Heavy Quarks, from Discovery to Precision

Matteo Cacciari - LPTHE Paris

La Thuile - February 2011

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

The 'Cambridge papers'

VOLUME 34, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JANUARY 1975

Is Bound Charm Found?*

A. De Rújula
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

and

S. L. Glashow†
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 27 November 1974)

We argue that the newly discovered narrow resonance at 3.1 GeV is a $^3S_1$ bound state of charmed quarks and we show the consistency of this interpretation with known meson systematics. The crucial test of this notion is the existence of charmed hadrons near 2 GeV.

Heavy Quarks and $e^+ e^-$ Annihilation*

Thomas Appelquist† and H. David Politzer‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 19 November 1974)

Mario's charm

The 'Mexican' paper

LETTERE AL NUOVO CIMENTO VOL. 12, N. 12 22 Marzo 1975

Charm, EVDM and Narrow Resonances in e^+e^- Annihilation.

C. A. DOMINGUEZ

Departamento de Fisica,
Centro de Investigation y de Estudios Avanzados del I.P.N. - Mexico

M. GRECO

Laboratori Nazionali di Frascati del CNEN - Frascati

(ricevuto il 30 Dicembre 1974)

The 'Mexican' paper

LETTERE AL NUOVO CIMENTO VOL. 12, N. 12 22 Marzo 1975

Typo in the title....: EVMD!

Charm, EVDM and Narrow Resonances in e^+e^- Annihilation.

C. A. DOMINGUEZ

Departamento de Fisica,
Centro de Investigation y de Estudios Avanzados del I.P.N. - Mexico

M. GRECO

Laboratori Nazionali di Frascati del CNEN - Frascati

(ricevuto il 30 Dicembre 1974)

(10) $$\sigma_{\text{had}} = 2.7 \cdot 10^{-4} \frac{1}{s} = 104.7 \frac{1}{s(\text{GeV}^2)} \text{ nb} ,$$

(11) $$R = \frac{\sigma(e^+e^- \to \gamma \to \text{hadrons}) + \sigma(e^+e^- \to \psi_n \to \text{hadrons})}{\sigma(e^+e^- \to \gamma \to \mu^+\mu^-) + \sigma(e^+e^- \to \psi_n \to \mu^+\mu^-)} \simeq$$

$$\simeq \frac{\sigma(e^+e^- \to \gamma \to \text{hadrons}) + \sigma(e^+e^- \to \psi_n \to \text{hadrons})}{\sigma(e^+e^- \to \gamma \to \mu^+\mu^-)} \equiv R_{\text{normal}} + R_{\text{charm}} \simeq 2.5 + 1.2 = 3.7 .$$

The ψ_n contribution to R, R_{charm} is in agreement with the prediction of the enlarged quark model, as is also the case for the normal contribution.

We want to stress the fact that no special assumptions have been made regarding

tions (7). The second component being responsible for the observed rising of R and for the break-down of scaling in single inclusive distributions at low x.

However, in view of the new experimental results it seems possible that the first two narrow resonances discovered so far can account (after inclusion of radiative tails) for the difference between experimental cross-sections (SPEAR I) and a constant R (8). Adding the possibility that there might be more ψ-states, so far undetected, one would have a way of explaining the rise of R. Combining this with the magnitudes of the widths, eq. (1), one is naturally led to think of the new narrow resonances as charm-anticharm vector mesons (9). The properties of such states have been discussed by CARLSON and FREUND (10) who have suggested that they should be searched for in photoproduction and hadron formation experiments. A charm-anticharm vector

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

Mario's bottom

Mario's beauty

Volume 77B, number 1 PHYSICS LETTERS 17 July 1978

ϒ PRODUCTION FROM DUALITY AND THE CHARGE OF THE NEW QUARK

M. GRECO
INFN, Laboratori Nazionali di Frascati, Italy

Received 23 January 1978

Duality

quark mass is provided by $V(r) \sim r$ in V_0, as noticed by Quigg and Rosner [4].

A simple consequence of eq. (5), implemented by duality (eq. (2)) is

$$\Gamma_\rho^{e\bar{e}} : \Gamma_\omega^{e\bar{e}} : \Gamma_\varphi^{e\bar{e}} : \Gamma_\psi^{e\bar{e}} : \Gamma_\Upsilon^{e\bar{e}} = 9 : 1 : 2 : 8 : 2\,(8), \quad (6)$$

where the last factor 2 (8) in the r.h.s. of eq. (6) refers to the case $Q = -1/3$ ($Q = 2/3$). The approximate validity of eq. (6) for $\rho, \ldots, \psi$ mesons was noted empirically by Yennie [12]. We would therefore predict

$$\Gamma(\Upsilon \to e\bar{e}) \approx 1.2 \text{ keV}, \quad (7)$$

for the case $\Upsilon \equiv (b\bar{b})$. For comparison the corresponding estimate by Eichten and Gottfried [2], based on

Use $m\Gamma/\Delta M^2$ = constant to estimate other widths:

≈ 98 nb).

