Effective Field Theory & New Physics @ LHC

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1. Introduction to Effective Field Theory

   Georgi, EFT, ARNPP 43(93) 209
   (one of my all-time favourite papers)

   - *what* is it? (perturbation theory in scale ratios)
   - *how* to implement in QFT (?loops with $p_{loop} \to \infty$)

     to organise the SM/NP calculation, need: $\left\{ \begin{array}{l} \text{basis of } d > 4 \text{ operators,} \\ \text{recipe for changing scale} \end{array} \right.$
   - *why*: two perspectives: $\left\{ \begin{array}{l} \text{top} - \text{down} \\ \text{bottom} - \text{up} \end{array} \right.$

2. How well does bottom-up EFT work? ($\Leftrightarrow$ (when) are dim 6 operators a good approx to NP?)
   - Lepton Flavour Violation
   - contact interaction searches

3. The interest of looking for everything...

NP $\equiv$ New Physics , $\hat{s}$ = partonic centre-of-mass energy , **dim** = dimension

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- EFT $=$ recipe to study observables at scale ℓ
  1. choose $appropriate$ variables to describe $relevant$ dynamics (eg use $\vec{E}$, $\vec{B}$ and currents for radio waves, electrons and photons at LEP)
  2. 0th order interactions, by sending all parameters $\left\{ \begin{array}{ll} L \gg \ell & \to \infty \\ \delta \ll \ell & \to 0 \end{array} \right.$
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Example : leptogenesis in the early Universe of age τ_U ($\tau_U \sim 10^{-24}$ sec)

$\star$ processes with $\tau_{int} \gg \tau_U$ ...neglect!

$\star$ processes with $\tau_{int} \ll \tau_U$ ...assume in thermal equilibrium!

$\star$ processes with $\tau_{int} \sim \tau_U$ ...calculate this dynamics

$\star$ can then do pert. theory in slow interactions and departures from thermal equil.

Pre-implementation of EFT in the SM , and for NP

- take scale to be energy E : GeV $\to \Lambda_{NP}(\gtrsim$ few TeV) (then do pert. theory in $E/M, m/E$ for $m \ll E \ll M$)

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  $\Rightarrow$ machinery to regularise (loop integrals) and renormalise (coupling constants)

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$\Rightarrow$ like in SM, EFT coupling constants (= operator coefficients) live in $\mathcal{L}$ rather than real world, are *not* observables...

Can parametrise NP@LHC in S-matrix-based approach = "pseudo-observables"/(form factors), more general, less QFT-detail-dependent, more difficult?

EFT for the SM and heavy NP ($\Lambda_{NP} \gg m_W$)

1. choose energy scale E of interest

$\Lambda_{NP} \gtrsim$ few TeV

$m_W \sim m_h \sim m_t$

GeV $\sim m_c, m_b, m_\tau$

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4. perturb in E/M (and m/E): allow $d > 4$ local operators $\Leftrightarrow$ exchange of $M \gg E$ particles

d counts field dims in interaction: $(\overline{\psi}\psi)(\overline{\psi}\psi) \leftrightarrow$ dim 6

$\Lambda_{NP} \gtrsim$ few TeV

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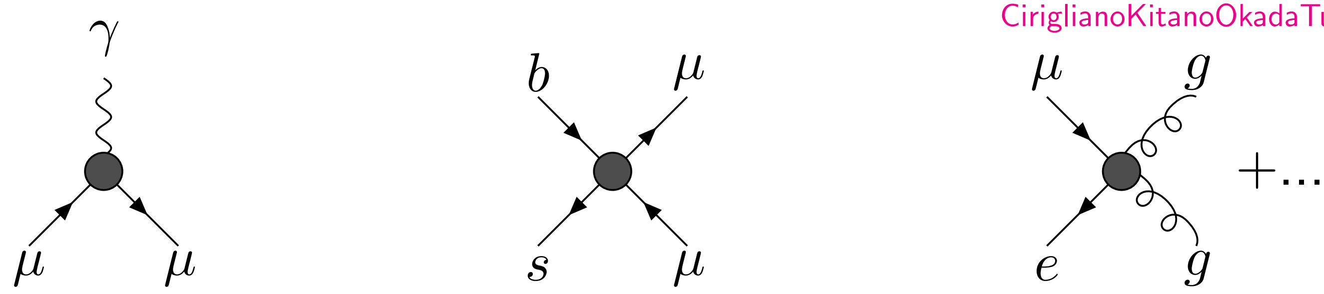
To implement in practise, need operator basis $+$ recipe to change scale

at scale E, need a basis of operators, of dimension $d > 4$

1. $E < m_W$: 3- and 4-point interactions of $f', \gamma, g \Leftrightarrow$ dimension 5,6,7 QCD*QED-invariant operators:

Kuno-Okada
CiriglianoKitanoOkadaTuscon



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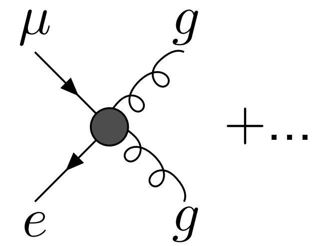

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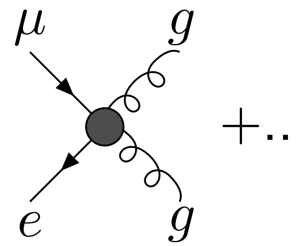

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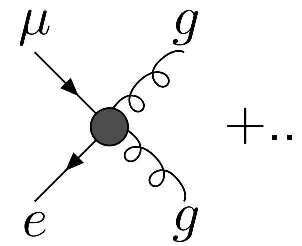

