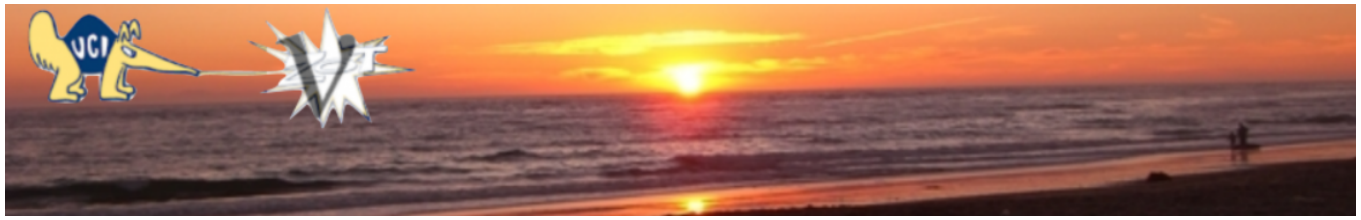
# Flavor/Precision WG Theory Summary

**We-Fu Chang**

國立清華大學
NATIONAL TSING HUA UNIVERSITY

WIN2017, U.C.Irvine, June 24, 2017

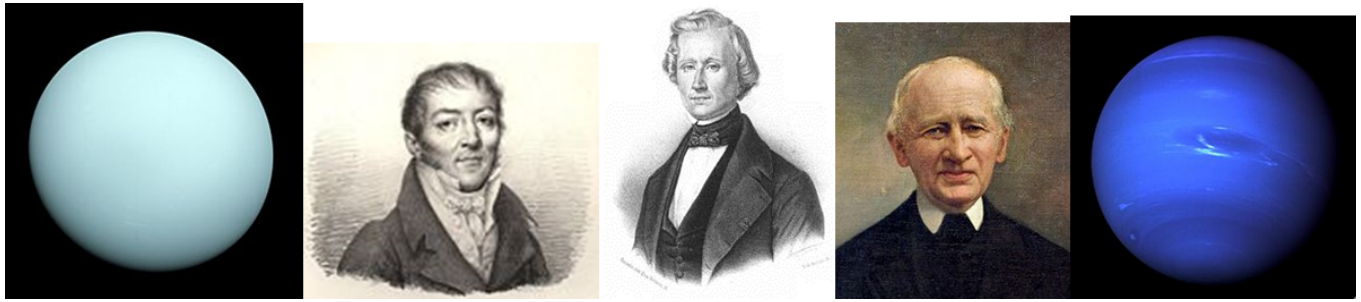


# Flavor

- Flavor: the mismatch between the mass and interaction basis.
- The pattern of masses and mixings of SM particles are a total mystery.
- Need new physics BSM ($m_\nu$, DM, DE, CPV)
- High scale to suppress the BSM FCNC (e.g. $c/\Lambda^2 < 10^{-5}/(\text{TeV})^2$ for $(\bar{s}_L\gamma^\mu d_L)^2$ from $\Delta m_K, \epsilon_K$)
- TeV New Phys. must have special flavor structure.
- No sign of any other new particles at LHC yet.
- Indirect probe BSM from precision tests?

# A classic example: discovery of Neptune

- Some deviation of the Uranus orbit.
- Alexis Bouvard suggested it's due to gravitational perturbation from an outer planet.
- Urbain Le Verrier calculated the orbit of the yet unknown planet.
- Neptune was observed by Johann Gottfried Galle within $1^o$ at the predicted position.



- anomalies $\Rightarrow$ Model builder $\Rightarrow$ 4-loop calculation $\Rightarrow$ experimentalists $\Rightarrow$ discovery
- Good because (1) Newtonian gravity is complete, just adding a new particle (2) perturbation is valid

# Some modern textbook examples

- GIM and charm form $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K^+ \to \mu^+\nu)$
- $m_c$ from $\triangle m_K$.
- $m_t$ from $\triangle m_B$.
- $m_t$ from $T, \epsilon_1$ parameter.
- Not sure for BSM because (1) SM is not complete (2) perturbative + non-perturbative
- (1a) Usually not a problem, just place an order to the model builders they will deliver it for free.
- (1b) maybe something totally new (Newtonian gravity $\Rightarrow$ GR )
- (2) QCD is intrinsically hard.

# Beautiful Models!

The model builders are good!
Just place your order(any) they will deliver the models to you for free in a few weeks/months.

Model builders receiving an order.

v.s.

Experimentalist listening to the talks.

I will simply flash most of the models.

# Main themes in WIN2017

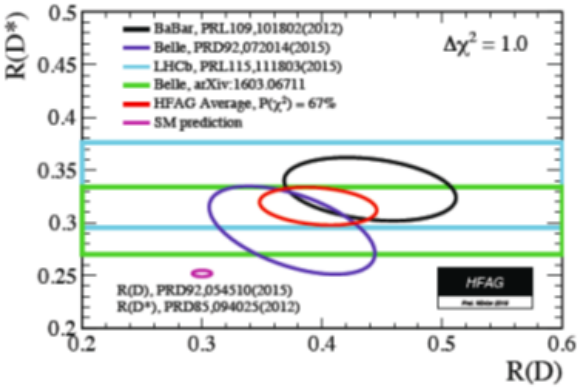
- B Anomalies: B. Grinstein, A. Datta, X.G. He
- proton radius: G. Paz(review), Y.S. Liu
- EW precision: J. Erler(review)
- model building/EFT analysis: XG He(review)
- CLFV, g-2, neutrino mixing pattern, 17MeV: I. Galon, Y.Uesaka, Jurciukonics, XG He, M. Platscher

# B anomalies

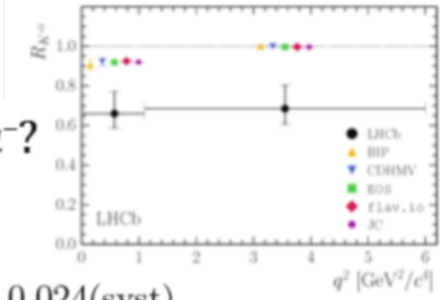
"$R_{D^{(*)}}$ anomaly"

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

Excesses observed at more than $4\sigma$




Is there NP in $B$ decays to $K^{(*)}\mu^+\mu^-$?




$$R_{K^*} = \frac{\mathrm{Br}(B \to K^*\mu\mu)}{\mathrm{Br}(B \to K^*ee)}$$

$$\langle R_{K^*}\rangle_{[0.045,1.1]} = 0.660^{+0.110}_{-0.070}(\mathrm{stat}) \pm 0.024(\mathrm{syst})$$

$$\langle R_{K^*}\rangle_{[1.1,6]} = 0.685^{+0.113}_{-0.069}(\mathrm{stat}) \pm 0.047(\mathrm{syst})$$

$$R_K = \left.\frac{\mathrm{Br}(B \to K\mu\mu)}{\mathrm{Br}(B \to Kee)}\right|_{[1,6]}$$

$$\langle R_K\rangle_{[1,6]} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

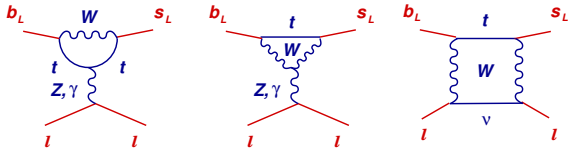
LHCb PRL113(2014)151601

[ B. Grinstein ]

## Why the Excitement on Anomalies in $B$ decays?

Slide for non-specialist

The SM of EW intearctions predicts




$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

- This is same for all lepton flavors: lepton univesality (LU)
- LU violation (LUV) reported by LHCb in $b \to s\mu\mu$ vs $b \to see$
- LUV could arise from new physics (NP):
  - At very short distances, with SM below scale $\Lambda \gg M_W$
  - Short distances at SM scale, $\Lambda \sim M_W$ (*e.g.*, strongly coupled EW symmetry breaking)
  - Long distances: new light particles
- Worse case scenario: $\Lambda \gg M_W$: $NP = \frac{g^2}{\Lambda^2}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$
- Fits of reported LUV require

$$\frac{g^2}{\Lambda^2} \approx 0.25 \times G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)} \quad \Rightarrow \quad \frac{\Lambda}{g} \approx 28 \text{ TeV}$$

- Best argument to build VLHC! (or find NP sooner!!)

## The shape of the new physics

- Assume hereafter: $R_{K,K^*}$ and $P_5'$ are NP
- Stick to SM-EFT

**Simplest example: chiral solution**

$$\delta C_9^\mu = -\delta C_{10}^\mu = -0.5$$
$$\delta C_9^e = \delta C_{10}^e = 0$$

Hiller and Schmaltz'14, Straub *et al*'14'15, Ghosh *et al*'14,...

