Inspired by precision
From QED to QCD...and back to QED

Bologna, December 10, 2021

Riccardo Barbieri
SNS, Pisa

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Summer 1975

QED at higher loops

ON NIELSEN'S GENERALIZED POLYLOGARITHMS AND THEIR NUMERICAL CALCULATION

K.S. Kolbig (CERN), J.A. Mignoco (CERN), E. Remiddi (CERN) (Jul, 1969)

Fourth-order radiative corrections to electron-photon vertex and the lamb-shift value

R. Barbieri (Pisa, Scuola Normale Superiore), J.A. Mignaco (Rosario U.), E. Remiddi (Bologna U.) (1971)

Published in: *Nuovo Cim.A* 6 (1971) 21-28

$$m^2 F_1'(0) = \frac{\alpha}{\pi}\left[-\frac{1}{3}\log\frac{\lambda}{m} - \frac{1}{8}\right] + $$
$$+\left(\frac{\alpha}{\pi}\right)^2\left[-\frac{4819}{5184} - \frac{49}{72}\,\zeta(2) + 3\zeta(2)\log 2 - \frac{3}{4}\,\zeta(3)\right] =$$
$$= \left(-\frac{1}{3}\log\frac{\lambda}{m} - 0.125\right)\frac{\alpha}{\pi} + 0.46994\left(\frac{\alpha}{\pi}\right)^2$$

Appelquist-Brodsky
December 1970

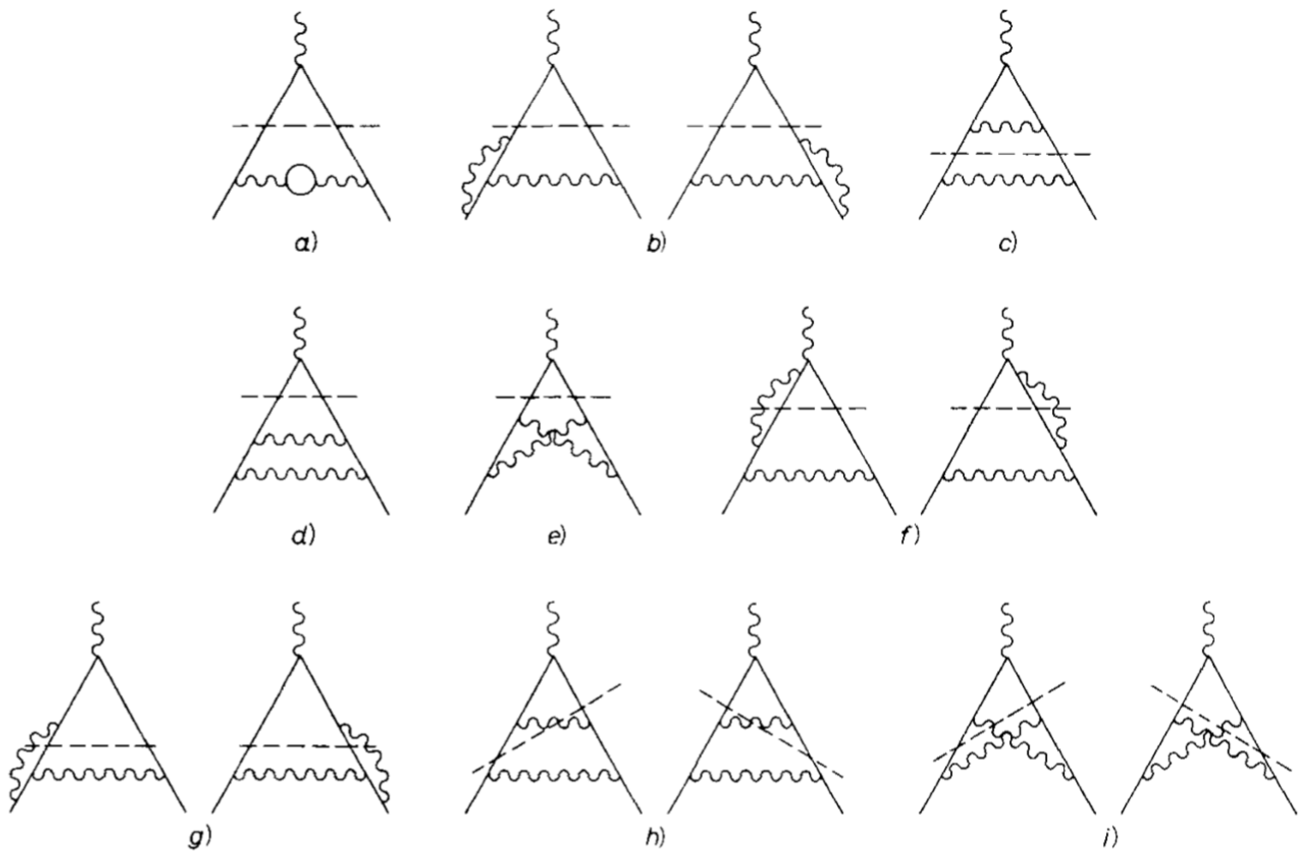
$$m^2 F_1'(0) = (\frac{\alpha}{\pi})^2(0.48 \pm 0.07)$$

$$\Delta E = \mathcal{O}(\alpha^2 (Z\alpha)^4 m_e c^2)$$

Electron form-factors up to fourth order. 1.

Riccardo Barbieri (Pisa, Scuola Normale Superiore), J.A. Mignaco (Rosario U.), E. Remiddi (Bologna U. and INFN, Bologna) (Jan, 1972)

Published in: *Nuovo Cim.A* 11 (1972) 824-864



Cutkosky rules, dispersion relations, SCHOONSHIP, polylogs and all that

Manipulated on the CDC 6600 of Casalecchio with decks of punchcards

(while living in Pisa!)

