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Measurement of double Higgs production at the LHC and beyond

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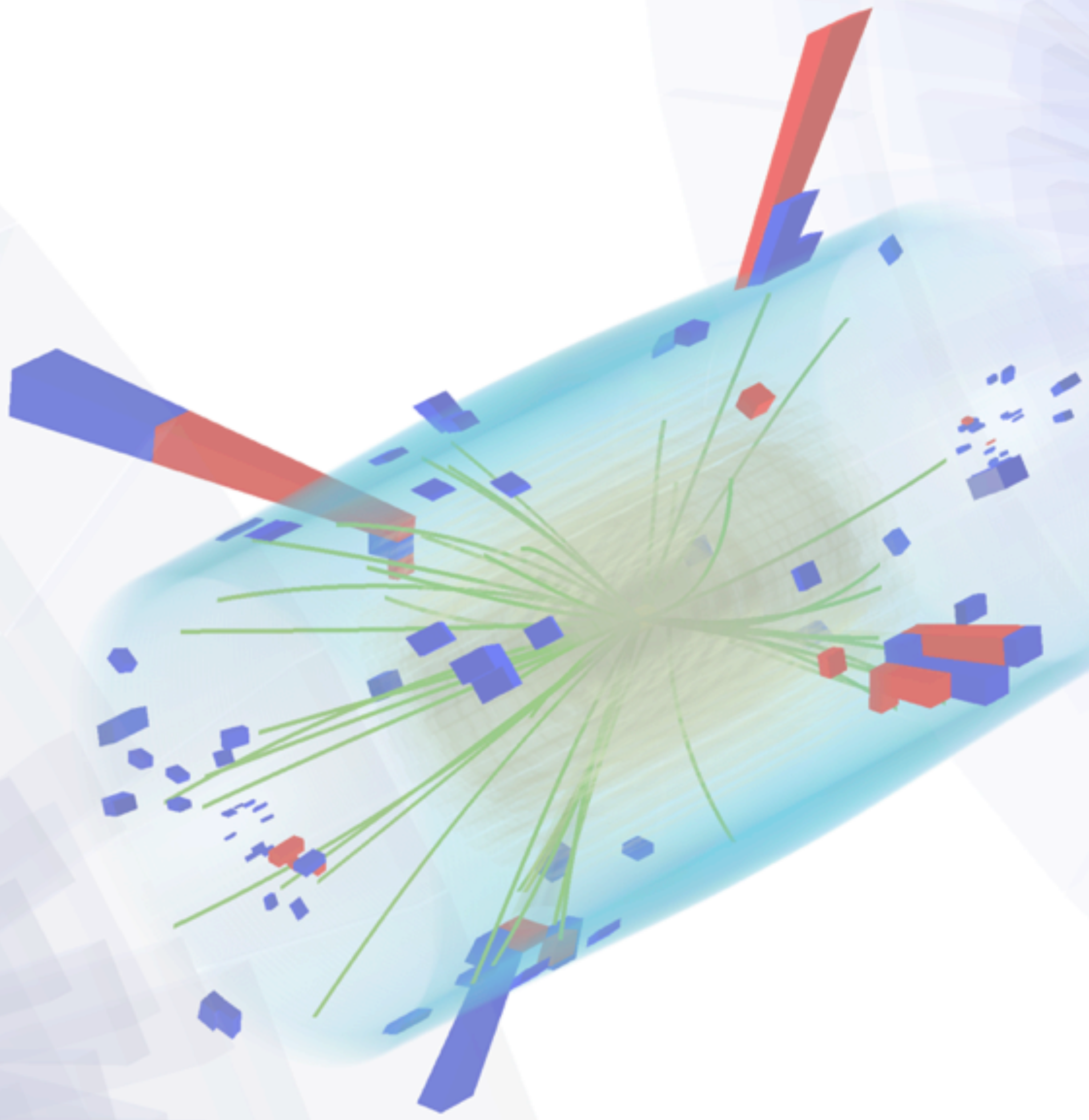
Outline



- Introduction and motivations
- The CMS experiment
- Double Higgs searches at LHC
- Results
- Beyond LHC
- Conclusions

The Higgs role

LHC delivered amazing results in Higgs physics. In 7 years of running:

- Discovery
- Spin and parity have been assessed, mass and couplings with ever higher precision.
- Observed (most) Higgs production and decay modes (VBF, ttH, VH, HVV, H$\gamma\gamma$, H$\tau\tau$…)

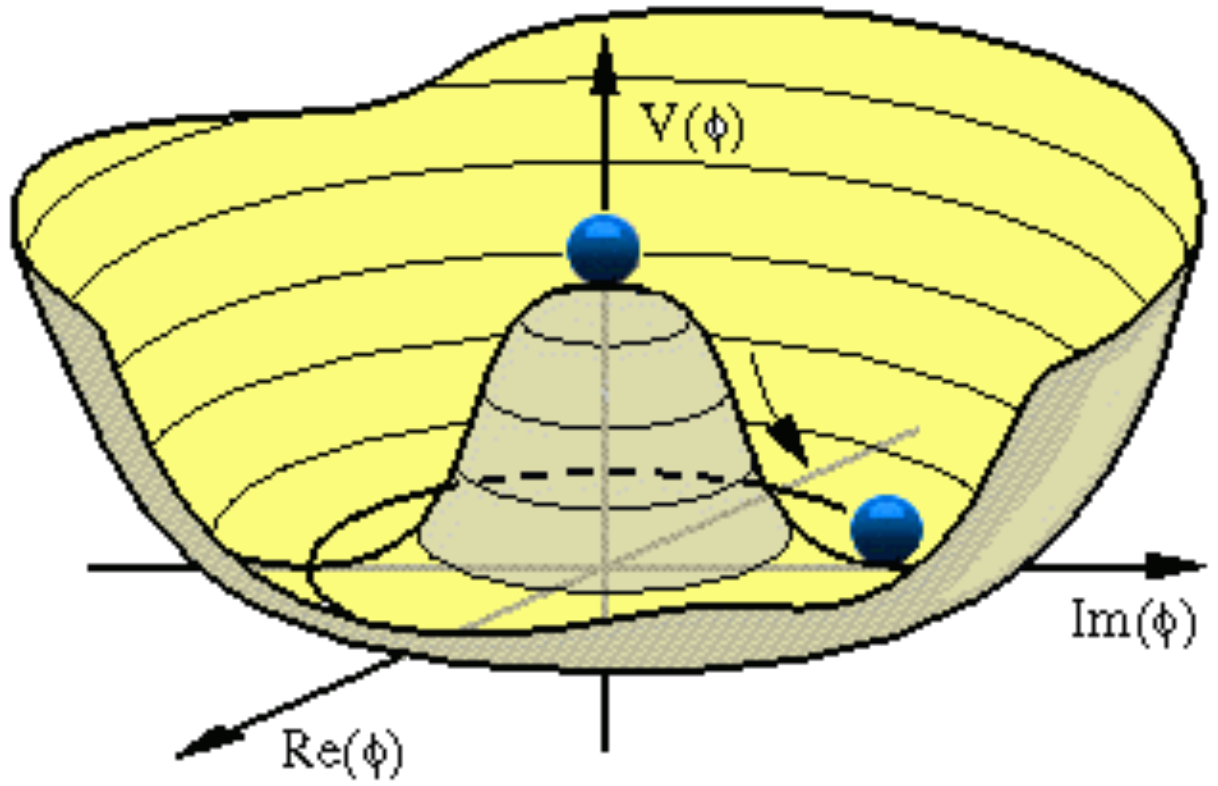
But searches for deviations from the SM have so far turned out empty-handed

The ElectroWeak Symmetry Breaking is the central feature of the Standard Model

- “Precision" Higgs measurements are meant to provide access and test this feature

$$\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda^2_{\mathrm{BSM}}}$$

With O(10%) precision on the couplings, we can probe the region $\Lambda_{\mathrm{BSM}} > 500(g_*/g_{\mathrm{SM}})$ GeV

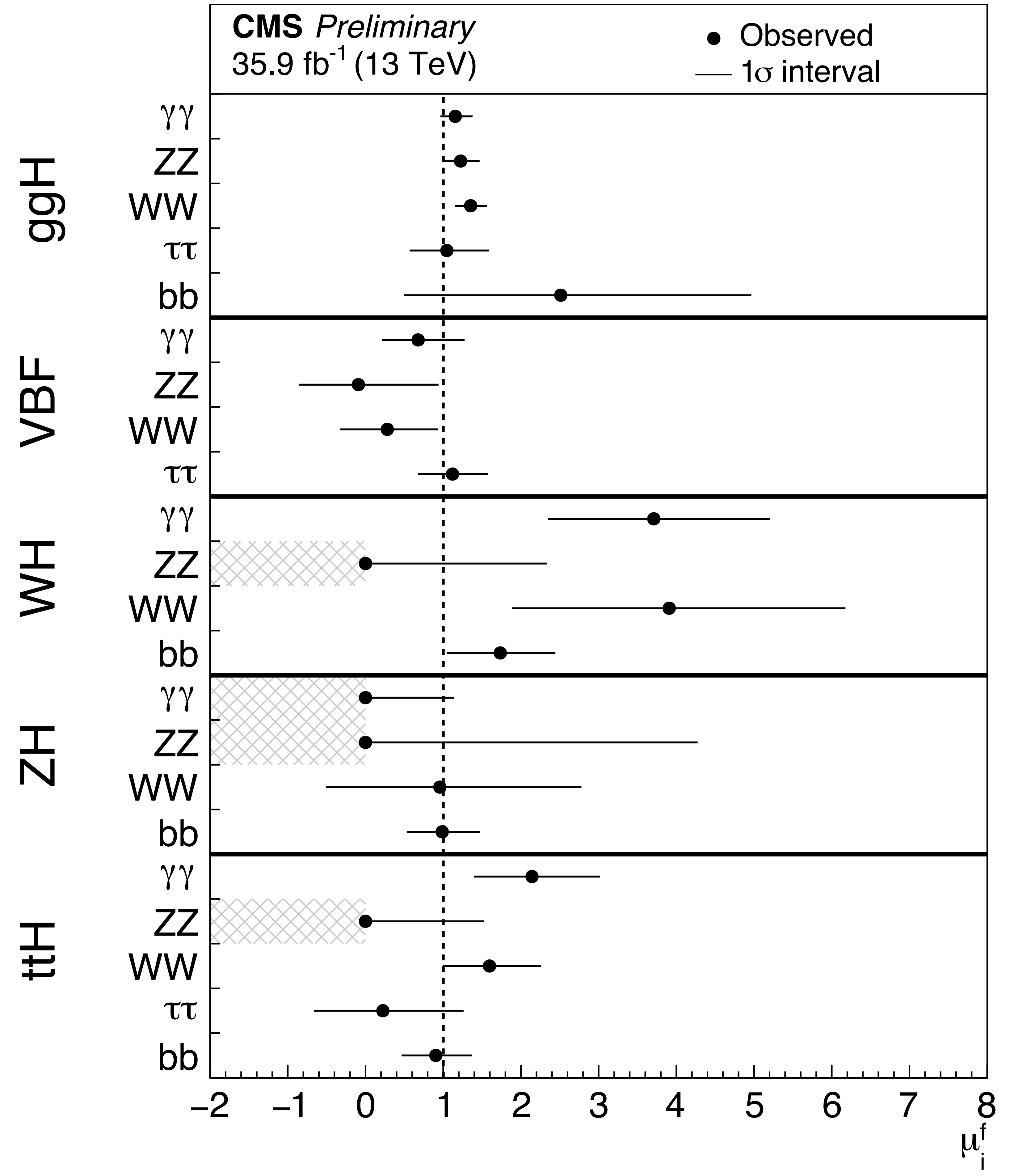


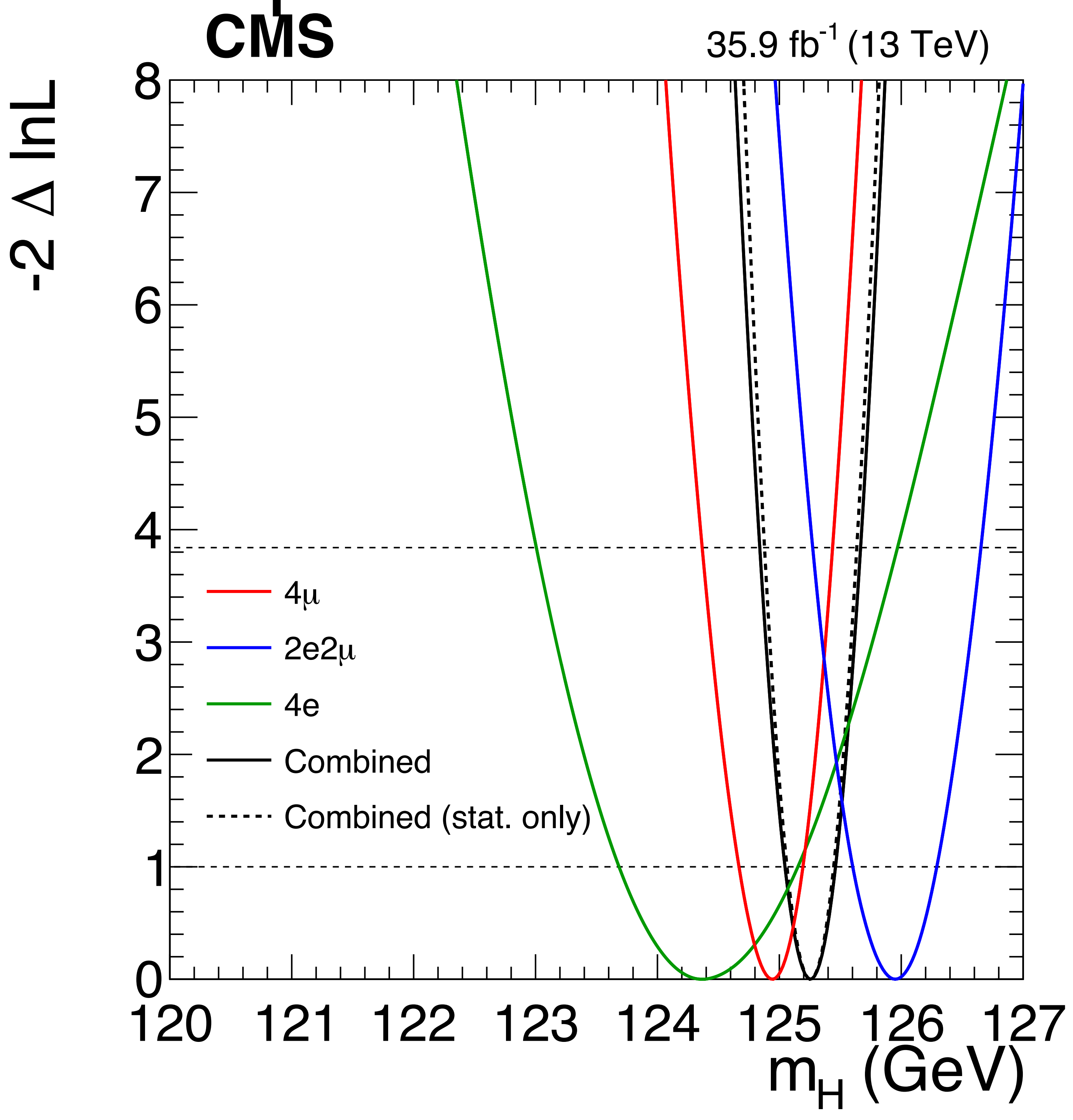
The Standard Model as of today

The precise knowledge of the Higgs couplings and mass is crucial to test the SM

Most general parametrisation for couplings: product of production x decay signal strength with all parameters floating

- 5x5 matrix μ_i={ggH, VBF, WH, ZH, ttH} x μ^f={$\gamma\gamma$, ZZ, WW, bb, ττ}
- 22/25 measurements available
- Most precise measurements: ggH, ZZ, WW, $\gamma\gamma$ (10% precision)





- Starting to explore differential measurements

Higgs mass determination

- CMS HZZ alone $m_H = 125.26 \pm 0.21$ GeV (0.2% uncertainty)

NB: double Higgs is not present in this picture!

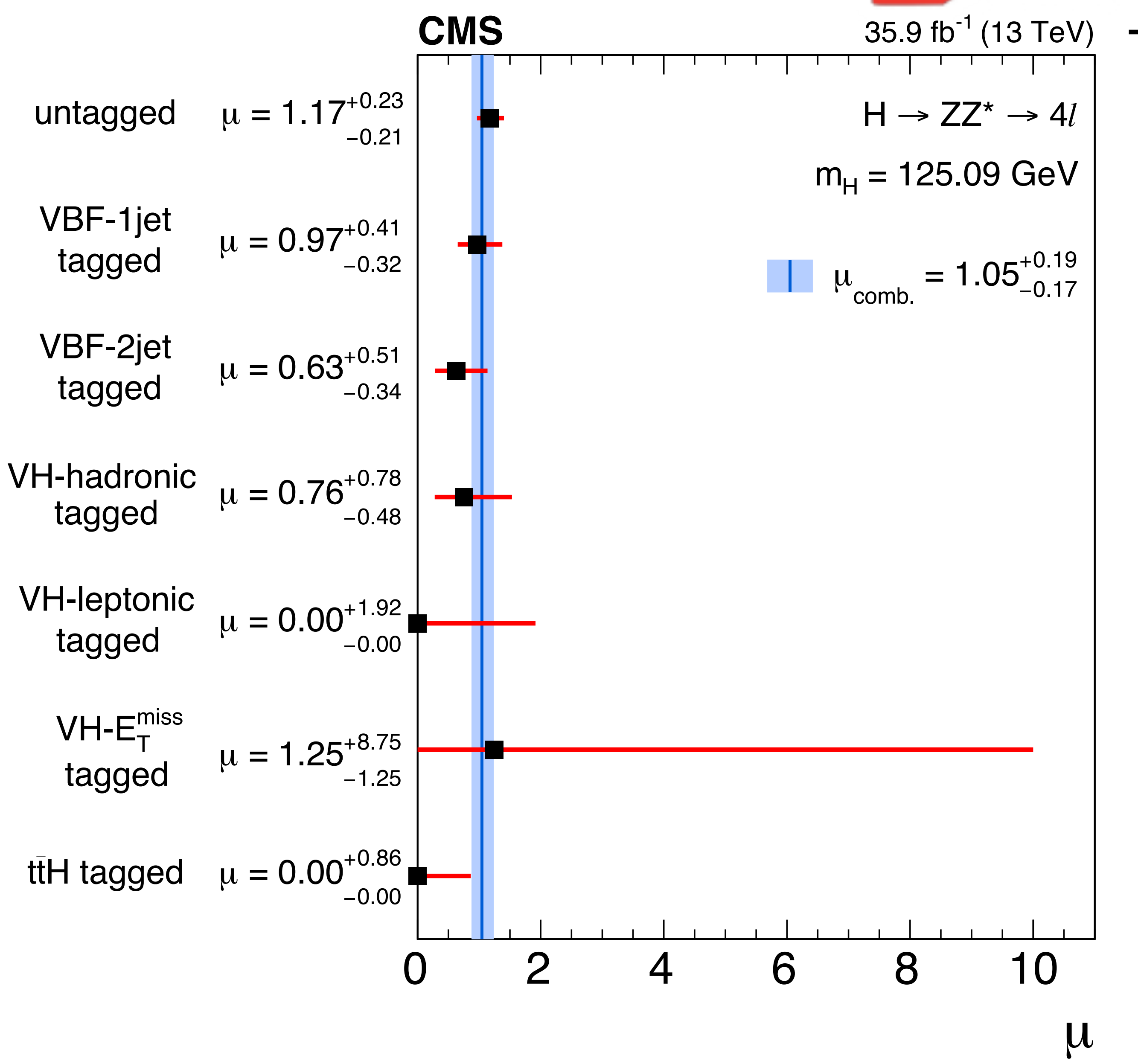
Higgs couplings

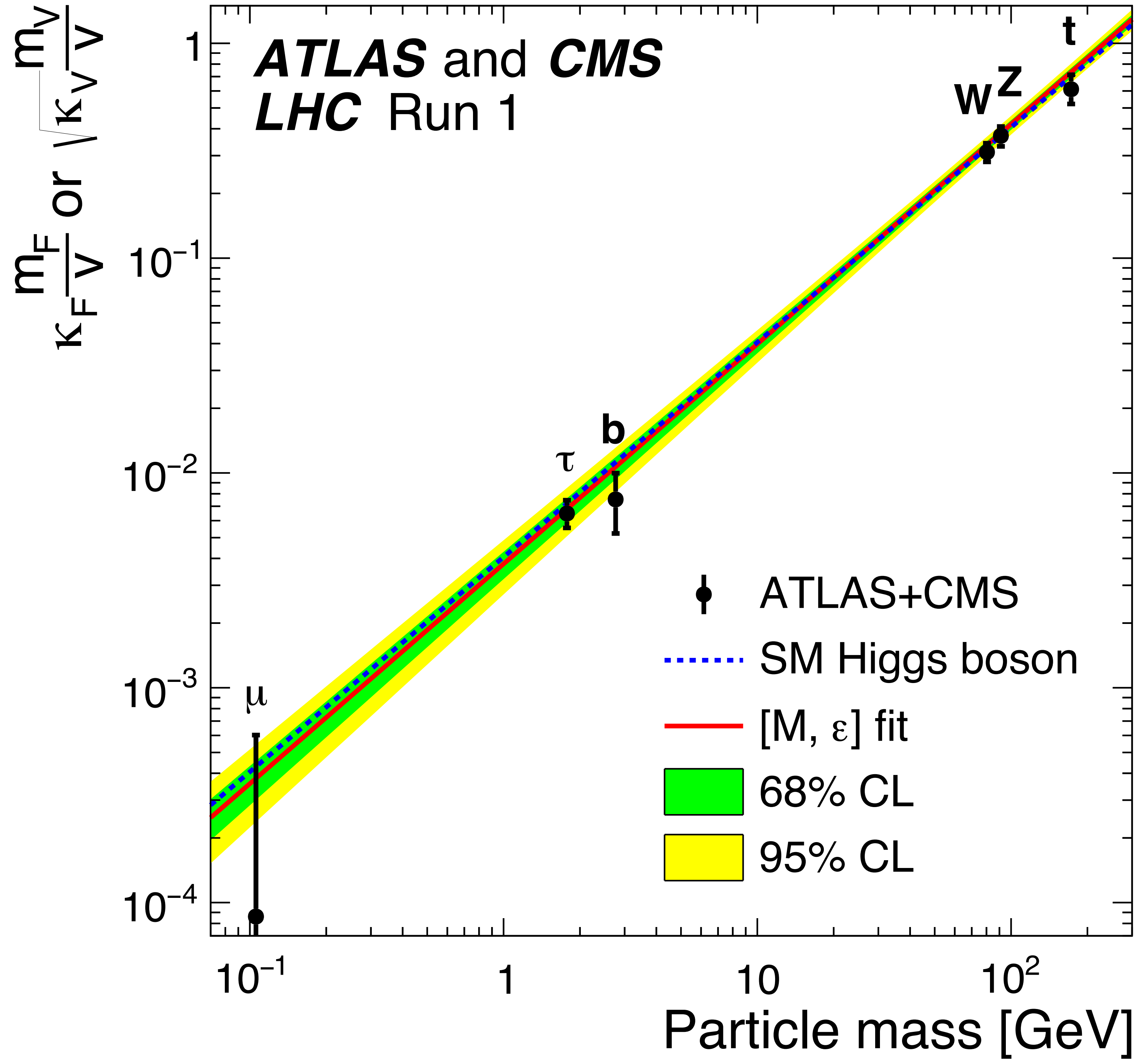
LHC run1&2 allowed to study the Higgs boson properties

Main focus: mass and **couplings**

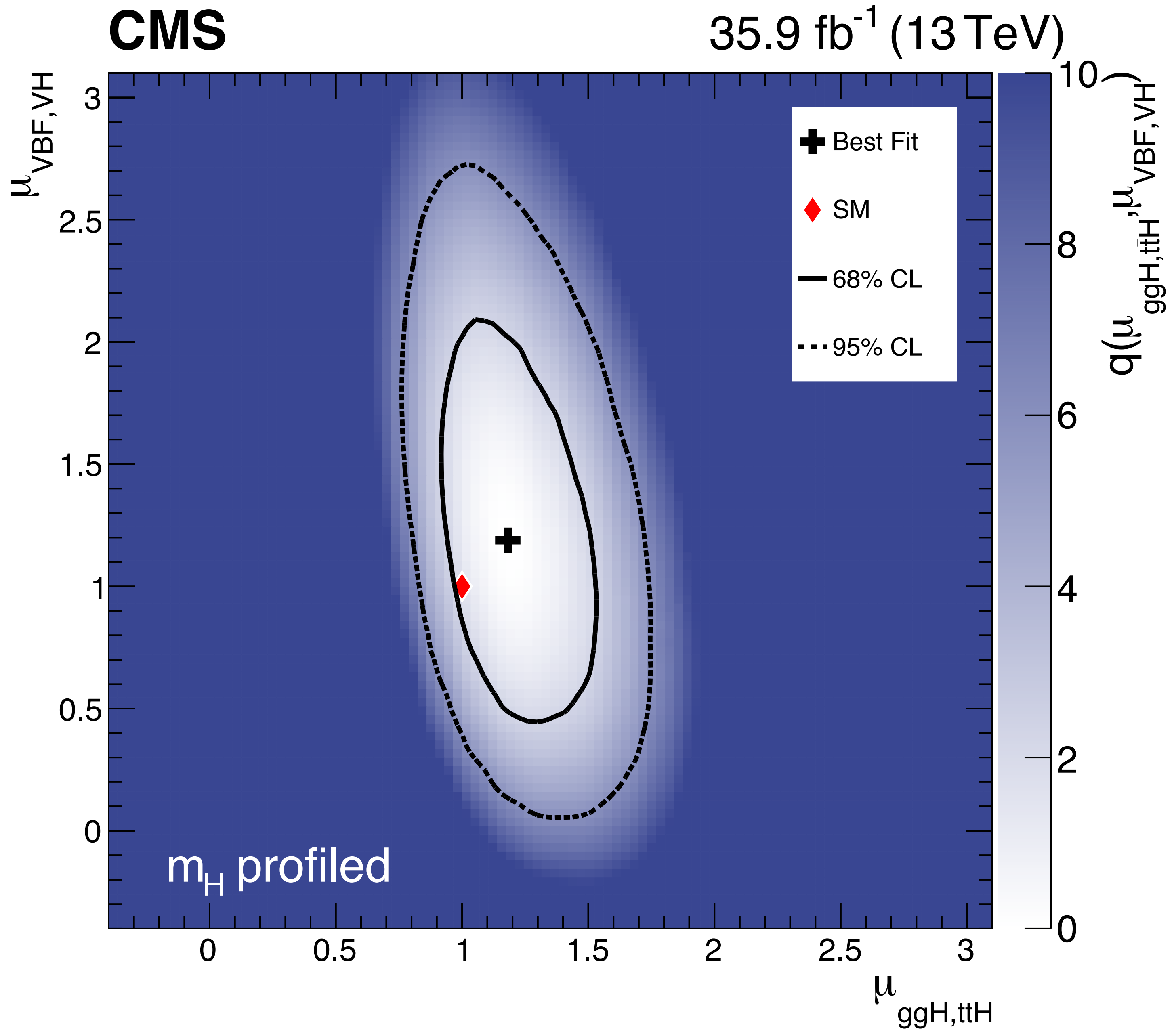
- Signal strengths, **k-framework**, anomalous couplings used to quantify possible BSM effects

General strategy: identify selection/categories sensitive to different production/decay modes





Overall picture from couplings highly consistent with the Standard Model expectations



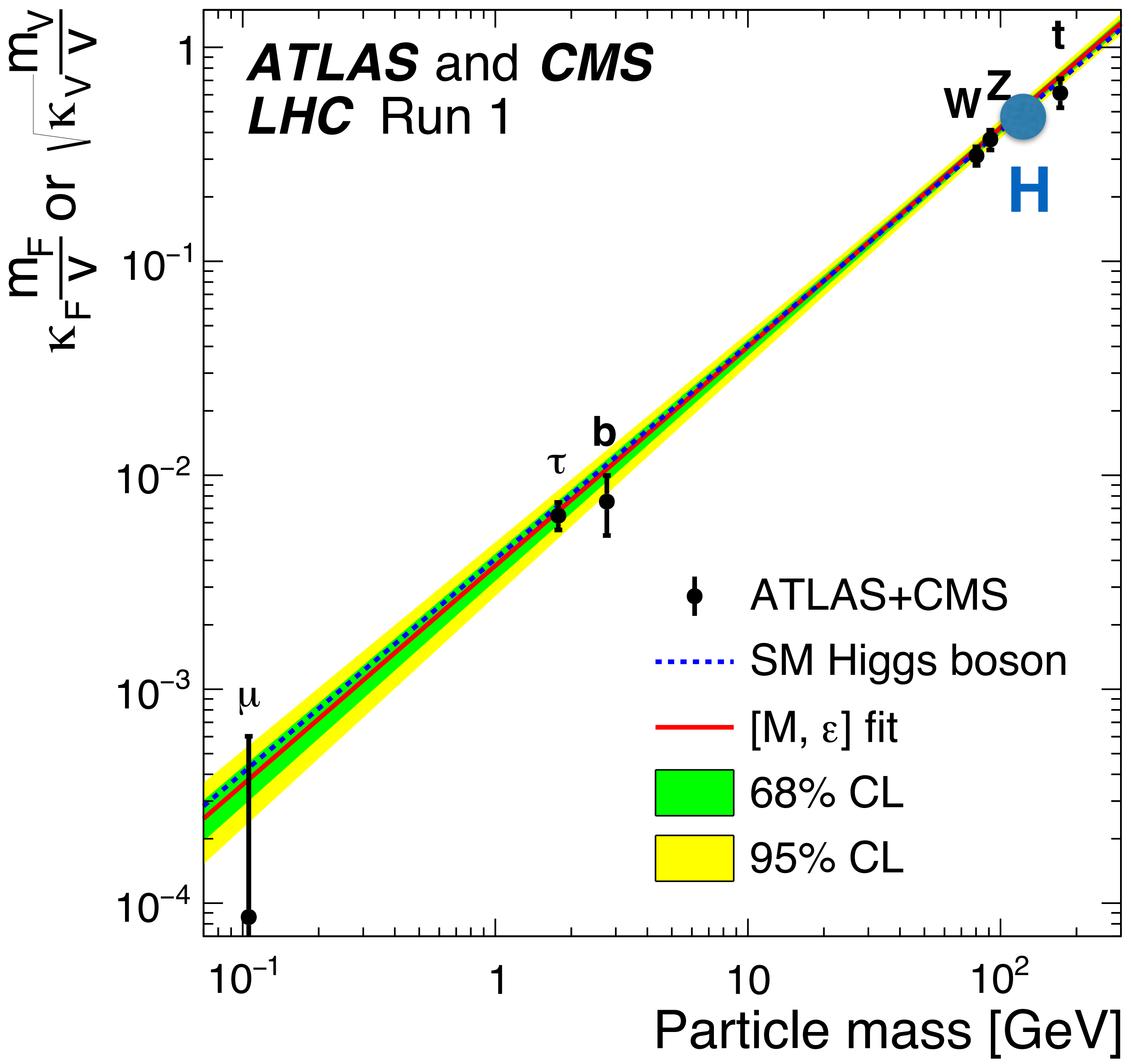
Why measure HH?

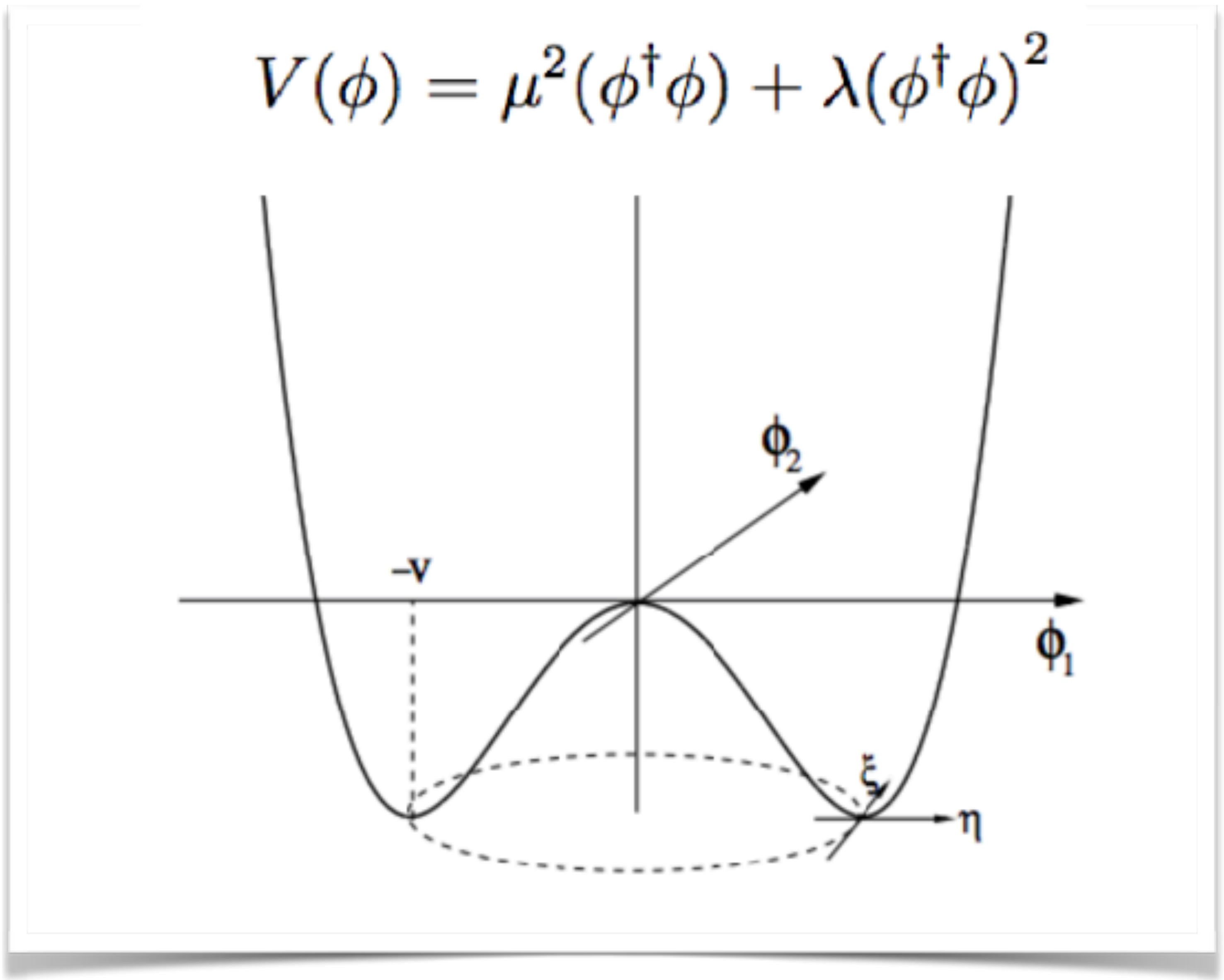
Measurement of HH gives access to the magnitude of the Higgs self-interaction:

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

Higgs trilinear coupling constant **λ** only depends on the Higgs field VEV and Higgs mass. Purely determined by EWSB (in the SM).

The shape of the Higgs potential is determined by the self coupling value (EWPT)





1) Linked to naturalness/hierarchy problem

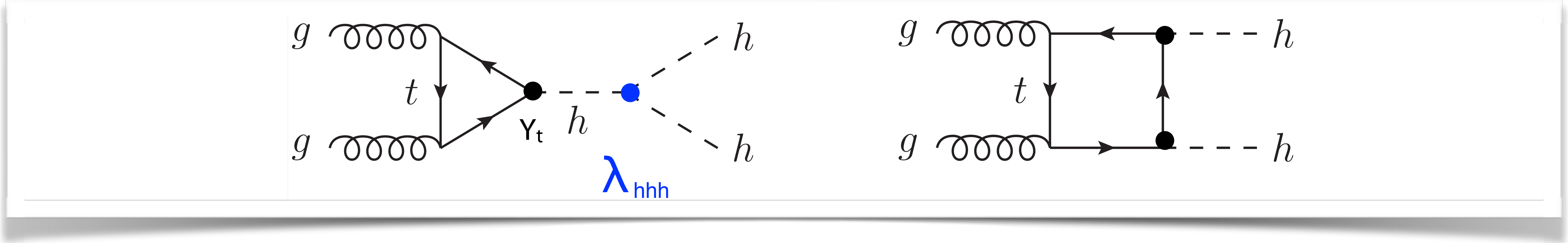
2) Controls the stability of the EW vacuum

3) Dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

4) Constraints on couplings assume k_λ=1

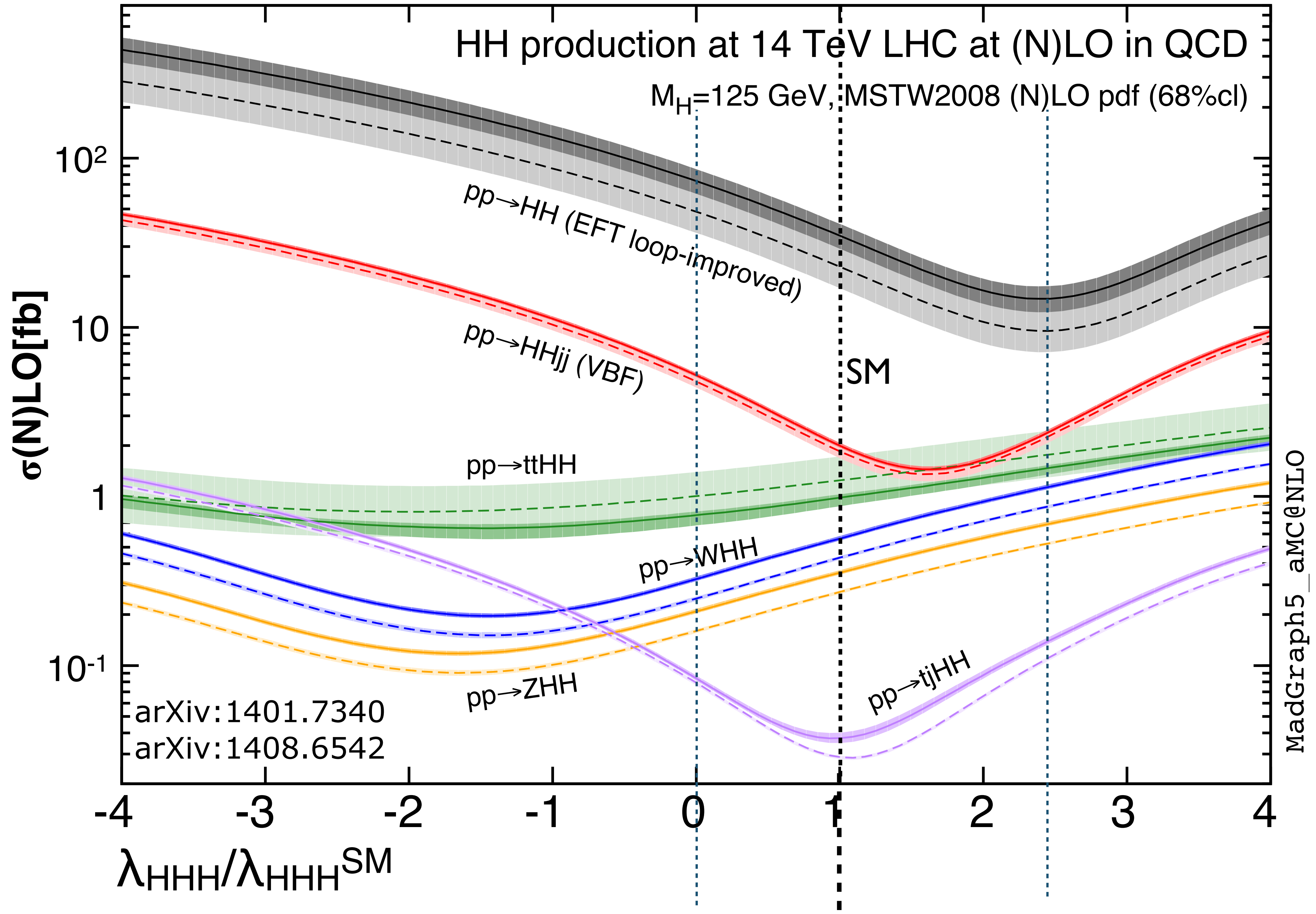
5) Access to off-shell Higgs properties

The Higgs trilinear coupling



$\sigma^{SM}_{hh}(13\text{TeV}) = 33.45\text{fb}^{+4.3\%}_{-6.0\%}$(scale unc.) ±3.1%(PDF+$\alpha_S$ unc)[1]

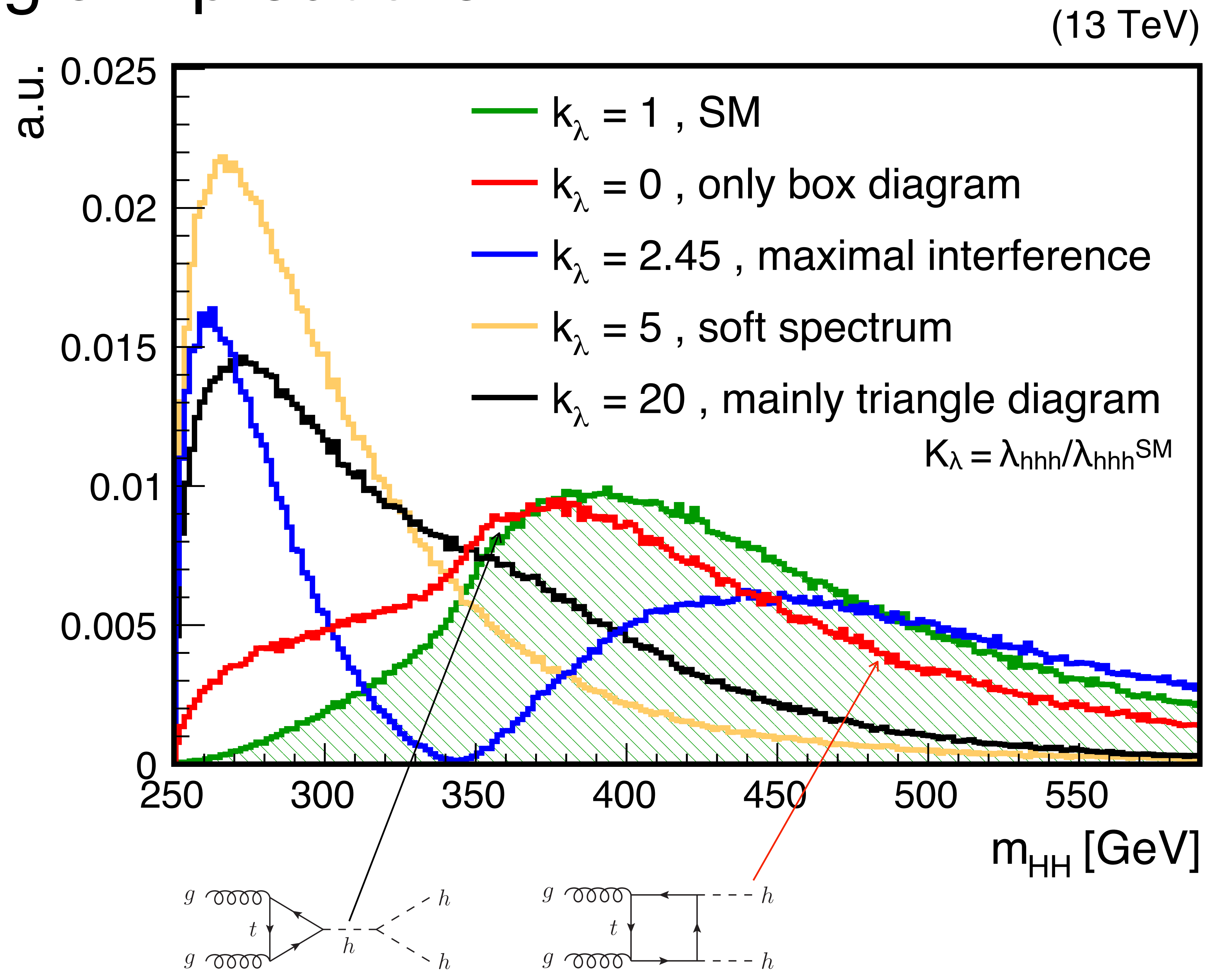
About 1/1000 smaller then single H production



