8.882 LHC Physics

Experimental Methods and Measurements

Review

[Lecture 26, May 13, 2009]

Organization

Final – Students Conference

- Tuesday May 19, starts at 12:00am in 26-528
- please ask questions as early as possible
- I am available in the Geneva (Switzerland)
- arrange for a rehearsal and discussion session

Physics
Colloquium Series

‘09

Spring

The Physics Colloquium Series

Thursday, May 14 at ***4:15 pm*** *in room* ***10-250***

Xiaowei Zhuang

Harvard University

"Imaging the Nanoscopic World of Living Systems"

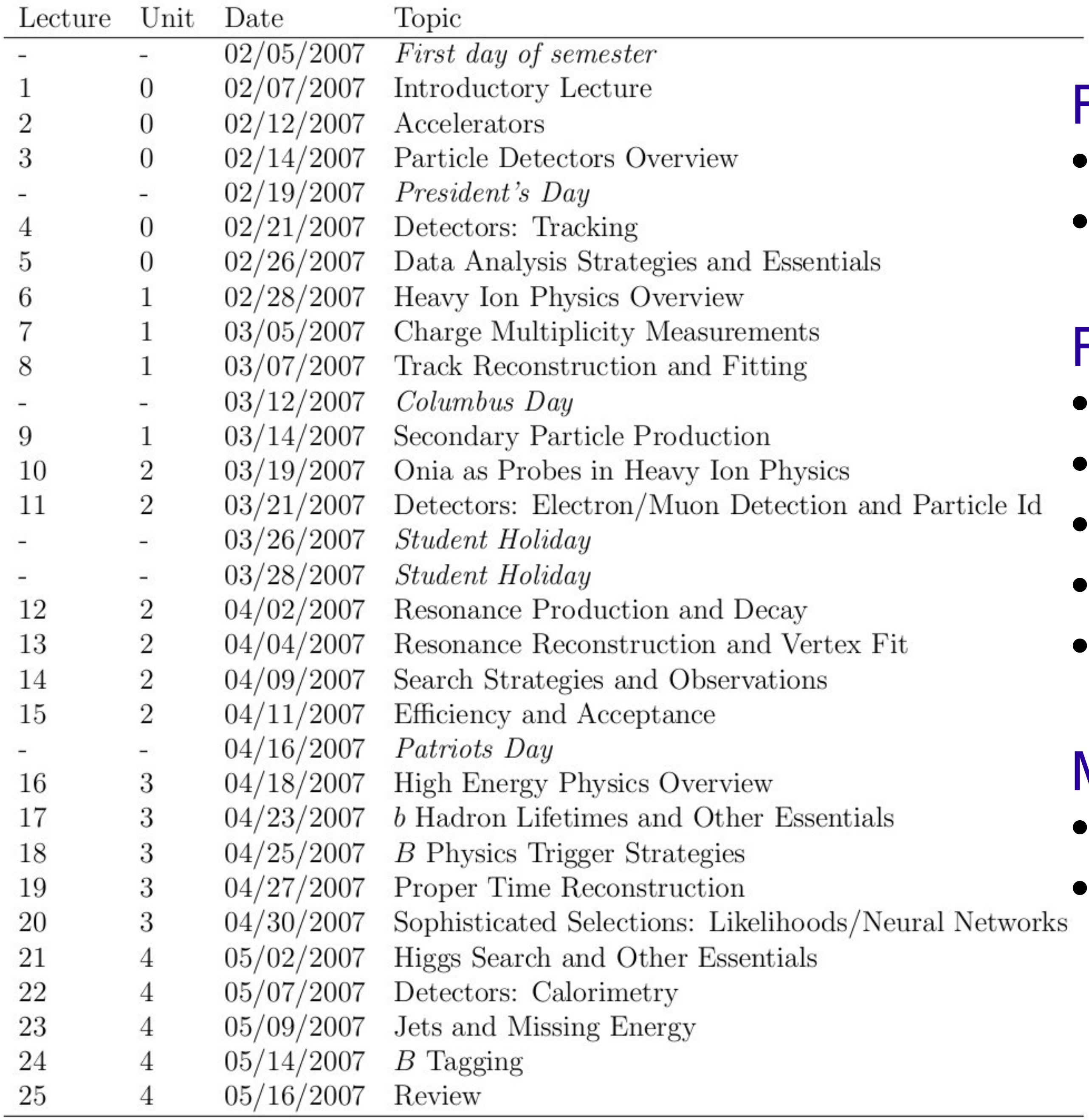
For a full listing of this semester’s colloquia,
please visit our website at web.mit.edu/physics

Lecture Outline

Review

- Lecture layout and what we really covered
- LHC project and the Tevatron
  - Physics goals and Accelerators
- Particle Detectors
- Heavy Ion Physics
  - Charge Multiplicity and Resonances – Cross Sections
- *B* Physics
  - Lifetime
- The Standard Model Higgs – Searches
- Thoughts ....

Lecture Layout



Lecture	Unit	Date	Topic
-	-	02/05/2007	*First day of semester*
1	0	02/07/2007	Introductory Lecture
2	0	02/12/2007	Accelerators
3	0	02/14/2007	Particle Detectors Overview
-	-	02/19/2007	*President's Day*
4	0	02/21/2007	Detectors: Tracking
5	0	02/26/2007	Data Analysis Strategies and Essentials
6	1	02/28/2007	Heavy Ion Physics Overview
7	1	03/05/2007	Charge Multiplicity Measurements
8	1	03/07/2007	Track Reconstruction and Fitting
-	-	03/12/2007	*Columbus Day*
9	1	03/14/2007	Secondary Particle Production
10	2	03/19/2007	Onia as Probes in Heavy Ion Physics
11	2	03/21/2007	Detectors: Electron/Muon Detection and Particle Id
-	-	03/26/2007	*Student Holiday*
-	-	03/28/2007	*Student Holiday*
12	2	04/02/2007	Resonance Production and Decay
13	2	04/04/2007	Resonance Reconstruction and Vertex Fit
14	2	04/09/2007	Search Strategies and Observations
15	2	04/11/2007	Efficiency and Acceptance
-	-	04/16/2007	*Patriots Day*
16	3	04/18/2007	High Energy Physics Overview
17	3	04/23/2007	b Hadron Lifetimes and Other Essentials
18	3	04/25/2007	B Physics Trigger Strategies
19	3	04/27/2007	Proper Time Reconstruction
20	3	04/30/2007	Sophisticated Selections: Likelihoods/Neural Networks
21	4	05/02/2007	Higgs Search and Other Essentials
22	4	05/07/2007	Detectors: Calorimetry
23	4	05/09/2007	Jets and Missing Energy
24	4	05/14/2007	B Tagging
25	4	05/16/2007	Review

Foreseen Schedule
- largely carried through
- modifications in last third

Five main blocks
- introductory
- charge multiplicity
- upsilon cross section
- B meson lifetime
- Standard Model Higgs

Modifications
- extended Higgs section
- no b-tagging section

Heavy Ion Physics

Goals

- find regime to set the quarks and gluons free
- we know, they are asymptotically free (QCD)
- matter has to be extremely dense that protons break up
- recreates phase of the universe close to the big bang
- quark-gluon-plasma (quark gluon gas, weakly coupled)

Implementation

- accelerates many neutrons and protons to very large energies and collide them
- best done by using heavy ions (heavy = large A)
- ions to accelerate, electrons completely removed

Quark Gluon Plasma or what?

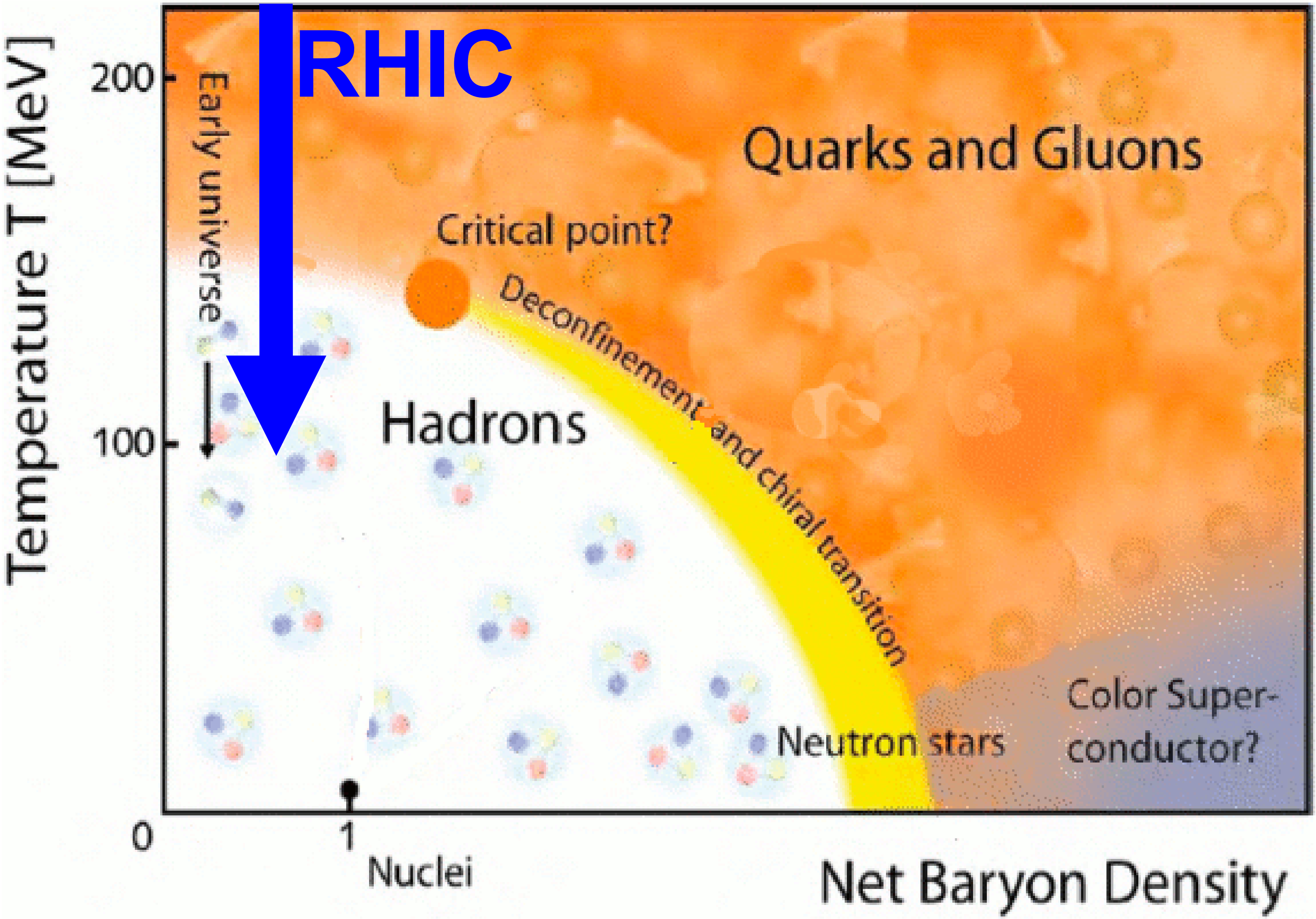
Expected to find Quark-Gluon Plasma

- gas in which quarks and gluons are free
- naïve starting point: put quarks/gluons close together but give them lots of energy (10-20 times then in proton)
- expect asymptotic freedom to do the rest
- subtle balance between energy and force required
- problem: calculations are close to impossible

