di-Higgs production at 100 TeV:

the search for a golden channel

Andreas Papaefstathiou,
CERN

HPPC, MITP, Mainz
27-30 April 2015

the plan

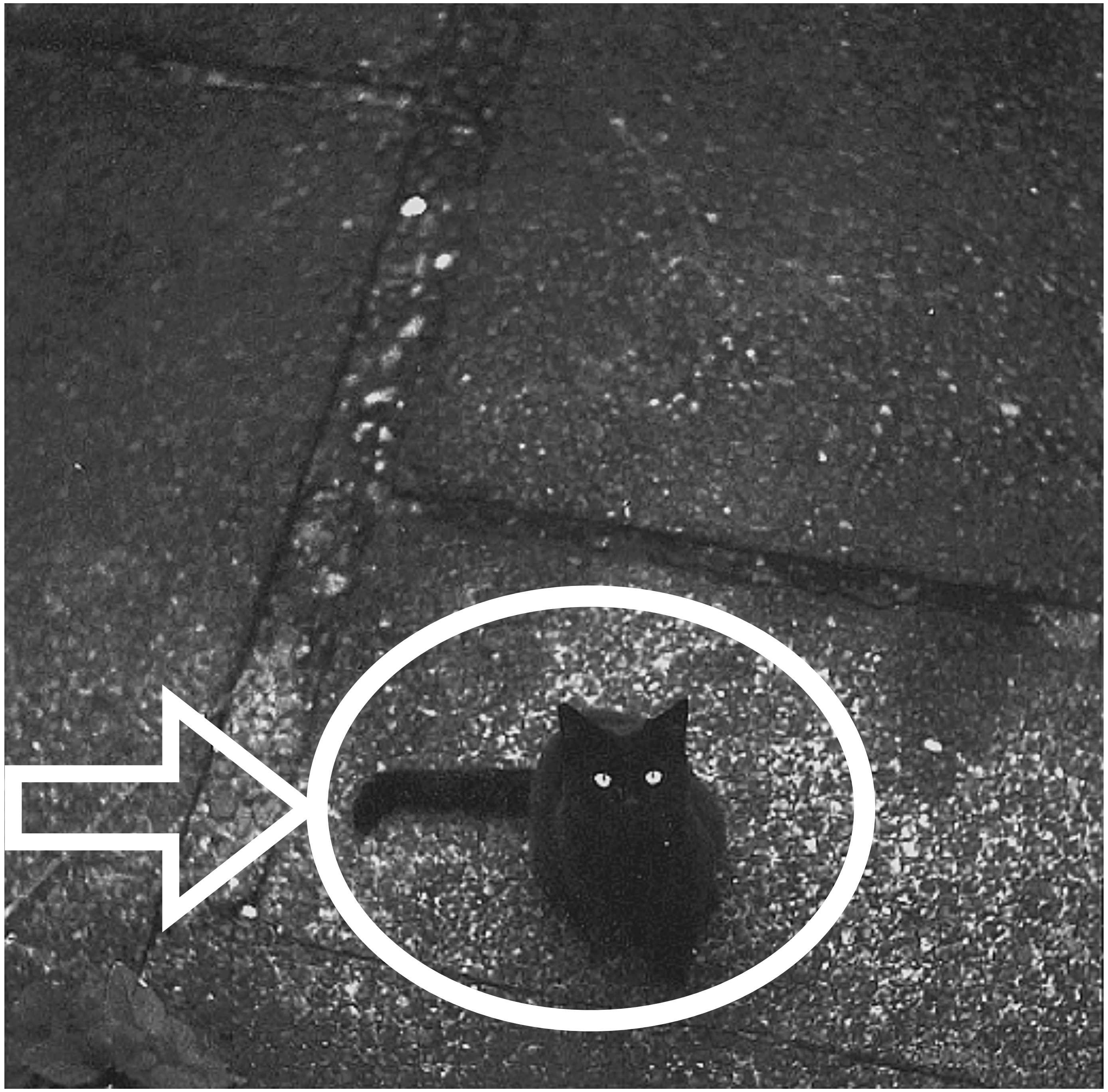
- **motivation**: has already been provided!

- describe what the FCC-hh is,

  (contrasting with high lumi.-LHC),

- consider channels for di-Higgs production at 100 TeV.

searching for **di-Higgs production** is like looking for **a black cat in a coal cellar**:



basic questions:

1. can a **future 100 TeV pp** collider **in principle** contribute to the investigation of **di-Higgs** production?

[note: will not discuss extraction of couplings here.]

2. furthermore: can it **compete/improve** on HL-LHC for di-Higgs?

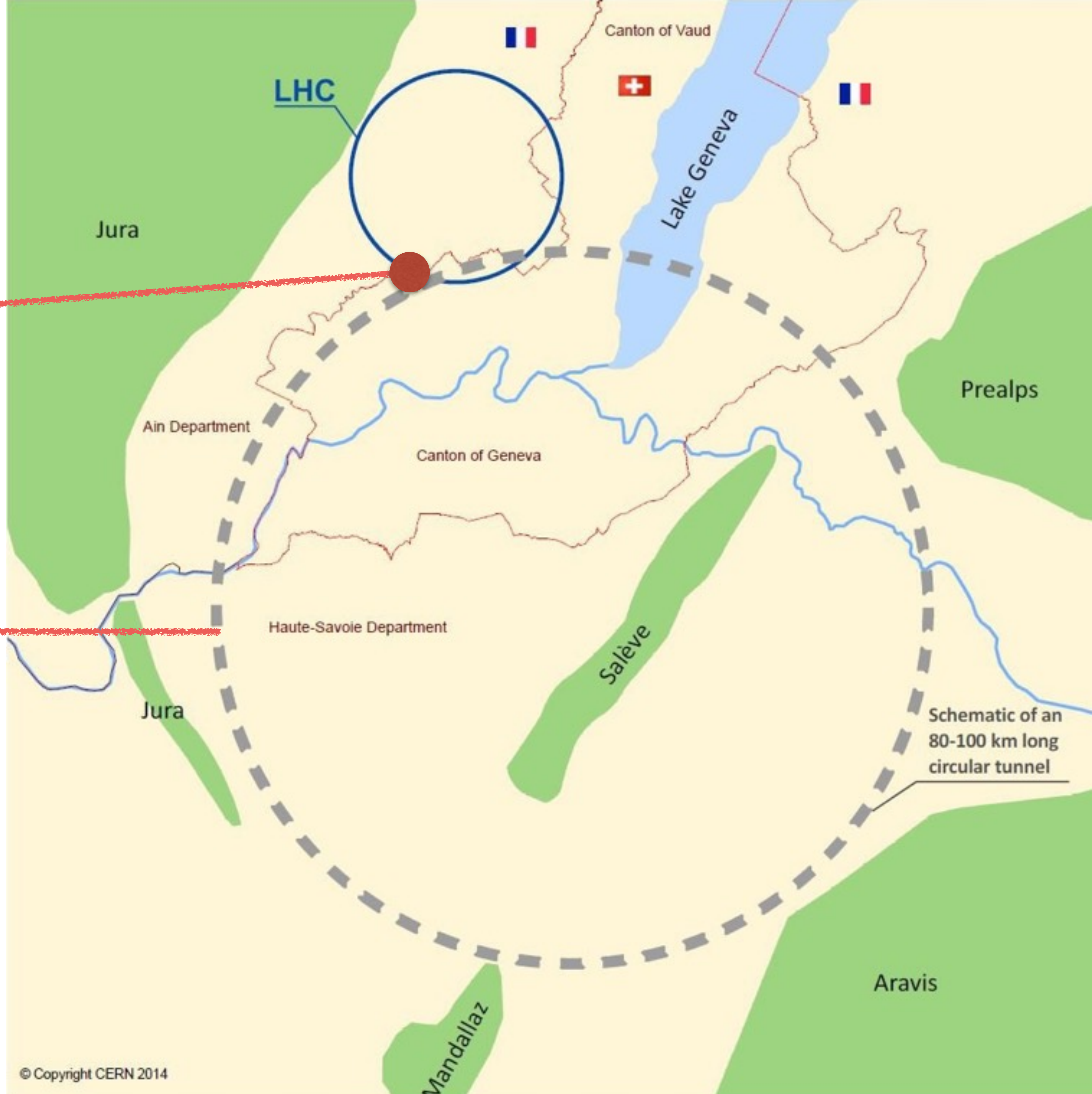
3. what are the **basic requirements** for future colliders/detectors to achieve this?

FCC = **F**uture **C**ircular **C**ollider

- [hopefully: provisional name!]
- FCC-hh = hadron-hadron.
- “an ambitious post-LHC accelerator project”, pp C.O.M. energy: 100 TeV.
- conceptual design report to be published before end of 2018.
- potential materialisation in the 40s-50s? [my guess].

