The Standard Model

and Beyond

Ioannis Bakas

Memorial Conference

NTU-Athens, March 2018

John Iliopoulos

ENS Paris

- Yannis left us in August 2016

- Yannis left us in August 2016
- He was fully active until the last moment

On Elliptic String Solutions in AdS_3 and dS_3

Ioannis Bakas and Georgios Pastras

Department of Physics, School of Applied Mathematics and Physical Sciences
National Technical University, Athens 15780, Greece

E-mail: bakas@mail.ntua.gr, pastras@mail.ntua.gr

ABSTRACT: Classical string actions in AdS_3 and dS_3 can be connected to the sinh-Gordon and cosh-Gordon equations through Pohlmeyer reduction. We show that the problem of constructing a classical string solution with a given static or translationally invariant Pohlmeyer counterpart is equivalent to solving four pairs of effective Schrödinger problems. Each pair consists of a flat potential and an $n = 1$ Lamé potential whose eigenvalues are connected, and, additionally, the four solutions satisfy a set of constraints. An approach for solving this system is developed by employing an interesting connection between the specific class of classical string solutions and the band structure of the Lamé potential. This method is used for the construction of several families of classical string solutions, one of which turns out to be the spiky strings in AdS_3. New solutions include circular rotating strings in AdS_3 with singular time evolution of their radius and angular velocity as well as classical string solutions in dS_3.

Self-similar equilibration of strongly interacting systems from holography

Ioannis Bakas,[1] Kostas Skenderis,[2] and Benjamin Withers[2,3,4]

[1]*Department of Physics, School of Applied Mathematics and Physical Sciences, National Technical University, 15780 Athens, Greece*
[2]*STAG Research Centre and Mathematical Sciences, University of Southampton, Southampton, UK*
[3]*School of Mathematical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, UK*
[4]*DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, UK*

(Dated: June 1, 2016)

We study the equilibration of a class of far-from-equilibrium strongly interacting systems using gauge/gravity duality. The systems we analyse are 2+1 dimensional and have a four dimensional gravitational dual. A prototype example of a system we analyse is the equilibration of a two dimensional fluid which is translational invariant in one direction and is attached to two different heat baths with different temperatures at infinity in the other direction. We realise such setup in gauge/gravity duality by joining two semi-infinite asymptotically Anti-de Sitter (AdS) black branes of different temperatures, which subsequently evolve towards equilibrium by emitting gravitational radiation towards the boundary of AdS. At sufficiently late times the solution converges to a similarity solution, which is only sensitive to the left and right equilibrium states and not to the details of the initial conditions. This attractor solution not only incorporates the growing region of equilibrated plasma but also the outwardly-propagating transition regions, and can be constructed by solving a single ordinary differential equation.

PACS numbers:

Aspects of non-associative structures in physics*

Ioannis Bakas

Department of Physics, School of Applied Mathematics and Physical Sciences
National Technical University, 15780 Athens, Greece

bakas@mail.ntua.gr

Abstract

We summarize the emergence of non-commutative/non-associative structures in Dirac's generalization of Maxwell theory, focusing mostly on the magnetic field analogue of the non-geometric R-flux string model. The cohomological interpretation of the obstructions to associativity in terms of 3-cocycles and the use of the star product as alternative to ordinary quantization are also discussed in this context.

*Contribution to the *Workshop on Non-commutative Field Theory and Gravity*, 21–27 September 2015, Corfu, Greece; to appear in the Proceedings of Science. Also, based on a lecture delivered at the *Workshop on Quantized Geometry and Physics*, 23–26 May 2014, Bayrischzell, Germany and at the *Joint ERC Workshop on MassTeV, Superfields and Strings & Gravity*, 16–18 October 2013, Munich,

LMU-ASC 09/16
MPP-2016-24

Towards a world-sheet description of doubled geometry in string theory

Ioannis Bakas[1], Dieter Lüst[2,3], Erik Plauschinn[3]

[1] *Department of Physics*
School of Applied Mathematics and Physical Sciences
National Technical University
15780 Athens, Greece

