THEORETICAL DEVELOPMENTS IN HIGGS PHYSICS

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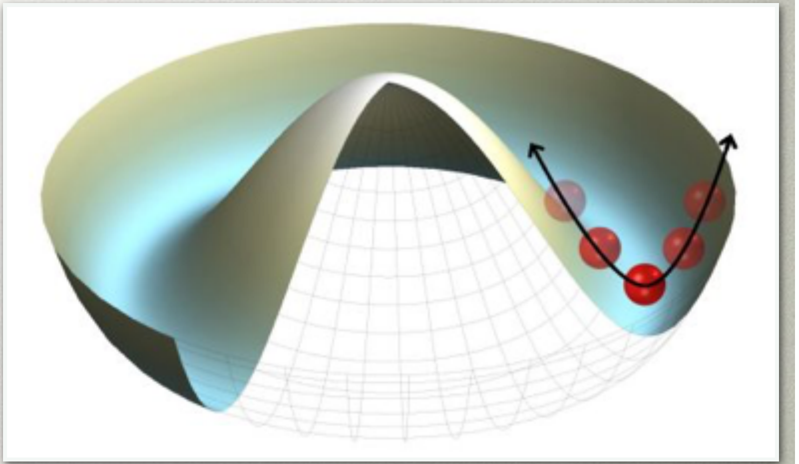
Annual Theory Meeting, IPPP Durham, Dec 19 2016

HIGGS AS A PROBE OF NP



- in the SM Higgs sector defined by only two parameters, μ, λ

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

- both of these are now well known

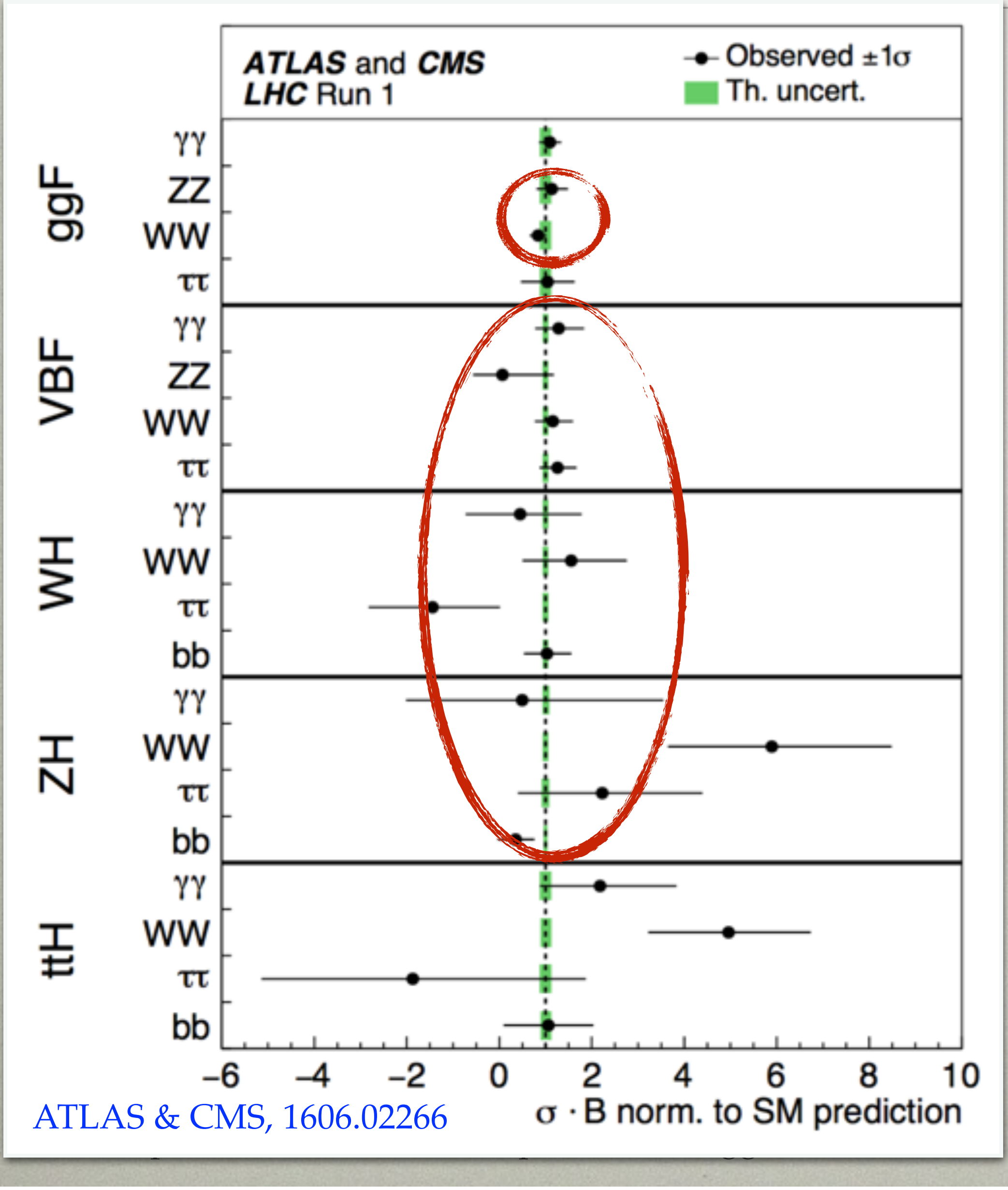
$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \qquad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \qquad \Longrightarrow \qquad \begin{array}{l} \mu = m_H \\ \lambda = m_H^2/(2v^2) \end{array}$$

- the couplings of the Higgs to gauge bosons, fermions now completely known in the SM
- can use Higgs as a probe of NP

HIGGS PHYSICS IN A NUTSHELL

- Higgs has a dual role in the SM
  - breaks EW symmetry, gives masses to W and Z
  - gives masses to all charged fermions
- 2 related questions:
  - is it the dominant source of EWSB?
  - are the Yukawas the SM ones?
- hierarchy problem
  - why $m_h \ll M_{Planck}$

DOMINANT SOURCE OF EWSB?

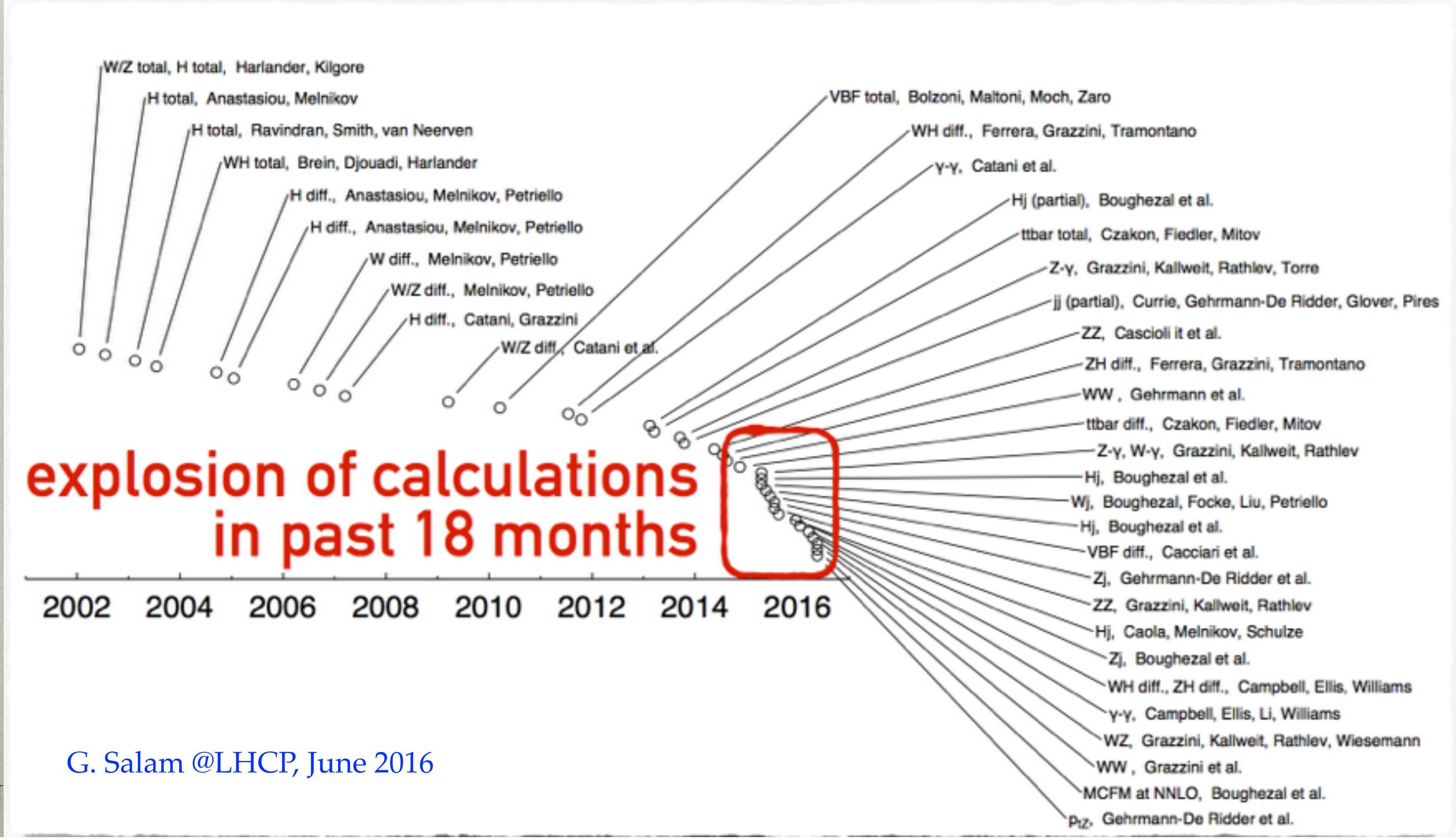


ATLAS & CMS, 1606.02266

- experimental precision of Higgs couplings *O(10%)*
- from couplings to W,Z
  - Higgs the dominant source of EWSB
- no clear signs of NP deviations

THE YEAR OF NNLO AND N3LO

- precision higher order calculations essential part of the program
- both for Higgs signal and backgrounds



G. Salam @LHCP, June 2016

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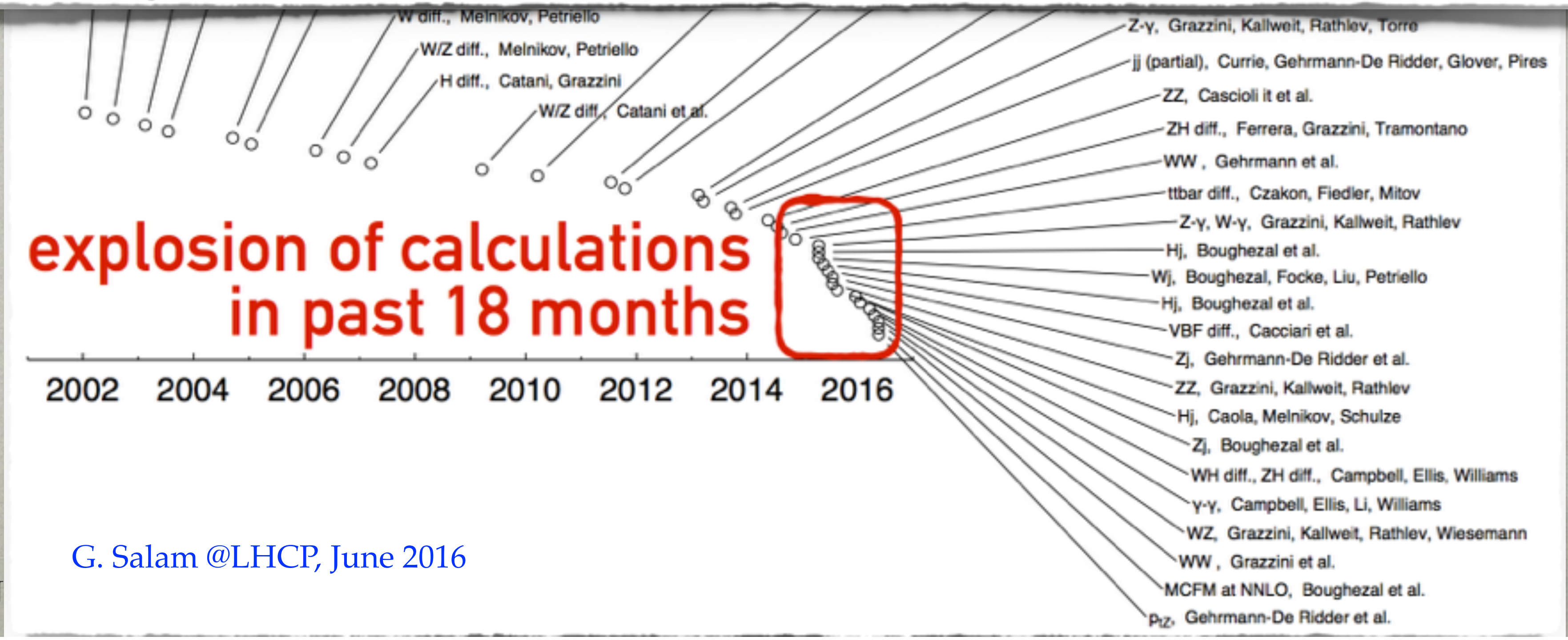
THE YEAR OF NNLO AND N3LO

- precision higher order calculations essential part of the program
- both for Higgs signal and backgrounds

Mangano @ Higgs couplings 2016

Message:

- *by and large,* today's studies of Higgs production and properties are not limited by TH systematics



explosion of calculations in past 18 months

G. Salam @LHCP, June 2016

OUTLINE

- Higgs as probe of origin of flavor
- SM-EFT and NP in the Higgs sector
- Higgs as probe of exotica

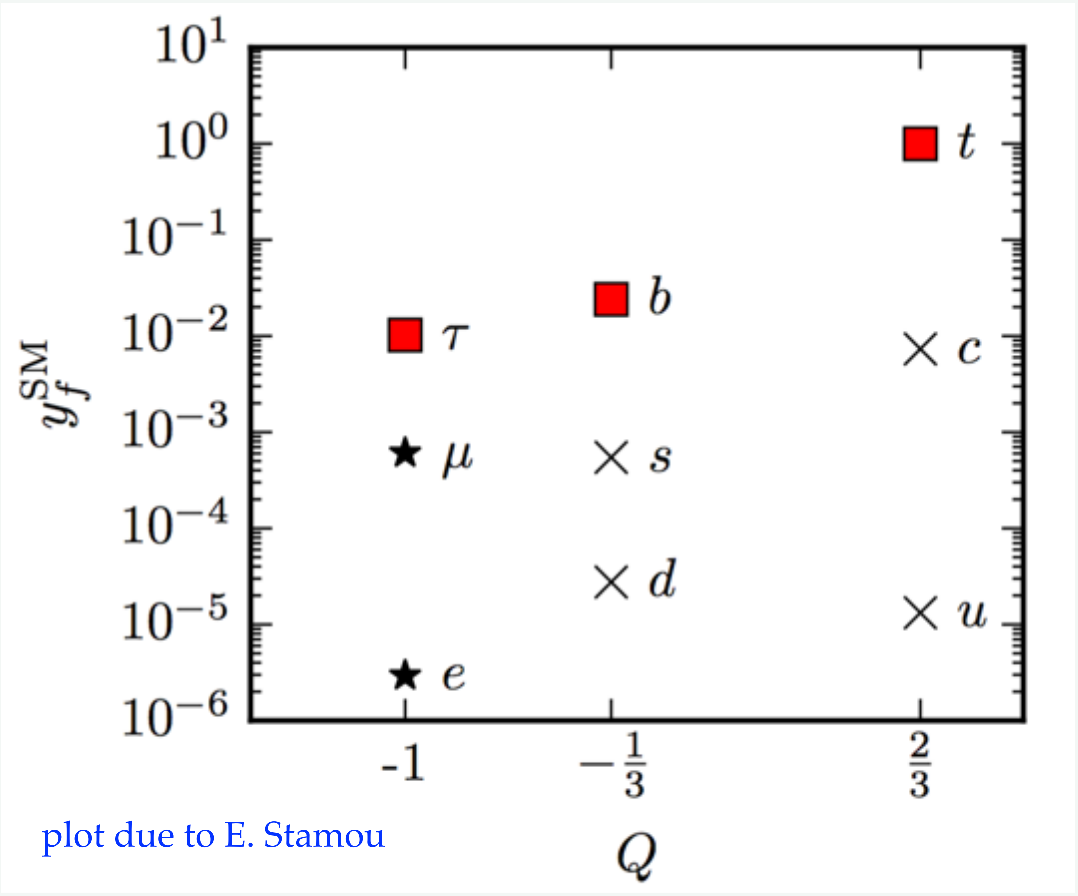
HIGGS AS PROBE OF FLAVOR

YUKAWA COUPLINGS : NONTRIVIAL FLAVOR STRUCTURE

- fermion masses are very hierarchical
- what is the origin of this?
  - the **SM flavor puzzle**
- in the SM

$$y_f = \sqrt{2} m_f / v$$

- implies Higgs has very hierarchical couplings to fermions
- how well have we tested this?



plot due to E. Stamou

HIGGS YUKAWAS

- if SM an EFT, then Yukawas get corrected by higher dim. ops

$$\mathcal{L}_{SM} = -\left[\lambda_{ij}(\bar{f}^i_L f^j_R)H + h.c.\right]$$

$$\Delta\mathcal{L}_Y = -\frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}^i_L f^j_R)H(H^\dagger H) + h.c. + \cdots$$

  - decouples mass terms from Yukawas

$$\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + h.c. + \cdots ,$$

- can lead to flavor violating Higgs decays
- can lead to CPV Higgs decays

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433

- several questions
  - proportionality

    $$y_{ii} \propto m_i$$

  - factor of proportionality

    $$y_{ii}/m_i = \sqrt{2}/v$$

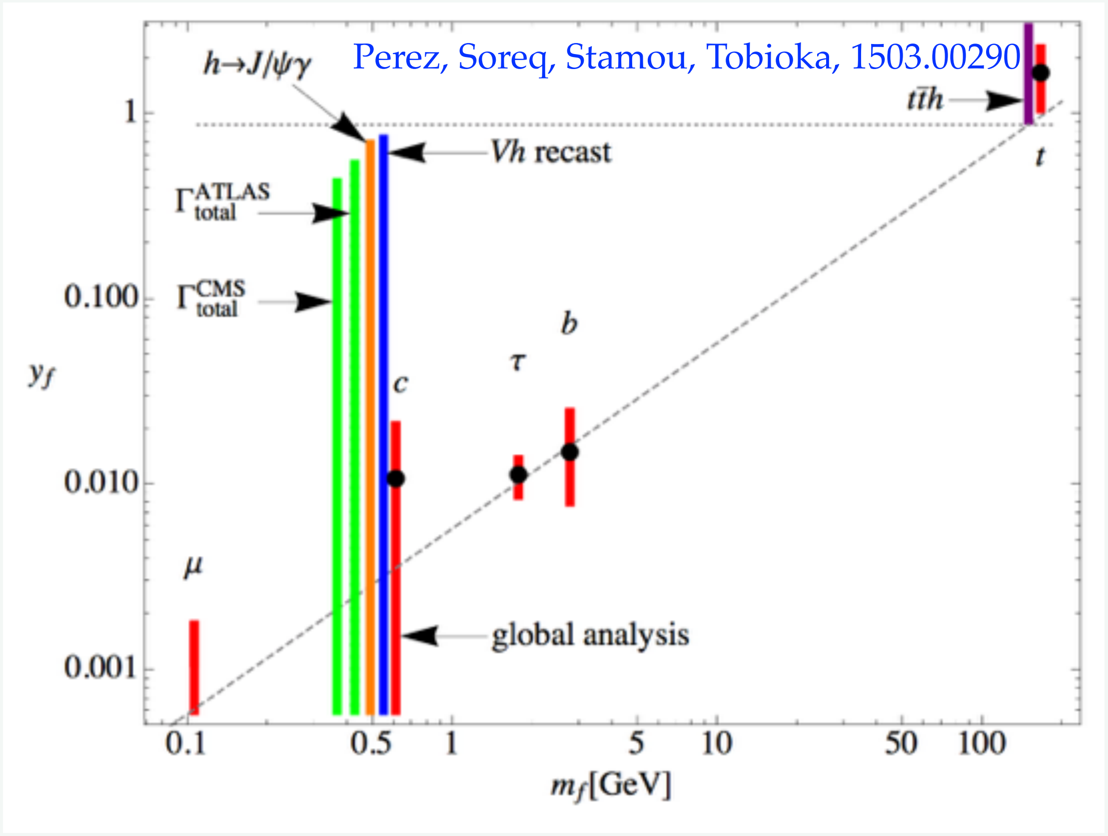
  - diagonality (flavor violation)

    $$y_{ij} = 0, \quad i \neq j$$

  - reality (CP violation)

    $$\mathrm{Im}(y_{ij}) = 0$$

$$y_f^{\mathrm{SM}} = \sqrt{2} m_f / v$$



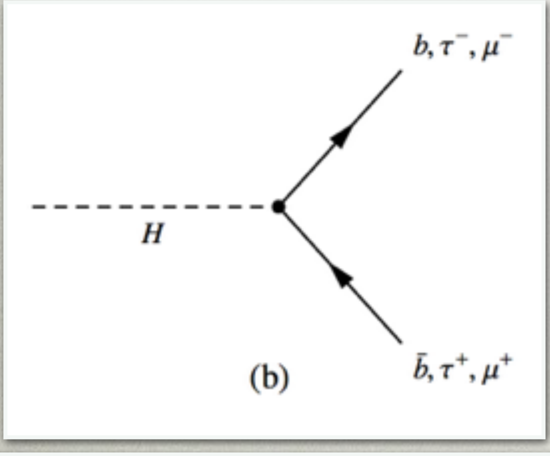
PROPORTIONALITY

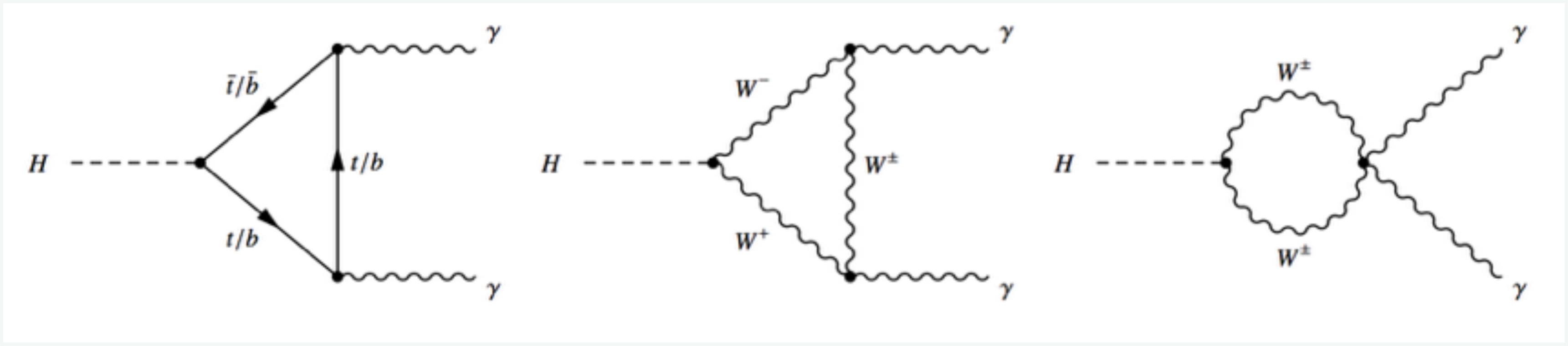
- “proportionality” and “factor of proportionality”