The leptonic widths for the $\Upsilon'(10.0)$ and $\Upsilon''(10.4)$ can be estimated in analogy to eq. (4). We obtain $\Gamma(\Upsilon' \to e\bar{e}) \approx 0.65$ keV and $\Gamma(\Upsilon'' \to e\bar{e}) \approx 0.55$ keV, having assumed a level spitting of 50–100 MeV of the two S-

Compare to modern values

$\Gamma_{e^+e^-}$ (keV)	Υ	Υ'	Υ''
Mario	1.2	0.65	0.55
PDG 2008	1.34	0.61	0.44

...not too bad....

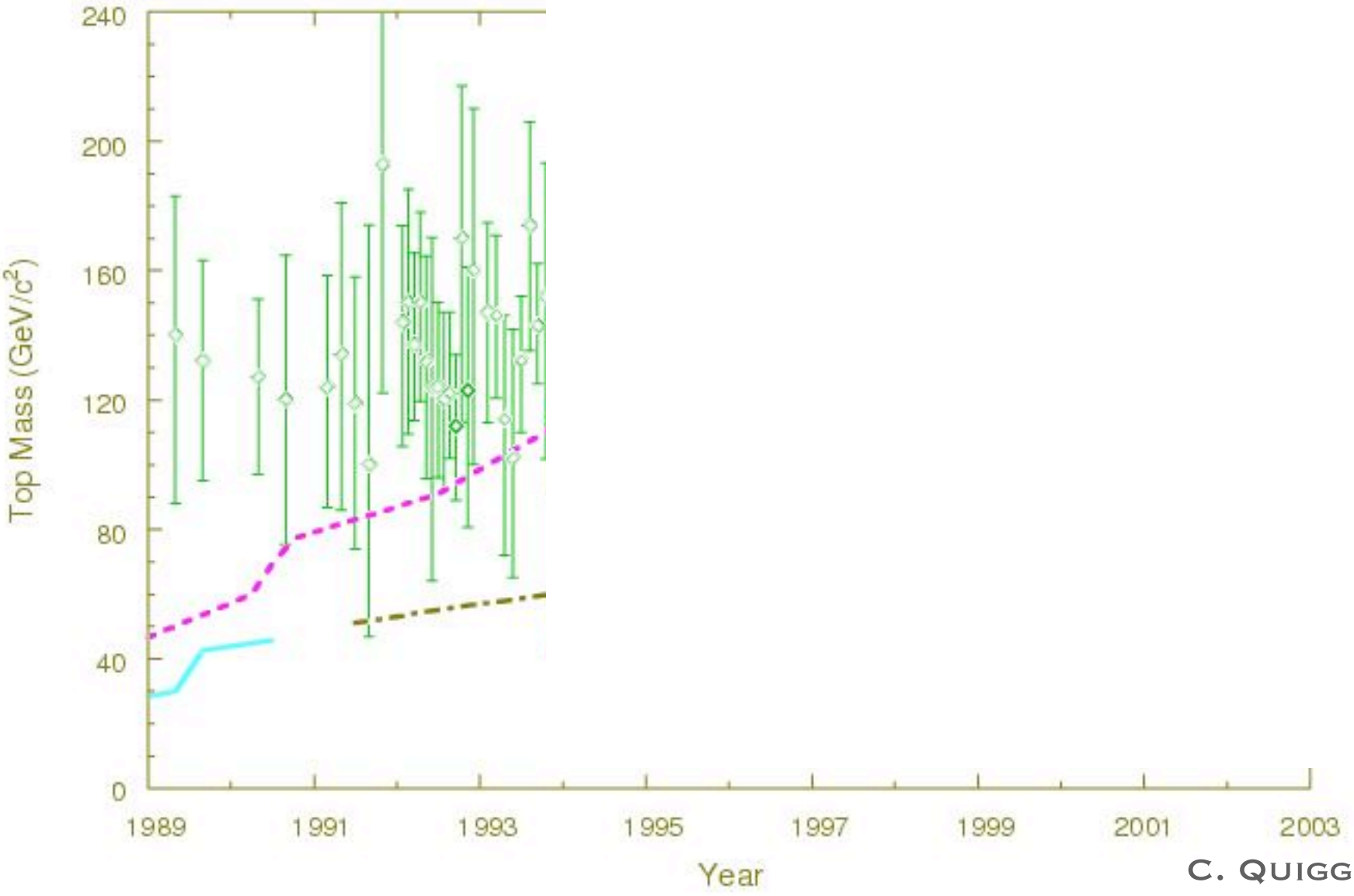
The next heavy quark discovery took a while...

Top discovery

Presented at La Thuile 1995 (LIV AM)

Observation of the top quark production in anti-p p collisions with the Collider Detector at Fermilab.
D. Gerdes, (Michigan U.) . Mar 1995.
Prepared for 9th Les Rencontres de Physique de la Vallee d'Aoste: Results and Perspectives in Particle Physics, La Thuile, Italy, 5-11 Mar 1995.
In *La Thuile 1995, Results and perspectives in particle physics* 713-722.