CERN

FCC ring



FCC-hh VS HL-LHC
Round 1: data

attribute	HL-LHC	FCC-hh
pp centre-of-mass energy	14 TeV	100 TeV
circumference	26.7 km	100 (83) km
stored beam energy	0.694 GJ	8.4 (7.0) GJ
integrated luminosity [over lifetime]	3 ab^{-1}	3/10/30 ab^{-1}

what about detector performance?

- at this point, the attributes of the FCC-hh detectors are left to the **phenomenologist's imagination**.

- assume:

    - **minimum performance**: HL-LHC, [**1412.7154** Barr, Dolan, Englert, Ferreira de Lima, Spannowsky, **1504.04621** AP, from ATL-PHYS-PUB-2013-009, ATL-PHYS-PUB-2013-004]

    - **ideal performance**: 100% efficiencies, no smearing of momenta. [**1504.04621** AP]

HL-LHC parametrization

[**1412.7154** Barr, Dolan, Englert, Ferreira de Lima, Spannowsky, **1504.04621** AP]

- efficiencies:

$$\epsilon(j) = 0.75 + p_t/150\ \text{GeV}$$

$$\epsilon(\gamma) = 0.76 - 1.98\,\text{exp}(-p_t/16.1\ \text{GeV})$$

$$\epsilon(e) = 0.85 - 0.191\,\text{exp}(1 - p_t/20\ \text{GeV})$$

$$\epsilon(\mu) = 0.97\ (|\eta| > 0.1),\ 0.54\ (|\eta| < 0.1)$$

- mistagging:

$$p(j \to X) = \alpha_X\,\text{exp}(-\beta_X p_t/\text{GeV})$$

$$\alpha_\gamma = 0.0093,\ \beta_\gamma = 0.036$$

$$\alpha_\ell = 0.0048,\ \beta_\ell = 0.035$$

- smearing: [ATL-PHYS-PUB-2013-009, ATL-PHYS-PUB-2013-004].

ideal parametrization

- efficiencies: [**1504.04621** AP]

$\epsilon(j)$

$\epsilon(\gamma)$

$\epsilon(e)$ $= 1$

$\epsilon(\mu)$

- mistagging: [turns out to be not so significant]

$$p(j \to X) = \alpha_X \exp(-\beta_X p_t/\text{GeV})$$
$$\alpha_\gamma = 0.0093,\ \beta_\gamma = 0.036$$
$$\alpha_\ell = 0.0048,\ \beta_\ell = 0.035$$

- ~~smearing: [ATL-PHYS-PUB-2013-009, ATL-PHYS-PUB-2013-004].~~

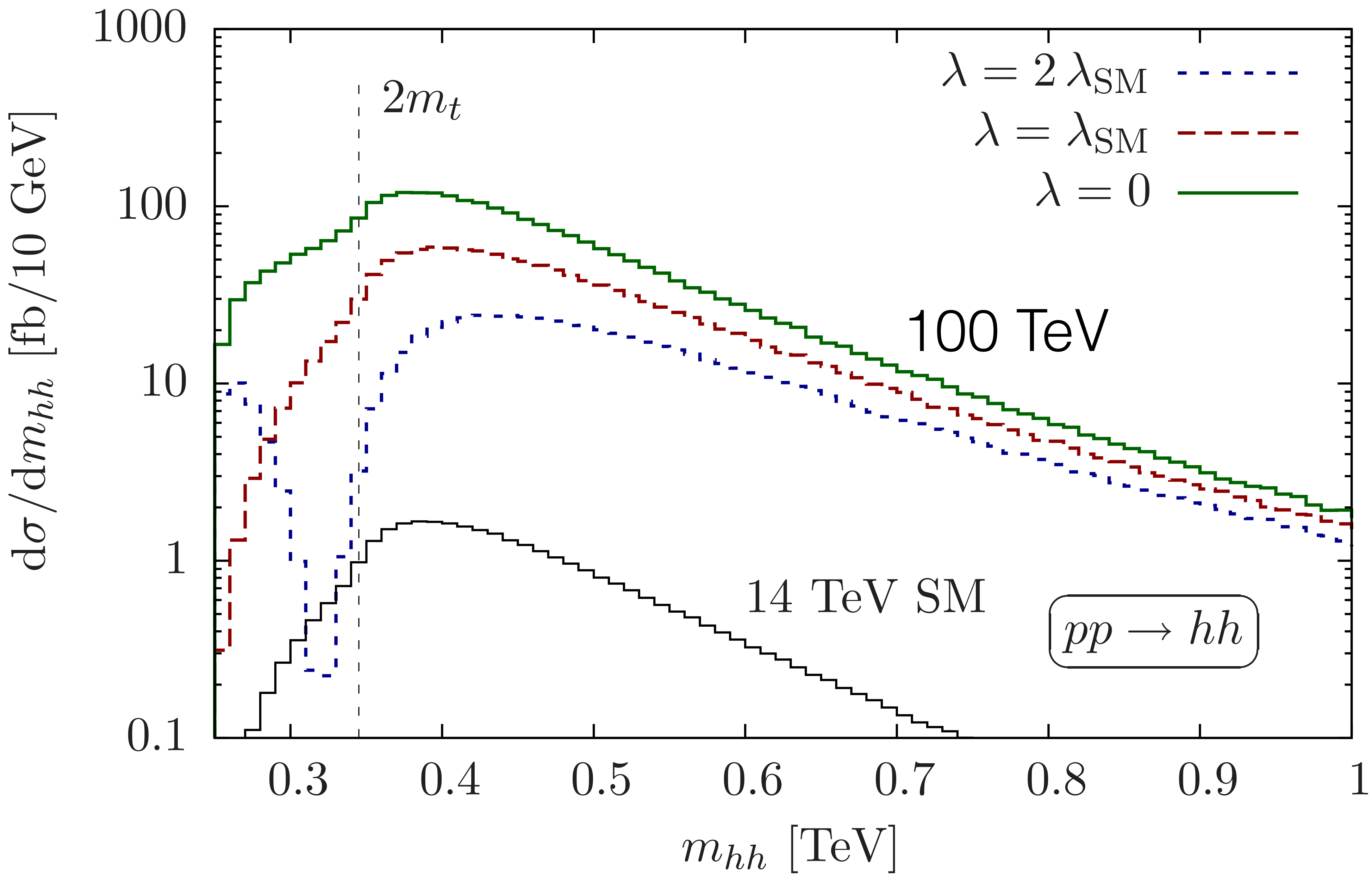
FCC-hh VS HL-LHC
Round 2: di-Higgs Physics

- here: focus on **gluon-initiated** di-Higgs.
- **VBF & associated production** will be important too.
- in the SM: σ(**hh@100 TeV**) ~ **40x** σ(**hh@14 TeV**):

~**1600 fb** versus ~**40 fb,** [NNLO in low-energy thm]**.**

- backgrounds, 14 TeV to 100 TeV:
  - ~**40-50x** if gluon-initiated,
  - ~**10-20x** if qq-initiated.

