

Bottom quark

Pesznyák Dávid

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Experiments in Modern Physics Seminar



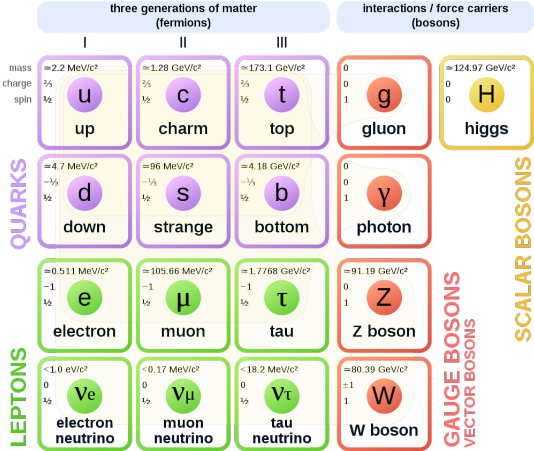
Eötvös Loránd Tudományegyetem

Structure of talk

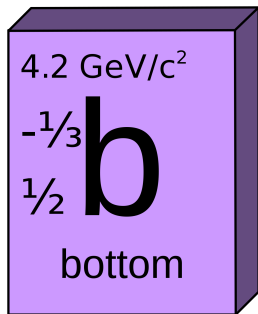
- ▶ short introduction
- ▶ the saga of b -quark
- ▶ b -quark physics – not just “another quark”
- ▶ experiments and collaborations – beauty factories
- ▶ remarks on calculating quark masses

Introduction – Standard Model in a nutshell

Standard Model of Elementary Particles



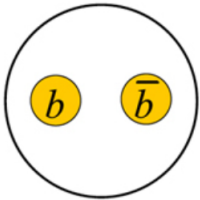
Introduction – b = bottom = beauty



- ▶ third generation ~ a bit mystical
- ▶ quite heavy (for a quark. . .)
($m_{\text{bottom}} \approx 4m_{\text{proton}} \gg m_{\text{up,down}}$)
- ▶ lifetime in general:
 $\tau_{\text{charm}} < \tau_{\text{bottom}} < \tau_{\text{strange}}$
- ▶ in theory since 1973
(Kobayashi & Maskawa)
- ▶ discovered in 1977
(Lederman et al.)

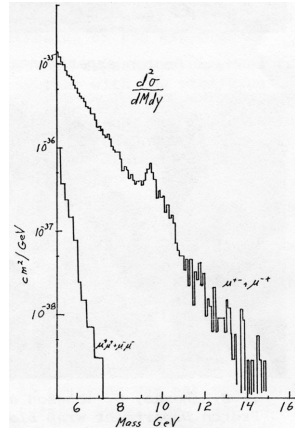
History – another day at Fermilab

- ▶ 1977 (actually 1976, then upgraded)
- ▶ CFS collaboration – E288 experiment
- ▶ discovery of Υ -meson (≈ 9.5 GeV)
(alongside “Oops-Leon”)



