



Particle Data Group

From Wallet Cards to Smartphone Apps

58 years of evaluating data





Introduction





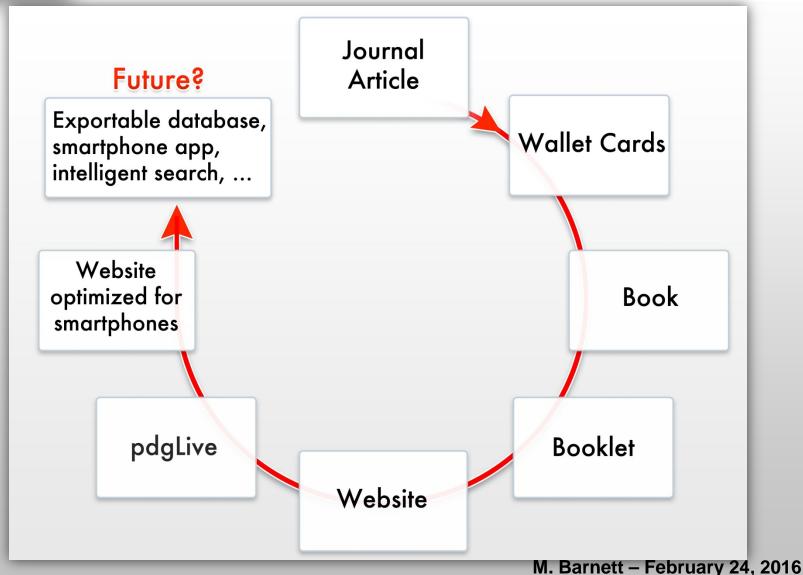
Three goals of PDG:

- Highest Quality
- Innovation
- Timeliness



PDG Innovations







Timely Additions



LIGO announcement Feb. 11, 2016: already in PDG Review on: "Experimental Tests of Gravitational Theory"

... The existence of transverse-traceless quadrupolar gravitational waves (in the wave zone), and a direct observational proof of the existence of coalescing black holes, ...

Similarly the July 4, 2012 announcement of the Higgs boson discovery appeared in the PDG book soon thereafter as a July 12 Addendum to the review on Higgs Bosons:

On July 4, 2012, the ATLAS and CMS collaborations simultaneously announced observation of a new particle produced in pp collision data at high energies ...



Art Rosenfeld 1975 review article



THE PARTICLE DATA GROUP: GROWTH AND OPERATIONS

Excerpts:

A single international group, the Particle Data Group (PDG), compiles all the data on particle properties.

We briefly discuss how the data rate grew from a trickle to a fairly steady flood.... We outline how PDG has learned to

collect, evaluate, correct, verify, analyze, and distribute the data,...

PDG has taken on the responsibility of critically reviewing the results of experiments.

Of over 154 pages of "Listings," 50 pages are actually not listings, but figures, or ...reviews.

In our experience, transatlantic collaboration works surprisingly well, but only after people have worked together and grown to know one another well.





PDG Collaboration



206 authors from 140 institutions plus 700 consultants





Fermilab Collaborators in PDG



Authors

(2014 edition)

- Marcela Carena
- Bogdan Dobrescu
- Lynn Garren
- Tom Junk
- Michael Syphers
- Ruth Van de Water
- Geralyn (Sam) Zeller

Chair of the PDG Advisory Committee (2014)

Deborah Harris

And many consultants including Dmitri Denisov



Fermilab Discoveries in PDG



b Quark Discovery (1977)

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1 M	FROM 2-PEAK FIT				12/77
	49 UPS	(LON1 WIOTH (GEV)			
н А	(100.) OR LESS	INNES	77 SPEC	0 400 P+4,MU+MU-	12/77
	FROM QUOTED RESOLUTIO				
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P2	UPSILONI INTO E+ E- 49 UPSI UPSILONI INTO MU+ MU- SEEN	ILCN1 BRANCHING RA		105+ 105 -5+ -5	12/77
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PDG Database 1980







Fermilab Discoveries in PDG



t Quark Discovery (1995)

And more discoveries

t-Quark Mass in pp Collisions I

The t quark has now been observed. Its mass is sufficiently high that decay is expected to occur before hadronization.

Preliminary results for the top mass based on the full (Run Ia+Ib) data set have been presented by CDF and DØ at conferences in early 1996:

$$\begin{split} m_t &= 175.6 \pm 5.7 \pm 7.1 \text{ GeV} &\quad \text{CDF} \quad \text{lepton} + \text{jets} \\ m_t &= 159 {}^{+24}_{-22} \pm 17 \text{ GeV} &\quad \text{CDF} \quad \text{dilepton} \\ m_t &= 187 \pm 8 \pm 12 \text{ GeV} &\quad \text{CDF} \quad \text{hadronic} \\ \\ m_t &= 170 \pm 15 \pm 10 \text{ GeV} &\quad \text{DØ} \quad \text{lepton} + \text{jets} \\ m_t &= 158 \pm 24 \pm 10 \text{ GeV} &\quad \text{DØ} \quad \text{e} \, \mu \end{split}$$

Because of the high current interest, we mention these preliminary results here but do not average them or include them in the Listings or Tables. See the note on the top quark for references.

Search limits, which are now primarily of historical interest, are based on the assumption that no nonstandard decay modes such as $t \to bH^+$ are available, except as noted in the comments.

VALUE (GeV)	CL%	DOCUMENT I	D	TECN	COMMENT	
180±12 OUR AV	ERAGE					
$199^{+19}_{-21}\pm22$		¹ ABACHI	95	D0	ℓ + jet	
176± 8±10		² ABE	95F	CDF	ℓ + b -jet	



Full Summary Table 1957



(from Wallet Cards)

Barkas and Rosenfeld UCRL-8030 Table I

Masses and mean lives of elementary particles; November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)	Mass difference (Mev)		Mean life (sec)		Decay rate (number per second)
Photon	Υ	1	0			stable		0
Lepton	ν. «- μ-	† † †	0 0,510976 (a) 105,70 ±0,06 (a)			stable stable (2.22 ±0.02) ×10 ⁻⁶		0 0 0.45 × 10 ⁶
Mesons	# [†] # ⁰ K [†] K ⁰	0 0 0	139.63 ±0.06 (a) \\ 135.04 ±0.16 (a) \\ 494.0 ±0.2 (g) \\ 494.4 ±1.8 (i)	4.6 (a) 0.4±1.8	к ₁ : к ₂ :	(2.56 ±0.05) ×10-8 <4 ×10-16 (1.224±0.013)×10-8 (0.95 ±0.08) ×10-10 (4< \tau<13) ×10-8	(h)	0.39 × 10 ⁸ > 2.5 × 10 ¹⁵ 0.815 × 10 ⁸ 1.05 × 10 ¹⁰ (0.07 < \tau < 0.25) × 10 ⁸
Baryons	P n A E+ E- E ⁰ = 0	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	938.213±0.01 (a) 939.506±0.01 (a) 1115.2 ±0.14 (j) 1189.4 ±0.25 (l) 1196.5 ±0.5 (n) 1190.5 ^{+0.9} _{-1.4} (p) 1320.4 ±2.2 (q)	7.1 ± 0.4 $6.0^{+1.4}_{-0.9}$		stable (1.04 ±0.13) $\times 10^{+3}$ (2.77 ±0.15) $\times 10^{-10}$ (0.83 $^{+.06}_{05}$) $\times 10^{-10}$ (1.67 ±0.17) $\times 10^{-10}$ (<0.1) $\times 10^{-10}$ theoretically $\sim 10^{-10}$ (4.6 < τ < 200) $\times 10^{-10}$?	(m) (o) (b)	0.0 0.96 × 10 ⁻³ 0.36 × 10 ¹⁰ 1.21 × 10 ¹⁰ 0.60 × 10 ¹⁰ > 10 × 10 ¹⁰ theoretically ~ 10 ¹⁵ (>0.005, ≪0.2) × 10 ¹⁰