hh distributions: 14→100 TeV

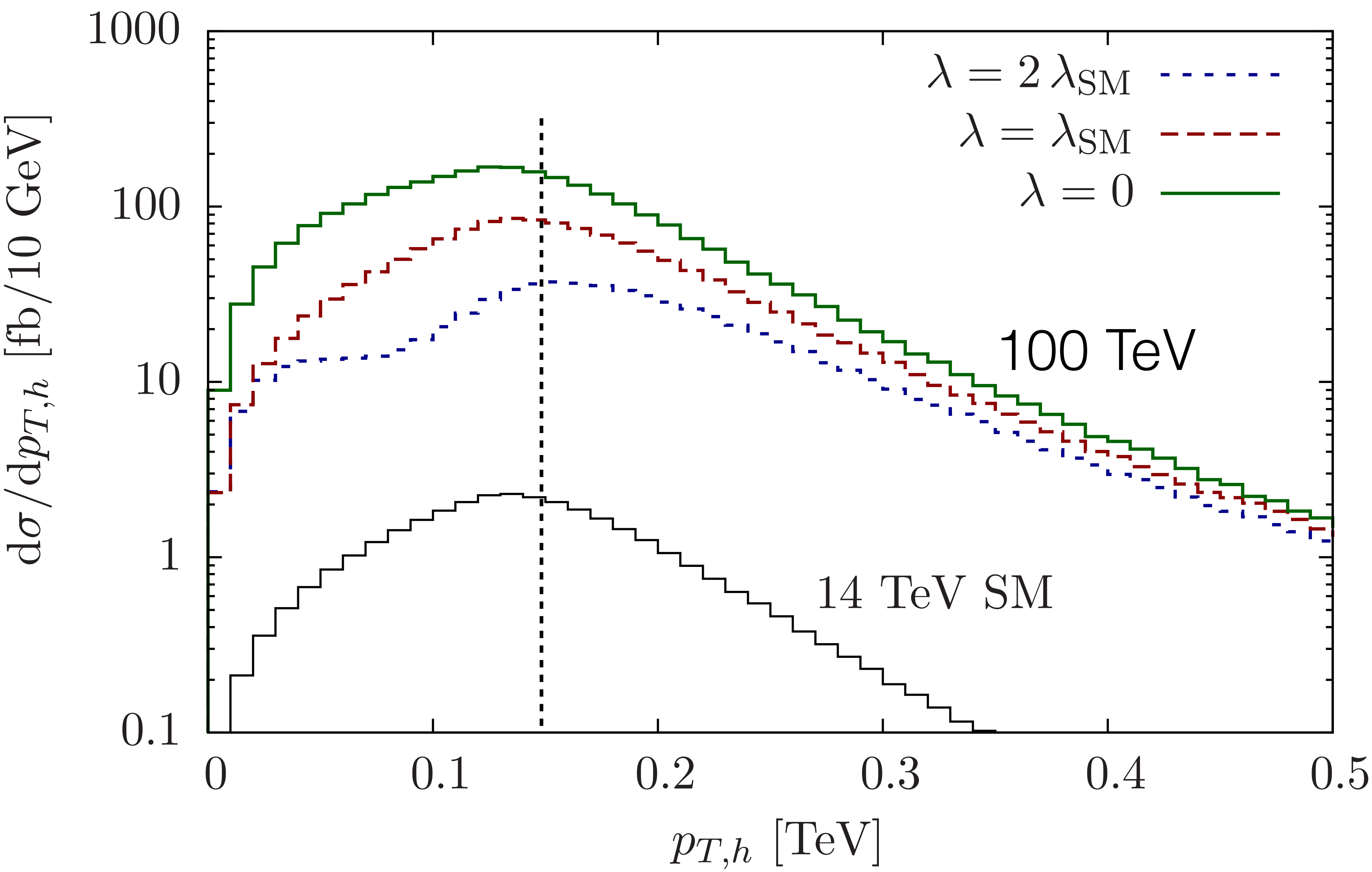


[**1412.7154** Barr, Dolan, Englert, Ferreira de Lima, Spannowsky]

[see also **1502.00539**, Azatov, Contino, Panico, Son]

- distributions have considerably longer tails,
- broadly similar to 14 TeV case: $\mathbf{m_{hh}}$ peak ~ 400 GeV

hh distributions: 14→100 TeV



[**1412.7154** Barr, Dolan, Englert, Ferreira de Lima, Spannowsky]

[see also **1502.00539**, Azatov, Contino, Panico, Son.]

- $\mathbf{p_{T,h}}$ peak ~ $\mathbf{m_t}$.

hh@14 vs hh@100 TeV

- **bottom line:**
    - at 100 TeV: **hh** signal has longer tails,
    - higher cross sections: assume σ_{total} ~1638 fb at pp@100 TeV.
    - physics of the "self-coupling Higgs sector" still lies broadly in the same phase space regions.
    - versus backgrounds: **not** clear if translating a 14 TeV analysis to 100 TeV would yield similar results.

ggF hh final states

~~$\mathrm{BR}[(b\bar{b})(b\bar{b})] = 33.3\%$~~ → large QCD bkgs.

$\mathbf{BR}[(b\bar{b})(WW)] = 24.8\%$

$\mathbf{BR}[(b\bar{b})(WW) \Rightarrow (b\bar{b}) 2\ell + E^{\mathrm{miss}}] = 1.7\%$

$\mathbf{BR}[(b\bar{b})(\tau\bar{\tau})] = 7.29\%$

$\mathbf{BR}[(b\bar{b})(\tau\bar{\tau}) \Rightarrow (b\bar{b}) 2\ell + E^{\mathrm{miss}}] = 0.9\%$

$\mathrm{BR}[(b\bar{b})(\mu\bar{\mu})] = 0.025\%$

$\mathbf{BR}[(WW)(WW)] = 4.62\%$

$\mathbf{BR}[(WW)(WW) \Rightarrow \ell^{\pm}\ell^{\pm}\ell'^{\mp} + E^{\mathrm{miss}} + j] = 0.016\%$

$\mathrm{BR}[(b\bar{b})(\gamma\gamma)] = 0.263\%$

$\mathbf{BR}[(b\bar{b})(ZZ)] = 3.05\%$

$\mathbf{BR}[(b\bar{b})(ZZ) \Rightarrow (b\bar{b}) 4\ell] = 0.016\%$

$\mathrm{BR}[(b\bar{b})(Z\gamma)] = 0.178\%$

$\mathrm{BR}[(b\bar{b})(Z\gamma) \Rightarrow (b\bar{b}) 2\ell + \gamma] = 0.013\%$

hh final states

~~$\mathrm{BR}[(b\bar{b})(b\bar{b})] = 33.3\%$~~

$\mathrm{BR}[(b\bar{b})(WW) \to (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 1.7\%$

$\mathrm{BR}[(b\bar{b})(\tau\bar{\tau}) \to (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 0.9\%$

$\mathrm{BR}[(b\bar{b})(\mu\bar{\mu})] = 0.025\%$

$\mathrm{BR}[(WW)(WW) \to \ell^{\pm}\ell^{\pm}\ell'^{\mp} + E^{\mathrm{miss}} + j] = 0.016\%$

$\mathrm{BR}[(b\bar{b})(\gamma\gamma)] = 0.263\%$

$\mathrm{BR}[(b\bar{b})(ZZ) \to (b\bar{b}) + 4\ell] = 0.016\%$

$\mathrm{BR}[(b\bar{b})(Z\gamma) \to (b\bar{b}) + 2\ell + \gamma] = 0.013\%$

$$hh \to (b\bar{b})(\gamma\gamma)$$

[100 TeV: **1412.7154** Barr, Dolan, Englert, Ferreira de Lima, Spannowsky, **1502.00539**, Azatov, Contino, Panico, Son, see also relevant talk at "Higgs & BSM at 100 TeV" workshop: He, Ren, Yao and **1308.6302**, Yao. 14 TeV: **hep-ph/0310056**, Baur, Plehn, Rainwater, **1212.5581**, Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira]

- the "most investigated" at 100 TeV: rare (**0.263%**) but clean,
- good mass reconstruction from **γγ**: significant at HL-LHC and perhaps even more so at pp@100 TeV.
- could be the "golden" channel for **hh @ 100 TeV**, for 3 ab^{-1}:
    - He, Ren, Yao: **S ~ 420, B ~ 650,**
    - Barr, Dolan, Englert, Ferreira de Lima, Spannowsky: **S ~ 31.8, B ~ 88,**
    - Azatov, Contino, Panico, Son: **S ~ 279, B ~ 339.**
- **[differences due to: cuts (crucially $M_{\gamma\gamma}$) + detector effect simulation + event generation + more…]**

hh final states

~~$\mathrm{BR}[(b\bar{b})(b\bar{b})] = 33.3\%$~~

$\mathrm{BR}[(b\bar{b})(WW) \to (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 1.7\%$

$\mathrm{BR}[(b\bar{b})(\tau\bar{\tau}) \to (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 0.9\%$

$\mathrm{BR}[(b\bar{b})(\mu\bar{\mu})] = 0.025\%$

$\mathrm{BR}[(WW)(WW) \to \ell^{\pm}\ell^{\pm}\ell'^{\mp} + E^{\mathrm{miss}} + j] = 0.016\%$

✓ $\mathrm{BR}[(b\bar{b})(\gamma\gamma)] = 0.263\%$

$\mathrm{BR}[(b\bar{b})(ZZ) \to (b\bar{b}) + 4\ell] = 0.016\%$

$\mathrm{BR}[(b\bar{b})(Z\gamma) \to (b\bar{b}) + 2\ell + \gamma] = 0.013\%$

$$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$$

- branching ratio (incl. taus) = **0.016%** (!),
- for **σ(100 TeV) ~ 0.26 fb**. (c.f. σ(14 TeV) ~ 0.006 fb)
- ~ 780 events at 3000/fb.
- can reconstruct **hh** final state: sensitivity to new effects in the process over a wide range of phase space.

$$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$$

- **backgrounds:**

$t\bar{t}h,\ t\bar{t}Z,\ b\bar{b}h,\ ZZh,\ ZZZ, b\bar{b}ZZ$ (**irreducible**),

ZZ, hZ (**reducible**, 2 mis-tagged b-jets),

$W^{\pm}Zh,\ W^{\pm}ZZ$ (**reducible**, 1 mis-tagged lepton),

[+ > 1 mis-tagged leptons: will **not** consider.]

- **Monte Carlo simulation:**

  - signal (LO): OpenLoops + Herwig++,

  [**1401.0007** AP, Maierhoefer]

  - backgrounds (NLO): MG5/aMC@NLO + Herwig++.

