# Scrutinising *hhh* production with *b*-jets, taus and photons


**Benjamin Fuks**

**LPTHE / Sorbonne Université**


**HHH workshop**

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# Setting the stage…

## The Higgs potential in the SM - very few freedoms

- The Higgs mass and vev the (known) keys

$$V_h = \frac{1}{2} m_h^2 h^2 + \lambda_{hhh} v h^3 + \frac{1}{4} \lambda_{hhhh} h^4$$

with $\lambda_{hhh} = \lambda_{hhhh} = \frac{m_h^2}{2v^2}$

- Higgs self-couplings: *direct* verification in order
  - ➙ Better knowledge of EWSB
  - ➙ Access to an extended scalar sector
  - ➙ Nature of the electroweak phase transition

## Simplest new physics parameterisation

- SM coupling modifiers

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

- In the SM $\kappa = 0$
  - ➙ Experimental constraints at the LHC and beyond
  - ➙ Requires multi-Higgs production
- Signature studied: 4 *b*-jets + either $2\gamma$ or 2 $\tau$

## The golden (clean) $4b2\gamma$ mode

- Extremely efficient *b*-tagging desirable
- Good photon resolution
- $2\sigma$ reachable in the SM
- Excellent probe of BSM

[Papaefstathiou & Sakurai (JHEP`16)]
[BF, Kim & Lee (PRD`16)]
[Chen, Yan, Zhao, Zhao & Zhong (PRD`16)]

## The $4b2\tau$ mode

- Exploiting boosted Higgses and high-level variables
- Good double-tau tagging crucial
- $2\sigma$ reachable in the SM

[BF, Kim & Lee (PLB`17)]

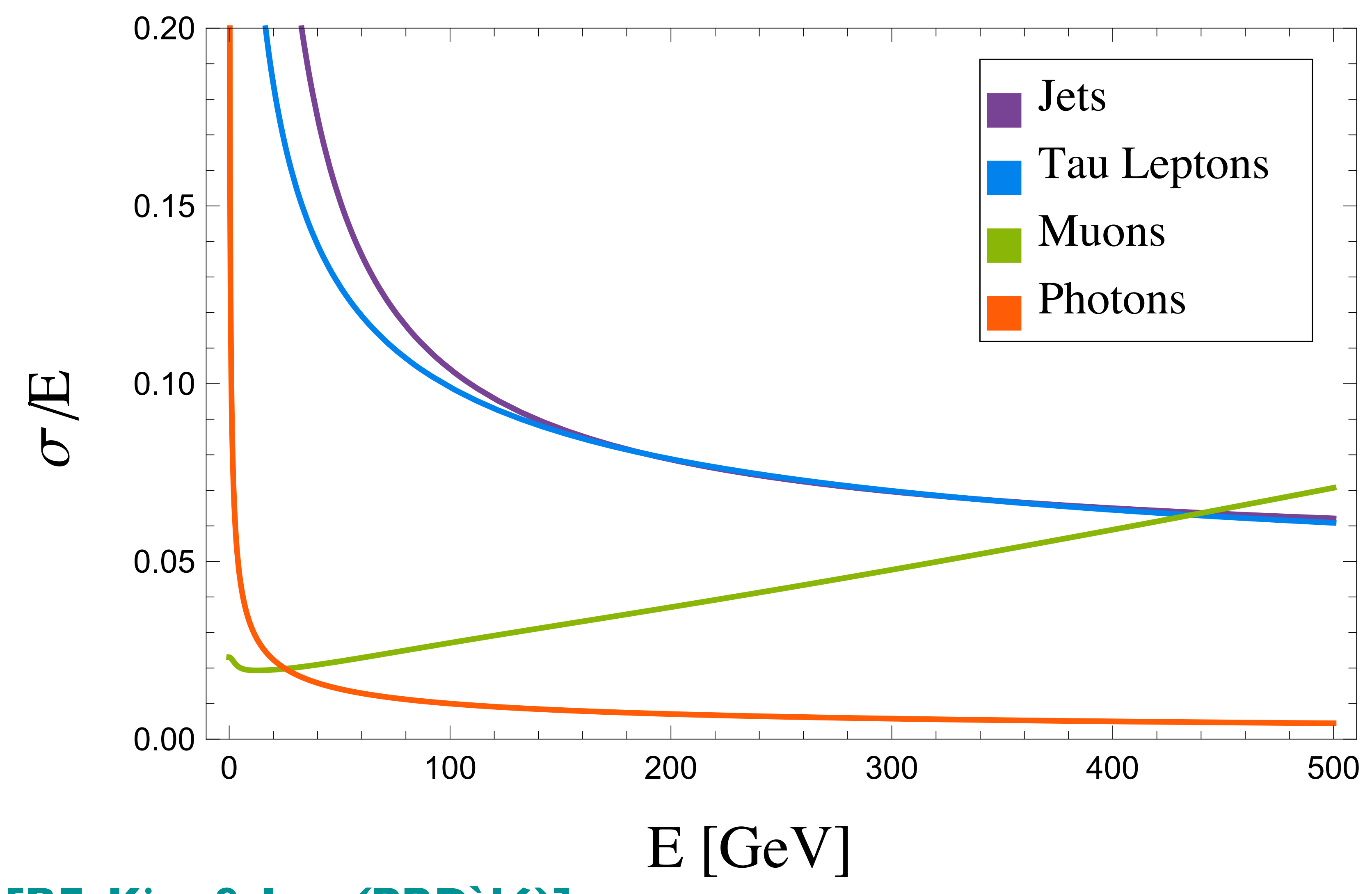
# Triple Higgs production in the 4b2$\gamma$ mode

## Simulation details

- Monte Carlo study + smearing of the four-momenta (à la ATLAS)
- *b*-tagging performance: two LHC-inspired working points
  → 70% efficient ⊕ large fake rates (18%, for *c*-jets, 1% for light jets)
  → 60% efficient ⊕ small fake rates (1.8%, for *c*-jets, 0.1% for light jets)

Can we be more aggressive?
Are the choices realistic?