[2] *Max-Planck-Institut für Physik*
Föhringer Ring 6
80805 München, Germany

[3] *Arnold-Sommerfeld-Center für Theoretische Physik*
Department für Physik
Ludwig-Maximilians-Universität München
Theresienstraße 37, 80333 München, Germany

Abstract

Starting from a sigma-model for a doubled target-space geometry, we show that the number of target-space dimensions can be reduced by half through a gauging procedure. We apply this formalism to a class of backgrounds relevant for double field theory, and illustrate how choosing different gaugings leads to string-theory configurations T-dual to each other. We furthermore discuss that given a conformal doubled theory, the reduced theories are conformal as well.
As an example we consider the three-dimensional $SU(2)$ WZW model and show that the only possible reduced backgrounds are the cigar and trumpet

THE STANDARD MODEL

$\cdots$ and BEYOND

THE STANDARD MODEL

$\cdots$ and BEYOND

- With the discovery of the BEH scalar boson the Standard Model is **complete**

THE STANDARD MODEL

$\cdots$ and BEYOND

- With the discovery of the BEH scalar boson the Standard Model is **complete**
- It is no more The Standard Model

THE STANDARD MODEL

$\cdots$ and BEYOND

- With the discovery of the BEH scalar boson the Standard Model is **complete**
- It is no more The Standard Model
- But **The Standard Theory**

THE STANDARD THEORY

THE STANDARD THEORY

- The Standard Theory has been enormously successful

THE STANDARD THEORY

- The Standard Theory has been enormously successful
- It contains $17 + \cdots$ arbitrary parameters *(masses and coupling constants)* and they have all been determined experimentally

THE STANDARD THEORY

- The Standard Theory has been enormously successful
- It contains $17 + \cdots$ arbitrary parameters *(masses and coupling constants)* and they have all been determined experimentally
- This number is irreducible
  Any relation of the form $\lambda = f(g)$ will not be respected by renormalisation

THE STANDARD THEORY

- The Standard Theory has been enormously successful
- It contains $17 + \cdots$ arbitrary parameters *(masses and coupling constants)* and they have all been determined experimentally
- This number is irreducible
  Any relation of the form $\lambda = f(g)$ *will not be respected by renormalisation*
- The Standard Theory is the absolute totalitarian system. Whatever is not forbidden, it is compulsory

THE STANDARD THEORY

Our confidence in this theory is fully justified by its successes in predicting new phenomena and its impressive agreement with experiment:

THE STANDARD THEORY

Our confidence in this theory is fully justified by its successes in predicting new phenomena and its impressive agreement with experiment:

- The discovery of weak neutral currents (CERN 1973)

THE STANDARD THEORY

Our confidence in this theory is fully justified by its successes in predicting new phenomena and its impressive agreement with experiment:

- The discovery of weak neutral currents (CERN 1973)
- The discovery of charmed particles (SLAC-Brookhaven 1974-1976)

THE STANDARD THEORY

Our confidence in this theory is fully justified by its successes in predicting new phenomena and its impressive agreement with experiment:

- The discovery of weak neutral currents (CERN 1973)
- The discovery of charmed particles (SLAC-Brookhaven 1974-1976)
- The discovery of QCD and asymptotic freedom (SLAC-$\cdots$ 1973-$\cdots$)

THE STANDARD THEORY

Our confidence in this theory is fully justified by its successes in predicting new phenomena and its impressive agreement with experiment:

- The discovery of weak neutral currents (CERN 1973)
- The discovery of charmed particles (SLAC-Brookhaven 1974-1976)
- The discovery of QCD and asymptotic freedom (SLAC-$\cdots$ 1973-$\cdots$)
- The discovery of the gauge bosons (CERN 1983)

THE STANDARD THEORY

Our confidence in this theory is fully justified by its successes in predicting new phenomena and its impressive agreement with experiment:

- The discovery of weak neutral currents (CERN 1973)
- The discovery of charmed particles (SLAC-Brookhaven 1974-1976)
- The discovery of QCD and asymptotic freedom (SLAC-$\cdots$ 1973-$\cdots$)
- The discovery of the gauge bosons (CERN 1983)
- The discovery of b and t flavours (FermiLab, LEP ??)