Two loop form-factors in QED

P. Mastrolia (Bologna U. and Karlsruhe U., TTP), E. Remiddi (Bologna U. and INFN, Bologna) (Feb, 2003)

Published in: *Nucl.Phys.B* 664 (2003) 341-356 • e-Print: hep-ph/0302162 [hep-ph]

For later use in this talk

A contribution to the sixth-order electron and muon anomalies

D. Billi (Bologna U.), Michele Caffo (Bologna U.), E. Remiddi (Bonn U.) (1972)

Published in: *Lett.Nuovo Cim.* 4S2 (1972) 657-660, *Lett.Nuovo Cim.* 4 (1972) 657-660

A contribution to sixth-order electron and muon anomalies. 2.

R. Barbieri (Pisa, Scuola Normale Superiore), Michele Caffo (Bologna U.), E. Remiddi (Bonn U.) (1972)

Published in: *Lett.Nuovo Cim.* 5S2 (1972) 769-773, *Lett.Nuovo Cim.* 5 (1972) 769-773

On the theoretical value of positronium ground state splitting

Riccardo Barbieri (Pisa, Scuola Normale Superiore), P. Christillin (Pisa, Scuola Normale Superiore), E. Remiddi (Bologna U.) (1973)

Published in: *Phys.Lett.B* 43 (1973) 411-412

Absence of the Anomalous Magnetic Moment in a Supersymmetric Abelian Gauge Theory

S. Ferrara (CERN), E. Remiddi (CERN and Bologna U.) (Sep, 1974)

By 1973 the full SM was completely formulated

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}\,\not{D}\psi$$ (∿1975-2000)

$$+|D_{\mu}h|^{2} - V(h)$$ (∿1990 -2012- now)

$$+\psi_{i}\lambda_{ij}\psi_{j}h + h.c.$$ (∿2000 - now)

passing over our heads (my head)

QCD in $\bar{Q}Q$ states

The narrowness of charmonia

Discovery: Nov 1974

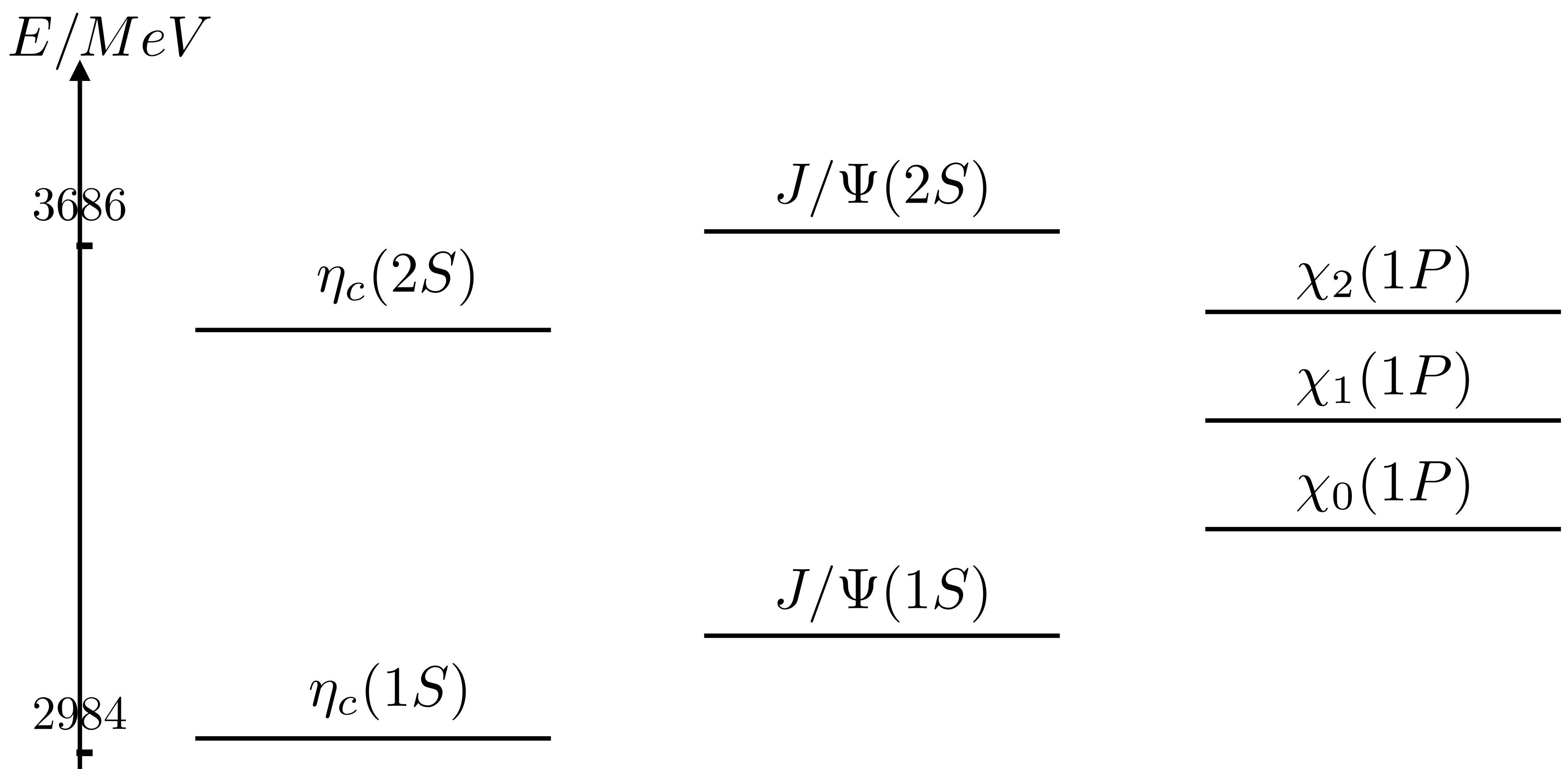
"The November revolution"

Appelquist, Politzer (1975) and De Rujula, Glashow (1975) interpret the narrowness of $J/\Psi(1^{--})$ as a consequence of its 3 gluon decay

$$\frac{\Gamma(\psi \to \mathrm{hadrons})}{\Gamma(\psi \to e^+e^-)} \approx \frac{5(\pi^2-9)}{18\pi} \frac{\alpha_s^3}{\alpha^2}$$

