Light Yukawa couplings

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Light Yukawa couplings

http://www.lifevesting.com/blog/wp-content/uploads/2012/02/confused.jpg

Higgs boson

Greatest recent triumph is Higgs discovery!!

- Main role of the Higgs is to break EW symmetry.
- In the SM, the Higgs does another an important role: giving mass to fermions

Higgs Mass, Coupling

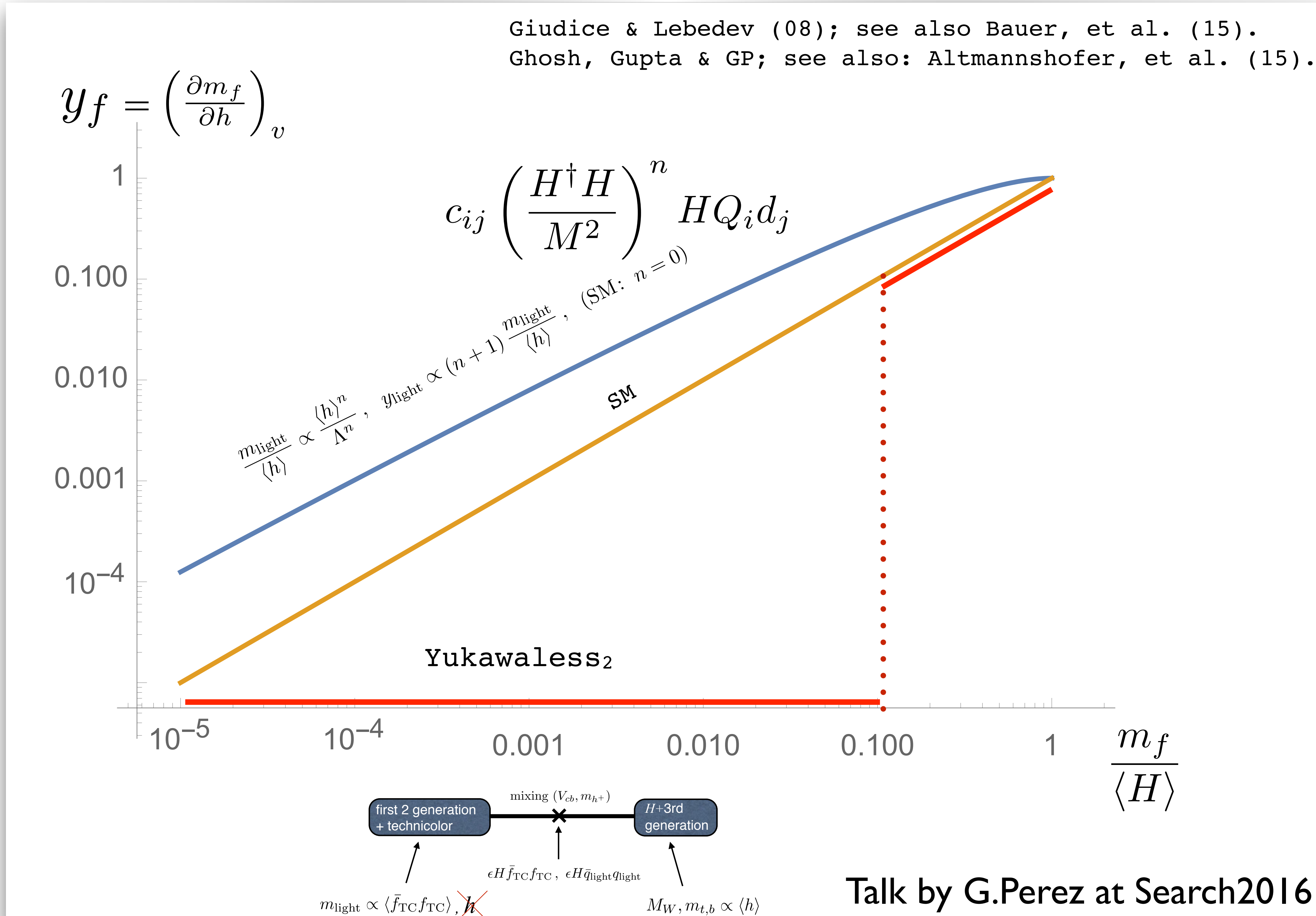
Measure Unknown SM parameter

Predicted as $y_X \simeq \sqrt{2}\frac{m_X}{v}$.

measurement⇒Window of Beyond SM

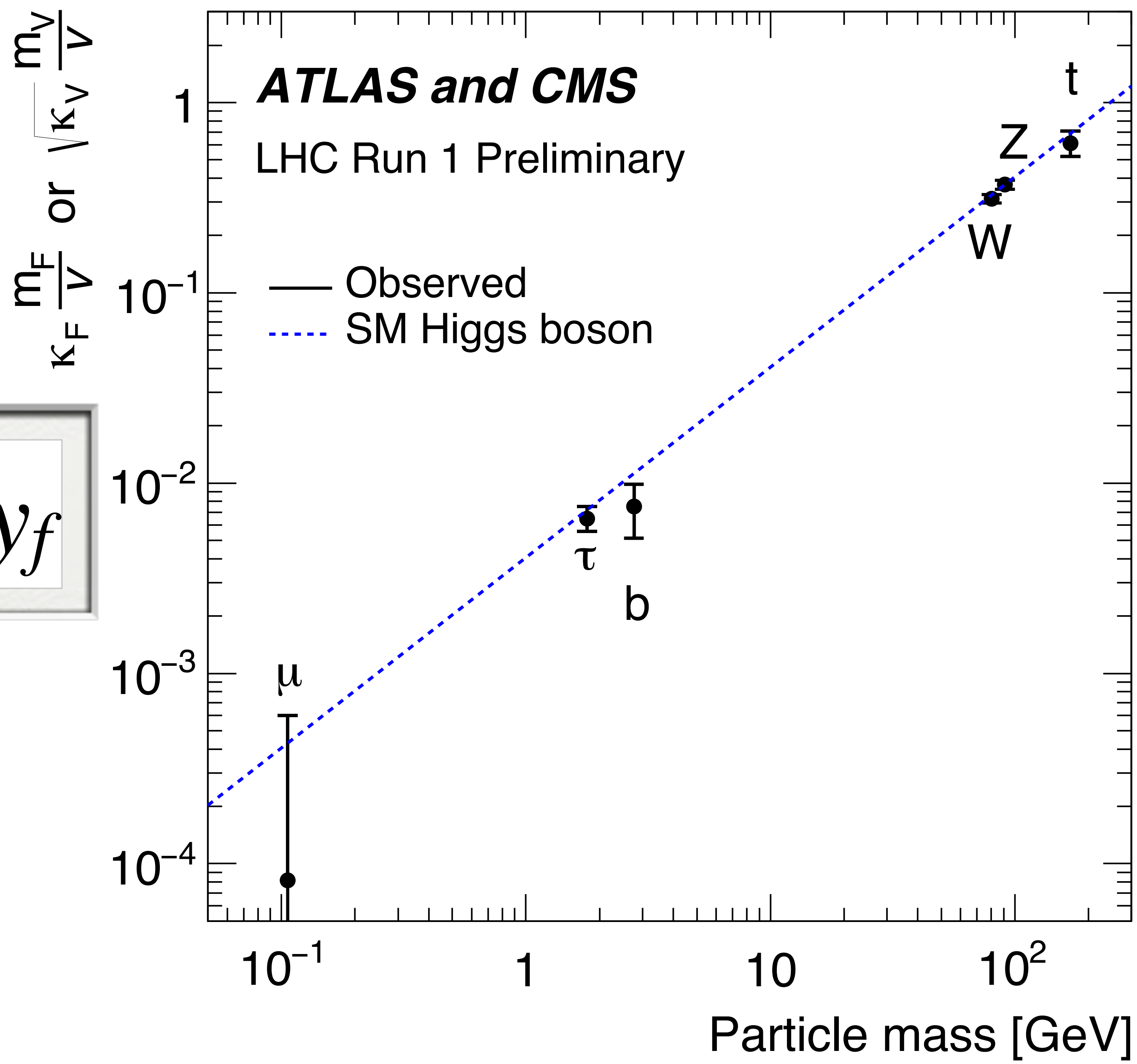
Fermion mass vs coupling

Fermion masses could come from non-SM ways



Higgs coupling measurements at Run 1

g_v, y_f



ATLAS-CONF-2015-044

$$\kappa_X \equiv \frac{g_X}{g_X^{\rm SM}}$$

Measuring Higgs couplings at LHC constraints various models
So far, done for Z,W and 3rd generation

What can we do for 1,2 generations at LHC? (charm, strange..)

