Prospects for Higgs self-coupling measurements at the FCC

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Benjamin Fuks, J. H. Kim, Seung J. Lee, arXiv:1704.04298

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What triggers EWSB

$$V_h = \frac{m_h^2}{2}h^2 + (1+\kappa_3)\lambda_{hhh}^{\mathrm{SM}} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\mathrm{SM}} h^4 \qquad \left(\lambda_{hhh}^{\mathrm{SM}} = \lambda_{hhhh}^{\mathrm{SM}} = \frac{m_h^2}{2v^2}\right)$$

Measured
$m_h \simeq 125$ GeV

Is $\kappa_3 = 0$?

Is $\kappa_4 = 0$?

- Only the first term has been probed
- It's just a local minimum!
- We're blind to the shape of Higgs potential which actually triggers EWSB dynamics
- Measuring a trilinear and quartic couplings provides crucial information

What determines the shape

- From EFT point of view, in a model-independent way, we can consistently add gauge-invariant D = 6 operators…

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \boxed{\frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}|H|^6} \qquad (\Lambda \gg v)$$

- which induce modified Higgs potential:

$$V_h = \frac{m_h^2}{2}h^2 + \left[1 + \frac{c_6 v^2}{\Lambda^2} - \frac{3c_H v^2}{2\Lambda^2}\right]\lambda_{hhh}^{\rm SM} v h^3 + \frac{1}{4}\left[1 + \frac{6c_6 v^2}{\Lambda^2} - \frac{25 c_H v^2}{3\Lambda^2}\right]\lambda_{hhhh}^{\rm SM} h^4$$

κ_3 κ_4

- The SM potential is completely fixed ($\kappa_3 = 0$ and $\kappa_4 = 0$)
- Any deviation stands out the evidence that EWSB is triggered by something else…

What determines the shape

$$V_h = \frac{m_h^2}{2}h^2 + \left[1 + \frac{c_6 v^2}{\Lambda^2} - \frac{3c_H v^2}{2\Lambda^2}\right]\lambda_{hhh}^{\rm SM} v h^3 + \frac{1}{4}\left[1 + \frac{6c_6 v^2}{\Lambda^2} - \frac{25c_H v^2}{3\Lambda^2}\right]\lambda_{hhhh}^{\rm SM} h^4$$

κ_3 κ_4

$$\mathcal{L} \supset -\frac{m_t}{v}\left(1 - \frac{c_H v^2}{2\Lambda^2}\right)\bar{t}_L t_R h$$

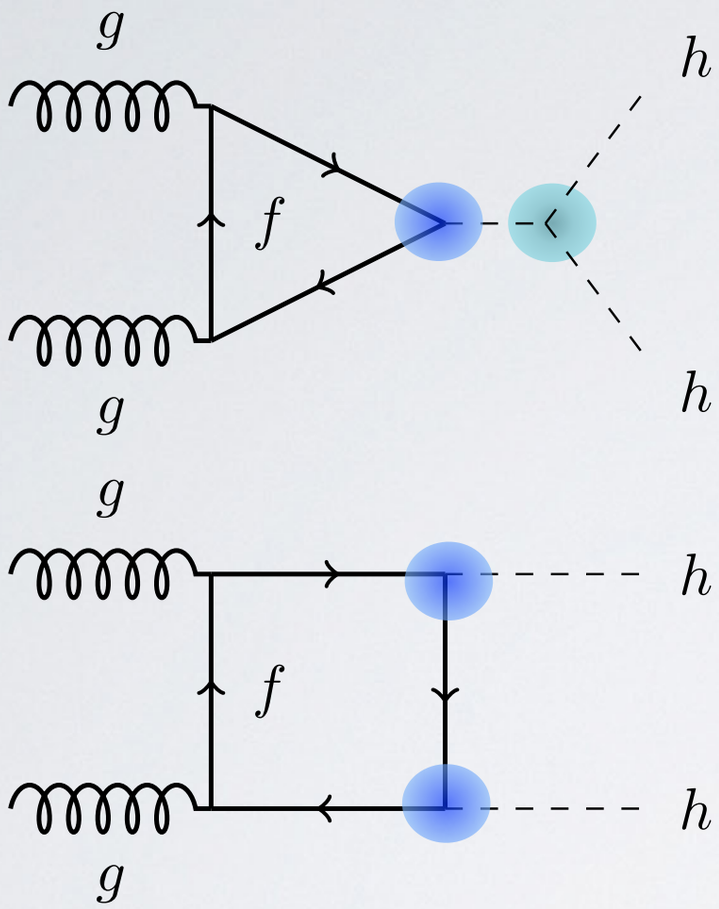
top Yukawa

- Canonical normalization of the Higgs kinetic term induces ``non-linear shift`` in the Higgs field
- The shift appears in the top Yukawa interaction too
- So in general, all these couplings are related with each other
- We will assume the SM top Yukawa, and vary κ_3 and κ_4 independently…

How well can we measure the trilinear coupling?

$$V_h \supset (1+\kappa_3)\lambda_{hhh}^{\rm SM} v h^3$$

Double Higgs production!



In the end of days…

- $(b\bar{b})(\gamma\gamma)$ channel
  - ⋯ Significance = 1.6 σ
  - ⋯ $N_s = 2 \sim 9$ events
- $(b\bar{b})(\tau\tau)$ channel
  - ⋯ Significance = 0.7 ~ 0.9 σ
  - ⋯ $N_s = 5 \sim 6$ events

HL-LHC

3000 fb^{-1}

SM prediction

CMS PAS FTR-15-002

$\sigma^{\text{NNLO}}_{14\text{TeV}} \sim 40.7$ fb

- Di-Higgs production has been a major playground for the trilinear coupling measurement:

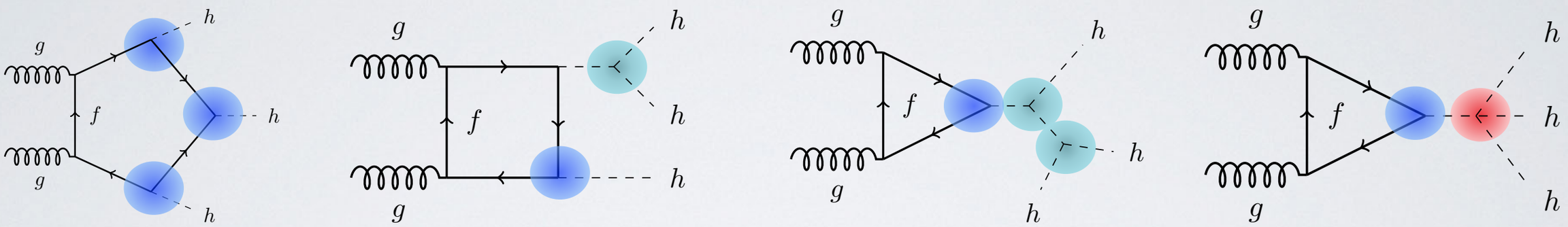
$$0.3 < \kappa_3 < 1.5$$

None of these searches are designed to probe a quartic coupling!

$$V_h \supset \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\mathrm{SM}} h^4$$

- which is so far an important missing piece of the Higgs potential.

