The known, the novel, the unexpected: Particle Physics in the LHC era

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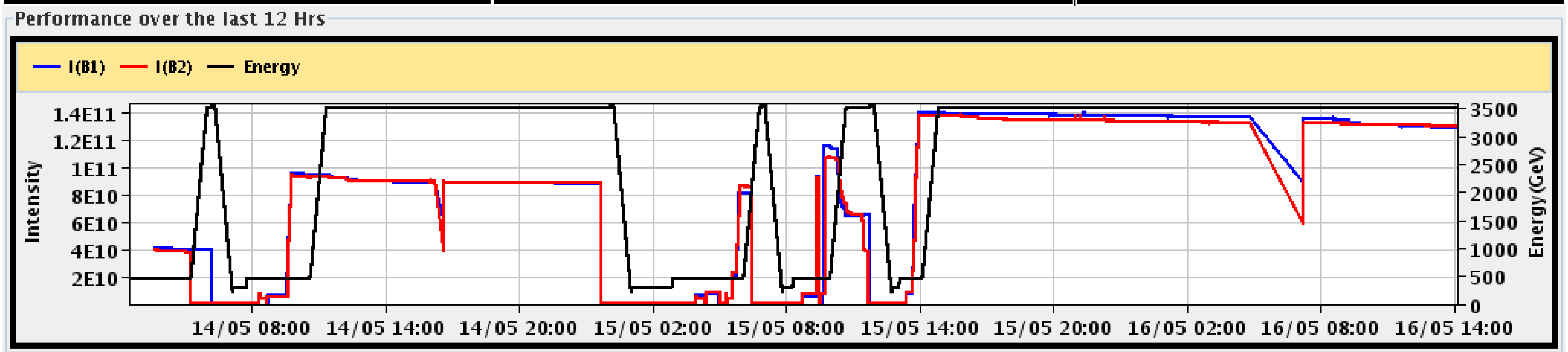
Bielefeld Physics Colloquium, 17 May 2010

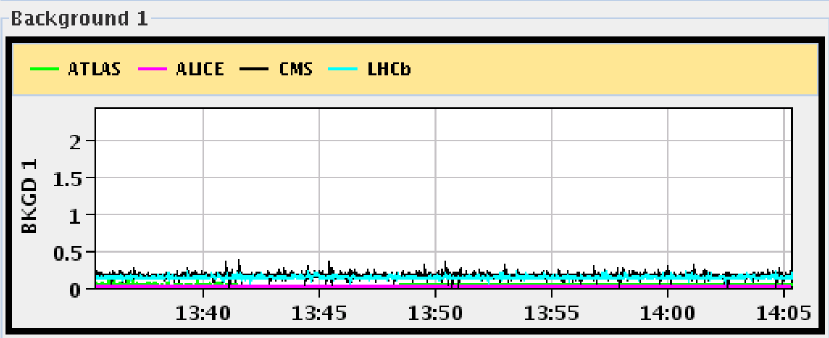
LHC: Status 16-05-2010

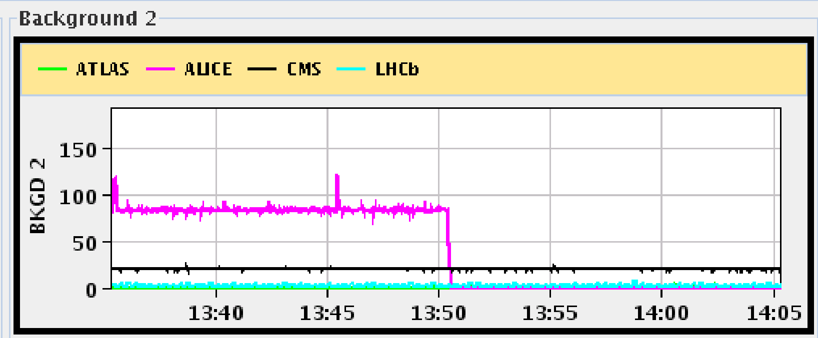
16-May-2010 14:07:08 Fill #: 1104 Energy: 3500.3 GeV I(B1): 1.28e+11 I(B2): 1.30e+11

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	CALIBRATION	STAND...	STAND...
Instantaneous Luminosity	5.114e-02	0.000e+00	5.072e-02	3.755e-02
BRAN Count Rate	6.900e+02	2.960e+02	1.110e+03	8.450e+02
BKGD 1	0.042	0.006	0.140	0.122
BKGD 2	0.000	0.000	19.268	2.781
BKGD 3	0.000	0.002	0.003	0.034

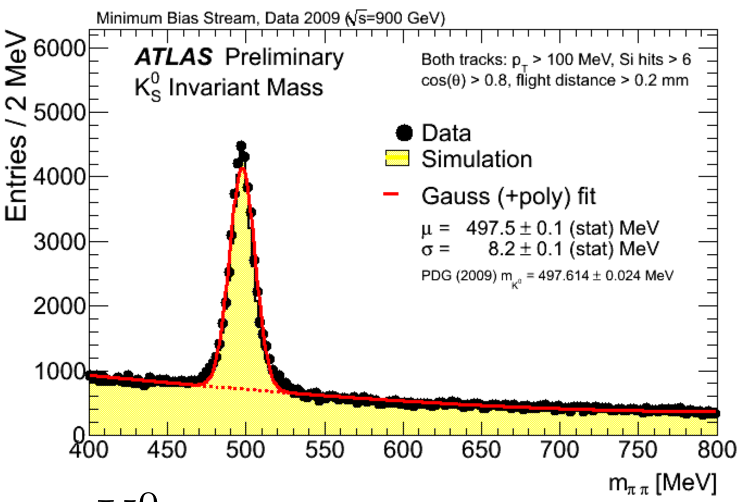
LHCf MOVING Count(Hz): 0.000 | LHCb VELO Position ... Gap: -0.0 mm | TOTEM: CALIBRATION



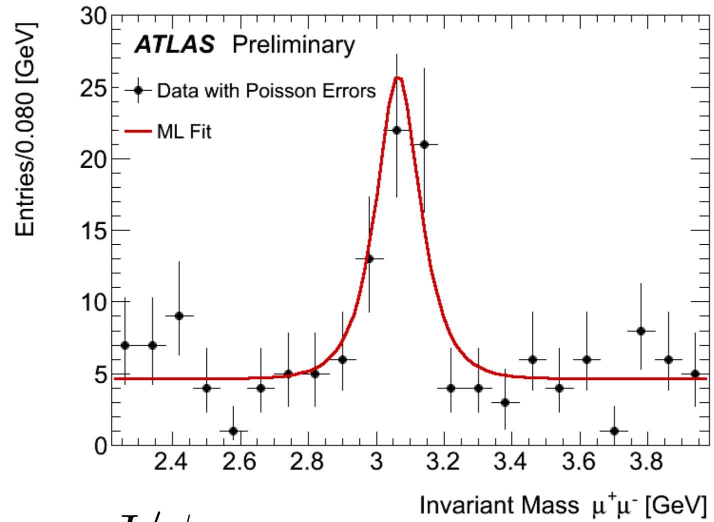




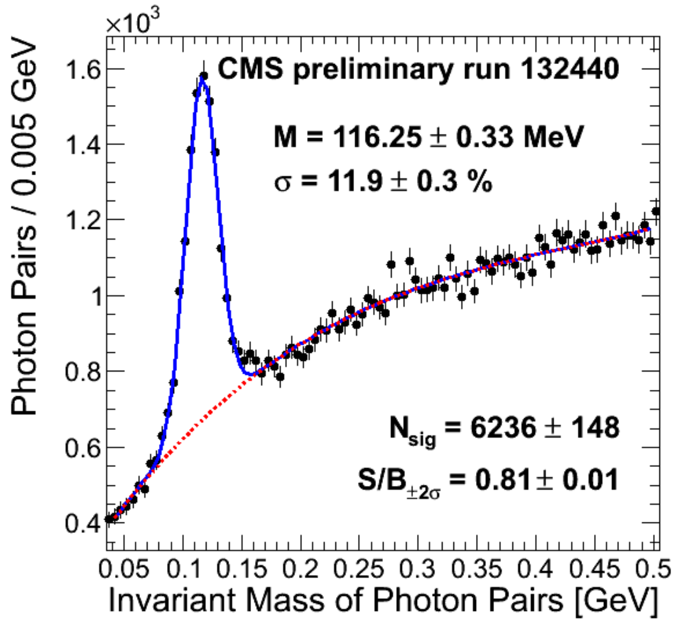
SM rediscovered at LHC: heavy flavor and W



