Future of Particle Physics

Pierre Binétruy

Memorial Conference

APC-Paris, May 2018

Jean Iliopoulos

ENS Paris

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- Several articles in which he had collaborated appeared even after his death

Closed trapping horizons without singularity

Pierre Binétruy[1], Alexis Helou[1,2], Frédéric Lamy[1*]

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Cedex 13, France
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Theresienstr. 37, 80333 München, Germany

April 10, 2018

We dedicate this article to the memory of Pierre Binétruy, who passed away on April 1, 2017. He was our guide in the journey through the darkest regions of the Universe.

Abstract

In gravitational collapse leading to black hole formation, trapping horizons typically develop inside the contracting matter. Classically, an ingoing trapping horizon moves towards the centre where it reaches a curvature singularity, while an outgoing horizon moves towards the surface of the star where it becomes an isolated, null horizon. However, strong quantum effects at high curvature close to the centre could modify the classical picture substantially, e.g. by deflecting the ingoing horizon to larger radii, until it eventually reunites with the outgoing horizon. We here analyse some existing models of regular "black holes" of finite lifespan formed out of ingoing null shells collapsing from $\mathscr{I}^-$, after giving general conditions for the existence of (singularity-free) closed trapping horizons. We study the energy-momentum tensor of such models by solving Einstein's equations in reverse and give an explicit form of the metric to model a Hawking radiation reaching $\mathscr{I}^+$. A major flaw of the models aiming at describing the formation of black holes (with a Vaidya limit on $\mathscr{I}^-$) as well as their evaporation is finally exhibited: they necessarily violate the null energy condition up to $\mathscr{I}^-$, i.e. in a non-compact region of spacetime.

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Universality in generalized models of inflation.

P. Binétruy[a,b,1,2], J. Mabillard[c,3], M. Pieroni[a,b,4].

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[c] *School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3JZ, United Kingdom*

Abstract

We discuss the cosmological evolution of a scalar field with non standard kinetic term in terms of a Renormalization Group Equation (RGE). In this framework inflation corresponds to the slow evolution in a neighborhood of a fixed point and universality classes for inflationary models naturally arise. Using some examples we show the application of the formalism. The predicted values for the speed of sound c_s^2 and for the amount of non-Gaussianities produced in these models are discussed. In particular, we show that it is possible to introduce models with $c_s^2 \neq 1$ that can be in agreement with present cosmological observations.

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Primordial gravitational waves for universality classes of pseudoscalar inflation.

Valerie Domcke[1], Mauro Pieroni[2], Pierre Binétruy[3]

AstroParticule et Cosmologie (APC)/Paris Centre for Cosmological Physics, Université Paris Diderot, CNRS, CEA, Observatoire de Paris, Sorbonne Paris Cité University.

arXiv:1603.01287v2 [astro-ph.CO] 26 Sep 2016

Abstract

Current bounds from the polarization of the CMB predict the scale-invariant gravitational wave (GW) background of inflation to be out of reach for upcoming GW interferometers. This prospect dramatically changes if the inflaton is a pseudoscalar, in which case its generic coupling to any abelian gauge field provides a new source of GWs, directly related to the dynamics of inflation. This opens up new ways of probing the scalar potential responsible for cosmic inflation. Dividing inflation models into universality classes, we analyze the possible observational signatures. One of the most promising scenarios is Starobinsky inflation, which may lead to observational signatures both in direct GW detection as well as in upcoming CMB detectors. In this case, the complementarity between the CMB and direct GW detection, as well as the possibility of a multi-frequency analysis with upcoming ground and space based GW interferometers, may provide a first clue to the microphysics of inflation.

