PRISMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Discovering the $h \to Z\gamma$ Decay in $t\bar{t}$ Associated Production

arXiv:1909.07390

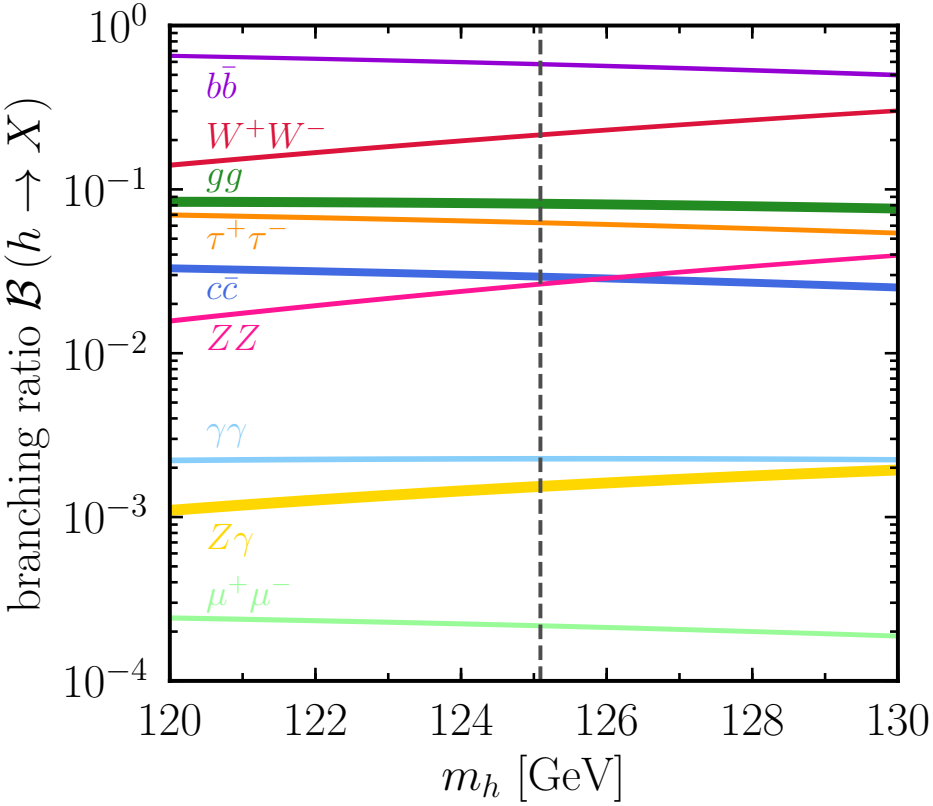
Eric Madge

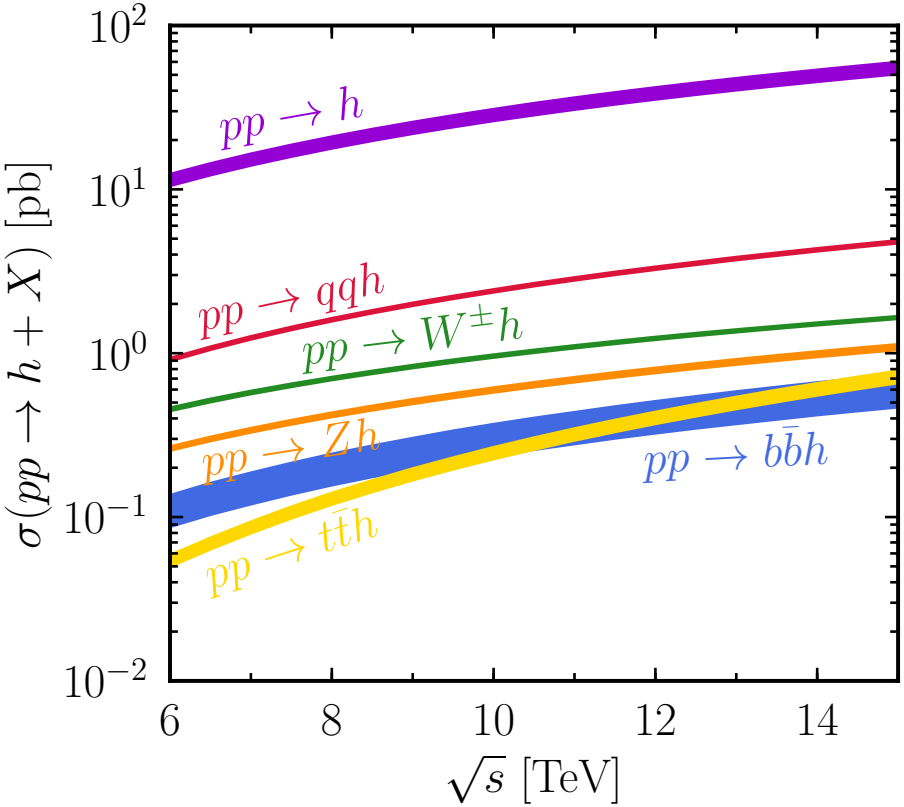
in collaboration with

Florian Goertz, Pedro Schwaller, and Valentin Tenorth

13th Annual Helmholtz Alliance Workshop
"Physics at the Terascale"

Introduction





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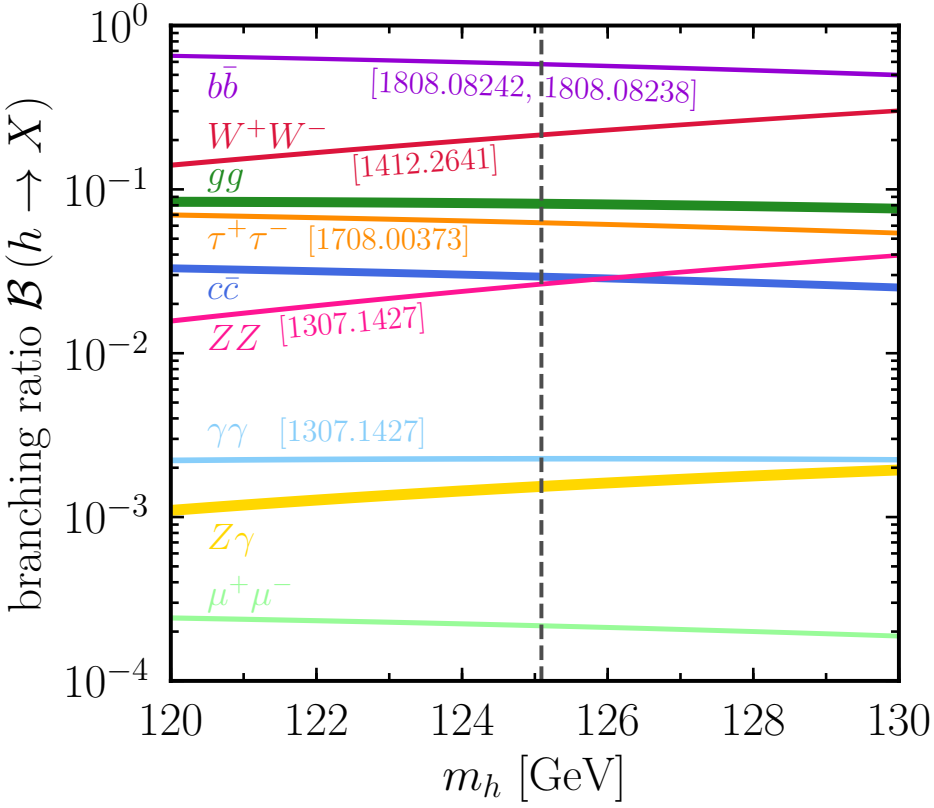