Wallet Cards 1957



Barkas	and	Rosenfeld	UCRL-8030	Table I
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	Particle	Spin	Mass (Errors represent standard deviation) (Mev)	difference (Mev)		Mean life (sec)		Decay rate (number per second)
Photon	Y	1	0			stable	,	0
:		ł	0			etable		0
ů.	•	+	0.510976 (a)			etable		0
3	μ-	t	105.70 ±0.06 (a)			(2.22 ±0.02) ×10-6		0.45 × 10 ⁶
	•	0	139,63 ±0,06 (a)			42.56 a 0.05) ×10-8	(a)	0.39 × 10 ⁸
	•0	0	135.04 ±0.16 (a)	4.6 (a)		<4 ×10-16	(d)	> 2.5 × 1015
8	K+	0	494.0 ±0.2 (4)			(1.224±0.013)×10-8	(b)	0.815 × 108
9	K0	0	494.4 al.8 (i)	0.4 ± 1.8	K1:	(0.95 ±0.08) ×10-10	(e)	1.05 × 10 ¹⁰
^			.,		K2:	(4< 7<13) ×10-8	(c)	(0.07 < 7 < 0.25) × 108
		1	938.213 ± 0.01 (a)			stable	•••••	0.0
	p n	1	939.506 +0.01 (a)			(1.04 ±0.13) ×10 ⁺³	(a)	0.96 × 10-3
	Α.	1	1115.2 40.14 (1)			(2.77 ±0,15) ×10-10	(k)	0.36 × 10 ¹⁰
	E+	1	1189.4 +0.25 (1) }			(0.83 +.06) ×10-10	(m)	1,21 × 10 ¹⁰
Ř	Σ-		1196.5 ±0.5 (n)	7.1 ± 0.4		(1.67 ±0.17) ×10-10	(0)	0.60 × 10 ¹⁰
Dary	E°	1	1190.5 ^{+0.9} _{-1.4} (p)	6.0+1.4		(<0.1) ×10 ⁻¹⁰ theoretically ~10 ⁻¹⁹	(P)	>10 ×10 ¹⁰ theoretically ~10 ¹⁹
	r.	7	1320.4 ± 2.2 (a)			(4.6 < 7 < 200) ×10-10	(1)	(>0.005, €0.2) ×10 ¹⁶
	¥ 0	2	,			?	***	, , , , , , , , , , , , , , , ,

Table IV

Atomic and nuclear constants in units of Mev, cm, and sec

- N = 6.0249 × 10²³ molecules/gram
- c = 2.99793 × 10¹⁰ cm/sec e = 4.80286 × 10⁻¹⁰ esu = 1.6021×10⁻¹⁹ coulomb.
- 1 Mev = 1.6021 ×10⁻⁶ erg [1 ev = e(10⁸/c)] 1 = 6.5817 ×10⁻²² Mev sec = 1.054 ×10⁻²⁷ erg sec.
- Tic = 1.9732 × 10⁻¹¹ Mev cm [= ** for p = 1Mev/c] k = 8.6167 × 10⁻¹¹ Mev/°C'[Boltzmann constant]
- $a = \frac{e^2}{6c} = 1/137.037; e^2 = 1.44 \times 10^{-13} \text{ Mev cm}$

QUANTITIES DERIVED FROM THE ELECTRON MASS, m

m = 0.510976 Mev = 1/1836.12 mp = 1/273.26 mg

Rydberg, $R_{\infty} = \frac{\text{me}^4}{2\hbar^2} = \text{mc}^2 \times \frac{a^2}{2} = .13.605 \text{ ev}$

Length (1 fermi = 10⁻¹³cm; 1 % = 10⁻⁸ cm) r_e = e²/mc² = 2.81785 fermi

 $\pi_{\text{Compton}} = \frac{\pi}{\text{mc}} = r_e a^{-1} = 3.8612 \times 10^{-11} \text{ cm}$ $\pi_e = \text{Bohr} = \frac{\pi^2}{\text{me}^2} = r_e a^{-2} = 0.52917 \text{ R}$

σ_{Thompson} = 8/3 πr_e² = 0.6652×10⁻²⁴cm² = 0.6652 barn

Magnetic Moment and Cyclotron Angular Frequency $=\frac{e\hbar}{2mc} = 0.57883 \times 10^{-14} \text{ Mev/gauss}$

 $\frac{1}{2}\omega_{\text{cyclotron}} = \frac{e}{2mc} = 8.7945 \times 10^6 \text{ rad sec}^{-1}/\text{gauss}$ $g_{electron} = 2[1 + \frac{\alpha}{2\pi} + 0.328 (\frac{\alpha}{\pi})^2] = 2[1.001163]^b$

 $= 2[1 + \frac{a}{2\pi} + 0.75 (\frac{a}{\pi})^2] = 2[1.001172]^b$

QUANTITIES DERIVED FROM THE PROTON MASS, mp Rest mass = 938.211 Mev/c² = 1836.12 m_e = 6.719 m_e = 1.007593 mm (m = 1 amu = 1 016)

Magnetic Moment and Cyclotron Angular Frequency $=\frac{e\hbar}{2m.c}$ = 3.1524 × 10⁻¹⁸ Mev/gauss

 $\frac{1}{2}\omega_{\text{cyclotron}} = \frac{e}{2m_{\text{n}}c} = 4.7896 \times 10^3 \text{ rad sec}^{-1}/\text{gauss}$

 $g_p = \frac{\mu}{\mu_p} = 2.79275;$ $g_n = \frac{\mu}{\mu_p} = -1.9128$

(continued below)

QUANTITIES DERIVED FROM THE MASS OF THE CHARGED PION, m. Rest mass = 139.63 Mev/c2 = 273.26 m = 0.14882 m Length

= 1.4132 fermi (~√2 fermi) Natural (≈ "geometrical") Nucleon Cross Section $\frac{h}{m_{\pi}c}$ = 62.7344 mb (1 mb = 10⁻²⁷ cm²)

(3/2, 3/2) **p Resonance

Center-of-mass momentum: p = 230 Mev/c Lab-system momentum: P = 303 Mev/c (T = 194 Mev)

1 curie = 3.7 × 10¹⁰ disintegrations/sec

1 r = 87.8 ergs/g air = 5.49×10⁷ Mev/g air Fluxes (per cm2) to liberate 1 r in carbon:

Natural background: 100 mr/year "Tolerance" 100 millirem/week [Note, 1 r may produce up to 10 "rem" (r equivalent for man), depending on type of radiation.]

3 ×10⁷ minimum ionizing singly charged particles 0.9×10⁹ photons of 1 Mev energy. (These fluxes are are actually correct to within a factor of two for all materials.)