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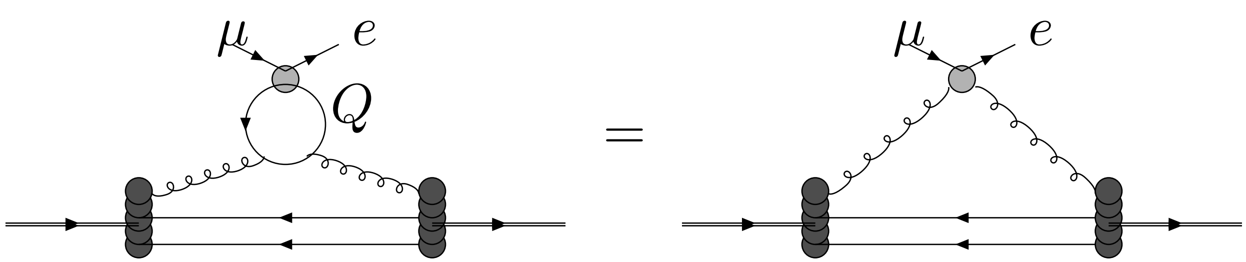
top-down: imagine an interaction $(\bar{e}\mu)(\overline{Q}Q)$ for heavy quarks $Q \in \{c, b, t\}$
contributes to $\mu \to e$ conversion on a proton via:



ShifmanVainshteinZakarov

so below m_Q, replace $\dfrac{C}{\Lambda^2_{NP}}(\bar{e}\mu)(\bar{Q}Q) \;\to\; \dfrac{C}{\Lambda^2_{NP}m_Q}(\bar{e}\mu)G^{A\ \alpha\beta}G^A_{\alpha\beta}$

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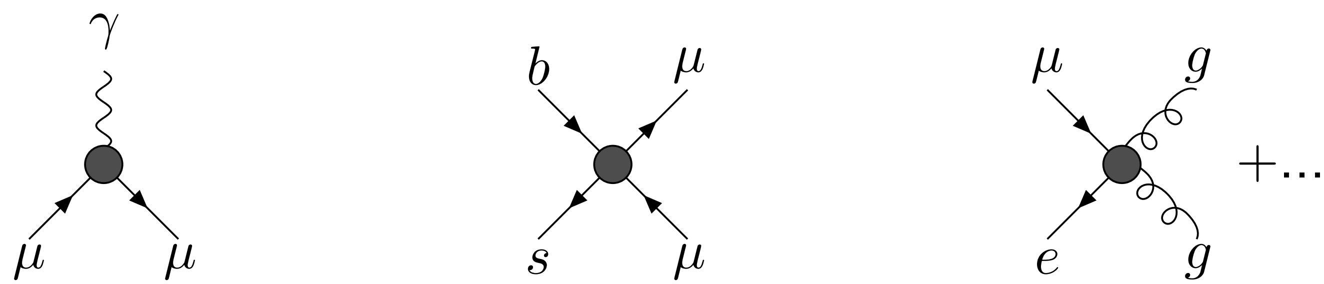
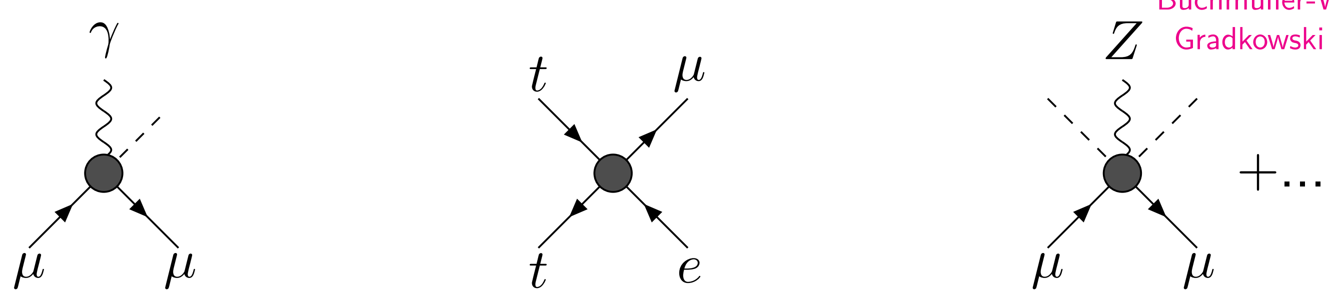


2. $E > m_W$: dim 6 $SU(3) \times SU(2) \times U(1)$-invar operators (neglect Majorana ν mass operators)

Buchmuller-Wyler
Gradkowski etal



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   match (= set equal) Greens functions
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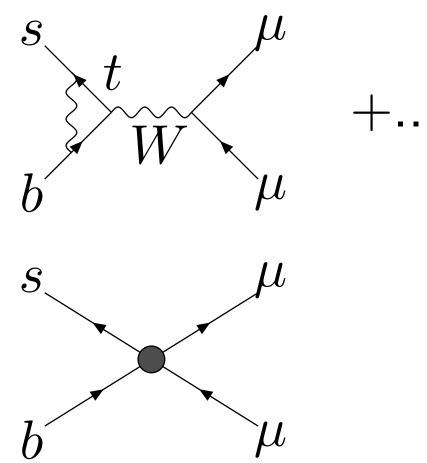

$G_F C_V (\bar{s}\gamma b)(\bar{\mu}\gamma\mu)$

$$\Rightarrow C_V(m_W) \sim \frac{V_{ts}}{16\pi^2}$$

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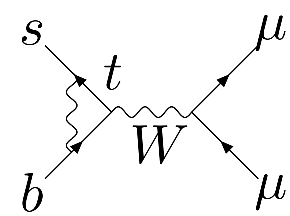
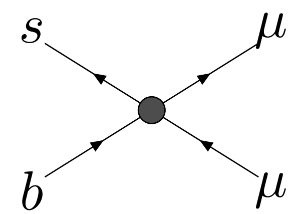


+...