See talks by Liu & Kolosova




[BF, Kim & Lee (PRD`16)]

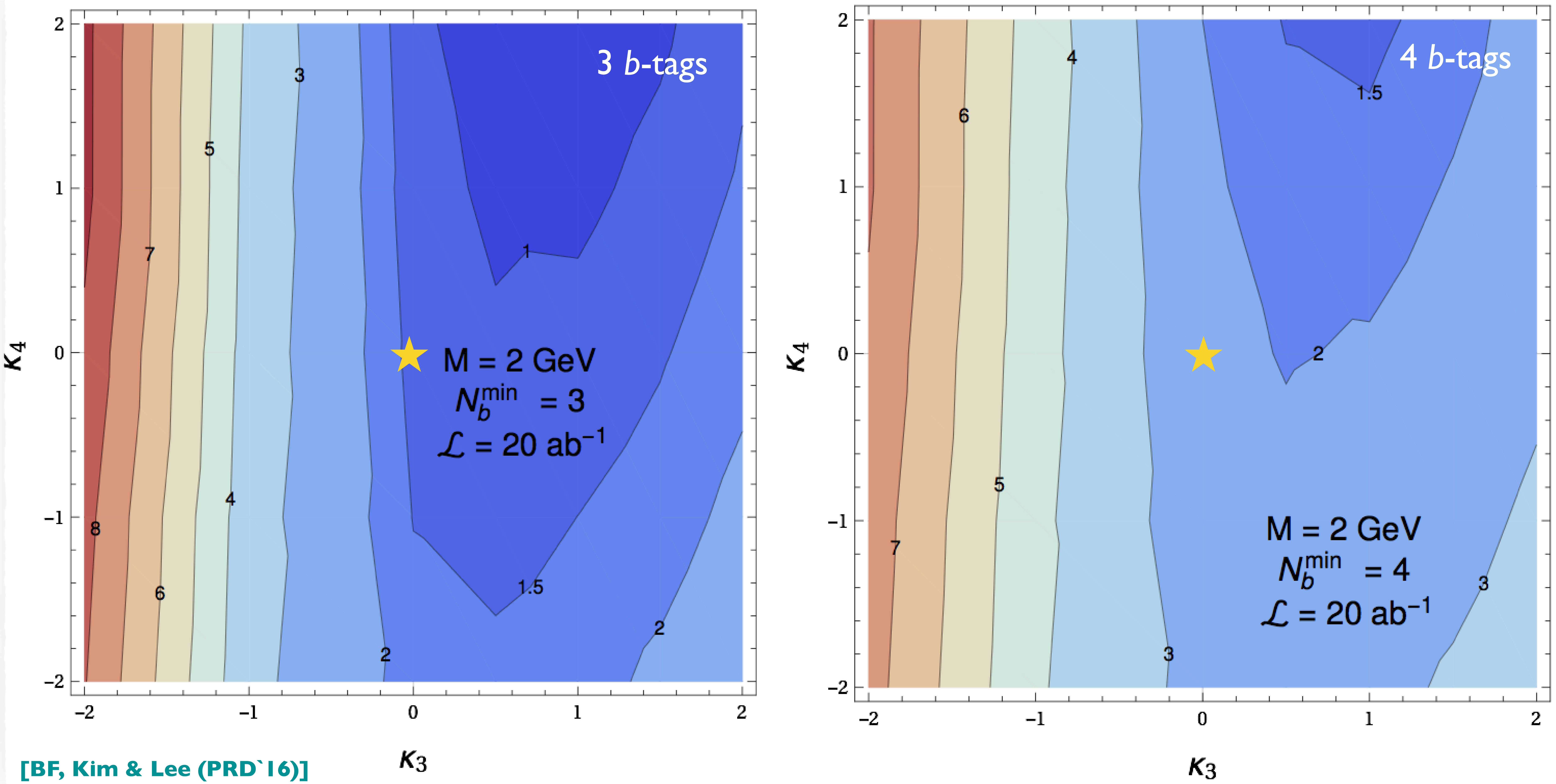
- Main backgrounds: $\gamma\gamma bbjj$, $\gamma\gamma tt$, $\gamma\gamma Z_{bb}jj$, $h_{\gamma\gamma}h_{bb}Z_{bb}$, $h_{\gamma\gamma}bbbb$
- Secondary backgrounds: $\gamma\gamma bbbb$, $\gamma\gamma Z_{bb}Z_{bb}$

## (Naive) analysis details targeting 20 ab$^{-1}$

- Signature: 4 jets (with $m_{4j}$ < 600 GeV), 2 photons
- Two di-jet systems compatible with a Higgs ($m_{jj} \in$ [105, 140] GeV)
- The di-photon system compatible with a Higgs ($m_{\gamma\gamma} \in$ [125-$M$, 125+$M$] GeV)
- At least $N_b$ *b*-tagged jets

What is the best *M* value?
How many *b*-jets?

# $hhh$ in the $4b2\gamma$ mode: impact of $b$-tagging




[BF, Kim & Lee (PRD`16)]

**Default photon resolution**

- $m_{\gamma\gamma} \in [123, 127]$ GeV

**Significance (in standard dev.)**

$$\sigma \equiv \sqrt{-2 \ln \frac{L(S+B|B)}{L(B|B)}}$$

***b*-tagging**

- 60% working point better
  - → low fake rate crucial
  - → 18% *c*-fake rates kills
- 4 *b*-jets better
  - → $1.5\sigma$ vs $2.5\sigma$ for the SM

# *hhh* in the 4b2$\gamma$ mode: impact of photon resolution


[BF, Kim & Lee (PRD`16)]

Photons with $p_T$ > 20 GeV well reconstructed ( $\sigma/E \sim 0.1/\sqrt{E}$ )

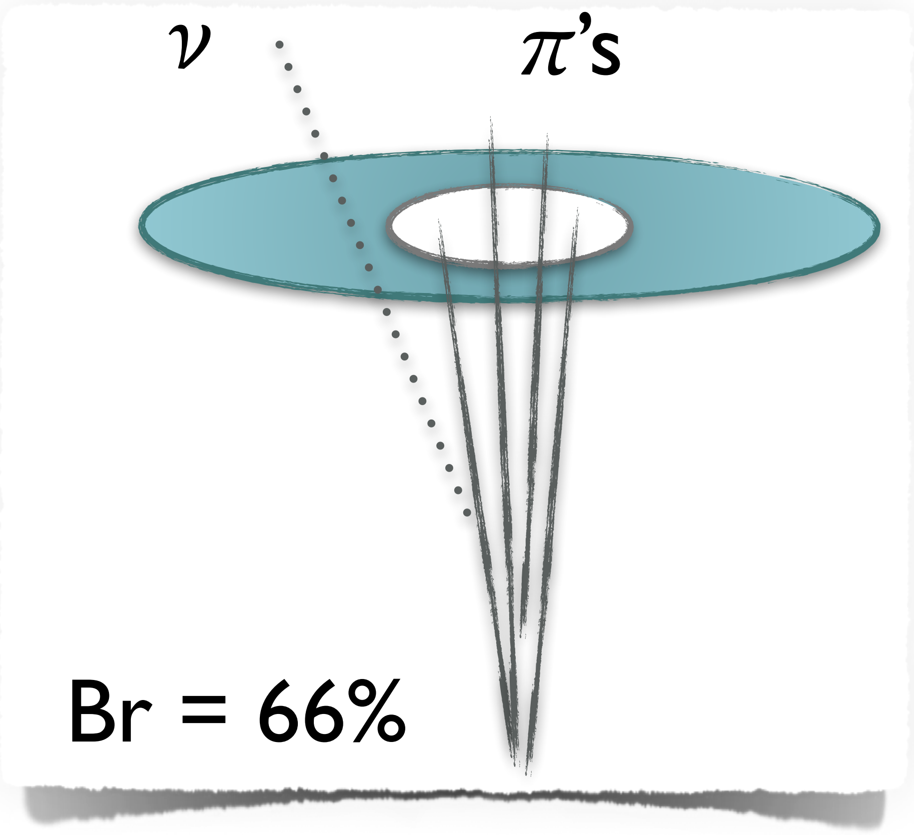
- A large signal efficiency ➝ a not too small $m_{\gamma\gamma}$ window
- A too large $m_{\gamma\gamma}$ window ➝ larger background contamination