Time evolution of top mass fits



Precision physics at LEP

Volume 113B, number 5 PHYSICS LETTERS 1 July 1982

BHABHA SCATTERING AROUND THE Z_0 POLE

M. CONSOLI, S. LO PRESTI
Istituto di Fisica, Università di Catania, Catania, Italy
and INFN, Sezione di Catania, Italy

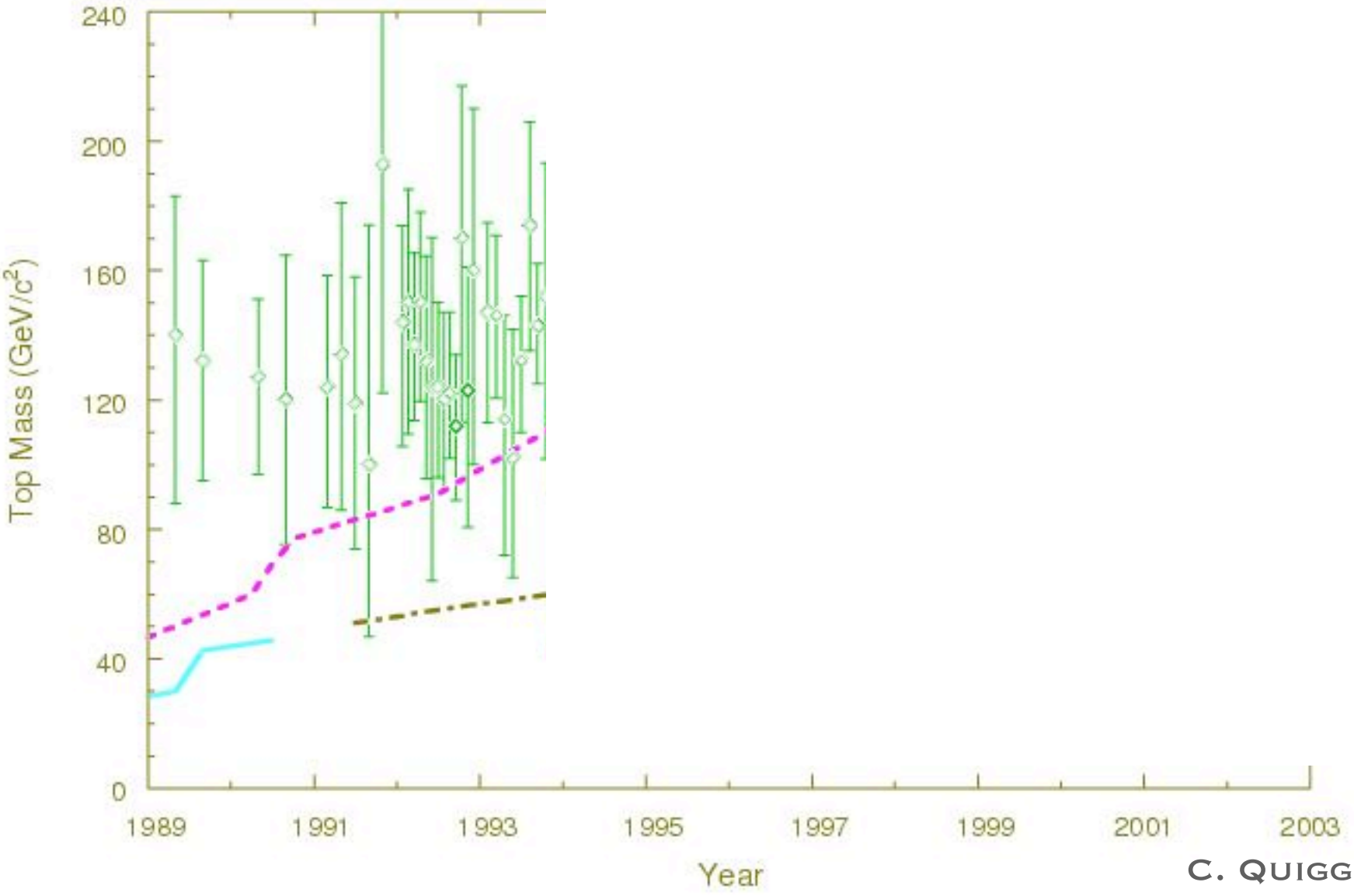
and

M. GRECO
INFN, Laboratori Nazionali di Frascati, Frascati, Italy

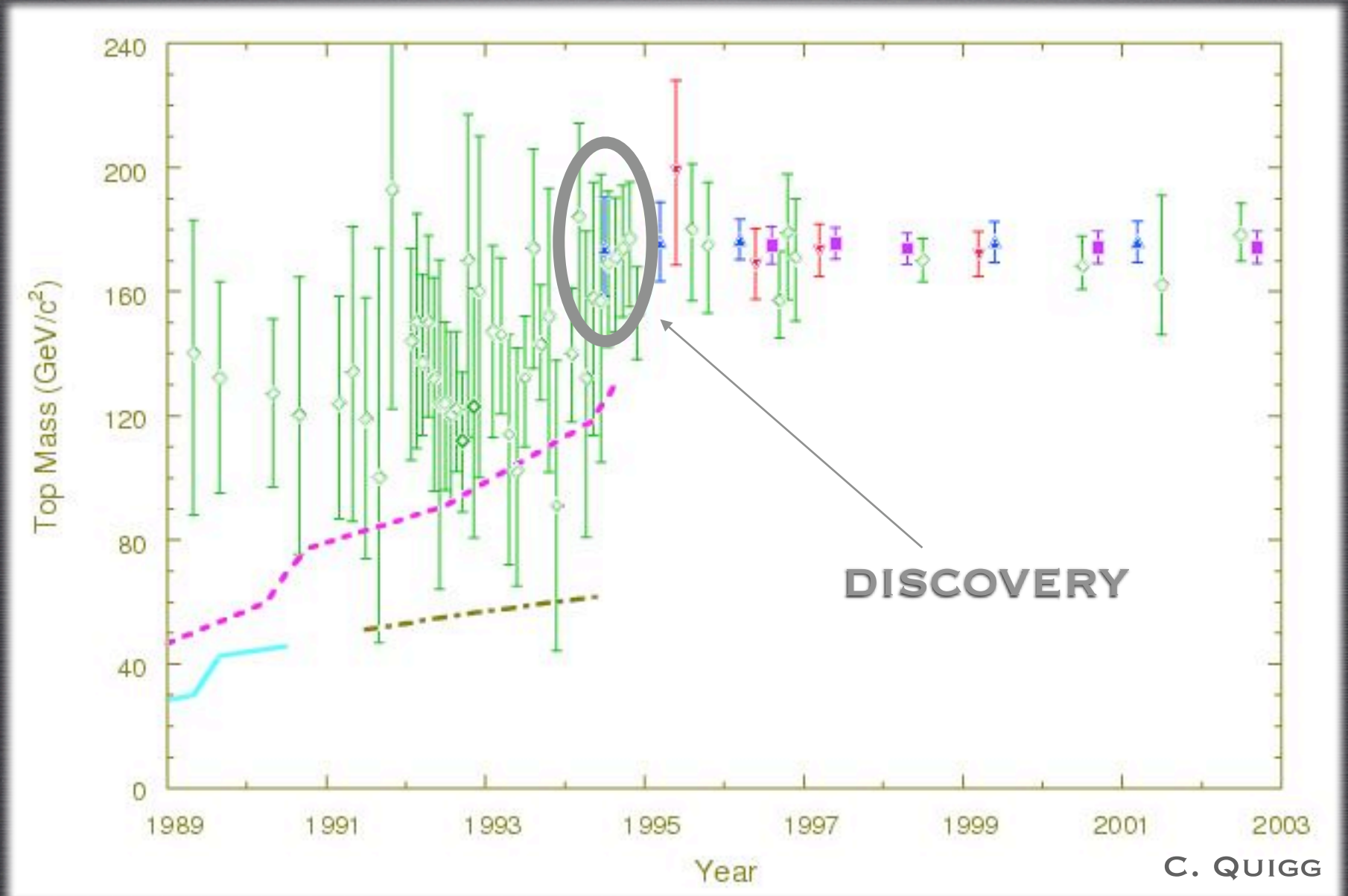
Received 12 February 1982

An accurate investigation of electromagnetic and finite-width effects for Bhabha scattering near the Z_0 pole is presented. Analytical expressions are given which contain all finite first-order corrections as well as soft-photon effects resummed to all orders. Weak interactions are only considered to renormalize the mass and the width of the vector boson. Some numerical results are also presented.

Time evolution of top mass fits



Time evolution of top mass fits



After discoveries, ‘precision’ physics

1989 : HEAVY QUARKS @ NLO

Nuclear Physics B327 (1989) 49–92
North-Holland, Amsterdam

THE ONE PARTICLE INCLUSIVE DIFFERENTIAL CROSS SECTION FOR HEAVY QUARK PRODUCTION IN HADRONIC COLLISIONS

P. NASON*

Institute of Theoretical Physics, ETH-Hönggerberg, CH-8093 Zurich, Switzerland

S. DAWSON

Brookhaven National Laboratory, Upton, NY 11973, USA

R.K. ELLIS

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA

Received 19 April 1989

1998 (LVII AM)
HEAVY QUARKONIUM @ NLO

ELSEVIER

Nuclear Physics B 514 (1998) 245–309

NUCLEAR PHYSICS B

NLO production and decay of quarkonium

Andrea Petrelli [a,1], Matteo Cacciari [b,2], Mario Greco [c,3], Fabio Maltoni [d,4], Michelangelo L. Mangano [d,5]

