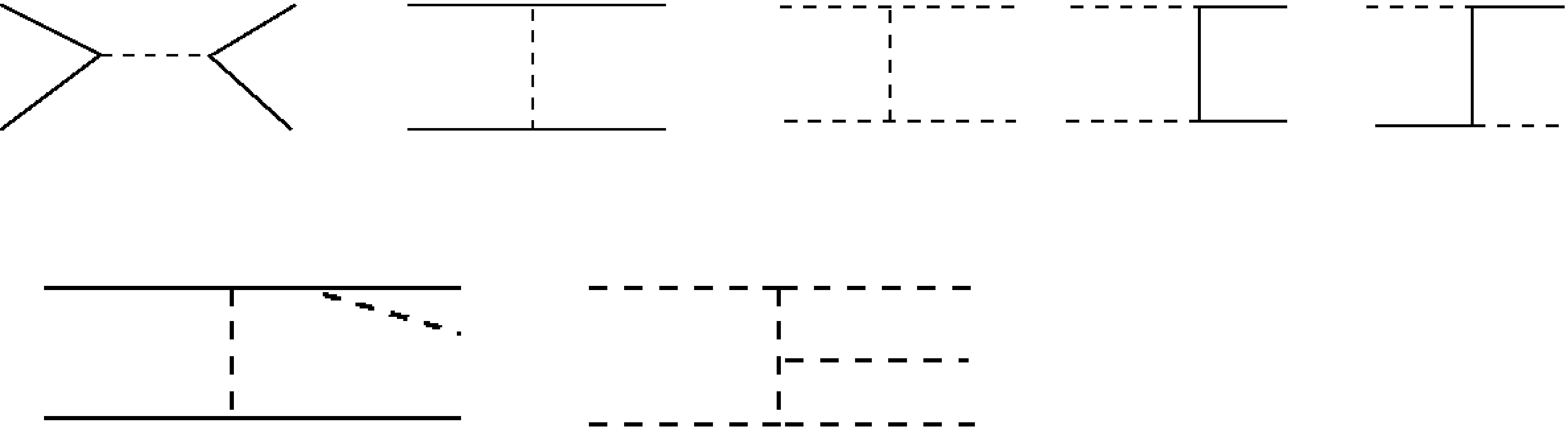


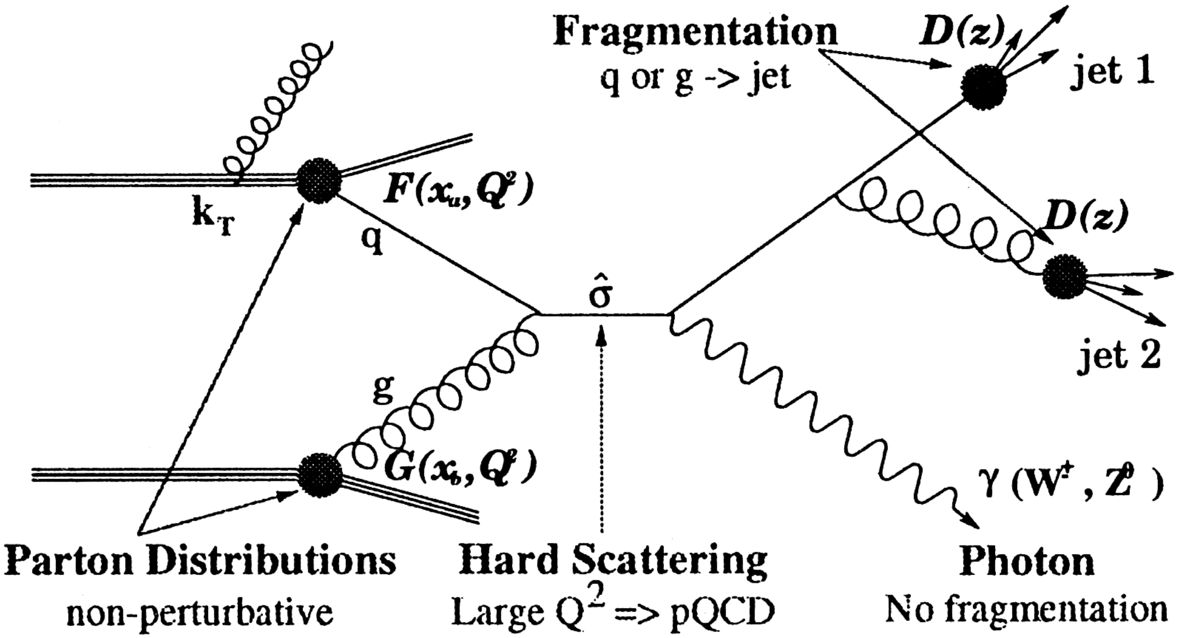


Hadronization: non-perturbative

⇒ need models!

Calculation of QCD processes



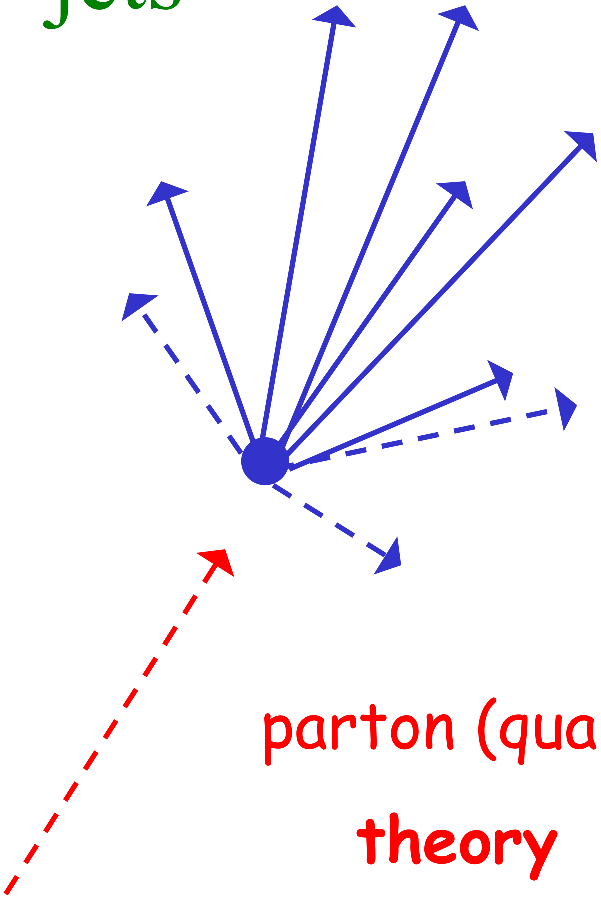


jets

Typical: 100
particles total

(14 TeV)

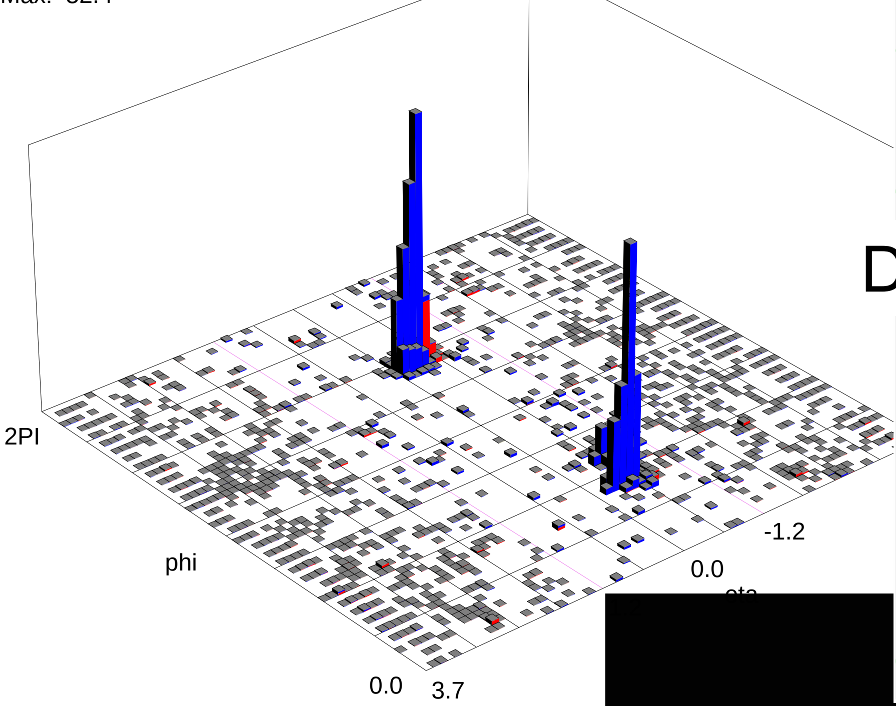
2-5 jets per event

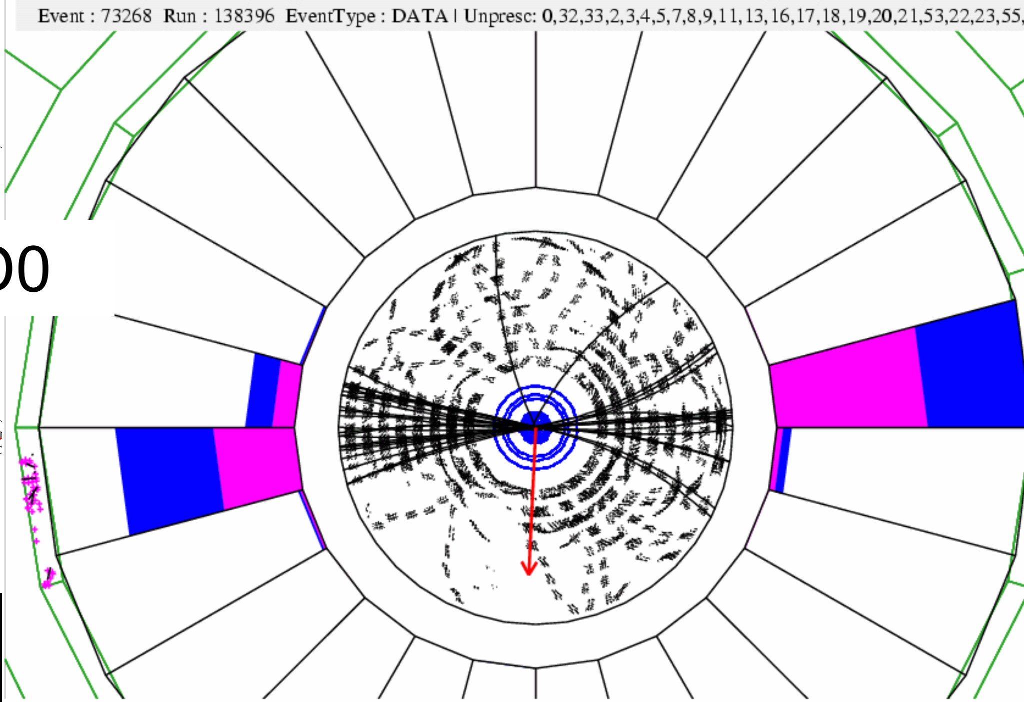


jets reveal hard processs (direction, energy)

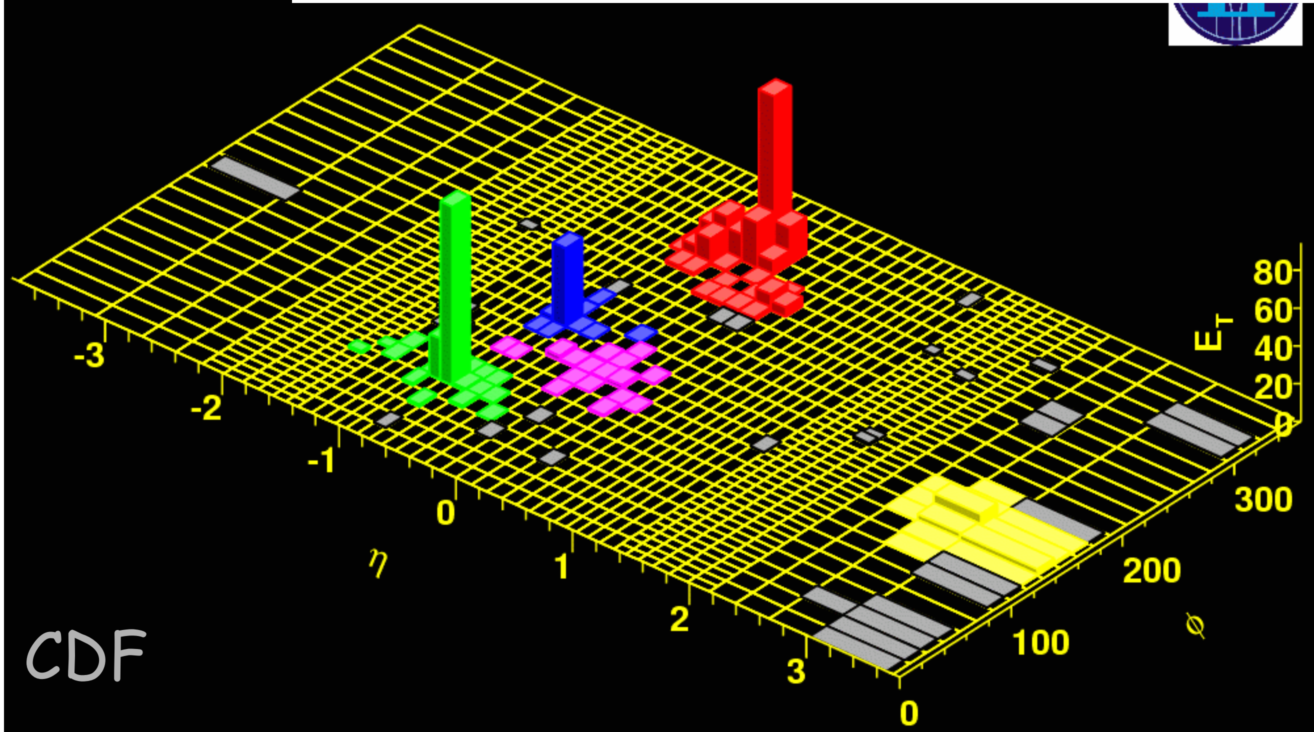
experiment and theory must use the same language:

jets need to be defined: „jet algorithm"

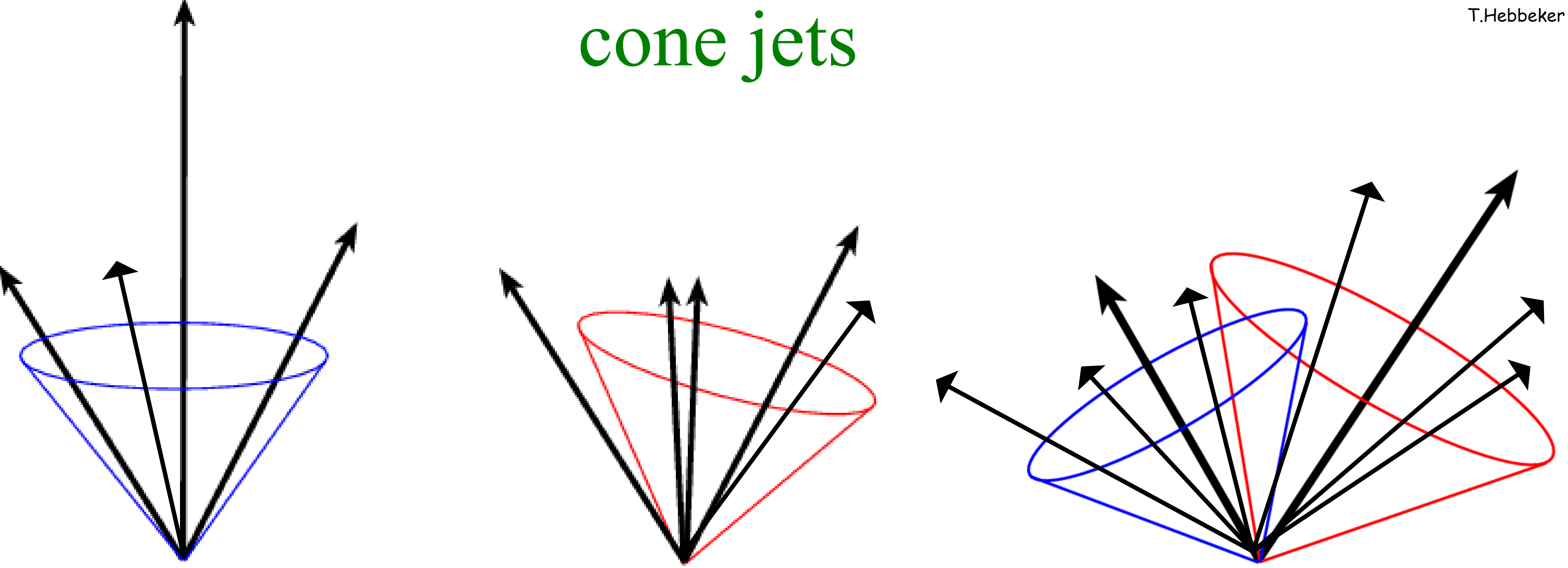

2PI
phi
0.0
3.7
-1.2
0.0
eta


Event : 73268 Run : 138396 EventType : DATA | Unpresc: 0,32,33,2,3,4,5,7,8,9,11,13,16,17,18,19,20,21,53,22,23,55,
D0

Jet events


80
60
40
20
0
E_T
-3
-2
-1
0
1
2
3
η
0
100
200
300
ϕ
CDF

cone jets



Cone defined in η,φ projection, radius = $\sqrt{(\Delta\eta)^2+(\Delta\varphi)^2}$ (typ = 0.7)

Isolated low energy particles are ignored

Sum of 4-momenta of objects inside cone = jet 4-momentum

potential problems: seed dependence, infrared sensitivity ...

several variations exist

kT jets

a) list of hadrons = clusters

b) each cluster:

$$d_i = p_{T,i}^2$$

each pair of clusters:

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \cdot R_{ij}^2$$

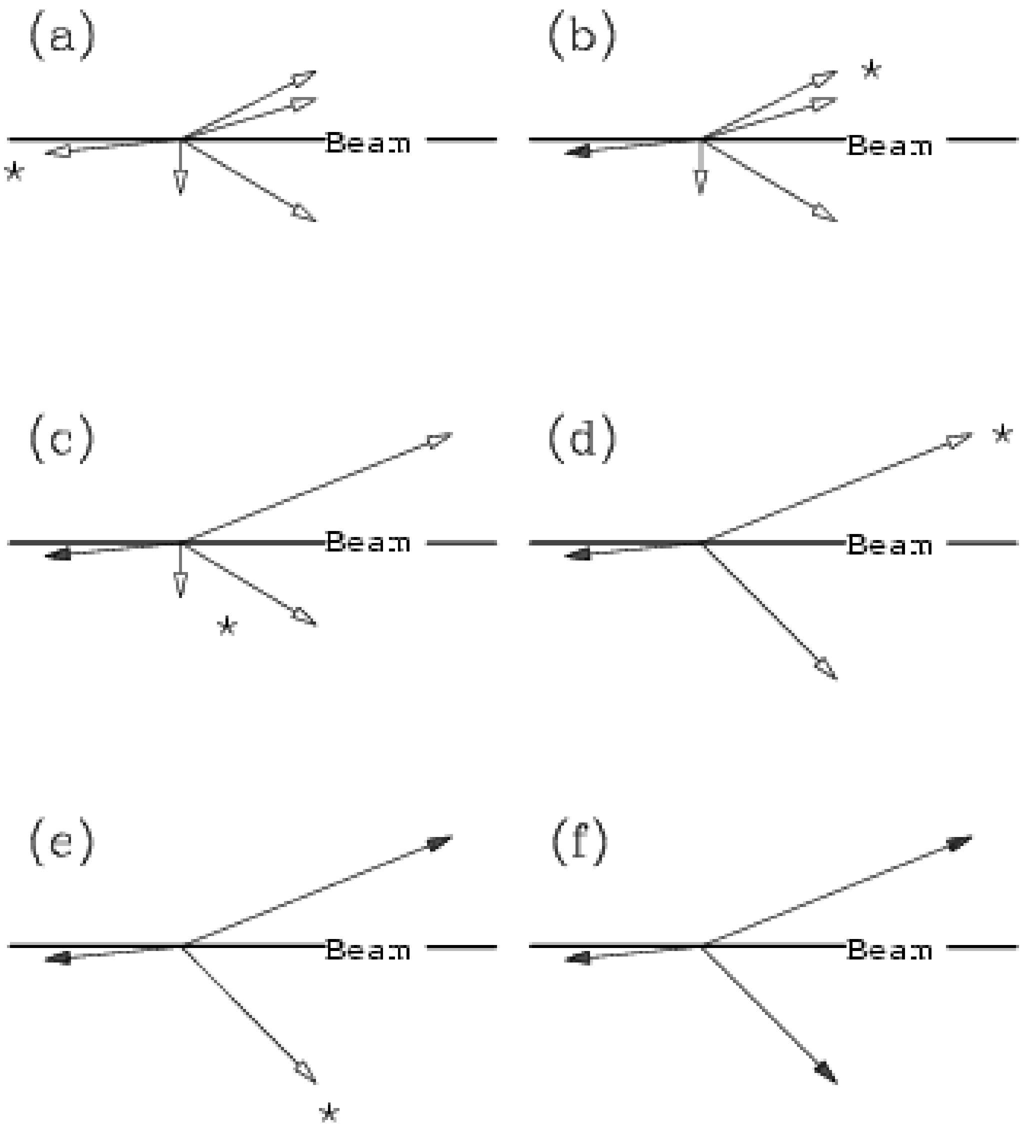
c) minimum of d_{ij}, d_i

→combine or remove from list)

d) iterate: goto b)

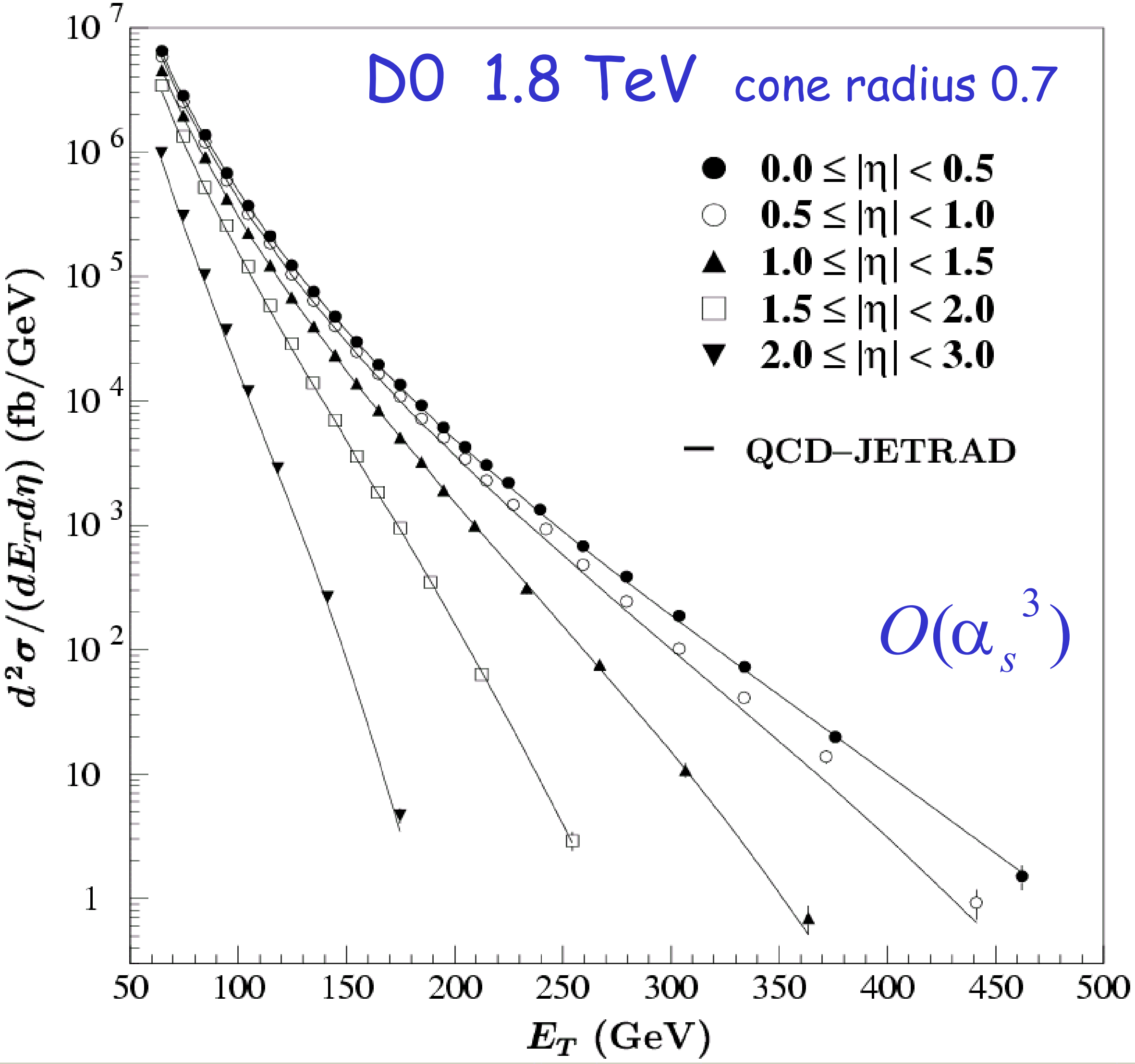
till list empty

Example:



... several variations exist

Inclusive jet production

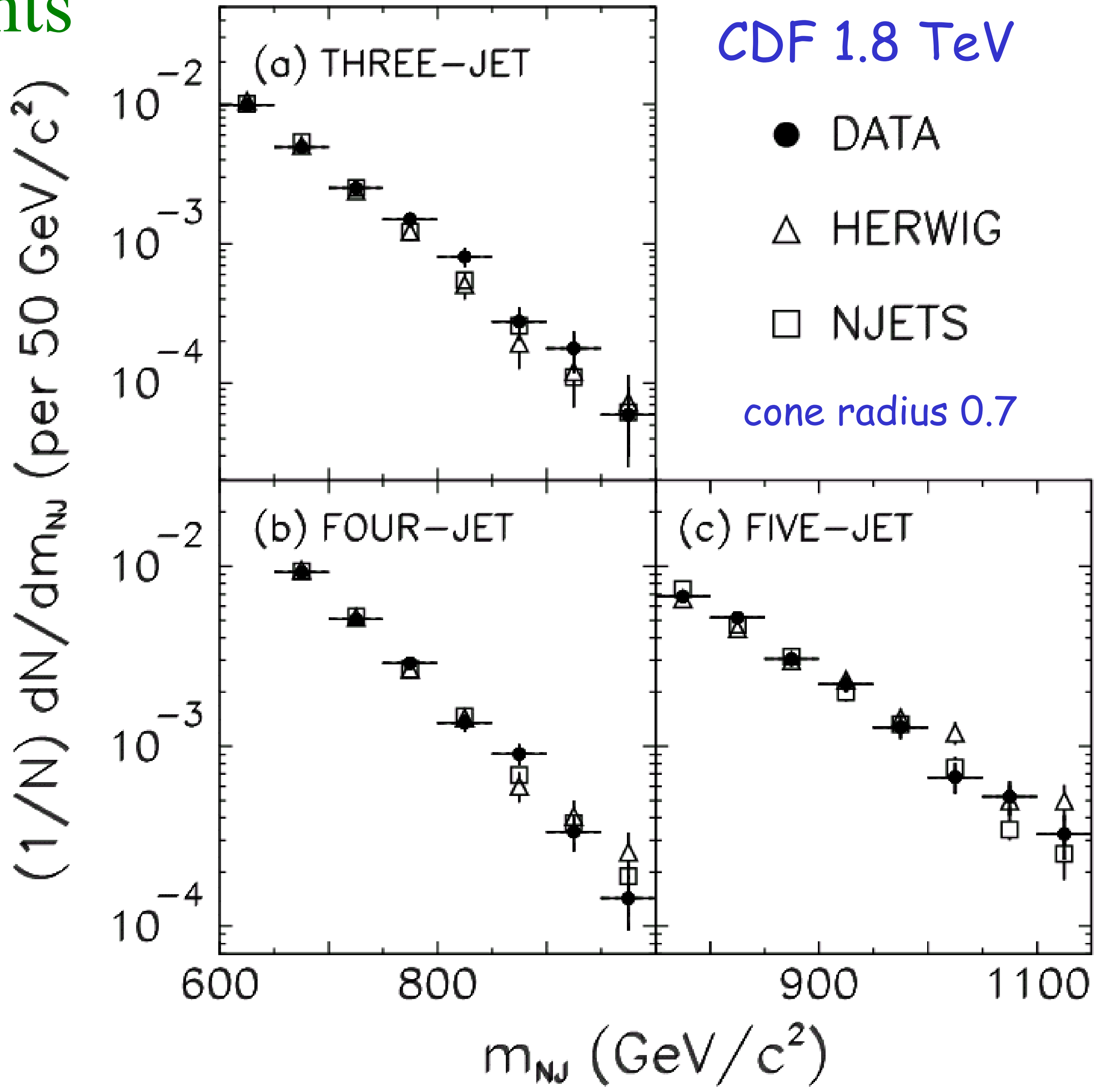


Conclusion: agreement with QCD over many orders of magnitude!

multijet events

Test
QCD

Measure alphas from relative fraction of events with 2,3,... jets



W and Z

measured at LEP
reference for W mass measurement

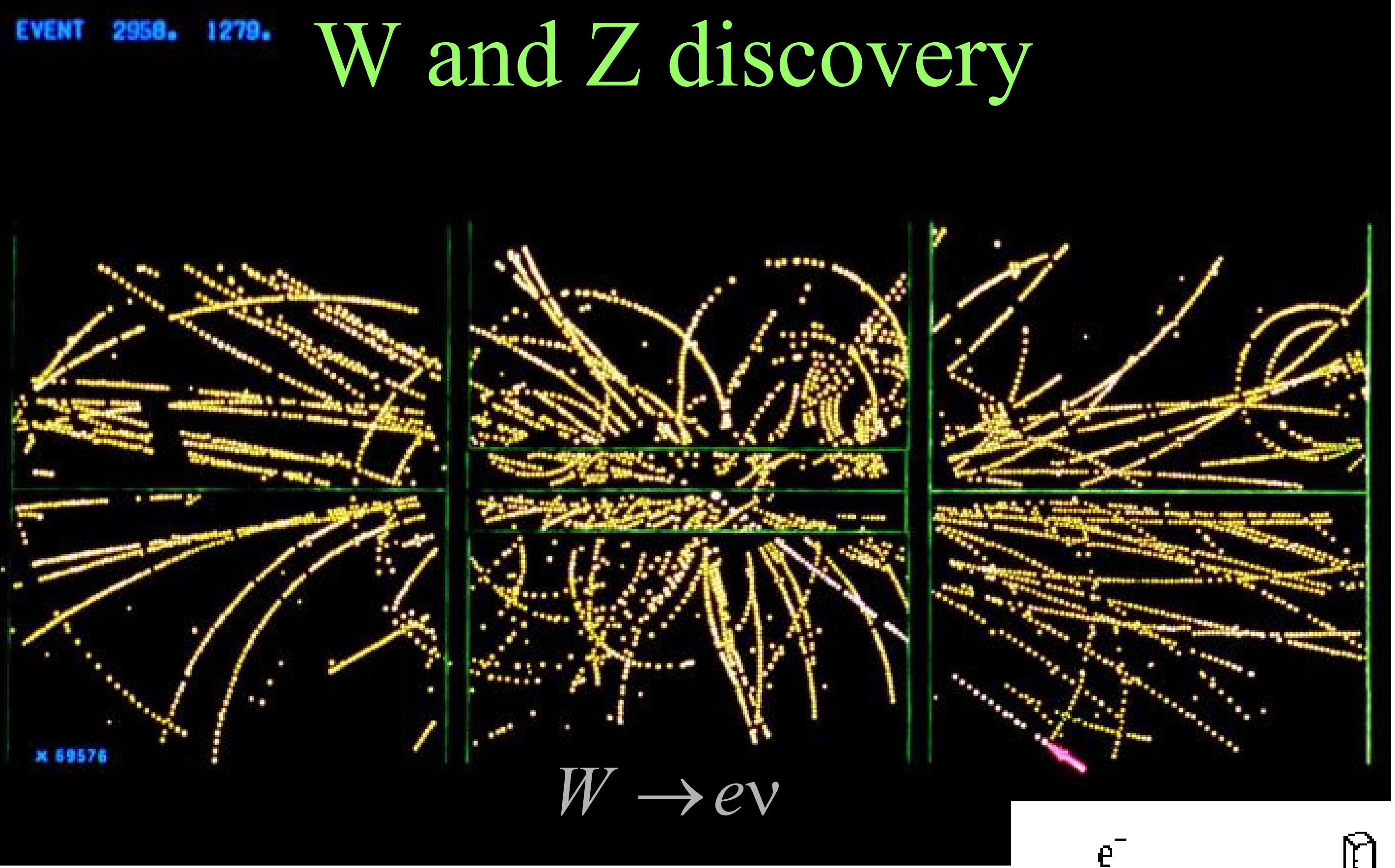
- production cross section
- decay modes
- W mass

$$\left(\frac{m_W}{m_Z}\right)^2 = \cos^2\theta_W = 1 - \sin^2\theta_W$$

Test of SM !

- W width
- ...