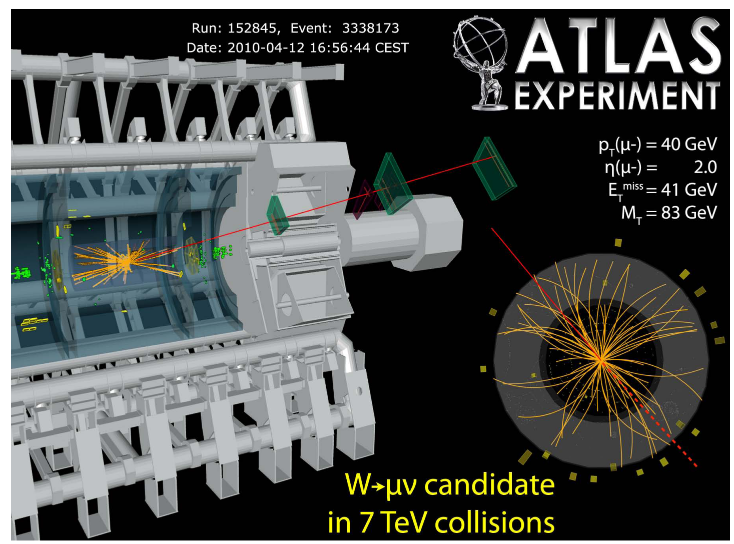
$K^0_s \to \pi\,\pi$



$J/\psi \to \mu\,\mu$

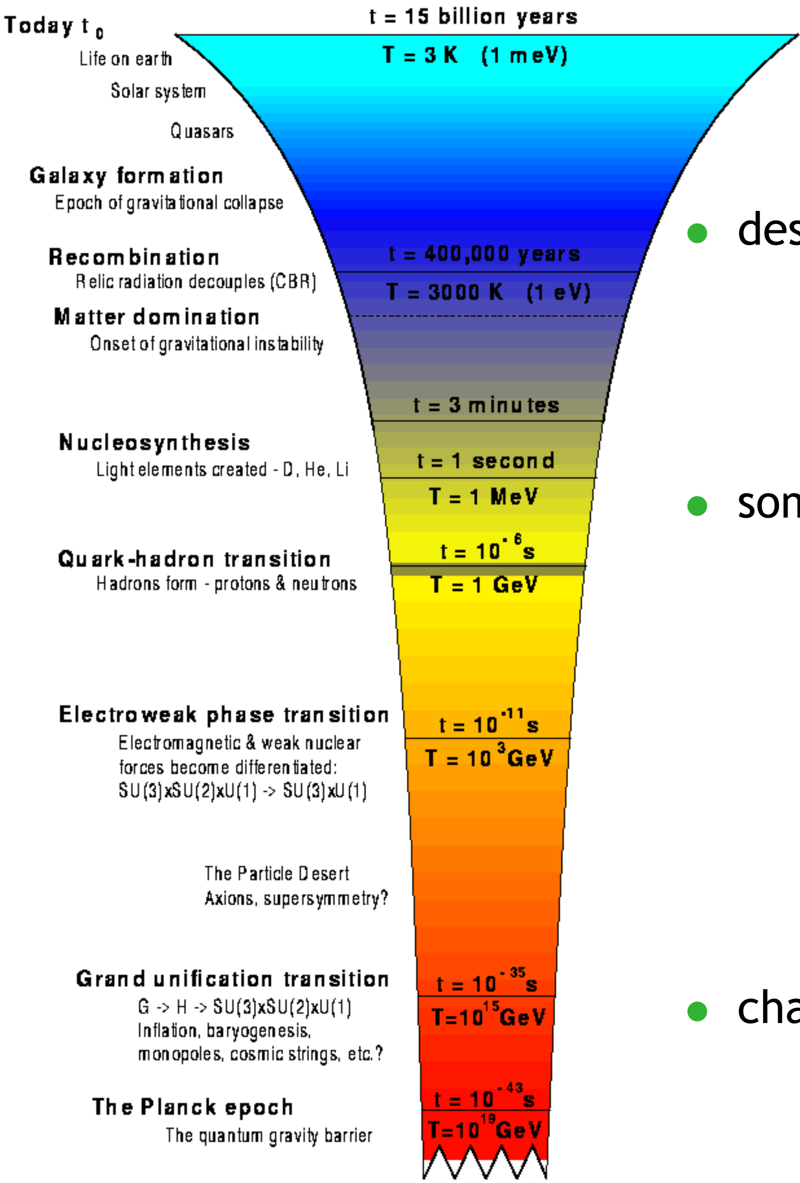


$\pi^0 \to \gamma\,\gamma$



$W \to \mu\,\nu$ candidate

Motivation: think BIG!



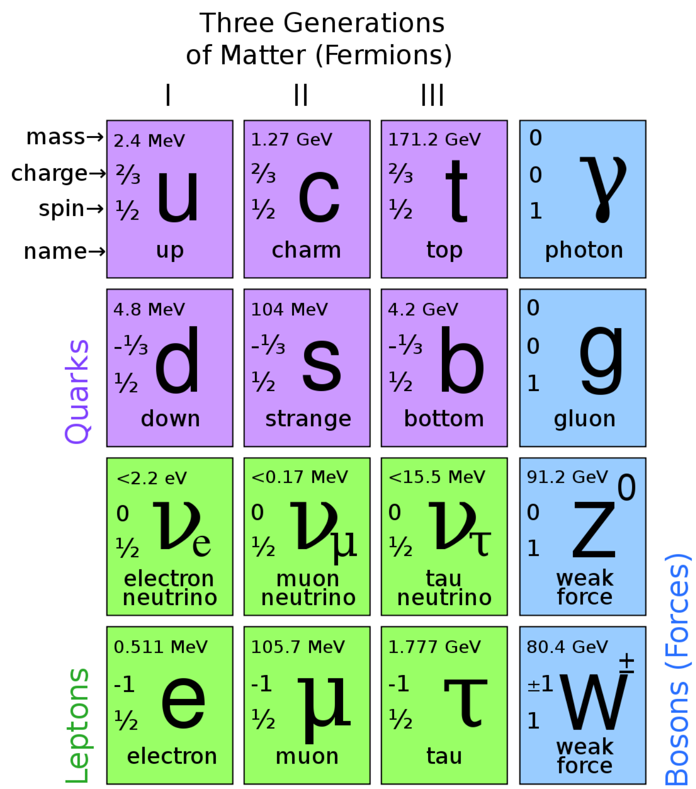
ask fundamental questions about physics
$\longrightarrow$ deepest laws of nature?
$\longrightarrow$ structure of space and time?

- describe physics in universal framework
  - ▷ QFT (= QM + Rel) + SM + (class.) Grav [YS, Colloq 2007]
  - ▷ ø universe - particles - Planck length
    10^{28} cm - 10^{-17}cm - 10^{-33} cm
- some of the big open questions
  - ▷ nature of electroweak symmetry breaking?
  - ▷ nature of Quark-Gluon plasma?
  - ▷ origin of matter/antimatter asymmetry?
  - ▷ Quark or Lepton substructure?
  - ▷ supersymmetry? dark matter?
  - ▷ embedding of SM in GUT?
  - ▷ QM $\cap$ Gravity; strings? extra dimensions?
- challenging questions; concern smallest distance scales
  - ▷ use powerful microscope to explore
  - ▷ Uncertainty (Heisenberg) + Relativity $\Rightarrow$ high E, m

Standard Model (SM)

Elementary particles $\equiv$ ultimative building blocks

- known:



- predicted / anticipated:
  - ▷ Higgs-Boson(s)
  - ▷ SUSY-particles, dark matter [5$\times$ ordinary baryonic matter!]
  - ▷ axions?, …

Quantum Field Theory (QFT)

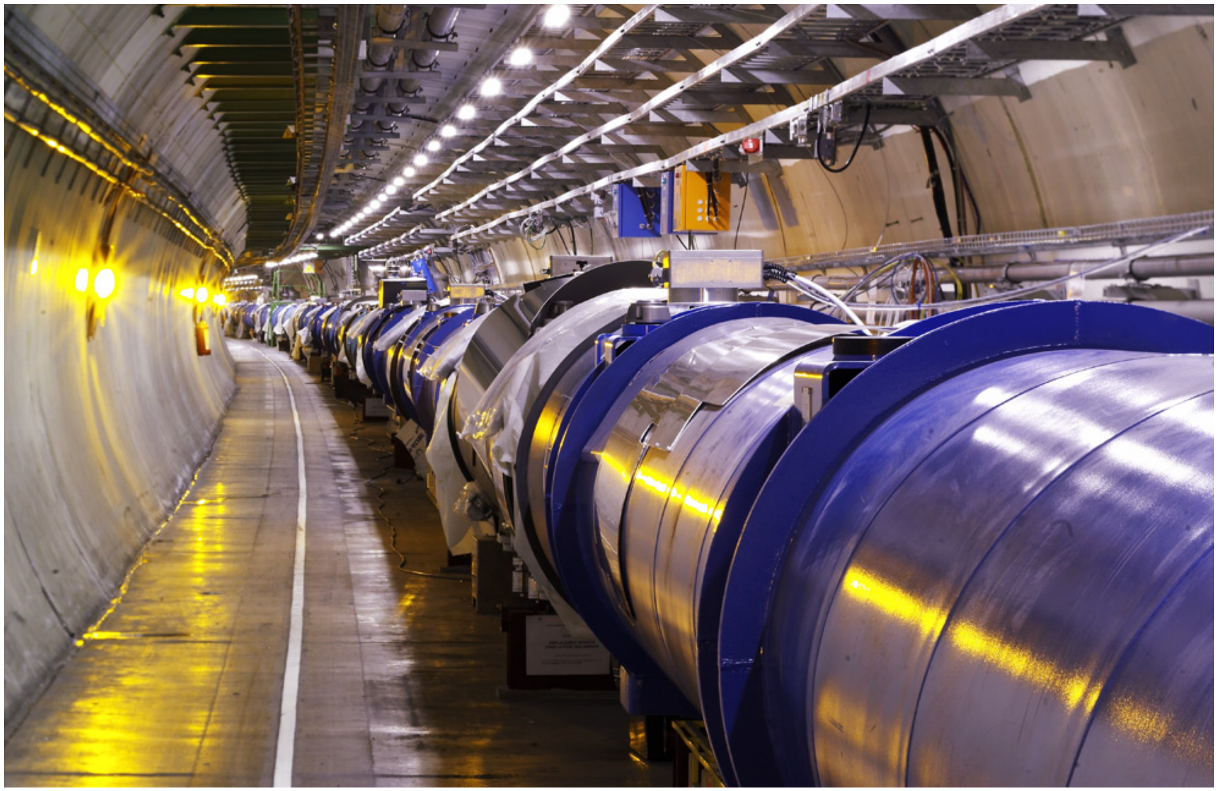
Quantum Field Theory $\equiv$ nature of interactions

- known: $\mathcal{L}_{SM} = \mathcal{L}_{QCD} + \mathcal{L}_{EW}$
- predicted / anticipated:
  - ▷ healthy local gauge theory SU(3)$_C\times$SU(2)$_L\times$U(1)$_Y$ (g-WZ-γ)
  - ▷ extra dimensions?
  - ▷ monopoles? strings?
  - ▷ grand unification (GUT)
  - ▷ ...
- some important experiments (colliders since 70s; here $\geq$ 90s)

name	place	type	E_{cm}[GeV]	time	highlight
LEP	CERN, Geneva	e+e	209	1989-2000	Z-, W-Boson
HERA	DESY, Hamburg	e+p	318	1992-2007	Gluon
Tevatron	Fermilab, Chicago	p+p	2000	1983-2010(?)	Top-Quark
LHC	CERN, Geneva	p+p	14000	2009 -	Higgs-Boson?, ...
ILC	?	e+e	500-1000	20?? -	...