The best: a 4 GeV window

# Triple Higgs production in the 4b2$\tau$ mode

## Tau-tagging performance inspired by the LHC

- Efficiency of 50%; mistagging rate of 5%
  - ➙ Narrow jet with no activity around it
  - ➙ The fake rate potentially smaller




## Various background contributions

- $t/W$ backgrounds: $t_\tau t_\tau h_{bb}$, $t_\tau t_\tau Z_{bb}$, $t_\tau t_\tau bb$, $W_\tau W_\tau bbbb$, $tttt$
- $Z_{\tau\tau}/h_{\tau\tau}$ backgrounds: $X_{\tau\tau}bbbb$, $X_{\tau\tau}bbjj$, $X_{\tau\tau}t_h t_h$, $X_{\tau\tau}X_{bb}bb$, $X_{\tau\tau}X_{bb}X_{bb}$
- $hh$ background

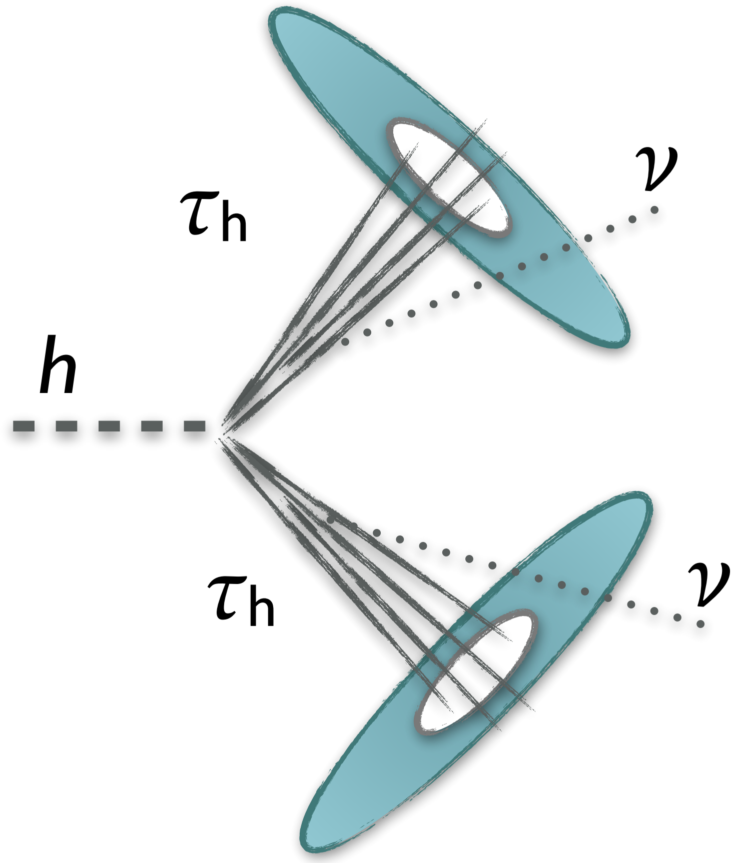
## Analysis details

- Signature: 4 jets, 2 taus
- Di-tau constraints
- Semi-boosted di-$h_{bb}$ system (one boosted, one resolved)
- High-level variables

# *hhh* in the 4b2$\tau$ mode: the di-tau system

## Di-tau reconstruction: lesson learned from *hh* analyses

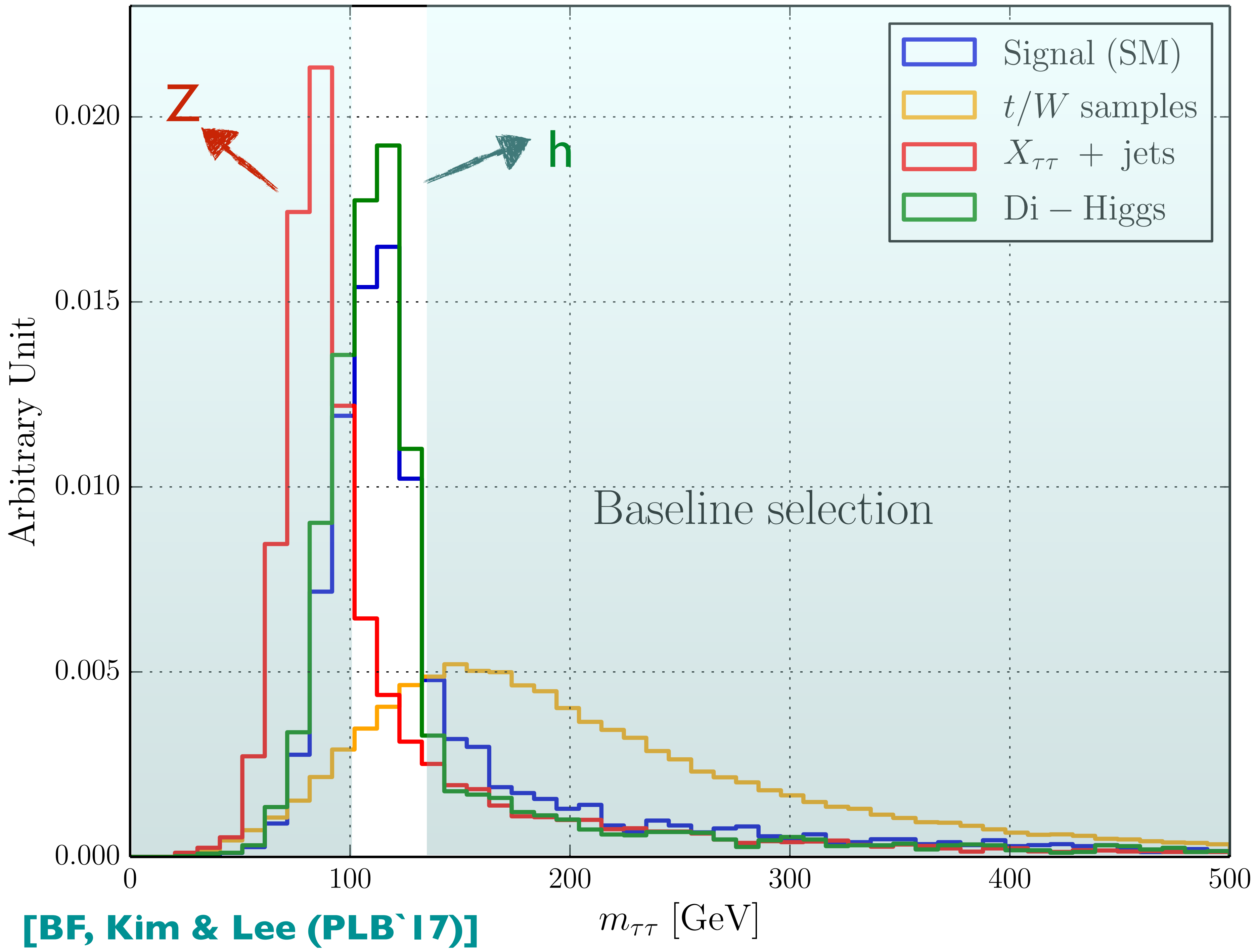
- Dedicated high-level variables ('Higgs-bound invariant mass' and 'true transverse mass')