W and Z discovery

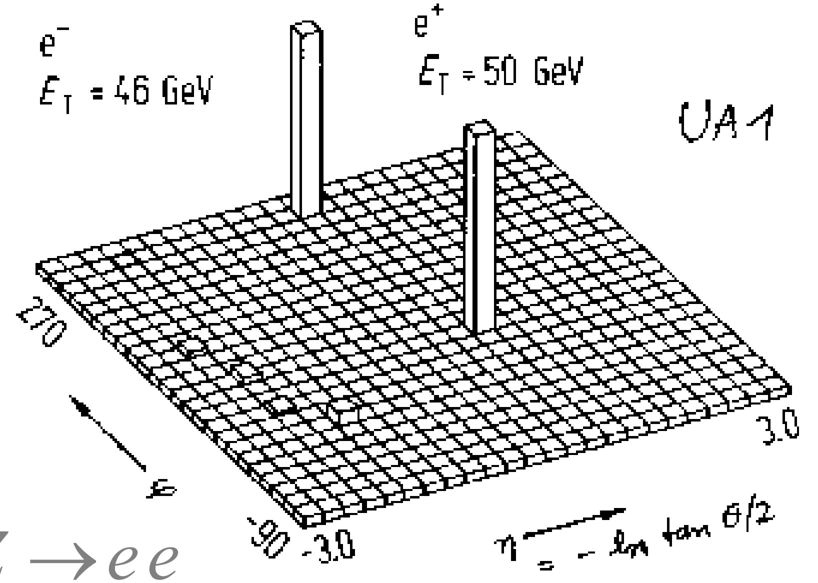


$W \rightarrow e\nu$

Discovery:

UA1, UA2

(1983)



$Z \rightarrow ee$

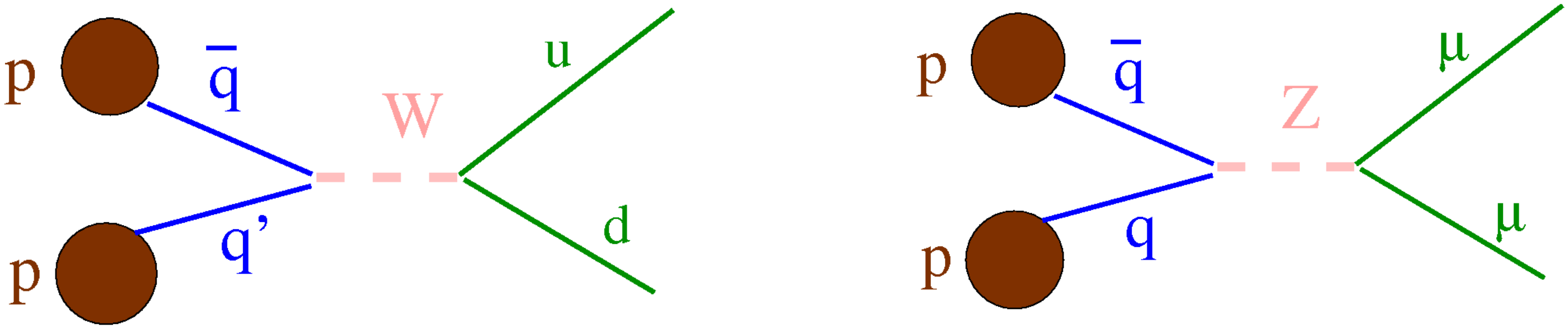
Precision measurement

Z mass at LEP:

91.1876 +- 0.0021 GeV

T.Hebbeker

W,Z: production and decay



W decay probability:

$$\boxed{Br \sim N_C}$$

$e\nu$	11%
$\mu\nu$	11%
$\tau\nu$	11%
ud	33%
cs	33%

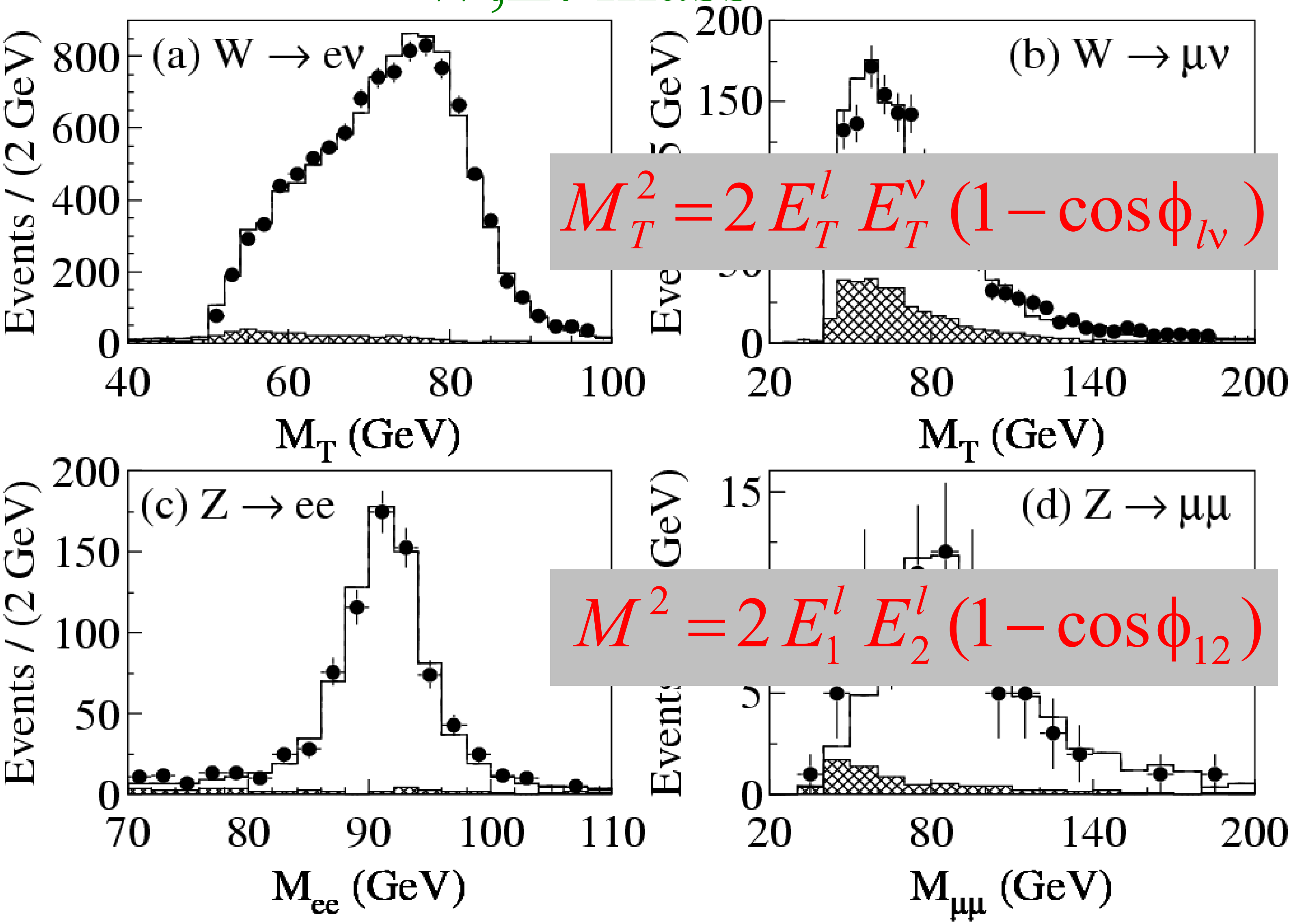
Clear signature

Z decay probability:

$$\boxed{Br \sim N_C(g_V^2 + g_A^2)}$$

$e\,e$	3%
$\mu\,\mu$	3%
$\tau\,\tau$	3%
$uu + dd + ss + cc + bb$	70%
$\nu\nu$	20%

W,Z: mass



$$M_T^2 = 2\,E_T^l\,E_T^\nu\,(1-\cos\phi_{l\nu})$$

$$M^2 = 2\,E_1^l\,E_2^l\,(1-\cos\phi_{12})$$

D0 1.8 TeV

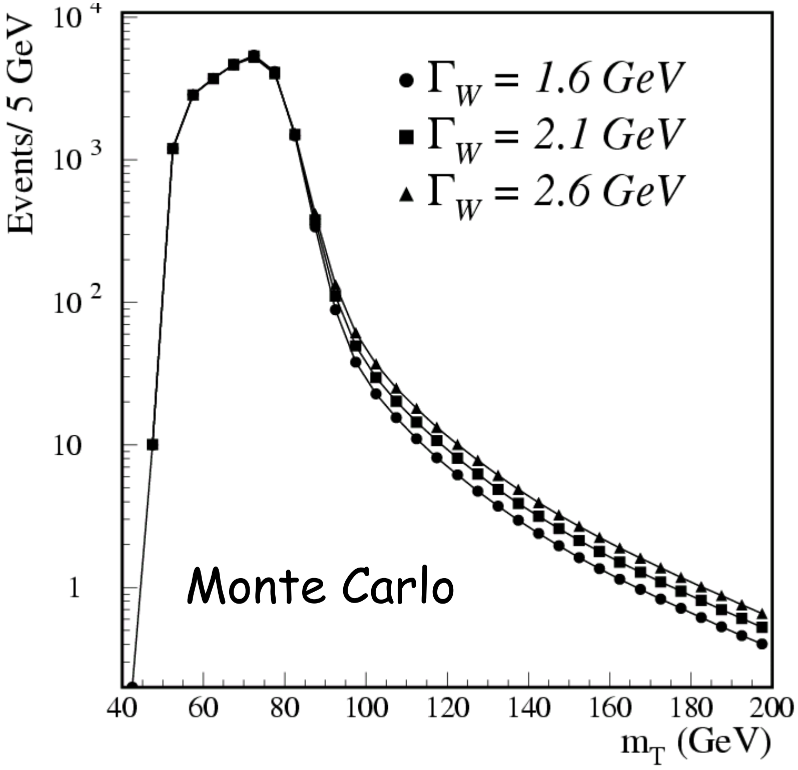
Tevatron combined: $\boxed{80.456 \pm 0.059\,GeV}$

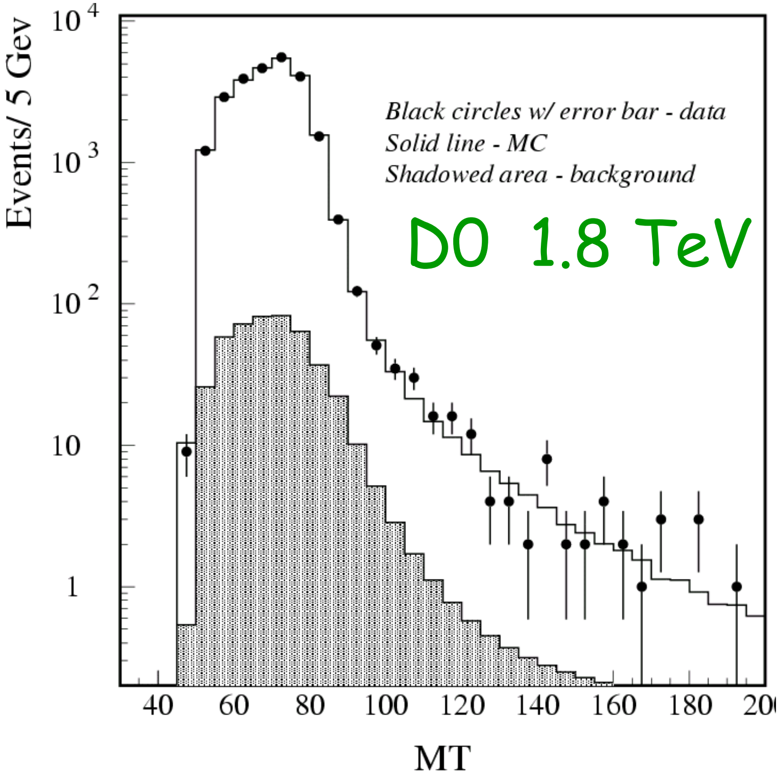
Run I

LEP: $\pm 0.042\,GeV$

LHC: $\pm 0.015\,GeV$

W: width

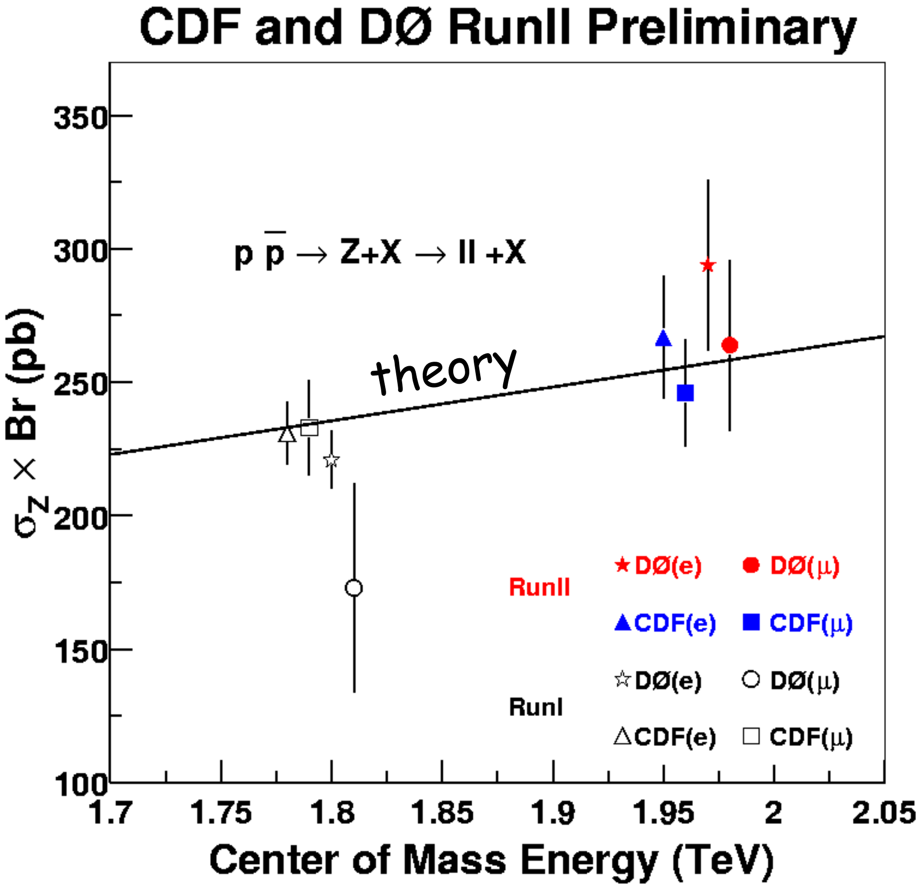


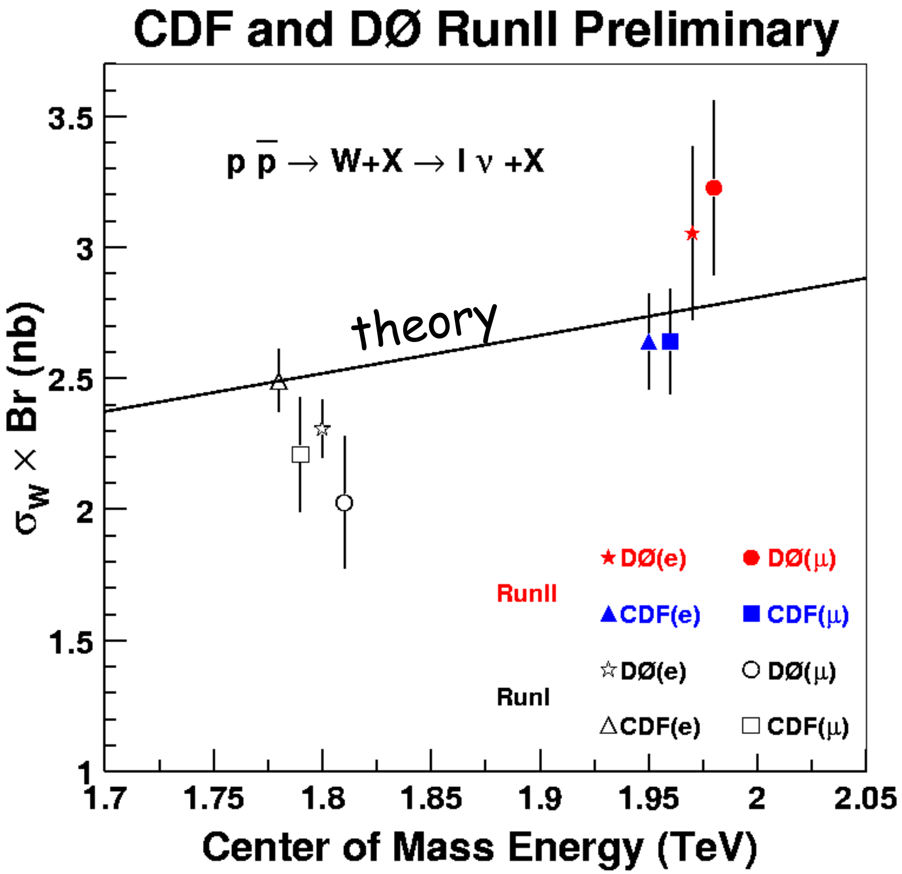


... difficult...

Tevatron combined: $2.160 \pm 0.047\, GeV$ (indirect+direct)

W,Z: production cross section

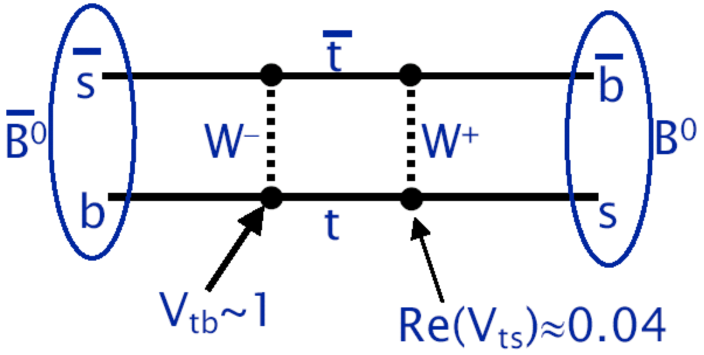




pp-physics with charm and bottom

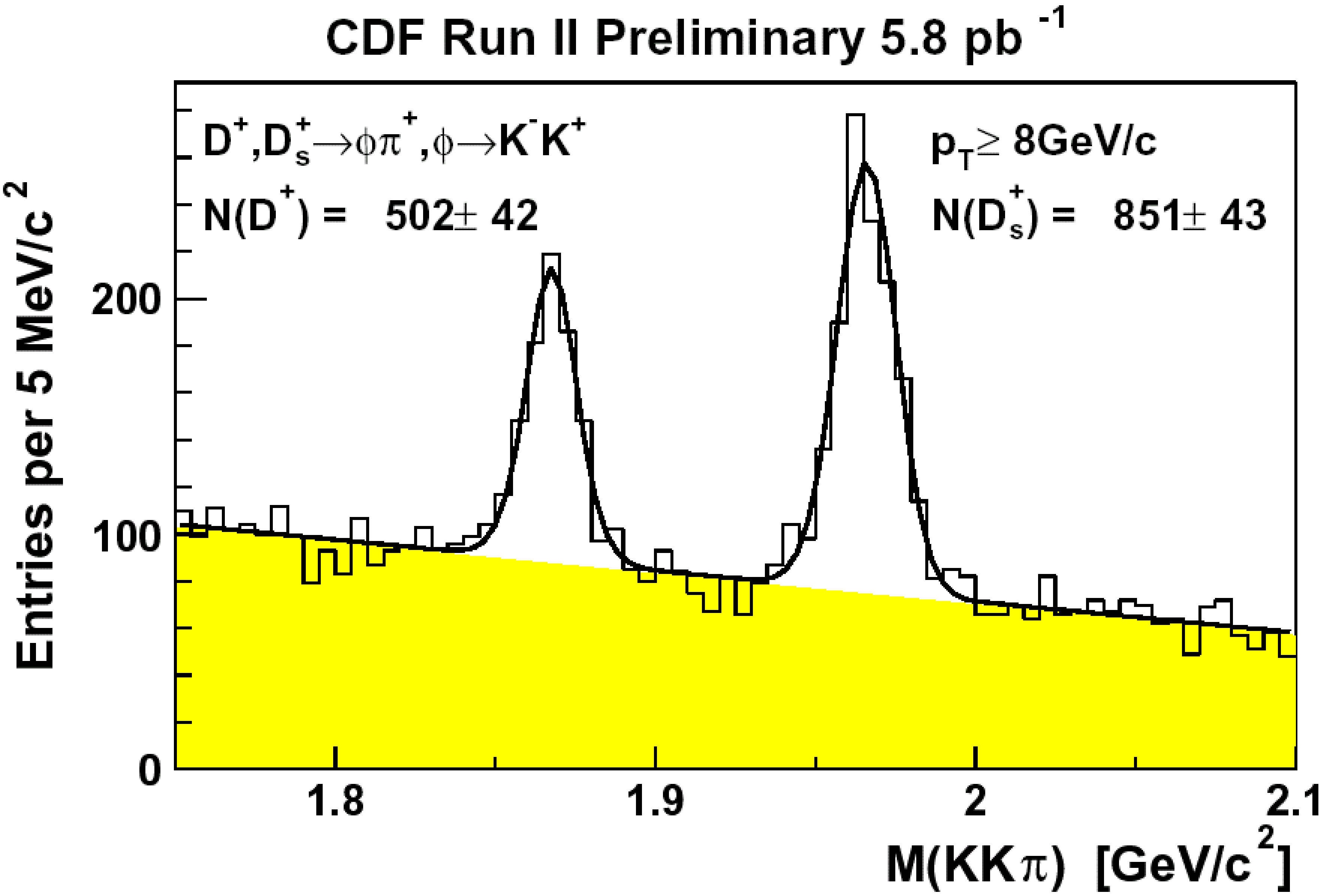
cross section huge !

- cross section
- new mesons/baryons/hybrids/... ?
- hadron masses
- hadron lifetimes
- branching fractions (rare decays ?)
- B_s^0 mixing



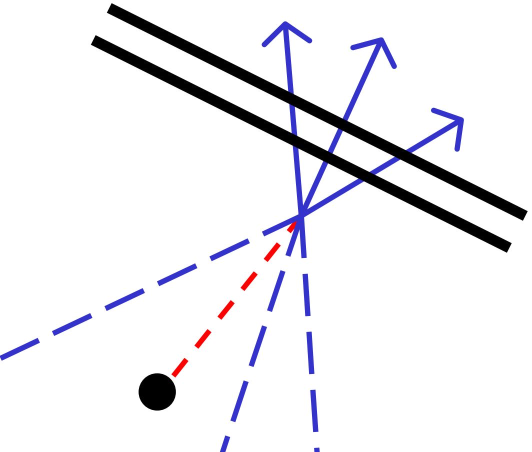
- CP violaton

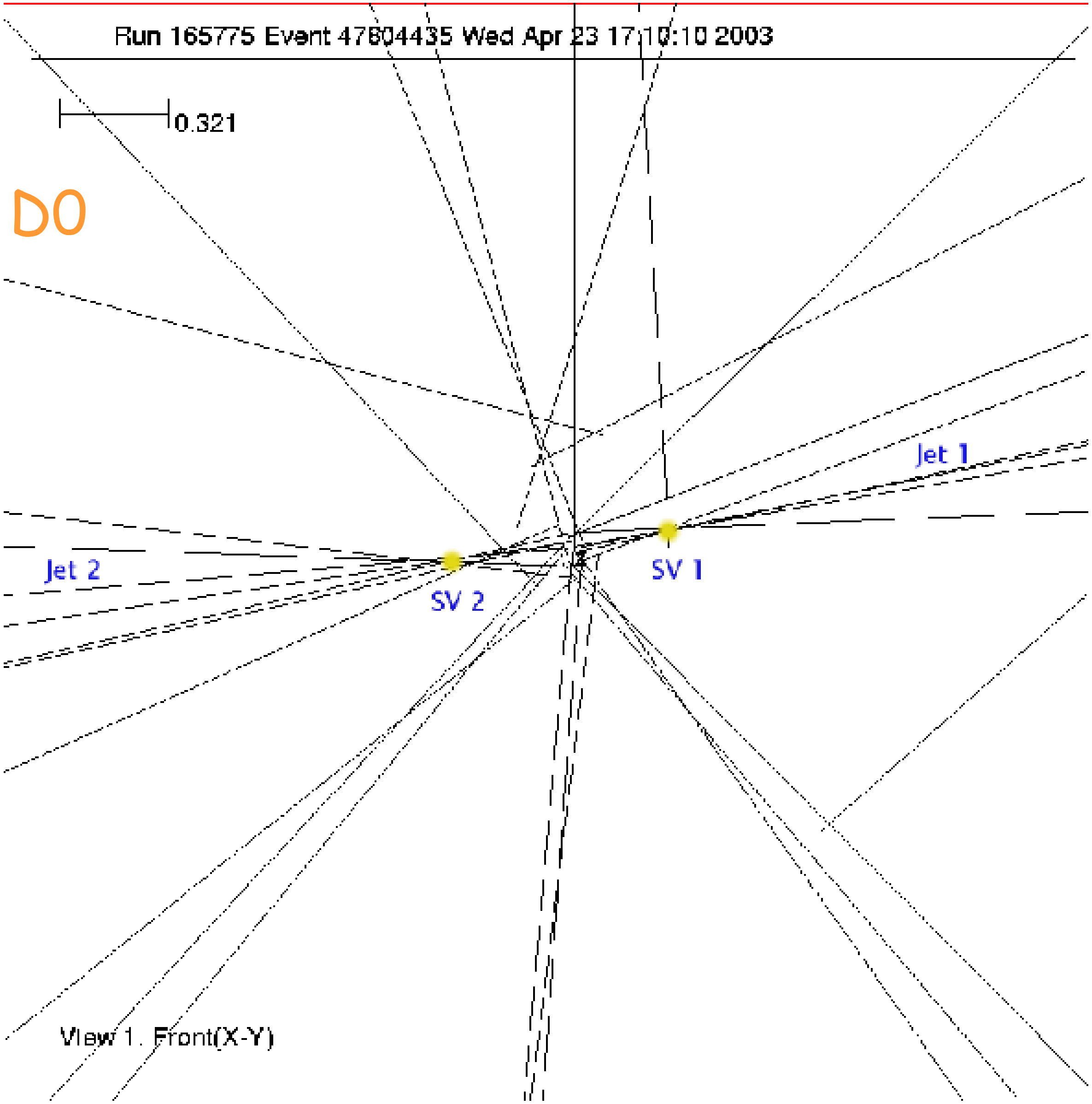
Example: D meson masses



Reconstruction of decay vertices

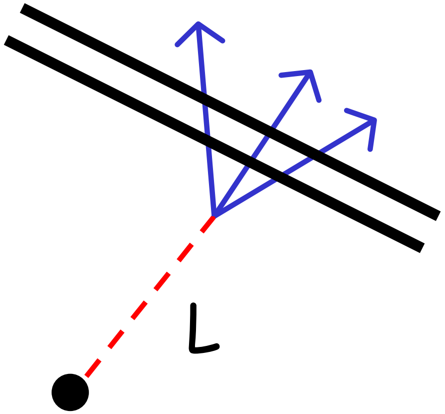
$$Z \rightarrow b\bar{b}$$





Example:

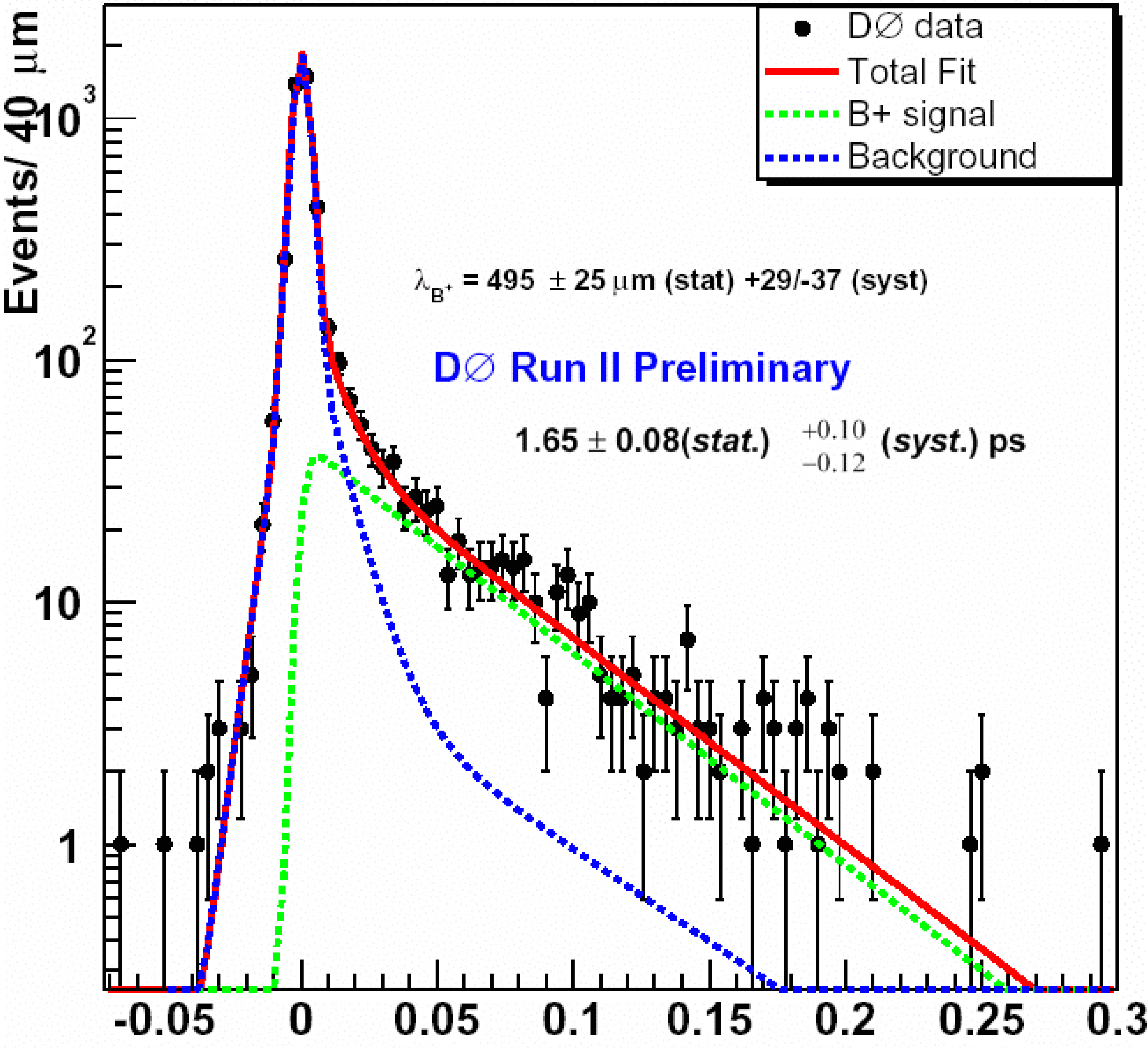
B^+ Lifetime $115 pb^{-1}$



decay length:

Lab frame:

$$L = ct\,\beta\gamma$$



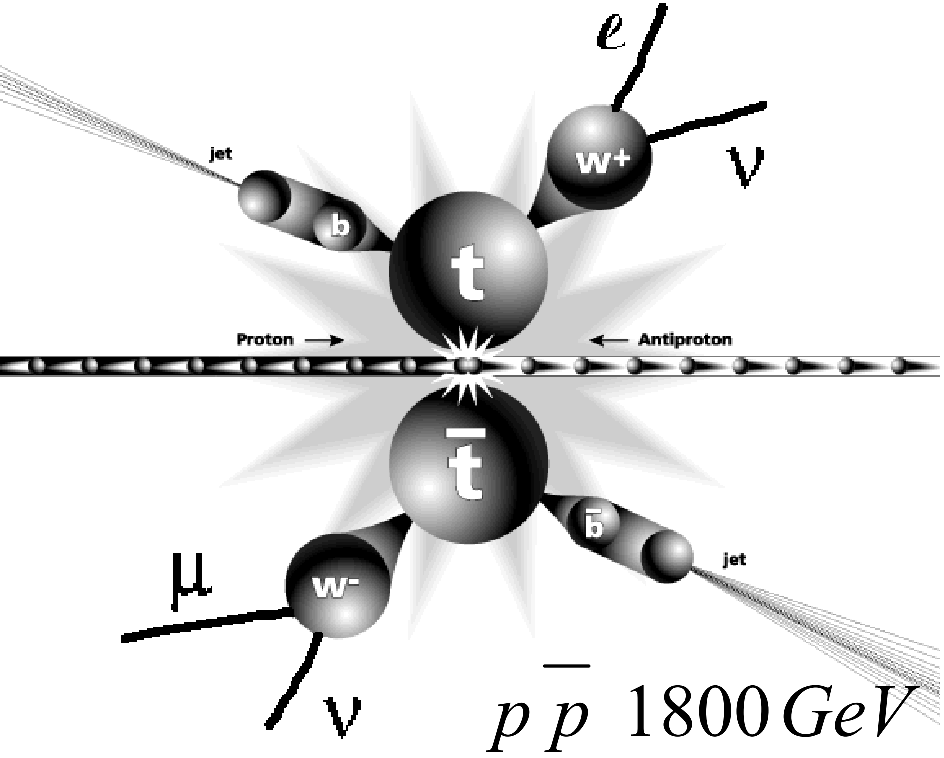
cm

decay length $L/(\beta\gamma)$

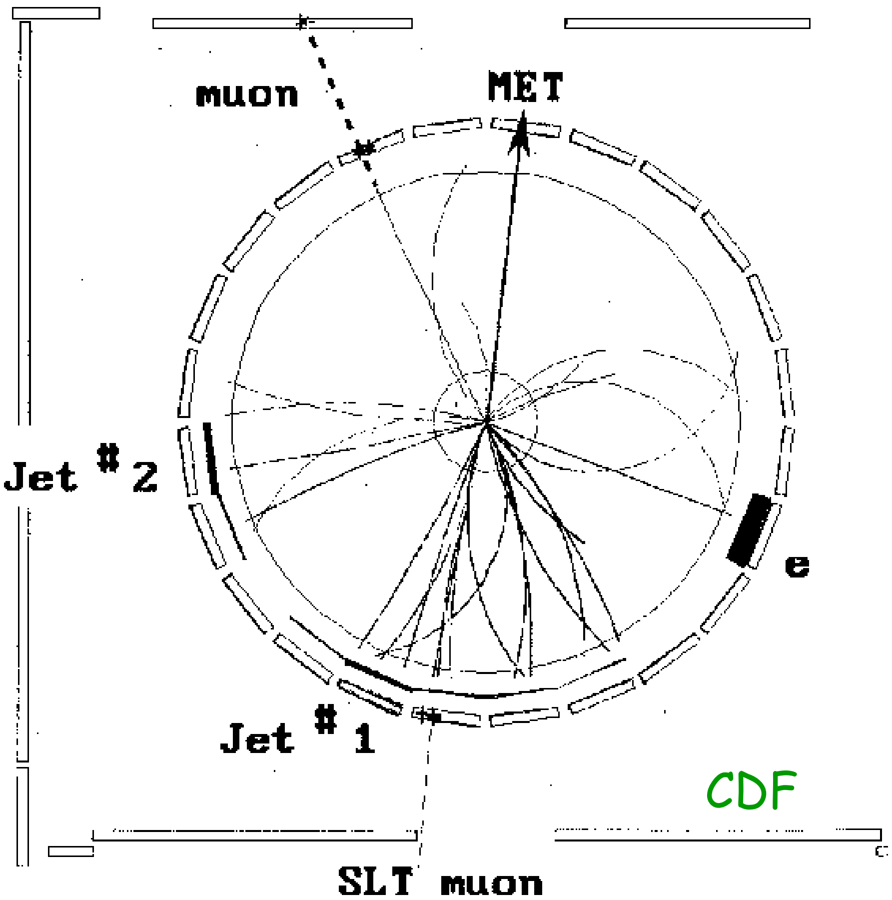
Top Discovery

Fermilab, 1995

CDF, D0



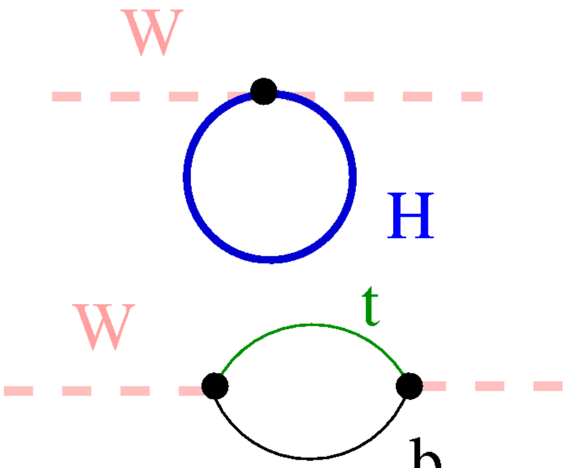
$p\,\overline{p}\ \ 1800\,GeV$

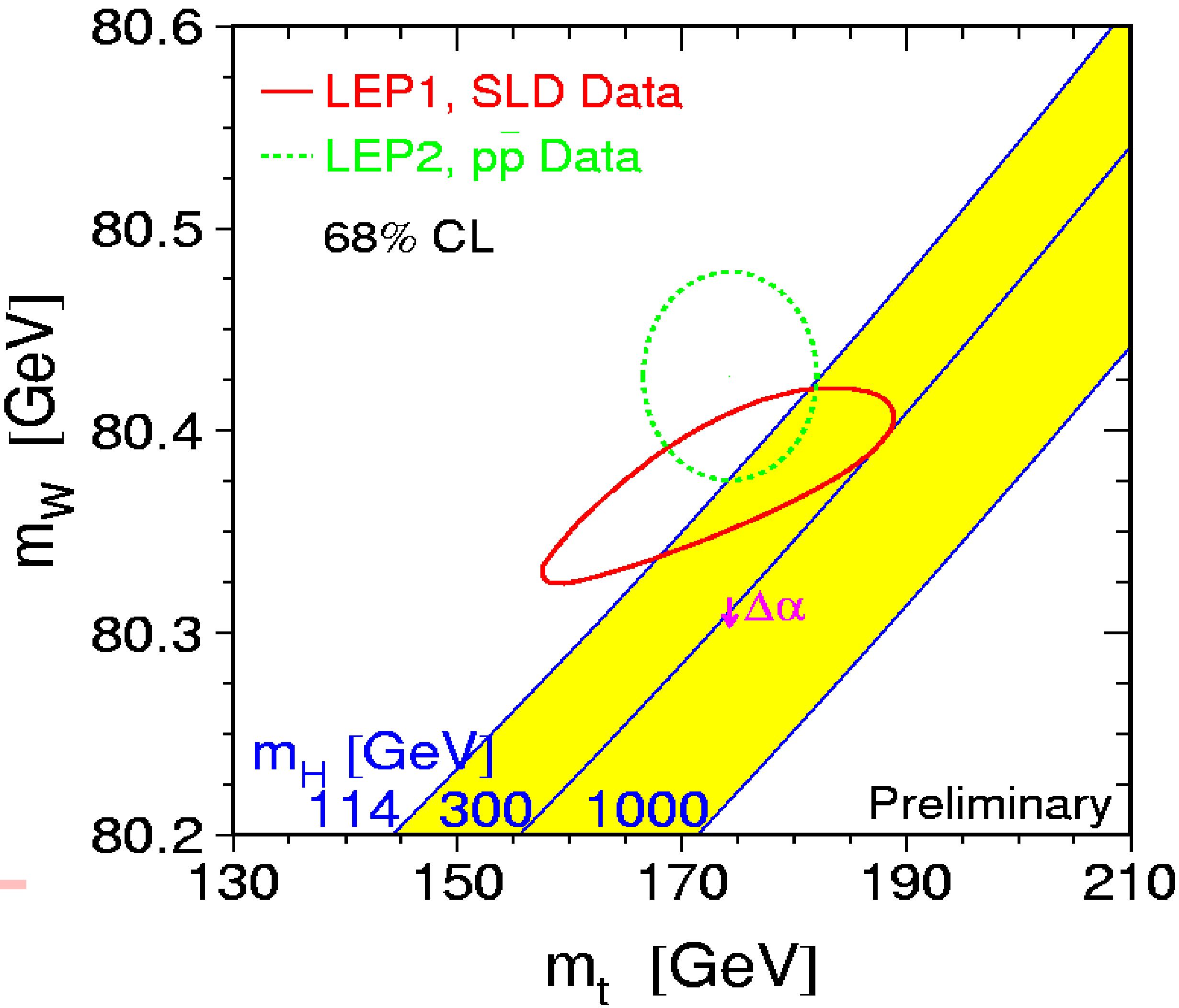


m ~ 175 GeV

Top Physics

- cross section
- decay modes
- top mass
- ...





$$m_W = \left(\frac{\pi\,\alpha}{\sqrt{2}G_F}\right)^{1/2} \cdot \frac{1}{\sin\theta_W \sqrt{1-\Delta r(m_t, \ln m_H)}}$$

Top Identification

cross section small (at 2 TeV)