- Only 2 dim-6 $SU(2)_L \times U(1)_Y$-invariant operators

$$Q_{\ell q}^{(1)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^\mu q_L)(\bar{\ell}_L \gamma_\mu \ell_L) \qquad Q_{\ell q}^{(3)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^\mu \vec{\tau} q_L)\cdot(\bar{\ell}_L \gamma_\mu \vec{\tau} \ell_L)$$

1. **Lepton Universality Violation $\Rightarrow$ Lepton flavor Violation**?
2. **Operators with $SU(2)_L$ quark doublets $\Rightarrow$ new correlations,** *i.e.*,**:**
   - FCNC with neutrinos and/or up quarks
   - $V-A$ Contributions CC ($b \to c\ell\bar{\nu}$, $t \to b\bar{\ell}\nu\ldots$)

## Survey of leptoquark models

- **Scalar** LQ

$$\mathcal{L}_\Delta = \left(y_{\ell u}\,\bar{\ell}_L\,u_R + y_{eq}\,\bar{e}_R\,i\tau_2\,q_L\right)\Delta_{-7/6}$$
$$+ y_{\ell d}\,\bar{\ell}_L\,d_R\,\Delta_{-1/6} + \left(y_{\ell q}\,\bar{\ell}^c_L i\tau_2\,q_L + y_{eu}\bar{e}^c_R\,u_R\right)\Delta_{1/3}$$
$$+ y_{ed}\,\bar{e}^c_R\,d_R\,\Delta_{4/3} + y'_{\ell q}\,\bar{\ell}^c_L i\tau_2\vec{\tau}q_L\cdot\vec{\Delta}'_{1/3}$$

- **Vector** LQ

$$\mathcal{L}_V = \left(g_{\ell q}\,\bar{\ell}_L\gamma_\mu q_L + g_{ed}\,\bar{e}_R\gamma_\mu d_R\right)V^\mu_{-2/3}$$
$$+ g_{eu}\,\bar{e}_R\gamma_\mu u_R\,V^\mu_{5/3} + g'_{\ell q}\,\bar{\ell}_L\gamma_\mu\vec{\tau}q_L\cdot\vec{V}'^\mu_{-2/3}$$
$$+ \left(g_{\ell d}\,\bar{\ell}_L\gamma_\mu d^c_R + g_{eq}\,\bar{e}_R\gamma_\mu q^c_L\right)V^\mu_{-5/6} + g_{\ell u}\,\bar{\ell}_L\gamma_\mu u^c_R\,V^\mu_{1/6}$$

Büchmuller and Wyler'87, Davidson *et al.*'94,...

- Assume $M_{LQ} \gg v$: Only $\vec{\Delta}'_{1/3}$, $V^\mu_{-2/3}$, $\vec{V}^\mu_{-2/3}$ can work.
  - (x)MSSM? Only $\Delta_{1/6}$, the doublet squark (with R-parity breakaing); does not work.

| LQ | $C_9$ | $C_{10}$ | $C'_9$ | $C'_{10}$ | $C_S$ | $C_\nu$ | $C'_\nu$ |
|---|---|---|---|---|---|---|---|
| $\vec{\Delta}'_{1/3}$ | $y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$ | $-y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$ | 0 | 0 | 0 | $-\frac{1}{2}y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$ | 0 |
| $\Delta_{7/6}$ | $-\frac{1}{2}y^{\alpha i,A}_{eq}(y^{\beta j,A}_{eq})^*$ | $-\frac{1}{2}y^{\alpha i,A}_{eq}(y^{\beta j,A}_{eq})^*$ | 0 | 0 | 0 | 0 | 0 |
| $\Delta_{1/6}$ | 0 | 0 | $-\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$ | $\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$ | 0 | 0 | $-\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$ |
| $\Delta_{4/3}$ | 0 | 0 | $\frac{1}{2}y^{\beta i,A}_{ed}(y^{\alpha j,A}_{ed})^*$ | $\frac{1}{2}y^{\beta i,A}_{ed}(y^{\alpha j,A}_{ed})^*$ | 0 | 0 | 0 |
| $V^\mu_{2/3}$ | $-g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*$ | $g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*$ | $-g^{\alpha i,A}_{ed}(g^{\beta j,A}_{ed})^*$ | $-g^{\alpha i,A}_{ed}(g^{\beta j,A}_{ed})^*$ | $2g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{ed})^*$ | 0 | 0 |
| $\vec{V}^\mu_{2/3}$ | $-g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*$ | $g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*$ | 0 | 0 | 0 | $-2\,g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*$ | 0 |
| $V^\mu_{5/6}$ | $g^{\beta i,A}_{eq}(g^{\alpha j,A}_{eq})^*$ | $g^{\beta i,A}_{eq}(g^{\alpha j,A}_{eq})^*$ | $g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$ | $-g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$ | $2g^{\alpha j,A}_{\ell d}(g^{\beta i,A}_{eq})^*$ | 0 | $g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$ |

- Assume, in addition, MLFV: $B \to K\nu\bar{\nu} \;\Rightarrow\; C_\nu \lesssim 10$, 3rd gen has $\times(m_\tau/m_\mu)^2$

Alonso *et al.* JHEP 1510 (2015) 184

  - Only $V^\mu_{-2/3}$ can work!

## Conclusions

1. EFT approach very efficient method to investigate anomalies
   - Assumptions: New Physics is heavy and EW is linearly realized
   - Constraints between low-energy operators
     - **2** out of **4** independent **scalar** operators and **no tensors** in $d_i \to d_j \ell\ell$
     - $B_q \to \ell\ell$: remove **scalar** operators
2. The $b \to s\ell\ell$ anomalies
   - The $P_5'$ anomaly in $B \to K^* \mu\mu$: prefer NP in $C_9^{(\prime)}$ in $\mu$-sector
   - $R_{K,K^*}$ in $B \to K^{(*)}\ell\ell$: (slightly) prefer NP in $C_{10}$, then $C_9$ (no $C'_{9,10}$)
   - Global fit: $\delta C_9$ and $\delta C_{10}$, attractively chiral: $\delta C_9 = -\delta C_{10}$ $(V-A)\otimes(V-A)$
3. New Physics
   - Heavy/medium/light? $M_{NP} < 50$ TeV; VLHC territory!
   - Does NP come with more/less symmetry? Does it lead to **LFV** vs **MLFV**?
   - Connection to charged current tauonic $B$ decays: The $R_{D^{(*)}}$ anomalies?

With the LHC run2 and Belle II, very exciting times ahead!

## Recent Fits after $R_{K^{(*)}}$

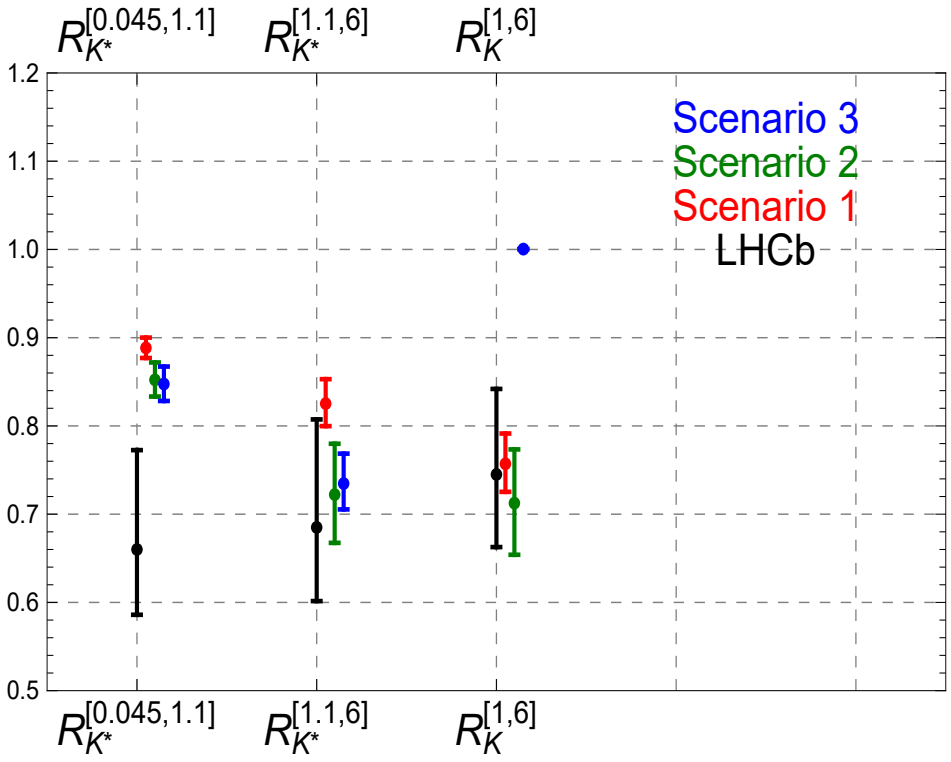
$$R_{K^*}^{\rm expt} = \begin{cases} 0.660^{+0.110}_{-0.070}\ (\text{stat}) \pm 0.024\ (\text{syst})\ , & 0.045 \le q^2 \le 1.1\ \text{GeV}^2\ , \\ 0.685^{+0.113}_{-0.069}\ (\text{stat}) \pm 0.047\ (\text{syst})\ , & 1.1 \le q^2 \le 6.0\ \text{GeV}^2\ . \end{cases}$$

arXiv:1704.07397 : Alok et.al.