Experiments find

- no quark-gluon plasma
- instead the quark-gluon conglomerate that behaves like a liquid

State Diagram



High Energy Physics

Big questions in High Energy Physics

- the matter problem(s)
  - where does matter originate from? which mechanism?
  - what is the large amount of dark matter in the universe?
  - (what is the even larger amount of dark energy?)

- matter anti-matter asymmetry and *CP* violation
  - why is there so much matter and so little anti-matter?
  - big bang should have produced them in equal amounts
  - *CP* operation has to be asymmetric (violates symmetry)
  - Standard Model *CP* violation cannot explain observed asymmetry
    - could explain existence of just one galaxy but not the universe
    - there must be something else, *CP* violating, generating the rest

High Energy Physics

Big questions in High Energy Physics, *continued*

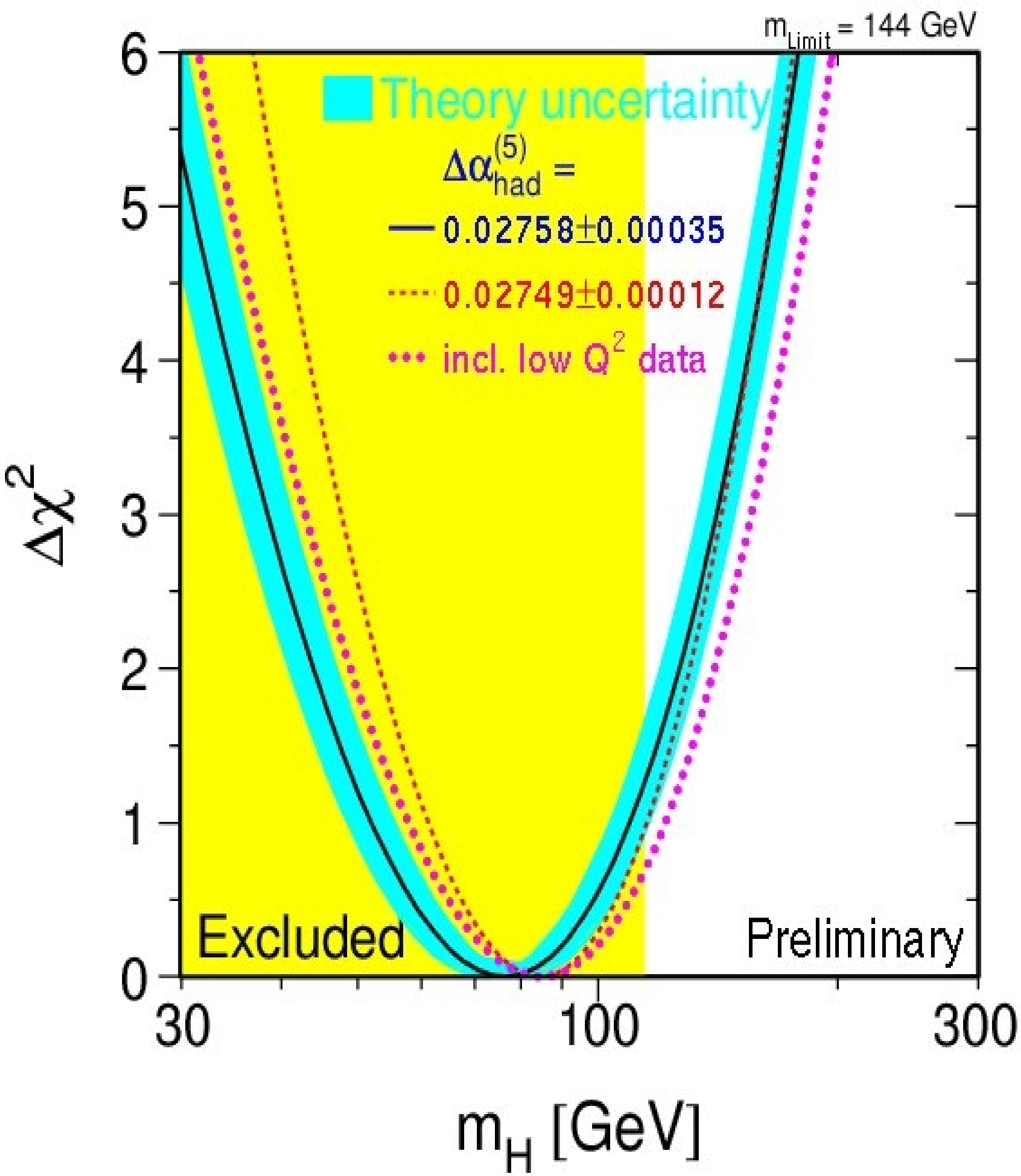
- Hierarchy problem(s)
  - general idea: fundamental parameters are much smaller/bigger than parameters measured in the experiment
  - why is the weak force 10^{32} times stronger than gravity?
  - or otherwise put: why is the Higgs mass that much smaller then the Planck mass? to explain this in a natural fashion new physics should appear in vicinity of the Higgs boson, what ever that means

Minimum Design Goal of LHC

Either Higgs is found or Standard Model is shown to be wrong

Radiative corrections

- the one free unknown is m_H and obviously the most important goal
- Higgs mass enters as a logarithm into the electroweak corrections
- precision measurements give stringent constraints

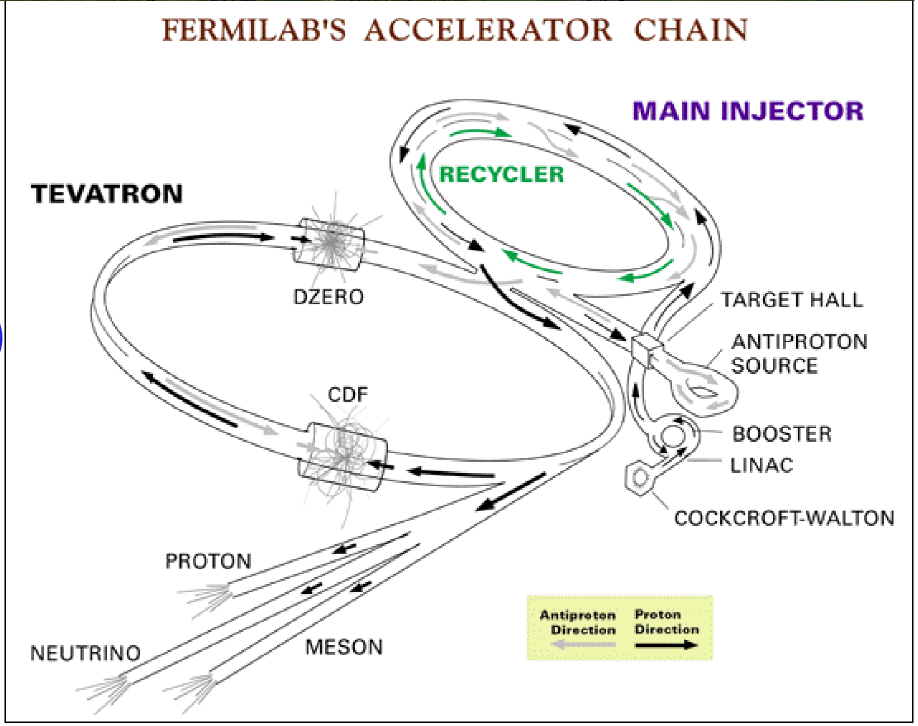


Present Energy Frontier

TeVatron

- Synchrotron: 1 km radius
- operational: 1985-today (2009)
- at Fermilab (Chicago, USA)
- detectors: CDF, Dzero
- Ebeam: 1 TeV, p-pbar (1 mA)
- physics goals: Higgs, NP,top, *b*
- superconducting magnets: 4.2T
- complex acceleration chain
  - Cockroft-Walton (750 keV, H^{--})
  - LINAC(400 MeV, strip to create *p*)
  - Booster (8 GeV)
  - Main Injector (120 GeV)
  - Tevatron (1 TeV)

Data for projects 1-3 from CDF



Near Future Energy Frontier

Large Hadron Collider (LHC)

- Synchrotron: 4.5 km radius
- operational: 2009-20??
- at CERN (Geneva, Switzerland)
- detectors: Alice, Atlas, CMS, LHCb
- E_{beam}: 7 TeV proton (0.5 A)
- schedule: physics run 2009 (at 10 TeV)
- physics goals: Higgs and New Physics Discovery
- dipole magnets, the core of LHC (1232)
  - superconducting dipoles: B=8.4 T; T=1.9 K, I=11.7 kA
  - superfluid helium cooling

Huge press coverage: articles in NY Times, Boston Globe, Science, ...

