Probing the Higgs-light-quarks couplings
&
uncharming the Higgs

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Delaunay, Golling, GP & Soreq (13)
Bodwin, Petriello, Stoynev & Velasco (13)
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)
GP, Soreq, Stamou & Tobioka (Feb/15)

Aspen Winter 2015
Exploring the Physics Frontier with Circular Colliders

Status: two paths to measuring light-quark Yukawas

Recent rapid (th+exp) progress (things are still preliminary, tons of info missing)

	Inclusive (c-tagging)	exclusive (formalism: Neubert's talk)
quarks	c	$udsc$
th.	Delaunay, Golling, GP & Soreq (13) GP, Soreq, Stamou & Tobioka (Feb/15)	Bodwin, Petriello, Stoynev & Velasco (13); Kagan, GP, Petriello, Soreq, Stoynev & Zupan; Bodwin, Chung, Ee, Lee & Petriello (14); Grossmann, Konig & Neubert (15); GP, Soreq, Stamou & Tobioka (Feb/15)
exp.	ATLAS-CONF-2013-068 ATLAS-CONF-2014-063	ATLAS: 1501.03276

Outline

- Intro': Higgs & flavor physics within the standard model (SM) & beyond.

- Charming the Higgs, an inclusive approach. (charm-tagging)
Recent developments, establishing Higgs-quark non-univ. & more.

- Brief: exclusive approach, unique window to Higgs-light quarks couplings.

- Some projections & summary.

Higgs & flavor physics within the SM

♦ Higgs in minimal SM, 2 roles:

(i) induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);

(ii) induce fermion masses & unitarization (high-E consistency).

(i) was already tested in a quantitative way (ii) much less & mostly for 3rd gen'.
We focus on (ii), significant progress can be made.

♦ Recall: in the SM we have 2 type of interactions:

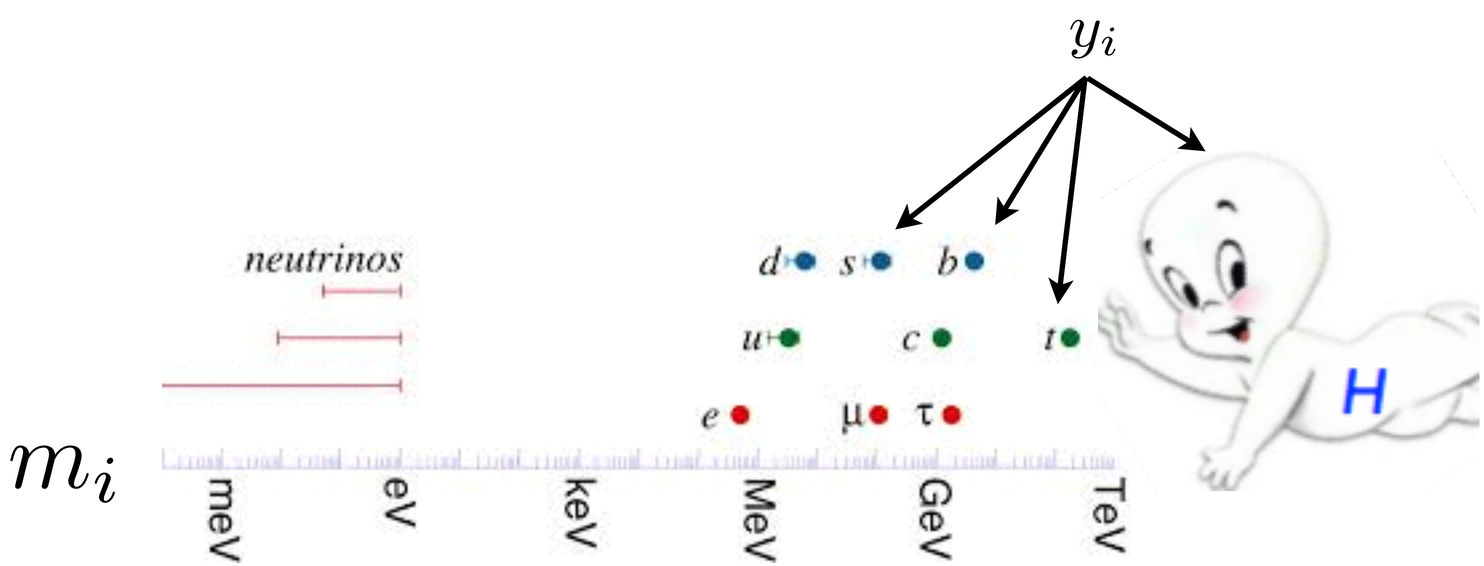
(i) gauge interactions: these are flavor blind/universal/same for all quarks;

(ii) Yukawa interactions: generation-dependent, non-universal, but to a single scalar.

Higgs & flavor physics within the SM

♦ The above 2 facts + renormalizability leads to a simple relations, up two small corrections (1loop+GIM suppressed)

SM: Higgs couples like the mass - $y_i = m_i/v$

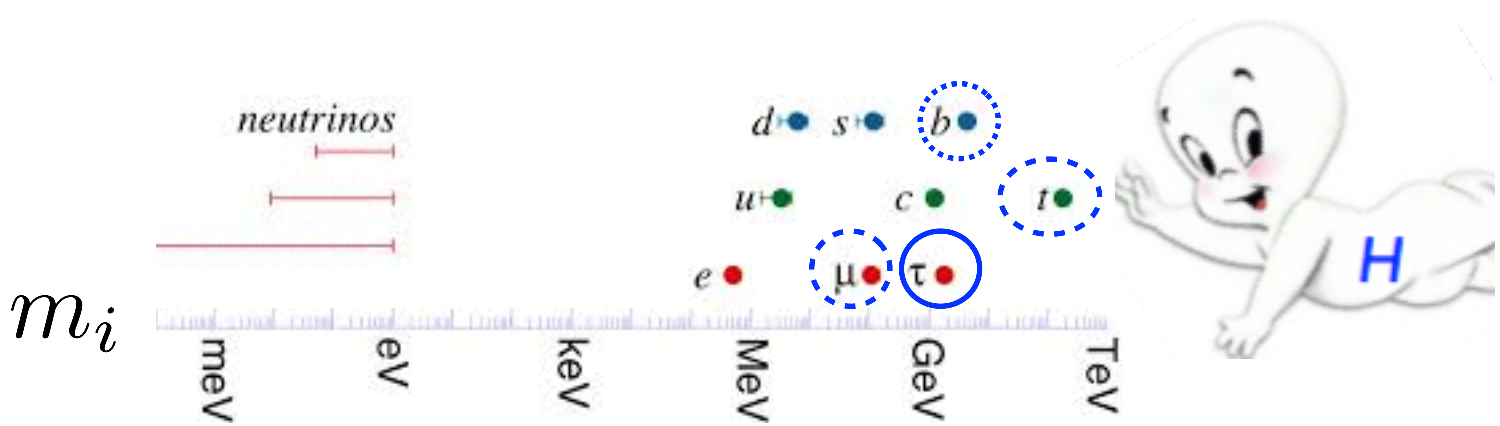


How much is known experimentally

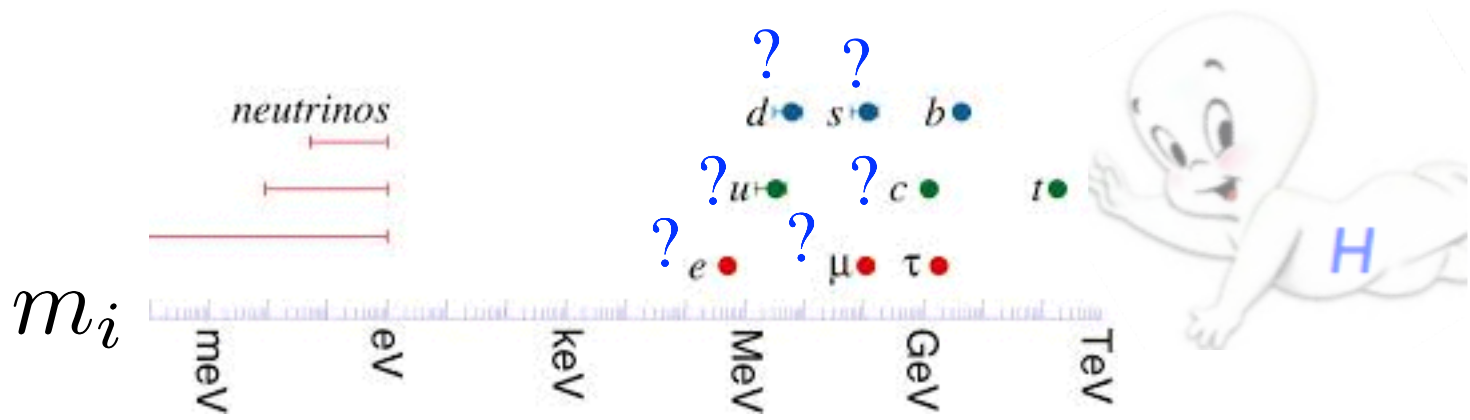
μ_x	ATLAS+CMS
τ	0.97±0.23
b	0.71±0.31
t	2.4±0.81