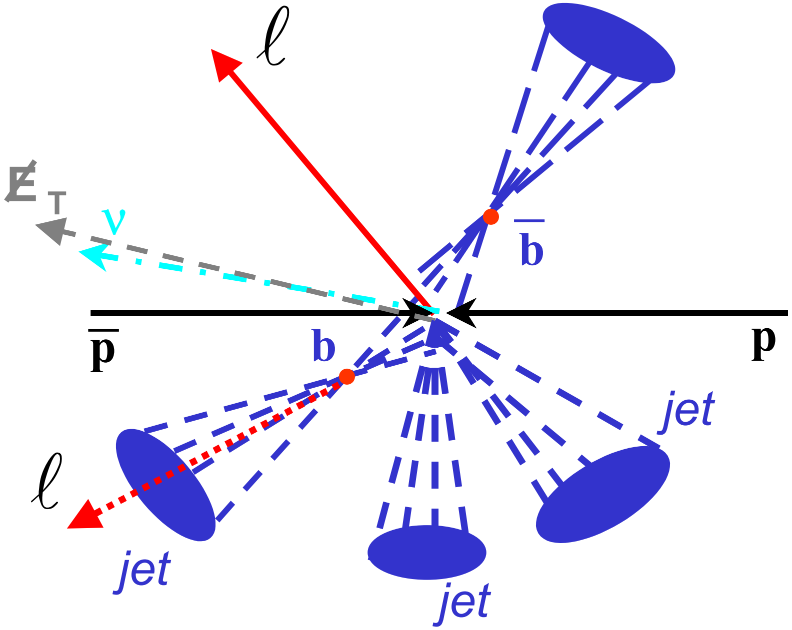
production:

$$p\,\bar{p} \rightarrow t\,\bar{t}$$

decay:

$$t \rightarrow W\,b$$

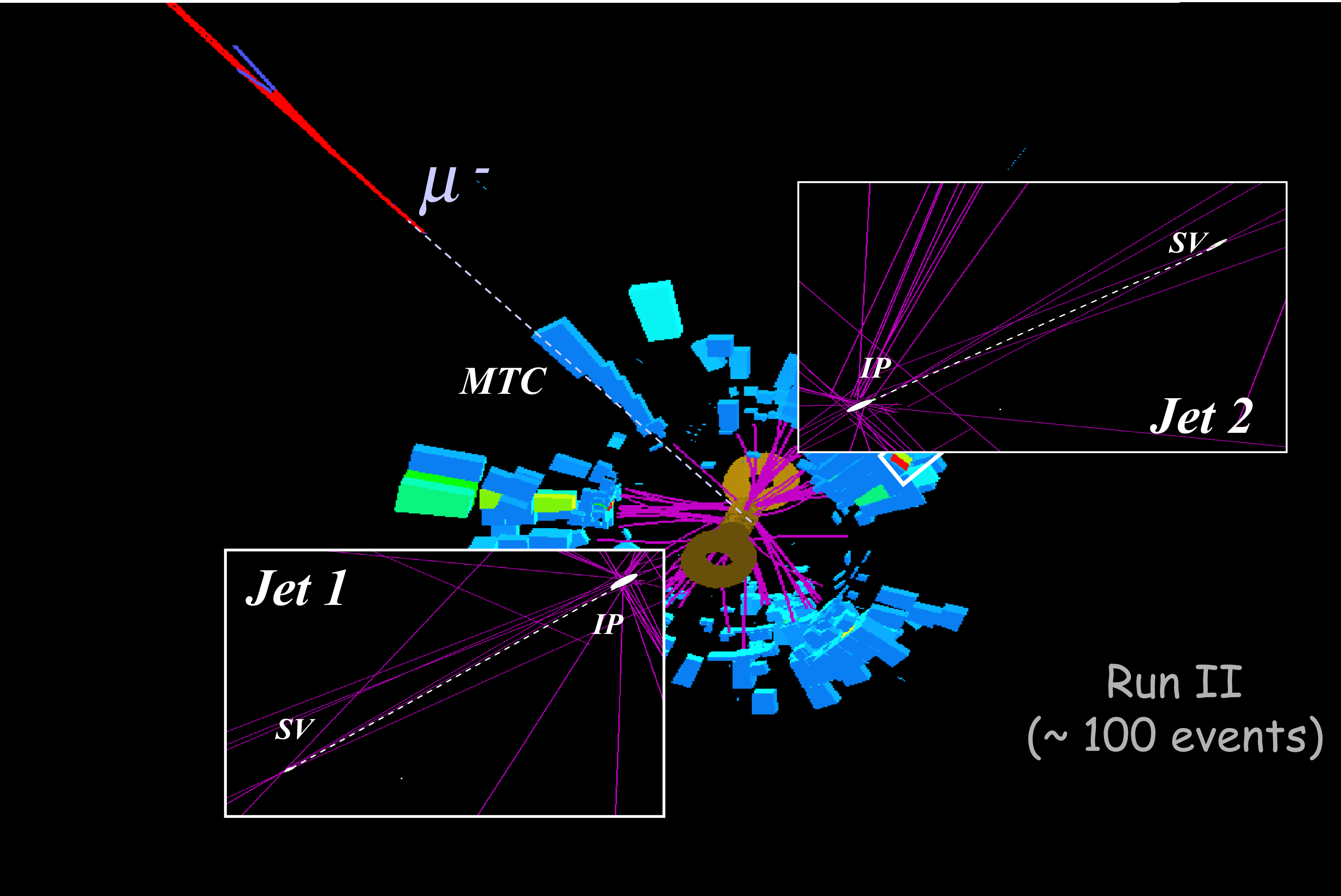
$$W \rightarrow q\,q, l\nu$$



Signature:

2 b jets
+ leptons/jets/missing energy

Top event in D0

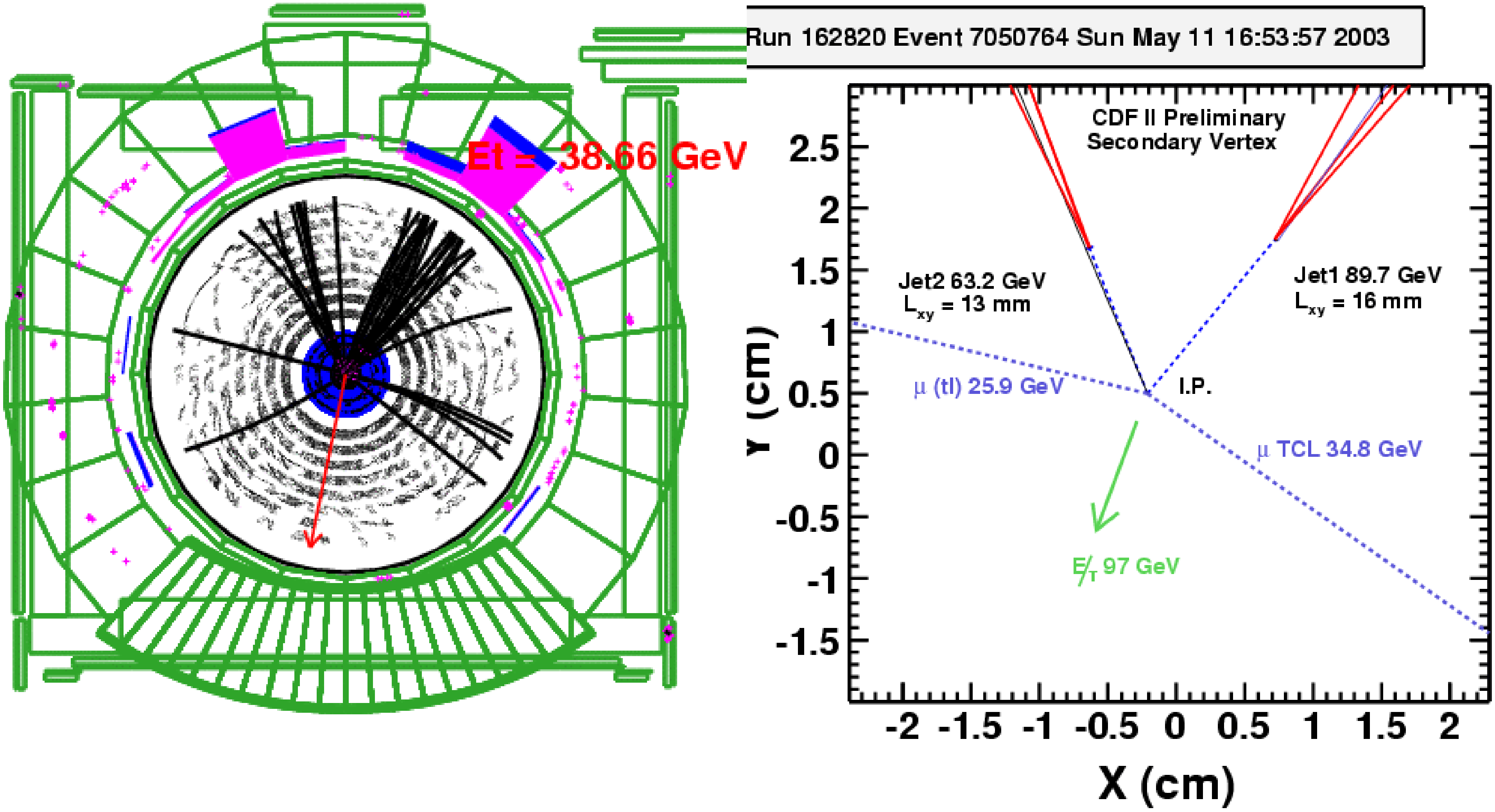


Run II
(~ 100 events)

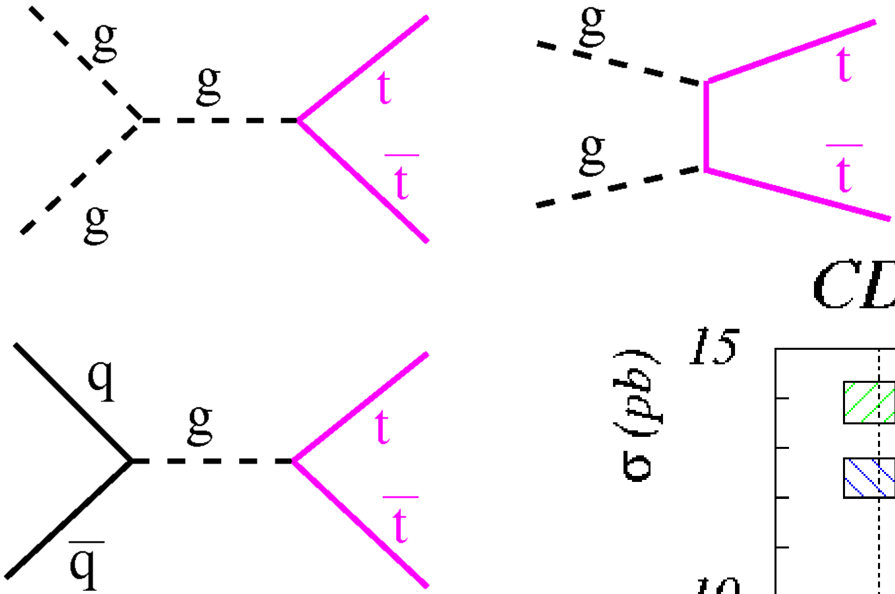
Top event in CDF

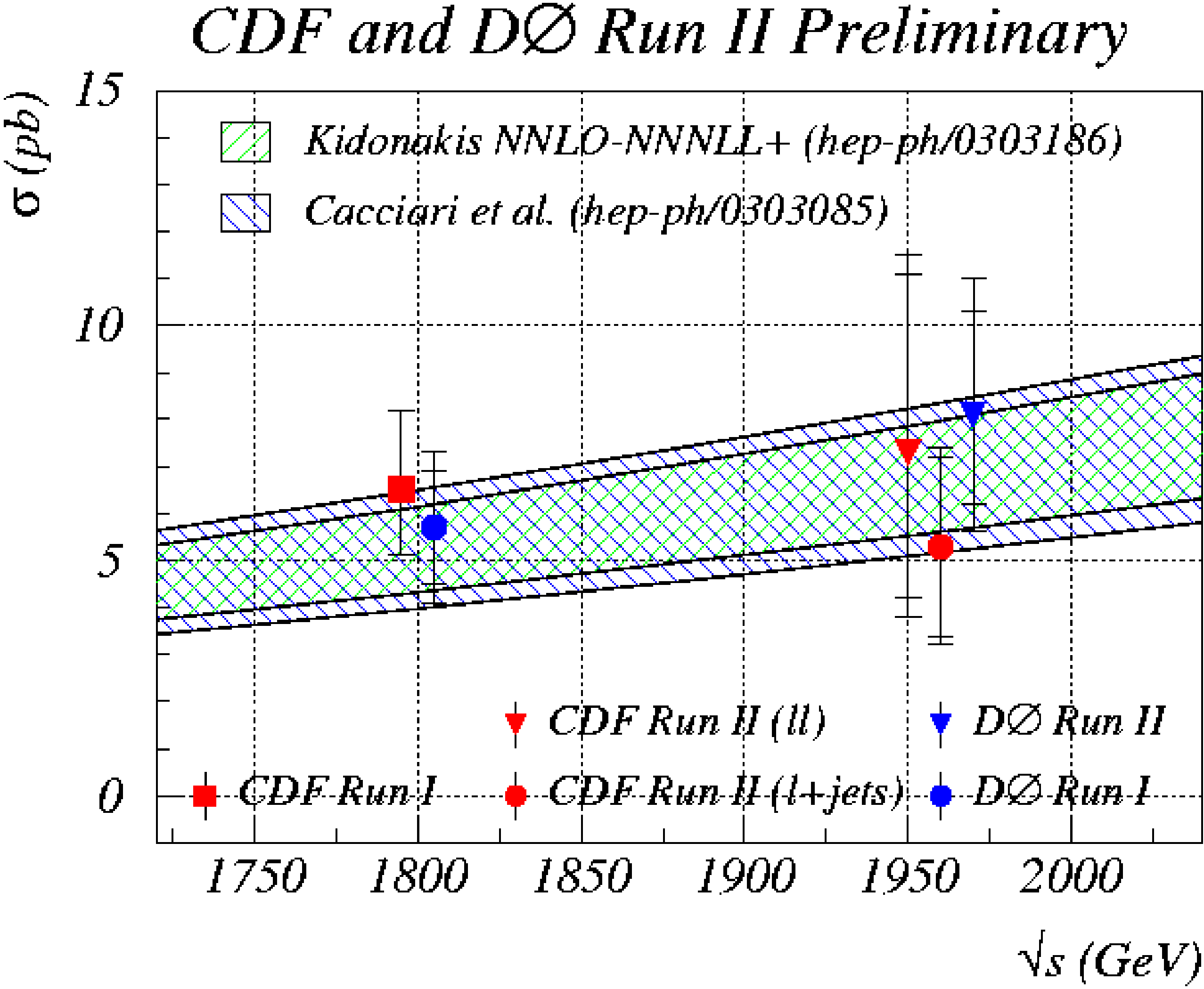
Run II

(~ 100 events)



Top Pair Production

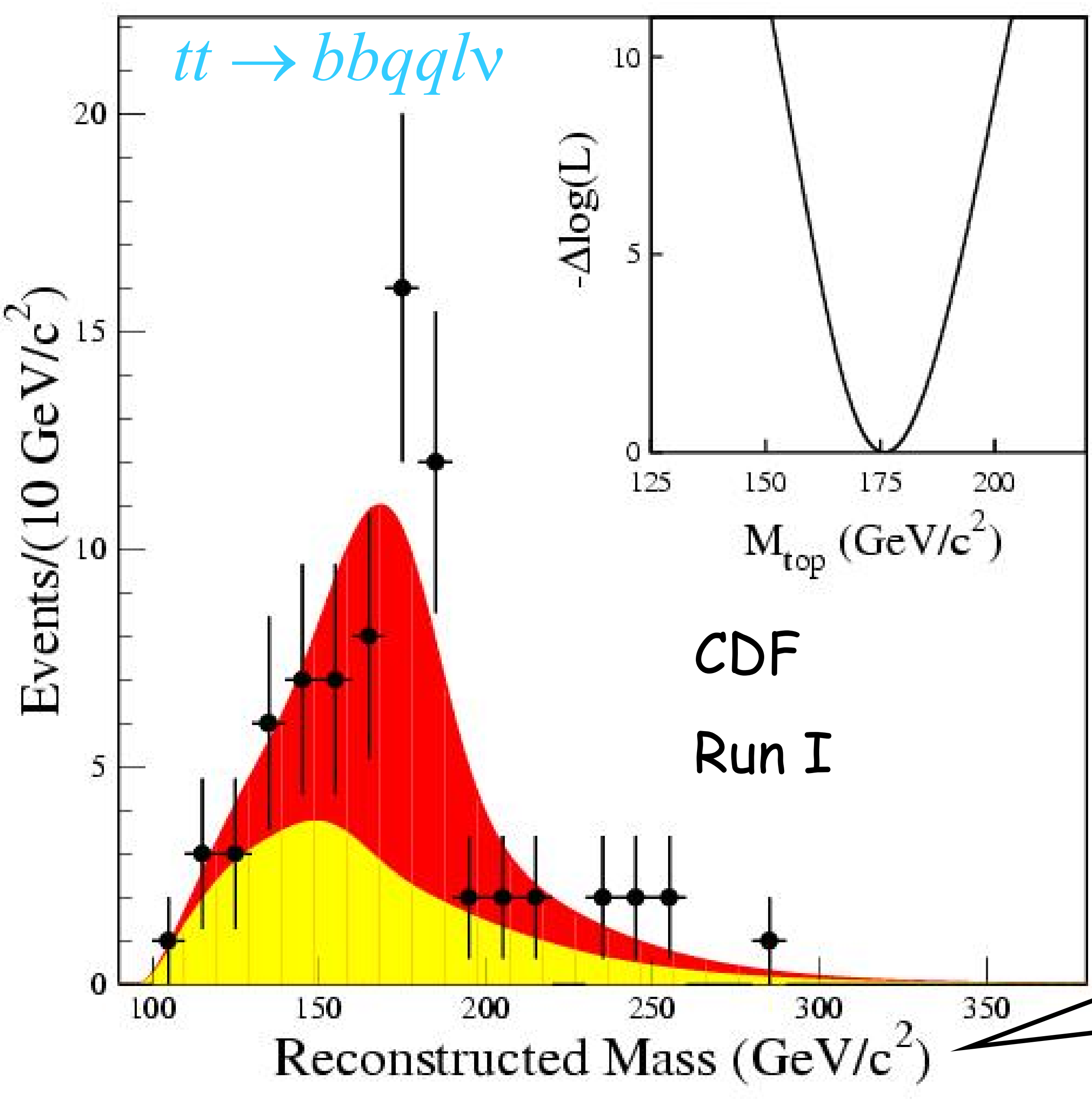




gg contributes

- 15% at 2 TeV
- 95% at 14 TeV

Top Mass



Tevatron Run I

CDF + D0:

$$174.3 \pm 5.1 GeV$$

LHC: +- 1 GeV

Using mass constraints

$W \to l\nu$ ...

Part I Introduction

Part II Standard Model Physics

- cross section calculation
- QCD and jets
- W and Z
- charm and bottom
- top

Part III Higgs

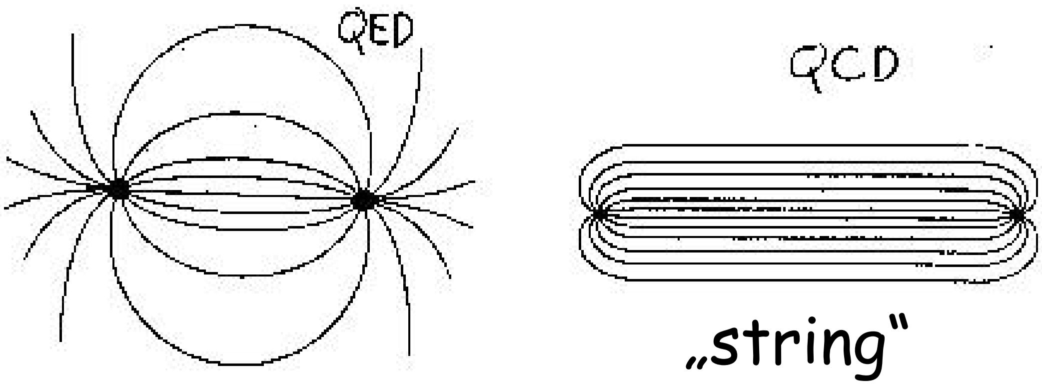
Part IV New Phenomena

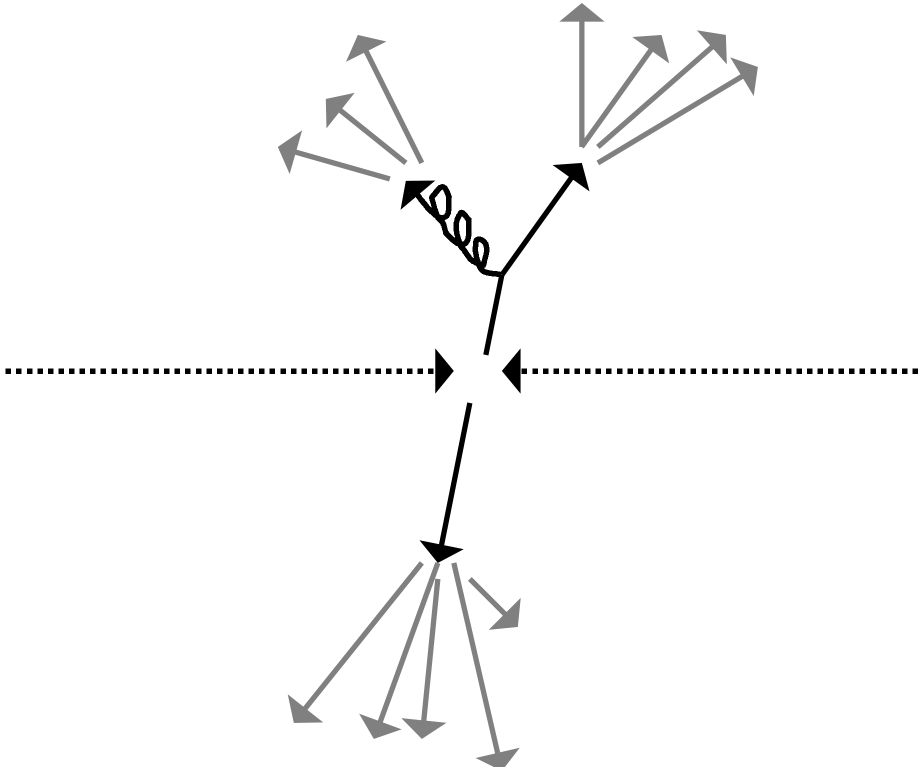
References

Appendices

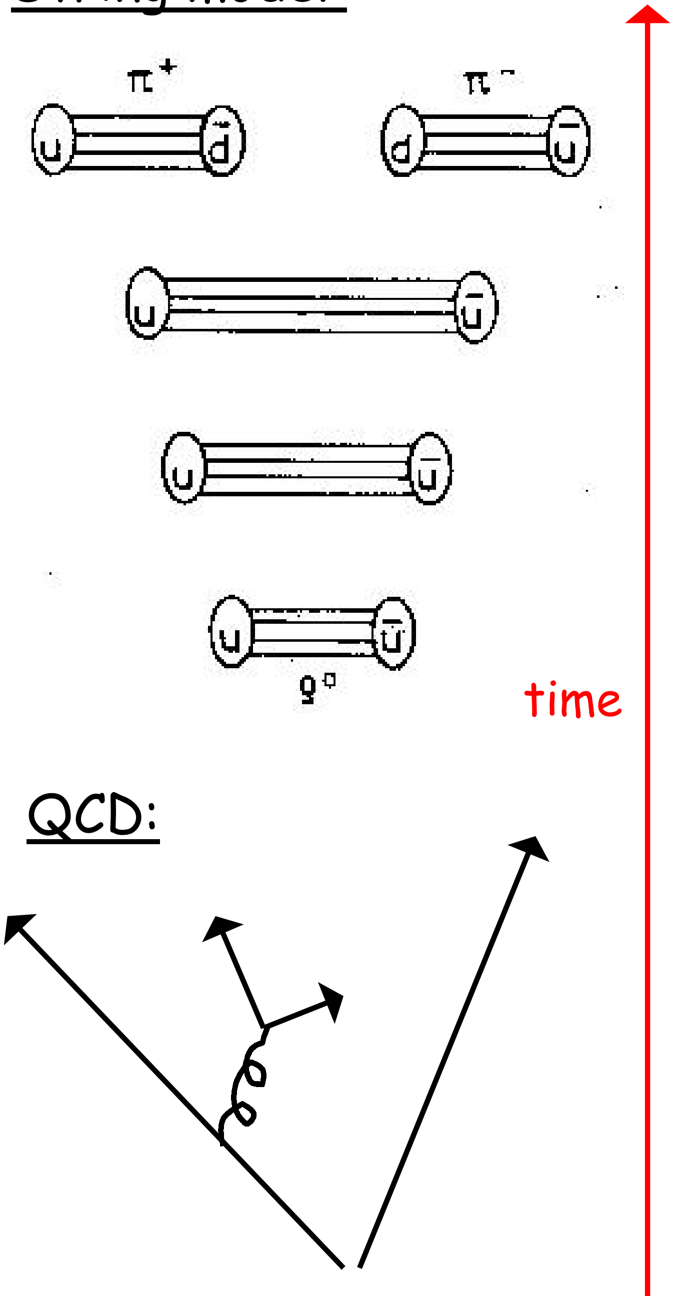
T.Hebbeker

Hadronization





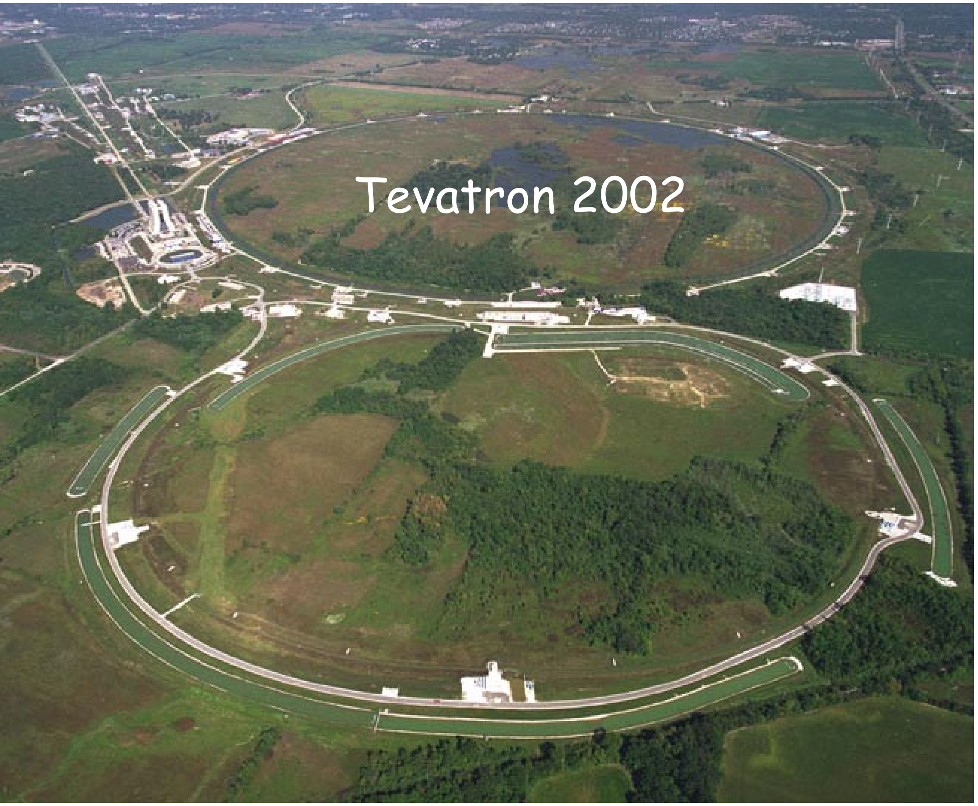
String model:



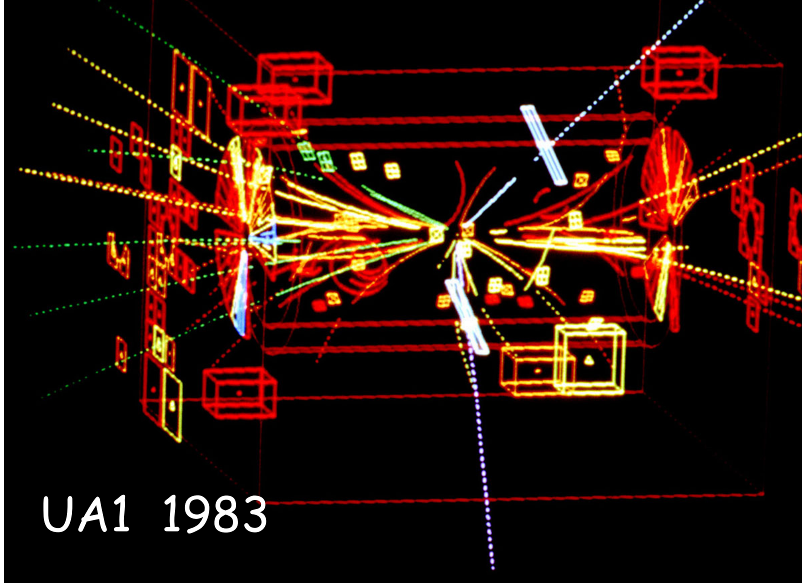
Thomas Hebbeker, RWTH Aachen
Belgian-Dutch-German school
September 2003

part III

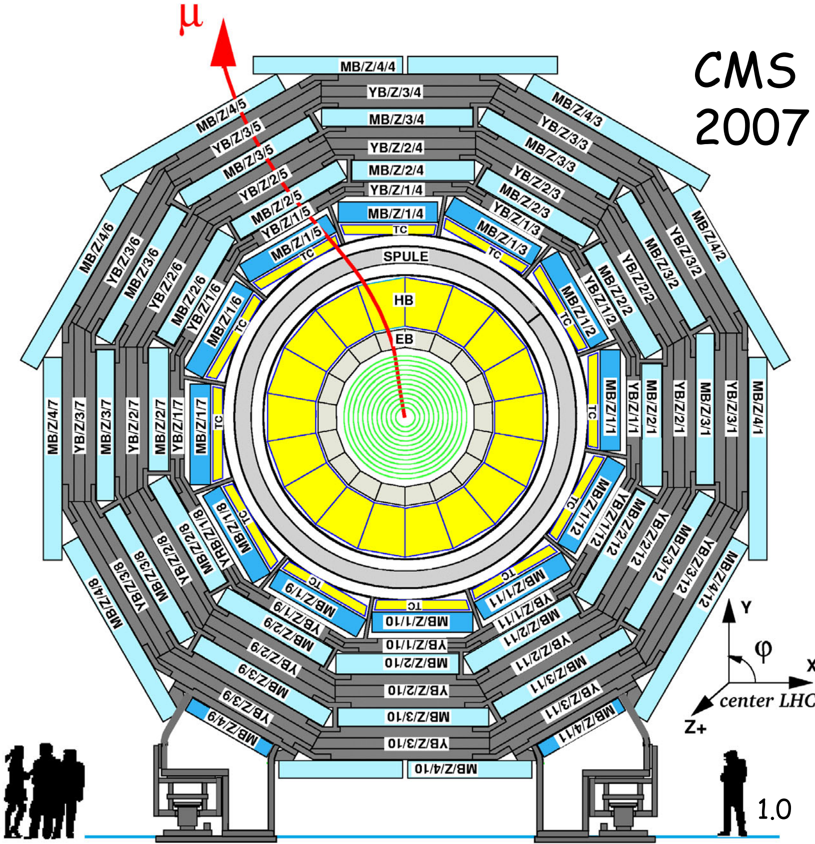
pp physics



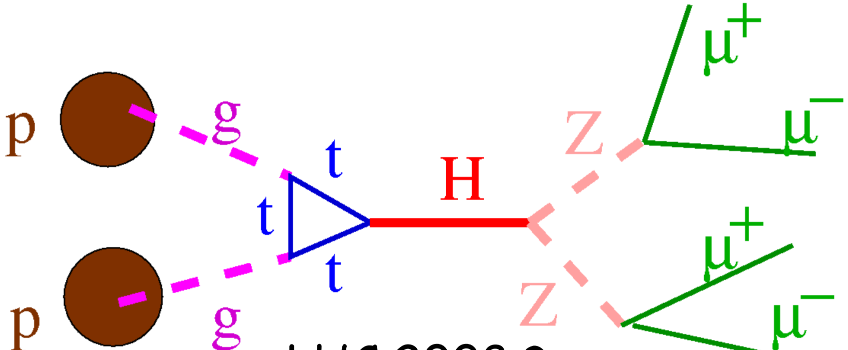
Tevatron 2002



UA1 1983



CMS 2007



LHC 2008 ?

Part I Introduction

Part II Standard Model Physics

Part III Higgs

- SM higgs:
  what do we know ?
  production and decay
  detection
- extended higgs models

Part IV New Phenomena

References

The SM Higgs

Known (if exists):

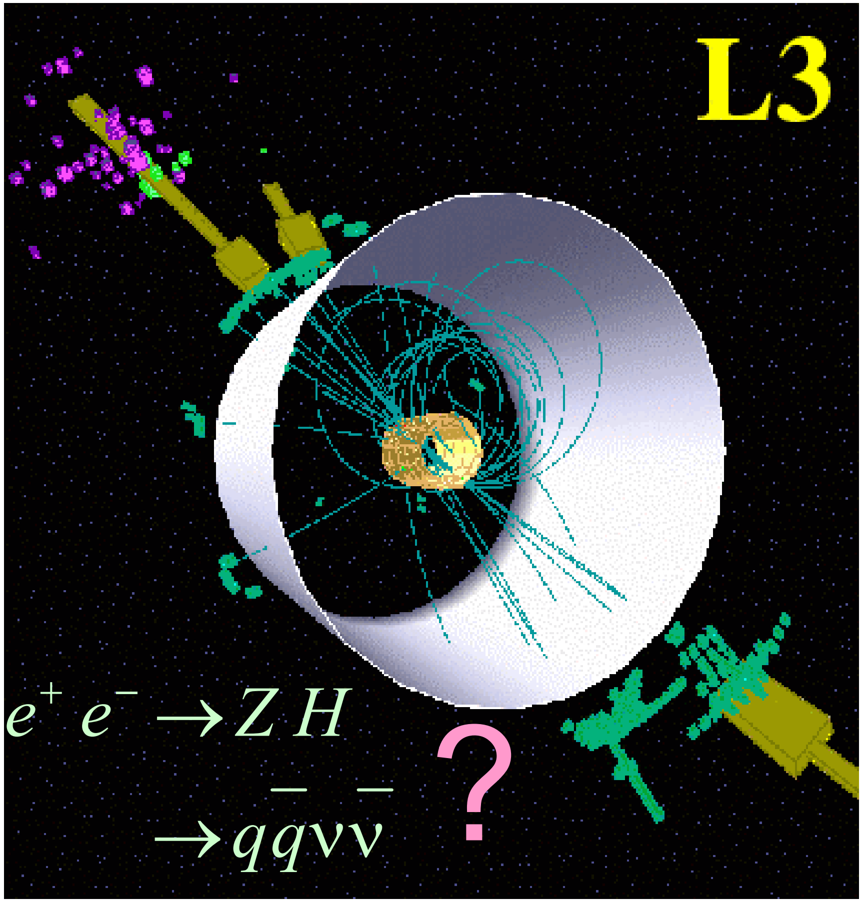
- couples to mass (!): bosons and fermions
- scalar, no elm. or strong interactions
- properties calculable as a function of m_H
- LEP: 114 GeV < m_H < 219 GeV (95%)

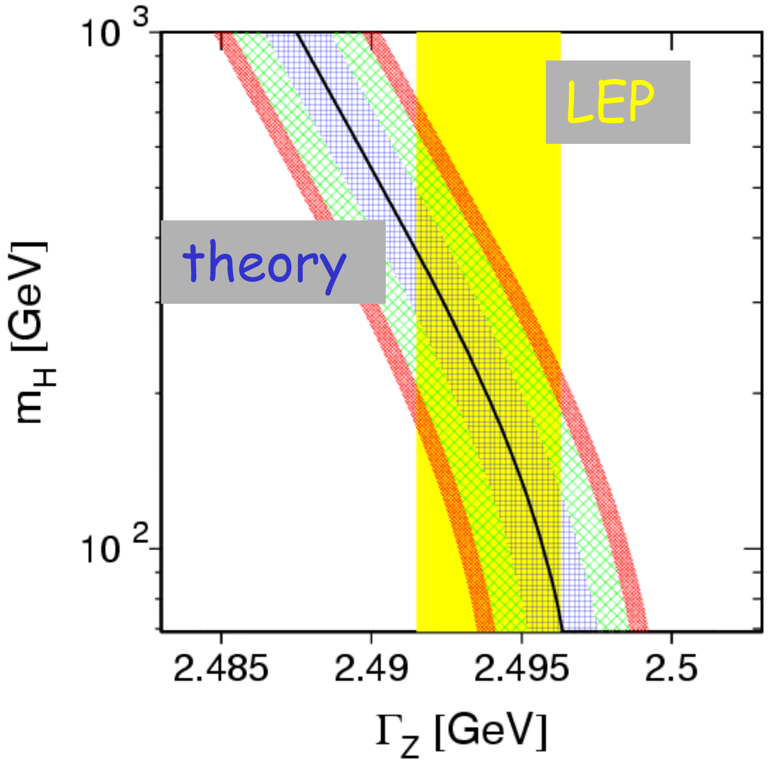
To be explored:

- existence ? produce and detect !
- properties ? precise measurements $\longrightarrow$ $e^+ e^-$ collider

Historical reminiscence: LEP and Higgs

direct | indirect





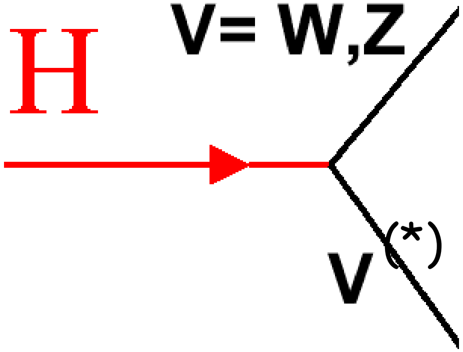
$$\boxed{m_H > 114\,GeV}$$ (95%)

(LEP)

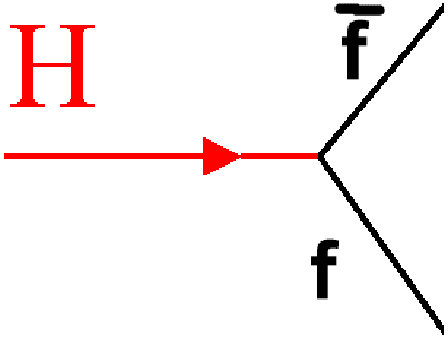
$$\boxed{m_H < 219\,GeV}$$ (95%)

(LEP, SLD, Tevatron, NuTeV...)