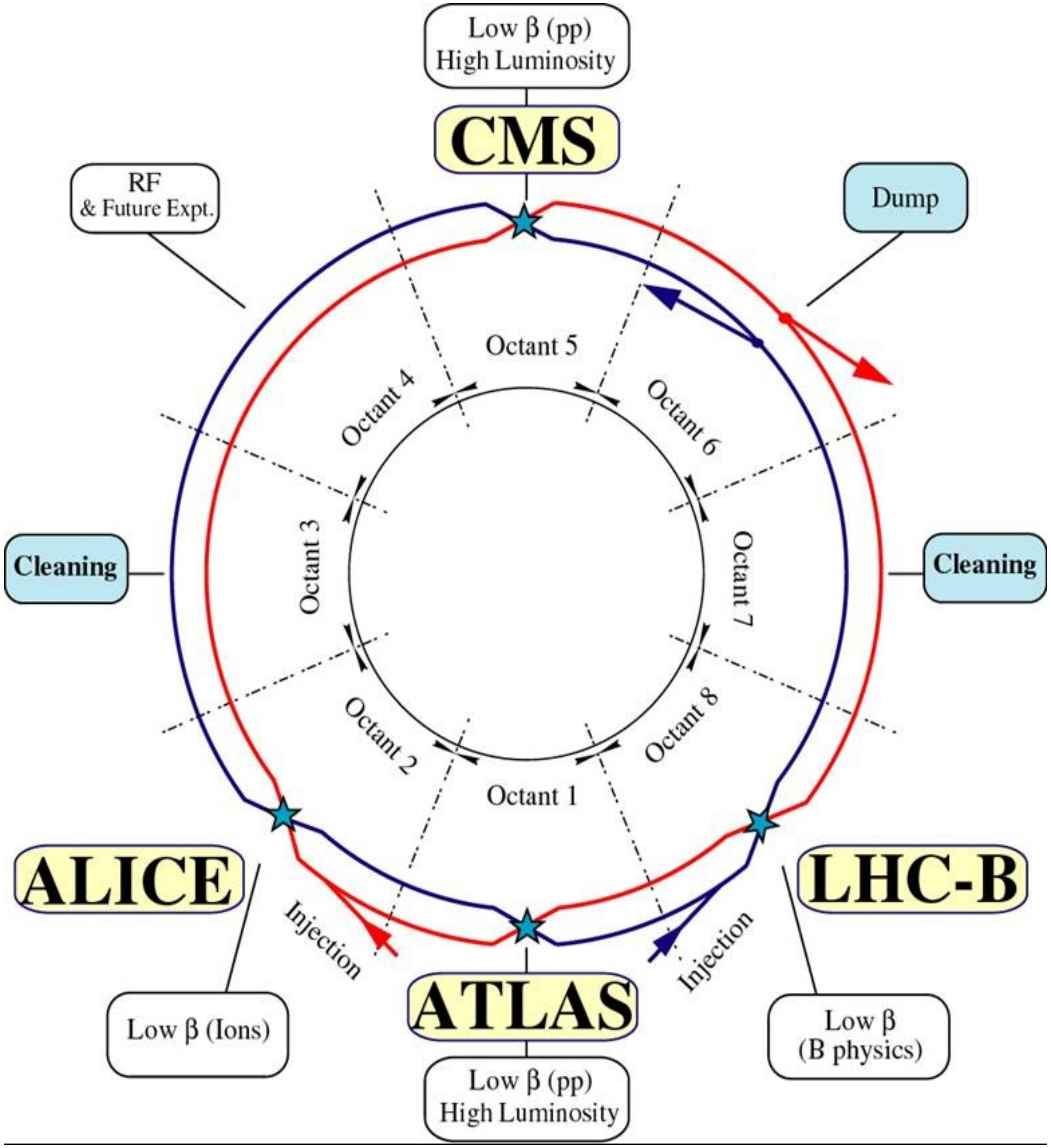
LHC Dipoles Complete

LHC Layout

Dipoles at 8.4 T

$$B[T] = \frac{2\pi}{0.3}\frac{p[\mathrm{GeV}]}{FL[m]}$$

- momentum: 7000 GeV
- tunnel: 27000 m
- arcs length: 22200 m
- 80% of arcs filled: F = 0.8
- compare to
  - iron saturation: 2 T $0.3 \times 10^{-4} T$
  - Earth magnet:



Particle Acceleration Principle

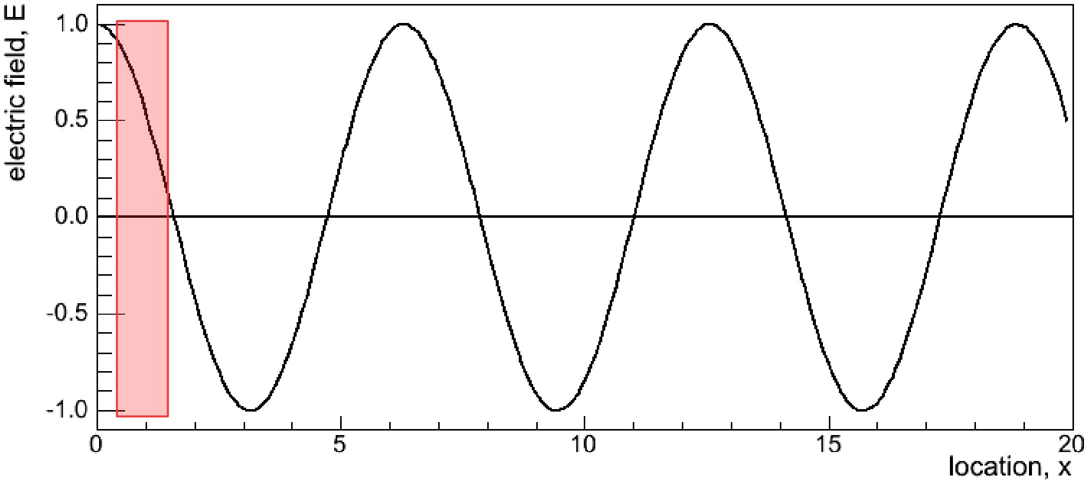
Charged particle ride the electromagnetic wave

- create standing wave
- use an RF cavity
- high frequency
- high amplitude
- make particles arrive on time

Photos: Ron Stoner Words: Matt Warshaw Audi

Self regulating

- slow particle, larger push
- fast particle, small push
- oscillatory behavior



Particle Detectors

The ultimate goal of particle detectors is to determine the particles creation/decay point, its momentum and its type (mass).

Detecting particles always implies to interact with them. Path is thus always affected by observation. *If it's perfect it ain't real.*

Particle detectors always rely on electromagnetic interaction (photons or charged particles).

Following a Particle

Scattering with the nucleus, charge *Z* (Rutherford)

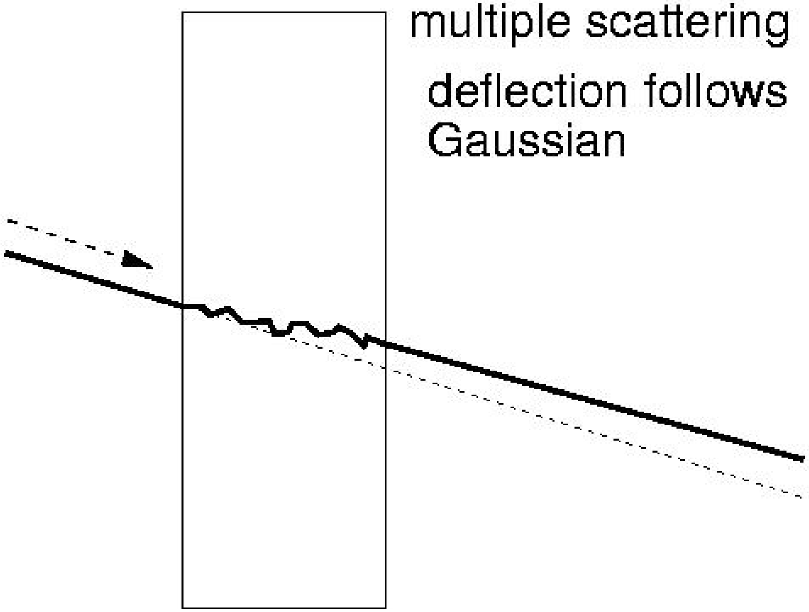
$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$

particles do not scatter or very little

- if the material is thick they may scatter multiple times

Multiple scattering

- particle scatters multiple times on the heavy nucleus (elastic)
- the smaller the momentum the larger the effect
- Gaussian around original direction



multiple scattering

deflection follows Gaussian

Following a Particle

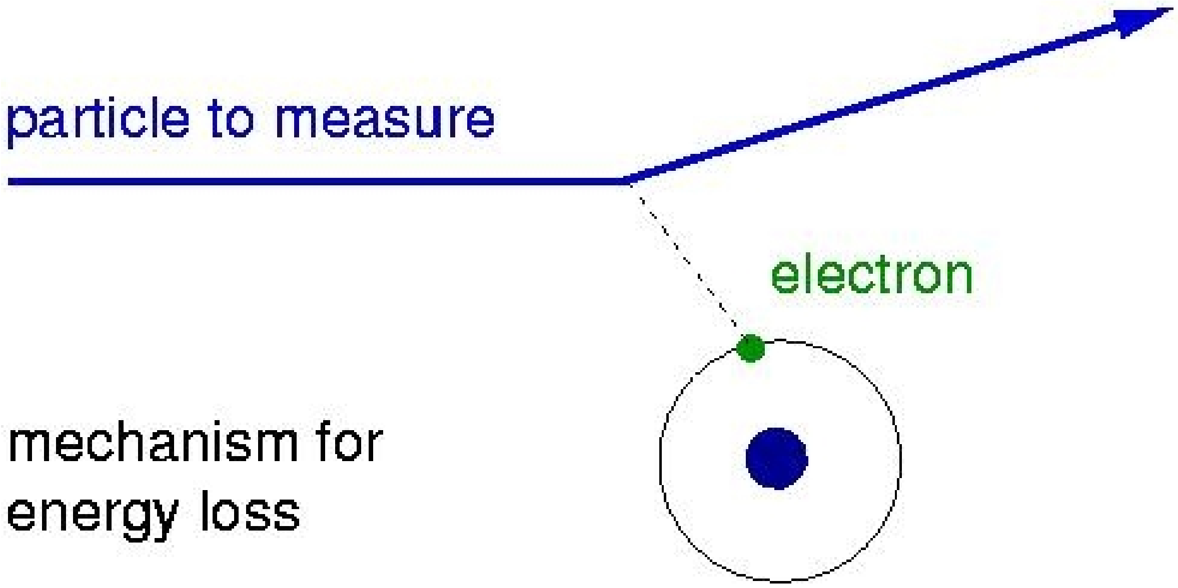
Energy loss in matter

- due to multiple scattering? no! collision elastic with heavy nucleus
- scattering with electrons from the atoms
- energy loss per length *x*