Outline

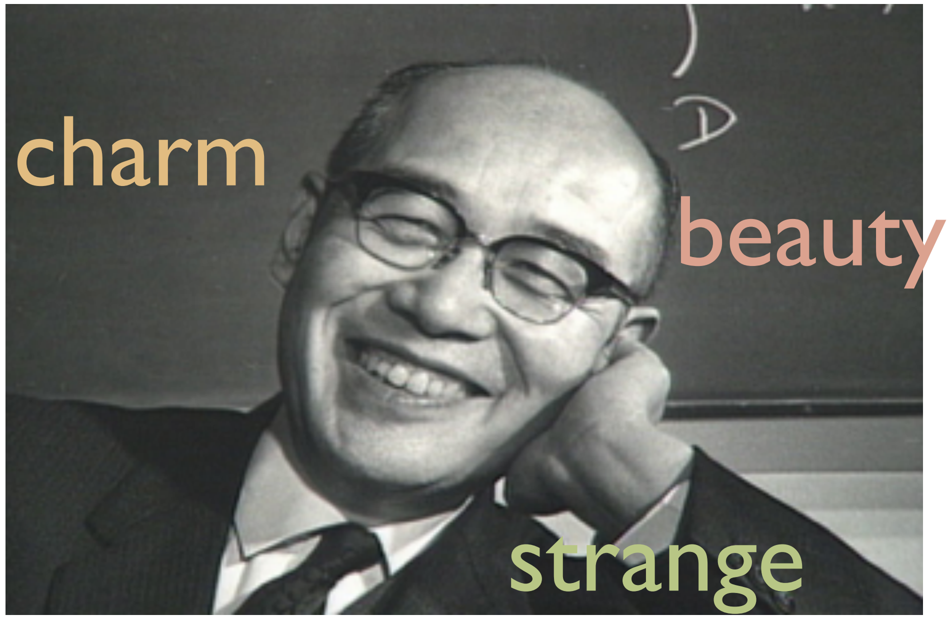
Recent Activities of Yukawa measurements

1. Exclusive decay:
   Higgs to vector-meson(J/ψ, Υ, ϕ)+γ

2. Inclusive decay:
   Higgs to flavored jets($h \to cc$, bb)

3. Production via Yukawa couplings
   extra jet, kinematics

4. Summary

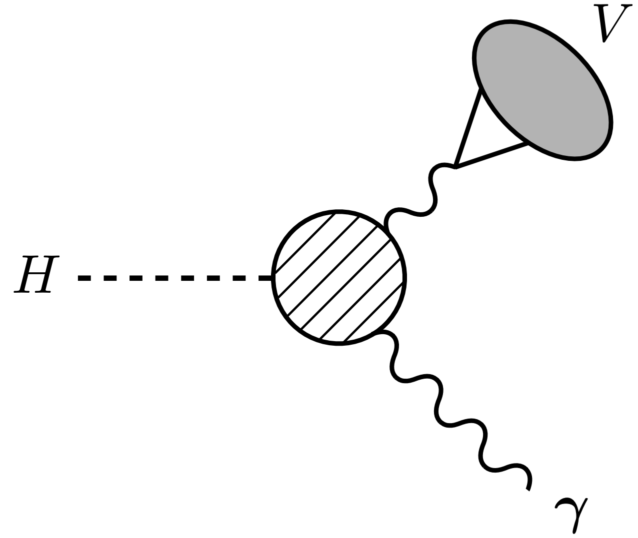


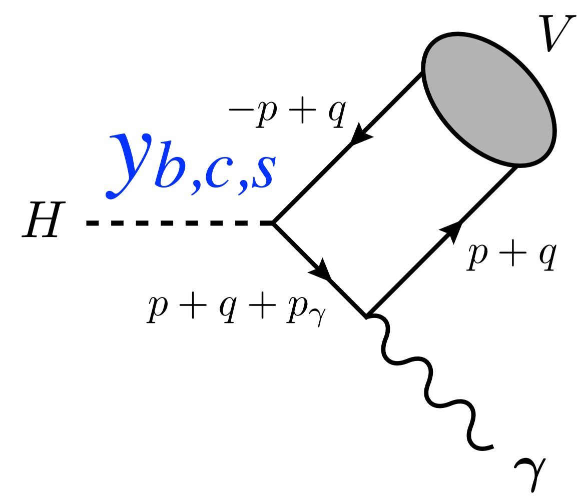
Eclusive decay

$$h \to (J/\psi, \Upsilon, \phi) + \gamma$$

Higgs decay to vector-meson(J/ψ, ϕ,..)+γ

access light Yukawa by interference





Theory calculations

Bodwin, Petriello, Stoynev, Velasco ('13)
Bodwin, Chung, Ee, Lee, Petriello ('14)
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan('14)
Koenig, Neubert ('15)

e.g.

$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

SM Predicts small rates

Koenig, Neubert ('15)

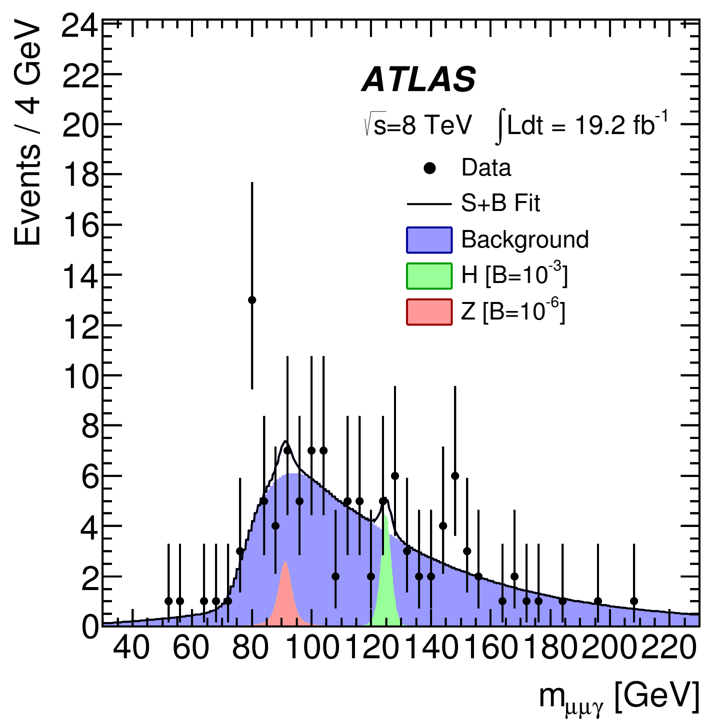
$$\mathrm{Br}(h \to \phi\gamma) = (2.31 \pm 0.03_{f_\phi} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}\,,$$

$$\mathrm{Br}(h \to J/\psi\,\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\mathrm{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}\,,$$

$$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma) = (4.61 \pm 0.06_{f_{\Upsilon(1S)}}\,{}^{+1.75}_{-1.21}{}_{\mathrm{direct}} \pm 0.22_{h\to\gamma\gamma}) \cdot 10^{-9}\,,$$

Higgs decay to vector-meson(J/ψ, ϕ,..)+γ

Measurements are going on for J/ψ, Υ, ϕ



8TeV, 20fb^{-1}

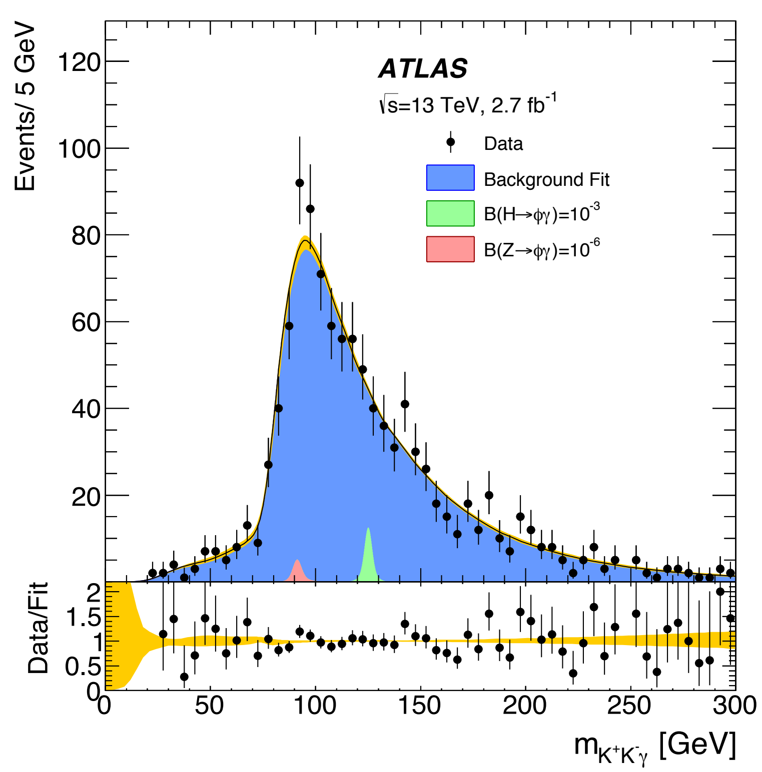
ATLAS [1501.03276]

CMS [1507.03031]

$$\sigma \mathrm{Br}(h \to J/\psi\gamma) < 33 \text{ fb}$$

$$\sigma \mathrm{Br}(h \to \Upsilon(1S)\gamma) < 29 \text{ fb}$$

@95%CL



13TeV, 2.7fb^{-1}

ATLAS [1607.03400] new!