Particle Colliders: LHC data sheet

- 2 $\times$ 2800 bunches à 12 billion protons; collisions every 25 ns
- max. p+p energy in center-of-mass-(=lab)-system: $\sqrt{s}$ = 14 TeV [cf. Tevatron: 1.96 TeV]

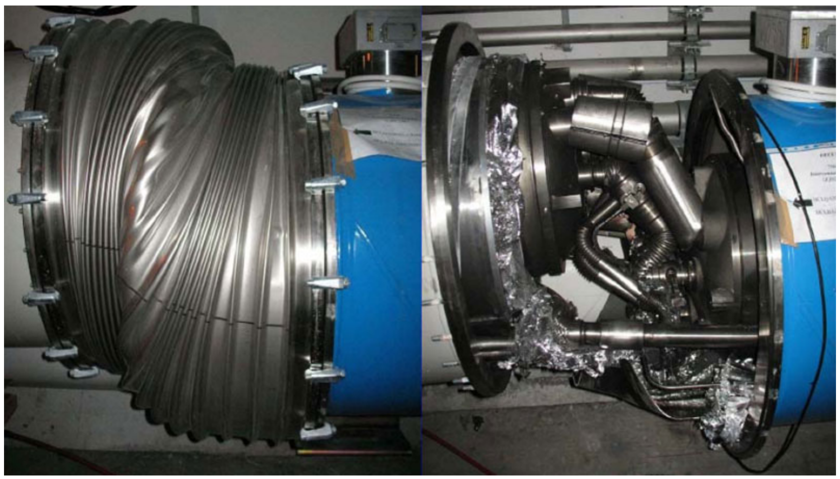


- ca 3 billion Euro
- 27 km tunnel
- 1200 dipole-magnets
- B-field up to 8.6 Tesla
- 1.9^{o}K; 90t liquid He
- these parameters
  $\rightarrow E_{max}$ = 7 TeV
  $\rightarrow v = 0.999999991\, c$

- central quantity: Luminosity; designed for $L = \frac{10^{33} \ldots 10^{34}}{cm^2\, s}$ [or $\frac{1 \ldots 10}{nb\ s}$]
- for a specific process: Event rate = Luminosity $\times$ Cross section

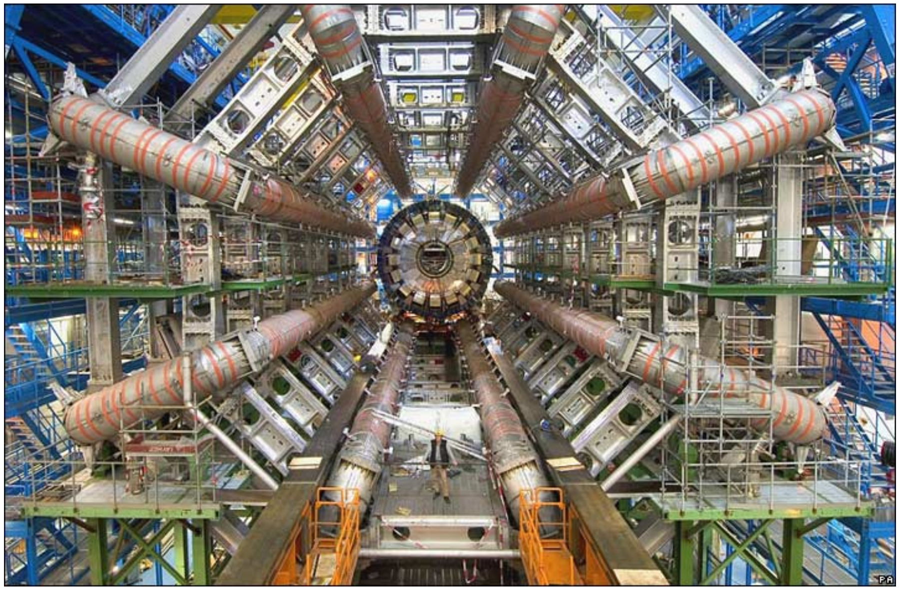
Operational challenges

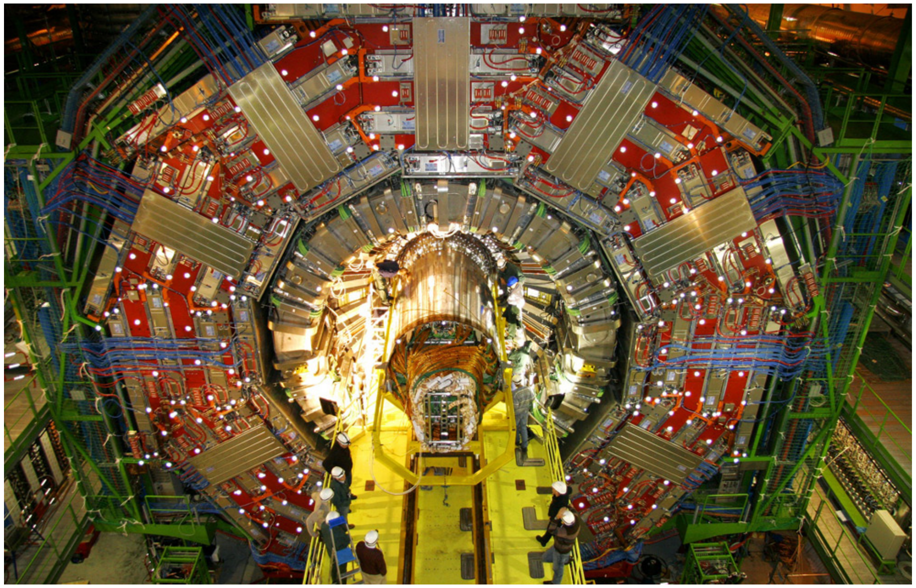
- have built the LHC - now learn how to operate powerful machine
- energy stored in magnets(beam): 10(0.7) GJ $\approx$ 2.4(0.2) tons of TNT
  - ▷ beam dump!
  - ▷ compare: 1 fill $\approx 10^{-9}$ grams of Hydrogen
  - ▷ loss of 10^{-7} part of beam $\longrightarrow$ supercond. magnet quench



- 2008 run
  - ▷ 10 Sep: Protons circulating
  - ▷ 19 Sep: quench in dipole magnets!!
  - ▷ loss of 6t He; 1 year repair
- 2009 run
  - ▷ 23 Nov: collisions at 450 GeV (1 bunch)
  - ▷ 30 Nov: 1.18 TeV per beam (beat 0.98)
- 2010/2011 run
  - ▷ Mar: ramp up Energy to 3.5 TeV
  - ▷ since 30 Mar: 3.5 TeV + 3.5 TeV collisions (4 bunches)
  - ▷ operate continuously to end of 2011; or until 1 fb^{-1} seen per experiment
  - ▷ current status: each expt has recorded 1 nb^{-1}

Main LHC - Detectors



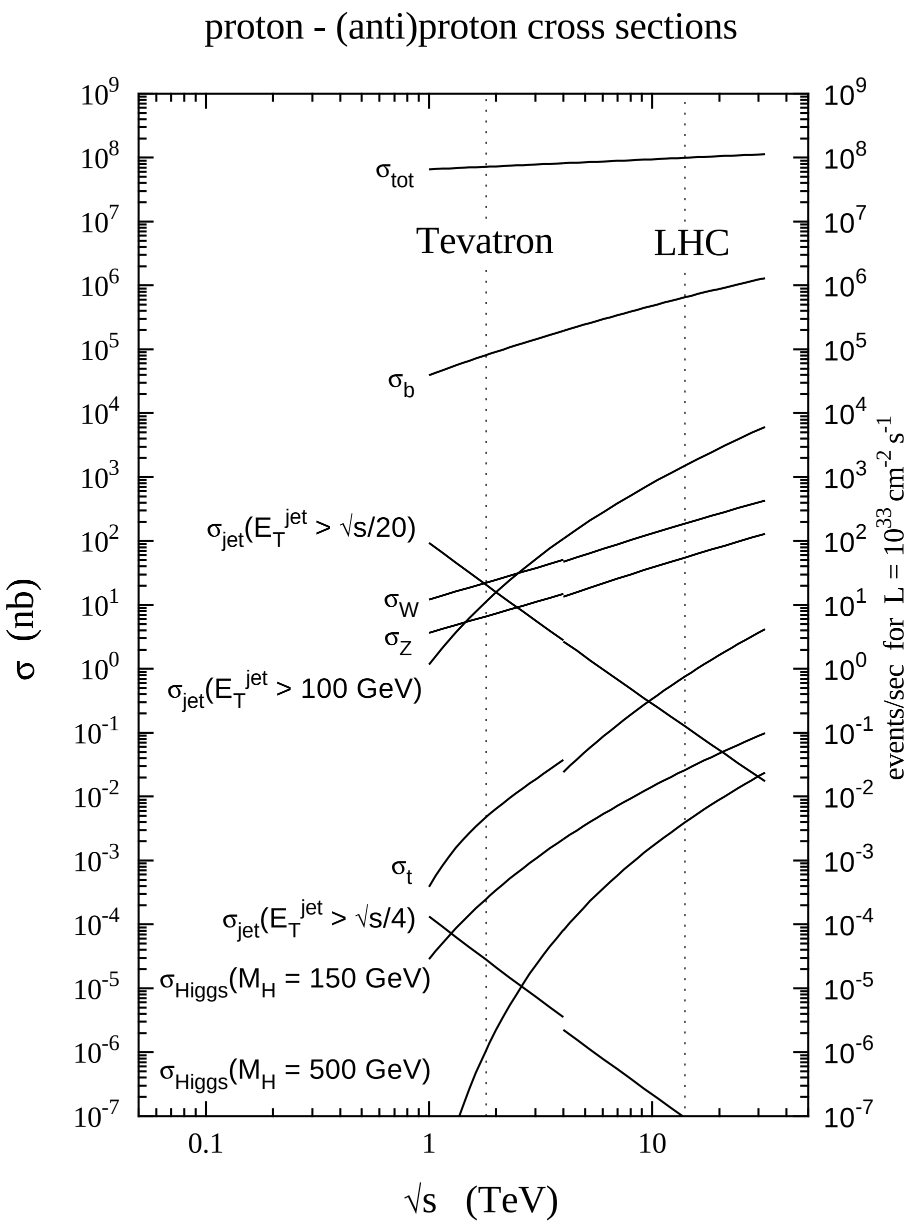


- ATLAS - A Toroidal LHC Apparatus
- $45 \times 22 \times 22$ m, 7000 tons
- 1870 physicists $\in$ 150 institutes

- CMS - Compact Muon Solenoid
- $21 \times 16 \times 16$ m, 12500 tons
- 2300 physicists $\in$ 159 institutes

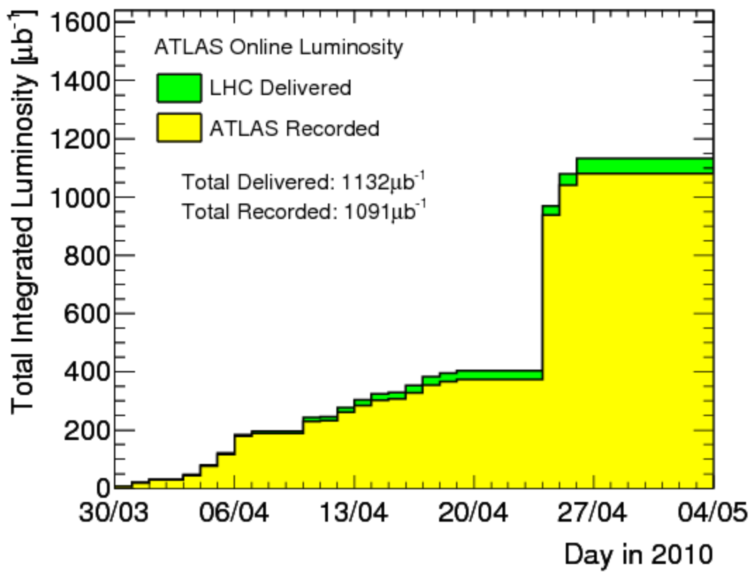
- data rate 100000 CD's/sec $\longrightarrow$ save 27 CD's/min
- 22 simultaneous pp-collisions per "event" (on average)
- often signal/background $< 10^{-10}$!!