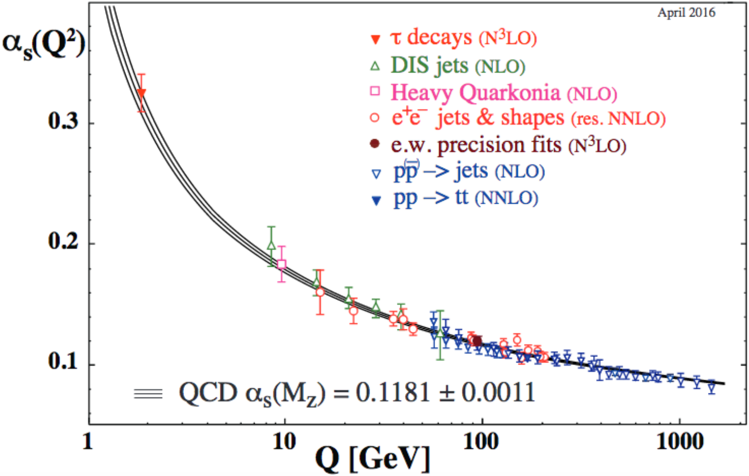
THE STANDARD THEORY

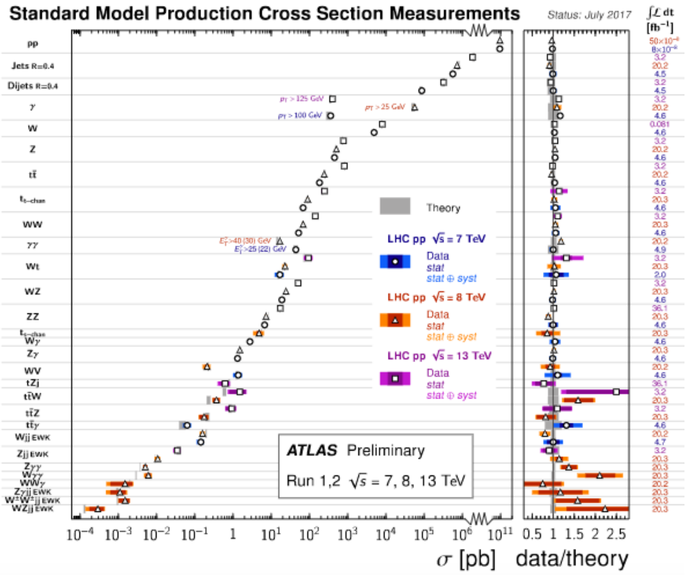
Our confidence in this theory is fully justified by its successes in predicting new phenomena and its impressive agreement with experiment:

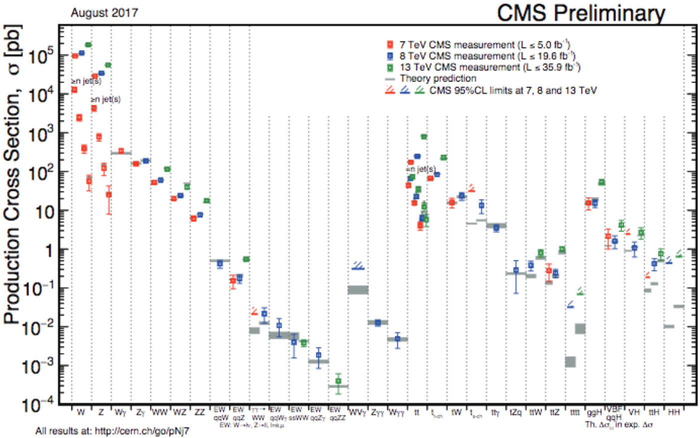
- The discovery of weak neutral currents (CERN 1973)
- The discovery of charmed particles (SLAC-Brookhaven 1974-1976)
- The discovery of QCD and asymptotic freedom (SLAC-$\cdots$ 1973-$\cdots$)
- The discovery of the gauge bosons (CERN 1983)
- The discovery of b and t flavours (FermiLab, LEP ??)
- The discovery of the BEH boson (CERN 2012)

THE STANDARD THEORY

In addition, it shows an impressive agreement with experiment in a very large number of detailed measurements.