$$m_{\tau\tau}^2 = \min_{\not p_1 + \not p_2 = \not p} \left[ p(\tau_1^{\rm vis}) + \not p_1 + p(\tau_2^{\rm vis}) + \not p_2 \right]^2$$

if possible: $\left[ p(\tau_i^{\rm vis}) + \not p_i \right]^2 = m_\tau^2$

[ Barr, Gripaios & Lester (JHEP`09) ]
[ Barr, French, Frost & Lester (JHEP`11) ]




[BF, Kim & Lee (PLB`17)]

- A [105, 135] GeV window
  - ➝ Good rejection of Z backgrounds
  - ➝ But signal efficiency of 50%

# $hhh$ in the $4b2\tau$ mode: playing with $h_{bb}$ systems

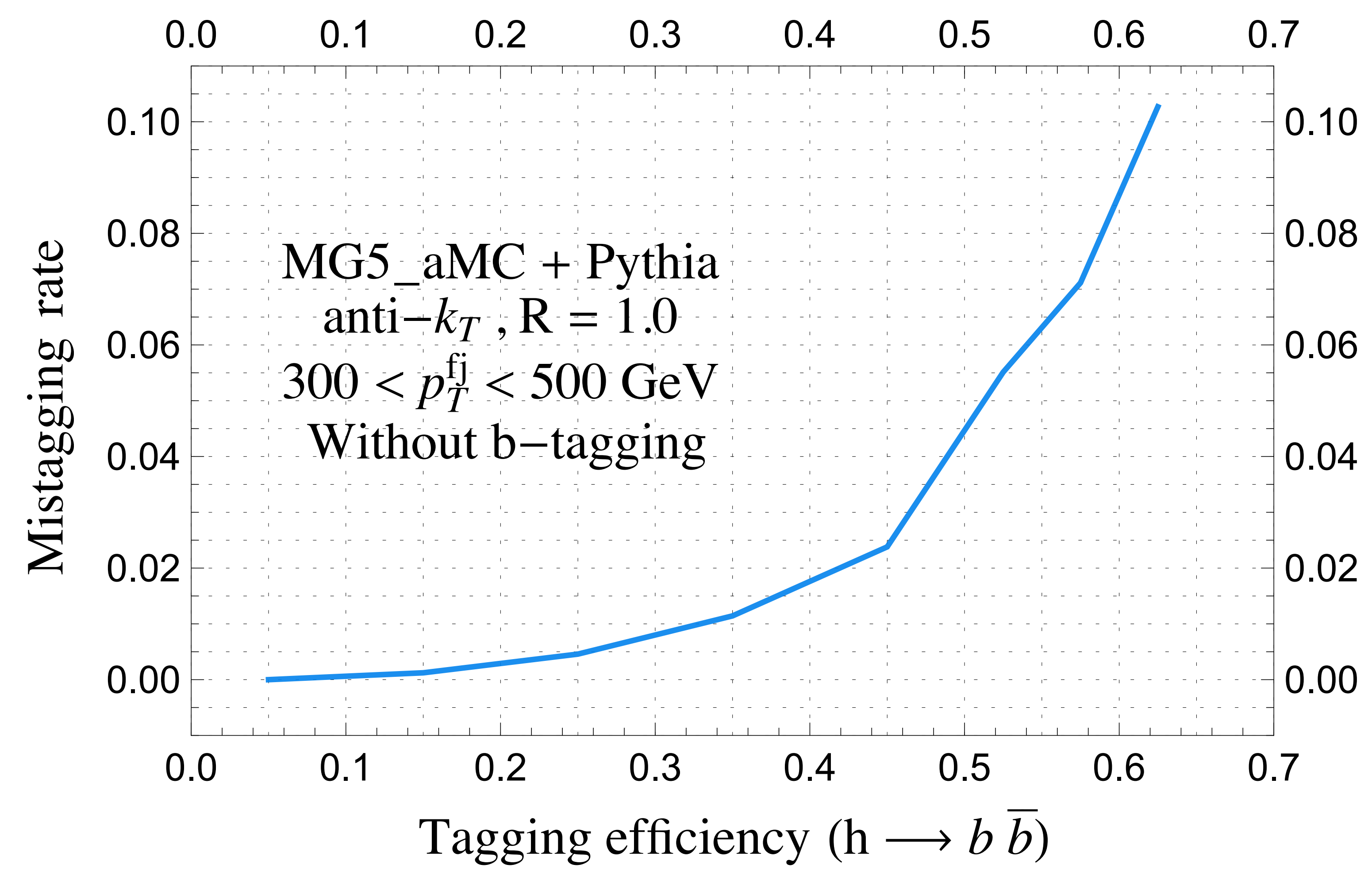
## Boosted Higgs boson

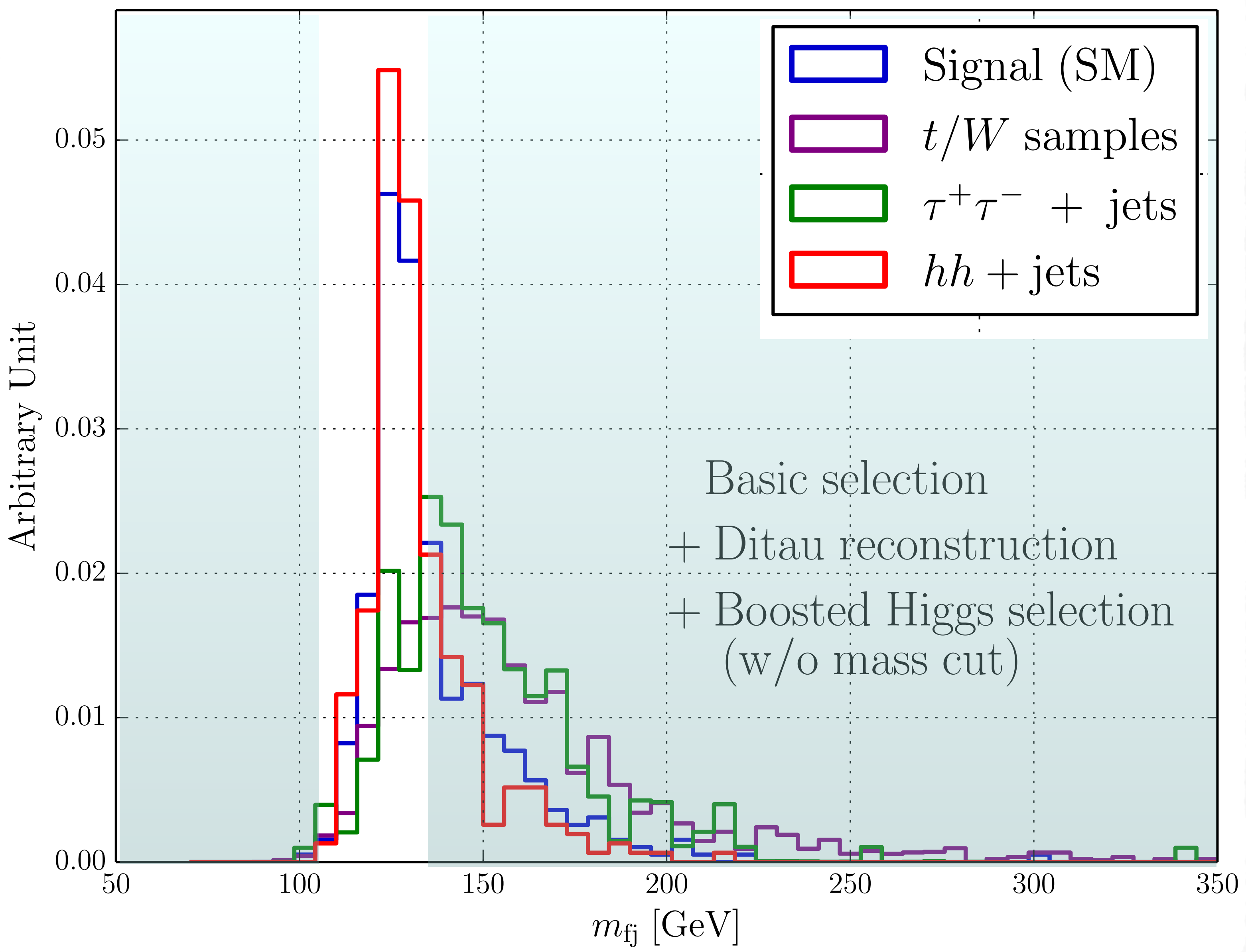
- Usage of the Template Overlap Method
  - ➙ Templates for the fat jet substructure