$$\sigma \mathrm{Br}(h \to \phi\gamma) < 69 \text{ fb}$$

see talk by Chisholm

$\longrightarrow$

$$\mu(h \to J/\psi\gamma) < 535,$$

$$\mu(h \to \Upsilon(1S)\gamma) < 2.1 \times 10^6,$$

$$\mu(h \to \phi\gamma) < 608$$

Bound on Br is ~10^{-3}

Higgs decay to vector-meson(J/ψ, ϕ,...)+γ

★Take ratios with more established channels

⇒cancel total width and cross section dependence

$$\frac{\sigma(pp\to h)\times \mathrm{BR}_{h\to J/\psi\gamma}}{\sigma(pp\to h)\times \mathrm{BR}_{h\to ZZ^*\to 4\ell}} = \frac{\Gamma_{h\to J/\psi\gamma}}{\Gamma_{h\to ZZ^*\to 4\ell}} = 2.79\frac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2}\times 10^{-2} < 9.3$$

[95%CL]

$$-210\kappa_V + 11\kappa_\gamma < \kappa_c < 210\kappa_V + 11\kappa_\gamma$$

Perez, Soreq, Stamos
KT ('15)

compared with $h\to\gamma\,\gamma$ $\kappa_c \lesssim 430$ **Koenig, Neubert ('15)**

Future prospects with 3000fb^{-1} $-30 \lesssim \kappa_c \lesssim 50$ [95%CL]

★Do the same for κ_s with $h\to\phi\gamma$ with 13TeV $h\to ZZ^*$

ATLAS-CONF-2016-081

$$\mu_{\phi\gamma}/\mu_{ZZ^*} \lesssim 481 \;\Rightarrow\; -83\kappa_V + 3.8\kappa_\gamma \lesssim \frac{\kappa_s}{100} \lesssim 83\kappa_V + 3.8\kappa_\gamma$$

KT(Preliminary)

Inclusive decay

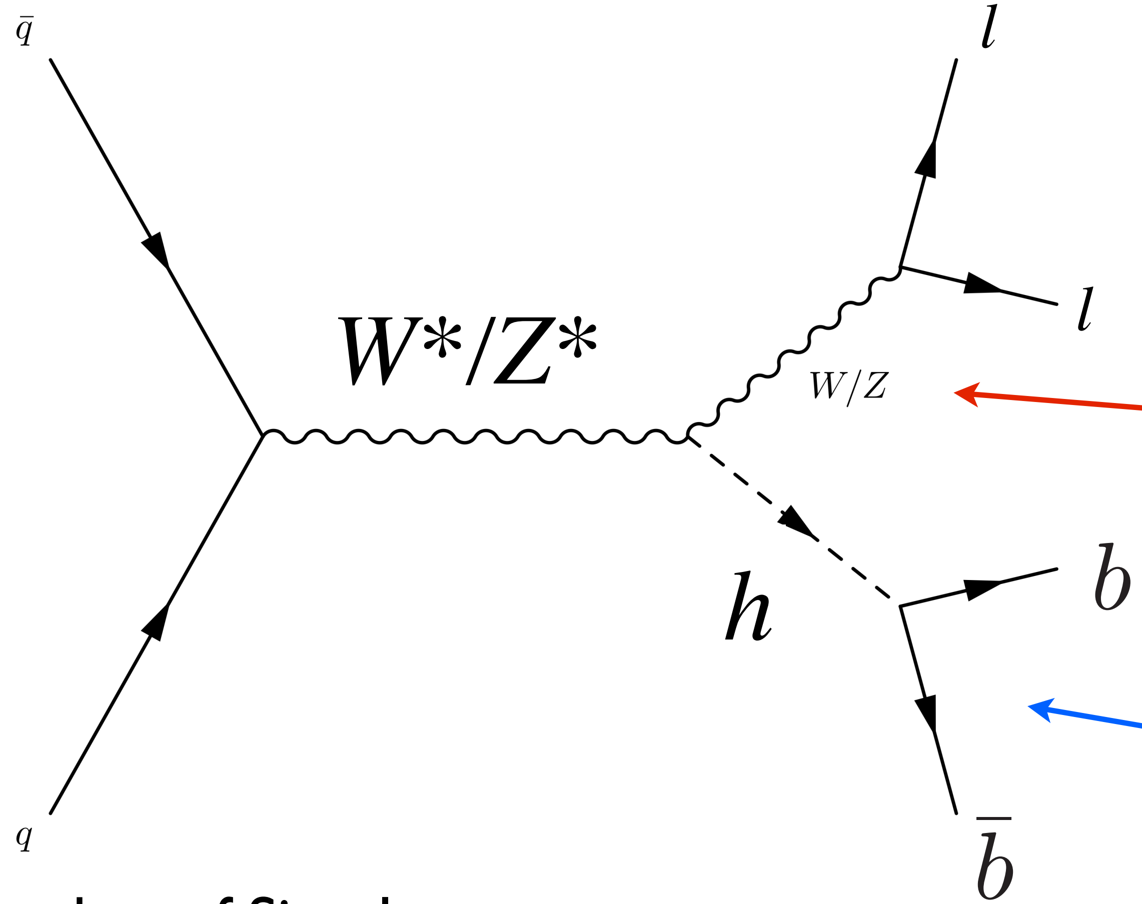
$h \to cc, \mathrm{bb}$

recasting $h \to bb$ analysis

Perez, Soreq, Stamou, **KT** (1505.06689, 1505.00290)

Higgs decay to flavored jets($h \to$ cc, bb)

Perez, Soreq, Stamou, **KT** ('15)



0,1, 2 lep

W/Z reconstructed

2 b-tags required

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%

mistag c-jet! ε_c=4-47%

Number of Signal

$$S^{VH} = \mathcal{L} \cdot \sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1} \epsilon_{b_2} \cdot \epsilon$$

Tagging Efficiency of b-jet

Signal strength

$$\mu_b = \frac{S^{VH}_{obs}}{S^{VH}_{exp}} = \frac{\mathcal{L} \cdot \sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1} \epsilon_{b_2} \cdot \epsilon}{\mathcal{L} \cdot \sigma_{SM} \cdot \mathrm{Br}_b^{SM} \cdot \epsilon_{b_1} \epsilon_{b_2} \cdot \epsilon} = \frac{\sigma \cdot \mathrm{Br}_b}{\sigma_{SM} \cdot \mathrm{Br}_b^{SM}}$$

$\mu_b^{\mathrm{ATLAS}} = 0.52 \pm 0.32 \pm 0.24$ $\quad \mu_b^{\mathrm{CMS}} = 1.0 \pm 0.5$ ⇒ bottom Yukawa

ATLAS [arXiv:1409.6212] CMS [arXiv:1310.3687]

What if H→cc is enhanced?

Perez, Soreq, Stamou, **KT** ('15)

$$\mu_b = \frac{S^{VH}_{obs}}{S^{VH}_{exp}} = \frac{\cancel{\mathcal{L}} \cdot \sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1}\epsilon_{b_2} \cdot \cancel{\epsilon}}{\cancel{\mathcal{L}} \cdot \sigma_{SM} \cdot \mathrm{Br}_b^{SM} \cdot \epsilon_{b_1}\epsilon_{b_2} \cdot \cancel{\epsilon}}$$

$$\Rightarrow \frac{\sigma \cdot \mathrm{Br}_b \cdot \epsilon_{b_1}\epsilon_{b_2} + \sigma \cdot \mathrm{Br}_c \cdot \epsilon_{c_1}\epsilon_{c_2}}{\sigma_{SM} \cdot \mathrm{Br}_b^{SM} \cdot \epsilon_{b_1}\epsilon_{b_2}}$$

$$= \mu_b + \frac{\mathrm{Br}_c^{SM}}{\mathrm{Br}_b^{SM}} \frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}} \mu_c$$

$$\mathrm{Br}^{\mathrm{SM}}(h \to c\bar{c}) = 2.9\%$$

$$\mathrm{Br}^{\mathrm{SM}}(h \to b\bar{b}) = 58\%$$

$$\epsilon_{c/b} \equiv \frac{\epsilon_{c1}\epsilon_{c2}}{\epsilon_{b1}\epsilon_{b2}}$$

$$\mu_b + (0.05\, \epsilon_{c/b})\mu_c$$

Large $\epsilon_{c/b}$, more sensitive to μ_c
but only constrain a combination (degeneracy)

⇒ Need very different working points $\epsilon_{c/b}$

Disentangle degeneracy

Perez, Soreq, Stamou, **KT** ('15)