April 2016
$\alpha_s(Q^2)$
τ decays (N³LO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e⁺e⁻ jets & shapes (res. NNLO)
e.w. precision fits (N³LO)
pp(̄) –> jets (NLO)
pp –> tt (NNLO)
0.3
0.2
0.1
QCD $\alpha_s(M_Z) = 0.1181 \pm 0.0011$
1
10
100
1000
Q [GeV]

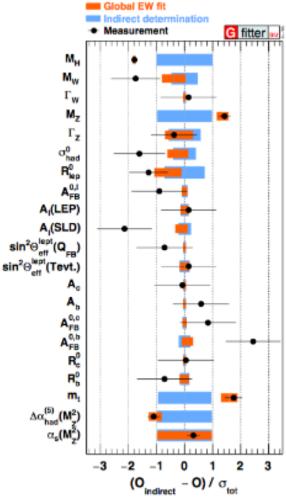

Standard Model Production Cross Section Measurements
Status: July 2017
∫ℒ dt [fb⁻¹]
pp
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t_t-chan
WW
γγ
Wt
WZ
ZZ
t_s-chan
Wγ
Zγ
WV
tZj
tt̄W
tt̄Z
tt̄γ
Wjj EWK
Zjj EWK
Zγγ
Wγγ
WWγ
Zγjj EWK
W±W±jj EWK
WZjj EWK
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
σ [pb]
data/theory



August 2017
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqZZ WVγ Zγγ Wγγ tt t-ch tW s-ch ttγ tZq ttW ttZ tttt ggH VBF qqH VH ttH HH
EW: W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

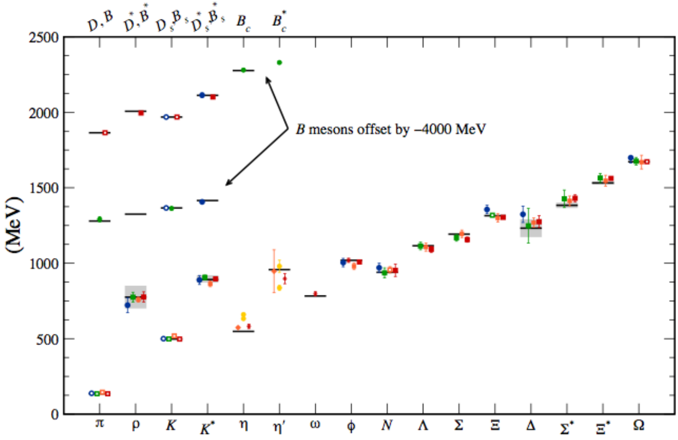
Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1880 ± 0.0020	-0.2
Γ_Z [GeV]	2.4952 ± 0.0023	2.4943 ± 0.0008	0.4
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7420 ± 0.0008	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.66 ± 0.05	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.995 ± 0.010	—
σ_{had}[nb]	41.541 ± 0.037	41.484 ± 0.008	1.5
R_e	20.804 ± 0.050	20.734 ± 0.010	1.4
R_μ	20.785 ± 0.033	20.734 ± 0.010	1.6
R_τ	20.764 ± 0.045	20.779 ± 0.010	-0.3
R_b	0.21629 ± 0.00066	0.21579 ± 0.00003	0.8
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00009	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0003	-2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0736 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0003	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23152 ± 0.00005	0.7
	0.23185 ± 0.00035		0.9
	0.23105 ± 0.00087		-0.5
A_e	0.15138 ± 0.00216	0.1470 ± 0.0004	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0002	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

Quantity	Value	Standard Model	Pull
m_t [GeV]	173.34 ± 0.81	173.76 ± 0.76	-0.5
M_W [GeV]	80.387 ± 0.016	80.361 ± 0.006	1.6
	80.376 ± 0.033		0.4
Γ_W [GeV]	2.046 ± 0.049	2.089 ± 0.001	-0.9
	2.195 ± 0.083		1.3
M_H [GeV]	125.09 ± 0.24	125.11 ± 0.24	0.0
$\rho_{\gamma W}$	-0.03 ± 0.20	-0.02 ± 0.02	0.0
$\rho_{\tau Z}$	-0.27 ± 0.31	0.00 ± 0.03	-0.9
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0002	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0003	1.3
$Q_W(p)$	0.064 ± 0.012	0.0708 ± 0.0003	-0.6
$Q_W(\mathrm{Cs})$	-72.62 ± 0.43	-73.25 ± 0.02	1.5
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.91 ± 0.02	0.1
$\hat{s}_Z^2(\mathrm{eDIS})$	0.2299 ± 0.0043	0.23129 ± 0.00005	-0.3
τ_τ [fs]	290.88 ± 0.35	289.85 ± 2.12	0.4
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.18 \pm 0.78) \times 10^{-9}$	$(4507.89 \pm 0.08) \times 10^{-9}$	4.2