Only box diagram

SM

Maximal interference between diagrams

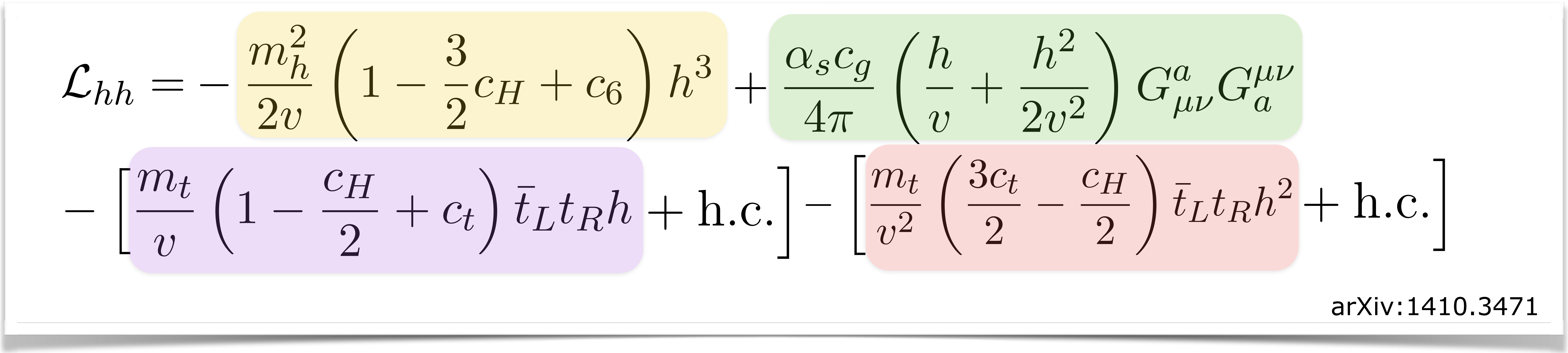


The value of λ_{hhh} affects both the production cross-section and the hh kinematics

[1] S. Borowka, N. Greiner, G. Heinrich, S.P. Jones, M. Kerner, J. Schlenk, U. Schubert, T. Zirke Phys. Rev. Lett. 117, 012001 (2016)

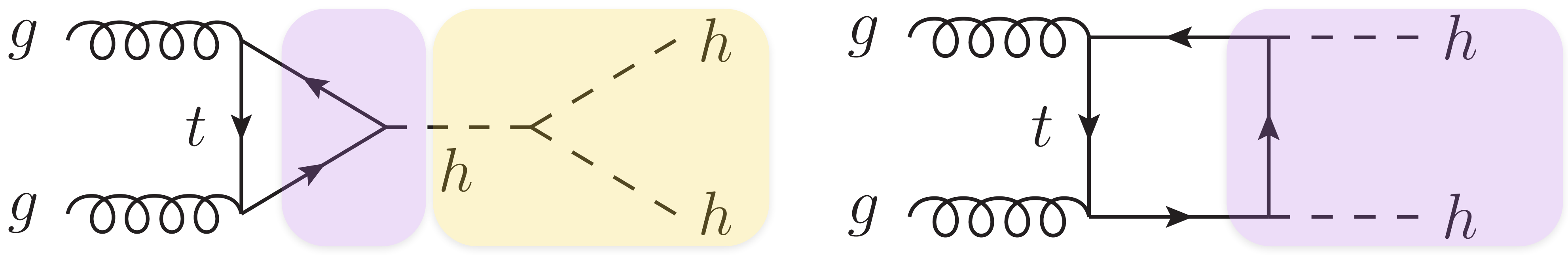
gg→hh parametrization

The relevant lagrangian terms of gg→HH production in D=6 EFT

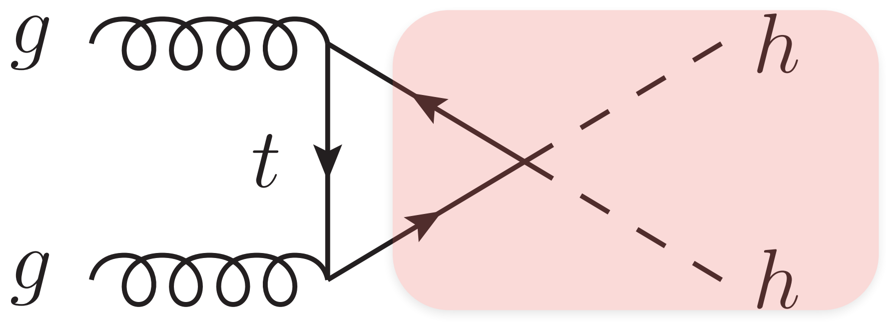


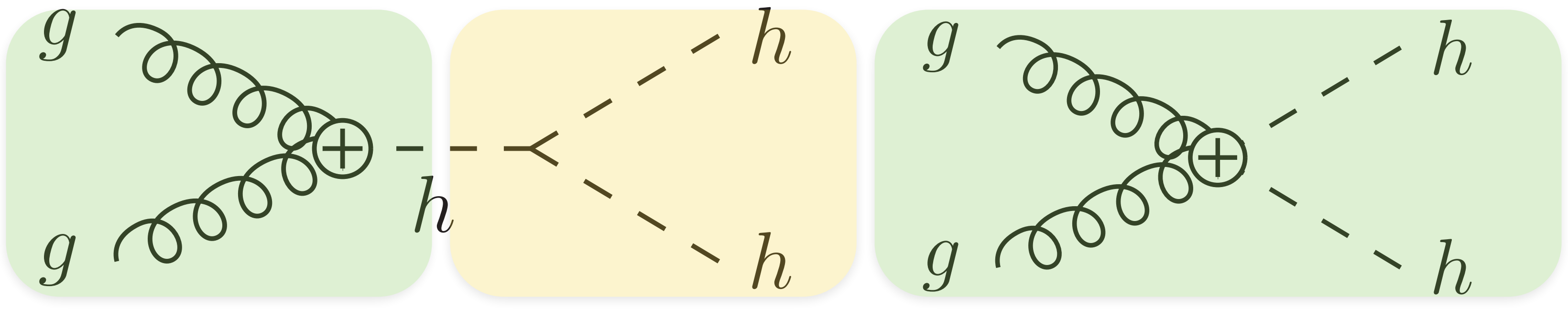
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H+c_6\right)h^3 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a - \left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \mathrm{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \mathrm{h.c.}\right]$$

arXiv:1410.3471



SM diagrams

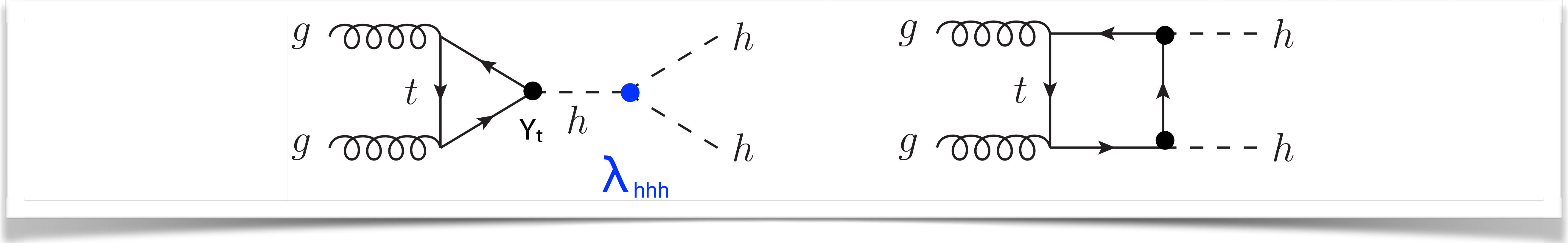




ttHH non-linear interaction

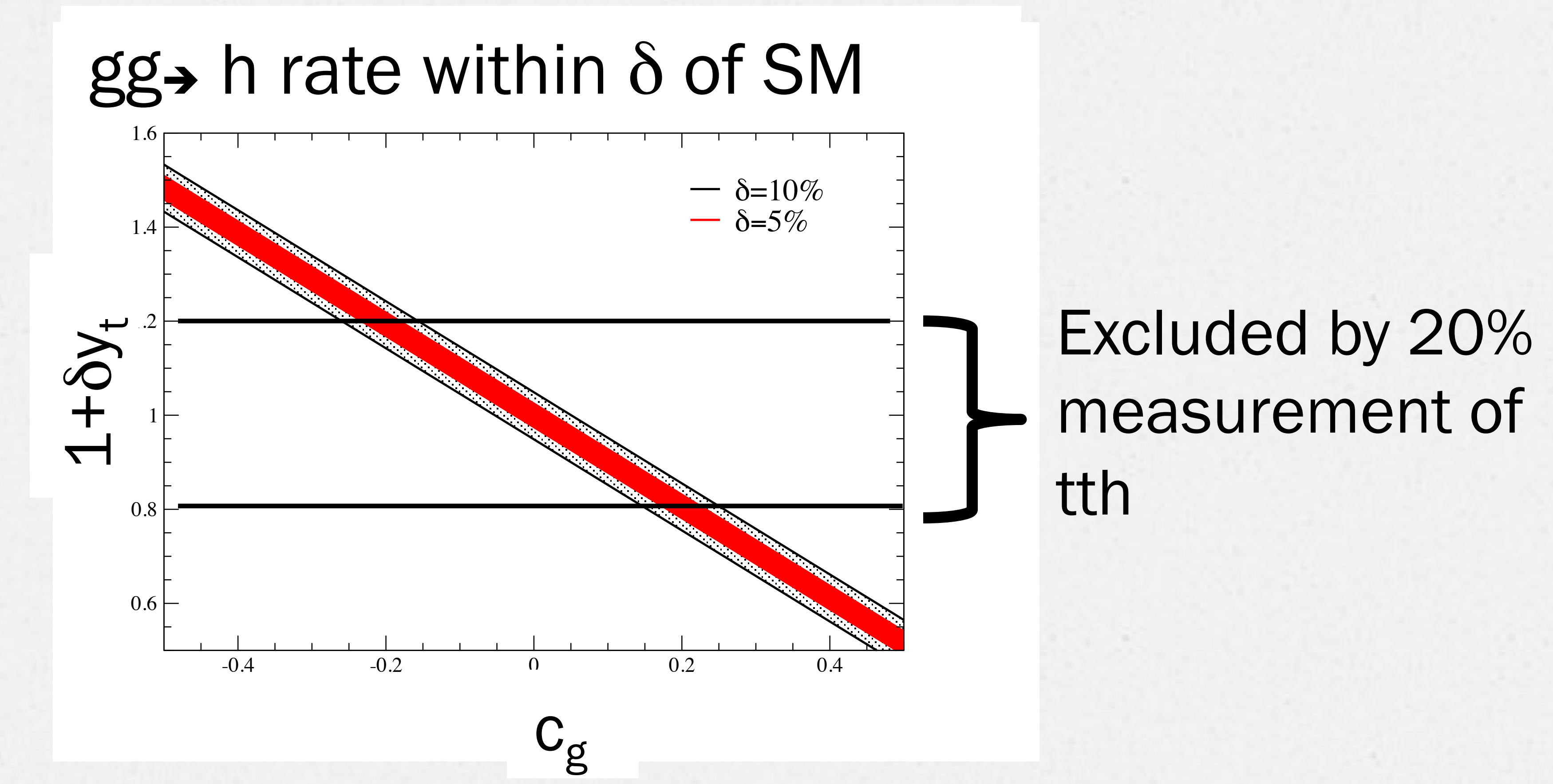
Higgs-gluon contact interactions

Motivations: BSM searches



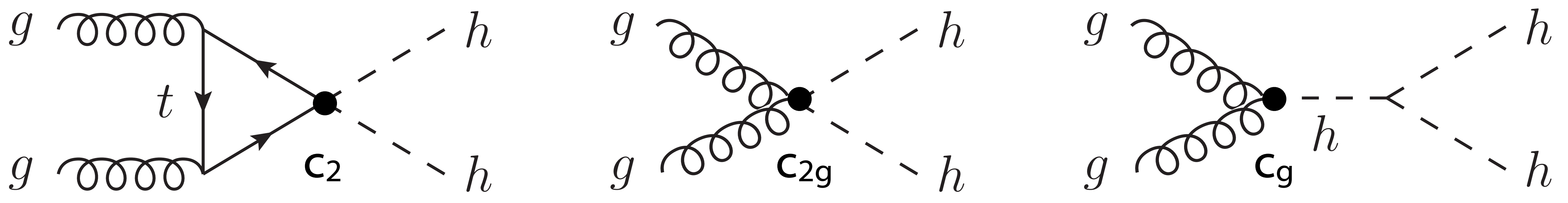
$\sigma^{SM}_{hh}(13TeV) = 33.45fb^{+4.3\%}_{-6.0\%}$(scale unc.) ±3.1%(PDF+$\alpha_S$ unc)[1]

The non-resonant double Higgs production allows to directly probe the Higgs trilinear coupling (λ_{hhh}).



Even if in Run2 we do not have full sensitivity to "measure" SM λ_{hhh} → The BSM physics can be modelled in EFT adding dim-6 operators[2] to the SM Lagrangian, and the physics can be described with 5 parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

- Non SM top Yukawa and λ_{hhh} couplings
- New diagrams and couplings in the game



[1] S. Borowka, N. Greiner, G. Heinrich, S.P. Jones, M. Kerner, J. Schlenk, U. Schubert, T. Zirke Phys. Rev. Lett. 117, 012001 (2016)
[2] S. Dawson et al. *Phys. Rev.* **D91** (2015), no. 11, 115008

An EFT implementation for hh

2D (M_{HH},cosϑ^*) signal shapes from different points in the 5D EFT phase space are clustered together.

12 clusters are identified according to there kinematical properties

Inside each cluster, a representative shape is identified, as the one with the minimum distance (in the test statistics) from all other shapes in the cluster

$$R_{hh} \equiv \frac{\sigma_{hh}}{\sigma_{hh}^{SM}} \overset{LO}{=} A_1\kappa_t^4 + A_2c_2^2 + (A_3\kappa_t^2 + A_4c_g^2)\kappa_\lambda^2 + A_5c_{2g}^2 + (A_6c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\kappa_t\kappa_\lambda + A_9c_g\kappa_\lambda)c_2 + A_{10}c_2c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2$$
$$+(A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_gc_{2g}\kappa_\lambda\,.$$

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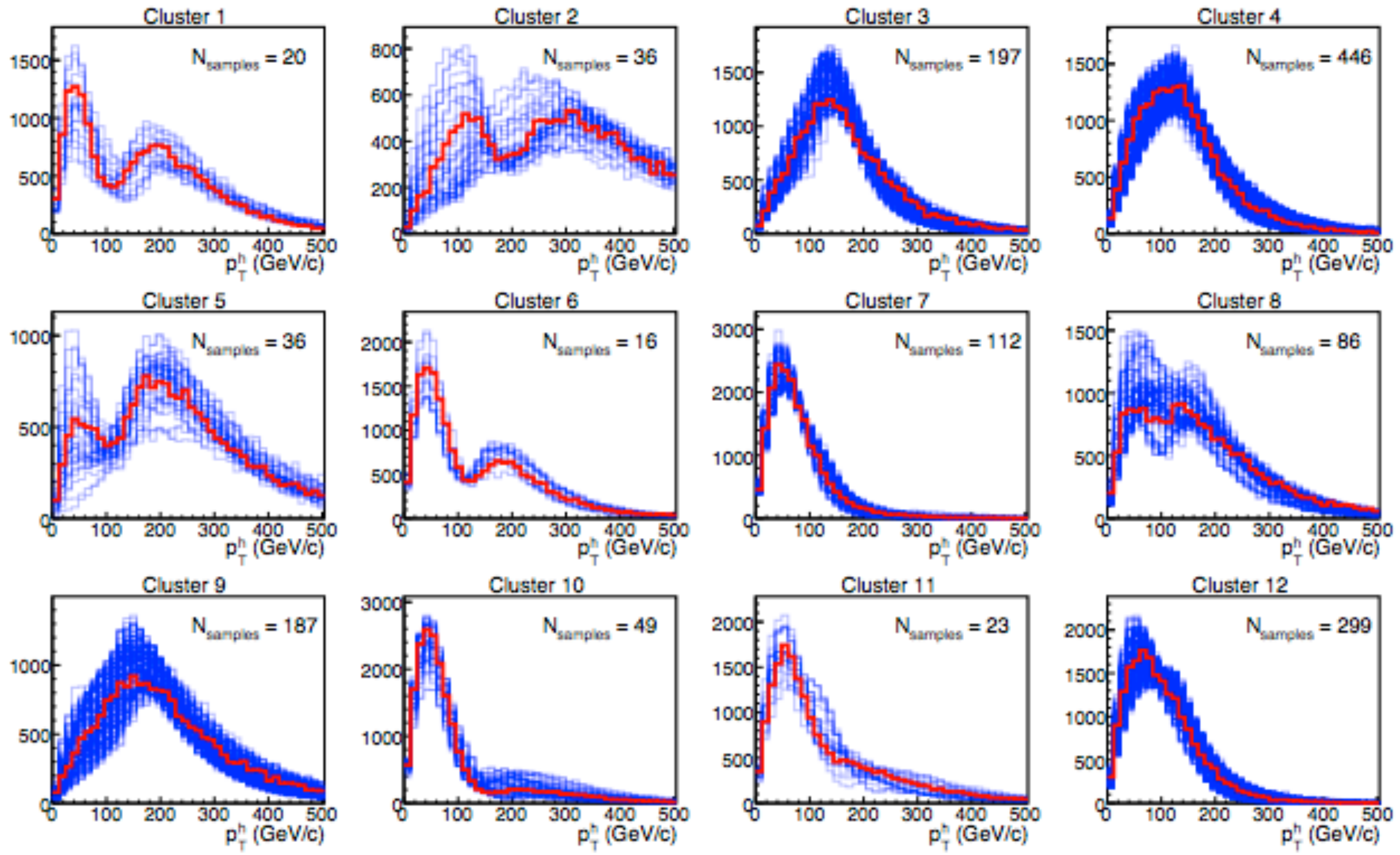
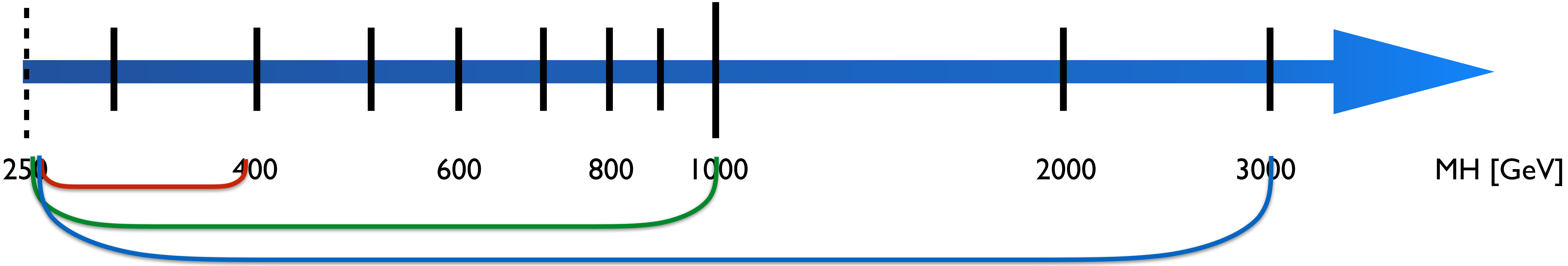


The double Higgs production cross section can be written as a function of the 5 EFT parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

Each point of the phase space can be mapped by means of its cross-section and representative shape

Motivations: Resonant searches



MSSM/2HDM: Additional Higgs doublet→CP-even scalar H.

- We can probe the low m_A/low tanβ region where BR(H→h(125)h(125)) is sizeable.

Singlet model: Additional Higgs singlet with an extra scalar H.

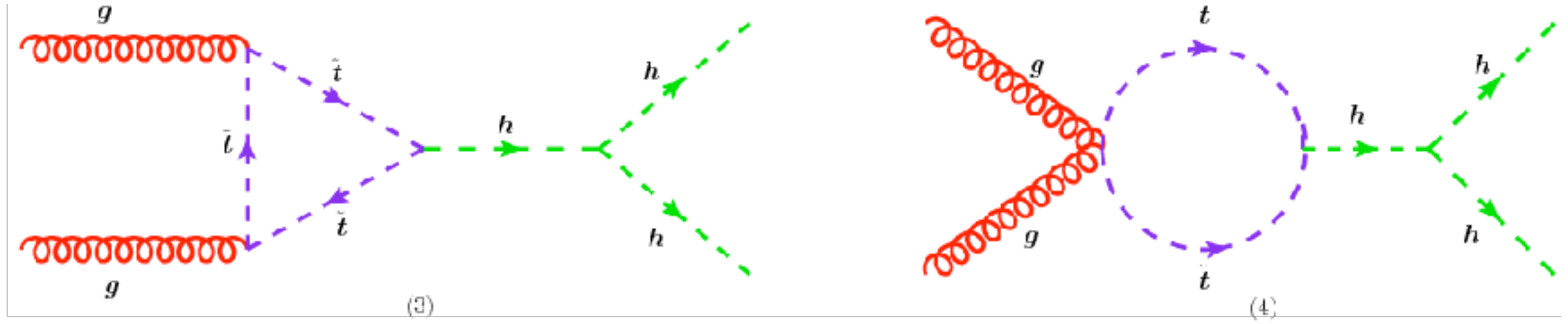
- Sizeable BR beyond 2xm_{top}, non negligible width at high m_H.

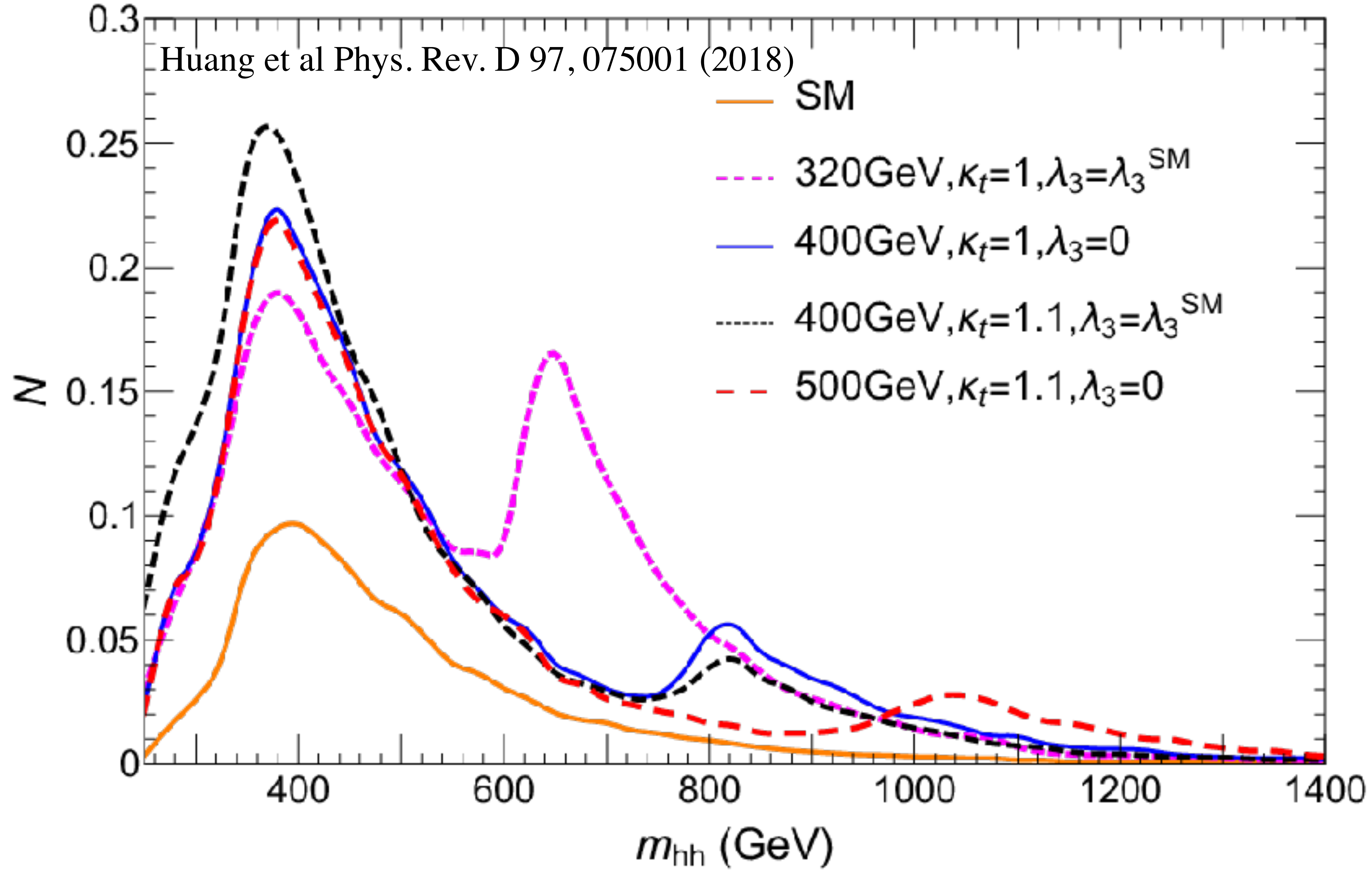
Warped Extra Dimensions:

spin-2 (KK-graviton) and spin-0 (radion) resonances.

- Different phenomenology if SM particles are allowed (bulk RS) or not (RSI model) in the extra dimensional bulk

HH Studies: Resonant




Huang et al Phys. Rev. D 97, 075001 (2018)

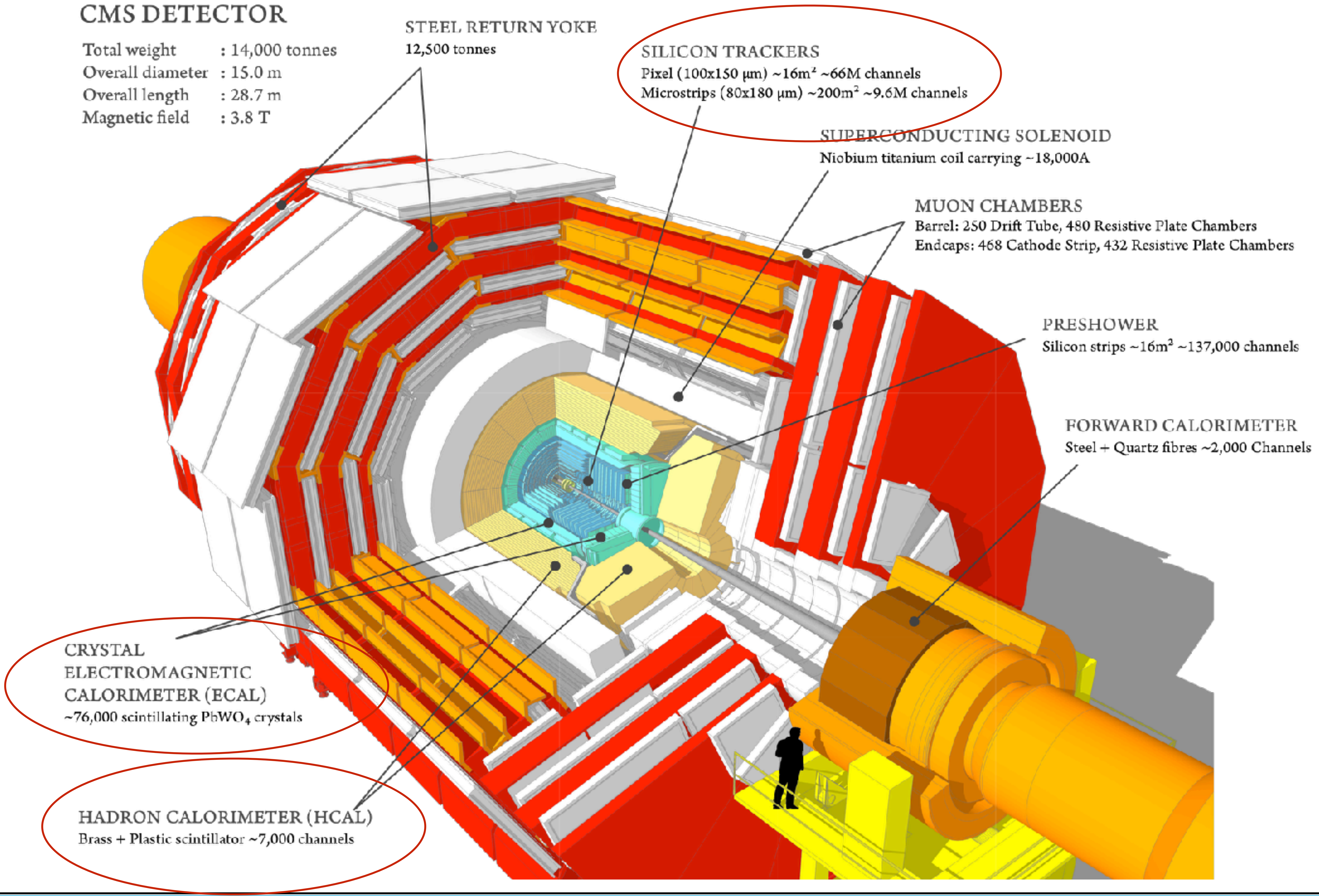
Non-resonant production is a SM process, but there is interest in probing resonant HH production

Higgs couples to massive particles. We can think of a particle with $M_X>2M_H$ that in the SM sector mostly couples with the Higgs

Such a particle would only be visible through its HH decay, and would appear as a resonance (peak) in the double Higgs invariant mass spectra

Several theoretical model available for such a particle (SUSY, extra dimensions…)

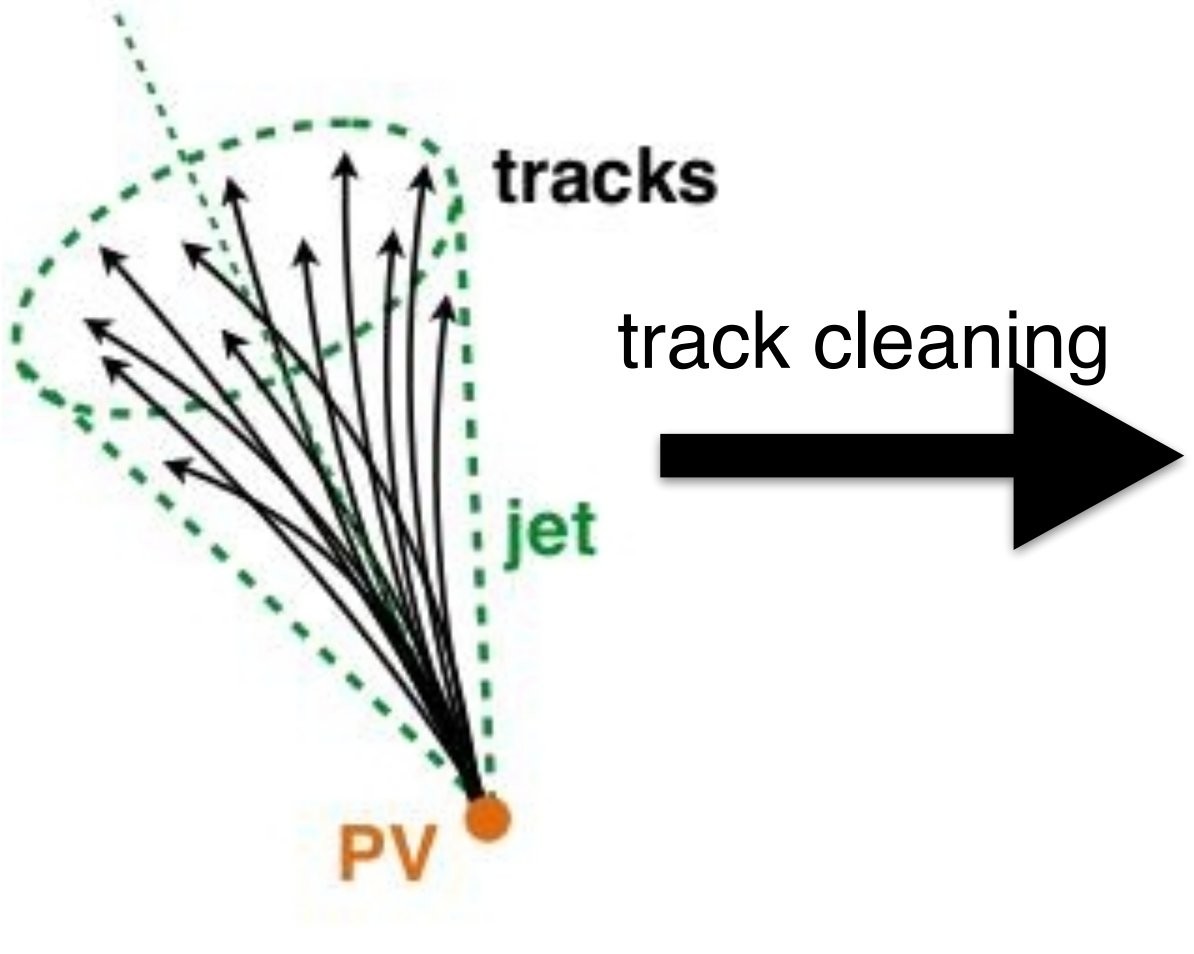
The CMS detector



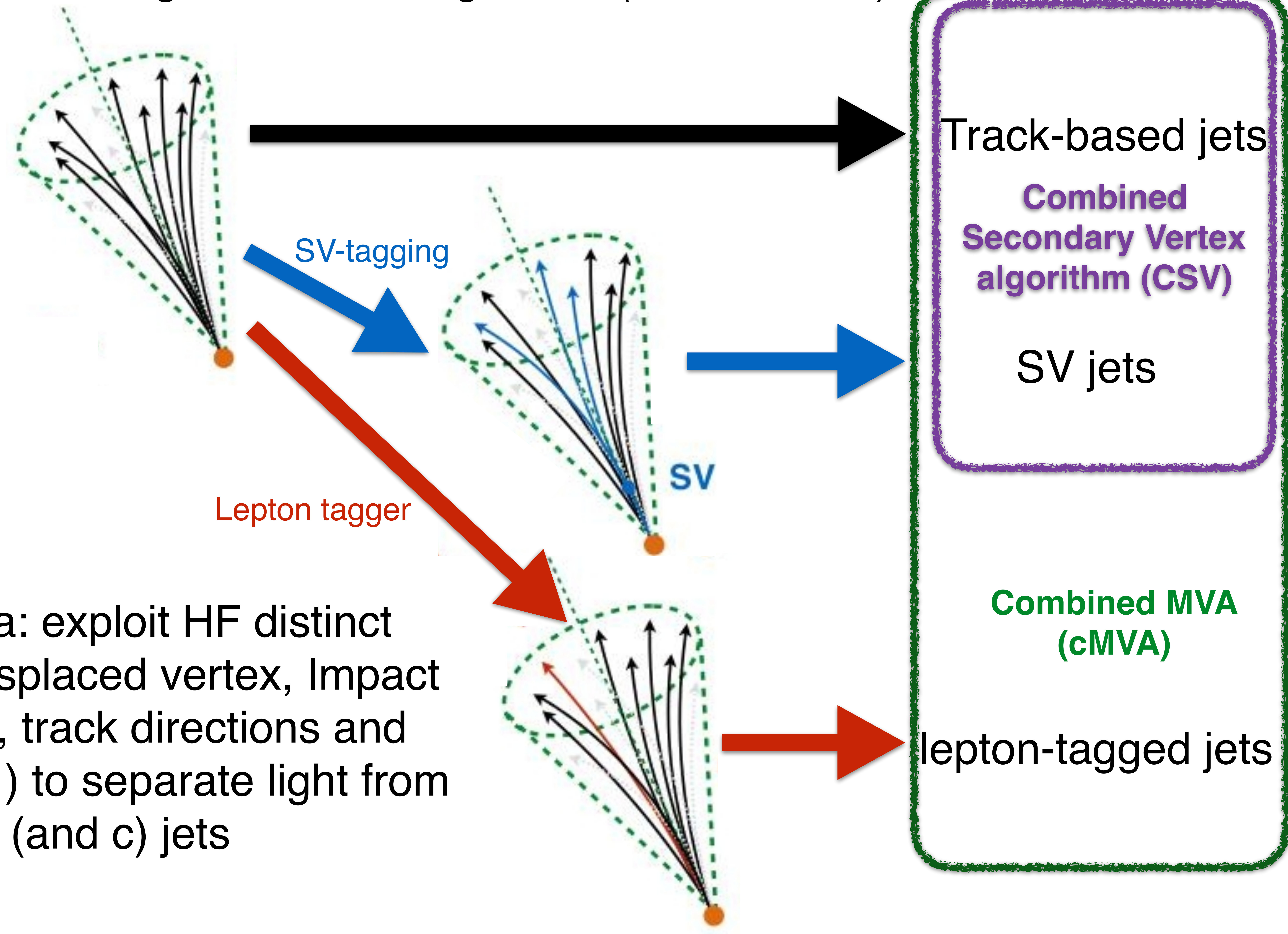
- Most of this presentation will focus focuses on CMS results
- Similar sensitivities/ strategies in ATLAS

B-jets identification at CMS

Start: AK4 jets. Jets are reconstructed using the anti-KT algorithm (radius of 0.4)



track cleaning



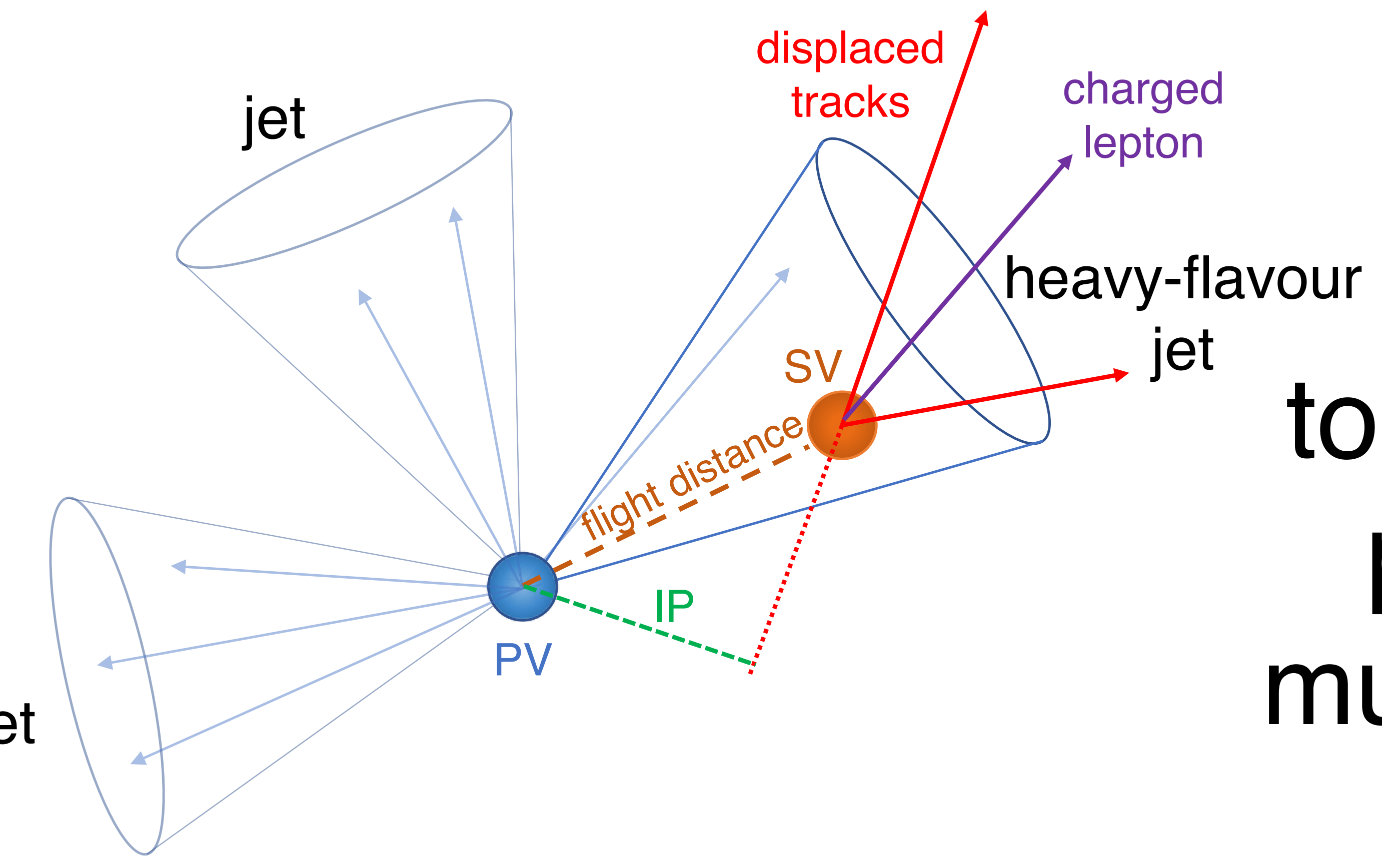
Track-based jets

Combined Secondary Vertex algorithm (CSV)