$$\frac{dE}{dx} = -\int NE\frac{d\sigma}{dE}\hbar d\omega.$$

electron density

cross section per energy



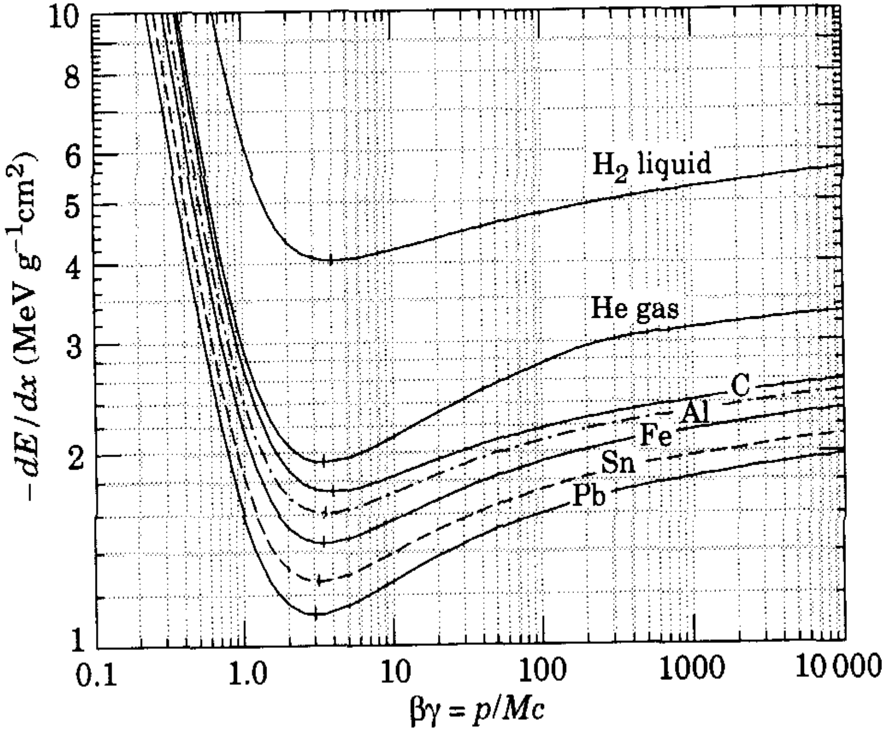
for large enough interaction causes ionization sometimes photon exits medium (later)

Bethe Bloch Formula

Average differential energy loss *dE/dx*

$$\frac{dE}{dx} = -4\pi N_A r_e^2 c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

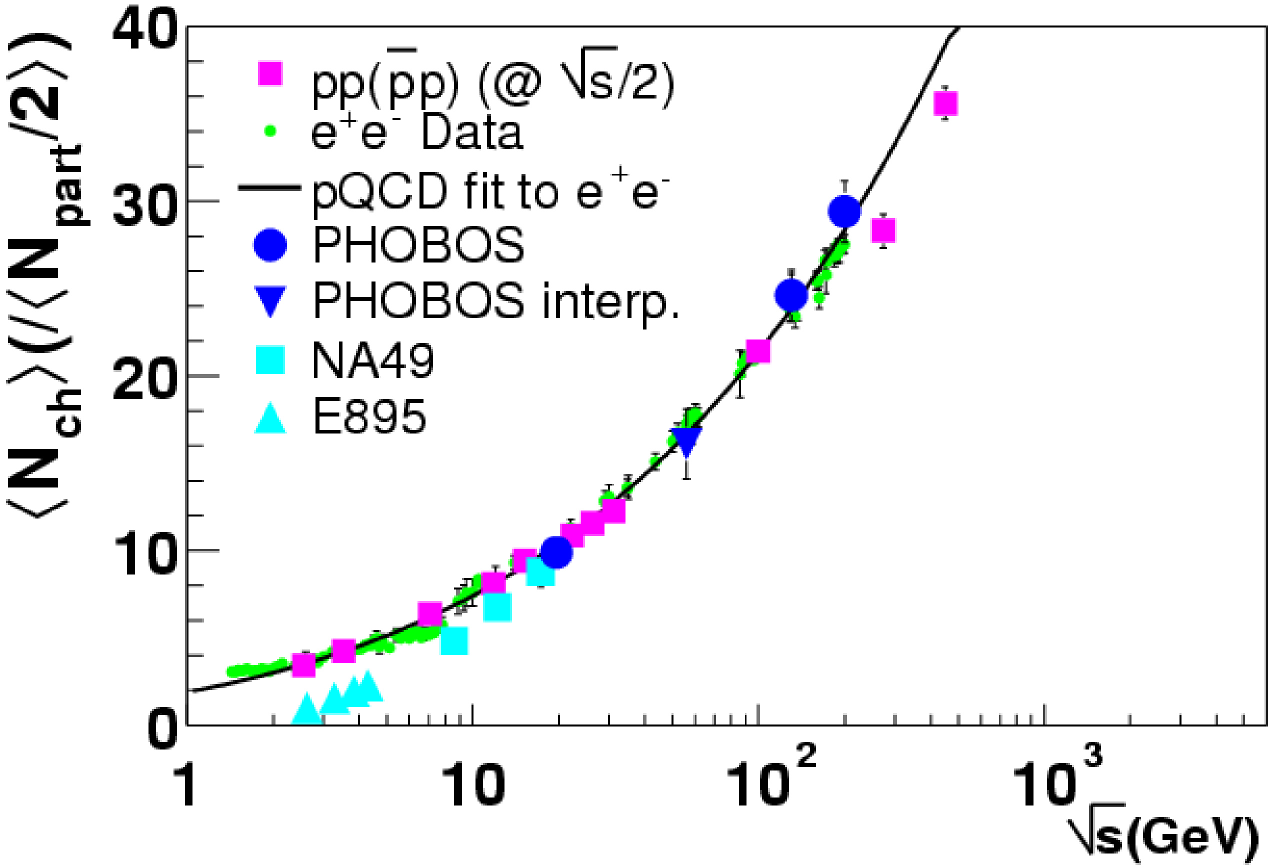
- in MeV/g/cm^2
- only valid for “heavy” particles (m>m$_\mu$)
- independent of *m*, only depends on β
- to first order proportional to *Z/A* (density of electrons)



Charged Particles in Heavy Ions

Very relevant

- simple observable to characterize the fireball
- identify state transition using charge multiplicity

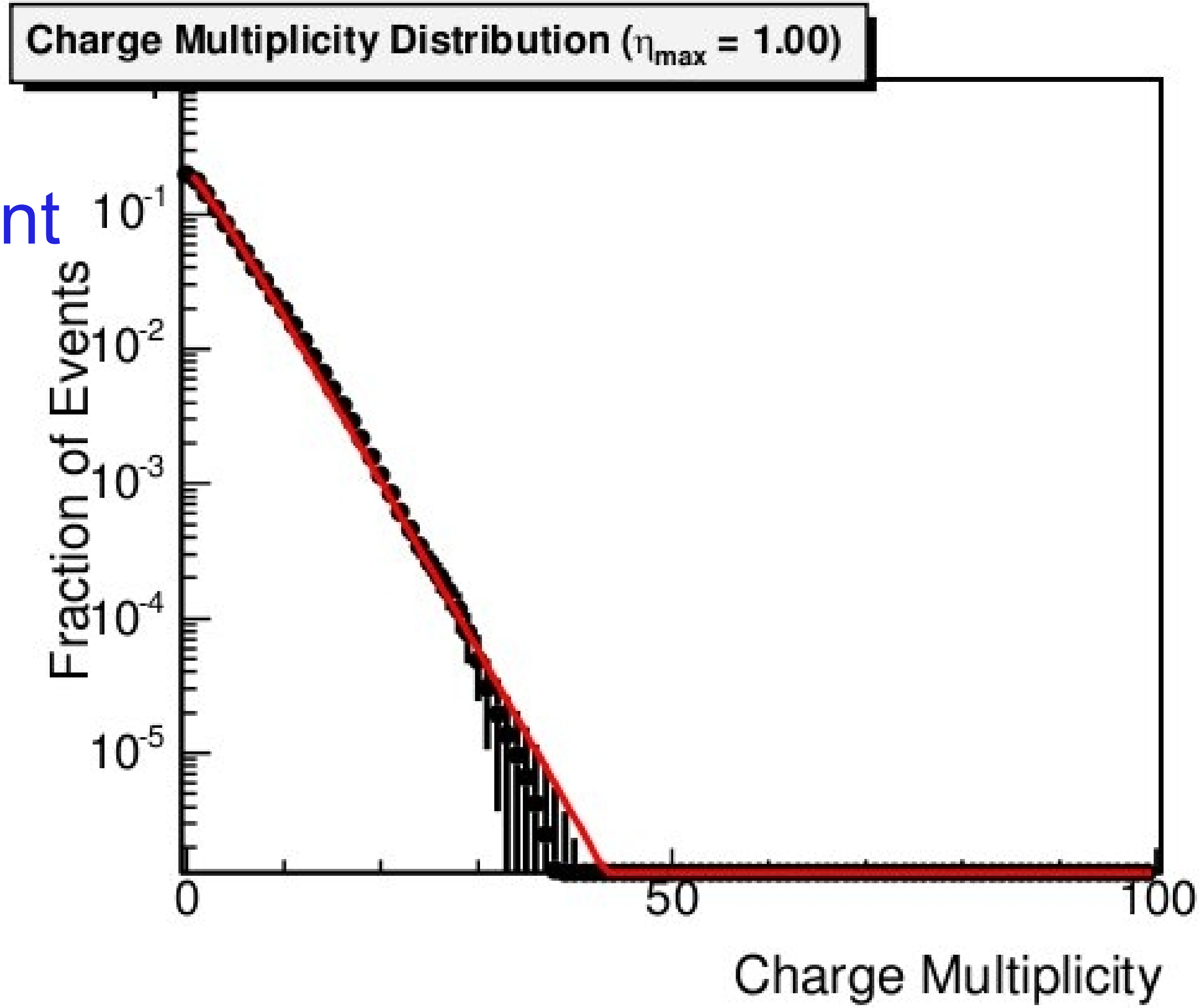


Compare interactions in HI collisions with proton-proton or proton-antiproton collisions → are HI interactions independent?