  - ➙ Include higher-order effects
  - ➙ Efficiency of 40% for a mistagging rate of 2%

[ Almeida, Lee, Perez, Sterman & Sung (PRD`10) ]
[ Almeida, Erdoğan, Juknevich, Lee, Perez & Sterman (PRD`12) ]

- $p_T$ > 300 GeV, double $b$-tag, mass in [105, 135] GeV

Improvements (cost in signal efficiency large)?
See talk by Karkout



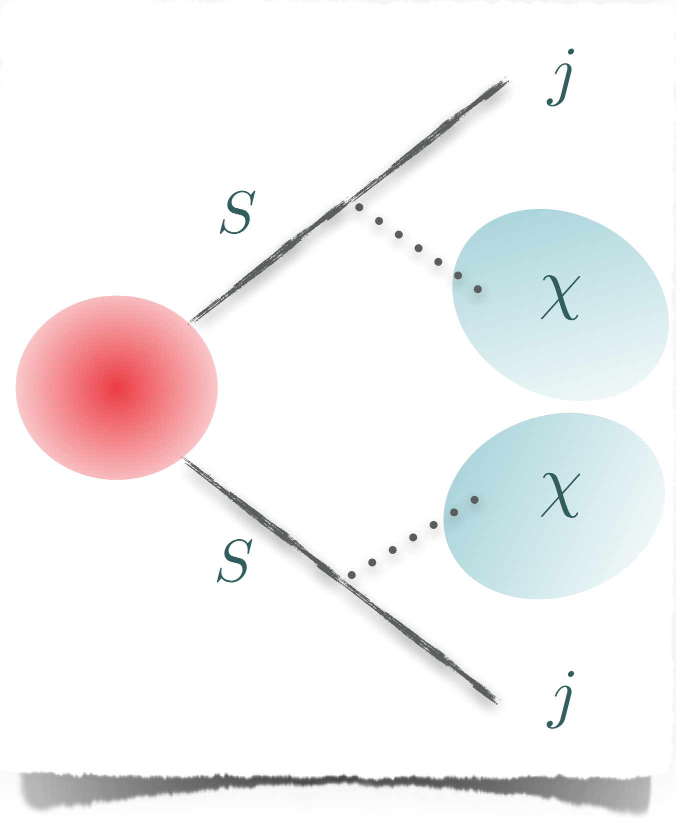

## One resolved Higgs boson

- Single $b$-tag, di-jet mass in [105, 135] GeV

S/B still smaller than 0.01*cf.* the *t/W* background

- Cut on $m_{hhh}$
- Use of the $m_{T2}$ variable introduced in the SUSY context
  - ➞ Decay of states in visible and invisible objects
  - ➞ Minimisation of the maximum transverse mass of two branches