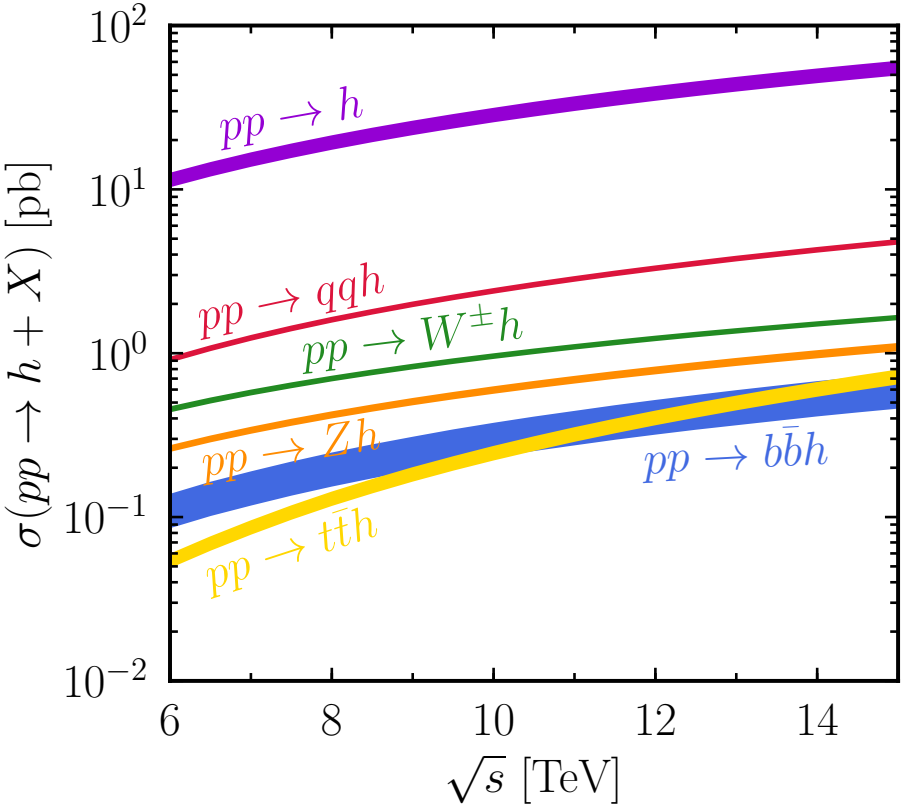

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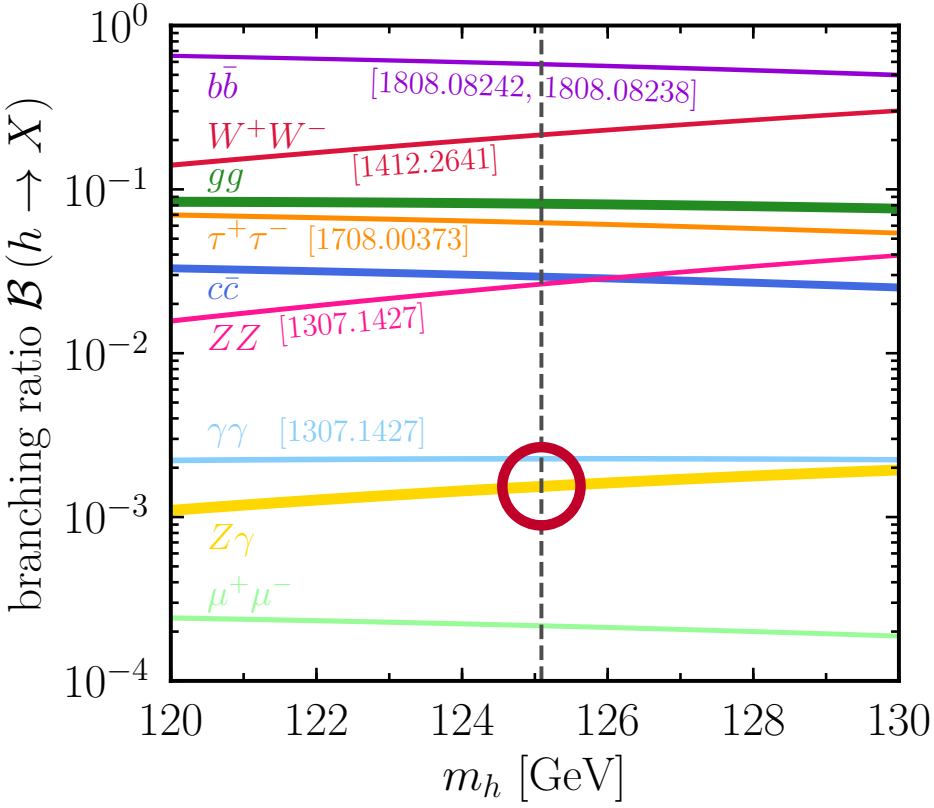