  [**1405.0301**, Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro]

$$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$$

before analysis

channel	σ(100 TeV) (fb)
$\mathbf{hh} \to (b\bar{b})(\ell^+\ell^-\ell'^+\ell'^-)$	0.26
$\mathbf{t\bar{t}h} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	193.6
$\mathbf{t\bar{t}Z} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	256.7
$\mathbf{b\bar{b}h} \to b\bar{b}(4\ell)$, $p_{T,b} > 15$ GeV	0.26
$\mathbf{ZZh} \to (4\ell)(b\bar{b})$	0.12
$\mathbf{ZZZ} \to (4\ell)(b\bar{b})$	0.53
$\mathbf{ZZ} \to (4\ell)$+mis-tagged $b\bar{b}$	781.4
$\mathbf{hZ} \to (4\ell)$+mis-tagged $b\bar{b}$	68.2
$\mathbf{W} \pm \mathbf{ZZ} \to (\ell\nu_\ell)(\ell^+\ell^-)(b\bar{b})$ + mis-tagged ℓ	7.5
$\mathbf{W^\pm Zh} \to (\ell\nu_\ell)(\ell^+\ell^-)(b\bar{b})$ +mis-tagged ℓ	1.4

note: $\ell \in \{e, \mu\}$

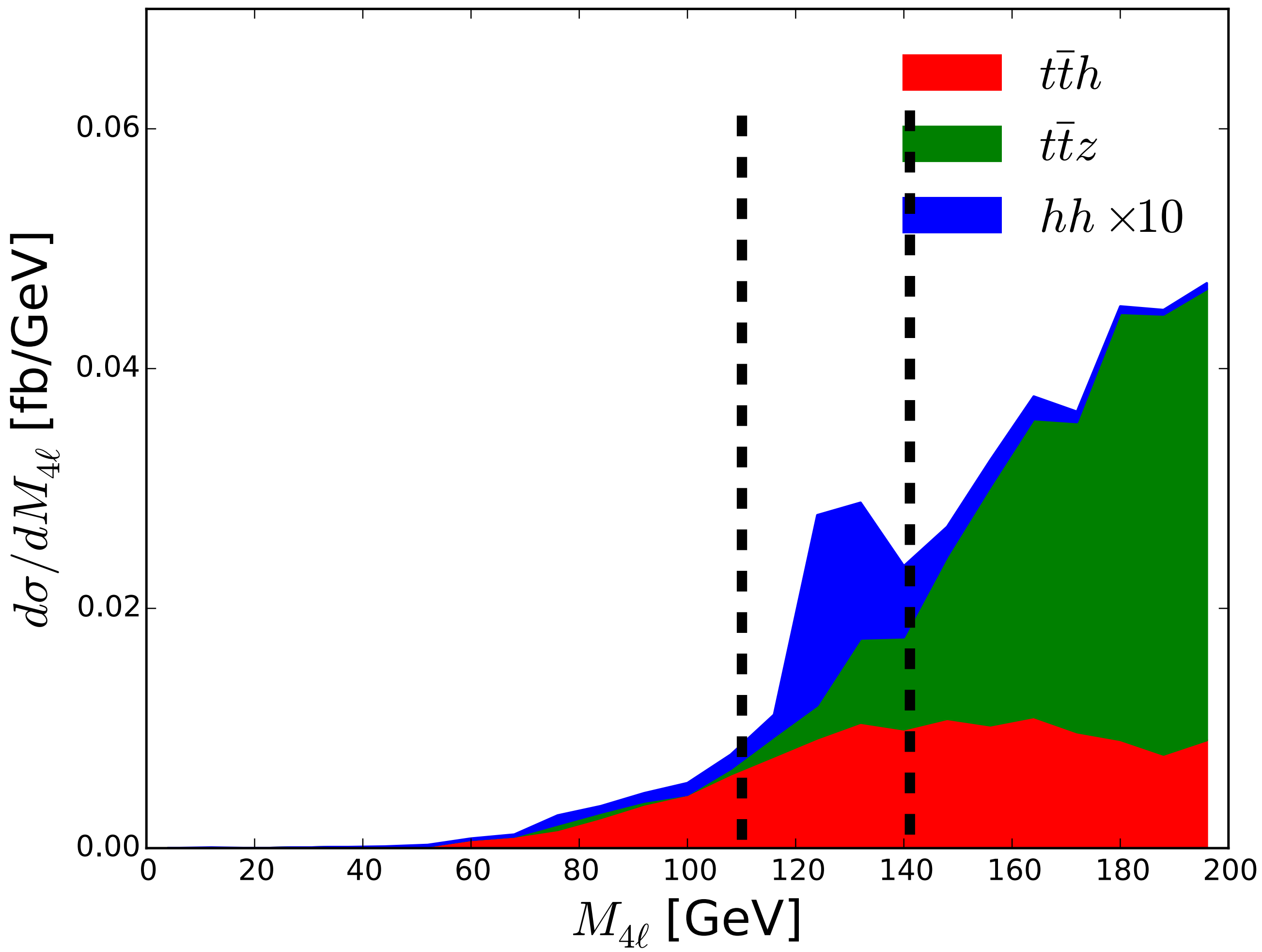
$$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$$

- a simple analysis, asking for:
  - 4 isolated leptons with p_T > (35, 30, 25, 20) GeV,
  - two R=0.4 anti-k_T b-jets with p_T > 40 GeV,

  } crucial!
  - MET < 100 GeV,
  - veto events with two on-shell Zs,
  - ΔR(lepton, lepton) < 1.0,
  - construct $\mathbf{M_{bb}}$, $\mathbf{M_{4l}}$ [and after cuts: $\mathbf{M_{bb4l}}$].

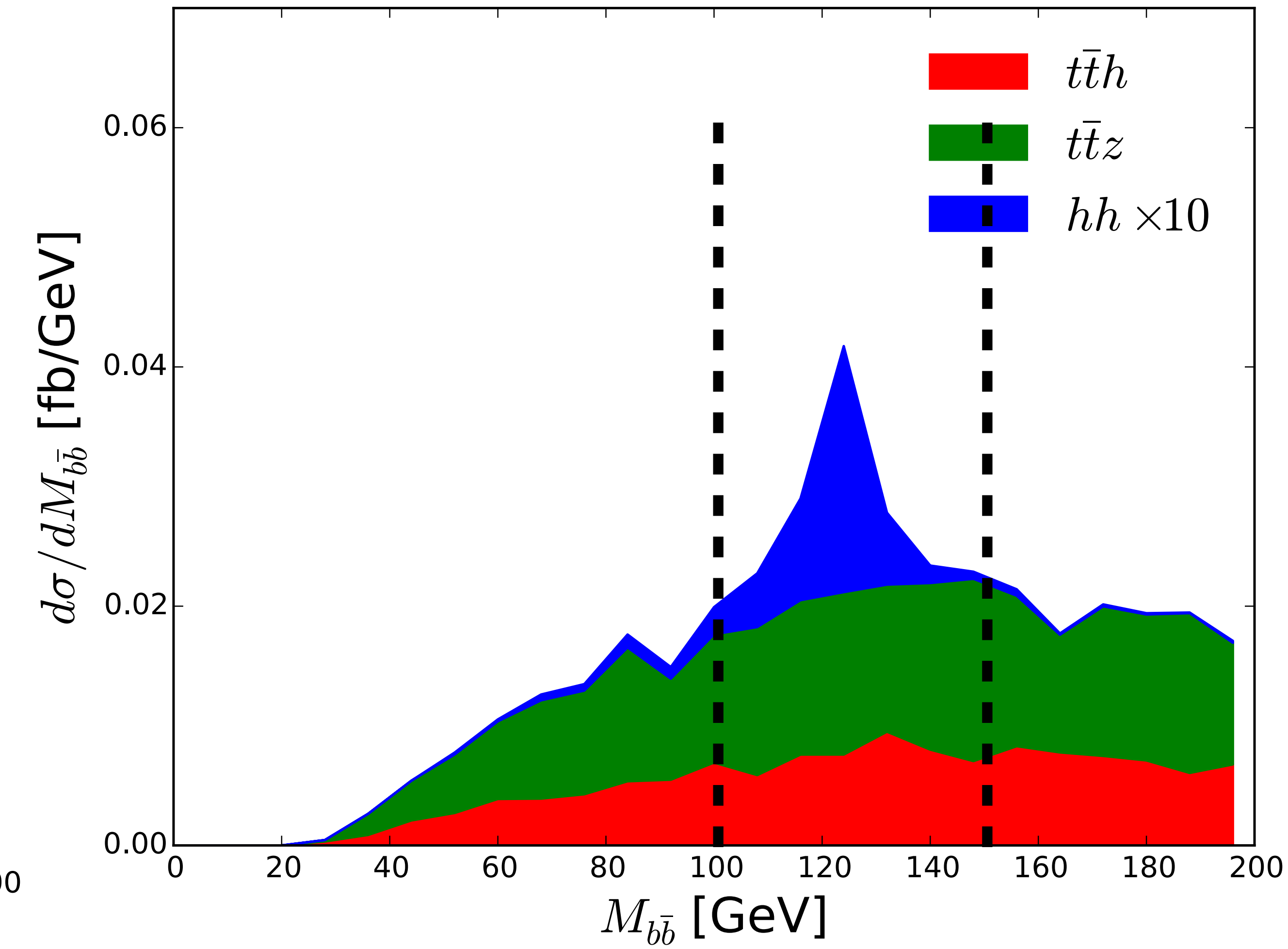
$$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$$