SV jets

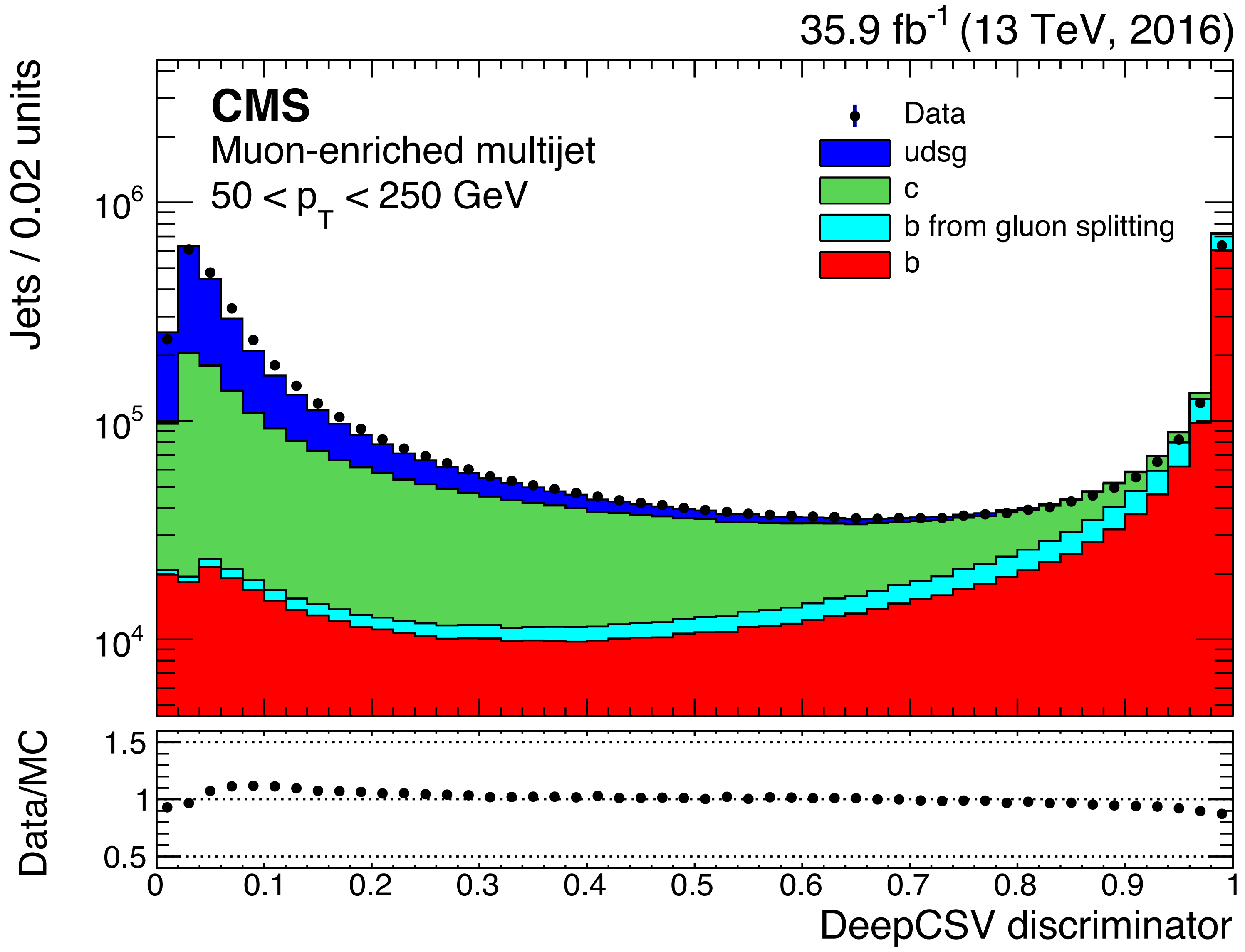
Combined MVA (cMVA)

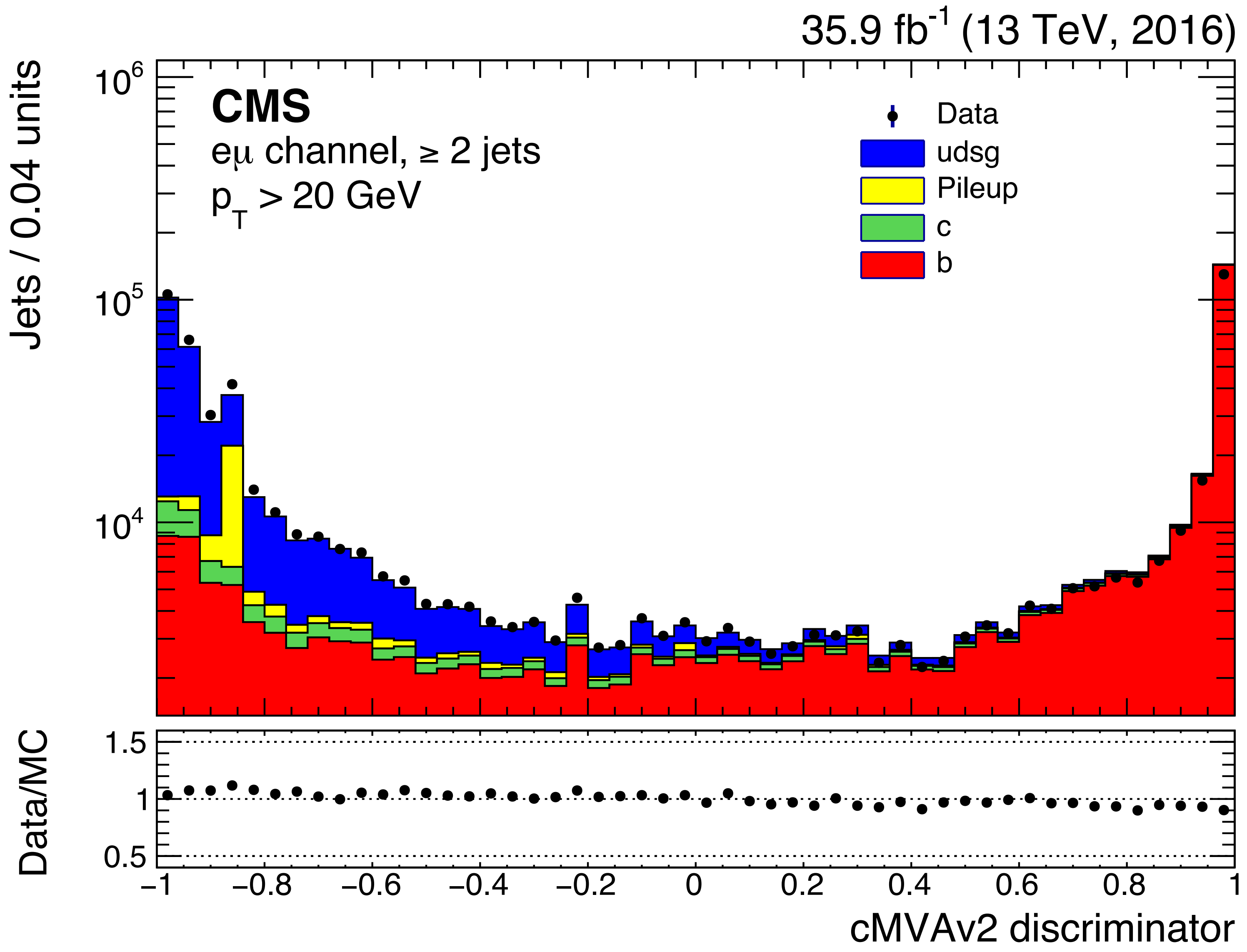
lepton-tagged jets

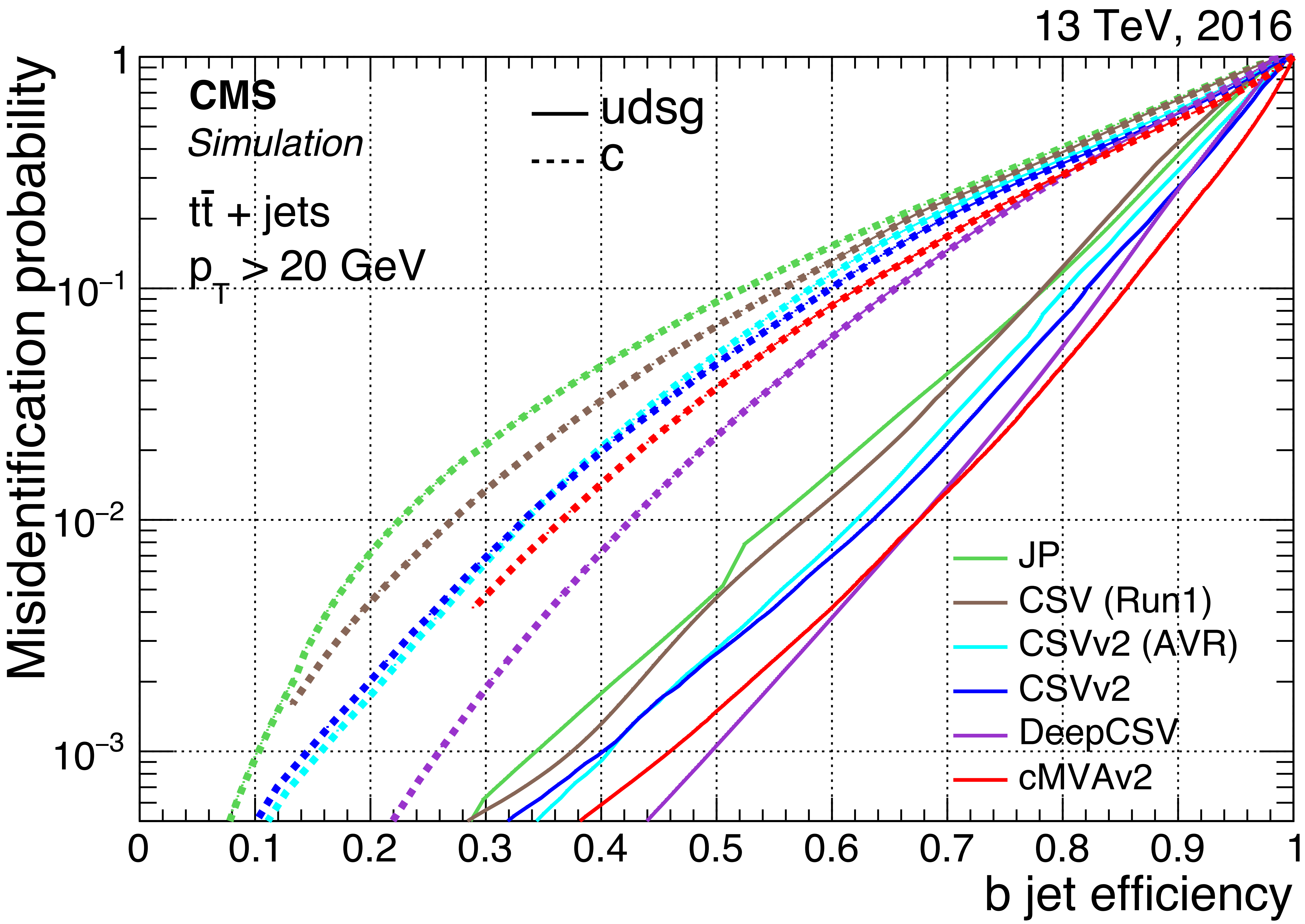


Basic idea: exploit HF distinct topology (displaced vertex, Impact parameter, track directions and multiplicity…) to separate light from b (and c) jets

B-jets Performances

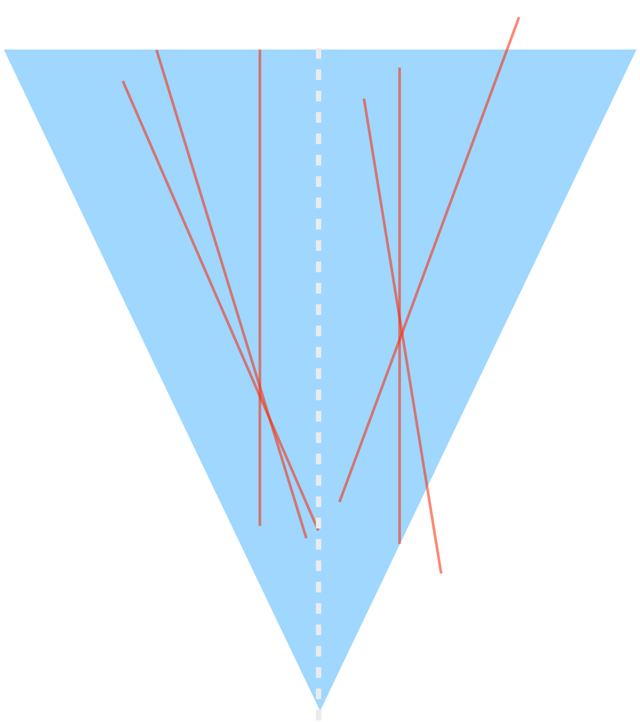




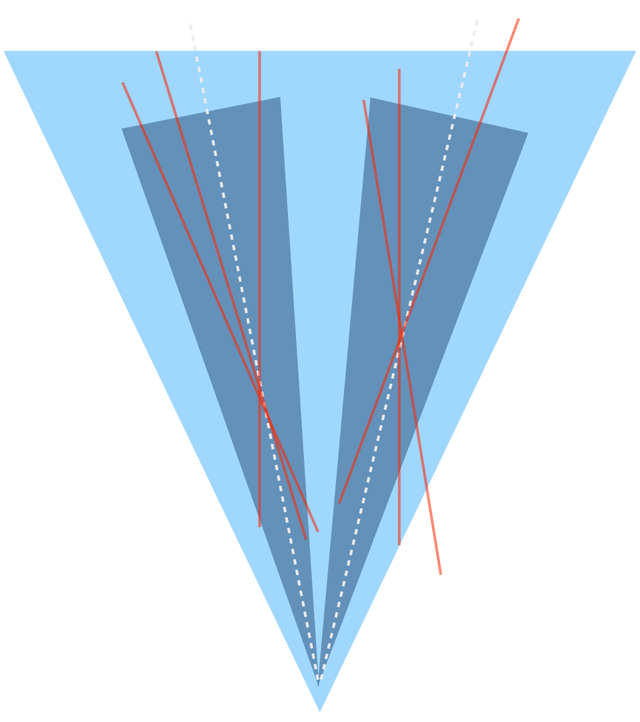


Best performing algorithm depends on the main background of each analysis.
For double Higgs in CMS, we use DeepCSV, cMVA, CSV

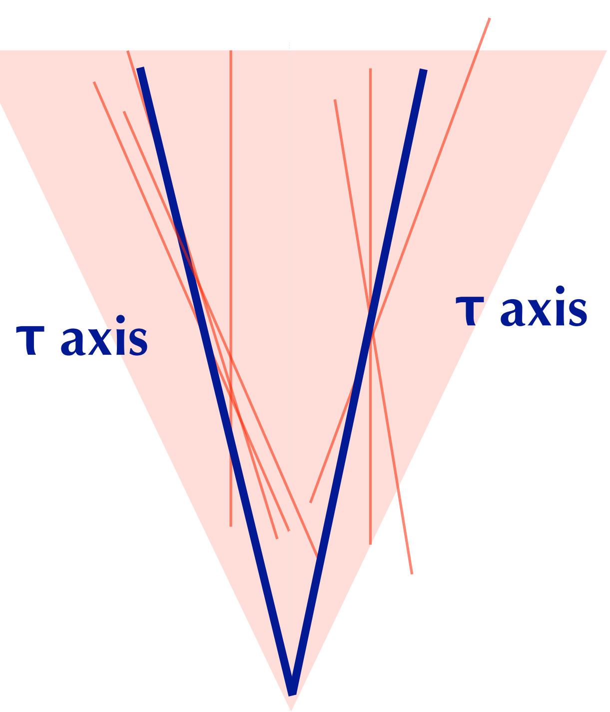
B-jets identification at CMS: boosted topologies



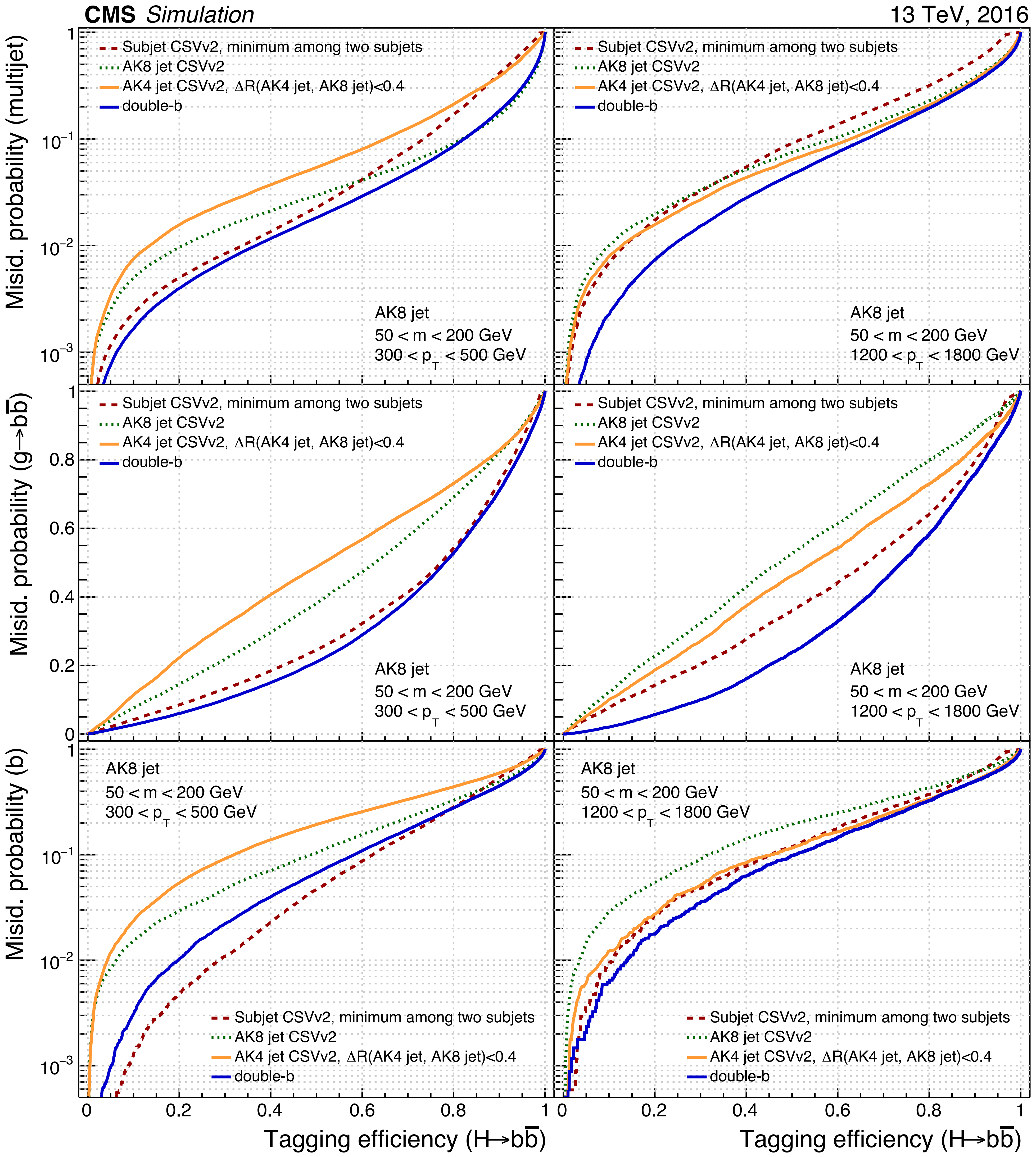
AK8 jet



subjets



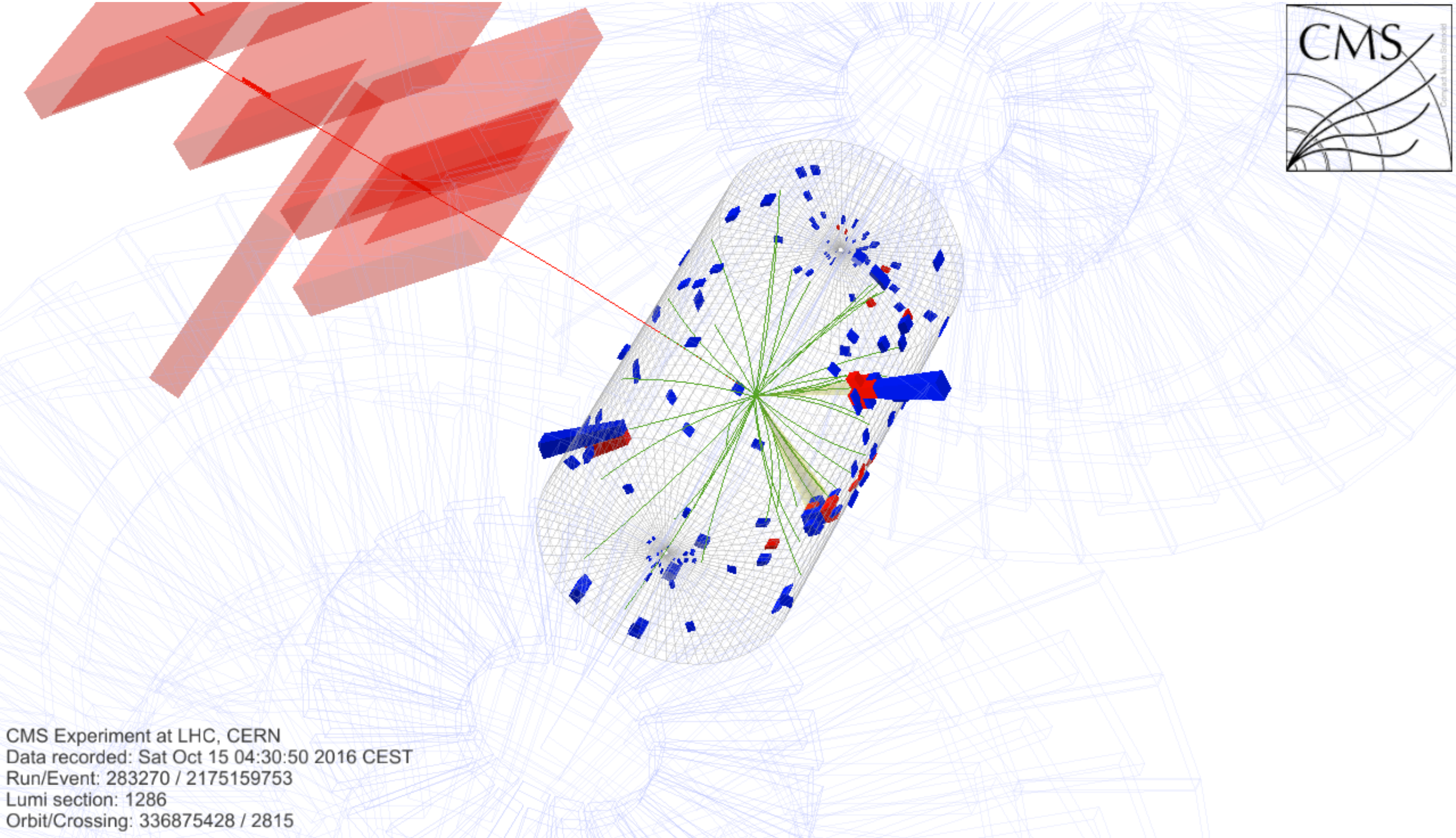
double-b



- Boosted topologies: 2 or more final state objects are close (merged) together
- Sensitive to high mass resonances, or particular non-resonant topologies.
- Most HH analyses in CMS have at least one boosted category to enhance sensitivity
- Dedicated double b-tagger algorithms/subjet taggers are used to identify the 2 component jets and identify their properties

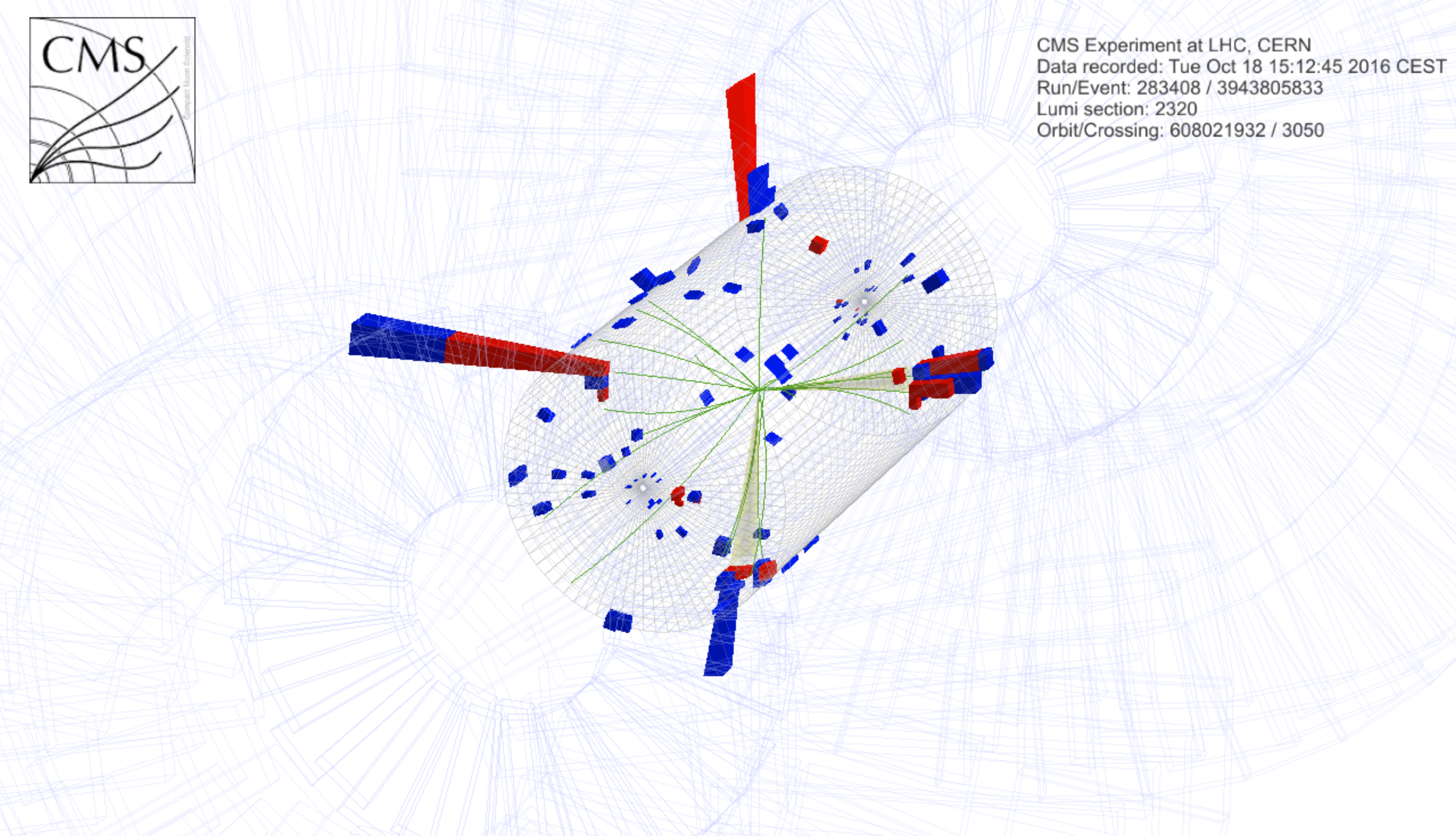
hh searches at CMS

hh searches at CMS



CMS Experiment at LHC, CERN
Data recorded: Sat Oct 15 04:30:50 2016 CEST
Run/Event: 283270 / 2175159753
Lumi section: 1286
Orbit/Crossing: 336875428 / 2815

hh searches at CMS



CMS Experiment at LHC, CERN
Data recorded: Tue Oct 18 15:12:45 2016 CEST
Run/Event: 283408 / 3943805833
Lumi section: 2320
Orbit/Crossing: 608021932 / 3050

CMS searches

4 main channels presented today:

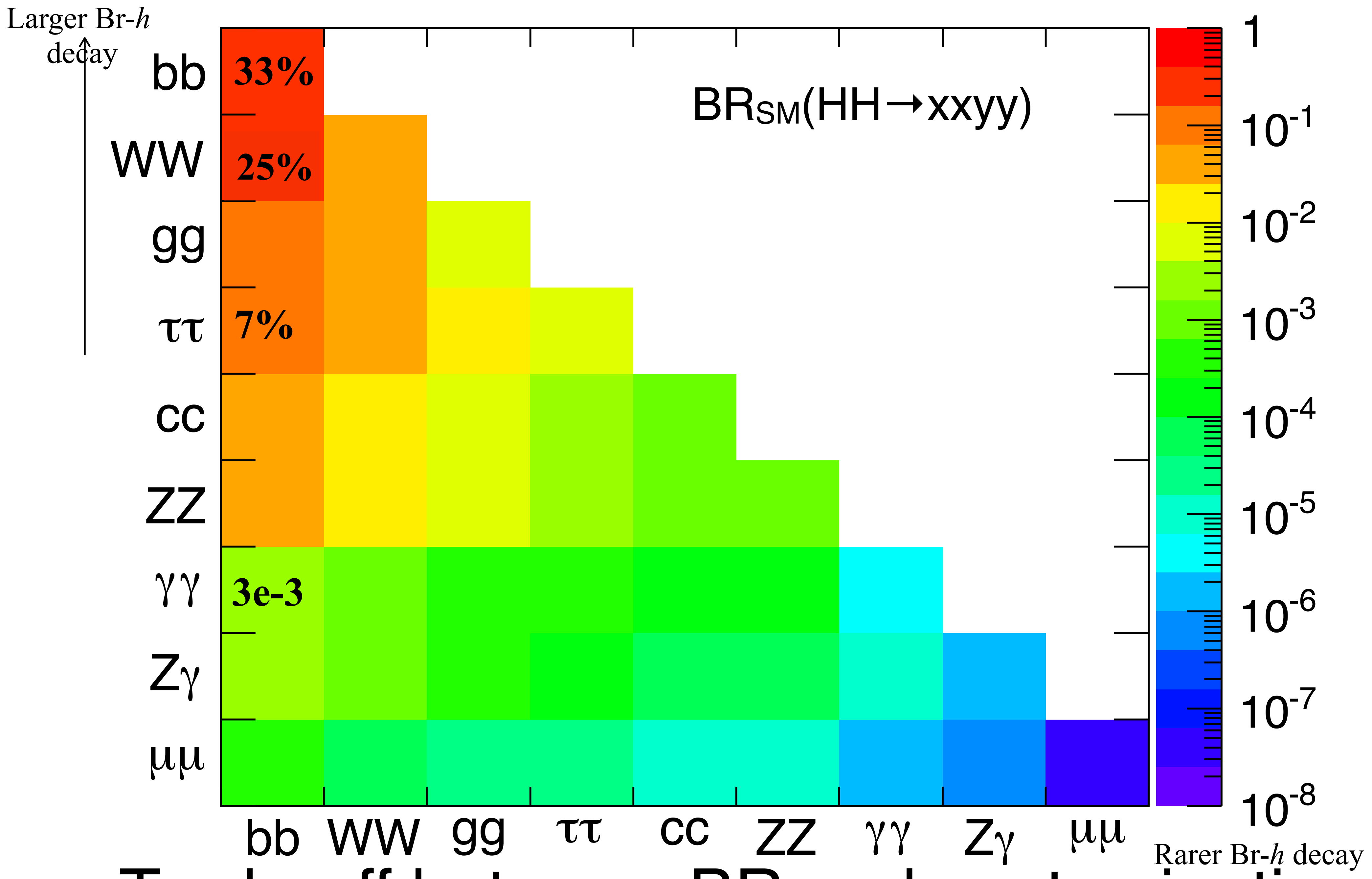
- bbbb, bbWW, bb$\tau\tau$, bb$\gamma\gamma$

At least one h→bb to have large enough BR

Rare processes, low σ, complex environment

Covering both resonant and non-resonant searches

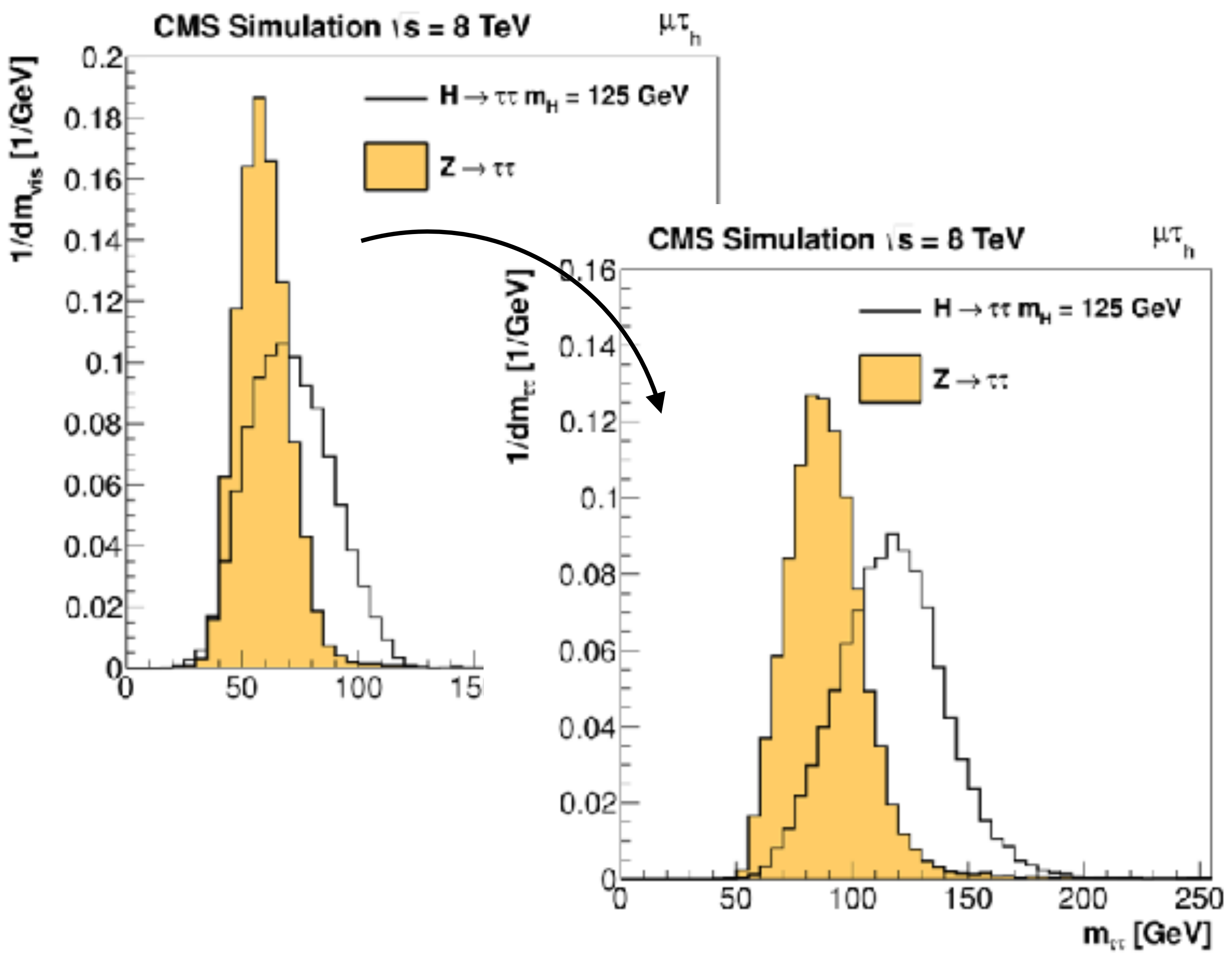
- Run2:
  - bb$\tau\tau$ Resonant and non-resonant PLB 778 (2018) 101/PAS-B2G-17-006
  - bbWW Resonant and non-resonant JHEP01(2018)054
  - bb$\gamma\gamma$ Resonant and non-resonant PAS-HIG-17-008
  - bbbb Resonant PAS-HIG-17-009/arXiv:1710.04960 non-resonant PAS-HIG-16-026
- Run1:
  - bbbb Resonant: PLB 749 (2015) 560, arXiv:1602:08762
  - bb$\tau\tau$ Resonant: PLB 755 (2016) 217, PAS-EXO-15-008 Non-resonant PAS-HIG-15-013
  - bb$\gamma\gamma$ Resonant and Non-resonant: arxiv:1603.06896

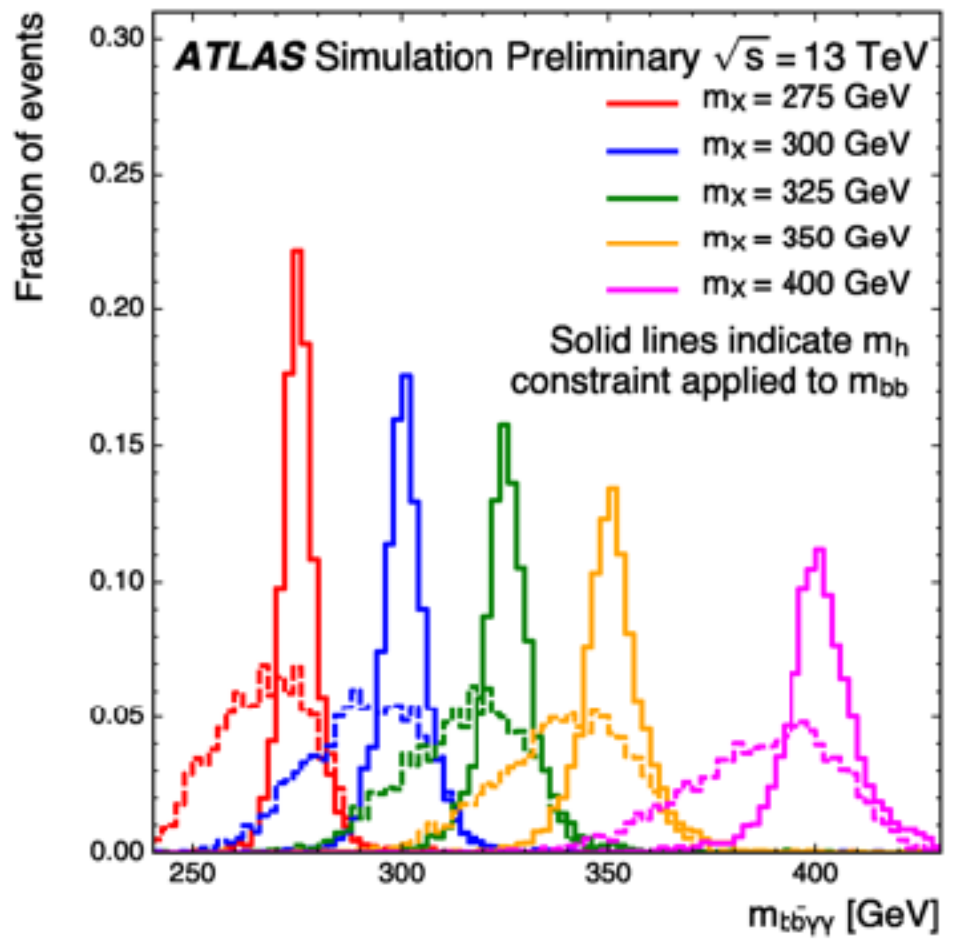


Trade-off between BR and contamination, complementarity among channels

- bbbb: highest BR, high QCD/$t\bar{t}$ contamination
- bbWW: high BR, large irreducible $t\bar{t}$ background
- bb$\tau\tau$: relatively low background and BR
- bb$\gamma\gamma$: high purity, very low BR

Experimental challenges



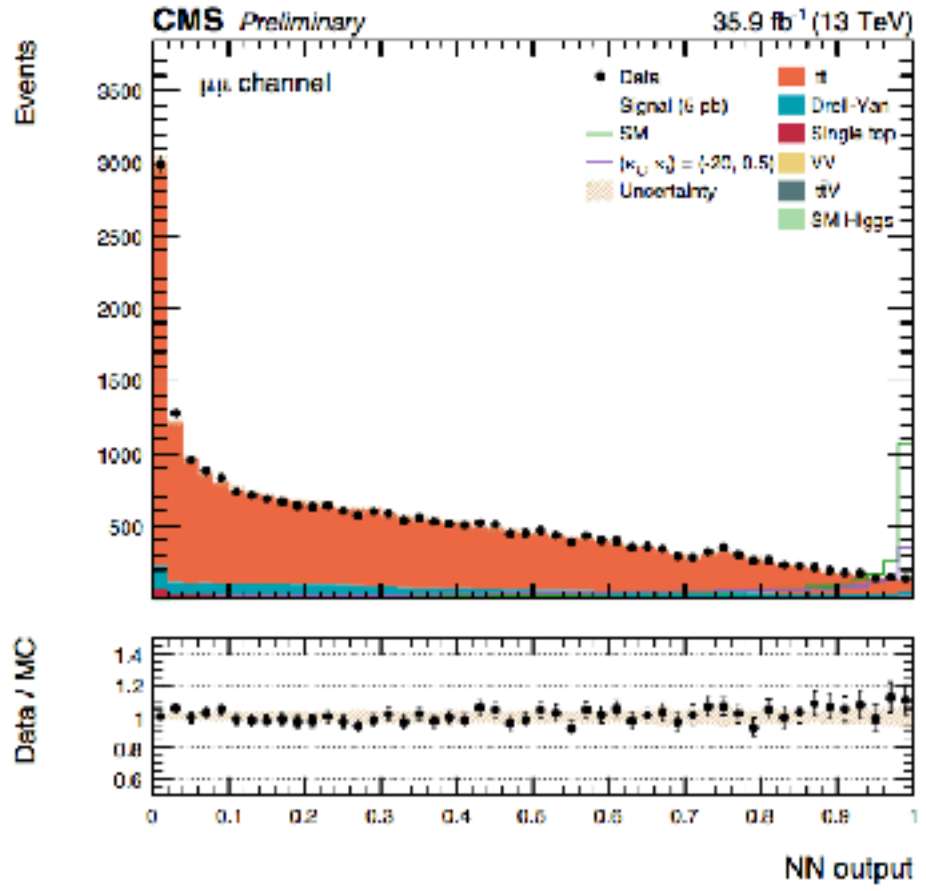


Difficult event reconstruction

- Limited resolution on bjet invariant mass
  → regression / mH rescale
- Missing energy in $\tau\tau$/WW searches
  → likelihood methods

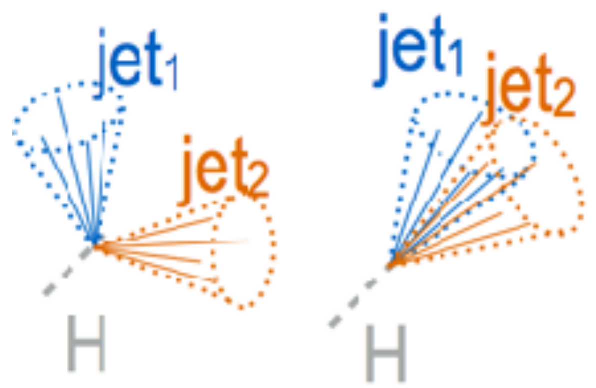
Looking for signal using 4-body invariant mass