Charmonium spectroscopy

$e^+e^- \to J/\Psi \to e^+e^-$ Discovery: Nov 1974



Γ's between 100 keV and 30 MeV

$p\bar{p} \to (c\bar{c}) \to e^+e^-$

$p\bar{p} \to (c\bar{c}) \to \gamma\gamma$

R704 (CERN)
E760 (FNAL)
E835 (FNAL)

SINGULAR BINDING DEPENDENCE IN THE HADRONIC WIDTHS OF 1^{++} AND 1^{+-} HEAVY QUARK ANTIQUARK BOUND STATES

R. BARBIERI and R. GATTO*

CERN, Geneva, Switzerland

and

E. REMIDDI

Istituto di Fisica dell'Università, Bologna,
Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy

Received 10 February 1976

The annihilation rates into hadrons of P-wave heavy quark-antiquark bound states are calculated within SU(3) colour gauge theory (in particular for the charm scheme). An interesting feature we find is a logarithmic divergence for small binding for the states 1^{++} and 1^{+-}. Implications for the asymptotic freedom approach to the decay rates of the new particles are discussed. An attempt to use quantitatively the obtained results for all the C-even P-waves gives $\Gamma_{\text{ann}}(0^{++}) : \Gamma_{\text{ann}}(2^{++}) : \Gamma_{\text{ann}}(1^{++}) \approx 15:4:1$.

First measured in 1986 at Crystal Ball (SLAC)

Now:

$$\Gamma(\chi_{c0}) = 10.5 \pm 0.6 \qquad \Gamma(\chi_{c2}) = 1.93 \pm 0.11 \qquad \Gamma(\chi_{c1}) = 0.84 \pm 0.04 \qquad MeV$$

$$\Gamma(0^{++}) : \Gamma(2^{++}) : \Gamma(1^{++}) = 12 : 2.4 : 1$$

Needed refinements

virtual

	$^{2S+1}L_J$	$I^G(J^{PC})$	gluons	photons
η_c, η_b	$^1S_0$	$0^+(0^{-+})$	2g	2γ
$J/\psi, \Upsilon(1S)$	$^3S_1$	$0^-(1^{--})$	$(3g)_d$	γ
h_c, h_b	$^1P_1$	$0^-(1^{+-})$	$(3g)_d$	3γ
χ_{c0}, χ_{b0}	$^3P_0$	$0^+(0^{++})$	2g	2γ
χ_{c1}, χ_{b1}	$^3P_1$	$0^+(1^{++})$	2g	2γ
χ_{c2}, χ_{b2}	$^3P_2$	$0^+(2^{++})$	2g	2γ

$\Longrightarrow$ "Colour-singlet" model (+ NLO) $2m$

Relativistic, colour-octet, binding corrections

NRQCD $mv, \Lambda_{QCD}, mv^2, \ldots$

#8

Strong Radiative Corrections to Annihilations of Quarkonia in QCD

Riccardo Barbieri (Pisa, Scuola Normale Superiore and INFN, Pisa), E. d'Emilio (Pisa, Scuola Normale Superiore and INFN, Pisa), G. Curci (CERN), E. Remiddi (Bologna U.) (Jan, 1979)