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THE STANDARD MODEL

$\cdots$ and BEYOND

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- It is no more The Standard Model

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- But **The Standard Theory**

THE STANDARD THEORY

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- 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:

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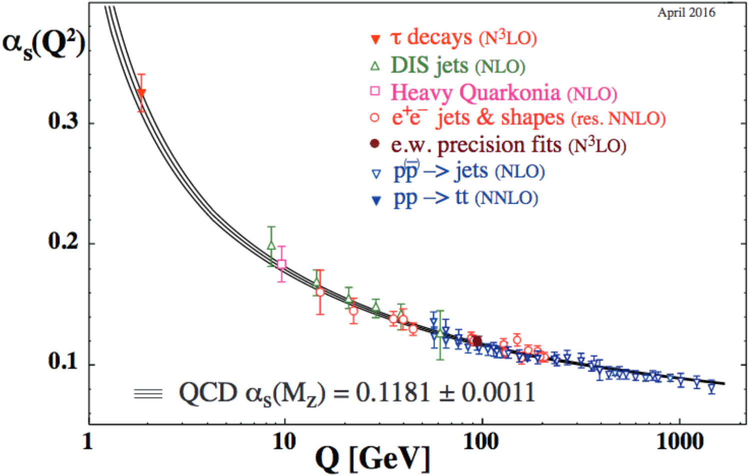
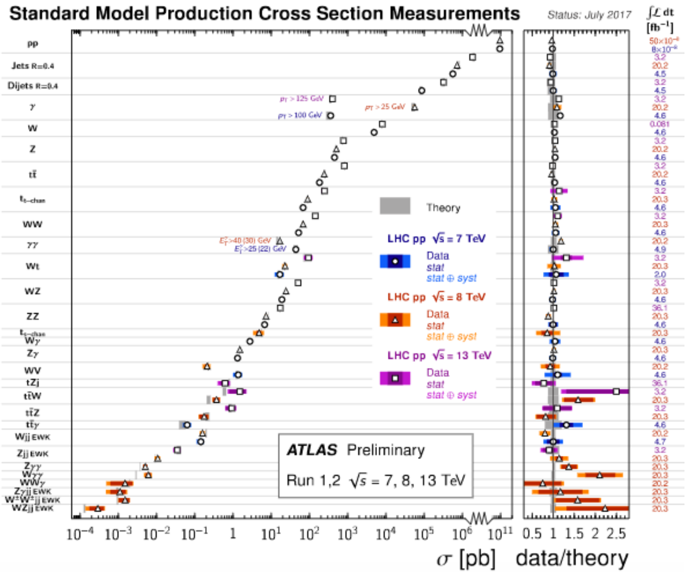
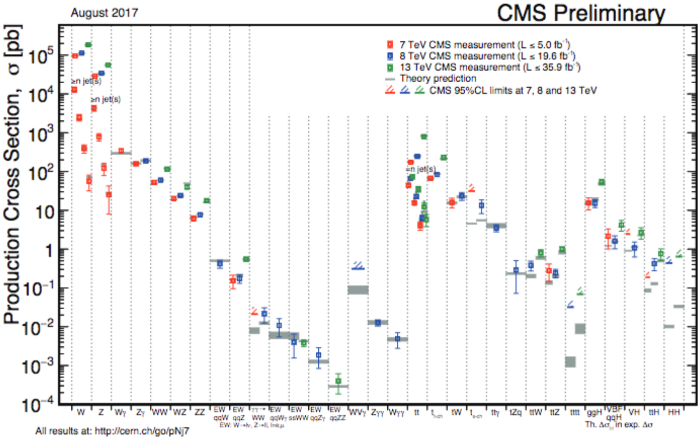
- The discovery of *b* and *t* flavours (FermiLab, LEP)
- The discovery of the BEH boson (CERN 2012)

