Exploring the structure of LFU violations at colliders

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Flavour physics is one of the best probes of BSM physics

There are several indications pointing towards the possible existence of NP

Anomalies in the decay of the B meson were reported through the measurements of the $b \to sll$ transitions in the form of foll. ratio:

Hiller,Kruger
0310219

LFU violations??

$2.6 - 2.7\sigma$

$$R_K = \left.\frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}\right|_{q^2=1-6\ GeV^2} = 0.745^{+0.090}_{-0.074}\ (stat) \pm 0.036\ (syst)$$

LHCB
1406.6482

$R_K^{SM} = 1.003$

This was further corroborated by the measurement of the following ratio:

$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)} = \begin{cases} 0.660^{+0.110}_{-0.070}(stat) \pm 0.024(syst), & 0.045 \leq q^2 \leq 1.1\ \mathrm{GeV}^2 \\ 0.685^{+0.113}_{-0.069}(stat) \pm 0.047(syst), & 1.1 \leq q^2 \leq 6.0\ \mathrm{GeV}^2 \end{cases}$$

Things are looking GOOD!!

$R_{K^*}^{SM} \simeq 0.93$ for low q^2 while $R_{K^*}^{SM} = 1$ elsewhere

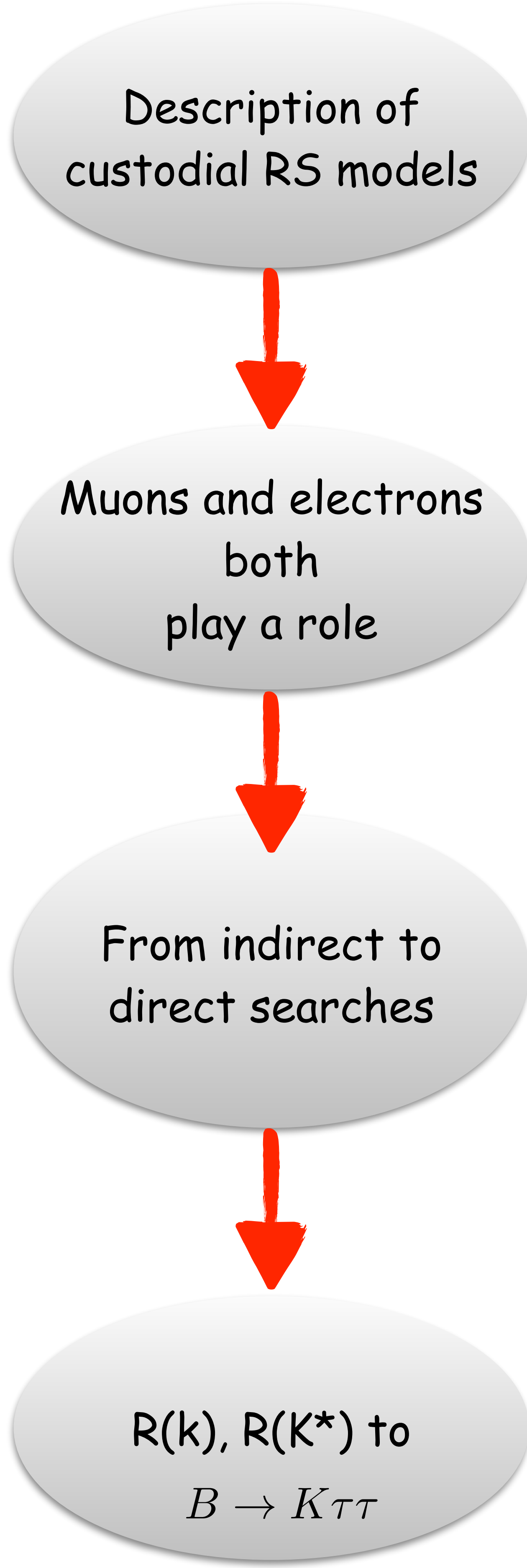
LHCB, BELLE

Motivated by the P_5' anomaly, it is not uncommon to consider NP purely in the muon sector

However, this will not necessarily constitute the holy grail for our analysis, leaving the door open for electrons as well

As a model building exercise, we focus on custodial models of RS and present example where electron and muons contribute

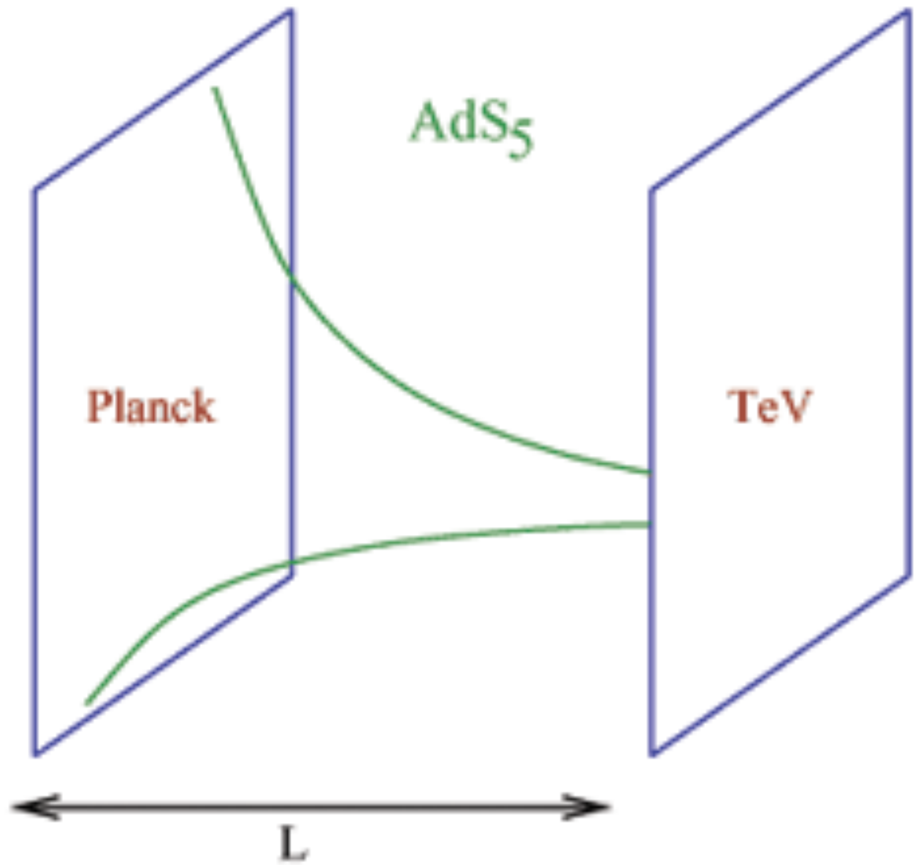
Electrons or muons or both? We try to address this question for the structure of solutions to the anomalies at the LHC.



Possible hint on the structure of the solutions

Randall Sundrum Model

Randall, Sundrum '99



S_1/Z_2 compactified

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

effective 4D scale depends on the position in the bulk

One Fundamental gravity scale!!

Hierarchy problem Solved!!

$$M_{ew} = e^{-kL}M_{Pl}$$

- Provides insight on strongly coupled theories #win
- Solution to the Yukawa hierarchy problem #win

Elements of the framework 1.:

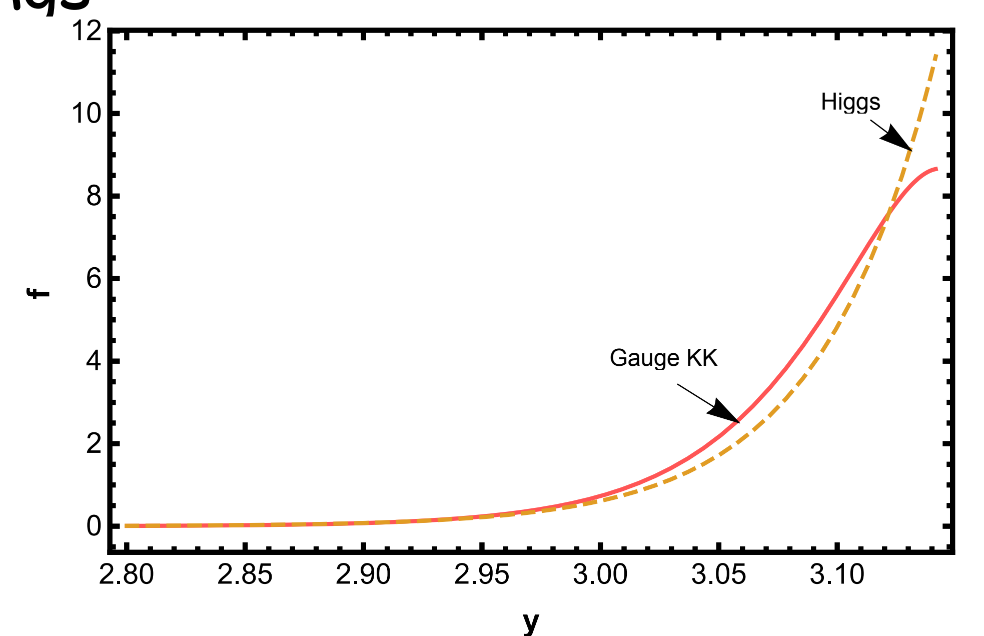
Gauge bosons in RS

The bulk gauge symmetry is: $SU(2)_L \times SU(2)_R \times U(1)_X$

KK excitations of the corresponding bulk gauge fields lead to a tower of states: We consider the lowest scale with mass $M_{KK} = 3$TeV

In the mass basis there are three neutral states with similar mass contributing to the $Z', Z_X, A^{(1)}$ FCNC