$y_{ii} \propto m_i$

$y_{ii}/m_i = \sqrt{2}/v$

- tested for 3rd generation fermions





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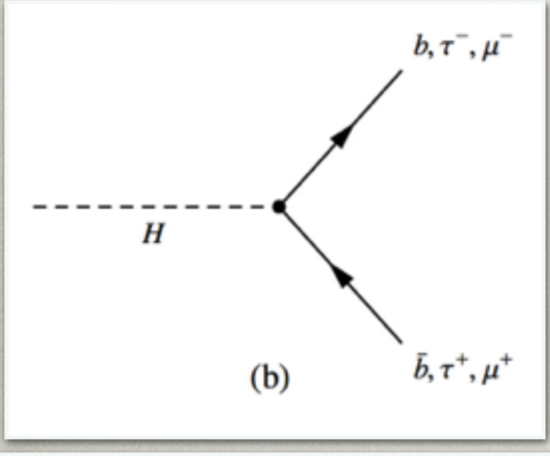
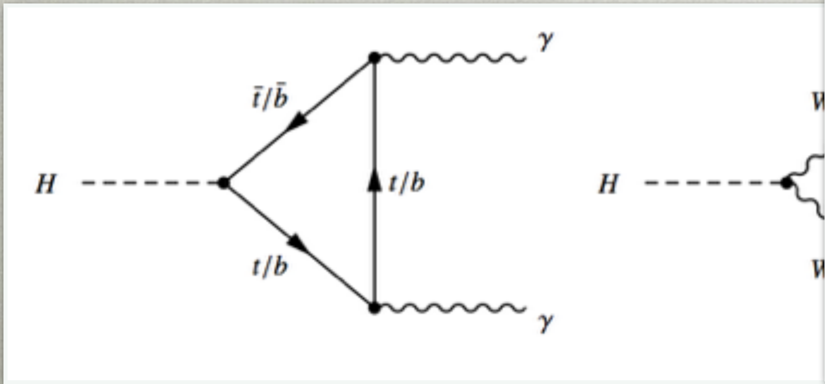
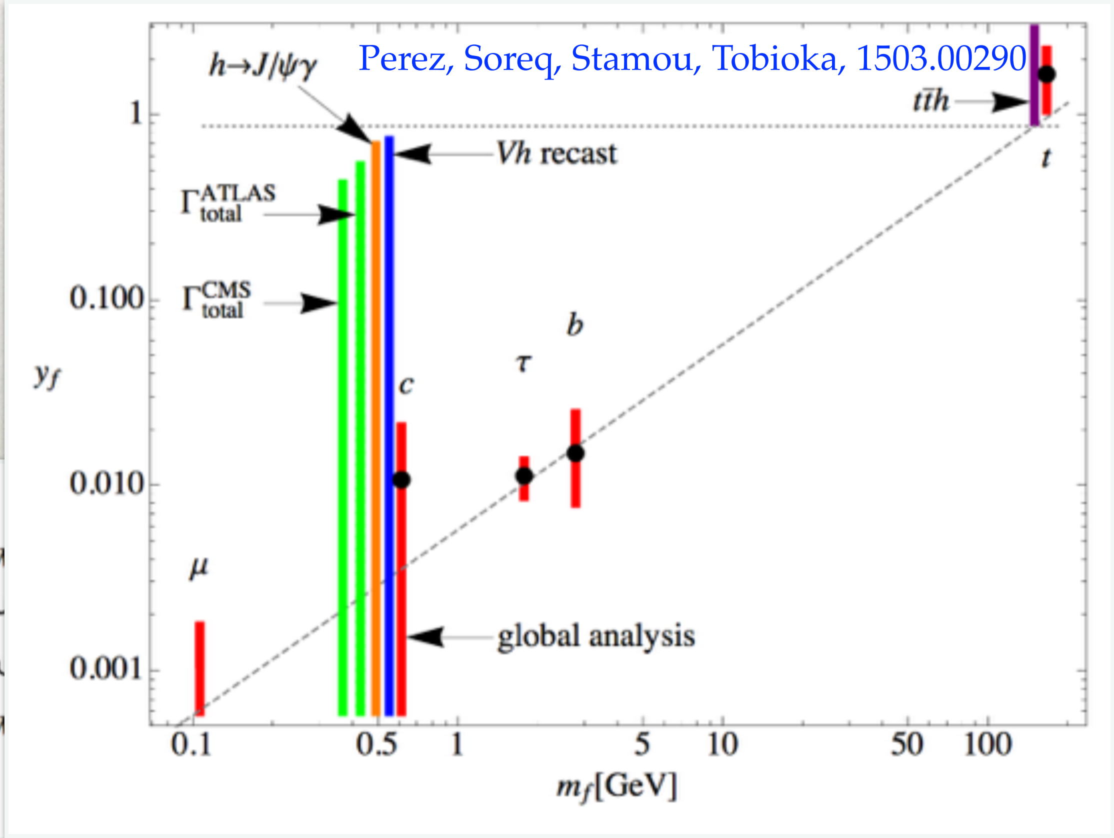
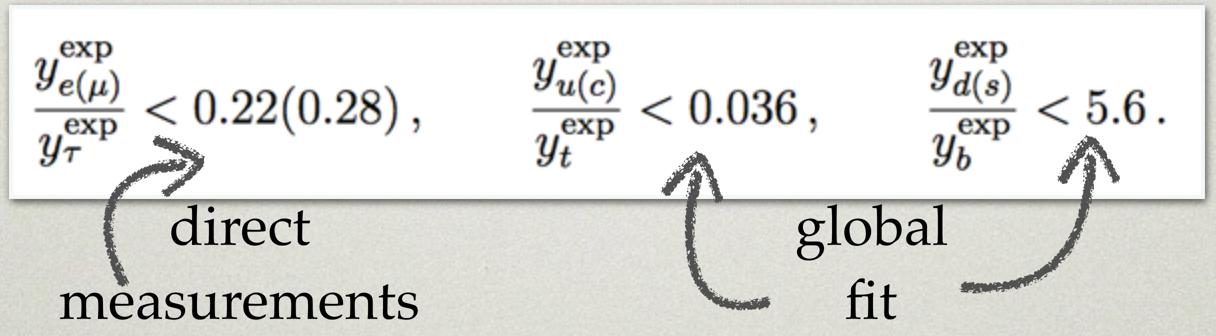





Perez, Soreq, Stamou, Tobioka, 1503.00290

HIERARCHICAL COUPLINGS?

- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - already known for leptons and up-quarks



$$\frac{y_{e(\mu)}^{\exp}}{y_\tau^{\exp}} < 0.22(0.28)\,, \qquad \frac{y_{u(c)}^{\exp}}{y_t^{\exp}} < 0.036\,, \qquad \frac{y_{d(s)}^{\exp}}{y_b^{\exp}} < 5.6\,.$$

direct measurements

global fit

  - can we establish this for down quarks?
- how well can we do in the future?

DIFFERENT PROBES

- several probes of 1st and 2nd generation Higgs yukawas proposed
  - using charm tagging for $h \to c\bar{c}$ inclusive decays

    Perez, Soreq, Stamou, Tobioka, 1503.00290
  - exclusive decays: $h \to \Upsilon\gamma$ (y_b), $h \to J/\psi\gamma$ (y_c), $h \to \phi\gamma$ (y_s)

    Bodwin, Petriello, Stoynev, Velasco, 1306.5770

    Konig, Neubert, 1505.03870

    Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
  - isotopic shift measurements

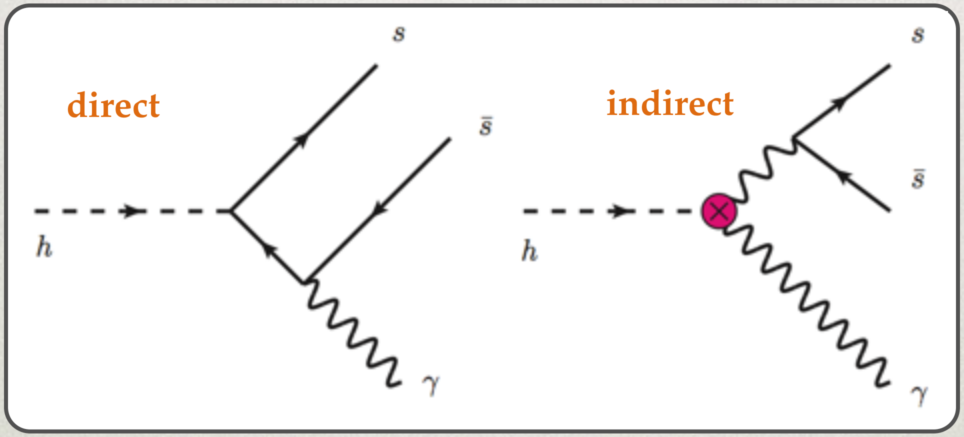
    Delaunay, Ozeri, Perez, Soreq, 1601.05087
  - Higgs p_T distributions

    Bishara, Haisch, Monni, Re, 1606.09253

    Soreq, Zhu, JZ, 1606.09621

$h \to \phi\gamma$

- for s Yukawa $h \to \phi\gamma$ (where $\phi{\sim}\bar{s}s$; $J^{PC}=1^{--}$; $m_\phi=1.02$GeV)
- two amplitudes, direct is subleading



- prediction at NLO

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(2.3\pm0.1)\kappa_\gamma - 0.43\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

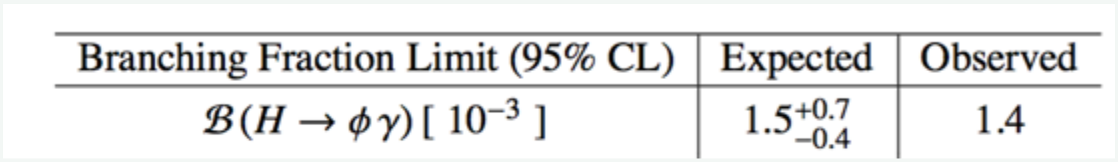
$$Y_{ss} = \bar{\kappa}_s m_b/v$$

Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
Konig, Neubert, 1505.03870

ATLAS MEASUREMENT

ATLAS, 1607.03400

- first bound on
  Br(h→φγ) by ATLAS



Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)$ [10^{-3}]	$1.5^{+0.7}_{-0.4}$	1.4

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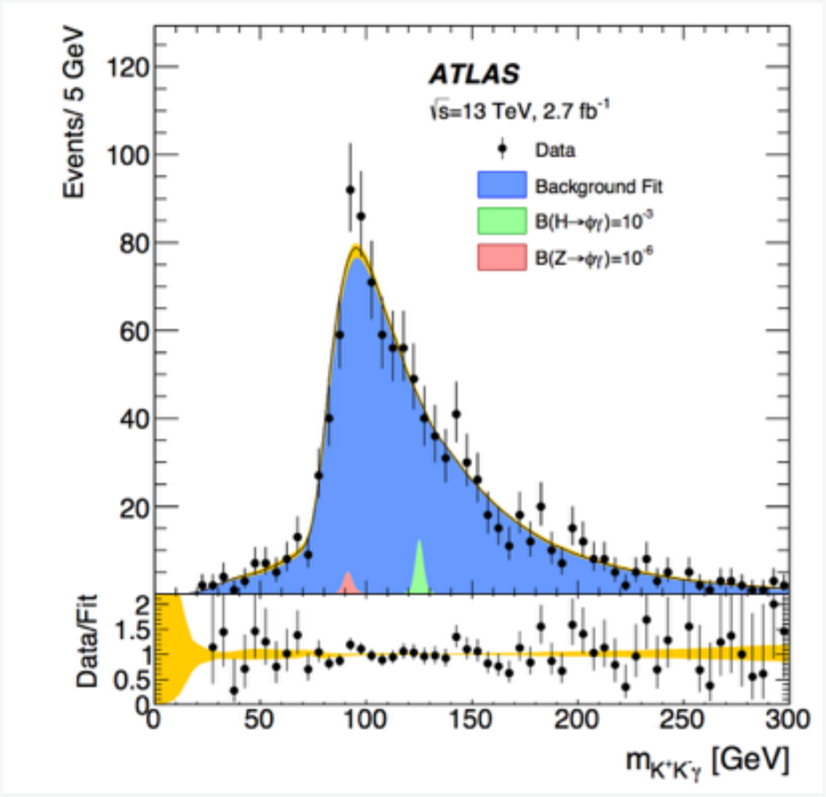


- projecting to 100 TeV, 2x3ab^{-1}, same S/B

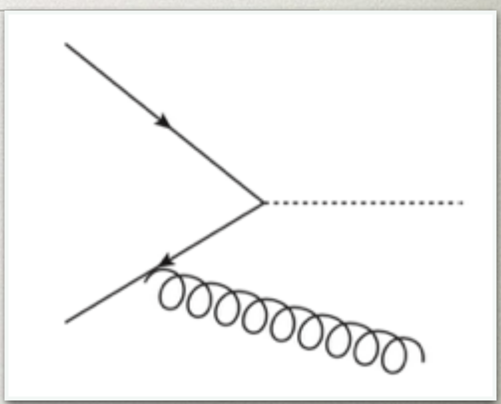
$$Y_{ss} = \bar{\kappa}_s m_b / v$$

$$\mathrm{BR}_{h\to\phi\gamma} < 7\cdot 10^{-6}$$

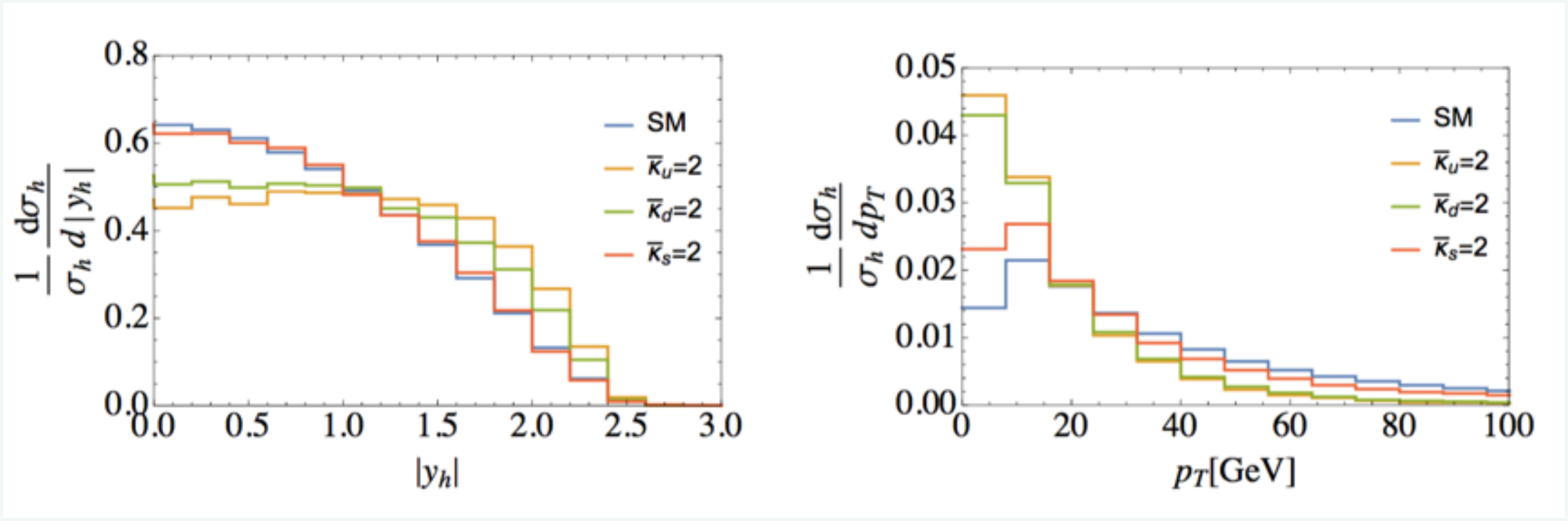
$$\bar{\kappa}_s < 12$$

Soreq, Zhu, JZ, 1606.09621

HIGGS KINEMATICS



- can we do better?
- using Higgs production kinematics
- light quarks in the initial state,
  change the Higgs p_T, or rapidity distribs.