- Latest global EW fit
- Agreement with SM continues as measurements improve
- Tension between A^l_{FB}, A_l(LEP & SLD), A_b(SLD) & A^b_{FB} remains…

Gfitter 1803.01853


D, B
D*, B*
D_s, B_s
D*_s, B*_s
B_c
B*_c
2500
2000
1500
1000
500
0
(MeV)
B mesons offset by –4000 MeV
π
ρ
K
K*
η
η′
ω
φ
N
Λ
Σ
Ξ
Δ
Σ*
Ξ*
Ω

THE STANDARD THEORY

- Most of these successes constitute in fact a triumph of **renormalised perturbation theory**

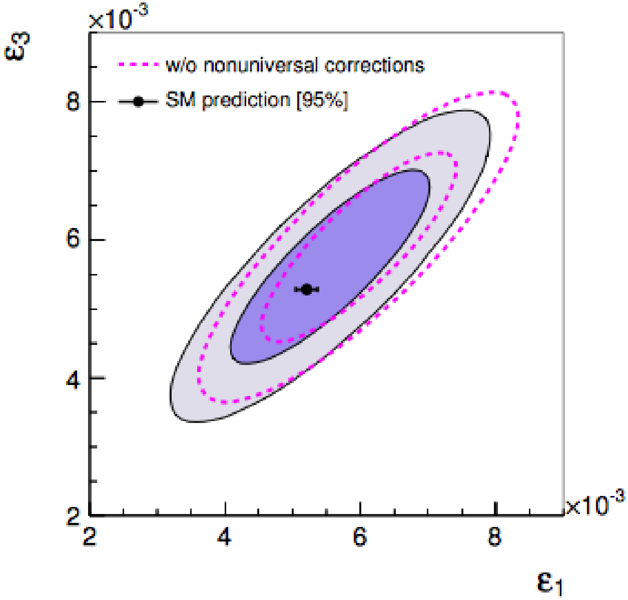
THE STANDARD THEORY

- Most of these successes constitute in fact a triumph of **renormalised perturbation theory**

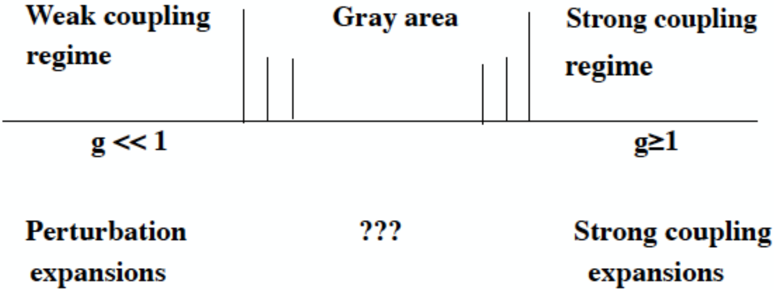
- For the first time we check weak interactions at the level of radiative corrections

THE STANDARD THEORY

- Most of these successes constitute in fact a triumph of **renormalised perturbation theory**
- For the first time we check weak interactions at the level of radiative corrections
- The Standard Theory has become a **high precision theory**


w/o nonuniversal corrections
SM prediction [95%]
ε_3
$\times 10^{-3}$
8
6
4
2
2
4
6
8
$\times 10^{-3}$
ε_1

The ST is a renormalisable Quantum Field Theory



In a large part of present energies QCD is in the gray area !

Perturbation theory has been remarkably reliable outside the region of strong interactions

- Do we understand why?