| Scenario | WC | pull |
|---|---|---|
| (I) $\Delta C_9^{\mu\mu}(\text{NP})$ | $-1.25 \pm 0.19$ | 5.9 |
| (II) $\Delta C_9^{\mu\mu}(\text{NP}) = -\Delta C_{10}^{\mu\mu}(\text{NP})$ | $-0.68 \pm 0.12$ | 5.9 |
| (III) $\Delta C_9^{\mu\mu}(\text{NP}) = -\Delta C_9^{\prime\mu\mu}(\text{NP})$ | $-1.11 \pm 0.17$ | 5.6 |

Table: Model-independent scenarios: best-fit values of the WCs (taken to be real), as well as the pull $= \sqrt{\chi^2_{SM} - \chi^2_{min}}$ for fit (B) (CP-conserving $b \to s\mu^+\mu^-$ observables + $R_{K^*}$ and $R_K$). For each case there are 115 degrees of freedom.

## Motivating light $Z'$




Question: Can we explain the $R_K$ and $R_{K^{(*)}}$ measurements in all bins with light mediators. I will focus on $M < 200$ MeV mediators.

## $b \to s\ell^+\ell^-$

Case A: The Hamiltonian for $b \to s\ell\ell$ decays,

$$H_{bsll} = -\left[\frac{g^*}{q^2 - m_{Z'}^2}\right]\left[g_{bs}\frac{q^2}{m_B^2}\right]\bar{s}\gamma^\mu P_L b\bar{\ell}\gamma_\mu\ell\,.$$

Assume no NP with electrons. For $q^2 >> m_{Z'}^2$ the $q^2$ dependence cancels and a good fit to all observables except $R_{K^{(*)}}$ in the low $q^2$ bin be explained.

Case B: The Hamiltonian for $b \to s\ell\ell$ decays,

$$H_{bsll} = -\left[\frac{g^*}{q^2 - m_{Z'}^2}\right]\bar{s}\gamma^\mu P_L b\bar{\ell}\gamma_\mu\ell\,.$$

Assume no NP with electrons. The $q^2$ dependence does not cancel and a good fit to all observables cannot be obtained even for $R_{K^{(*)}}$ in the low $q^2$ bin.

## Light Scalars and $Z'$ coupling to electrons: Datta, Marfatia, Kumar, Liao

- Still need to explain low $q^2$, $R_{K^{(*)}}$ measurement.
- $S$ coupling to muons does not work: $R_K$ and $R_{K^{(*)}}$ increased from SM values.
- $Z'$ couplings to muons do not work.
- We have to invoke NP coupling to electrons. $S(Z') \to e^+e^-$.
- We choose the mass of the new boson $\sim$ 25 MeV to avoid branching ratio constraints. ( All measurements have $m_{ee}$ above 30 MeV.)

## Electron couplings are constrained

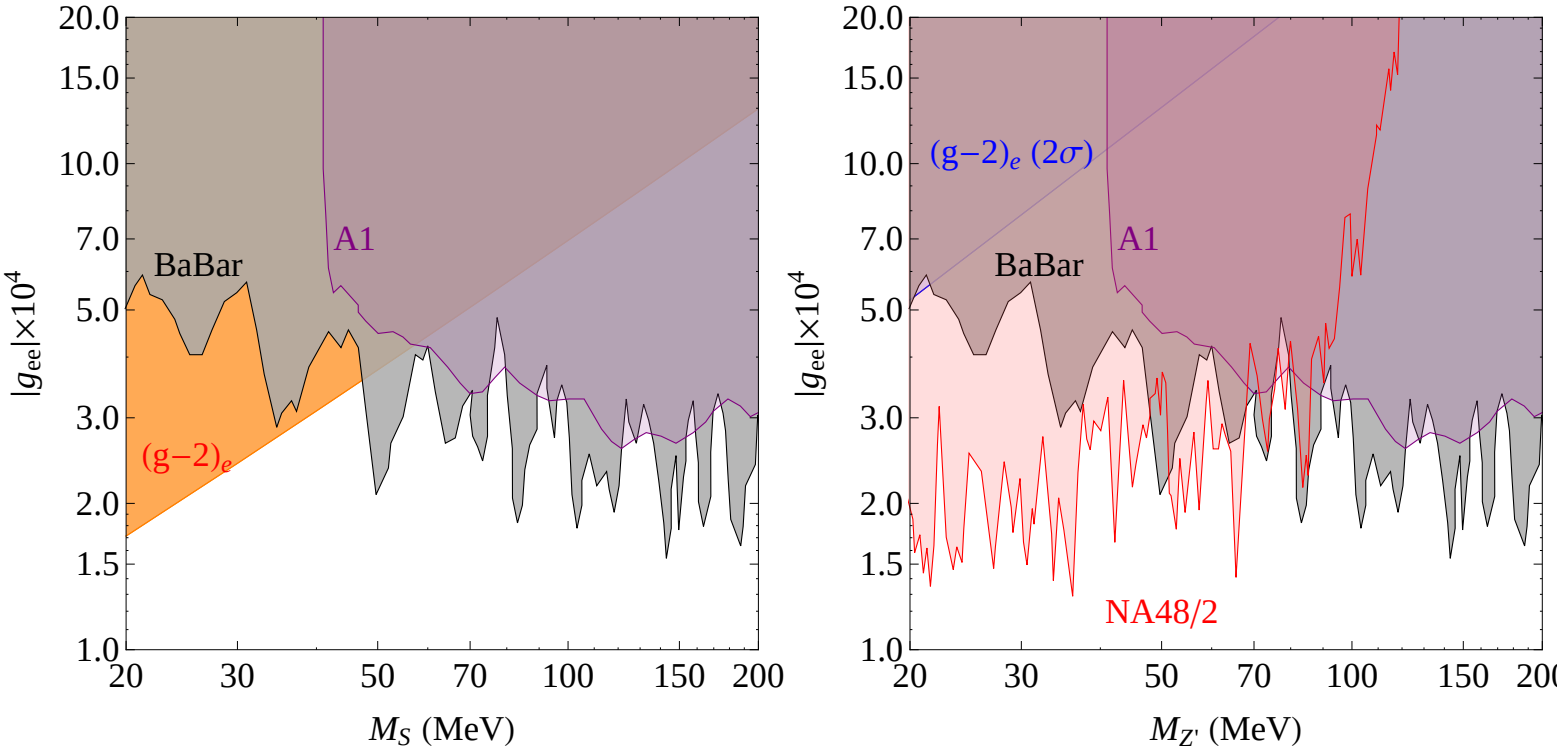



Figure:

# $R(D^{(*)}) + b \to s\mu\mu$ : XG He

- order placed: $R(D^{(*)}) + b \to s\mu\mu$
- delivered model: scalar leptoquark bonus: muon g-2

## Bring $R(D^{(*)})$ and b -> s μμ anomalies together

### A role of a leptoquark scalar

Bauer&Neubert, arXiv: 1511.01900, N. Deshpande&X-G He, arXiv:1608.04817, D. Becirevic et al., Y. Cai et al, arXiv: 1704.05849.

$$L_{int} = \frac{1}{2m_\phi^2}[x_{ij}x_{i'j'}\bar{\nu}_L^{i'}\gamma^\mu\nu_L^i\bar{d}_L^{j'}\gamma_\mu d_L^j + z_{ij}z_{i'j'}\bar{e}_L^{i'}\gamma^\mu e_L^i\bar{u}_L^{j'}\gamma_\mu u_L^j]$$

K-> π νν, B-> K(*) νν  D->μμ, πμμ

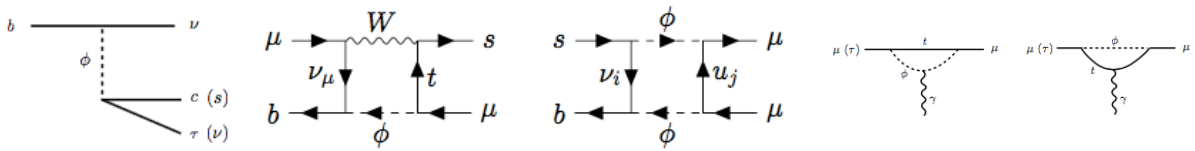
$$-\frac{1}{2m_\phi^2}[x_{ij}z_{i'j'}\bar{\nu}_L^{i'}\gamma^\mu e_L^i\bar{d}_L^{j'}\gamma_\mu u_L^j - x_{ij}z_{i'j'}\bar{e}_L^{i'}\gamma^\mu\nu_L^i\bar{u}_L^{j'}\gamma_\mu d_L^j]$$