THE STANDARD THEORY

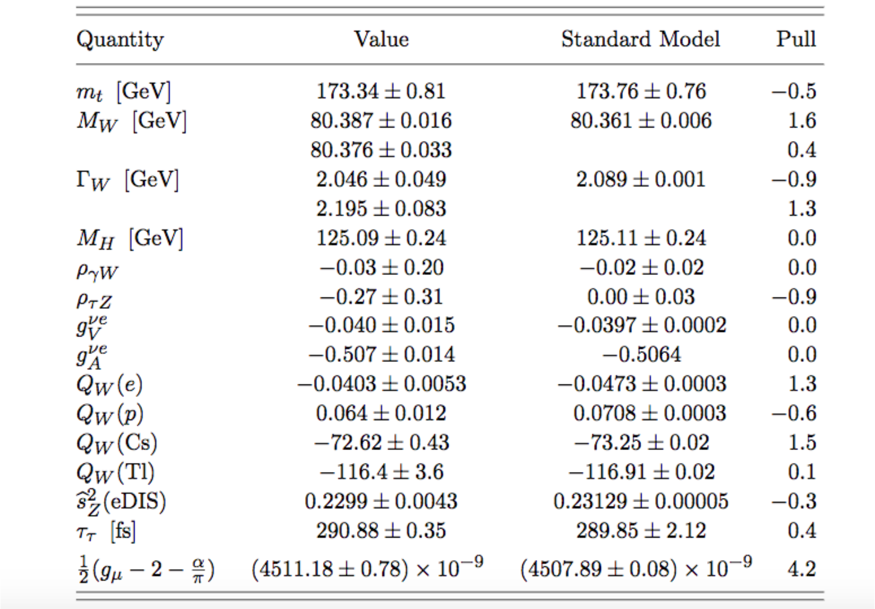
In addition, it shows an impressive agreement with experiment in a very large number of detailed measurements.


April 2016
$\alpha_s(Q^2)$
▼ τ decays (N^{3}LO)
△ DIS jets (NLO)
□ Heavy Quarkonia (NLO)
○ e^+e^- jets & shapes (res. NNLO)
● e.w. precision fits (N^{3}LO)
▽ $p\overset{(-)}{p}$ –> 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]

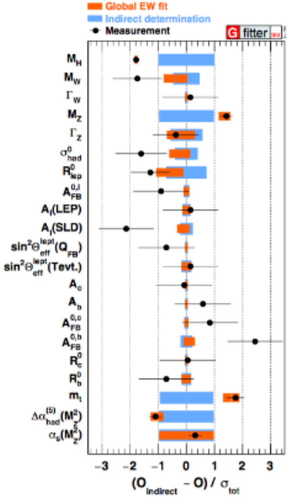

Standard Model Production Cross Section Measurements
Status: July 2017
∫ℒ dt [fb⁻¹]
pp
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t_t-chan
WW
γγ
Wt
WZ
ZZ
t_s-chan
Wγ
Zγ
WV
tZj
tt̄W
tt̄Z
tt̄γ
Wjj EWK
Zjj EWK
Zγγ
Wγγ
WWγ
Zγjj EWK
W±W±jj EWK
WZjj EWK
p_T > 125 GeV
p_T > 100 GeV
p_T > 25 GeV
E_T^γ > 40 (30) GeV
E_T^γ > 25 (22) GeV
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
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1 1.5 2 2.5
data/theory
50×10⁻⁸
8×10⁻⁸
3.2
20.2
4.5
3.2
4.5
3.2
20.2
4.6
0.081
4.6
3.2
20.2
4.6
3.2
20.2
4.6
3.2
20.3
4.6
3.2
20.3
4.6
20.2
4.9
3.2
20.3
2.0
3.2
20.3
4.6
36.1
20.3
4.6
20.3
4.6
20.3
4.6
20.2
4.6
36.1
3.2
20.3
3.2
20.3
4.6
20.2
4.7
3.2
20.3
20.3
20.3
20.2
20.3
20.3
20.3


August 2017
CMS Preliminary
Production Cross Section, σ [pb]
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
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)
≥n jet(s)
≥n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→WW
EW qqWγ
EW ssWW
EW qqZγ
EW qqZZ
EW: W→lν, Z→ll, l=e,μ
WVγ
Zγγ
Wγγ
tt
$t_{t\text{-}ch}$
tW
$t_{s\text{-}ch}$
ttγ
tZq
ttW
ttZ
tttt
ggH
VBF qqH
VH
ttH
HH
Th. $\Delta\sigma_H$ in exp. $\Delta\sigma$
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