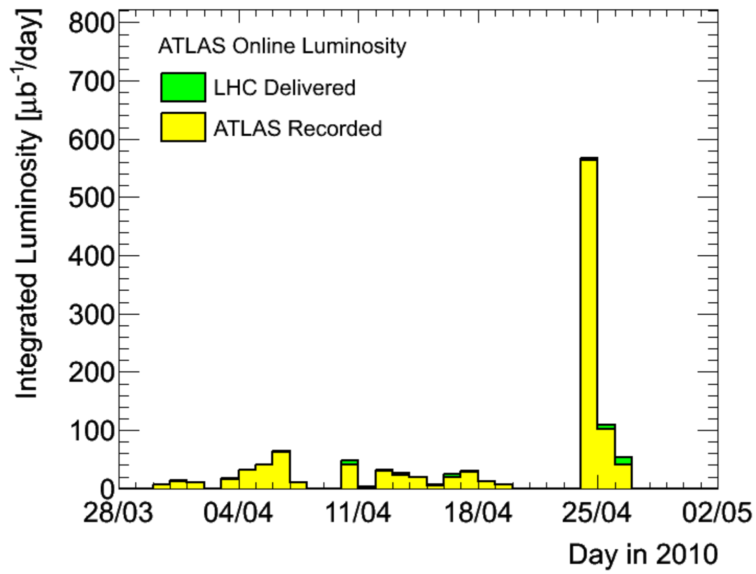
LHC - typical event rates

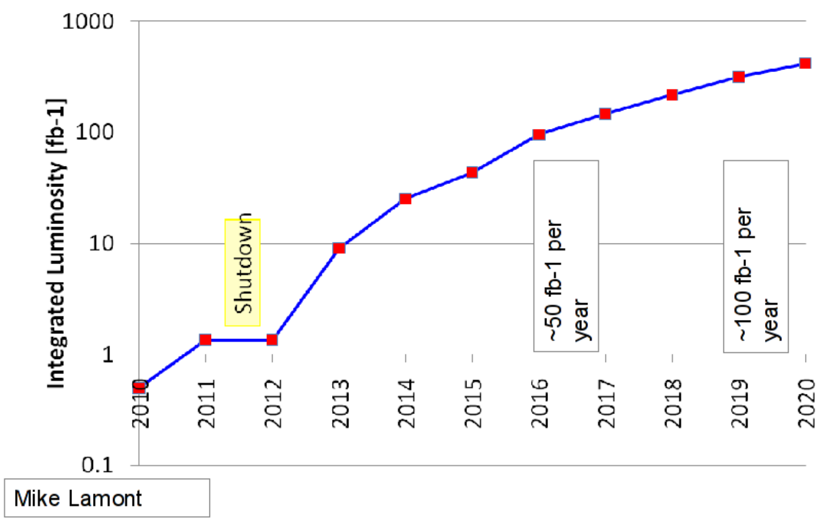


- low LHC (design-) Luminosity
- 10^8 pp-collisions per second
- signal vs background!
- in each second produce:
  - ▷ 200 W-Bosons
  - ▷ 50 Z-Bosons
  - ▷ 1 $\bar{t}t$-pair
- in each minute produce:
  - ▷ 1 light Higgs
- currently ≈ (these #s)/10^5

LHC - Luminosisty



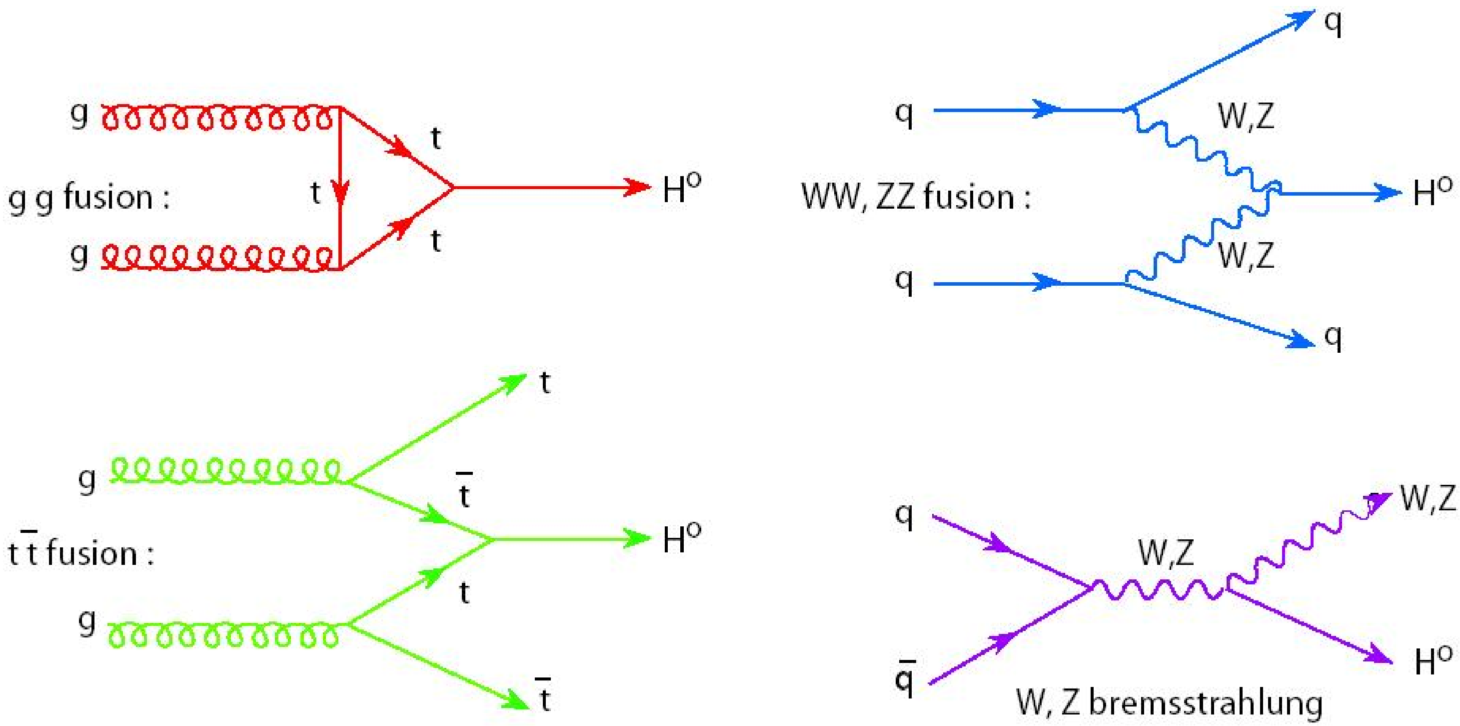




- ▷ ATLAS/CMS have recorded $\sim$ 1 nb^{-1} each (see above)
- ▷ LHC running at E/2 and L/10^{6}
- ▷ cf. Tevatron record: total 8 fb^{-1}
  2 fb^{-1}/yr; 250 pb^{-1}/mo; 73 pb^{-1}/wk
- ▷ much more to come (see left)

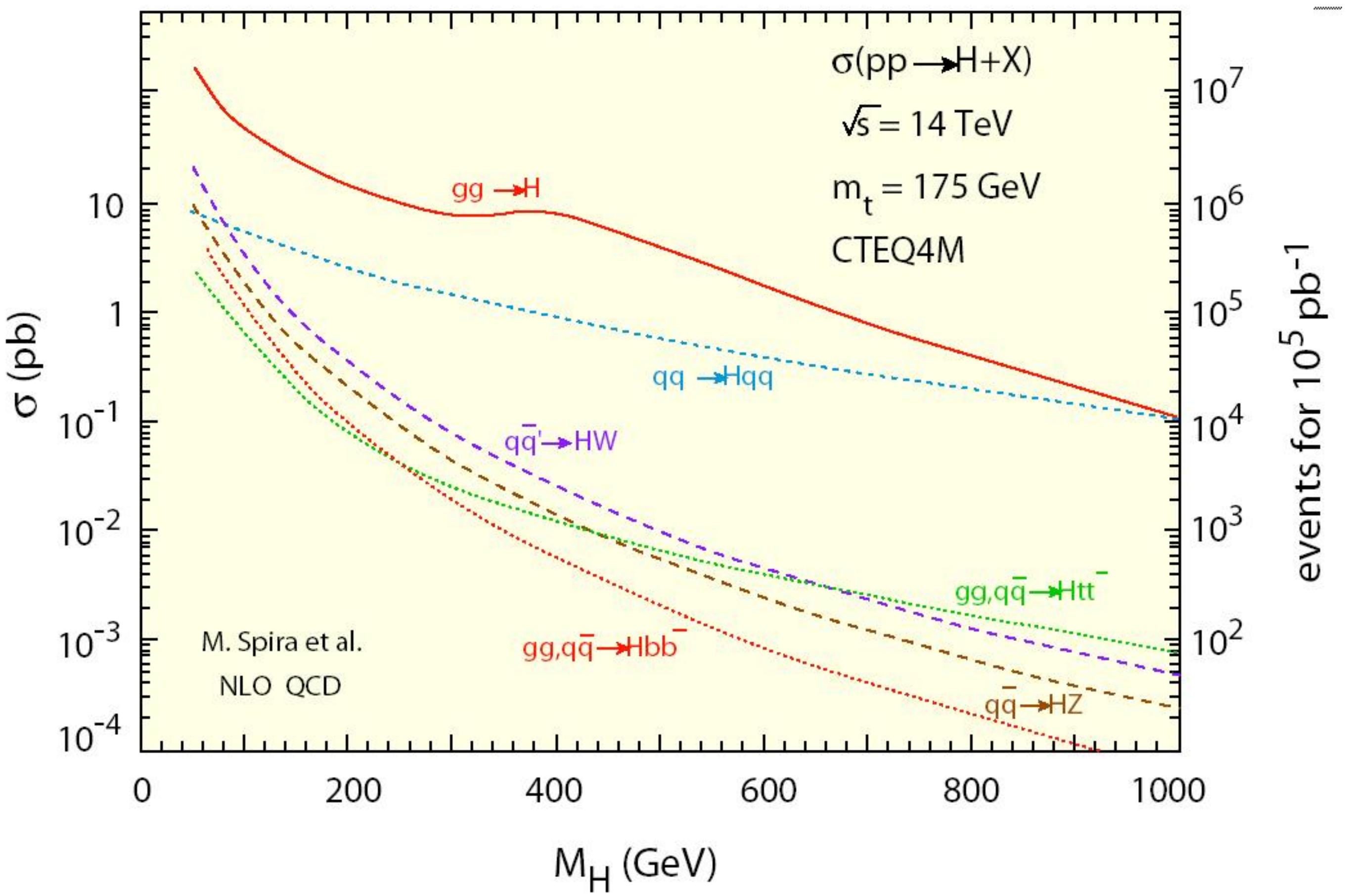
How are Higgs-Bosons produced?