M_{4l}



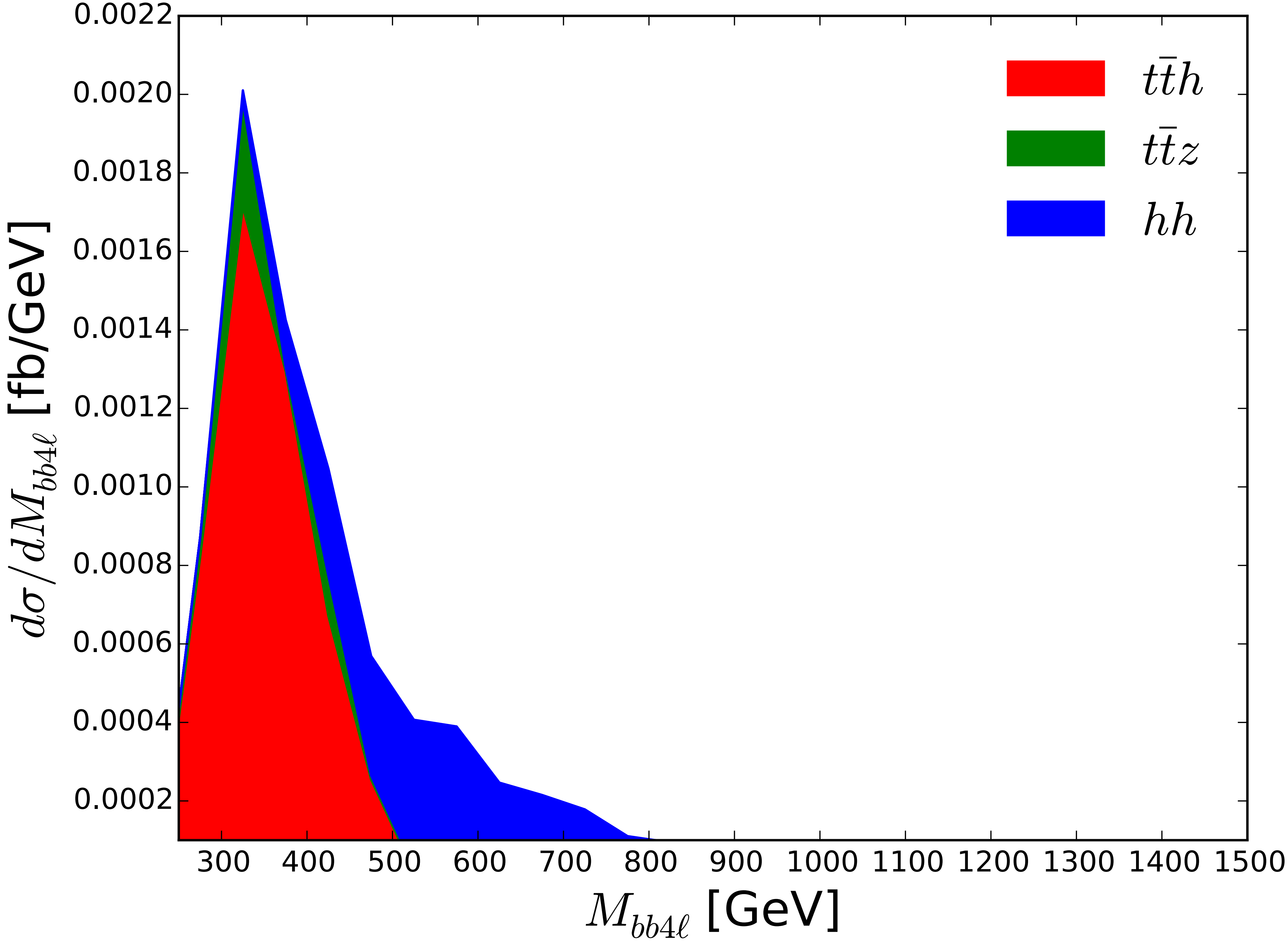
[110, 140] GeV

M_{bb}



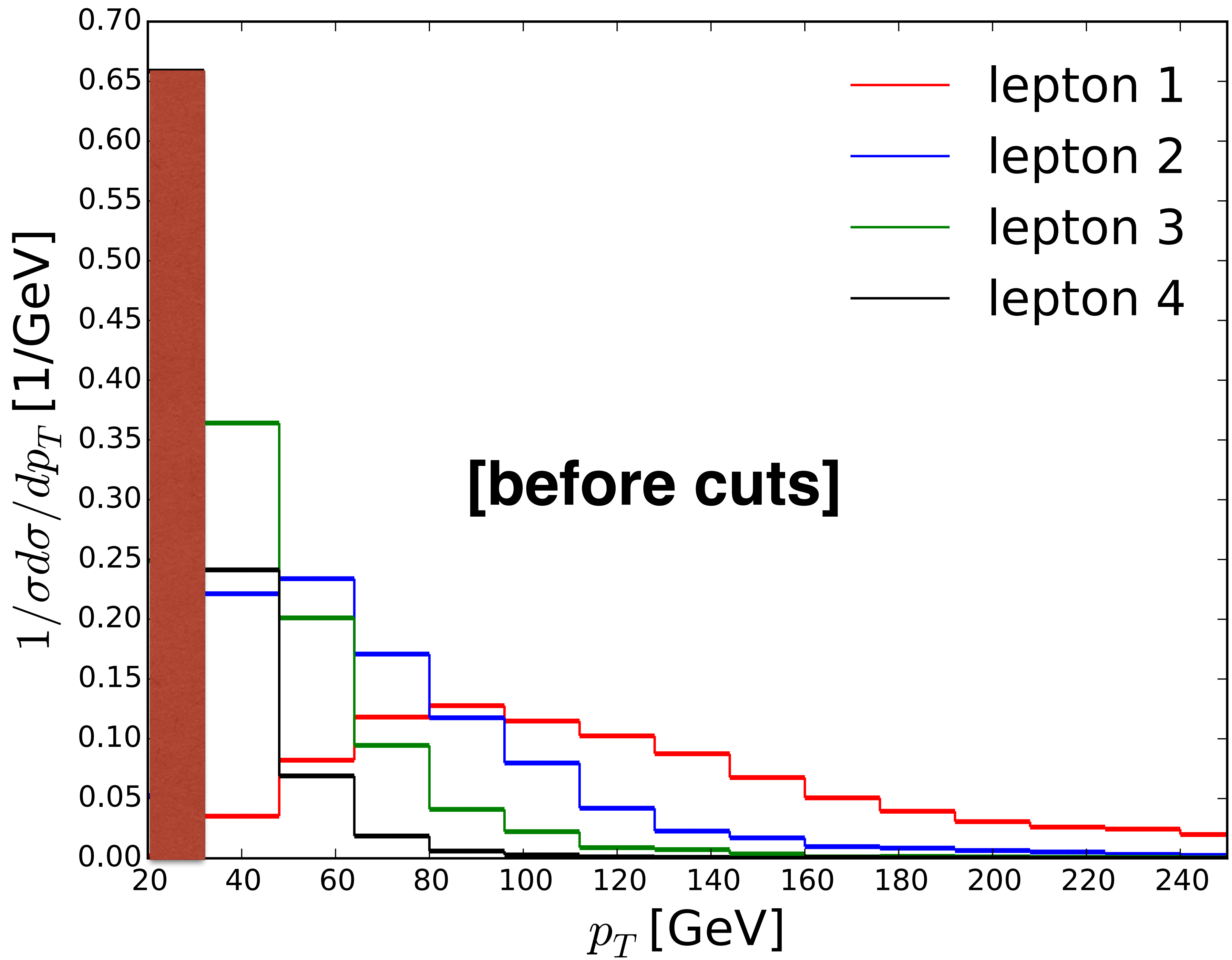
[100, 150] GeV

$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$



$$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$$

- 4 isolated leptons with p_T > (35, 30, 25, 20) GeV.