μ_μ : σ.Br < 7.0 (7.2)$(\sigma.\mathrm{Br})_{SM}$

Universal couplings
~260 times SM

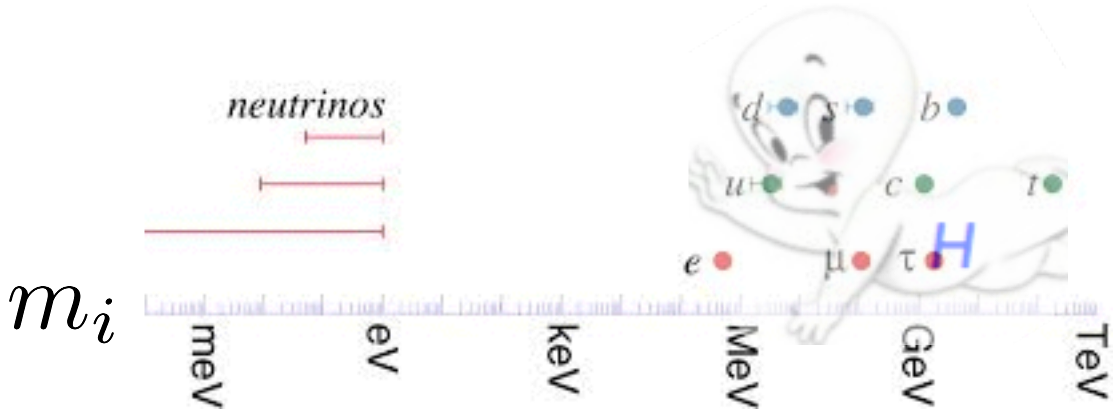


Higgs & flavor physics within the SM



Does the Higgs couples like the mass - $y_i = m_i/v$??

Higgs & flavor physics within the SM



Does the Higgs couples like the mass - $y_i = m_i/v$??

♦ This could dramatically change if non-SM exists, especially because the Higgs is light and its decay (& production) is controlled by small couplings. Let us see a trivial example.

Charming the Higgs

- Currently not much known directly on the charm Yukawa:

  (i) SM - $y_c = m_c/\mathrm{v} \sim 0.4\ \%$ => $BR(H \to c\bar{c}) \sim 4\%$, very non-trivial to observe...

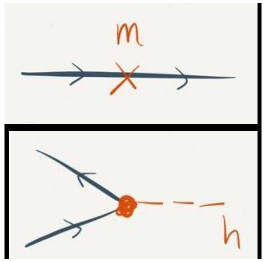
- However, as $y_b \sim 2\%$ & $BR(H \to b\bar{b}) \sim 60\%$, Higgs collider pheno' is susceptible to small perturbation.

- Enlarging charm Yukawa by few leads to dramatic changes, for instance:

Delaunay, Golling, GP & Soreq (13)

$$\mathcal{L}_{\rm EFT} \supset \lambda^u_{ij}\bar{Q}_i\tilde{H}U_j + \frac{g^u_{ij}}{\Lambda^2}\bar{Q}_i\tilde{H}U_j\left(H^\dagger H\right) + \text{h.c.}$$

$$\mathcal{L}_0 = \frac{h}{v}\Big[c_V\left(2m_W^2 W^+_\mu W^{\mu-} + m_Z^2 Z_\mu Z^\mu\right) - \sum_q c_q m_q \bar{q}q - \sum_\ell c_\ell m_\ell \bar{\ell}\ell\Big]\,,$$



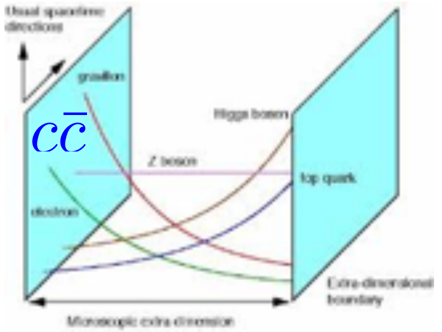
$$= \frac{v}{\sqrt{2}}\left(\lambda^u_{ij} + g^u_{ij}\frac{v^2}{2\Lambda^2}\right),$$

$$= \frac{1}{\sqrt{2}}\left(\lambda^u_{ij} + 3g^u_{ij}\frac{v^2}{2\Lambda^2}\right).$$

$$\Lambda \simeq \frac{44\,\text{TeV}}{\sqrt{c_c - 1}}$$

- Or is it simply technicolor for the light quarks ?

If you really care, more models: Delaunay, Grojean & GP (13); Kagan, GP, Volansky & Zupan (09); Dery, Efrati, Hiller, Hochberg & Nir (13); Giudice & Lebedev (08)



Charming the Higgs, current status & few projections

Delaunay, Golling, GP & Soreq (13)

- Ball park bounds are from Higgs "invisible" bound (assumes $c_V=1$):

if all other "visible" couplings set to SM values:

$Br_{inv} \sim< 22\%$ @95%CL

adding a new physics source of ggh: $Br_{inv} \sim< 50\%$ @95%CL

BR($H \to bb$) is significantly suppressed:

$$\mathrm{BR}_{h\to b\bar{b}} = \frac{\mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}}}{1+(|c_c|^2-1)\mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}}\,. \approx 40\%\ (20\%)$$

with $c_{gg}>0$

$$\hat{c}_{gg} = c_{gg} + \Big[1.3\times 10^{-2}c_t - (4.0-4.3i)\times 10^{-4}c_b - (4.4-3.0i)\times 10^{-5}c_c\Big]\,,$$

$$\sigma_{c\bar{c}\to h} \simeq 3.0\times 10^{-3}\,|c_c|^2\,\sigma^{\mathrm{SM}}_{gg\to h}\,,$$

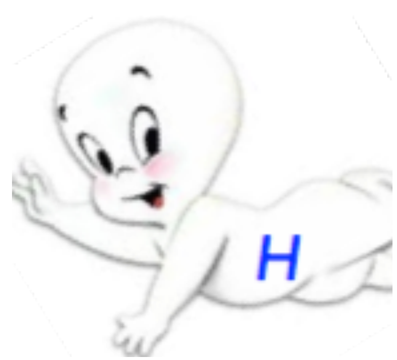
assume instead a speculative ε_c=40% c-tagging efficiency:

$\to \mu_{bb+cc} \approx 0.9\ (0.6)$ @8TeV

Uncharming the Higgs, establishing non-universality & more

GP, Soreq, Stamou & Tobioka (Feb/15)

$c\bar{c}$



Before talking about our work, 2 slides about an experimental break through

Charm tagging at the LHC

- In new ATLAS search for stop decay to charm + neutralino ($\tilde{t} \to c + \chi^0$) charm jet tagging has been employed for the first time at LHC

ATLAS-CONF-2013-068

- charm jets identified by combining "information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices" using multivariate techniques

  - 'medium' operating point: c-tagging efficiency = 20%, rejection factor of 5 for b jets, 140 for light jets. #'s obtained for simulated $t\bar{t}$ events for jets with $30 < p_T < 200$, and calibrated with data

More recently, constraining (non-deg.) scharms

- An interesting viable possibility is anarchic squark spectrum. `Nir & Seiberg (93)`

- Scenario still viable and the bounds on scharms are very weak.