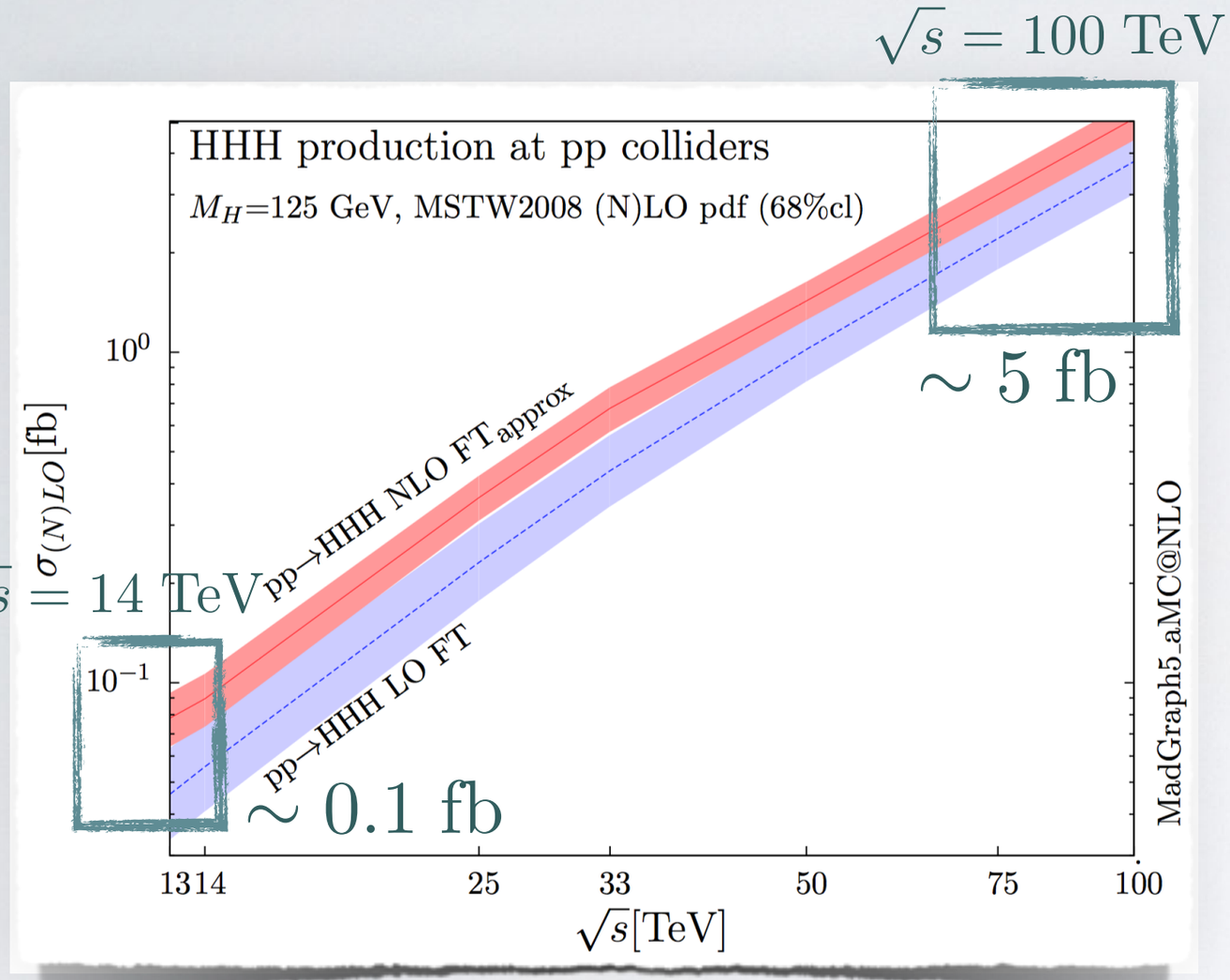
Tiple Higgs production



- Triple Higgs production has a mild dependence on κ_4
- But it has strong dependences on the top Yukawa coupling and κ_3

  hopefully constrained by HL-LHC
- It receives a phase space suppression (*cf.* double Higgs production)
- So the signal rate is expected to be small

Tiple Higgs production



F. Maltoni, E. Vryonidou, M. Zaro [2014]

Impossible to probe at LHC

- Signal rate is 0.1 fb …

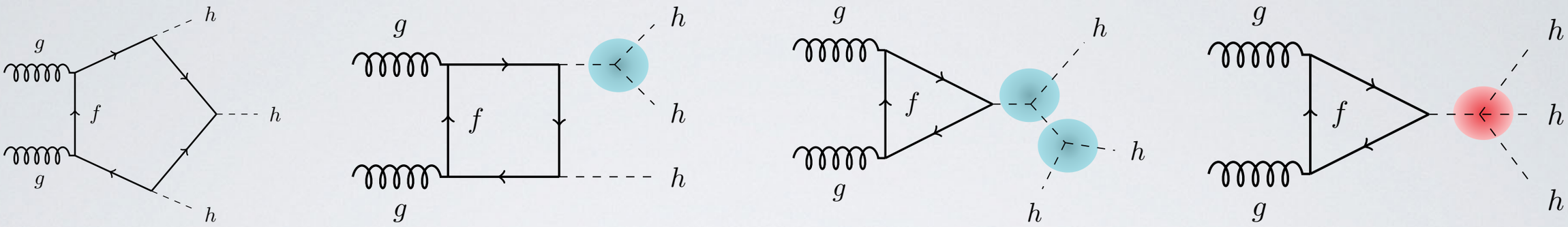
Post-LHC era

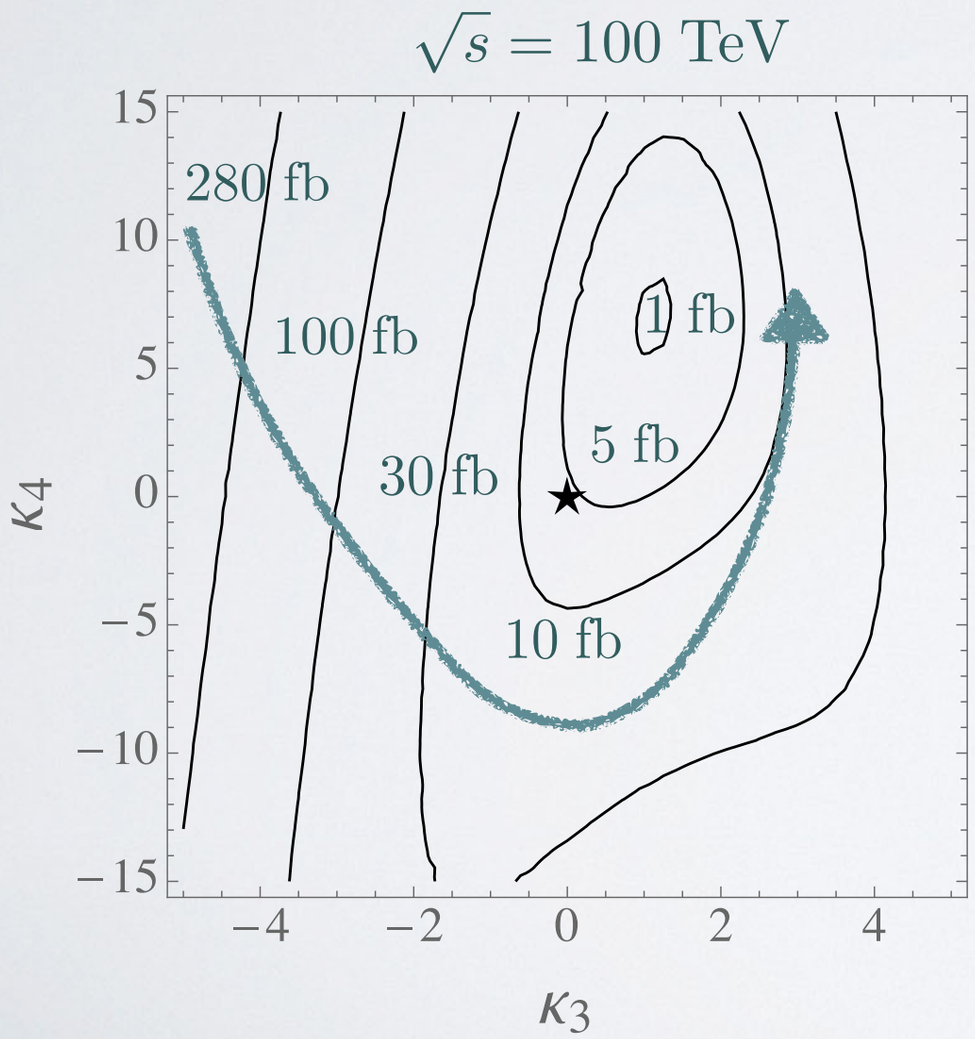
- Future experimental program that is currently under consideration at CERN