Charge Track Multiplicity

CDF II and 8.882 course from this year

- very detailed work on vertex and track corrections
- good data fit agreement

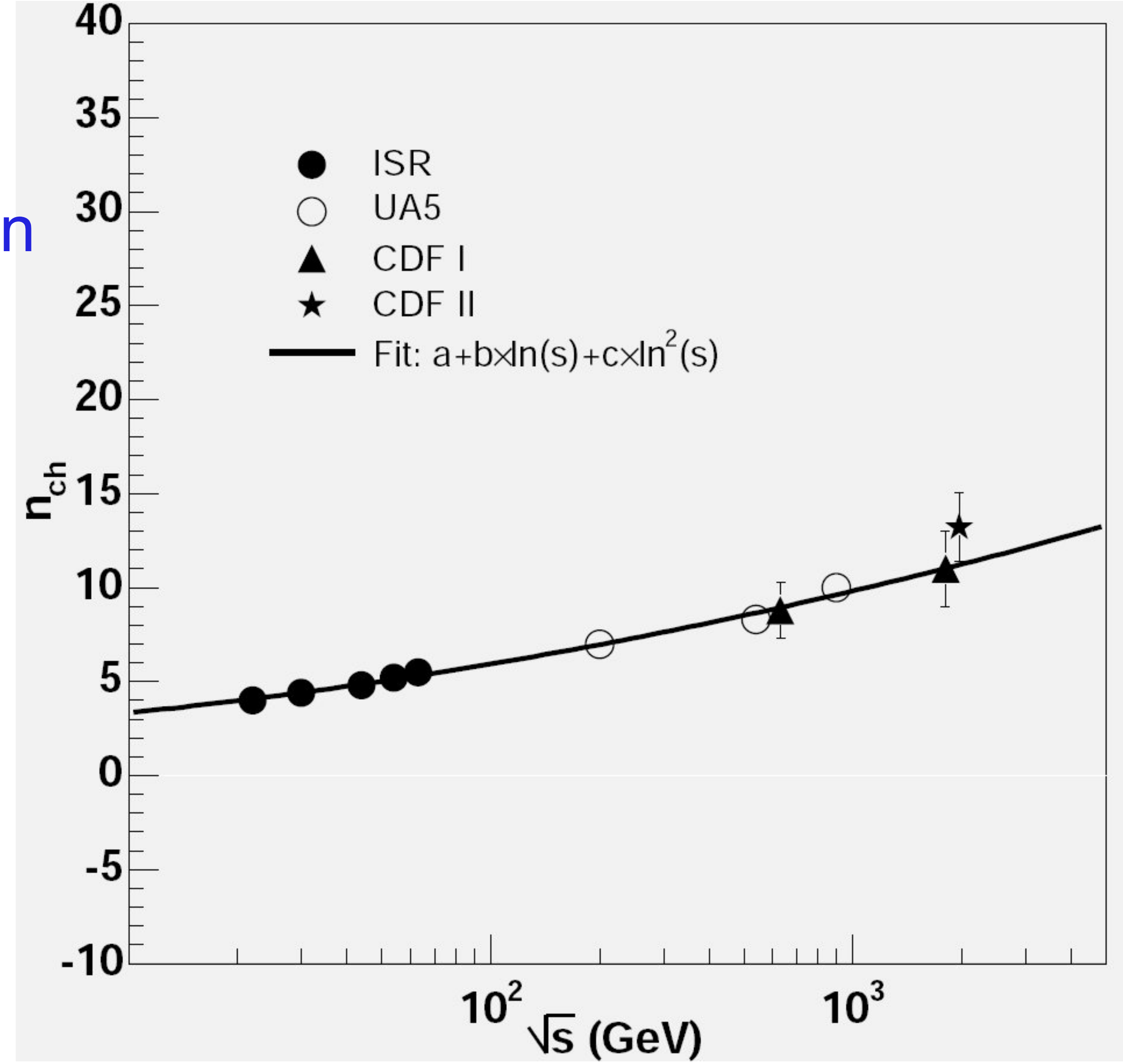


from JTM, this year

Charge Track Multiplicity

CDF II and 8.882 course from last year

- added a new point
- matches expectation

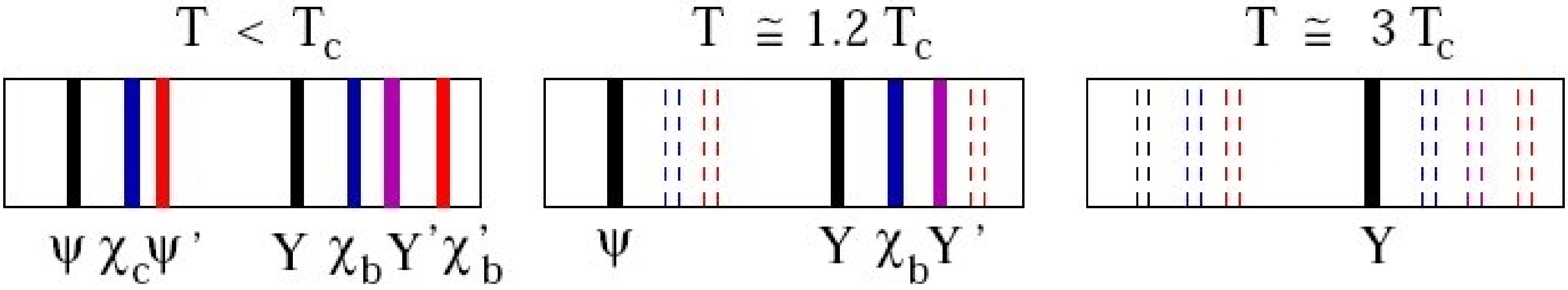


from Wei Li, last year

Screening in Heavy Ion Collisions

Quark Gluon Plasma *or better the liquid*

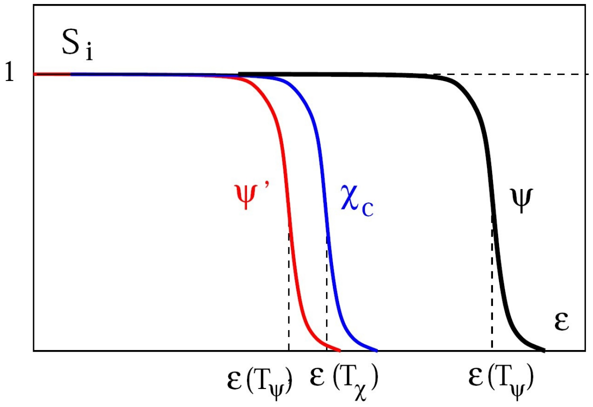
- de-confined color charges
- color charge screening for color dipoles: $q\overline{q}$
- screening radius decreases with temperature: $\lambda_D(T)$
- at critical temperature T_c onia radii equal Debye length
- states begin to disappear, starting from the 'largest' ones