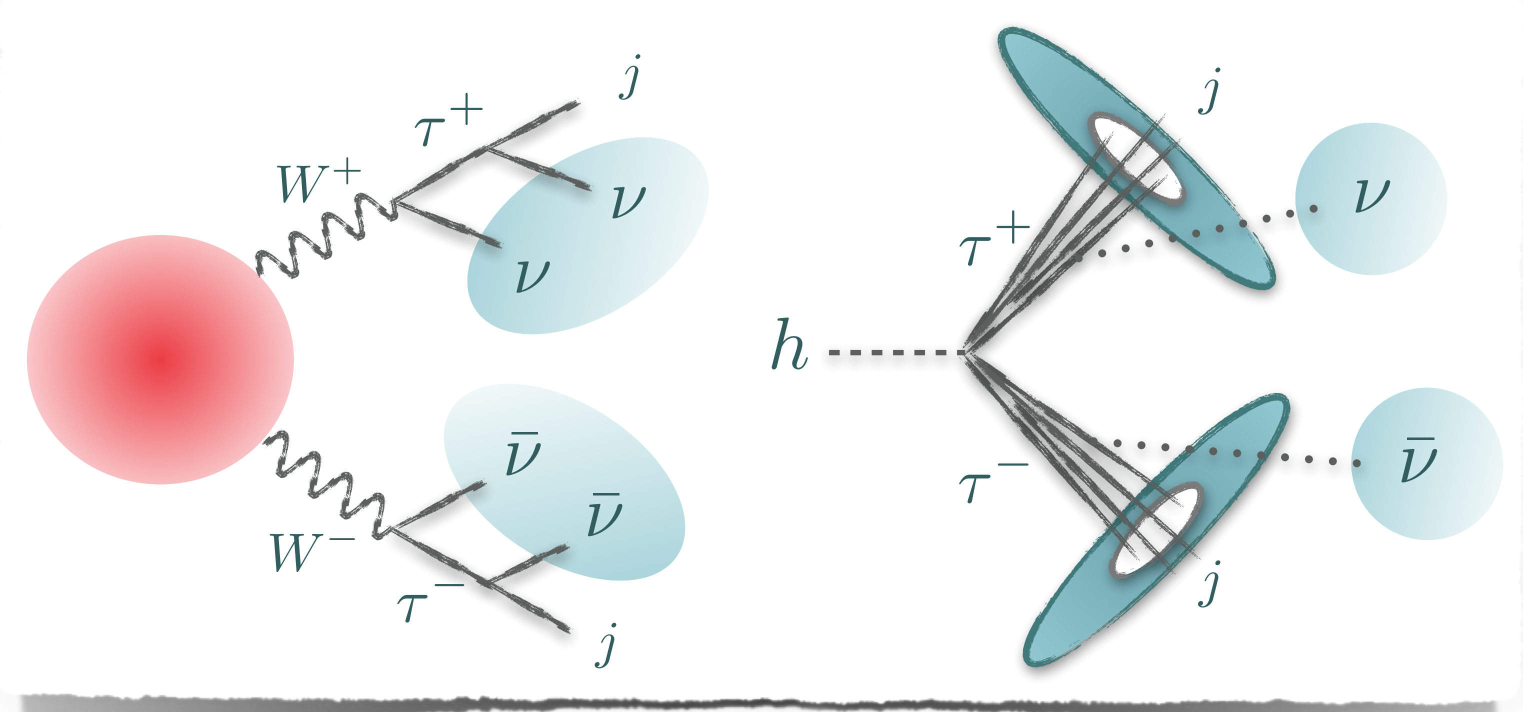
$$m_{T2} = \min_{\not{p}_T^{(1)}+\not{p}_T^{(2)}=\not{p}_T} \max\left[m_T(j_1,\not{p}_T^{(1)},m_\chi), m_T(j_2,\not{p}_T^{(2)},m_\chi)\right]$$

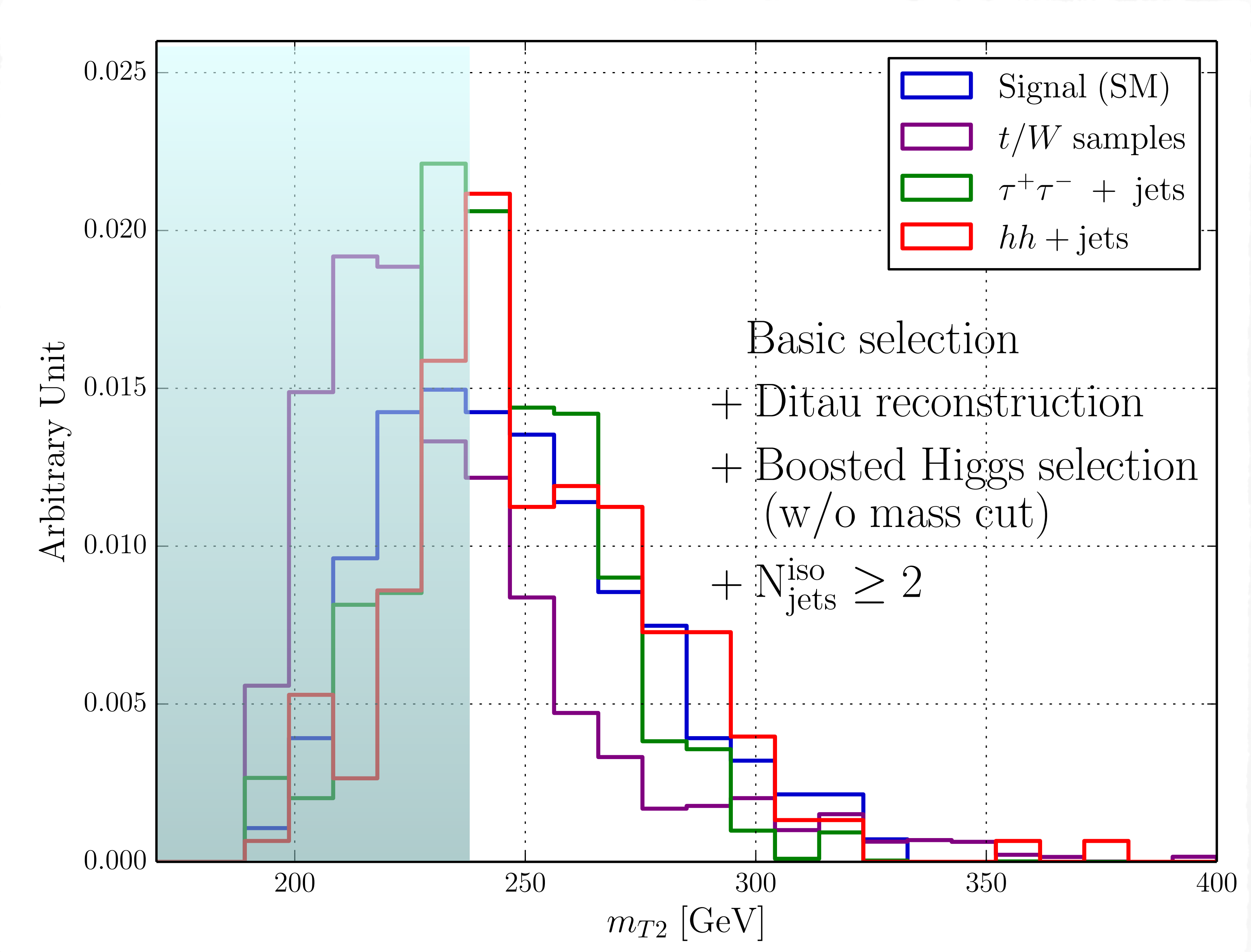



[ Lester & Summer (PLB`99) ]
[ Barr, Lester & Stephens (JPG`03) ]