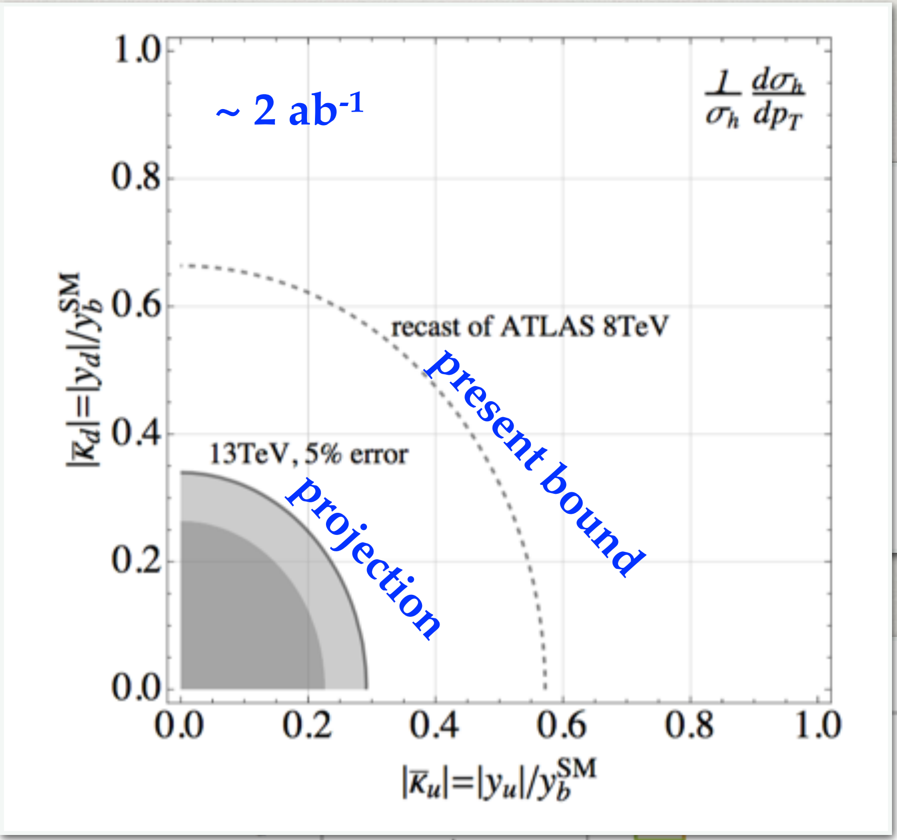


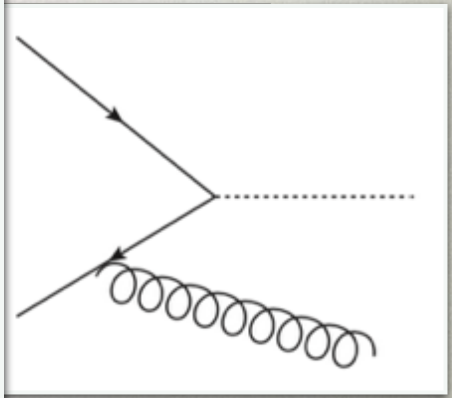
- more sensitive to valence quarks

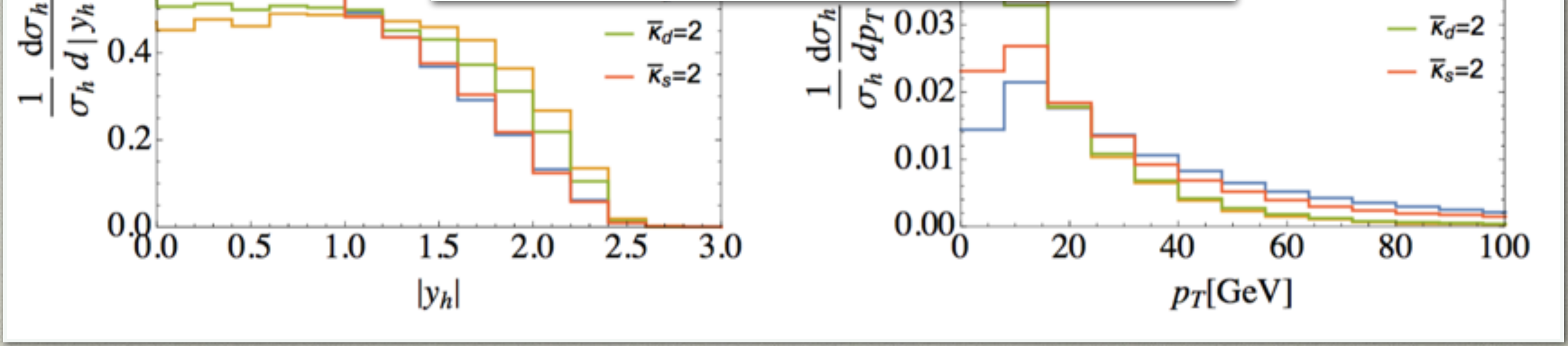
Soreq, Zhu, JZ, 1606.09621

HIG

- can we do l
- using Higg
- light quark change the







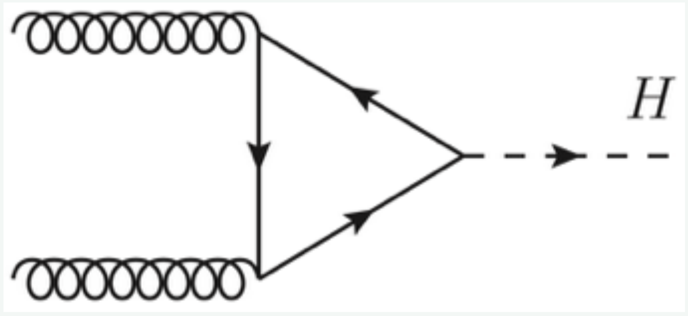
- more sensitive to valence quarks

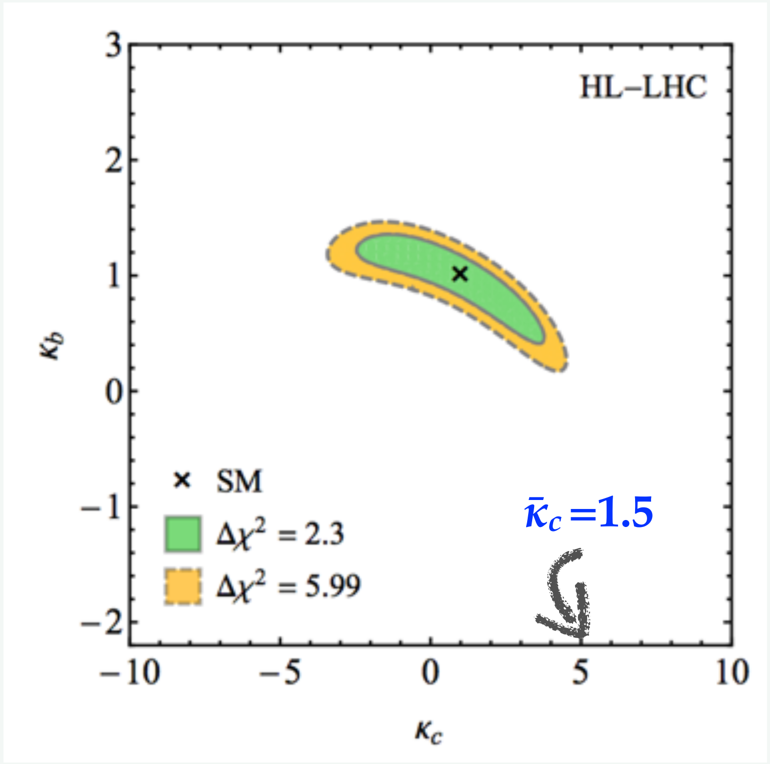
CHARM QUARK

Bishara, Haisch, Monni, Re, 1606.09253

- Higgs p_T also sensitive to charm quark, if enhanced Yukawa
- sensitivity from the charm loop in gluon fusion
- log enhanced

$$\kappa_Q \frac{m_Q^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_Q^2}\right)$$





$\bar{\kappa}_c = 1.5$

CPV AND FV HIGGS COUPLINGS TO SM FERMIONS

- flavor violating couplings?

$$\boxed{y_{ij} = 0, \quad i \neq j}$$

  - very sensitive indirect probes (from precise bounds on FCNCs, such at $\tau \rightarrow \mu\gamma$)
  - from Higgs decays (e.g. $h \rightarrow \tau\mu$)

- CP violating couplings?

$$\boxed{\mathrm{Im}(y_{ij}) = 0}$$

  - severe bounds from precision measurements of CP violating observables (such as electric dipole moments, EDMs)

HOW LARGE?

- a useful rule of thumb for maximal FV
  - do not want fine-tuned cancelations when diagonalizing mass matrix

$$y_{\tau\mu} y_{\mu\tau} \lesssim 2 \frac{m_\tau m_\mu}{v^2}$$

  - also what we would expect for $\Lambda \gtrsim v$
- come from dimension 6 ops. due to NP

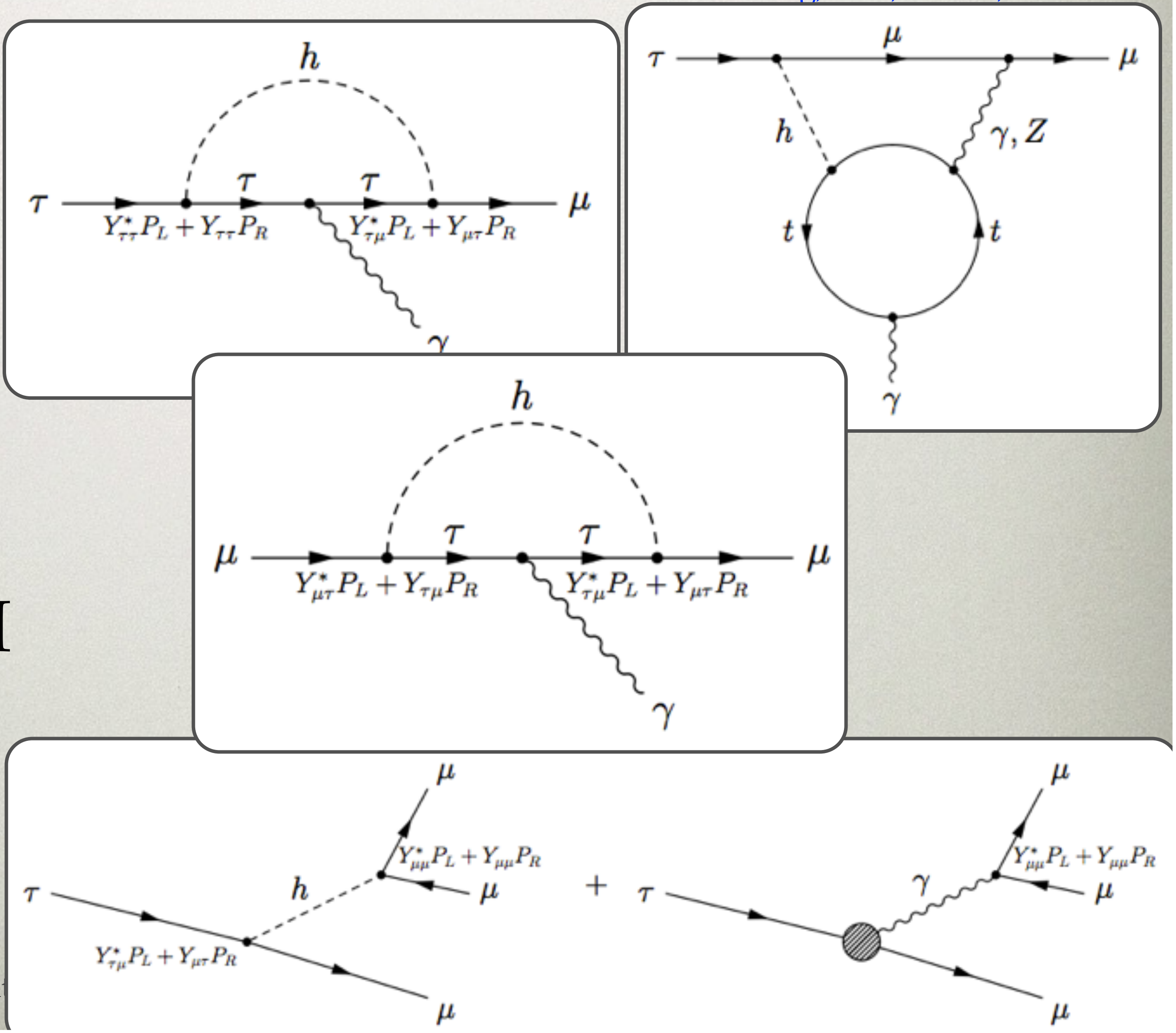
$$\Delta\mathcal{L}_{\text{Yuk}} = -\frac{\lambda'_{ij}}{\Lambda^2} \left(\bar{f}_L^i f_R^j\right) \phi \left(\phi^\dagger \phi\right) + \text{h.c.} + \cdots$$

$h \to \tau\mu$

Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- bounds from
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$
  - muon g-2
  - muon EDM



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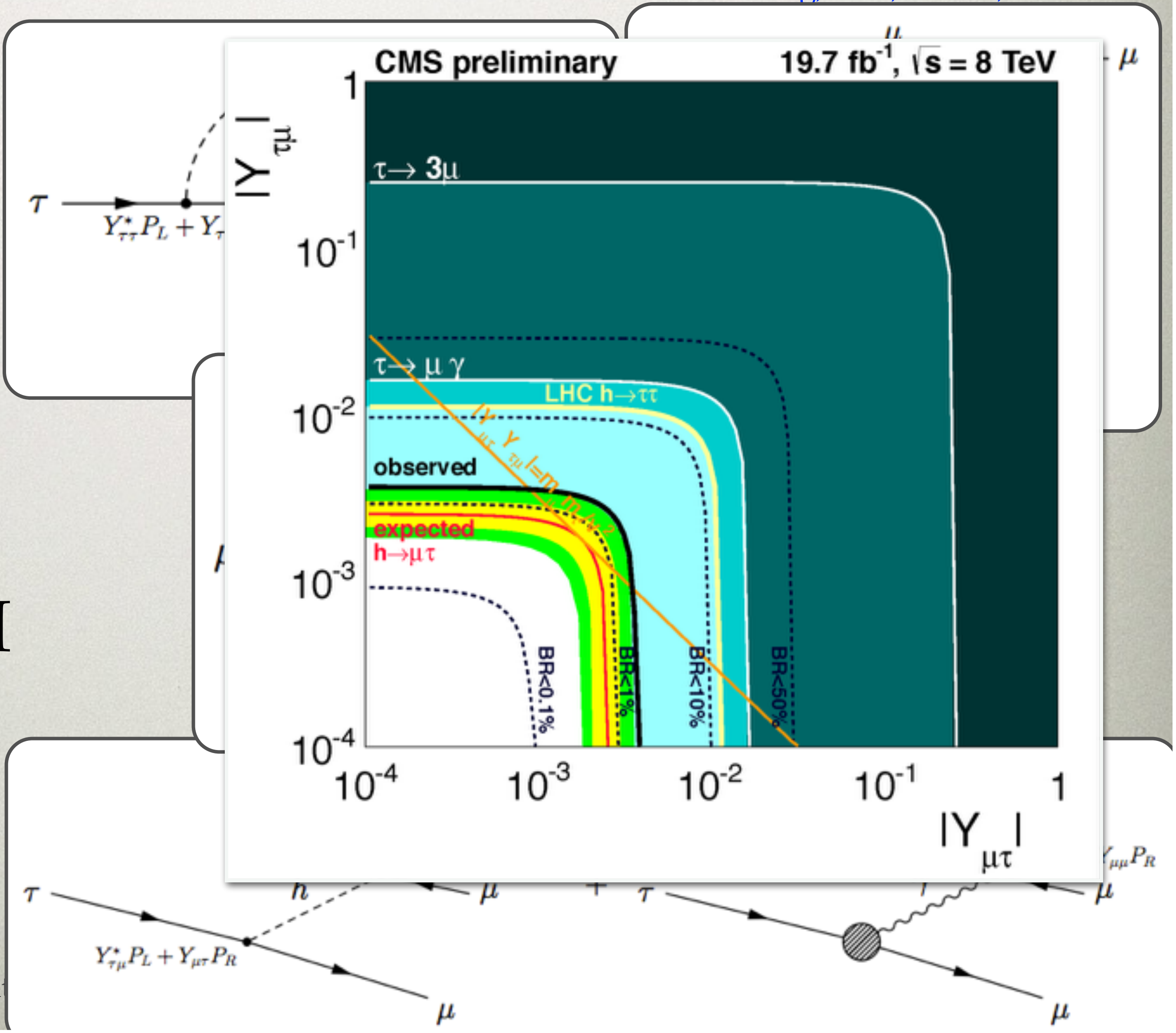
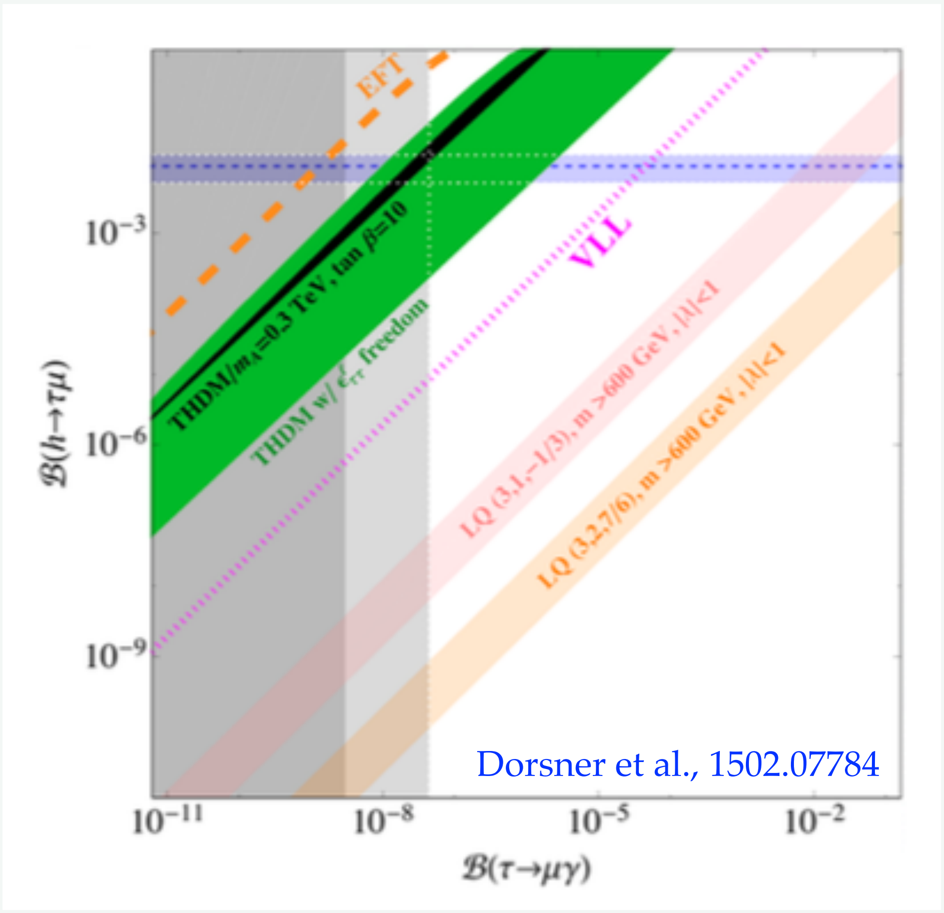


LARGE FV HIGGS DECAYS?

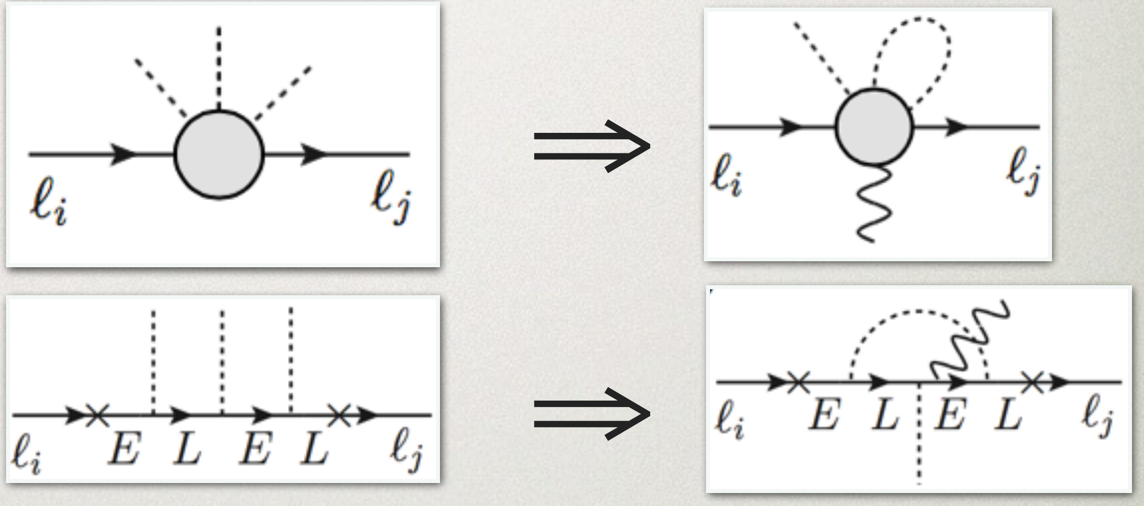
- Can one have large flavor violating Higgs decays in reasonable NP models?
- What is so special about type III 2HDM?



Dorsner et al., 1502.07784

WHAT KIND OF NEW PHYSICS?