- Improve resolution with kinematic fit



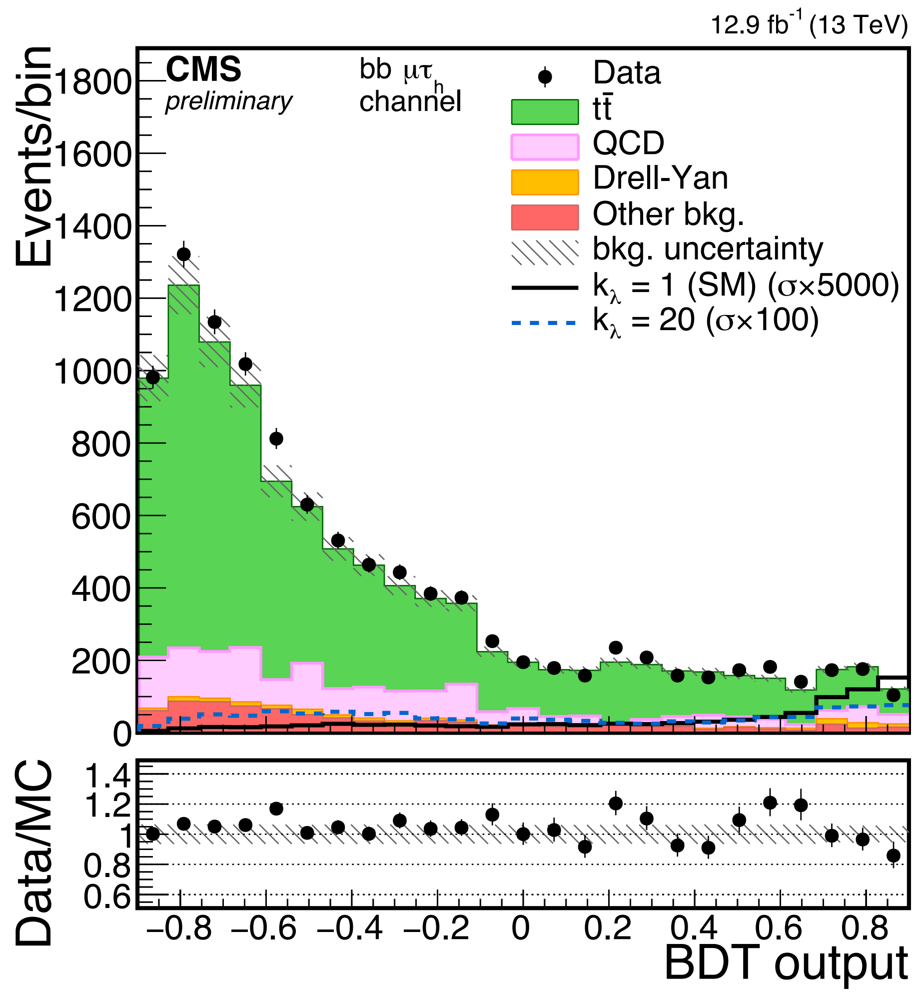
b-jets from high mass resonances overlap

- jet substructure techniques



Small signals with large backgrounds

- MVA methods to separate from overwhelming backgrounds

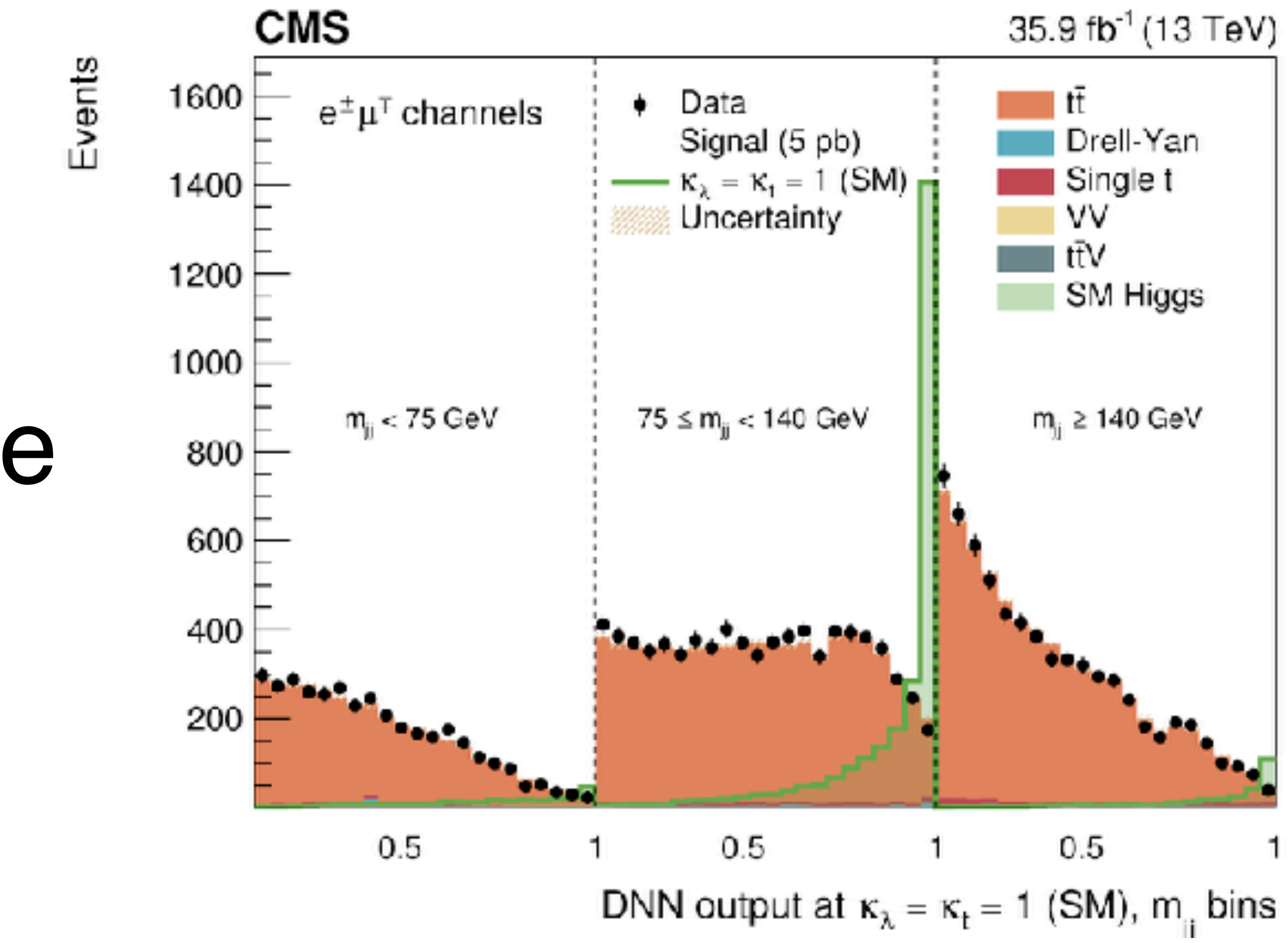


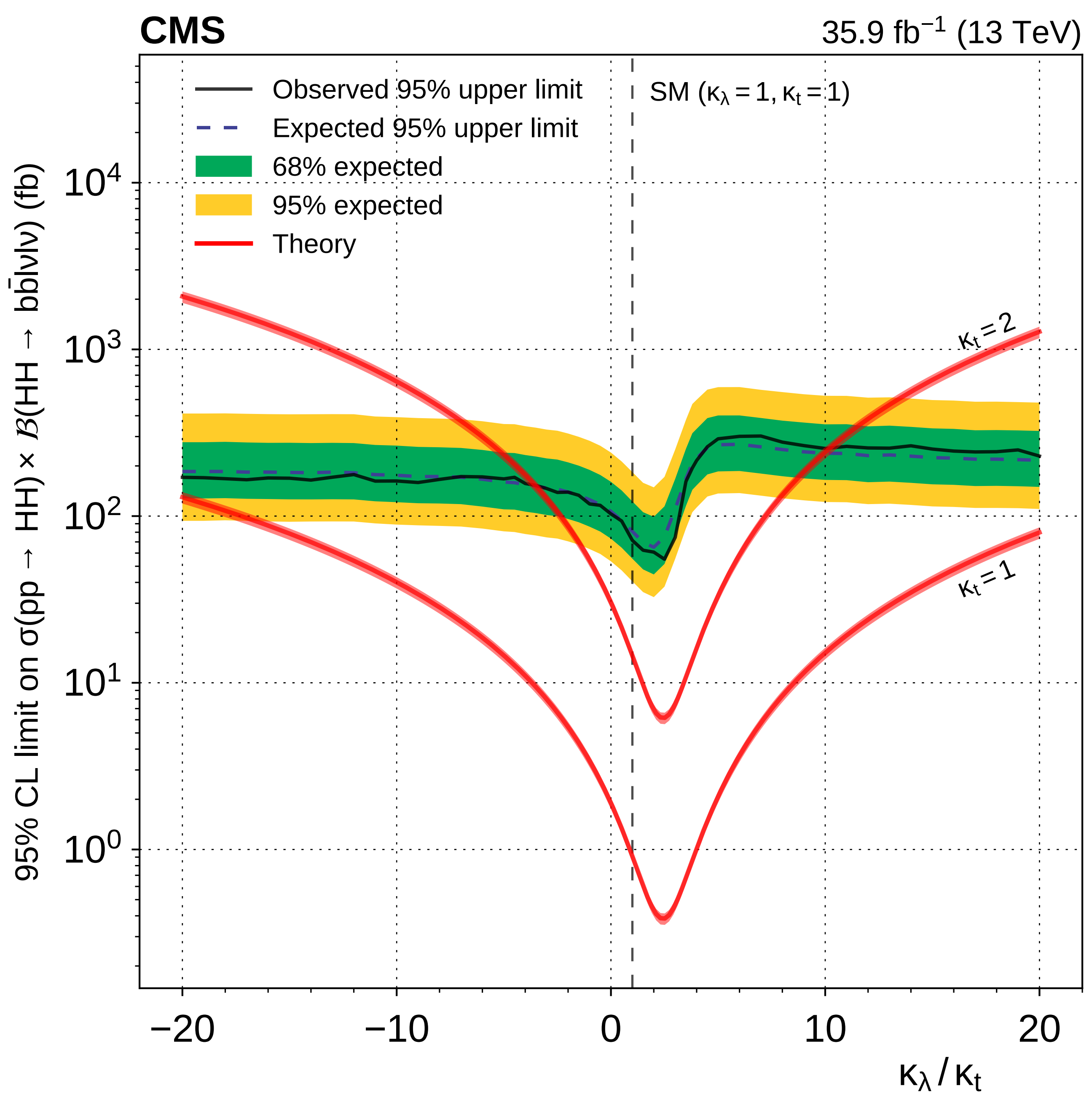
JHEP01(2018)054

bbVV(2l2ν)

35.9 fb^{-1} (2016). Low BR in the 2l2ν final state (2.72%)

- 2 OS leptons (ee, eμ, μe, μμ)
- Focus on the bbWW channel, Invariant mass cut to remove Z(ll) contributions
- Large background contamination from tt, Z+jets (from MC)



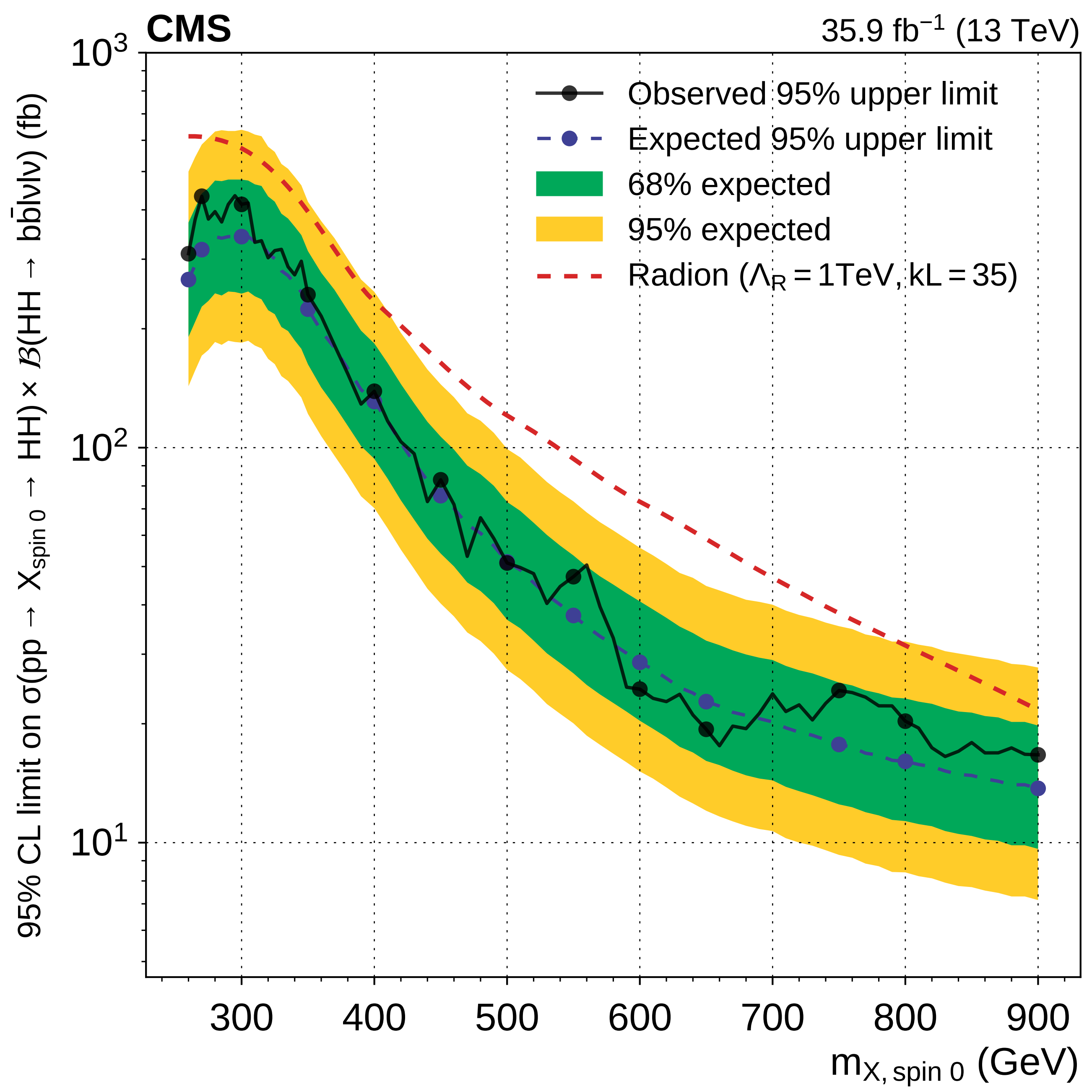


Parametrised DNNs used to discriminate against background

- Resonant: m_X, non-resonant k_t, $k\lambda$
- Limit extraction from DNN shape in 3 m_{jj} bins

Results

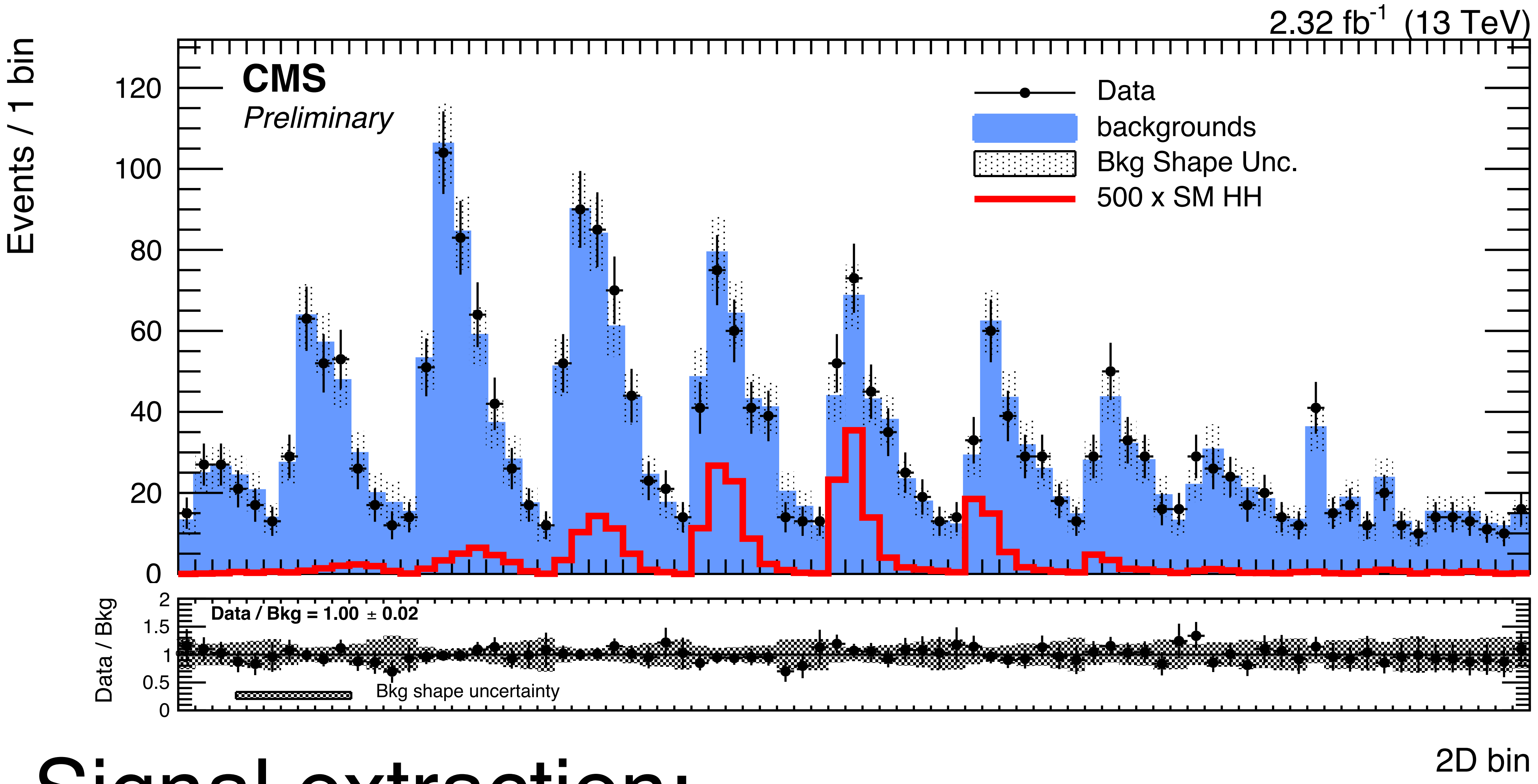
- SM σxBR<72fb
- Obs.(exp.): $\sigma/\sigma_{SM} < 79$ (89)



Non-resonant bbbb

35.9 fb^{-1} (2016)

- Highest BR among HH searches
- 4 jets, 3/4 b-tagged jets
- Pairing: 2 pairs closest in mass



Signal extraction:

2D shape of leading vs. sub-leading m_{jj}

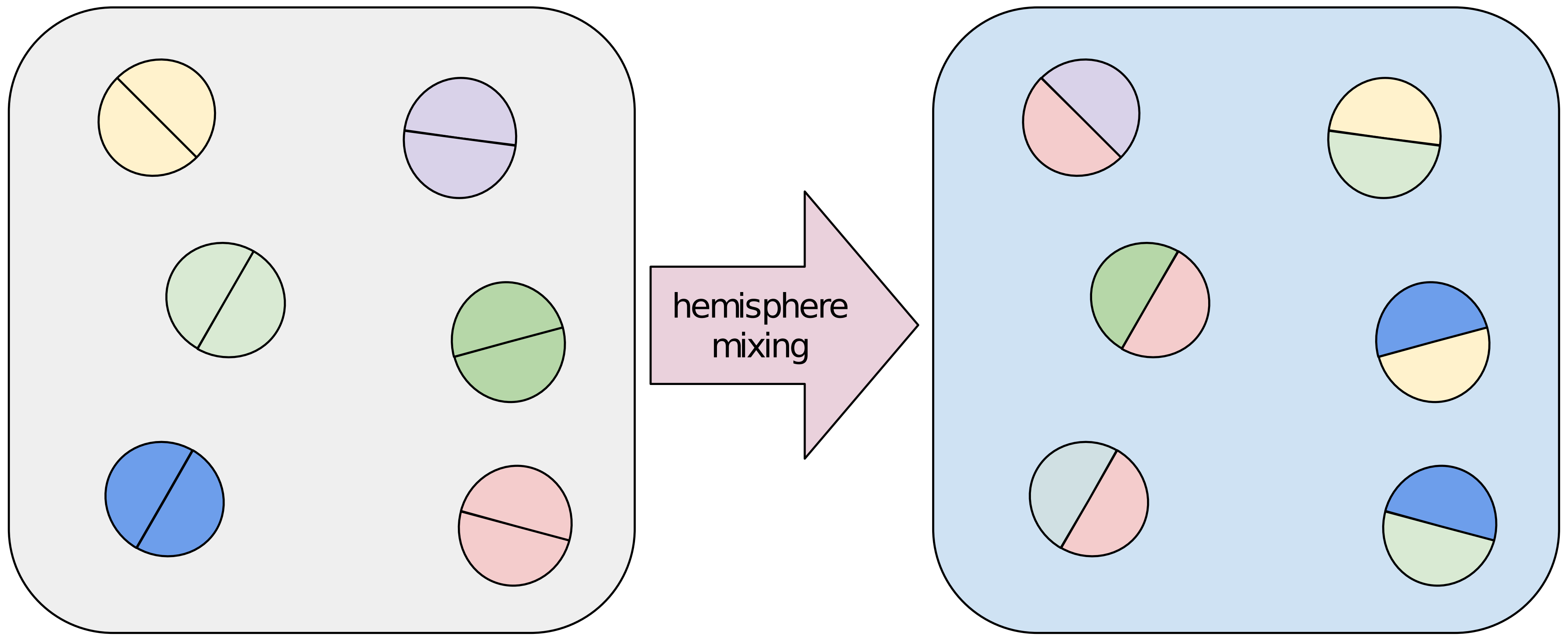
SM σxBR < 669 fb

Obs.(exp.): $\sigma/\sigma_{SM} < 59$ (30)

Large Multijet (and tt) backgrounds. We want reliable background estimation with large statistics

→ Hemisphere mixing

- Data events cut in 2 hemispheres
- Hemisphere library → recreate events
- Pairing: nearest neighbour (kinematics)
- Validated in BDT sideband
- Small bias → systematic on bkg.
- Cut on BDT



Original dataset: bkgs and potentially a small signal fraction

Mixed dataset: new composed event that represent bkg-only

PAS-HIG-17-009

Resonant resolved bbbb

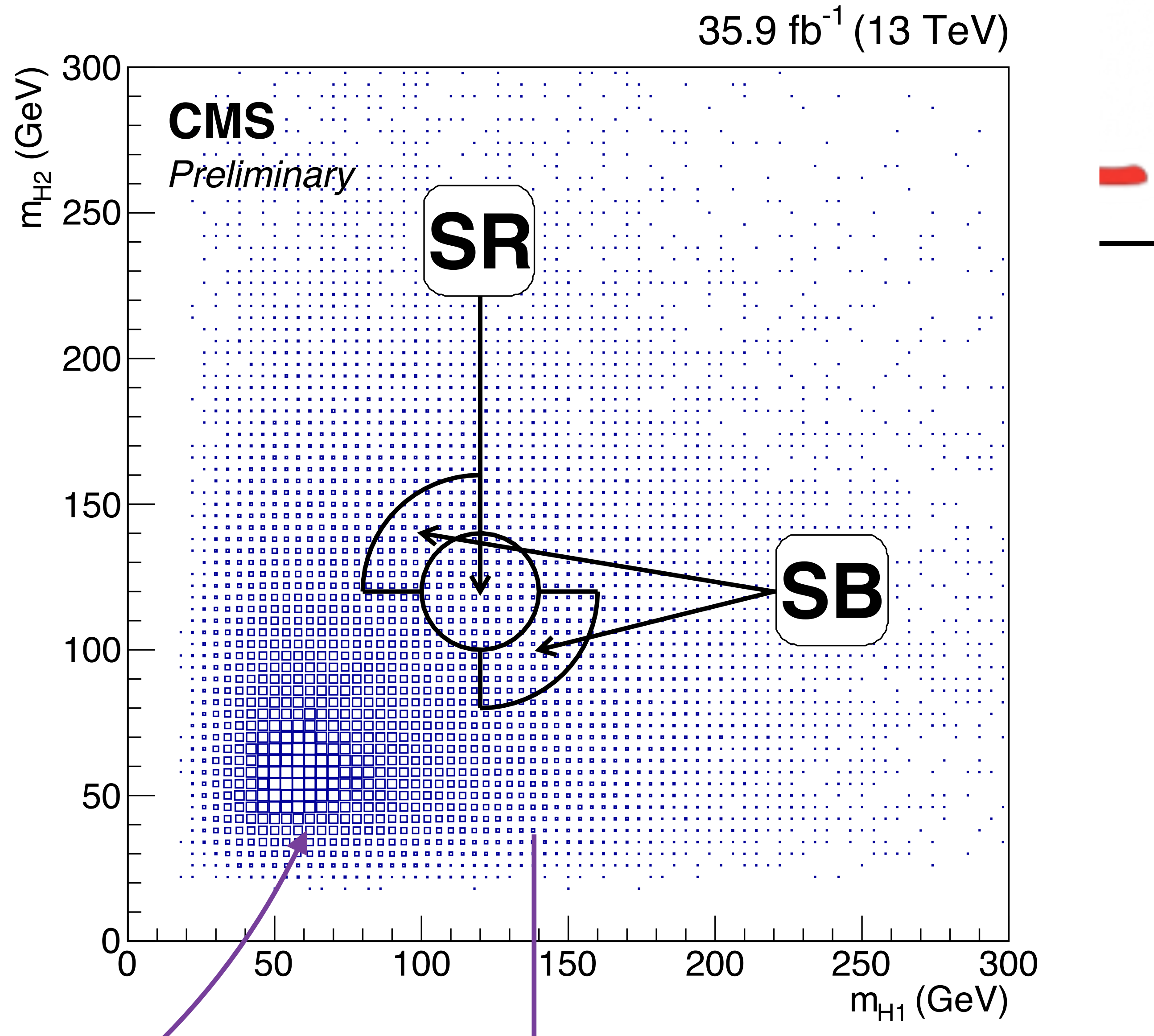
35.9 fb^{-1} (2016)

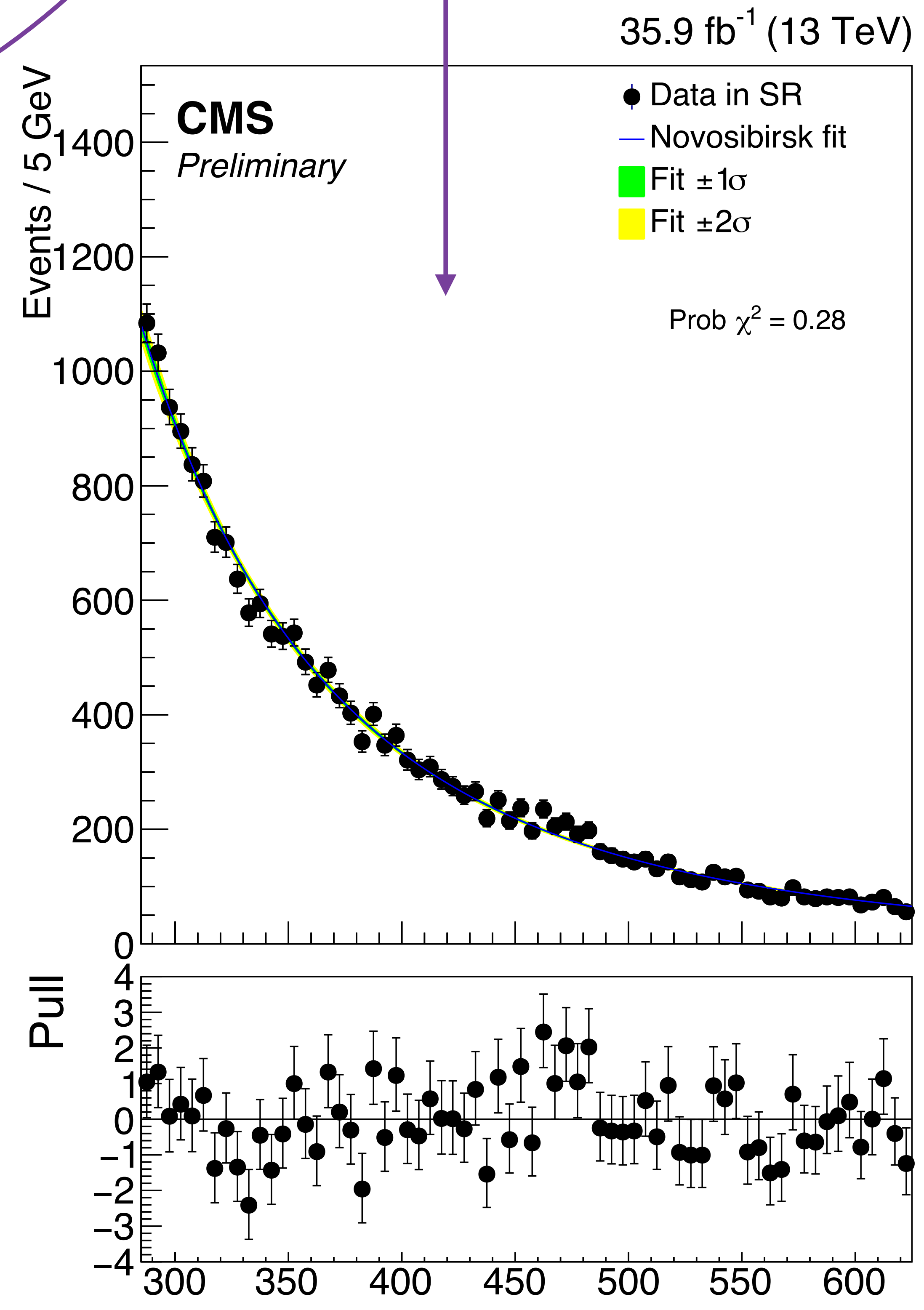
4 b-tagged jets, deepCSV algorithm

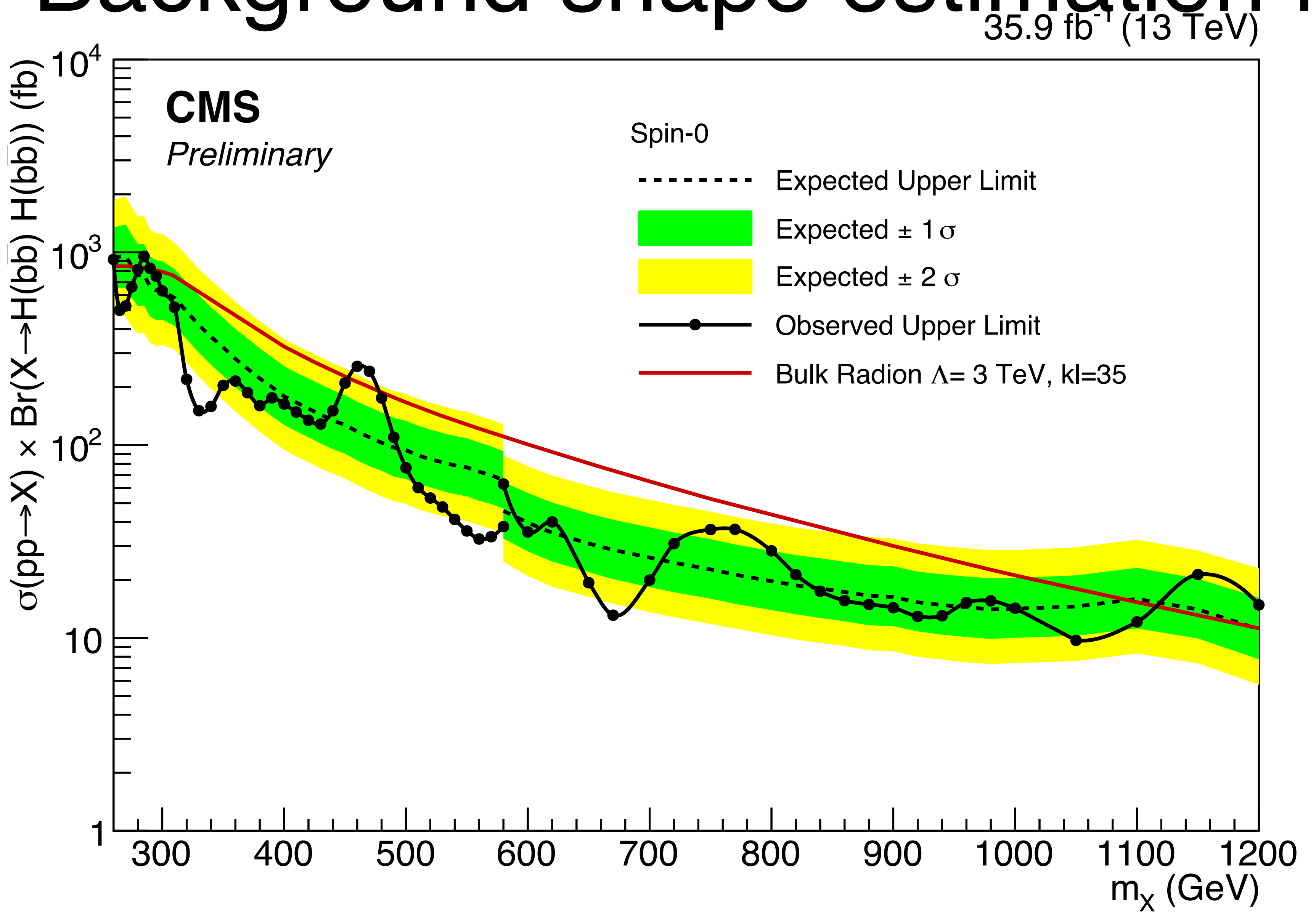
b-jet energy regression to improve resolution, Kinematic fit for m_{HH}

Low Mass Region (m_H<400) and High Mass Region (400<m_H<1200) studied separately to exploit kinematic properties of the signal

Background shape estimation from data in LMR, HMR







Background estimation cross-checked

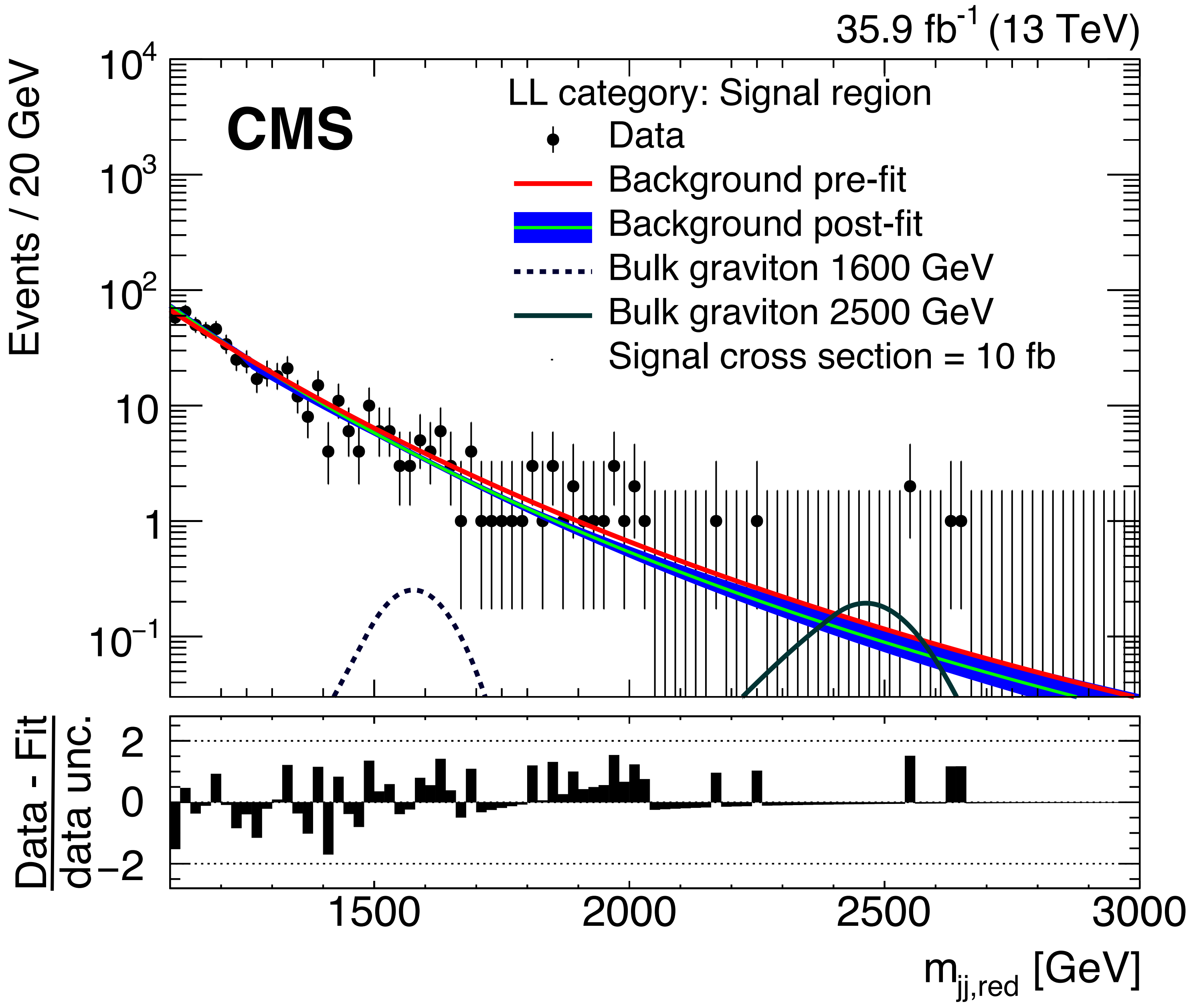
- In <4 b-tag side bands
- With alternate SR definitions

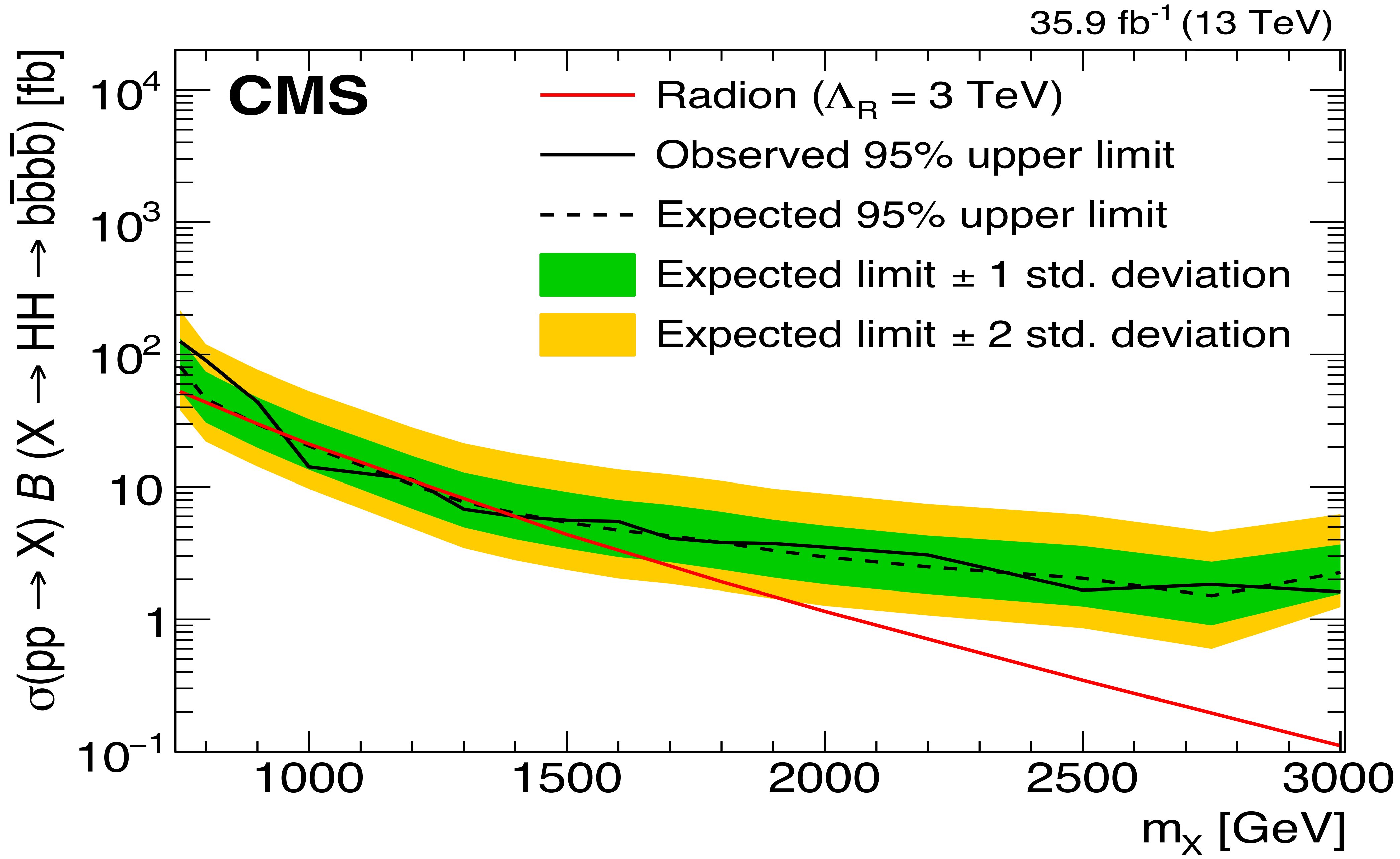
arXiv:1710.04960

Resonant boosted bbbb

35.9 fb^{-1} (2016)

- Search for a heavy (MX>800GeV) resonance
- 2 “fat” jets (R=0.8), with double b-tagging
- B-tag based categories (LL, TT)
- Use constituent jets properties (“soft-drop” mass, N-subjettiness)
- Signal extraction → reduced mass: $M_{red}=m_{jj}-(m_{j1}-m_H)-(m_{j2}-m_H)$





Multijet background estimation

M_{red} < 1200 GeV: refined ABCD method

- m_{j1} and b-tag sidebands
- Interpolate dependence on m_{j1}

M_{red} > 1200 GeV:

- Parametric fit
- Same shape SB & SR, yields from ABCD

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bb$\tau\tau$

35.9 fb^{-1} (2016)

3 final states ($e\tau_H$, $\mu\tau_H$, $\tau_H\tau_H$), covering 88% of the BR

3rd lepton veto

Kinematic fit (SVFit) to reconstruct $m(\tau\tau)$

Discriminant variable:

- Non-resonant: Stransverse mass M_{T2}
- Resonant: Kinematic Fit of $m(jj\tau\tau)$

Main backgrounds: tt, Z+jets (from MC) DY, multijet (from data)