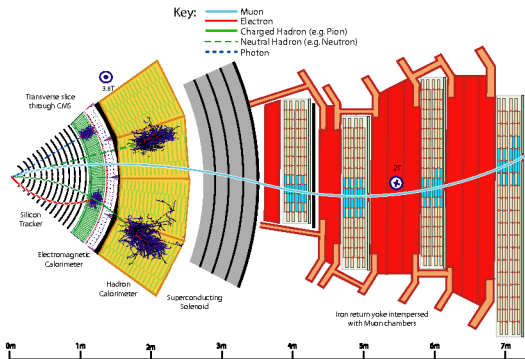
Υ -meson, aka *bottomonium*

... and a very important figure

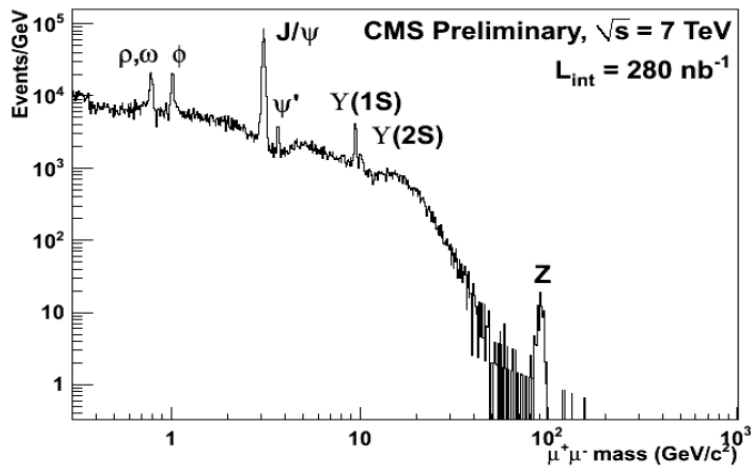


History – and let there be dimuons

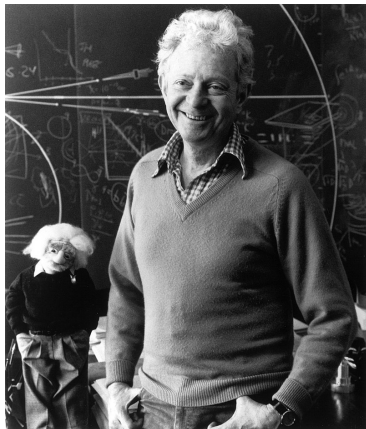
- ▶ $\Upsilon \xrightarrow{\text{decay}} \mu^- \mu^+$
(also true for $\rho, \phi, J/\psi, Z^0, \pi, K$, etc.)
- ▶ μ -s penetrate matter quite easily
- ▶ must look for characteristic μ -pairs \sim dimuons
- ▶ peaks at $\sqrt{s_{\mu^- \mu^+}}$ values above background



History – since then...



History – the “Oops-Leon”-meson



Leon M. Lederman

b -quark (related) physics (1) – B - \bar{B} oscillation

- ▶ with neutral B - ($d\bar{b}$) and B_s -mesons ($s\bar{b}$):
particle-antiparticle oscillations

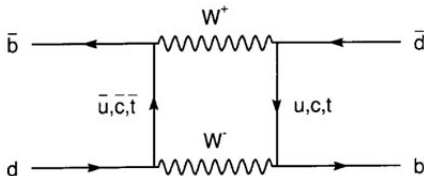
- ▶ mixing: $|\Psi(t)\rangle = c_1(t)|B\rangle + c_2(t)|\bar{B}\rangle + \text{decays}$

- ▶ projecting to B -meson subspace:

$$H_{\text{eff}}|B_{S,L}\rangle = \lambda_{S,L}|B_{S,L}\rangle = (m_{S,L} - i\Gamma_{S,L}/2)|B_{S,L}\rangle$$

- ▶ with $|\Psi_B(0)\rangle = c_S|B_S\rangle + c_L|B_L\rangle$:

$$|\langle\Psi_B(t)|\Psi_B(t)\rangle|^2 = |c_S|^2 e^{-\Gamma_S t} + |c_L|^2 e^{-\Gamma_L t} + 2\Re(c_S^* c_L e^{i(m_S - m_L)t} e^{-\frac{\Gamma_S + \Gamma_L}{2}t} \langle B_S|B_L\rangle)$$



b -quark (related) physics (2) – study of CP violation

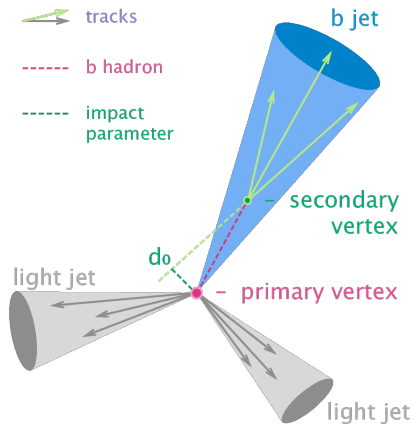
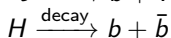
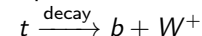
- ▶ if CP was a symmetry: $[CP, H_{\text{eff}}] = 0$
with $|B_{S,L}\rangle := |B_{1,2}\rangle$ as CP eigenstates
- ▶ BUT!
if CP was NOT a symmetry:
$$|B_{S,L}\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}} (|B_{1,2}\rangle + \varepsilon|B_{2,1}\rangle) \sim \text{admixture}$$
- ▶ $\varepsilon (\neq 0)$ can be measured in experiments
(e.g. via studying decay processes)
- ▶ notion of matter-antimatter asymmetry