- if Higgs the only source of EWSB ⇒ the *Br(h→τμ)* hint typically too large
- same diagrams give $\tau\to\mu\gamma$ and the correction to Higgs Yukawa



- experimental bound on Br($\tau\to\mu\gamma$) + NDA estimate of NP contribs.

$$\sqrt{|Y_{\tau\mu}|^2+|Y_{\mu\tau}|^2} < 2.2\cdot 10^{-5}$$

- in contrast CMS hint *Br(h→τμ)=(0.89±0.39)%* requires

$$\sqrt{|Y_{\tau\mu}|^2+|Y_{\mu\tau}|^2} = (2.6\pm 0.6)\cdot 10^{-3}$$

VIABLE MODELS: SEQUESTERED MASS GENERATION

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

- a family of viable new physics models
  - lepton mass matrix of the form

$$\mathcal{M}^{\ell} = \mathcal{M}_0^{\ell} + \Delta\mathcal{M}^{\ell},$$

rank 1 matrix, from ϕ

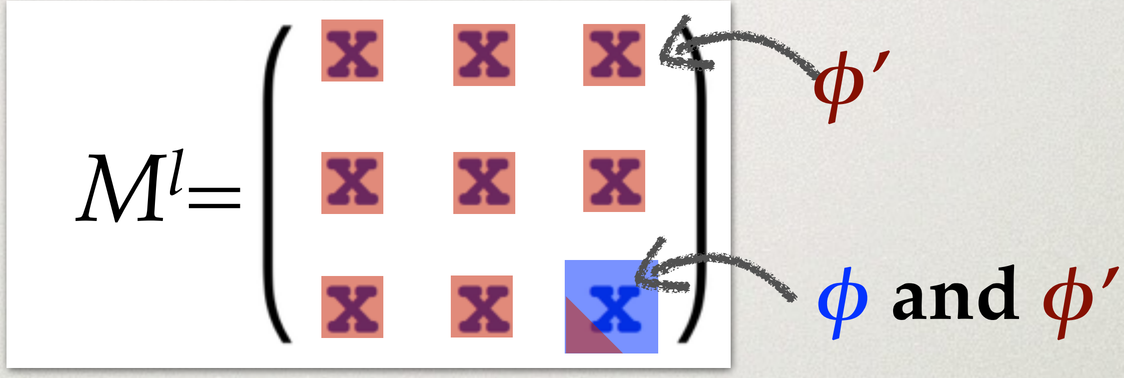
rank 2 or 3 matrix

  - scalar ϕ the primary component of the Higgs
    - accounts for the bulk of m_τ
  - ΔM_l due to an additional source of EWSB
    - accounts for m_e and m_μ

2HDM

- two Higgs doublets, neutral compts: ϕ, ϕ',vevs v, v'
    - ϕ couples to 3rd family, ϕ' to all three

$$\tan\beta = v/v'$$

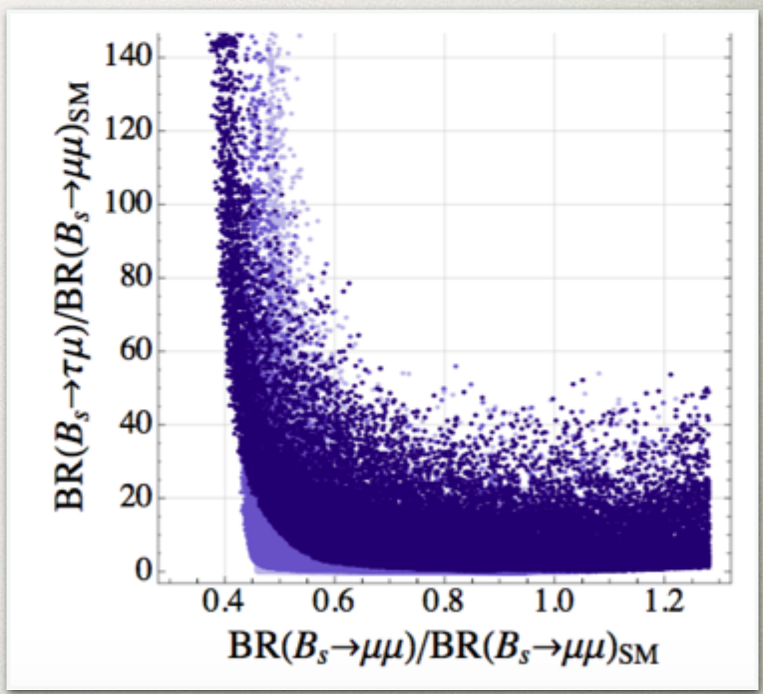


$$M^l=\begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

    - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- can saturate $Br(h \to \tau\mu)$
- $Br(\tau \to \mu\gamma)$ parametrically suppressed
    - (there is an extra y_τ insertion)
- predicts modified phenomenology of heavy Higgses

PHENOMENOLOGICAL IMPLICATIONS

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927



- $B_s \to \mu\mu$ can be modified by $O(1)$
- sizable $B_s \to \tau\mu$, $B \to K\tau\mu$, $B \to K^*\tau\mu$
- anomalies could be seen in B_s mixing, $\tau \to \mu\gamma$, $b \to s\gamma$
- leptonic heavy Higgs (H) decays to $\mu\mu$ could dominate over $\tau\tau$
  - opposite to Type-II 2HDMs
- $t \to hc$ potentially sizable
- a general sum rule

$$\hat{y}_\mu \hat{y}_\tau - \hat{y}_{\tau\mu}\hat{y}_{\mu\tau} = \hat{y}_{t,b}(\hat{y}_\mu + \hat{y}_\tau - \hat{y}_{t,b})$$

$$\hat{y}_{ij} \equiv Y_{ij}/Y_{ii}^{\mathrm{SM}}$$

- valid to the extent that both ΔM^l and ΔM_0 are rank 1

Altmannshofer, Eby, Gori, Lotito, Martone, Tuckler, 1610.02398

COLLIDER SIGNATURES

- *h* couplings to 3rd and 2nd generation

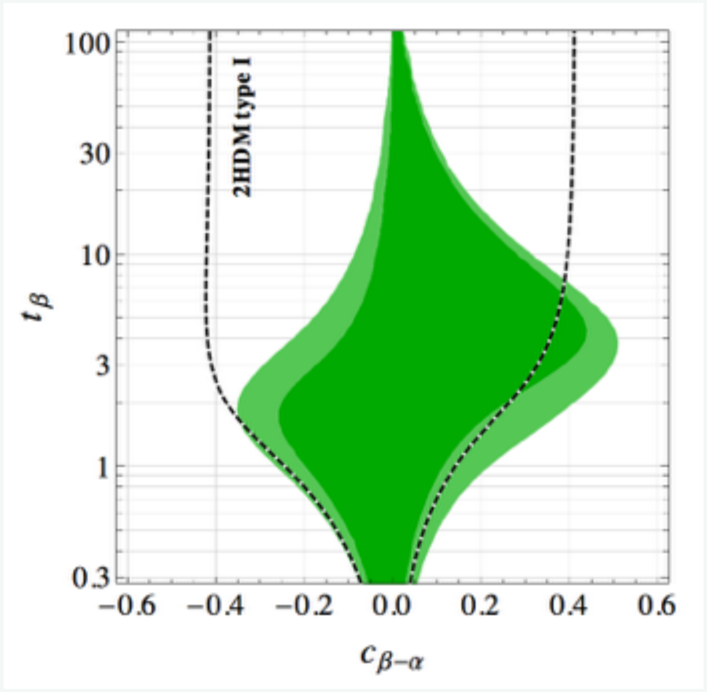
differs from natural f.c.

$$\kappa_t \equiv \frac{Y_t}{Y_t^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_c}{m_t}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_b \equiv \frac{Y_b}{Y_b^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_s}{m_b}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_\tau \equiv \frac{Y_\tau}{Y_\tau^{\rm SM}} = \frac{c_\alpha}{s_\beta} + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,.$$

like 2HDM type I

$$\kappa_\mu \equiv \frac{Y_\mu}{Y_\mu^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_c \equiv \frac{Y_c}{Y_c^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_c}{m_t}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$
$$\kappa_s \equiv \frac{Y_s}{Y_s^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_s}{m_b}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,.$$

- for large tanβ $h \to \mu\mu, cc$ can dominate Γ_h
  - modifies the global fit
- for heavy *H* the dominant decay can be flavor violating



Altmannshofer, Eby, Gori, Lotito, Martone, Tuckler, 1610.02398

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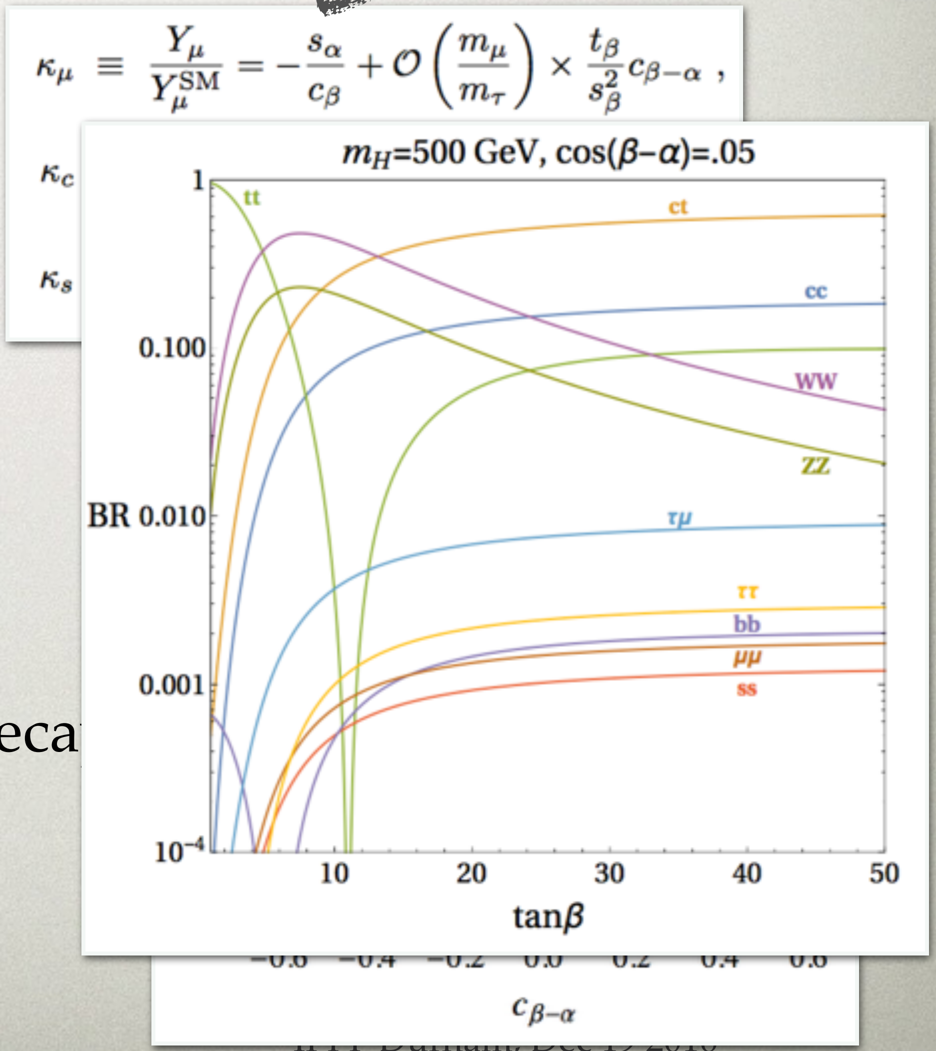
like 2HDM type I

differs from natural f.c.



$$\kappa_\mu \equiv \frac{Y_\mu}{Y_\mu^{\rm SM}} = -\frac{s_\alpha}{c_\beta} + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right) \times \frac{t_\beta}{s_\beta^2} c_{\beta-\alpha} \,,$$

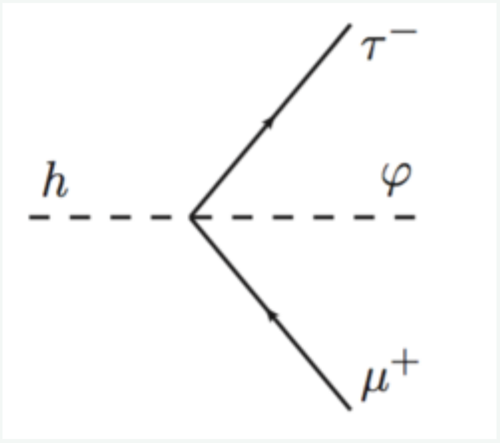
- for large tanβ $h\to\mu\mu, cc$ can dominate Γ_h
    - modifies the global fit
- for heavy *H* the dominant deca can be flavor violating

FLAVORFUL DARK MATTER

Galon, JZ, to appear

- $h \to \tau\mu$ could be $h \to \tau\mu + MET$,
  no flavor violation if dark sector flavorful

$$\frac{Br(h\to \tau^{\pm}\mu^{\mp}\varphi\ /\varphi^{*})}{Br(h\to\tau^{+}\tau^{-})} \simeq \frac{1}{6}\left(\frac{m_h}{2\pi\Lambda y_\tau}\right)^2 = 0.66\times\left(\frac{\text{TeV}}{\Lambda}\right)^2\left(\frac{0.01}{y_\tau}\right)^2$$



- φ is the mediator to dark matter
  - dark matter can be a thermal relic
- satisfies FCNC constraints

SMEFT

SMEFT vs. HEFT

- in the general EFT of Higgs interactions many more operators

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{d\leq 4} + \sum_i \frac{O_i^{(d)}}{\Lambda} + \sum_i \frac{O_i^{(6)}}{\Lambda^2} + \cdots$$

- two expansions
  - SMEFT (Standard Model Effective Field Theory, a.k.a. "linear")
    - h assumed to be part of doublet ϕ
  - HEFT (Higgs Effective Field Theory, a.k.a. "non-linear")
    - no relation between h and π^a

$$\mathcal{L}_{\mathrm{SMEFT}}\big(\phi = (v+h)\exp(iT^a\pi^a)\big)$$

$$\mathcal{L}_{\mathrm{HEFT}}\big(h, \exp(iT^a\pi^a)\big)$$

- both L_{SMEFT} and L_{HEFT} infinite number of terms
  - are they equivalent?
  - nonpert./geometric answer: yes, iff L_{HEFT} has $O(4)$ symm. IR fixed point
  - HEFT includes SMEFT

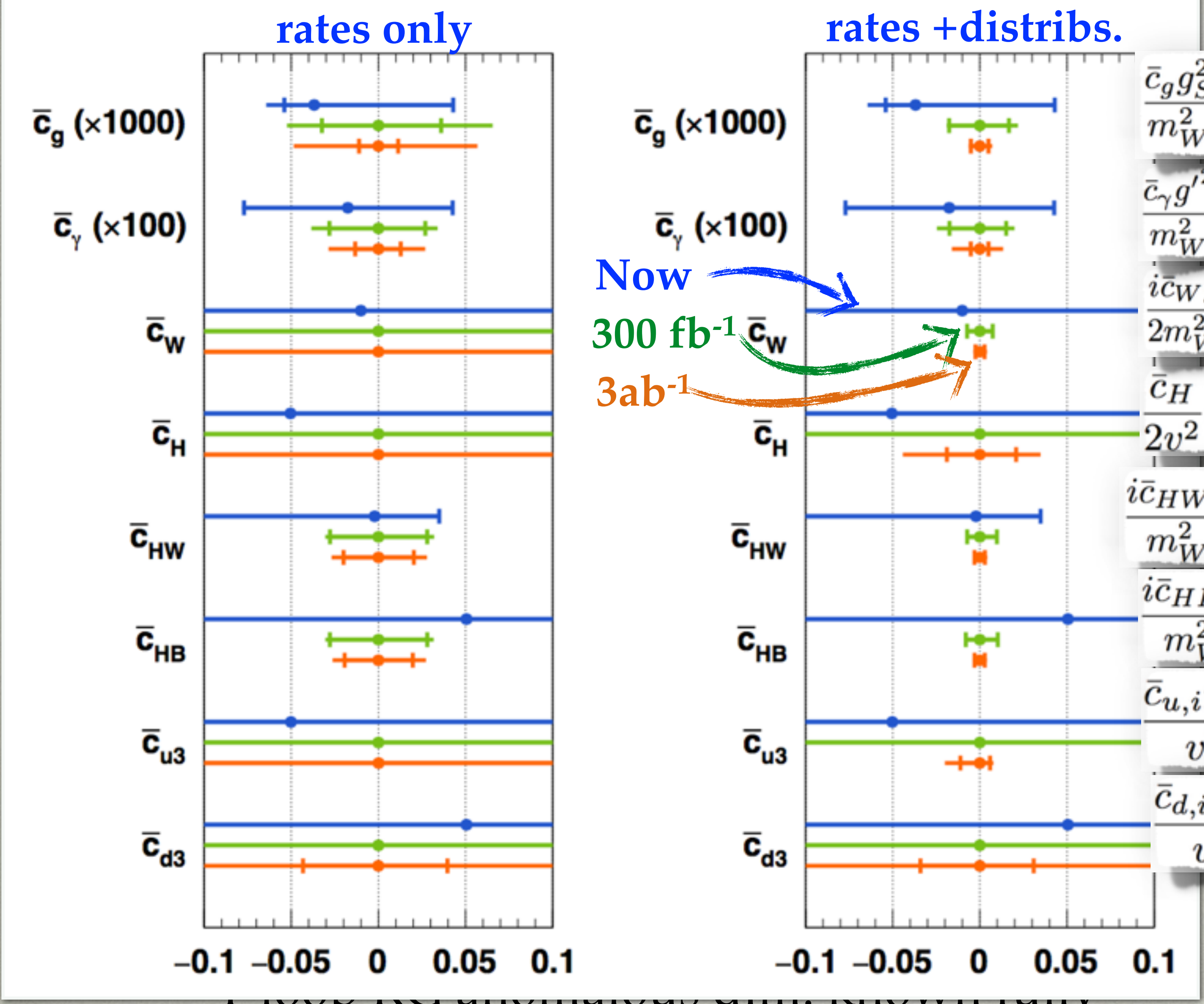
Alonso, Jenkins, Manohar, 1511.00724, 1605.03602

SMEFT

- much more work done in SMEFT (either Warsaw or SILH basis)
  - dim5 and dim7 are *L*, *B*-*L* violating, thus small
  - dim6 first relevant for Higgs physics
    - assuming B+MFV+CP: 59 indep. ops.
    - at tree level only a subset bounded by LHC data
- when extracting bounds from data radiative corrections may be important
- 1-loop RG anomalous dim. known fully

Alonso, Jenkins, Manohar, Trott, 1312.2014, 1310.4838, 1308.2627

Englert, Kogler, Schulz, Spannowsky, 1511.05170



$\frac{\bar c_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$

$\frac{\bar c_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$

$\frac{i\bar c_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$

$\frac{\bar c_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)$

$\frac{i\bar c_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$

$\frac{i\bar c_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$

$\frac{\bar c_{u,i} y_{u,i}}{v^2} H^\dagger H \bar u_L^{(i)} H^c u_R^{(i)}$

$\frac{\bar c_{d,i} y_{d,i}}{v^2} H^\dagger H \bar d_L^{(i)} H d_R^{(i)}$

1-loop RG anomalous dim. known fully

Alonso, Jenkins, Manohar, Trott, 1312.2014, 1310.4838, 1308.2627

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- much more work done in SMEFT (either Warsaw or SILH basis)
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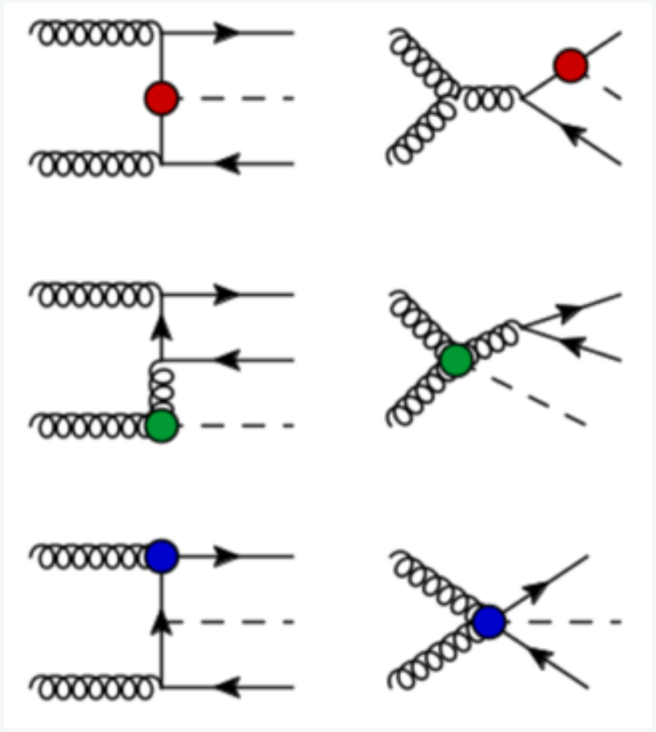
- 1-loop RG anomalous dim. known fully

Alonso, Jenkins, Manohar, Trott, 1312.2014, 1310.4838, 1308.2627

FINITE CORRECTIONS

- finite corrections can be larger than the log pieces
- example: $t\bar{t}H$ production at NLO in α_S

Maltoni, Vryonidou, Zhang, 1607.05330



$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) (\bar{Q}t)\, \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

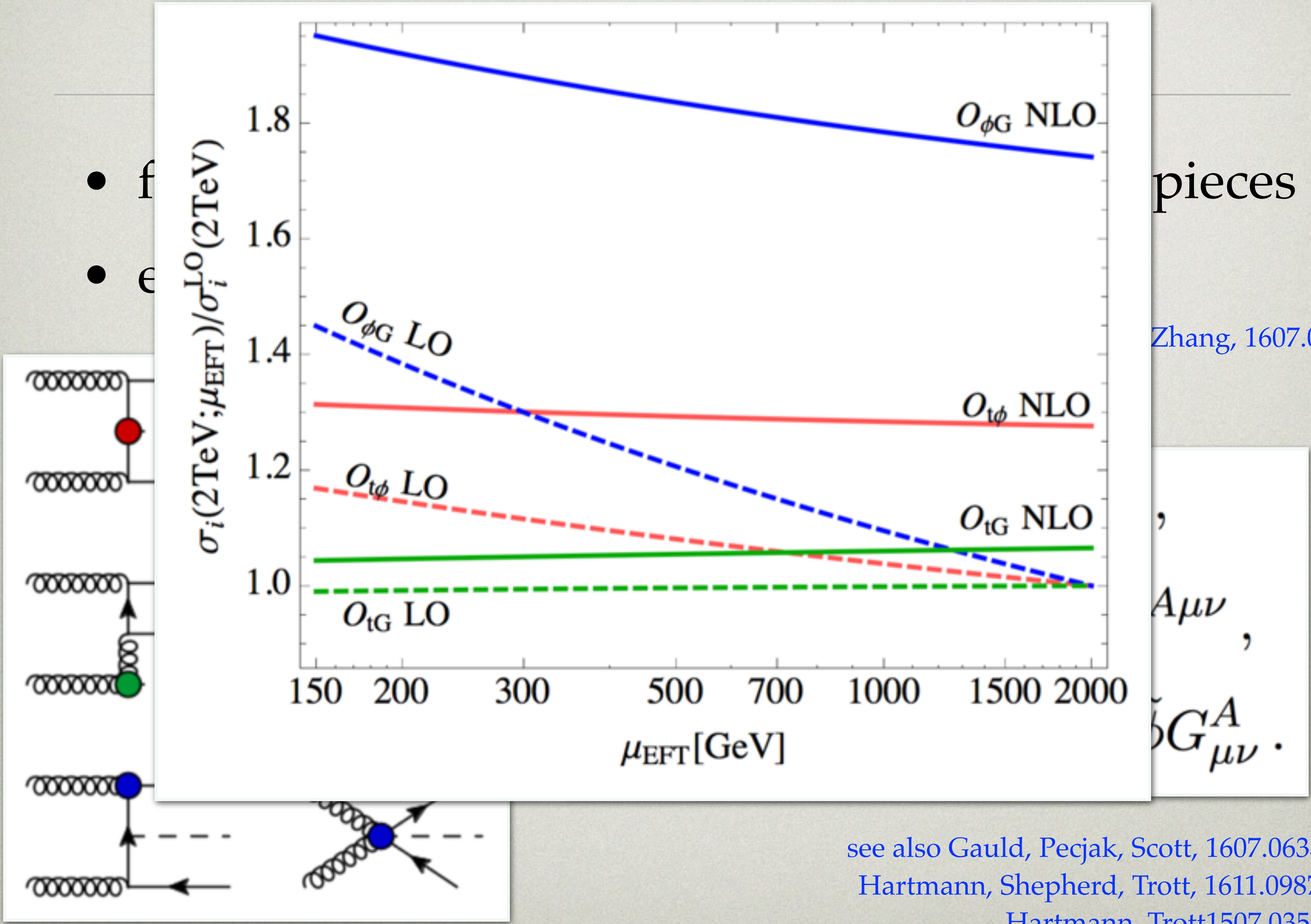
see also Gauld, Pecjak, Scott, 1607.06354: $h \to b\bar{b}$