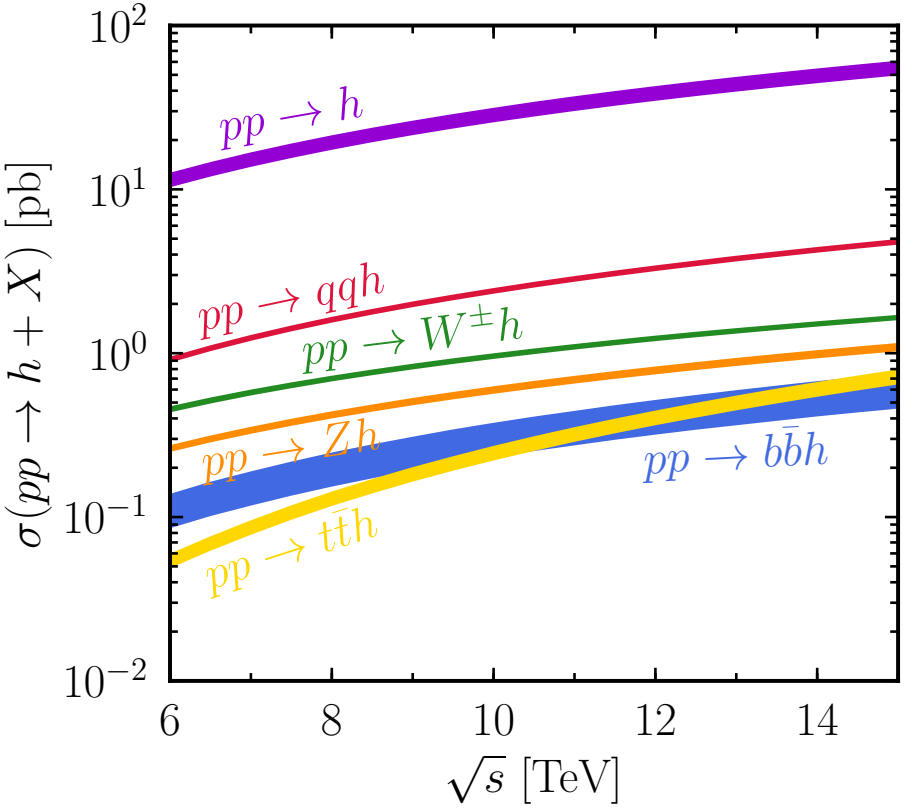

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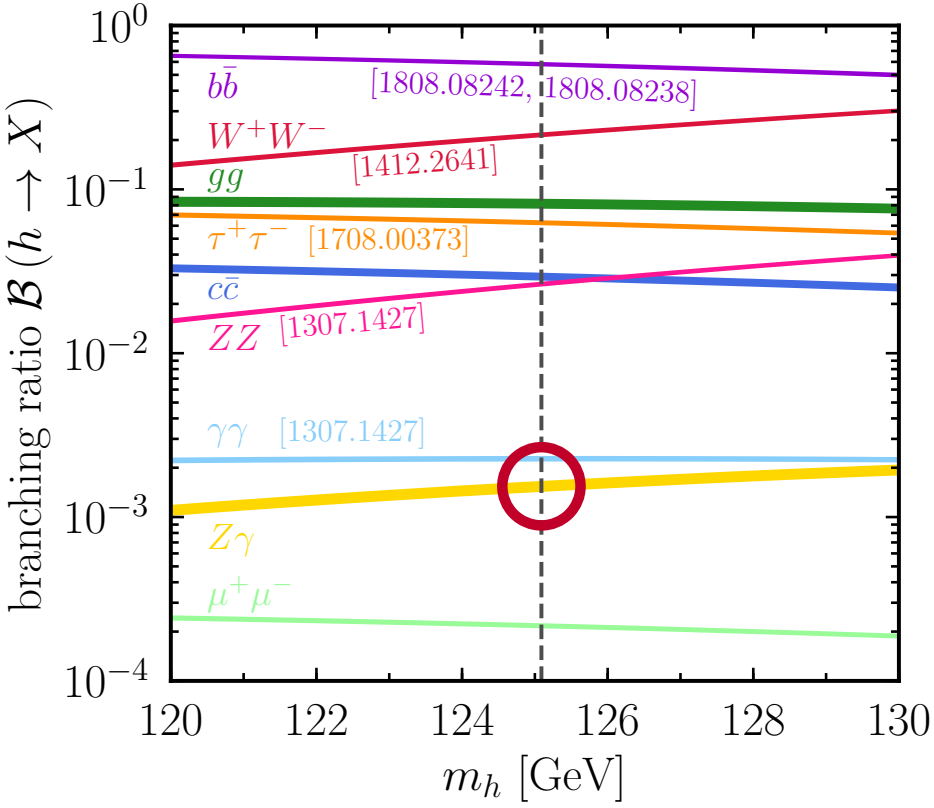