They have a similar wave function profile which is peaked near the IR brane: Origin of non-universal couplings



Elements of the framework 2.:

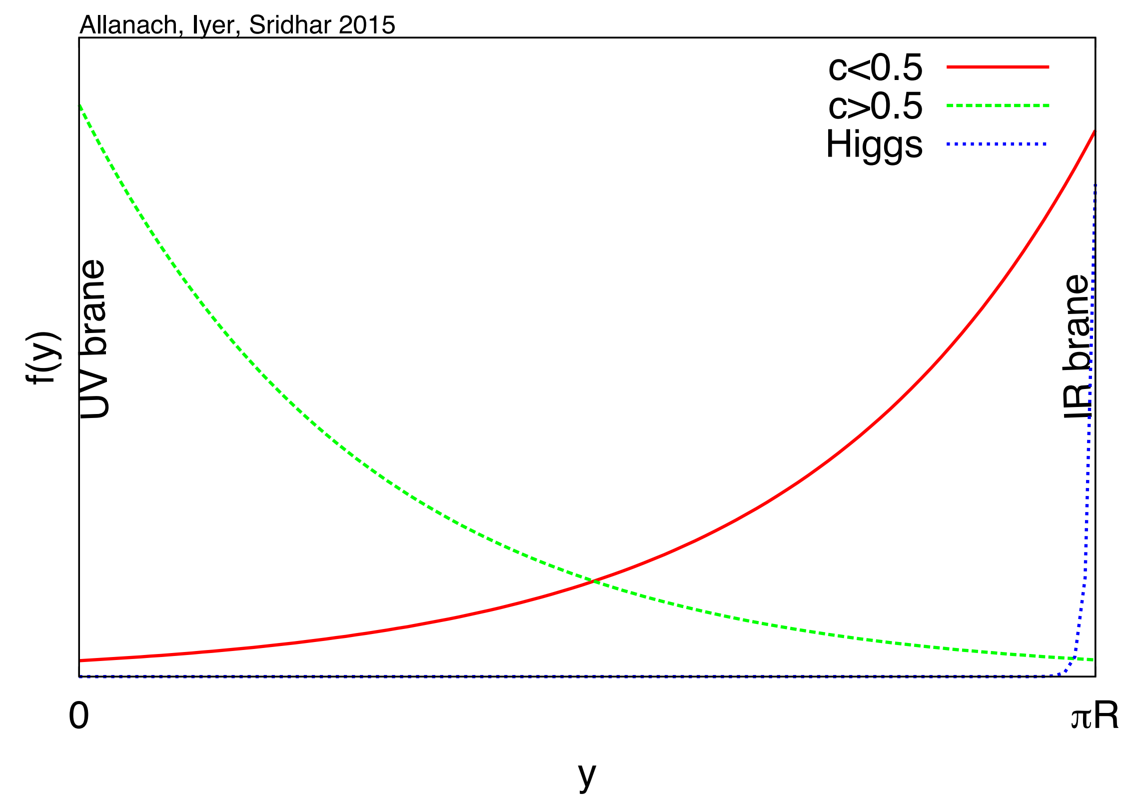
Dimensionless
O(1) parameters

Fermions in RS

We consider fermion field with a bulk mass parametrised as: $m_\Psi = ck$

These bulk masses control the localisation of the fermion zero mode (SM fermions) in the bulk

$$Y^{(4)} = Y^{(5)} \int_0^{\pi R} dy\ f_0^{(0)}(b,y) f_{1/2}^{(0)}(c_L,y) f_{1/2}^{(0)}(c_R,y)$$



The choices are governed by the proximity to the Higgs field and hence a relatively larger effective Yukawa coupling

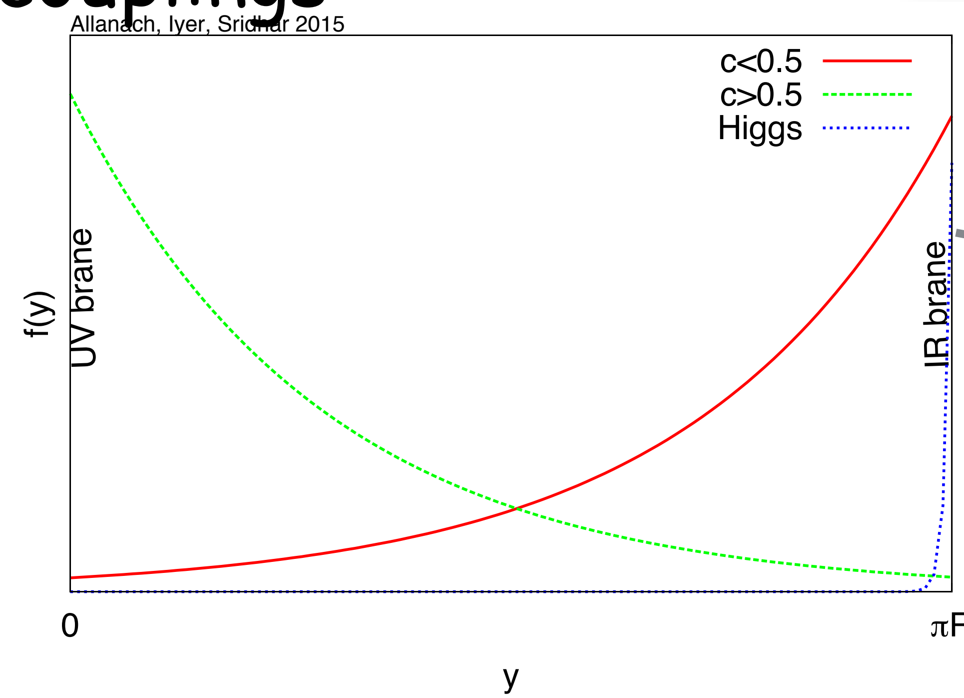
Except for the third generation doublet and top singlet, other fields are away from the IR brane

Elements of the framework 3.:

Gauge KK states here too!!

Non-universal couplings

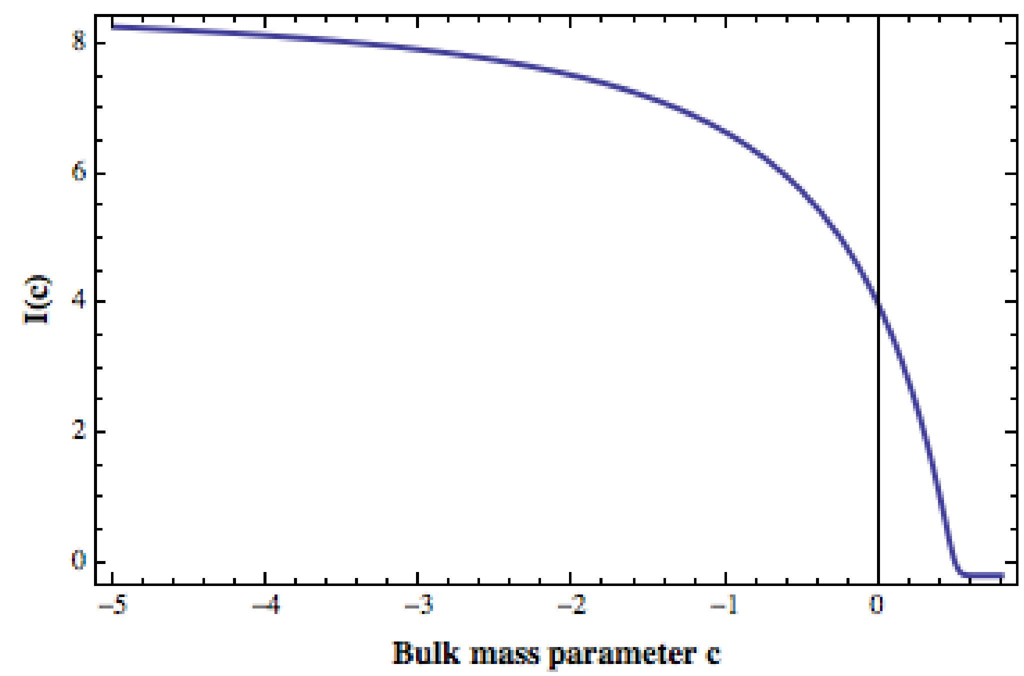
Since the fermions are at different points in the bulk: Non universality is in built



The third generation quarks are likely to be closer to the Higgs and hence the gauge KK states -> Larger coupling

The coupling of a pair of SM fermions to KK states can be expressed as

$$I(c) = \frac{1}{\pi R}\int_0^{\pi R} dy e^{\sigma(y)} (f_i^{(0)}(y,c))^2 \xi^{(1)}(y)_{Z^{(1)},Z'}$$



We assume universal coupling between the first two generations: U(2)

The flavour violating couplings are:

$$a^{12} = \tilde{g}\,(D^*_{21}D_{22}(I(2)-I(1)) + D^*_{31}D_{32}(I(3)-I(1)))$$
$$a^{23} = \tilde{g}\,(D^*_{12}D_{13}(I(1)-I(2)) + D^*_{32}D_{33}(I(3)-I(2)))$$
$$a^{13} = \tilde{g}\,(D^*_{21}D_{23}(I(2)-I(1)) + D^*_{31}D_{33}(I(3)-I(1)))$$

We are now in a position to understand the contributions to b-sll transitions

The effective operator contributing to this process is given as

$$\mathcal{L} \supset \frac{V_{tb}^* V_{ts} G_F \alpha}{\sqrt{2}\pi} \sum_i C_i \mathcal{O}_i$$

$$\mathcal{O}_9 = (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu l) \qquad \mathcal{O}_{9'} = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu l)$$
$$\mathcal{O}_{10} = (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu \gamma^5 l) \qquad \mathcal{O}_{10'} = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu \gamma^5 l)$$

The couplings α^{ij} are related to the FV co-eff a^{ij} defined earlier

The tree level contributions to b-sll is simply

$$\mathcal{L}_{NP} \subset \sum_{X=Z_{SM},Z_H,Z_X,\gamma^{(1)}} X_\mu \left[\alpha_L^{bs}(X)(\bar{s}_L\gamma^\mu b_L) + \alpha_R^{bs}(X)(\bar{s}_R\gamma^\mu b_R) + \bar{l}\left(\alpha_V^l(X)\gamma^\mu - \alpha_A^l(X)\gamma^\mu\gamma^5\right) l\right]$$

Using this the WC are simply

$$\Delta C_9 = -\frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_L^{bs}(X)\alpha_V^l(X), \qquad \Delta C_9' = -\frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_R^{bs}(X)\alpha_V^l(X)$$
$$\Delta C_{10} = \frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_L^{bs}(X)\alpha_A^l(X), \quad \Delta C_{10}' = \frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_R^{bs}(X)\alpha_A^l(X)$$

Two scenarios are possible

Will de discussed here.