Hartmann, Shepherd, Trott, 1611.09879: Γ_Z

Hartmann, Trott1507.03568: $h \to \gamma\gamma$

- f pieces
- e

Zhang, 1607.05330



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Hartmann, Trott1507.03568: $h \to \gamma\gamma$

DI-HIGGS PRODUCTION

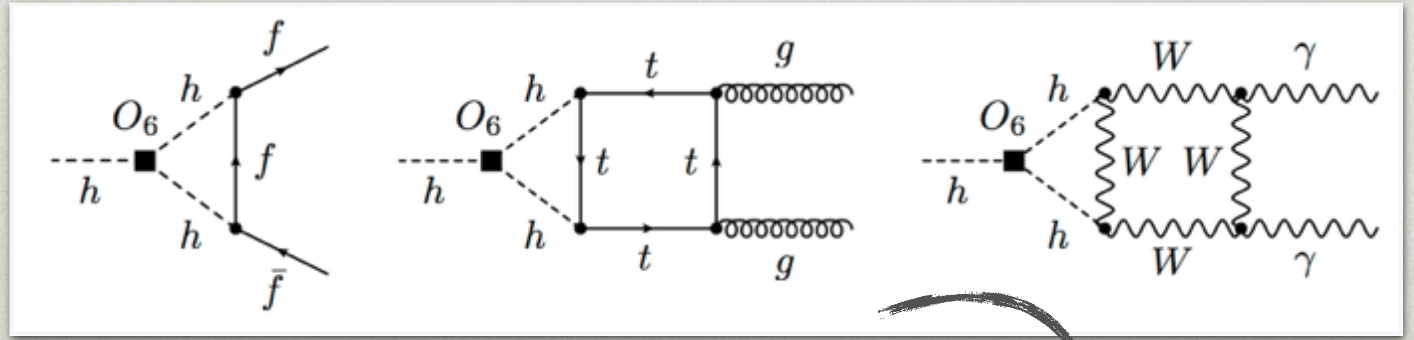
Bizon, Gorbahn, Haisch, Zanderighi, 1610.05771

- the operators modifying HH production

$$O_6 = -\lambda\left(H^\dagger H\right)^3\,, \qquad O_H = \frac{1}{2}\,\partial_\mu\left(H^\dagger H\right)\partial^\mu\left(H^\dagger H\right),$$

$$\mathcal{L} \supset -\lambda c_3 v h^3 = -\lambda\left(1 + \bar{c}_6 - \frac{3\bar{c}_H}{2}\right) v h^3\,,$$

- at 1- and 2-loop order modify single *H* prod. properties



- at HL-LHC

$$\bar{c}_6 \in [-2.3, 7.7]\,,$$

direct HH production

ATL-PHYS-PUB-2014-019

indirect constraint

$$\bar{c}_6 \in [-6.7, 9.7]\,,$$

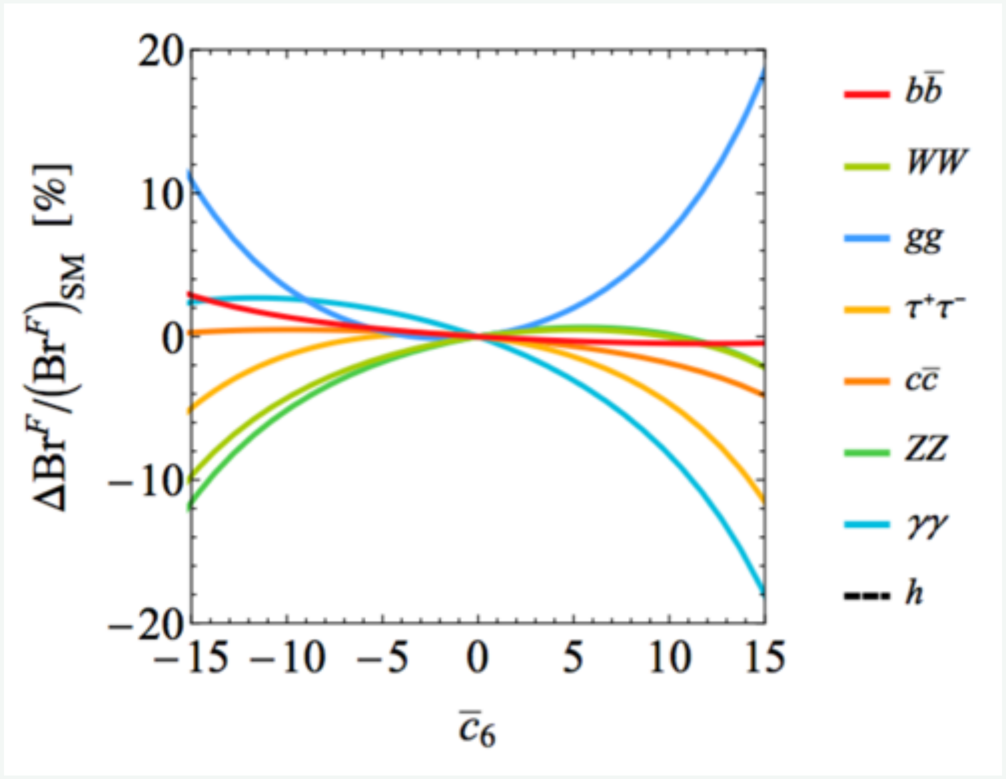
DI-HIGGS

- the operators modifying H

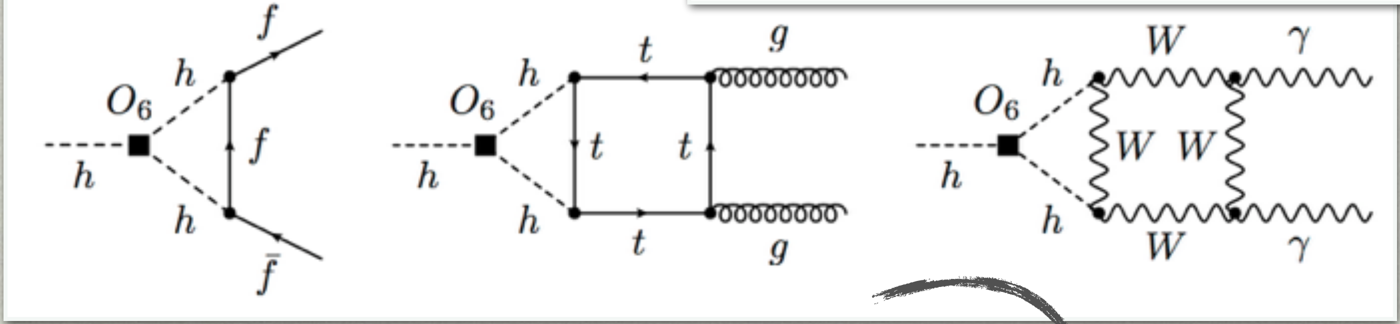
$$O_6 = -\lambda\left(H^\dagger H\right)^3, \qquad O_H = \frac{1}{2}\partial_\mu(H^\dagger$$

$$\mathcal{L} \supset -\lambda c_3 v h^3 = -\lambda\Big(1 + \bar{c}_6 -$$

771



- at 1- and 2-loop order mod



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ATL-PHYS-PUB-2014-019

indirect constraint

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HIGGS AS PROBE OF EXOTICA

HIGGS PORTAL

- Higgs can act as a portal to NP
  - Higgs portal DM
  - mono-Higgs
  - relaxion
  - Twin Higgs/Neutral naturalness
  - ….

HIGGS PORTAL TO DM

Patt, Wilczek, hep-ph/0605188

- minimal choice for mediator between DM and the SM
- add to SM a Z_2-odd neutral DM field
  - a scalar ϕ, fermion ψ, vector V_μ

$$\mathcal{H}^0_{\rm eff} = \lambda' H^\dagger H \times \phi^\dagger \phi\,,$$

$$\mathcal{H}^{1/2}_{\rm eff} = \frac{c_S}{\Lambda} H^\dagger H \times \bar\psi\psi + \frac{i c_P}{\Lambda} H^\dagger H \times \bar\psi\gamma_5\psi$$

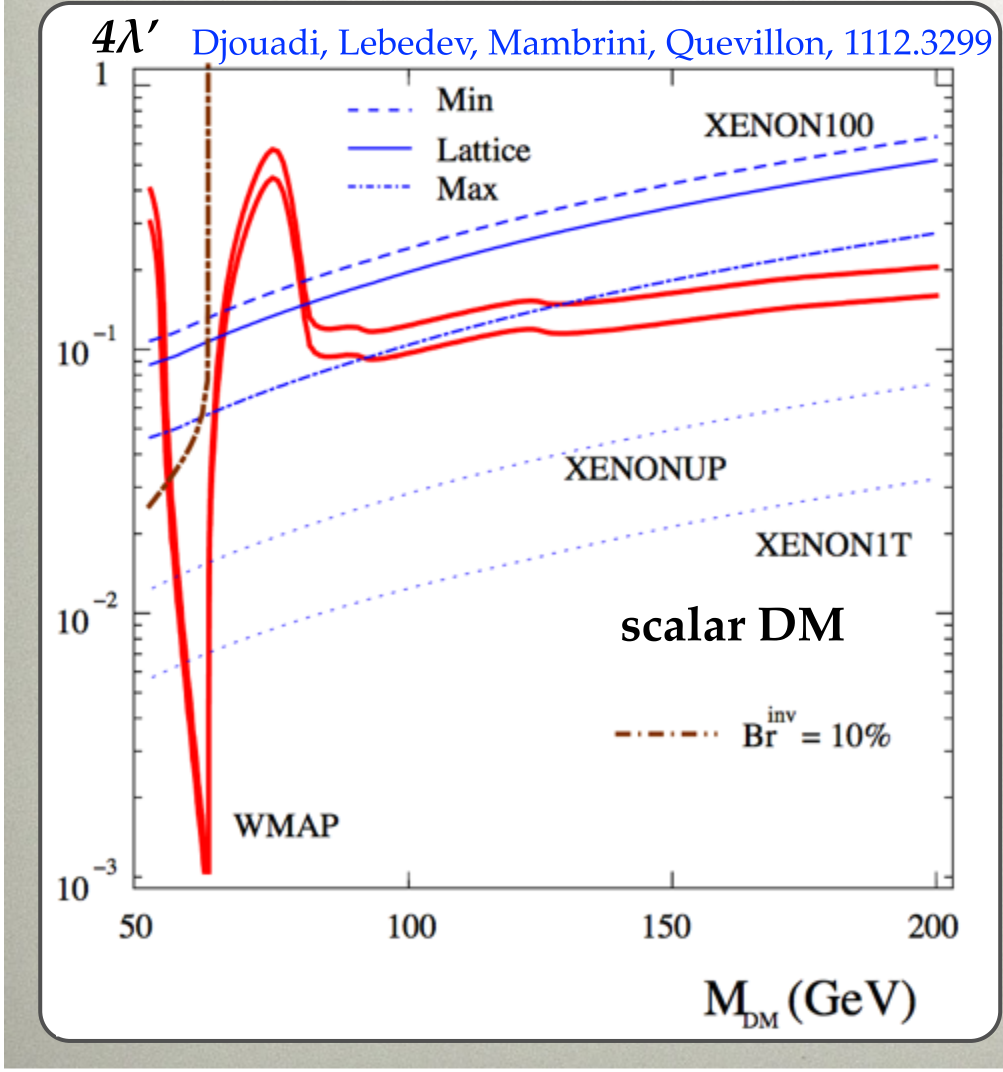
$$\mathcal{H}^1_{\rm eff} = \epsilon_H H^\dagger H \times V^\mu V_\mu\,.$$

  - after EWSB coupling with the Higgs

$$H^\dagger H \to \frac{1}{2}(v_{\rm EW}^2 + 2 v_{\rm EW} h + h^2)$$

LIGHT DM AND MINIMAL HIGGS PORTAL

- for $m_{DM} \lesssim m_h/2$ Higgs portal excluded from $Br(h \rightarrow inv.)$



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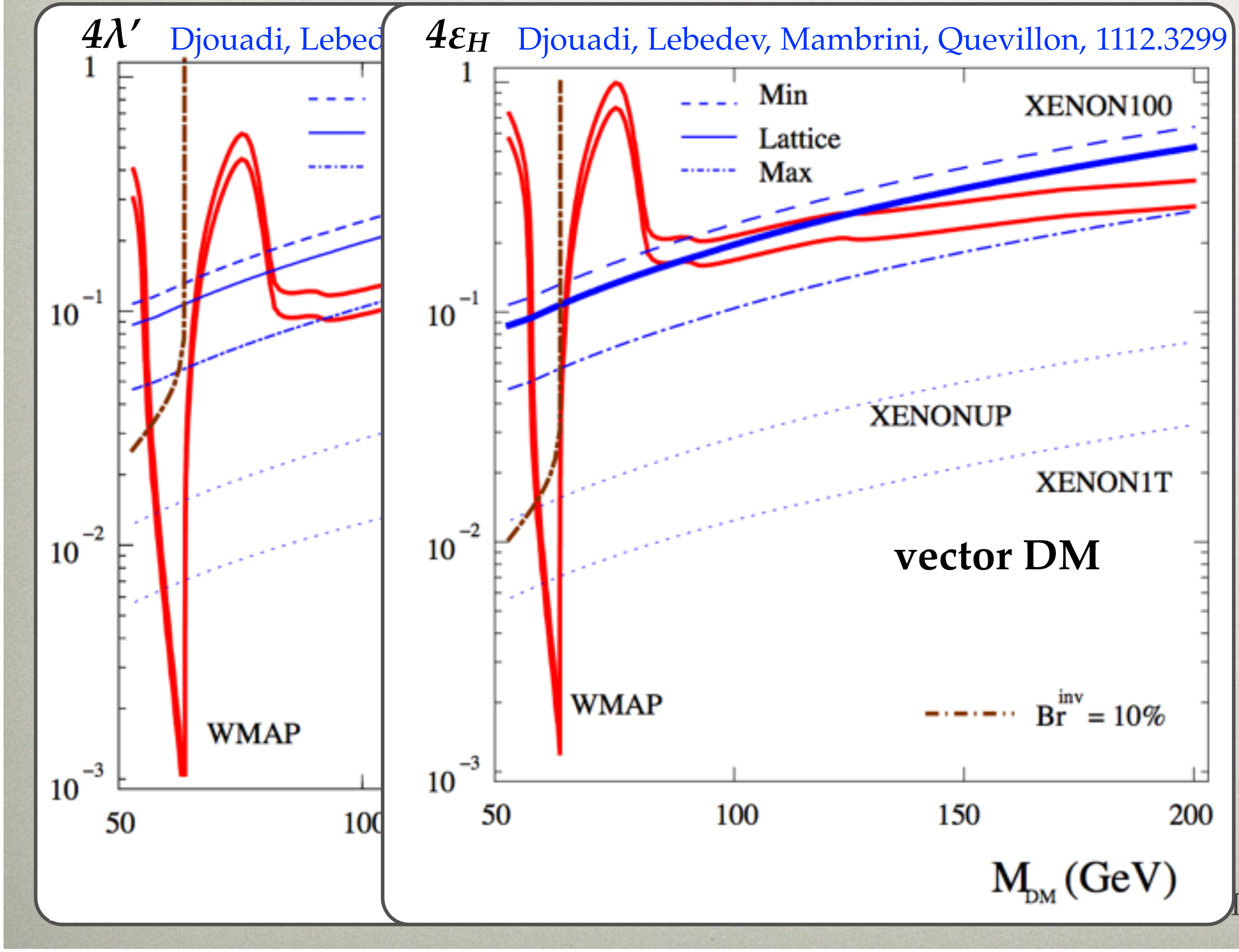
Djouadi, Lebedev, Mambrini, Quevillon, 1112.3299

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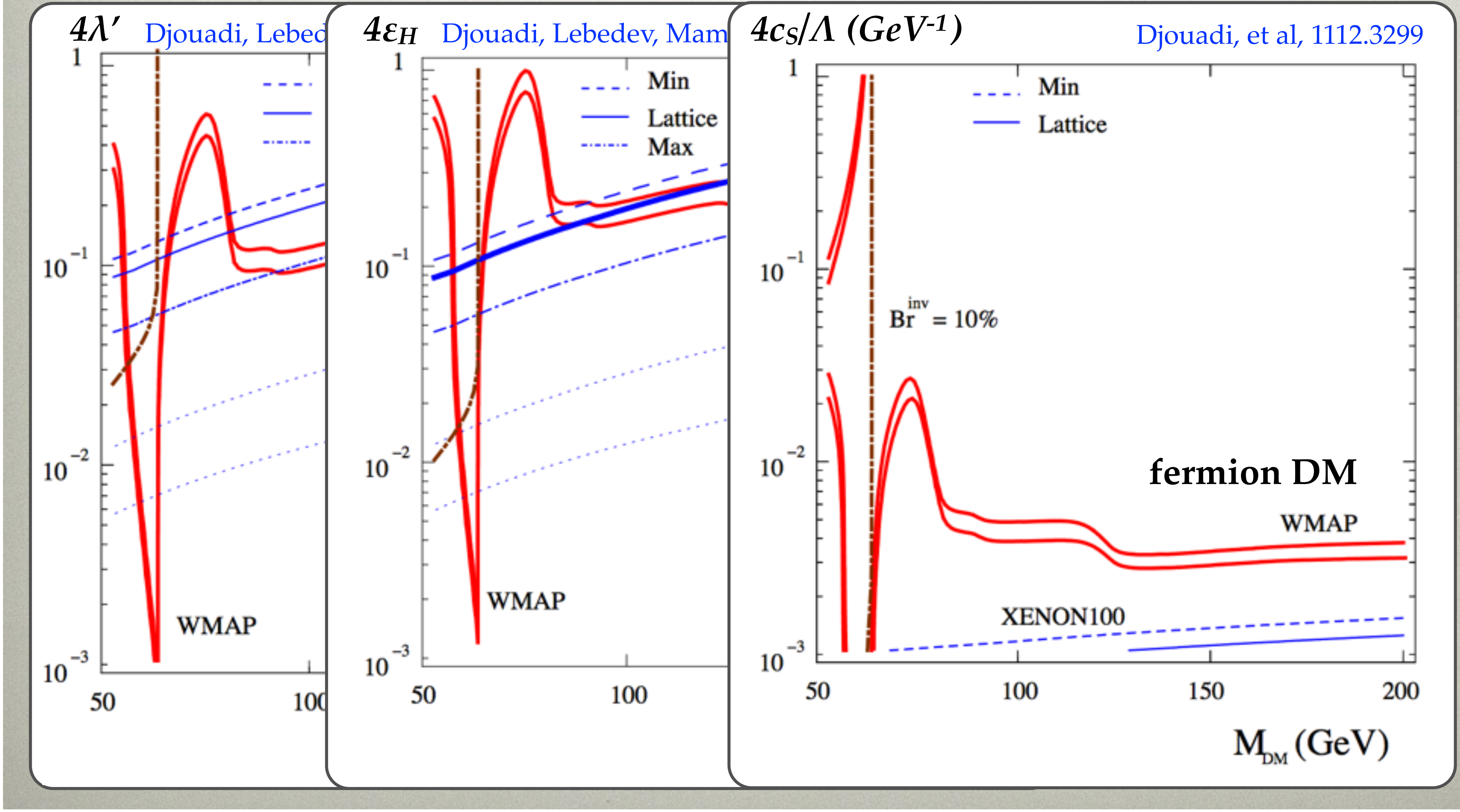