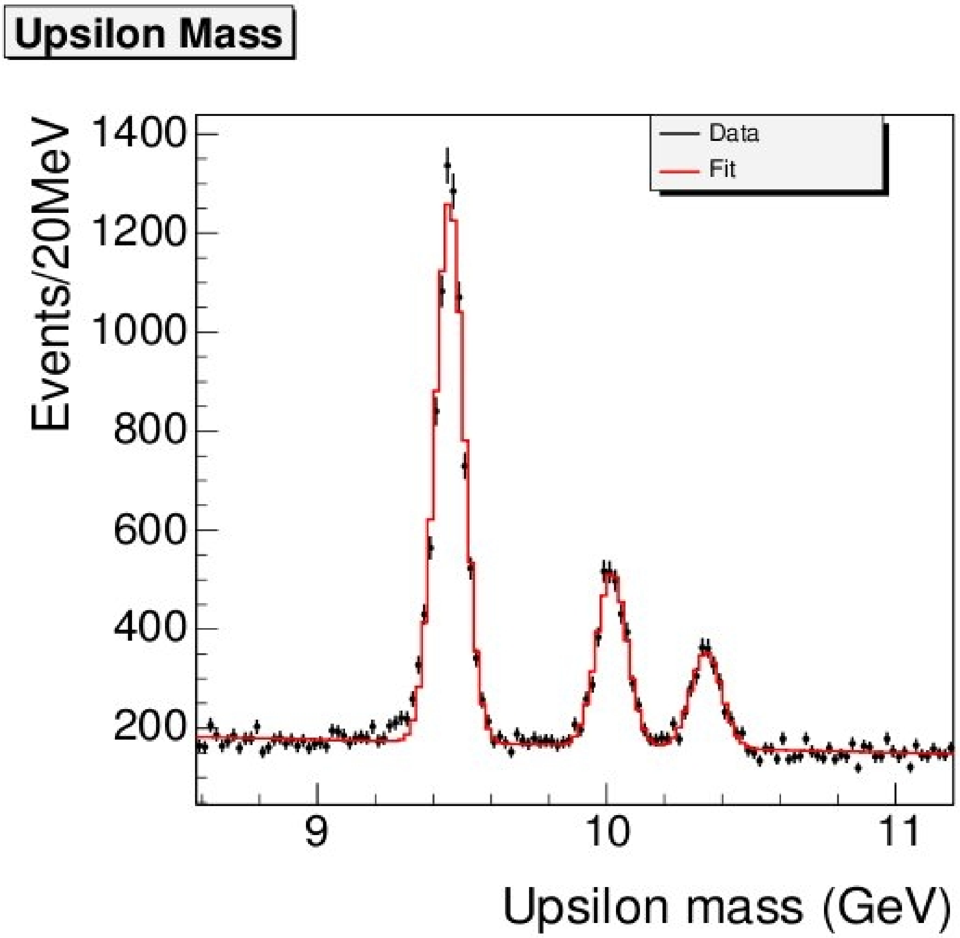
Disappearance of Onia

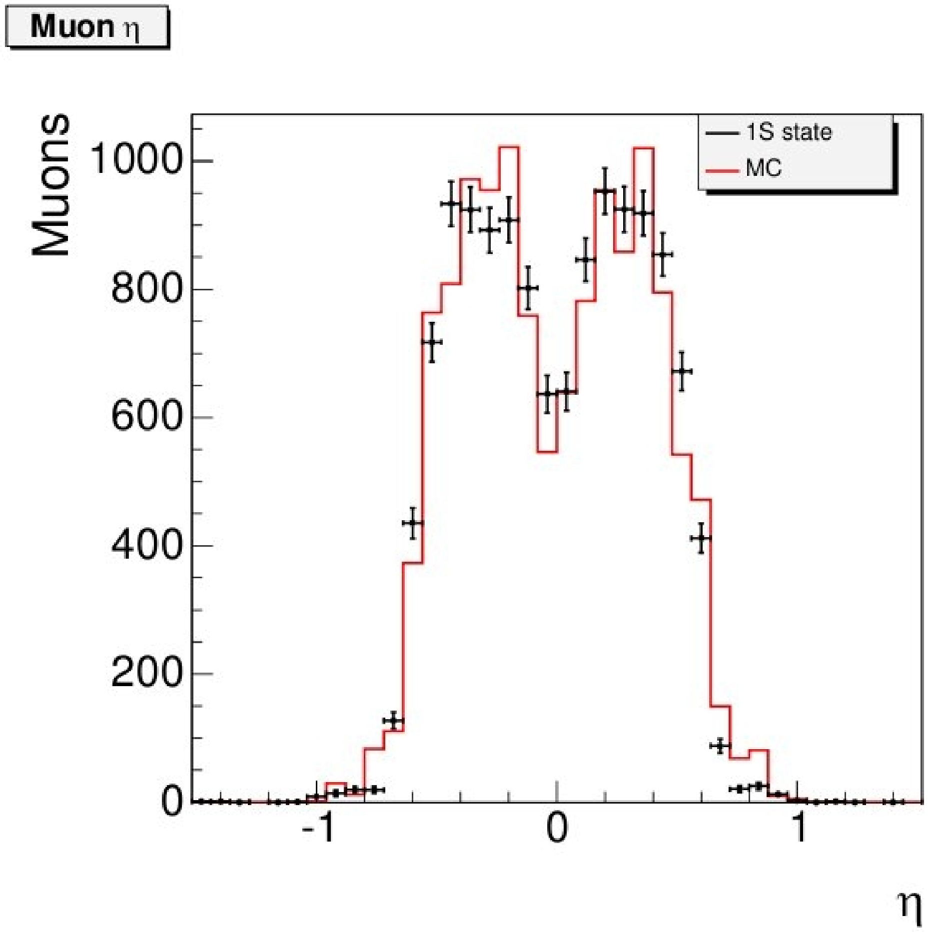
Experimental signature

- vary temperature of quark gluon plasma
- carefully observe the various onia and their excited states
- determine dissociation point as T_i as $\lambda_D(T_i) = r_i$
- gradual disappearance should manifest as changes in the measured cross sections
- avoid overall normalization by measuring ratios with respect to the lowest (and most stable) state
- variation of the temperature achieved by variation of collision energy and centrality of the collision



Cross Section of the Upsilons



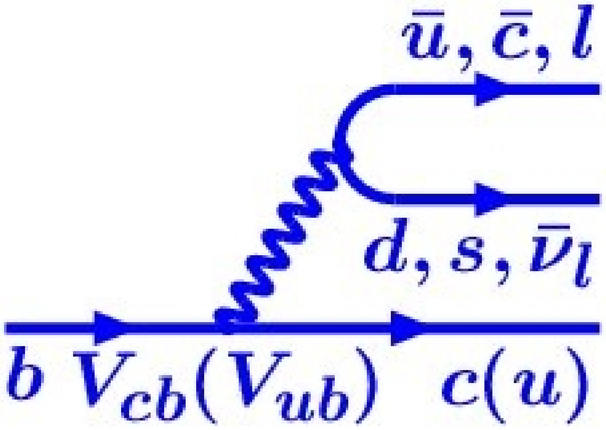


(a) $\Upsilon(1S)$ state in Monte Carlo and data.

from JTM, this year

Quarks and Hadrons

Lowest order: bare *b* quark width – spectator picture



$$m_{\ell\overline{\nu}_\ell}(b \to q) \approx \frac{-G_F}{\sqrt{2}} V_{bq} \cdot \overline{q}\gamma^\mu(1-\gamma_5)b \cdot \overline{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell$$

$$\Gamma_{\ell\overline{\nu}_\ell}(b \to q) = \frac{G_F^2 m_b^5}{192\pi^3} \left|V_{qb}\right|^2 F\left(\frac{m_q}{m_b}\right)$$

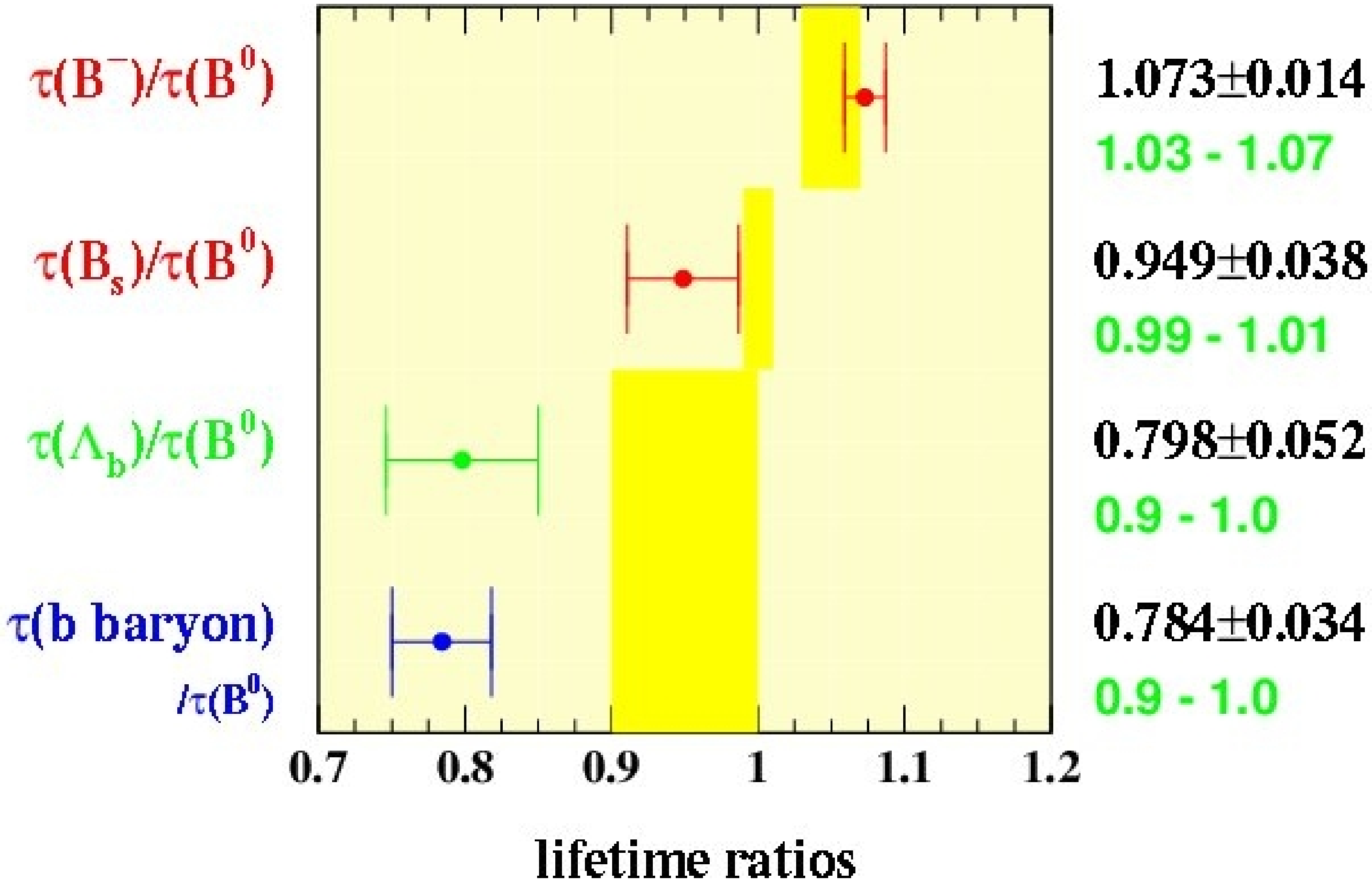
$$\frac{Br}{\Gamma} = \frac{1}{\Gamma_b} = \tau_b$$

receives modifications by quark and gluon clouds

Test Heavy Quark Expansion

Measure all *b* hadron lifetimes

- form ratios for comparisons
- HFAG pages (http://www.slac.stanford.edu/xorg/hfag)