MISCELLANEOUS Physical Constants

1 year = 3.1536×10⁷ sec (* * ×10⁷ sec) Density of air = 1.205 mg/cm3 at 20°C Acceleration by gravity = 980.67 cm/sec2 1 calorie = 4,184 joules

1 atmosphere = 1033.2 g/cm2

Numerical Constants

1 radian = 57.29578 deg; e = 2.71828 ln 2 = 0.69315; log₁₀ e = 0.43429; ln 10 = 2.30259; log₁₀ 2 = 0.30103.

Stirling's approximation $\sqrt{2\pi n} \left(\frac{n}{a}\right)^n < n! < \sqrt{2\pi n} \left(\frac{n}{a}\right)^n \left(1 + \frac{1}{12n-1}\right)$ Gaussianlike Distributions

For n > -1 but not necessarily integral: $\int_0^\infty x^{2n+1} \exp \left[-\frac{x^2}{2\sigma^2} \right] dx = 2^n n! \ \sigma^{2n+2}; (\frac{1}{2})! = \sqrt{\pi/2}$

Relation between standard deviation of and mean

2σ² = πα²; σ = 1.4826 probable error.

Odds against exceeding one standard deviation = 2.15:1 two, 21:1; three, 370:1; four, 16,000:1; five, 1,700,000:1

*Based mainly on Cohen, Crowe, and Dumond, The Fundamental Constants of Physics (Interscience, New York, 1957). ^bC. Sommerfield, Phys. Rev. 107, 328 (1957).

Front (



Back

Summary Table

dE/dx, Radiation lengths, etc.

Atomic & Nuclear Constants

> **Multiple Scattering**

Physical Constants, Num'l Constants, Gaussian Dist's, etc.

> Particle Ranges, **Energy Loss** Rates

ERKELEY NATIONAL LA

Atomic and nuclear properties (dE/dx, collision mean free path,

Material	<u>z</u>		Cross section σ [a] (barns)	dE [b] dk min Mev g/cm ²	Collis length,	ion [a] L _{coll}	Radiat length,		Density p (g/cm ³)
H ₂	1 3	1.01	0.063	4.14	26.5	374 94.3	58 77.5	819.0 145	0.0708 0.534
C	6	12.00	0.33	1.86	60.4	39.0	42.5	27.4	1.55 (variable)
Al	13	26.97	0.57	1.66	79.2	29.3	23.9	8.86	2.70
Cu	29	63.57	1.00	1.45	105.4	11.8	12.8	1.44	8.9
Sn	50	118.70	1.55	1.27	129.7	17.8	5.54	1.17	7.30
Pb	82	207.21	2,20	1.12	156.2	13.8	5.8	0.51	11.34
U	92	238.07	2.42	1.095	163.6	8.75	5.5	0.29	18.7
			0.243 Mev/cm	26.5	452	58	990	0.0586	
			0.935 Mev/cm	48.9	119.3	44.7	109.0	0.41	
Polystyrene (OH scintillator)			2.14 Mev/cm 5.49 Mev/cm	54.9	52.3	43.4	41.3	~ 1.05	



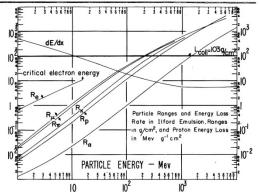
 θ_{mp} is the mean projected angle in radians between tangents to the particle trajectories

 $|\theta|_{\text{average}} = \theta_{\text{mp}} = z \frac{12(\text{Mev})}{\text{pv(Mev})} \sqrt{\frac{L}{L_{\text{rad}}}} (1 + \epsilon)^{-\frac{4}{3}}$

L is the thickness, and $L_{\rm rad}$ the radiation length (from Table II) for the absorber (atomic number Z). For particles of charge ze and velocity Sc. the following table for e applies:

						Lrad
	10	1	10-1	10-2	10-3	z
	+0.02	-0.03	-0.08	-0.14	-0.20	1
$\beta/z = 0.1$	+0.12	+0.06	-0.00	-0.07	-9.14	6
(4.7-Mev proton	+0.13	+0.06	-0.01	-0.10	-0.18	29
	+0.10	+0.02	-0.07	-0.16	-0.27	82
-	-0.03	-0.08	-0.14	-0.20	-0.26	1
$\beta/z = 0.3$	+0.07	+0.01	-0.05	-0.12	-0.20	6
(45-Mev proton)	+0.12	+0.05	-0.03	-0.11	-0.20	29
(45-mer proton)	+0.09	+0.08	-0.07	-0.17	-0.28	82
	-0.07	-0.12	-0.18	-0.24	-0.31	1
B/z = 0.7	+0.03	+0.03	-0.10	-0.18	-0.26	6
(380-Mey proton	+0.09	+0.02	-0.06	-0.15	-0.25	29
(sas mer proton	+0.09	-0.01	-0.08	-0.17	-0.29	82
	-0.08	-0.14	-0.20	-0.26	-0.34	1
	-0.01	-0.05	-0.12	-0,20	-0.29	6
$\beta/z = 1.0$	-0.03	-0.05	-0.13	-0,23	-0.34	29
	-0.08	-0.00	-0.09	-0.19	-0.31	82

*Note that in the Gaussian approximation the root-mean-square projected angle is obtained from the formula above by substituting 15 for the coefficient 12.





The Essence of PDG



- Listings of Data (with Summary Tables)
- Reviews of Essential Topics
- pdgLive (an interactive combination of Listings and Reviews)



Listings and Reviews



The Web allows us to see what most interest our readers.

The hits (page views) on

Data Listings = Reviews

almost exactly equal.

Clearly people care about both.





About Data Listings



Huge Increase in Search Papers

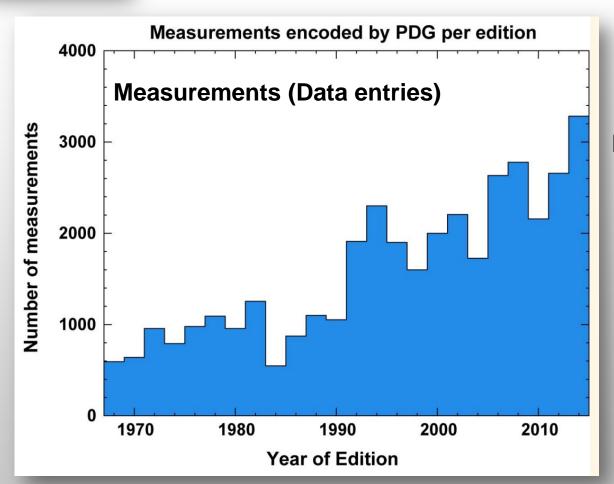


Year of Book	Number of Search Papers
2010	136
2014	509



Workload Trends





Some editions are more or less than 24 months, yielding fluctuations in graphs.

LHC bump

So there is an increasing workload on the LBNL group.



Highlights in 2014 Listings



899 new papers with 3283 new measurements.

330 LHC papers: ATLAS, CMS, and LHCb

Extensive Higgs boson coverage from 138 papers with 258 measurements.

Supersymmetry: 123 papers, many from LHC experiments.

Cosmology reviews updated to include 2013 Planck.

Updated and new results in neutrino mixing on Δm^2 and mixing angle measurements.