Non-universality in muon singlets. Lepton doublets universal but non-negligible

Scenario A: The muon singlets are closer to the gauge KK states (couple more). The lepton doublets are universal.

Unorthodox scenario as there are contributions to the WC from the lepton doublets as well

These are largely due to ensure fits to the muon mass with O(1) Parameters.

The fit in this case is 4D scenario with C9, C10 for both electron and muon contributing

Scenario B: The lepton singlets now have near universal coupling and smaller coupling to the gauge KK states. The muon doublets are now closer to the KK states and hence larger coupling

The fits to muon mass is better with O(1) Parameters.

Will not be discussed here

Mainly C9 and C10 for the muon contribute with a possibility of C9=-C10

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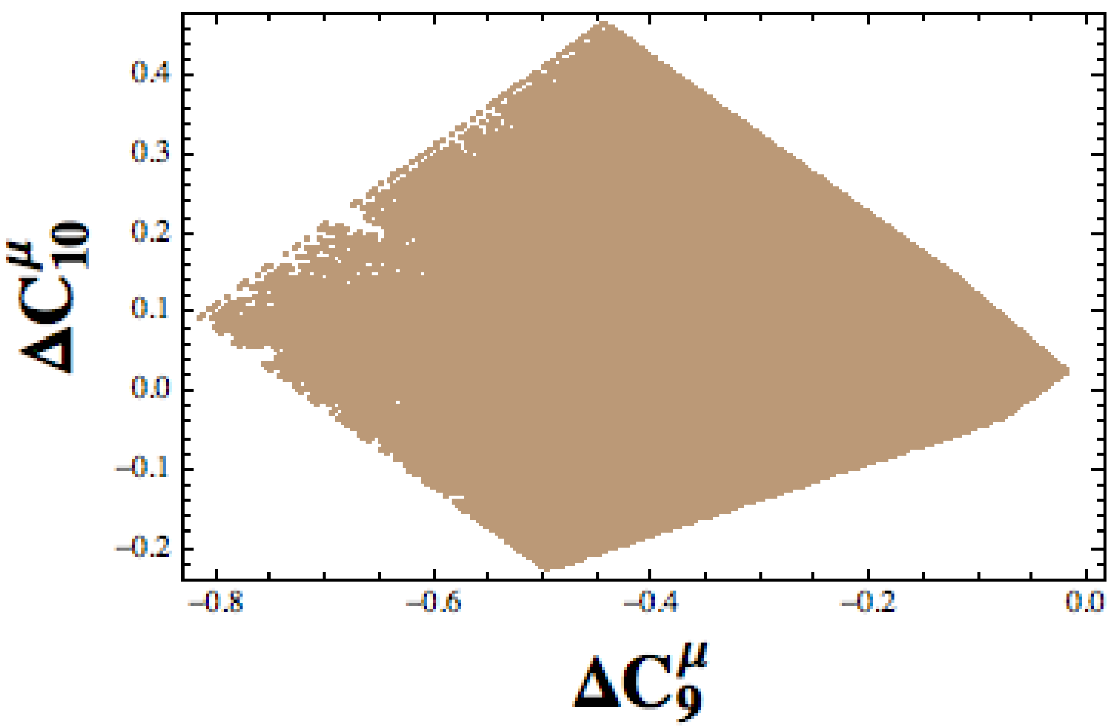
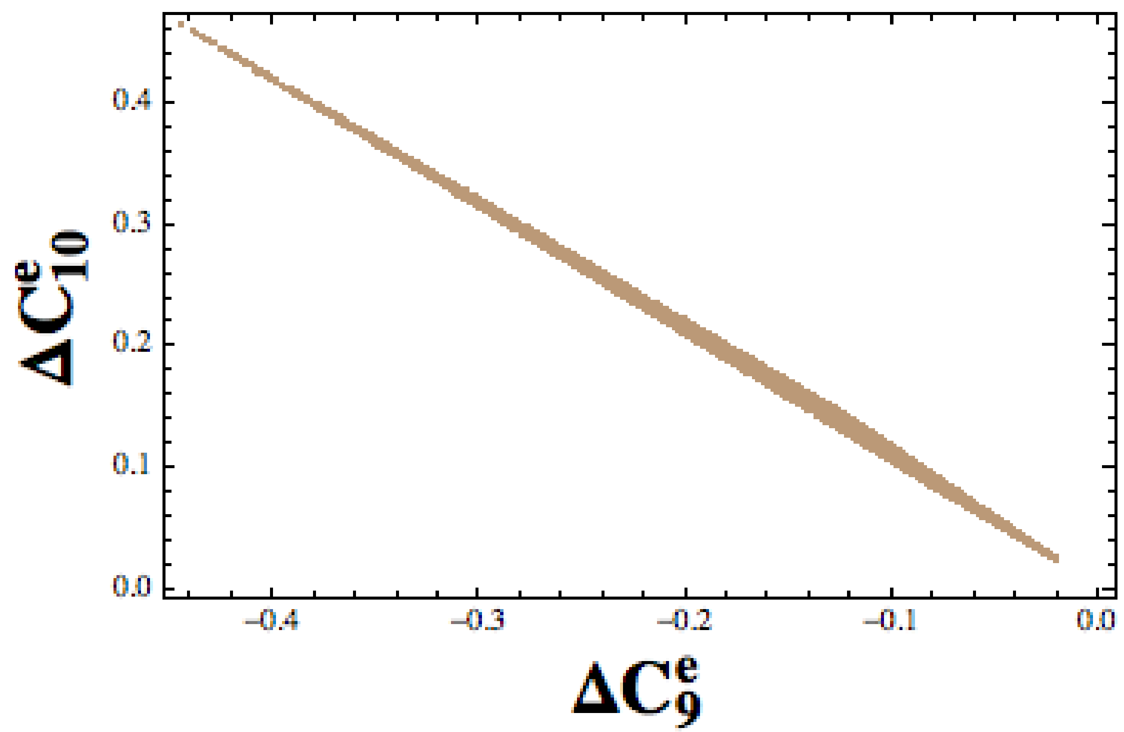
1712.08122

Scenario A





The following ranges were used in the scan:

$$c_{\mu_R} \in [0.45, 0.55] \quad c_{Q_3} \in [0.4, 0.5] \quad c_L \in [0.45, 0.55]$$

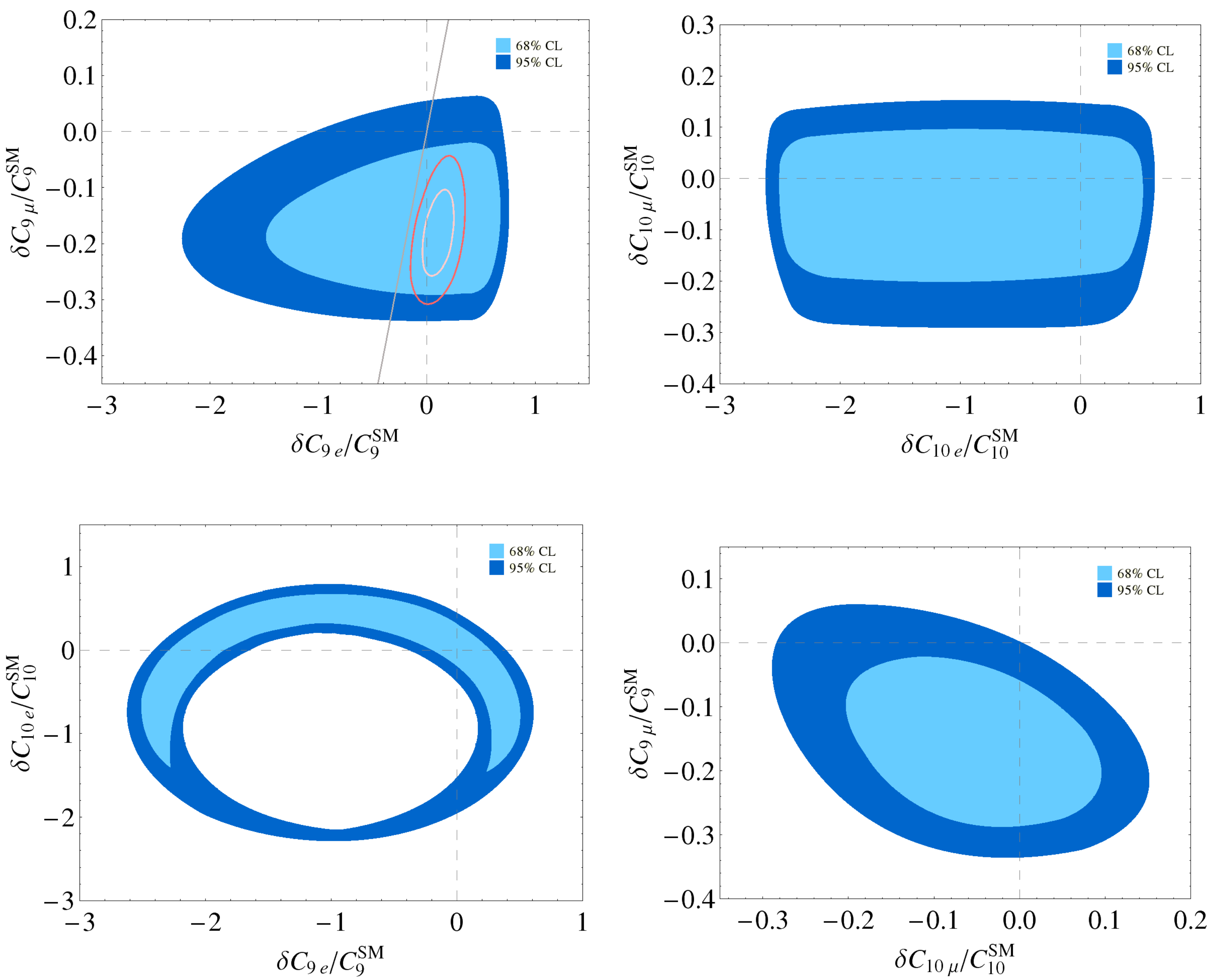
The Z- mu mu coupling is not a problem as the singlets are also embedded in custodial representations!