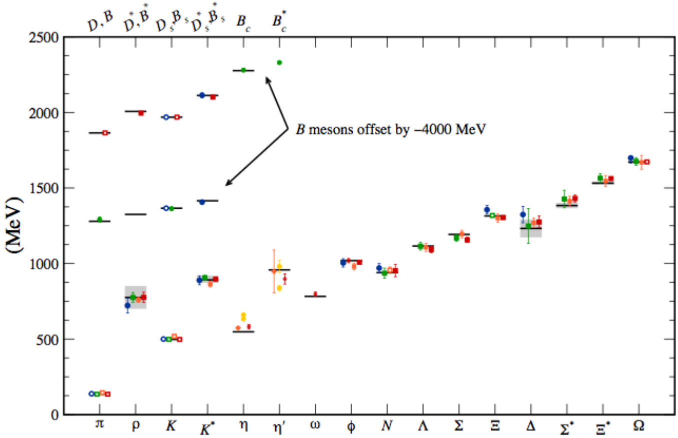


Quantity	Value	Standard Model	Pull
m_t [GeV]	173.34 ± 0.81	173.76 ± 0.76	-0.5
M_W [GeV]	80.387 ± 0.016	80.361 ± 0.006	1.6
	80.376 ± 0.033		0.4
Γ_W [GeV]	2.046 ± 0.049	2.089 ± 0.001	-0.9
	2.195 ± 0.083		1.3
M_H [GeV]	125.09 ± 0.24	125.11 ± 0.24	0.0
$\rho_{\gamma W}$	-0.03 ± 0.20	-0.02 ± 0.02	0.0
$\rho_{\tau Z}$	-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

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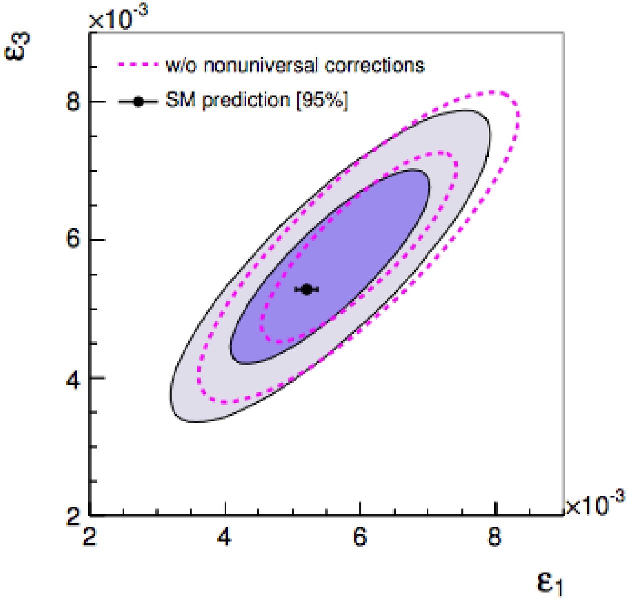
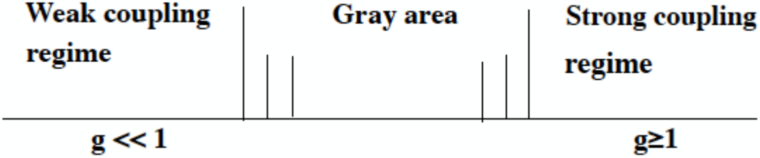
- For the first time we check weak interactions at the level of radiative corrections

- The Standard Theory has become a **high precision theory**



w/o nonuniversal corrections
SM prediction [95%]
ε_3
$\times10^{-3}$
8
6
4
2
2
4
6
8
$\times10^{-3}$
ε_1