  `Gedalia, Kamenik, Ligeti & GP (12)`
  `Mahbubani, Papucci, GP, Ruderman % Weiler (13)`

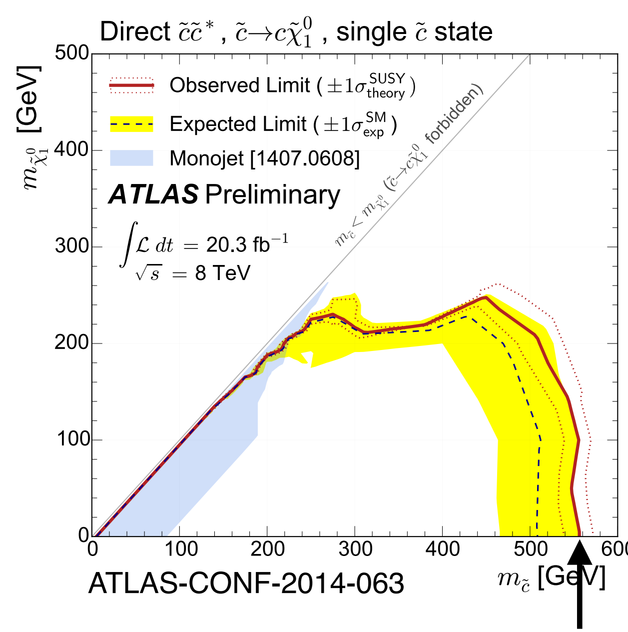
- Has potential consequences for naturalness ("flavorful naturalness").

  `Blanke, Giudice, Paradisi, GP & Zupan (13)`

- ATLAS: light scharms search \w new working point for charm tagging:

Search for Scalar-Charm Pair-Production with the ATLAS Detector in pp Collisions at $\sqrt{s} = 8$ TeV

$$\epsilon_c = 19\% \quad \epsilon_b = 12\%$$



ATLAS-CONF-2014-063

Executive sum.: Constraining Higgs-charm univ.

GP, Soreq, Stamou & Tobioka (Feb/15)

- Bottom line: can use existing data to constrain Higgs-quarks univ..

(i) Direct constraint: recast *VH(bb)*, taking advantage of 2 working point $c_c < 250$.

(ii) the recent ATLAS search to h → J/ψγ (see later) yield $c_c < 210$;

(assumes Higgs coupling to two photons and/or four leptons is not significantly modified by new physics);

(iii) the direct measurement of the total width yield $c_c < 150$ (ATLAS),120 (CMS).;

(iv) Global fit to the Higgs signal strength, $c_c < 6$.

(v) *tth* data => $c_t > 0.9$ (equivalence to $c_c > 280$).

#1 Direct constraint: recast *VH(bb) (preliminary)*

GP, Soreq, Stamou & Tobioka (Feb/15)

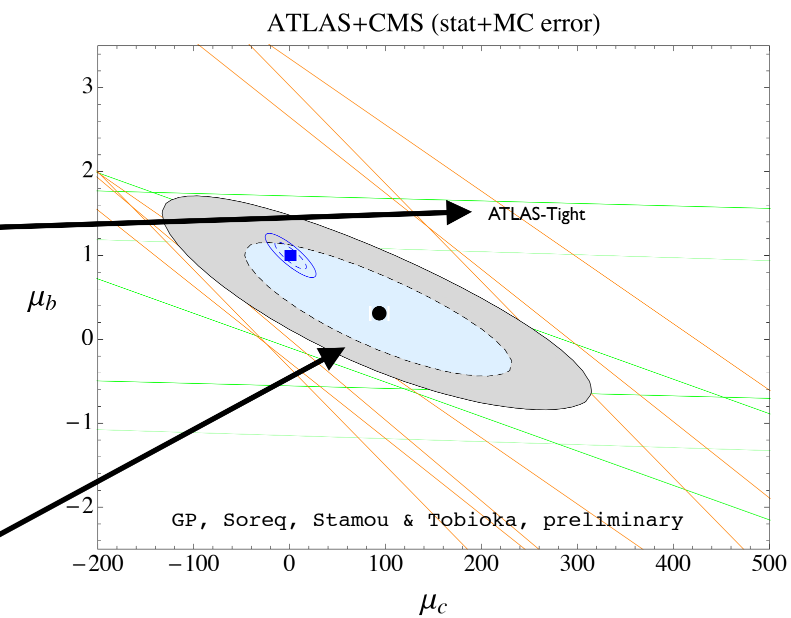
- Idea: use several charm-tagging working points of ATLAS & CMS in their *VH(bb)* analysis.

$$\mu_b = \frac{\sigma}{\sigma_{SM}} \frac{\mathrm{BR}_{b\bar{b}}}{\mathrm{BR}_{b\bar{b}}^{SM}} \rightarrow \mu_b + \frac{\mathrm{Br}_c^{SM}}{\mathrm{Br}_b^{SM}} \frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}} \mu_c$$

where $\epsilon_{b_{1,2}}$ and $\epsilon_{c_{1,2}}$ are efficiencies to tag jets originating from bottom and charm quark, respectively. μ_c is normalized to be 1 in a case of the SM.

- Each working point yields flat direction:

ATLAS	Med	Tight	CMS	Loose	Med1	Med2	Med3
ϵ_b	70%	50%	ϵ_b	88%	82%	78%	71%
ϵ_c	20%	3.8%	ϵ_c	47%	34%	27%	21%

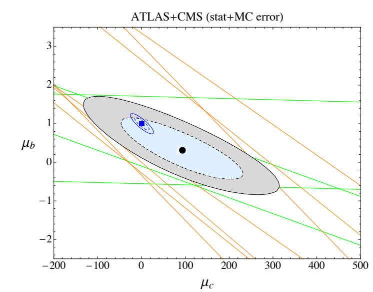


- However, combining points => bound.

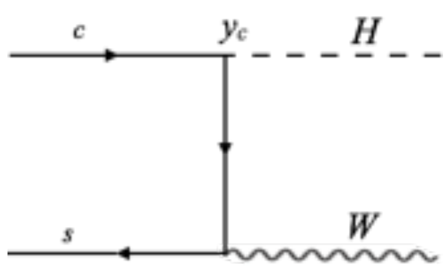
New production mechanism *VH(bb) (preliminary)*

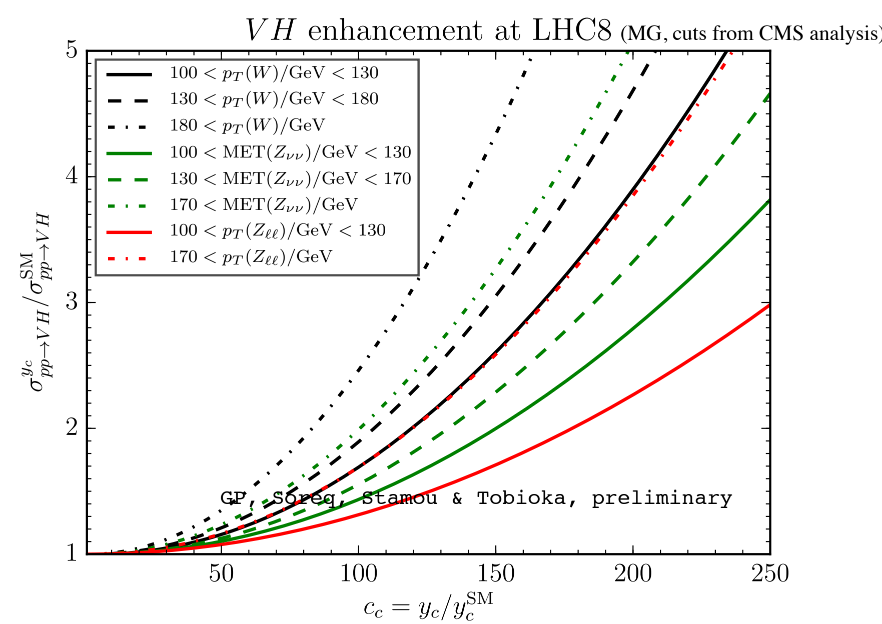
GP, Soreq, Stamou & Tobioka (Feb/15)

- $\mu_c = \frac{\sigma}{\sigma^{\rm SM}} \frac{\rm Br}{{\rm Br}_c^{\rm SM}}$ => \w SM *VH*-production $\mu_c < 30$ => no constraint on y_c.



- However $\mu_c < 30$ for large $c_c > 50$ new production mechanism:





No runaway for c_c → $c_c < 250.$

Constraining Higgs-quark universality #1 (model indep')

- New production eliminates the y_c runaway $\Longrightarrow$ $c_c < 250$ what about y_t ?