The c values for the lepton doublets are chosen such that to ensure an extension into 5D leptonic MFV.

This is a 4D fit to b-s ll data.

A model independent fit along these lines was performed in Hurth, Mahmoudi, Neshatpour 1603.00865

It was shown to relax the allowed ranges on the WC required to fit the data.



From indirect searches to colliders

Electrons or muons or both?

We found that solutions are possible in a consistent model with even electrons playing a role

These were associated with fits to data on 2D or 4D plane involving both electrons & muons

That brings us to the question: Is it possible to get a hint on the structure of WC from colliders

We present an explicit example with an effective Z′ model

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Consider a Z' model with the following effective lagrangian

$$\begin{aligned}\mathcal{L}_{eff} =& \frac{\lambda_{bs}\lambda_e}{M^2}\left[(\bar{s}\gamma_\mu b)(\bar{e}\gamma^\mu e)\right] + \frac{\lambda_{bs}\lambda_\mu}{M^2}\left[(\bar{s}\gamma_\mu b)(\bar{\mu}\gamma^\mu \mu)\right] + \frac{\lambda_{bs}\lambda_\tau}{M^2}\left[(\bar{s}\gamma_\mu b)(\bar{\tau}\gamma^\mu \tau)\right] \\ &+ \frac{\lambda_b\lambda_\tau}{M^2}\left[2V_{cb}(\bar{c}\gamma_\mu b)(\bar{\tau}\gamma^\mu \nu_\tau) + (\bar{b}\gamma_\mu b)(\bar{\tau}\gamma^\mu \tau)\right] \\ &+ \left[\frac{\lambda_b\lambda_\mu}{M^2}(\bar{b}\gamma_\mu b)(\bar{\mu}\gamma^\mu \mu) + \frac{\lambda_c\lambda_\mu}{M^2}(\bar{c}\gamma_\mu c)(\bar{\mu}\gamma^\mu \mu)\right]\end{aligned}$$

The Wilson co-efficients for the R(K) and R(K*) anomalies are given as

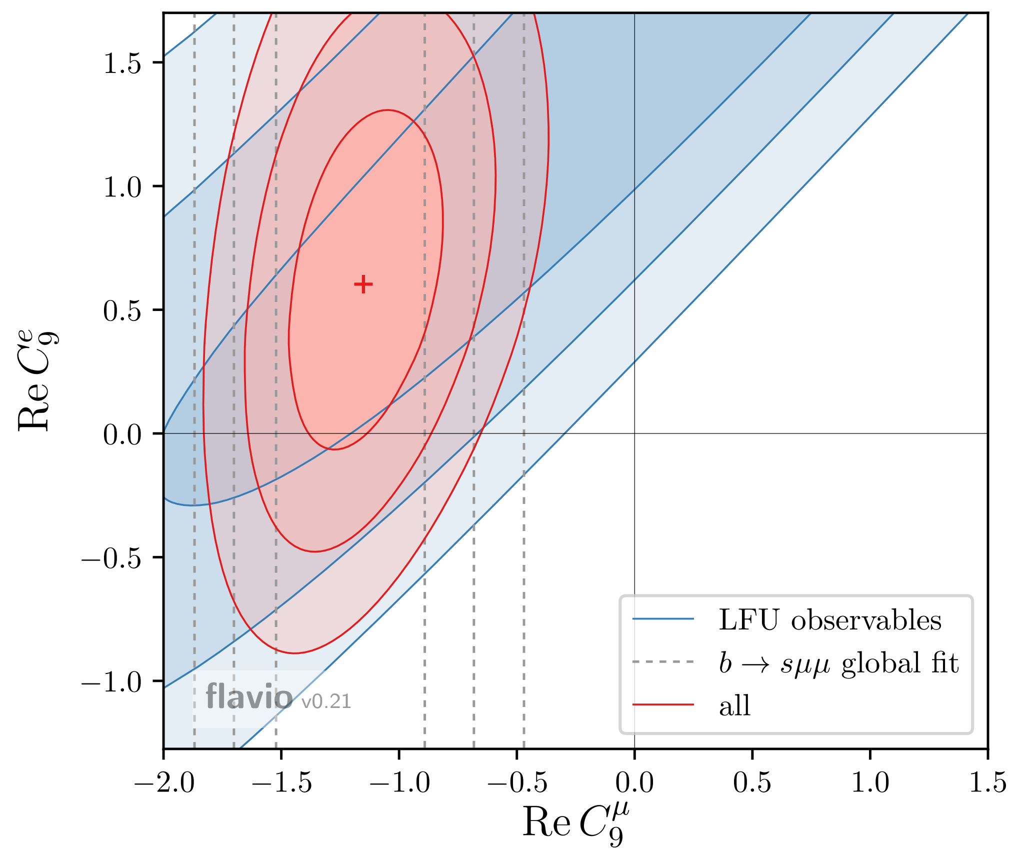
$$C_9^e = -\frac{\sqrt{2}\pi}{G_F\alpha}\frac{\lambda_{bs}\lambda_e}{M^2} \quad C_9^\mu = -\frac{\sqrt{2}\pi}{G_F\alpha}\frac{\lambda_{bs}\lambda_\mu}{M^2}$$

The ratio of WC is simply $\frac{\lambda_e}{\lambda_\mu}$

A key part of this ratio is that the quark dependance cancels out as it is common for both

Example of a fit to the anomalies with both electron and muon

Altmanshoffer, Strangl, Straub
1704.05435



The fit admits a wide parameter space of WC. Is there a way to explore the structure of these WC at colliders?

Consider the on-shell production of Z′ at colliders and consider the following ratio

$$\delta = \frac{\sigma_{Z'}\lambda_\mu^2 \mathcal{L}\epsilon_\mu}{\sigma_{Z'}\lambda_e^2 \mathcal{L}\epsilon_e} = \frac{N_\mu}{N_e}$$

Now the electron and muon are in general associated with different acceptance efficiencies

Is there a way for the above ratio to roughly reflect the ratio of WC

Its clear that if $\epsilon_\mu \simeq \epsilon_e$ then

$$\delta \simeq \frac{\lambda_\mu^2}{\lambda_e^2} = \left(\frac{C_9^\mu}{C_9^e}\right)^2$$

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Typically muons have a larger acceptance that electrons

$m_{Z'} = 1500$ GeV

	$Z \to \mu\mu$	$Z \to ee$
Simple Isolation(>1 leptons)	71.73	51.4
Mass cuts ($> 800GeV$)	**67.85**	48.50

$m_{Z'} = 3000$ GeV

	$Z \to \mu\mu$	$Z \to ee$
Simple Isolation(>1 leptons)	59.33	39.79
Mass cuts ($> 1000GeV$)	**58.79**	39.61