[a] *INFN, Sezione di Pisa, Italy*

[b] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*

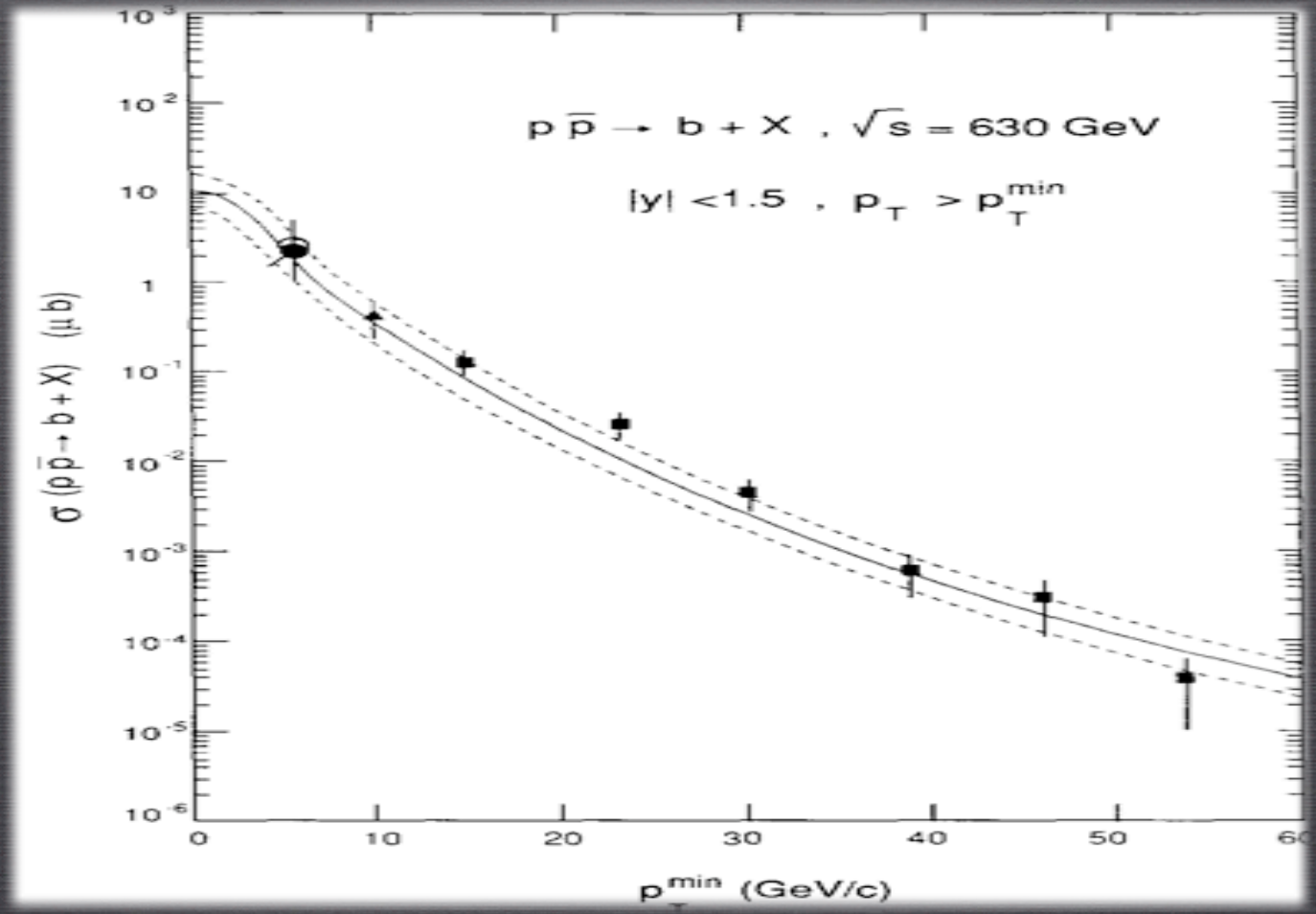
[c] *Dipartimento di Fisica E. Amaldi, Università di Roma III, and INFN, Laboratori Nazionali di Frascati, Italy*