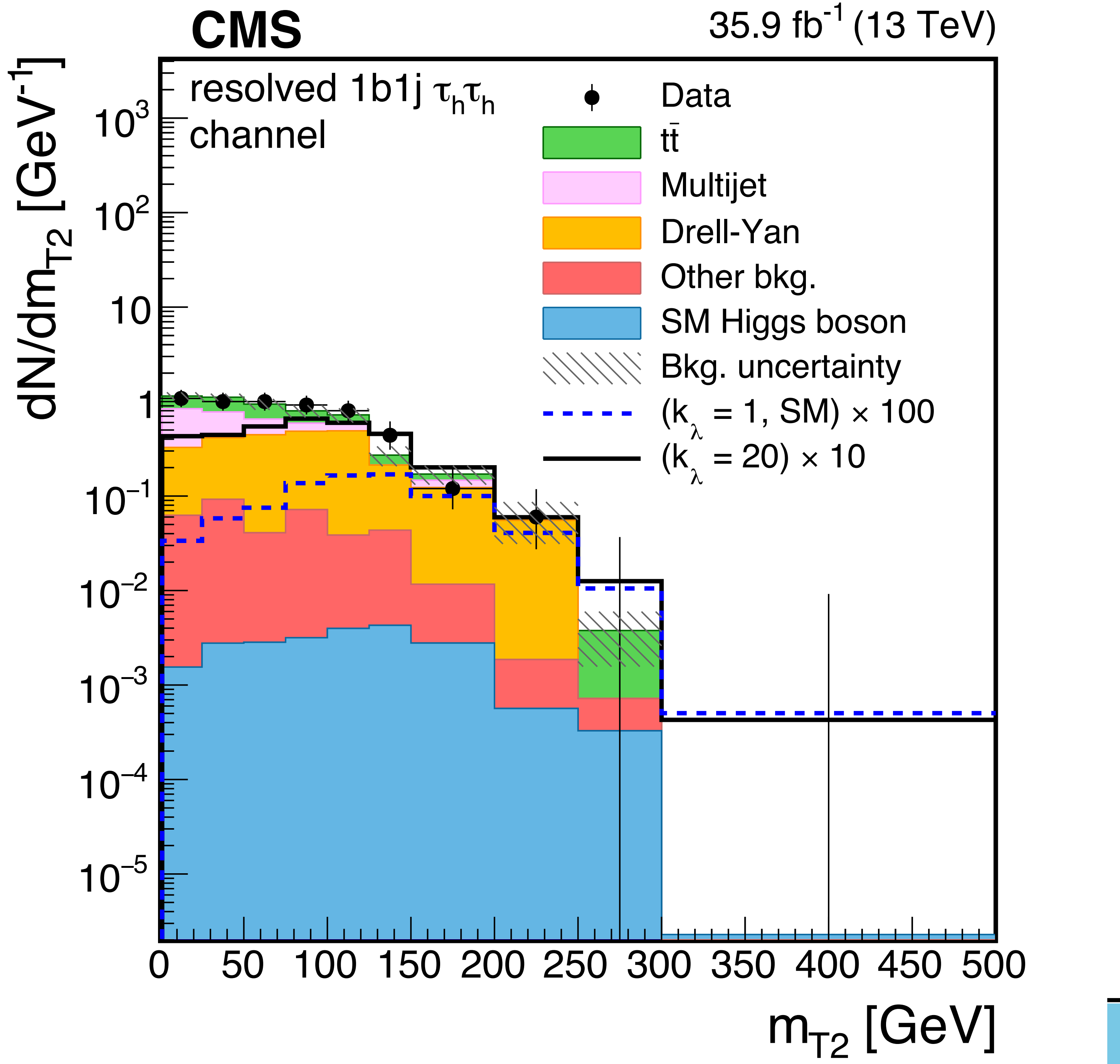
- BDTs (low/high mass) to reject tt in semileptonic categories

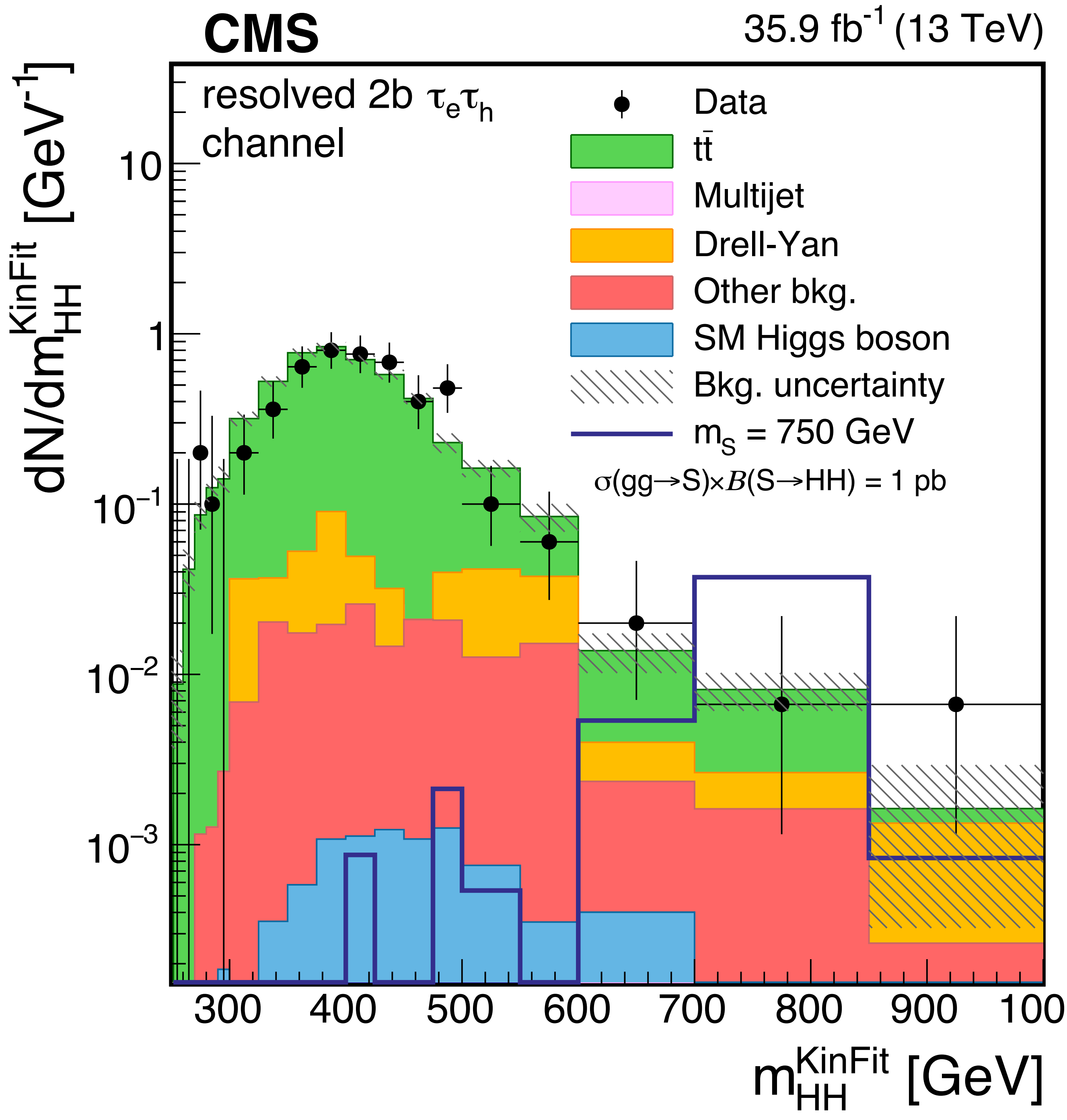
Resolved analysis:

- 2 categories (1 or 2 b-jets)
- Elliptical cut in $m(\tau\tau)$,m(jj)

Boosted (bb) analysis

- 1 (R=0.8 jet), subjet b-tagging
- cut in $m(\tau\tau)$,m(j)





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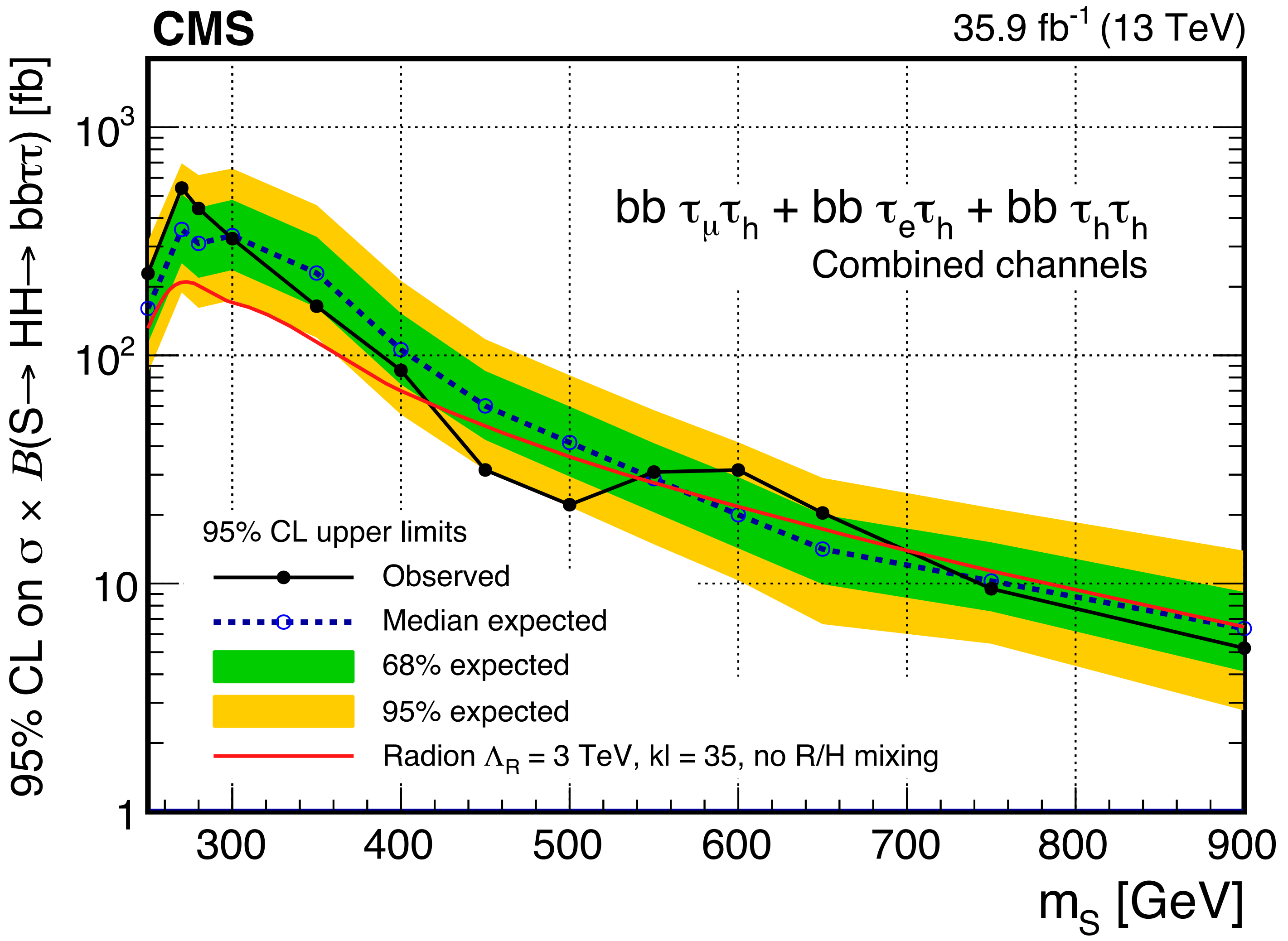
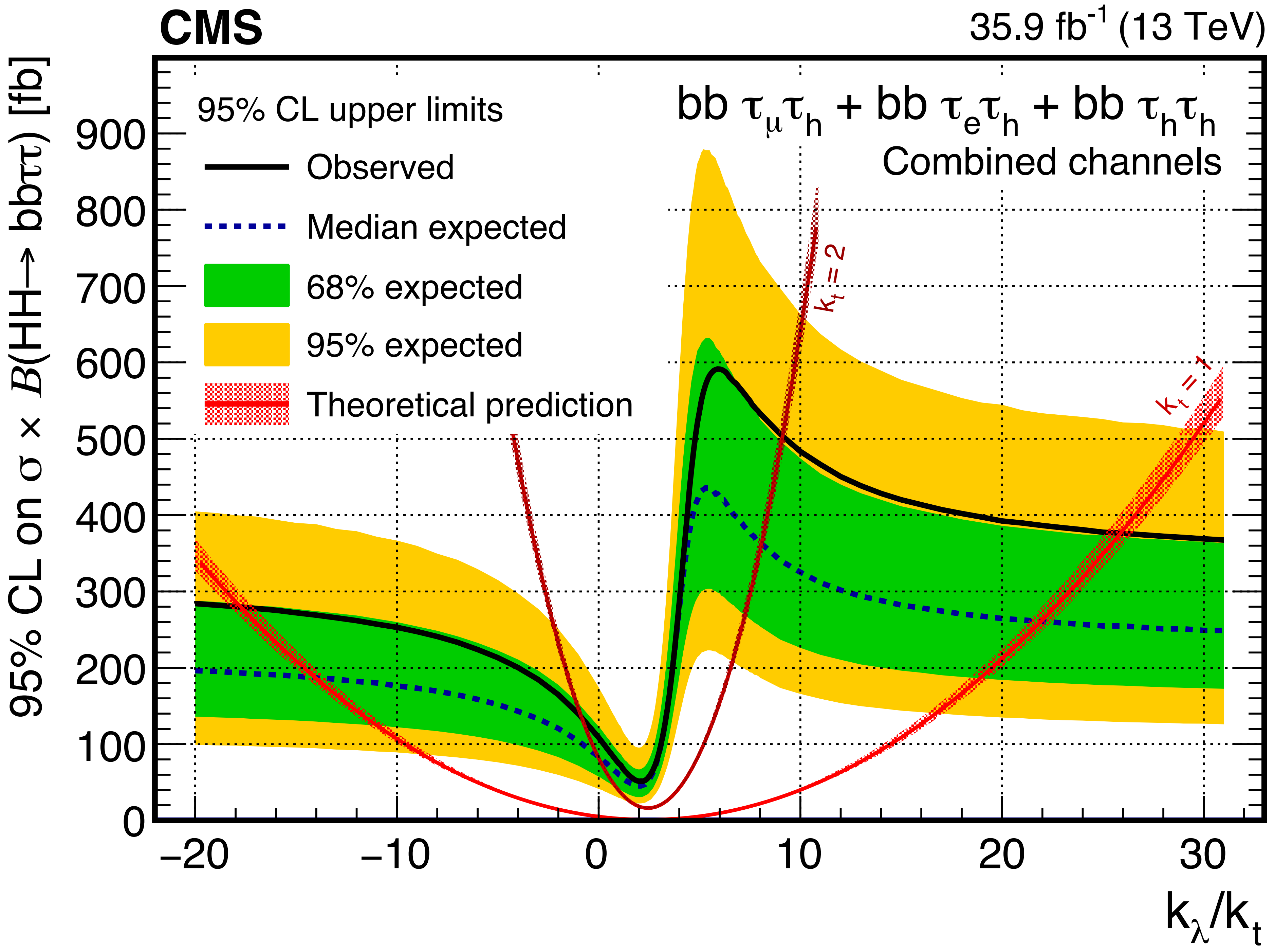
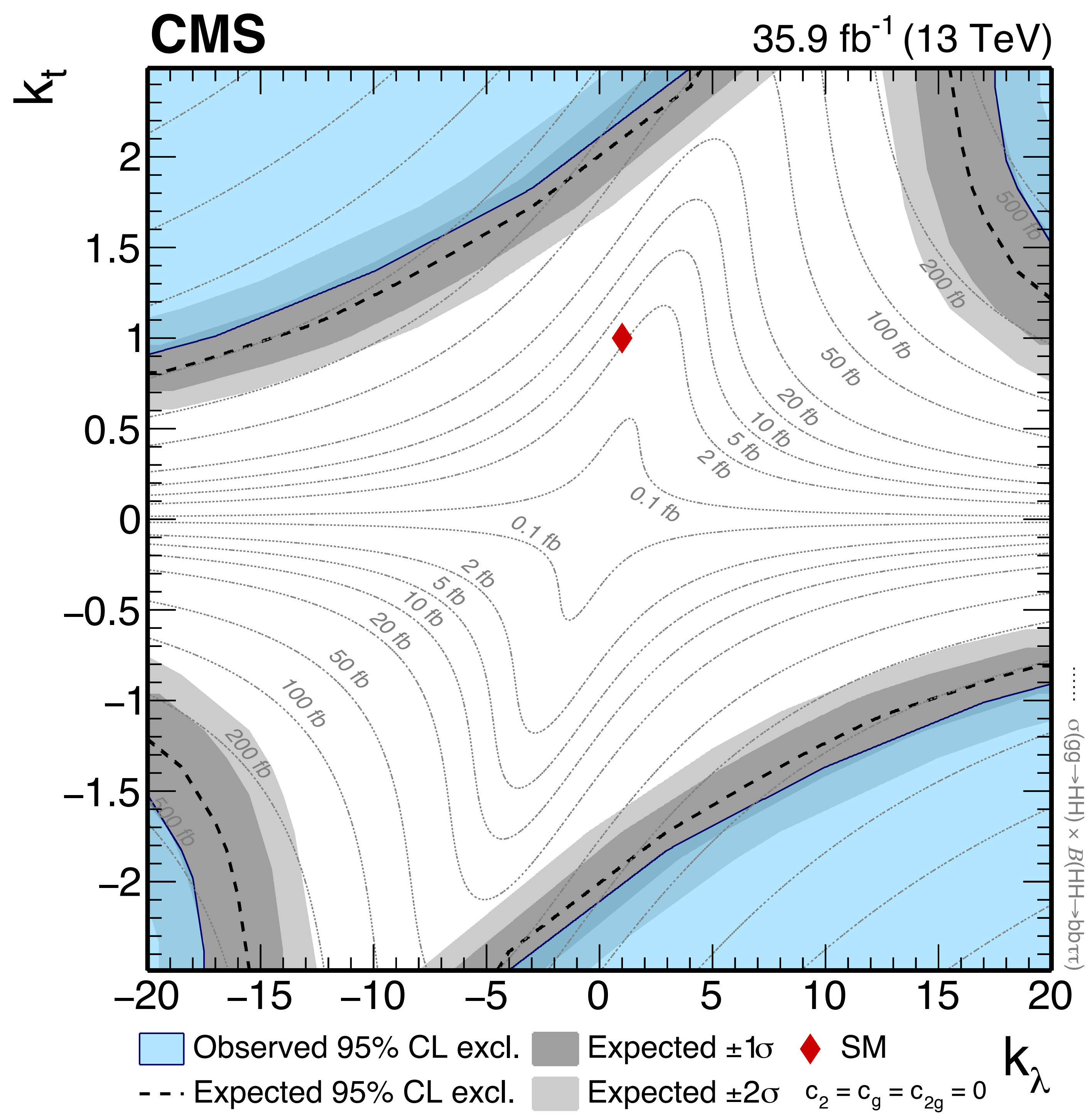
bb$\tau\tau$ - Results

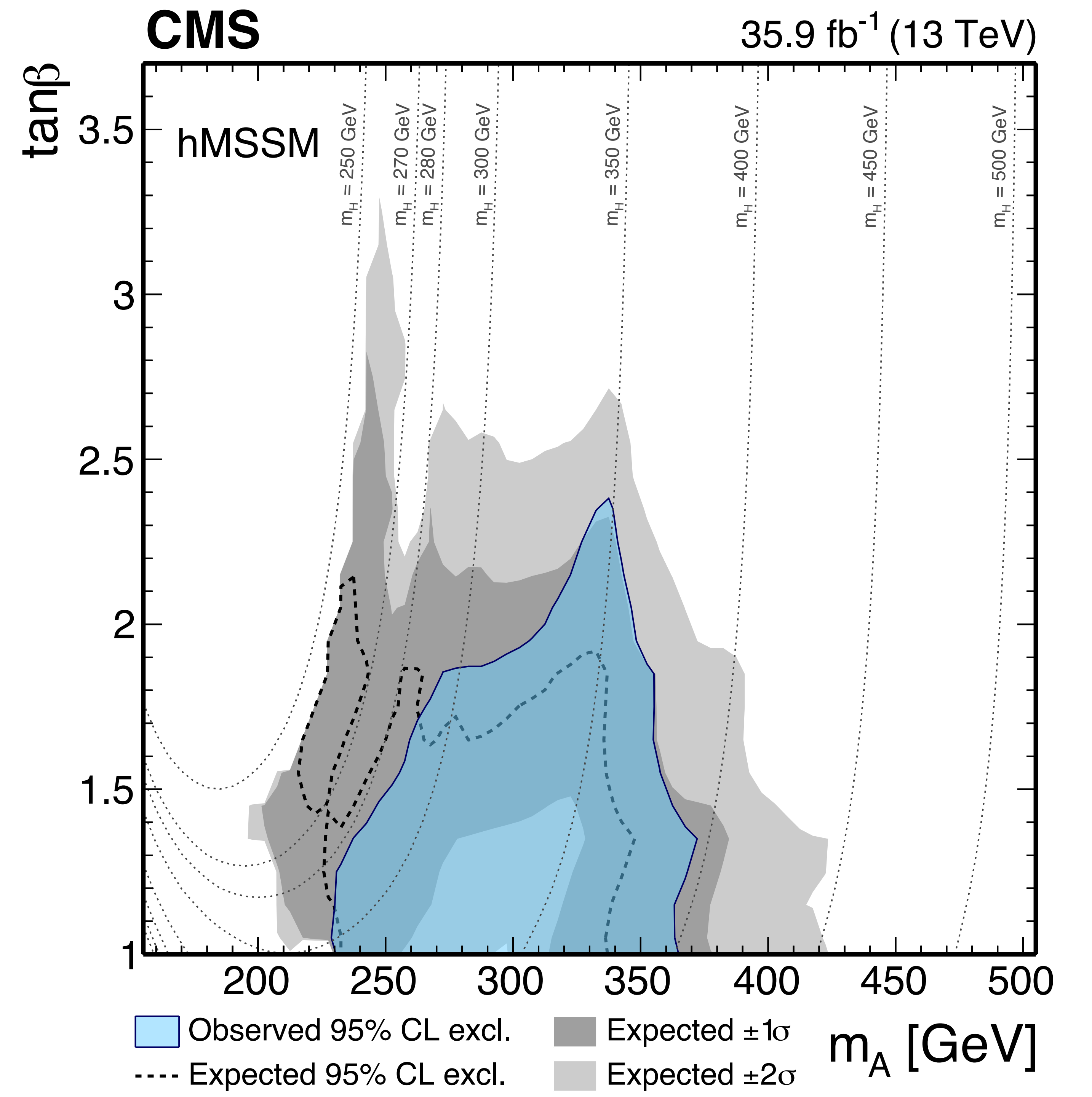
Non-resonant limits:
- SM σxBR<75.4fb
- Obs.(exp.): σ/σ_{SM}< 30 (25)

hMSSM interpretation on top of narrow width resonant searches









PAS-B2G-17-006

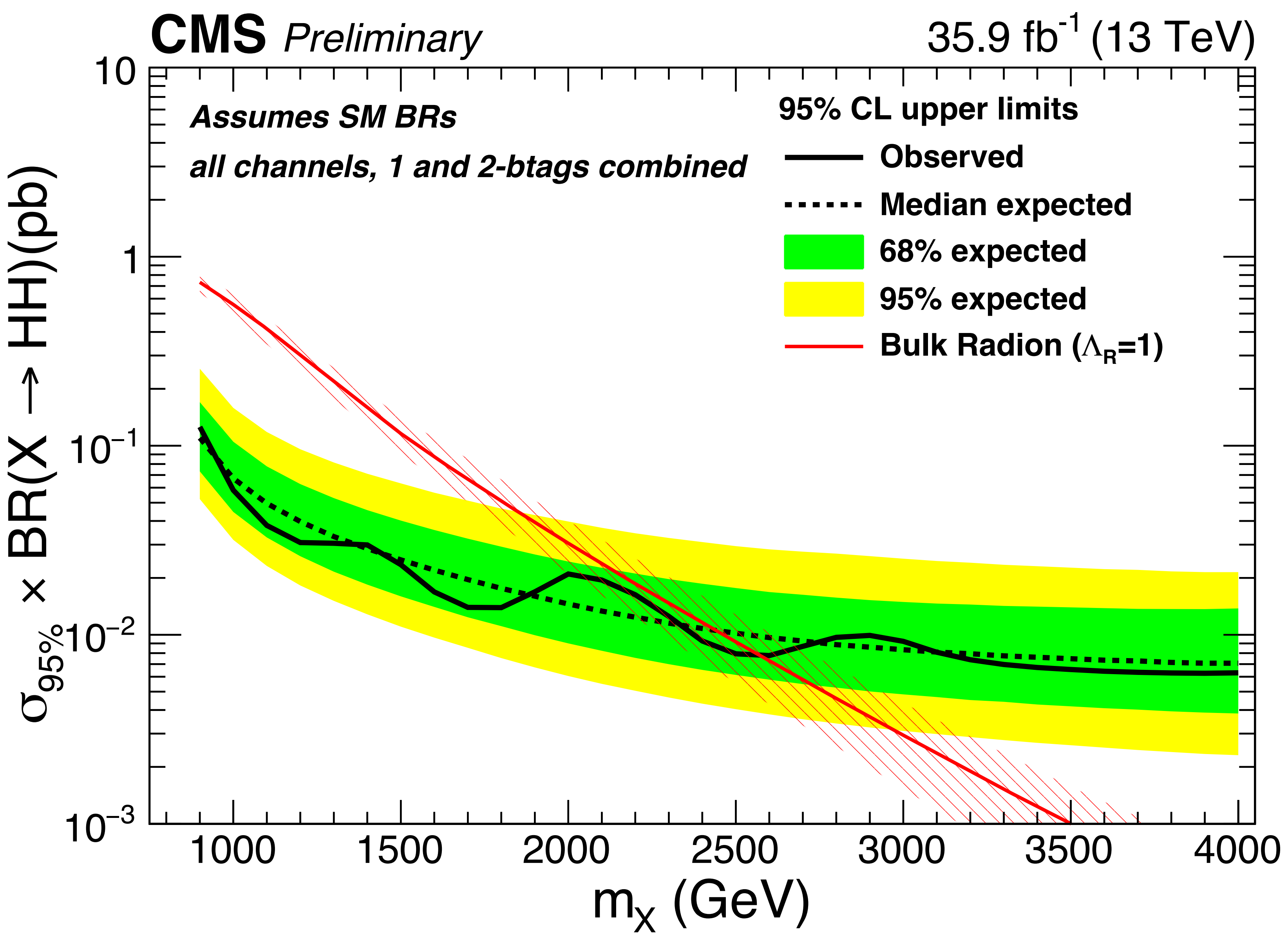
Resonant boosted bb$\tau\tau$

35.9 fb^{-1} (2016), search for heavy mass resonances

Boosted b-jet (anti-kT,R=0.8) and boosted $\tau\tau$ ($l\tau_H$,$\tau_H\tau_H$)

Kinematic fit to reconstruct $50<m_{\tau\tau}<150$GeV

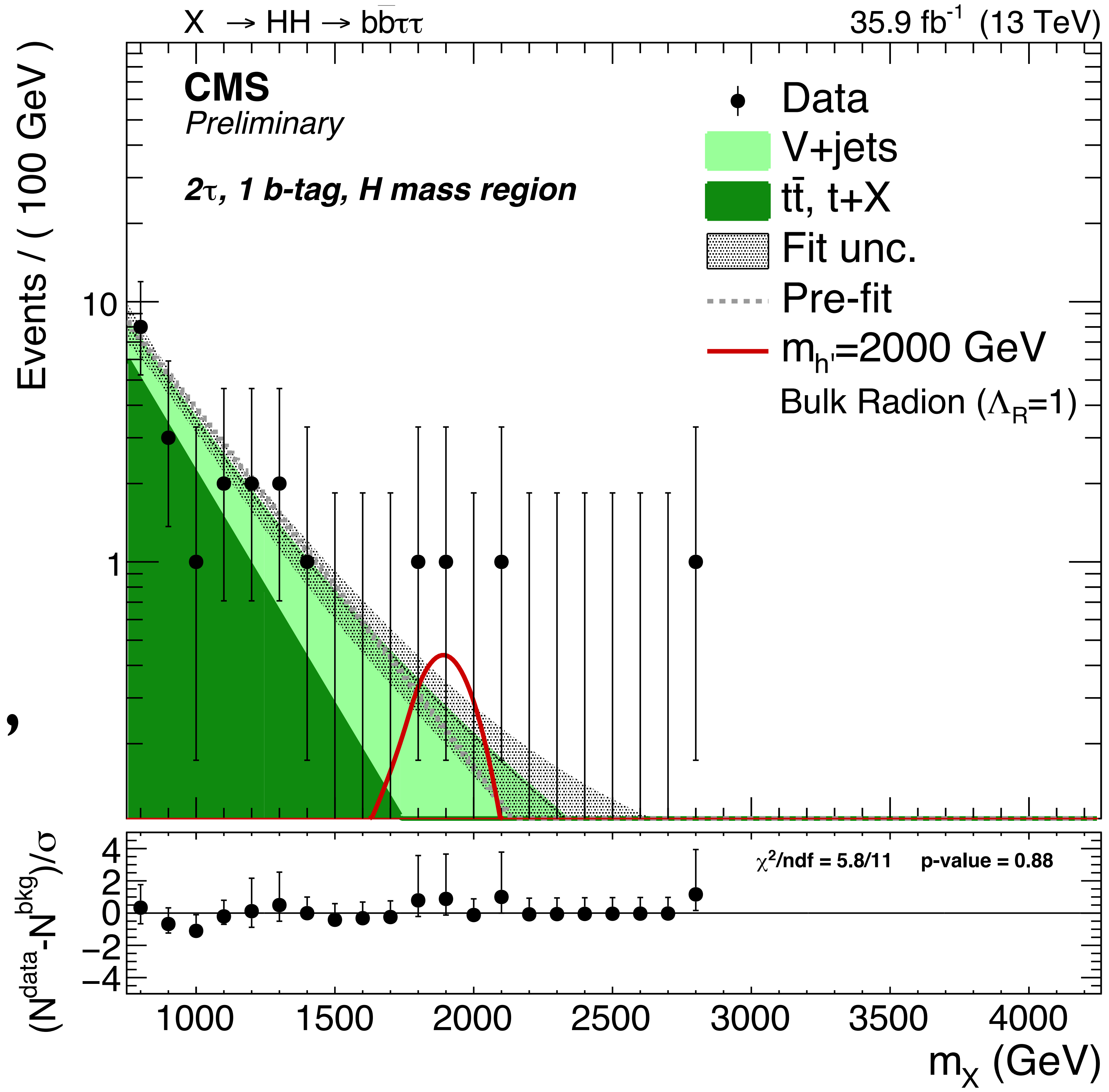
>0 b-tagged sub-jet, $105<m_j<135$ GeV



Main backgrounds: tt, t+X, V+jets

- tt, t+X: Shape from MC simulation, normalisation from CR
- V+jets: from mj sidebands, shape corrected with simulation

Fit on the m_X distribution



Search performed up to 4TeV, excludes narrow width radion up to 2.5TeV

bbγγ

35.9 fb^{-1} (2016)

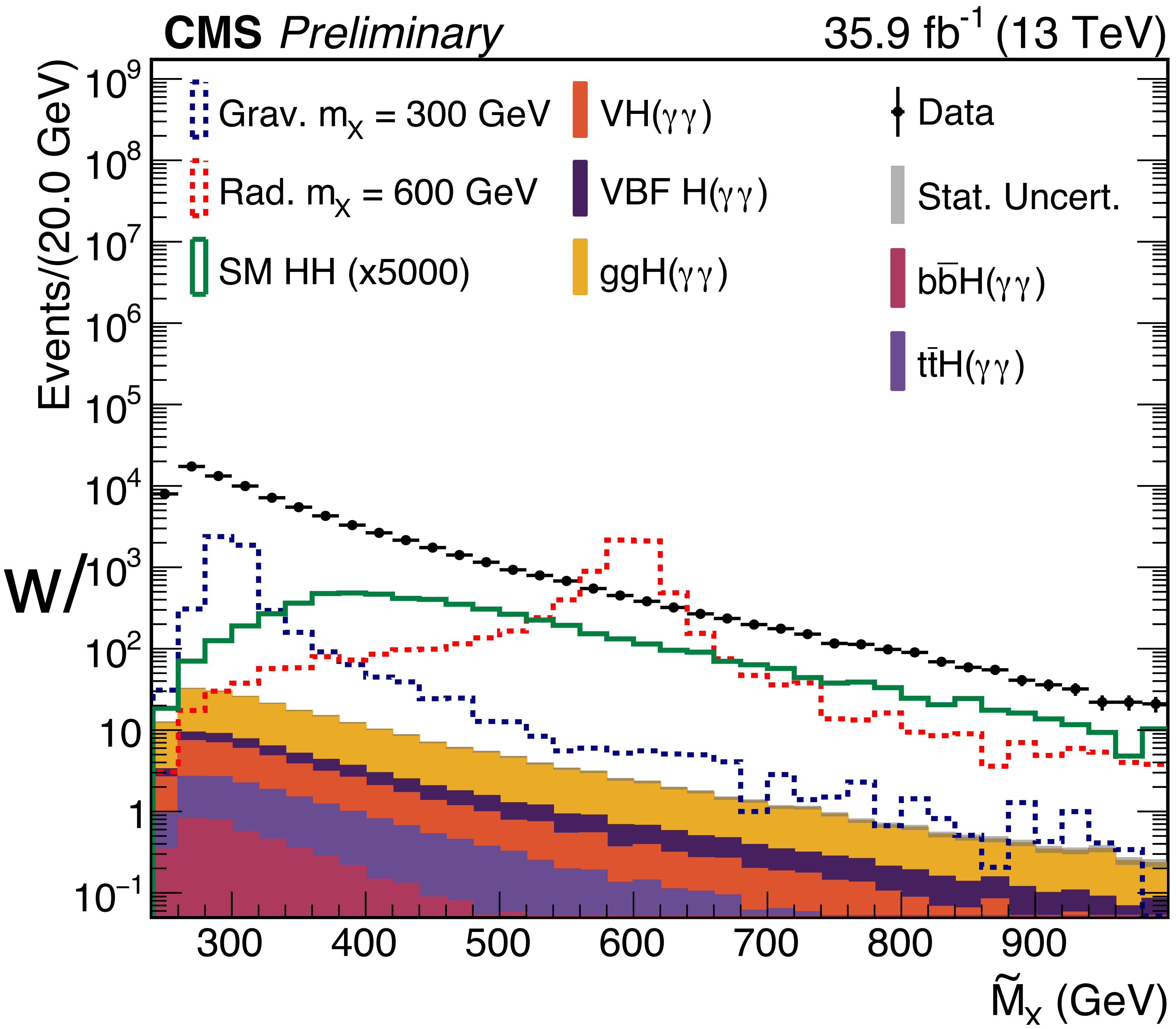
Low BR (0.26%), excellent resolution, clear signature

2 photons, 2 b-tagged jets (R=0.4)

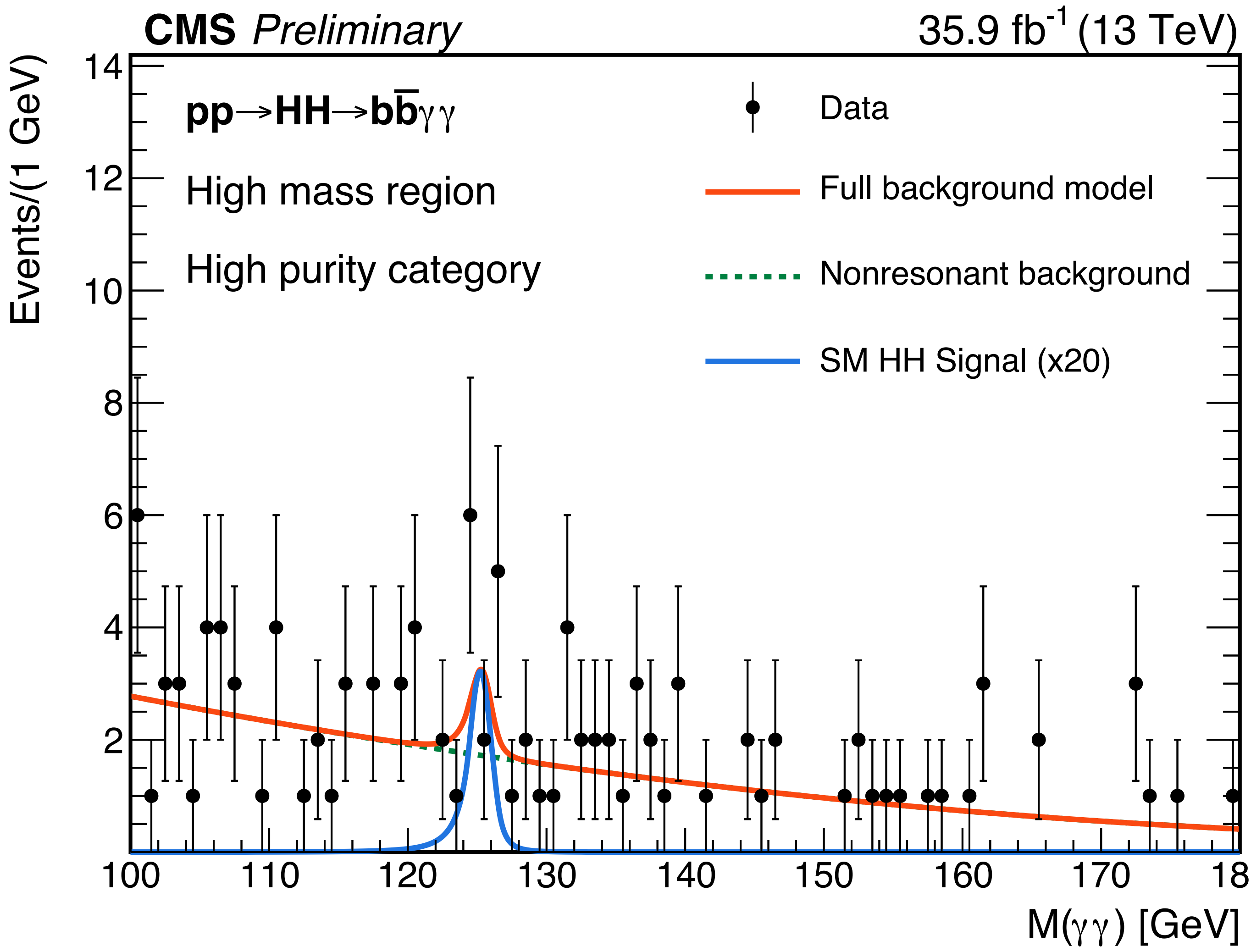
Reduced mass: $M_{\tilde{X}} = m_{jj\gamma\gamma} - m_{jj} - m_{\gamma\gamma} + 250$ GeV

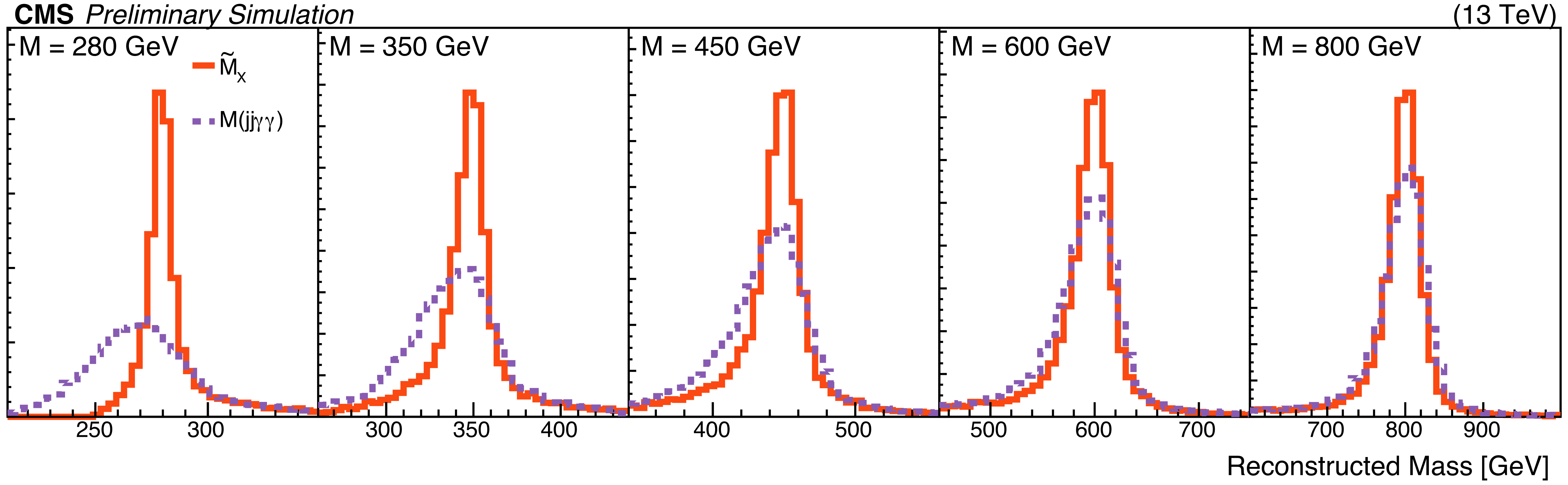
BDT x $M_{\tilde{X}}$ categorization: medium/high BDT purity and low/high reduced mass $M_{\tilde{X}} < 350$GeV/$M_{\tilde{X}} > 350$GeV)