  - ➞ $m_\chi$ ≡ an estimation of the invisible state mass

- Use of the dependence of the edge of the $m_{T2}$ spectrum on $m_\chi$
  - ➞ Sharp rise with $m_\chi$ above its true mass
  - ➞ Optimisation

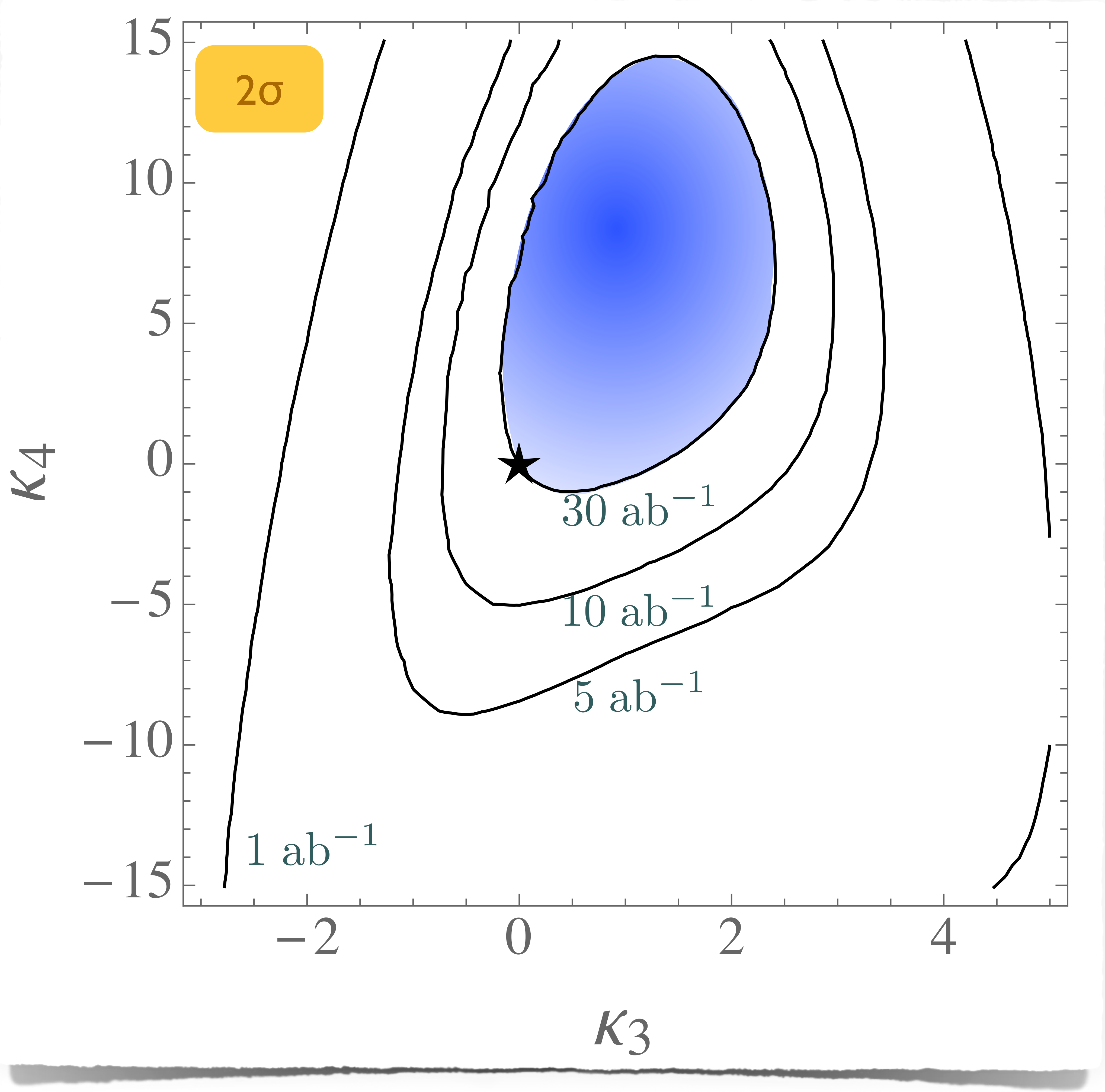


# 2$\sigma$ on the SM with 30 ab$^{-1}$

The $4b2\tau$ mode as a probe of new physics

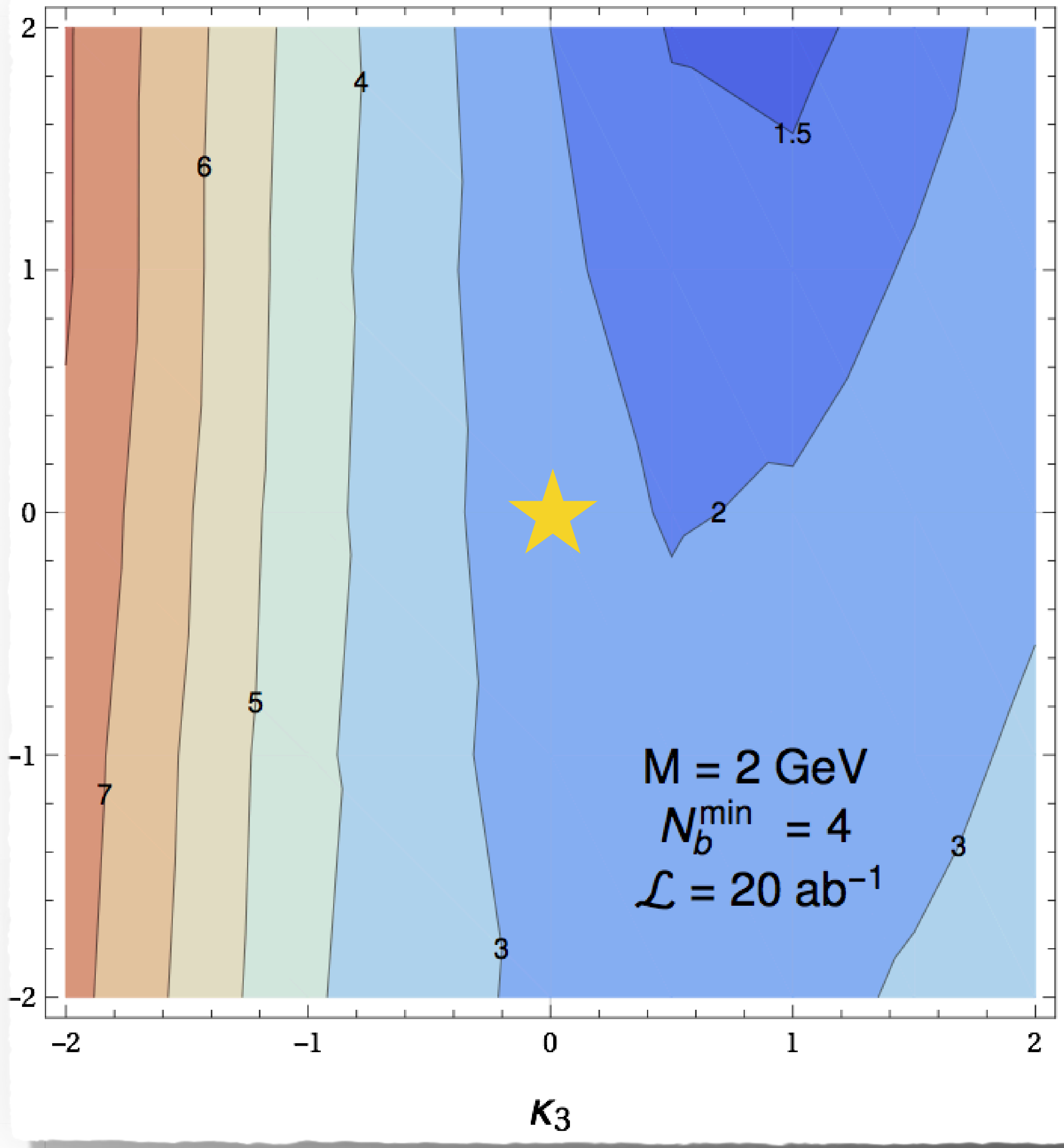
- Complicated analysis required
- Negative $\kappa_3$ severely constrained (larger rates)
- If $\kappa_3$ constrained otherwise, then potential $\kappa_4$ constraints