- ATLAS+CMS tth: $\mu_{tth}^{\rm avg} = 2.41 \pm 0.81 \Rightarrow$ $c_t > 0.9\sqrt{\frac{{\rm Br}^{\rm SM}_{h\to{\rm relevant\ \ modes}}}{{\rm Br}_{h\to{\rm relevant\ \ modes}}}} > 0.9$

$$\frac{c_c}{c_t} = \frac{y_t^{\rm SM}}{y_c^{\rm SM}}\frac{y_c}{y_t} = 280\frac{y_c}{y_t} < 250 \quad \Rightarrow \quad y_c < y_t\,!$$

GP, Soreq, Stamou & Tobioka (Feb/15)

As shown below: the method works much better via real c-tagging working point.

Constraining Higgs-quark universality #2+3

- Width bound: $\Gamma_h < 2.6\,\mathrm{GeV}$ **(ATLAS),** $\Gamma_h < 1.7\,\mathrm{GeV}$ **(CMS) =>** $c_c < 150,\, 120\,.$

GP, Soreq, Stamou & Tobioka (Feb/15)

- Interpretation of ATLAS recent $h \to J/\psi\gamma$ (1501.03276): $\sigma(pp \to h) \times \mathrm{BR}_{h\to J\psi\gamma} < 33\,\mathrm{fb}\,,$

- As discussed below, this implies: $\Gamma_{h\to J/\psi\gamma} = 1.42\,(\kappa_\gamma - 0.087\kappa_c)^2 \times 10^{-8}\,\mathrm{GeV}$

Bodwin, Petriello, Stoynev & Velasco (13); Bodwin, Chung, Ee, Lee & Petriello (14)

- Getting rid of production: $\mathcal{R}_{J/\psi,Z} = \dfrac{\sigma(pp\to h)\times \mathrm{BR}_{h\to J/\psi\gamma}}{\sigma(pp\to h)\times \mathrm{BR}_{h\to ZZ^*\to 4\ell}} = \dfrac{\Gamma_{h\to J/\psi\gamma}}{\Gamma_{h\to ZZ^*\to 4\ell}} = 2.79\dfrac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2}\times 10^{-2}\,,$

$$\mathcal{R}_{J/\psi,Z} = \frac{33\,\mathrm{fb}}{\mu_{ZZ^*}\sigma^{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{h\to ZZ^*\to 4\ell}} < 9.32 \quad \Longrightarrow \quad c_c < 210 c_V + 11 c_\gamma\,.$$

(LEP: $c_V = 1.08 \pm 0.07$)

GP, Soreq, Stamou & Tobioka (Feb/15)

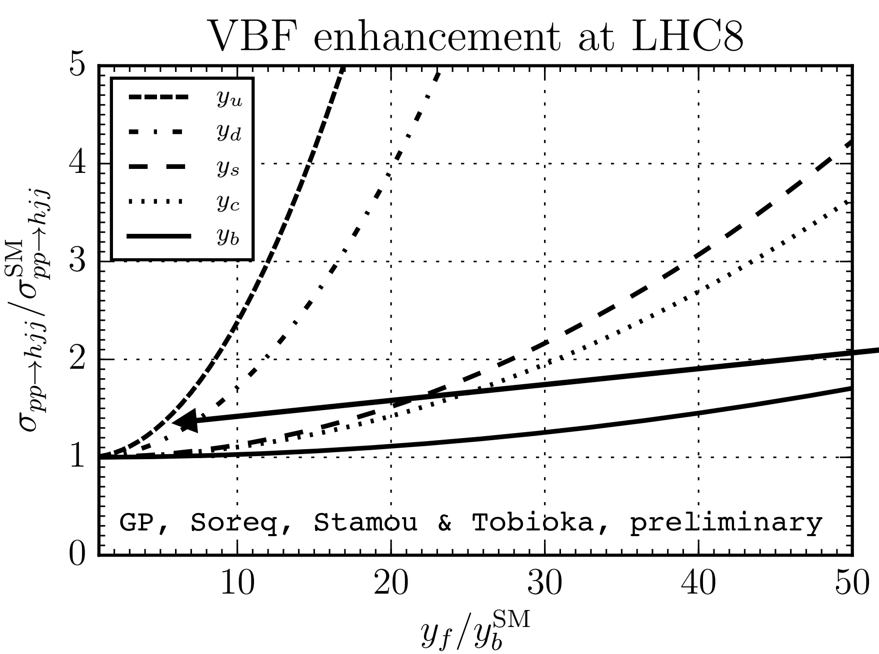
Finally global analysis

- The conventional way of doing the fit leads to: $c_c < 6.$

- It is equivalence to the invisible (untagged) Higgs decay bound, driven by VBF:

$$\mu_{\mathrm{VBF}\to h\to WW^*} = 1.27^{+0.44+0.30}_{-0.40-0.21} = 1.27^{+0.53}_{-0.45}\,, \qquad \Longleftrightarrow \qquad \mu_{\mathrm{VBF}\to h\to WW^*} = \left(\kappa_V^2 + \bar{\sigma}_{\mathrm{VBF}}^{\mathrm{non-SM}}\right)\frac{\kappa_V^2}{R_\Gamma}$$

where $R_\Gamma = \Gamma_h/\Gamma_h^{\mathrm{SM}}$

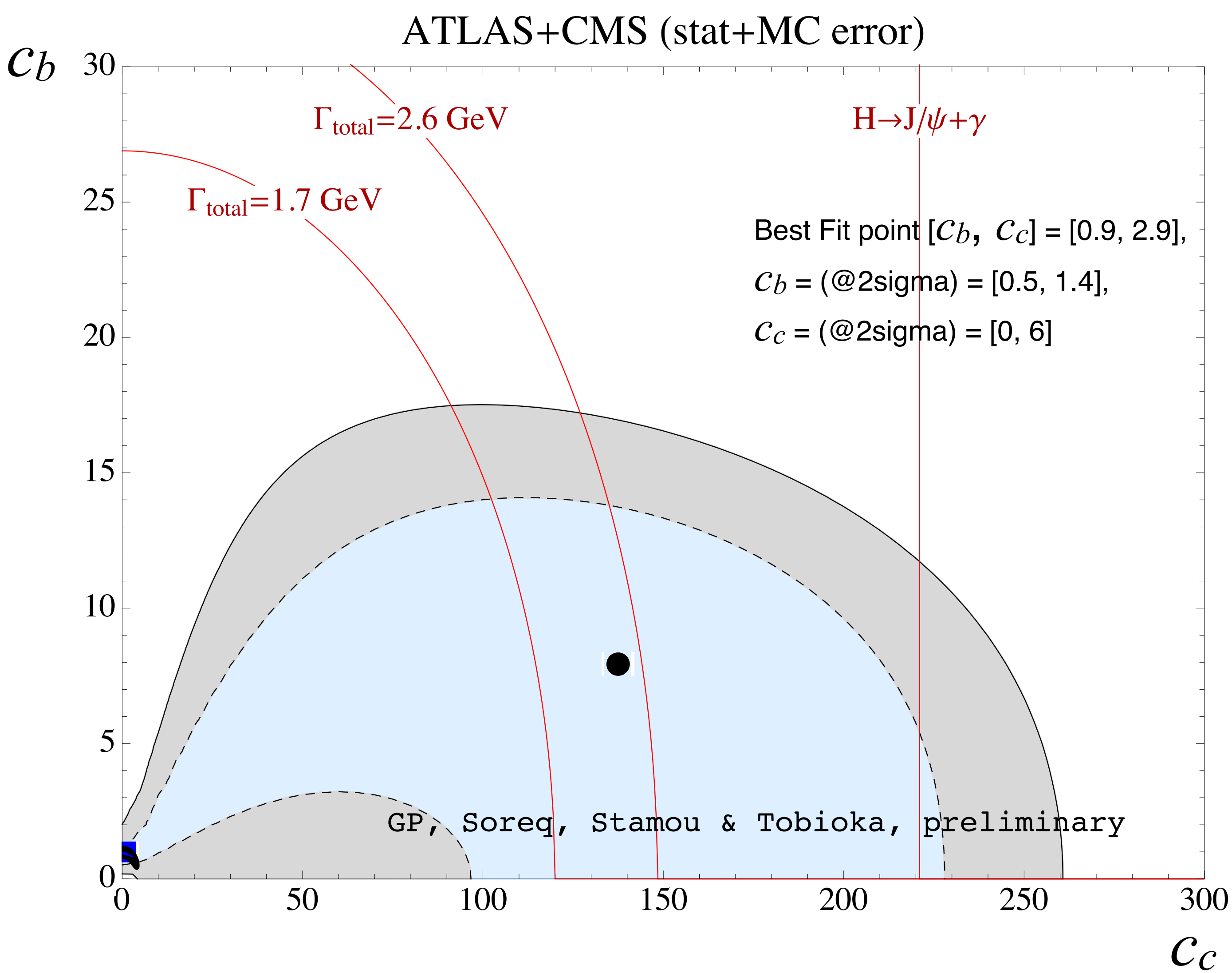


always set to zero, however not necessarily negligible.