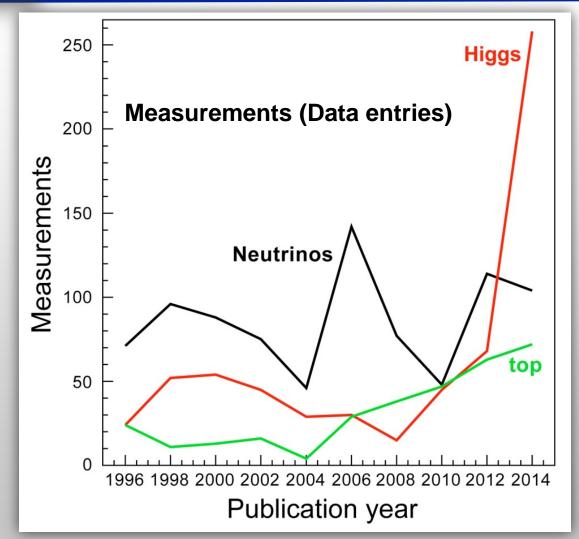
Latest from B meson physics: 183 papers with 803 measurements, including first observation of $B_s \to \mu^+ \mu^-$ from LHCb and CMS.

And much more...



Data versus time

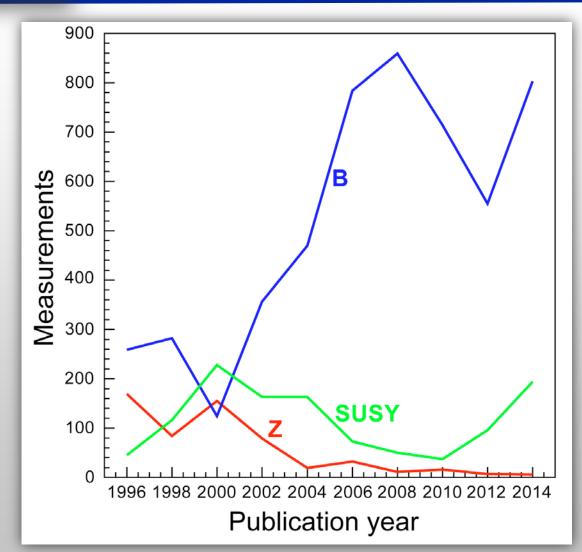






Data versus time



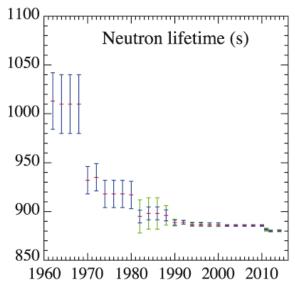


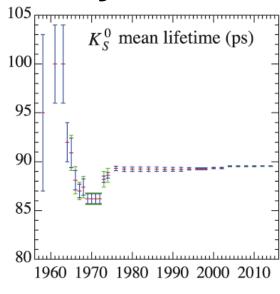
Measurements (Data entries)

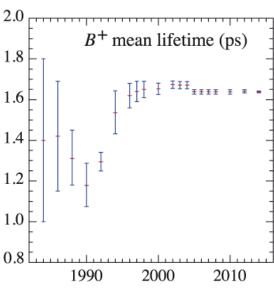


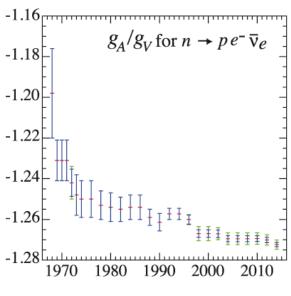
History Plots

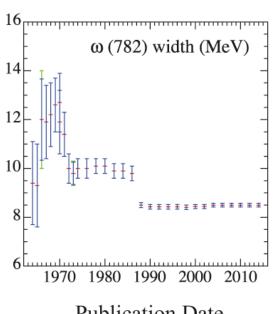


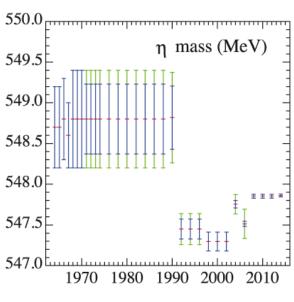












Publication Date

Publication Date

Publication Date

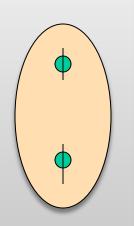


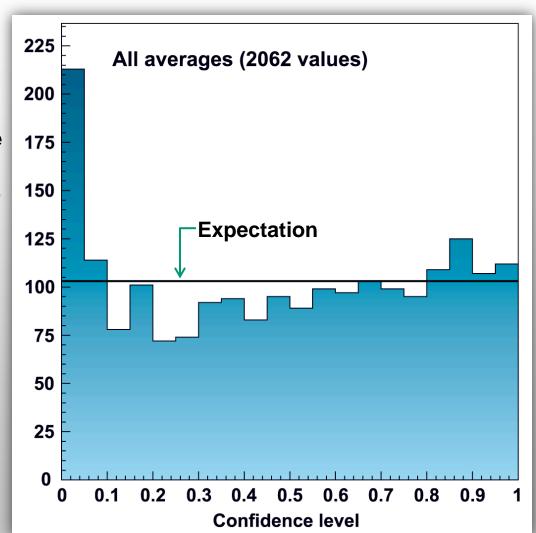
Confidence Levels in PDG Averages



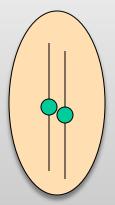
Each point is one average.

Peak at left due to conflicting measurements.





Broad peak at right due to conservative error bars.

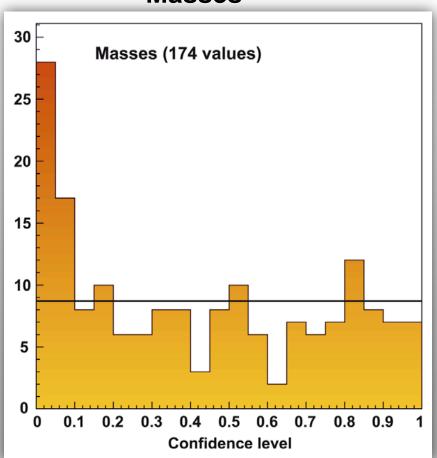




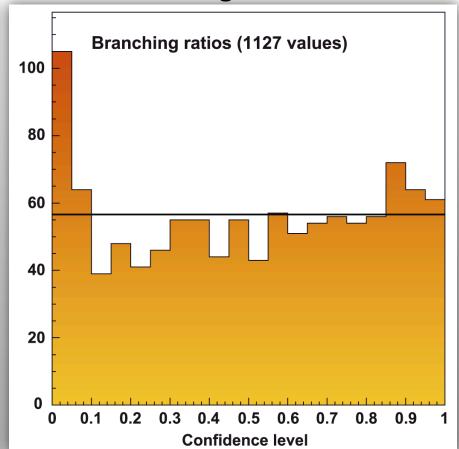
Confidence Levels in PDG Listings







Branching Ratios







About Reviews

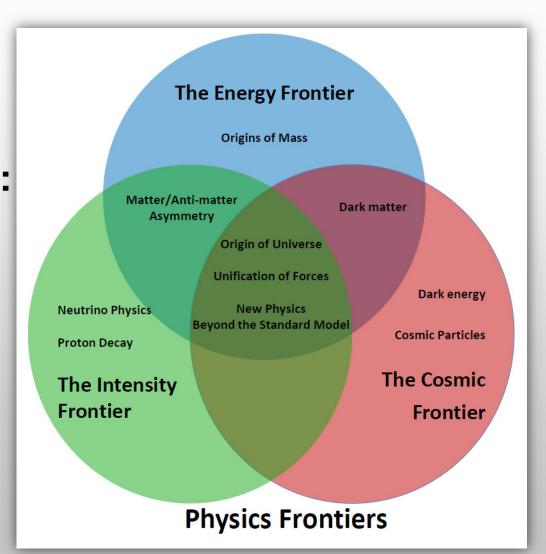


Covered by PDG



PDG leverages all frontier areas:

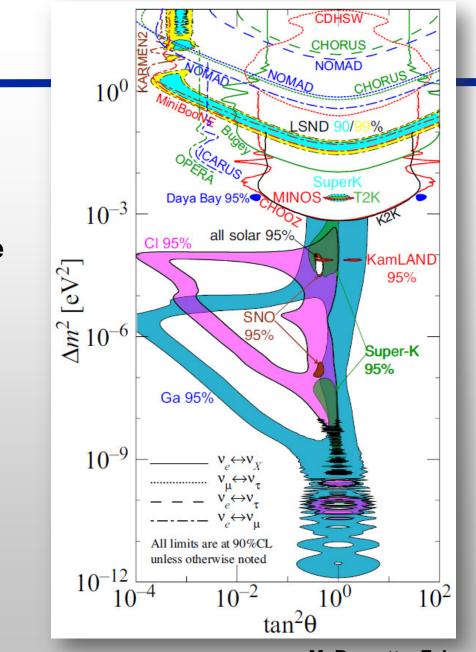
- Energy,
- Intensity,
- Cosmic.





Neutrinos

Latest plot shows large mixing of neutrinos





Hitoshi Murayama

M. Barnett – February 24, 2016



Astrophysics & Cosmology



Downloads of

Reviews:

Astrophysical Constants 6091

Big Bang Cosmology 7799

Cosmological Parameters:

 $H_0, \Lambda, \Omega,$ etc.

Experimental Tests of Gravitational Theory 4234

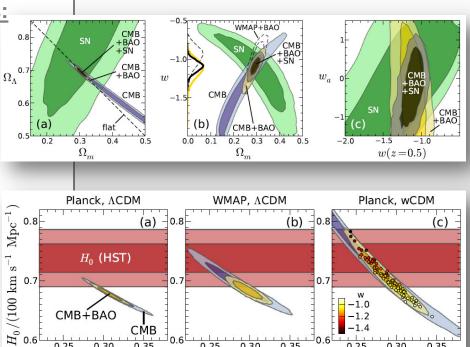
Dark Matter 8591

Dark Energy

Cosmic Background Rad.

Big Bang Nucleosynthesis 4343

Total Cosmology Downloads 58,041 (9.4%)



(from Dark Energy review)

0.30

0.35

CMB+BAO

 Ω_m

CMB



Reviews: Linked or Not to Listings



616,000 downloads of Reviews per year.

Linked Reviews:

2/3 of reviews are linked to the Listings

(Higgs, neutrinos, top quarks, K mesons, B mesons, SUSY, etc.).

Vital to understanding content of Listings.

Non-linked Reviews:

The 1/3 non-linked reviews are both vital and among the most downloaded.

(Electroweak Model, Statistics, Particle Detectors, Cosmological Parameters, etc.)



112 reviews in 2014 Edition

(most are revised or new)



New reviews on:

Higgs Boson Physics

Dark Energy

Monte Carlo Neutrino Generators

Resonances

New in 2016 Edition:

Inflation

Grand Unified Theories

Pentaquarks

etc.

Significant update/revision to reviews on:

Top Quark

Dynamical Electroweak Symmetry Breaking

Astrophysical Constants

Dark Matter

Big Bang Nucleosynthesis

Neutrino Cross Section Measurements

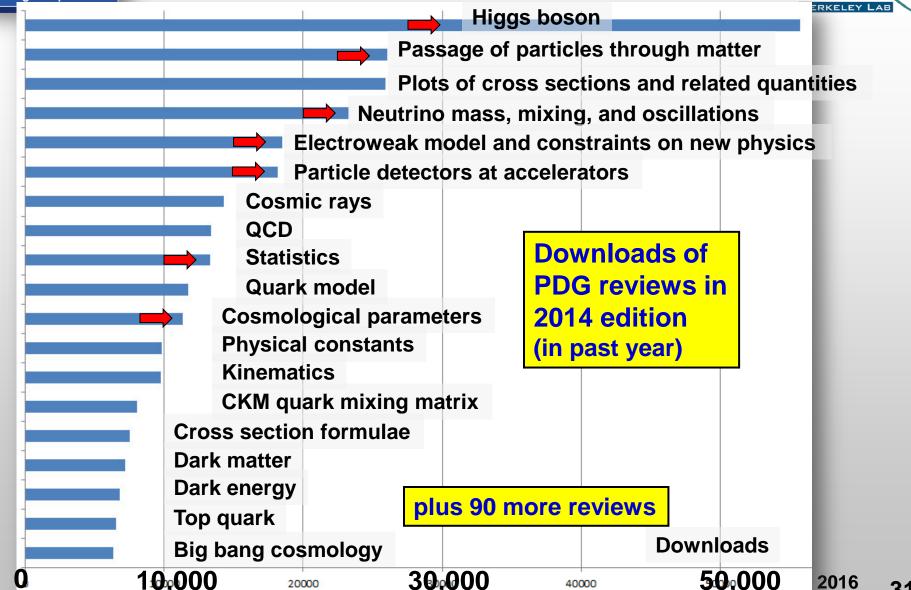
Accelerator Physics of Colliders

High Energy Collider Parameters



Amazing Diversity of Topics Interest Our Community









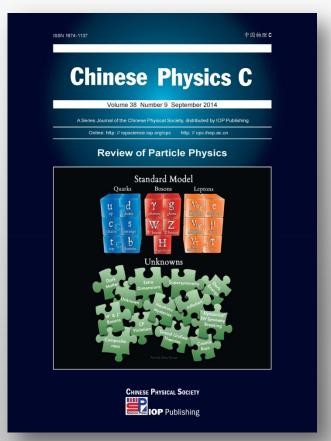
PDG Products

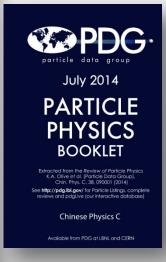


Review of Particle Physics

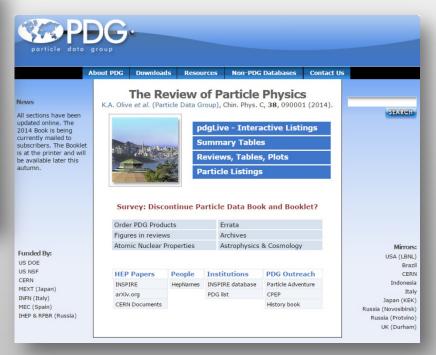


2014 Edition (book, booklet, web, pdgLive)











What PDG Produces



Review of Particle Physics

Formats:

Printed – updated in even years



Book – 14,000 copies



▶ Booklet – 32,000 copies

Online - updated once a year.

More than 100 million hits total.