(might remember $K^0 - \bar{K}^0$ oscillation from last semester's *Particle Physics* lectures)

b-quark (related) physics (3) – *b*-tagging

- ▶ method of jet-tagging
- ▶ $\tau_{M_b, H_b} \gg$ usual \sim longer paths taken (not too long: still decays in detector)
- ▶ $m_b \gg$ usual
 - ▶ wider jets
 - ▶ higher particle multiplicities
 - ▶ greater CM energies
 - ▶ low-energy leptonic decay products

- ▶ importance:



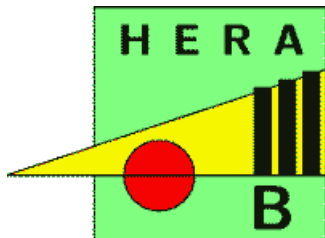
beauty factories

- ▶ collider experiments focusing on B -mesons
- ▶ main purpose: CP violation + CKM matrix
- ▶ three “generations”



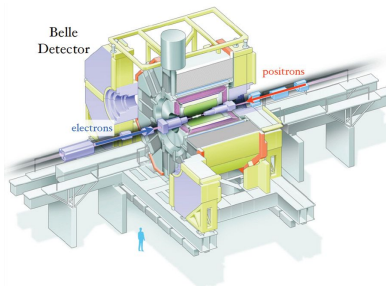
beauty factories (0th gen) – HERA-B

- ▶ first experiment to study B -meson decays
- ▶ DESY (Germany) ('90s)
- ▶ wire target to 920 GeV p -beam
“waste” halo



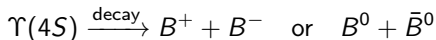
beauty factories (1st gen) – Belle experiment

- ▶ KEK (Japan) (1999-2010)
- ▶ asymmetric energy e^-e^+ collider (8-3.5 GeV)
- ▶ highlights
 - ▶ CP -violation of B -mesons
 - ▶ $B \xrightarrow{\text{decay}} K + l^+ + l^-$
 - ▶ ub and cb CKM matrix elements



beauty factories (1st gen) – BaBar experiment

- ▶ SLAC (USA) (1999-2008)
- ▶ asymmetric energy e^-e^+ collider (9-3.1 GeV)
 $\implies \sqrt{s} \approx 2\sqrt{E_+E_-} \approx 10.58 \text{ GeV} \approx m(\Upsilon(4S)) \text{ GeV}$
(about the same for Belle)



- ▶ highlights
 - ▶ bottomonium ground state: η_b
 - ▶ bSM suggestions from B -meson decay rates (not 5σ yet)



beauty factories (2nd gen) – SuperB & SuperPEP-II

proposed b-factories that didn't happen

SuperB

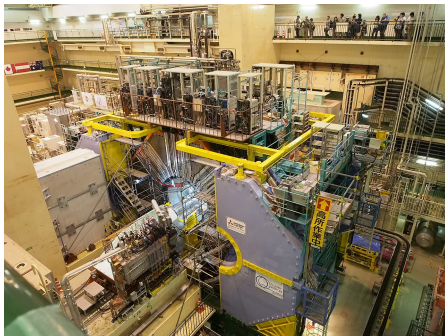
- ▶ University of Rome, then INFN (Italy) (2001-2012)
- ▶ asymmetric energy e^-e^+ collider (7-4 GeV)
- ▶ elliptic collider
- ▶ budget at cancellation $\approx 10^9$ € (LHC $\approx 4 \times$ more expensive)

SuperPEP-II

- ▶ proposed, then quickly forgotten

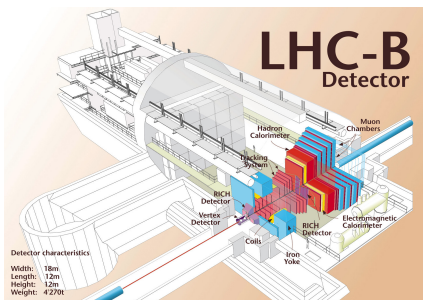
beauty factories (2nd gen) – Belle II

- ▶ upgrade to Belle
- ▶ increased luminosity $\sim 40 \times$ more data
- ▶ 2019-