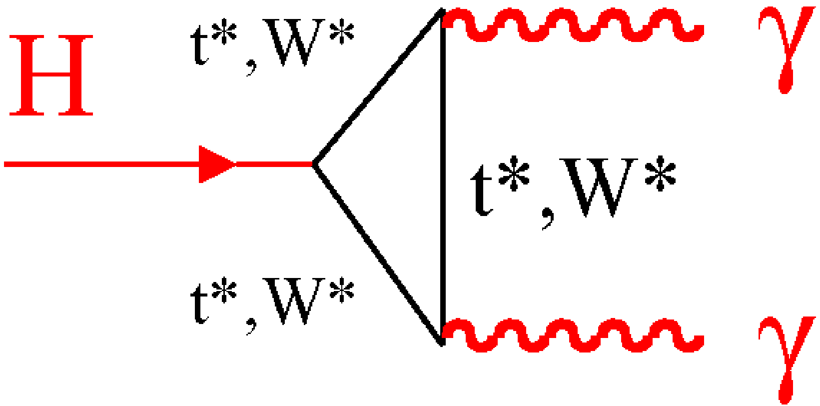
Higgs Decay Modes



$$\boxed{\Gamma(H\to VV)\to G_F\,\enclose{circle}{m_H^3}}$$



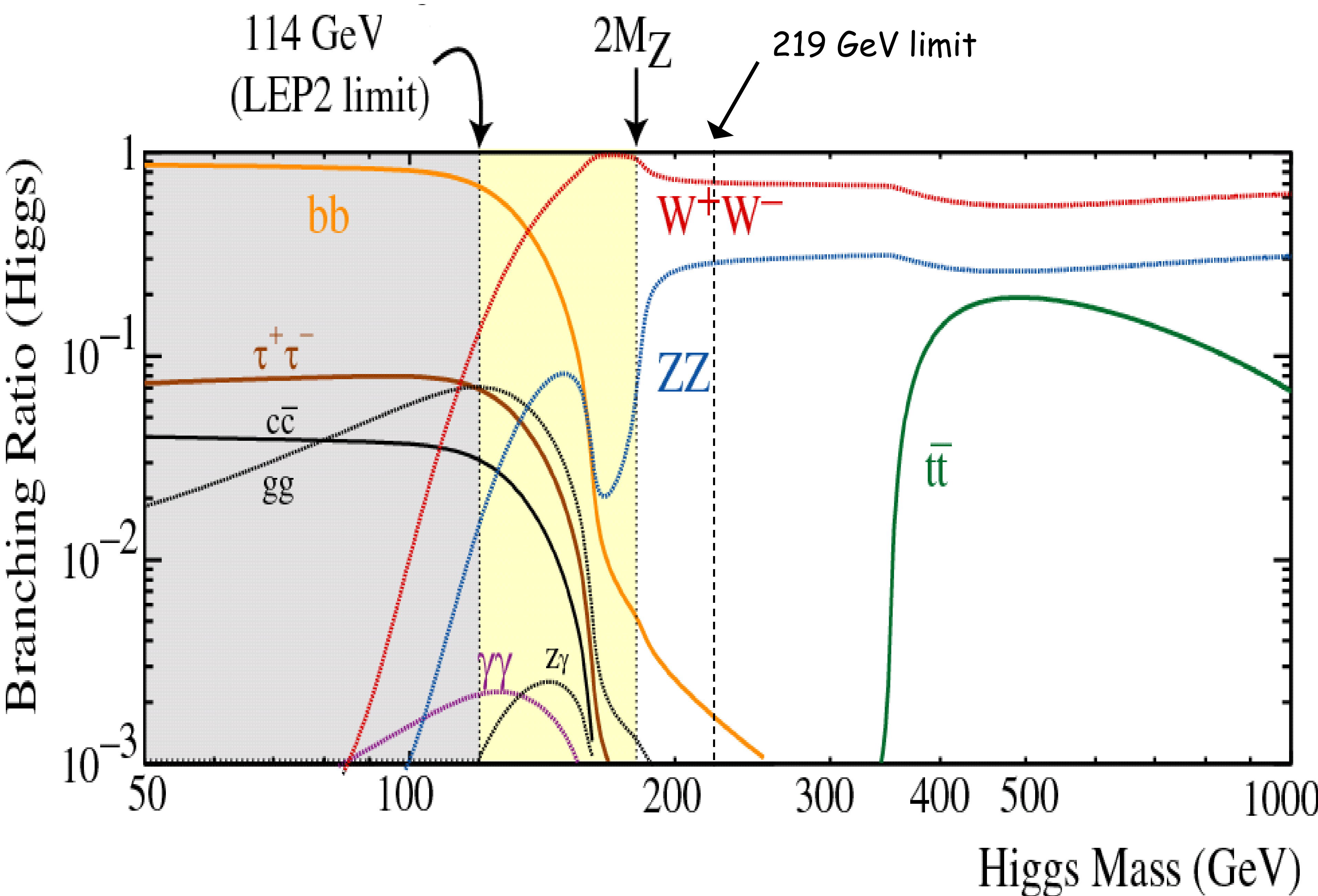
$$\boxed{\Gamma(H\to f\bar{f})\to G_F\,m_f^2\,\enclose{circle}{m_H}}$$



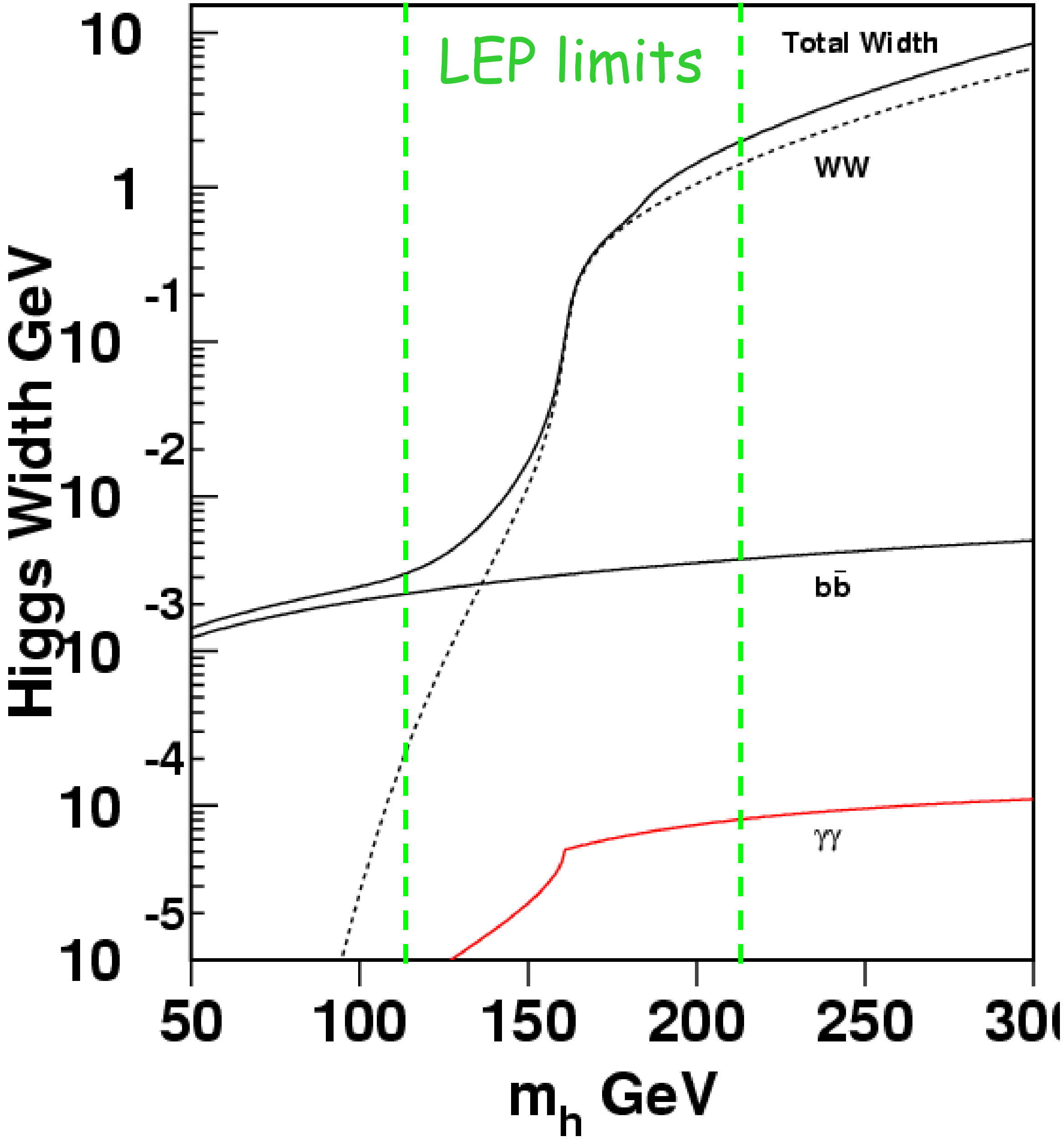
$$\boxed{\Gamma(H\to\gamma\gamma)\to\alpha^2 G_F\,\enclose{circle}{m_H^3}}$$

Higgs Branching Fractions

T.Hebbeker



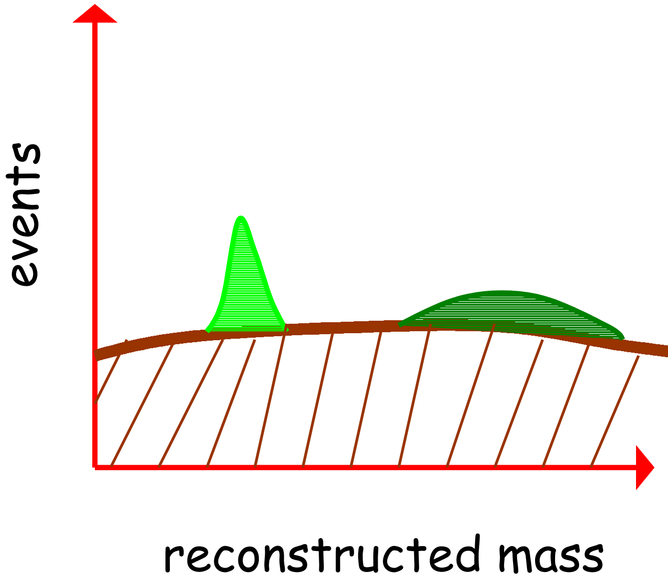
Higgs Decay Width



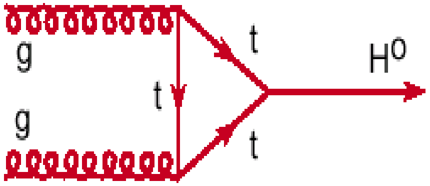
$$\boxed{\Gamma \sim m_H^3}$$

Important for

Signal/background!



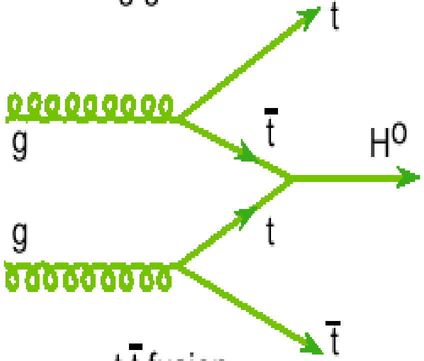
Higgs production in pp



g g fusion

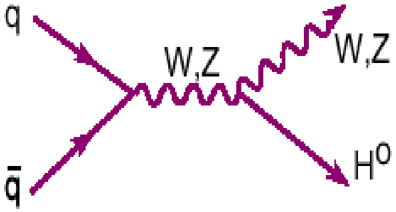
Xsection largest

$$H \rightarrow \gamma\,\gamma\,,(leptons)$$



t t̄ fusion

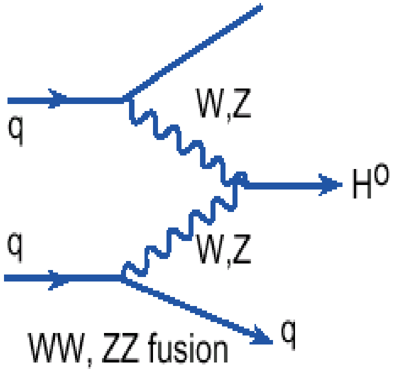
Xsection small



W, Z bremsstrahlung

Xsection „large" at 2 TeV

$$W, Z \rightarrow leptons$$



WW, ZZ fusion

Xsection „large" at 14 TeV

$$H \rightarrow \gamma\,\gamma\,,(leptons)$$

photons, leptons:

- less background
- mass resolution !

Higgs cross section 2 TeV

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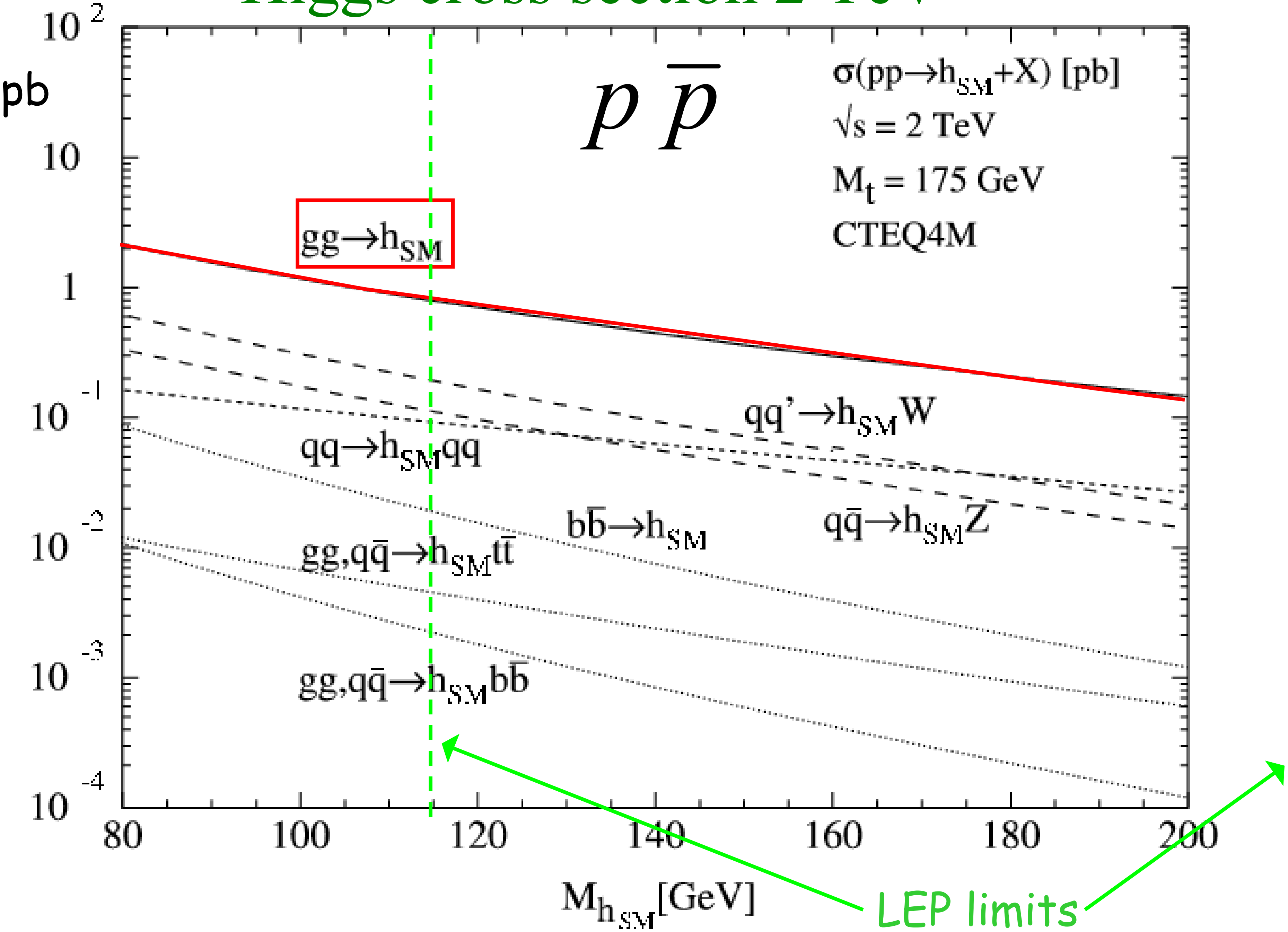

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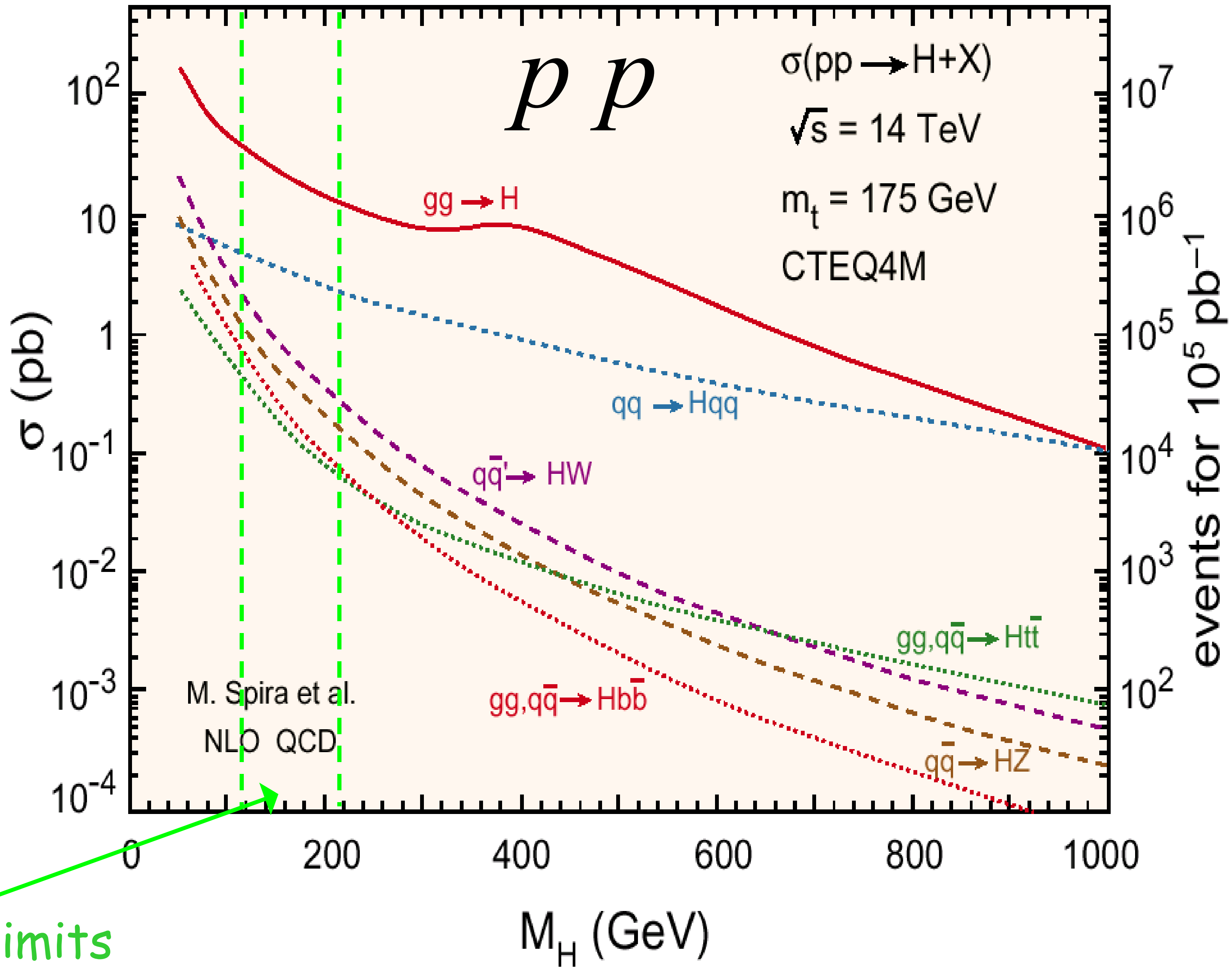
Higgs cross section 14 TeV



LEP limits

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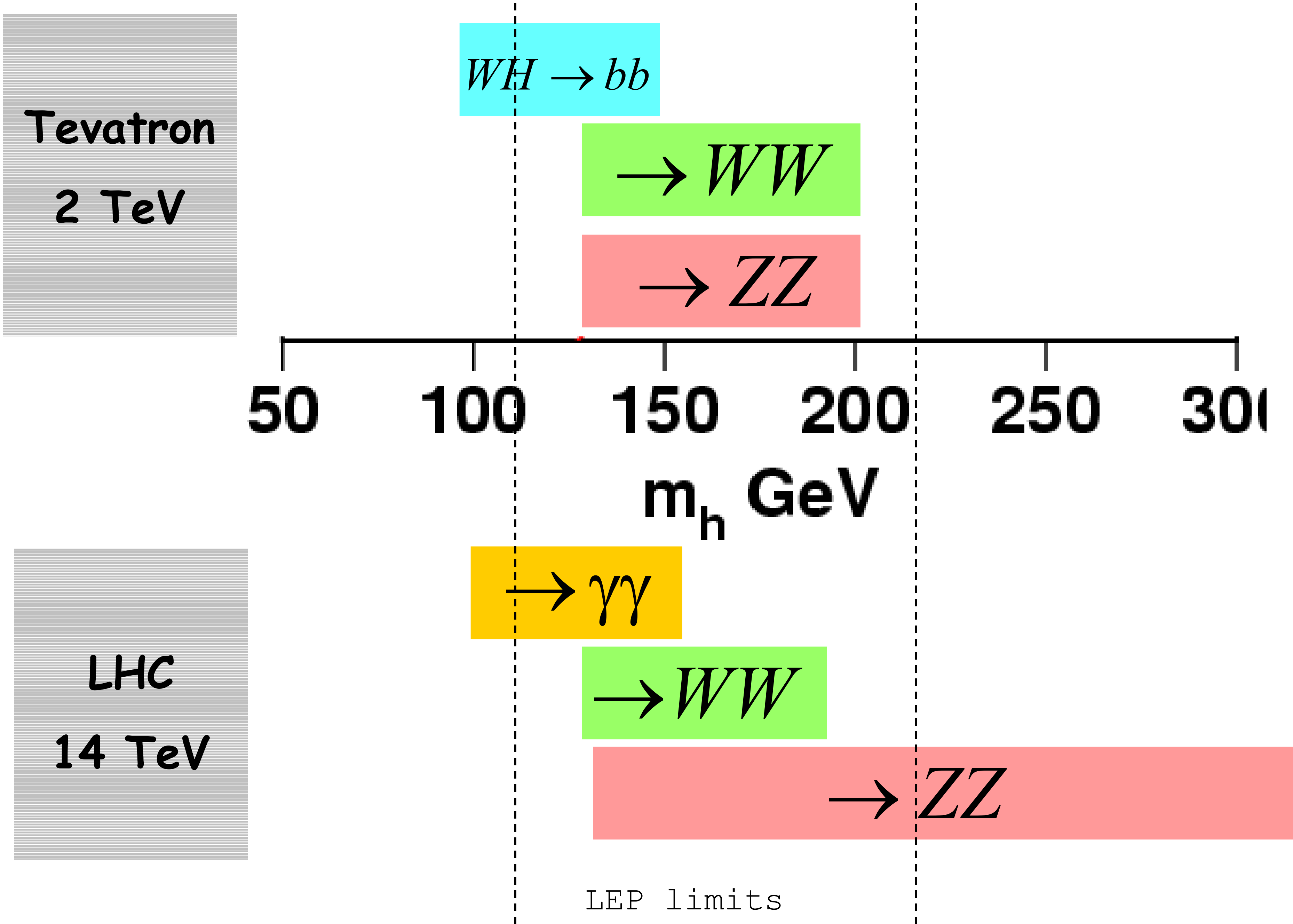
Higgs search strategies



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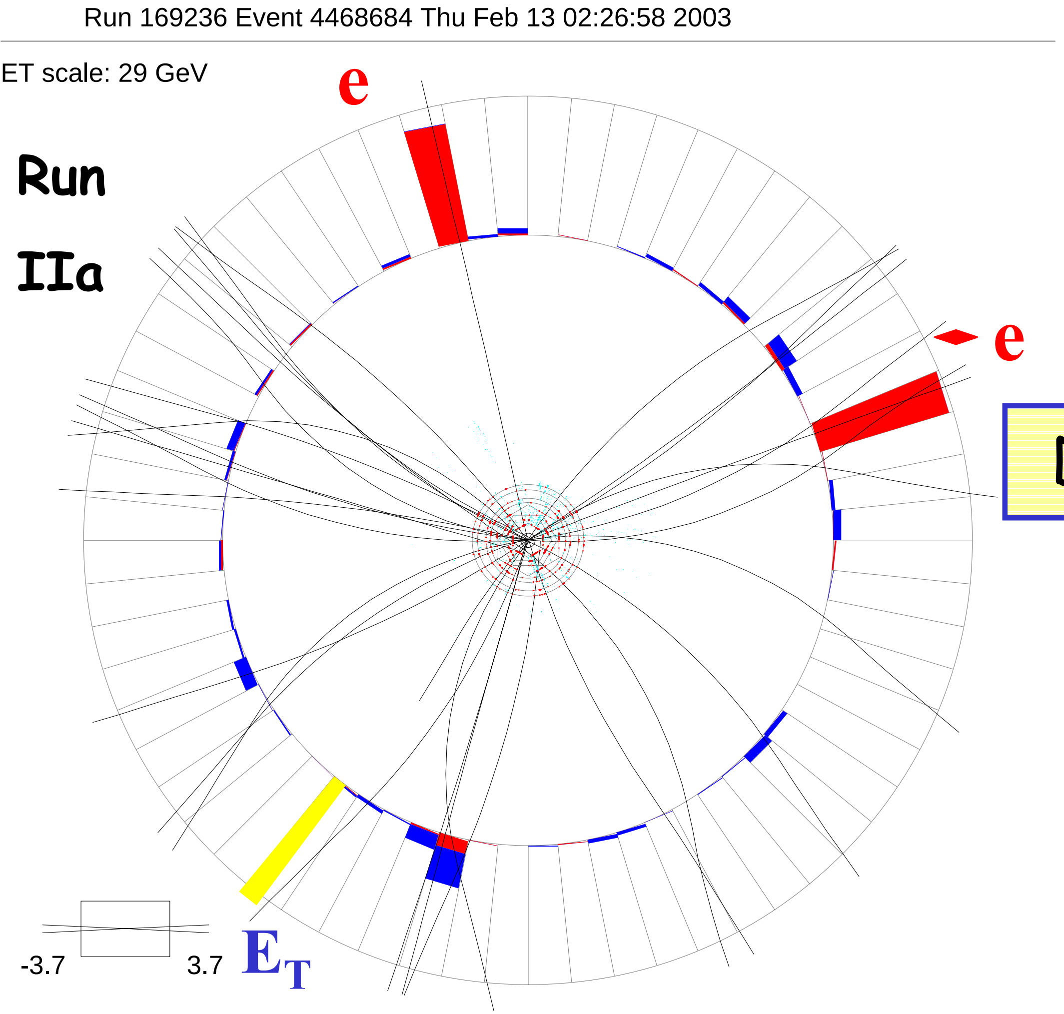
Higgs (130-190 GeV) $\rightarrow WW$ [2 TeV]

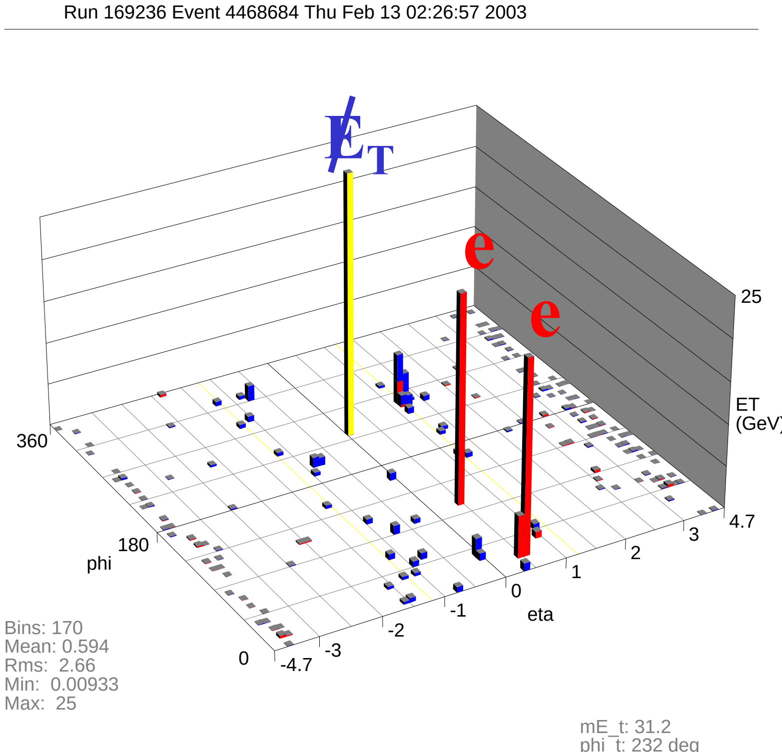


Run

IIa

$H \rightarrow WW^{(*)} \rightarrow e^+e^-\nu\nu$

D0



Background: $WW^{(*)}, Z\gamma^{(*)}, tt$

Higgs (110-150 GeV) → γγ [14 TeV]

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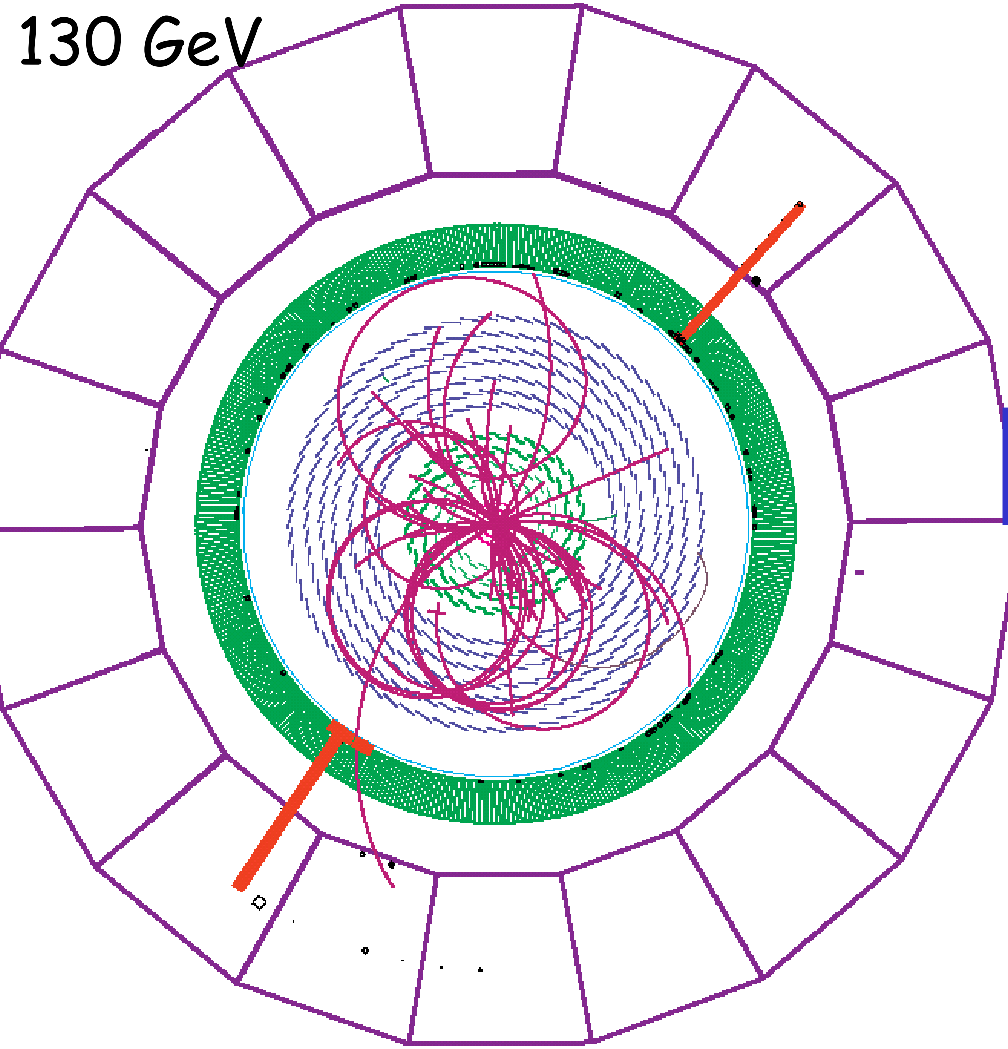
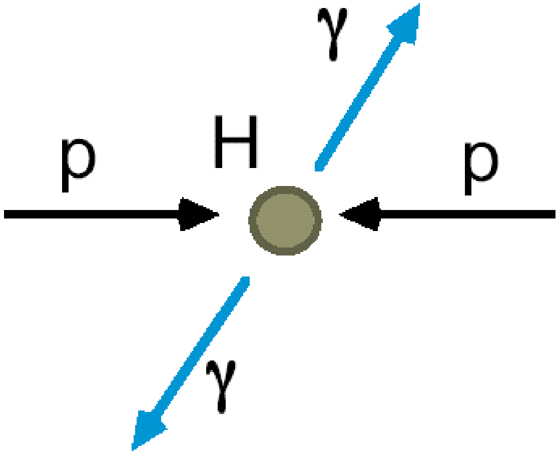
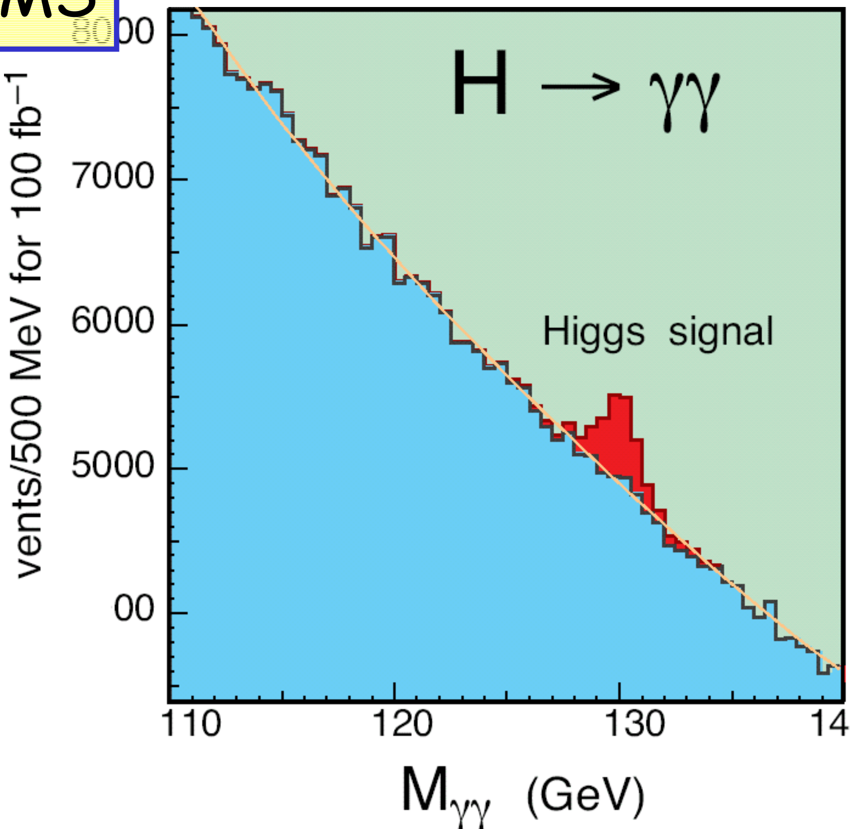
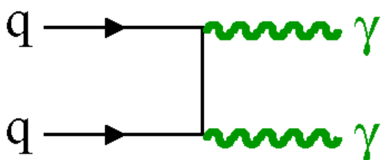
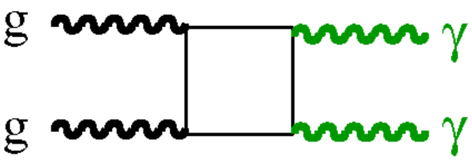






Background:





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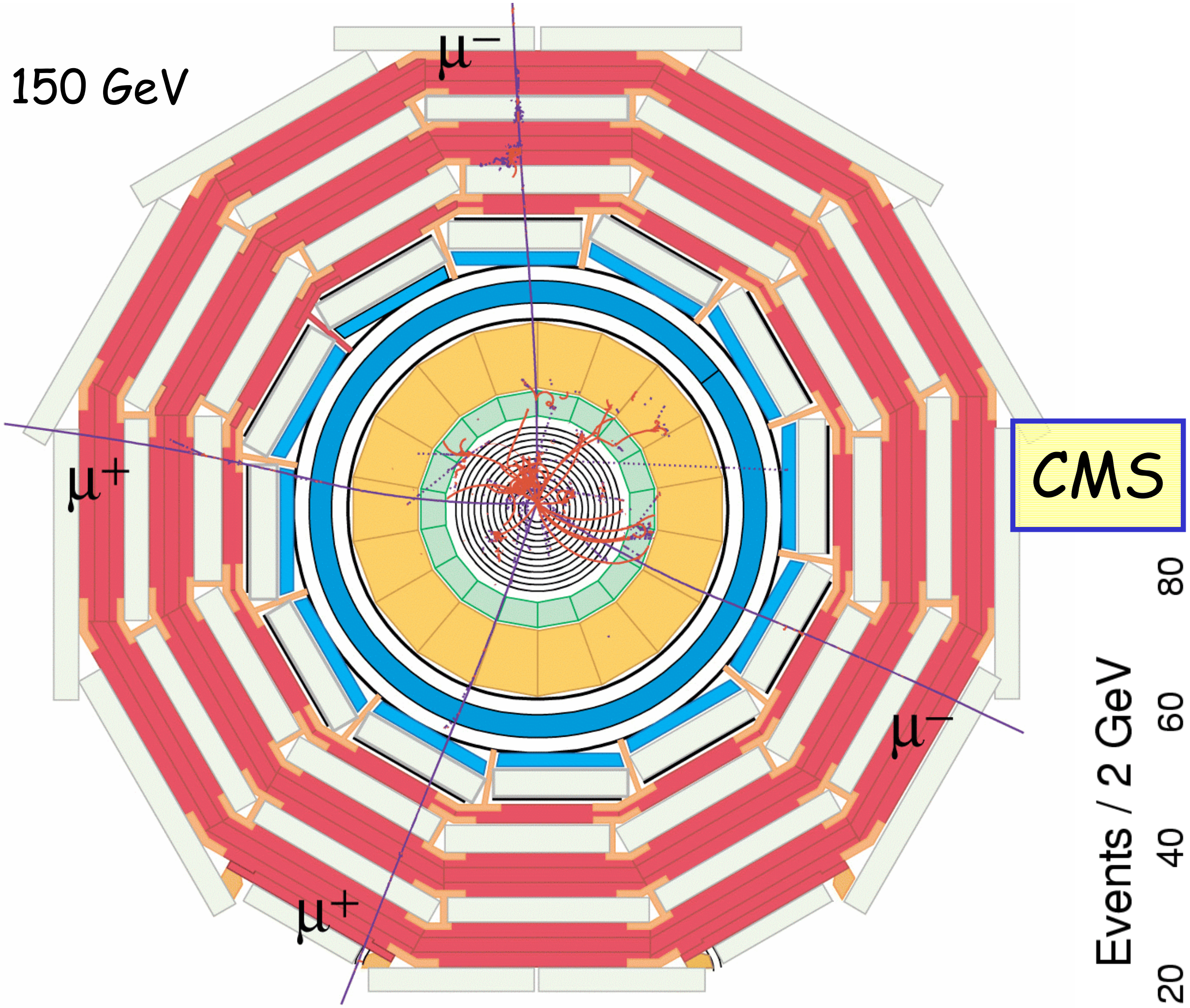
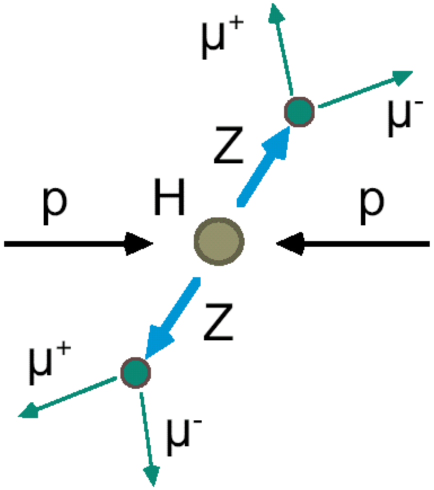
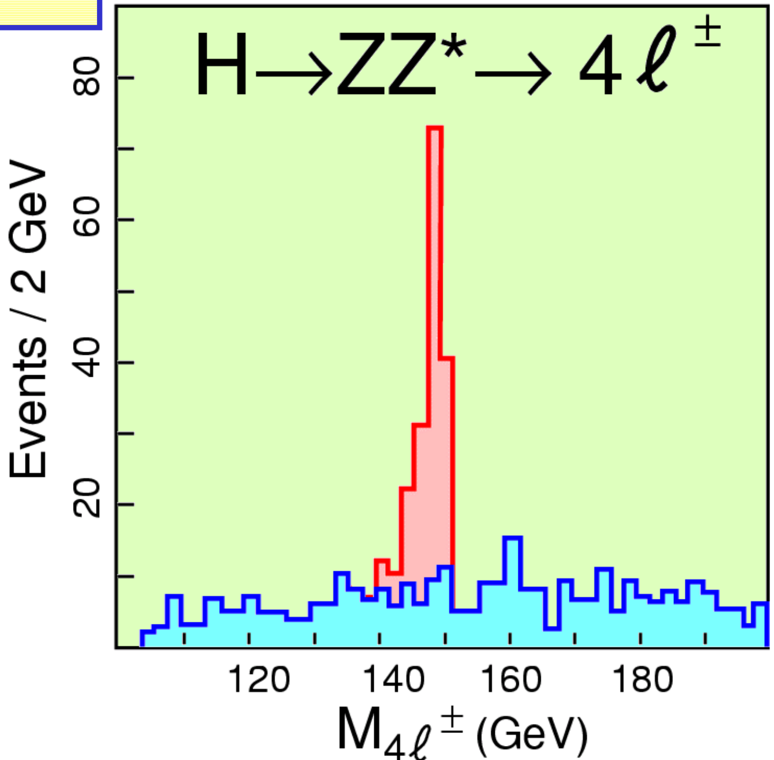
Higgs (130-700 GeV) $\rightarrow Z\,Z^{(*)}$ [14 TeV]