Main backgrounds: multijet, fake photons, SM Higgs production

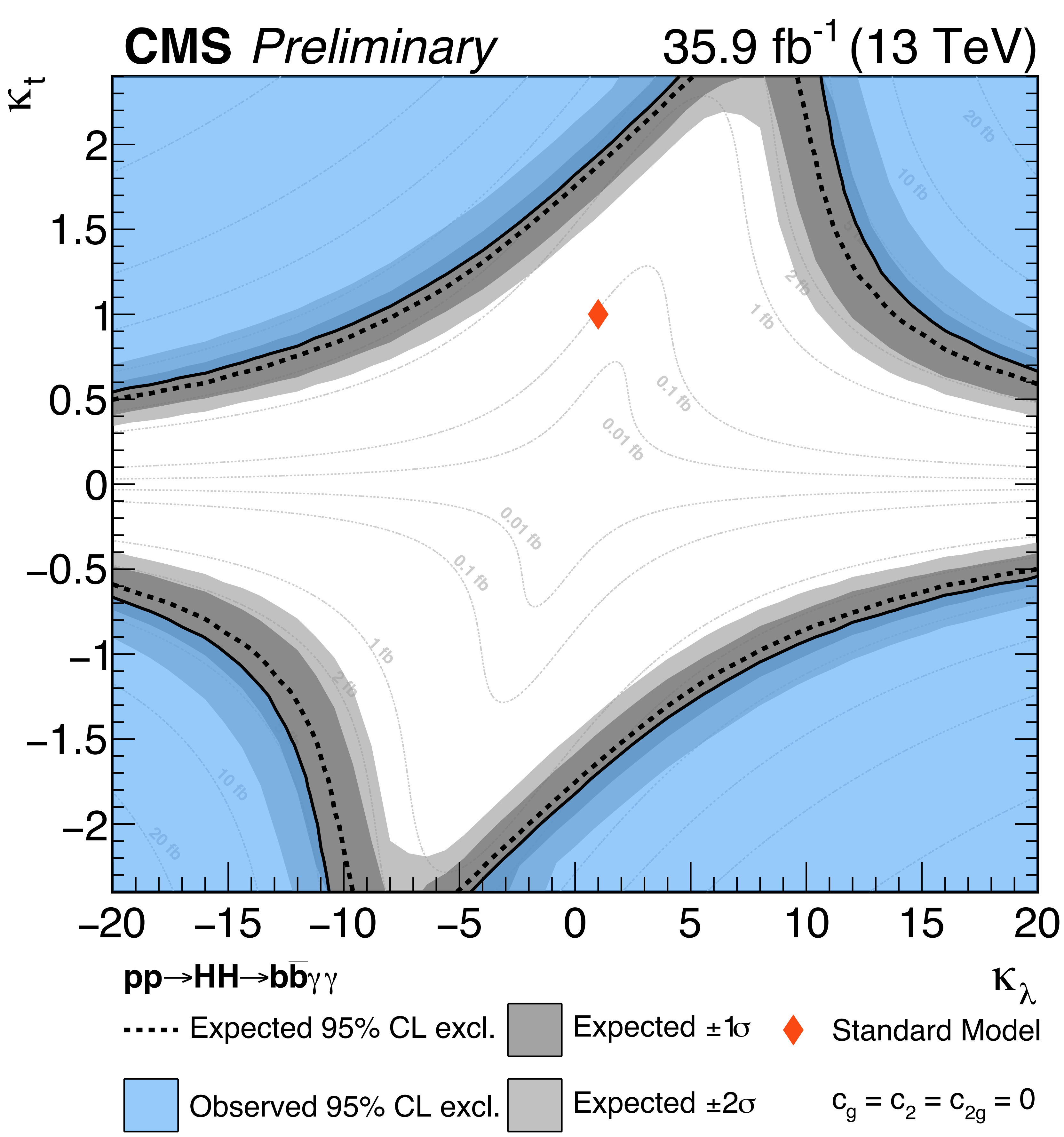


2D parametric fit in (m_{jj},$m_{\gamma\gamma}$) for signal extraction





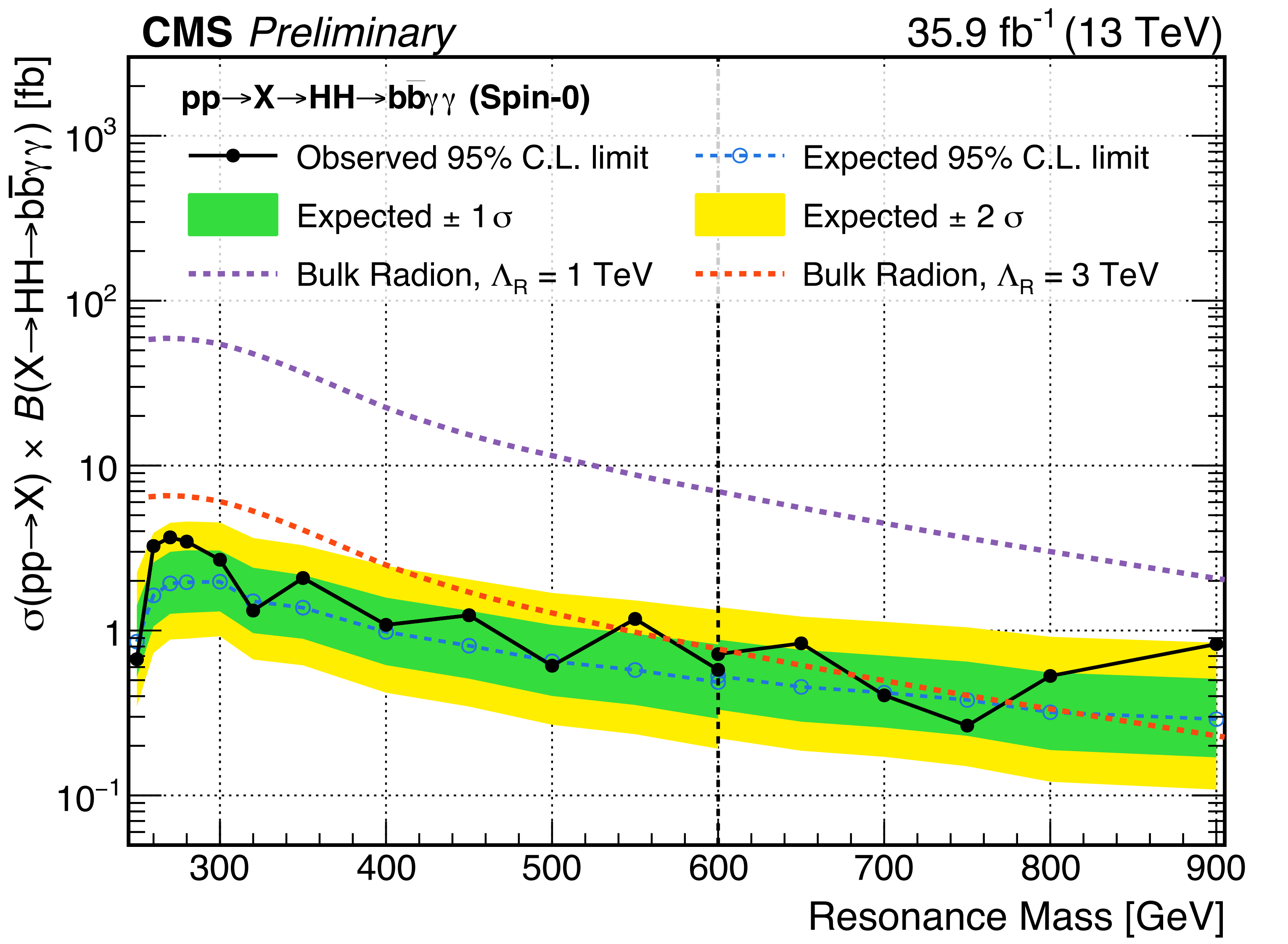
bbγγ - Results

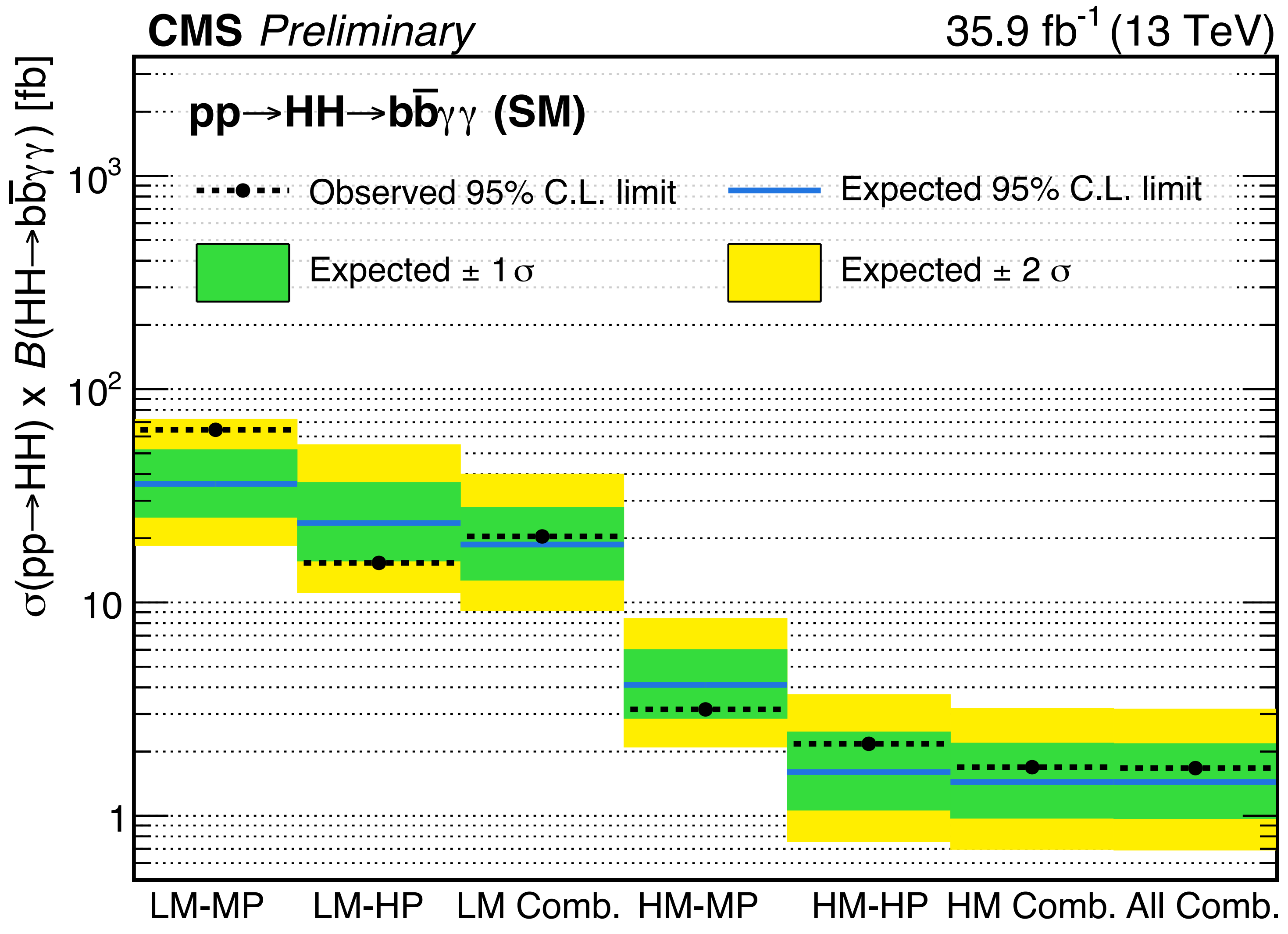


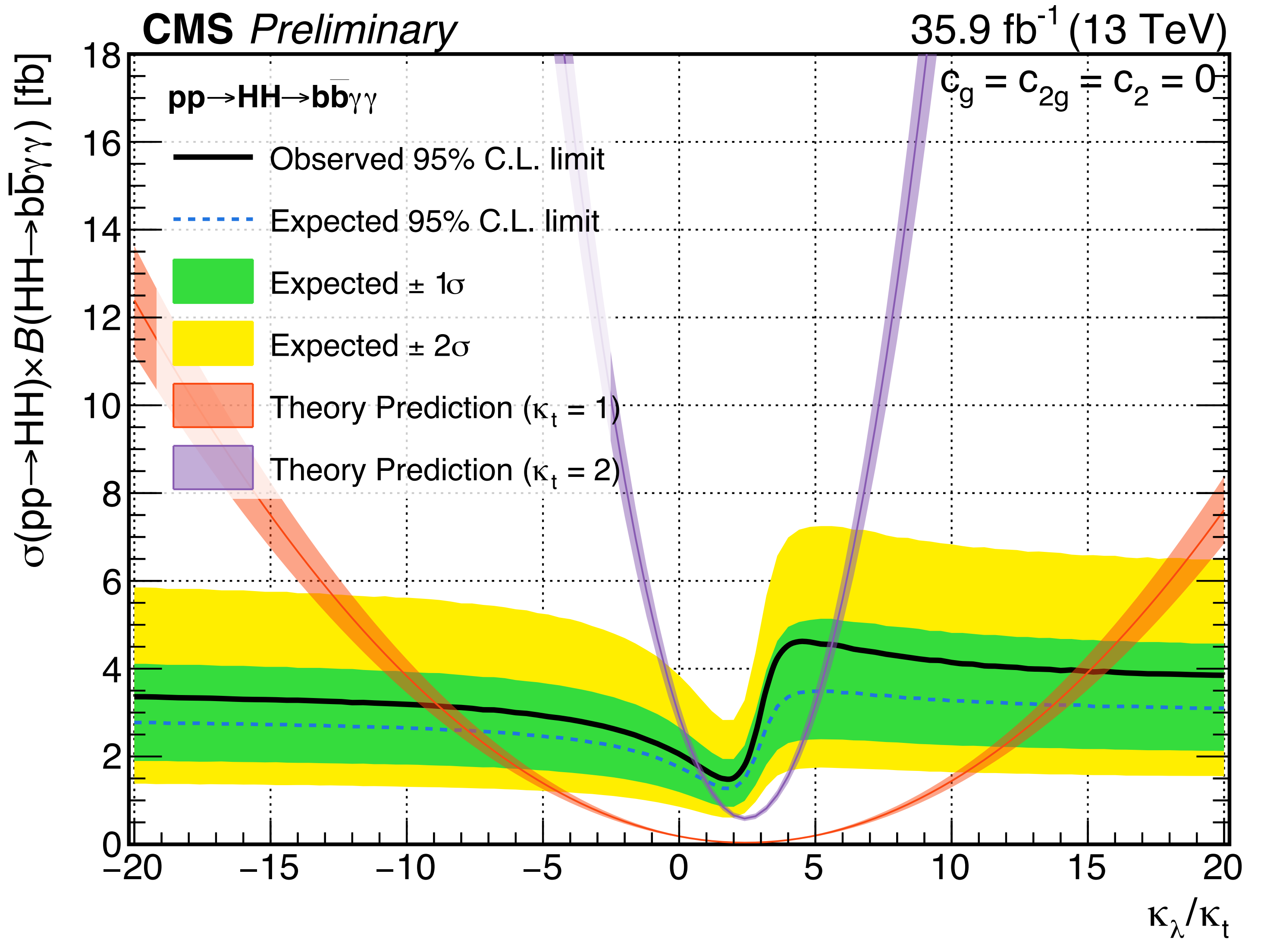
Sensitivity to non-resonant production dominated by the high mass/high purity category

Most performant CMS channel:

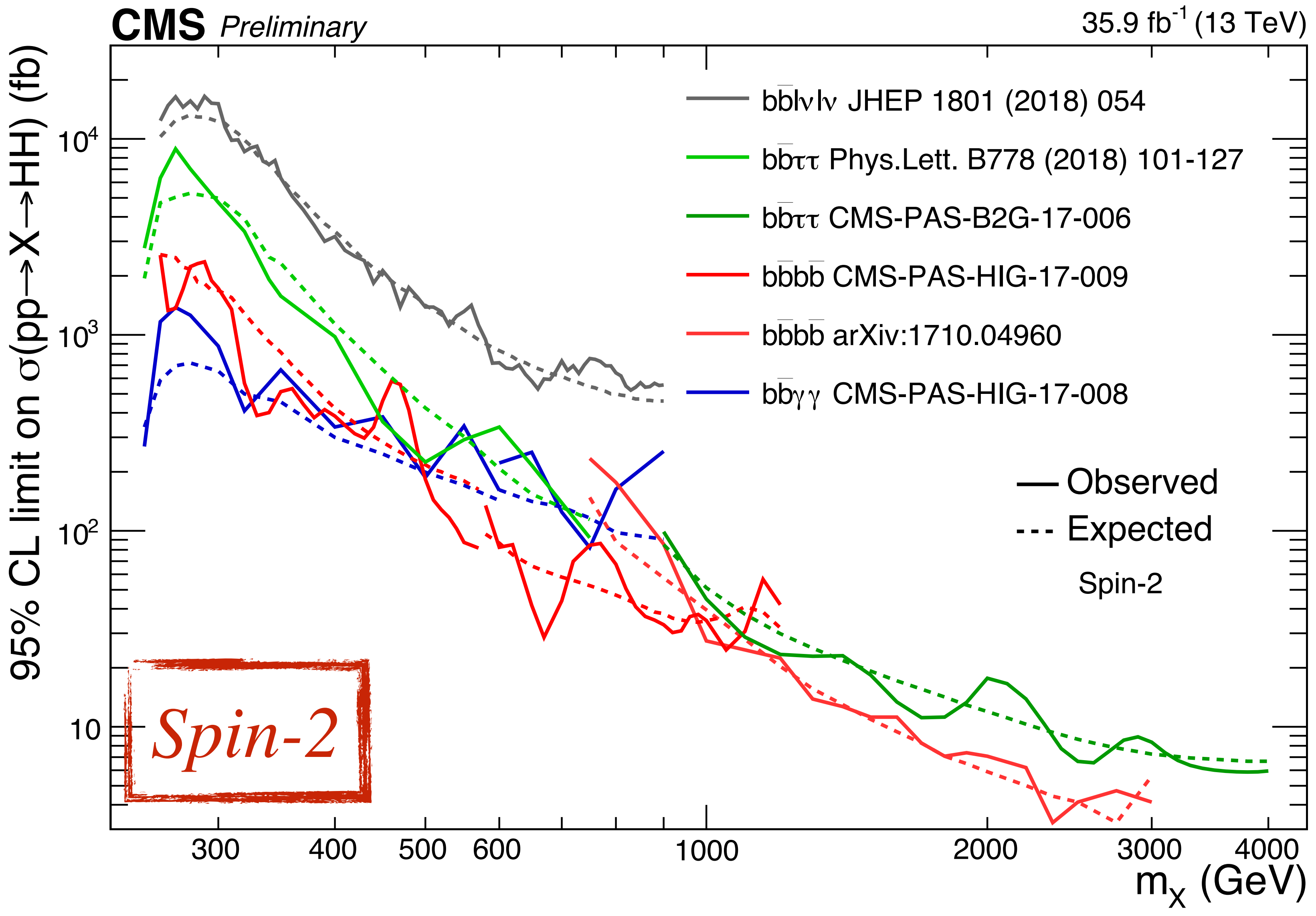
- SM σxBR<1.67 fb
- Obs.(exp.): σ/σ_{SM}< 19.2 (16.5)

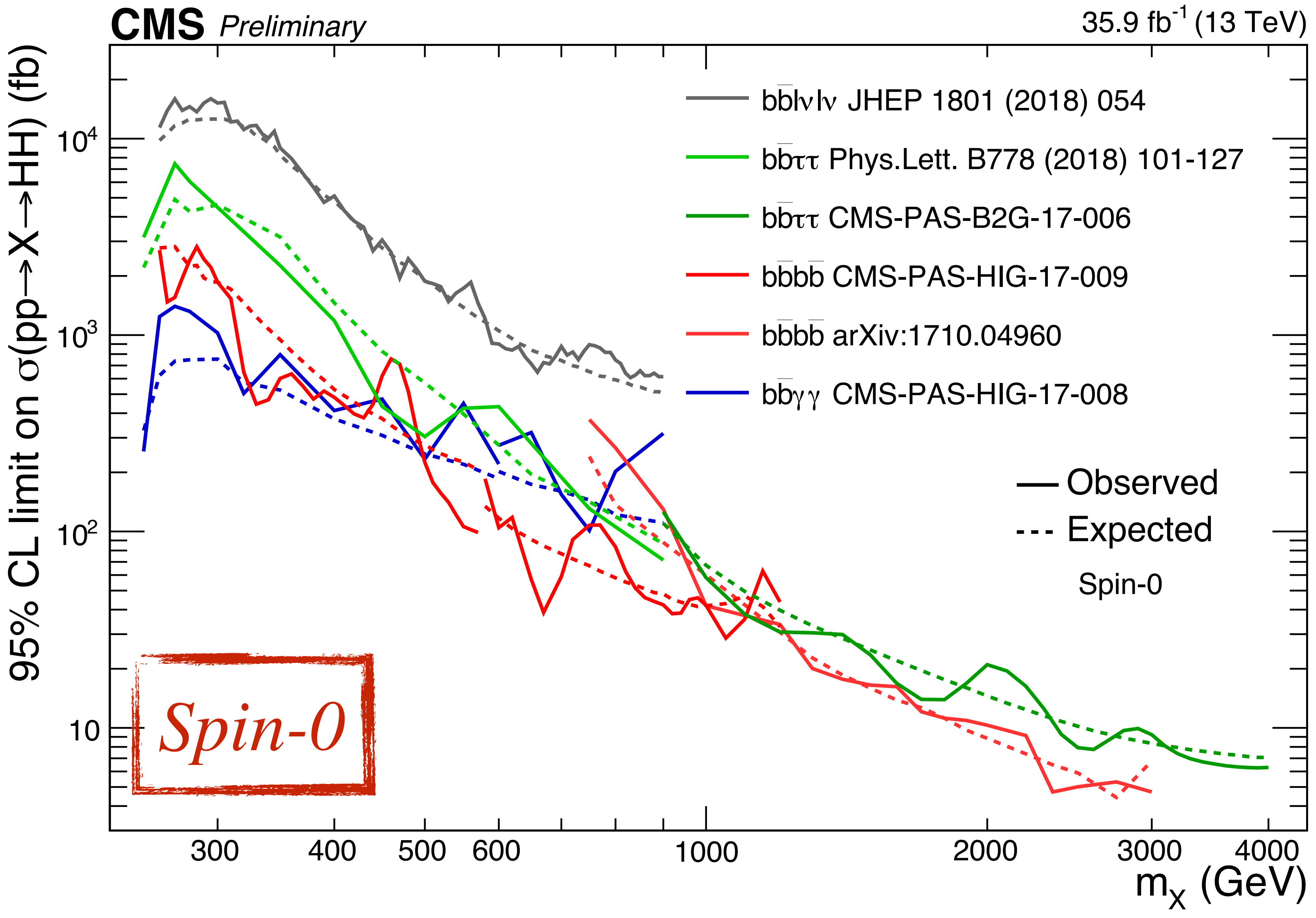






Summary





No evidence for either spin-0 or spin-2 resonance up to 4 TeV

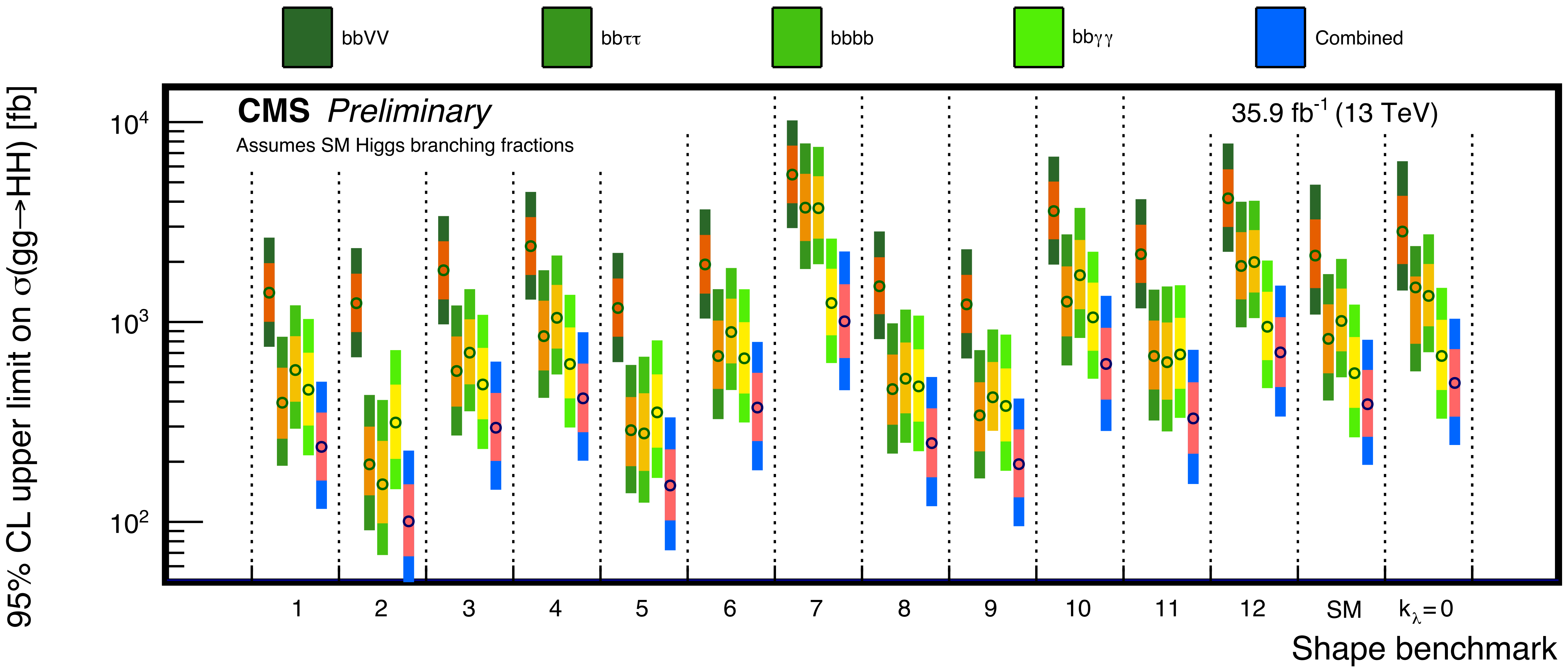
Excluded cross-section ranges from <1pb (300 GeV) to ~4 fb (3 TeV)

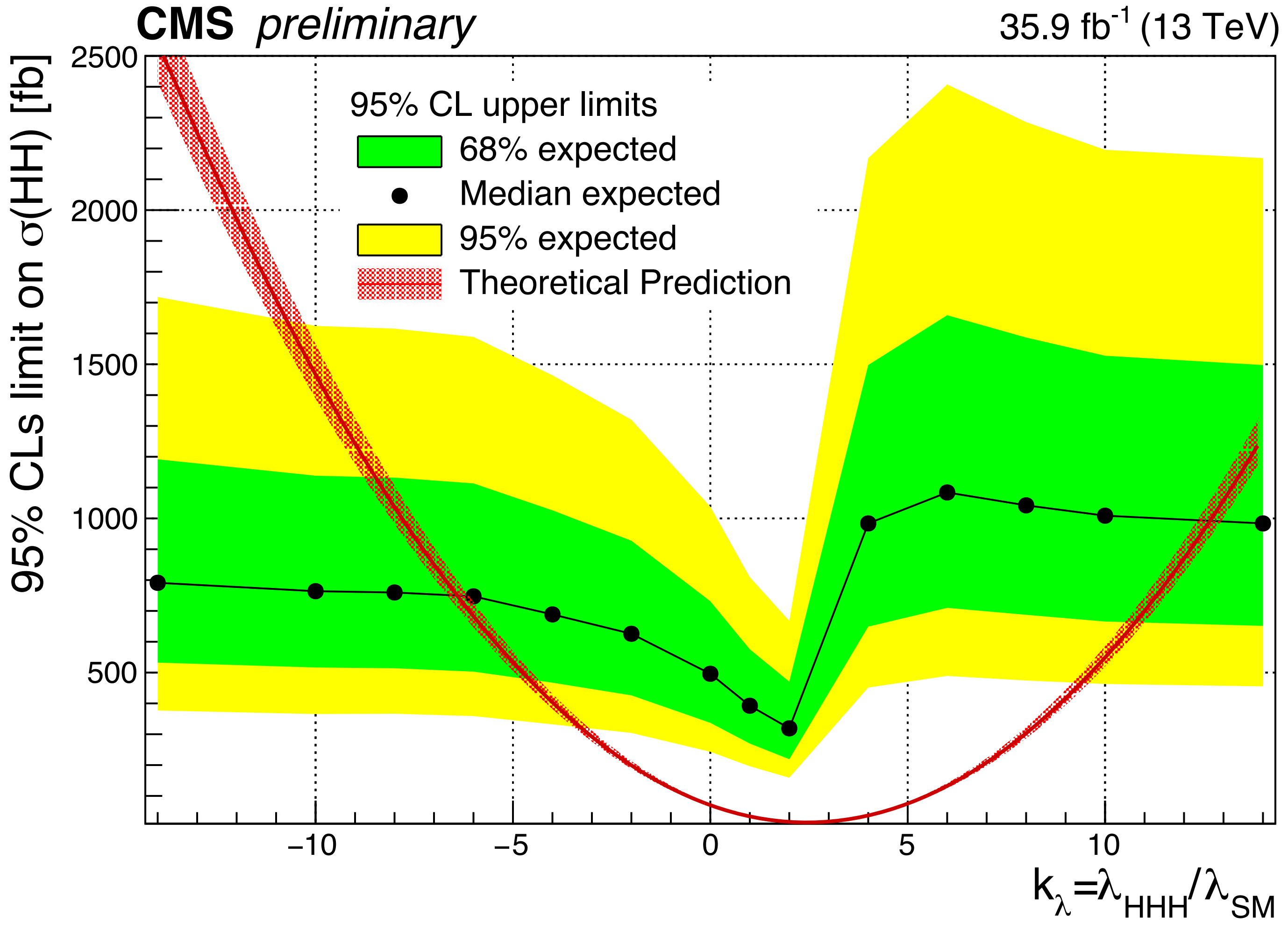
Sensitivity to non-resonant at ~15 times the SM expectation

Anomalous Higgs trilinear coupling constrained in the region $-8.8 < \lambda/\lambda_{SM} < 15$

Final state	**Obs. (Exp.) limit on σ/σ_{SM}**	
bbWW	79 (89)	35.9 fb^{-1}
bbbb	59 (30)	2.3 fb^{-1}
bbττ	30 (25)	35.9 fb^{-1}
bbγγ	19 (16)	35.9 fb^{-1}

Summary (II)

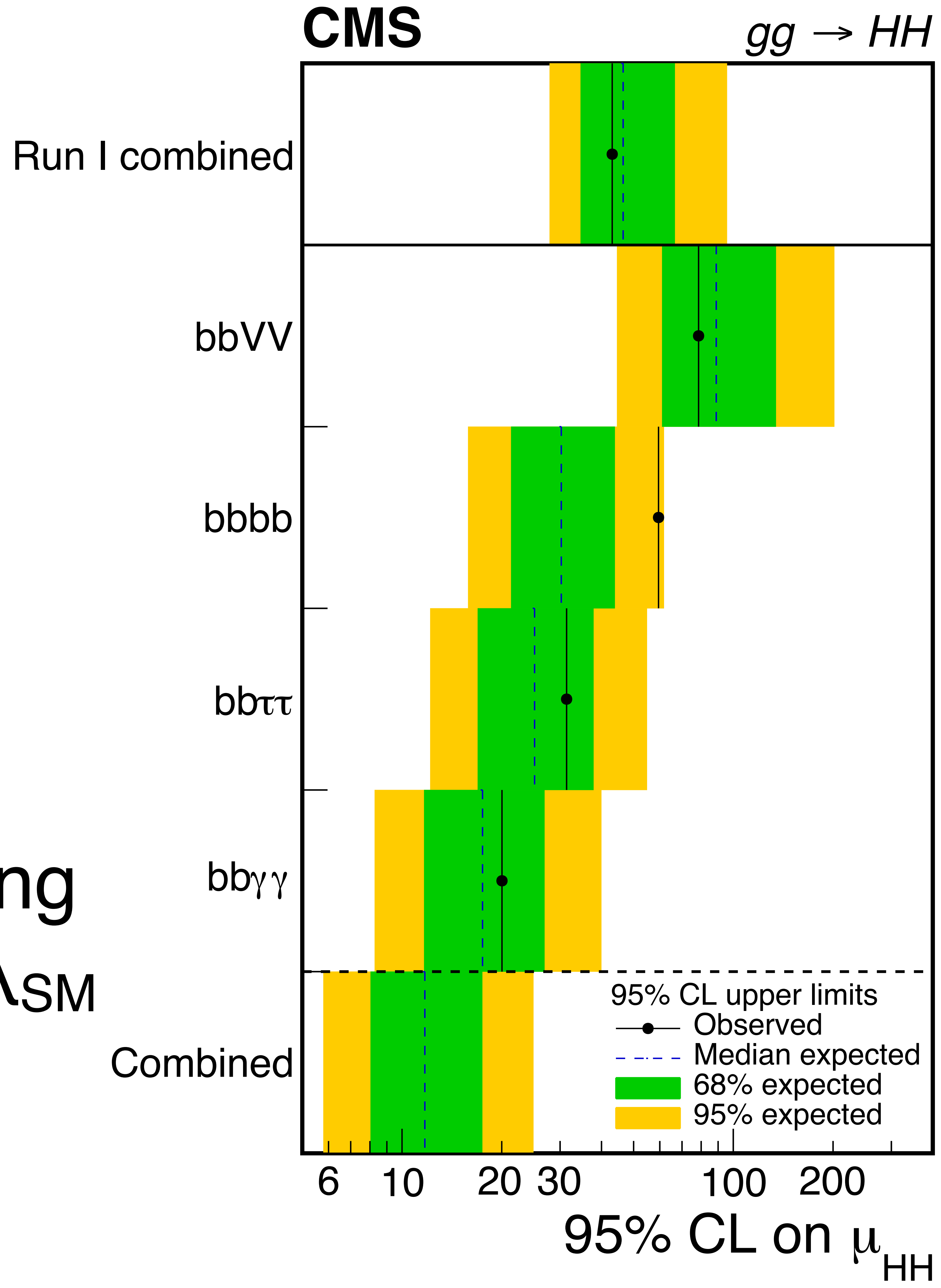




Combination ongoing. Expected limit at around ~11xSM

Anomalous Higgs trilinear coupling constrained in the region $-6 < \lambda/\lambda_{SM} < 12$

Each channel constrain different benchmarks



CMS vs ATLAS

Both CMS and ATLAS perform resonant and non-resonant searches in the 4 main channels

- bb$\tau\tau$, bb$\gamma\gamma$, bbbb, bbWW

On top of these, ATLAS is considering $\gamma\gamma$WW and WWWW, and CMS is studying bbZZ

Some strategies are significantly different across the experiments. Discussion is starting on the best practices.

ATLAS has better trigger on b-jet. Significantly better results in bbbb:

- 21xSM expected exclusion (13 observed) with 27fb^{-1}

CMS outperforming ATLAS in bb$\gamma\gamma$ (~27xSM expected)

Similar sensitivity in bb$\tau\tau$ (ATLAS paper not out yet)

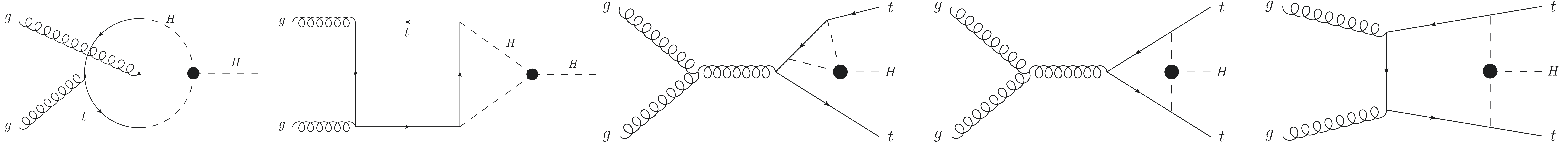
The combined ATLAS result should be similar to CMS one (~10xSM)

If this holds, for the legacy we can expect:

- 10 x SM / $\sqrt{3}^{\text{lumi}}$ /$\sqrt{2}^{\text{experiments}}$ ~ 5 x SM exclusion after LHC-Run2

Constraints from single Higgs production

Anomalous trilinear coupling affects single H production @NLO



Precision at the % level expected on most H couplings at the (HL-)LHC

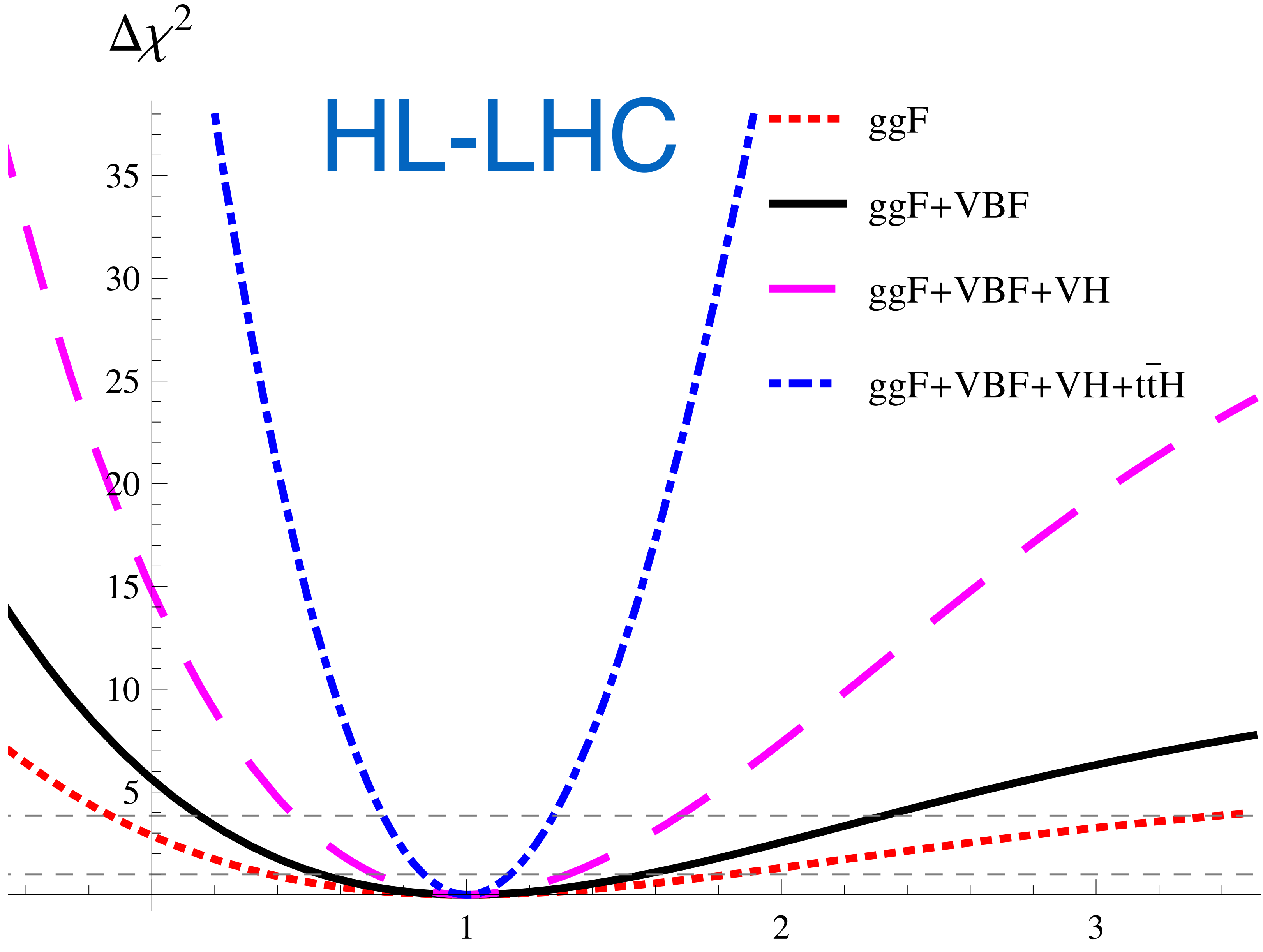
Constraints on anomalous Higgs couplings can be translated into constraints on kλ

- Assuming all anomalies are due to kλ deformations

Otherwise, double Higgs data can be used to constrain flat direction in the global fit

Most of the sensitivity is obtained by ttH, VH production modes.