R(D(*)), B->D(*) (ρ,π) lν, $B_c$ -> τ ν

$$+\frac{1}{2m_\phi^2}[y_{ij}y_{i'j'}\bar{e}_R^{i'}\gamma^\mu e_R^i\bar{u}_R^{j'}\gamma_\mu u_R^j + x_{ij}y_{i'j'}(\bar{e}_R^{i'}\nu_L^i\bar{u}_R^{j'}\gamma_\mu d_L^j - \frac{1}{2}\bar{e}_R^i\sigma_{\mu\nu}\nu_L^{i'}\bar{u}_R^{j'}\sigma_{\mu\nu}d_L^j)]$$

D->μμ, π μμ  R(D(*)), B->D(*) (ρ,π) lν, $B_c$ -> τ ν

One loop contributions for b -> s μμ

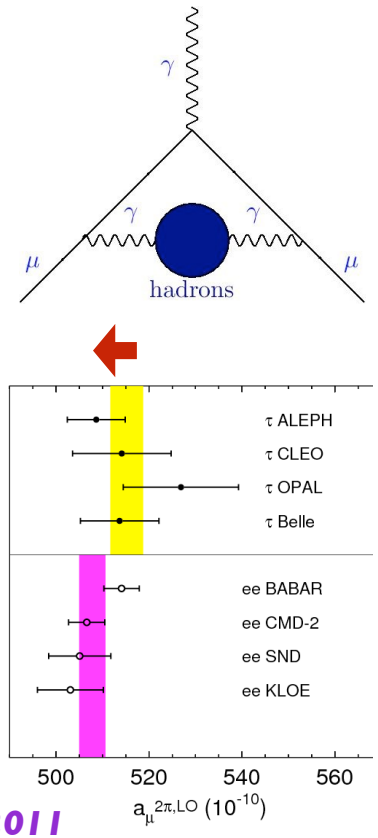



Significant contribution needed from $\bar{e}_R Y U_R^c \phi$ coupling! Can also solve (g-2)μ anomaly!

light-by-light and vacuum polarization under control

# $g_\mu - 2$

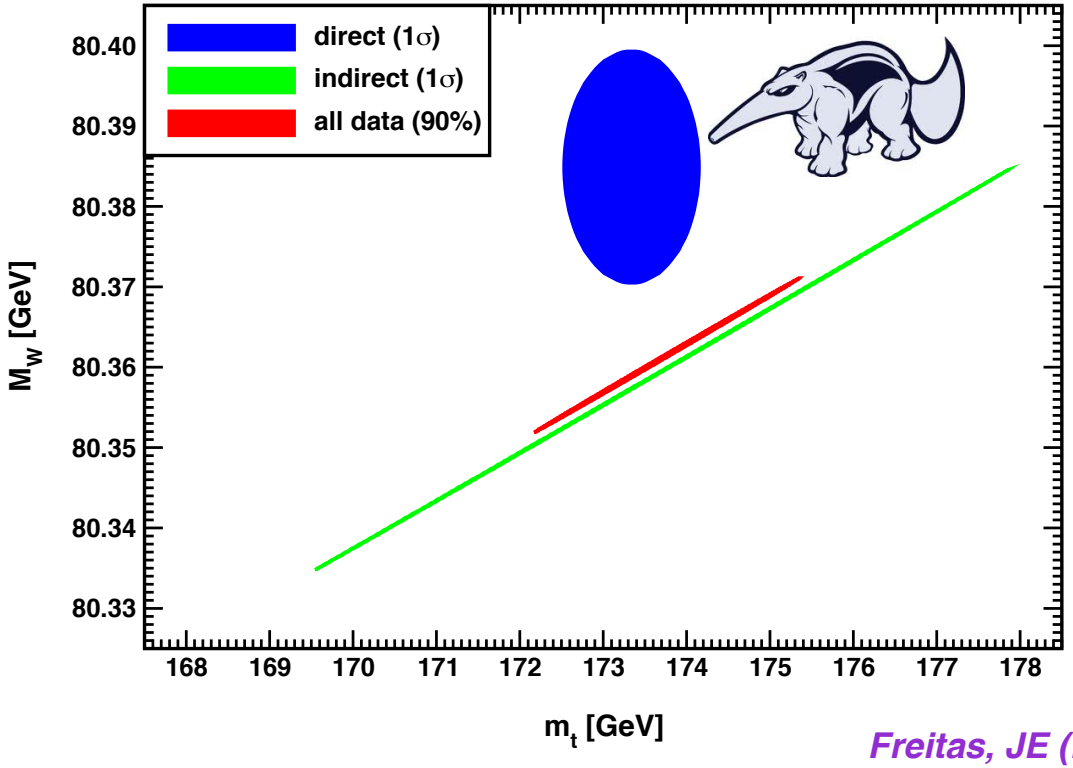
- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ ***BNL-E821 2004***
- SM: $a_\mu = (1165918.21 \pm 0.48)\times 10^{-9}$
- 4.2 $\sigma$ deviation
- hadronic vacuum polarization
  - consistency between exp. $B(\tau^- \to \nu\, \pi^0\, \pi^-)$ and prediction from $e^+e^-$ and CVC after accounting for $\gamma$-$\rho$ mixing ***Jegerlehner, Szafron 2011***
  - 1.9 $\sigma$ conflict between *KLOE* and *BaBar*




***Davier et al. 2011***

- precision inputs: $\alpha$(Ry), $G_F$($\mu$ decay), $M_Z$, $M_H$,$\alpha_s$ (Z)

## $M_W$ — $m_t$




*Freitas, JE (PDG 2016)*

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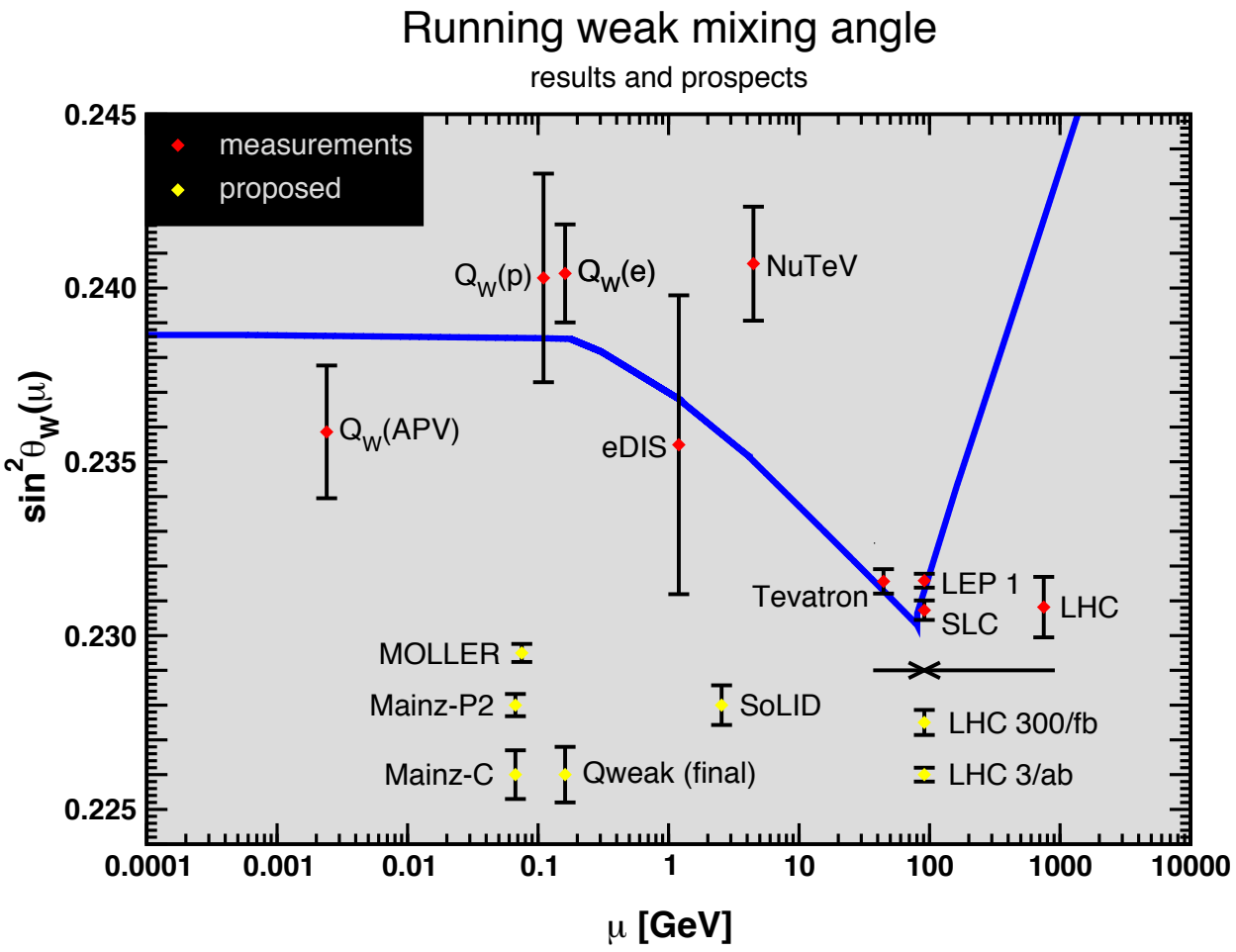
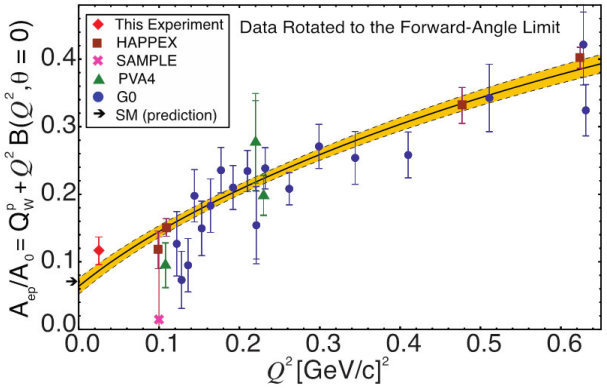
# EW precision J. Erler