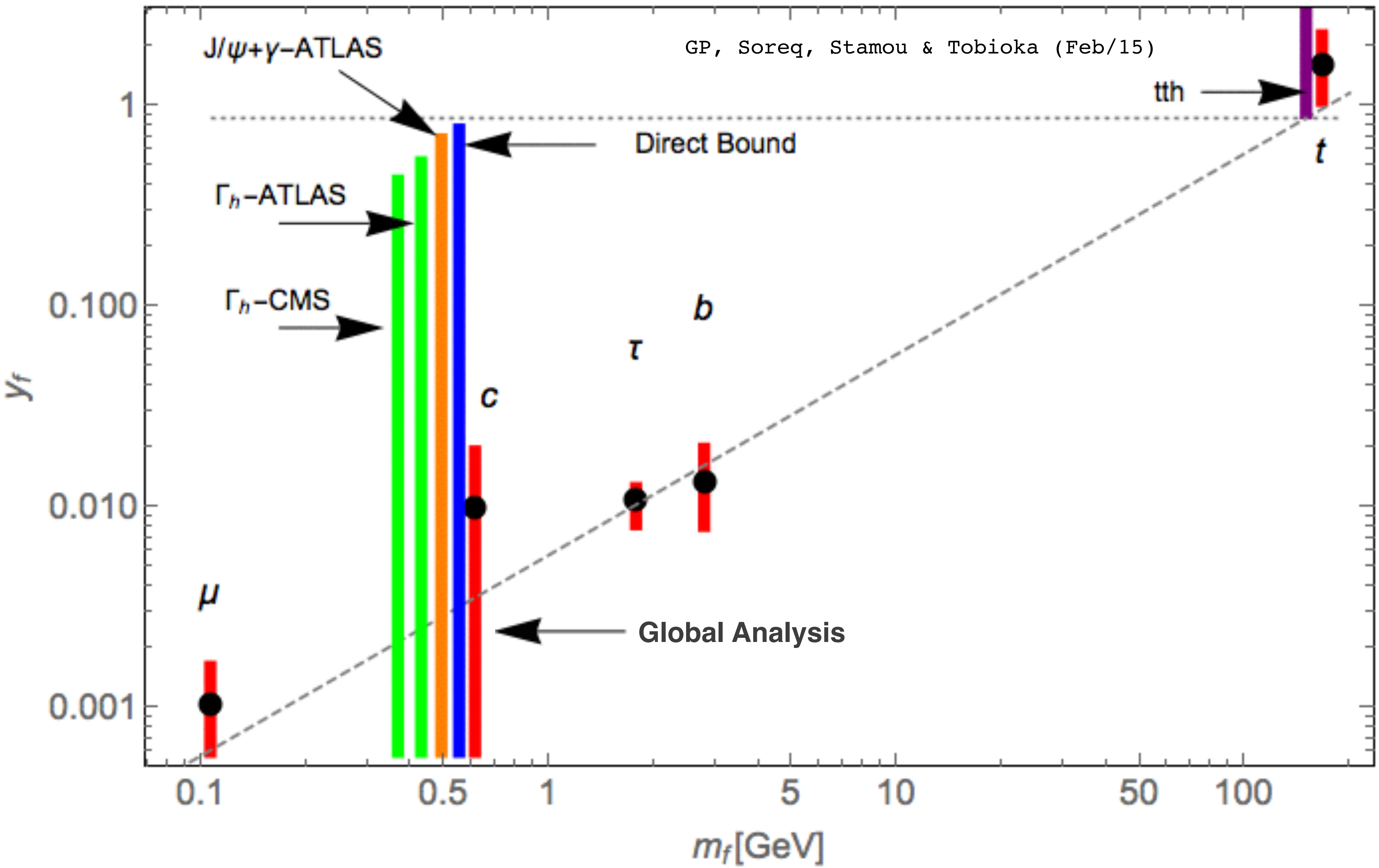
Currently small effect but might not be in the future.

VBF & Vh can be compared to other machines, leptons? hadrons?

Showing all constraints together



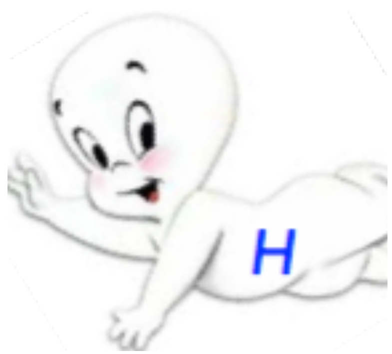
Preliminary summary/money plot …



An Exclusive Window onto Higgs Yukawa Couplings to light quarks

Bodwin, Petriello, Stoynev & Velasco (13)
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

$s\bar{b}$ $s\bar{s}$
$d\bar{b}$ $d\bar{d}$
$d\bar{s}$ $u\bar{u}$



Exclusive path towards Higgs-light quark couplings

- Use the eff. Lagrangian:

$$\mathcal{L}_{\rm eff} = -\sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q\neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c. + \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu} \,,$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\rm SM}$, (sorry different notation)

in the SM:

$$\bar{\kappa}_s = m_s/m_b \simeq 0.020$$

$$\bar{\kappa}_d = m_d/m_b \simeq 1.0 \cdot 10^{-3}$$

$$\bar{\kappa}_u = m_u/m_b \simeq 4.7 \cdot 10^{-4}$$

$$\kappa_\gamma = \kappa_V = 1$$

Exclusive path towards Higgs-light quark couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- Use the eff. Lagrangian: $$\mathcal{L}_{\rm eff} = -\sum_{q=u,d,s} \bar\kappa_q \frac{m_b}{v} h \bar q_L q_R - \sum_{q\neq q'} \bar\kappa_{qq'} \frac{m_b}{v} h \bar q_L q'_R + h.c. + \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi}\frac{h}{v} F^{\mu\nu}F_{\mu\nu}\,,$$

Notice that: $$\bar\kappa_q = y_q / y_b^{\rm SM}\,,$$

where generically: $$|\bar\kappa_u| < 0.98\,,\quad |\bar\kappa_d| < 0.93\,,\quad |\bar\kappa_s| < 0.70$$

varying only one at the time (95%CL)

$$|\bar\kappa_u| < 1.3\,,\quad |\bar\kappa_d| < 1.4\,,\quad |\bar\kappa_s| < 1.4$$