$\mu_b + (0.05\ \epsilon_{c/b})\mu_c$ ATLAS&CMS have different working points

	1st Tag	2nd Tag	$\epsilon_{c/b}$
(a)ATLAS	Med	Med	8.2×10^{-2}
(b)ATLAS	Tight	Tight	5.9×10^{-3}
(c)CMS	Med1	Med1	0.18
(d)CMS	Med2	Loose	0.19
(e)CMS	Med1	Loose	0.23
(f)CMS	Med3	Loose	0.16

$$L(\mu) = \prod_i P_{poiss}(k_i, N^{BG}_{SM,i} + \mu N^{signal}_{SM,i}).$$

Disentangle degeneracy

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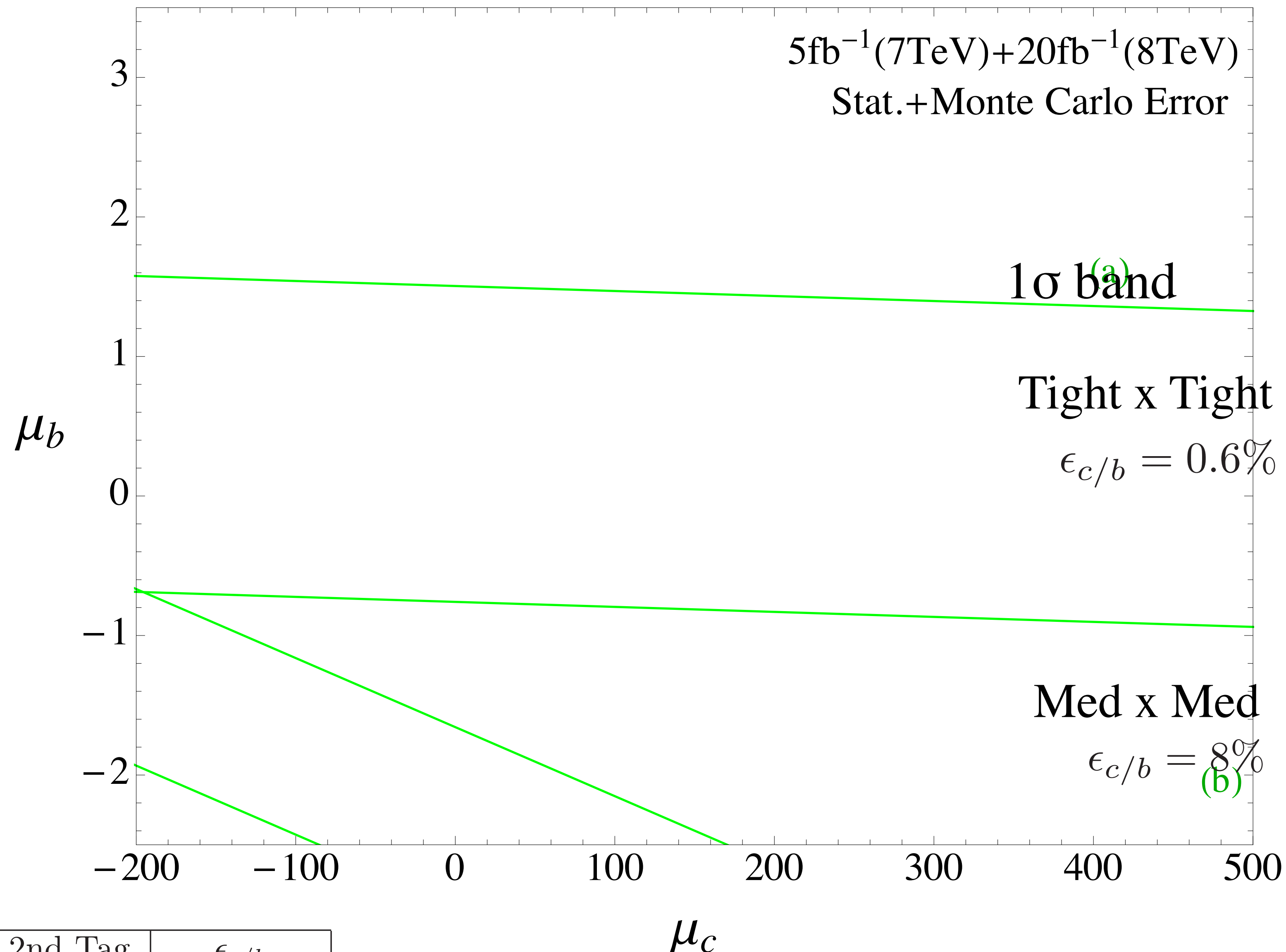

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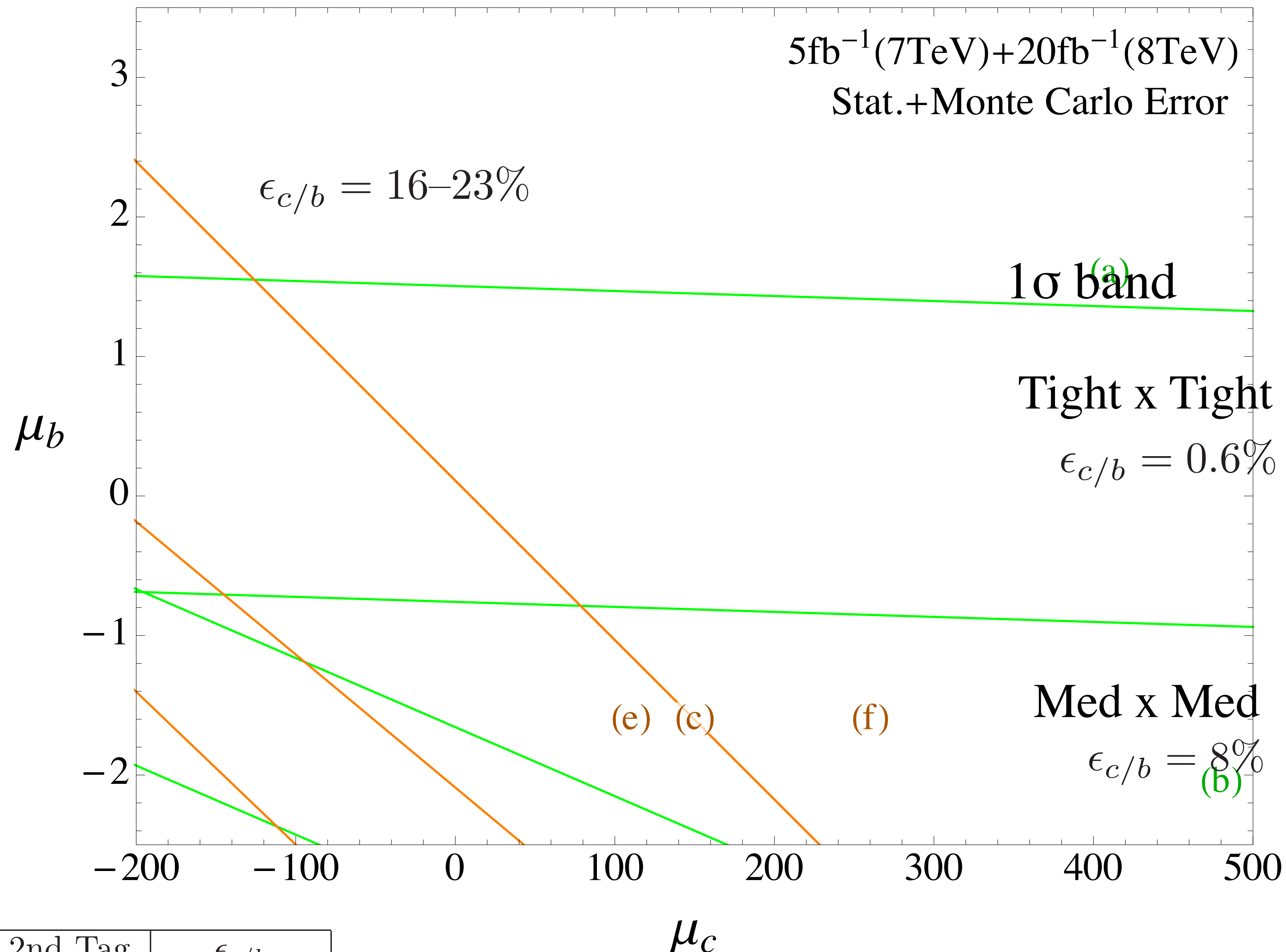