- Protons consist of Quarks+Gluons (LHC as Gluon-collider)



- graphical representation: Feynman diagrams
- sometimes, loops are dominant! (cf. next pg)

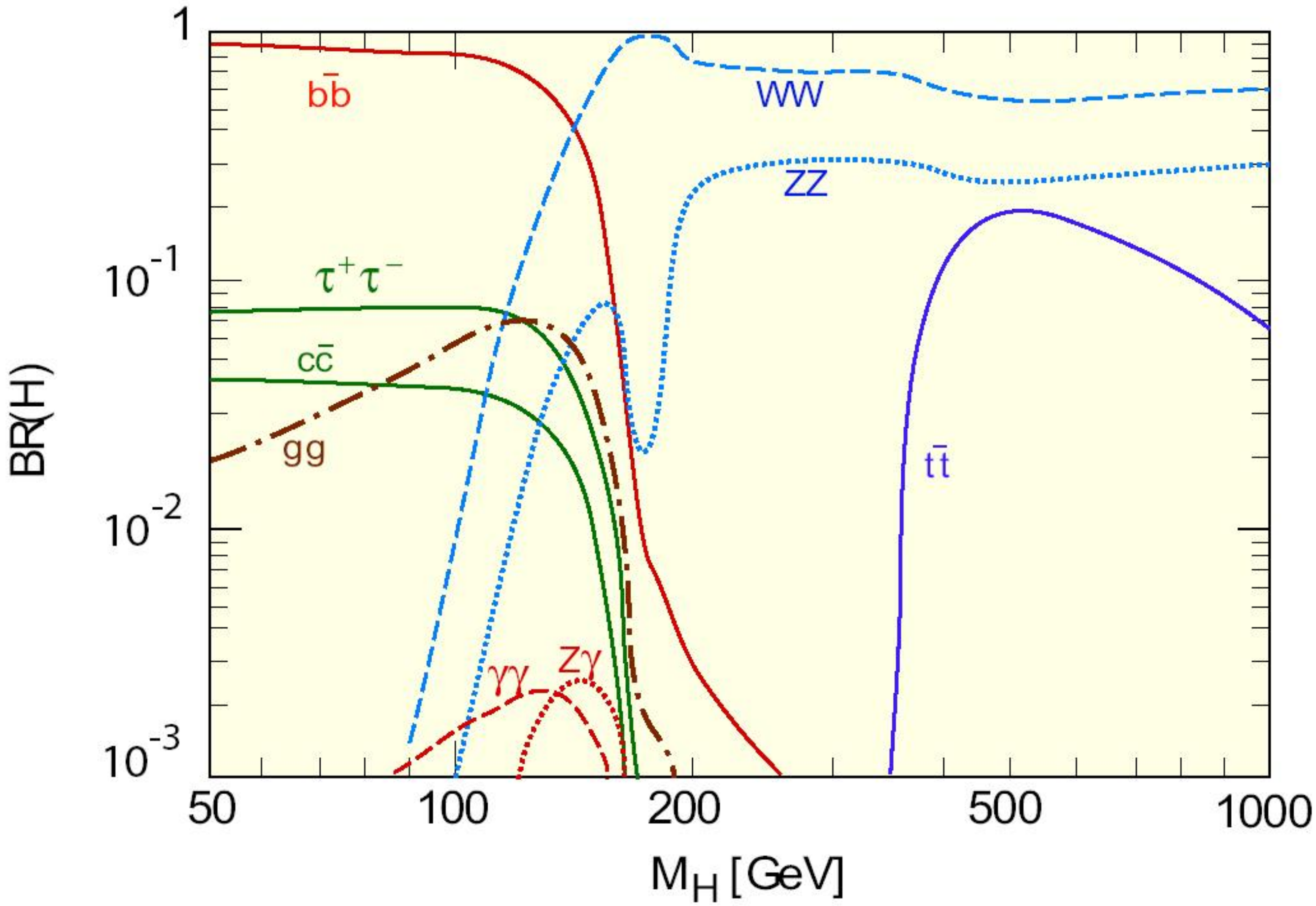
How many Higgs-Bosons are produced?



- CTEQ4M are ''structure functions'': distribution of Quarks+Gluons in Proton
- events per year (eff. 10^7 sec) at LHC with high Luminosity (1 pb = 10^{-36} cm^2)
- most important production process: Gluon fusion

Higgs decay rates

- branching ratios show strong dependence on Higgs-mass

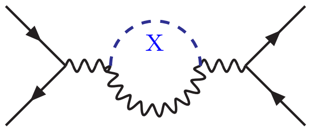


- most important decay channel: $\bar{b}b$ / WW
- number of observed events is $N_{x,obs} = L \cdot \sigma_x \cdot BR \cdot \Delta t \cdot \varepsilon$

Sensitivity on yet-unknown physics

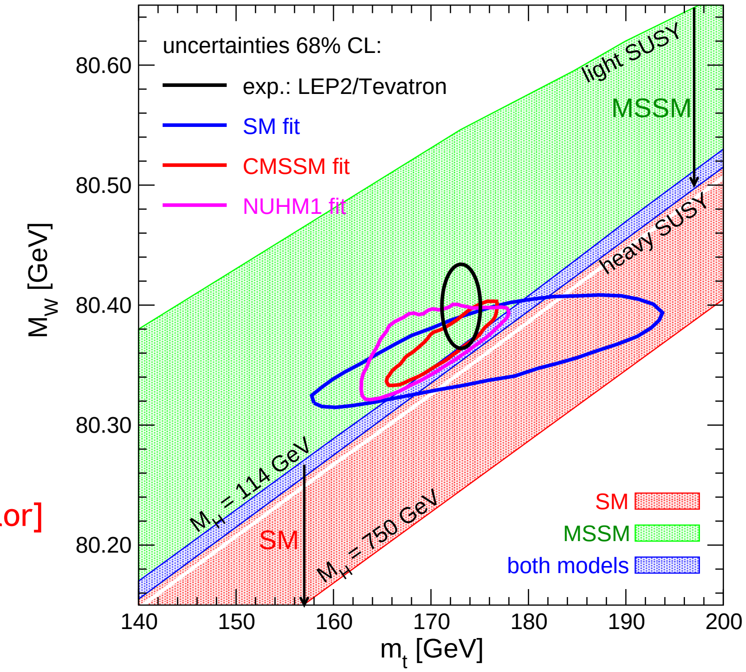
- explore a new energy range
  - ▷ search for "expected" signals of new physics (e.g. Higgs) [known unknowns]
  - ▷ keep an open mind for unexpected new physics [unknown unknowns]

- perform precise SM tests
  - ▷ high sensitivity on BSM physics in precision measurements: quantum corrections!

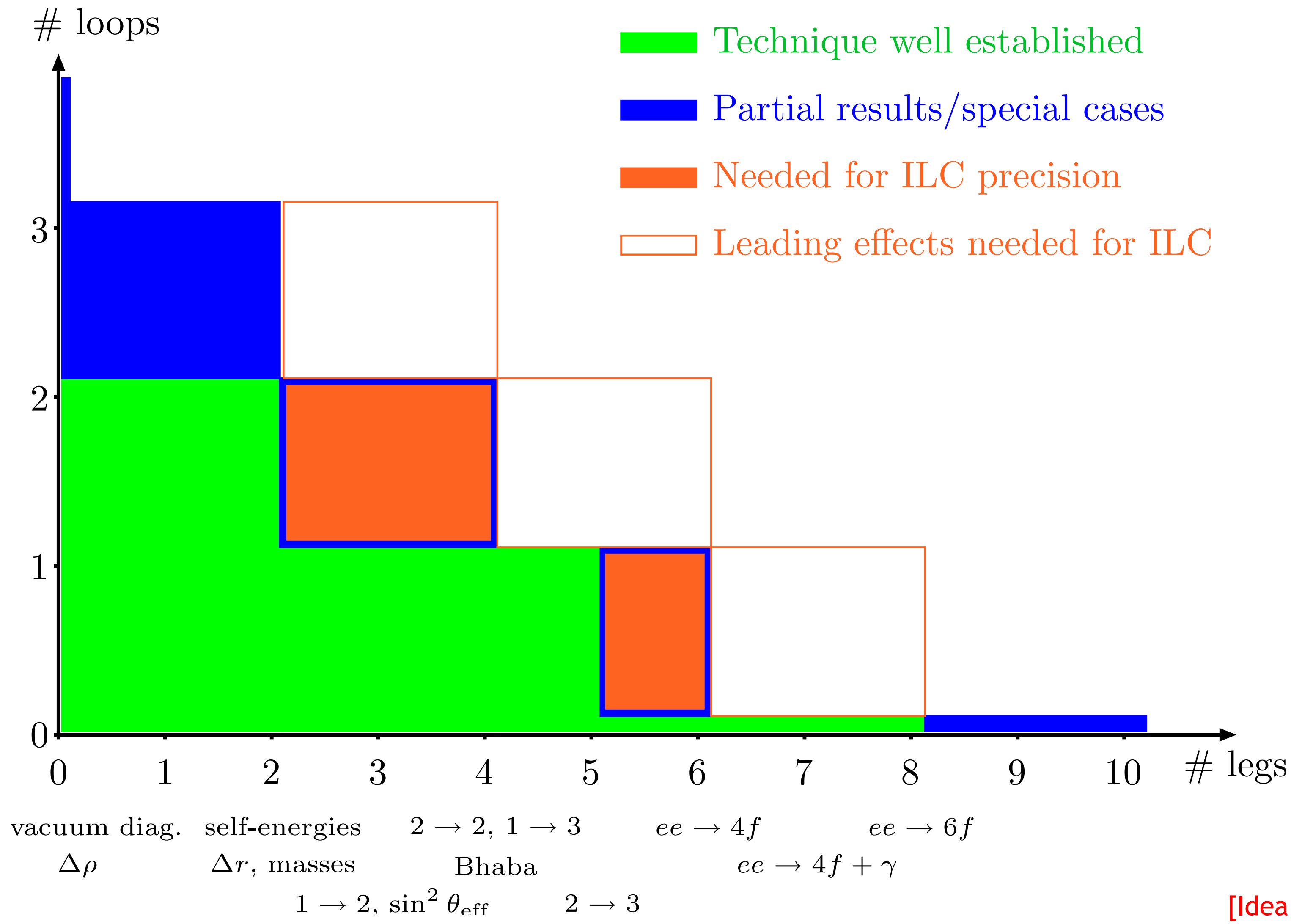


  - ▷ use SM measurements to "gauge" detectors
  - ▷ understand SM at $\sqrt{s} = 14$ GeV; check Monte-Carlo generators etc.