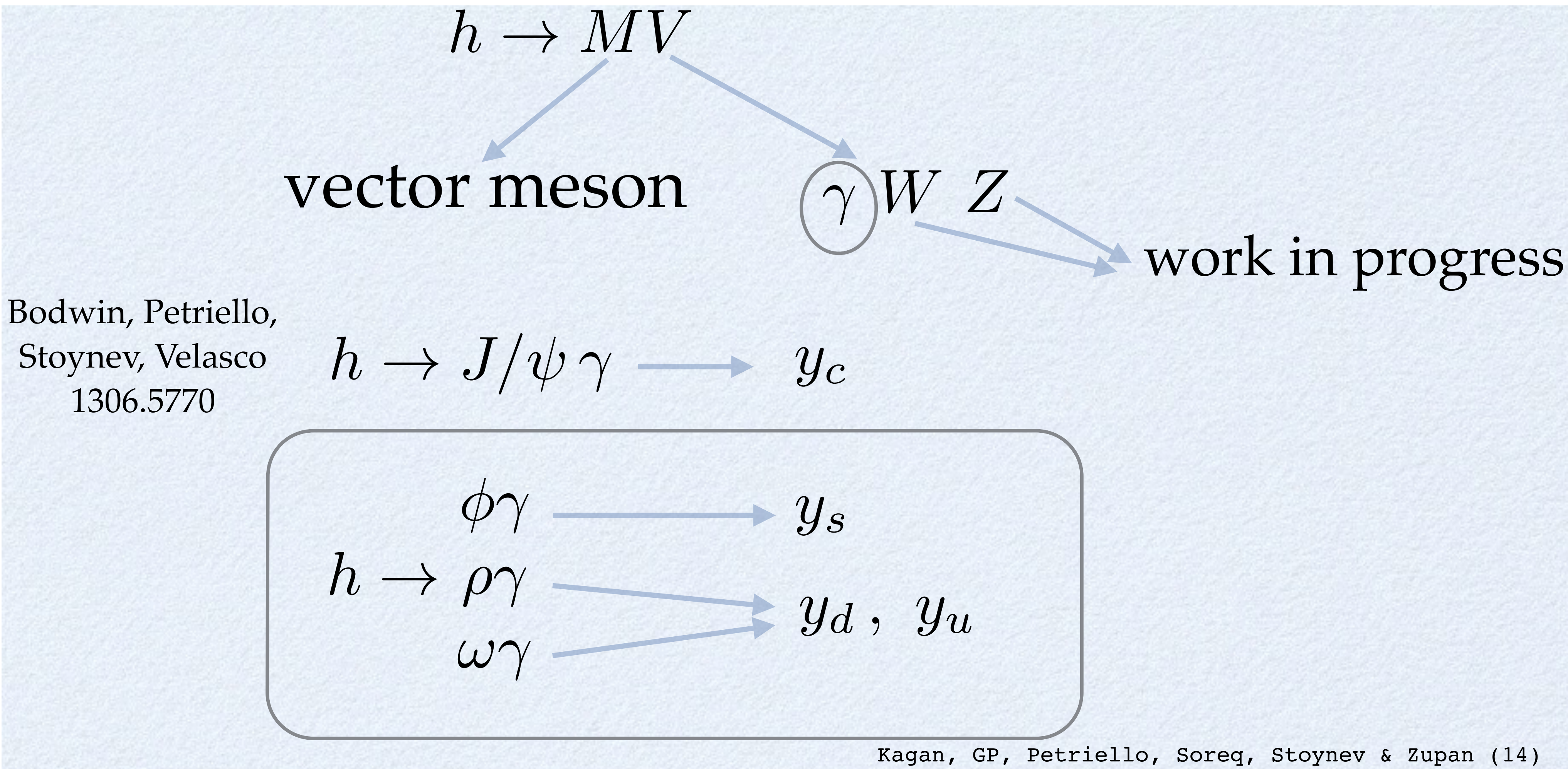
varying all couplings (95%CL)

$|\bar\kappa_{qq'}| < 0.6\,(1)$ for $q, q' \in u, d, s, c, b$ and $q \neq q'$

same for the flavor violating case

(FCNC non-robust bound: $|\bar\kappa_{bs}| < 8\cdot 10^{-2}$ Harnik, Kopp & Zupan; Blankenburg, Ellis, Isidori, (12))

The main idea



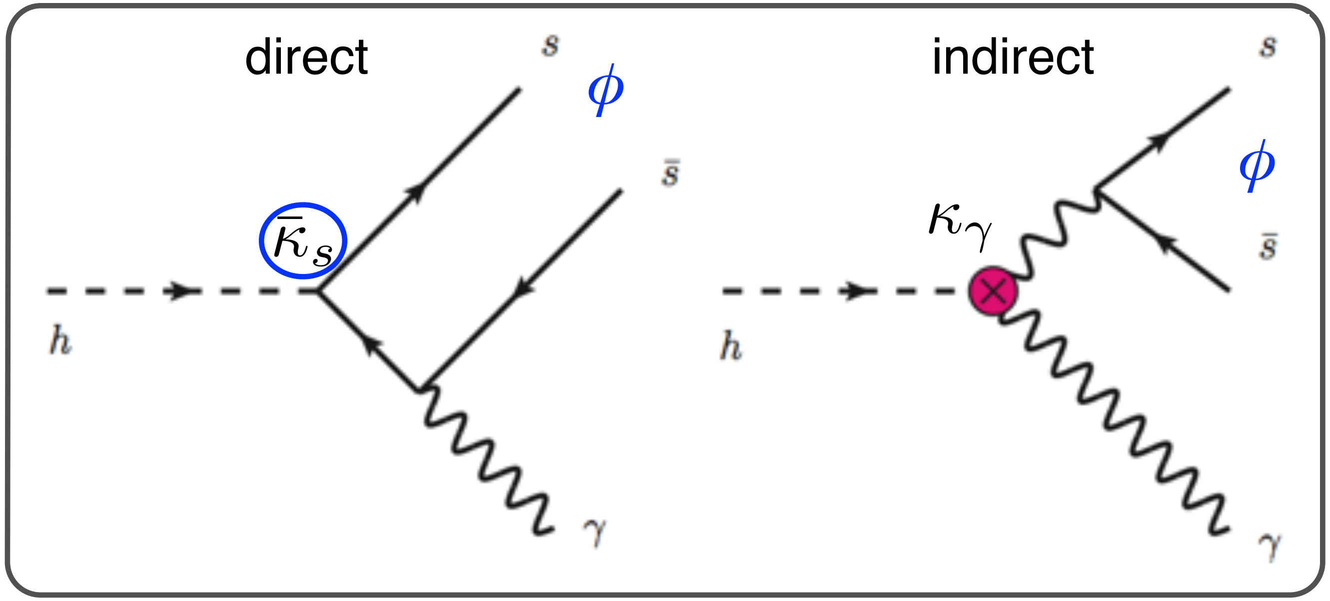
Adding off-diagonal: $h \to \bar{B}^{0*}\gamma$, $h \to \bar{B}^{0*}\gamma$, $h \to K^{0*}\gamma$, $h \to D^{0*}\gamma$

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

Ex.: $h \to \phi\gamma$

$$\Gamma_{h\to\phi\gamma} = \frac{1}{8\pi}\frac{1}{m_h}|M_{ss}^{\phi}|^2,$$

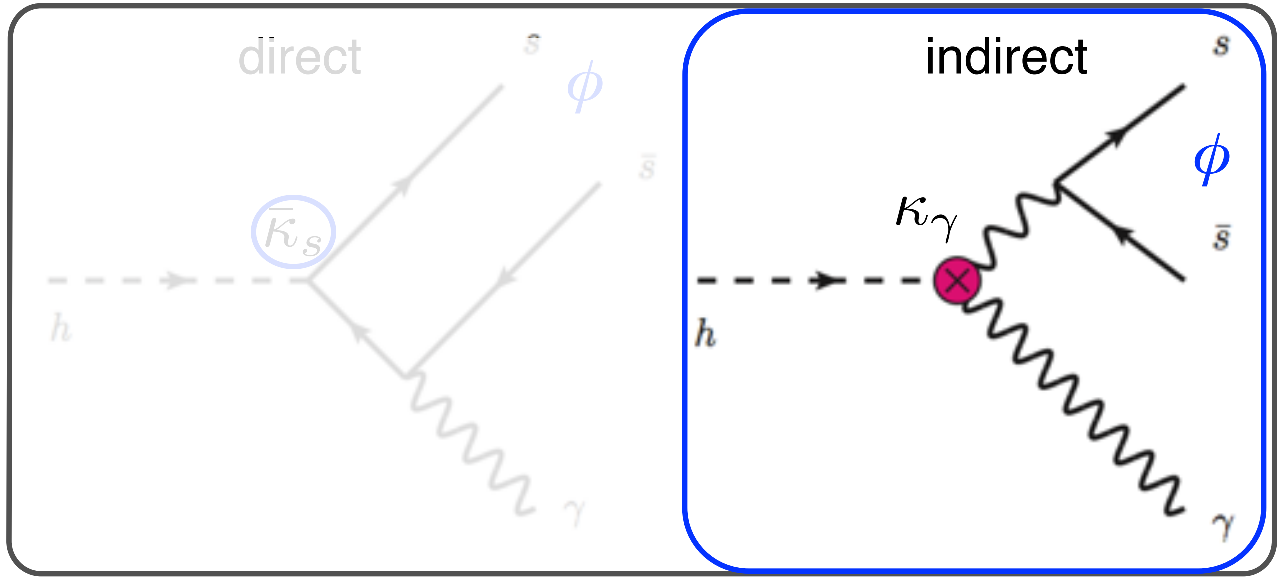
- Two paths to get $h \to \phi\gamma$:

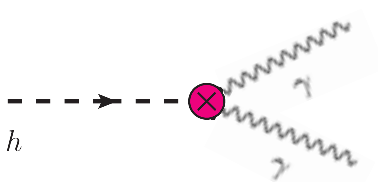


- Let us understand them one by one.