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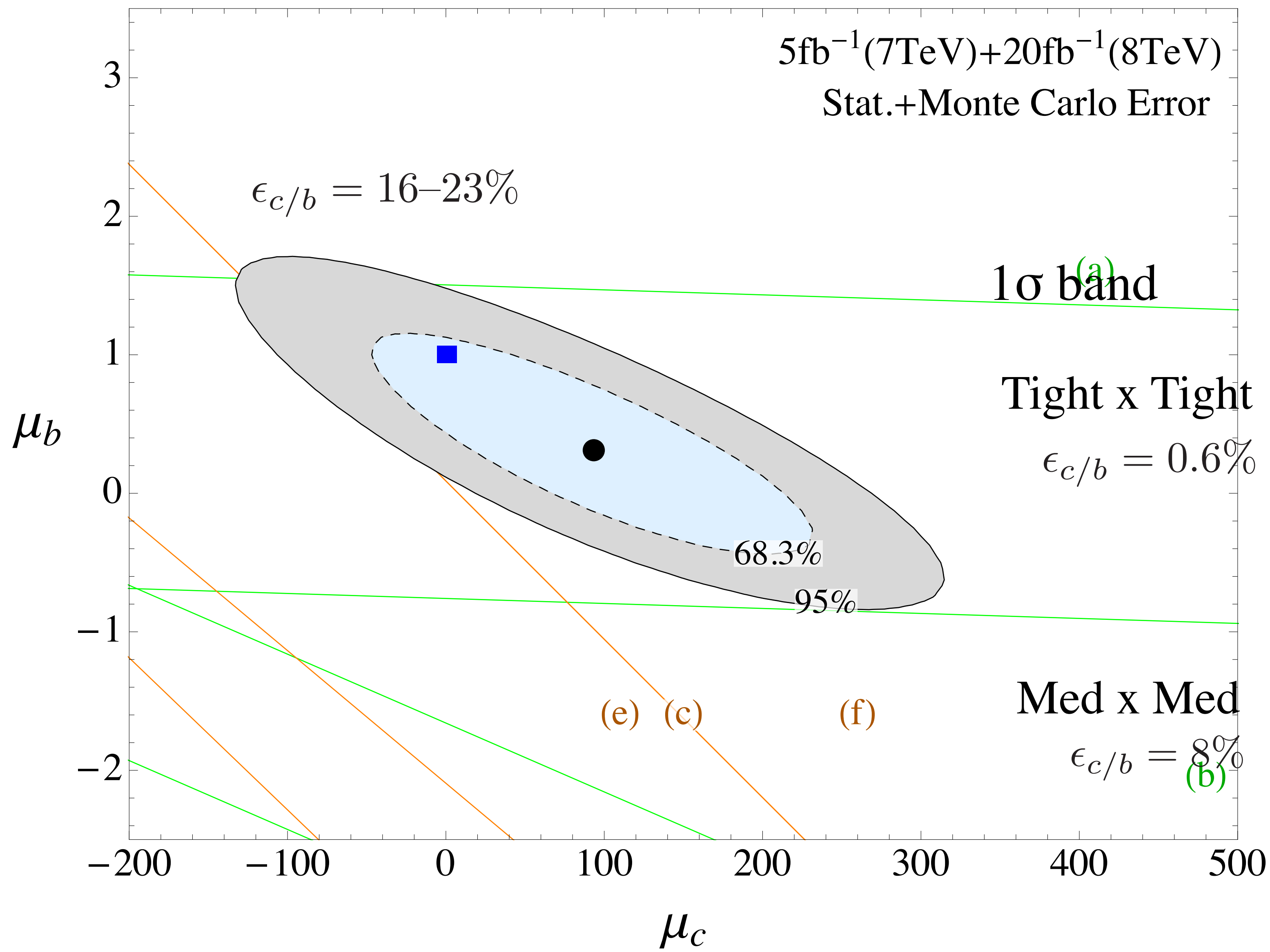


profiled μ_b

First bound on signal strength!

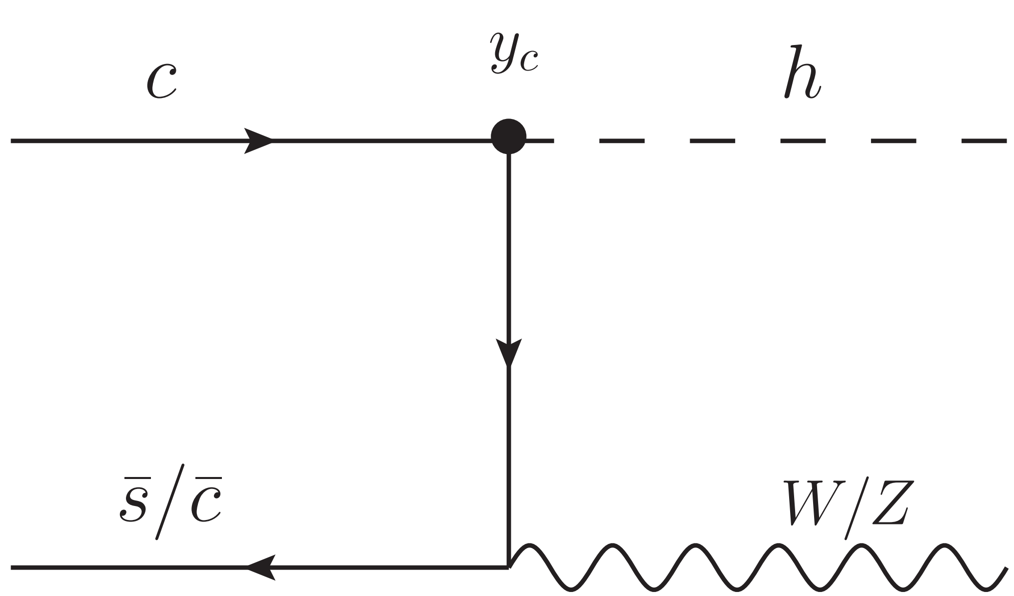
$$\mu_c = 95^{+90(175)}_{-95(180)} \text{ at } 68.3(95)\% \text{ CL.}$$

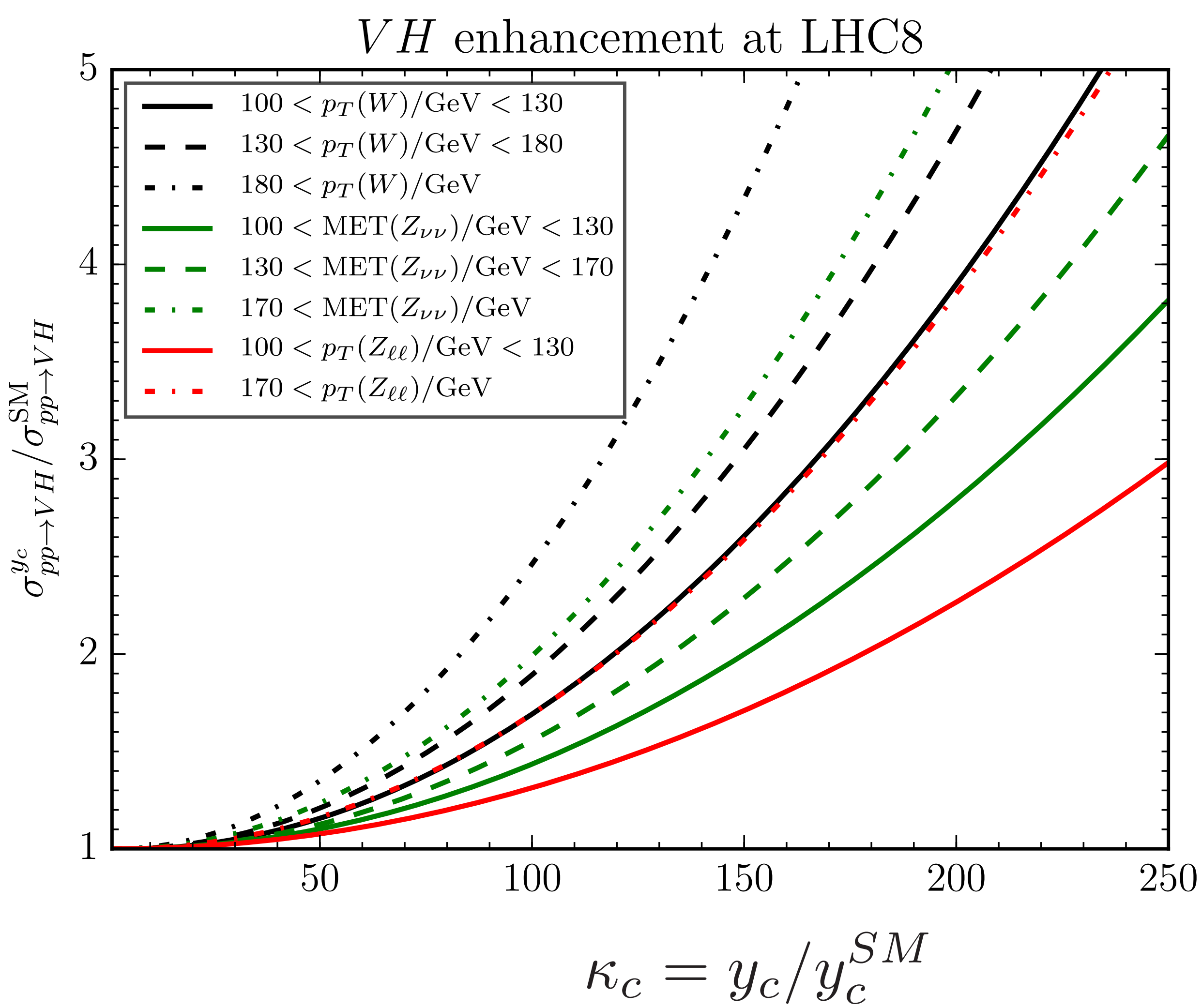
New Production by large Yukawa

Perez, Soreq, Stamou, **KT** ('15)