Published in: *Nucl.Phys.B* 154 (1979) 535-546

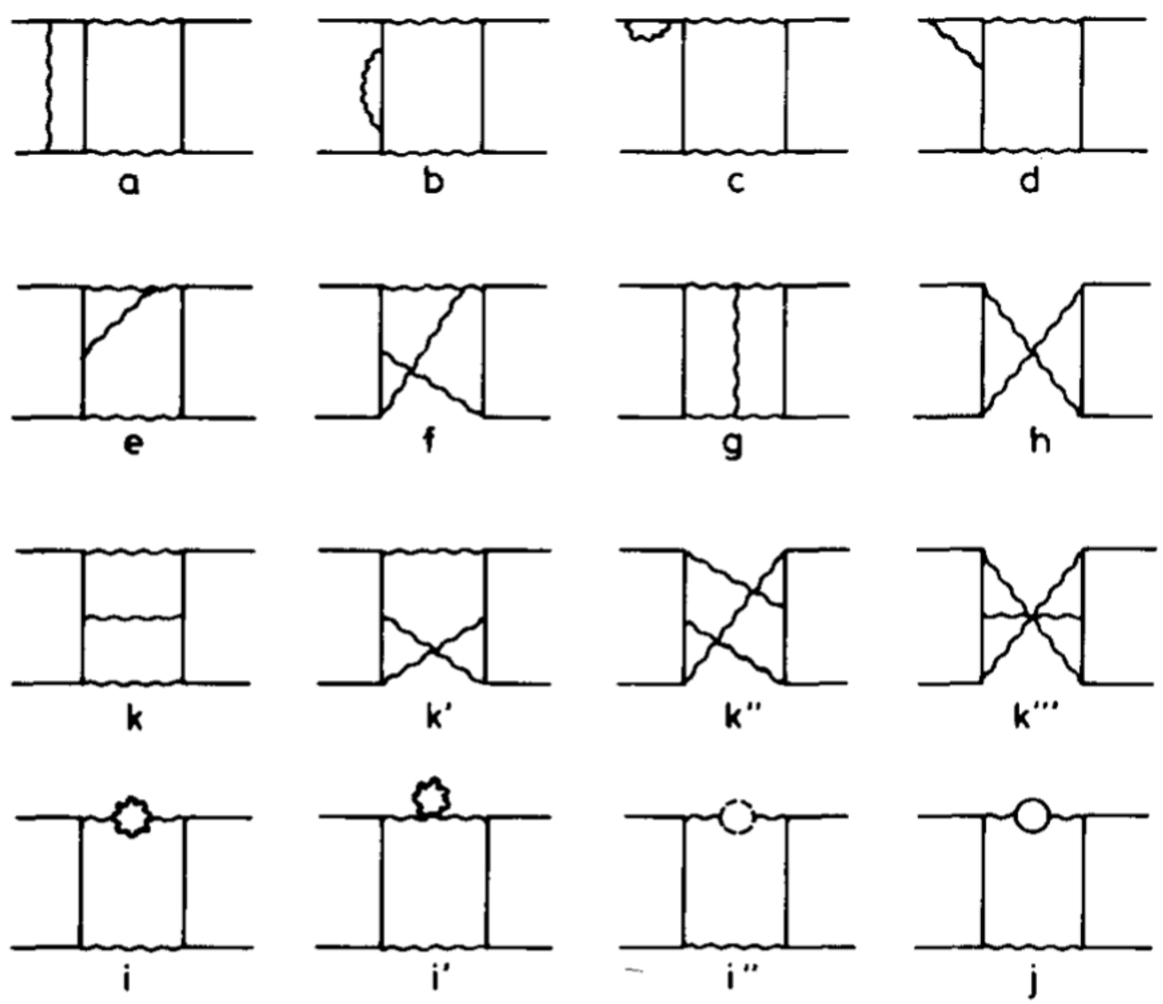
η_c

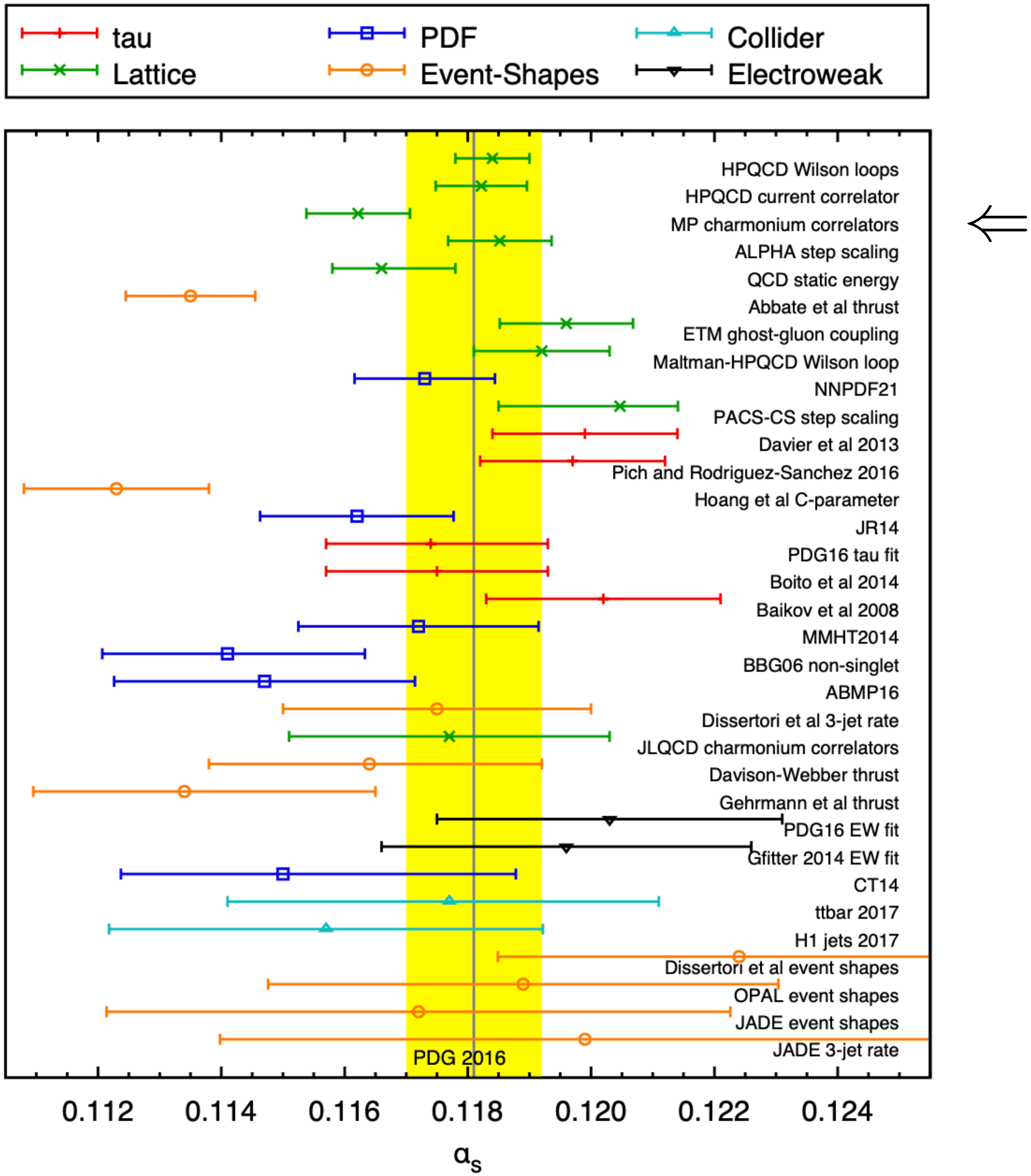
Strong QCD Corrections to p Wave Quarkonium Decays

Riccardo Barbieri (CERN and Pisa, Scuola Normale Superiore), Michele Caffo (INFN, Bologna), Raoul Gatto (Geneva U.), E. Remiddi (Geneva U. and Bologna U. and INFN, Bologna) (Jul, 1980)

Published in: *Phys.Lett.B* 95 (1980) 93-95

χ_0, χ_2





tau
Lattice
PDF
Event-Shapes
Collider
Electroweak
HPQCD Wilson loops
HPQCD current correlator
MP charmonium correlators
ALPHA step scaling
QCD static energy
Abbate et al thrust
ETM ghost-gluon coupling
Maltman-HPQCD Wilson loop
NNPDF21
PACS-CS step scaling
Davier et al 2013
Pich and Rodriguez-Sanchez 2016
Hoang et al C-parameter
JR14
PDG16 tau fit
Boito et al 2014
Baikov et al 2008
MMHT2014
BBG06 non-singlet
ABMP16
Dissertori et al 3-jet rate
JLQCD charmonium correlators
Davison-Webber thrust
Gehrmann et al thrust
PDG16 EW fit
Gfitter 2014 EW fit
CT14
ttbar 2017
H1 jets 2017
Dissertori et al event shapes
OPAL event shapes
JADE event shapes
JADE 3-jet rate
PDG 2016
0.112
0.114
0.116
0.118
0.120
0.122
0.124
α_s