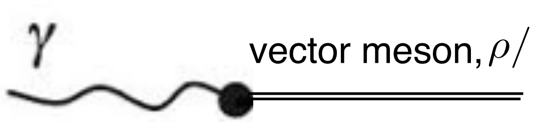
Ex.: $h \to \phi\gamma$, indirect contribution

- Two paths to get $h \to \phi\gamma$:





X



vector meson, ρ/ϕ $\propto \dfrac{f_{\rho,\phi}}{m_{\rho,\phi}}$

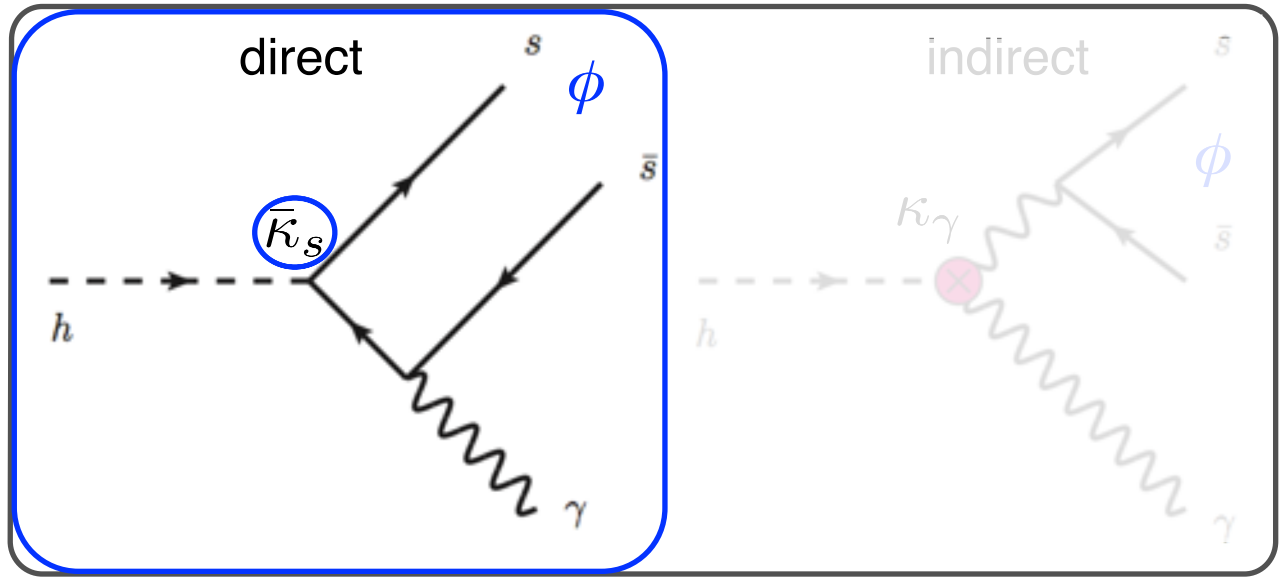
from experiment, $\phi \to e^+e^-$

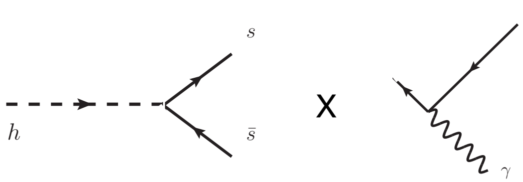
($f_\phi = 0.235(5)\,\mathrm{GeV}$)

$$\left(M_{ss}^{\phi}\right)_{\rm indir} \approx \frac{f_{\rho,\phi}}{m_{\rho,\phi}}\,\kappa_\gamma A_\gamma \frac{4\alpha m_h^2}{\pi v}$$

Ex.: $h \to \phi\gamma$, direct contribution

- Two paths to get $h \to \phi\gamma$:





$$\propto \frac{\bar{\kappa}_s m_b}{v}\frac{f^{\perp}_{\rho,\phi}}{m_h}$$

$(\text{"local" structure} : \bar{s}\sigma_{\mu\nu}s \times F^{\mu\nu})$

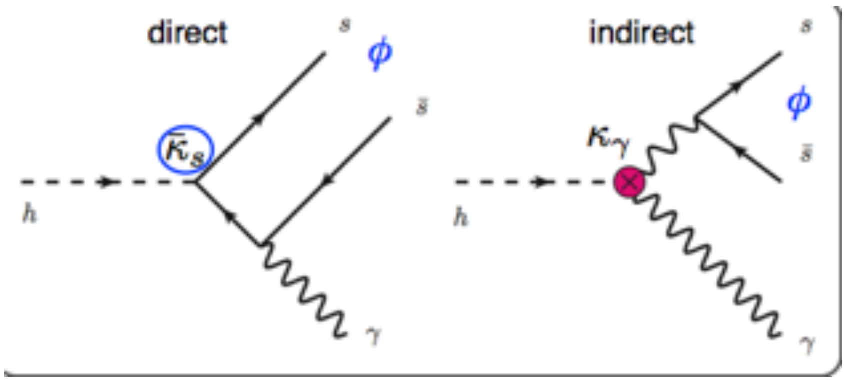
from experiment, $\phi \to e^+e^-$

$(f_\perp^\phi = 0.191(28))$

$$\left(M^{\phi}_{ss}\right)_{\rm dir} \approx \frac{\bar{\kappa}_s m_b}{v} f^{\perp}_{\phi}$$

Final result for the BR($h \to \phi\gamma$)

$$\Gamma_{h\to\phi\gamma} = \frac{1}{8\pi}\frac{1}{m_h}|M^{\phi}_{ss}|^2,$$



- The resulting sensitivity:

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[\left(3.0 \pm 0.13\right)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

Similar holds for 1st generation:

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9 \pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]\cdot 10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.6 \pm 0.17)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

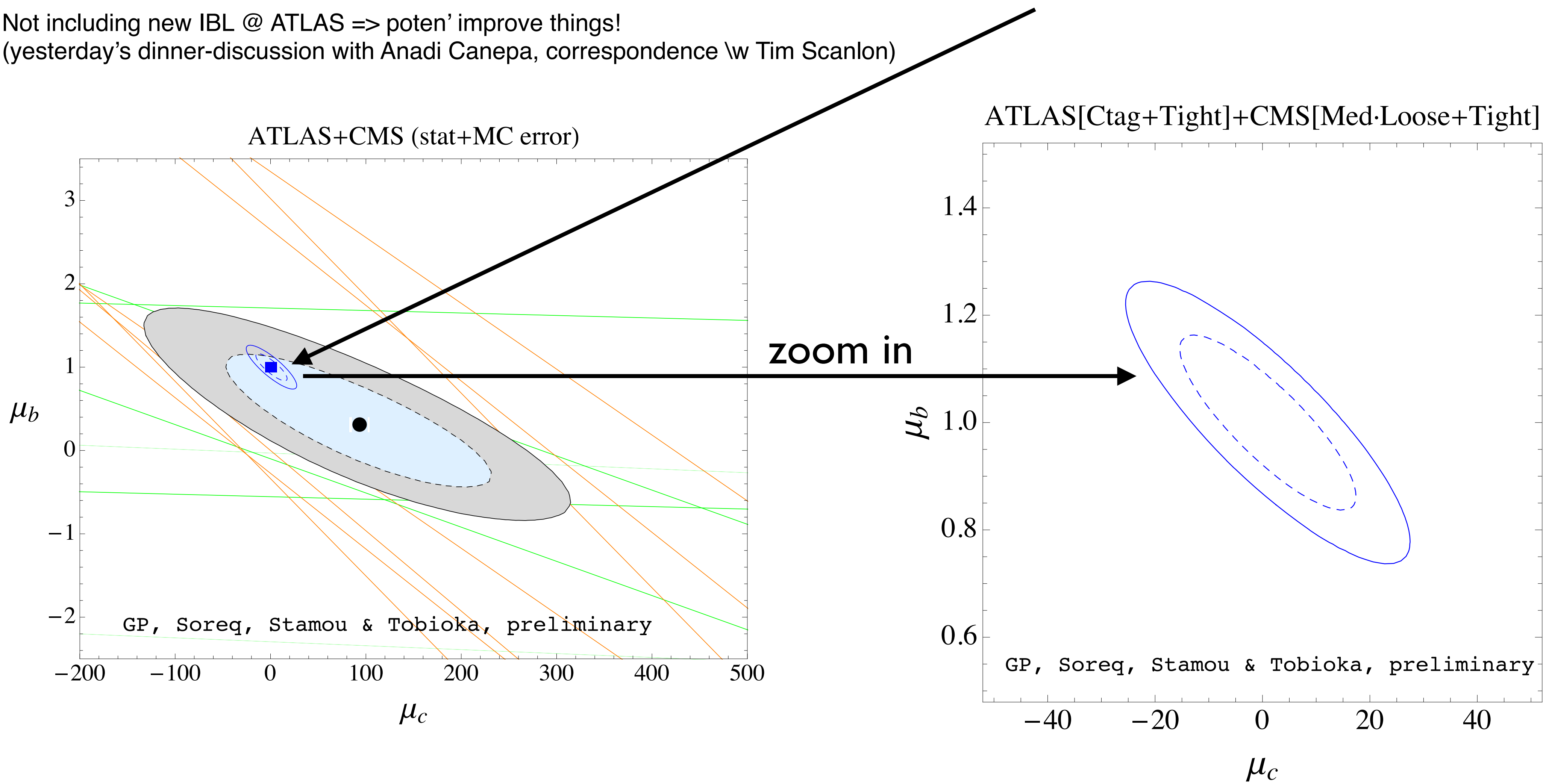
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