$4\lambda'$ Djouadi, Lebed

$4\epsilon_H$ Djouadi, Lebedev, Mam

$4c_S/\Lambda$ (GeV^{-1}) Djouadi, et al, 1112.3299

FERMIONIC DM HIGGS PORTAL

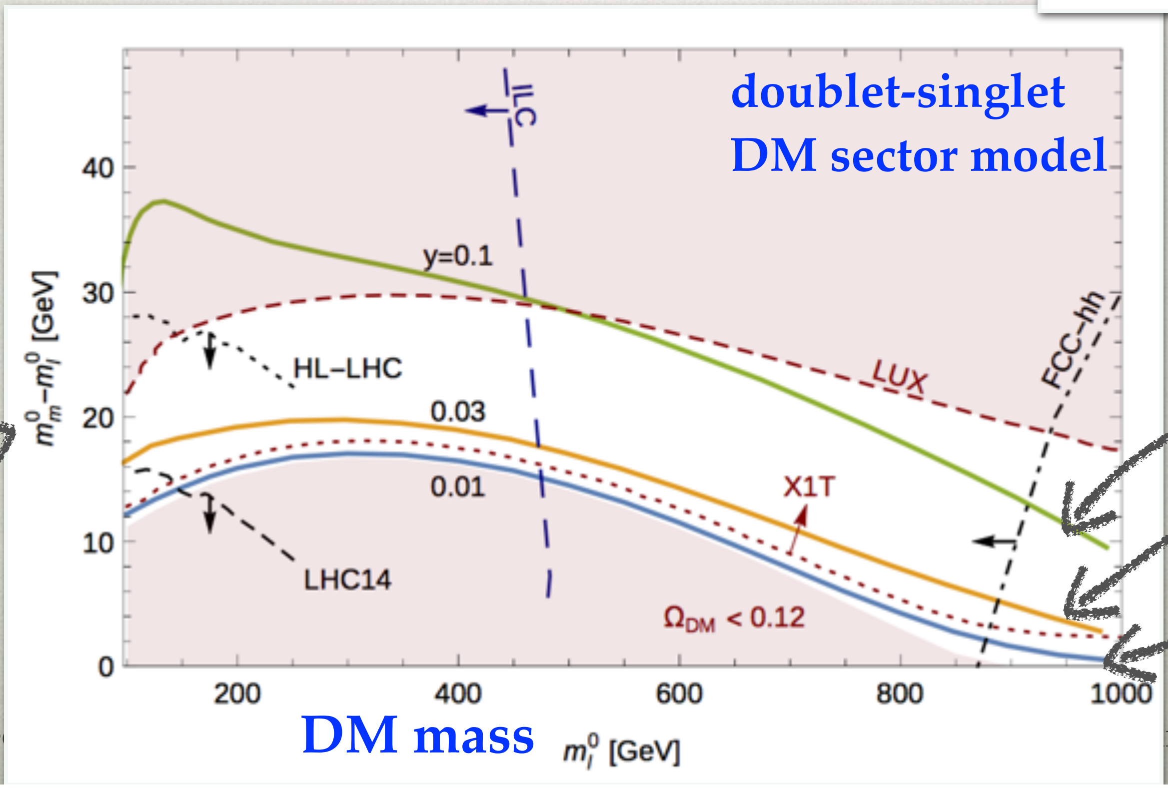
- fermionic DM Higgs portal is dimension 5

Freitas, Westhoff, JZ, 1506.04149

$$\mathcal{H}_{\rm eff}^{1/2} = \frac{c_S}{\Lambda} H^\dagger H \times \bar{\psi}\psi + \frac{i c_P}{\Lambda} H^\dagger H \times \bar{\psi}\gamma_5\psi$$

- EFT description suspect since relic abundance requires $\Lambda \sim m_\chi$
- is seen in explicit (simplified) models

$$y(H^\dagger \chi_D \chi_S - \chi_S \chi_D^c \epsilon H)$$

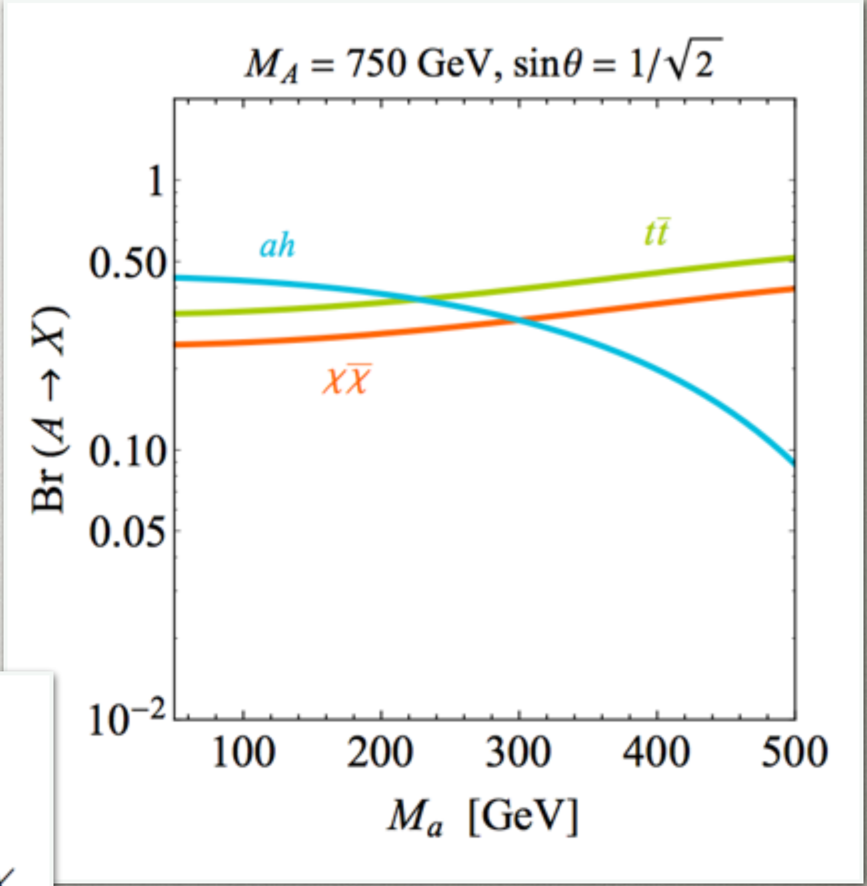


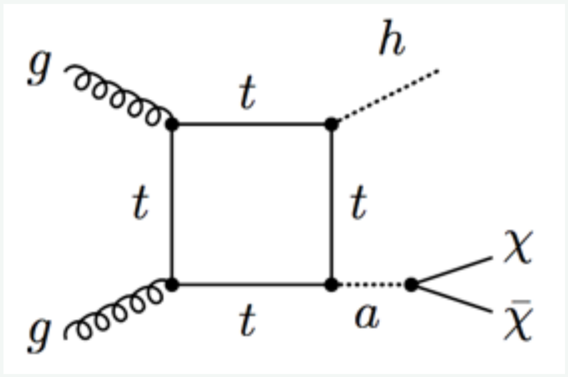
next-to--lightest state

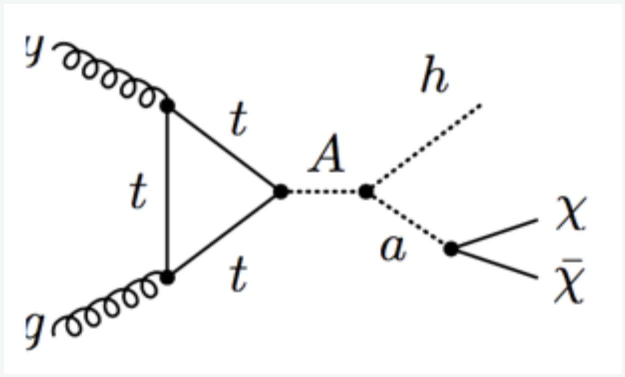
relic abundance curves

MONO-HIGGS

- mono-jet typically the most sensitive probe of DM at the LHC
- for pseudoscalar mediator mono-Higgs can be dominant signal
- example:2HDM+mediator+DM
    - resonantly enhanced





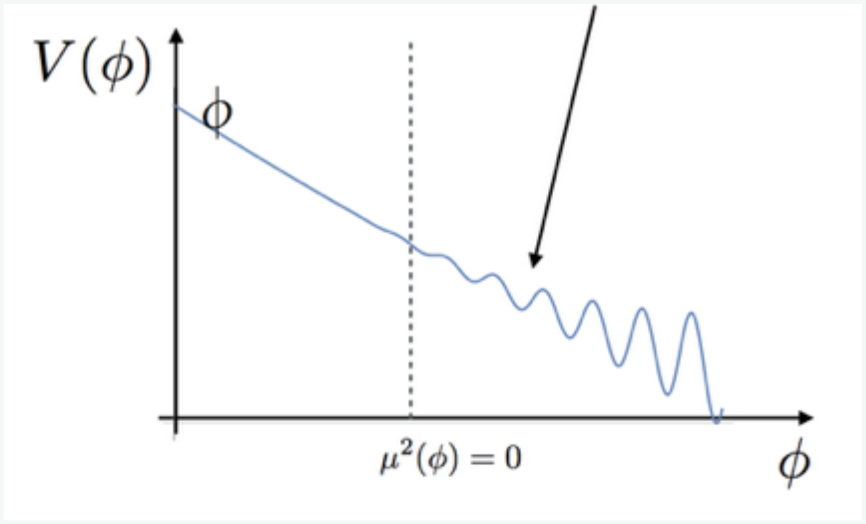


M. Bauer @LHC DM WG, Dec 15 2016

RELAXION FROM FLAVOR

Graham, Kaplan, Rajendran, 1504.07551

Flacke, Frugiuele, Fuchs, Gupta, Perez, 1610.02025



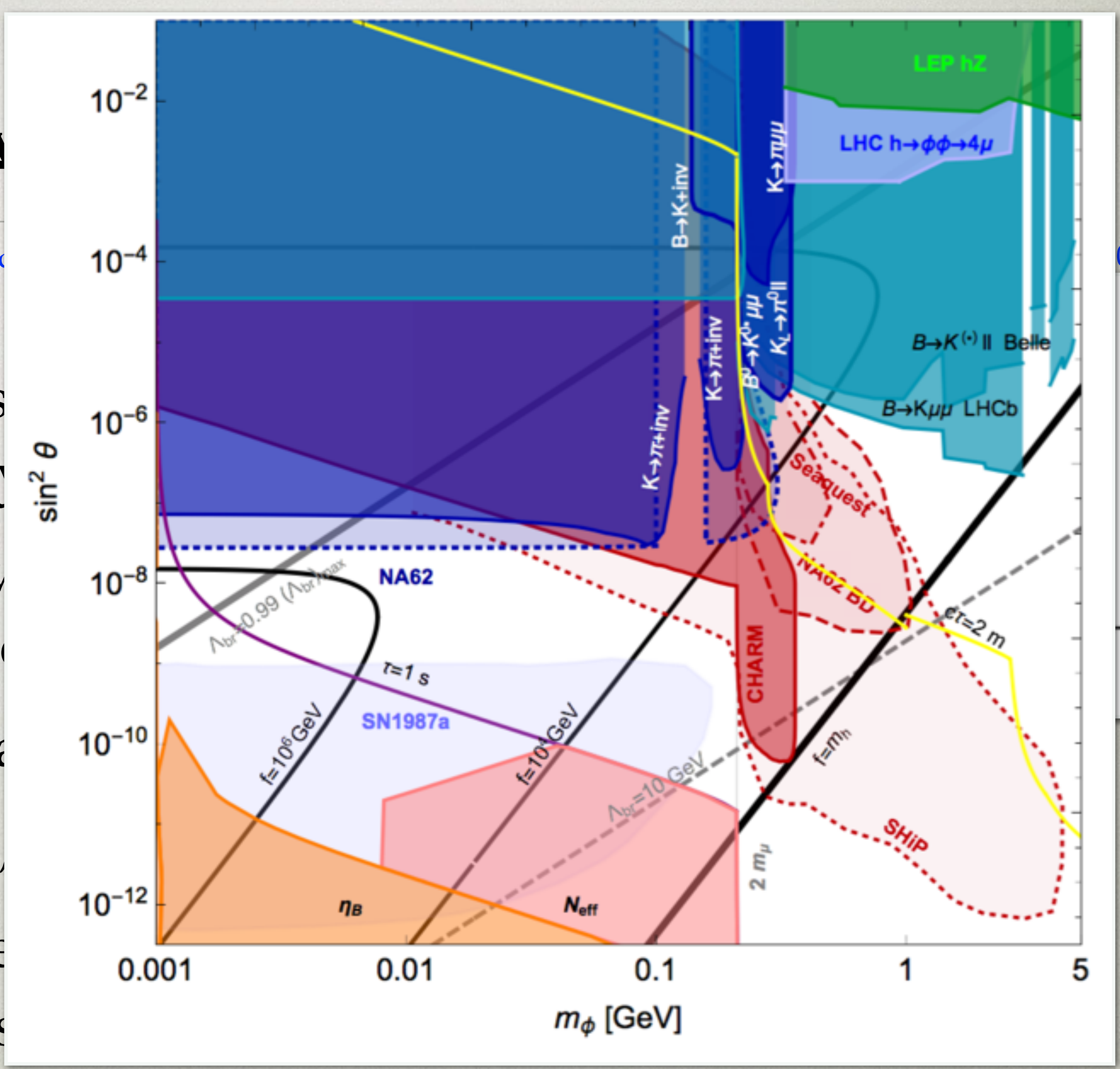
- relaxion - a technically natural solution to the hierarchy problem
  - no new EW states required in principle
- in general relaxion-higgs mixing
  - $\phi \rightarrow ee, \mu\mu, \ldots$ decays controlled by m_ϕ, $\sin\theta$
  - for MeV$\lesssim m_\phi \lesssim$GeV can search for ϕ in rare decays: $K \rightarrow \pi^+\phi$, $B \rightarrow K^+\phi$
  - for $m_\phi \gtrsim 5GeV$ most important $h \rightarrow \phi\phi$ searches

RELA

Graham, Kaplan, Rajend

0.02025

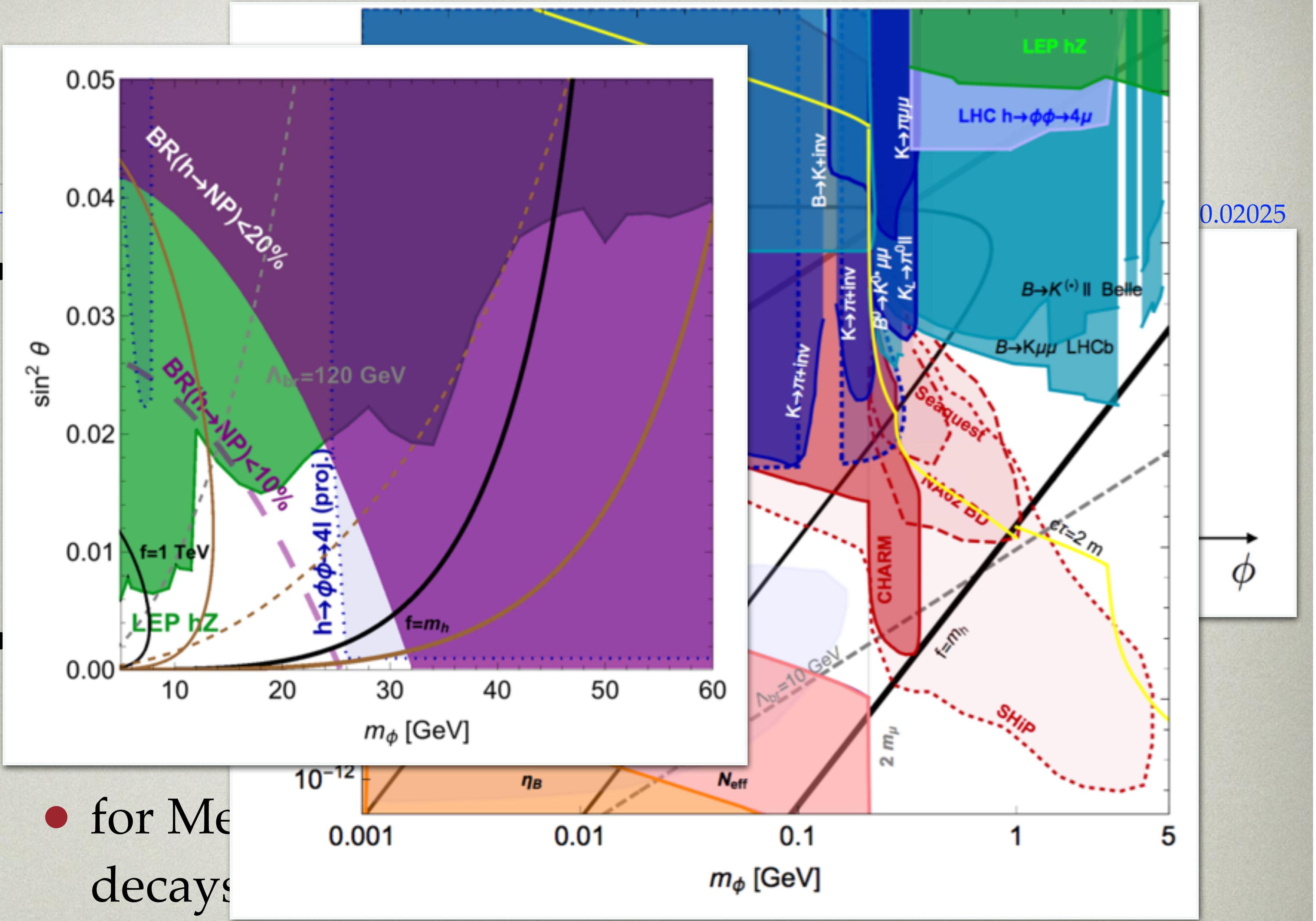
- relaxion
  natural s
  hierarchy
  - no new
    requir
- in genera
  - $\phi \rightarrow ee$,
  - for Me
    decays



- for $m_\phi \gtrsim 5GeV$ most important $h \rightarrow \phi\phi$ searches

Grah

0.02025



- for Me
  decays

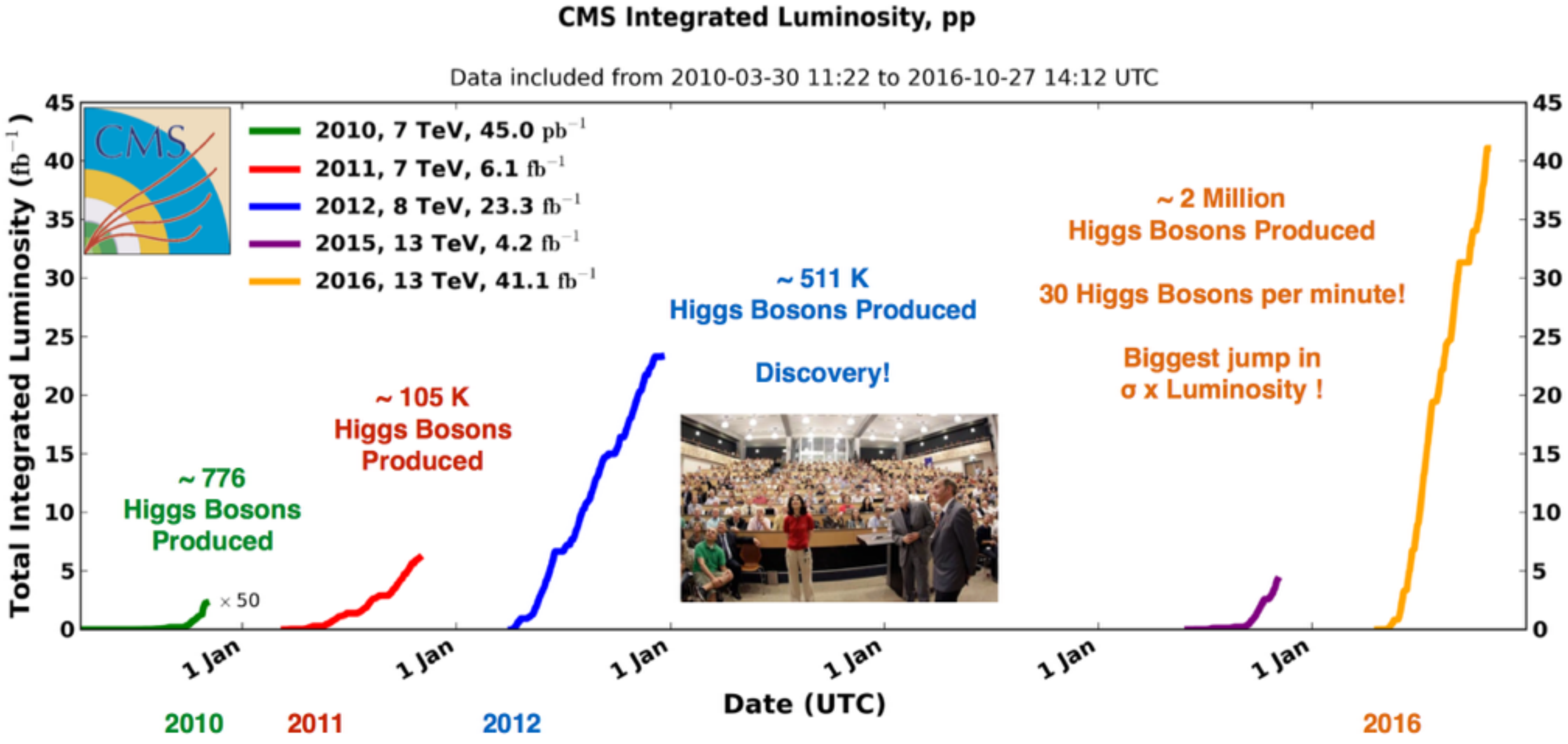
- for $m_\phi \gtrsim 5 GeV$ most important $h \to \phi\phi$ searches