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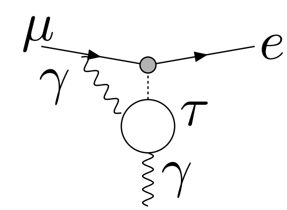
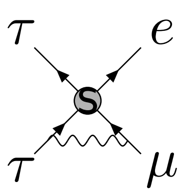
2. Within an EFT: couplings (= operator coefficients) run and mix with scale. Can
   mix to other operators, (better?) constrained at other scales





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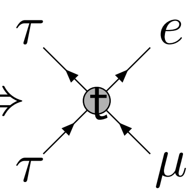
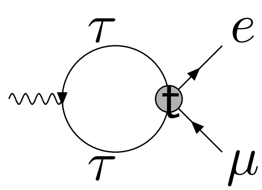


$(\bar{\tau}\sigma\tau)(\bar{e}\sigma\mu)$



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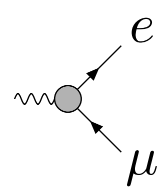

1) dominant part of 2-loop caln
   from (trivial 1-loop caln)^2 !

2) sensitivity of $\mu \to e\gamma$ to
   scalar $\bar{\tau}\tau\bar{e}\mu$ operator !

(replace $\tau \to t$ if you like)

Why do EFT: top-down vs bottom-up

Two perspectives in EFT:

top-down: EFT as the simple way to get the right answer

know the high-scale theory = can calculate the coefficients of dim > 4 operators (because know cplings $\Leftrightarrow$ other perturbative expansions)

recall: EFT is perturbative expansion in scale ratios (eg m_B/m_W)

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bottom-up: EFT as a parametrisation of ignorance

not know NP masses, or couplings = other perturbative expansions

⇒ use lowest order EFT expansion (in scale ratio m_{SM}/Λ_{NP}) to parametrise ... (?we hope??) many models

⇒ how well does bottom-up EFT work?

How well does bottom-up EFT work?

(top-down: just do perturbative expansion to sufficient order...)

1. How precisely are the SM dynamics included?
   (non-trivial problem: perturb in loops$+$ Yukawa$+$ gauge cplings $y_t^2/16\pi^2 \sim y_c^2$.
   In addition, matching at m_W delicate due to appearance of Higgs vev which changes operator dimensions)

2. How good is lowest order EFT (dim 6 operators), as a parametrisation of New Physics?

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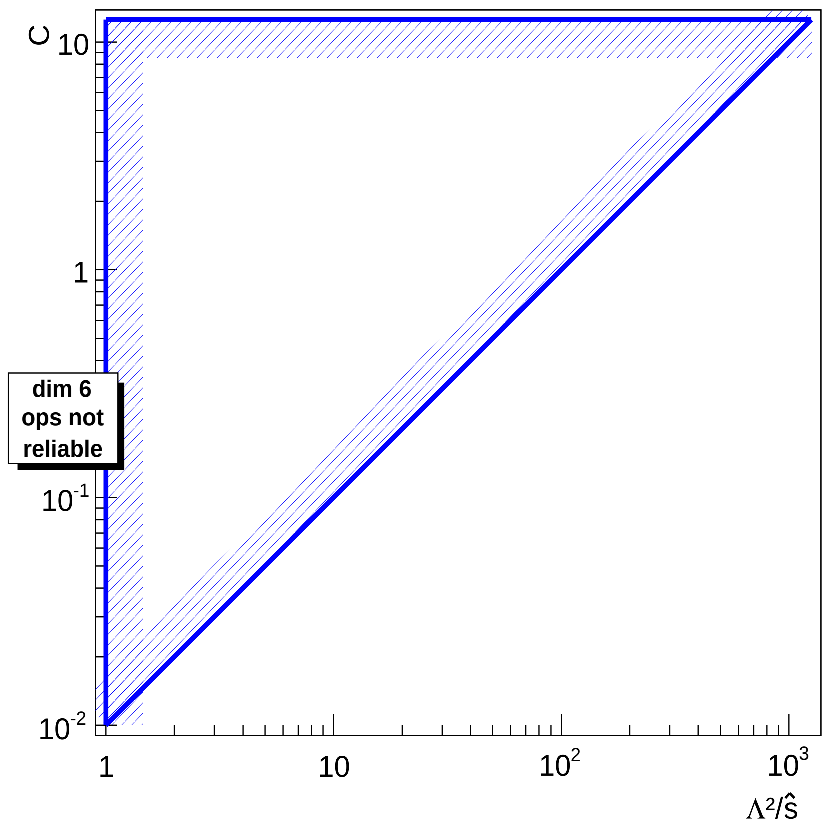
($\epsilon = 10^{-2}$ in the plot)

Bigger triangle for smaller ϵ (more lumi?);
more models fit in bigger triangle...



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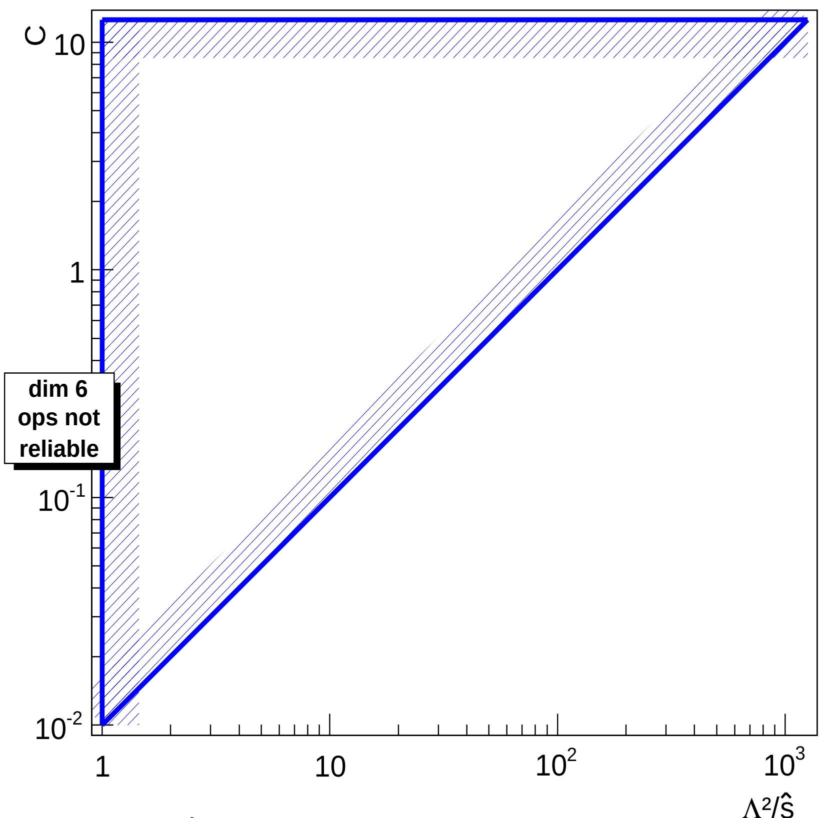