Experiments are looking into the feasibility of this approach for Run2 already



[1] Degrassi et al, JHEP12(2016)080
[2] Di Vita et al 1704.01953

Single and Double Higgs production

HL-LHC Projections show this method has similar sensitivity to direct HH searches

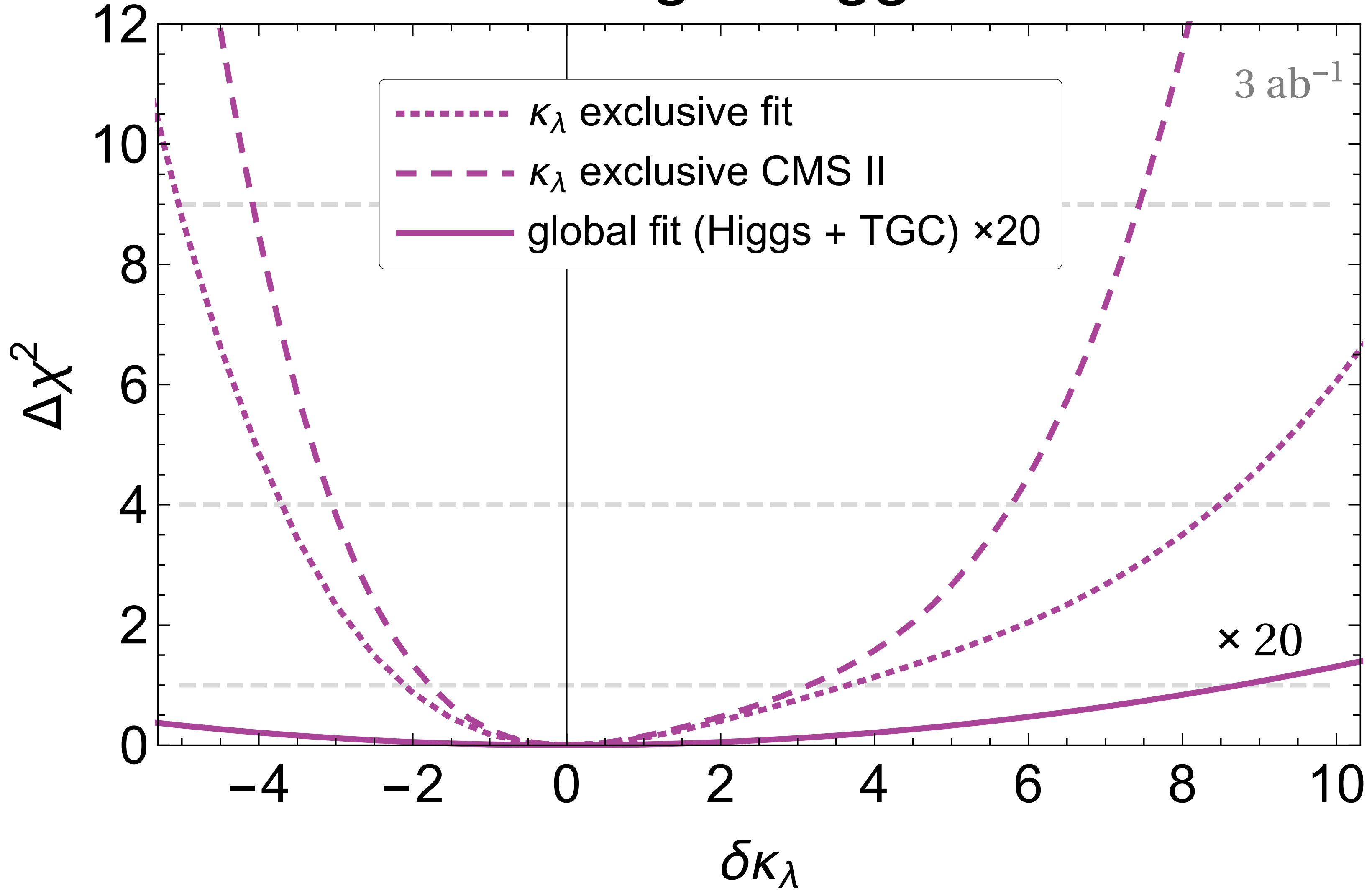
Different systematics, different parametric and theoretical uncertainties

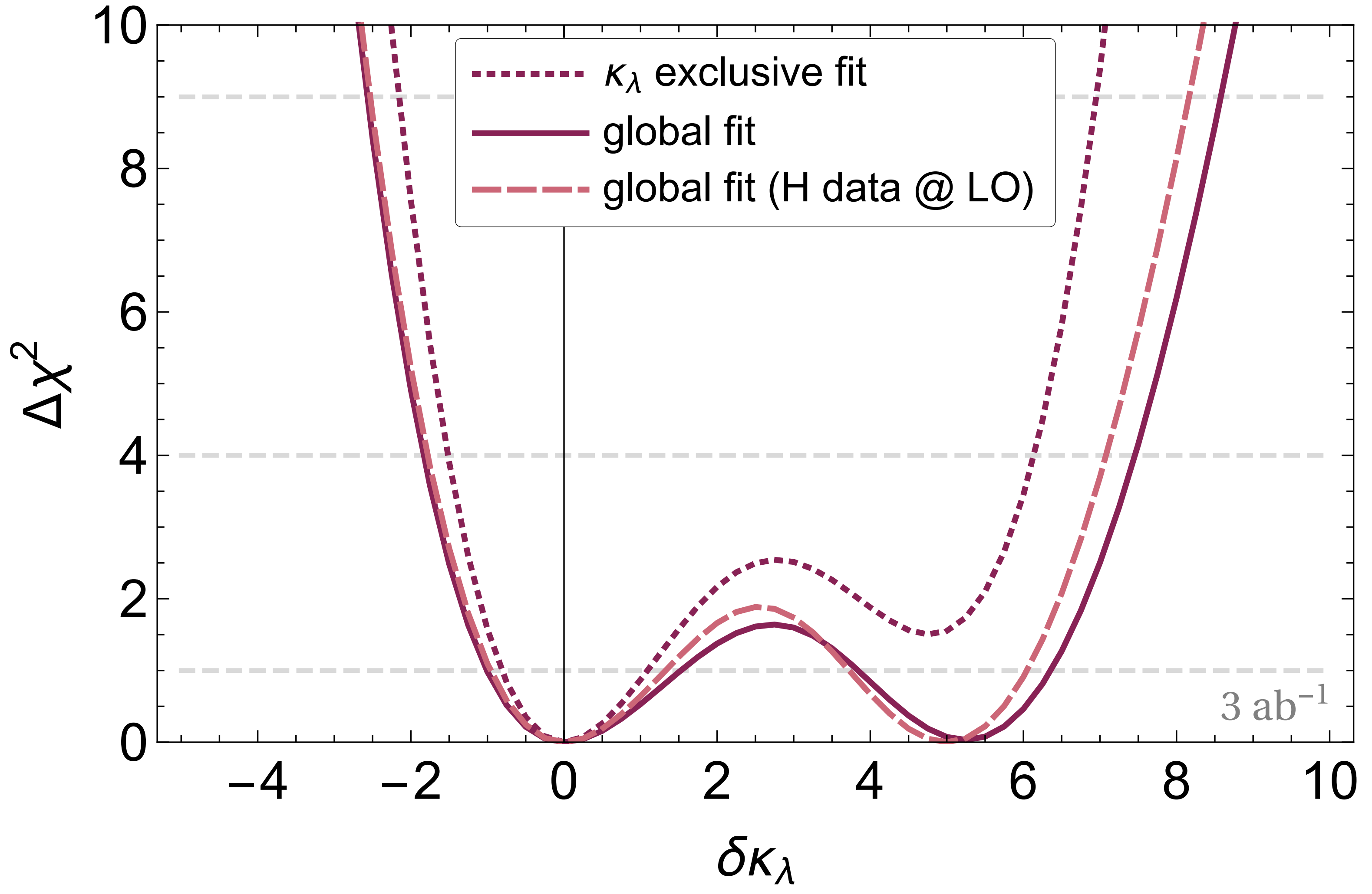
Good complementarity between single and double Higgs measurements

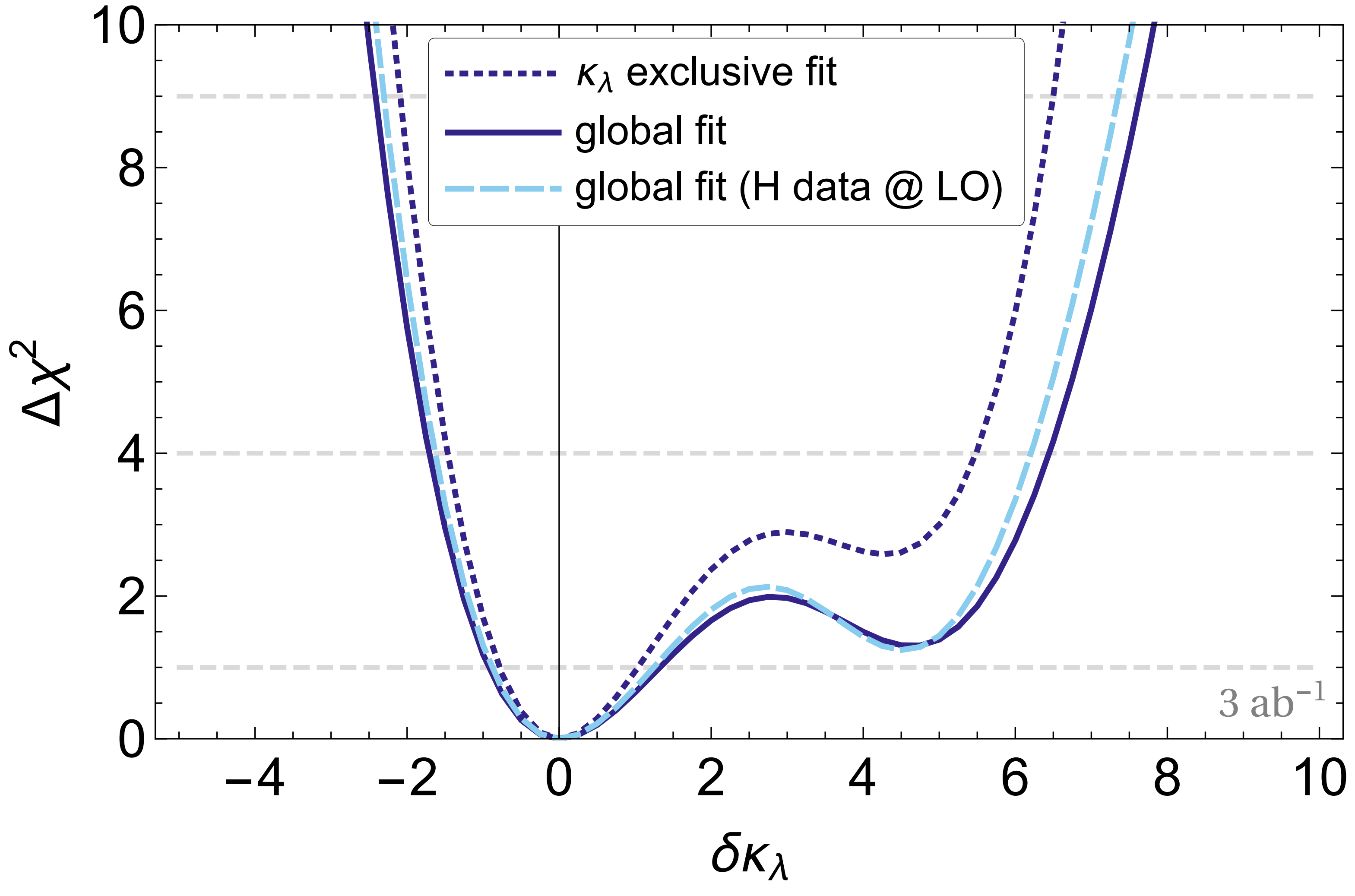
A global fit of all the SM couplings is probably the best approach if we want to narrow down the SM trilinear coupling

Differential measurements can provide further handles

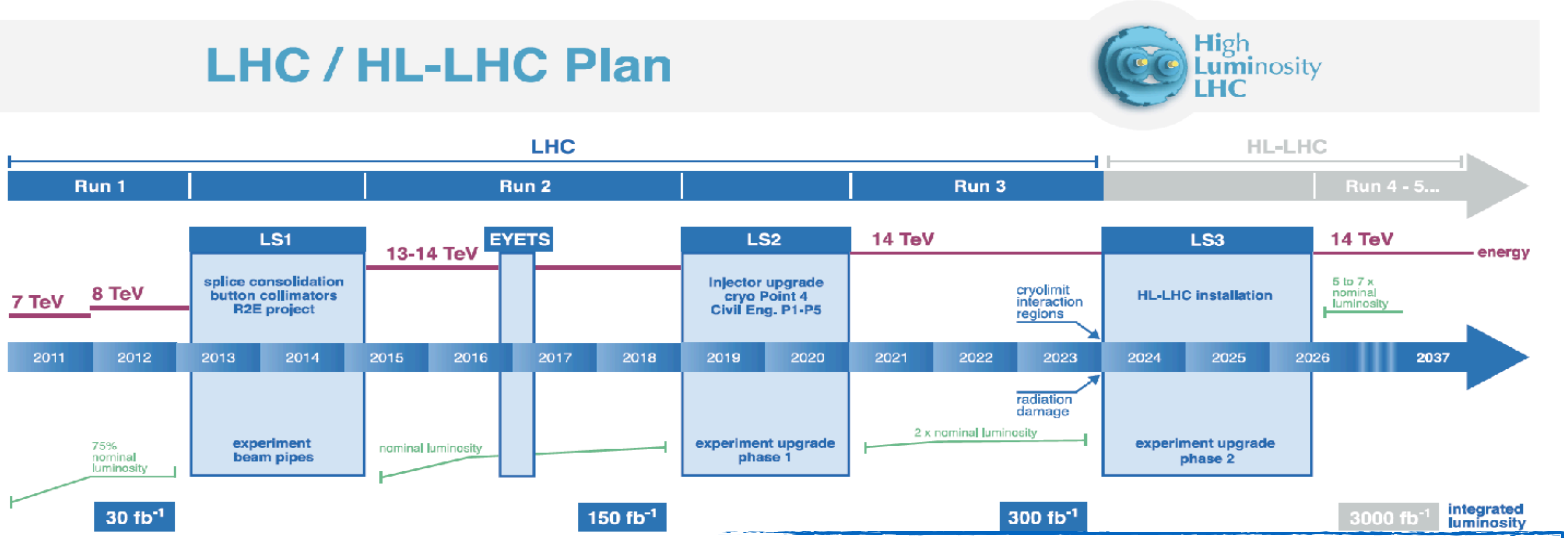
It must include double Higgs data to work properly


Incl. single Higgs data


H & HH all inclusive


incl. H & diff. HH

Double Higgs at HL-LHC



Double Higgs searches are an important physics case for HL (and HE) LHC

CMS will undergo relevant upgrades for the HL-LHC phase.

New all-silicon tracker, |η|<4, track-trigger

Barrel calorimeters: new electronics

New endcap calorimeter (high granularity)

Muon detectors to |η|<2.8

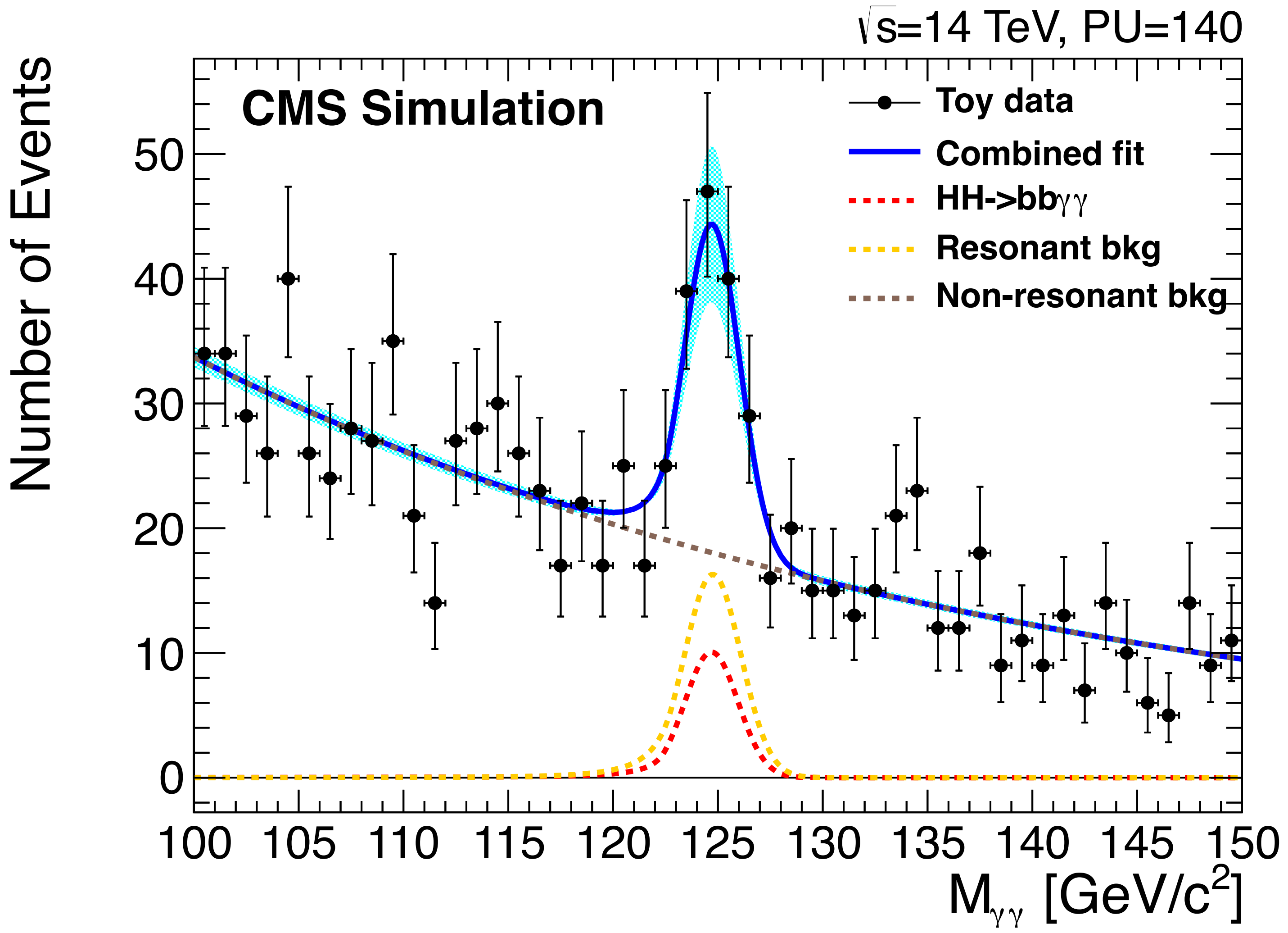
Trigger: L1 @ 750 kHz, HLT @ 7.5 kHz

PAS-FTR-15-002
PAS-FTR-16-002

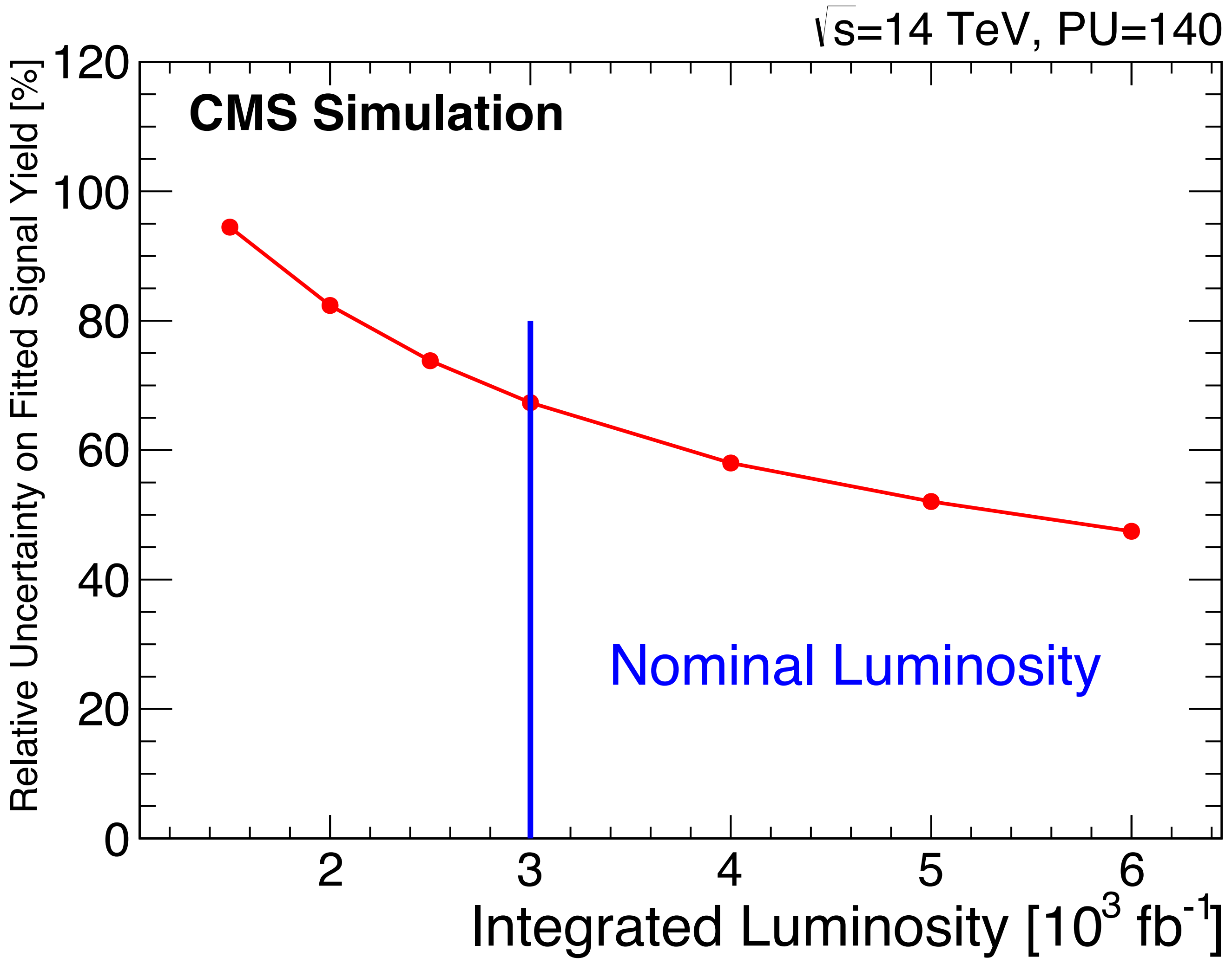
Double Higgs at HL-LHC, Projections

Dedicated studies: PAS-FTR-15-002

bbγγ, bbττ, bbVV(lνlν, lνjj) ~50% precision



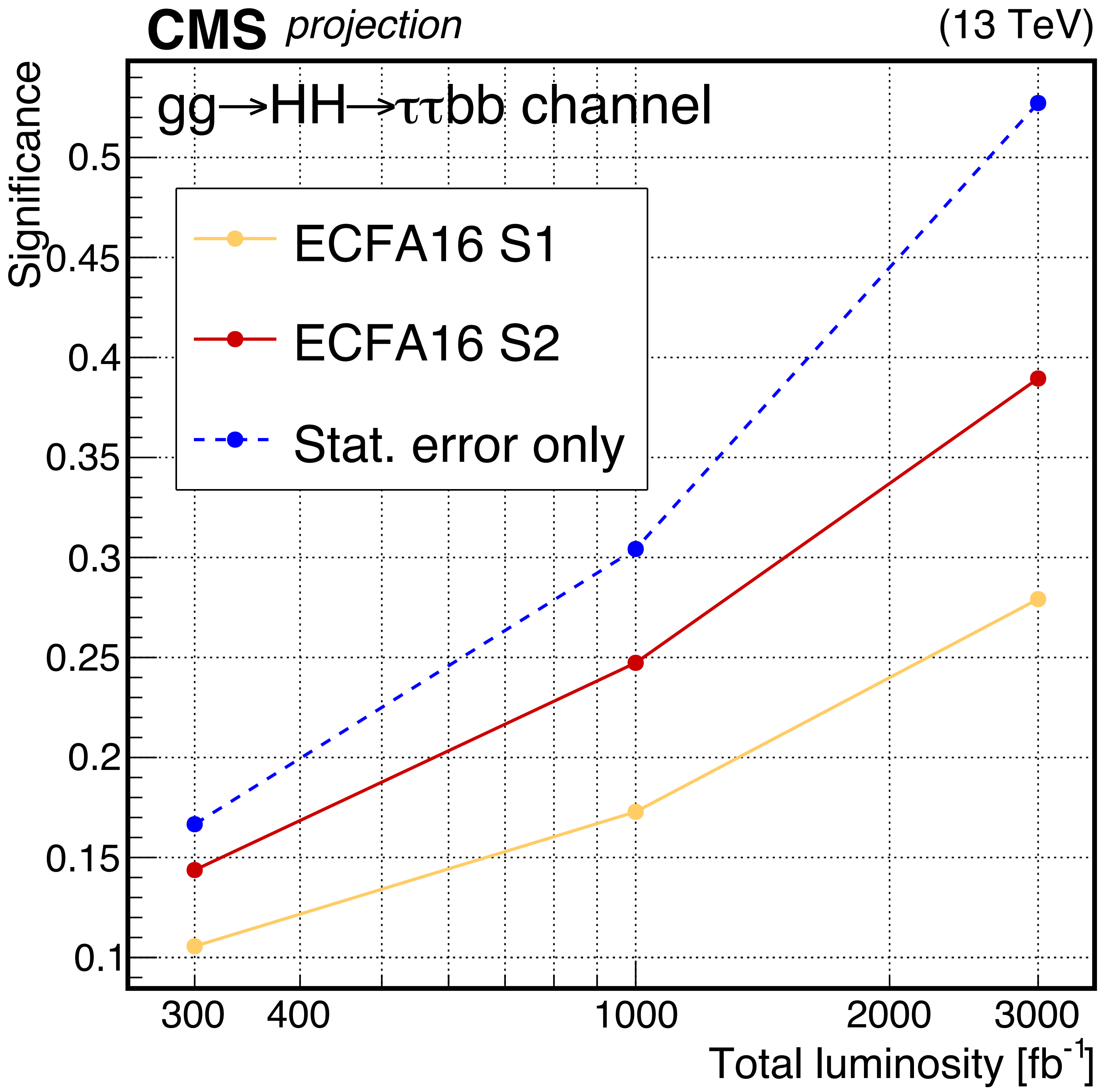
Significance: 1.9σ

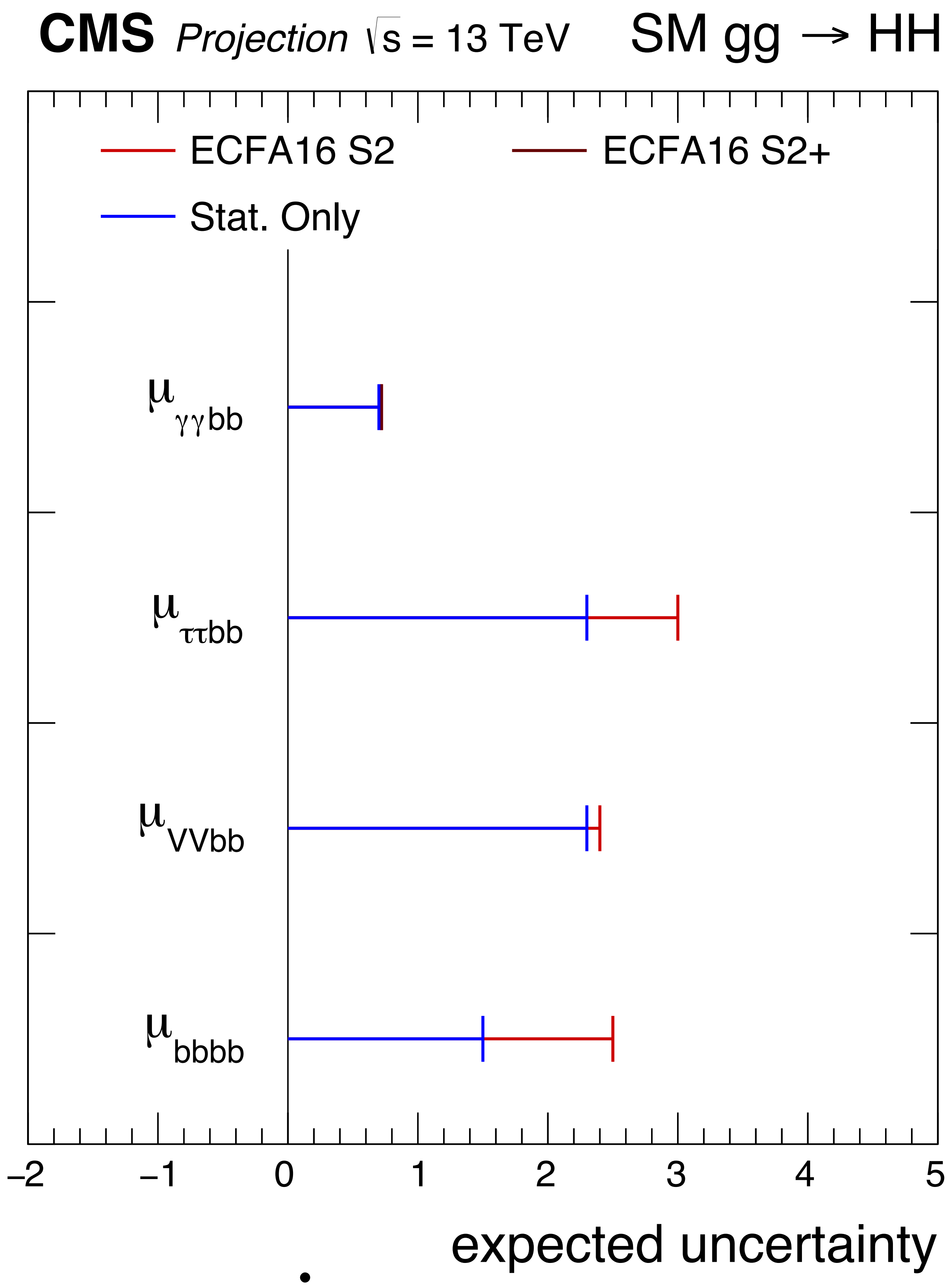


Extrapolations of 2015 analyses: PAS-FTR-16-002

bbγγ, bbττ, bbbb, bbVV(lνlν)

Poor stat. for projections





New studies with updated CMS simulations coming soon

Beyond HL-LHC: HH@FCC-hh

80-100km accelerator, targeting 100 TeV pp collisions

LHC can get evidence of anomalous trilinear coupling

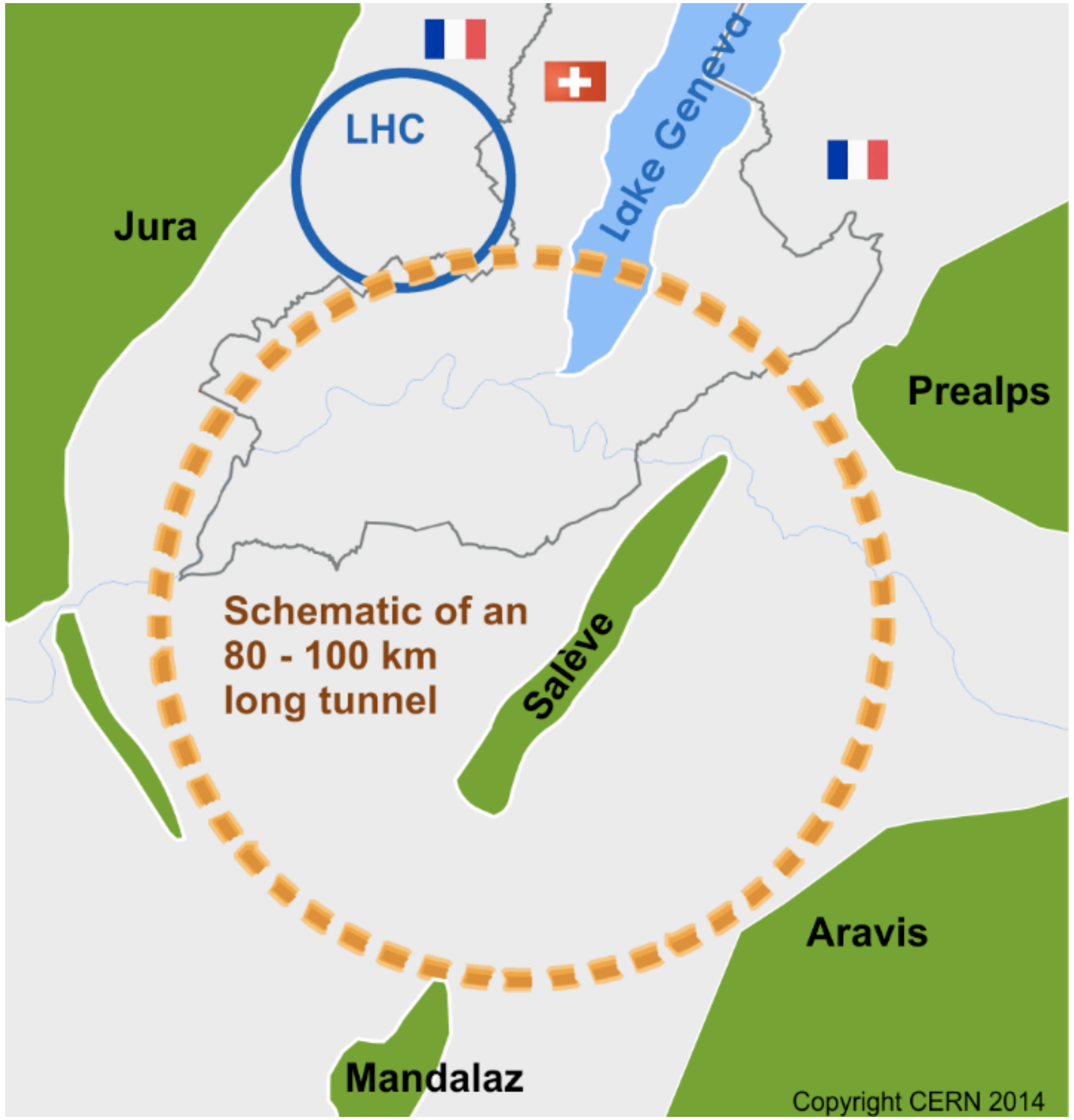
HL-LHC can observe double Higgs production

To actually measure λ_{HHH} we need the FCC

Several channels are being studied for FCC: bb$\tau\tau$, bb$\gamma\gamma$, bbbb, bbWW, bbZZ

Higher energy enhance HH production (x40), large PU, large background

Can study recoil against high p_T jets for non-resonant production



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HH→bbγγ (I)

Acceptance cuts

γ isolation $R = 0.4$
$(p_T(had)/p_T(\gamma) < 0.15)$
jets: anti-k_T, parameter $R = 0.4$

$|\eta_{b,\gamma,j}| < 6$

$p_T(b), p_T(\gamma), p_T(j) > 35$ GeV

$m_{bb} \in [60, 200]$ GeV

$m_{\gamma\gamma} \in [100, 150]$ GeV

Backgrounds

- ttH
- jjɣɣ
- jjjɣ (fake photons, fake b's)

$$p_{j\to\gamma} = \alpha \exp(-p_{T,j}/\beta)$$

Final selection

γ isolation $R = 0.4$
$(p_T(had)/p_T(\gamma) < 0.15)$
jets: anti-k_T, parameter $R = 0.4$