Background: $Z\,Z^{(*)}, Z\,\lambda^{(*)}$

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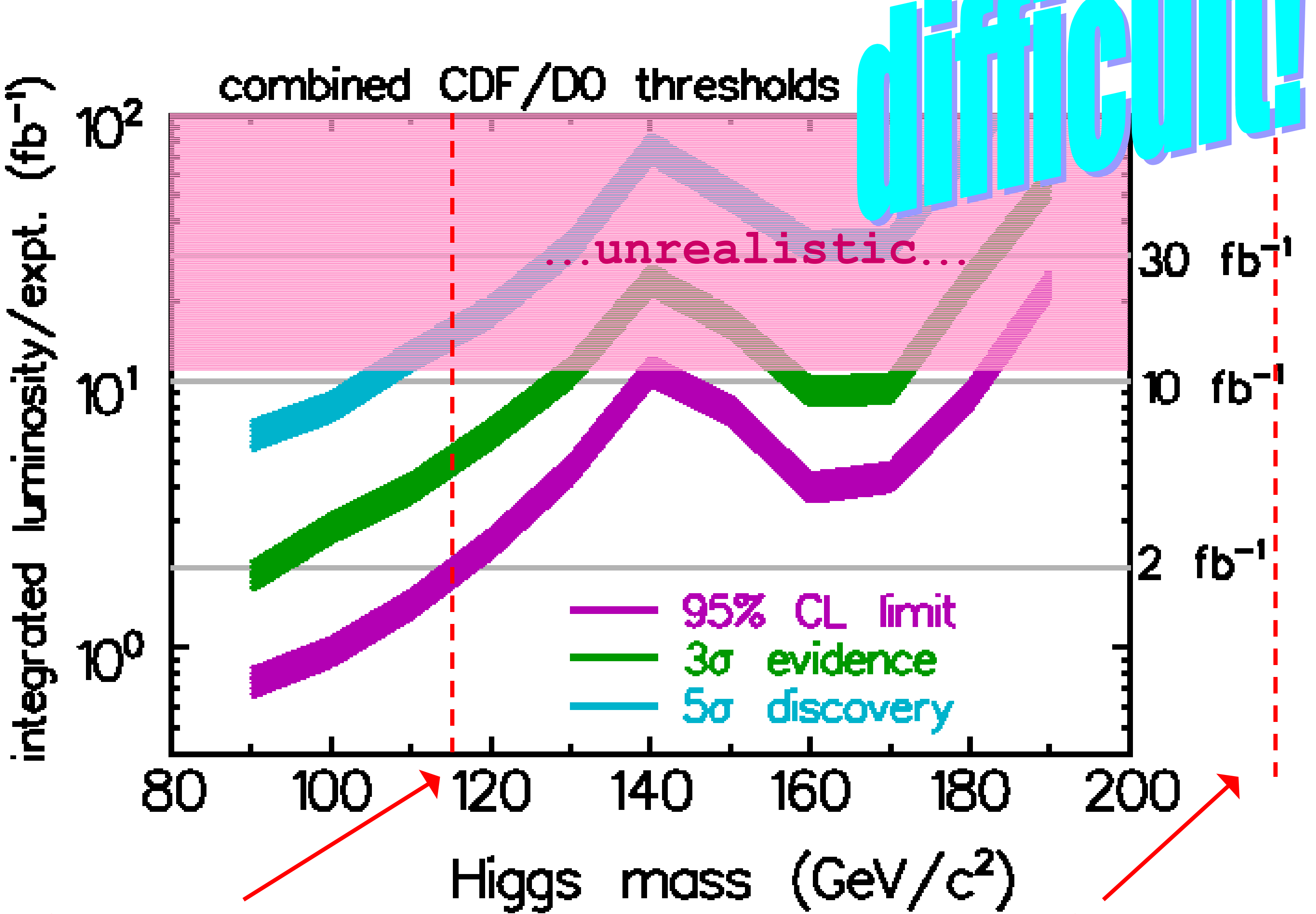
Higgs discovery prospects at Tevatron

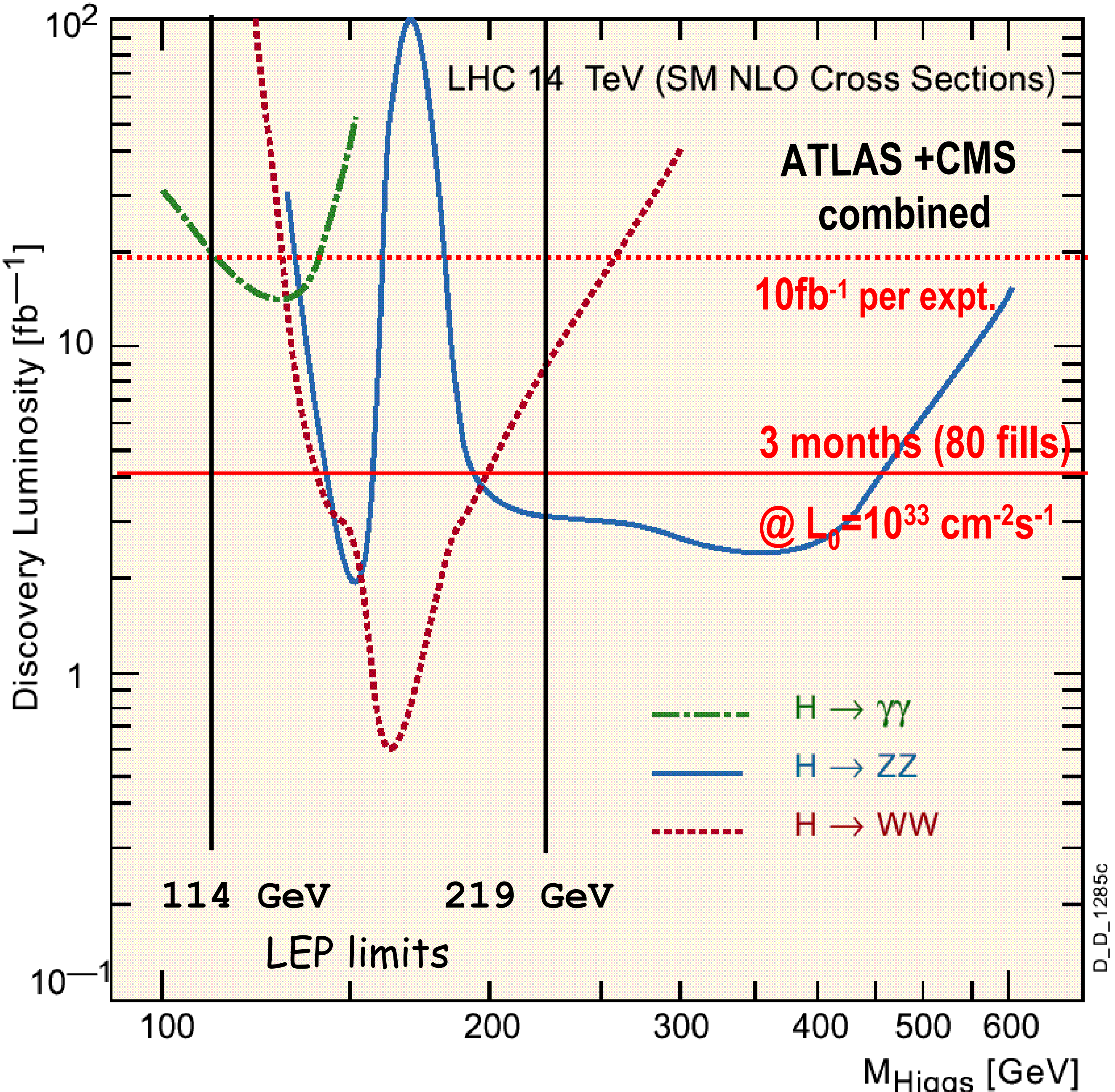
difficult!



LEP limit 114 GeV

limit 219 GeV

Higgs discovery prospects at LHC



yes!

experimentum crucis:

if SM Higgs exists

<->

it can/will be seen

Extended Higgs Models - Supersymmetry

Minimal SuSy = MSSM: $\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$ $\begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}$

couples to up-fermions

couples to down-fermions

8 real fields – 3 (W^+ W^- Z) = 5 higgs bosons:

$$\boxed{h \quad H \quad A \quad H^+ \quad H^-}$$

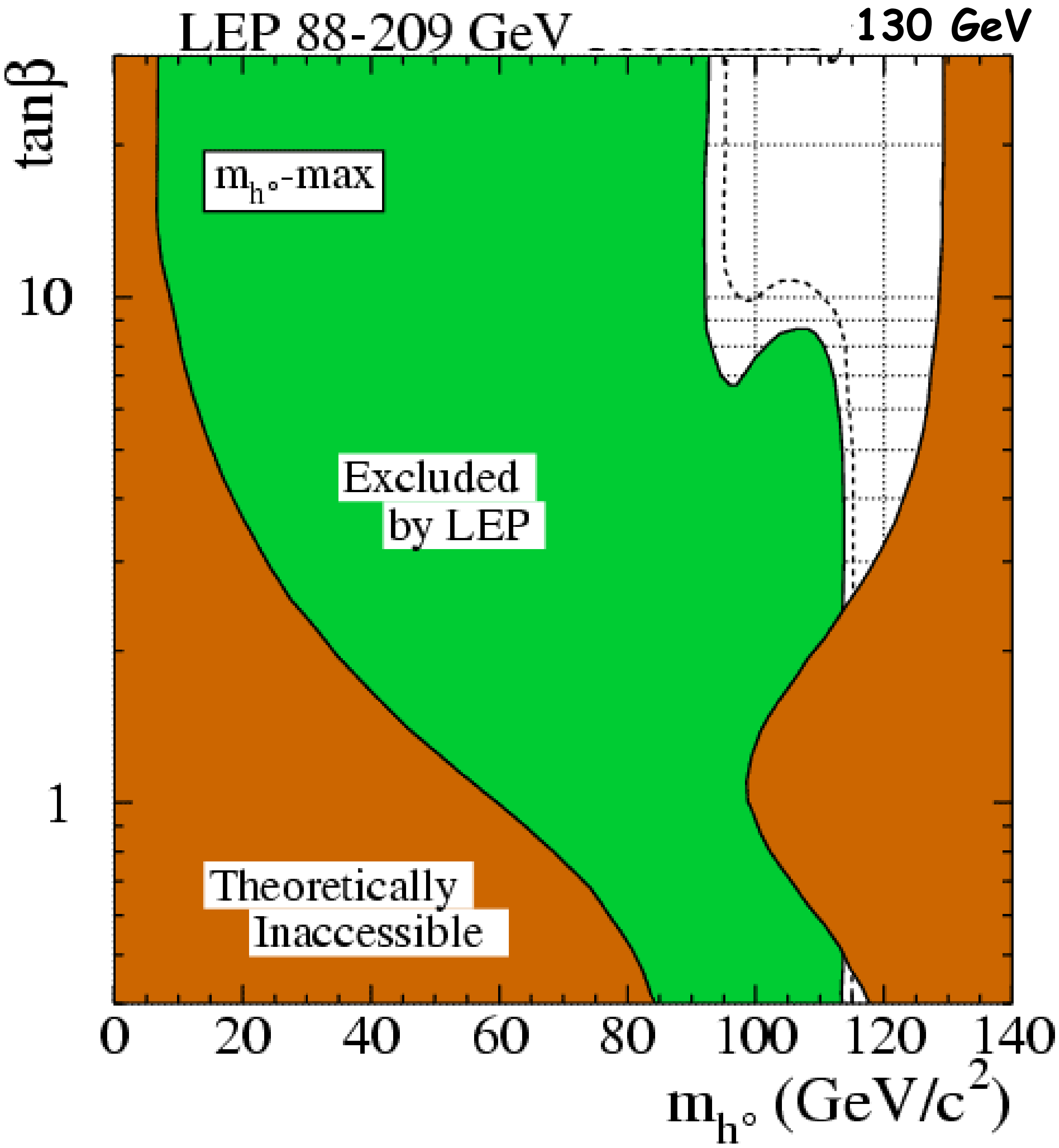
CP odd

mass relations (lowest order):

$$m_h < m_Z < m_H \qquad m_h < m_A \qquad m_W < m_{H^\pm}$$

$$m_h < 130\,GeV$$ incl. radiative corrections

MSSM Higgs Limits LEP



In addition:

limits on charged higgses...

$\tan\beta > 2.4$

MSSM Higgs Masses

All higgs masses fixed by two parameters:

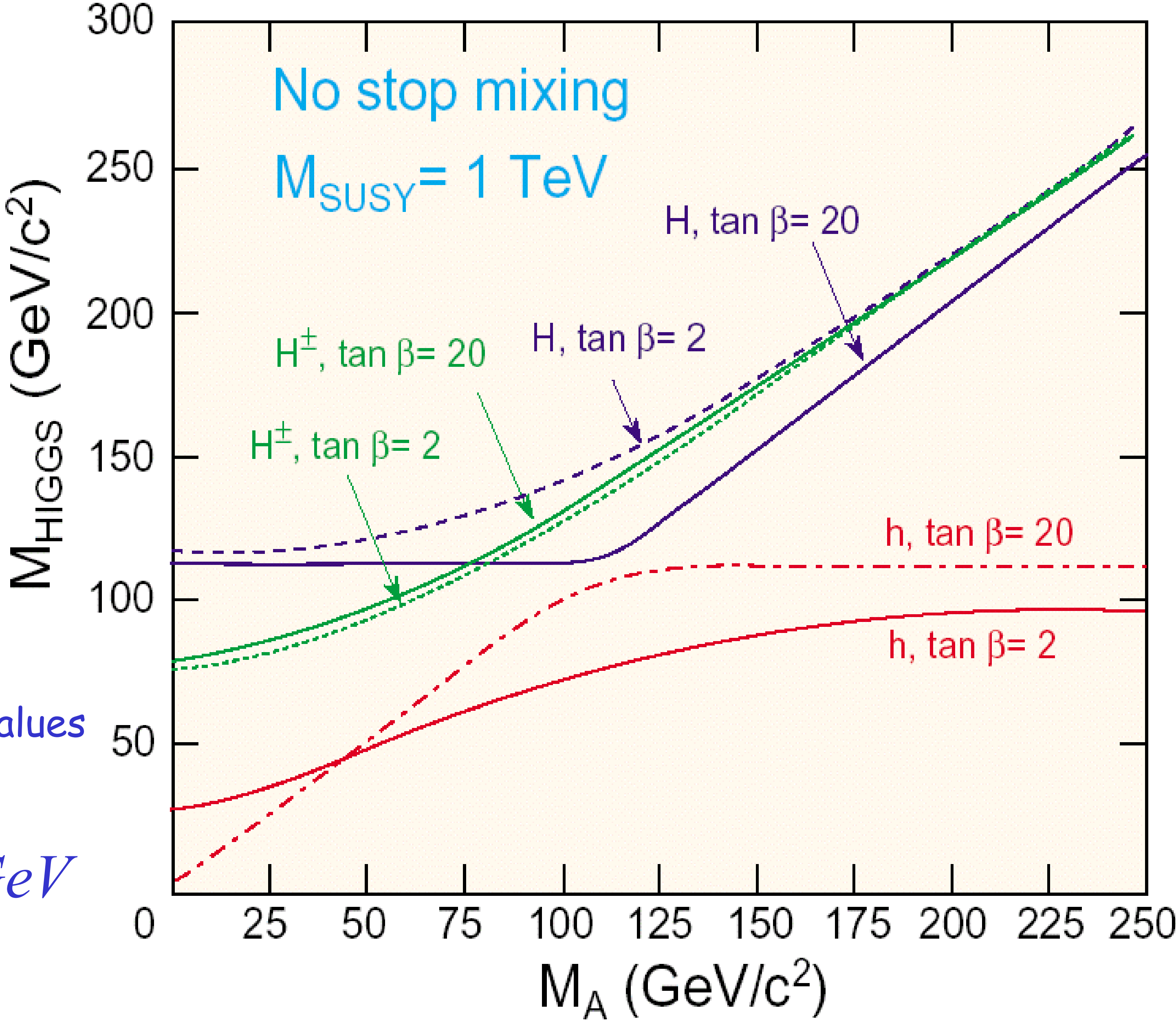
$$m_A$$

$$\tan\beta = {v_u}/{v_d}$$

= vacuum expect. values

$$m_A = 90 \ldots 500\, GeV$$

$$\tan\beta = 1 \ldots 50$$

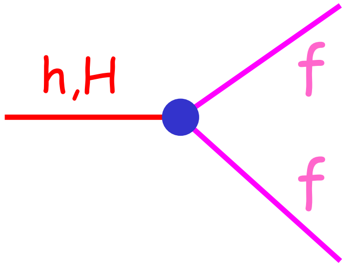


MSSM Higgs Couplings

also fixed by m_A , $\tan\beta$!

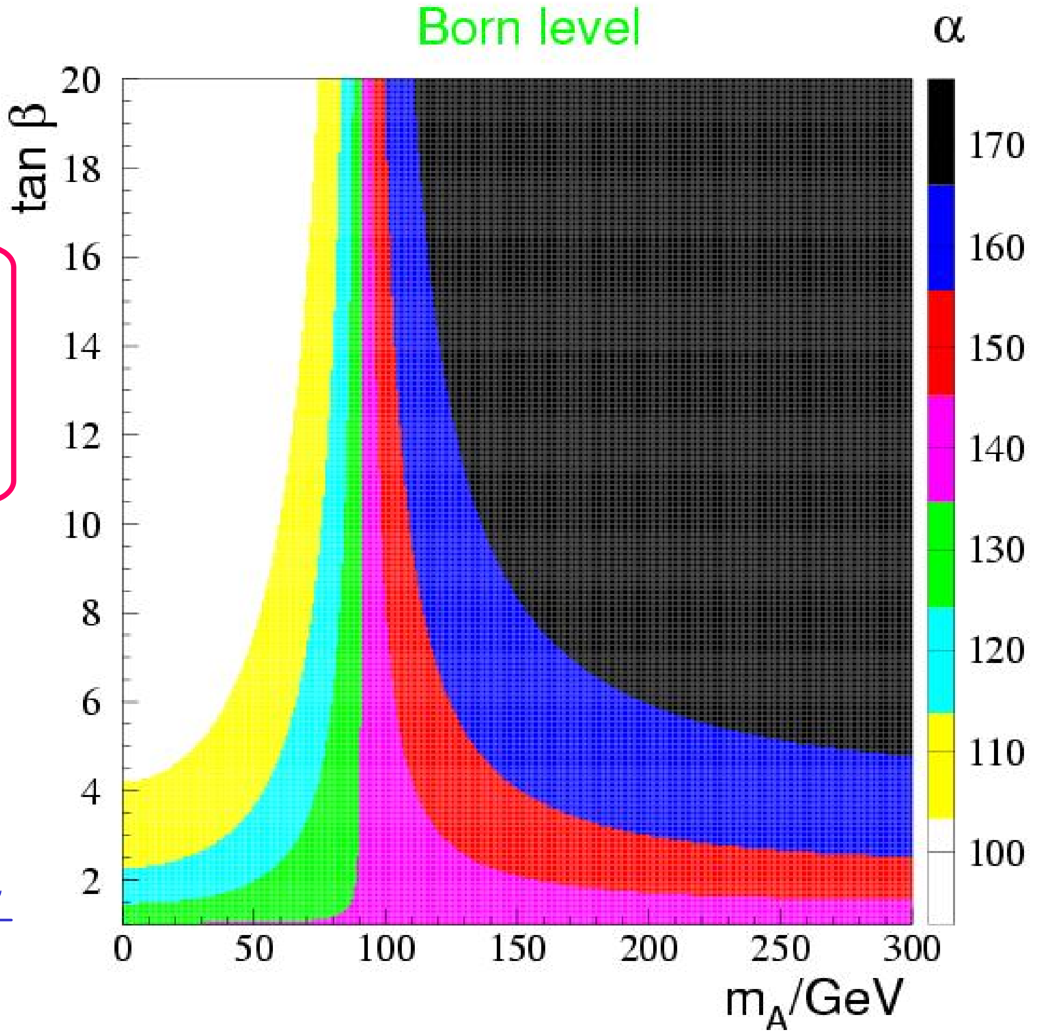
in particular h, H:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix}$$



$$uu\,h \sim \frac{m_u \cos\alpha}{\sin\beta} \qquad dd\,h \sim \frac{m_d \sin\alpha}{\cos\beta}$$

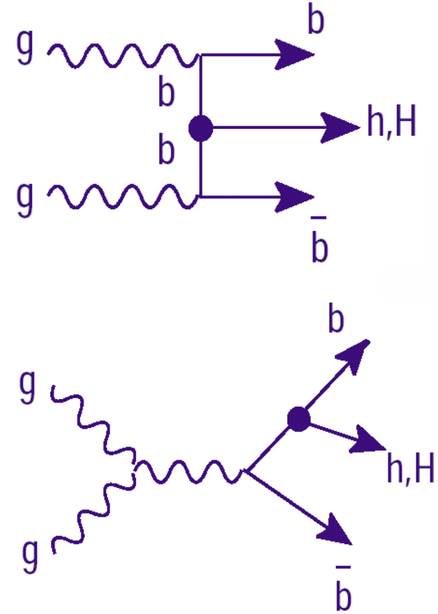
$$uu\,H \sim \frac{m_u \sin\alpha}{\sin\beta} \qquad dd\,H \sim \frac{m_d \cos\alpha}{\cos\beta}$$

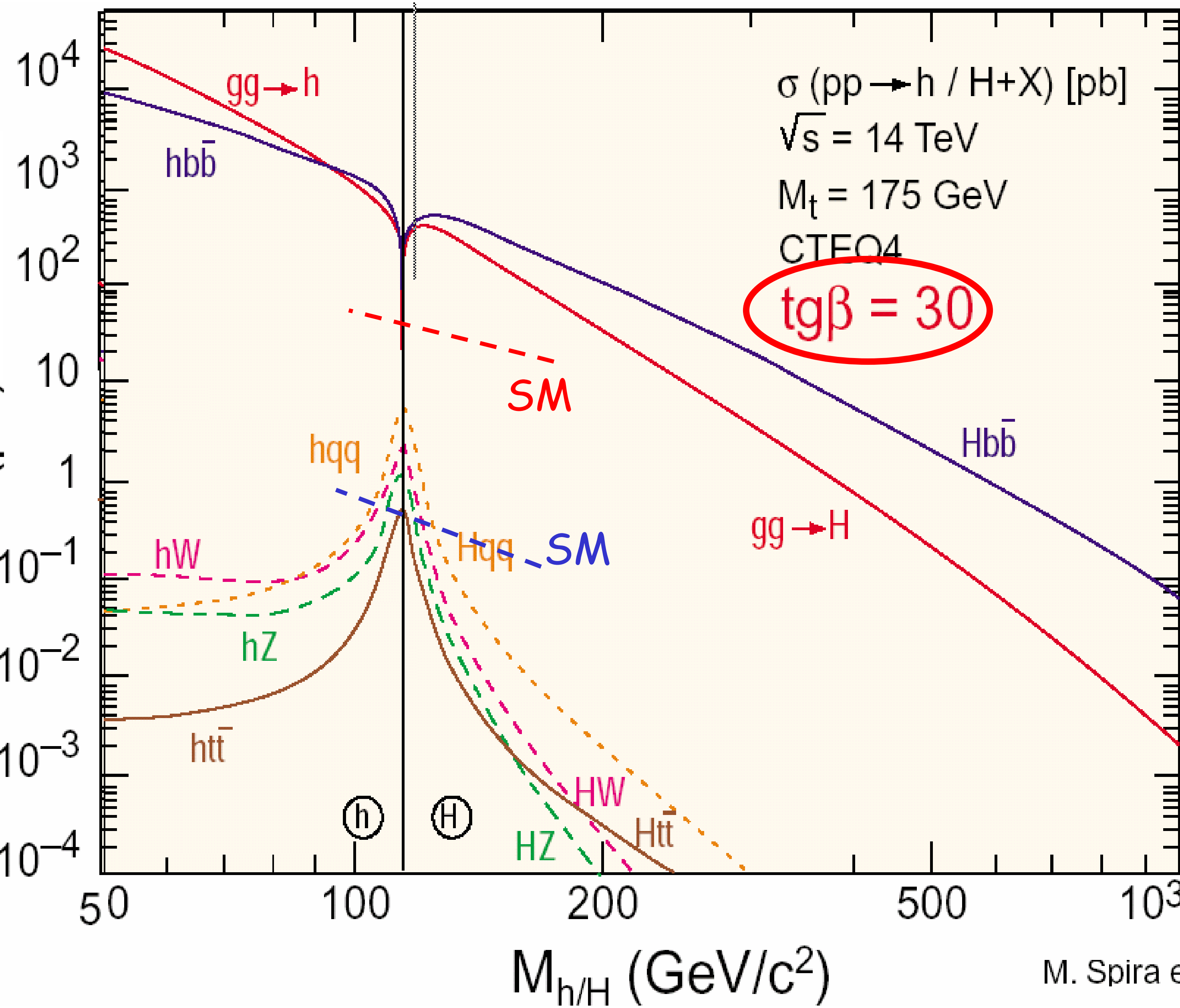


For large $\tan\beta$ coupling $h, H \leftrightarrow bb$ very large ! (similar for A)

MSSM Higgs Xsections

T.Hebbeker





M. Spira e

some xsections very large compared to SM !

MSSM Higgs Search LHC

Many channels:

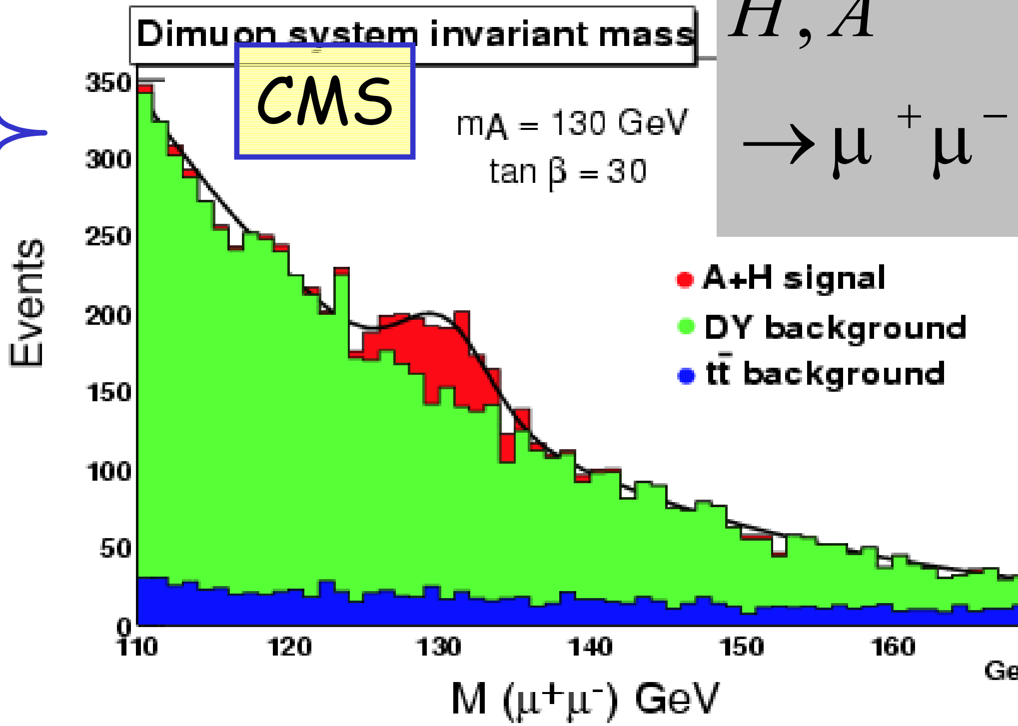
- charged Higgs H^+, H^-
- if $\tan\beta$ small, h decay signatures ~ SM
- if $\tan\beta$ large, „down“ fermions preferred
- \`cascade decays'

  eg $A \rightarrow Zh$
- if sparticles light:

  eg $H \rightarrow \chi^0 \chi^0$

  $H^+ \rightarrow \chi^+ \chi^0$

$H, A \rightarrow \mu^+ \mu^-$



Charged Higgses

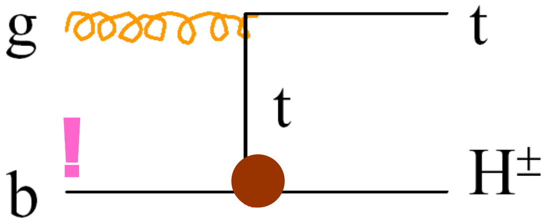
a) $m_{H^{\pm}} < m_t$

$gg \to tt$

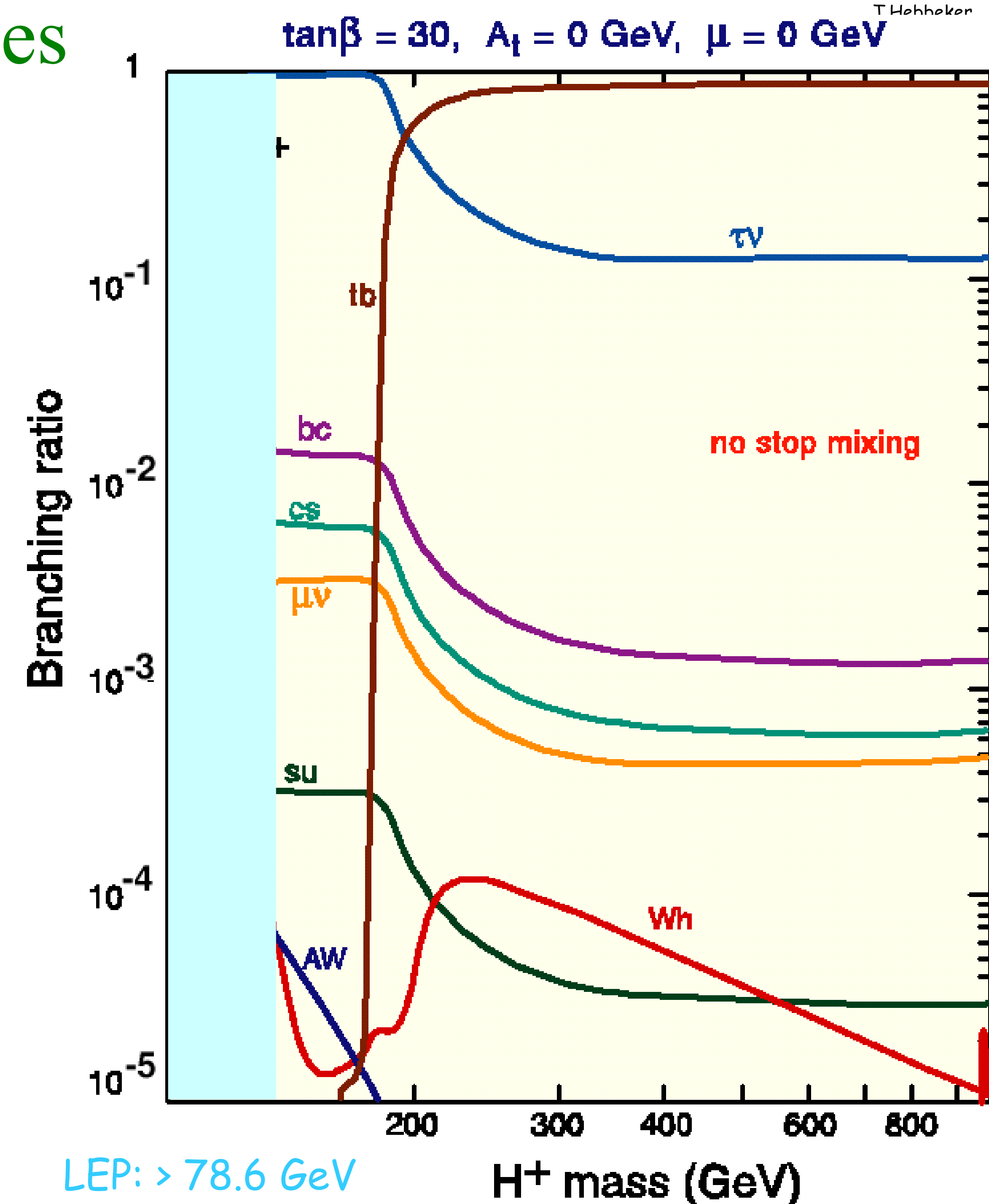
$t \to bH$

$H \to \tau\nu$

b) $m_{H^{\pm}} > m_t$

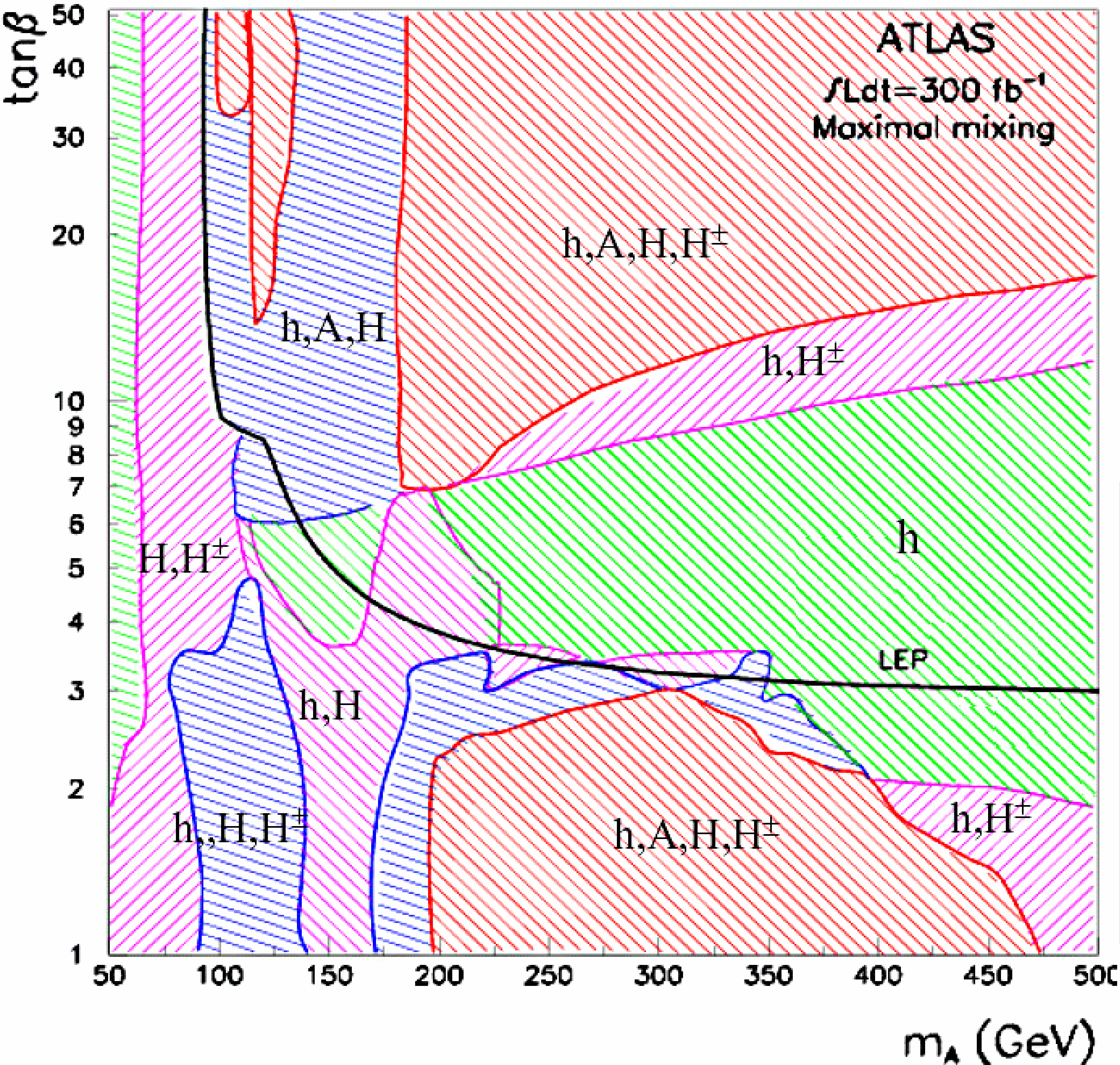


$H \to t\, b$



LEP: > 78.6 GeV

MSSM Higgs Discovery at LHC ?