Ex: $BR(h \to \tau^+\mu^-) \sim .01$, induced by $\frac{C}{\Lambda_{NP}^2} H^\dagger H \overline{\ell_\mu} H \tau_R$:

$$\sqrt{BR} y_b < C \frac{m_h^2}{\Lambda_{NP}^2} < 4\pi$$

...can probe $\left\{ \begin{array}{c} C \gtrsim 1 \\ C \gtrsim 0.1 \end{array} \right\}$ for $\left\{ \begin{array}{c} \Lambda_{NP} \gtrsim 10 m_h \\ \Lambda_{NP} \gtrsim 3 m_h \end{array} \right\}$.

If a model induces dim-6 ops in that triangle,
are they a good approx to the model?

? maybe ? I think no answer in EFT — depends on model

EFT is a perturbative expansion in scale ratios ($eg\ \hat{s}/\Lambda_{NP}^2$)
...so if know $\hat{s}/\Lambda_{NP}^2$, could estimate size of next order term
...but measure $C_6\frac{\hat{s}}{\Lambda_{NP}^2}$, C_6 unknown (model-dep)
$\Rightarrow$ size of $C_8\frac{\hat{s}^2}{\Lambda_{NP}^4}$model-dependent too ??

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to get an idea if dim 6 ops are a good approximation:

1. Consider the formula for your favourite observable in your favourite model
2. expand in $\frac{1}{\Lambda_{NP}^2}$
3. check if the $\mathcal{O}(\frac{1}{\Lambda_{NP}^2})$ terms are a good approximation?

Repeat many times.

Are lowest order operators a good approximation? (examples)

1. $gg \rightarrow h$ in the SM
   m_h^2/m_t^2 is not small...
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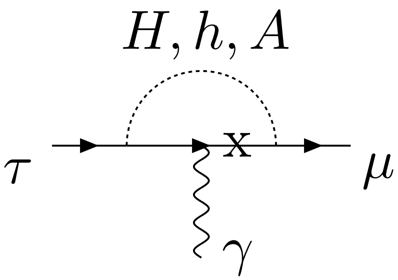
2. $h \to \tau^+\mu^-$ and $\tau \to \mu\gamma$ in the 2HDM with LFV, decoupling limit.



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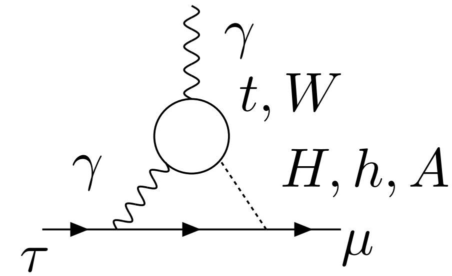
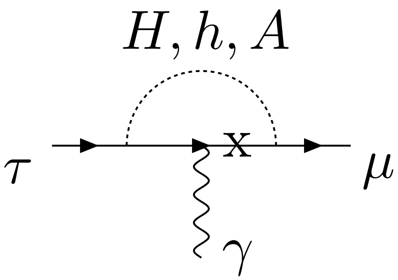


- decoupling limit: $m_{H,A,H^\pm} \approx \Lambda_{NP} \sim 10\, m_{W,h}$
  $h \approx$ doublet-with-vev, $+$ other (heavy) doublet $\propto \lambda v^2/\Lambda^2$

- LeptonFlavourViolation: only for doublet sans-vev ($\approx$ heavy one)



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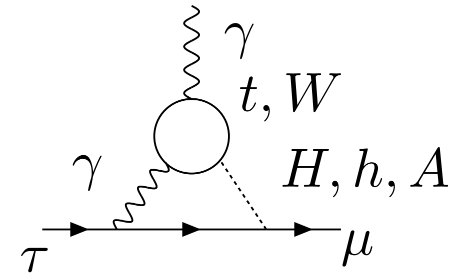

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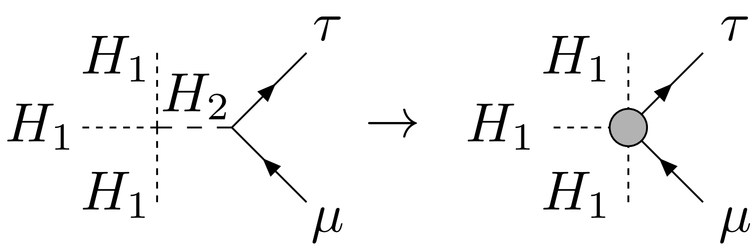

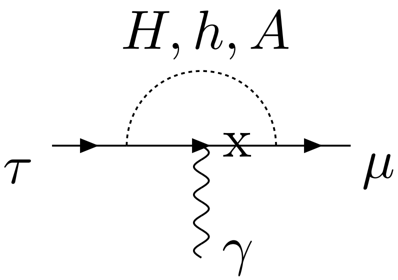

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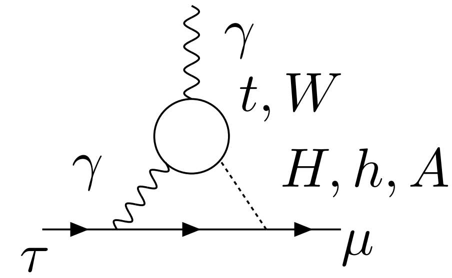