- An important fraction of the parameter space not probed
  ➞ Destructive interferences

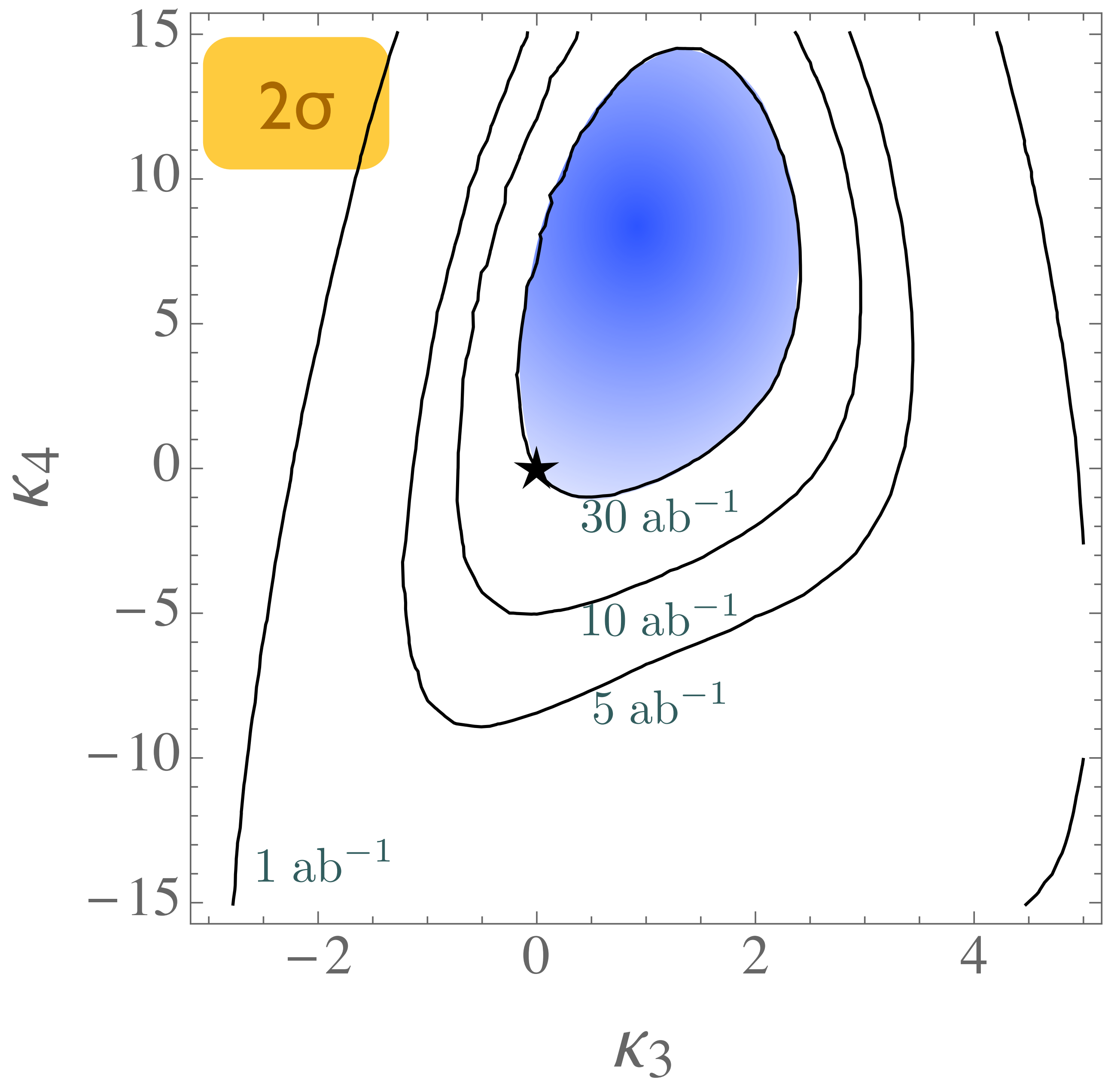



Potential for combination with the $4b2\gamma$ and $6b$ modes

- Also with more modern techniques (boosted Higgs)
- Also with better $b$-tagging performance

# Summary




## Strong constraints on the $\varkappa$ parameters obtainable from *hhh* production

- Especially for negative $\varkappa_3$
- The SM point reachable at about 2σ for both channels

## Outlook

- Revisiting studies with a modern perspective
- What could be done at 13 TeV?