A. Papaefstathiou

$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$

<u>results:</u> # of events @ 3 ab^{-1}.

channel	$N_{3\ \text{ab}^{-1}}$(cuts, ideal)	$N_{3\ \text{ab}^{-1}}$(cuts, LHC)
$\mathbf{hh} \to (b\bar{b})(\ell^+\ell^-\ell'^+\ell'^-)$	13.0	4.1
$\mathbf{t\bar{t}h} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	30.4	10.9
$\mathbf{t\bar{t}Z} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	6.6	2.5
$\mathbf{b\bar{b}h} \to b\bar{b}(4\ell)$, $p_{T,b} > 15$ GeV	$\mathcal{O}(1)$	$\mathcal{O}(10^{-1})$
$\mathbf{ZZh} \to (4\ell)(b\bar{b})$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-3})$
$\mathbf{ZZZ} \to (4\ell)(b\bar{b})$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$
$\mathbf{ZZ} \to (4\ell)$+mis-tagged $b\bar{b}$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$
$\mathbf{hZ} \to (4\ell)$+mis-tagged $b\bar{b}$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-3})$
$\mathbf{W} \pm \mathbf{ZZ} \to (\ell\nu_\ell)(\ell^+\ell^-)(b\bar{b})$ + mis-tagged ℓ	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$
$\mathbf{W^\pm Zh} \to (\ell\nu_\ell)(\ell^+\ell^-)(b\bar{b})$ +mis-tagged ℓ	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-3})$

"ideal" S ~ 13, B ~ 37

$\Rightarrow$ **definitely one to look out for!**

hh final states

~~$\mathrm{BR}[(b\bar{b})(b\bar{b})] = 33.3\%$~~

$\mathrm{BR}[(b\bar{b})(WW) \to (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 1.7\%$

$\mathrm{BR}[(b\bar{b})(\tau\bar{\tau}) \to (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 0.9\%$

$\mathrm{BR}[(b\bar{b})(\mu\bar{\mu})] = 0.025\%$

$\mathrm{BR}[(WW)(WW) \to \ell^{\pm}\ell^{\pm}\ell'^{\mp} + E^{\mathrm{miss}} + j] = 0.016\%$

✓ $\mathrm{BR}[(b\bar{b})(\gamma\gamma)] = 0.263\%$

✓ $\mathrm{BR}[(b\bar{b})(ZZ) \to (b\bar{b}) + 4\ell] = 0.016\%$

$\mathrm{BR}[(b\bar{b})(Z\gamma) \to (b\bar{b}) + 2\ell + \gamma] = 0.013\%$

$$hh \to (b\bar{b})(Z\gamma) \to (b\bar{b})(\ell^+\ell^-\gamma)$$

- backgrounds: $t\bar{t}\gamma$, $b\bar{b}Z\gamma$ + mis-tag backgrounds:

channel	σ(100 TeV) (fb)
$\mathbf{hh} \to (b\bar{b})(\ell^+\ell^-\gamma)$	0.21
$\mathbf{b\bar{b}Z}\gamma \to b\bar{b}(\ell^+\ell^-)\gamma$, $p_{T,b} > 30$ GeV	26.00×10^3
$\mathbf{t\bar{t}}\gamma \to (L^+ b\nu_L l)(L^- \bar{b}\bar{\nu}_L)\gamma$	7.94×10^3
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$+mis-tagged γ , $p_{T,b} > 30$ GeV	107.36×10^3
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$+mis-tagged γ, [generation-level cuts]	25.08×10^3

- irreducible backgrounds much larger than in 4 lepton case.

$$hh \to (b\bar{b})(Z\gamma) \to (b\bar{b})(\ell^+\ell^-\gamma)$$

- a simple analysis, asking for:
  - 2 isolated leptons with p_T > (40, 35) GeV,
  - 1 isolated photon with p_T > 40 GeV,
  - R=0.4 anti-k_T b-jets with p_T > (60, 40) GeV,
  - MET < 80 GeV,
  - $\mathbf{M_{bb}}$ in (100, 150) GeV,
  - $\mathbf{M_{ll\gamma}}$ in (110, 140) GeV,
  - [+ some other cuts taking into account distances between reconstructed objects.]

$$hh \to (b\bar{b})(Z\gamma) \to (b\bar{b})(\ell^+\ell^-\gamma)$$

<u>results:</u> # of events @ 3 ab^{-1}.

channel	$N_{3\ \mathrm{ab}^{-1}}(\mathrm{cuts,\ ideal})$	$N_{3\ \mathrm{ab}^{-1}}(\mathrm{cuts,\ LHC})$
$\mathbf{hh} \to (b\bar{b})(\ell^+\ell^-\gamma)$	14	8
$\mathbf{b\bar{b}Z}\gamma \to b\bar{b}(\ell^+\ell^-)\gamma$, $p_{T,b} > 30$ GeV	266	203
$\mathbf{t\bar{t}}\gamma \to (L^+b\nu_L l)(L^-\bar{b}\bar{\nu}_L)\gamma$	78	79
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$+mis-tagged γ , $p_{T,b} > 30$ GeV	20	21
$\mathbf{t\bar{t}} \to (\ell^+b\nu_\ell)(\ell'^-\bar{b}\bar{\nu}_{\ell'})$+mis-tagged γ	14	10

"ideal" S ~ 14, B ~ 378.

$\Rightarrow$ **most likely does not qualify for the podium…**

hh final states

~~$\mathrm{BR}[(b\bar{b})(b\bar{b})] = 33.3\%$~~

$$\mathrm{BR}[(b\bar{b})(WW) \rightarrow (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 1.7\%$$

$$\mathrm{BR}[(b\bar{b})(\tau\bar{\tau}) \rightarrow (b\bar{b}) + 2\ell + E^{\mathrm{miss}}] = 0.9\%$$

$$\mathrm{BR}[(b\bar{b})(\mu\bar{\mu})] = 0.025\%$$

$$\mathrm{BR}[(WW)(WW) \rightarrow \ell^{\pm}\ell^{\pm}\ell'^{\mp} + E^{\mathrm{miss}} + j] = 0.016\%$$

✓ $\mathrm{BR}[(b\bar{b})(\gamma\gamma)] = 0.263\%$

✓ $\mathrm{BR}[(b\bar{b})(ZZ) \rightarrow (b\bar{b}) + 4\ell] = 0.016\%$

~~$\mathrm{BR}[(b\bar{b})(Z\gamma) \rightarrow (b\bar{b}) + 2\ell + \gamma] = 0.013\%$~~

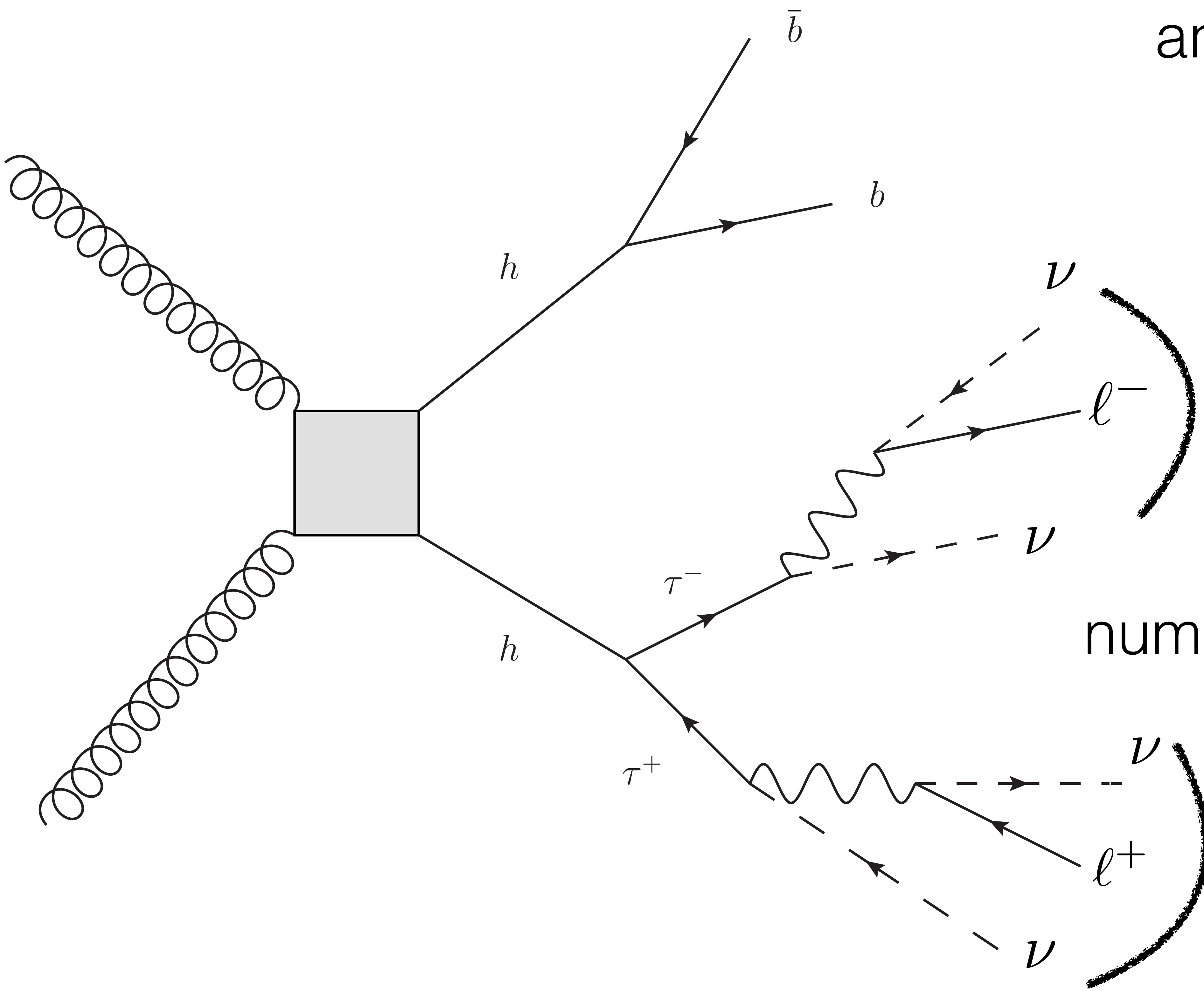
$hh \to (b\bar{b})(\ell^+\ell^- + \not{E})$