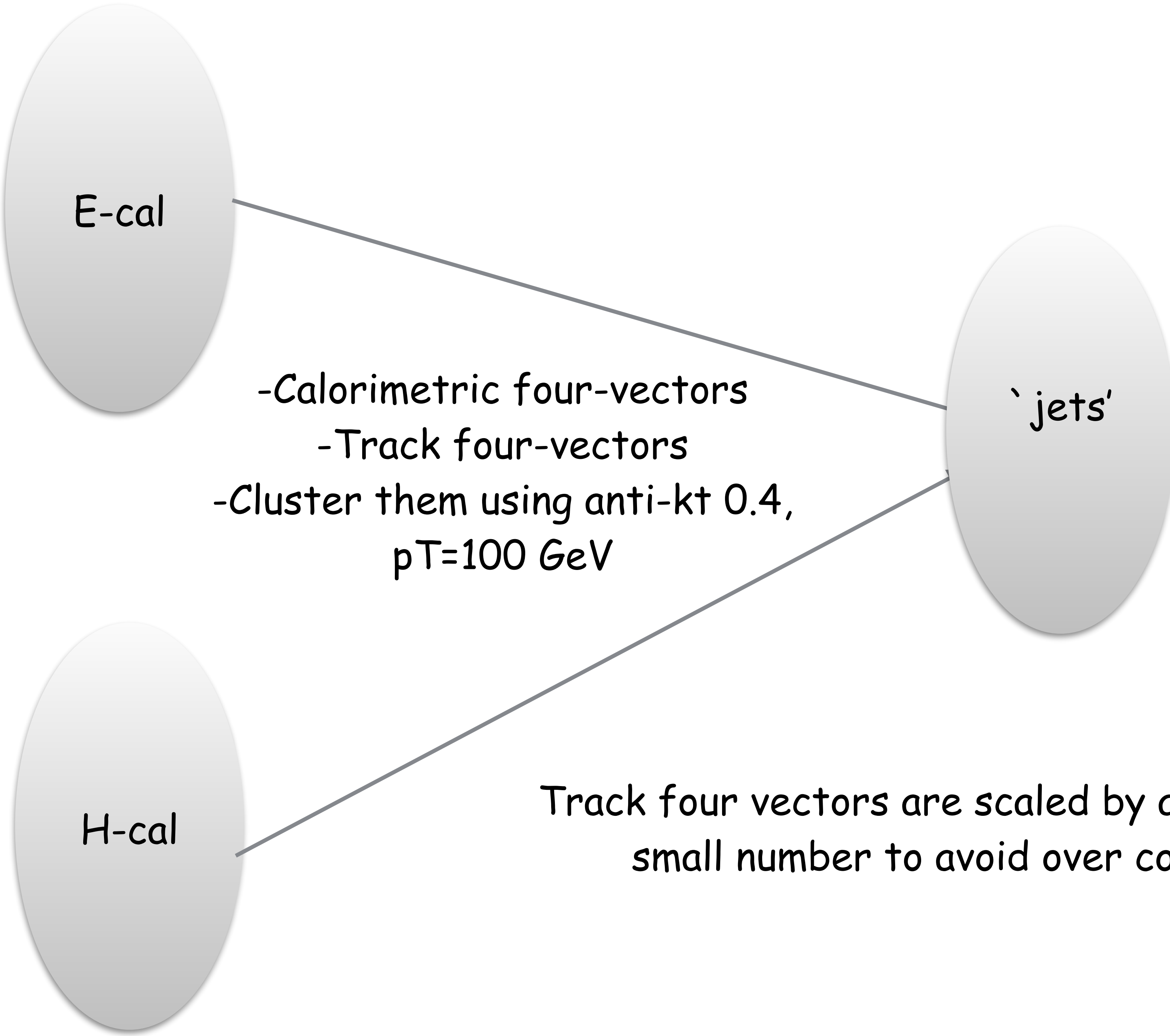
Is there a way to get them as close to each other as possible!!
So the analysis is democratic?

Move from conventional electrons to electron jets!

One way to pull up `electron' efficiency is to use electron-jets

`jets'

Give up isolation



QCD,tau,e, photon
all fall under jets
nomenclature

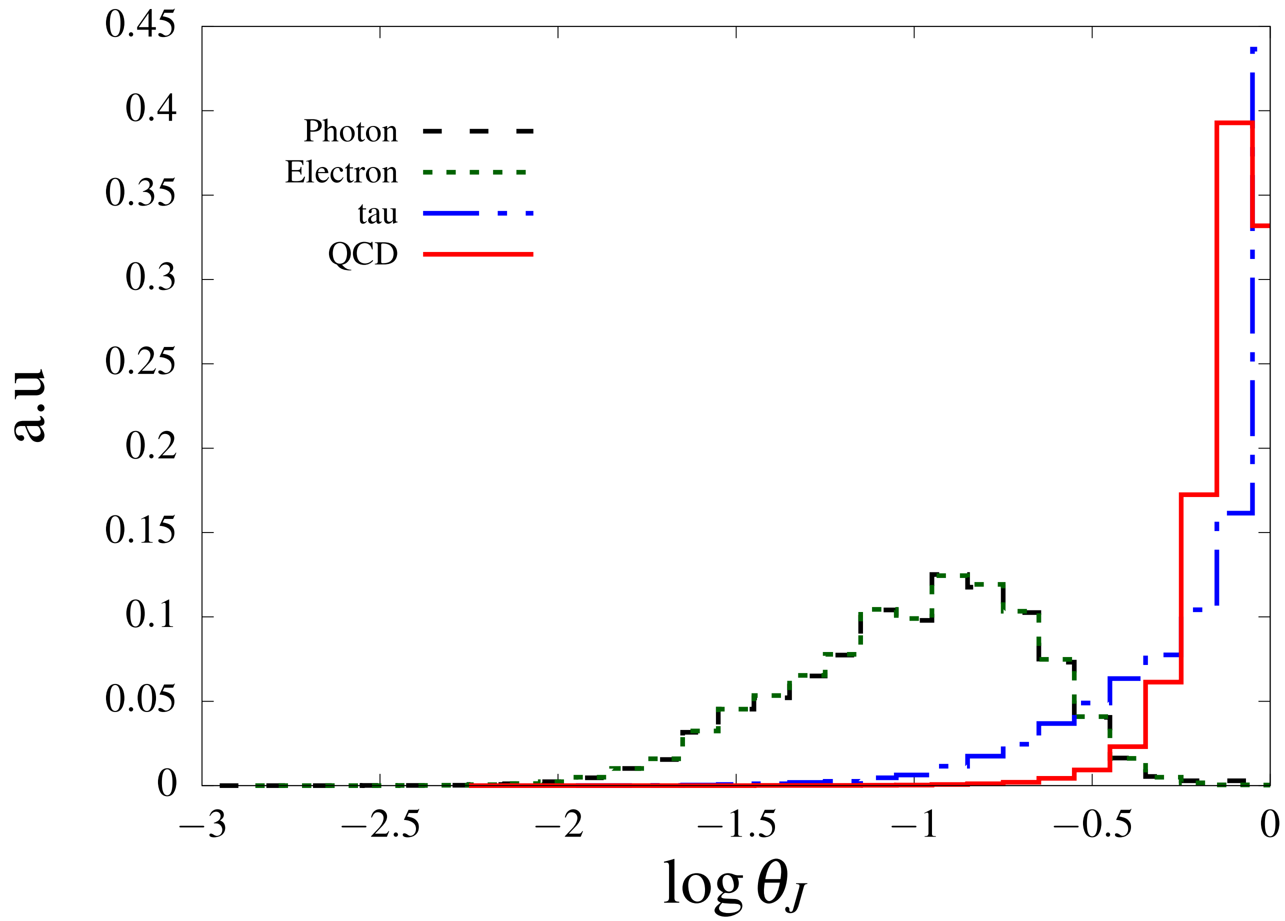
Track four vectors are scaled by an arbitrary
small number to avoid over counting

Different samples can be distinguished by studying the properties of jets:-JET SUBSTRUCTURE

Chakraborty, Iyer, Roy '17
1707.07084

Hadronic Energy fraction

$$\theta_J = \frac{1}{E_J} \sum_{i \in H_{cal} \in J} E_i$$

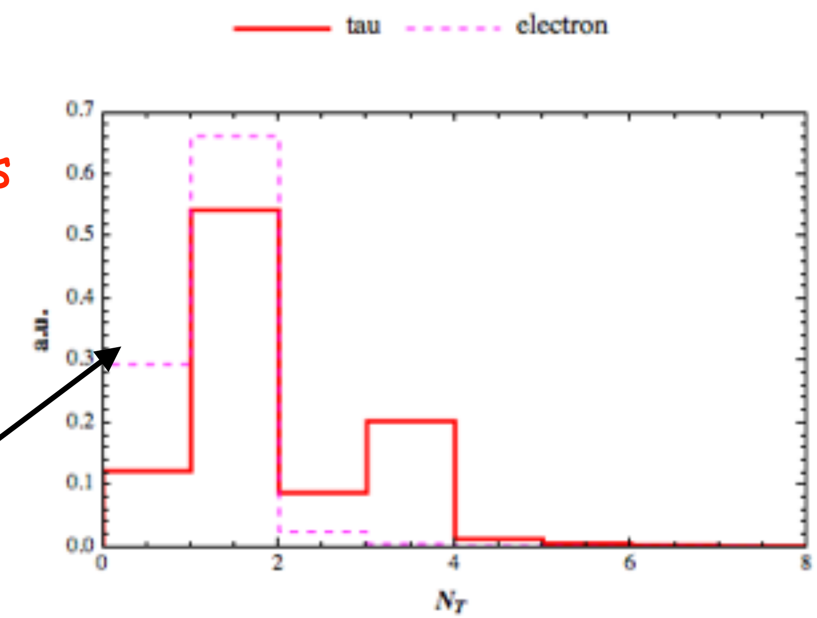


Select jets with very small hadron content

$$Log[\theta_J] < -0.5$$

To extract maximum information from the electron jet system we make the following selection

Use substructure variables to distinguish electron jets from QCD jets



Some Tracks getting lost?

Capture Missing Tracks!!

- Leading jet has exactly one track: Takes care of photon fakes
- Sub-Leading jet may have either one or zero track. This is to capture events lost by tracker.

We put a min invariant mass cut of 1000 GeV on leading jets to ensure a democratic analysis

QCD fake rate was found to be < 1 event in 300000

$m_{Z'}$ (GeV)	$Z \to \mu\mu$	$Z \to ee$ (Electron jets)
2000	71.45	64.75
2500	66.35	63.06
3000	58.79	60.37
3500	51.68	59.50

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A Brief comment on $Z' \to \tau\tau$

This could give a rough estimate of $B \to K^* \tau\tau \ (C^{\tau}_{9,10})$

We look at hadronic decay of tau.