- experimental limits ↔ theoretical precision
  - ▷ e.g. SUSY search
$\tilde{q}, \tilde{g}$ produced via strong int
cascade decay ⟶ LSP
  - ▷ missing energy? e.g. Jets + E_T^{miss}
  - ▷ establish SUSY mass scale
  - ▷ determine model parameters (hard! ILC..)
  - ▷ cave: only two models here [O.Buchmüller et al.]
many alternatives [little Higgs, Xtra dim, ext technicolor]
all predict new sub-TeV particles!



Loops+Legs - sports



[Idea: S. Dittmaier]

$\longrightarrow$ in the following: three examples; mostly from ''upper left''

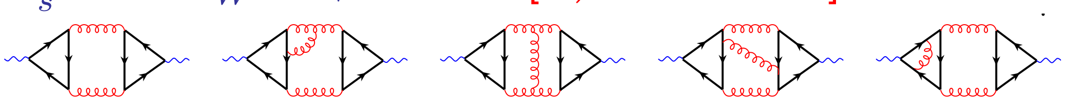
(1) Gauge boson masses at high precision

- experiment: ILC @ Z-resonance ($M_W = 80404$ MeV)
  - ▷ $\longrightarrow$ measurement with $\delta M_W^{exp} = 6$ MeV possible
  - ▷ compare with current $\delta M_W^{exp} = 30$ MeV

- theory: SM contains prediction for $M_W(M_Z, G_F, \alpha, \delta\rho)$

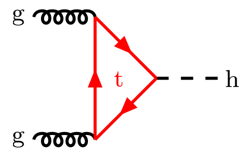
$$\text{where} \quad \delta\rho \;=\; \text{elektroweak rho parameter} \quad \text{[Veltman 1977]}$$
$$=\; \text{ratio of neutral to charged current}$$
$$=\; \frac{\Pi_T^{ZZ}(0)}{M_Z^2} - \frac{\Pi_T^{WW}(0)}{M_W^2}$$

- computation: $\delta\rho = 1 + \#\alpha_s + \#\alpha_s^2 + \#\alpha_s^3 + \ldots$
  where $\alpha_s \approx 1/10$
  - ▷ $\alpha_s^1 \Rightarrow \delta M_W = -60$ MeV [Djouadi 1988]
  - ▷ $\alpha_s^2 \Rightarrow \delta M_W = -10$ MeV [Fleischer,Tarasov 1994]
  - ▷ $\alpha_s^3 \Rightarrow \delta M_W = +0.2$ MeV [YS,Steinhauser 2005]



(2) Heavy quark decoupling relations

- primary production channel for Higgs-Bosons at LHC: Gluon fusion ($g+g \to H$)
- decay channel analogous ($H \to g+g$)



- theory: processes are loop-induced (see above)

  $\to$ higher perturbative orders extremely important!

  ▷ e.g. $\Gamma(H \to gg) = \frac{G_F M_H^2}{36\pi\sqrt{2}} \left(\frac{\alpha_s}{\pi}\right)^2 \cdot K$

  ▷ where $K \sim 1 + \#\alpha_s + \#{\alpha_s}^2 + \#{\alpha_s}^3 + \ldots$

  resp $K \sim 1 + 0.656 + 0.204 + 0.019 + \ldots$ [Baikov,Chetyrkin 2006]

- need to know coupling α_s with extreme precision
- experiment: determine α_s at ''low'' energy

  e.g. in Tau decays ($M_\tau = 1.777$ GeV)

  $\to \quad \alpha_s(M_\tau) = 0.345 \pm 0.004_{exp} \pm 0.008_{th}$

- strategy: evolve α_s to higher energies

  e.g. to $\alpha_s(M_Z) = 0.1216 \pm 0.0004_{exp} \pm 0.0010_{th} \pm 0.0004_{evol}$ ($M_Z = 91.2$ GeV)

  $\to$ running coupling; RG-equations; beta function $\beta(N_f = \#$ of light Quarks)

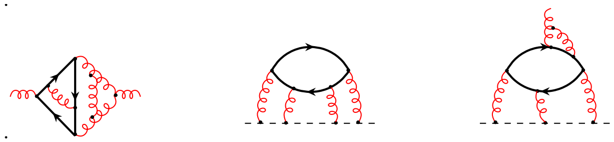
  $\to$ cf. mass$(u, d, s, c, b, t) \approx (0.002, 0.004, 0.095, 1.25, 4.2, 174)$ GeV

(2) Heavy quark decoupling relations

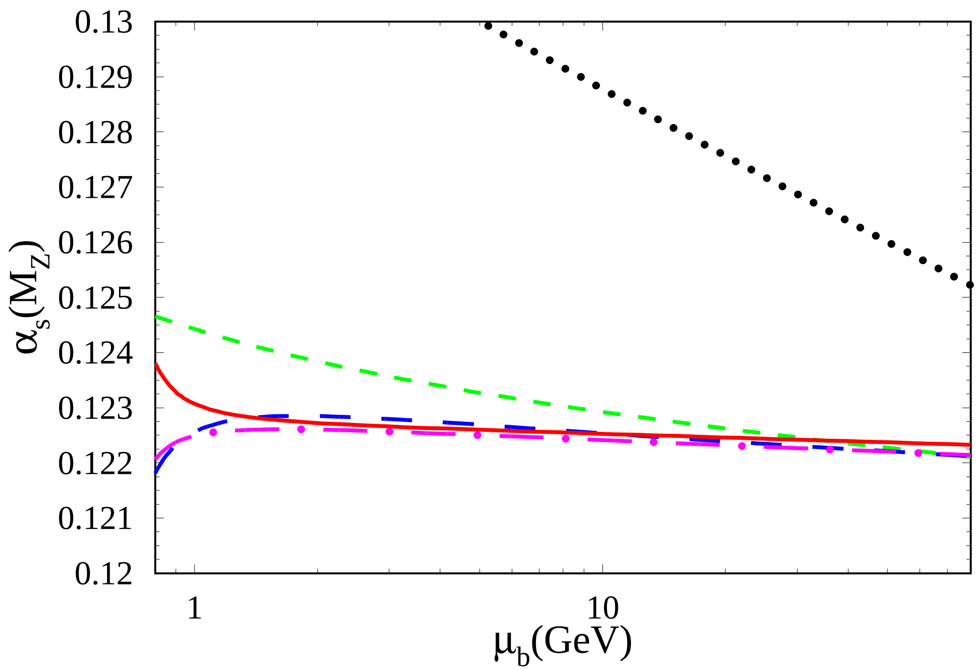
- crossing the b-Quark threshold

  $\longrightarrow$ main idea: integrate out effects of heavy Quarks

- strategy: $\alpha_s^{(4)}(M_\tau) \xrightarrow{\text{run } N_f=4} \alpha_s^{(4)}(\mu) \xrightarrow{\text{dec } 4\leftrightarrow 5} \alpha_s^{(4)}(\mu) \xrightarrow{\text{run } N_f=5} \alpha_s^{(5)}(M_Z)$

- computation: 

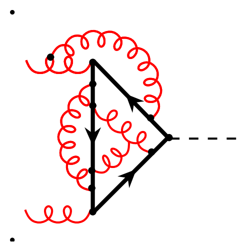
- μ scale depencence?
  - ▷ unphysical
  - ▷ has to vanish!
  - ▷ depends on decoupling precision
  - ▷ result: 4-loop flat [YS,Steinhauser 2006]



(2) Heavy quark decoupling relations

- $\Rightarrow$ precise evolution of ''running'' coupling $\alpha_s(E)$
- another amusing application of decoupling relations:

building block for (5-loop)
$\Gamma(H \to gg)$
$\sigma(gg \to H)$



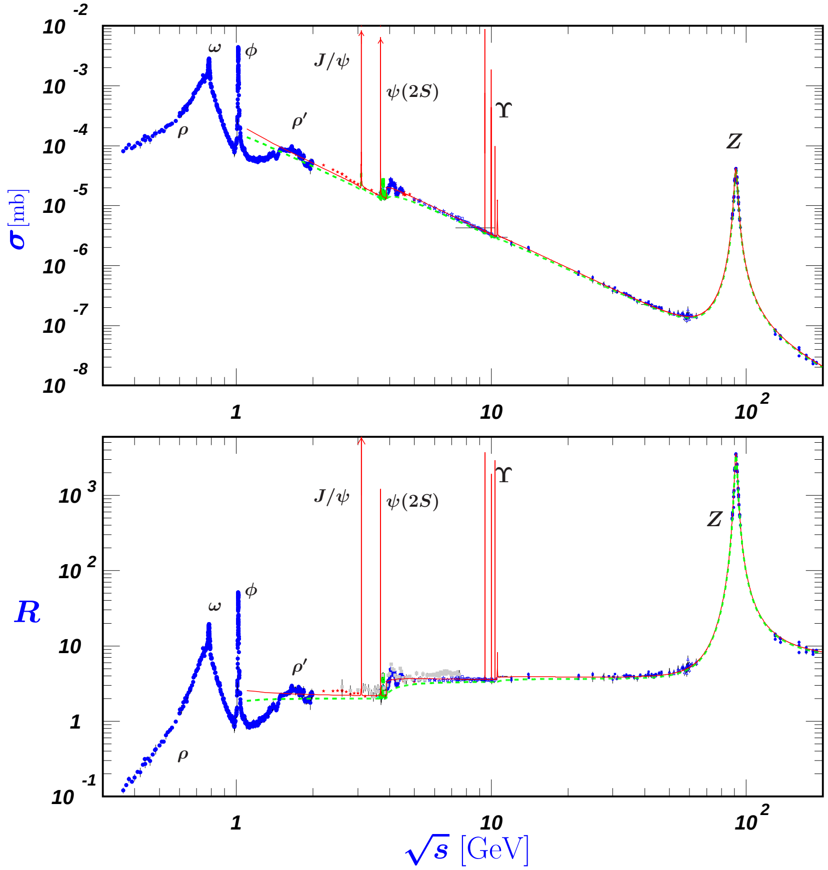
via low-energy theorem $\mathcal{L}_{\text{eff}} = \frac{H}{v} \left(G^a_{\mu\nu} \right)^2 \; \partial_{\ln m_t^2} \; \ln \frac{{\alpha_s}^{(5)}}{{\alpha_s}^{(4)}}$