Back to QED: the muon anomaly

R. Barbieri, L. Maiani, G. Martinelli, L. Paoluzi, N. Paver, R. Petronzio, E. Remiddi:

REPORT FROM THE Φ FACTORY WORKING GROUP May 1991

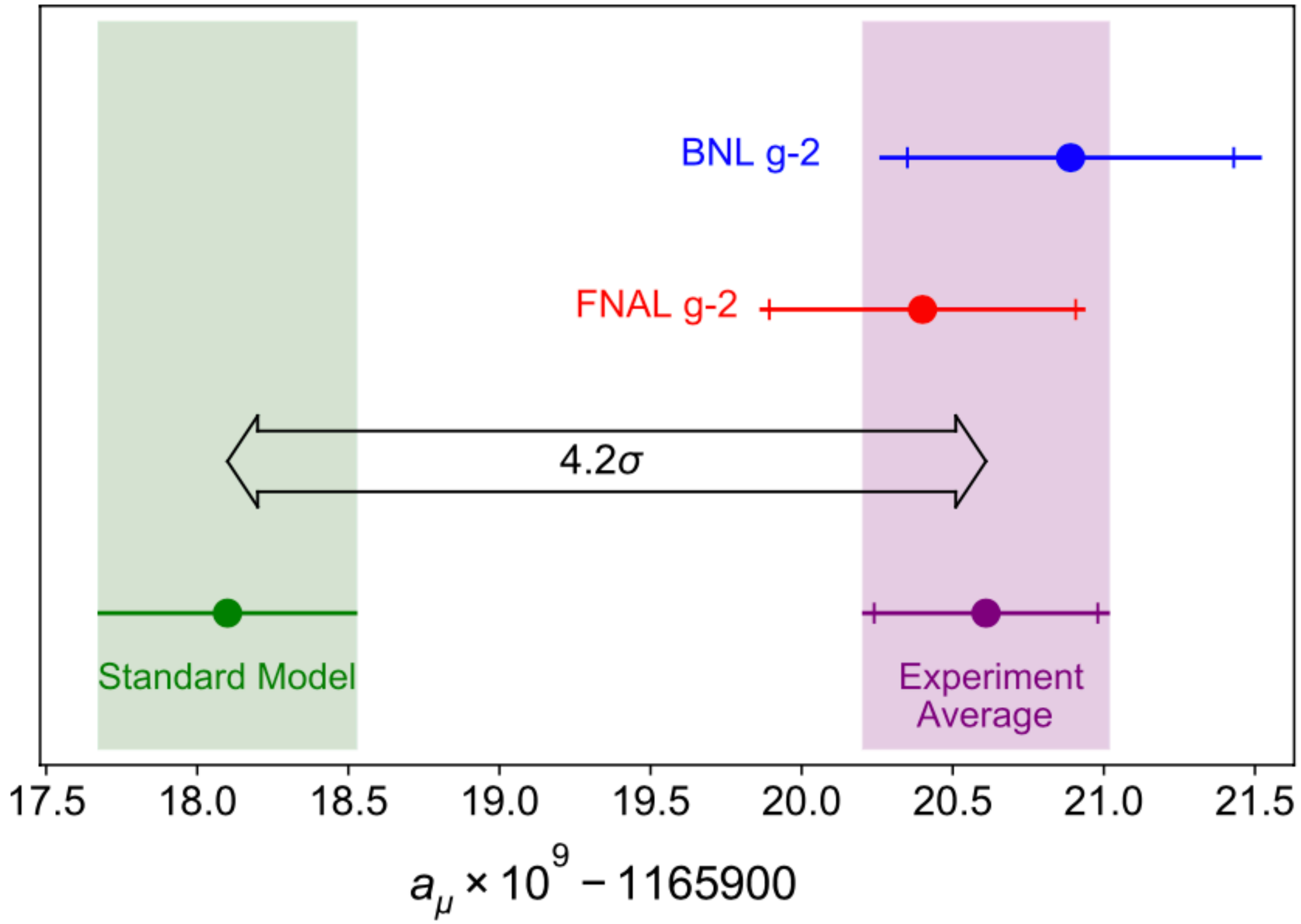
4 Total cross section and hadronic contribution to the muon g-2

A more detailed analysis of this issue is necessary. At the present time, it is not clear to us that a more precise determination of hadronic vacuum polarization can really lead to a prediction of $a(\mu)$ with an error smaller than the predicted weak contribution.

HLbL at that time:

$$a(\mu, h\ \gamma\gamma)_{quarks} = (60 \pm 4)10^{-11}$$
$$a(\mu, h\ \gamma\gamma)_{mesons} = (49 \pm 5)10^{-11}$$

Time to correct this view



2104.03281

$$\Delta a_\mu|_{HVP} = 6845(40) \cdot 10^{-11}$$

$$\Delta a_\mu|_{Weak} = 153(1) \cdot 10^{-11}$$

$$\Delta a_\mu|_{HLbL} = 92(18) \cdot 10^{-11}$$

$$a_\mu|_{exp} - a_\mu|_{th} = 250(60) \cdot 10^{-11}$$

Safe to add theory errors in quadrature? From 4.2 to 3.5σ

Theory errors going to dominate soon?