[d] *CERN, TH Division, Geneva, Switzerland*

Received 8 August 1997; revised 7 November 1997; accepted 21 November 1997

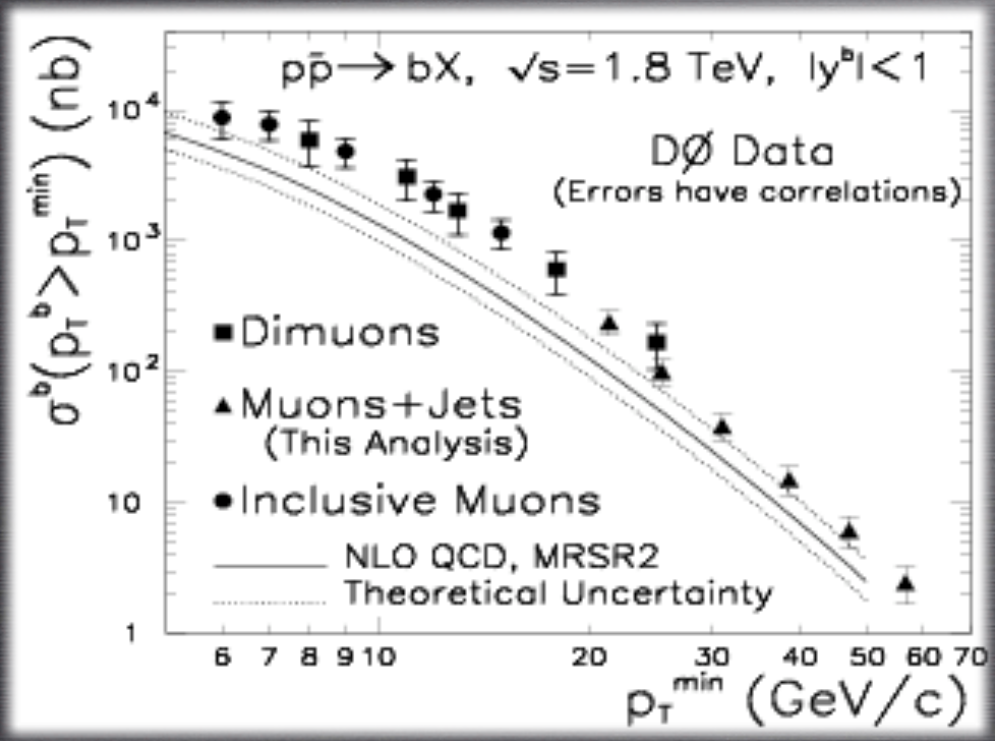
NLO works great at UA1....

PLB 213 (1991) 121

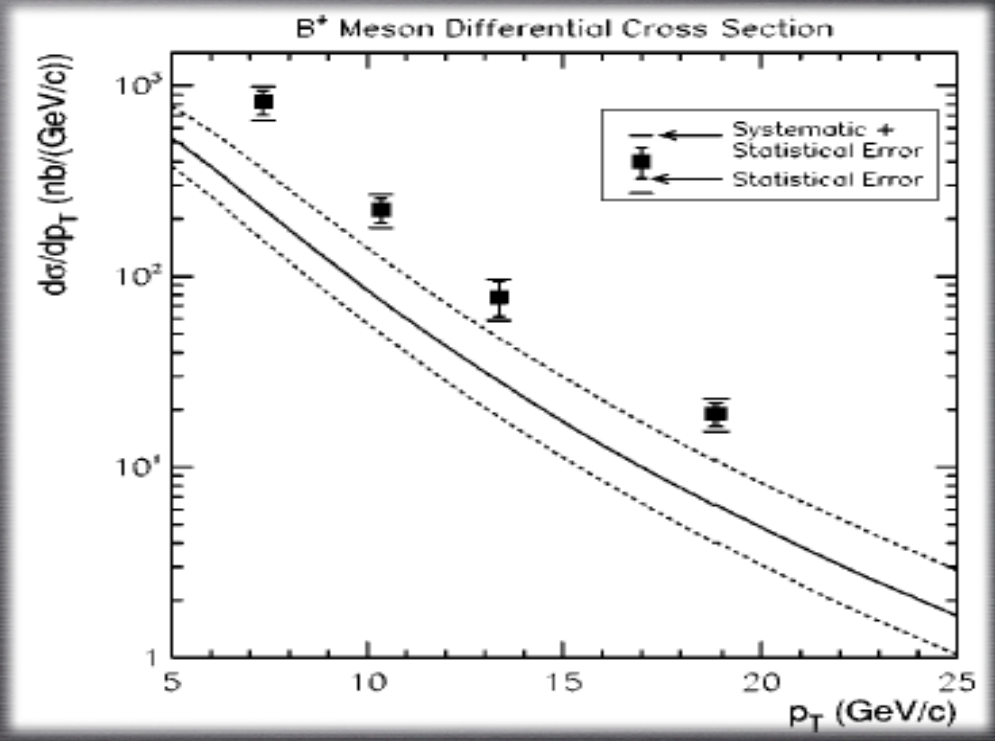


... but not at the Tevatron?