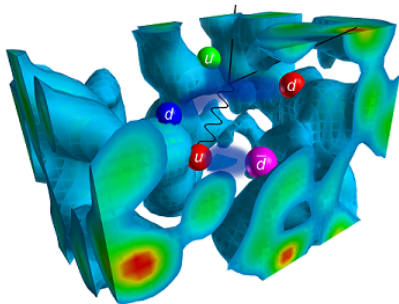
beauty factories (+1) – LHCb

- ▶ not really a b-factory \sim they do many other things (measurements of production cross sections, exotic hadron spectroscopy, charm physics and electroweak physics, pentaquarks)
- ▶ about the same story with CP violation
- ▶ MoEDAL experiment

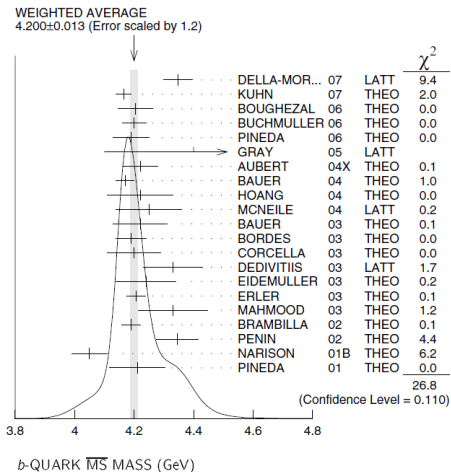


Remarks on quark masses

- ▶ “constituent” mass vs. “bare” mass
- ▶ perturbation theory + renormalisation
- ▶ “scheme”-dependence (\overline{MS})
- ▶ Lattice QCD
(from first principle, mass ratios, etc.)



Remarks on quark masses – b -quark



Summary

- ▶ great example of the power of the theoretical physics framework
- ▶ b /bottom/beauty is not just “another quark”
 - ▶ study of CP violation
 - ▶ b -tagging
- ▶ heaviest quark with stable mesons (see t)
- ▶ grand scale R&D in between 1990-2010
- ▶ who knows what's to come with Belle II?

References

- ▶ A. J. Bevan, *B Factories*, arXiv:1202.0733
- ▶ J. Yoh (Fermilab), *The Discovery of the B quark at Fermilab in 1977: The Experiment coordinator's story*, AIP Conf. Proc. 424 (1998) no.1, 29-42
- ▶ PDG, Notes on quark masses
- ▶ https://www.science20.com/quantum_diaries_survivor/upsilon_mesons_popping_lhc_data
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- ▶ <https://cerncourier.com/a/revisiting-the-b-revolution/>
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- ▶ <http://www-hera-b.desy.de/general/info/>
- ▶ <https://belle.kek.jp/>
- ▶ <https://babar.heprc.uvic.ca/>
- ▶ Wikipedia articles
 - ▶ Quark
 - ▶ Quarkonium
 - ▶ Bottom quark
 - ▶ Fermilab
 - ▶ B-meson
 - ▶ $B - \bar{B}$ oscillation
 - ▶ Neutral particle oscillation
 - ▶ Upsilon meson
 - ▶ Oops-Leon
 - ▶ B-tagging
 - ▶ B-factory
 - ▶ HERA-B
 - ▶ Belle experiment
 - ▶ BaBar experiment
 - ▶ SuperB
 - ▶ Belle II experiment
 - ▶ LHCb experiment

Figures

- ▶ https://en.wikipedia.org/wiki/Mathematical_formulation_of_the_Standard_Model
- ▶ https://commons.wikimedia.org/wiki/File:Bottom_quark.svg
- ▶ <https://www2.kek.jp/en/press/2012/011014/>
- ▶ <https://cds.cern.ch/record/2270046/plots>
- ▶ https://www.science20.com/quantum_diaries_survivor/plot_week_lovely_dimuon_mass_spectrum
- ▶ <https://en.wikipedia.org/wiki/B-tagging>
- ▶ https://www.vippng.com/preview/hmwTbmw_cape-town-based-fabrication-company-factory-cartoon-transparent/
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- ▶ <http://www-hera-b.desy.de/general/info/>
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- ▶ <https://babar.heprc.uvic.ca/>
- ▶ <https://sites.google.com/site/physicsandrelatedawesome/>

Thank you for your attention.