- Dyson's argument:

$A_n \sim \alpha^n (2n-1)!!$

Perturbation theory breaks down when $A_n \sim A_{n+1}$

$2n + 1 \sim \alpha^{-1}$

For QED $n >> 1$; For QCD ???

For some reason the validity of (improved) perturbation expansion seems to cover most of the gray area

- Given this impressive success...
  What does Beyond mean?

- Given this impressive success...
  What does Beyond mean?

- Or, What is wrong with the Standard Theory??

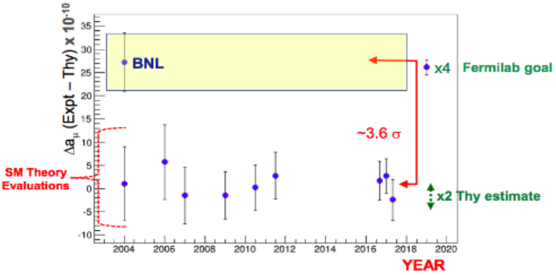
- Given this impressive success...
  What does Beyond mean?
- Or, What is wrong with the Standard Theory??
- I. General questions

- Given this impressive success...
  What does Beyond mean?
- Or, What is wrong with the Standard Theory??
- I. General questions
- II. Specific points

High precision measurements

Anomalous magnetic moment of the muon

Long-standing discrepancy with the SM

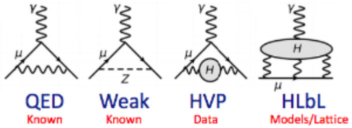


FNAL exp't in commissioning phase

a_μ is now measured to 540 ppb; Goal is 140 ppb

High precision measurements

Arduous computation of ever more precise SM prediction



New lattice computation for HLBL term

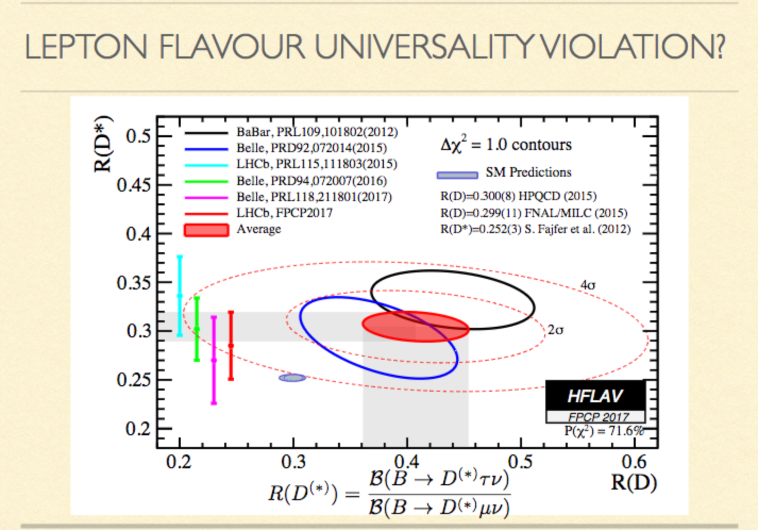
- physical pion mass and large lattice
- Statistical precision x2 improvement
- Systematics in progress

Blum etal, 1705.01067, 1610.04603

Contribution	Value $\times 10^{10}$	Uncertainty $\times 10^{10}$
QED	11 658 471.895	0.008
Electroweak Corrections	15.4	0.1
HVP (LO) [7]	692.3	4.2
HVP (LO) [8]	694.9	4.3
HVP (NLO)	-9.84	0.06
HVP (NNLO)	1.24	0.01
HLbL	10.5	2.6
Total SM prediction [7]	11 659 181.5	4.9
Total SM prediction [8]	11 659 184.1	5.0
BNL E821 result	11 659 209.1	6.3
Fermilab E989 target		≈ 1.6