▨ 4 Higgs observable

▨ 3 Higgs observable

▨ 2 Higgs observable

▨ 1 Higgs observable

5σ contours

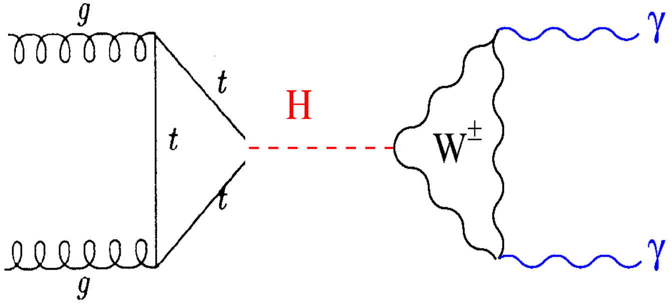
whole region covered!

Higgses cant escape !

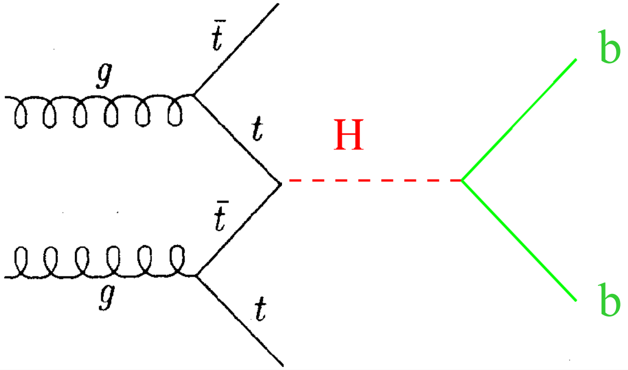
Appendices

Higgs production

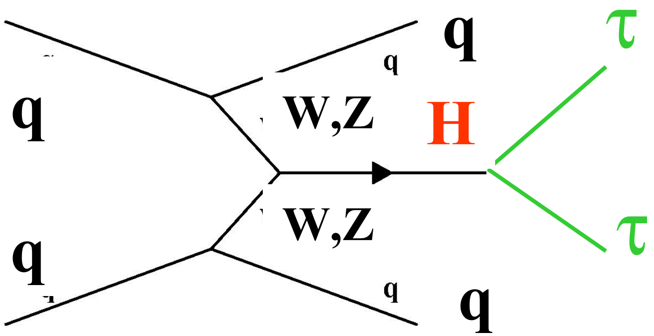
$H \rightarrow \gamma\gamma$



$t\bar{t}H \rightarrow t\bar{t}\,b\bar{b} \rightarrow b\ell\nu\ bjj\ b\bar{b}$



$qqH \rightarrow qq\tau\tau$



MSSM Higgs Limits LHC

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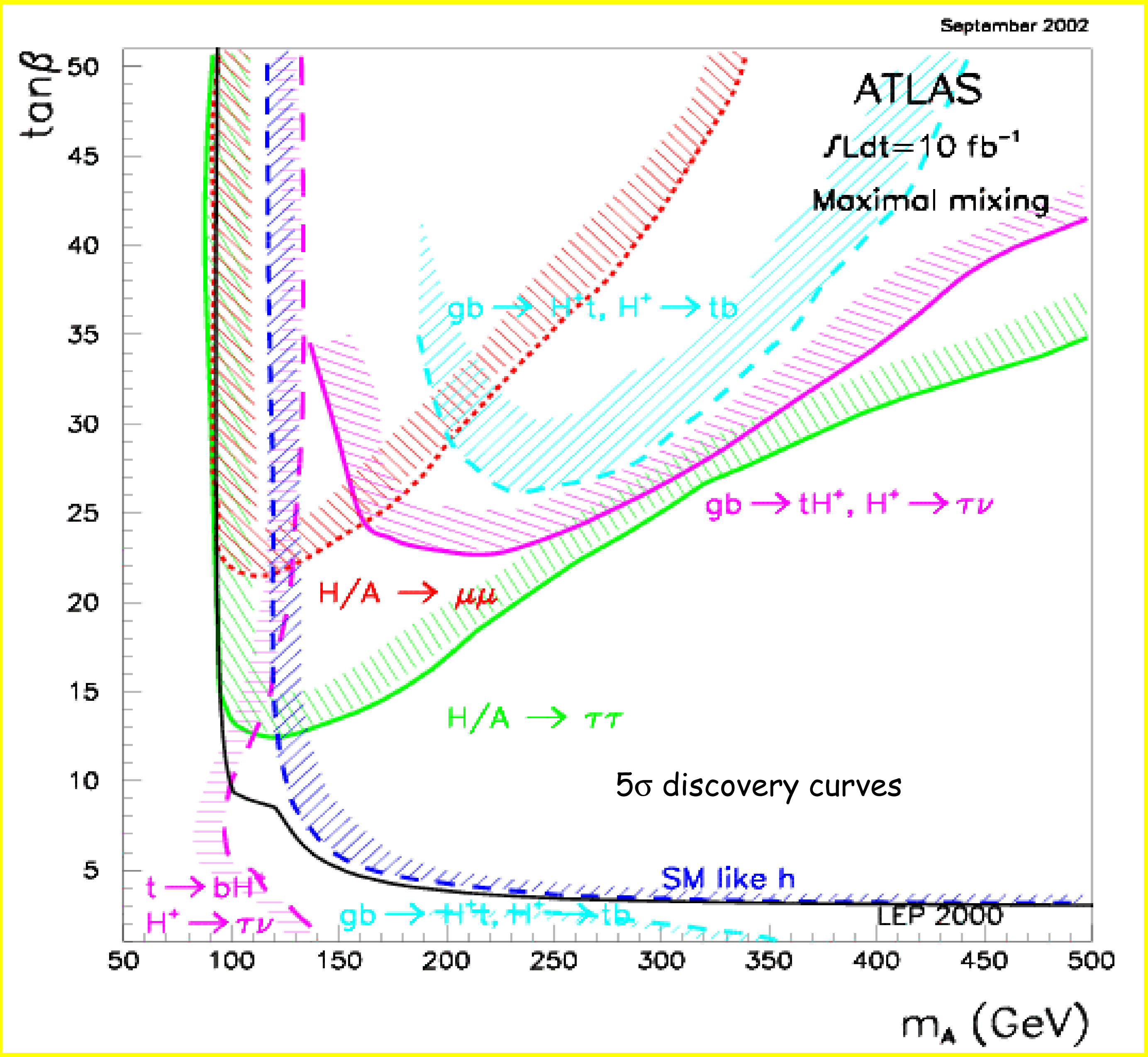
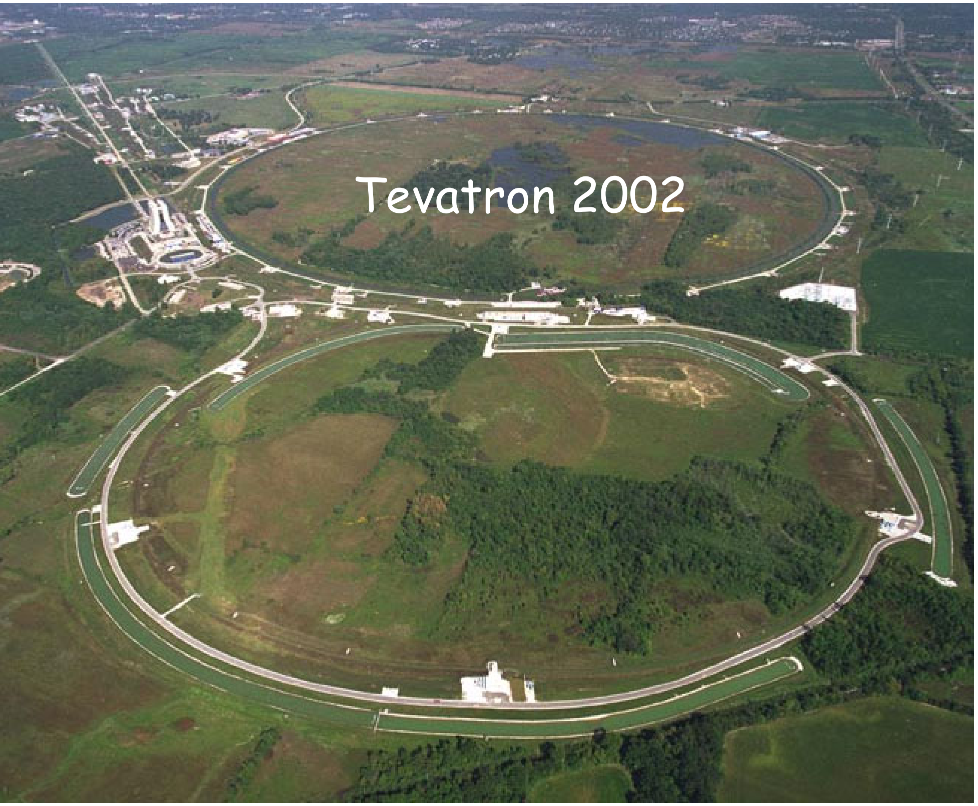


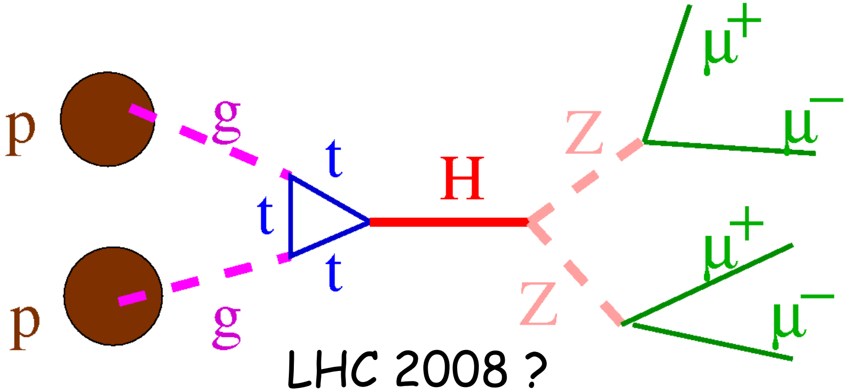
5σ discovery curves

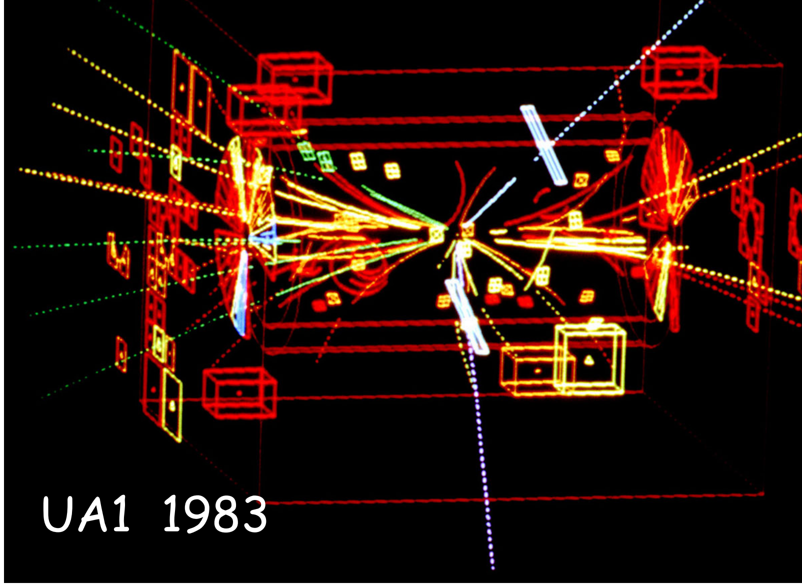
Thomas Hebbeker, RWTH Aachen
Belgian-Dutch-German school
September 2003

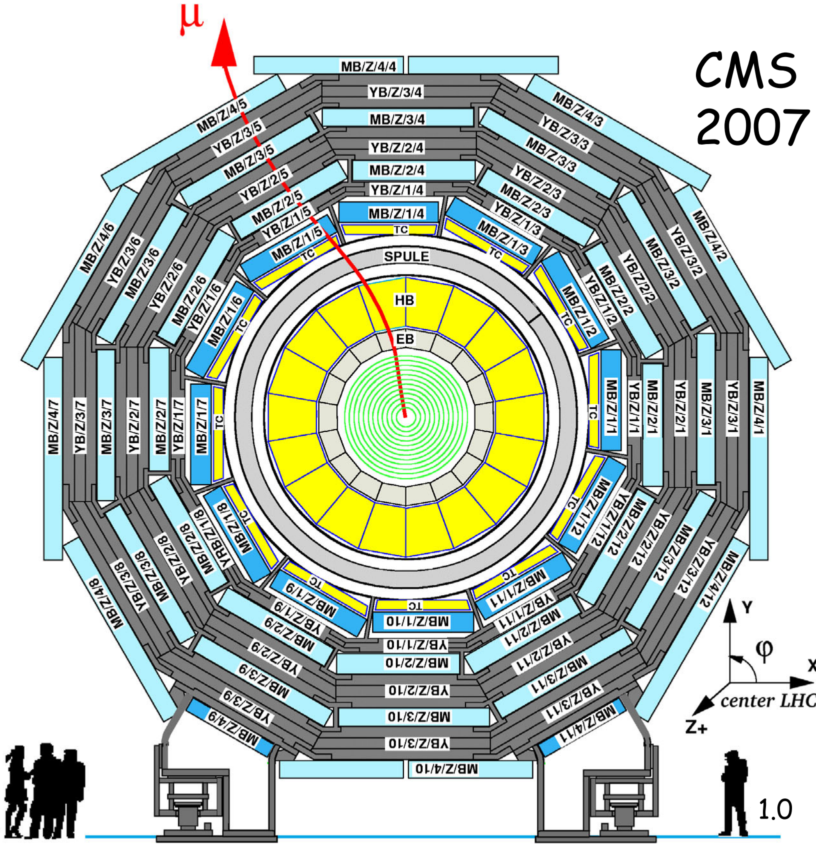
part IV

pp physics









Part I Introduction

Part II Standard Model Physics

Part III Higgs

Part IV New Phenomena

- SUSY
  motivation
  searches:
    R-Parity conserved
    R-Parity violated
- Extra dimensions
- Black holes

References

SUperSymmetry

Particle	**Spin**	**Susy-Partner**	**Spin**
ν_e	1/2	$\tilde{\nu}_e^L$	0
e^-	1/2	$\tilde{\mathrm{e}}_L^-, \tilde{\mathrm{e}}_R^-$	0
u	1/2	$\tilde{\mathrm{u}}_L, \tilde{\mathrm{u}}_R$	0
d	1/2	$\tilde{\mathrm{d}}_L, \tilde{\mathrm{d}}_R$	0
$\gamma, \mathrm{Z}, h, H, A$	1, 0	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	1/2
$\mathrm{W}^\pm, H^\pm$	1,0	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	1/2
g	1	$\tilde{\mathrm{g}}$	1/2

if R-parity (-1 for sparticles) is conserved:

⇨ LSP = Lightest SUSY particle = $\tilde{\chi}_1$ = stable

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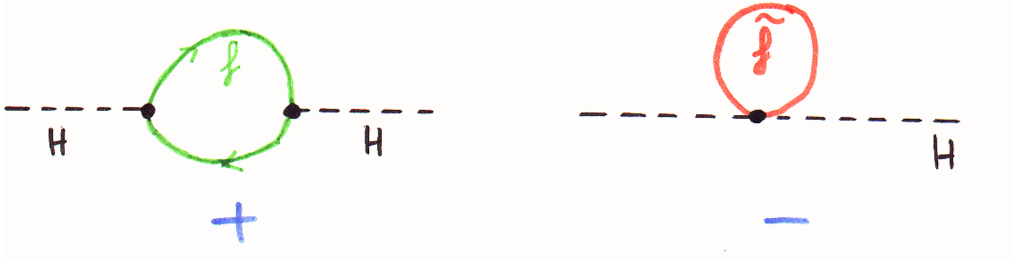
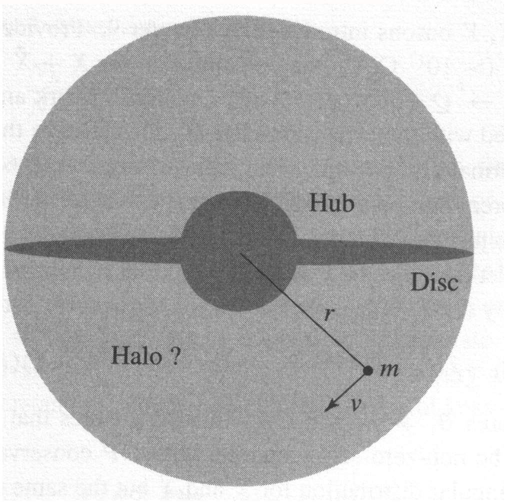
SUSY

Nice features:

- symmetry relating bosons (forces) ⟺ fermions (matter)
- higgs mass m_H under control



- grand unification (incl. gravity!) possible
- neutralino = dark matter candidate

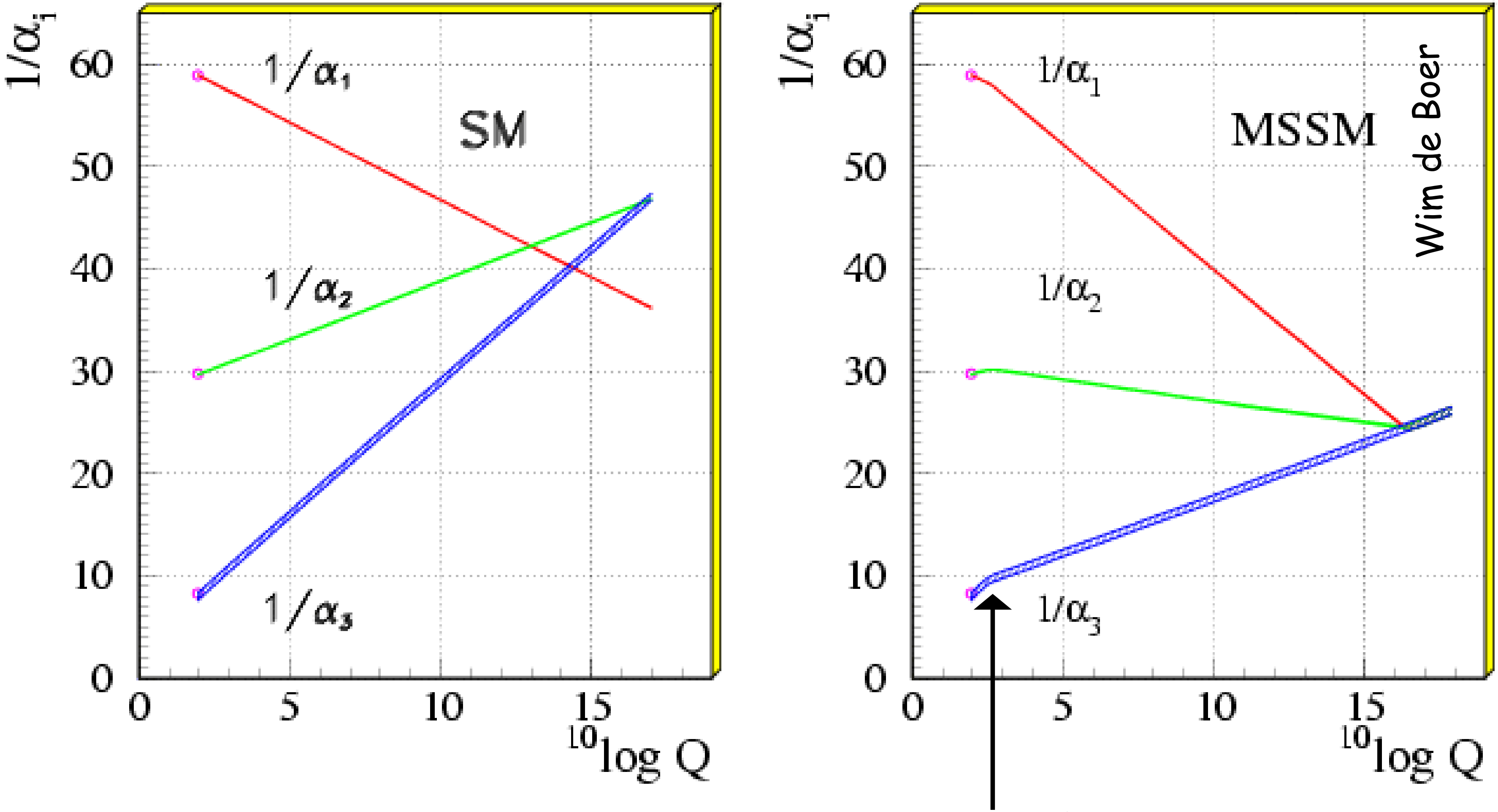


Other properties:

- SUSY broken: no sparticle seen yet
- > 100 new parameters ⟹ Minimal Model (MSSM, MSUGRA)

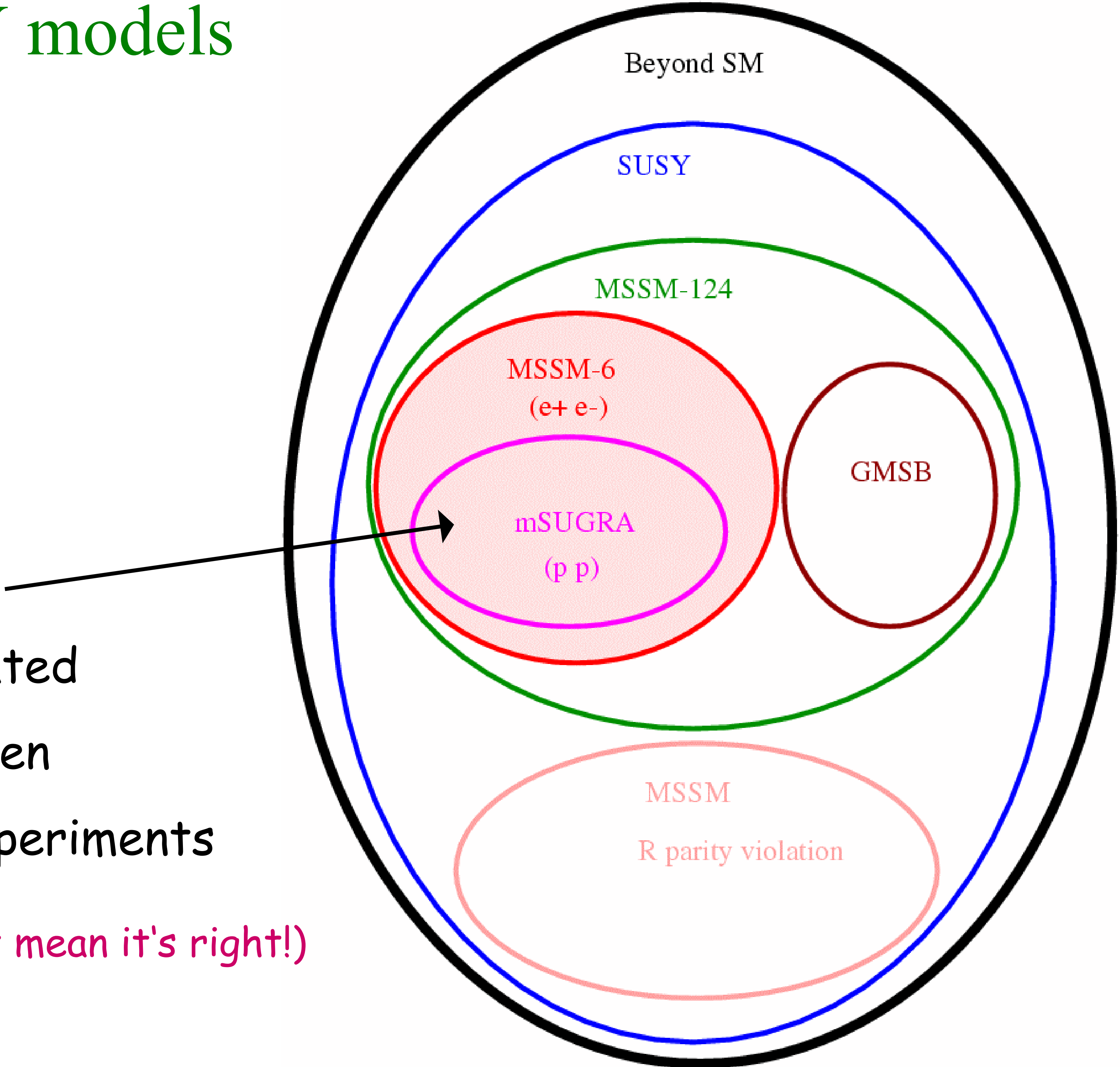
Grand Unification ?

Unification of the Coupling Constants in the SM and the minimal MSSM



SUSY mass scale ~ TeV

SUSY models



investigated

most often

by pp experiments

(does not mean it's right!)

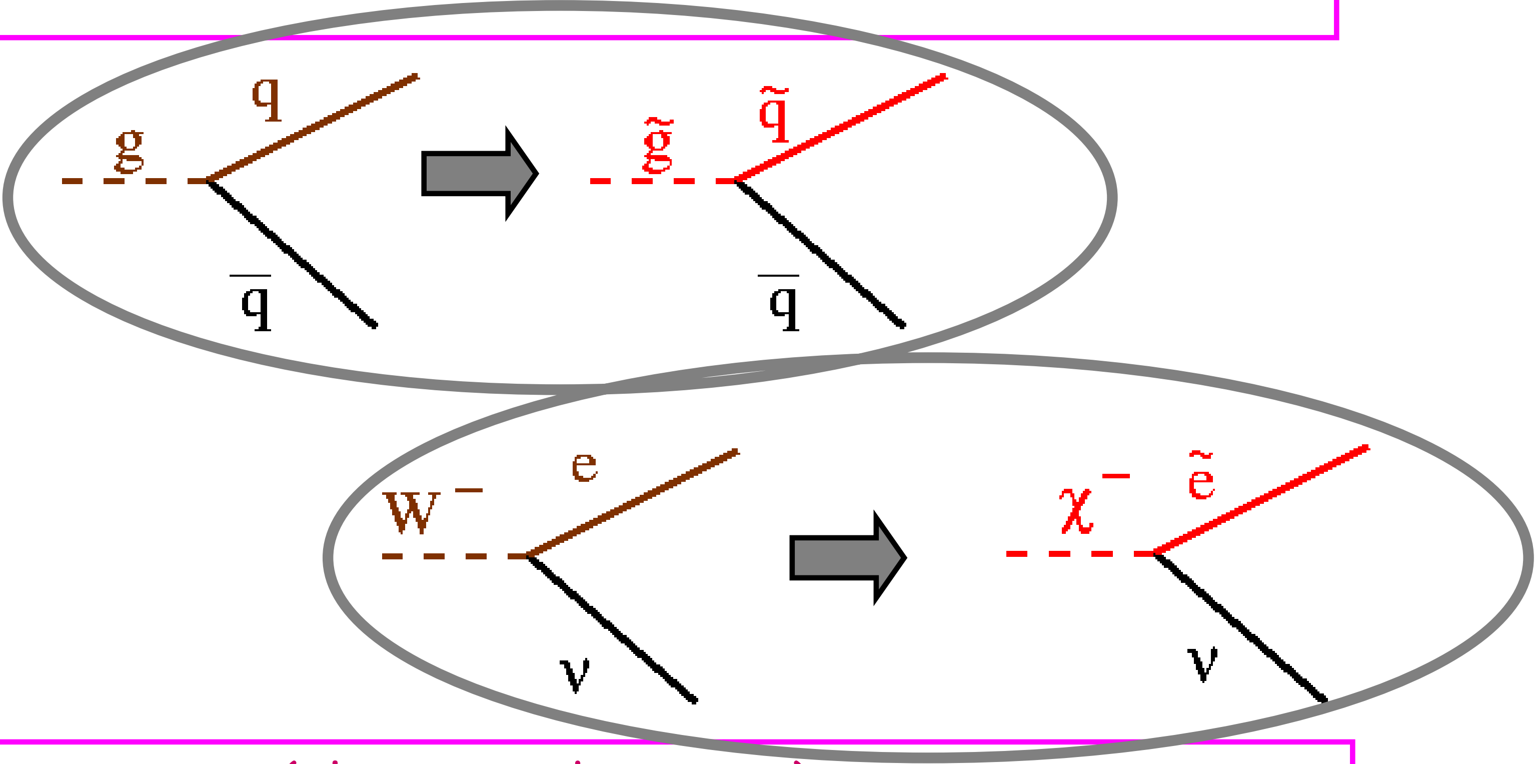
SUSY interactions (R conserved)

Feynman graphs:

take any SM vertex with 3 or 4 particles

replace two legs by the corresponding sparticles (~)

Examples



Coupling constants (electroweak, strong):

same as in SM !

MSUGRA parameters

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MSUGRA = Minimal SUperGRAvity model

m_0 = universal scalar mass at GUT scale (s..., higgs)

$m_{1/2}$ = universal gaugino mass at GUT scale (...inos)

$\tan\beta$ = v_2/v_1 = ratio of higgs vacuum expectation values

A_0 = universal sfermion mass mixing parameter [GUT]

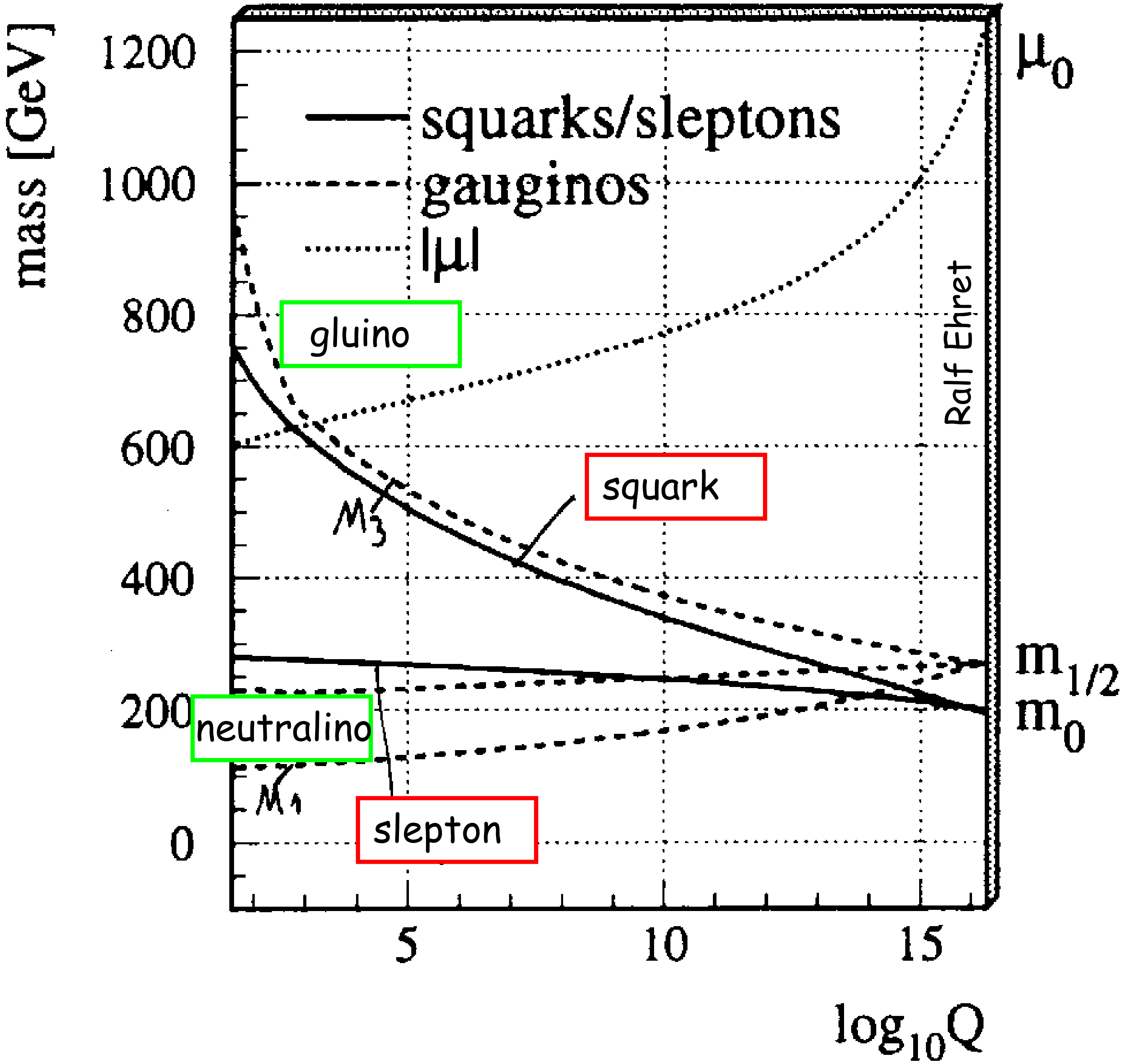
sgn μ = sign of higgsino mass parameter

Required:

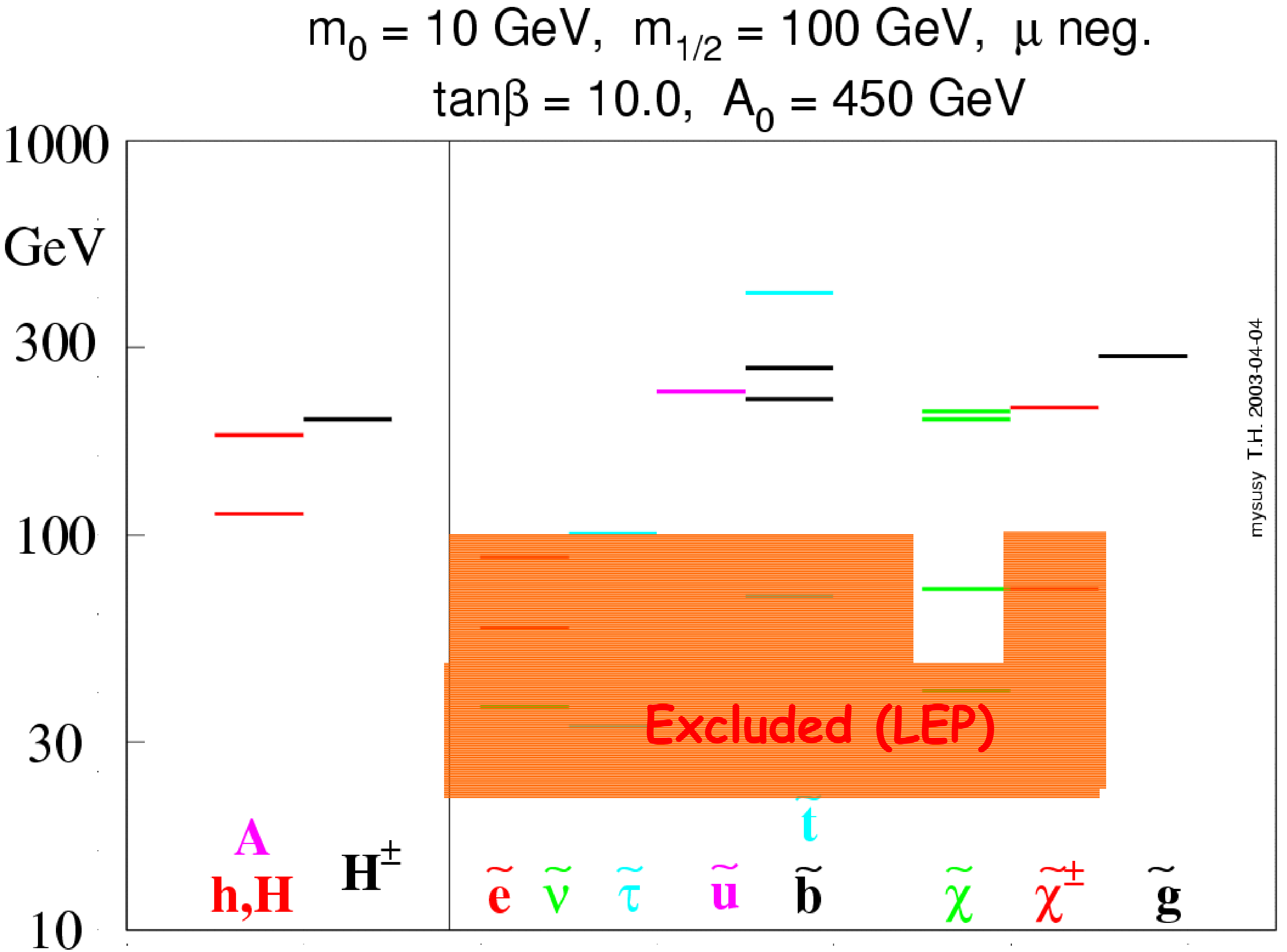
- M(SUSY) < 1 TeV
- LSP without electromagnetic and strong coupling