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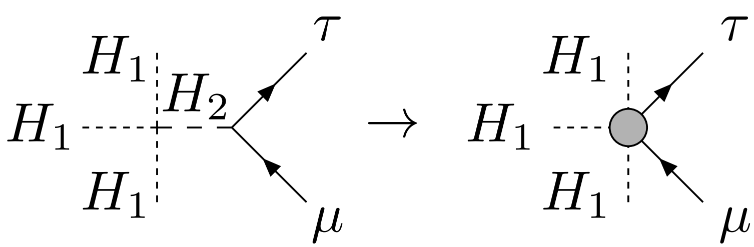
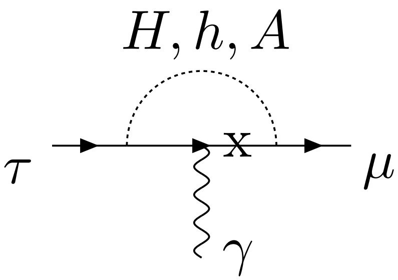


2. $\tau \to \mu\gamma$: dominant contributions from 2-loop diagrams

Bjorken-Weinberg



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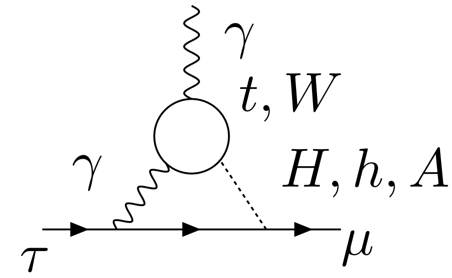

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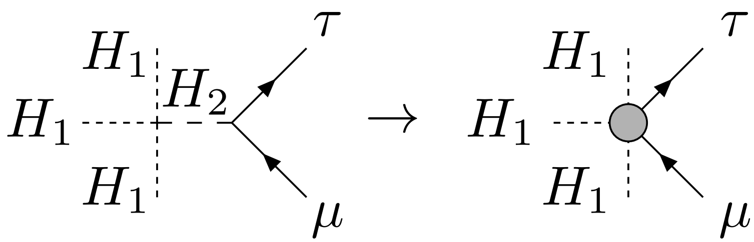

2. $\tau \to \mu\gamma$: dominant contributions from 2-loop diagrams
   dim 6 operators give 1 sig fig, for $v^2/\Lambda^2 \sim .01$ Bjorken-Weinberg

$$\frac{\text{dim } 8}{\text{dim } 6} \sim \quad \tan\beta \frac{v^2}{\Lambda_{NP}^2} \quad , \quad \frac{v^2}{\Lambda_{NP}^2} \ln^2\left(\frac{v^2}{\Lambda_{NP}^2}\right)$$

(ack: for $z = \frac{v^2}{\Lambda_{NP}^2} = .01, z \ln^2 z \simeq .2$. Also need 2-loop matching@m_W)

Are lowest order operators a good approximation? (examples)

1. $gg \to h$ in the SM
   m_h^2/m_t^2 is not small...
   but the lowest order terms (infinite m_t limit) are an excellent approximation!

2. $h \to \tau^+\mu^-$ and $\tau \to \mu\gamma$ in the 2HDM with LFV, decoupling limit.

   For $v/M_{H,A,H^\pm} \sim .1$, dim 6 operators give 1 sig. figure.

   (May need dim 8 operators for second sigfig, and LO includes 2-loop matching)

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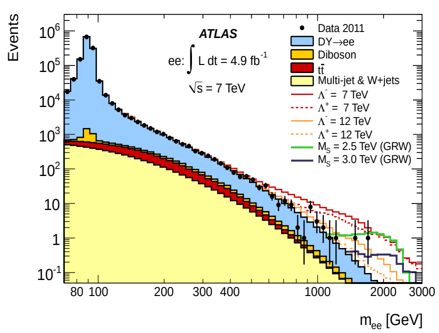
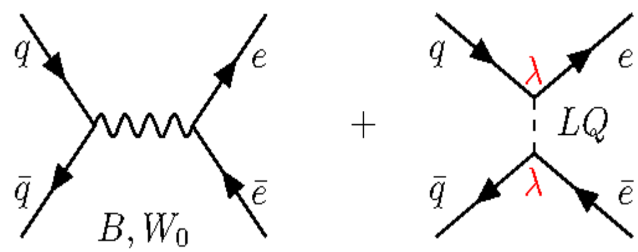
3. high-$\hat{s}$ tail of $pp \to \ell^+\ell^-$, mediated by a t-channel leptoquark with $m^2 \gtrsim \hat{s}_{max}$

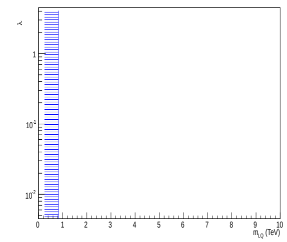




Leptoquarks in the tail of $pp \to \ell^+\ell^-$?

At 8 TeV LHC:

1. no pair production of 1st gen. LQ: $m_{LQ} \gtrsim 800$ GeV for $\lambda \gtrsim 10^{-7}$
2. Contact int. search in $pp \to e^+e^-$, with $\sqrt{\hat{s}_{max}} \lesssim 2$ TeV: $\Lambda_{CI} \gtrsim 10 - 20$ TeV.
   (depends on choice of operator, sign)
   $\Rightarrow$ does Λ_{CI} bd apply to LQ?