- In this stage, at 100 TeV FCC, signal rate can reach to 5 fb…

SM prediction

Cross section contours





B. Fuks, **J. H. Kim**, S. J. Lee [2015]

- Cross section contours in our parameter space
- Strong dependence on κ_3
- Mild dependence on κ_4
- There is a destructive interference on the upper-right-hand side!

Triple Higgs signals

- $(b\bar{b})(b\bar{b})(\gamma\gamma)$ channel

Papaefstathiou, Sakurai [2015] Chen, Yan, Zhao, Zhong, Zhao [2015]
B. Fuks, **J. H. Kim**, S. J. Lee [2015]

$$\kappa_4 \in [\, -5,\ 15\,]$$

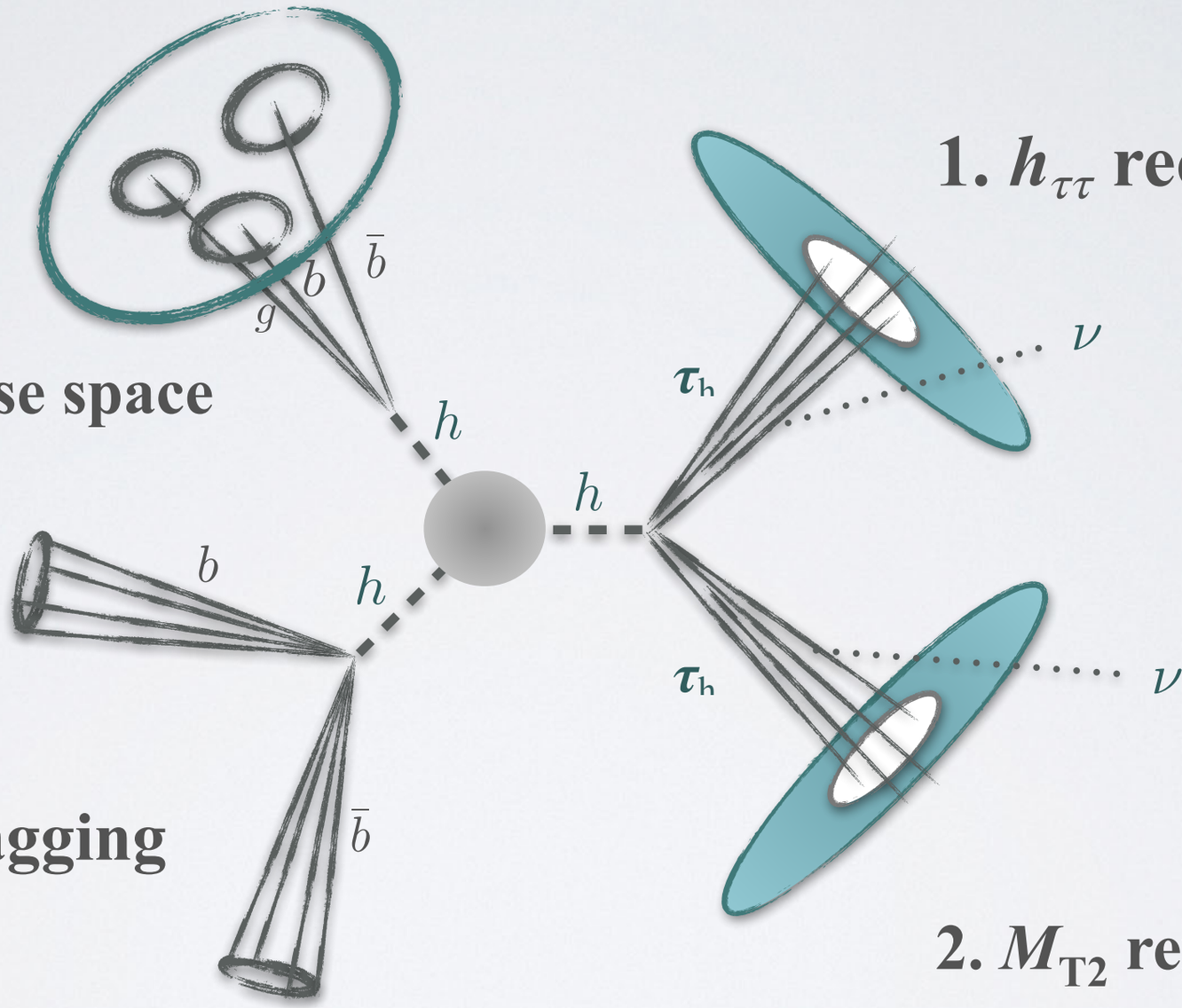
$$L = 30\ \mathrm{ab}^{-1} \quad N_s \sim 10\ \text{events}$$

  - ⋯ Small branching fraction (0.23%)
  - ⋯ Clean signature and low backgrounds
  - ⋯ κ_4 will remain to be largely unconstrined…

In this work…

- $(b\bar{b})(b\bar{b})(\tau\bar{\tau})$ channel B. Fuks, **J. H. Kim**, S. J. Lee [2017]
  - ⋯ Branching fraction (6.3%)
  - ⋯ With an advantage of $4b + 2\tau$ tagging