[Chetyrkin et al. 1998]

(3) Quark masses at high precision

- central quantity in particle physics: the ratio $$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

- experiment:



- theory (naive):

  parton model

$$R(s) \approx N_c \sum_q Q_q^2 \, \theta(\sqrt{s} - M_q)$$

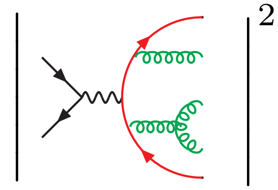
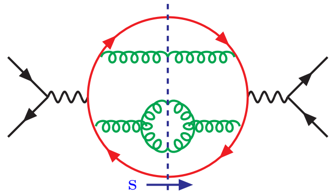
$$\sim \left(\frac{4}{3} + \frac{1}{3} + \frac{1}{3}\right) + \frac{4}{3} + \frac{1}{3} + \frac{4}{3}$$

$u \quad d \quad s \quad c \quad b \quad t$

- ▷ rough structure OK
- ▷ details → precision
- ▷ sharp resonances e.g. J/ψ $(\bar{c}c)$ or Υ $(\bar{b}b)$
- ▷ threshold behaviour

(3) Quark masses at high precision

- theory (precise):

  unitarity connects $R(s)$ to correlator: $\sum_{\text{had}}$  $=$ 

  - ▷ resp. $R(s) \approx \Im\, \Pi(s - i\varepsilon)$
  - ▷ dispersion relation $\Pi(q^2) \sim q^2 \int ds\, \frac{R(s)}{s(s-q^2)}$ + const

- strategy: $R^{exp} \stackrel{!}{=} R^{th}(\alpha_s, M_q)$
  - ▷ determination of $\alpha_s \leftarrow$ consistent RG evolution $\leftarrow \beta(N_f =$ light Quarks$)$
    + decoupling of heavy Quarks (see above)
  - ▷ determination of M_q

- main idea: Taylor coefficients of $\Pi \;\hat{=}\;$ moments of $R(s)$

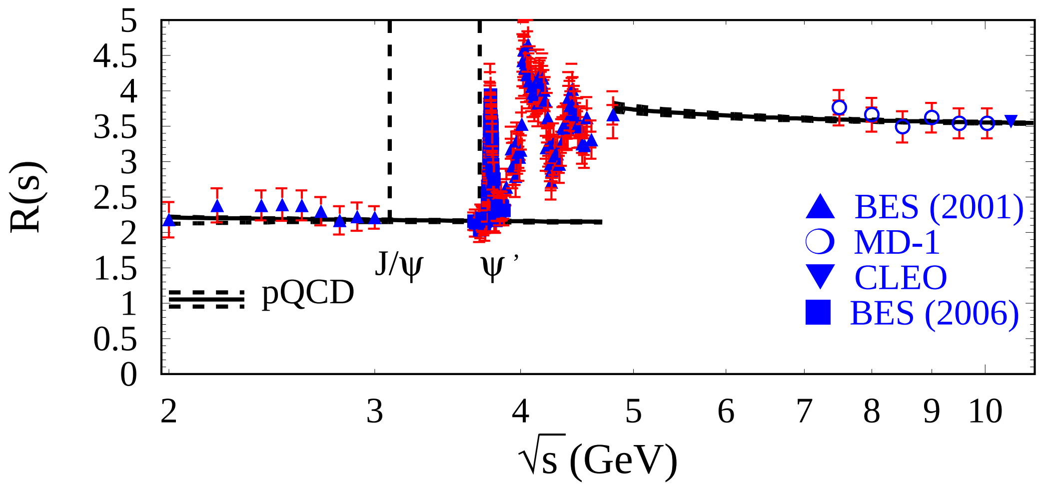
  $\mathcal{M}_n^{th} \sim \frac{1}{n!}\, \partial^n_{q^2}\, \Pi(q^2)\Big|_{q^2=0}$ vs $\mathcal{M}_n^{exp} \sim \int \frac{ds}{s^{n+1}}\, R^{exp}(s)$

  th: expansion in $q^2/{M_q}^2$

- calculation: building blocks are vacuum tadpoles [YS,Vuorinen 2005; Boughezal,Czakon 2006]

(3) Quark masses at high precision

- experimentally determined moments: c-Quark threshold, R(s) from 2⟶3.3



$$R^{exp} = R^{res} + R^{thr} + R^{cont}$$

- ▷ J/ψ: M 3 GeV, Γ 90 keV
- ▷ ψ: M 3.7 GeV, Γ 317 keV

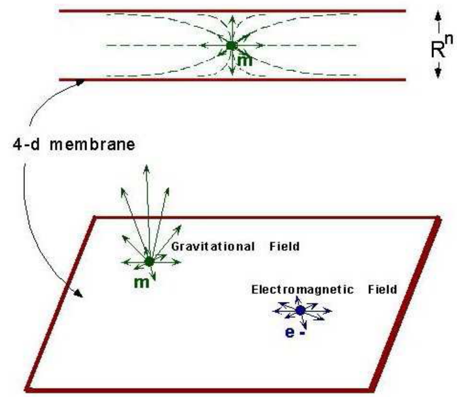
$\rightarrow \mathcal{M}_n^{exp}$

- comparison: $\mathcal{M}_n^{th} \stackrel{!}{=} \mathcal{M}_n^{exp}$
  - ▷ $N_f = 4$ analysis $\longrightarrow M_c(M_s) = 1.286(13)$ GeV [Kühn,Steinhauser,Sturm 2007]
  - ▷ $N_f = 5$ analysis $\longrightarrow M_b(M_b) = 4.164(25)$ GeV [dito]
  - ▷ cf. PDG 2008: 1.27(11) and 4.20(17)

- why are precise Quark masses so important? e.g.
  - ▷ B-Meson decays: $\Gamma(B \rightarrow X_u l \bar{\nu}) \sim G_F^2 M_b^5 |V_{ub}|^2$
  - ▷ Υ spectroscopy: $M_{\Upsilon(1s)} = 2M_b(1 - \frac{2}{9}\alpha_s^2 + \ldots)$
  - ▷ Higgs-Boson decay (ILC): $\Gamma(H \rightarrow \bar{b}b) \sim G_F M_H \, M_b^2(1 + \alpha_s + \ldots)$

What else could one dream to find?