The ST is a renormalisable Quantum Field Theory



Weak coupling regime

Gray area

Strong coupling regime

$g \ll 1$

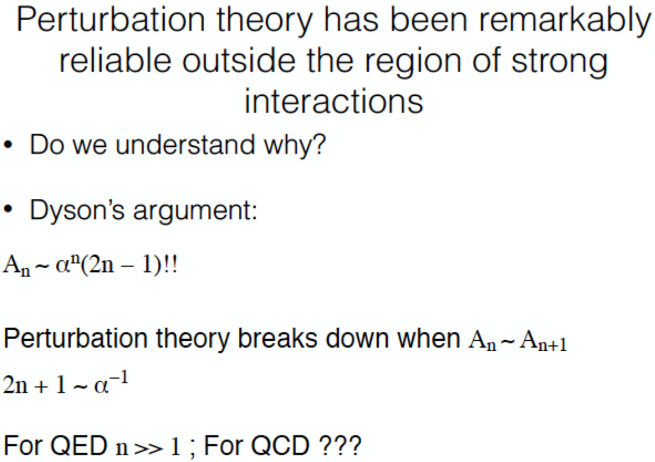
$g \geq 1$

Perturbation expansions

???

Strong coupling expansions

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?

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

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- I. General questions

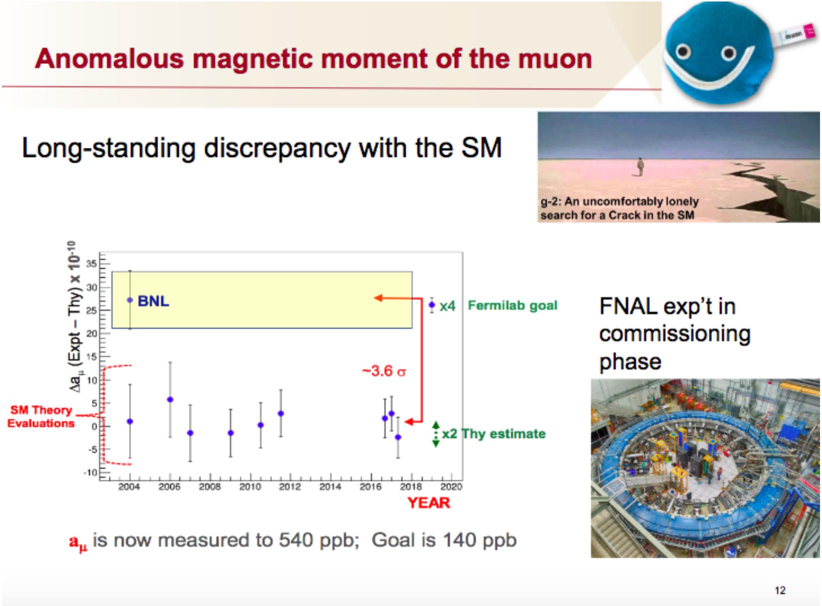
- Given this impressive success...
  What does Beyond mean?

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

- I. General questions

- II. Specific points

High precision measurements



Anomalous magnetic moment of the muon

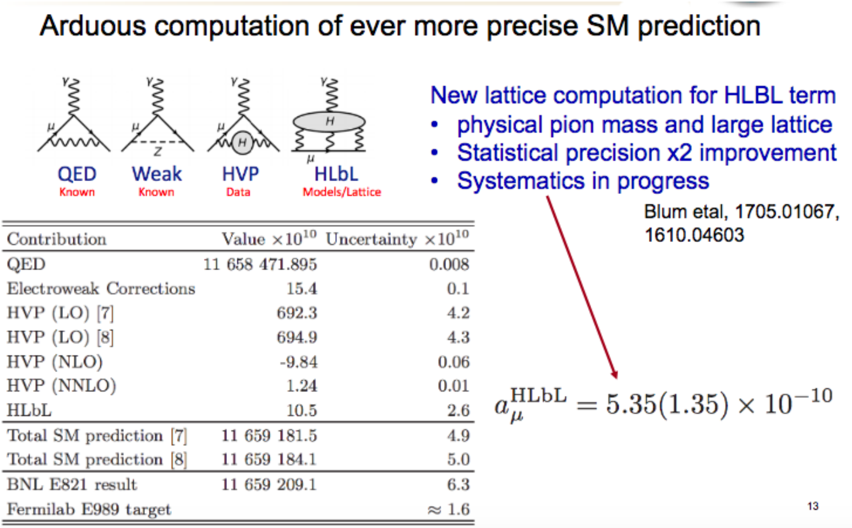
Long-standing discrepancy with the SM

g-2: An uncomfortably lonely search for a Crack in 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