Few projections

HL projection, inclusive c-tagging (sorry haven't finish the FCC ones)

Combining medium & charm-tagging points: $\epsilon_{b,c} = (0.7, 0.2), (0.12, 0.19)$

Not including new IBL @ ATLAS => poten' improve things!
(yesterday's dinner-discussion with Anadi Canepa, correspondence \w Tim Scanlon)



Of course O(5%) for y_c for lepton colliders (ex. of complementarity)

Exclusive modes, projections

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- focus on $h \to \phi\gamma$, use **`Pythia 8.1`**
  - main decay modes: $\phi \to K^+K^-(49\%)$, $K_L K_S\,(34\%)$, $\pi^+\pi^-\pi^0(15\%)$
  - for $pp \to h \to \phi\gamma$ at 14TeV LHC in 70 to 75% cases the kaons/pions and the prompt photon have $|\eta| < 2.4$
    - within the minimal fiducial volume of the ATLAS and CMS experiments
  - adopt the geometrical acceptance factor $Ag = 0.75$
    - do not include other efficiency or trigger factors
- assume $\kappa_\gamma = 1$, negligible background, 3σ reach

no theory error

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
14	3000	770	0.56 (−1.2)	0.27 (−0.81)
33	3000	1380	0.54 (−1.2)	0.22 (−0.75)
100	3000	5920	0.54 (−1.2)	0.13 (−0.63)

two detectors

one detector

5x SM strange Yukawa

J. Zupan An Exclusive Window onto Higgs... 15

Future experiments

- only a few events expected at e^+e^- colliders
  - ILC, ILC with luminosity upgrade, CLIC
  - probably too small for observation of $h \to \phi\gamma$
- $\approx$ 30 events expected at FCC-ee (TLEP)
  - too small to probe a deviation from the SM prediction
- $h \to \phi\gamma$ measurements unique to future hadron machines

Conclusions

♦ Is the Higgs-mechanism behind the light quark masses?.

♦ Order one modifications to Higgs light quark (charm) coupling lead to dramatic change in Higgs pheno'.

♦ Charm coupling is constrained via charm-tagging, or exclusively.

♦ The light quarks can be potentially probed via exclusive decays.

♦ Looked at $h \to M\gamma$, with $h \to \phi\gamma$ most promising.

♦ Established higgs-quarks non-universality.

Backups

Experimental sensitivity

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- focus on $h \to \phi\gamma$, use ...
  - main ... $\pi^+\pi^-\pi^0(15\%)$
  - ... he kaons/pions
  - ... AS and CMS
  - e...
  - adopt the geome... $Ag = 0.75$
    - do not include other efficiency or trigg... factors
- assume $\kappa_\gamma = 1$, negligible background, 3σ reach

$$\mathcal{S} = |\mathrm{BR}_{h\to\phi\gamma} - \mathrm{BR}^{\mathrm{SM}}_{h\to\phi\gamma}|/(\delta\mathrm{BR}_{h\to\phi\gamma}),$$

$$\text{where } (\delta\mathrm{BR}_{h\to\phi\gamma})^2 = \mathrm{BR}_{h\to\phi\gamma}/(\sigma_h \mathcal{L} A_g) + (\delta\mathrm{BR}^{\mathrm{th}}_{h\to\phi\gamma})^2$$

two detectors

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Thoughts about experimental strategy

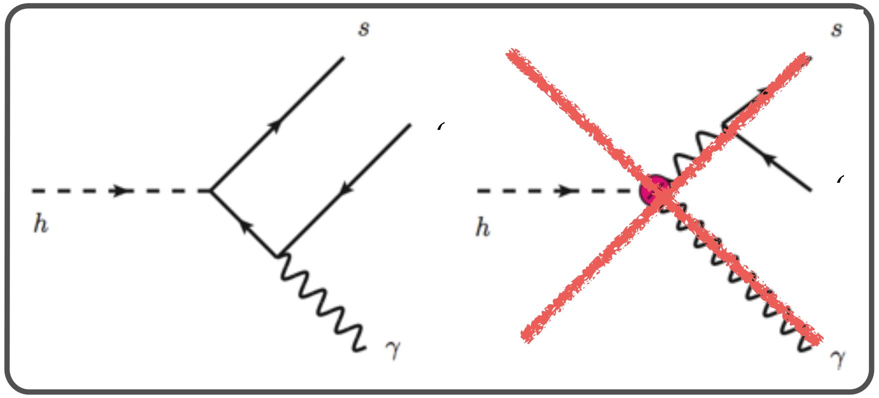
- for $h \to \phi\gamma$ decay most promising $\phi \to K^+K^-$
  - near collinearity of the photon and the ϕ-jet in the transverse plane
  - jet sub-structure information
    - two close high-p_T tracks in a narrow cone
  - di-track invariant mass distribution assuming kaons
    - 1.5% (better than 15 MeV) resolution (CMS)
- can probably be used to significantly cut on the background
  - on jet+γ QCD backgrounds
  - on $h \to \phi\gamma + n\pi^\circ,\ \eta^{(\prime)}(\to neutr.)\,\gamma$
- dedicated trigger probably required to enhance the reach

Thoughts about experimental strategy

- $h \rightarrow \varrho^\circ\gamma$ mode
  - $Br(\varrho^\circ \rightarrow \pi^+\pi^-) \sim 100\%$
  - relatively clean mode, similar to $\phi \rightarrow K^+K^-$ decay
- $h \rightarrow \omega\gamma$ mode
  - $Br(\omega \rightarrow \pi^+\pi^-\pi^\circ) \sim 89\%$
  - harder to trigger on
  - hard-to-identify π° smears the observable quantities
  - a detailed experimental study required

Flavor violating couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)



- FV modes $h \to \bar{B}_s^{0*}\gamma$, $h \to \bar{B}^{0*}\gamma$, $h \to \bar{K}^{0*}\gamma$, $h \to D^{0*}\gamma$
  - can probe $\bar{\kappa}_{bs,sb}$, $\bar{\kappa}_{bd,db}$, $\bar{\kappa}_{sd,ds}$ and $\bar{\kappa}_{cu,uc}$
- $h \to \bar{K}^{0*}\gamma$ similar expr. as $h \to \phi\gamma$
  - but only direct amplitude
- for $\bar{\kappa}_{ds} \sim O(1) \Rightarrow Br(h \to \bar{K}^{0*}\gamma) \sim O(10^{-8})$
  - not observable at planned future colliders

$$\frac{BR_{h\to \bar{B}_s^{*0}\gamma}}{BR_{h\to b\bar{b}}} = \frac{(2.1 \pm 1.0)\cdot 10^{-7}}{0.57\bar{\kappa}_b^2}\,\frac{|\bar{\kappa}_{bs}|^2 + |\bar{\kappa}_{sb}|^2}{2},$$

The production via $q\bar{q} \to h$ in pp with 8TeV are (the SM is 19 pb)

$$\sigma_{u\bar{u}\to h} = \left(\frac{y_u}{y_b^{\rm SM}}\right)^2 9.16\,{\rm pb}\,,$$

$$\sigma_{d\bar{d}\to h} = \left(\frac{y_d}{y_b^{\rm SM}}\right)^2 6.29\,{\rm pb}\,,$$

$$\sigma_{s\bar{s}\to h} = \left(\frac{y_s}{y_b^{\rm SM}}\right)^2 1.67\,{\rm pb}\,,$$

$$\sigma_{c\bar{c}\to h} = \left(\frac{y_c}{y_b^{\rm SM}}\right)^2 0.83\,{\rm pb}\,.$$