Decay Br(H→cc)=100%, still μ_c=34

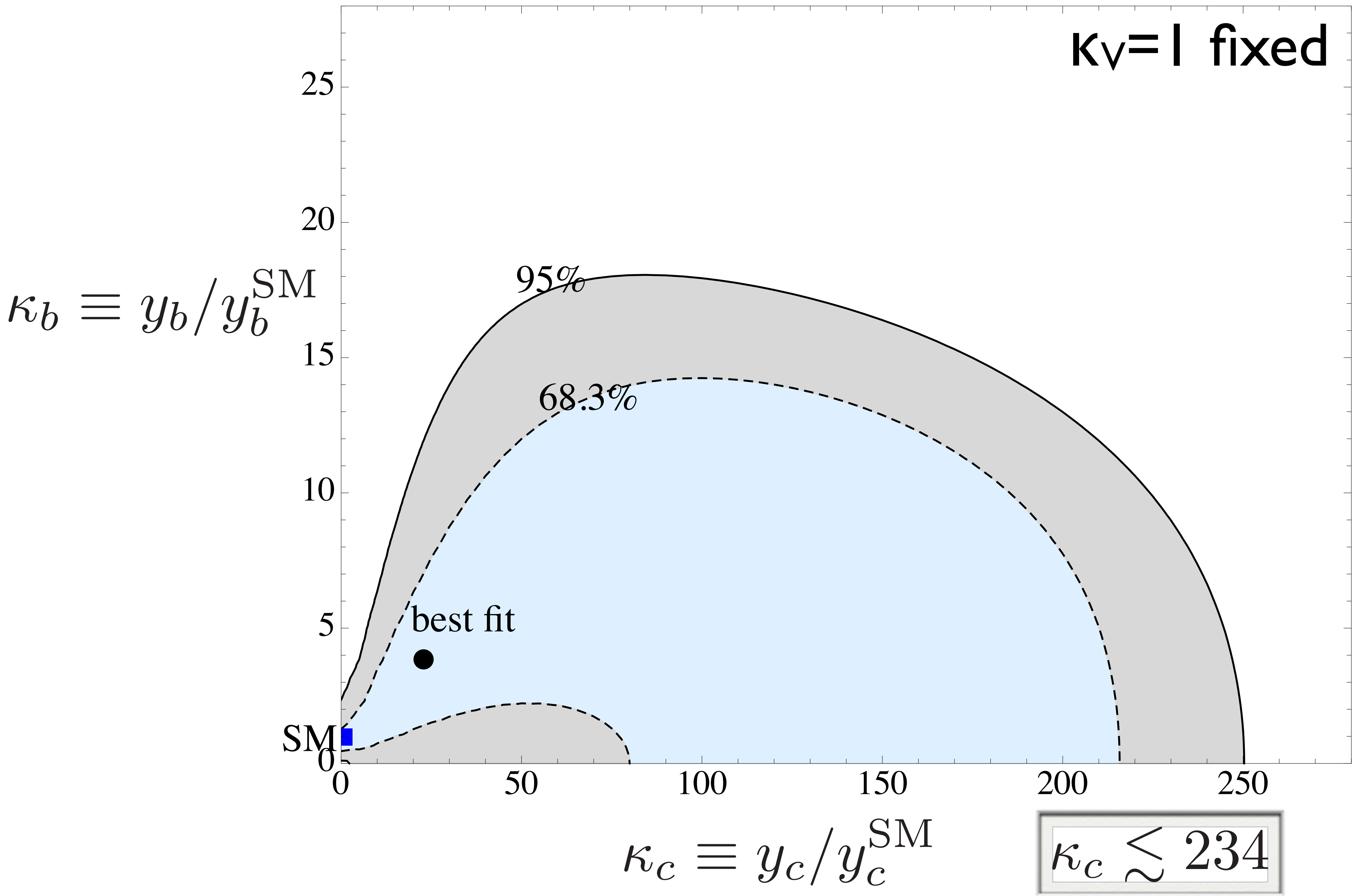
At large coupling $\kappa_c = y_c/y_c^{SM}$ ~100
switch on new production





First Bound on Coupling

Perez, Soreq, Stamou, **KT** ('15)