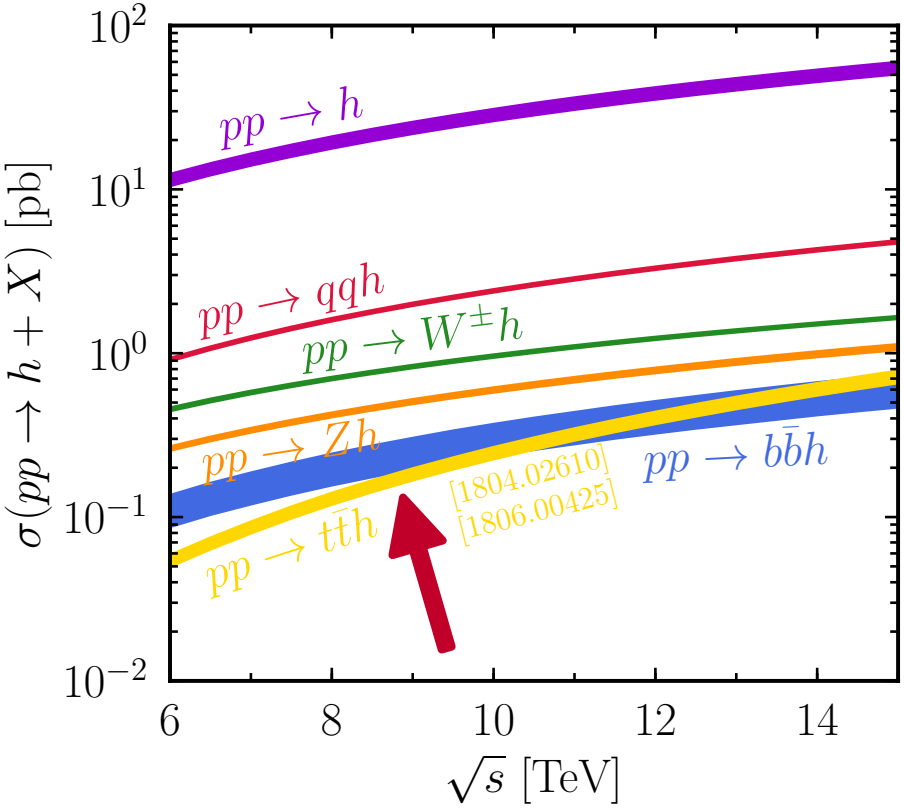

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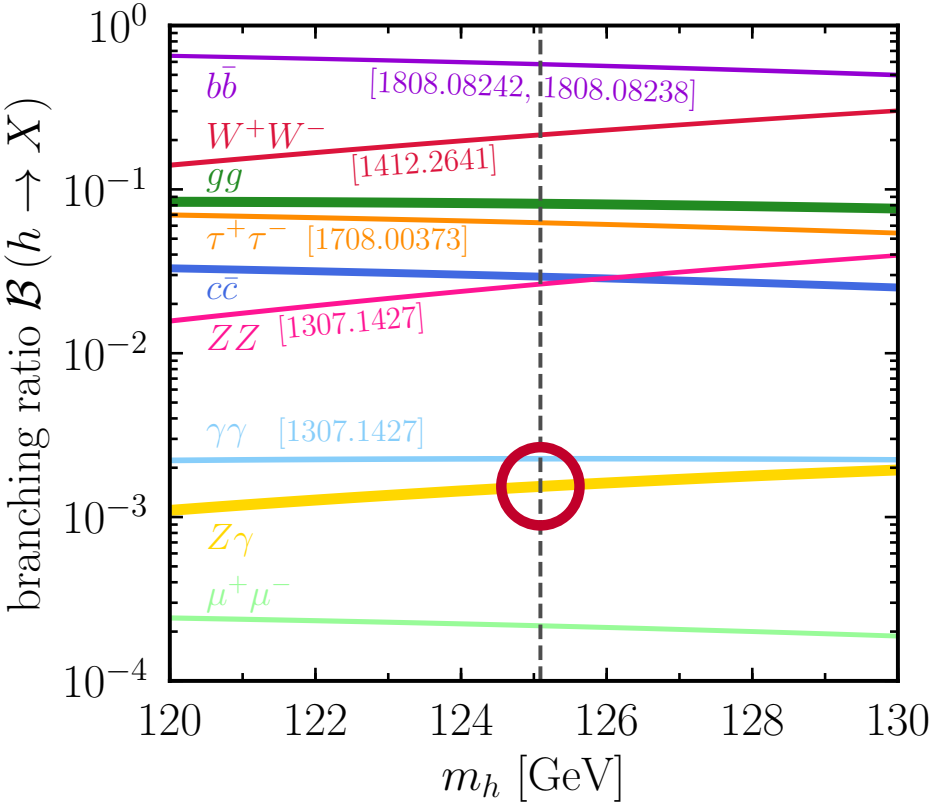
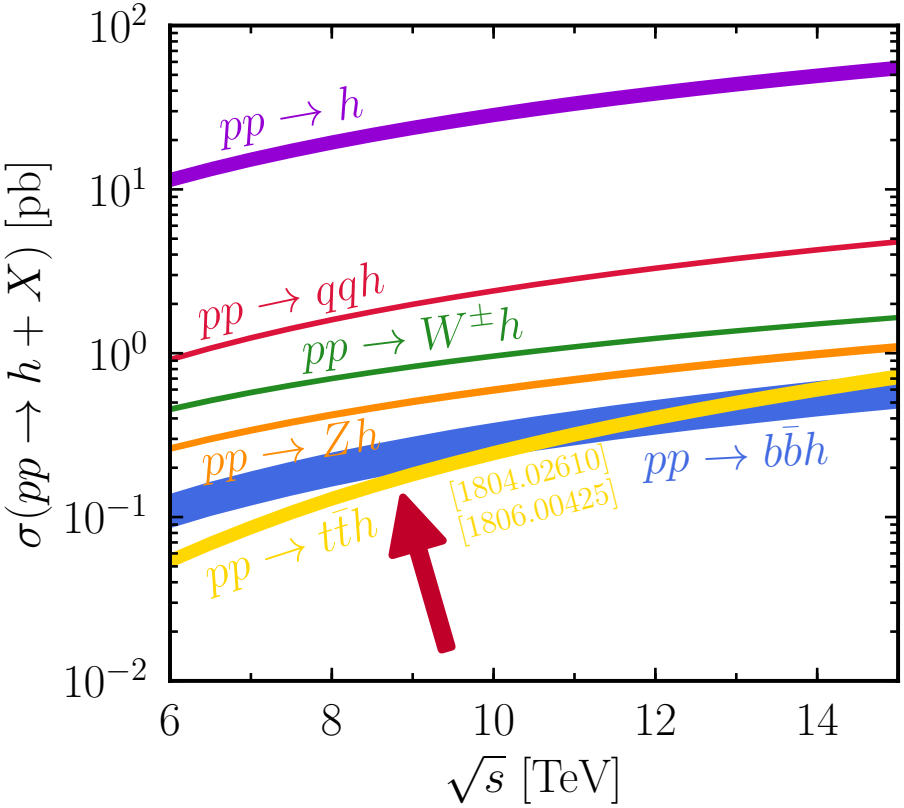
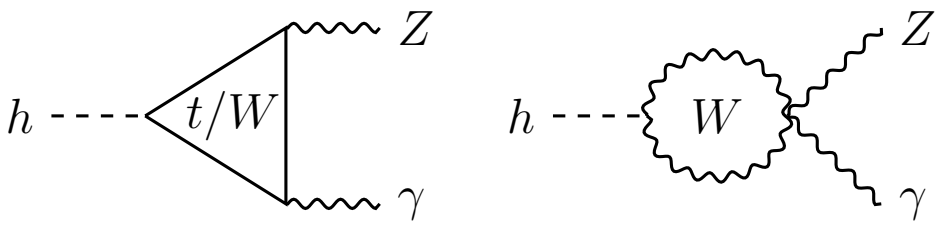


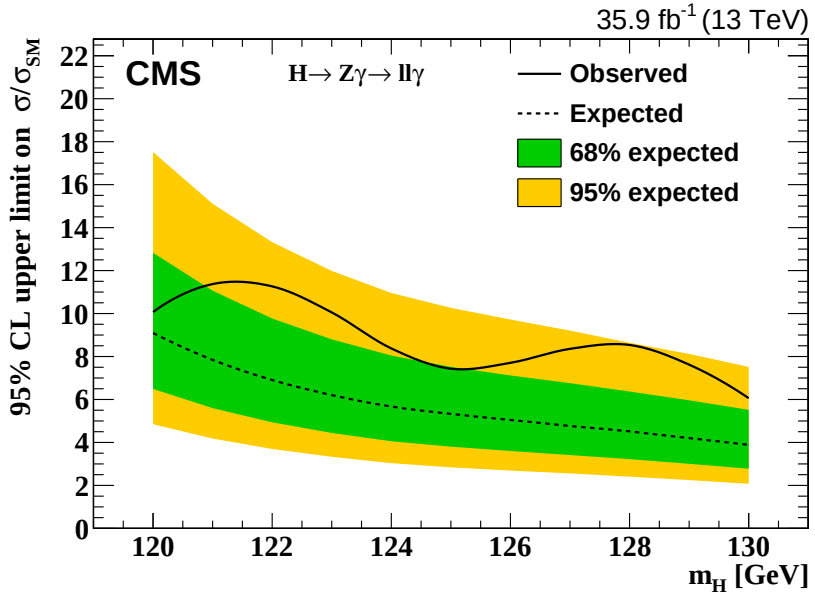


Idea: combine $t\bar{t}h$ production with $h \to Z\gamma$ decay,
use $t\bar{t}$ pair to suppress most backgrounds ($y_t \sim 1$)

But: very low cross section $\Longrightarrow$ need high luminosity
$\Longrightarrow$ Projections for HL-LHC, HE-LHC and FCC_{hh}

$h \to Z\gamma$





- SM: $\mathcal{B}(h \to Z\gamma) = 1.54 \cdot 10^{-3}$
  (cf. $\mathcal{B}(h \to \gamma\gamma) = 2.27 \cdot 10^{-3}$)
- $h \to Z\gamma$ not observed yet
- current limits ($36\,\text{fb}^{-1}$): ATLAS: $\sigma/\sigma_{\text{SM}} = 6.6$ [1708.00212]
  CMS: $\sigma/\sigma_{\text{SM}} = 7.4$ [1806.05996]
- HL-LHC: $4.9\,\sigma$ significance with $3\,\text{ab}^{-1}$ [ATL-PHYS-PUB-2018-054]
- FCC$_{\text{ee}}$($240\,\text{GeV}$): $\frac{S}{\sqrt{B}} \approx 3.6$ with $10\,\text{ab}^{-1}$ [No, Spannowsky (1612.06626)]

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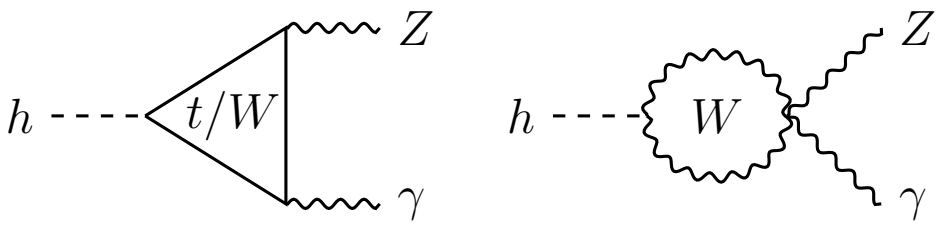