One way to possibly distinguish it from qcd jets is to look at track multiplicity

For leading jets we look at jets with either 1 or 0 tracks but with large hadronic content.
This distinguishes it from the electron jets.

QCD fake ~ 0.2%

$m_{Z'}$ (GeV)	$Z \to \mu\mu$	$Z \to ee$ (Electron jets)	$Z \to \tau\tau$ (tau jets)
2000	71.45	64.75	31.25
2500	66.35	63.06	37.28
3000	58.79	60.37	40.88
3500	51.68	59.50	43.98

What about leptoquarks!!

Disclaimer: Preliminary

Consider the following effective lagrangian

$$\mathcal{L} = \lambda^1_{\alpha k}\bar{Q^c_\alpha} i\tau_2 L_k (\Phi_1)^\dagger + \lambda^3_{\alpha k}\bar{Q^c_\alpha} i\tau_2 (\tau.\Phi_3)^\dagger L_k \ + \ h.c.$$

With the following hierarchy of couplings

$$\lambda^3_{sl} = \frac{m_s}{m_b}\lambda^3_{bl} \qquad \lambda^3_{cl} = \frac{m_c}{m_t}\lambda^3_{tl}$$

Gudrun Hiller's talk: Moriond QCD

Using this the WC are simply

$$C_9^e \propto \frac{\lambda_{be}\lambda_{se}}{M_{LQ}^2} = \frac{m_s \lambda_{be}^2}{m_b M_{LQ}^2} \quad ; \quad C_9^\mu \propto \frac{\lambda_{b\mu}\lambda_{s\mu}}{M_{LQ}^2} = \frac{m_s \lambda_{b\mu}^2}{m_b M_{LQ}^2}$$

With the ratio

$$\frac{C_9^e}{C_9^\mu} = \frac{\lambda_{be}^2}{\lambda_{b\mu}^2}$$

With this hierarchy, b quark fusion dominates over the charm contribution

We are interested in the T channel production: The cross-section goes as λ^4

Implying a pattern

$$\delta \simeq \left(\frac{C_9^\mu}{C_9^e}\right)^2$$

Similar to Z'

To Conclude…

We considered a scenario in a warped framework where both Muon and electron couple to NP

Extent of muon and Electron contribution can be extracted at LHC

The techniques can also be extended to di-tau final states with some hints on other flavour experiments.

Gherghetta, Pomarol

Elements of the framework 2.:

Fermions in RS

Bulk fermionic lagrangian in a warped background is written as

$$\mathcal{L}_{\mathrm{fermion}} \quad = \quad e^{-3\sigma}\overline{\Psi}\left[i\gamma^{\mu}\partial_{\mu} - \gamma_5\, e^{-\sigma}\left(\partial_5 - 2\sigma'\right)\right]\Psi$$

where $\sigma = k|y|$. Expanding the bulk field as

$$\Psi(x,y) = \frac{1}{\sqrt{\pi R}}\sum_n \left[\psi_L^{(n)}(x) f_L^{(n)}(y) + \psi_R^{(n)}(x) f_R^{(n)}(y)\right]$$

↓ But

5D theory is non-chiral

Scenario B:

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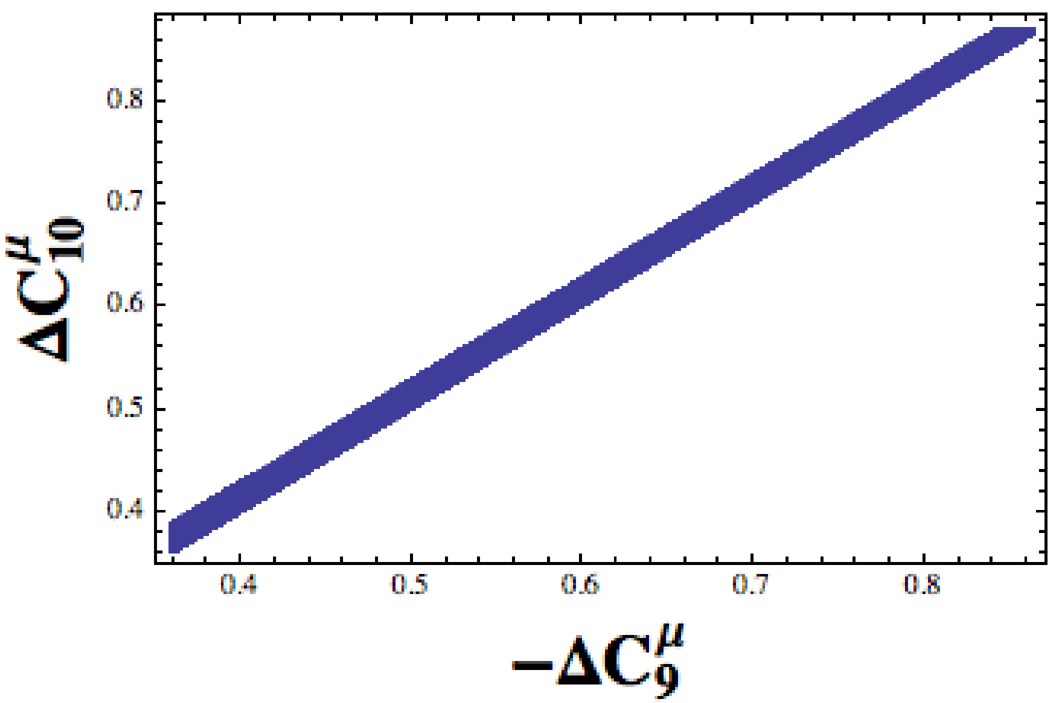

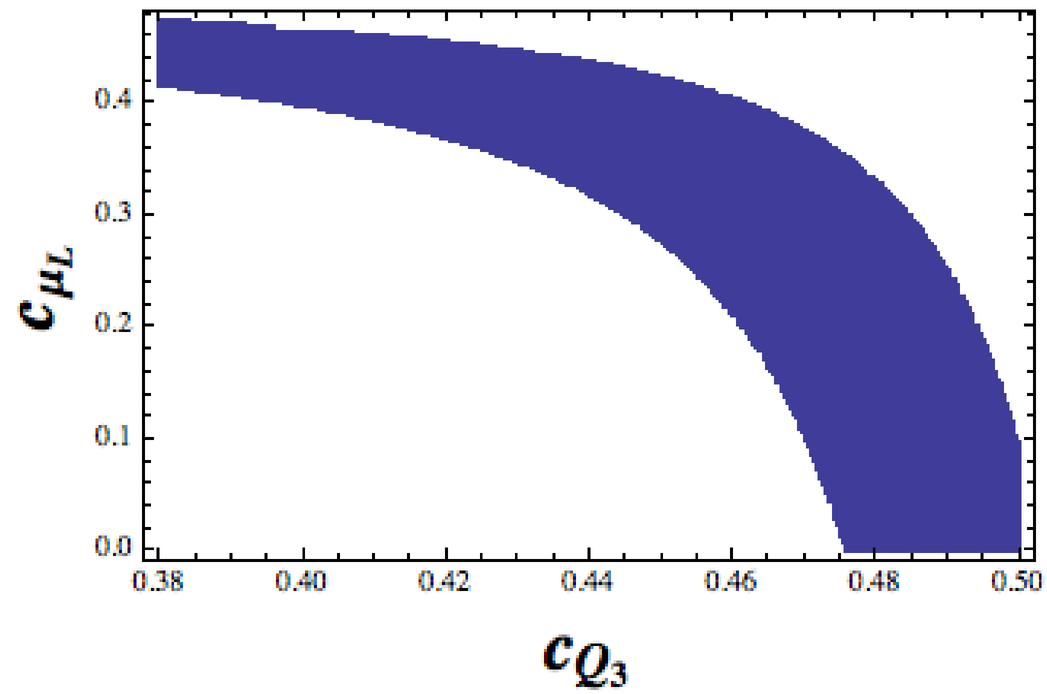

$$c_{\mu_R} \in [0.5, 0.6] \quad c_{Q_3} \in [0.4, 0.5] \quad c_{L_2} \in [0, 0.5]$$

The Z- mu mu coupling is not a problem as the doublets are also embedded in custodial representations!

From B anomalies to rare Kaon decays

Rare Kaon decays are likely to constitute the next probe for NP

The SM expectation is

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 8.3 \pm 0.3 \pm 0.3 \times 10^{-11} \quad \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = 2.9 \pm 0.2 \pm 0.0 \times 10^{-11}$$

The current experimental bound is

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11} \quad \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \leq 2.6 \times 10^{-8} \quad (90\% \text{ C.L.})$$

The NA62 aims to achieve 15% precision wrt SM in 2018

The KOTO experiment is focussed at measuring the KL decays

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Scenario A:

The effective lagrangian for $s \to d\nu\nu$ transitions is given as

$$\mathcal{L} = \frac{4G_F\alpha}{2\sqrt{2}\pi} V_{ts}^* V_{td} C_{ds,l} \left(\bar{s}_L \gamma_\mu d_L\right) \left(\bar{\nu}_l \gamma^\mu \nu_l\right)$$

Neutrino couplings are determined by the lepton doublet parameters!