# Polarized elastic scattering

- $A_{LR} \propto Q_W(p) + Q^2 B(Q^2, \theta)$
- Qweak (Jefferson Lab):
  - $Q^2 = 0.025$ GeV$^2$
  - extrapolation to $Q^2 = 0$
  - large γ-Z box ***Gorchtein, Horowitz, Ramsey-Musolf; Rislow, Carlson; Hall, Blunden, Melnitchouk, Thomas, Young***




- P2 (JGU Mainz): $Q^2 = 0.0045$ GeV$^2$ ($A_{LR} \sim 10^{-8}$)
  - γ-Z box correction (error) factor of 8 (5) smaller

Both $M_W$ and $\sin^2\theta_W$ are sensitive to all kind of New Phys.

# Conclusions

- SM almost 50 but in remarkable health: making us theorists sick
- SM over-constrained: derived quantities like $M_W$, $\sin^2\theta_W$, $g_\mu$–2 and weak charges computed and measured
- indirect $M_H$: 1.7 σ below direct (need precision and consistency in $m_t$)
- ρ-parameter: 1.9 σ high in SM + ρ fit (S = U = 0)
- Contact interactions: compare $\sin^2\theta_W$ at low $Q^2$ with Z-pole and test $\Lambda_{new}$ up to 50 TeV (in strong coupling case)
- **keep sniffing**

## Conclusions

- Proton radius puzzle: $> 5\sigma$ discrepancy between
  - $r_E^p$ from muonic hydrogen
  - $r_E^p$ from hydrogen and $e - p$ scattering

- Recent muonic deuterium results find similar discrepancies
  [Pohl et al. Science **353**, 669 (2016)]

- After more than 6 years the origin is still not clear

1) Is it a problem with the electronic extraction?
2) Is it a hadronic uncertainty?
3) is it new physics?

- Motivates a reevaluation of our understanding of the proton

## The bottom line

- Scattering:
  - World $e-p$ data [Lee, Arrington, Hill '15]
    $r_E^p = 0.918 \pm 0.024$ fm
  - Mainz $e-p$ data [Lee, Arrington, Hill '15]
    $r_E^p = 0.895 \pm 0.020$ fm
  - Proton, neutron and $\pi$ data [Hill , GP '10]
    $r_E^p = 0.871 \pm 0.009 \pm 0.002 \pm 0.002\,\mathrm{fm}$

- Muonic hydrogen
  - [Pohl et al. Nature **466**, 213 (2010)]
    $r_E^p = 0.84184(67)$ fm
  - [Antognini et al. Science **339**, 417 (2013)]
    $r_E^p = 0.84087(39)$ fm

- The bottom line:
  using $z$ expansion scattering disfavors muonic hydrogen

- Is there a problem with muonic hydrogen *theory*?

## Muonic hydrogen theory

- Is there a problem with muonic hydrogen *theory*?
- Potentially yes!
  [Hill, GP PRL **107** 160402 (2011)]
- Muonic hydrogen measures $\Delta E$ and translates it to $r_E^p$

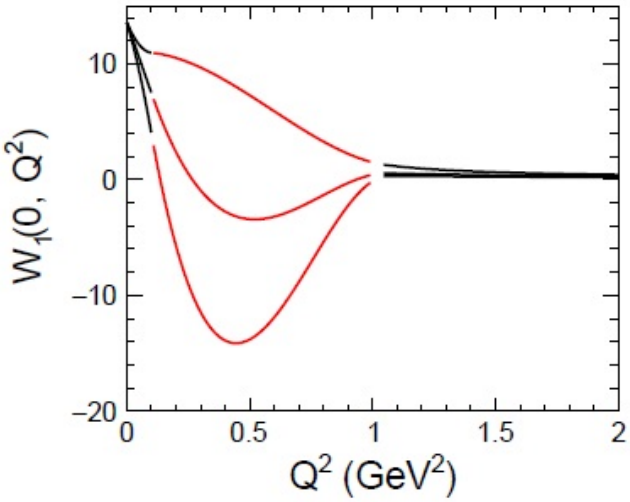
- [Pohl et al. Nature **466**, 213 (2010) Supplementary information]
  $\Delta E = 206.0573(45) - 5.2262(r_E^p)^2 + 0.0347(r_E^p)^3$ meV

- [Antognini et al. Science **339**, 417 (2013), Ann. of Phy. **331**, 127]
  $\Delta E = 206.0336(15) - 5.2275(10)(r_E^p)^2 + 0.0332(20)$ meV

- Apart from $r_E^p$ we need also the two-photon exchange
- Notice the change in the *theoretical* prediction
- Potential source of hadronic uncertainty

## Two Photon Exchange: Modeling

- "Aggressive" modeling: use OPE for $Q^2 \geq 1$ GeV$^2$
- Model unknown $Q^4$: add $\Delta_L(Q^2) = \pm Q^2/\Lambda_L^2$ with $\Lambda_L \approx 500$ MeV
- Model unknown $1/Q^4$: add $\Delta_H(Q^2) = \pm \Lambda_H^2/Q^2$ with $\Lambda_H \approx 500$ MeV
- Interpolating:




- Energy contribution: $\delta E(2S)^{W_1(0,Q^2)} \in [-0.046\,\text{meV},\ -0.021\,\text{meV}]$
  To explain the puzzle need this to be $\sim -0.3$ meV
- Caveats: OPE might be only valid for larger $Q^2$
  $W_1(0, Q^2)$ might be different than the interpolated lines

# proton radius puzzle: Gil Paz

- How to test?
- New experiment: $\mu - p$ scattering
  MUSE (MUon proton Scattering Experiment) at PSI
  [R. Gilman et al. (MUSE Collaboration), arXiv:1303.2160]

## Connecting muon-proton scattering to muonic hydrogen

- Matching

| | |
|---|---|
| QED, QCD | $G_{E,M}$, Structure func., $W_1(0, Q^2)$ |
| Scale: $m_p \sim 1$ GeV | $\Downarrow$ |
| QED-NRQED: *MUSE* | $r_E^p$, $\bar{\mu}\gamma^0\mu\psi_p^\dagger\psi_p$ |
| Scale: $m_\mu \sim 0.1$ GeV | $\Downarrow$ |
| NRQED-NRQED: *muonic H* | $r_E^p$, $\psi_\mu^\dagger\psi_\mu\psi_p^\dagger\psi_p$ |

- Need to match QED-NRQED contact interaction, e.g. $\bar{\mu}\gamma^0\mu\psi_p^\dagger\psi_p$ to NRQED-NRQED contact interaction, e.g. $\psi_\mu^\dagger\psi_\mu\psi_p^\dagger\psi_p$
  [Dye, Gonderinger, GP *in progress*]

1) Extraction of proton radii from scattering:
   Use an established tool of the $z$ expansion
   Studies disfavor the muonic hydrogen value

2) The first *full* and *correct* evaluation of
   large $Q^2$ behavior of forward virtual Compton tensor
   Can improve the modeling of two photon exchange effects