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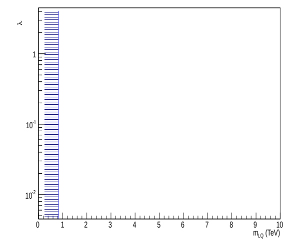
...but I can't apply Λ_{CI} bound to LQ :(



Two problems:

⋆ large uncertainties: could see $\mathcal{A}_{SM} \sim \mathcal{A}_{CI}$
$\Rightarrow$ sensitive to $\mathcal{A}_{SM} * \mathcal{A}_{\sum CI} + \sum |\mathcal{A}_{CI}|^2$
But to constrain arbitrary effective op
need separate bd on $\sum |\mathcal{A}_{CI}|^2$, $\mathcal{A}_{SM} * \mathcal{A}_{\sum CI}$!!

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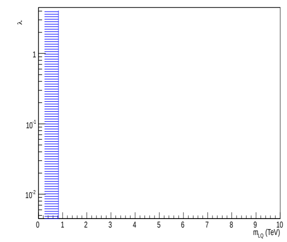

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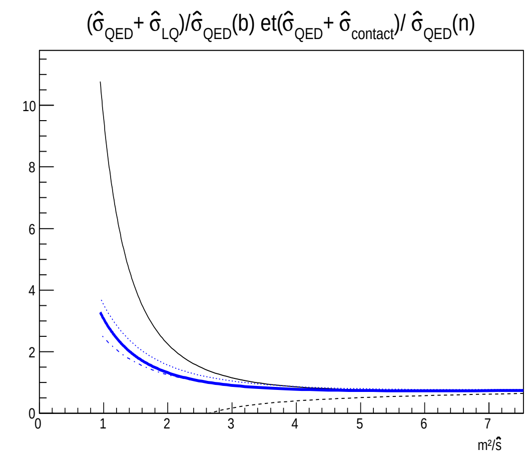
⋆ $\hat{s}/\Lambda^2$ not small ($\sim \alpha$)
  and poor convergence of $\sigma_{t-channel}$
  (expand in $\hat{s}/(\hat{s} + \Lambda^2)$ better)



$\Rightarrow$ fitting distribution tails to a form-factor-motivated function would allow to constrain many models...

Of the interest of many searches for New Physics

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• observable a function of a few (linear combos of) operators coefficents $C(\hat{s})$
• coefficients run and mix with scale
⇒ observables *sensitive* to many coefficients $C(\Lambda_{NP})$
constrain a few linear combination(s) of coefficients

⇒ need diverse observations to independently $\left\{ \begin{array}{c} \text{constrain all} \\ \text{determine non}-\text{zero} \end{array} \right\}$ coefficients

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ex $\mu \to e\gamma$:mediated at m_μ by dipole operators:

$$C_{\mu\to e\gamma,L} m_\mu 2\sqrt{2} G_F \overline{e} \sigma^{\alpha\beta} P_L \mu F_{\alpha\beta} \quad , \quad C_{\mu\to e\gamma,R} m_\mu 2\sqrt{2} G_F \overline{e} \sigma^{\alpha\beta} P_R \mu F_{\alpha\beta}$$

$$\begin{aligned} BR(\mu \to e\gamma) &= 384\pi^2 (|C_{\mu\to e\gamma,L}|^2 + |C_{\mu\to e\gamma,R}|^2) \leq 4.2 \times 10^{-13} \\ &\Rightarrow |C_{\mu\to e\gamma,L}|, |C_{\mu\to e\gamma,R}| < 10^{-8} \end{aligned}$$

MEG,1605.05081

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MEG,1605.05081

But (at some order in loop/coupling expansions), *all* dim 6 $\mu \to e$ operators contribute!
Eg, at Λ_{NP} (including 1-loop RGEs +some higher-loop matching corrections, $2\sqrt{2}G_F = 1/v^2 = 1/m_t^2$):

$$\begin{aligned} 10^{-8}\frac{\Lambda^2}{m_t^2} \gtrsim\ & C_{e\gamma}^{\mu e*}(\Lambda) - 0.016 C_{EH}^{\mu e*}(\Lambda) + 0.001 C_{HE}^{e\mu}(\Lambda) - 0.0043 C_{eZ}^{\mu e*}(\Lambda) \ln\frac{\Lambda}{m_W} - 59 C_{LEQU(3)}^{\mu ett*}(\Lambda) \ln\frac{\Lambda}{m_W} \\ & - C_{LEQU(3)}^{\mu ecc*}(\Lambda) \left(0.43 \ln\frac{\Lambda}{m_W} + 1.5 \right) + 0.039 C_{LEQU(1)}^{\mu ett*}(\Lambda) \ln^2\frac{\Lambda}{m_W} \\ & + 0.002 \left(1 + \ln\frac{\Lambda}{m_W} \right) C_{LEQU(1)}^{\mu ecc*}(\Lambda) - 4.8 \times 10^{-5} \ln^2\frac{\Lambda}{m_W} \left(C_{EQ}^{\mu ett*}(\Lambda) + C_{EU}^{\mu ett*}(\Lambda) \right) \end{aligned}$$

Does $BR(\mu \to e\gamma)$ imply that the LHC cannot see $h \to \mu^{\pm} e^{\mp}$?