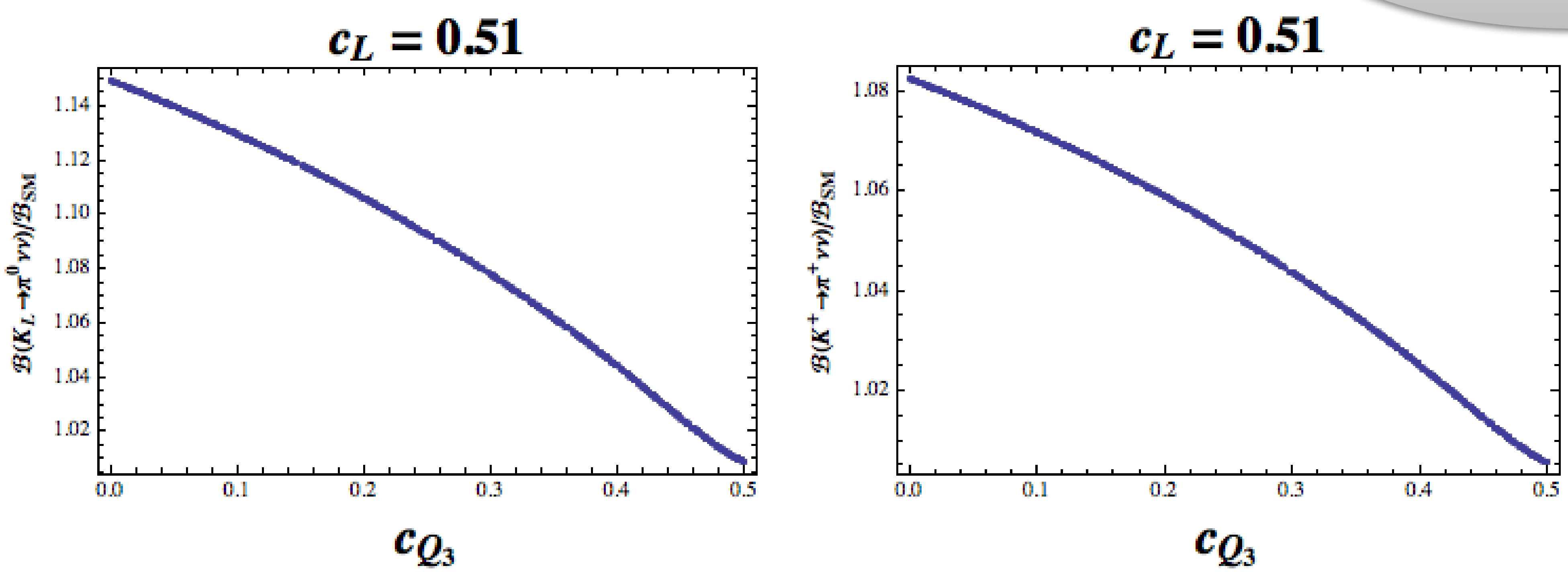

Figure 6: Scenario **A**: Plots depicting the excess over the SM expectation for the K decays modes. The c parameters for the doublets is universal and chosen to be $c_L = 0.51$.

Due to universality of lepton doublets, the contributions cannot be enhanced beyond a point!

Scenario B:

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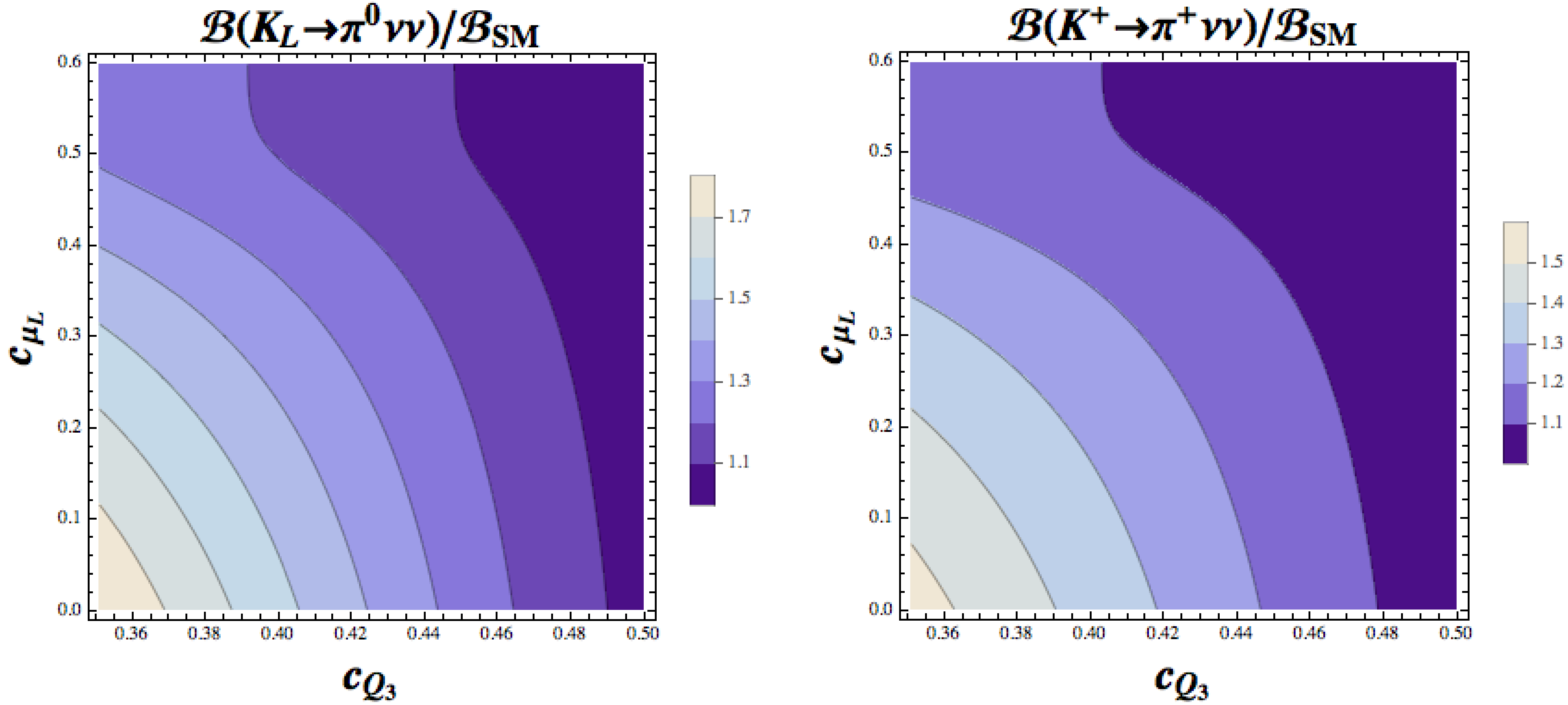


Figure 7: Scenario **B**: Plots depicting the excess over the SM expectation for the K decays modes. $c_{\tau_L} = 0.4$ and $c_{e_L} = 0.6$ are fixed for the computation while c_{μ_L} is varied.

The larger contributions in this case are primarily due c_{L_3} is free compared to Scenario A.

How do we reproduce chiral SM ?

Z_2

$$\Psi = \begin{bmatrix} \psi_L(+) \\ \psi_R(-) \end{bmatrix}$$

even -massless zero mode

odd -no zero mode

Zero mode for the Z_2 even field say $f_L^{(0)}$ satisfies

Localized profiles!!