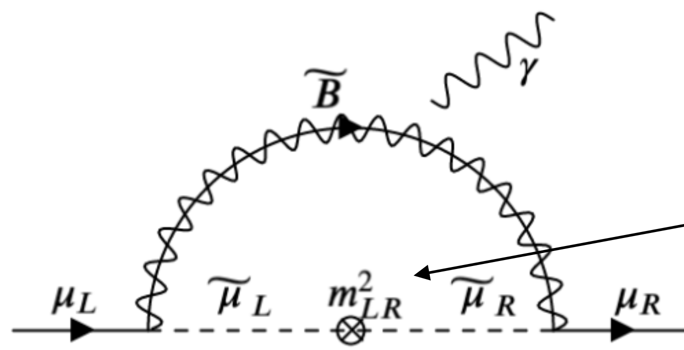
IF Δa_μ confirmed

SUSY as an "EASY" and "MOTIVATED"

1. Relevant (low energy)

$$M_1 \tilde{b}\tilde{b}, \quad M_2 \tilde{w}\tilde{w}, \quad m_{\tilde{\mu}_L} \tilde{\mu}_L^+ \tilde{\mu}_L, \quad m_{\tilde{\mu}_R} \tilde{\mu}_R^+ \tilde{\mu}_R, \quad \mu H_1 H_2, \quad \tan\beta = \frac{< H_2 >}{< H_1 >}$$

2. Size of the effect:



$$m^2_{LR} = m_\mu \mu \tan\beta$$

$$\Delta a_\mu|_{SUSY} \approx \frac{g_1^2}{16\pi^2} m_\mu^2 \frac{M_1 \mu \tan\beta}{m^2_{\tilde{\mu}_L} m^2_{\tilde{\mu}_R}} \approx 2.5 \cdot 10^{-9} (\frac{\tan\beta}{10})(\frac{\mu}{1\ TeV})(\frac{M_1}{100\ GeV})(\frac{200\ GeV}{m_{\tilde{\mu}_L}})^2(\frac{200\ GeV}{m_{\tilde{\mu}_R}})^2$$

3. Main constraints on parameter space (high energy)

- No coloured partners below $1 \div 2\ TeV$

$$M_3 \tilde{g}\tilde{g}, \quad M_3 \gtrsim a\ few\ TeV$$

- No flavour violations $\mu \to e\gamma,\ \tau \to \mu\gamma, etc$

$m_{\tilde{e}_L} = m_{\tilde{\mu}_L} = m_{\tilde{\tau}_L}$ (and similarly for $m_{\tilde{l}_R}$)

Due to $m^2_{LR}(\tau) = m_\tau \mu \tan\beta \approx (150\ GeV)^2 \frac{\tan\beta}{10} \frac{\mu}{TeV}$ $\Rightarrow \tilde{\tau} =$ lightest s-lepton

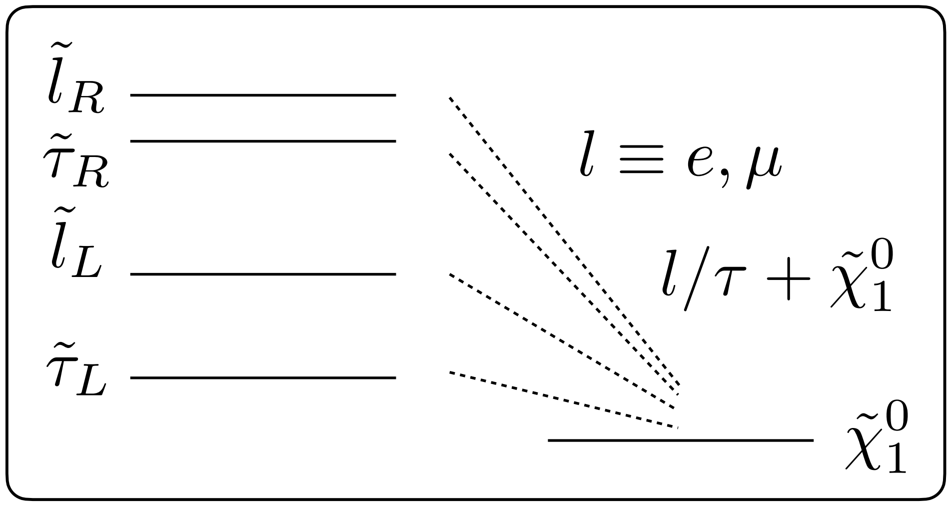
- Cancellations needed

$$m_Z^2 = -2(m_{H_2}^2 + |\mu|^2)$$

- If non-zero phases, from $d_e < 1.2 \cdot 10^{-29} e \cdot cm$

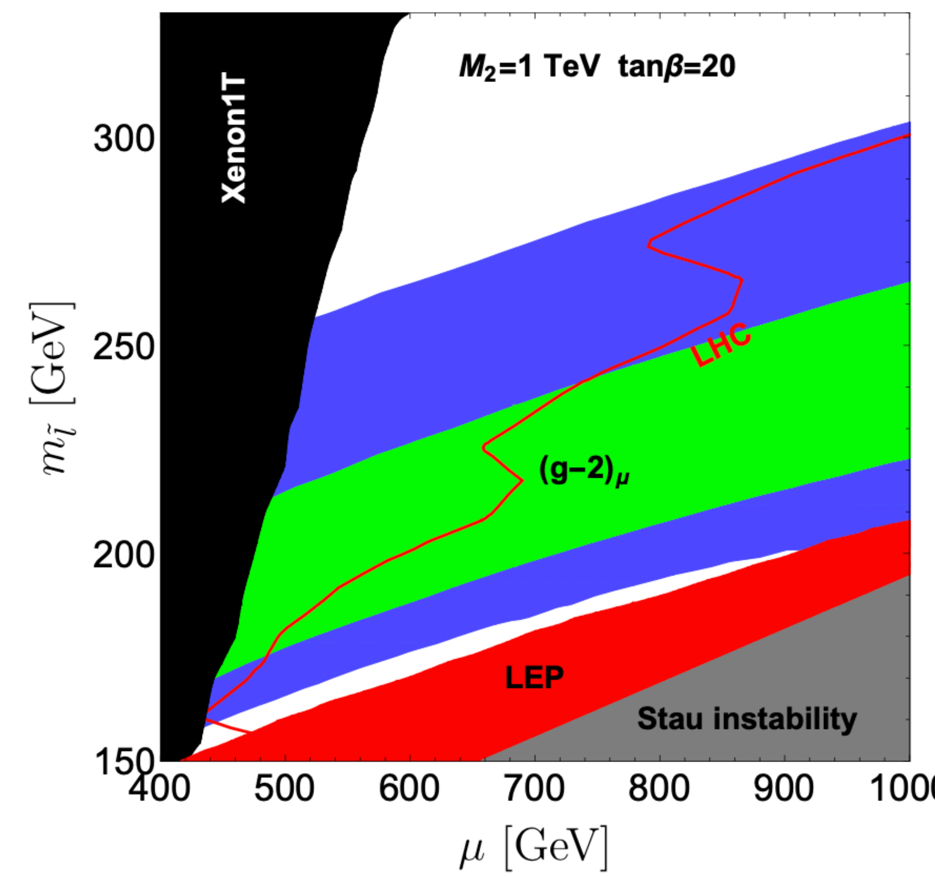
$$m_{\tilde{\nu}_{eL}} \gtrsim 40\ TeV (\sin\phi_\mu \tan\beta)^{1/2}$$