Note: m_h given by m_0 ... **LEP higgs limit = severe constraint**

MSUGRA masses



MSUGRA scenario 1



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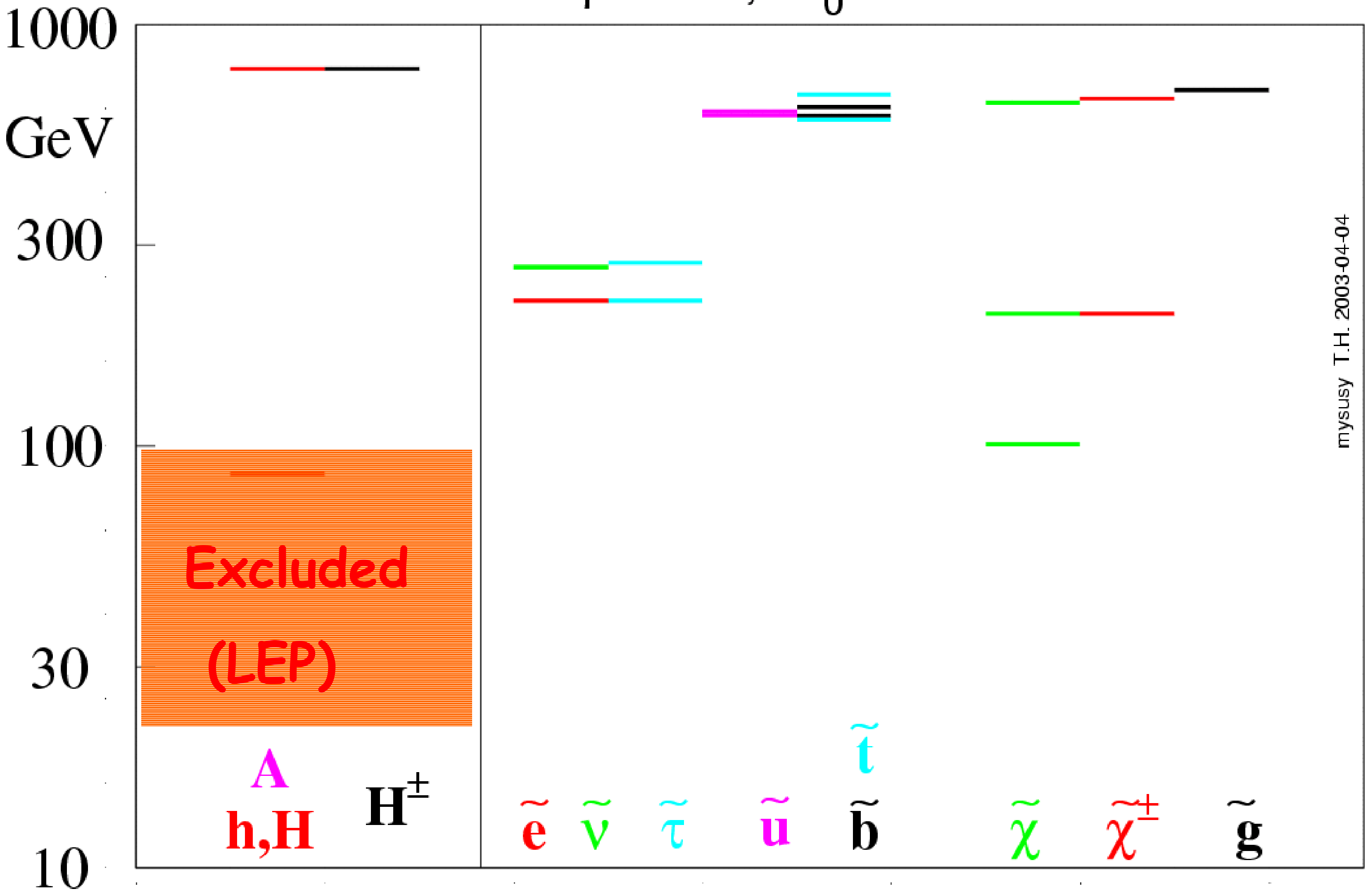
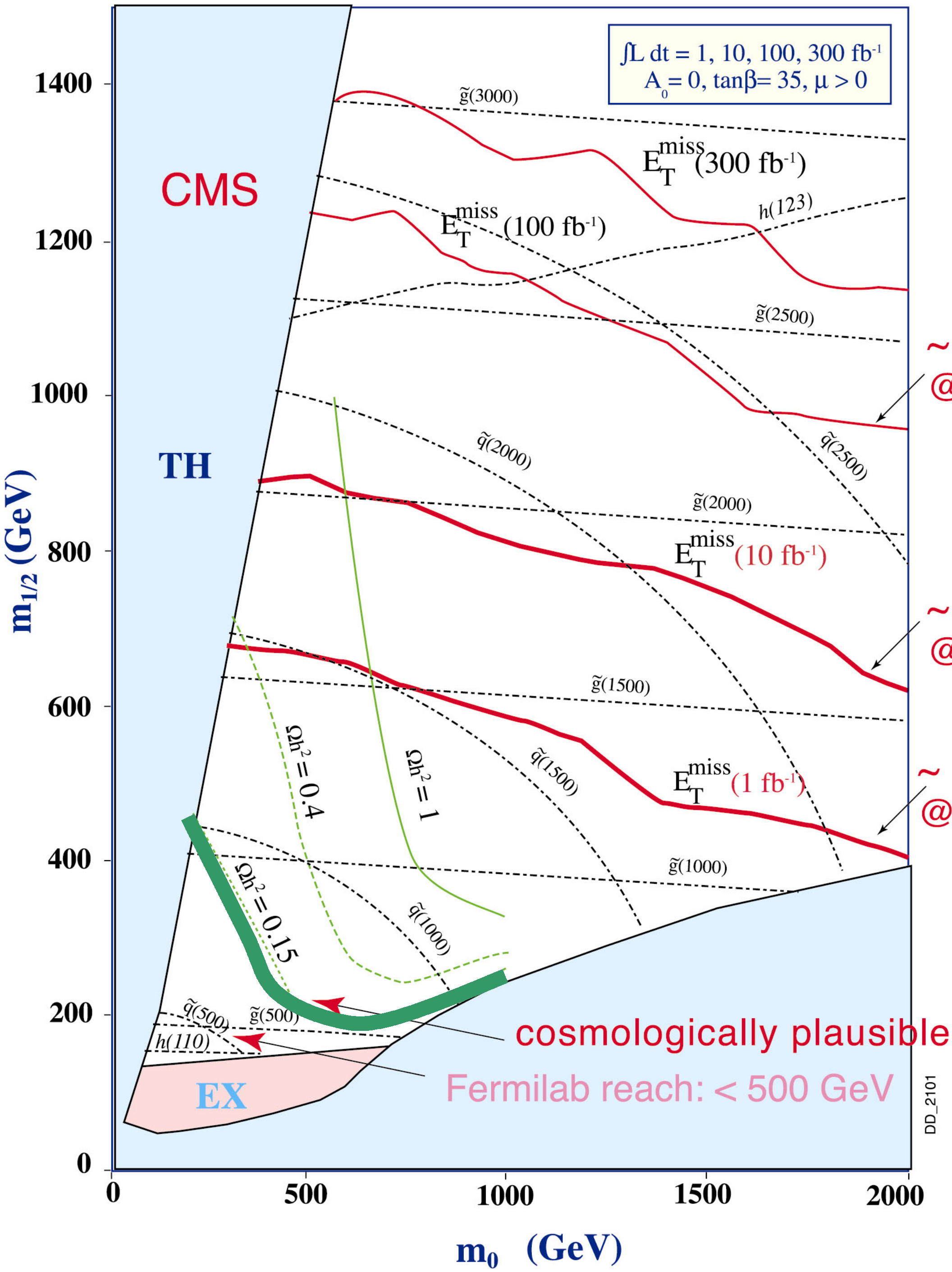
MSUGRA scenario 2

$m_0 = 200$ GeV, $m_{1/2} = 243$ GeV, μ neg.
$\tan\beta = 2.0$, $A_0 = 0$ GeV



SUSY reach



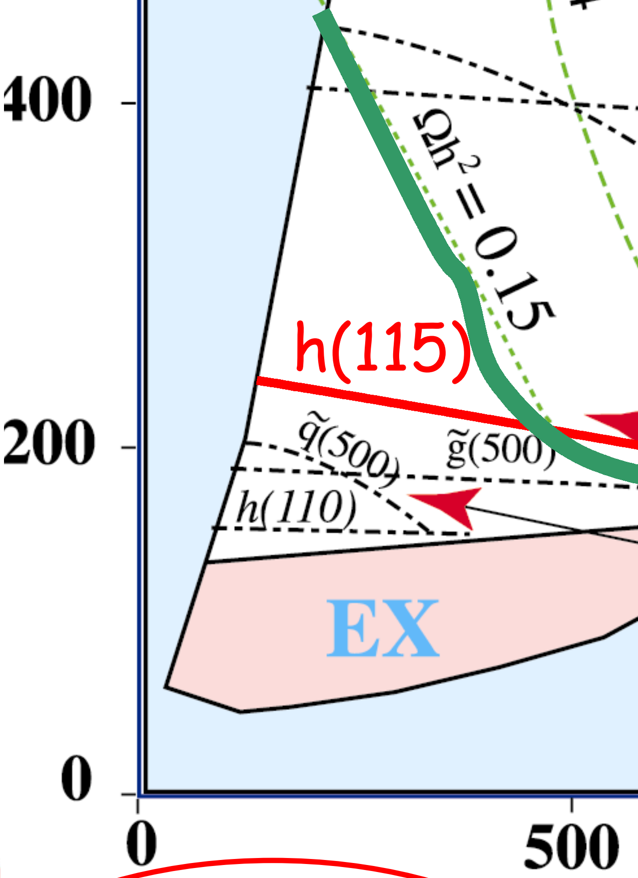
~ one year @10^{34}

~ one year @10^{33}

~ one month @10^{33}

cosmologically plausible region

Fermilab reach: < 500 GeV



Cosmological constraint (dark matter) essential!

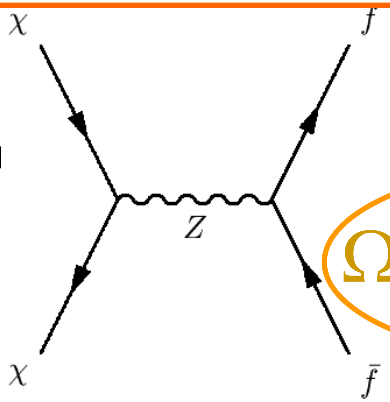
Cosmological Constraints I

Assume: neutralino = $\tilde{\chi}_0$ =dark matter = WIMP

Early universe:

theory

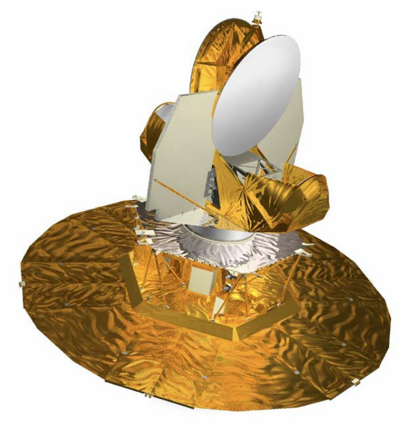
1) Very high temperature and pressure:
   creation and annihilation: equilibrium
2) High temperature and pressure:
   annihilation dominates: $N(\tilde{\chi}_0)\downarrow$
3) Low temperature and pressure:
   freeze out: $N(\tilde{\chi}_0) = const$



$$\Omega_{DM} = f(m_\chi,...)$$

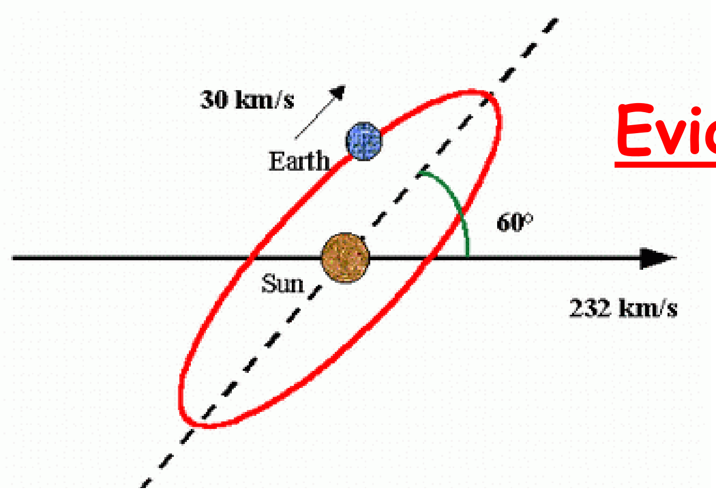
observation

WMAP
measurement of
cosmic microwave
background

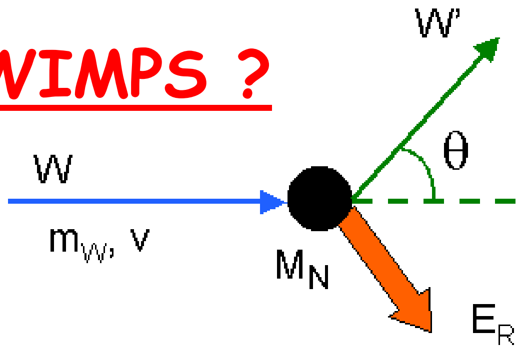


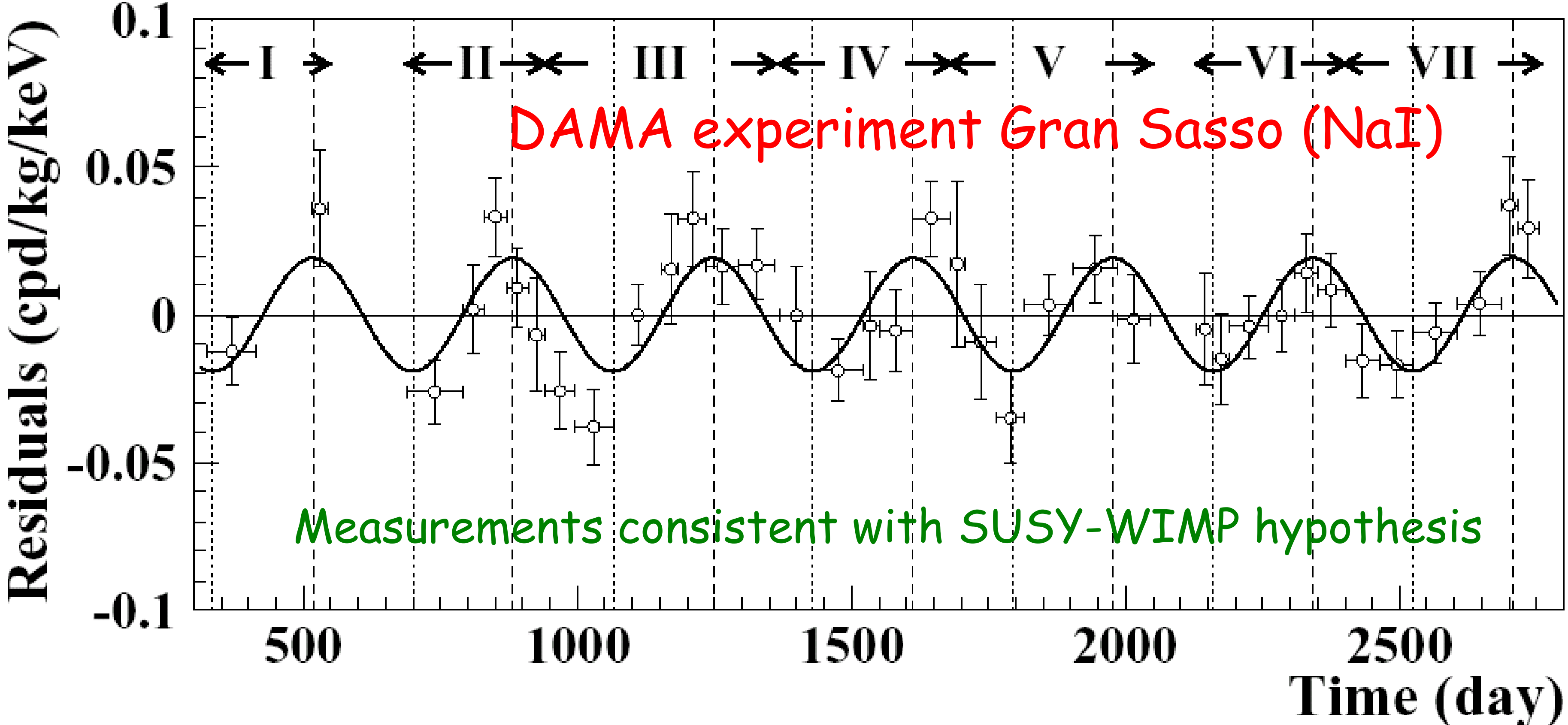
$$\Omega_{DM} = 0.23$$

Cosmological Constraints II



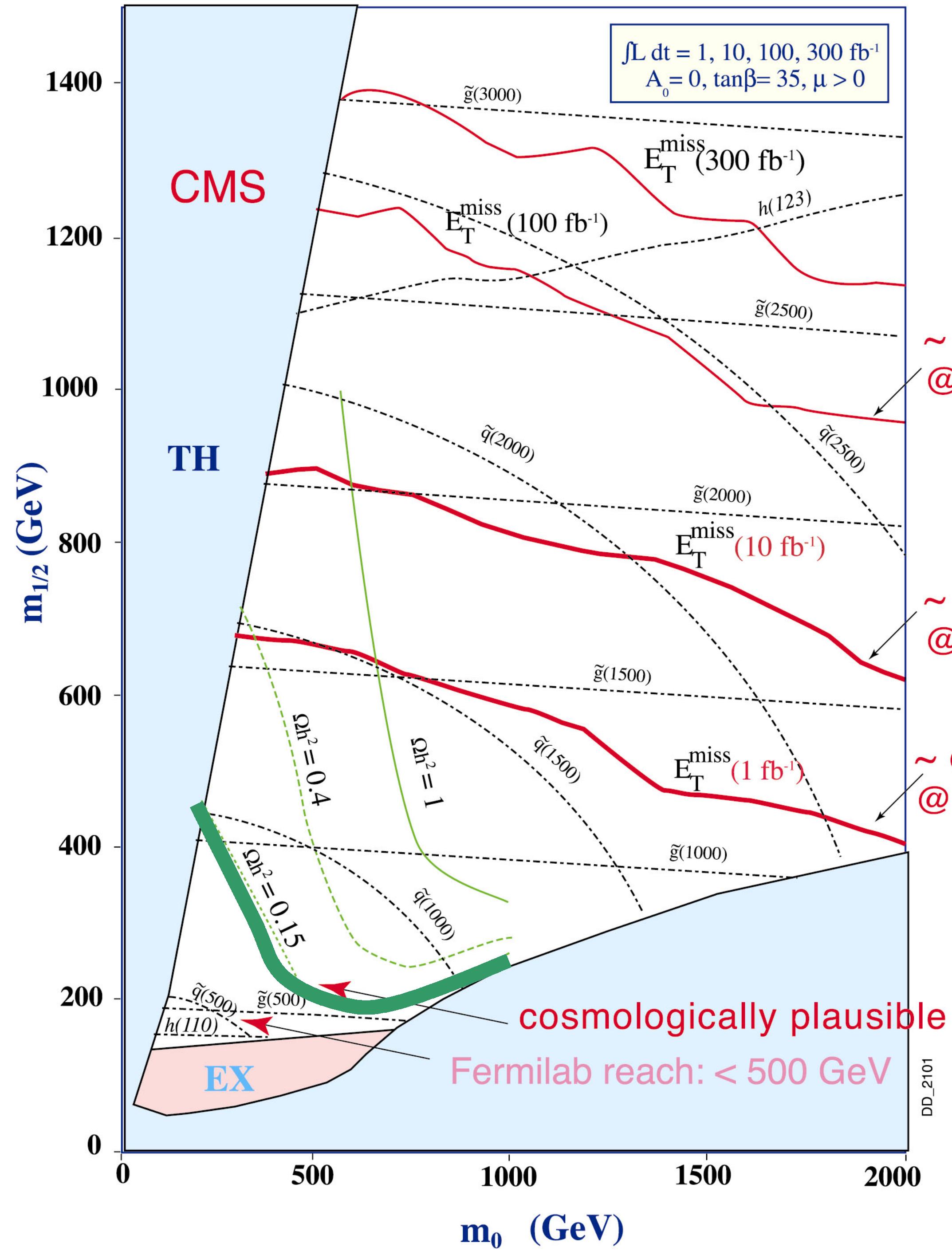
Evidence for relic WIMPS ?





DAMA experiment Gran Sasso (NaI)

Measurements consistent with SUSY-WIMP hypothesis



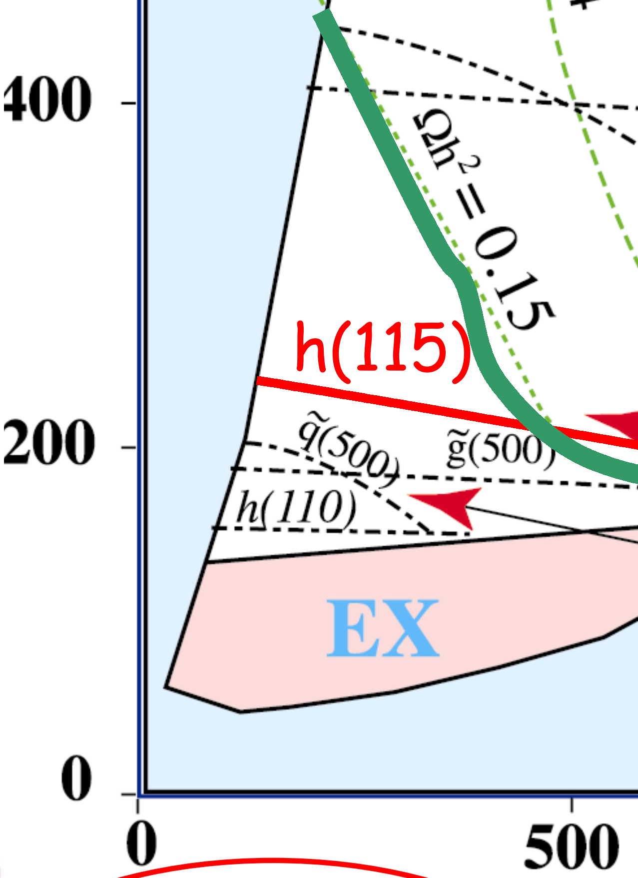
~ one year @10^{34}

~ one year @10^{33}

~ one month @10^{33}

cosmologically plausible region

Fermilab reach: < 500 GeV



If dark matter:

Fermilab: **NO**

LHC: **YES**

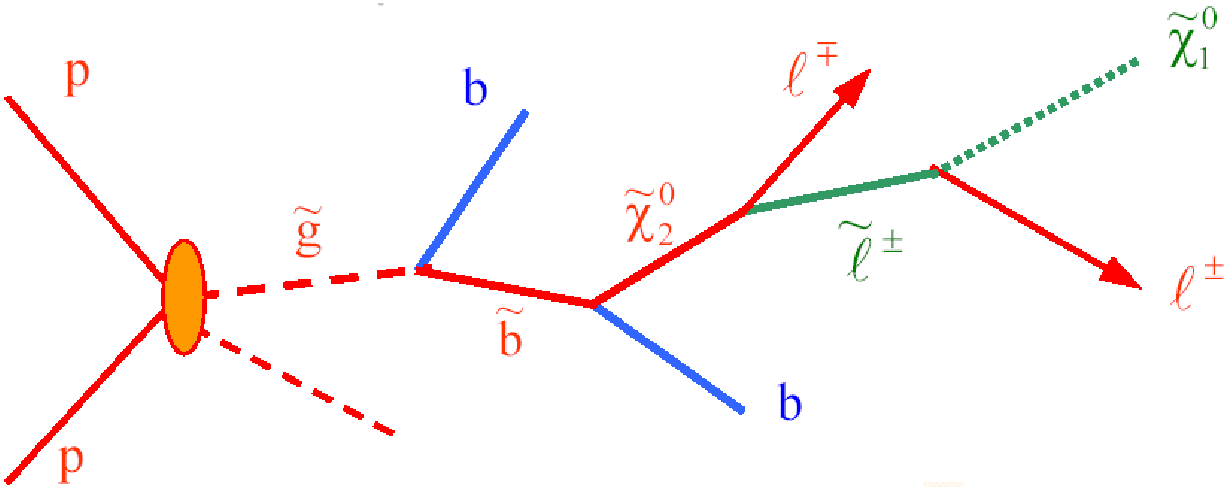
SUSY reach

SUSY search in pp

strategy:

high SM QCD background: jets

need something beyond: **leptons and/or missing energy**



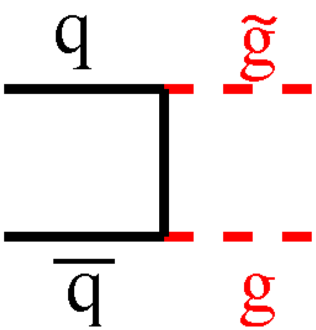
Examples:

- squarks and gluinos (missing energy) strong
- neutralinos and charginos (leptons and missing energy)

electroweak

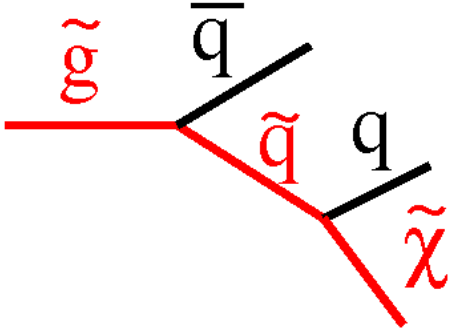
Jets + Missing Energy: Squark and Gluino Search

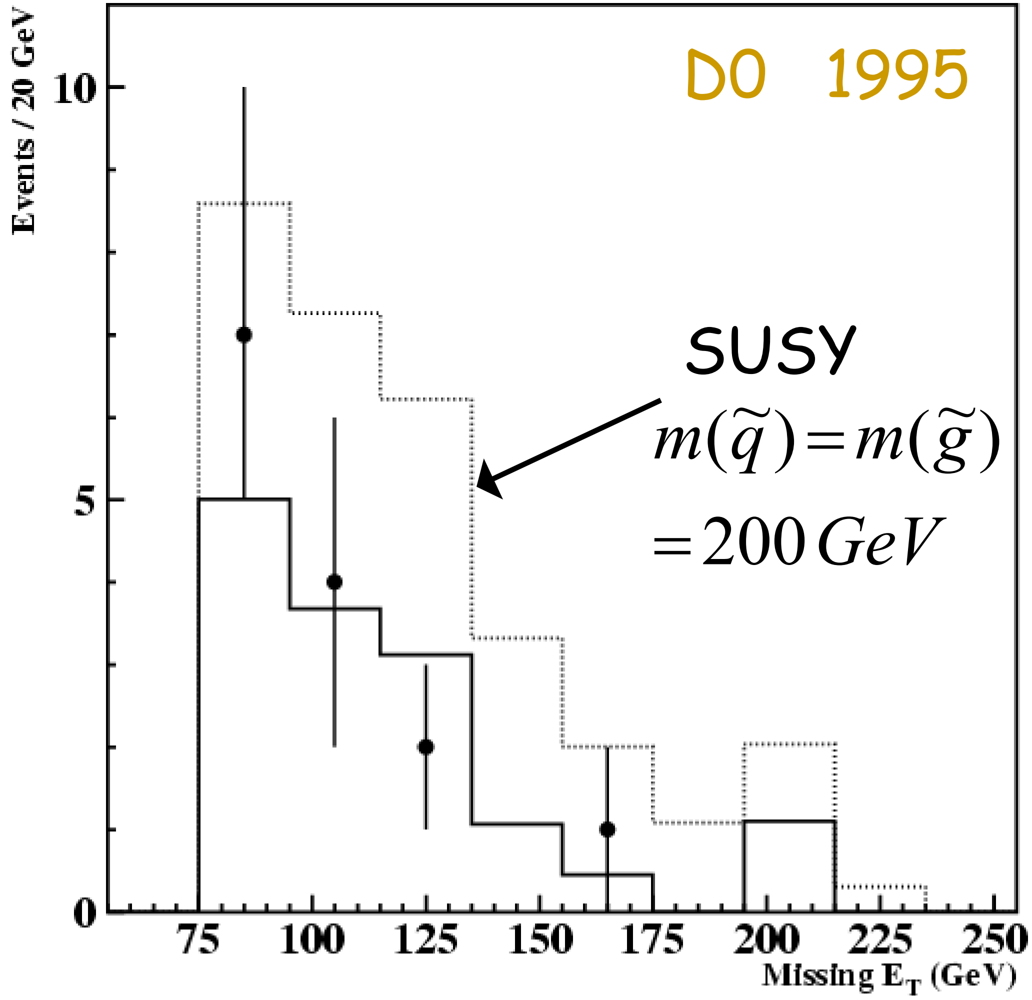
Production (ex.):



cross section large !

Decay (ex.):





Results

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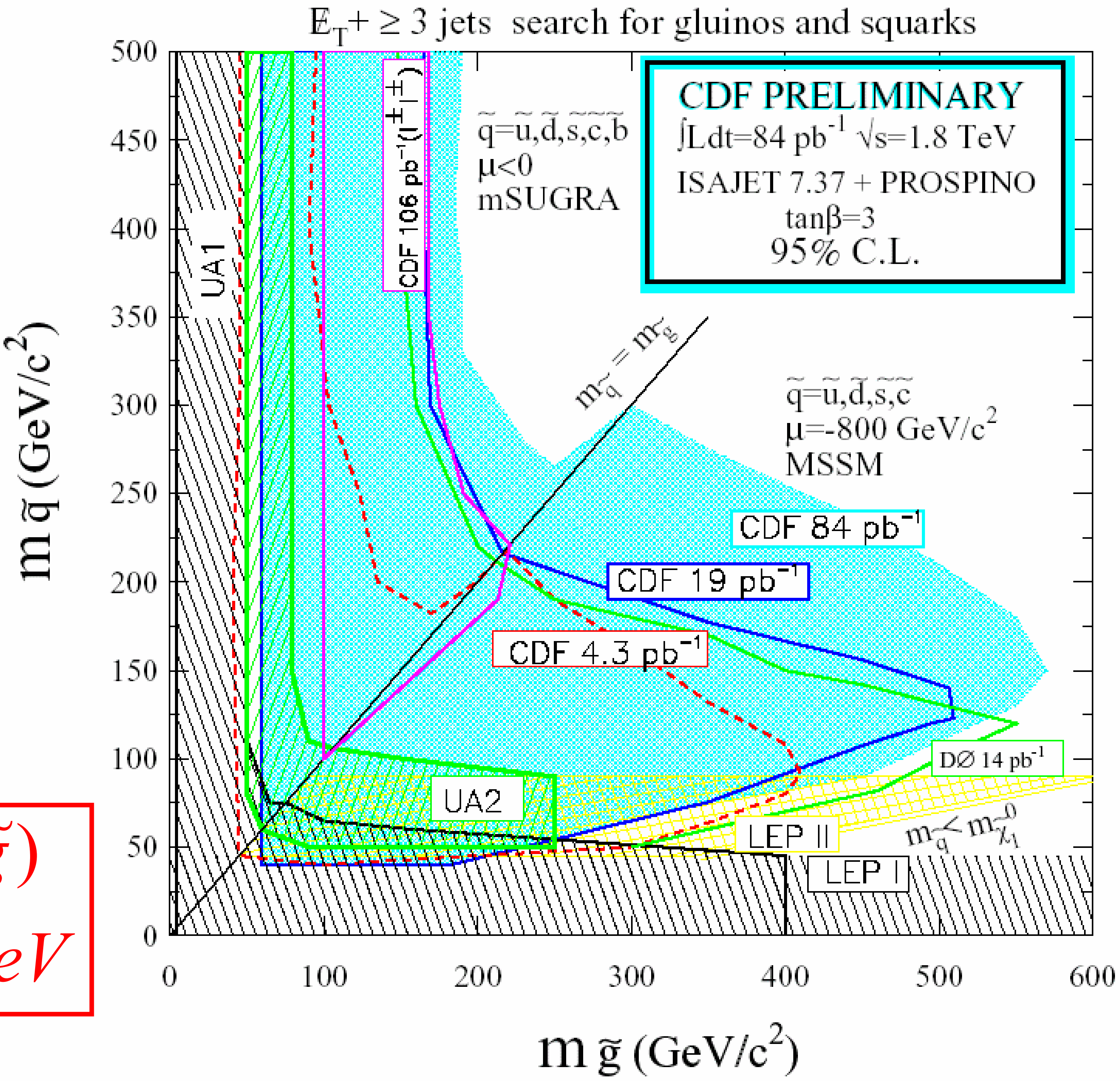
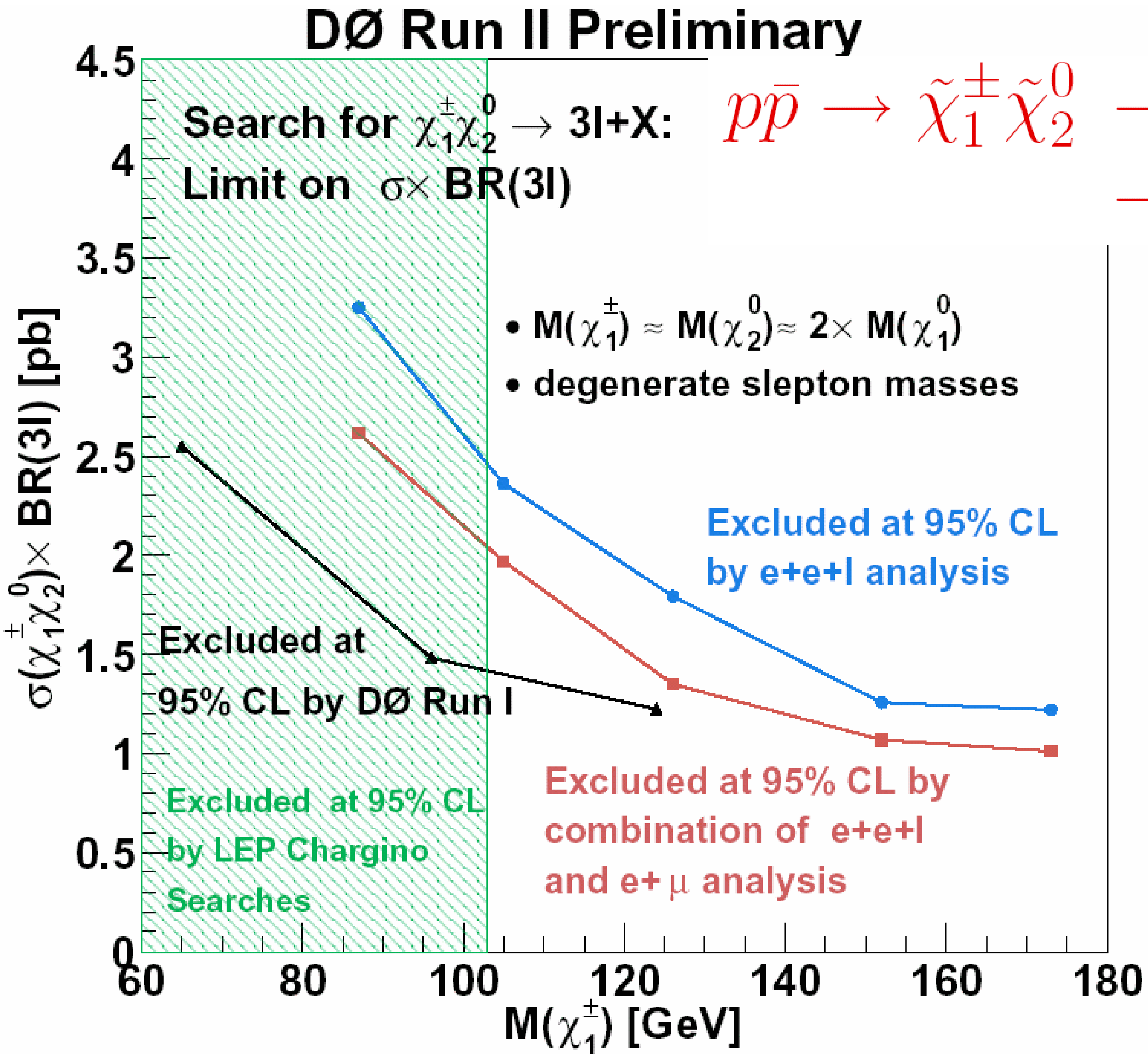


$$m(\tilde q), m(\tilde g)$$
$$>\sim 200\, GeV$$

Leptons: Hunting Charginos and Neutralinos

$$p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \ell e e \nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$\rightarrow \ell e \mu \nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$$



Expected SUSY xsection factor ~10 lower

No (improved) SUSY limit yet

SUSY particle reconstruction

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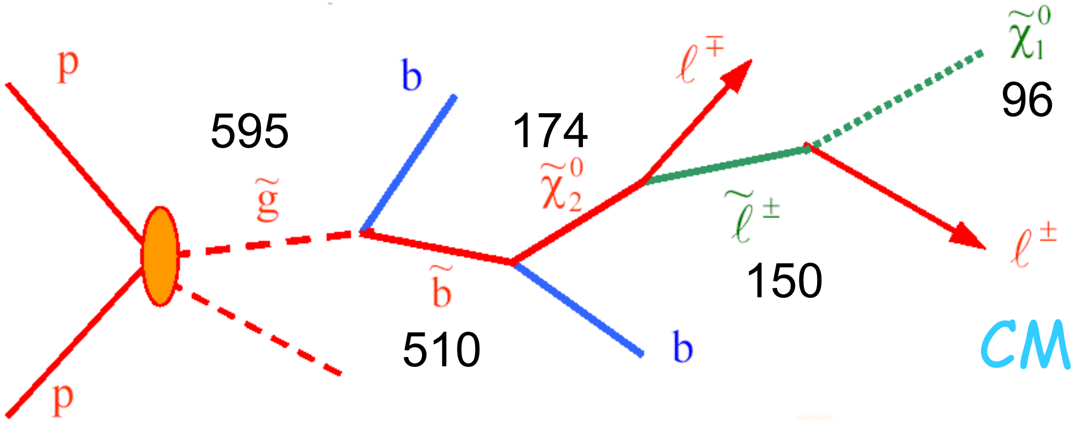
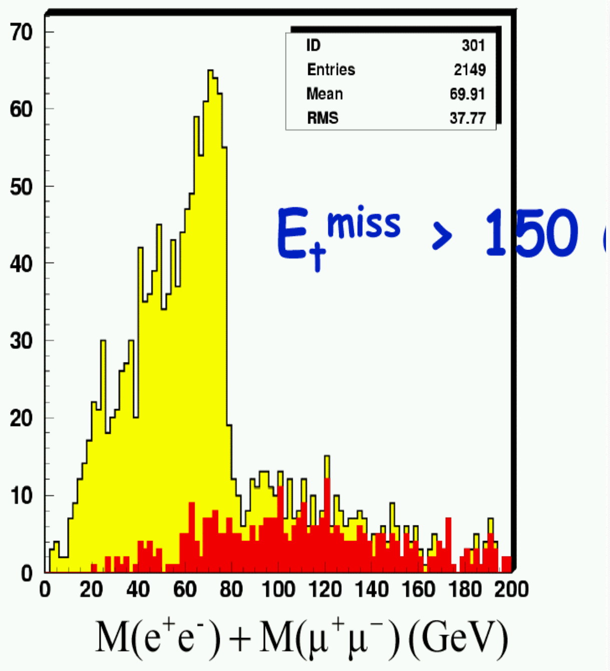