CONCLUSIONS

- there are many open questions in Higgs physics that will benefit from more data
    - structure of Yukawas, probing the Higgs potential, Higgs as a NP portal
- studying SMEFT could well lead to NP discovery

BACKUP SLIDES

PROGRESS IN LUMINOSITY



Zeynep Demiragli, talk at Council Open Session, Dec 16 2016

CHARM YUKAWA

- similarly Y_c from $h \to J/\psi\gamma$

Bodwin, Petriello, Stoynev, Velasco, 1306.5770

Konig, Neubert, 1505.03870

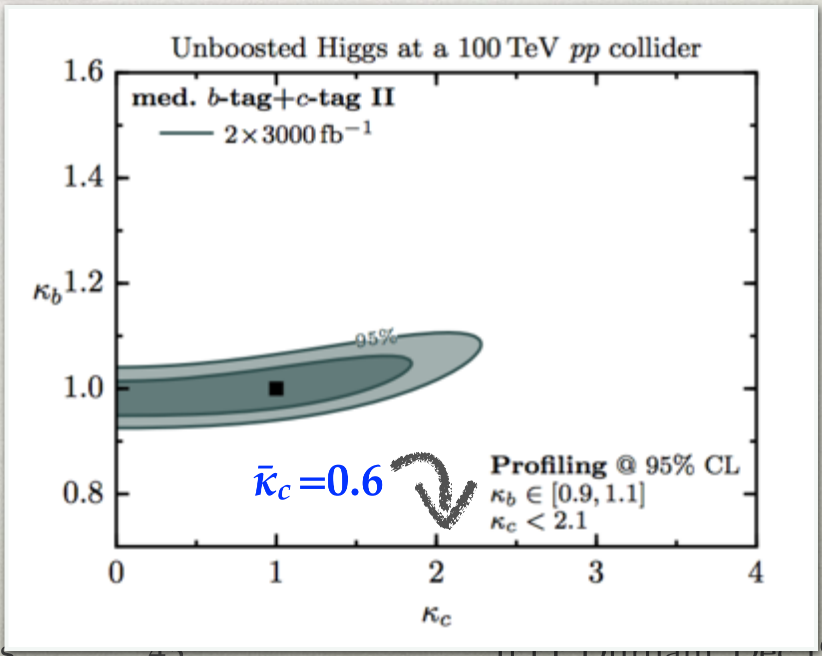
$$\frac{\mathrm{BR}_{h\to J/\psi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(3.0\pm0.15)\kappa_\gamma - 0.56\bar{\kappa}_c]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

ATLAS, 1501.03276

- projecting the ATLAS bound to 100TeV, 2x3ab^{-1}, same S/B: $\bar{\kappa}_c < 4$

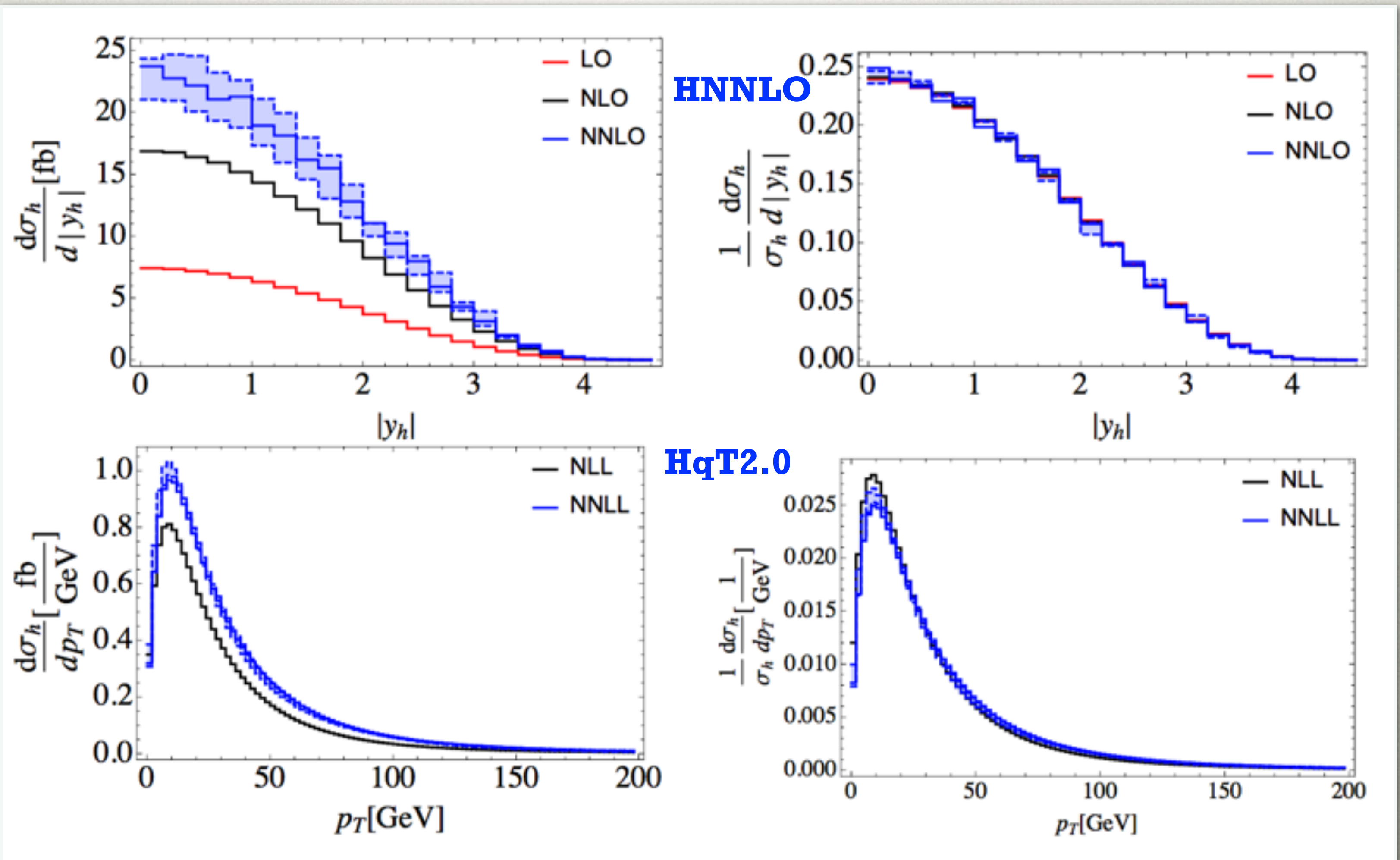
Perez, Soreq, Stamou, Tobioka, 1505.06689

- from inclusive, using charm tagging



HIGGS KINEMATICS

- important how well the distribs. under theoretical control
- using normalized distributions crucial

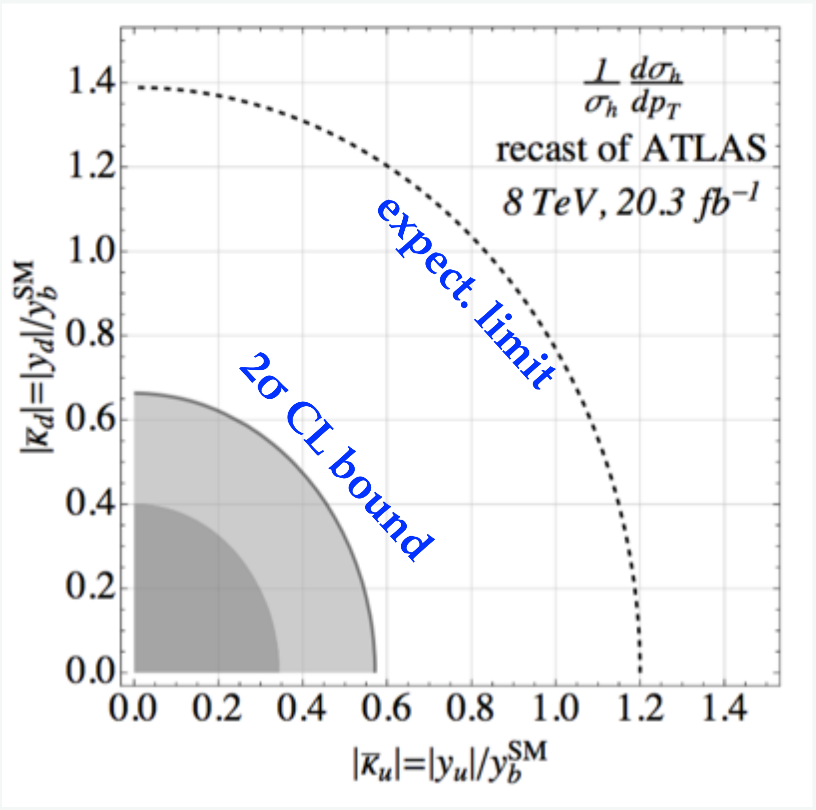


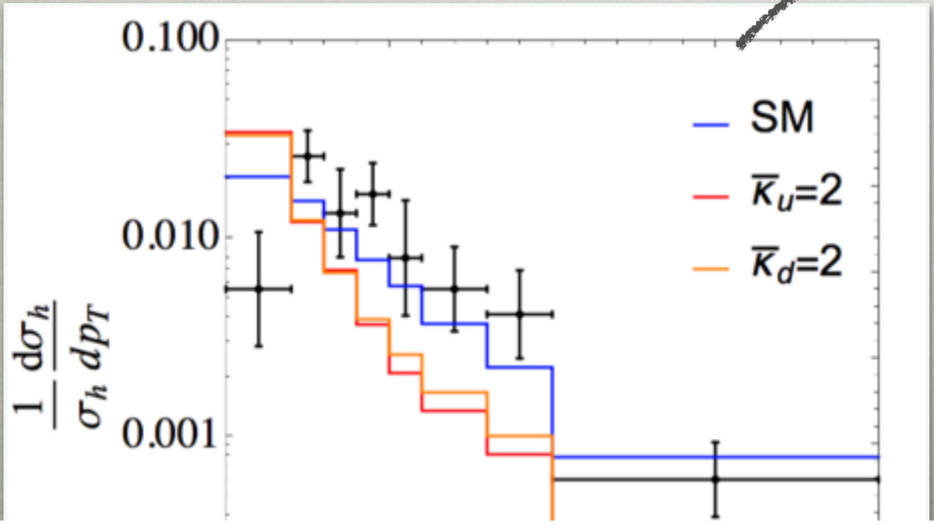
BOUNDS FROM HIGGS KINEMATICS

CMS, 1508.07819; ATLAS, 1504.05833;

09621

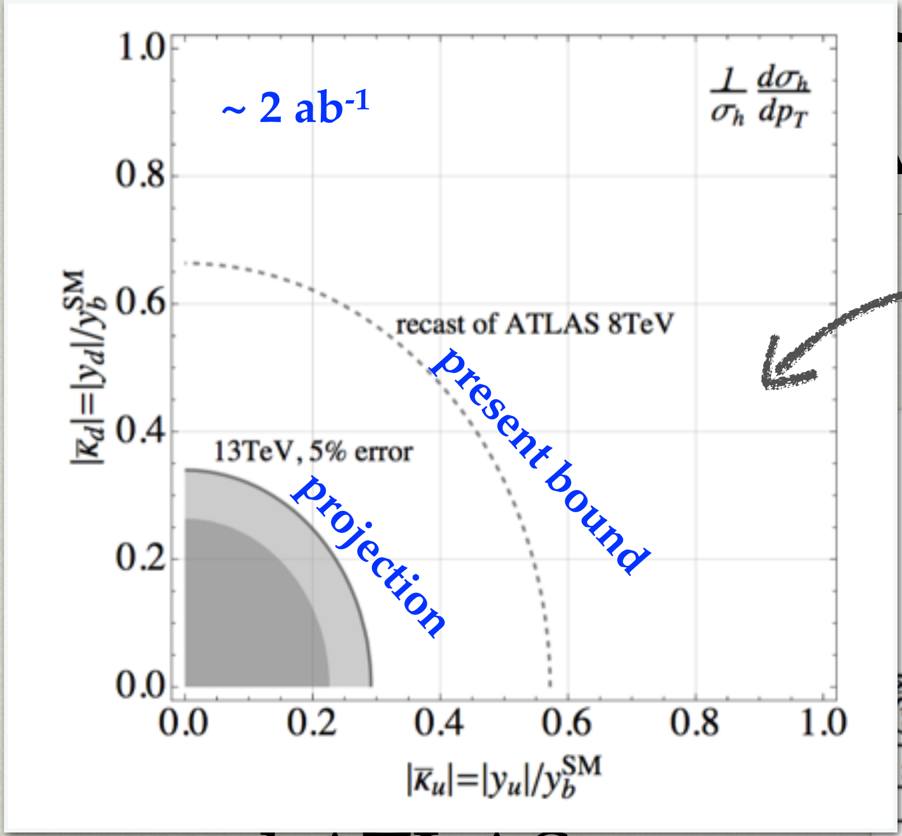
- Higgs p_T distributio
  and ATLAS



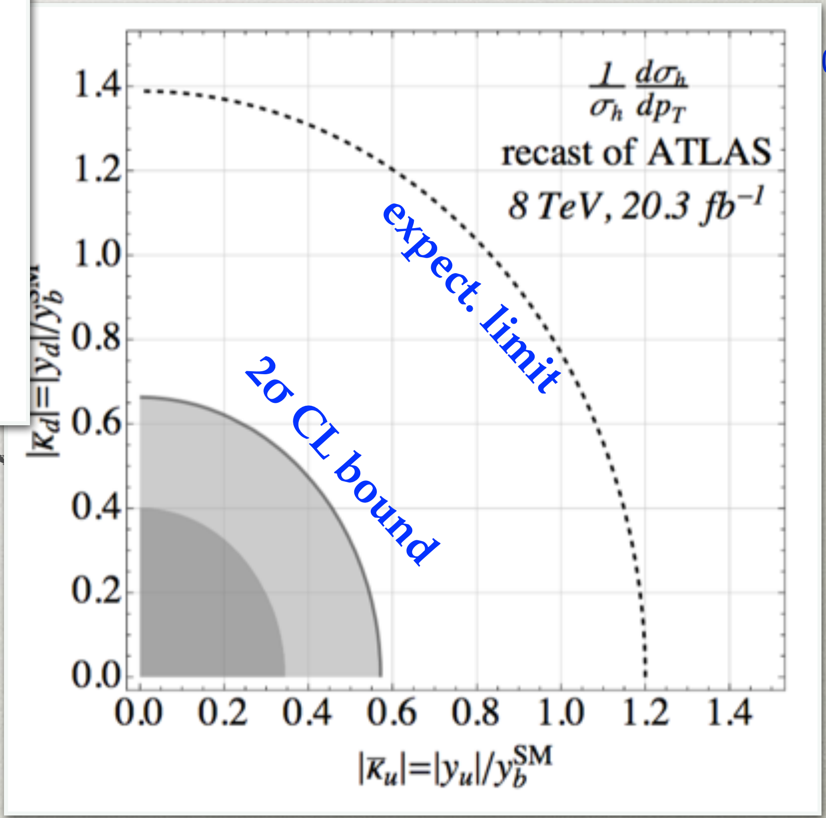


BOUNDS FROM HIGGS
ATICS

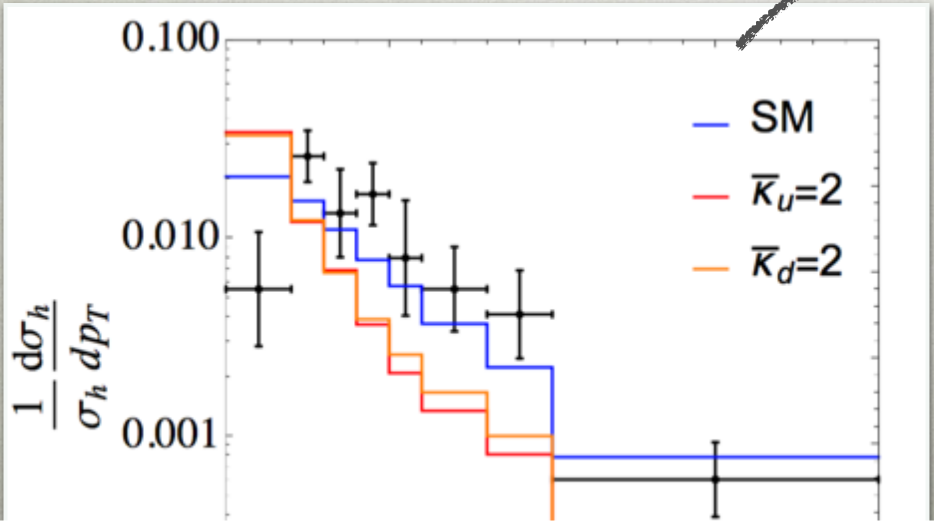
CMS, 1508.07819; ATLAS, 1504.05833;



09621



and ATLAS



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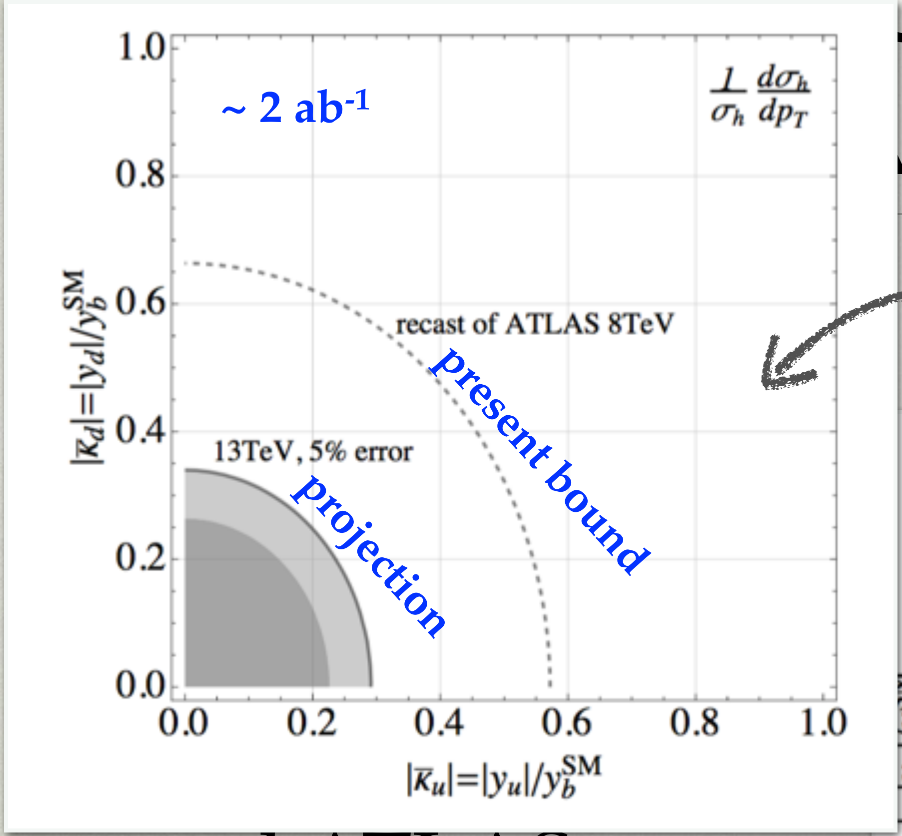

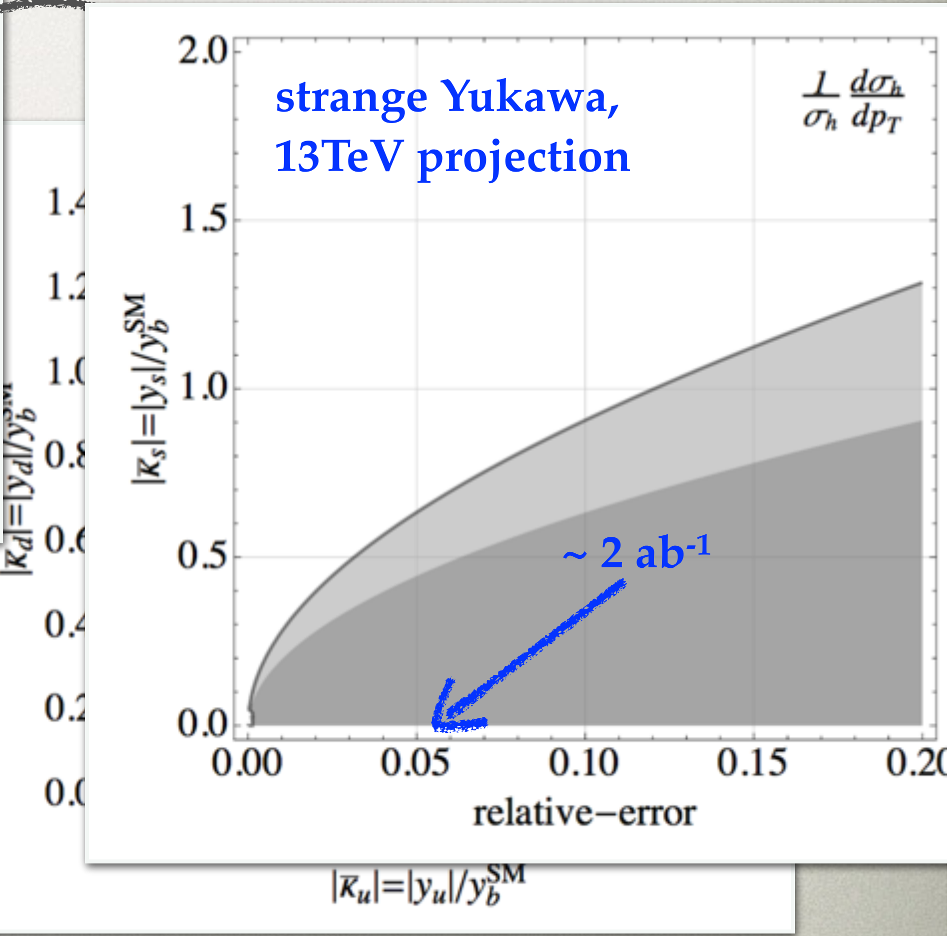

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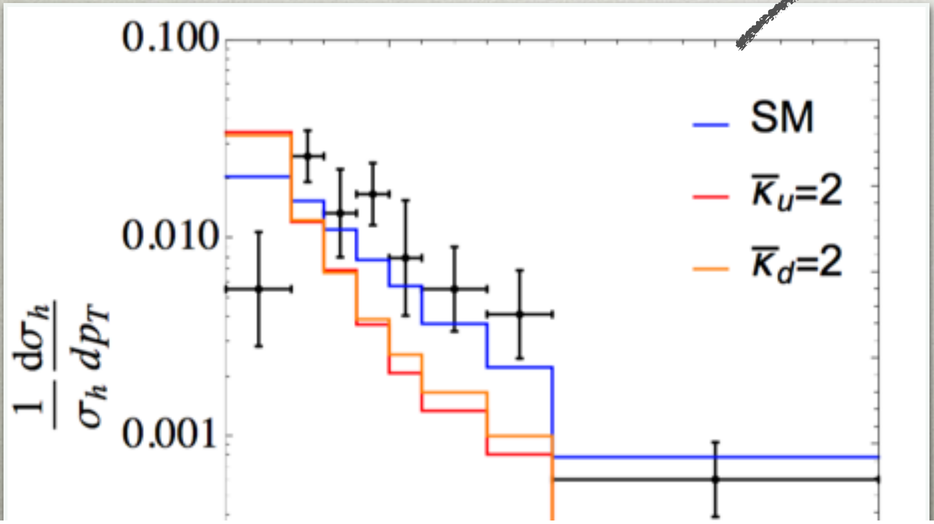


HIERARCHICAL COUPLINGS?