Suppose:

at Λ_{NP}: $\mathcal{L}_{SM} \quad + \quad \frac{C_h}{v^2} H^\dagger H \overline{\ell_\mu} H e \quad + \quad \ldots \qquad \ldots \qquad + \quad \frac{C_{\mu\to e\gamma} Y_\mu}{v^2} \overline{\ell_\mu} H \sigma \cdot F e$

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At m_h: h decays to $\mu^\pm e^\mp$; $BR < 0.04 \Rightarrow \frac{C_h v^2}{\Lambda_{NP}^2} \lesssim 5 \times 10^{-3}$. CMS,1607.03561

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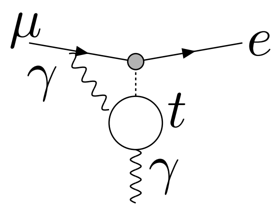
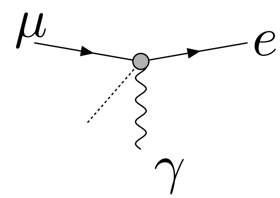
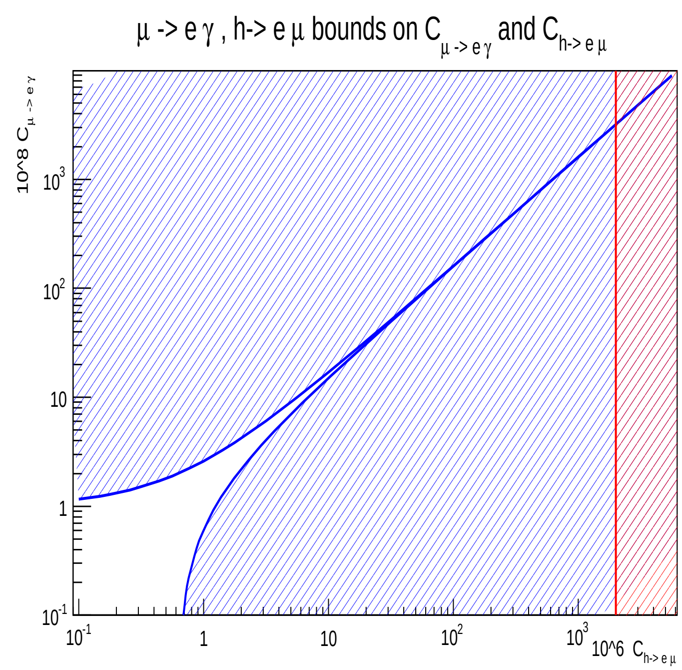


$+$



$$BR(\mu \to e\gamma) \Rightarrow \left| \frac{e\alpha}{8\pi^3 Y_\mu} C_h - C_{\mu\to e\gamma} \right| \lesssim 10^{-8} \frac{\Lambda^2}{v^2} \quad , \quad \frac{e\alpha}{8\pi^3 Y_\mu} \sim 10^{-2}$$

$\Rightarrow \mu \to e\gamma$ sensitive to $C_h v^2/\Lambda^2 \gtrsim 10^{-6}$...
but if you admit cancellation up to
one part per mil between C_h and C_{meg},
LHC can see $h \to \mu^{\pm}e^{\mp}$ now.



Summary

EFT is the way we do physics:

1. chose a scale E and relevant variables
2. perturb in scale ratios, eg E/M for $M \gg E$

   works for β-decay, quark flavour physics, etc

If you know the high-scale theory (top-down perpective), the EFT expansion in scale ratios is a simple way to get the answer to the desired accuracy = precision can be estimated

(just work to required order in all expansions)

precision harder to quantify "bottom-up": does EFT reproduce your favourite model?

(if not, explore your favourite model differently—simplified models, form factors, pseudo-observables etc)

Instead of a summary: why I do bottom-up EFT for leptons

There has to be New Physics in the lepton sector; we just don't know the mass scale of the couplings. Lets $assume$ its heavy NP.

Lots of models of heavy NP to give neutrino masses... but I don't know how to model-build, and anyway, why should new physics align with our cannons of beauty?

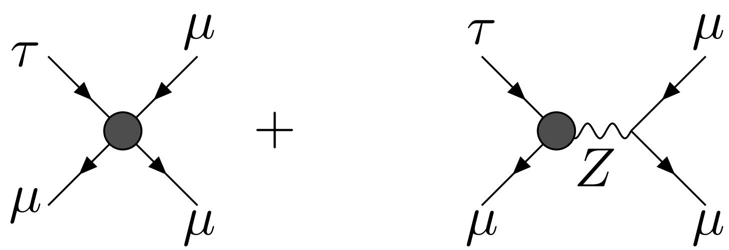
$\Rightarrow$ can I restrict/reconstruct the NP Lagrangian from the data?
1. using EFT, parametrise NP with dim 6 (maybe 8?) operators $\Leftrightarrow$ observables as a function of operator coefficients at exptal scale.
2. translate exptal bounds/observations to Λ_{NP} (in progress: dynamics is SM, nonetheless tricky).
3. *If I know $\mathcal{L}_{eff}(\Lambda_{NP})$, what can I learn about the fundamental Lagrangian?*

What does data tell me about New Physics?

Backup

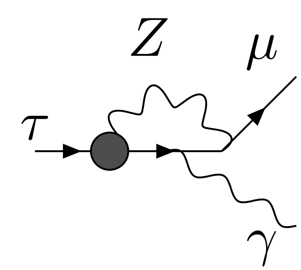
Why searching for all observables is interesting...(another example)

1. A Z penguin gives $\bar{\tau} \not{D} \mu$, which contributes at tree to $\tau \to \mu \bar{l} l$, in combination with $(\bar{\mu}\Gamma\tau)(\bar{l}\Gamma l)$:



2. Can ask "is is interesting for the LHC to search for $Z \to \tau^{\pm}\mu^{\mp}$?"
 For LHC8 to see, need penguin coefficient $\gtrsim$ "naive" bound from $\tau \to \mu \bar{l} l$
("naive" $=$ neglect possible cancellation with 4-f operator).

$\Rightarrow$ cancellations possible; but what about the bound on the penguin from $\tau \to \mu\gamma$?



$\tau \to \mu\gamma$ bound negligeable, so interesting for LHC to look for $\tau \to \mu\gamma$.
Same argument suggests they should not see $Z \to \mu^{\pm}e^{\mp}$.