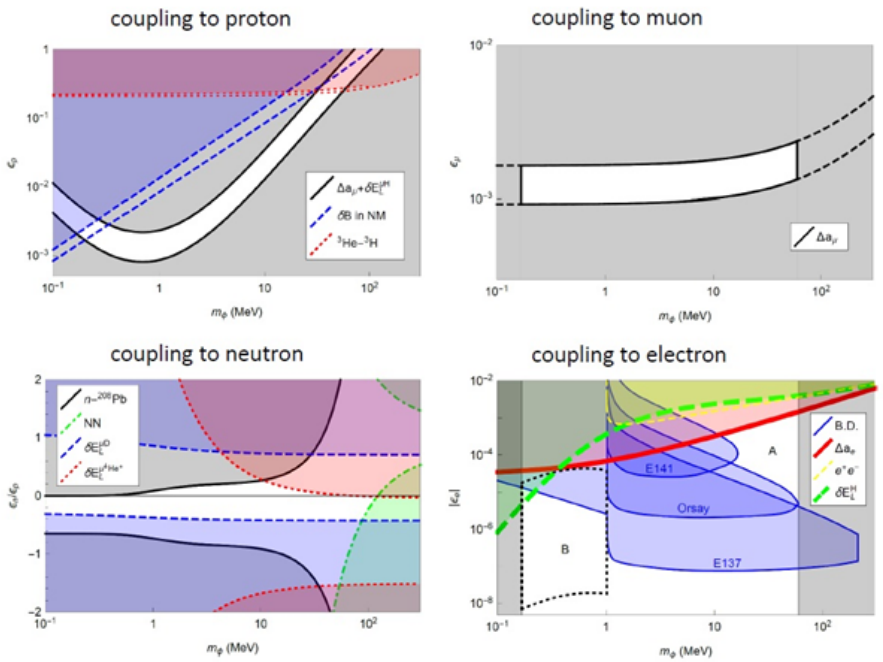
3) Direct connection between muon-proton scattering and muonic hydrogen using a new effective field theory: QED-NRQED

# $r_P + a_\mu$: Y.S. Liu

- order placed: proton radius + muon g-2
- delivered model: light scalar with special Yukawa

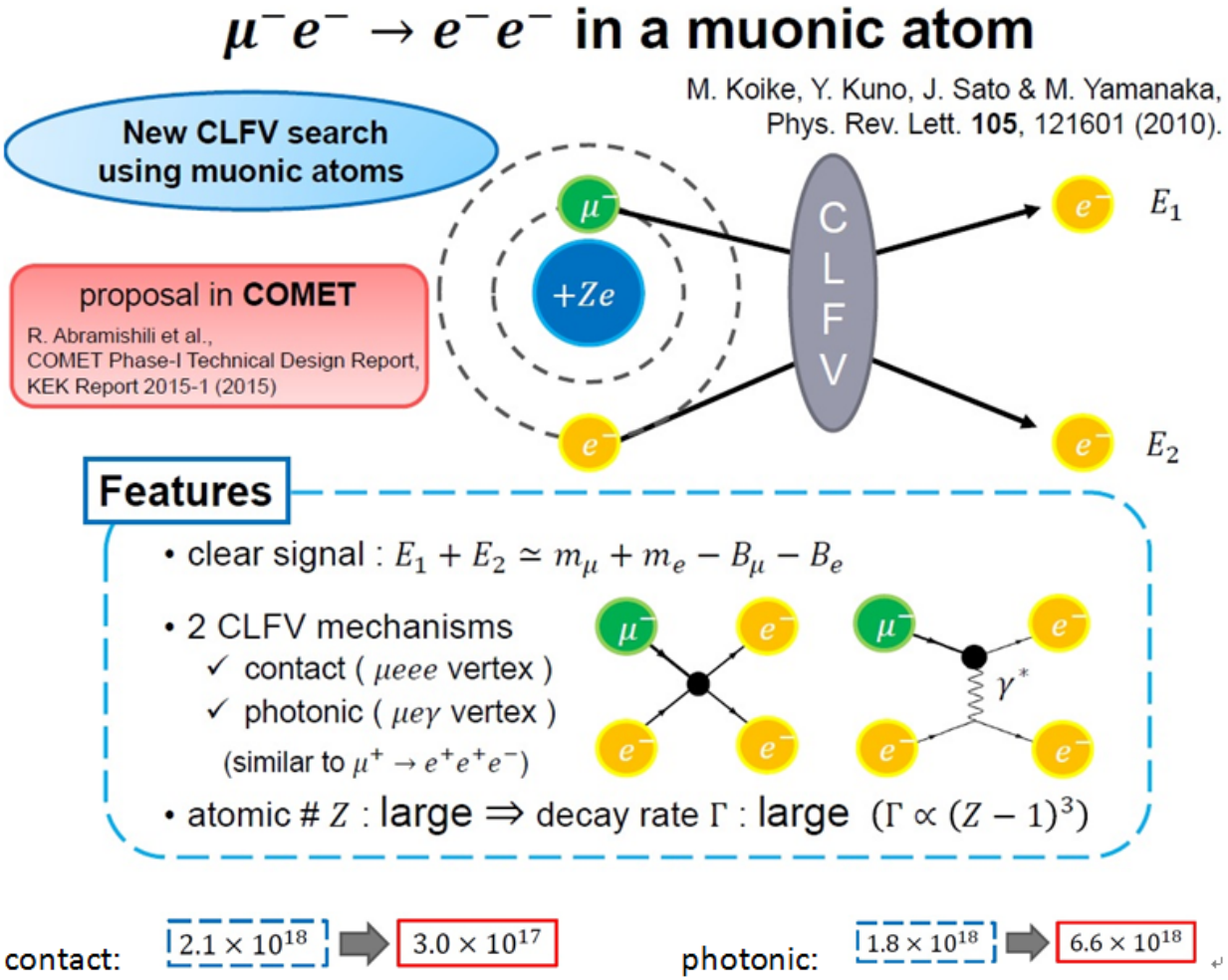
- Assume Yukawa Interaction $\mathcal{L} \supset e\epsilon_f \phi \overline{\psi}_f \psi_f$, where $\epsilon_f = \frac{g_f}{e}$, and $f = e, \mu, p, n$, etc.
- The classical potential between $f_1$ and $f_2$ by exchanging a scalar boson is

$$V_\phi(r) = -\epsilon_1 \epsilon_2 \alpha \frac{e^{-m_\phi r}}{r}.$$



# Muonic atom: Y. Uesaka

- Re-evaluate by taking into account the finite size of nuclear and solving Dirac equation.
- for highly intensive muon sources



# CLFV and 2HDM: D. Jurciukonis

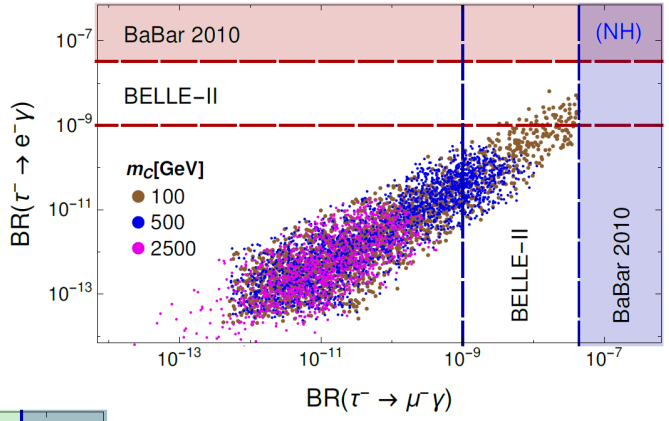
- order placed: detectable CLFV + neutrino masses
- delivered model: simple 2HDM + rather low scale type-I see-saw

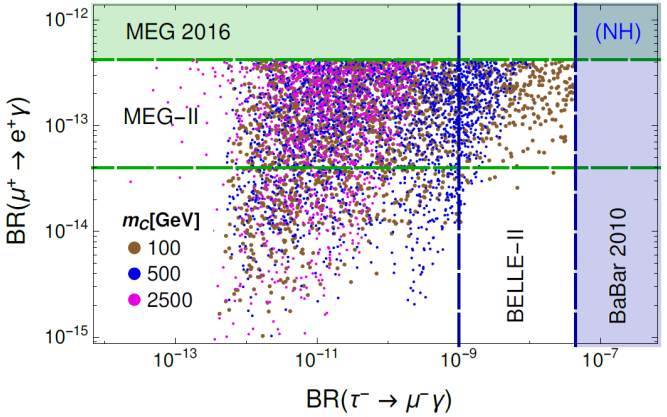
## Numerics

- **Scatter plots for different $m_C$**

Calculations were made assuming:

- $0.1 < a, b, c < 3$ MeV
- $0.1 < m_R < 500$ TeV
- $m_C = 500$ GeV
- $\delta_{l_1} = \delta_{l_2} = 5$