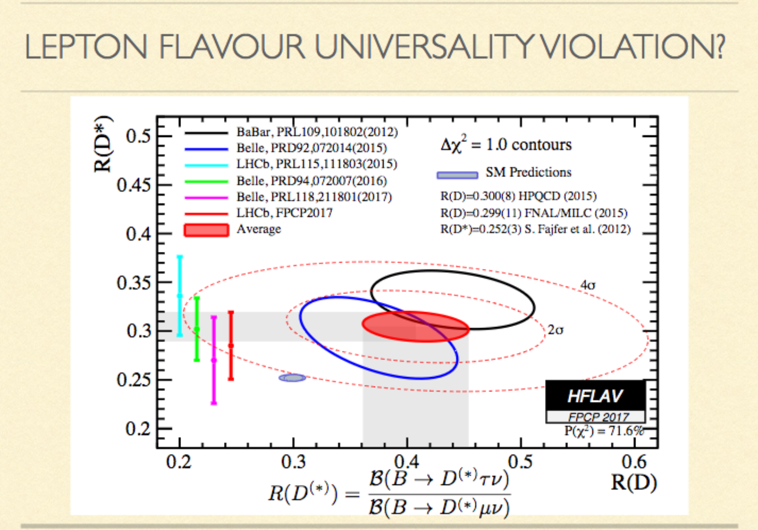
- physical pion mass and large lattice
- Statistical precision x2 improvement
- Systematics in progress

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

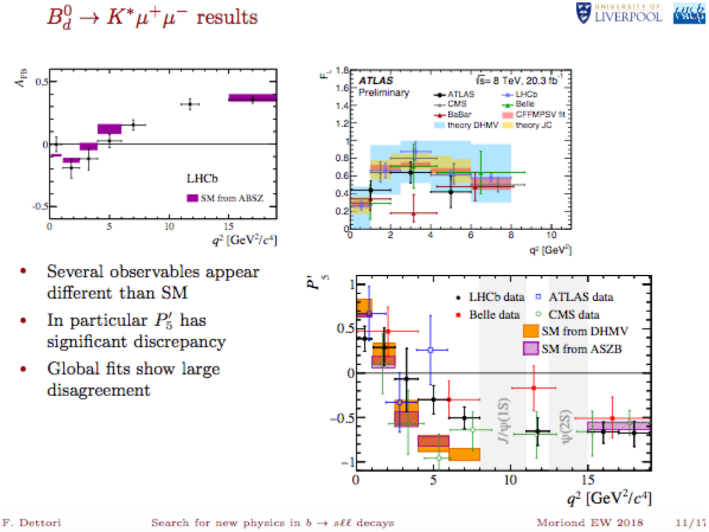


LEPTON FLAVOUR UNIVERSALITY VIOLATION?