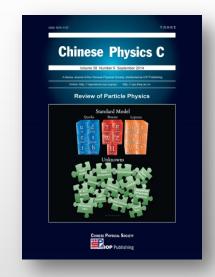
Full content of the book (PDF)



pdgLive - Interactive web app



8 Mirror sites









Mobile Version



New: Mobile-Friendly Version



All the content of the regular site including pdgLive: The entire book in your pocket.



pdg.lbl.gov

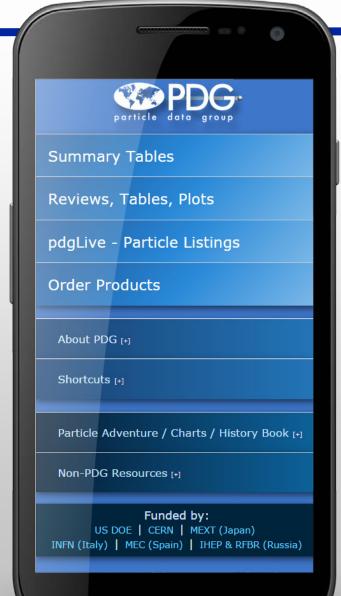
Google now gives priority to mobile-friendly websites for searches from smartphones.



New: Mobile-Friendly Version



All the content of the regular site including pdgLive The entire book in your pocket.



pdg.lbl.gov

Click

arnett – February 24, 2016



Mobile Summary Tables





Downloads below may take several seco

Gauge and Higgs Bosons (gamma, g, W, Z, ...)

Leptons

(e, mu, tau, ... neutrinos ...)

Quarks

(u, d, s, c, b, t, b', t', Free)

Mesons

Baryons

Searches

(Monopoles, SUSY, Technicolor...)

Tests of Conservation Laws





H⁰

J=0

Mass $m = 125.7 \pm 0.4 \text{ GeV}$

H⁰ Signal Strengths in Different Channels

Combined Final States = 1.17 ± 0.17 (S = 1.2)

 $WW^* = 0.87^{+0.24}_{-0.22}$ $ZZ^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)

 $\gamma \gamma = 1.58^{+0.27}_{-0.23}$

 $b\overline{b} = 1.1 \pm 0.5$

 $\tau^+\tau^- = 0.4 \pm 0.6$

 $Z\gamma < 9.5$, CL = 95%

Neutral Higgs Bosons, Searches for

Searches for a Higgs Boson with Standard Model Couplings

Mass m > 122 and none 128-710 GeV. CL = 95%

The limits for H_1^0 and A^0 in supersymmetric models refer to the m_h^{max} benchmark scenario for the supersymmetric parameters.

 H_1^0 in Supersymmetric Models $(m_{H_1^0} < m_{H_2^0})$

Mass m > 92.8 GeV, CL = 95%

A⁰ Pseudoscalar Higgs Boson in Supersymmetric Models [n]

Mass m > 93.4 GeV, CL = 95% $\tan \beta > 0.4$

Charged Higgs Bosons (H^{\pm} and $H^{\pm\pm}$), Searches for

 H^{\pm} Mass m > 80 GeV, CL = 95%

New Heavy Bosons

(W', Z', leptoquarks, etc.),

Searches for

Additional W Bosons

W' with standard couplings

Mass $m > 2.900 \times 10^3$ GeV, CL = 95% (pp direct search)

 W_R (Right-handed W Boson)

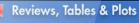
Mass m > 715 GeV, CL = 90% (electroweak fit)

Additional Z Bosons



Mobile Reviews





Downloads below may take several seconds

Introduction, History plots, Online information

Constants, Units, Atomic & Nuclear Properties

Standard Model & Related Topics

Quantum Chromodynamics

Electroweak model and constraints on new physics

Higgs Boson Physics, Status of

Cabibbo-Kobayashi-Maskawa quark-mixing matrix

CP violation in the quark sector

Neutrino mass, mixing, and oscillations

Ouark model

Grand Unified Theories

Heavy-Quark and Soft-Collinear Effective Theory

Lattice Quantum Chromodynamics



10. ELECTROWEAK MODEL AND CONSTRAINTS ON NEW PHYSICS

Revised November 2013 by J. Erler (U. Mexico) and A. Freitas (Pittsburgh U.).

- 10.1 Introduction
- 10.2 Renormalization and radiative corrections
- 10.3 Low energy electroweak observables
- 10.4 W and Z boson physics
- 10.5 Precision flavor physics
- 10.6 Experimental results
- 10.7 Constraints on new physics

10.1. Introduction

The standard model of the electroweak interactions (SM) [1] is based on the gauge group SU(2) × U(1), with gauge bosons W_{μ}^{i} , i = 1, 2, 3, and B_{μ} for the SU(2) and U(1) factors, respectively, and the corresponding gauge coupling constants g and g'. The left-handed fermion fields of the i^{th} fermion family transform as doublets $\Psi_i = \begin{pmatrix} \nu_i \\ \ell^- \end{pmatrix}$ and $\begin{pmatrix} u_i \\ \ell^\prime \end{pmatrix}$ under SU(2), where $d'_i \equiv \sum_j V_{ij} d_j$, and V is the Cabibbo-

Kobayashi-Maskawa mixing matrix. [Constraints on V and tests of universality are discussed in Ref. 2 and in the Section on "The CKM Quark-Mixing Matrix". The extension of the formalism to allow an analogous leptonic mixing matrix is discussed in the Section on "Neutrino Mass, Mixing, and Oscillations".] The right-handed fields are SU(2) singlets. In the minimal model there are three fermion families.

A complex scalar Higgs doublet, $\phi \equiv \begin{pmatrix} \phi^{\top} \\ \phi^{0} \end{pmatrix}$, is added to the model for mass generation through spontaneous symmetry breaking with potential* given by,

$$V(\phi) = \mu^2 \phi^{\dagger} \phi + \frac{\lambda^2}{2} (\phi^{\dagger} \phi)^2. \qquad (10.1)$$

For μ^2 negative, ϕ develops a vacuum expectation value, $v/\sqrt{2} = \mu/\lambda$, where $v \approx 246$ GeV, breaking part of the electroweak (EW) gauge symmetry, after which only one neutral Higgs scalar, H, remains in the physical particle spectrum. In non-minimal models there are additional charged and neutral scalar Higgs particles [3].

After the symmetry breaking the Lagrangian for the fermion fields, ψ_i , is

$$\mathcal{L}_F = \sum_{i} \overline{\psi}_i \left(i \partial \!\!\!/ - m_i - \frac{m_i H}{v} \right) \psi_i$$

* There is no generally accepted convention to write the quartic term. Our numerical coefficient simplifies Eq. (10.3a) below and the squared coupling preserves the relation between the number of external legs and the power counting of couplings at a given loop order. This structure also naturally emerges from physics beyond the SM, such as supersymmetry.