E.g. extra (compact) dimensions

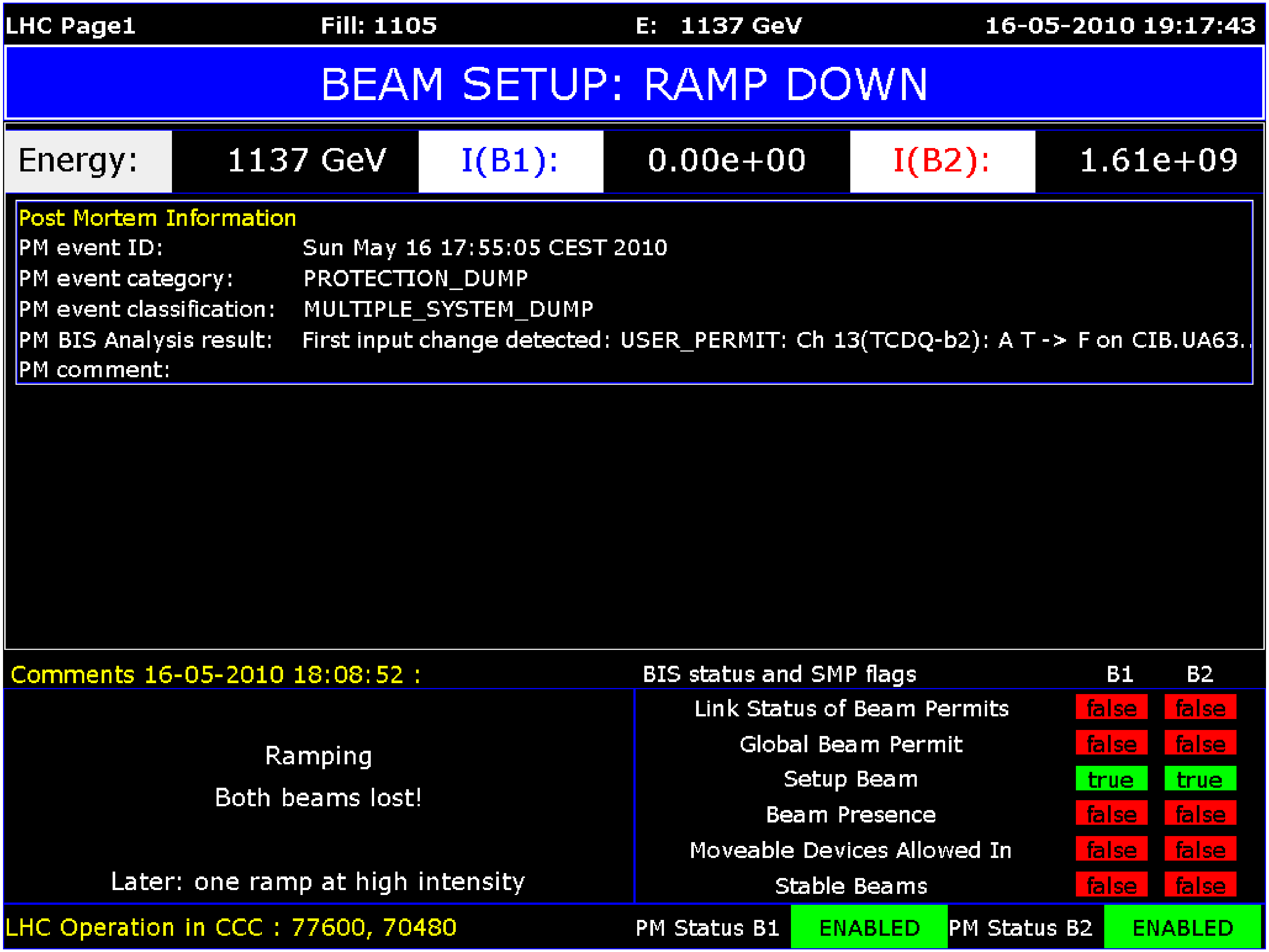


- main idea: explain feebleness of gravity by diluting it
  - ▷ gravitational fields allowed to fill more than 4 dimensions
  - ▷ ordinary matter and forces confined to (3+1) dim "3-brane"
  - ▷ $\leftrightarrow$ motivation from string theory, 3+1+6 dim
  - ▷ e.g. ADD model: n compact extra dims, M_F ~TeV: $M_P^2 \sim R^n\, M_F^{n+2}$
  - ▷ fm$\leq R \leq$mm (gravity tests) $\Rightarrow$ 6$\geq n \geq$2
- key collider signature: missing Energy! e.g. $q\,\bar{q} \to j\, G_{KK}(\not{E})$, $e^+e^- \to \gamma\, G_{KK}(\not{E})$
  - ▷ Gravitons carry energy into extra dim
  - ▷ black hole production for $\sqrt{s} \gg M_F$
- many model variants: large-, universal-, warped-, ... -Xtra dim

Outlook

- have a working description of nature: Standard Model (SM)
  - ▷ will SM ''survive'' next decade?
  - ▷ many theoretical ideas for SM extensions
  - ▷ which ones are realized in nature?
- enormous experimental efforts
  - ▷ LHC 2010+ $\longrightarrow$ unprecedented energy range
- signals of ''new'' physics are extremely small
  - ▷ highest precision needed for background subtraction
- many opportunities for theory
  - ▷ contribute with moderate budget
  - ▷ key building blocks: SM parameters
  - ▷ scale dependence (evolution), mass effects
  - ▷ Bielefeld contributions: QCD precision computations
- this is truly the dawn of the LHC decade
  - ▷ discoveries could happen fast
  - ▷ fasten your seat belts!

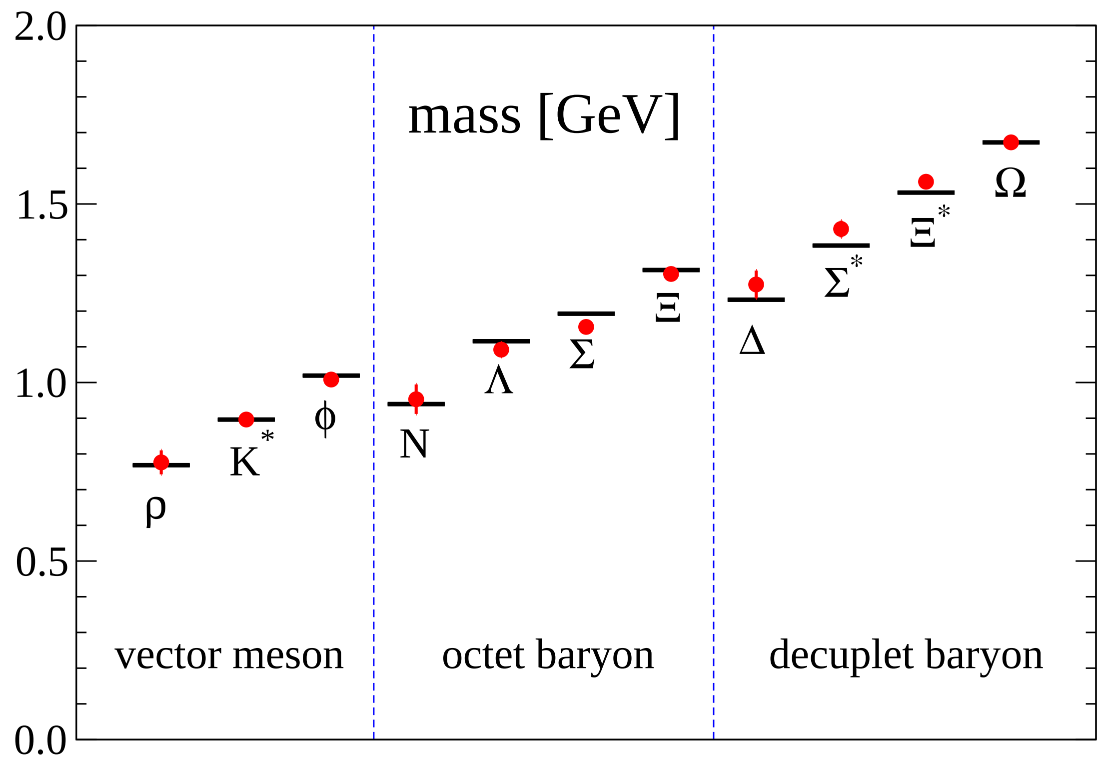
LHC: Status 16 May 2010



QCD - Test (via large computer)

look at hadron spectrum (hadrons: bound states of quarks; e.g. K=$s\bar{d}$, p=uud, Λ=uds)

- solve QCD eqs by computer
  [e.g. S. Aoki et.al., PACS-CS 2008]
- what does not come out:
  - ▷ gluons
  - ▷ fractional charges
- what one gets:
  - ▷ just the observed particles + masses
  - ▷ no more, no less!



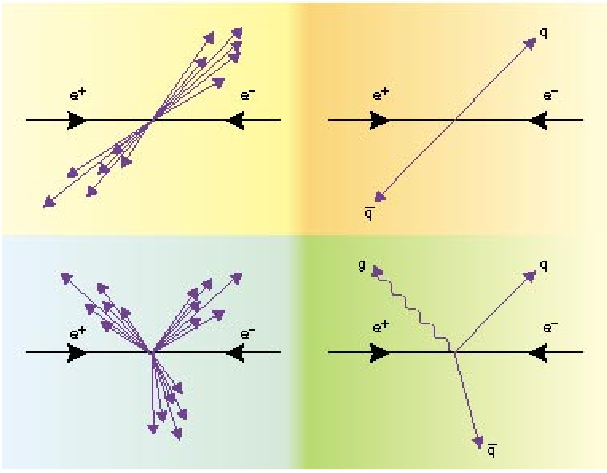
- punchline: QCD postdicts the low-lying hadron masses!
  - ▷ much development here; teraflop speeds, worldwide effort
  - ▷ $a = 0.091$ fm; $32^3 \times 64$ lattice; NP $\mathcal{O}(a)$ impr. Wilson quarks
  - ▷ 2+1 flavors; chiral logs; $m_q \approx 1.3\, m_l$; π, K, Ω as input

SM-Test (with colliders)

- e.g. LEP, $e^+e^- \longrightarrow X$ (stuff hitting detector): find 2 broad classes of events (QM!)

- (1) $X = e^+e^-$ or $\tau^+\tau^-$ or ... l^+l^-
  - ▷ leptons: no color charge $\longrightarrow$ mainly QED interactions
  - ▷ simple final state: coupling small ($\alpha = e^2/(4\pi) \approx 1/137$)
    most of the time (99%) nothing happens
  - ▷ $e^+e^-\gamma \sim$ 1% $\longrightarrow$ check details of QED
  - ▷ $e^+e^-\gamma\gamma \sim$ 0.01% $\longrightarrow$ ...

- (2) $X > 10$ particles: π, ρ, p, $\bar{p}$, ...
  - ▷ ''greek+latin soup'' constructed from qu+gl
  - ▷ pattern: flow of E+momentum in ''jets''
  - ▷ 2 jets $\sim$ 90%; 3 jets $\sim$ 9%; 4 jets $\sim$ 0.9%
  - ▷ direct confirmation of asy. freedom!
  - ▷ hard radiation is rare $\longrightarrow$ # of jets
  - ▷ soft radiation is common $\longrightarrow$ broadens jet



- nowadays: ''testing QCD'' $\longrightarrow$ ''calculating backgrounds'' in search for new phenomena
  discrepancies $\longrightarrow$ ''new'' physics

Concepts and Methods

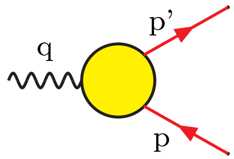
techniques used

- computer algebra
  - ▷ generation of Feynman diagrams
  - ▷ classification; scalarization
  - ▷ reduction to ‘‘master integrals’’ [J. Möller (PhD student)]
- evaluation of master integrals
  - ▷ numerical integration: precision ?
  - ▷ explicit integration: ‘‘art’’
  - ▷ difference equations: analytical/numerical solution [E. Bejdakic (PhD student)]
  - ▷ differential equations
- effective field theory $\longrightarrow$ integrate out heavy Quarks

tools

- FORM + computer cluster
- special functions
  - ▷ harmonic polylogarithms HPL(x) [Remiddi,Vermaseren 2000]
  - ▷ multiple harmonic sums S(N) [Vermaseren 1998]
- new/innovative/combined tools?! large N? AdS/CFT? Hopf algebra?

Lepton magnetic moments

- prediction of Dirac theory: $\mu_l = 2\,\frac{e\hbar}{2m_l}\,s \quad (l \in \{e,\mu,\tau\})$
- quantum corrections: $2 \longrightarrow 2(1 + a_l)$
- computation: 

$= \bar{u}(p')\left[\gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_l}F_2(q^2)\right]u(p)$
- relationship: $a_l = F_2(0)$
  - ▷ experiment: $a_\mu = 116592080(63)\cdot 10^{-11}$
  - ▷ theory: $a_\mu^{QED} = \frac{1}{2\pi}\alpha + \ldots + \#\alpha^4 + ??\alpha^5$
    where $\alpha \approx 1/137$
    α^1: [Schwinger 1948] [N.Groeger, T.Luthe, J.Schücker (BA students)]
    $\alpha^4 \approx 380\cdot 10^{-11}$ [Kinoshita et al. 2002; Laporta,Remiddi 2006]
    α^5: [Kinoshita et al., in progress]
  - ▷ theory: a_μ^{EW} incl 2-loop OK
- comparison: ''interesting discrepancy'' of 3σ
  (1.8σ with τ-data for hadronic effects)