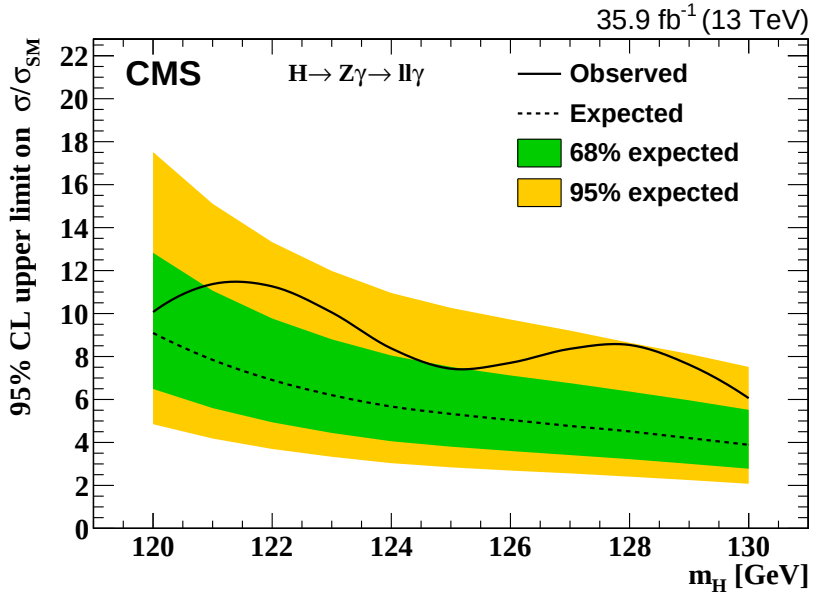

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Here: Consider $h \to Z\gamma, \quad Z \to \ell^+\ell^-$

Analysis

Strategy: consider semi-leptonic top channel and extrapolate to fully-hadronic and fully-leptonic top decays

loosely based on $pp \to t\bar{t}h,\ h \to \gamma\gamma$ search [ATLAS-CONF-2013-080]

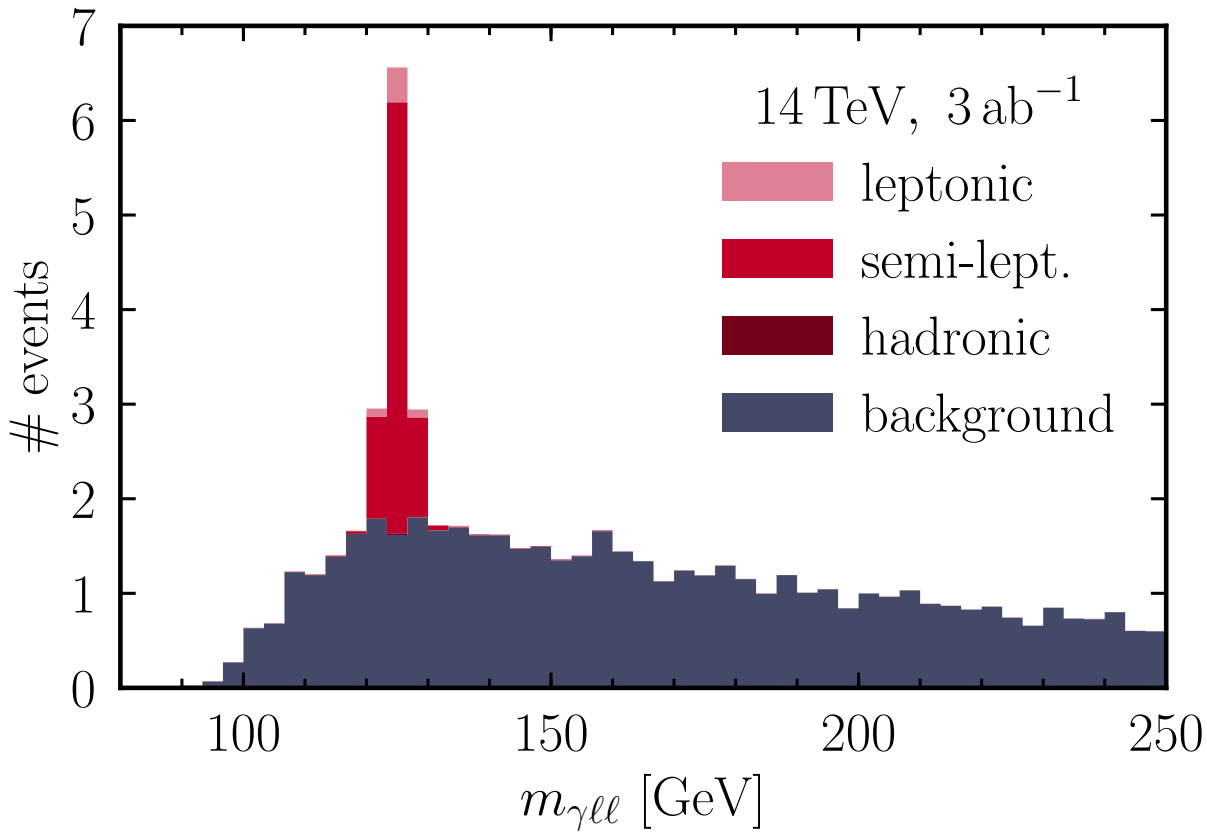
- exactly 3 leptons (e or μ)
- $\geq$ 3 jets
- $p_{T,j} > 30$ GeV for first 3 jets
- $\not{E}_T > 20$ GeV
- $\geq$ 1 b-tagged jet
- $\geq$ 1 photon w/ $p_{T,\gamma} > 15$ GeV
- Z-reconstruction: OSSF ℓ pair w/ 76 GeV $< m_{\ell\ell} <$ 106 GeV
- Higgs-reconstruction: 120 GeV $< m_{\gamma\ell\ell} <$ 130 GeV

Semi-Leptonic Channel at HL-LHC

Simulation: MadGraph5_aMC@NLO $\longrightarrow$ Pythia8 $\longrightarrow$ Delphes

- signal: $pp \to t\bar{t}\,h,\ h \to Z\gamma,\ Z \to \ell^+\ell^-$
- irreducible background: $pp \to t\bar{t}\,Z\gamma,\quad Z \to \ell^+\ell^-$

Cut	S	B
—	186	1862
$3\,\ell$	25	273
$\geq 3\,j$	15	170
$\not{E}_T$	14	160
$\geq 1\,b$	12	137
$\geq 1\,\gamma$	8.1	83
Z reco.	7.6	80
h reco.	7.3	5.2



Extrapolation to other top channels

$$\mathcal{B}(h \to Z\gamma) = 1.54 \cdot 10^{-3}, \quad \mathcal{B}(Z \to \ell^+\ell^-) = 0.067$$

- Signal: $\sigma(pp \to t\bar{t}h) = 613\,\text{fb}$ (at $\sqrt{s} = 14\,\text{TeV}$)
  $\Longrightarrow$ ~ 190 events at HL-LHC $(3\,\text{ab}^{-1})$
- Background: $\sigma(pp \to t\bar{t}Z\gamma) = 9.3\,\text{fb}$
  $\Longrightarrow$ ~ 1870 events at HL-LHC

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  $\epsilon_S = 0.14, \quad \epsilon_B = 0.0097$

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$\Longrightarrow$ total: $S \approx 25, \quad B \approx 27$