The BWP basis: 2q2l and 4l

$$\mathcal{O}_{LQ}^{(1)e\mu nm} = \frac{1}{2}(\overline{L}_e\gamma^\alpha L_\mu)(\overline{Q}_n\gamma^\alpha Q_m) \qquad \mathcal{O}_{LQ}^{(3)e\mu nm} = \frac{1}{2}(\overline{L}_e\gamma^\alpha \tau^a L_\mu)(\overline{Q}_n\gamma^\alpha \tau^a Q_m)$$

$$\mathcal{O}_{EQ}^{e\mu nm} = \frac{1}{2}(\overline{E}_e\gamma^\alpha E_\mu)(\overline{Q}_n\gamma^\alpha Q_m)$$

$$\mathcal{O}_{LU}^{e\mu nm} = \frac{1}{2}(\overline{L}_e\gamma^\alpha L_\mu)(\overline{U}_n\gamma^\alpha U_m) \qquad \mathcal{O}_{LD}^{e\mu nm} = \frac{1}{2}(\overline{L}_e\gamma^\alpha L_\mu)(\overline{D}_n\gamma^\alpha D_m)$$

$$\mathcal{O}_{EU}^{e\mu nm} = \frac{1}{2}(\overline{E}_e\gamma^\alpha E_\mu)(\overline{U}_n\gamma^\alpha U_m) \qquad \mathcal{O}_{ED}^{e\mu nm} = \frac{1}{2}(\overline{E}_e\gamma^\alpha E_\mu)(\overline{D}_n\gamma^\alpha D_m)$$

$$\mathcal{O}_{LEQU}^{e\mu nm} = (\overline{L}_e^A E_\mu)\epsilon_{AB}(\overline{Q}_n^B U_m) \qquad \mathcal{O}_{LEQU}^{\mu enm} = (\overline{L}_\mu^A E_e)\epsilon_{AB}(\overline{Q}_n^B U_m)$$

$$\mathcal{O}_{LEDQ}^{e\mu nm} = (\overline{L}_e E_\mu)(\overline{D}_n Q_m) \qquad \mathcal{O}_{LEDQ}^{\mu enm} = (\overline{L}_\mu E_e)(\overline{D}_n Q_m)$$

$$\mathcal{O}_{T,LEQU}^{e\mu nm} = (\overline{L}_e^A \sigma^{\mu\nu} E_\mu)\epsilon_{AB}(\overline{Q}_n^B \sigma_{\mu\nu} U_m) \qquad \mathcal{O}_{T,LEQU}^{\mu enm} = (\overline{L}_\mu^A \sigma^{\mu\nu} E_e)\epsilon_{AB}(\overline{Q}_n^B \sigma_{\mu\nu} U_m)$$

$$\mathcal{O}_{LL}^{e\mu ii} = \frac{1}{2}(\overline{L}_e\gamma^\alpha L_\mu)(\overline{L}_i\gamma^\alpha L_i)$$

$$\mathcal{O}_{LE}^{e\mu ii} = \frac{1}{2}(\overline{L}_e\gamma^\alpha L_\mu)(\overline{E}_i\gamma^\alpha E_i) \qquad \mathcal{O}_{LE}^{iie\mu} = \frac{1}{2}(\overline{L}_i\gamma^\alpha L_i)(\overline{E}_e\gamma^\alpha E_\mu)$$

$$\mathcal{O}_{EE}^{e\mu ii} = \frac{1}{2}(\overline{E}_e\gamma^\alpha E_\mu)(\overline{E}_i\gamma^\alpha E_i)$$

$$-\frac{1}{2}\mathcal{O}_{LE}^{e\tau\tau\mu} = (\overline{L}_e E_\mu)(\overline{E}_\tau L_\tau) \qquad -\frac{1}{2}\mathcal{O}_{LE}^{\mu\tau\tau e} = (\overline{L}_\mu E_e)(\overline{E}_\tau L_\tau)$$

The BWP basis: 2l

$$\mathcal{O}^{e\mu}_{EH} = H^\dagger H \overline{L}_e H E_\mu \qquad \mathcal{O}^{\mu e}_{EH} = H^\dagger H \overline{L}_\mu H E_e$$

$$\mathcal{O}^{e\mu}_{eW} = y_\mu (\overline{L}_e \vec{\tau}^a H \sigma^{\alpha\beta} E_\mu) W^a_{\alpha\beta} \qquad \mathcal{O}^{\mu e}_{eW} = y_\mu (\overline{L}_\mu \vec{\tau}^a H \sigma^{\alpha\beta} E_e) W^a_{\alpha\beta}$$

$$\mathcal{O}^{e\mu}_{eB} = y_\mu (\overline{L}_e H \sigma^{\alpha\beta} E_\mu) B_{\alpha\beta} \qquad \mathcal{O}^{\mu e}_{eB} = y_\mu (\overline{L}_\mu H \sigma^{\alpha\beta} E_e) B_{\alpha\beta}$$

$$\mathcal{O}^{(1)e\mu}_{HL} = i(\overline{L}_e \gamma^\alpha L_\mu)(H^\dagger \overset{\leftrightarrow}{D}_\alpha H)$$

$$\mathcal{O}^{(3)e\mu}_{HL} = i(\overline{L}_e \gamma^\alpha \vec{\tau} L_\mu)(H^\dagger \overset{\leftrightarrow}{D}_\alpha \vec{\tau} H)$$

$$\mathcal{O}^{e\mu}_{HE} = i(\overline{E}_e \gamma^\alpha E_\mu)(H^\dagger \overset{\leftrightarrow}{D}_\alpha H)$$

where $i(H^\dagger \overset{\leftrightarrow}{D}_\alpha H) \equiv i(H^\dagger D_\alpha H) - i(D_\alpha H)^\dagger H$, and $D_\alpha = \partial_\alpha + i\frac{g}{2} W^a_\alpha \tau^a + i\frac{g'}{2} B_\alpha$. (The sign in the covariant derivative fixes the sign of the penguin operator and the SM Z vertex.)