$$e^{-\sigma}\left(\partial_y - 2\sigma'\right) f_L^{(0)} = 0$$

Using orthonormality → field re-definitions

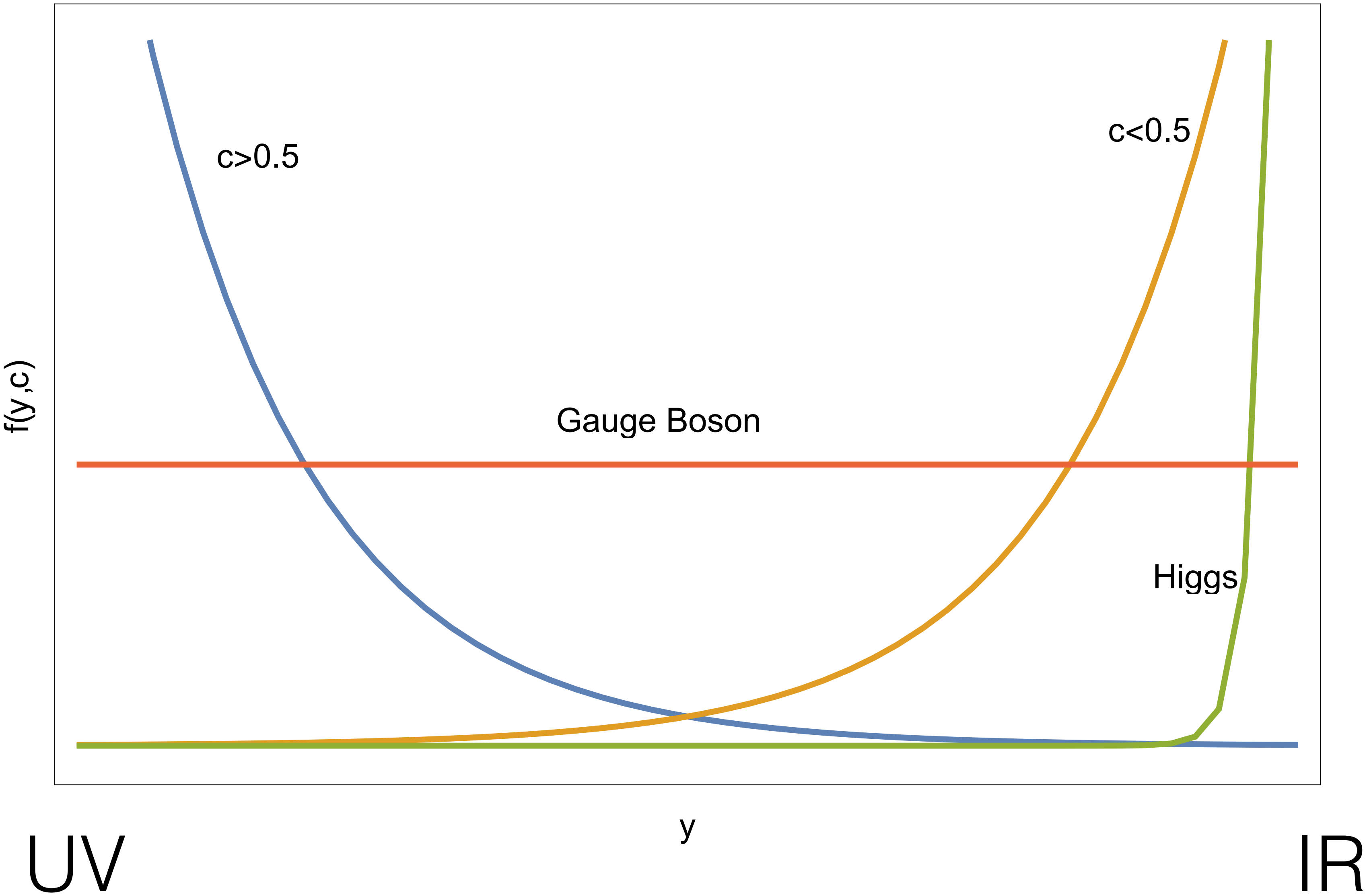
$$f_L^{(0)} = N e^{k0.5(y-\pi R)}$$

Introducing a bulk mass term $m_{1/2} = c\sigma' = ck$ modifies the solution to

$$f_L^{(0)} = N e^{(0.5-c)\sigma(y)}$$

Gherghetta, Pomarol

SM Couplings are given by the `overlap' of these profiles:



Yukawa hierarchy solved!!

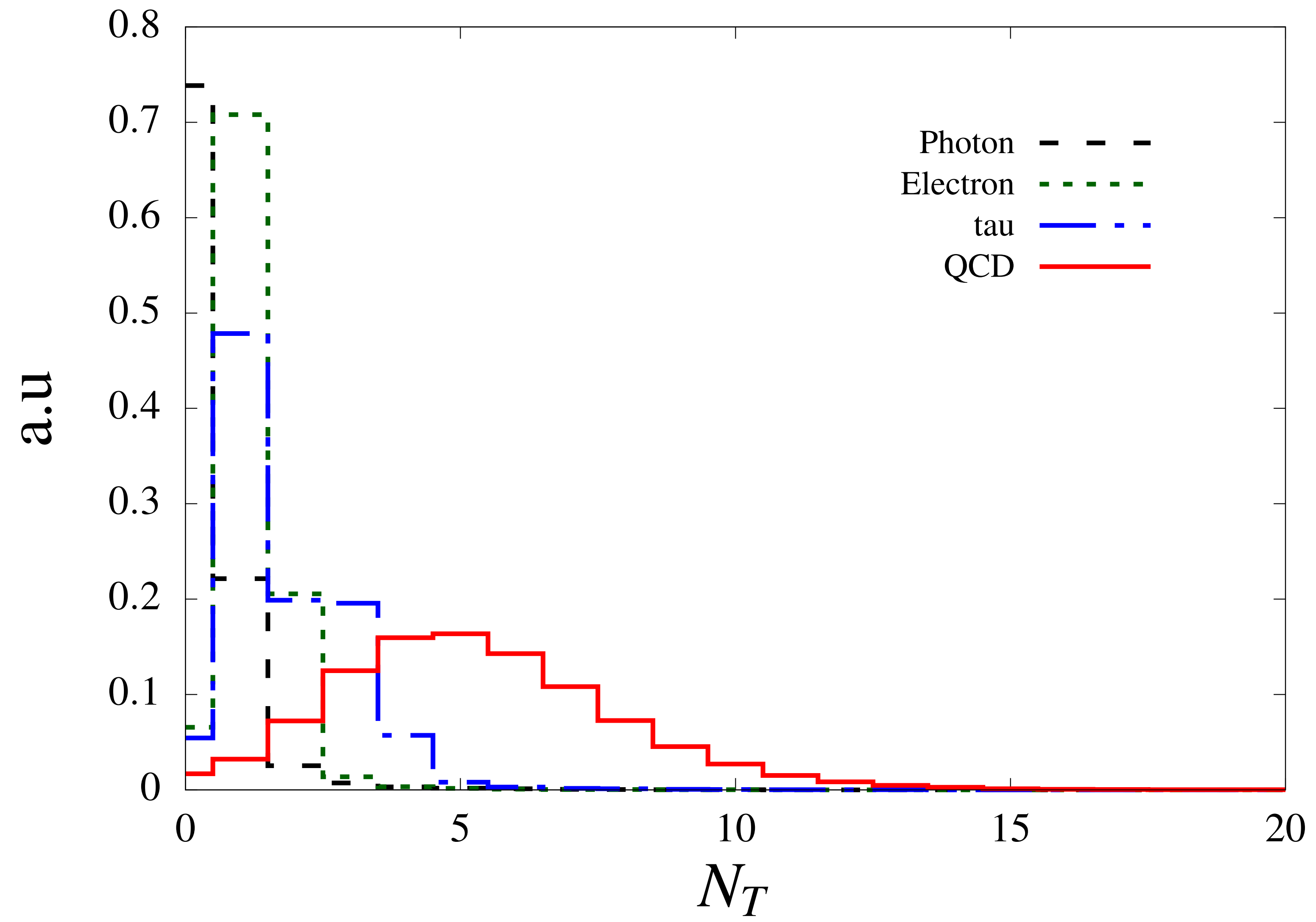
$$Y^{(4)} = Y^{(5)} \int_0^{\pi R} dy \; f_0^{(0)}(b,y) f_{1/2}^{(0)}(c_L, y) f_{1/2}^{(0)}(c_R, y)$$

How to get rid of QCD

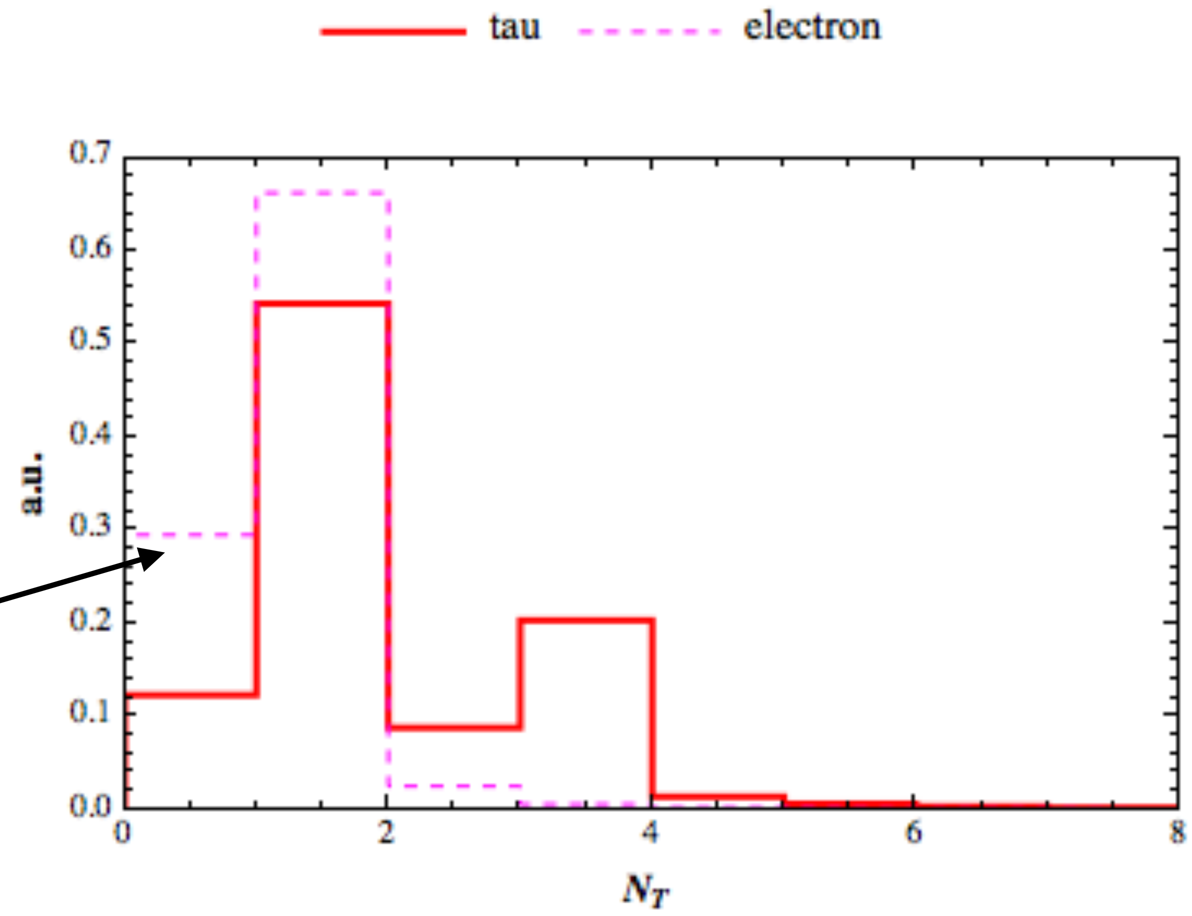
Chakraborty, Iyer, Roy '17
1707.07084

tracks

Select jets with zero tracks



tracks



Some Tracks getting lost?