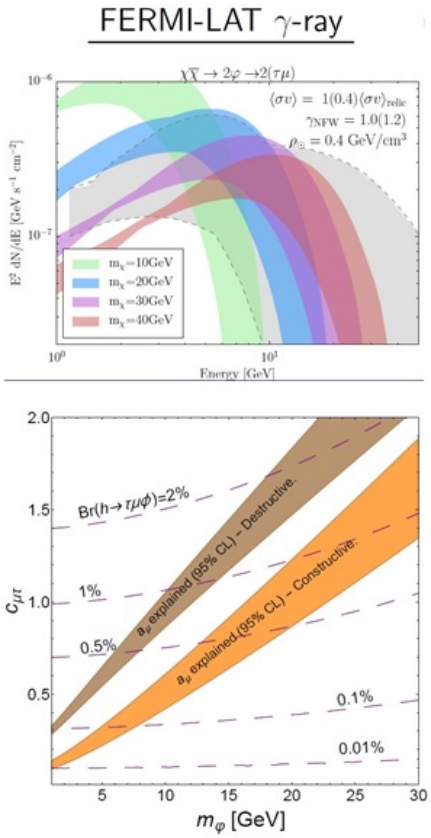



Smaller values of the mass of charged scalar gives larger values of branching ratio

# Dark sector and lepton-flavor violation, I. Galon

- order placed: GC $\gamma$-rays excess(connection to DM), no line, AMS2-$e^+$, CLFV bound, detectable $h \to \mu\tau$
- delivered model: $\mathcal{O}(10)$GeV scalar mediator, Froggatt-Nielsen for flavor with $\mathcal{O}(1)\tau\mu$ coupling, residual $U(1)_e \times U(1)_{\mu-\tau}$, bonus:muon (g-2)




The model: $\varphi$ = mediator to flavorful Dark-Sector

$$\mathcal{L}_{\text{vis.}} \supset -y^{\ell}_{ij}\bar{L}_i H E_j + \text{h.c.}$$

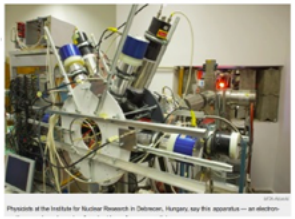
$$\mathcal{L}_{\text{vis-med.}} \supset \frac{c_{ij}}{\Lambda}\bar{L}_i H E_j \varphi + \frac{c'_{ij}}{\Lambda}\bar{L}_i H E_j \varphi^* + \text{h.c.}$$

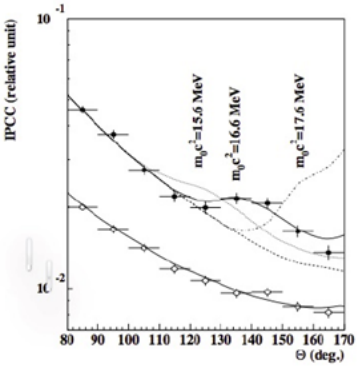
$$\mathcal{L}_{\text{dark}} \supset g^L_{ab}\varphi\,\bar{\chi}_a P_L \chi_b + g^R_{ab}\varphi\,\bar{\chi}_a P_R \chi_b + \text{h.c.}, \qquad a, b = 1, 2.$$

**A flavor theory at $\Lambda = 1$ TeV determines all couplings**

# 17 MeV X boson: X.G. He

- order placed: 17 MeV protophobic gauge boson+ muon g-2
- delivered model: $SU(3) \times SU(2) \times U(1)_Y \times U(1)_{Y'} \times U(1)_X$






(Pei-Hong Gu, Xiao-Gang He, Nucl. Phys. B919, 209 [arXiv: 1605.05171]

A protophobic gauge model $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$

$$
\begin{array}{lll}
Q_L^1 : (3,\ 2,\ 1/6)(-1)\ , & u_R^1 : (3,\ 1,\ 2/3)(5)\ , & d_R^1 : (3,\ 1,\ -1/3)(-7)\ , \\
L_L^1 : (1,\ 2,\ -1/2)(\beta)\ , & e_R^1 : (1,\ 1,\ -1)(\beta)\ , & \\
Q_L^2 : (3,\ 2,\ 1/6)(1)\ , & u_R^2 : (3,\ 1,\ 2/3)(-5)\ , & d_R^2 : (3,\ 1,\ -1/3)(7)\ , \\
L_L^2 : (1,\ 2,\ -1/2)(-\beta)\ , & e_R^2 : (1,\ 1,\ -1)(-\beta)\ , &
\end{array}
$$

Introduce an additional $U(1)_X$ which do not couple to SM fermions.
But has a kinetic mixing of $U(1)_{Y'}$ and $U(1)_X$ gauge fields, $-(\epsilon/2)Y'_{\mu\nu}X^{\mu\nu}$,
The $X$ boson to the $J^\mu_{Y'}$ current as, $\epsilon X_\mu J^\mu_{Y'}$.

$$
\begin{aligned}
\epsilon J^\mu_{Y'} &= \epsilon g_{Y'} \left[ \bar{u}\gamma^\mu(4+6\gamma_5)u - \bar{d}\gamma^\mu(8+6\gamma_5)d + \beta\bar{e}\gamma^\mu e + \frac{\beta}{2}\bar{\nu}_e\gamma^\mu(1-\gamma_5)\nu_e \right] , \\
&- \epsilon g_{Y'} \left[ \bar{c}\gamma^\mu(4+6\gamma_5)c - \bar{s}\gamma^\mu(8+6\gamma_5)s + \beta\bar{\mu}\gamma^\mu\mu + \frac{\beta}{2}\bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\nu_\mu \right] ,
\end{aligned}
$$

$g_{Y'}$ being the $U(1)_{Y'}$ gauge coupling.
The full gauge group is: $SM \times U(1)_{Y'} \times U(1)_X$.

# A4 neutrino model: X.G. He

- order placed: $\delta \simeq -\pi/2$, $\theta_{23} \simeq \pi/4$
- delivered model: $A4$ model with 10 Higgs bosons

| | | |
|---|---|---|
| $\sin^2\theta_{23}$, $\Delta m^2 > 0$ | 0.437 | $0.379 - 0.616$ |
| $\sin^2\theta_{23}$, $\Delta m^2 < 0$ | 0.569 | $0.383 - 0.637$ |
| $\sin^2\theta_{13}$, $\Delta m^2 > 0$ | 0.0214 | $0.0185 - 0.0246$ |
| $\sin^2\theta_{13}$, $\Delta m^2 < 0$ | 0.0218 | $0.0186 - 0.0248$ |
| $\delta/\pi$ | 1.35 (1.32) | $(0.92 - 1.99)$ |
| | | $((0.83 - 1.99))$ |

Leading approximation: $\delta_{CP} = -\pi/2$ and $\theta_{23} = \pi/4$.

Predictions: $|V_{i2}| = 1/\sqrt{3}$

$J = \mathrm{Im}(V_{11}V^*_{12}V^*_{21}V_{22}) = (s^2-c^2)/6\sqrt{3}$
independent of $\rho$

$A_4$ family symmetry properties

$$l_L : (1,2,-1)(3)\ ,\quad l_R : (1,1,-2)(1+1''+1')\ ,$$
$$\phi : (1,2,-1)(1)\ ,\quad \Phi : (1,2,-1)(3)\ ,$$
$$\Delta^{0,',''} : (1,3,-2)(1+1'+1'')\ ,\quad \chi : (1,3,-2)(3)\ .$$

The Lagrangian responsible for the lepton mass matrix is

$$L = y_e \bar{l}_L \tilde{\Phi} l_R^1 + y_\mu \bar{l}_L \tilde{\Phi} l_R^2 + y_\tau \bar{l}_L \tilde{\Phi} l_R^3$$
$$+ Y_\nu^0 \bar{l}_L \Delta^0 l_L^c + Y_\nu' \bar{l}_L \Delta' l_L^c + Y_\nu'' \bar{l}_L \Delta'' l_L^c + y_\nu \bar{l}_L \chi l_L^c + H.C.$$

# CP in $h\tau\tau$: X.G. He

- order placed: detectable CP in $h\tau\tau$ coupling
- delivered model: general Yukawa, future $e^+e^-$ collider

## CP violation in h -> ττ

Models beyond SM usually generate correction to h -> ττ coupling. If the corrections is CP violating, effects can show up in h -> ττ decay.

(Hayreter, He, Valencia, arXiv:1603.06326, arXiv:1606.00951)

$L_Y = -\bar{L}_L[y\frac{v}{\sqrt{2}} + (y+\delta y)\frac{h}{\sqrt{2}}]E_R$

Diagonalizing the mass term, $S_e^\dagger y T_e(v/\sqrt{2} = \hat{M}$,

the h interaction becomes $L_h = -\bar{l}_i(\frac{\hat{M}}{v} + \frac{1}{\sqrt{2}}S_e^\dagger \delta y T_e)l_j h$

If there is CP violation, the Higgs h coupling to tauon becomes

$L_{h\tau\tau} = -\frac{h}{v}m_\tau\bar{\tau}(r_\tau + i\tilde{r}_\tau\gamma_5)\tau, \quad r_\tau = 1+\epsilon_\tau$

For $\tau \to \pi^-\nu_\tau$, $\bar{\tau} \to \pi^+\bar{\nu}_\tau$,

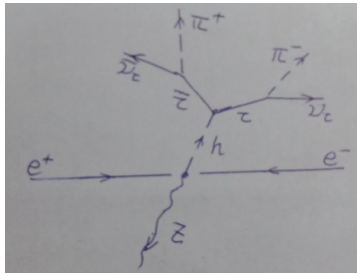
one can construct T odd operator $O_\pi = \vec{p}_\tau \cdot (\vec{p}_\pi^+ \times \vec{p}_\pi^-)$,

One construct CP violating observable

$$A_\pi = \frac{N(\mathcal{O}_\pi > 0) - N(\mathcal{O}_\pi < 0)}{N(\mathcal{O}_\pi > 0) + N(\mathcal{O}_\pi < 0)} = \frac{\pi}{4}\beta_\tau \frac{(r_\tau\tilde{r}_\tau)}{\beta_\tau^2 r_\tau^2 + \tilde{r}_\tau^2},$$

Data still allow A to be as large as π/8

Experiments should look such CPV.