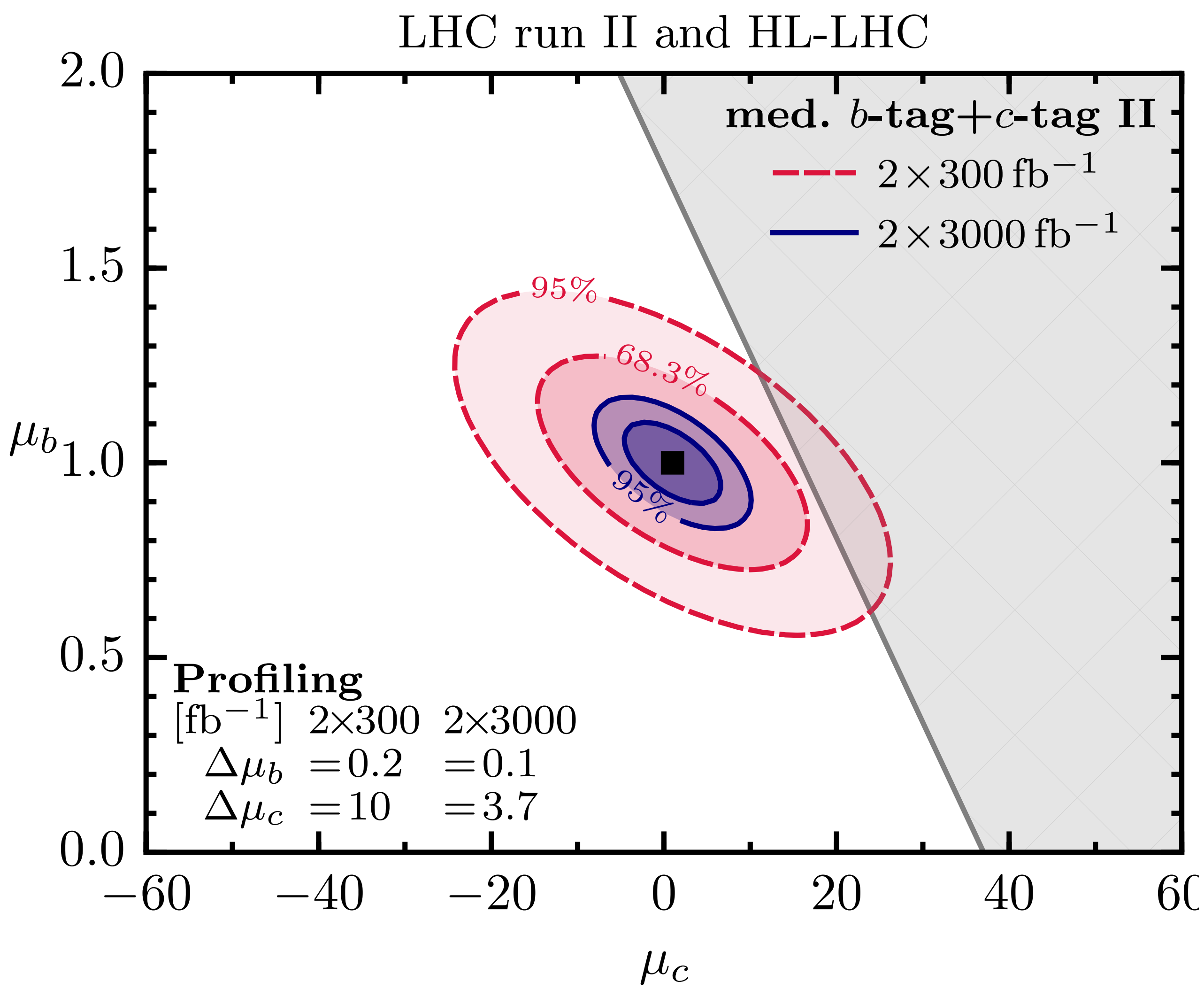


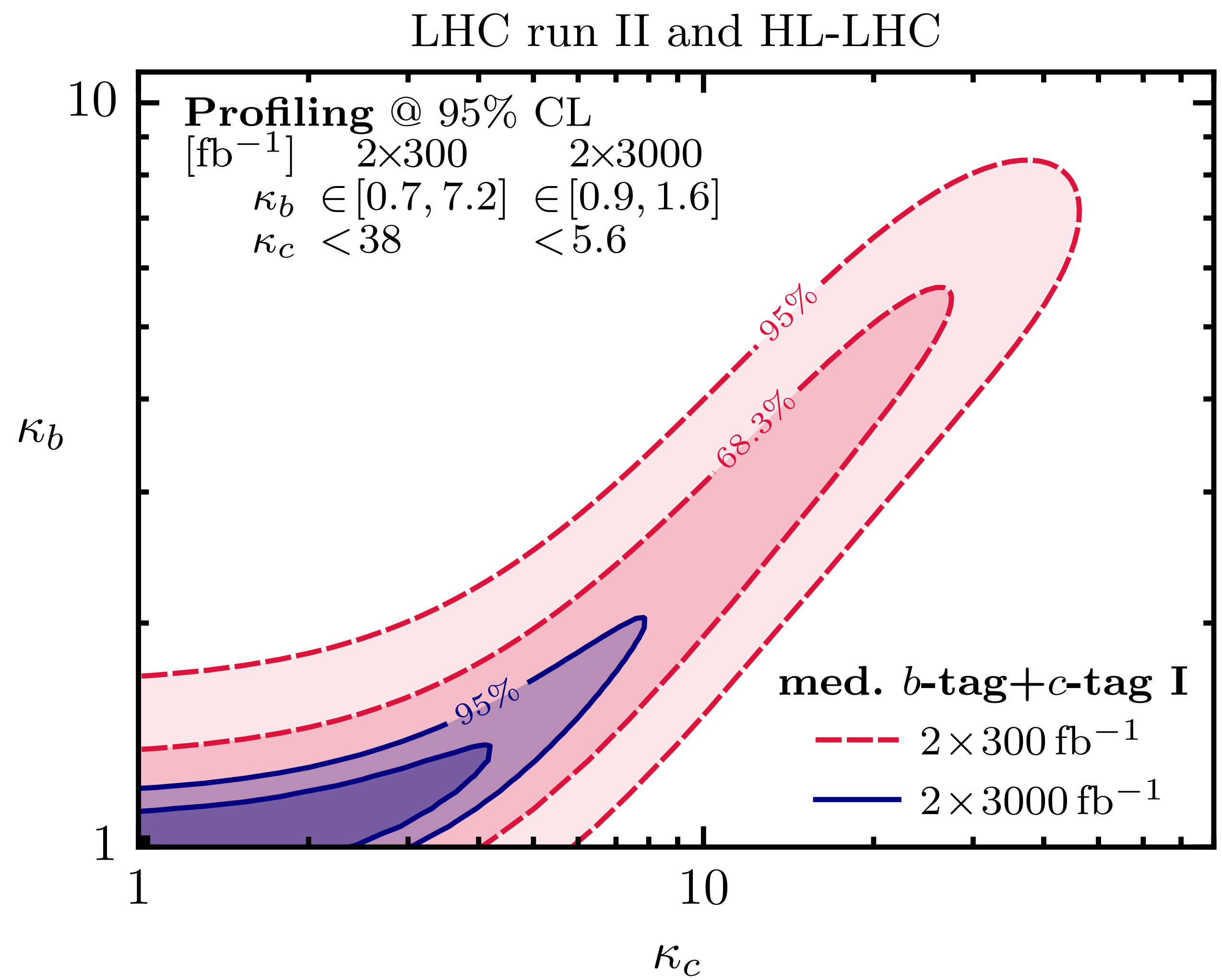
$\kappa_c \lesssim 234$

Inclusive channel at Future LHC

Perez, Soreq, Stamou, **KT** ('15)

	ϵ_b	ϵ_c	ϵ_{light}	
Charm-tag:	13,	19,	0.5	(%)





95%CL

$\Delta\mu_c = 10$ ($2\text{x}300\text{fb}^{-1}$)
$= 3.7$ ($2\text{x}3000\text{fb}^{-1}$)

$\kappa_c < 21$ ($2\text{x}300\text{fb}^{-1}$)
< 3.7 ($2\text{x}3000\text{fb}^{-1}$)

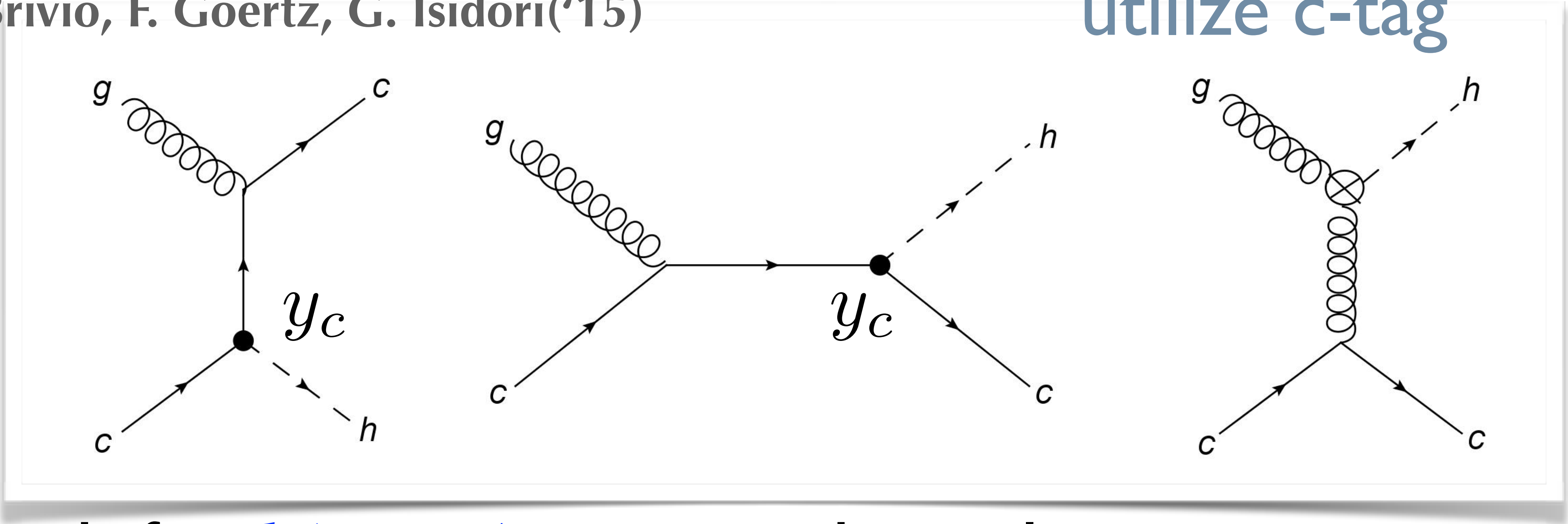
Yukawa measurements via production

other recent ideas

Higgs produced by Yukawa

I. Brivio, F. Goertz, G. Isidori('15)

utilize c-tag



Look for $h(\to\gamma\gamma)$+c-jet, and simply count events

$\kappa_c < 3.9$ ($3000 fb^{-1}$)   95%CL

fixed $\kappa_b = 1$, choose κ_γ to SM $Br_{\gamma\gamma}$

Need

- Total width modification since Br($h\to\gamma\gamma$) is fixed here
- QCD background estimation (non-Higgs continuum)
- float κ_b and include $h(\to\gamma\gamma)$+b-jet

Higgs produced by Yukawa

utilize precision calculation for Higgs production

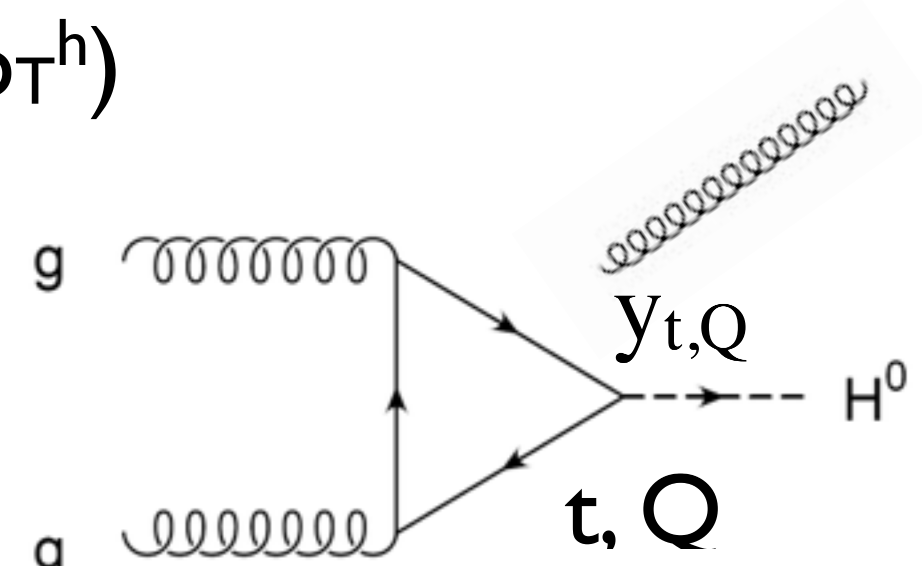
F. Bishara, U. Haisch, P. F. Monni, E. Re('16)

★Study $h(\rightarrow\gamma\gamma)$+jet *spectrum*($p_T^j$, p_T^h)

Q-loop interference

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

more effect
for lighter particle



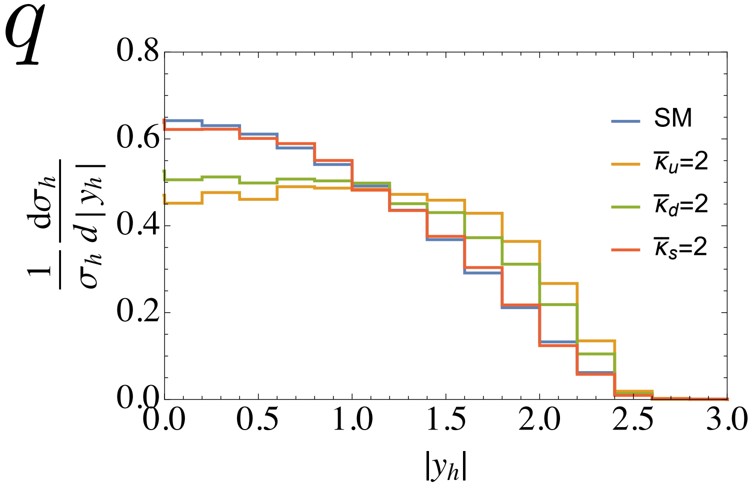
strong limit for charm Yukawa, already $\kappa_c<20$ at Run I(!?)