- fairly large signal cross section at 100 TeV, contribution from two different Higgs boson decays.
- but: top pairs and bbZ constitute large backgrounds.

channel	σ(100 TeV) (fb)
$\mathbf{hh} \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\ell^-\bar{\nu}_\ell)$	27.16
$\mathbf{hh} \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\bar{\nu}_\tau\ell^-\bar{\nu}_\ell\nu_\tau)$	14.63
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$, cuts as in Eq. 1	25.08×10^3
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	107.36×10^3
$\mathbf{b\bar{b}h} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	26.81
$\mathbf{b\bar{b}W^\pm} \to b\bar{b}(\ell^\pm\nu_\ell)$, $p_{T,b} > 30$ GeV +mis-tagged ℓ	1032.6
$\ell^+\ell^-$ + jets $\to (\ell^+\ell^-)$ + mis-tagged $b\bar{b}$	2.14×10^3

- [note: could also consider **M_{T2}**, but top pairs turns out to be the second most important background.]

$$hh \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell^+\ell^- + \not{E}_T)$$

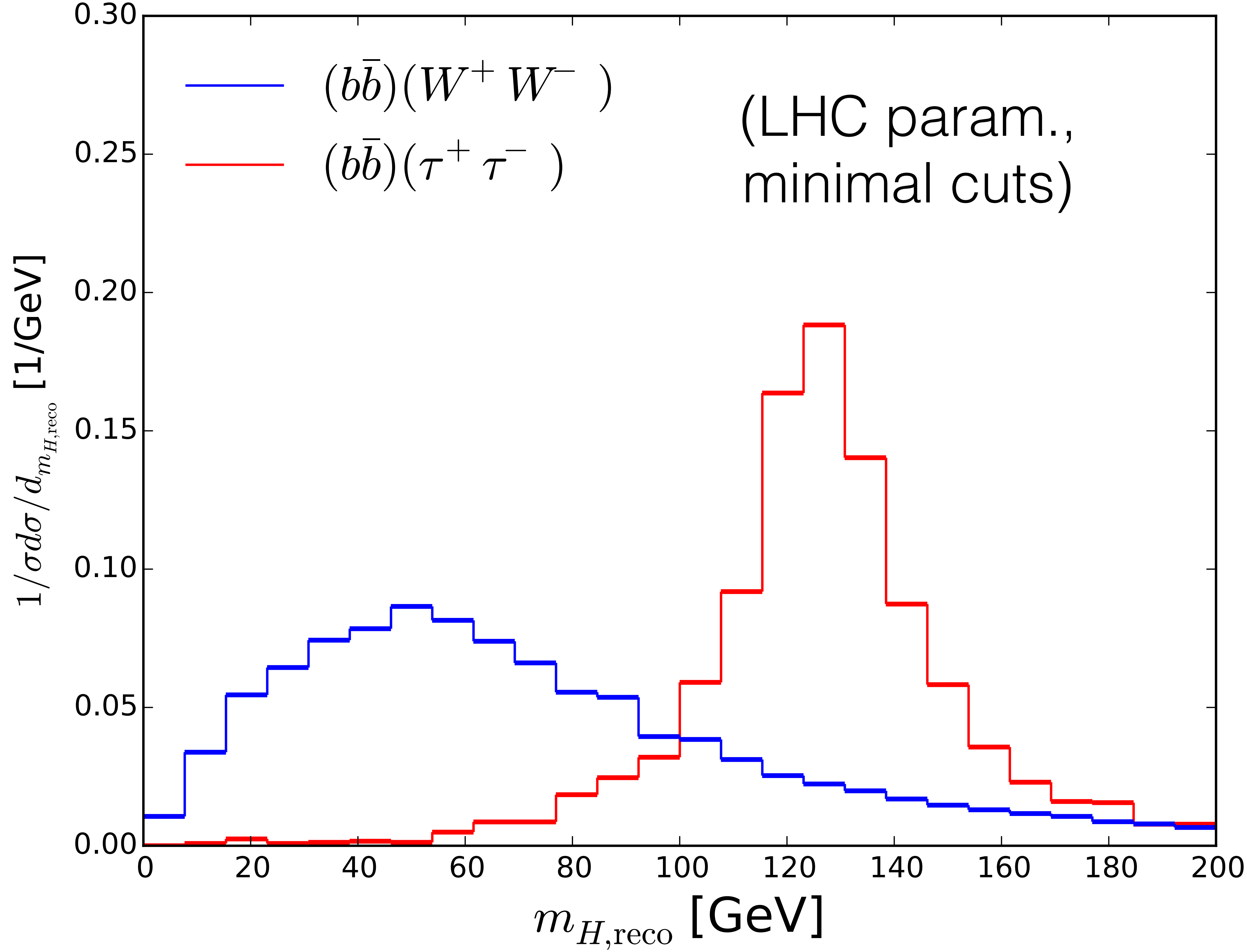


angles very small!

$\sim p_\ell \parallel \sum p_\nu$

number of unknowns reduced: (6 to 2)

$$hh \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell^+\ell^- + \not{E}_T)$$



$hh \to (b\bar{b})(\mu^+\mu^-)$

- top pairs and bbZ still constitute large backgrounds.
- low missing energy could help eliminate top pairs.

channel	σ(100 TeV) (fb)
$\mathbf{hh} \to (b\bar{b})(\mu^+\mu^-)$	0.42
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$, cuts as in Eq. 1	25.08×10^3
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	107.36×10^3
$\mathbf{b\bar{b}h} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	26.81
$\mathbf{b\bar{b}W^\pm} \to b\bar{b}(\ell^\pm\nu_\ell)$, $p_{T,b} > 30$ GeV +mis-tagged ℓ	1032.6
$\ell^+\ell^-$ + jets $\to (\ell^+\ell^-)$ + mis-tagged $b\bar{b}$	2.14×10^3

- design **two signal regions** to handle the two channels depending on amount of missing energy.

$$hh \to (b\bar{b})(\ell^+\ell^-) + (\not{E}_T)$$

- design **two signal regions** to handle the two channels depending on amount of missing energy.

observable	$\mathrm{SR}_{\not{E}}$	SR_{μ}
$\not{E}_T$	> 100 GeV	< 40 GeV
p_{T,ℓ_1}	> 60 GeV	> 90 GeV
p_{T,ℓ_2}	> 55 GeV	> 60 GeV
$\Delta R(\ell_1, \ell_2)$	< 0.9	$\in (1.0, 1.8)$
$M_{\ell\ell}$	$\in (50, 80)$ GeV	$\in (120, 130)$ GeV
p_{T,b_1}	> 90 GeV	> 90 GeV
p_{T,b_2}	> 80 GeV	> 80 GeV
$\Delta R(b_1, b_2)$	$\in (0.5, 1.3)$	$\in (0.5, 1.5)$
$M_{bb\ell\ell}$	> 350 GeV	> 350 GeV
M_{bb}	$\in (110, 140)$ GeV	$\in (110, 140)$ GeV
$M_{\mathrm{reco.}}$	> 600 GeV	none

$hh \to (b\bar{b})(\mu^+\mu^-)$?

results: # of events @ 3 ab^{-1}.

channel	$N_{3\ \mathrm{ab}^{-1}}$(cuts, ideal)	$N_{3\ \mathrm{ab}^{-1}}$(cuts, LHC param.)
$\mathbf{hh} \to (b\bar{b})(\mu^+\mu^-)$	8.6	1.8
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$, cuts as in Eq. 1	$32.0^{+25.3}_{-9.3}$	$24.5^{+19.3}_{-7.1}$
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	< 73.5	$49.4^{+113.4}_{-14.4}$
$\mathbf{b\bar{b}h} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathbf{b\bar{b}W^\pm} \to b\bar{b}(\ell^\pm\nu_\ell)$, $p_{T,b} > 30$ GeV +mis-tagged ℓ	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$
$\ell^+\ell^-$ + jets $\to (\ell^+\ell^-)$ + mis-tagged $b\bar{b}$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

- very few events after analysis with fairly large backgrounds.
- possible improvement by better muon resolution?