(assume neutralino
mass)

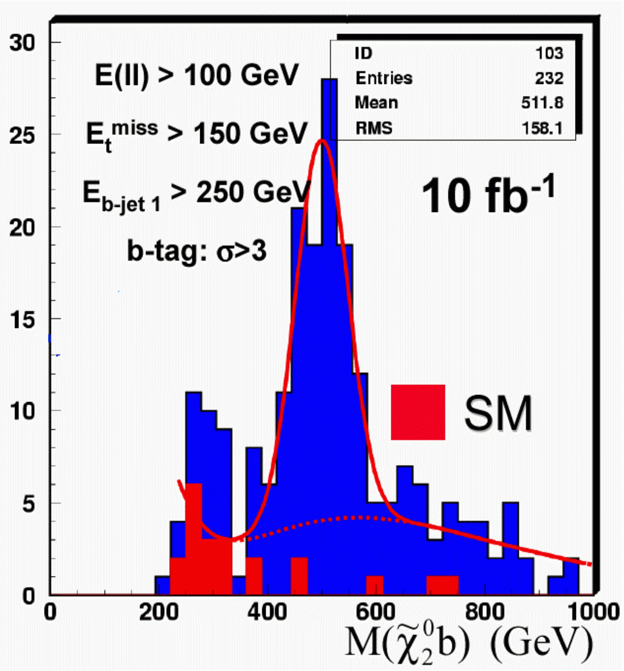
CMS MC study

(neutralino 2)



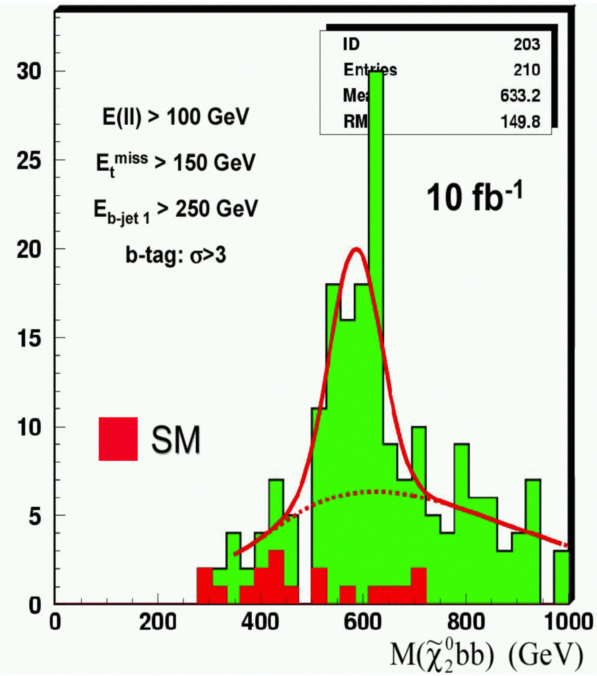
edge 78.9 +/- 2.1 GeV

sbottom



499.4 +/- 6.6 GeV

gluino



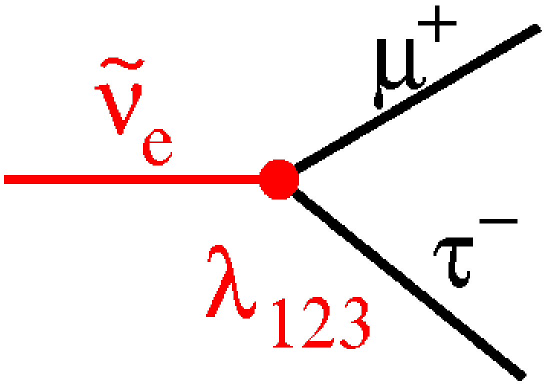
585.1 +/- 11.1 GeV

Chiorboli/Tricomi

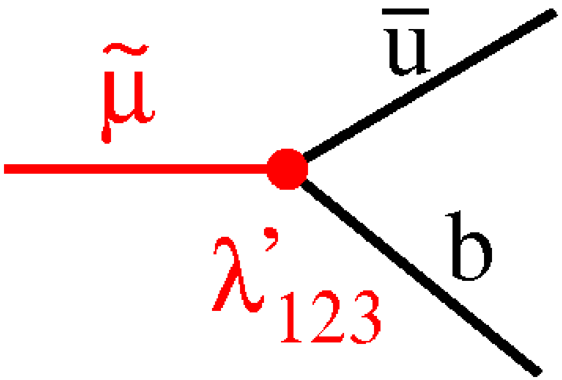
SUSY with R parity violation

- neutralino unstable, no dark matter candidate !
- lepton and/or baryon number violated

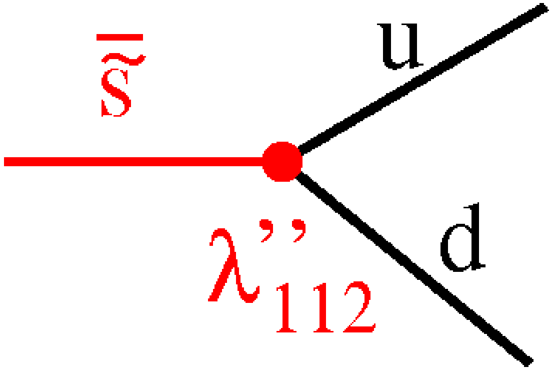
Example diagrams:



violates L



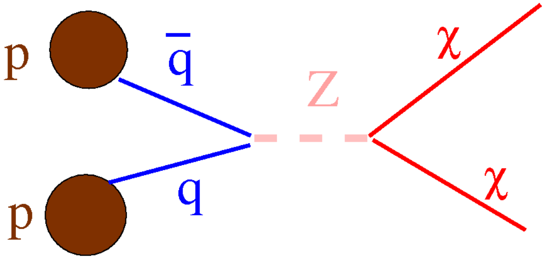
violates L



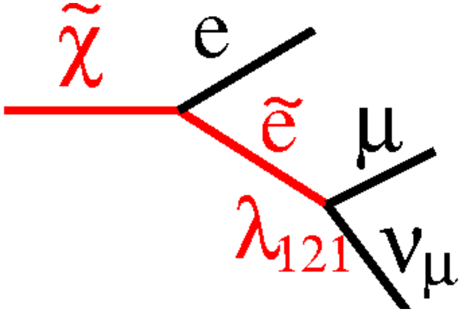
violates B

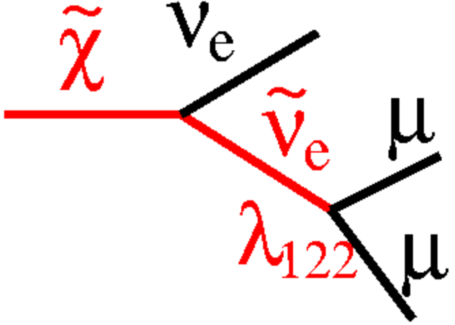
Example: Neutralino Decays via $\lambda_{121}, \lambda_{122}, \ldots$

production:

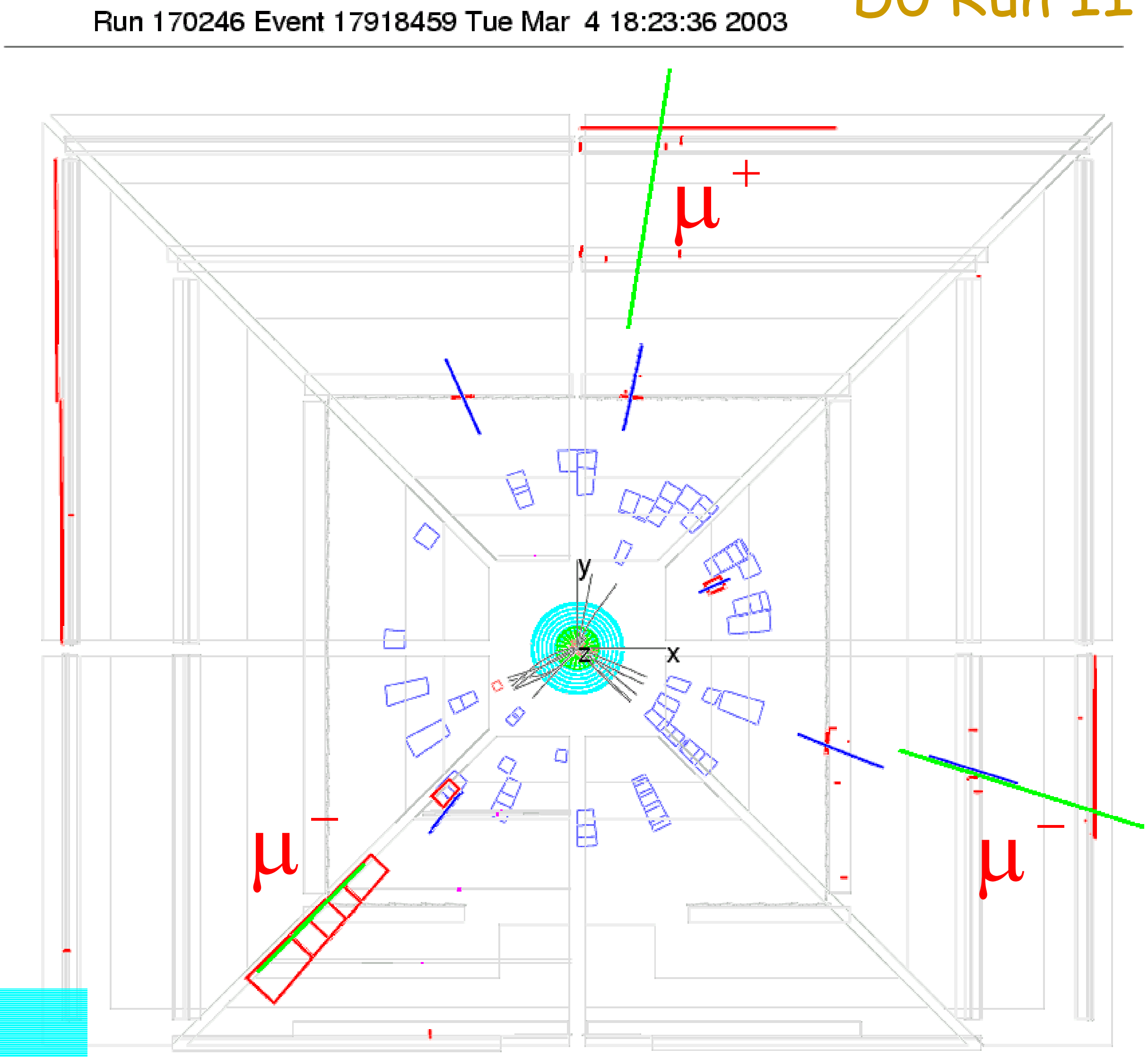


decay (examples):





D0 Run II



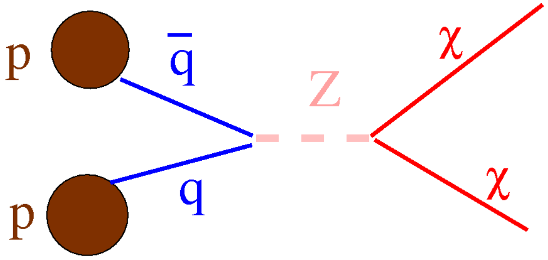
View 1, Front(X-Y)

signature:

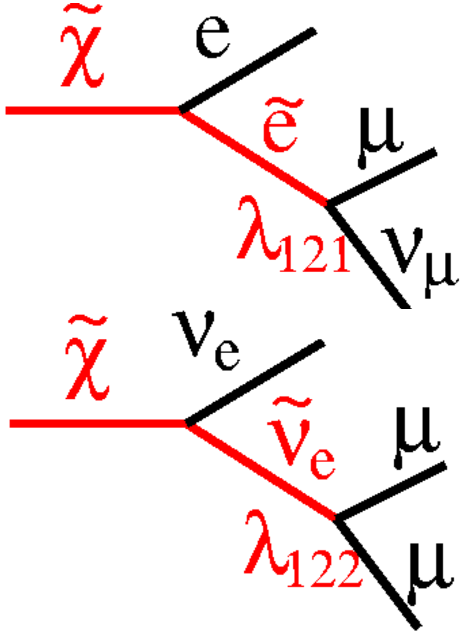
at least 3 charged leptons!

Example: Neutralino Decays via $\lambda_{121}, \lambda_{122}$,...

production:

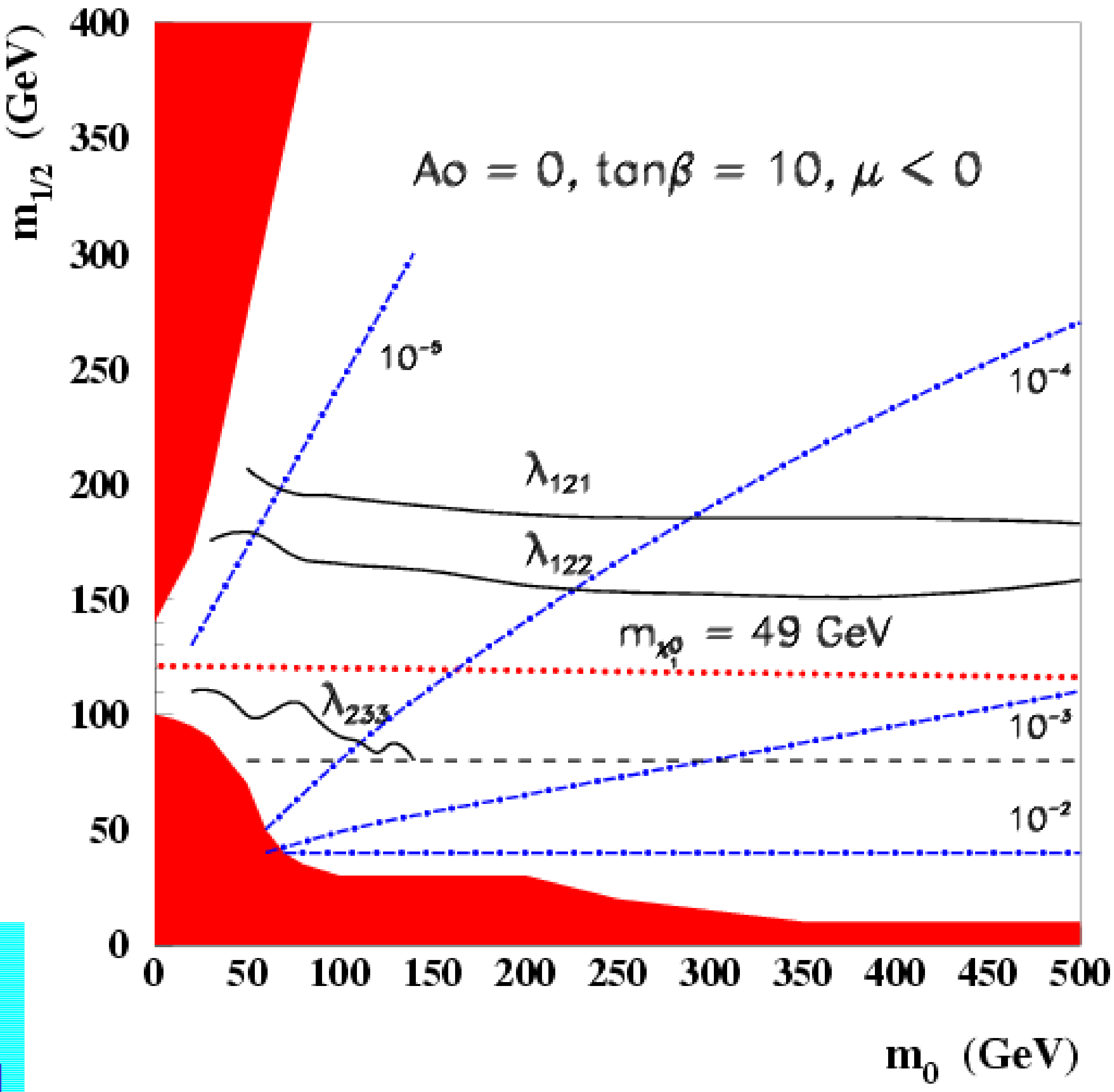


decay (examples):



upper limits:

D0 Run



experimental signature:

at least 3 charged leptons!

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(Large) Extra Dimensions

Why is gravity so different from the other interactions ?

mass and length scales:

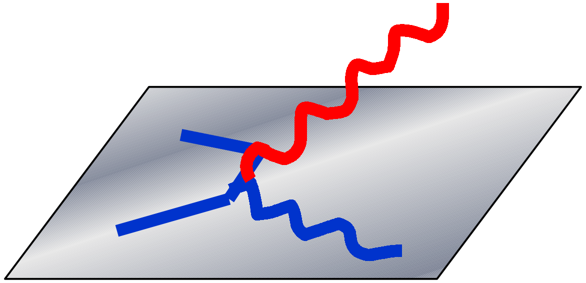
$$M_{ew} \sim 10^2\, GeV \qquad l_{ew} \sim 10^{-18}\, m$$

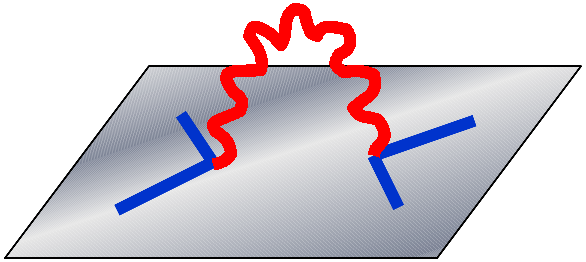
$$M_{Pl} \sim \frac{1}{\sqrt{G_N}} \sim 10^{19}\, GeV \qquad l_g \sim 10^{-35}\, m$$

Idea: only one fundamental scale M_S ~ 100 - 1000 GeV

gravity appears weak since gravitons propagate

in 4 + n dimensions („dilution")

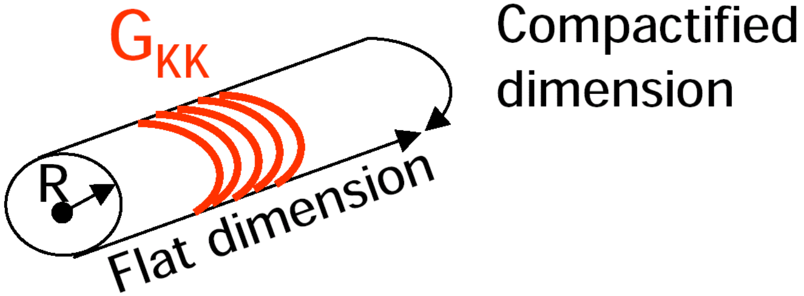




Arkani-Hamed, Dimopoulos, Dvali

Extra Dimensions: phenomenolgy

n extra dimensions of space with size R:



Escher

$$\boxed{V \sim \frac{1}{M_{Pl}^{2}} \frac{m_1 m_2}{r}} \Rightarrow \boxed{V \sim \frac{1}{M_S^{2+n}} \frac{1}{R^n} \frac{m_1 m_2}{r}}$$

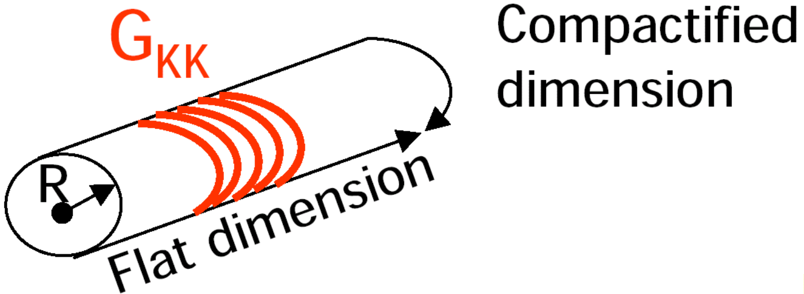
- deviations from Newton/Einstein laws for r < R

  therefore n=1 and n=2 ruled out!

- gravitons G show up in high energy physics experiments as real or virtual particles $\Big\}$ **pp colliders!**

Extra Dimensions: phenomenolgy

n extra dimensions of space with size R:



$$R = \frac{1}{2\sqrt{\pi} M_S}\left(\frac{M_{Pl}}{M_S}\right)^{2/n} \propto \begin{cases} 8\times 10^{12}\,m, & n=1 \\ 0.7\,mm, & n=2 \\ 3\,nm, & n=3 \\ 6\times 10^{-12}\,m, & n=4 \end{cases}$$

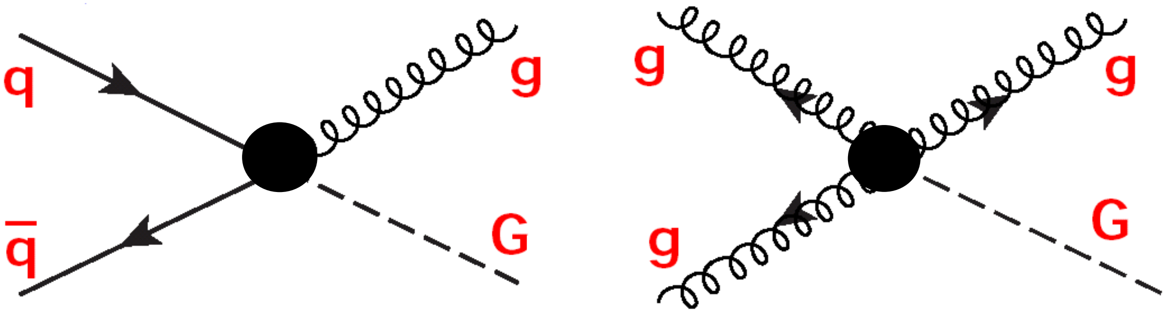

Escher

- deviations from Newton/Einstein laws for r < R

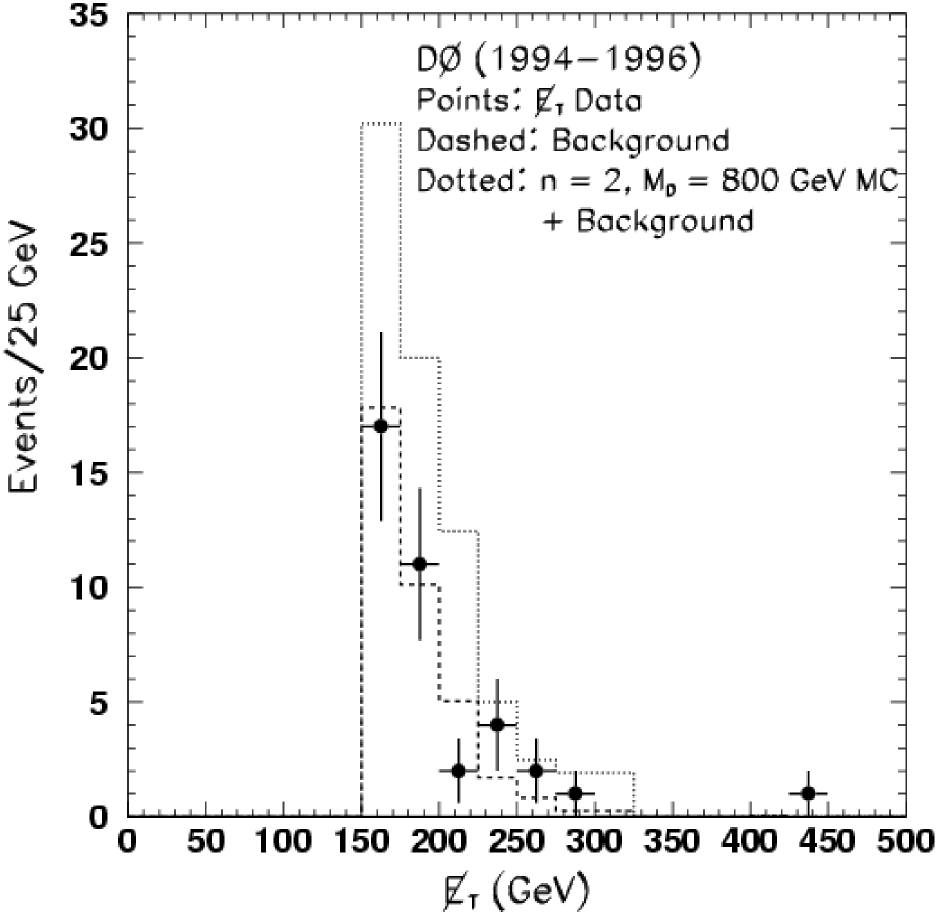
  therefore n=1 and n=2 ruled out!

- gravitons G show up in high energy physics
  experiments as real or virtual particles } **pp colliders!**

Real Graviton Emission in p p



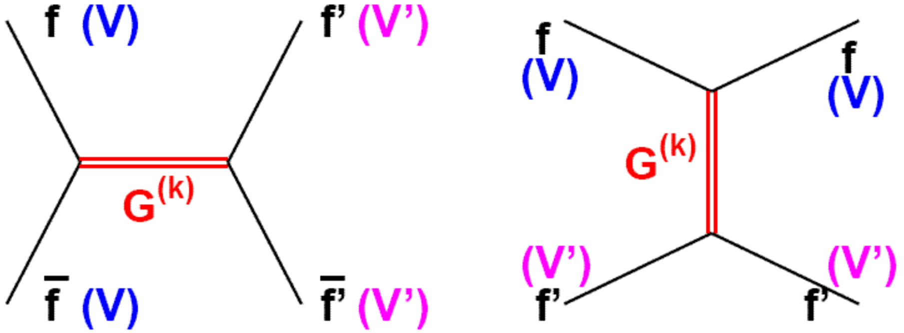
Monojet signatures!



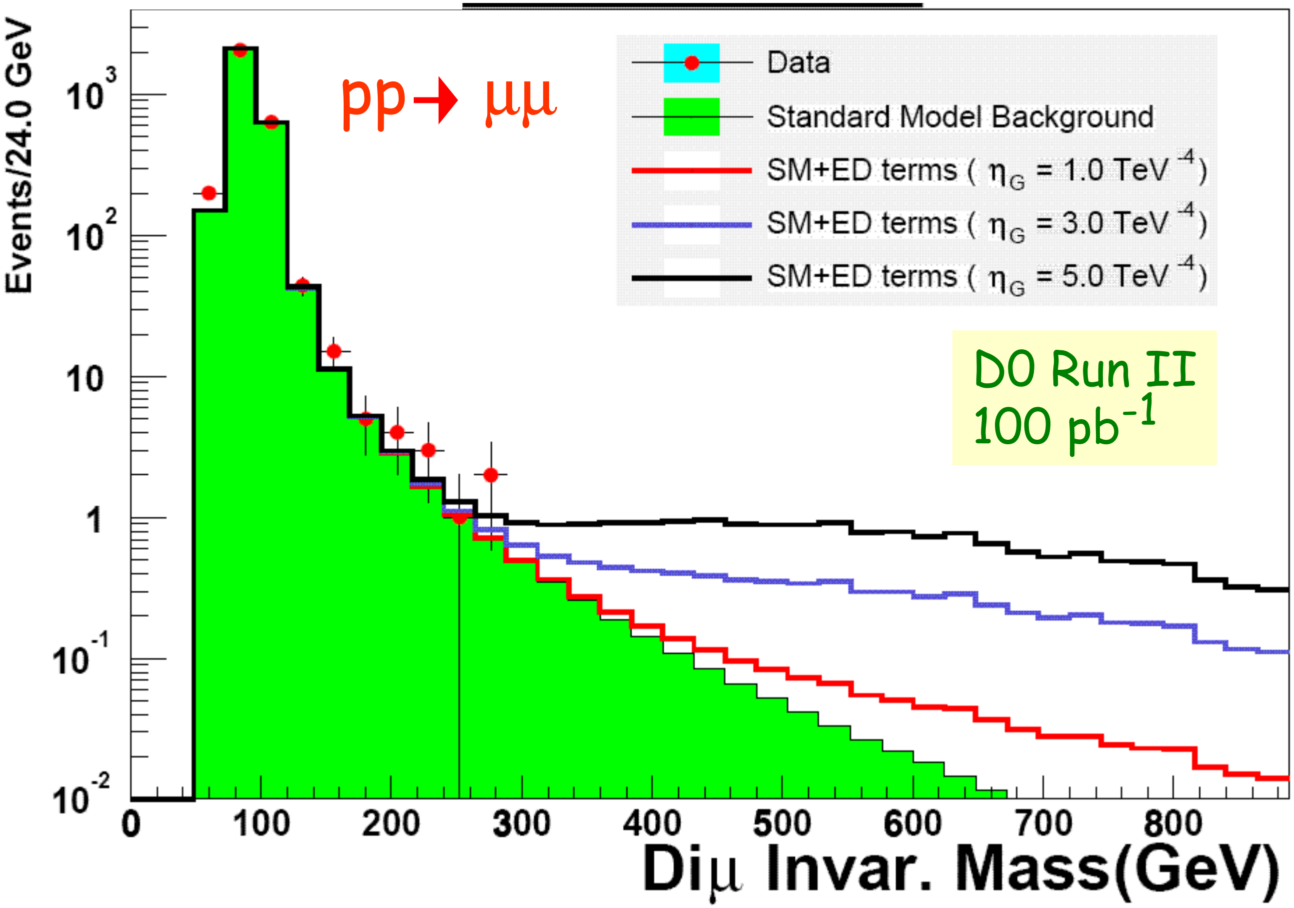
<u>resulting lower limits on M_S/GeV:</u>

n=2	n=3	n=4	n=5	n=7
890	730	680	640	620

Virtual Graviton effects in p p



SM cross sections modified!



All D0 analyses

$(ee, \mu\mu, \gamma\gamma)$

combined:

$$\boxed{M_S(n=2) > 1.38\,TeV}$$

Black holes ?

predicted in large extra dimension models

production: mass 1 - 10 TeV, xsection large (~ nb)

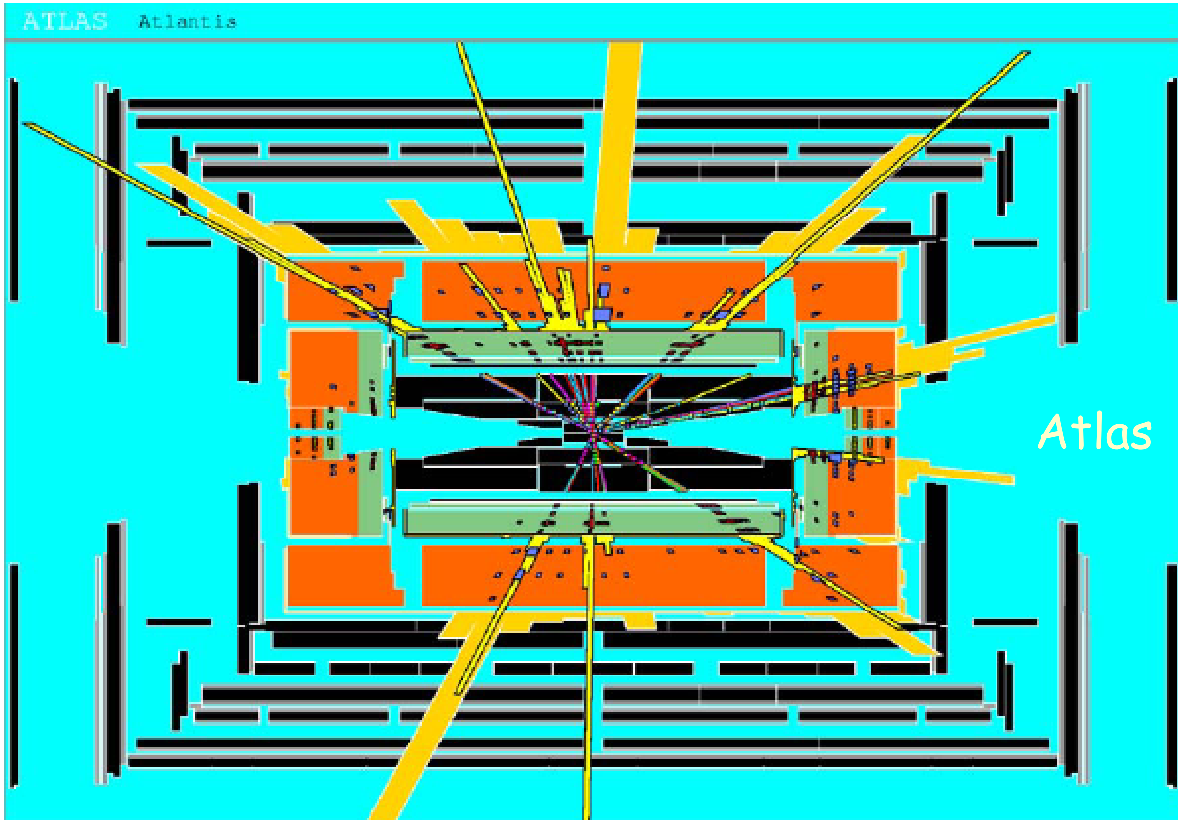
decay:

Hawking radiation

All SM d.o.f. equally likely

Multiplicity up to 30

Decay also into higgs!



Part I Introduction

Part II Standard Model Physics

Part III Higgs

Part IV New Phenomena

- SUSY
  motivation
  searches:
    R-Parity conserved
    R-Parity violated
- Extra dimensions
- Black holes

References

References

- lectures:

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- experimental homepages:

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  atlas.web.cern.ch

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- theory:

  Physics at Run II workshop

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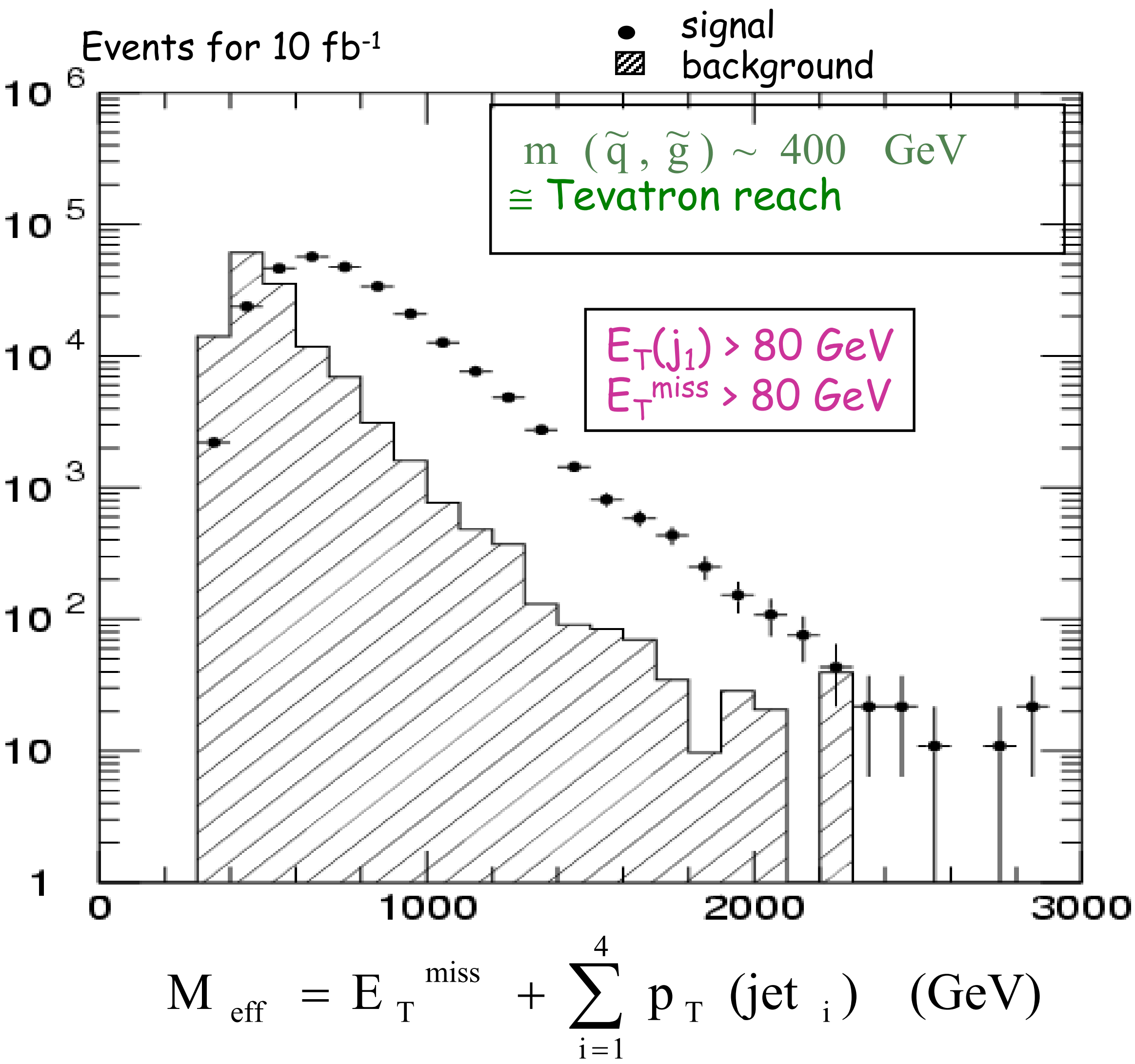
Appendices



$m\ (\tilde{q}\,,\ \tilde{g}\,)\sim\ 400\ \ \mathrm{GeV}$

$\cong$ Tevatron reach

$E_T(j_1) > 80$ GeV

$E_T^{miss} > 80$ GeV

$$M_{eff} = E_T^{miss} + \sum_{i=1}^{4} p_T\ (\mathrm{jet}_i)\quad (\mathrm{GeV})$$

Inclusive $\ell^+\ell^- + E_t^{miss}$ final states

m_0 = 200 GeV, $m_{1/2}$ = 160 GeV,
tgβ = 2, A_0 = 0, μ<0