4. Direct signals



$$M_1 < m_{\tilde{l}_L}, m_{\tilde{l}_R} < M_2 < \mu < M_3$$

Cox et al, 2021



- **LHC** $\sigma(pp \to \tilde{l}\tilde{\bar{l}}) \approx 1 \div 10\ fb$

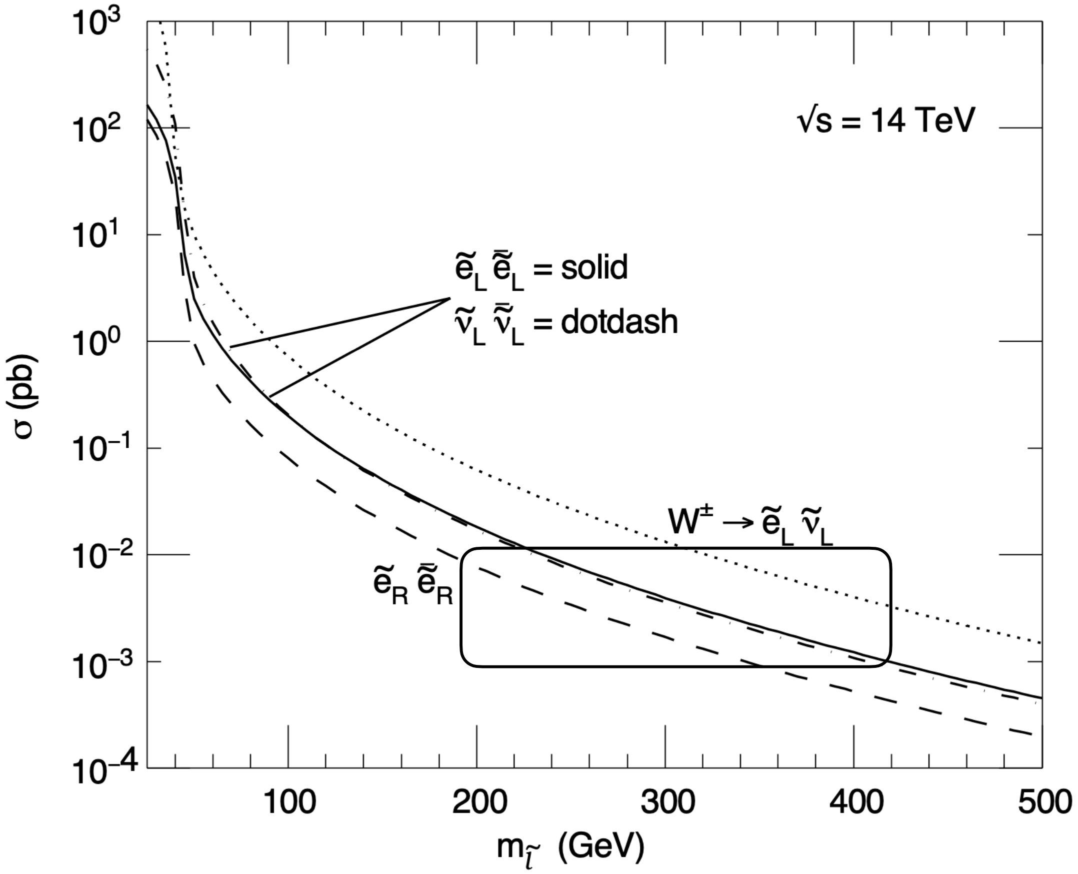
  backgrounds: $VV,\ V + jets,\ V^* \to l\bar{l},\ t\bar{t},\ t + V$