$hh \to (b\bar{b})(\ell^+\ell^- + \not{E})$

results: # of events @ 3 ab^{-1}.

channel	$N_{3\ \mathrm{ab}^{-1}}$(cuts, ideal)	$N_{3\ \mathrm{ab}^{-1}}$(cuts, LHC param.)
$\mathbf{hh} \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\ell^-\bar{\nu}_\ell)$	20.9	19.9
$\mathbf{hh} \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\bar{\nu}_\tau\ell^-\bar{\nu}_\ell\nu_\tau)$	38.5	24.3
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$, cuts as in Eq. 1	$16.0^{+21.1}_{-5.1}$	$6.1^{+14.1}_{-1.8}$
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	$257.9^{+203.7}_{-74.6}$	$493.7^{+224.9}_{-113.4}$
$\mathbf{b\bar{b}h} \to b\bar{b}(\ell^+\ell^-)$, $p_{T,b} > 30$ GeV	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathbf{b\bar{b}W}^\pm \to b\bar{b}(\ell^\pm\nu_\ell)$, $p_{T,b} > 30$ GeV +mis-tagged ℓ	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$
$\ell^+\ell^-$ + jets $\to (\ell^+\ell^-)$ + mis-tagged $b\bar{b}$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

"ideal" S ~ 60, B ~ 273* [* background uncertainty due to limited MC samples]

$\Longrightarrow$ **a silver channel?**

$$hh \to (W^+W^-)(W^+W^-) \to \ell^\pm \ell^\pm \ell'^\mp + E^{\mathrm{miss}} + j$$

[**1503.07611,** Li, Li, Yan, Zhao]

[see also **hep-ph/0206024** Baur, Plehn, Rainwater for high-mass Higgs]

- same-sign di-leptons kills a lot of background (particularly **ZW**),
- their analysis finds good significance at 100 TeV:
  - S~160, B~523 for 3 ab^{-1}.
- but assumes p_T > (30,10,10) GeV for the three leptons: this may be a little optimistic @ 100 TeV.
- [note: **4τ** and **2τ2W** final states can generate the same final state.]

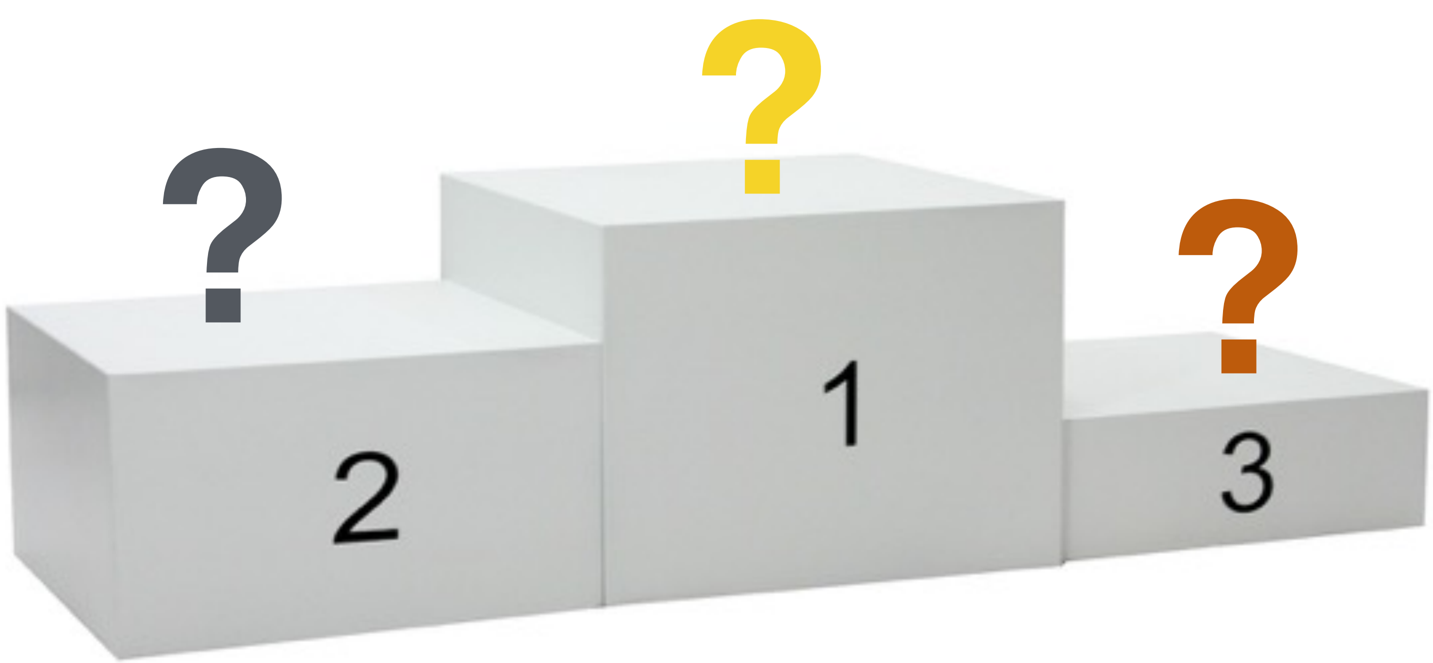
100 TeV: the story so far

	SM hh discovery
$hh \to (b\bar{b})(b\bar{b})$	?
$hh \to (b\bar{b})(\gamma\gamma)$	✓
$hh \to (b\bar{b})(ZZ) \to (b\bar{b})(4\ell)$	✓
$hh \to (b\bar{b})(Z\gamma) \to (b\bar{b})(\ell^+\ell^-\gamma)$	✗
$hh \to (b\bar{b})(\ell^+\ell^- + \not{E})$	✓
$hh \to (b\bar{b})(\mu^+\mu^-)$	?
$hh \to \ell^\pm\ell^\pm\ell'^\mp + \not{E} + j$	?

to do

- VBF/associated production @ 100 TeV.
- use of jet substructure techniques [particularly for high-invariant mass regions],
- include hadronic tau decays,
- extraction of self-coupling/D=6 EFT coefficients.
- examine details of the detector […].

thanks for your attention!



statistics for MC samples

- at 100 TeV, background cross sections are very large: we need to generate substantial Monte Carlo events samples.

- we can apply reasonable generation-level cuts.

- but: what if we are left with a low number of MC events?

- can still calculate a 1-σ uncertainty for the expectation values using Poisson statistics.

statistics for MC samples

- question: given that we have observed **N** Monte Carlo events after cuts, what are uncertainties $\mathbf{\Delta N_+}$ and $\mathbf{\Delta N_-}$, such that

$$N^{+\Delta N_+}_{-\Delta N_-}$$

defines a 68% confidence level (1-σ) interval?

- this can be determined by integrating the Poisson distribution:

$$\left.\begin{aligned} p(N+\Delta N_+) &= \int_{N+\Delta N_+}^{\infty} \mathrm{d}\lambda \, \frac{\lambda^N \mathrm{e}^{-\lambda}}{N!} \\ p(N-\Delta N_-) &= \int_{0}^{N-\Delta N_-} \mathrm{d}\lambda \, \frac{\lambda^N \mathrm{e}^{-\lambda}}{N!} \end{aligned}\right\} = 15.9\% \text{ for 1-}\sigma.$$

statistics for MC samples

$$\left.\begin{aligned} p(N+\Delta N_+) &= \int_{N+\Delta N_+}^{\infty} \mathrm{d}\lambda \, \frac{\lambda^N \mathrm{e}^{-\lambda}}{N!} \\ p(N-\Delta N_-) &= \int_{0}^{N-\Delta N_-} \mathrm{d}\lambda \, \frac{\lambda^N \mathrm{e}^{-\lambda}}{N!} \end{aligned}\right\} = 15.9\% \text{ for } 1\text{-}\sigma.$$

solve using standard gamma functions:

$$\frac{\Gamma(N+1, N+\Delta N_+)}{N!} = 15.9\%$$

$$\frac{\gamma(N+1, N-\Delta N_-)}{N!} = 15.9\%$$

(for N > 0)