Signal selections



1. $h_{\tau\tau}$ reconstruction

2. M_{T2} reinforcement

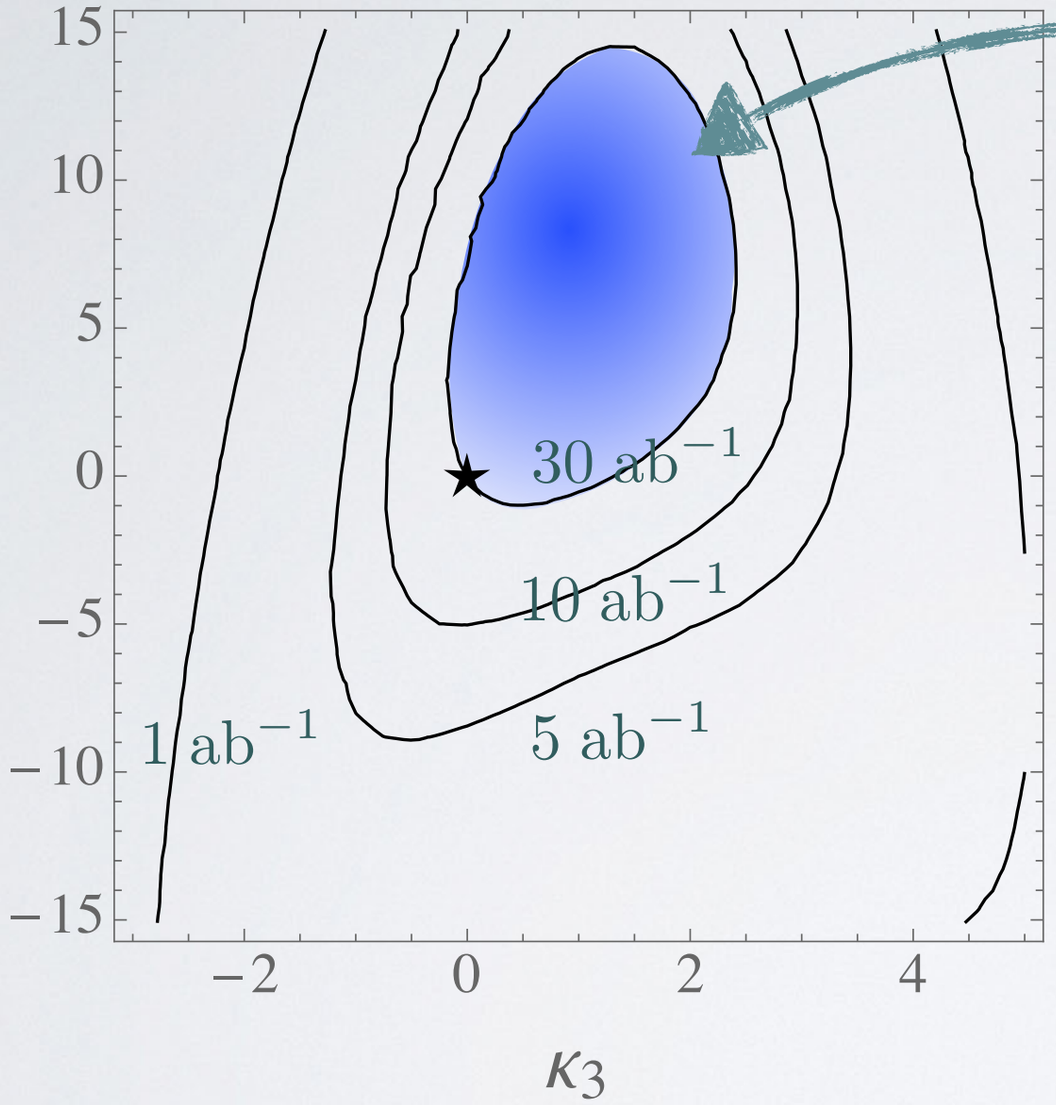
3. Boosted phase space

4. Extra b-tagging

Luminosity goals for 2σ

B. Fuks, **J. H. Kim**, S. J. Lee [2017]

Unconstrained deep well

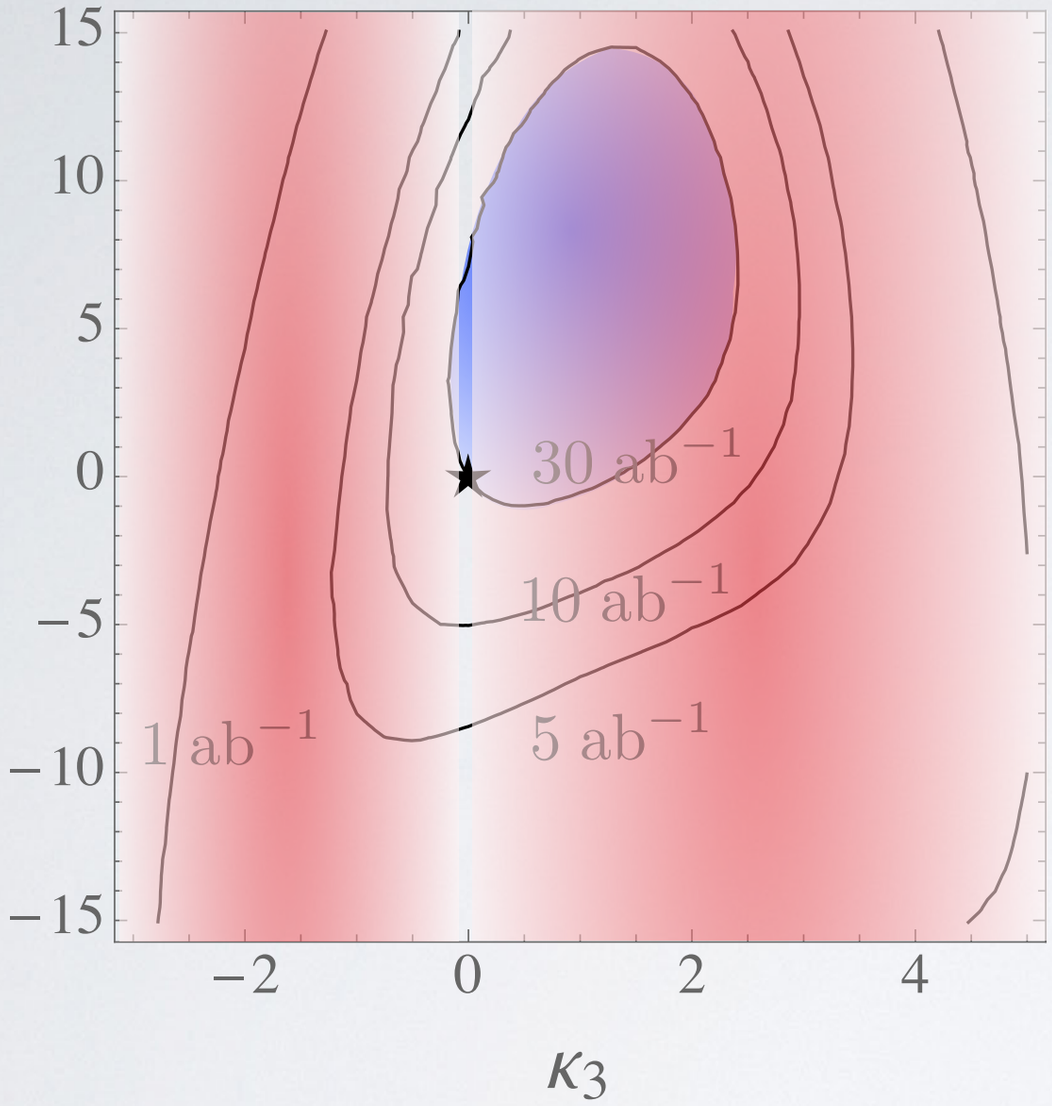


Destructive interference…

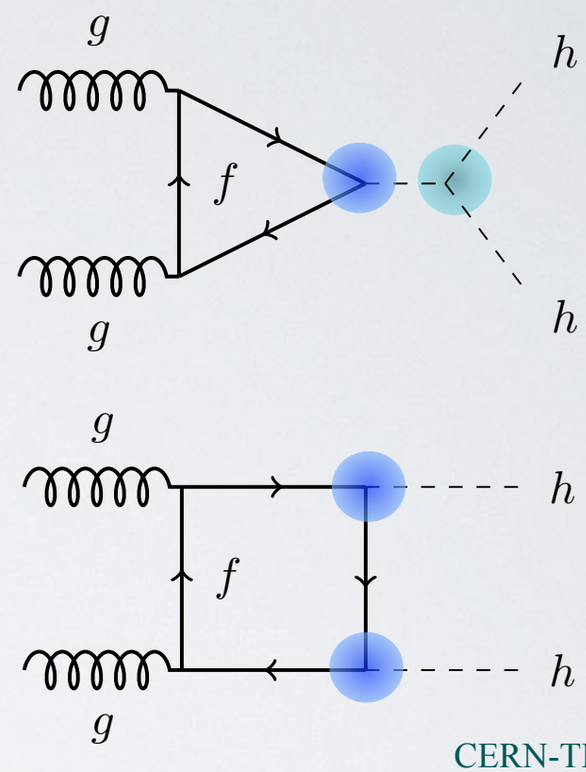
- Luminosity contours for 2σ exclusion.
- A good fraction of the parameter space is covered in HL-phase
- We might be able to just exclude the SM point!