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

Heavy flavour decays

Flavour changing neutral currents

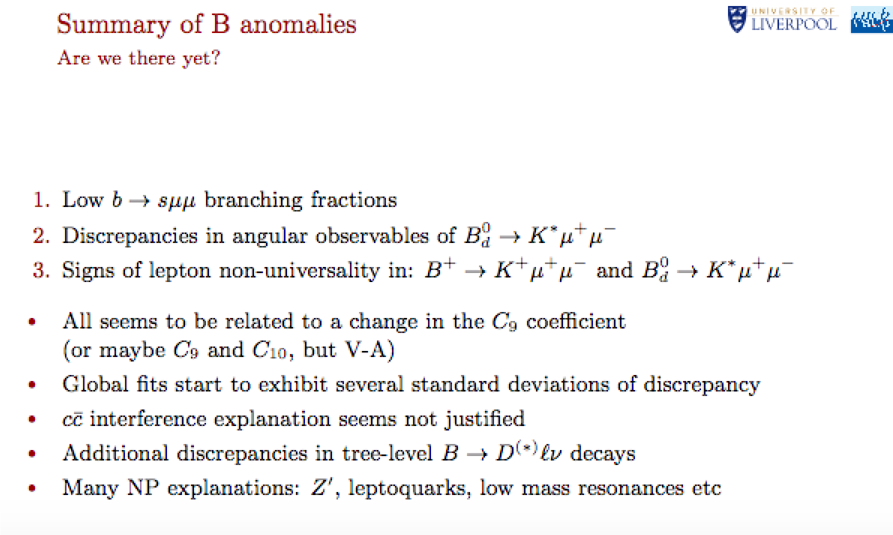


$B_d^0 \to K^* \mu^+ \mu^-$ results

- Several observables appear different than SM
- In particular P'_5 has significant discrepancy
- Global fits show large disagreement

F. Dettori   Search for new physics in $b \to s\ell\ell$ decays   Moriond EW 2018   11/1

Heavy flavour decays



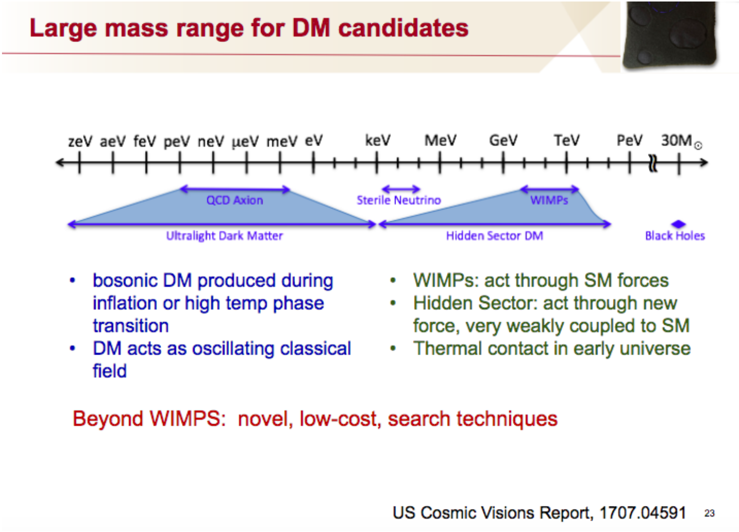
Summary of B anomalies

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

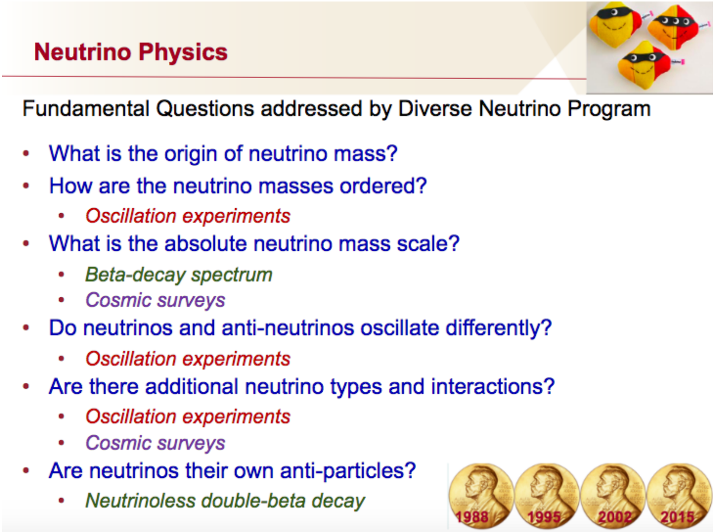
- bosonic DM produced during inflation or high temp phase transition
- DM acts as oscillating classical field

- 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.

• Substantial improvement in precision could be expected during the coming years.

• The significance of such improvements is not easy to judge.

• So far no real illumination came from leptons to be combined with the quark sector for a more complete theory of flavour *(see P. Ramond's talk)*

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

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- Many others you can add

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  But we see no corner
- The easy answer: We need more data
- Two problems: (i) We do not know what kind of data
  (ii) They will not come for quite a long time
- A rather frustrating problem!

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- The Future of Particle Physics will undoubtedly be bright, but....
- 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.....
- But now, they must do it without Pierre