K.A. Olive et al. (PDG), Chin. Phys. C38, 090001 (2014) (http://pdg.lbl.gov)



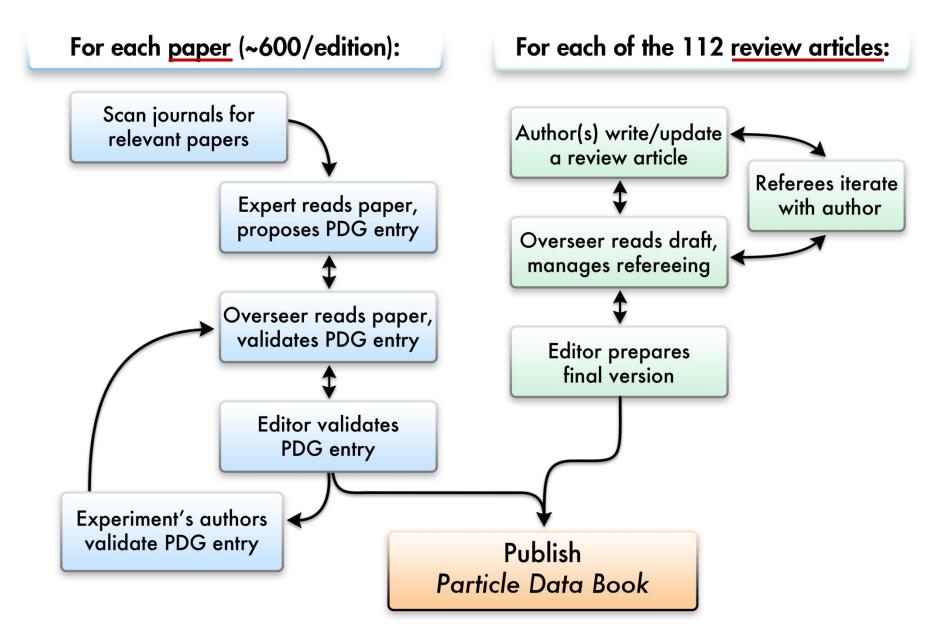


The Process of Producing the Particle Data Book



PDG Workflow







Community Connections



PDG Advisory Committee

Collaboration with Working Groups

PDG Workshops

Periodic Surveys

Input from users

Via membership in research collaborations



Collaboration with Working Groups



Working groups:

LHC, Tevatron, B-factories,...

- Higgs
- Electroweak fits,
- B lifetimes, B mixing,
- V_{cb} and V_{ub}
- top quark mass, etc.

Provide fits to our data using PDG guidelines.



Vital PDG Workshops



With experts lead to improved coverage:

Searches

Higgs

Neutrino

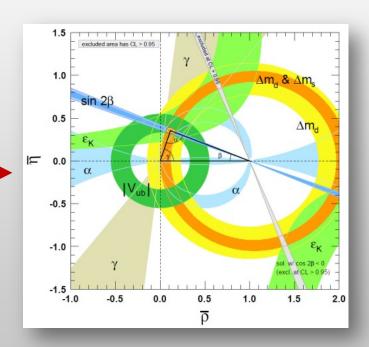
D meson

CKM

 τ lepton

Extra-dimensions

Statistics







Nature of PDG Collaboration





What is the PDG Collaboration?



PDG at LBNL (Central coordination, data evaluation, quality assurance, schedule control, and production)

3.5 FTE's (6 physicists: half research) + editor, programmer, etc.

PDG Collaborators outside of LBNL PDG

200 Physicists from 24 countries (volunteers at <5% level).

PDG Consultants – 700 physicists

- Experiments' Physics Coordinators (etc.) verifying data listings
- Referees of reviews (3-5 for each review)
- General consultants on content

PDG Users: tens of thousands

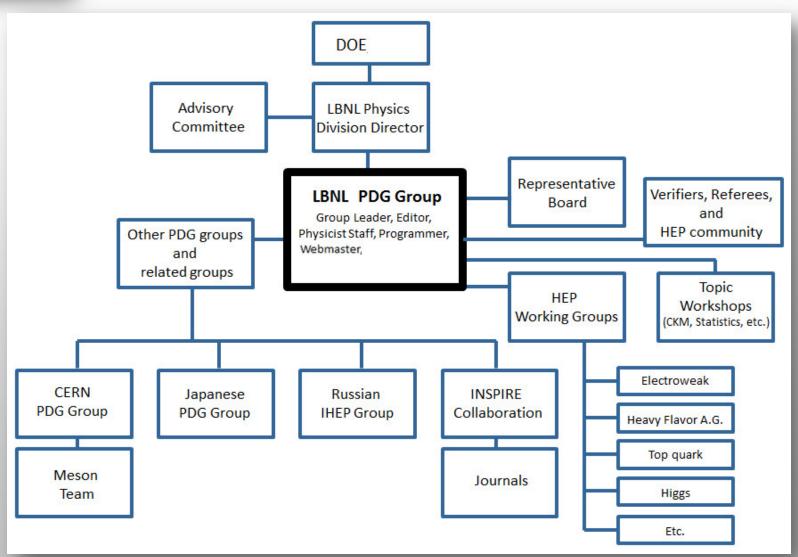
Clearly this cannot work without vital central coordination.



PDG Chart

(much to coordinate)







Central Leadership



PDG leadership group at LBNL coordinates the entire effort

- Produce and publish the Review (book, booklet, web, pdgLive)
- Data evaluation, all the final checking & editing
- Major contributor to the content
- Choose the authors and the content
- Maintain & drive the schedule
- Coordinate the input of 700 consultants from HEP community

Essential for

- High quality
- Timely publication





Survey and the Future



PDG Survey in 2014



Is having a copy of the full-sized book essential to your work or study?

Is a Book without Data Listings OK? (45% as big) (keeping online Data Listings)

How important is an app?

Similar questions were asked about the Booklet.



PDG Survey in 2014



An amazing 6172 readers responded, demonstrating the very high value our community places on PDG products (and 1495 comments).

The comments occupy 110 pages.

The book has been great (seriously, thanks!), but the age of ink marks on dead tree carcasses is over.

Nevertheless, keep some hard copies around for after the next big solar flare....

I think the smartphone app is a great idea but I would hate to see it supplant the printed form.



PDG Survey on Book



68% want the book, with or without the Data Listings

2/3 said app was important or very important.

82% want the booklet



Future of Book



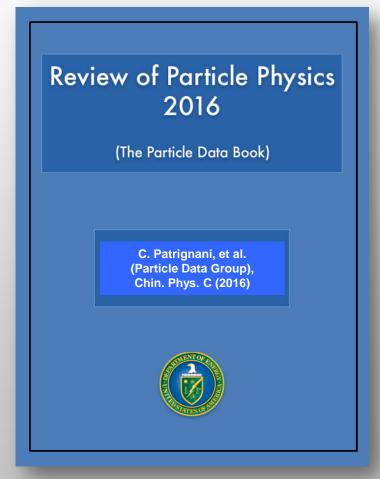
Issues:

- Declining budget makes full-size book too expensive.
- The book is too big and growing.

Next book will have only: Summary Tables and Reviews, but no Data Listings.

(Data Listings <u>remain</u> in journal article and online as PDF files and pdgLive.)

Reduces size to about 45%







Future Developments

(budget allowing)









Future Possibilities



- Downloadable PDG data
- pdgLive version for offline use (as an app)
- Emphasis on searching and indexing, rather than navigation
- Interactive plotting, data selection and evaluation
- User tagging or display of contributed content
- Cross-linking with other services (pdgLive ↔ INSPIRE available)

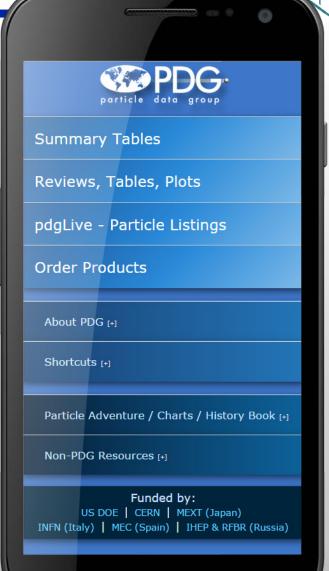
Implementing these new features is a long-term effort given our declining resources



PDG App (no Internet)

.....