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Significance

$$\frac{S}{\sqrt{B}} \approx 4.8 \qquad \text{@ HL-LHC}$$

HE-LHC and FCC_{hh}

HE-LHC: $27\,\text{TeV},\ 15\,\text{ab}^{-1}$

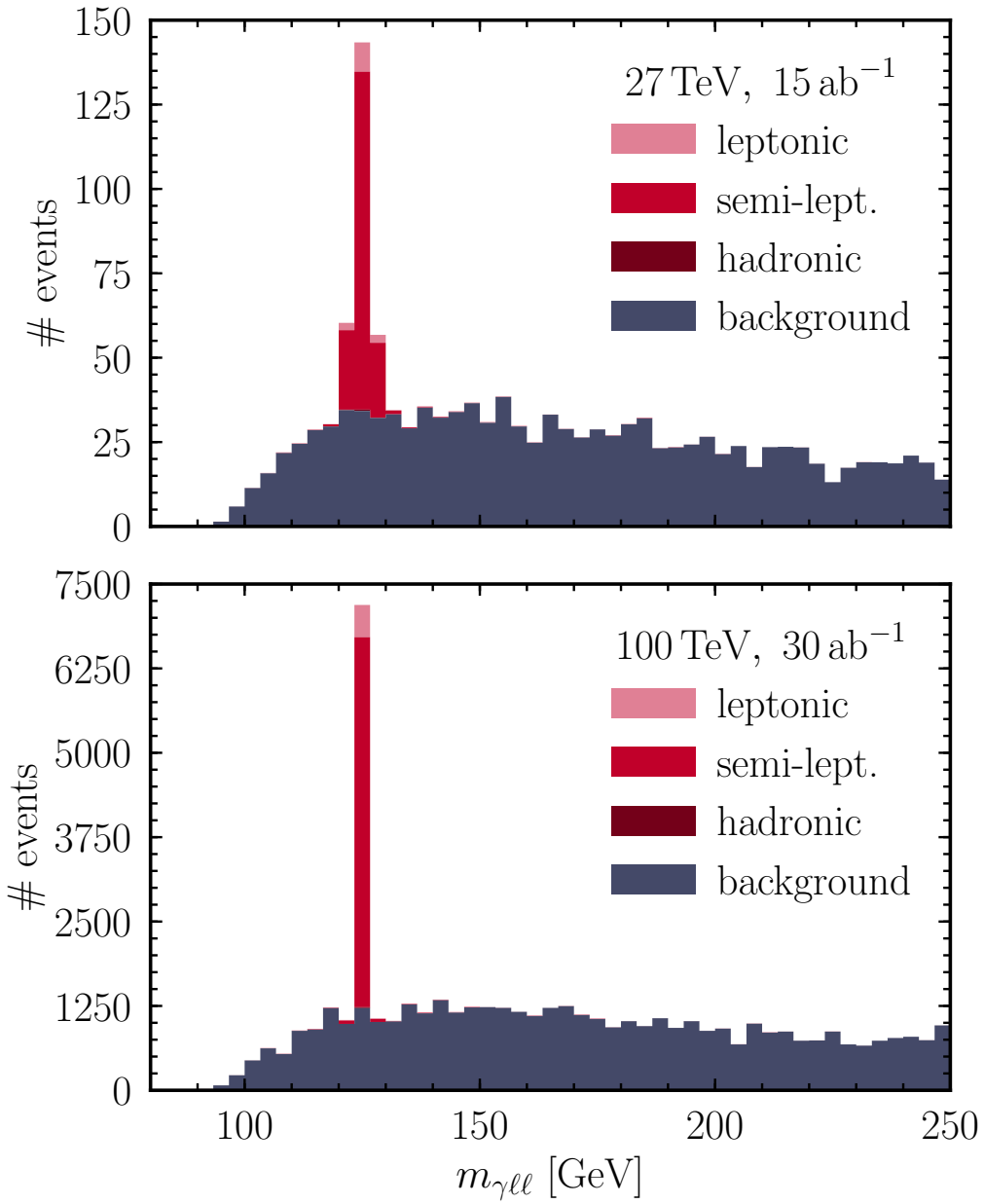
Cut	S	B
—	4.4k	47k
Z reco.	166	1.9k
h reco.	160	101

$S \approx 556, \quad B \approx 527$

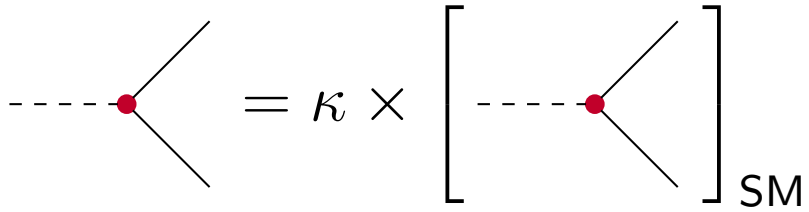
FCC_{hh}: $100\,\text{TeV},\ 30\,\text{ab}^{-1}$

Cut	S	B
—	112k	1.3M
Z reco.	6.3k	82k
h reco.	6.1k	3.2k

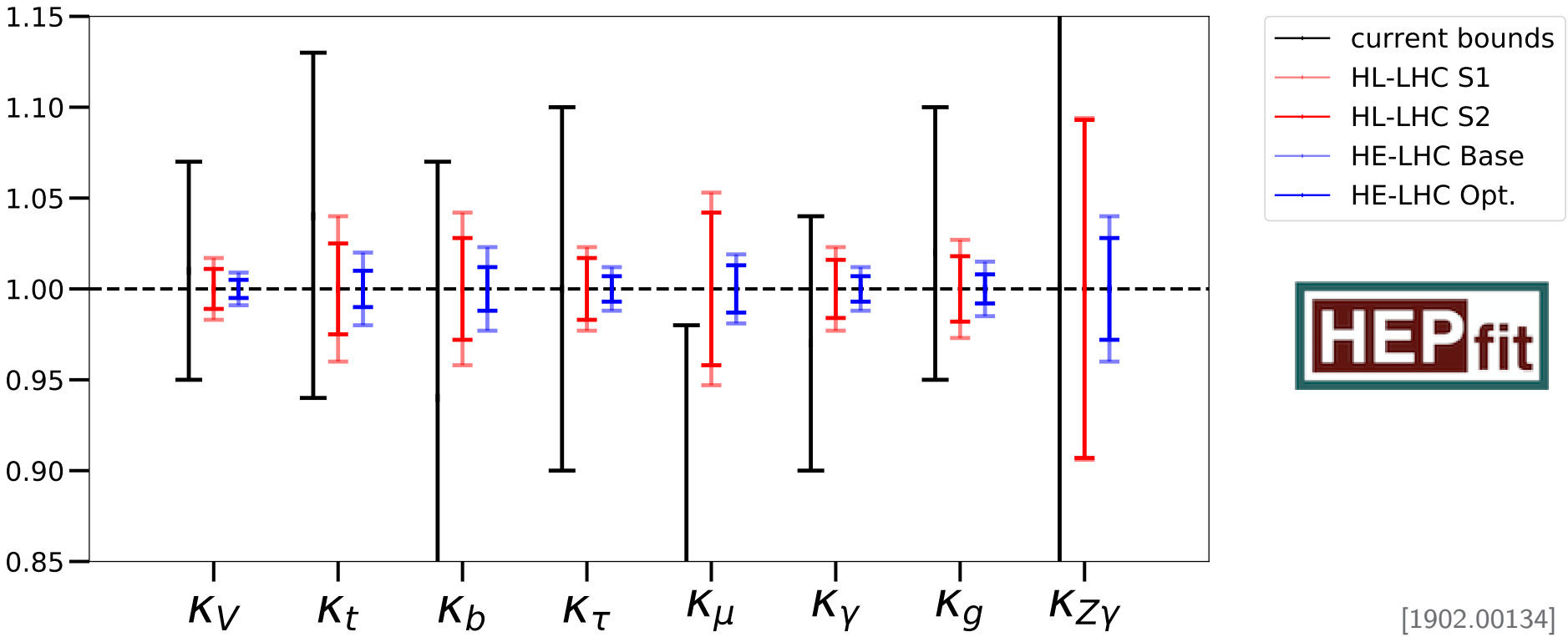
$S \approx 21.1\text{k}, \quad B \approx 16.8\text{k}$