D0 - PRL 85 (2000) 5068



CDF - PRD 65 (2002) 052005



'factor of 2-3 excess'

A precision evaluation of heavy quarks hadroproduction

A precision evaluation of heavy quarks hadroproduction

FONLL

MC, Greco '93
MC, Greco, Nason '98

NLO ⊕ Resummation ⊕ non-perturbative fragmentation

1989 (LVIII AM)

Nuclear Physics B327 (1989) 105–143
North-Holland, Amsterdam

QCD CORRECTIONS TO PARTON–PARTON SCATTERING PROCESSES

F. AVERSA*, P. CHIAPPETTA, M. GRECO*, J.Ph. GUILLET**

*Centre de Physique Théorique***, CNRS–Luminy, Case 907, F-13288 Marseille Cedex 9, France*

Received 12 January 1989
(Revised 29 March 1989)

Combridge '79
Nason, Dawson, Ellis '89

$$\frac{d\hat{\sigma}^{NLO}_{ij\to Q\,X}(p_T, m)}{dp_T}$$

Combridge '79
Nason, Dawson, Ellis '89

$$\frac{d\hat{\sigma}^{NLO}_{ij\to QX}(p_T, m)}{dp_T}$$

$\oplus$

$$\frac{d\hat{\sigma}^{NLO,\overline{MS}}_{ij\to kX}(p_T, \mu)}{dp_T}$$

Combridge, Kripfganz, Ranft '77
Ellis, Sexton '86
Aversa, Chiappetta, Greco, Guillet '89

Combridge '79
Nason, Dawson, Ellis '89

$$\frac{d\hat{\sigma}^{NLO}_{ij\to QX}(p_T, m)}{dp_T}$$

$$\oplus$$

$$\frac{d\hat{\sigma}^{NLO,\overline{MS}}_{ij\to kX}(p_T, \mu)}{dp_T} \otimes E(\mu, \mu_0)$$

Combridge, Kripfganz, Ranft '77
Ellis, Sexton '86
Aversa, Chiappetta, Greco, Guillet '89

Altarelli, Parisi '77
Curci, Furmanski, Petronzio '79

Combridge '79
Nason, Dawson, Ellis '89

$$\frac{d\hat{\sigma}^{NLO}_{ij\to QX}(p_T, m)}{dp_T}$$

$$\oplus$$

$$\frac{d\hat{\sigma}^{NLO,\overline{MS}}_{ij\to kX}(p_T, \mu)}{dp_T} \otimes E(\mu, \mu_0) \otimes D_{k\to QX}(\mu_0, m)$$

Combridge, Kripfganz, Ranft '77
Ellis, Sexton '86
Aversa, Chiappetta, Greco, Guillet '89

Altarelli, Parisi '77
Curci, Furmanski, Petronzio '79

Mele, Nason '91

Combridge '79
Nason, Dawson, Ellis '89

$$\left[\frac{d\hat{\sigma}^{NLO}_{ij\to QX}(p_T, m)}{dp_T} \right.$$

$$\oplus$$

$$\left. \frac{d\hat{\sigma}^{NLO,\overline{MS}}_{ij\to kX}(p_T, \mu)}{dp_T} \otimes E(\mu, \mu_0) \otimes D_{k\to QX}(\mu_0, m) \right] \otimes D^{NP}_{Q\to H_Q}$$

Combridge, Kripfganz, Ranft '77
Ellis, Sexton '86
Aversa, Chiappetta, Greco, Guillet '89

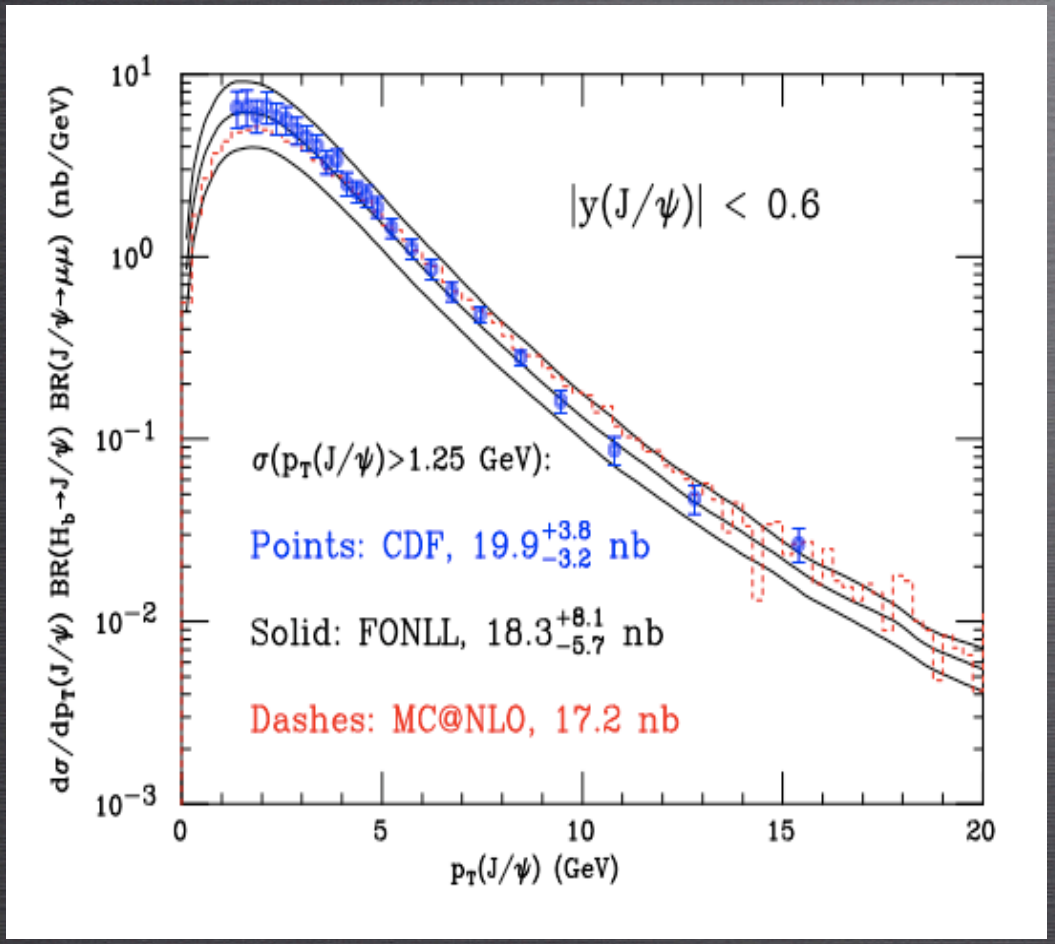
Altarelli, Parisi '77
Curci, Furmanski, Petronzio '79