κ_4 sensitivity

B. Fuks, **J. H. Kim**, S. J. Lee [2017]



+



CERN-TH-2016-113

$$\kappa_3 \in [\, -0.03,\ 0.03\,]$$

for 30 ab^{-1}

$$\boxed{\kappa_4 \in [\, 0,\ 8\,]} \quad \longleftrightarrow \quad \kappa_4 \in [\, -5,\ 15\,]$$

$(b\bar{b})(b\bar{b})(\tau_h\bar{\tau}_h)$ $\qquad$ $(b\bar{b})(b\bar{b})(\gamma\gamma)$

CERN-TH-2016-113

Conclusion

- **The Higgs potential consists of an unexplored territory in which the EWSB is triggered**
- **In this work, we have shown that in addition to $(b\bar{b})(b\bar{b})(\gamma\gamma)$ channel, the $(b\bar{b})(b\bar{b})(\tau_h\bar{\tau}_h)$ final state is a complementary to probe the quartic coupling**
- **The sensitivity reach of the FCC to measure the quartic coupling:**

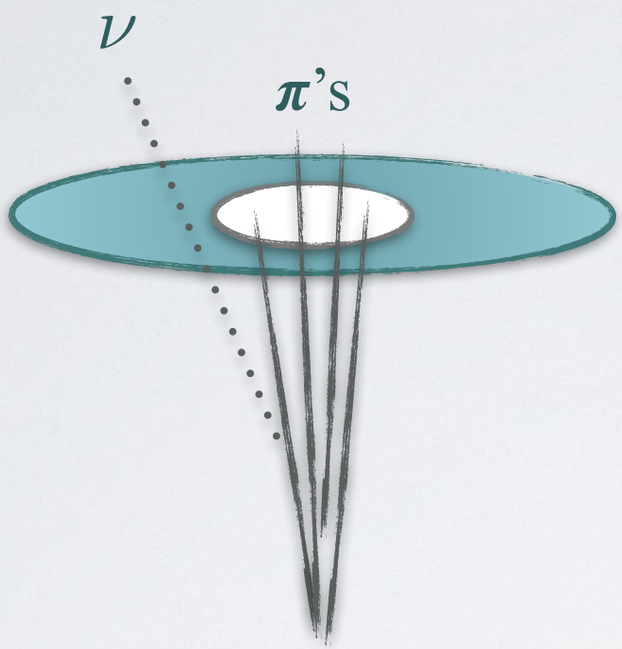
$$\kappa_4 \in [\,0,\ 8\,] \qquad \text{for } 30\ \text{ab}^{-1}$$

Back-up

Backgrounds

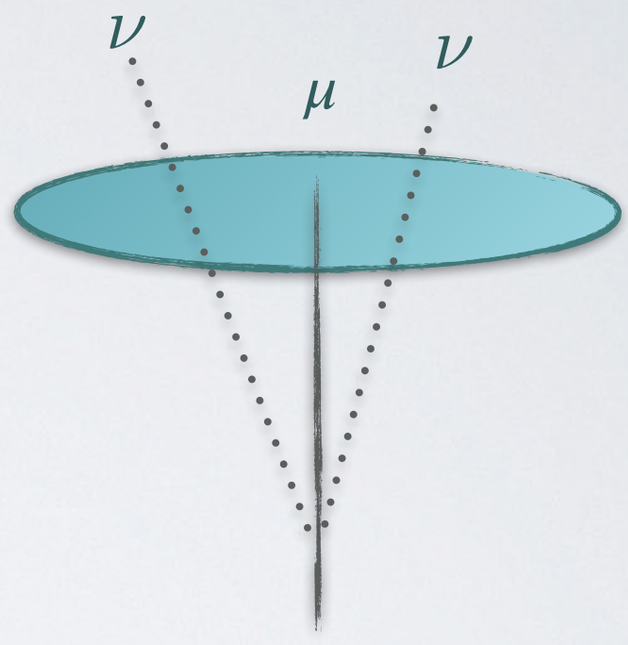
Class	Backgrounds	Cross section [fb]
t/W samples	$t_\tau \bar{t}_\tau h_{b\bar{b}}$	530
	$t_\tau \bar{t}_\tau z_{b\bar{b}}$	150
	$t_\tau \bar{t}_\tau b\bar{b}$	1.1×10^4
	$W_\tau^+ W_\tau^- b\bar{b}b\bar{b}$	1.1×10^4
	$t\bar{t}t\bar{t}$	6.0×10^3
$\tau^+\tau^-$ + jets	$\tau^+\tau^- bbbb$	1.5×10^3
	$\tau^+\tau^- b\bar{b}jj$	3.1×10^5
	$\tau^+\tau^- t_h \bar{t}_h$	1.6×10^3
	$\tau^+\tau^- z_{b\bar{b}} b\bar{b}$	38
	$\tau^+\tau^- z_{b\bar{b}} z_{b\bar{b}}$	0.38
Others	$h_{\tau\tau} h_{b\bar{b}} + \text{jet}$	15