κ Framework

coupling modifiers κ:  SM: $\kappa = 1$

$$\kappa_i^2 = \frac{\sigma\left(X \to h\right)}{\sigma\left(X \to h\right)_{\text{SM}}} \quad \text{or} \quad \kappa_i^2 = \frac{\Gamma\left(h \to X\right)}{\Gamma\left(h \to X\right)_{\text{SM}}}$$



[1902.00134]

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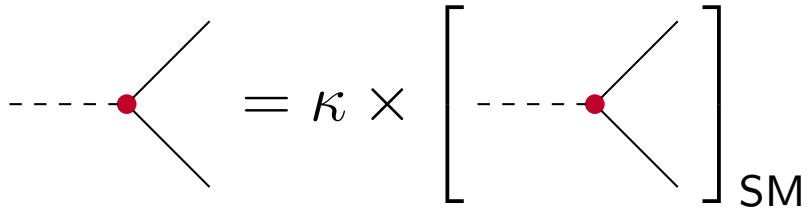
coupling modifiers κ:  $= \kappa \times$ SM

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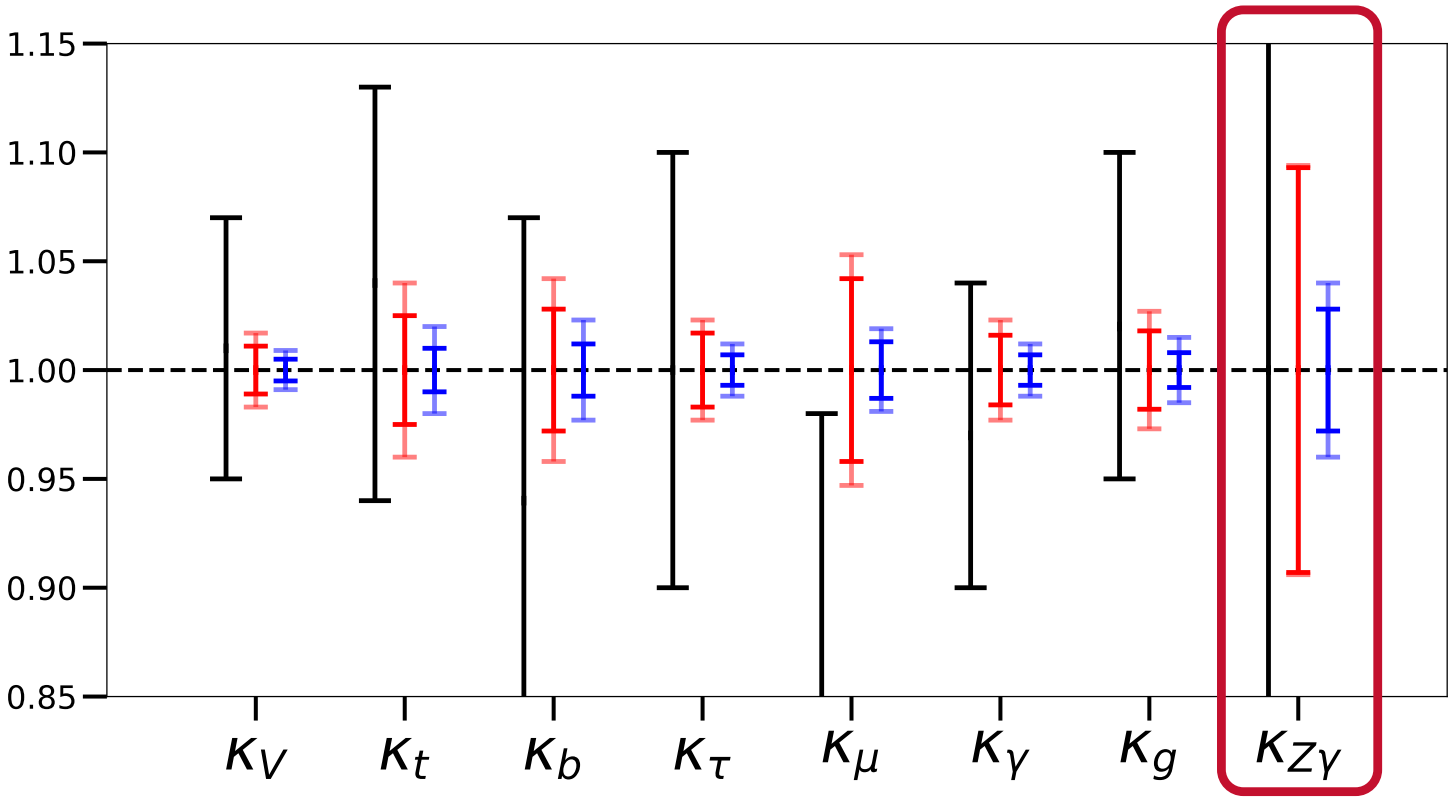


current bounds
HL-LHC S1
HL-LHC S2
HE-LHC Base
HE-LHC Opt.

HEPfit

68 % sensitivity to $\kappa_{Z\gamma}$:

HL-LHC S1:	± 0.094
HL-LHC S2:	± 0.093
HE-LHC Base:	± 0.040
HE-LHC Opt.:	± 0.028

[1902.00134]