Mele, Nason '91

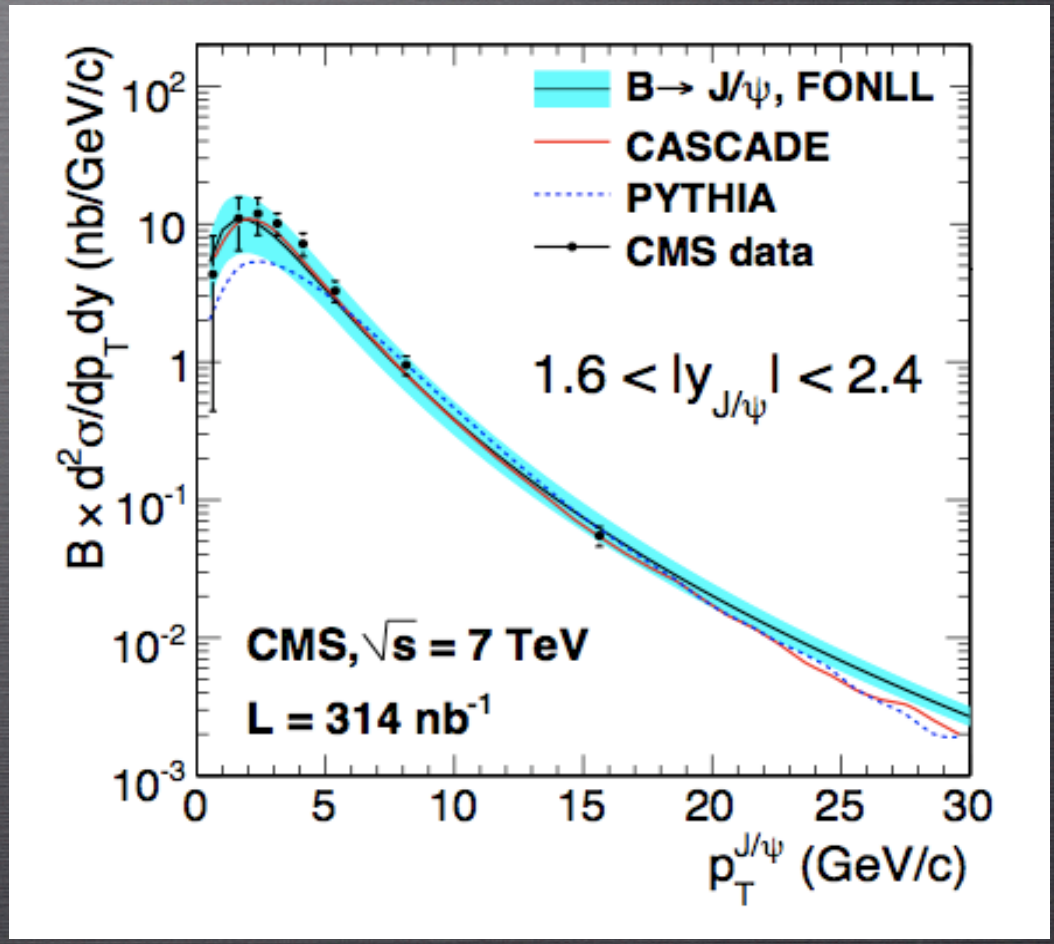
Kartvelishvili et al '78
Peterson et al '83
Braaten et al '95
....

$p^{(-)}\bar{p} \to b \to J/\psi$

CDF 2003



CMS 2010



Excellent agreement

The quest goes on...

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2011-009
2011/02/24

CMS-EXO-10-018

Search for a Heavy Bottom-like Quark in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Looking forward to LXXX AM and 21st century discoveries