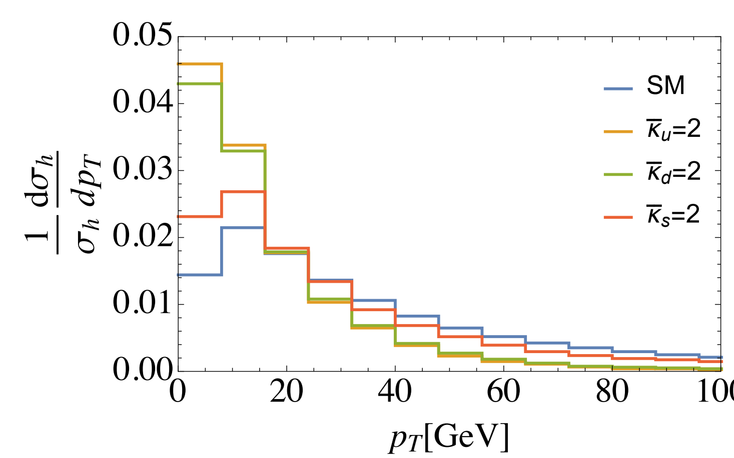
Y. Soreq, H. X. Zhu, J. Zupan('16)

★Higgs production by $\bar{q}q$

modify pT & rapidity

probe for u,d,s Yukawa





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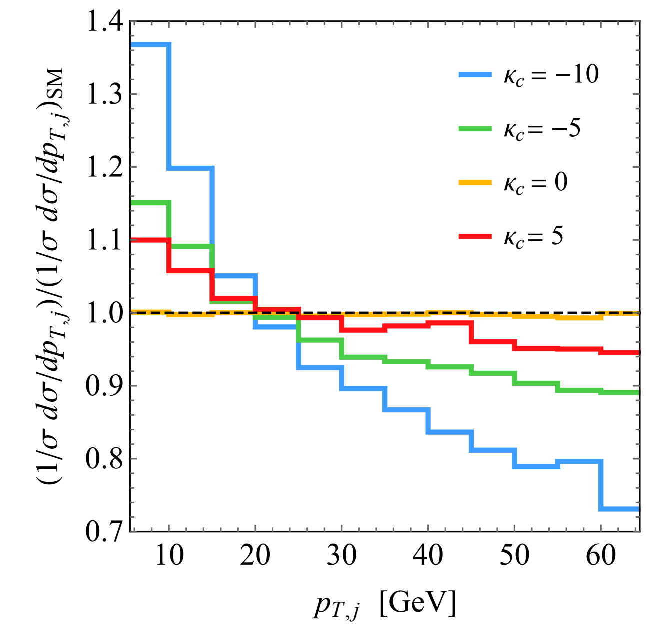

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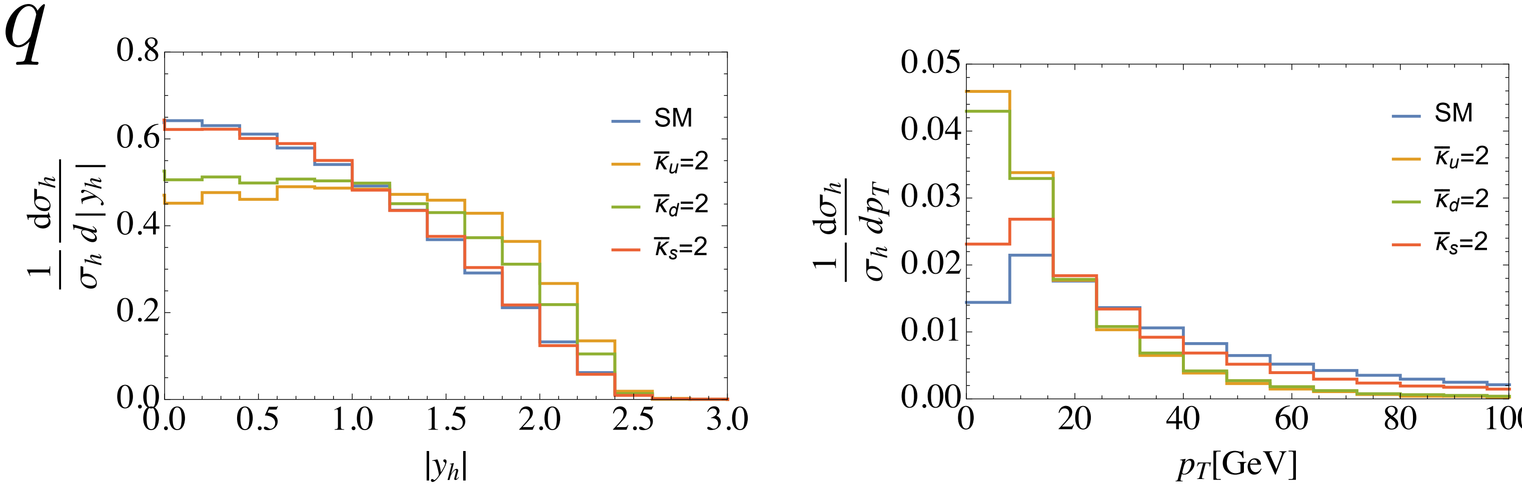
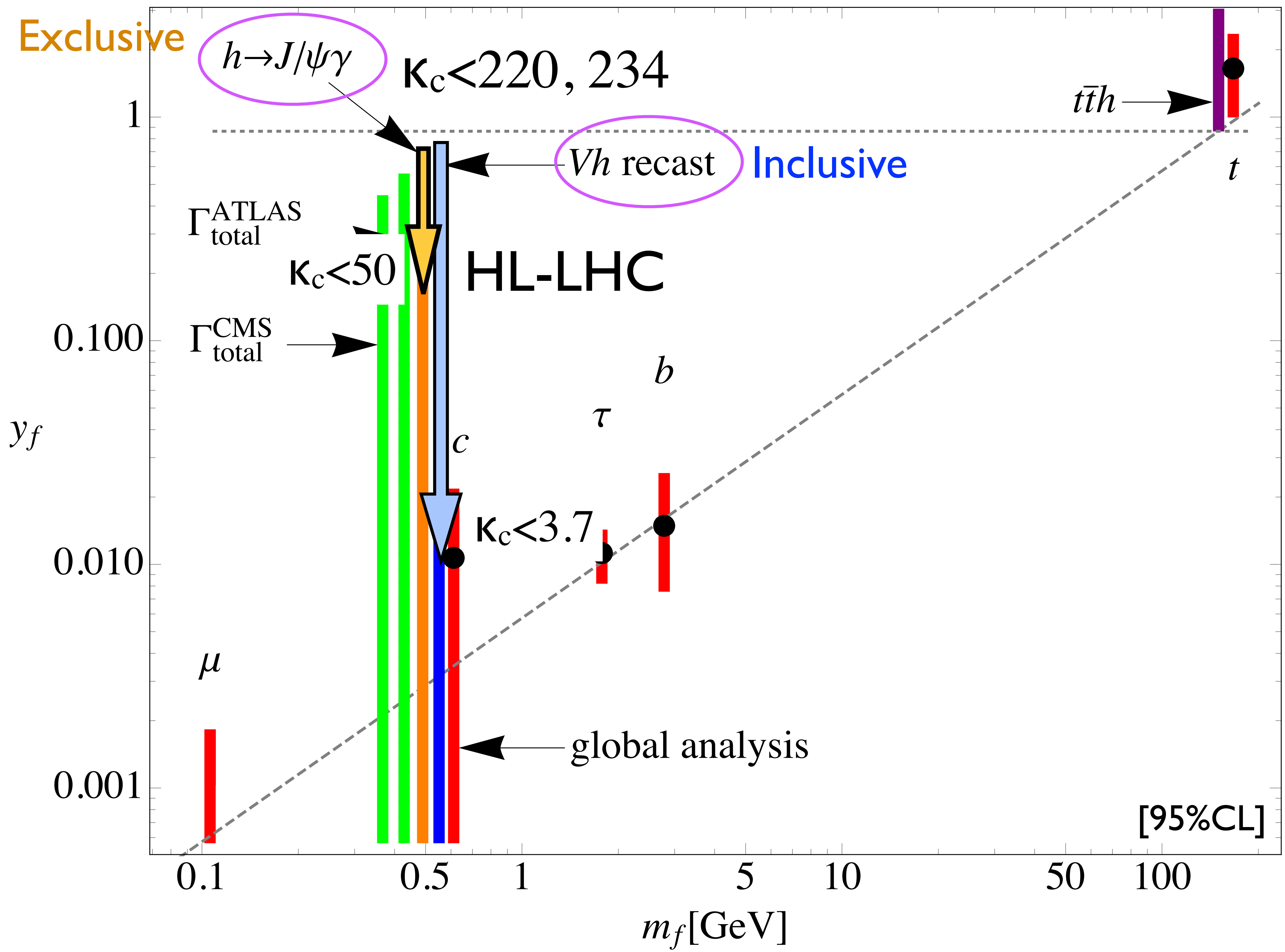


Summary

- Higgs Yukawa measurements are important to reveal fermion flavor puzzle
- Higgs decay to vector-mesons+γ, well studied by theory and already measurements
- Flavor-tagging is useful not only for y_b but also for y_c
- Various new ideas (using production) of Yukawa measurements are proposed

Thank you

Summary



Exclusive
$h \to J/\psi\gamma$
κ_c<220, 234
Vh recast
Inclusive
Γ_{total}^{ATLAS}
κ_c<50
HL-LHC
Γ_{total}^{CMS}
$t\bar{t}h$
t
b
τ
c
κ_c<3.7
μ
global analysis
[95%CL]
1
0.100
0.010
0.001
y_f
0.1
0.5
1
5
10
50
100
m_f[GeV]