B^+ Lifetime

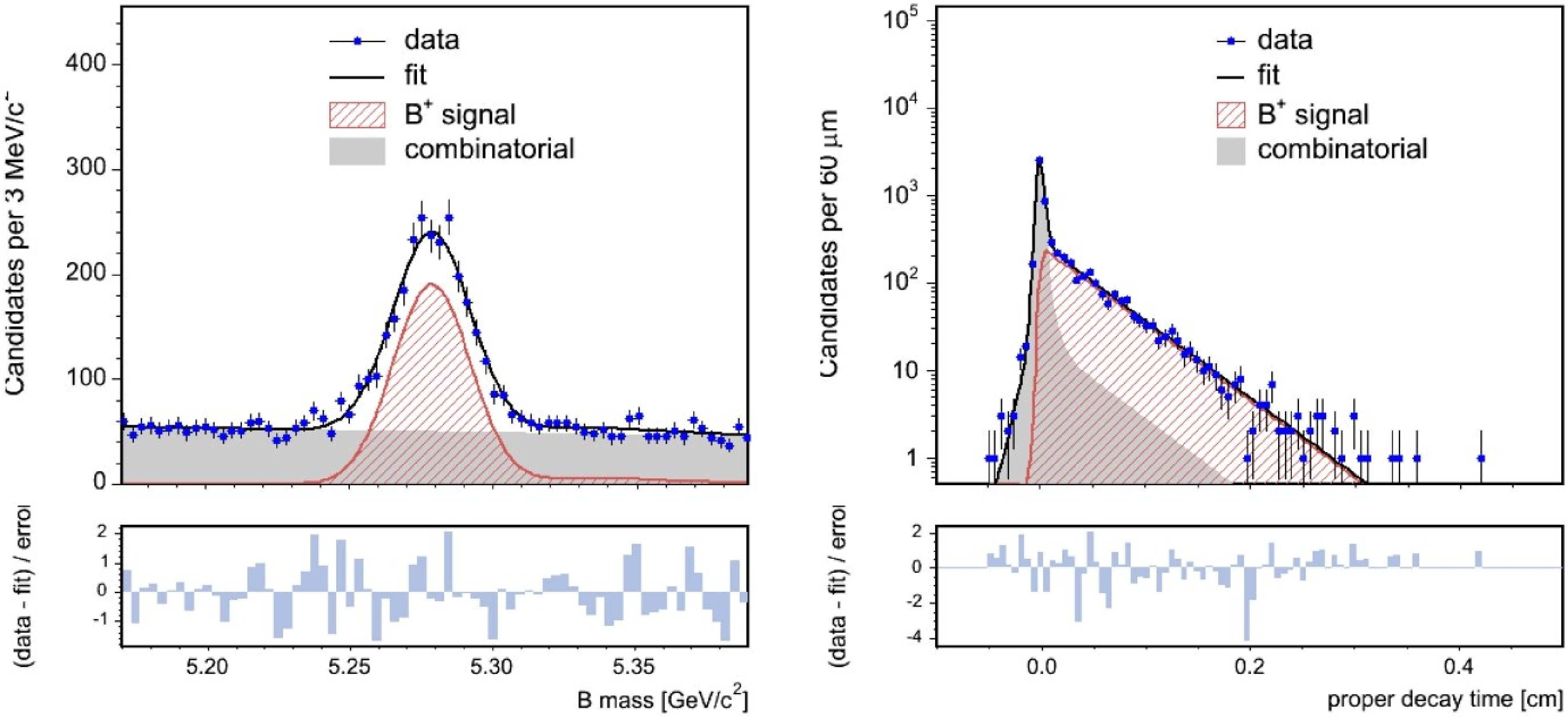


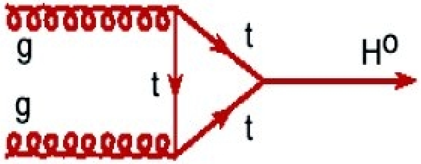
Figure 18: B_u mass(left) and the lifetime measurement (right) from the likelihood fit

Figure 18 displays the results of this fit for both the mass and the lifetime. From this fit we can extrapolate the lifetime and the mass we obtain:

$$c\tau = 491.83\mu m \pm 11.52(stat) \pm 9(sys)$$

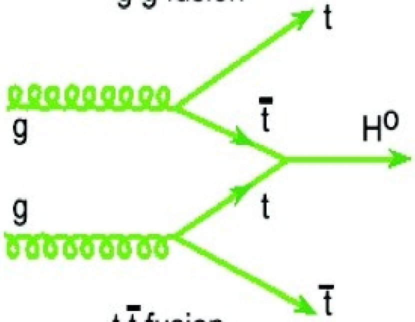
from Phil Harris, last year

Higgs Production



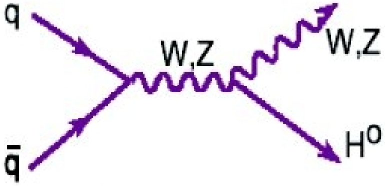
g g fusion

K ~ 2



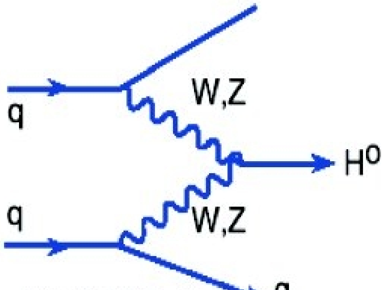
$t\bar{t}$ fusion

K ~ 1.2



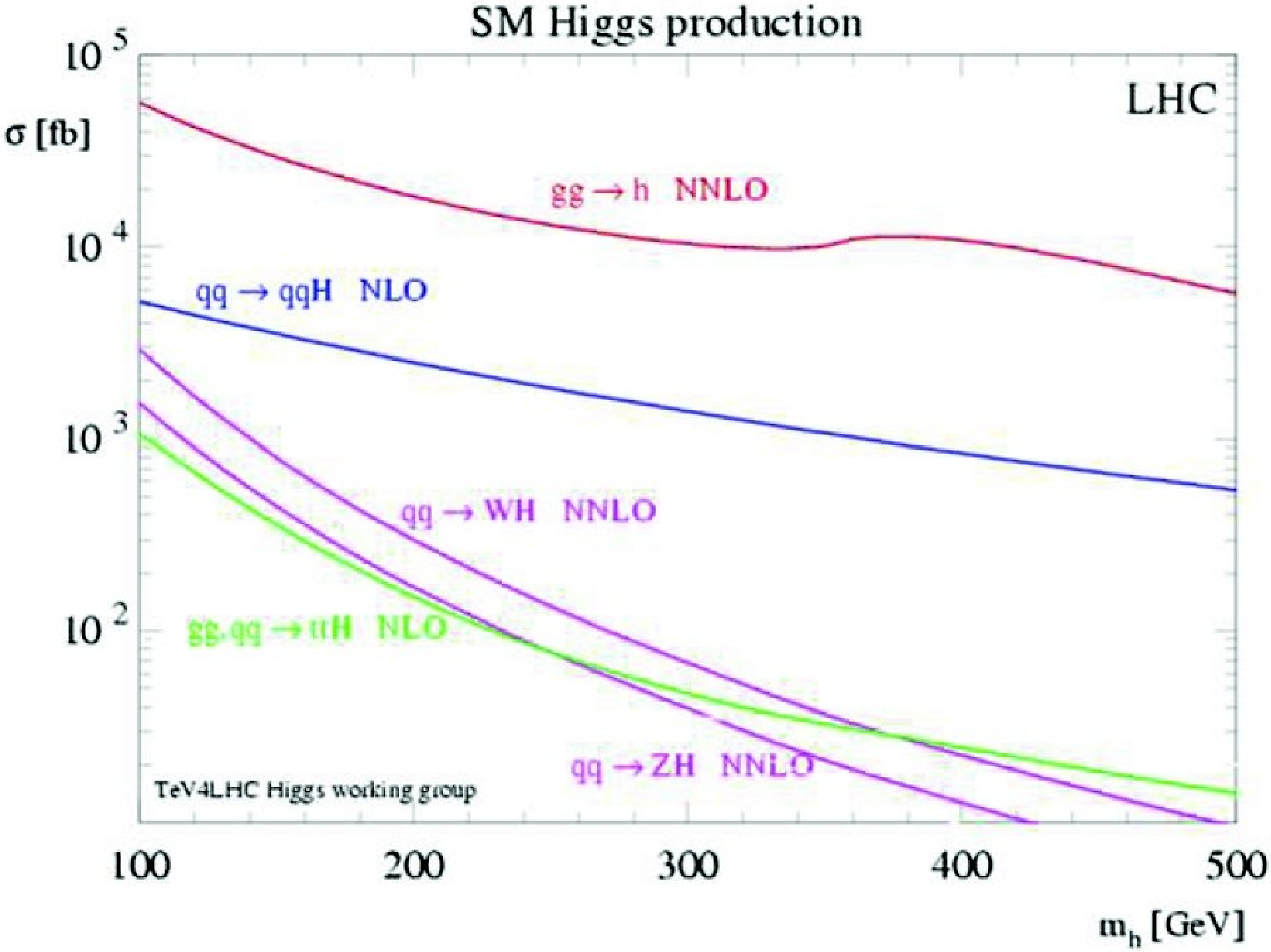
W, Z bremsstrahlung

K ~ 1.4



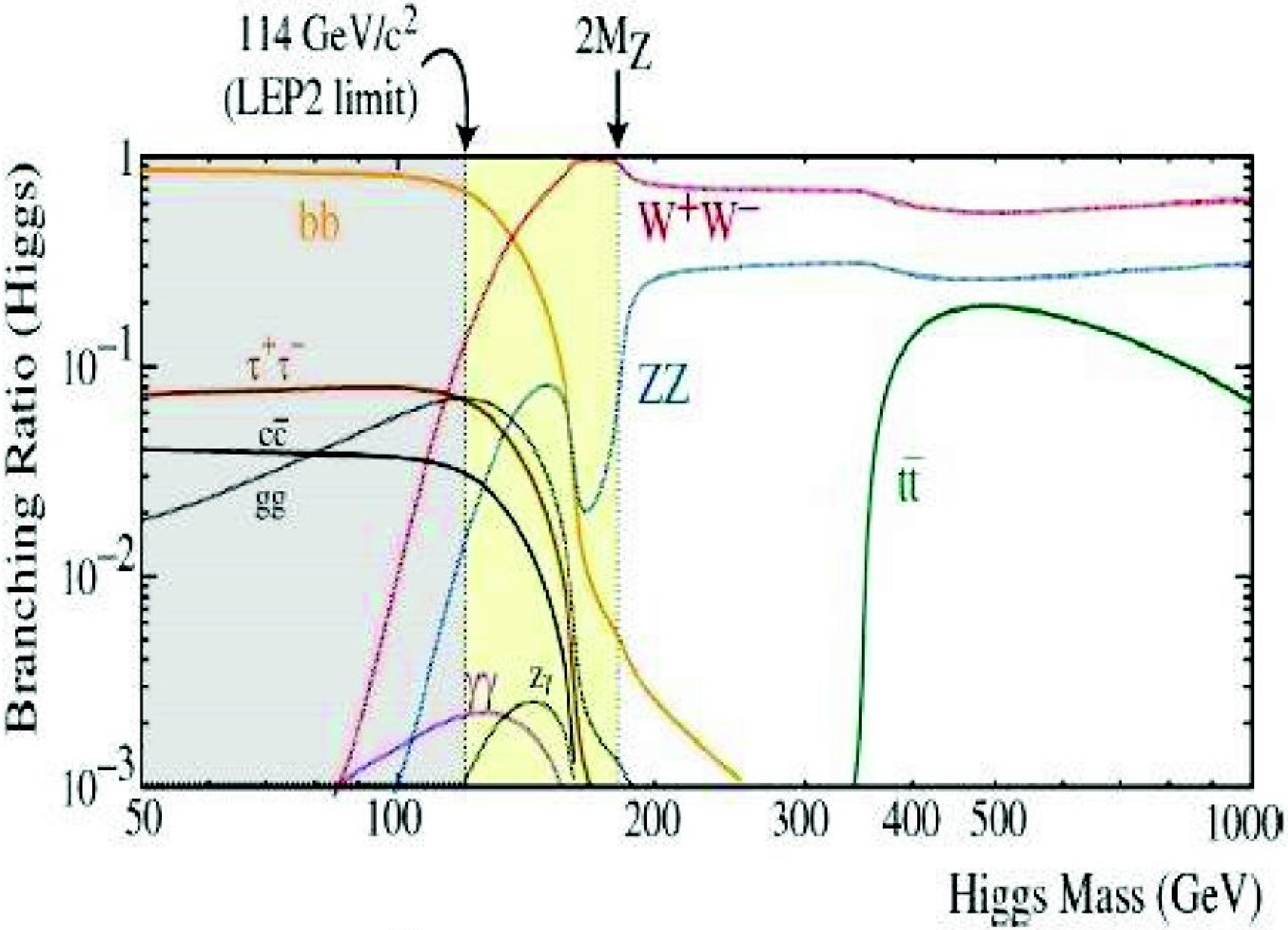
WW, ZZ fusion

K ~ 1.1



$$K = \sigma_{(N)NLO} / \sigma_{LO}$$

Higgs Decay

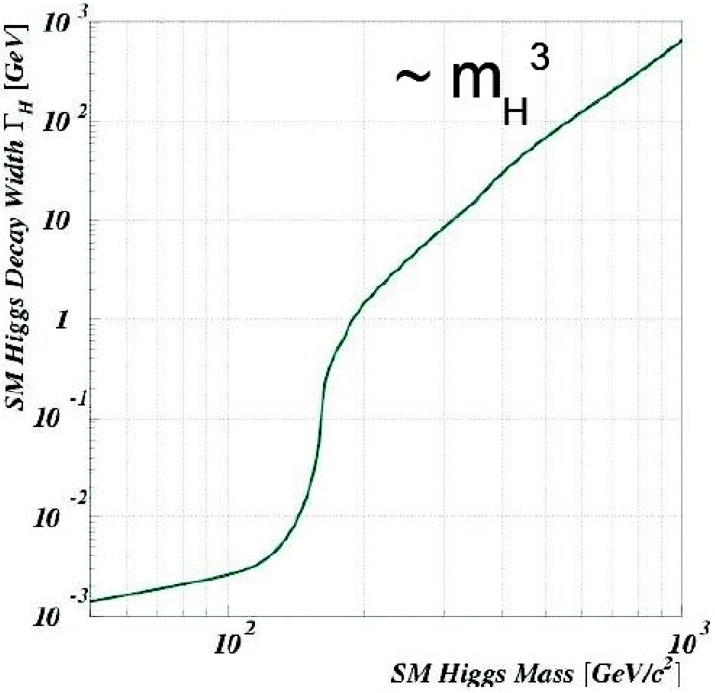


mH < 135 GeV:

bb, ττ dominant

mH > 135 GeV:

WW, ZZ dominant

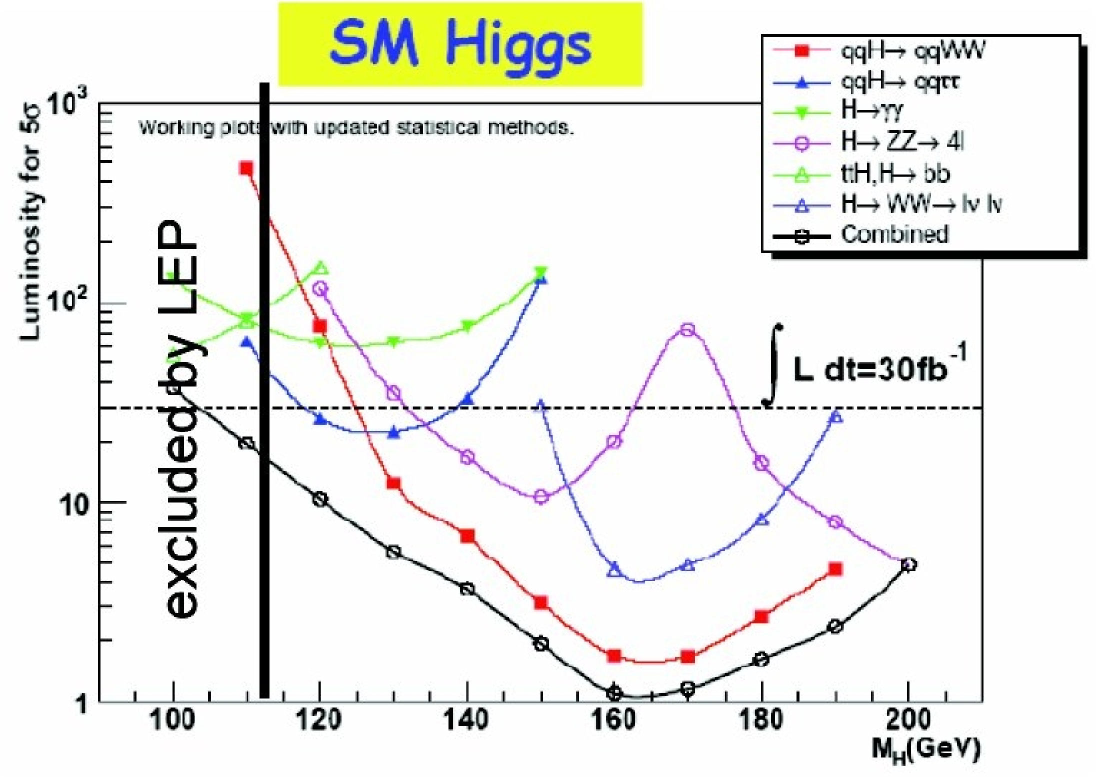


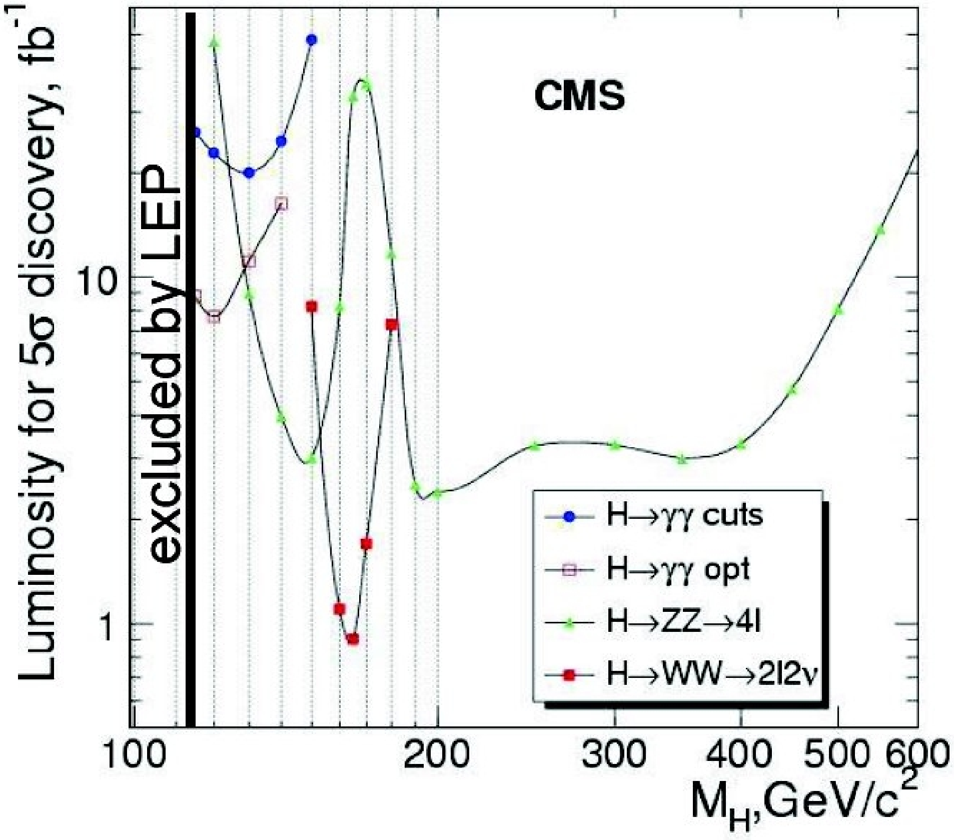
$\Gamma_{Hff} \sim m_f^2$

$\Gamma_{HVV} \sim m_V^4$

Higgs Observation Expectations

How much luminosity do we need to find the Higgs?





Conclusion

The LHC offer a spectacular opportunity for

- High Energy Physics
  - understand what mechanism is responsible for mass generation
  - potentially unveil a breakdown of the Standard Model
    - SUSY, extra dimensions, micro black holes, ... the totally unexpected
  - potentially find the explanation for dark matter
- Heavy Ion Physics
  - study the phase diagram and discover the phase transition
  - is the phase still a liquid at higher temperature?
- 2(+1) measurements have been very successfully performed and documented by everybody
  - track multiplicity, upsilon cross section (and B^+ lifetime)
  - impressive results in the hand ins, better than what I expected
- expect good results for the conference as well

For me: course was a full success (and a lot of fun)

The “Video Professor”

Course execution

- original plan was to do about 1/3 of the lecture at MIT
- this is roughly what we did
- I would have preferred to be even more at MIT and in the class room but it was quite constructive to do it this way
- it allowed me to do effective research during the course
- for some courses this way of teaching is a real option

Beyond the official course evaluation

- I am very interested in your opinion about the course
- in terms of the technical implementation and content
- come by or send me e-mail, tell me what you think, what was good, what could be improved