Terrible τ's



τ_h

Br = 66%

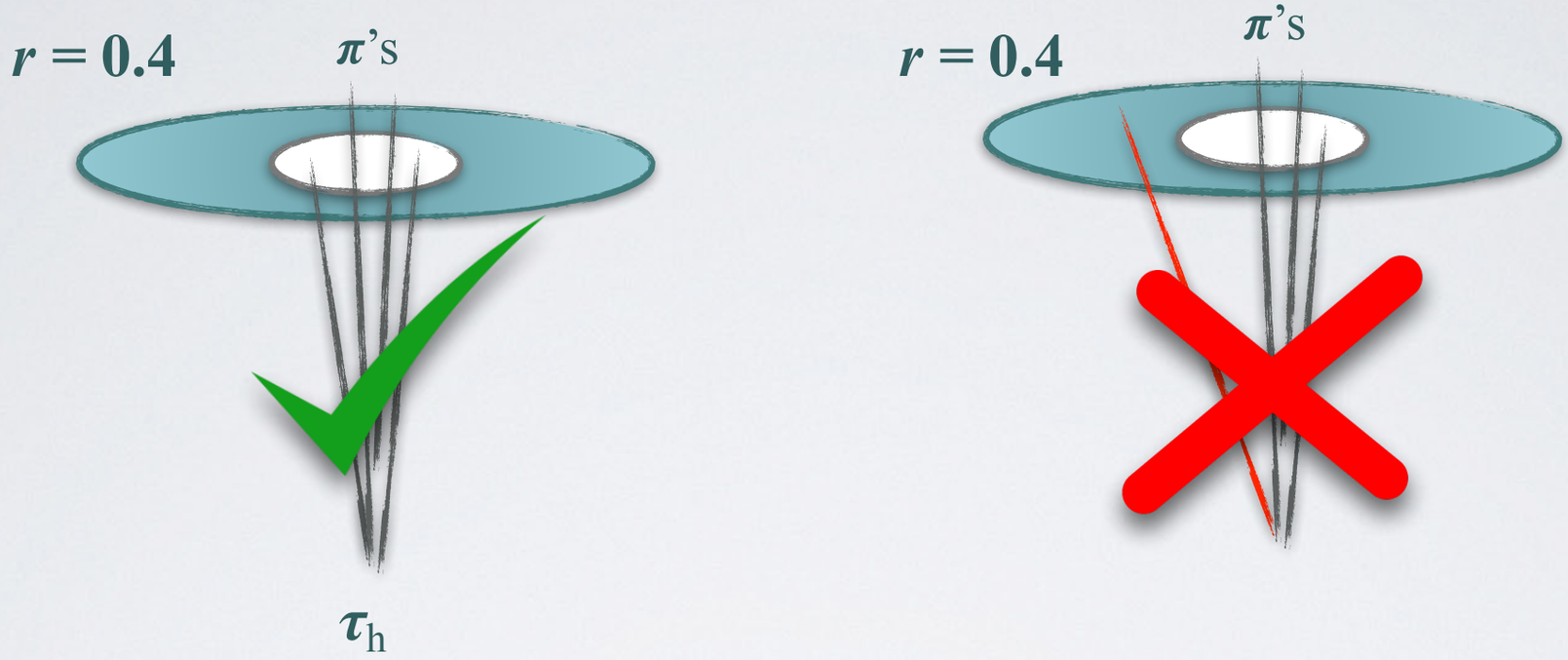


τ_μ

Br = 34%

- We don't see τ's directly
- Neutrinos escape without being detected
- τ_h is characterized by a narrow jet with no other jet activities around it
- τ_μ is an isolated lepton

τ_h-tagging

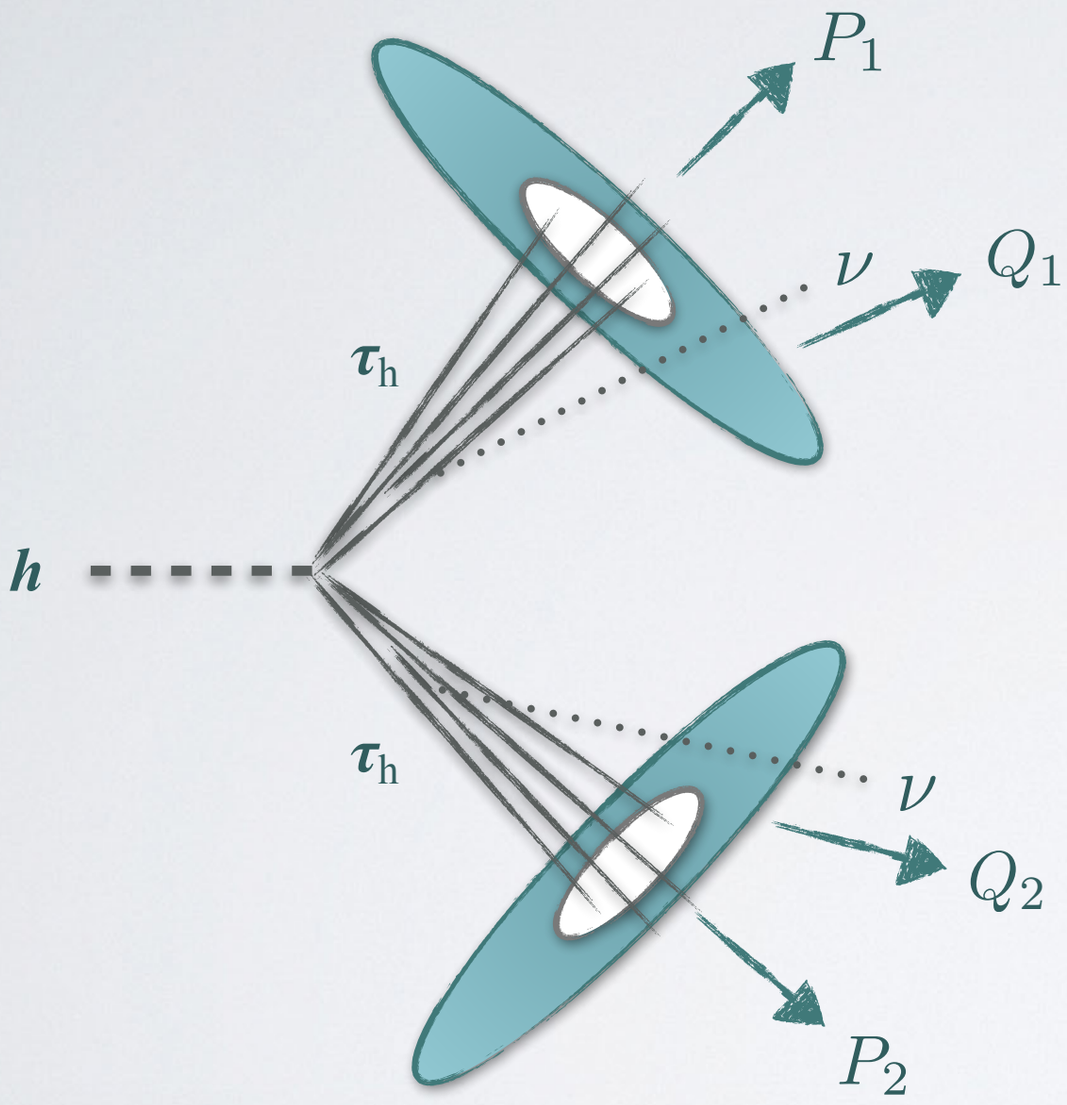


- τ_h-tagging efficiency is ~ 50%
- Fake rate of QCD jets is ~ 3% (*cf.* even 0.5% is possible)

CMS PAS FTR-15-002

- We focus on the fully-hadronic $\tau_h\tau_h$ final state

$h_{\tau\tau}$ reconstruction



- $h_{\tau\tau}$ reconstruction has been well-studied in previous Higgs searches
- Business here is to separate $h_{\tau\tau}$ against $Z_{\tau\tau}$
- We hypothesize missing momenta Q1 and Q2 with kinematic constraints
- Scan them over till they minimizes the mass variable:

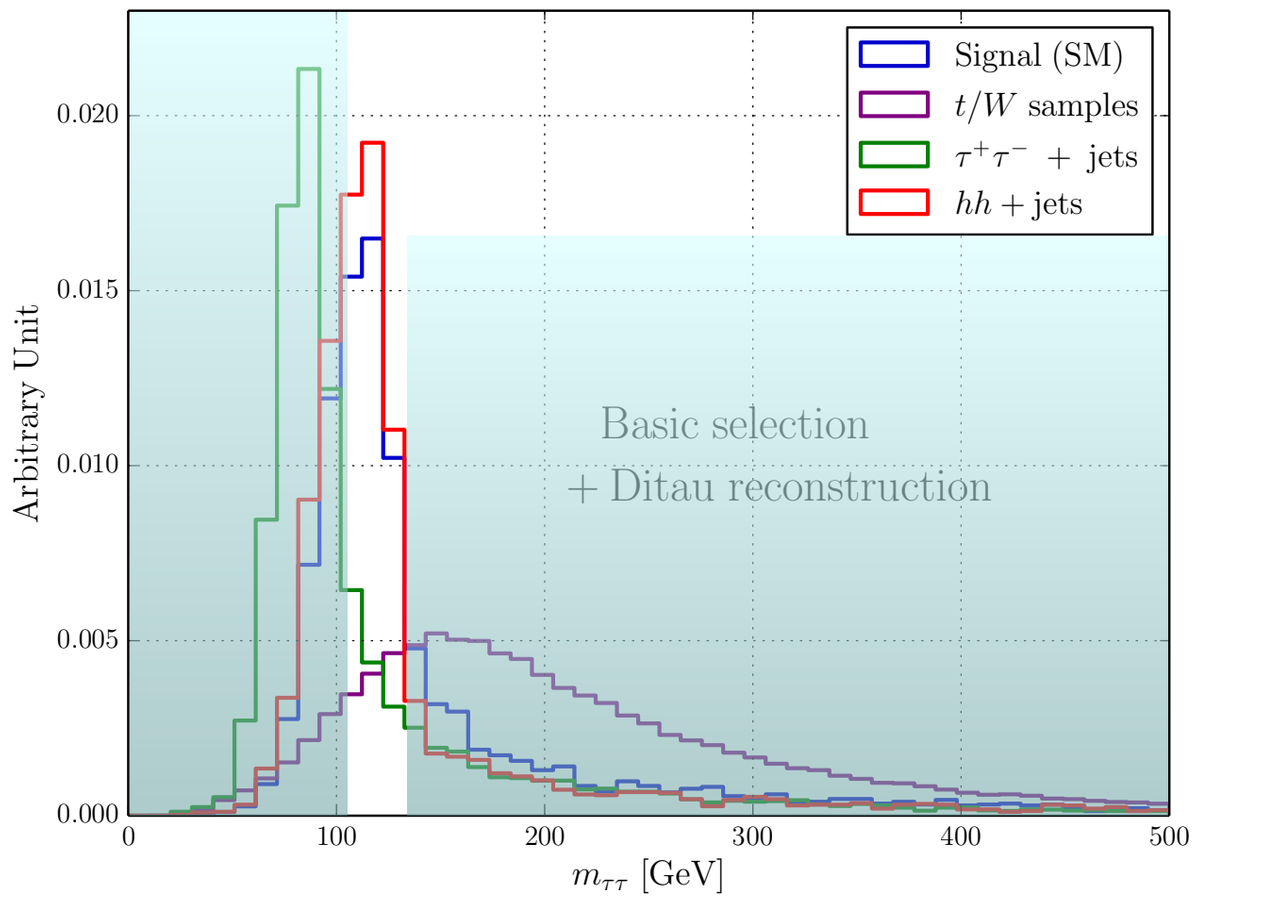
$$m_{\tau\tau}^{\mathrm{Higgs-bound}} \equiv \min_{\{Q_1^\mu, Q_2^\mu\}} \sqrt{H^\mu H_\mu}$$

$$H^\mu = P_1^\mu + Q_1^\mu + P_2^\mu + Q_2^\mu$$

A. J. Barr, S. T. French, J. A. Frost, C. G. Lester [2011]

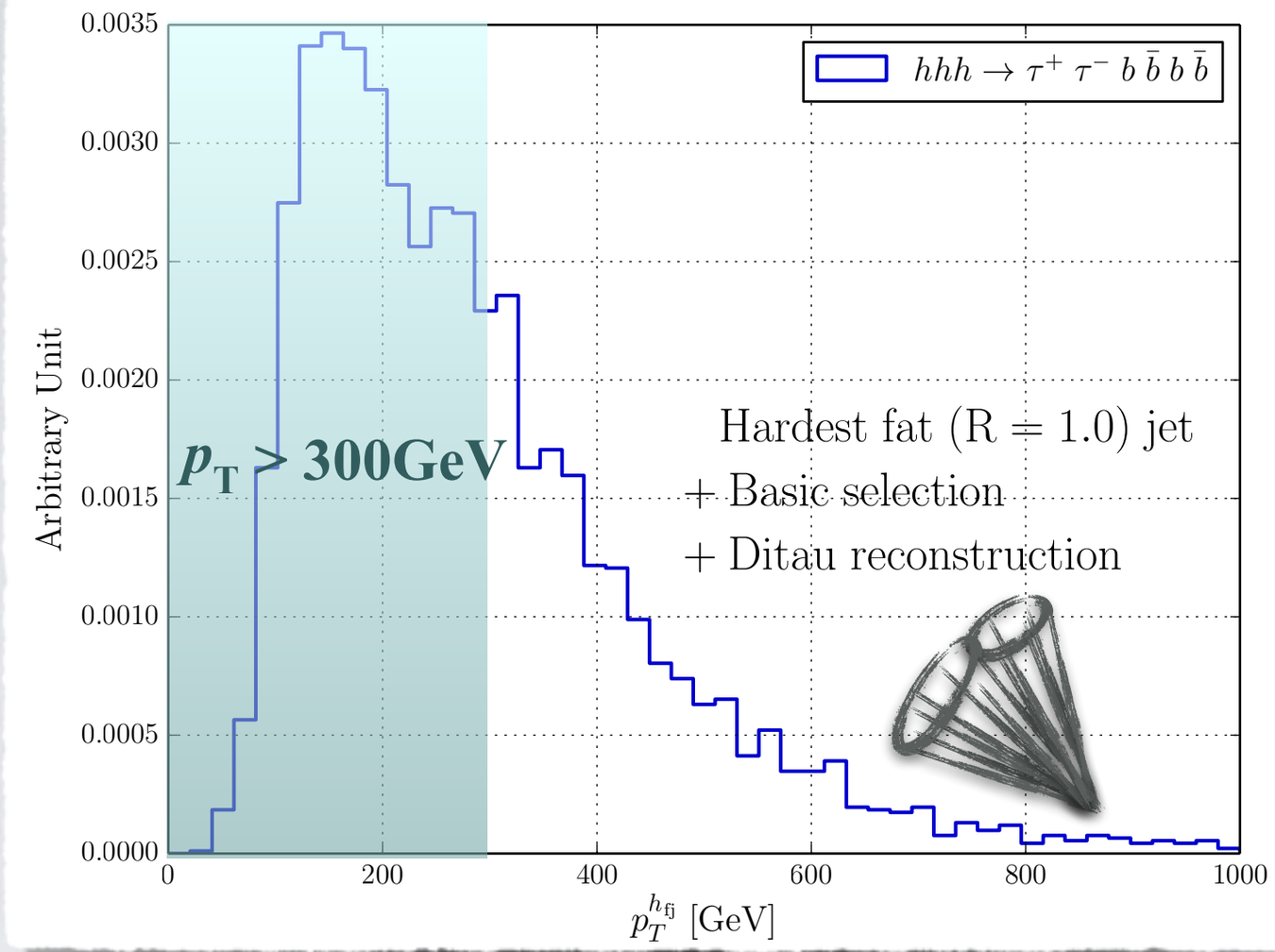
A. J. Barr, B. Gripaios, C. G. Lester [2009]