- Summary Tables
 Basically easy;
 just formatting for readability
- Review articlesEven easier
- pdgLive
 Not easy. Major programming to develop exportable database and to present on-the-fly.





Downloadable PDG Data



- Make complete PDG data available in machine-readable format (including especially branching fractions)
 - PDG production database not suitable for distribution
- Particle masses, widths and MC ID numbers have been available for many years
 - http://pdg.lbl.gov/2015/mcdata/mass_width_2015.mcd



Future Developments



Require substantial efforts and therefore budget, and are not possible in current declining funding.





PDG Impact



PDG Impact





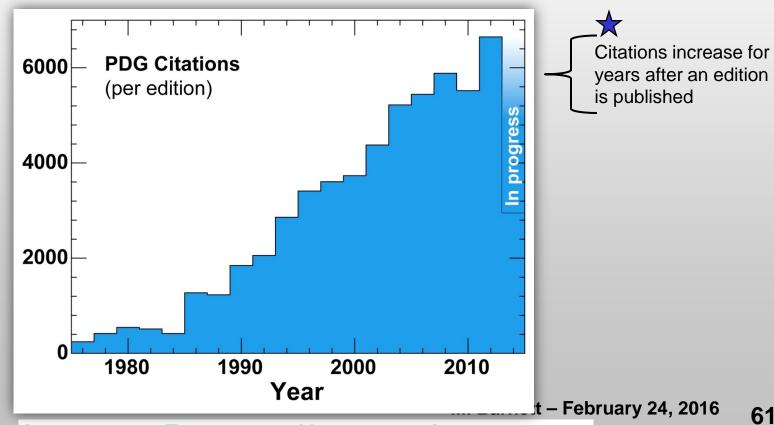
- 14,000 RPP books requested
- 9 million hits/year on website (>180 countries)
- 108 million hits on website in total
- 56,000 combined citations of RPP
- Most cited publication in HEP



Top Cited



The Review is the all-time top cited article in High Energy Physics with more than 56,000 citations (INSPIRE)





PDG Summary



PDG provides a vital, dynamic, innovative service. It leverages the work of all the HEP community.

The HEP community depends on PDG to provide standards and to assure integrity and quality in summarizing particle physics.

Your support has been vital to PDG success for the past 58 years. Thank you.

FROM THE PARTICLE DATA GROUP TO FERMILAB FOR THE DISCOVERY OF THE b QUARK AND t QUARK

1978 PDG Book First edition with b quark discovery

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1996 PDG Book First edition with t quark discovery

t-Quark Mass in pp Collisions

The t quark has now been observed. Its mass is sufficiently high that decay is expected to occur before hadronization.

Preliminary results for the top mass based on the full (Run la+lb) data set have been presented by CDF and D \emptyset at conferences in early 1996:

$$\begin{split} m_t &= 175.6 \pm 5.7 \pm 7.1 \text{ GeV} & \text{CDF} & \text{lepton} + \text{jets} \\ m_t &= 159 ^{+24}_{-22} \pm 17 \text{ GeV} & \text{CDF} & \text{dilepton} \\ m_t &= 187 \pm 8 \pm 12 \text{ GeV} & \text{CDF} & \text{hadronic} \\ \end{split}$$

$$m_t &= 170 \pm 15 \pm 10 \text{ GeV} & \text{DØ} & \text{lepton} + \text{jets} \\ m_t &= 158 \pm 24 \pm 10 \text{ GeV} & \text{DØ} & e\mu \end{split}$$

Because of the high current interest, we mention these preliminary results here but do not average them or include them in the Listings or Tables. See the note on the top quark for references.

Search limits, which are now primarily of historical interest, are based on the assumption that no nonstandard decay modes such as $t \to bH^+$ are available, except as noted in the comments.

VALUE (GeV)	CL%	DOCUMENT I	D	TECN	COMMENT
180±12 OUR AV	ERAGE				
$199^{+19}_{-21}\pm 22$		¹ ABACHI	95	D0	ℓ + jet
176± 8±10		² ABE	95F	CDF	$\ell + b$ -jet
• • • We do not us	se the following	ng data for avera	ges, fits	, limits	, etc. • • •
		3 ABACHI	95B	D0	$\ell\ell$ + jets, ℓ + jets
>128	95	⁴ ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
		⁵ ABE	950	CDF	
		⁶ ABE	95V	CDF	





Downloadable PDG Data



- Machine-readable table of particle masses, widths and MC ID numbers has been available for many years
 - http://pdg.lbl.gov/2015/mcdata/mass_width_2015.mcd
- Would like to make complete PDG data available in machinereadable format (including especially branching fractions)
 - PDG production database not suitable for distribution
 - Trying to find resources to develop a downloadable database that provides easy access to the evaluated PDG data
 - Also the first step towards allowing us to build the PDG app
 - A Python-based API that can be used to extract all PDG data from a database hosted by PDG will likely be an intermediate step
 - Same API can later be used with downloadable database



Towards a PDG App



- Goals for the PDG App (no Internet)
 - Interactive access to Listings ("pdgLive") plus all review articles
 - Optimal presentation on device (screen size and resolution)
 - Fully functioning without Internet access (on a plane, train, ...)
- To function without Internet access one needs
 - All relevant PDG data stored in database on the device
 - Database optimized for fast retrieval of the data to be presented
 - Rather than optimized for PDG data evaluation, as is the case for the master PDG database
 - Limited resources (CPU, RAM) on device do not allow full processing done by pdgLive (i.e. cannot simply copy PDG database onto device)
 - To minimize processing in app, database should contain preprocessed "snippets" of information (e.g. HTML for a full line in the summary table)
 - Review articles in HTML (allows dynamic rendering by the device's web browser), or in a format tailored to screen size and resolution



Implementing a PDG App



- Two main approaches for app implementation
 - Native app
 - Most flexible, but also most development effort
 - Need to develop separate app for Android, iOS, ...
 - Tools such as cross-compilers exist to help with this
 - How to display symbols and equations?
 - Web-based app
 - App runs essentially in the device's browser
 - Leverages work done for mobile PDG site
 - Need to develop backend web application server that will run on the device and generate or retrieve relevant pages using a local database
 - Need to have MathJax libraries installed on the device for displaying symbols and equations
- Some approaches and app development tools combine elements from both of the above
- Substantial development effort for PDG app in all approaches



PDG Advisory Committee



"The PDG is already operating at a very efficient level, which is how they have managed to expand the coverage into the field of cosmology and particle astrophysics while still maintaining the high standards in the rest of particle physics.

"This efficiency comes from several advances:

- the new software infrastructure that allows for more authors to enter data themselves,
- the fact that the PDG works in concert with experimental working groups when appropriate, and
- the fact that the PDG has been able to coax some 200 authors to contribute and a total of 700 physicists worldwide to provide input through the peer review process.

"The quality of the work that the PDG represents is part of what makes people want to provide input to the PDG process."



Quotes



"Several reviewers remarked that HEP would be a qualitatively weaker field if the PDG were not there as a current, growing resource."

DOE S&T review of LBNL

"This review is used by people at all levels in the both theory and experiment, and the committee frankly cannot imagine the field without the compilation that is embodied in the RPP.

"The importance of this work can not be overstated."

PDG Advisory Committee