Soreq, Zhu, JZ, 1606.09621
Bishara, Haisch, Monni, Re, 1606.09253

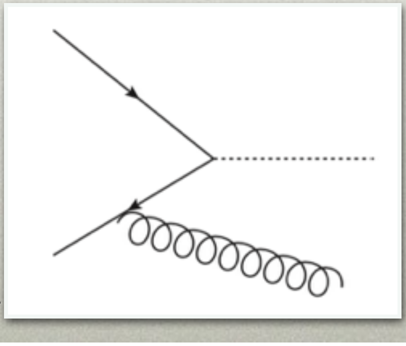
- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - already known for charged leptons and up-quarks

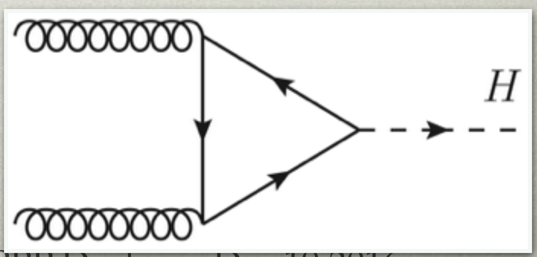
direct measurements

$$\frac{y^{\rm exp}_{e(\mu)}}{y^{\rm exp}_{\tau}} < 0.22(0.28)\,, \qquad \frac{y^{\rm exp}_{u(c)}}{y^{\rm exp}_{t}} < 0.036\,, \qquad \frac{y^{\rm exp}_{d(s)}}{y^{\rm exp}_{b}} < 5.6\,.$$

global fit

  - can we establish this for down quarks?
- seems possible to establish $y_d < y_b$ at high luminosity LHC (~300 fb^{-1})
  - from Higgs + jet p_T distributions





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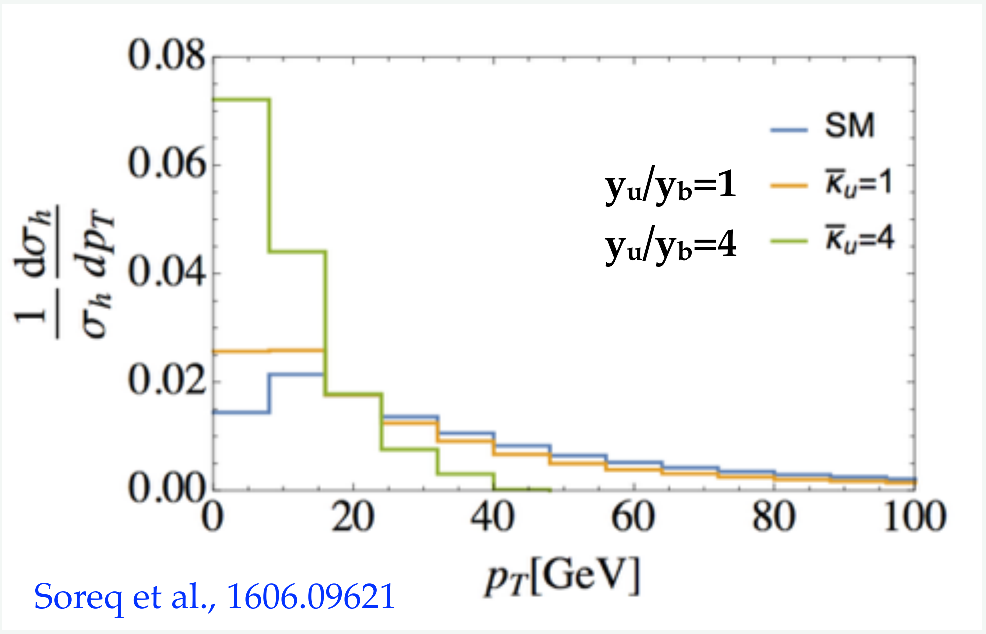
direct measurements



Soreq et al., 1606.09621

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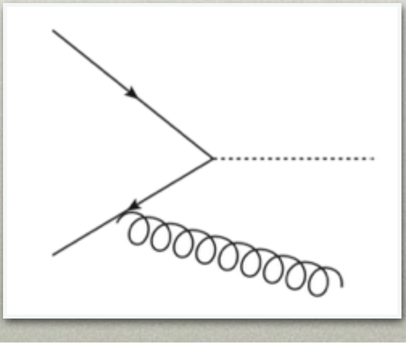
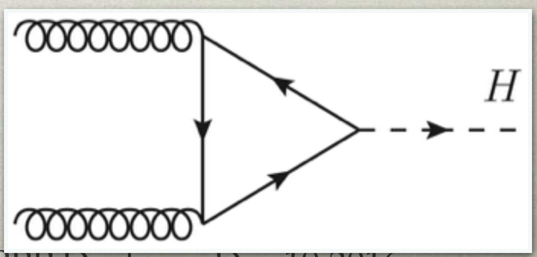
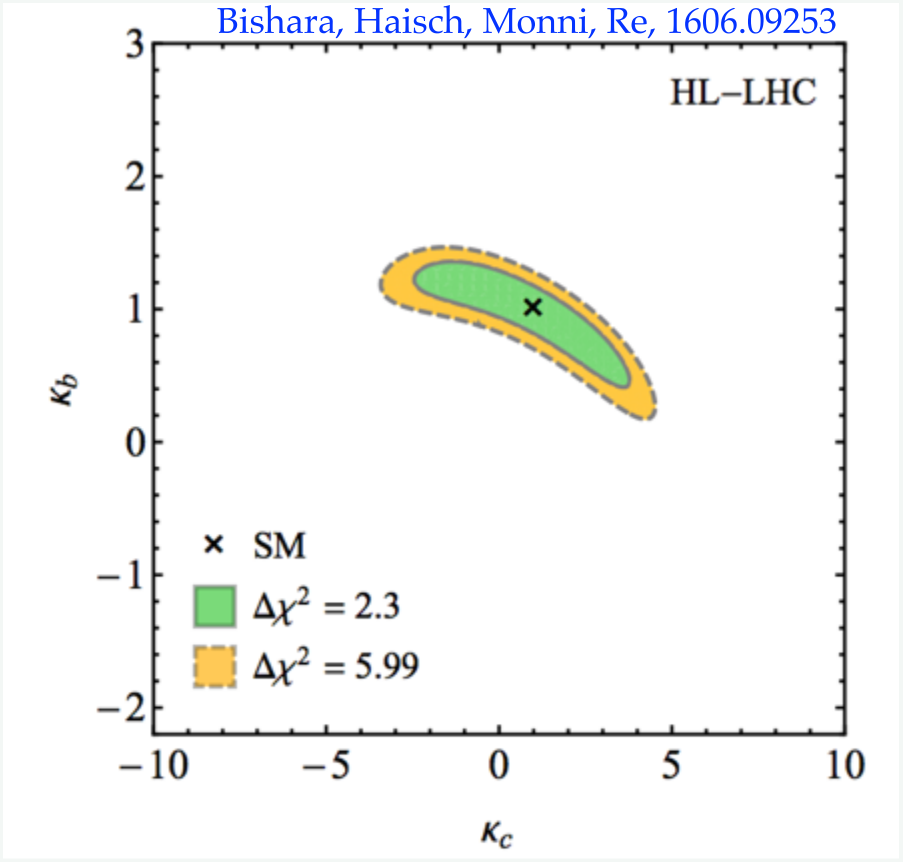




CHARM YUKAWA

- 3fb^{-1} HL-LHC could probe models of *O(1)* enhanced charm Yukawas

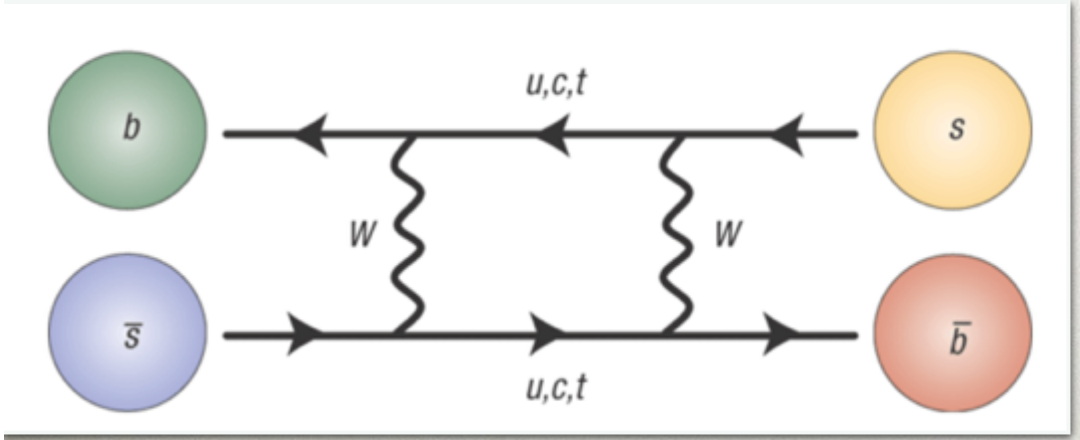

Bishara, Haisch, Monni, Re, 1606.09253

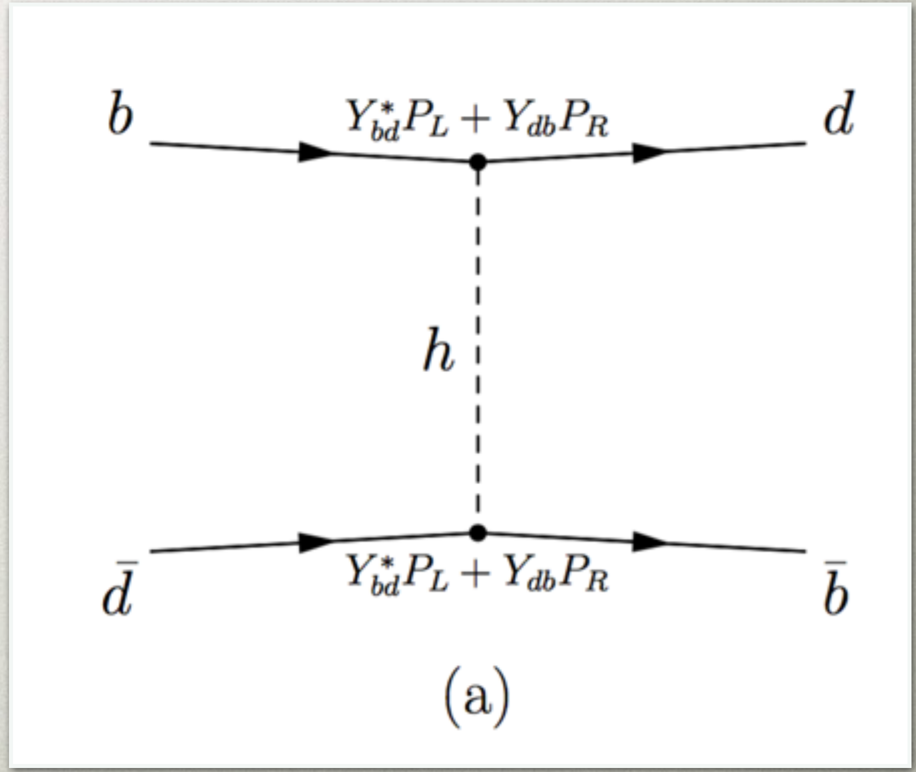
- compare with LHCb
  - present (8 TeV, 1.98fb^{-1}): κ_c<80 LHCb-CONF-2016-006
  - future HL-LHCb (13 TeV, 300fb^{-1}, simple scaling): κ_c≲4

using LHCb-CONF-2016-006+C.Parkes's talk at CKM 2016

MESON MIXING

- will induce K^0-$\bar{K}^0$, B_d-$\bar{B}_d$, B_s-$\bar{B}_s$, D^0-$\bar{D}^0$ at tree level





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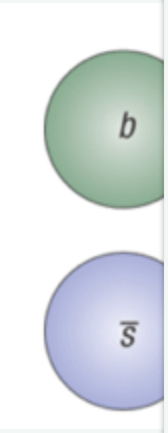

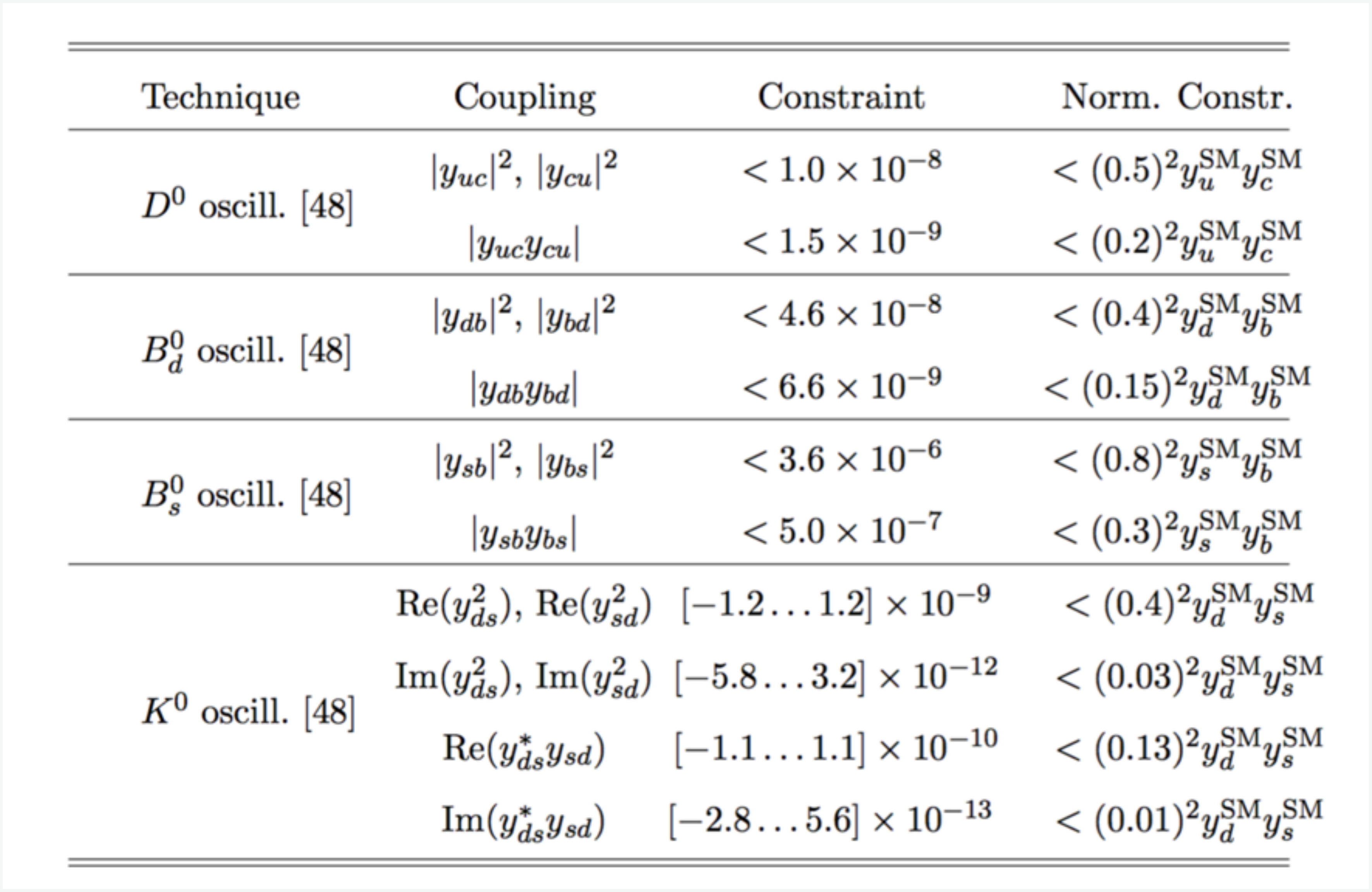

Technique	Coupling	Constraint	Norm. Constr.
D^0 oscill. [48]	$\lvert y_{uc}\rvert^2$, $\lvert y_{cu}\rvert^2$	$< 1.0 \times 10^{-8}$	$< (0.5)^2 y_u^{SM} y_c^{SM}$
	$\lvert y_{uc} y_{cu}\rvert$	$< 1.5 \times 10^{-9}$	$< (0.2)^2 y_u^{SM} y_c^{SM}$
B_d^0 oscill. [48]	$\lvert y_{db}\rvert^2$, $\lvert y_{bd}\rvert^2$	$< 4.6 \times 10^{-8}$	$< (0.4)^2 y_d^{SM} y_b^{SM}$
	$\lvert y_{db} y_{bd}\rvert$	$< 6.6 \times 10^{-9}$	$< (0.15)^2 y_d^{SM} y_b^{SM}$
B_s^0 oscill. [48]	$\lvert y_{sb}\rvert^2$, $\lvert y_{bs}\rvert^2$	$< 3.6 \times 10^{-6}$	$< (0.8)^2 y_s^{SM} y_b^{SM}$
	$\lvert y_{sb} y_{bs}\rvert$	$< 5.0 \times 10^{-7}$	$< (0.3)^2 y_s^{SM} y_b^{SM}$
K^0 oscill. [48]	$\mathrm{Re}(y_{ds}^2)$, $\mathrm{Re}(y_{sd}^2)$	$[-1.2 \ldots 1.2] \times 10^{-9}$	$< (0.4)^2 y_d^{SM} y_s^{SM}$
	$\mathrm{Im}(y_{ds}^2)$, $\mathrm{Im}(y_{sd}^2)$	$[-5.8 \ldots 3.2] \times 10^{-12}$	$< (0.03)^2 y_d^{SM} y_s^{SM}$
	$\mathrm{Re}(y_{ds}^* y_{sd})$	$[-1.1 \ldots 1.1] \times 10^{-10}$	$< (0.13)^2 y_d^{SM} y_s^{SM}$
	$\mathrm{Im}(y_{ds}^* y_{sd})$	$[-2.8 \ldots 5.6] \times 10^{-13}$	$< (0.01)^2 y_d^{SM} y_s^{SM}$

(a)

NEUTRAL NATURALNESS

- color neutral states could stabilize the Higgs at 1-loop
  - twin Higgs, folded SUSY
- need to be UV completed at ~10TeV
  - typically requires a bigger structure
  - will lead to FCNCs
  - example:
    composite Twin Higgs

Csaki, Geller, Telem, Weiler, 1512.03427