- **DM**

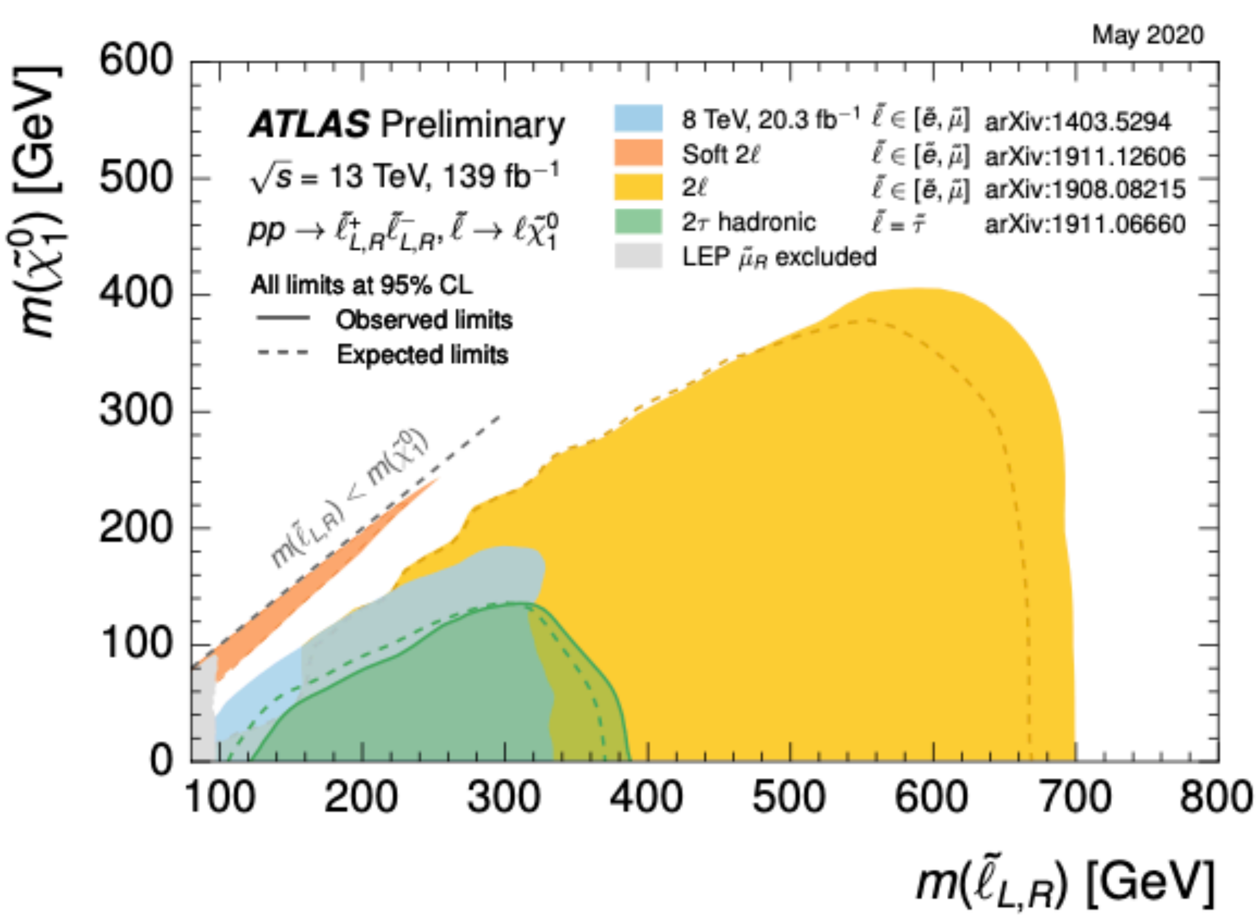
  $\tilde{\chi}_1^0 \tilde{\tau}$ co-annihilation $\Delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0} \lesssim 15\ GeV$

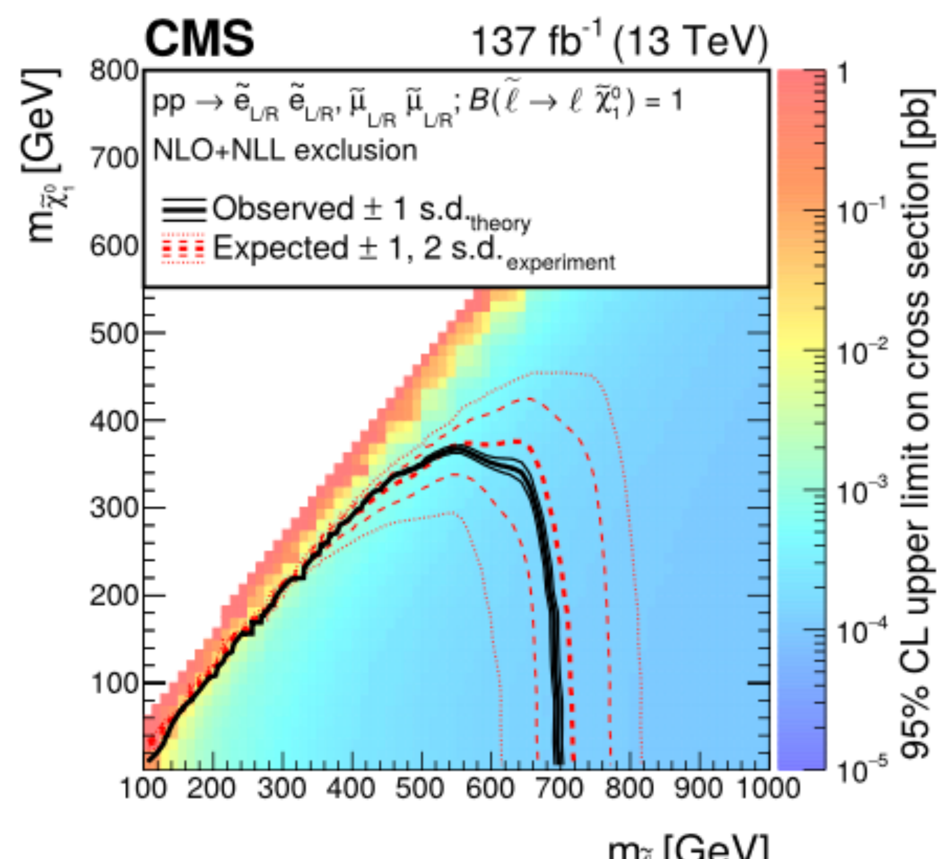
green: a_μ at 1σ

blue: a_μ at 2σ



Baer et al, 1993





A slide in epistemology

What convinces us that a theory is "true"?

Elegance, internal coherence, synthesis,
the number of independent predictions, ...

Quantitative precision in the comparison of theory and experiment

$$a_e^{exp} = 1\ 159\ 652\ 180.73(0.28) \times 10^{-12}$$

$$a_e^{th} = 1\ 159\ 652\ 181.78(6)(4)(3)(77) \times 10^{-12}$$

$$a_\mu^{exp} = 1\ 165\ 920\ 6.1(4.1) \times 10^{-10}$$

$$a_\mu^{th} = 1\ 165\ 918\ 1.0(4)(1.8) \times 10^{-10}$$