$$a_\mu^{\mathrm{HLbL}} = 5.35(1.35) \times 10^{-10}$$

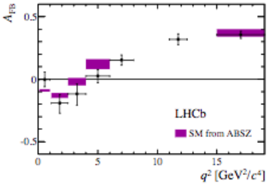
Heavy flavour decays

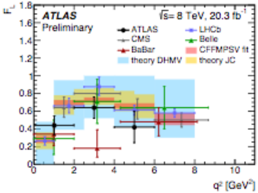


Heavy flavour decays

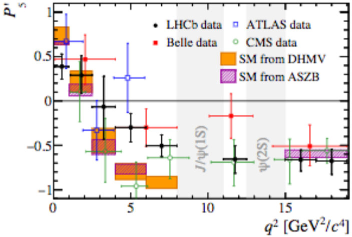
Flavour changing neutral currents

$B_d^0 \to K^* \mu^+ \mu^-$ results





- Several observables appear different than SM
- In particular P_5' has significant discrepancy
- Global fits show large disagreement



Heavy flavour decays

Summary of B anomalies

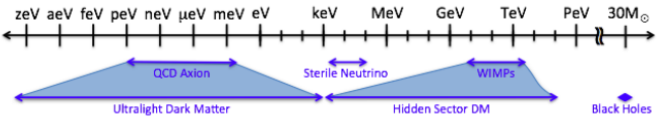
Are we there yet?

1. Low $b \to s\mu\mu$ branching fractions
2. Discrepancies in angular observables of $B_d^0 \to K^* \mu^+ \mu^-$
3. Signs of lepton non-universality in: $B^+ \to K^+ \mu^+ \mu^-$ and $B_d^0 \to K^* \mu^+ \mu^-$

- All seems to be related to a change in the C_9 coefficient (or maybe C_9 and C_{10}, but V-A)
- Global fits start to exhibit several standard deviations of discrepancy
- $c\bar{c}$ interference explanation seems not justified
- Additional discrepancies in tree-level $B \to D^{(*)} \ell \nu$ decays
- Many NP explanations: Z', leptoquarks, low mass resonances etc

Dark matter

Large mass range for DM candidates



- bosonic DM produced during inflation or high temp phase transition
- DM acts as oscillating classical field

- WIMPs: act through SM forces
- Hidden Sector: act through new force, very weakly coupled to SM
- Thermal contact in early universe

Beyond WIMPS: novel, low-cost, search techniques

US Cosmic Visions Report, 1707.04591

Neutrino masses and oscillations

Neutrino Physics

Fundamental Questions addressed by Diverse Neutrino Program

- What is the origin of neutrino mass?
- How are the neutrino masses ordered?
  - *Oscillation experiments*
- What is the absolute neutrino mass scale?
  - *Beta-decay spectrum*
  - *Cosmic surveys*
- Do neutrinos and anti-neutrinos oscillate differently?
  - *Oscillation experiments*
- Are there additional neutrino types and interactions?
  - *Oscillation experiments*
  - *Cosmic surveys*
- Are neutrinos their own anti-particles?
  - *Neutrinoless double-beta decay*

Neutrino masses and oscillations

My conclusion

A data-driven subject in which theorists have not played the major role.

So far no real illumination came from leptons to be combined with the quark sector for a more complete theory of flavour

The trouble is that I do not see how this could change!

More general questions

More general questions

- Why three families

More general questions

- Why three families
- Why so many mass scales

More general questions

- Why three families
- Why so many mass scales
- Hierarchy and fine tuning

More general questions

- Why three families
- Why so many mass scales
- Hierarchy and fine tuning
- Unification

More general questions

- Why three families
- Why so many mass scales
- Hierarchy and fine tuning
- Unification
- Quantum gravity

More general questions

- Why three families
- Why so many mass scales
- Hierarchy and fine tuning
- Unification
- Quantum gravity
- Many others you can add

Conclusions

Conclusions

- No coherent picture emerges

Conclusions

- No coherent picture emerges
- The easy answer: We need more data

Conclusions

- No coherent picture emerges
- The easy answer: We need more data
- The problem: We do not know which kind of data

Conclusions

- No coherent picture emerges
- The easy answer: We need more data
- The problem: We do not know which kind of data
- My conclusion: I will not learn the answer

Conclusions

- No coherent picture emerges
- The easy answer: We need more data
- The problem: We do not know which kind of data
- My conclusion: I will not learn the answer
- We have a very successful Standard Theory and we will leave the problem of its completion to the younger generation