Limits on $\kappa_{Z\gamma}$

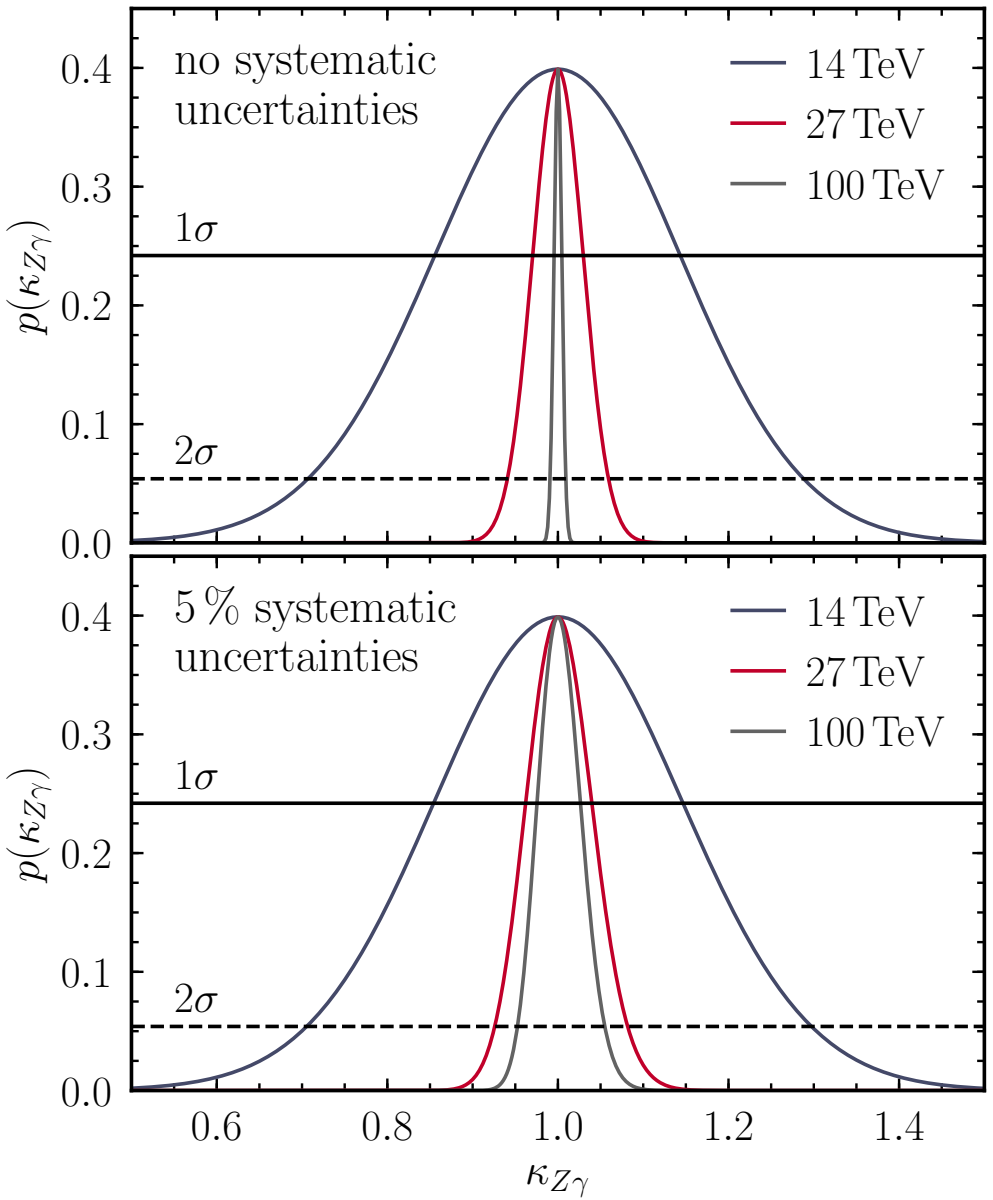
$N(\kappa^2_{Z\gamma}) = \kappa^2_{Z\gamma} S + B$

SM: $\kappa_{Z\gamma} = 1$

Exclude values of $\kappa_{Z\gamma}$ for which expected $N(\kappa^2_{Z\gamma})$ differs from SM prediction by more than $n\sigma$.

statistics only:
$\sigma^2 = N(\kappa^2_{Z\gamma})$

with systematics: $(\sigma_{\text{sys}} = 0.05\ S)$
$\sigma^2 = N(\kappa^2_{Z\gamma}) + \sigma^2_{\text{sys}}$

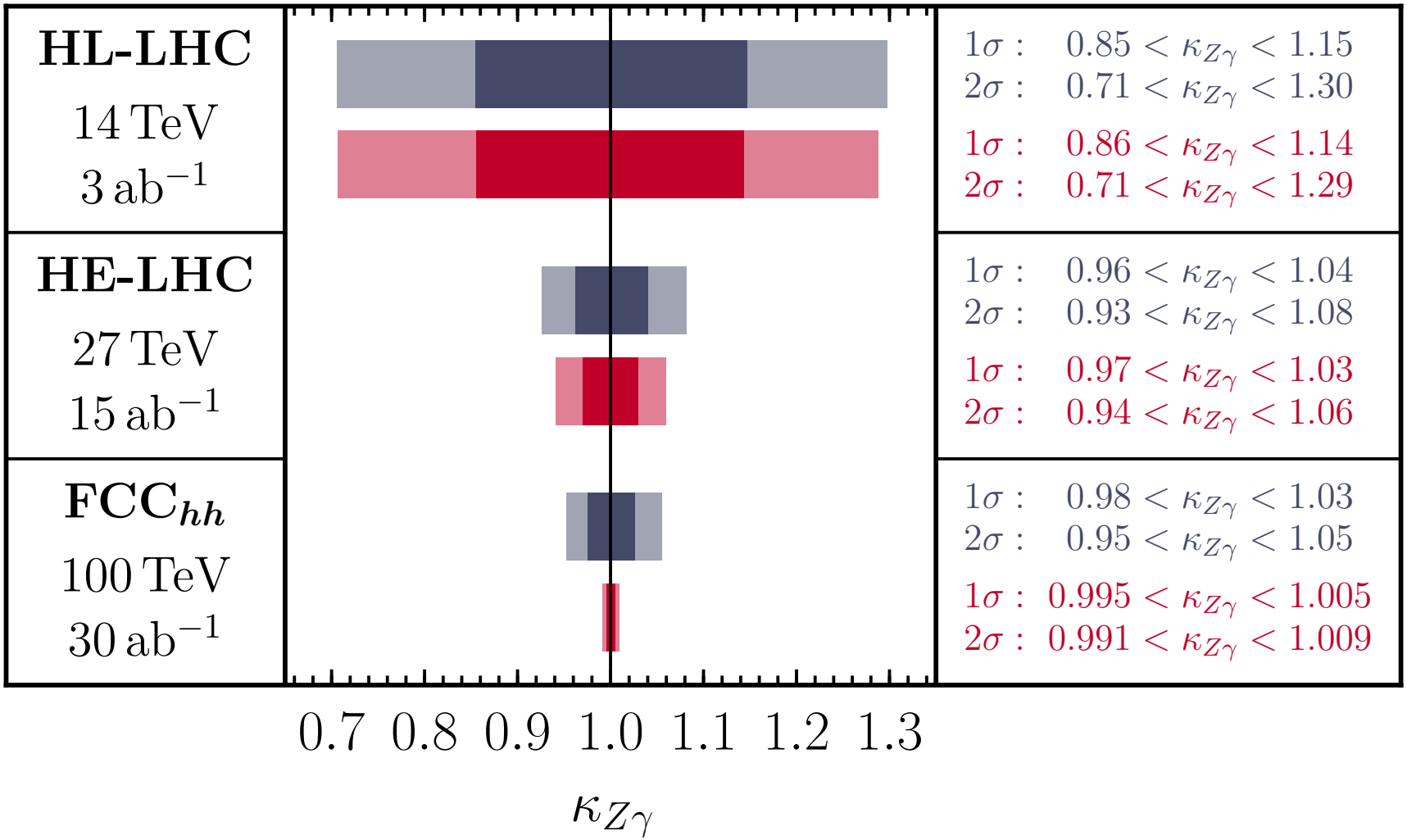


Results

$$\kappa_{Z\gamma}^2 = \frac{\Gamma\left(h \to Z\gamma\right)}{\Gamma\left(h \to Z\gamma\right)_{\mathsf{SM}}}$$

red: no systematic uncertainties

blue: 5 % uncertainties on S



Conclusion

- $t\bar{t}h$ can contribute significantly to $h \to Z\gamma$ discovery at HL-LHC
- Limits on $\kappa_{Z\gamma}$ (1σ):

HL-LHC	HE-LHC	FCC_{hh}
$\sim 15\,\%$	$\sim 4\,\%$	$\sim 3\,\%$

- Competitive to other h production channels / colliders:

HL-LHC	HE-LHC	ILC
$\sim 10\,\%$	$\sim 4\,\%$	$\sim 5\,\%$

[Durieux et al., 1704.02333]
[Cepada et al., 1902.00134]

- room for improvement:
  - full simulation (background, top channels, detector, . . .)
  - background determination using side-bands
  - sophisticated top-tagging
  - beyond cut-and-count (shape analysis)
  - . . .

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