$h_{\tau\tau}$ reconstruction



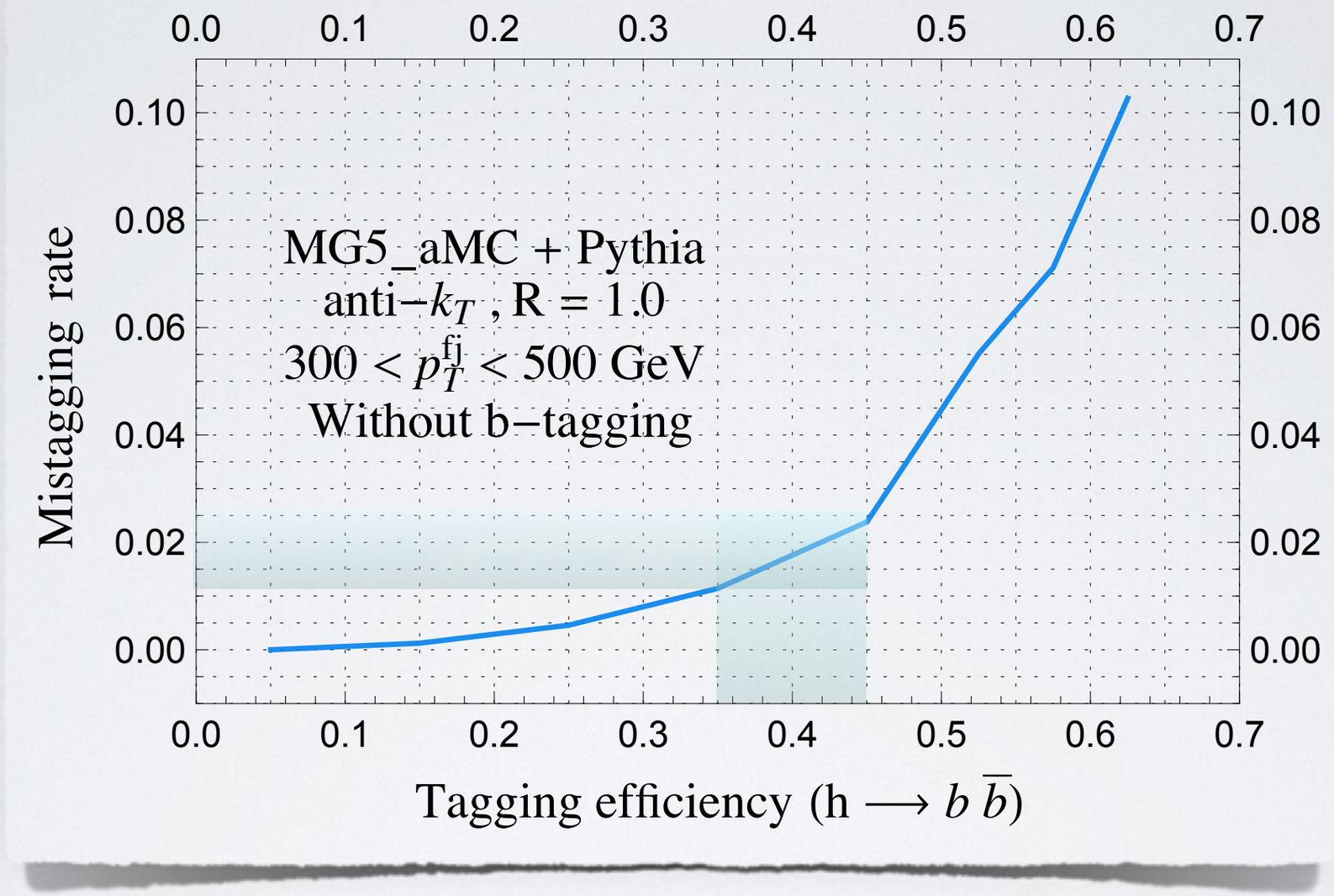
- Sensible separation between $h_{\tau\tau}$ and $Z_{\tau\tau}$
- We're able to put keen mass window cut to disentangle $Z_{\tau\tau}$ sample, since we don't use any mass information in the reconstruction procedure

Boosted phase space



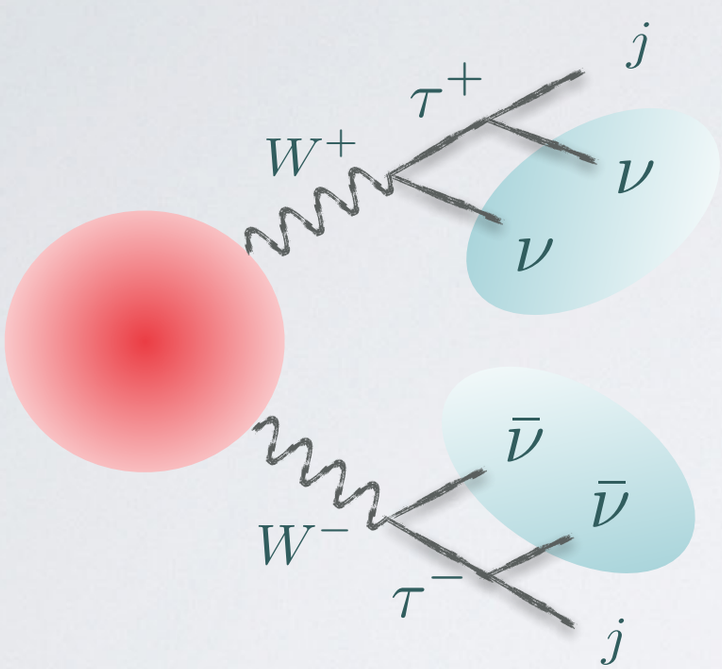
- It is signal-cost, but there is still a reasonable boosted phase space left
- Two *b* jets from a Higgs are collimated
- It is the sturcture that SM backgrounds can’t easily fake

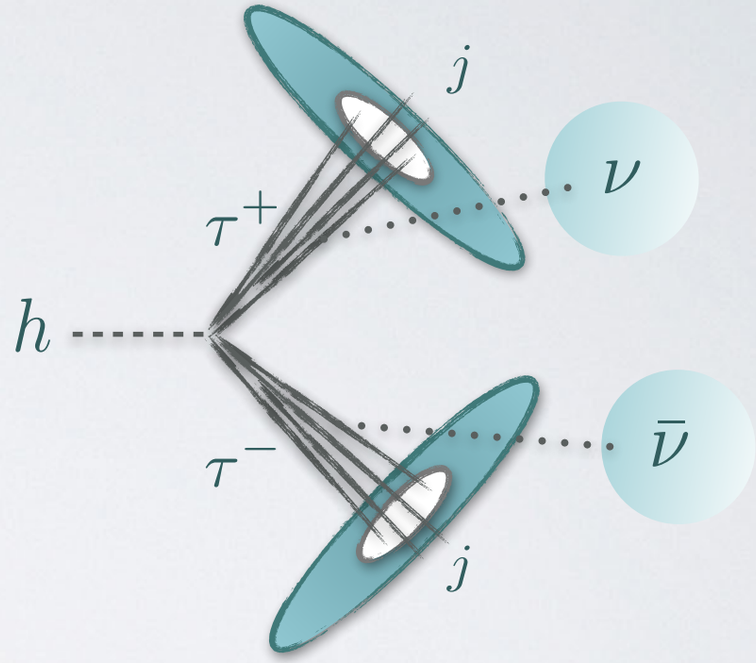
Boosted Higgs tagging



- ``ROC`` curve telling us a tagging efficiency vs mis-tagging rate
- We will focus on the tagging efficiency of 40% with a fake rate of 2%
- Note that this is even ``before`` applying b-tagging!

M_{T2} in Triple-Higgs search





- Now we want to eliminate $W_\tau^+ W_\tau^-$ containing backgrounds
- Similar M_{T2} topologies as the signal
- We don't expect a great separation power (*cf.* Double-Higgs case)
- But… parental masses and invisible masses are different. **Can this help?**