Br(h ->ττ) ~ $5\times10^{-2}$, Br(τ –> π ν) ~ 0.1

$10^6$ Higgs bosons, sensitivity to $A_\pi$ can be 10% at CEPC.

(He, Ma, McKellar, Mod. Phys Lett. A9, 205(1994); Berge, Bereuther, Kirchner, PRD92,096012(2015))

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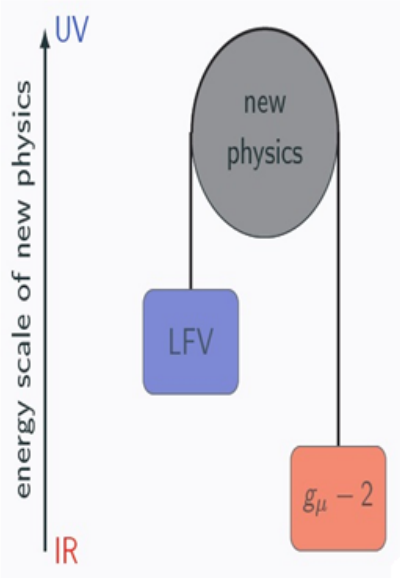
# connection between $g-2$ and $\mu \to e\gamma$: Moritz PLATSCHER

- In what model the two are connected?




Start from an EFT point of view (NP $\Rightarrow$ $d = 6$ operators):

$$\mathcal{L}_{\text{eff}} = \frac{\mu_{ij}^M}{2}\overline{\ell_i}\sigma^{\mu\nu}\ell_j F_{\mu\nu} + \frac{\mu_{ij}^E}{2}\overline{\ell_i} i\gamma^5\sigma^{\mu\nu}\ell_j F_{\mu\nu}$$

Consider form factors $\mu_{ij}^{M/E} \equiv e\, m_i A_{ij}^{M/E}/2$:

$$\Rightarrow \Delta a_{\ell_i} \equiv (g-2)/2 - (g-2)_{\text{SM}}/2 = A_{ii}^M m_i^2 \text{ (no sum)}$$

$$\Rightarrow BR(\ell_i \to \ell_j\gamma) = \frac{3(4\pi)^3\alpha_{\text{em}}}{4G_F^2}\left(\left|A_{ji}^M\right|^2 + \left|A_{ji}^E\right|^2\right) BR(\ell_i \to \ell_j\nu_i\overline{\nu_j})$$

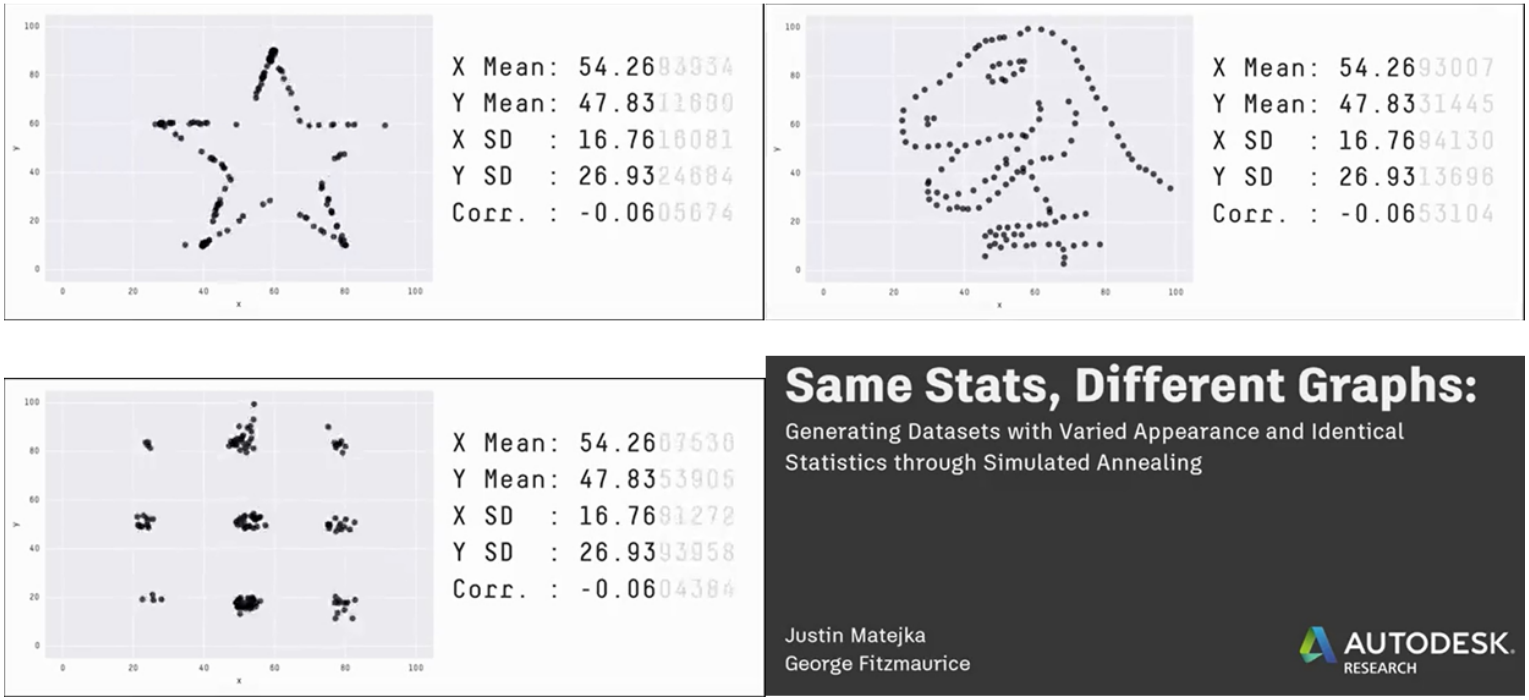
# Statistics-1

- Many "anomalies" had come and gone: 750GeV, $h \to \mu\tau$, di-boson near 2TeV..
- We should be very circumspect about the anomalies (especially in their early stage).
- A question:
  You are given a 2-D distribution $\{x, y\}$ with

$$\langle x \rangle = 54.26\,, \delta x = 16.76\,, \langle y \rangle = 47.83\,, \delta y = 26.93$$

  and correlation=-0.06.
  What does it look like?

# Statistics-1




- the original clip can be found in Youtube.
- Of course, any genetic 2D pattern can not be uniquely specified by only 5 numerical numbers.

# Statistics-2

From the 2nd neutrino conference(1974), Pennsylvania,
(As already pointed out by Y Uchida at CLFV2016.)

- The solar neutrino talk by R.K. Ulrik

The $^{37}$Ar production rates for the standard model and the low Z model are 5.6 ± 1.8 SNU and 1.4 ± 0.35 SNU, respectively. Taking Davis's result[1] without run 27 to be 0.2 ± 0.8 SNU I find that the discrepancy between the experiment and the standard model to be 2.7$\sigma$ and while the discrepancy with the low Z model is 1.4$\sigma$.

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- The Conference Summary by R.P. Feynman

> I see no reason to include the solar neutrino problem in here because it is only 1-1/2 standard deviations off of some solar models and the principle is, you don't make a new theory because of 1-1/2 standard deviations.

# Summary

- SM is healthy (J. Erler: makes us theorists sick) in general but incomplete(neutrino, DM, DE, hierarchy...).
- Some deviations: $a_\mu$, proton radius, a few anomalies in B flavor phys( (V-A) NP $\lesssim$ 50TeV ), $M_W$, $M_H$ ... seems to indicate lepton universality breaking?
- Try our best to keep the theory uncertainties below the experimental ones.
- Work hard to identify which processes are more sensitive to NP.
- Still far away from answering the hard questions.
- Let's keep looking carefully and thinking deeply and creatively.

## THANKS TO

- All the speakers for the inspiring talks and the slides.
- All the session chairmans/participants for the efforts/questions/discussion.
- All organizers and particular to Mu-Chun for this wonderful and smooth workshop.