$|\eta_{b,\gamma}| < 4.5$

$p_T(b_1), p_T(\gamma_1) > 60$ GeV

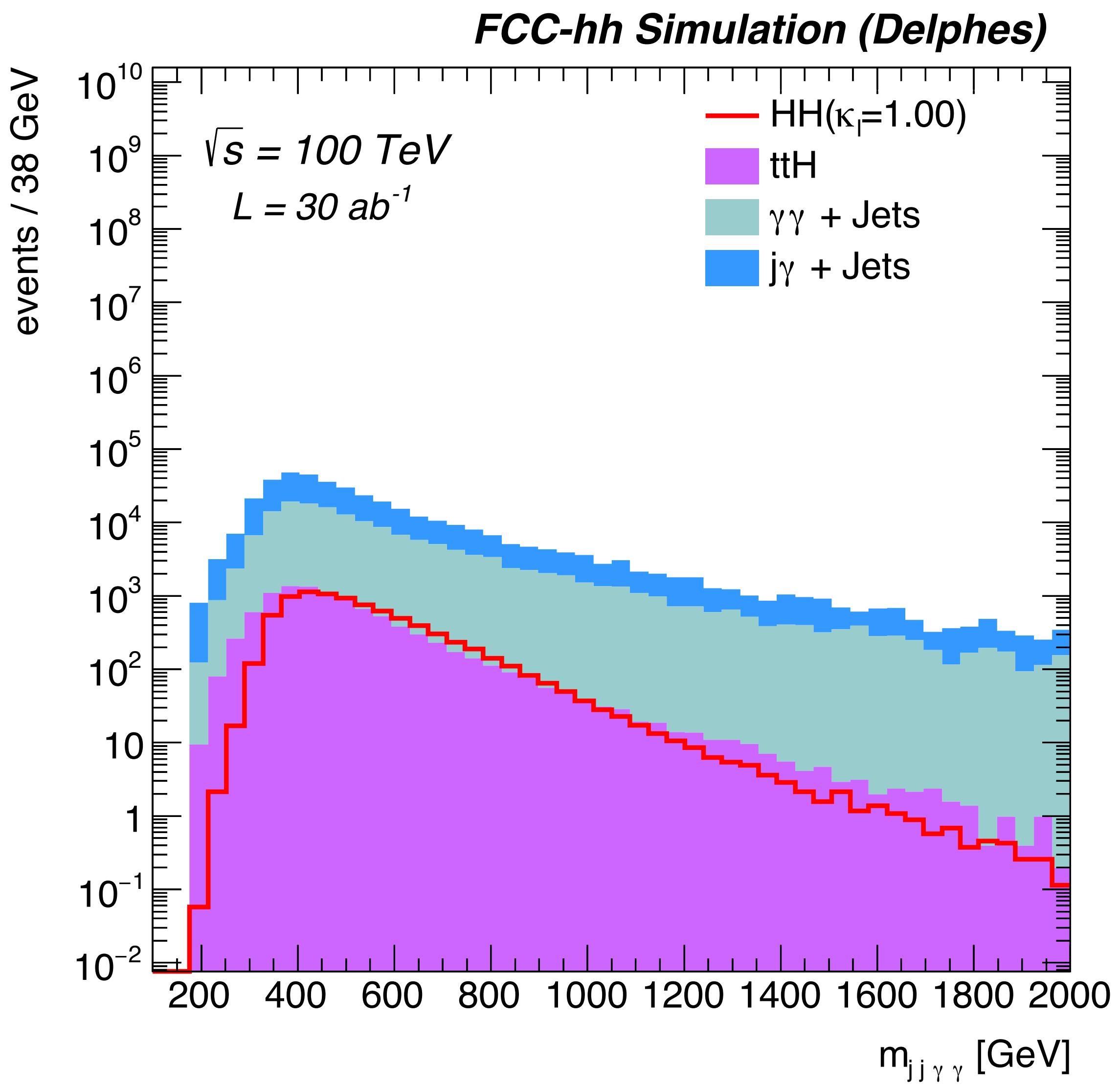
$p_T(b_2), p_T(\gamma_2) > 35$ GeV

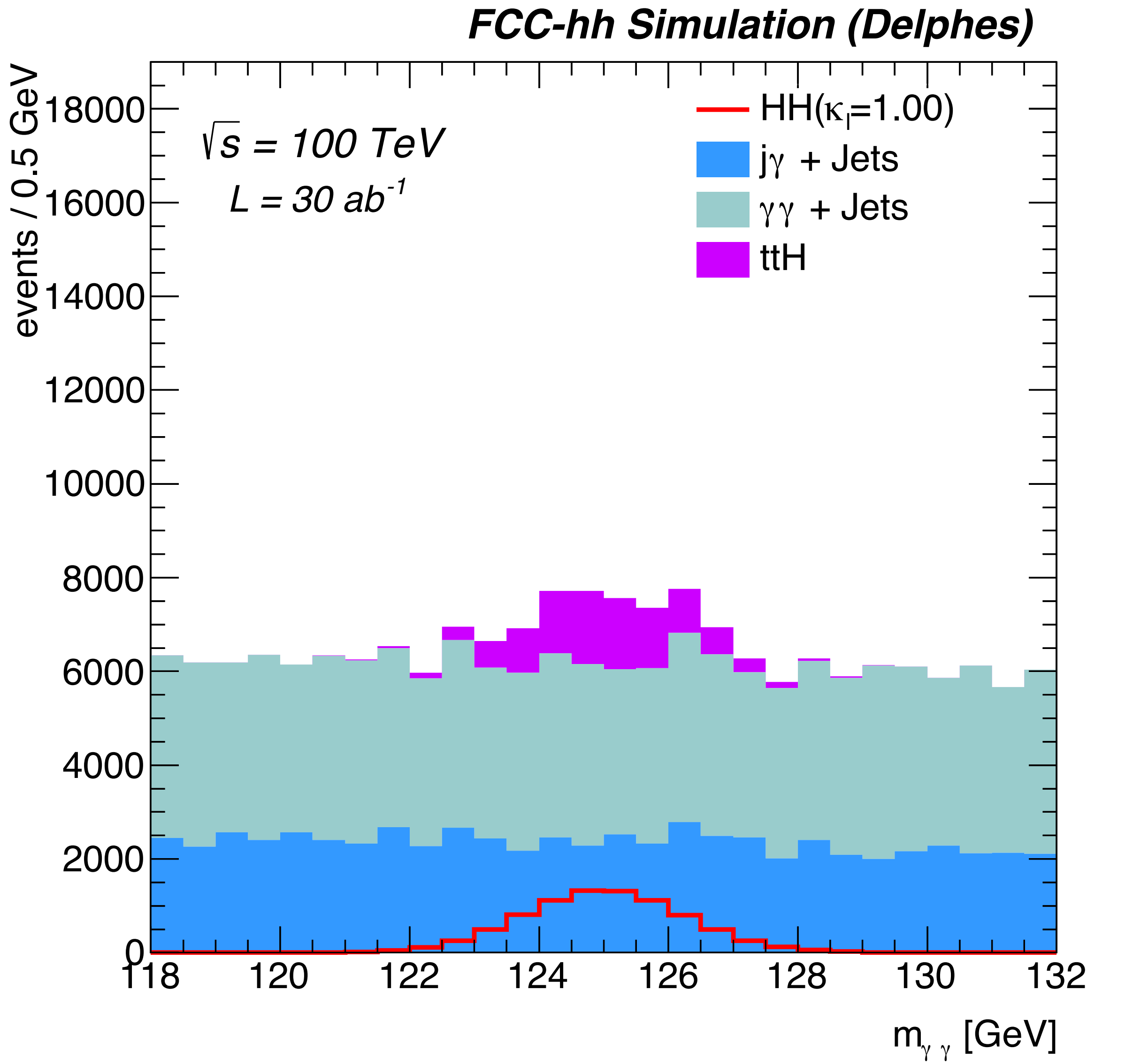
$m_{bb} \in [100, 150]$ GeV

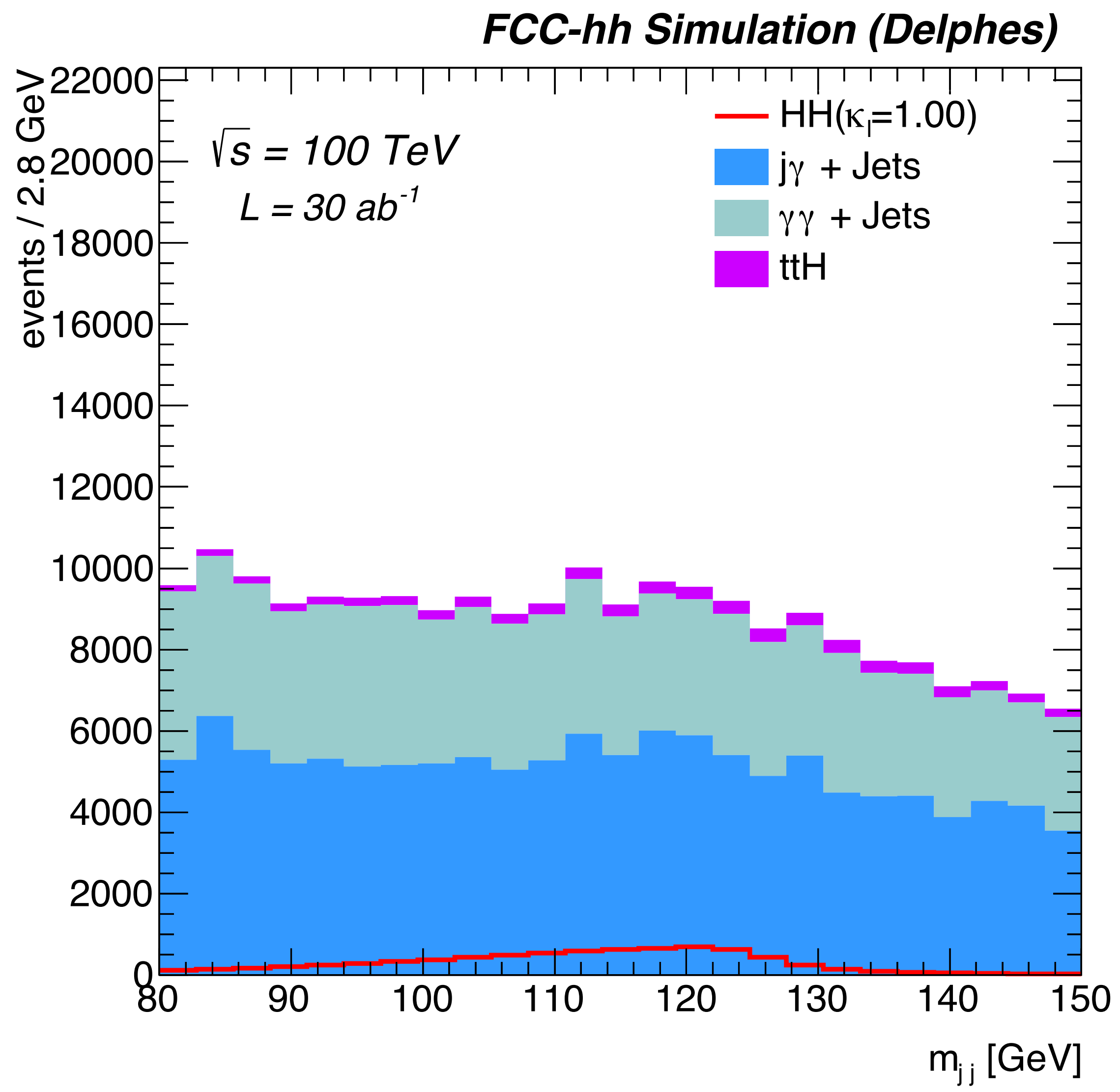
$p_T(bb), p_T(\gamma\gamma) > 100$ GeV

$\Delta R(bb), \Delta R(\gamma\gamma) <2.5, 3.0$

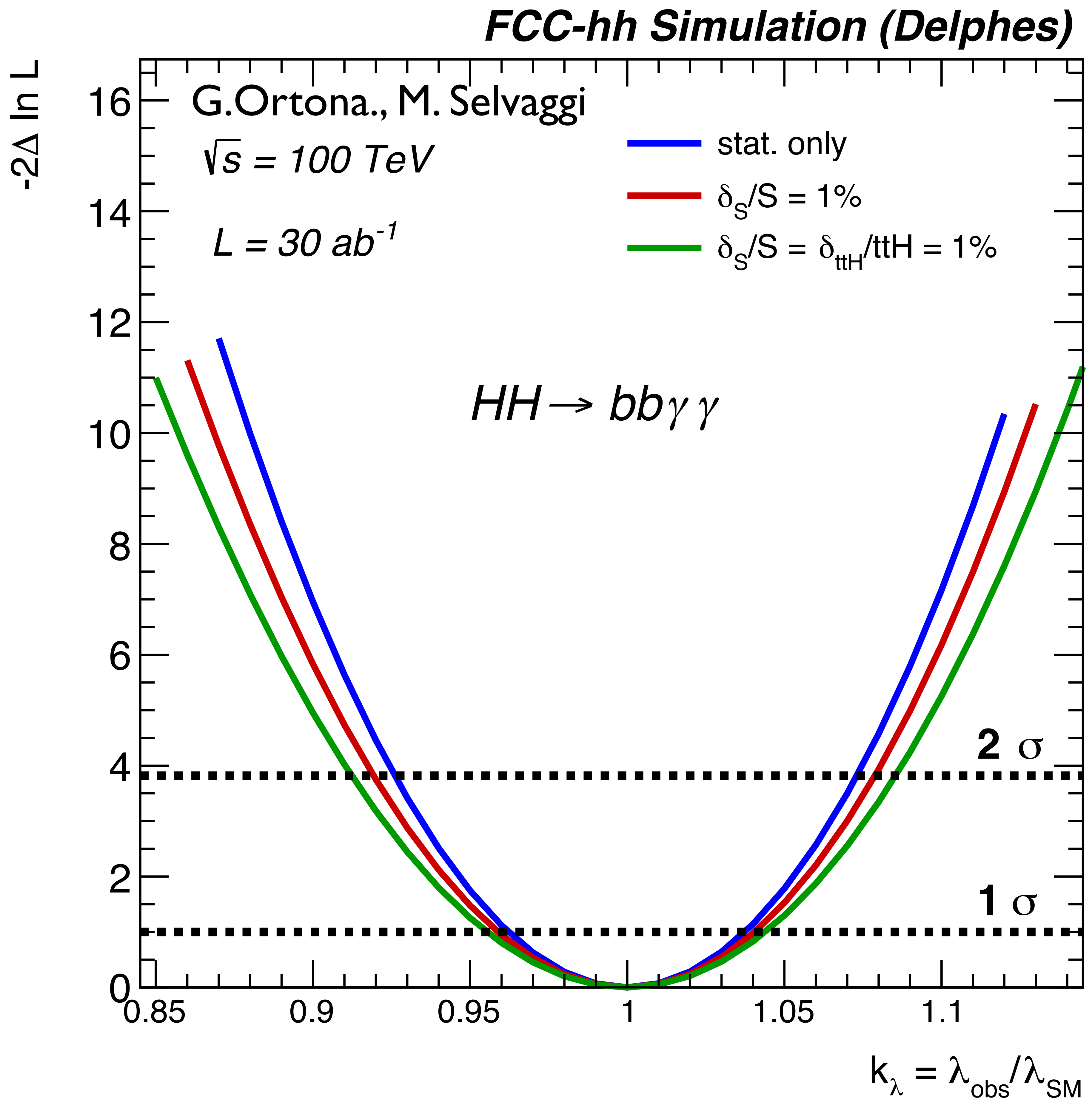
no isolated leptons with $p_T > 25$ GeV

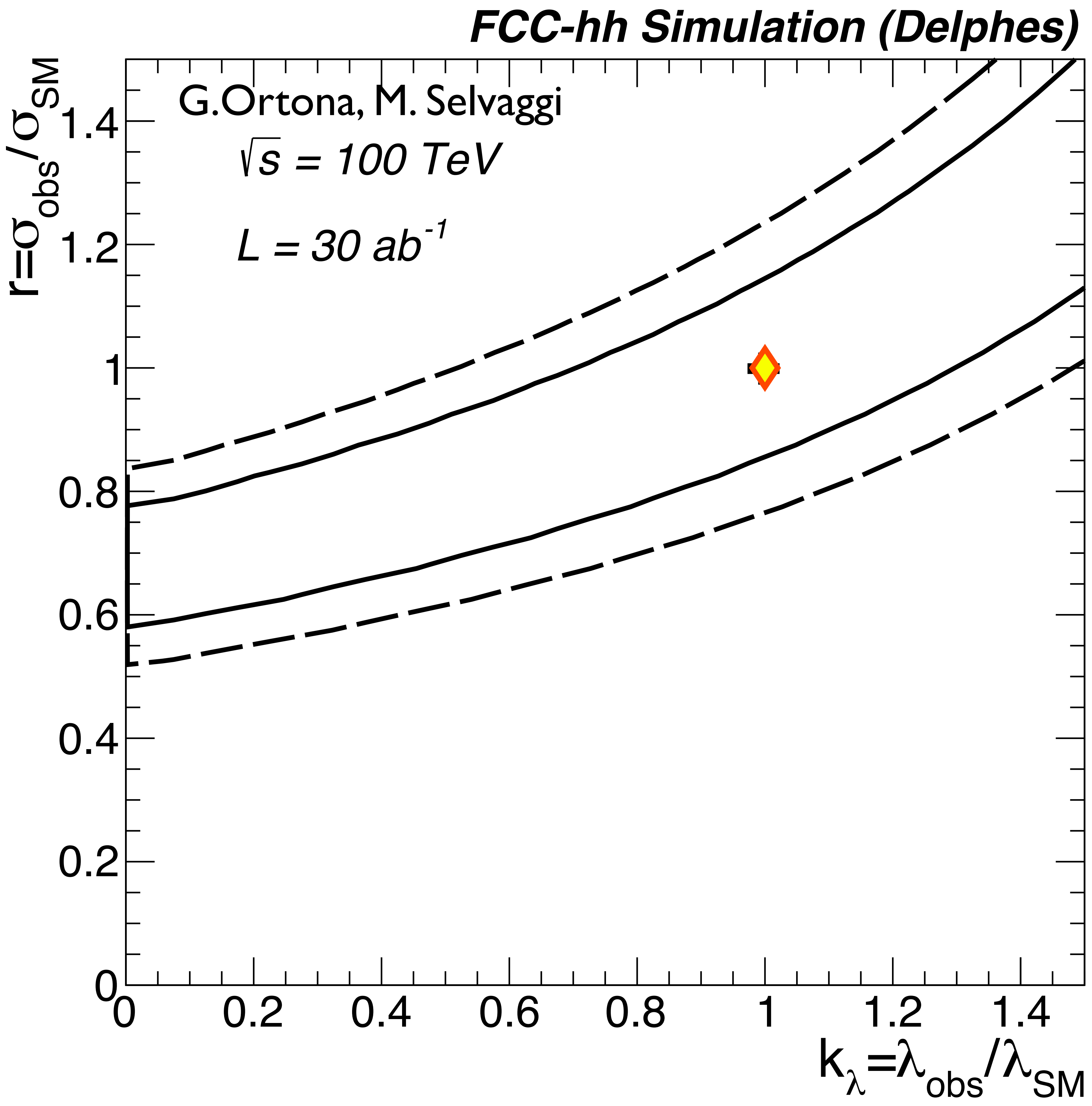






HH→bbγγ (II)





Delphes based study for hypothetical FCC-hh detector.

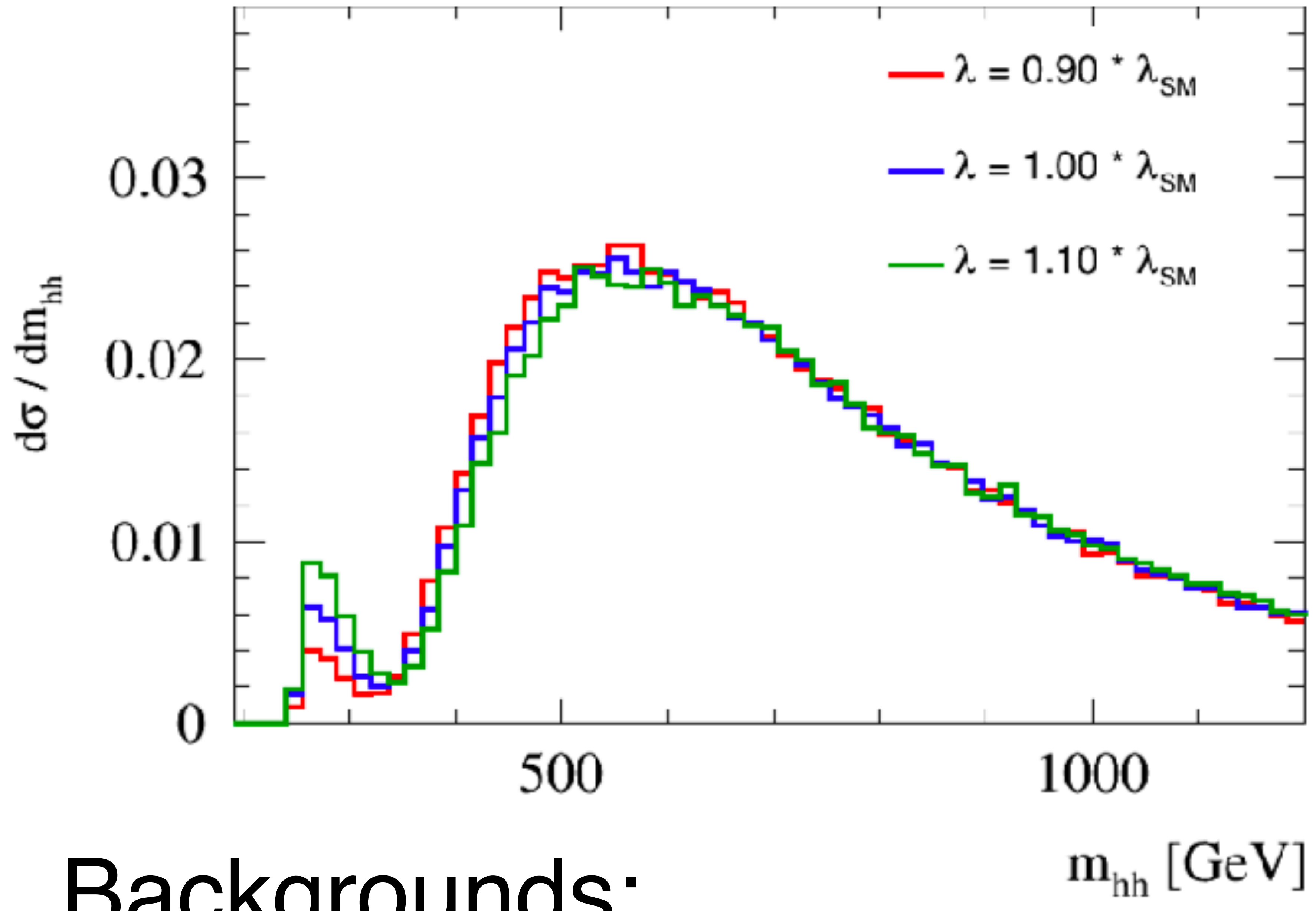
2D parametric fit on $\mathbf{m_{\gamma\gamma}}$: gauss, $\mathbf{m_{hh}}$: landau+exp

2D likelihood on signal strength/anomalous coupling

$\delta\kappa_\lambda(\text{stat}) \approx 3.5\ \%$
$\delta\kappa_\lambda(\text{stat + syst}) \approx 4.5\ \%$
$\delta r(\text{stat}) \approx 2.5\ \%$
$\delta r(\text{stat + syst}) \approx 3\ \%$

HH→bbττ (I)

Banerjee, Englert, Mangano, Selvaggi, Spannowsky1802.01607



Backgrounds:

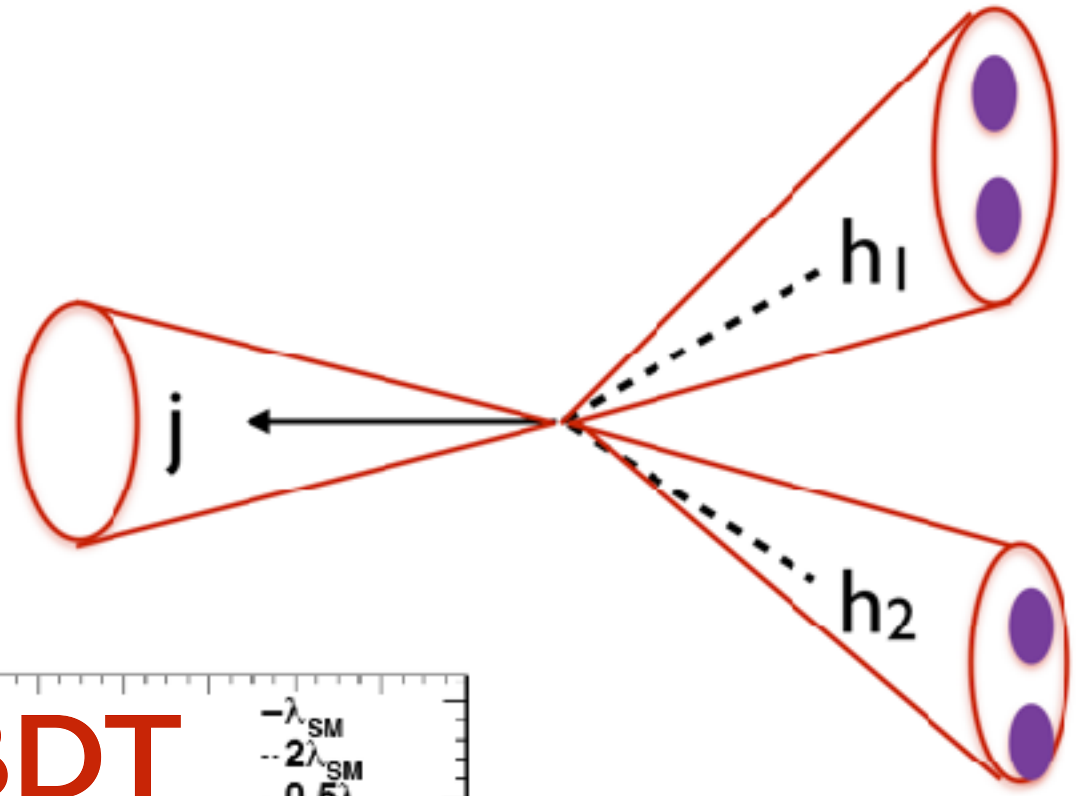
- tt+jets
- Z bb + jets (EWK + QCD)
- ZZ/ZH (EWK)
- W+jets (neglected)

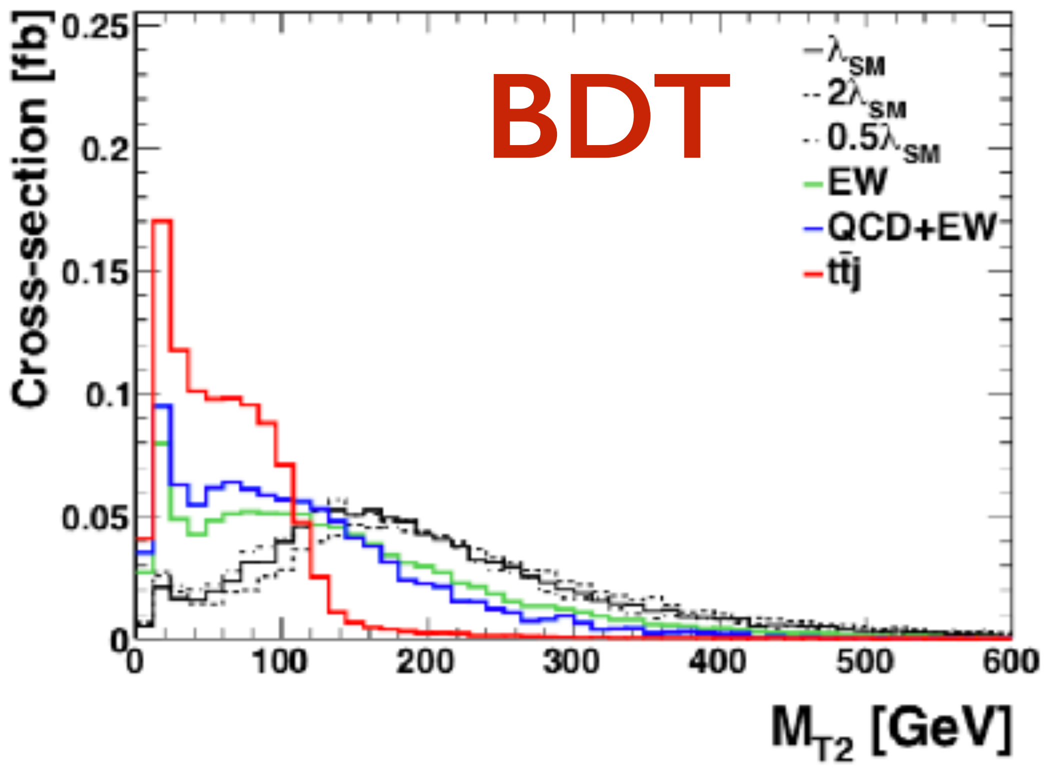
- σ(pp→hhj, 100 TeV) ≈ 100 * σ(pp→hhj, 14 TeV) , with $p_T(j) > 100$ GeV
- Exploit large branching ratio 2*BR(H→bb)*BR(H→ττ) ≈ 7%
- Requiring a boosted HH system recoiling against jet(s), contains the invariant mass to small values → maintain sensitivity to the self-coupling
- Final states: both $\tau_{lep}\tau_{had}$ and $\tau_{lep}\tau_{lep}$ considered, but $\tau_{lep}\tau_{had}$ by far the best…
- Resolved analysis and τhadτhad final state were not considered, but they are by far the most sensitive ones at LHC-PhaseII and in HL-LHC simulations

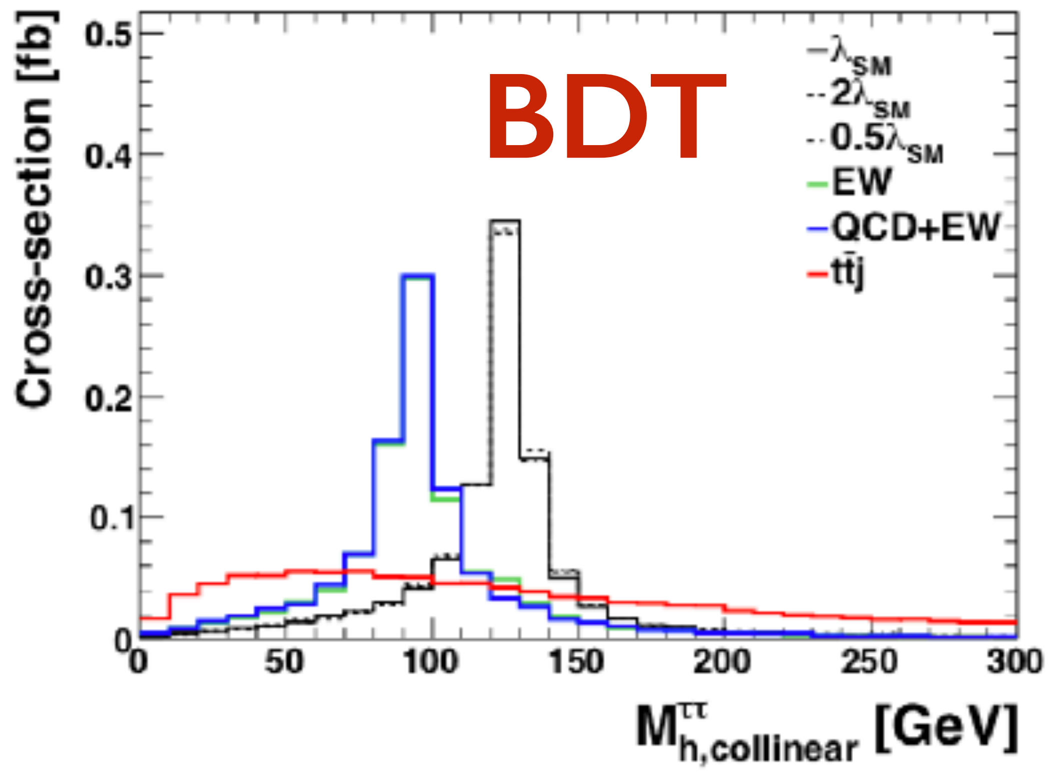
Caveat: no detector simulation!

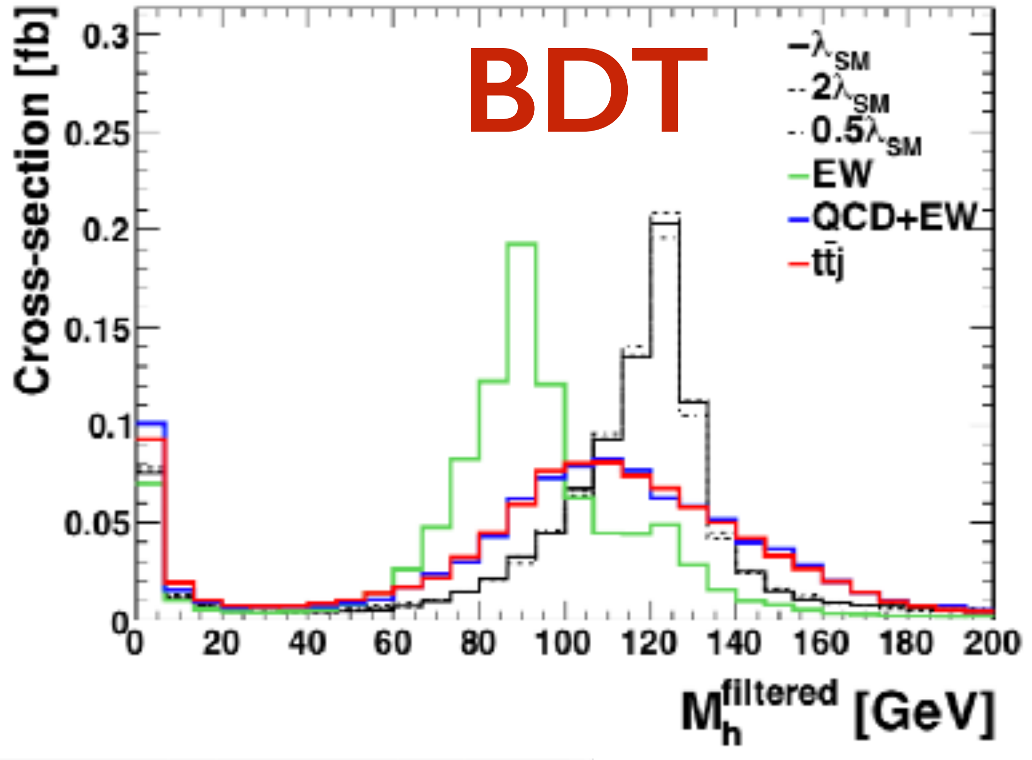
HH→bbττ (II)

- 1 Higgs tagged jet, with double-b tag , $p_T > 150$ GeV
- τ_{had} tagged
- lepton $p_T > 20$ GeV
- BDT based analysis









	signal	QCD+EW	EW	$t\bar{t}j$	tot. background	S/B	$S/\sqrt{B}$, 30/ab
$\kappa_\lambda = 0.5$	0.169	0.52	0.07	0.37	0.96	0.176	29.81
$\kappa_\lambda = 1$	0.141					0.147	24.97
$\kappa_\lambda = 2$	0.105					0.109	18.49

$$0.76 < \kappa_\lambda < 1.28 \quad 3/\text{ab}\,,$$
$$0.92 < \kappa_\lambda < 1.08 \quad 30/\text{ab}$$

→ **$\delta\kappa_\lambda$(stat) ≈ 8 %**

Banerjee, Englert, Mangano, Selvaggi, Spannowsky1802.01607

Conclusions

Several competing analyses in different final states under study in CMS and ATLAS, providing excellent coverage in different decay modes.

Non resonant double Higgs production is the main way to measure Higgs self-coupling.

- At the moment, we can probe O(10-100xSM).
- More luminosity is needed to reach SM sensitivity, but we are starting to probe BSM and to constraint exotic BSM
- Outperforming Run1 (scaled) results and projections.
- Similar sensitivities in ATLAS and CMS

Resonant searches can already provide important constrain on BSM physics (MSSM, WED, heavy scalars).

- KK-graviton excluded below 800 GeV, Λ_R=1TeV Radion excluded below 2.5 TeV
- Boosted categories enhance sensitivity to high mass resonances

Further improvement awaited from the combination of the results among all channels

Planning ahead for future facilities

Exciting prospects for double Higgs searches

Conclusions

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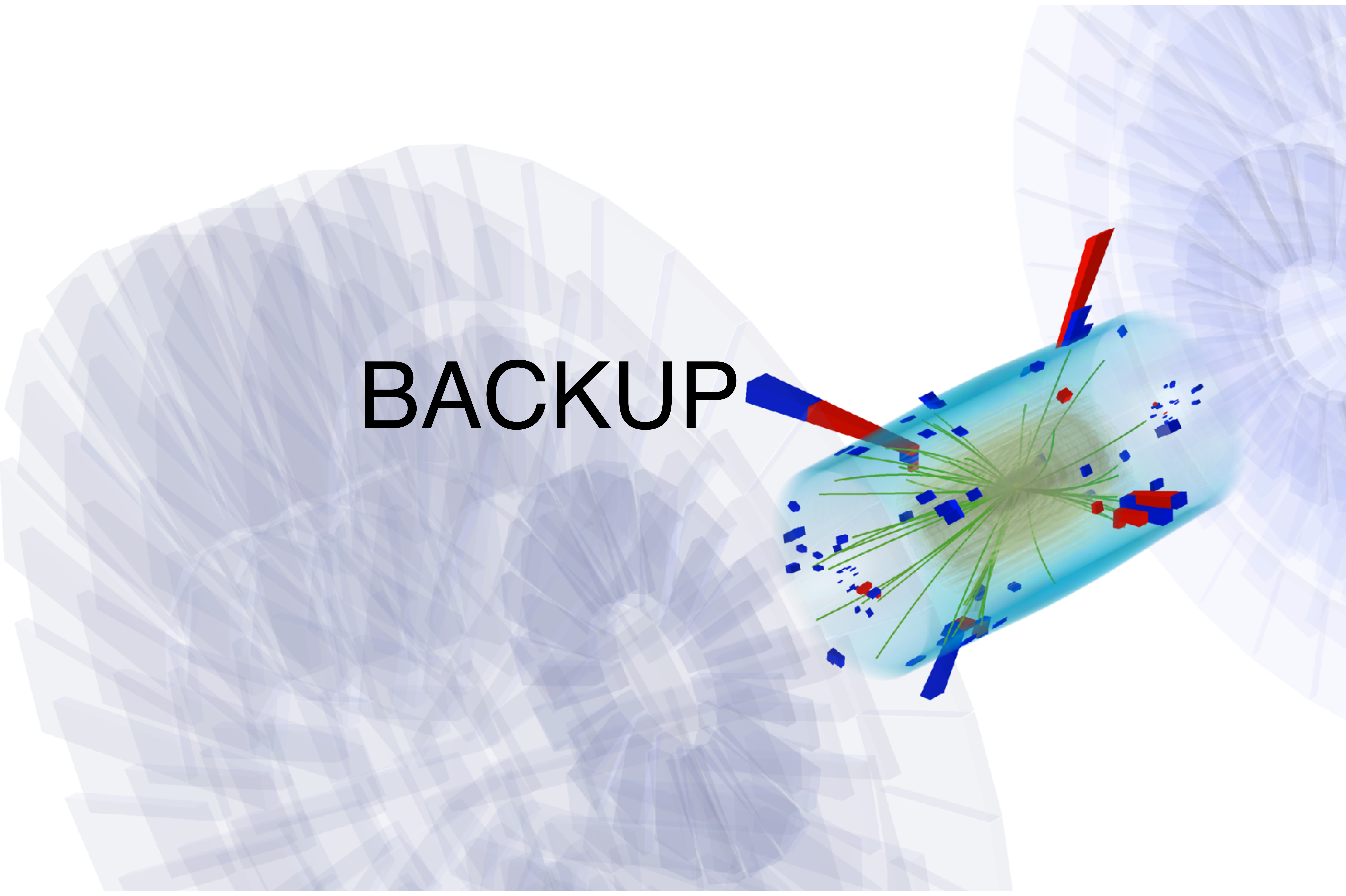
Planning ahead for futu acilities

An HH workshop is being organised for September 2018

Exciting prospects for double Higgs searches

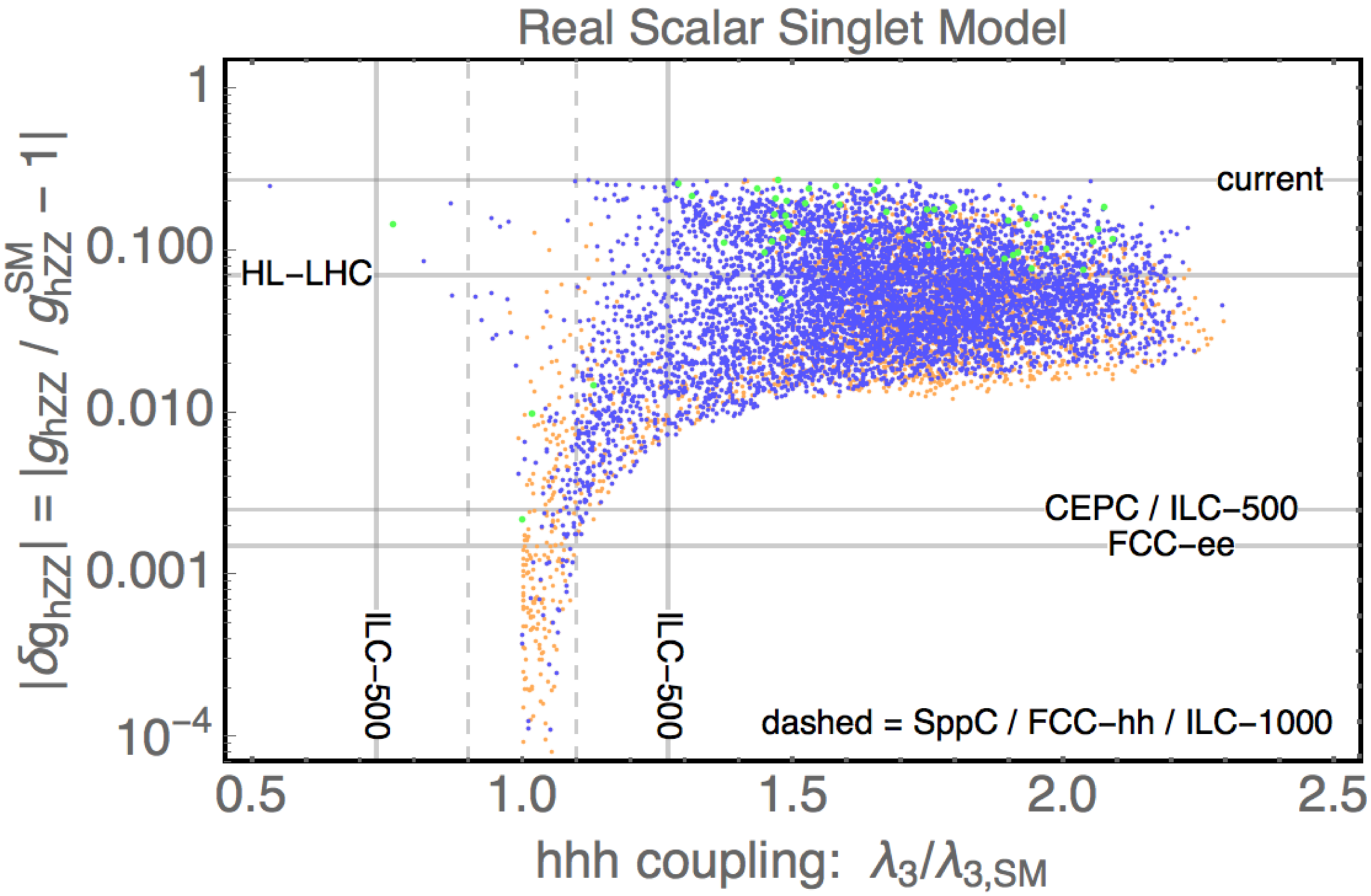
BACKUP



Huang, Lou, Wang, 1608.06619

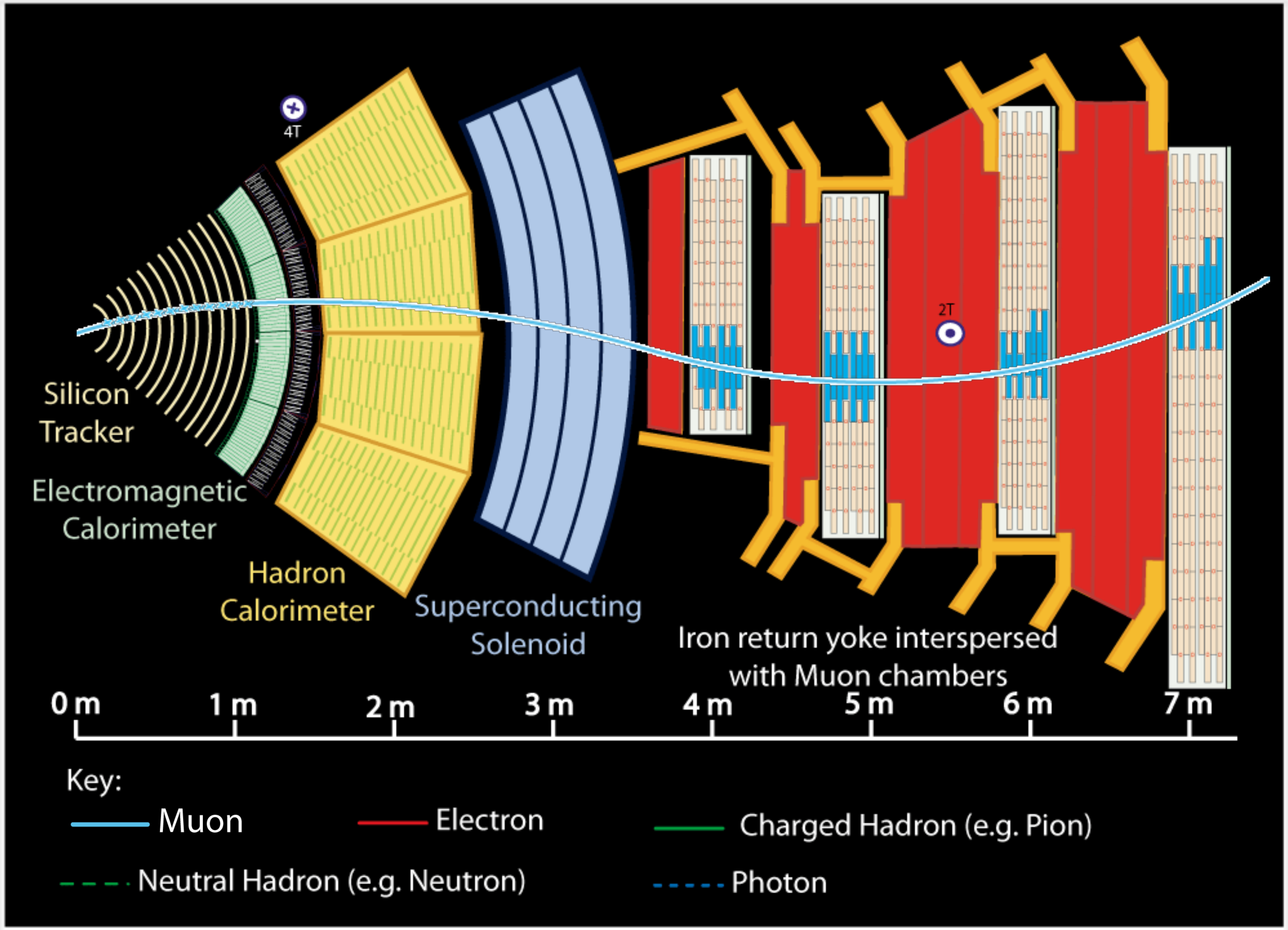
EWSB phase transition

- SM + a real scalar singlet
- Plot show phase space with a 1st order phase transition

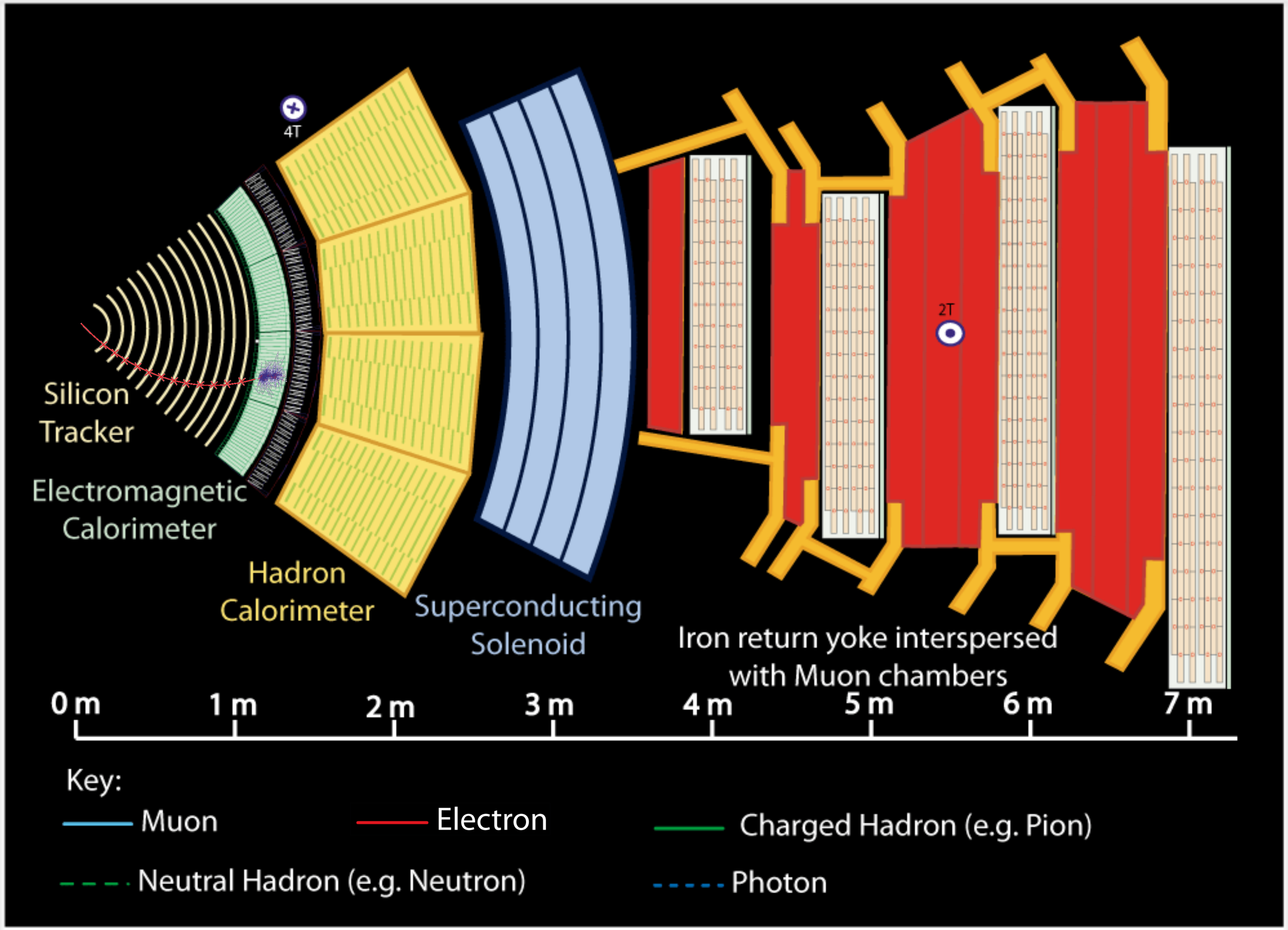


How CMS detects particles

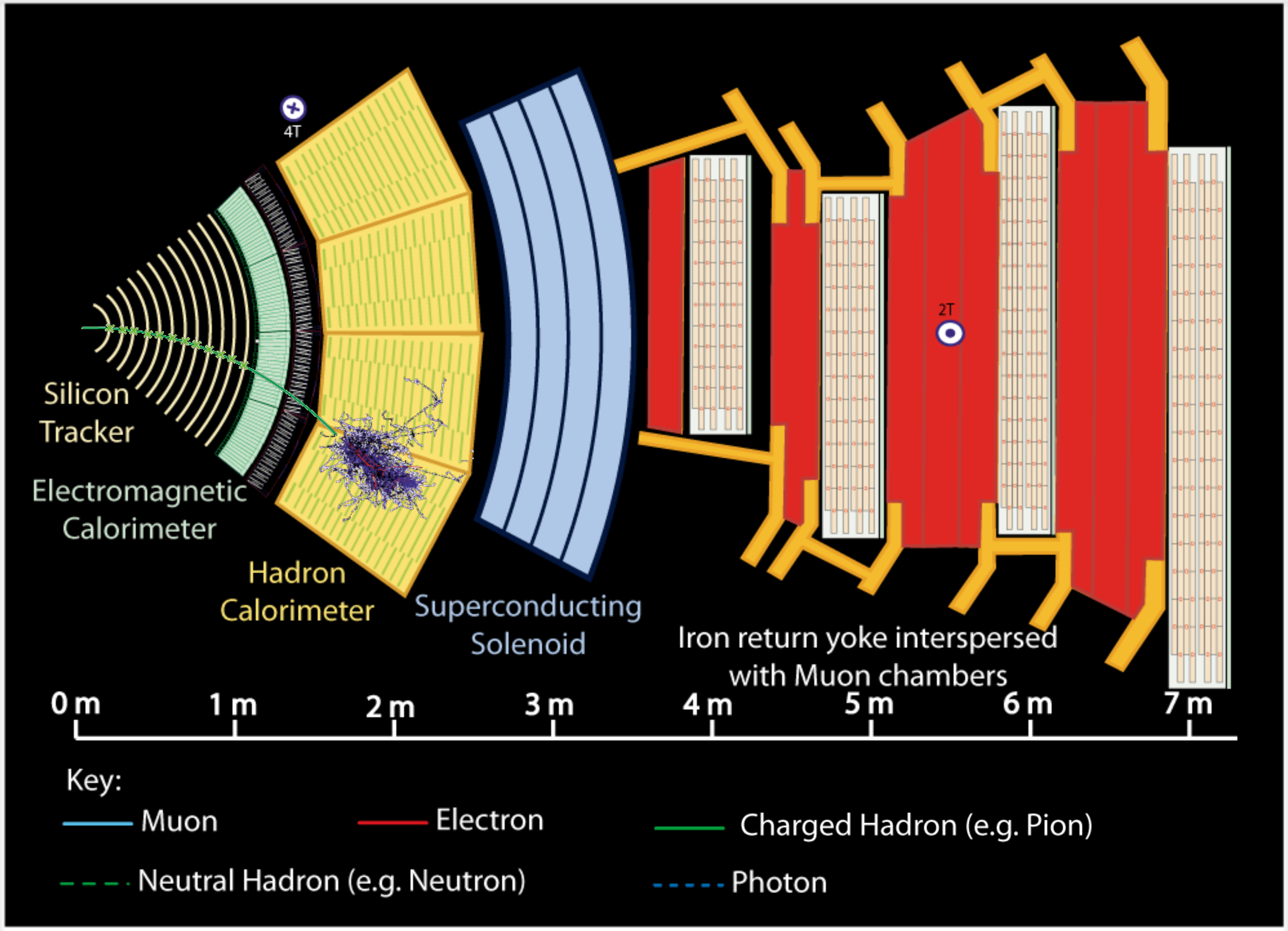
How CMS detects particles



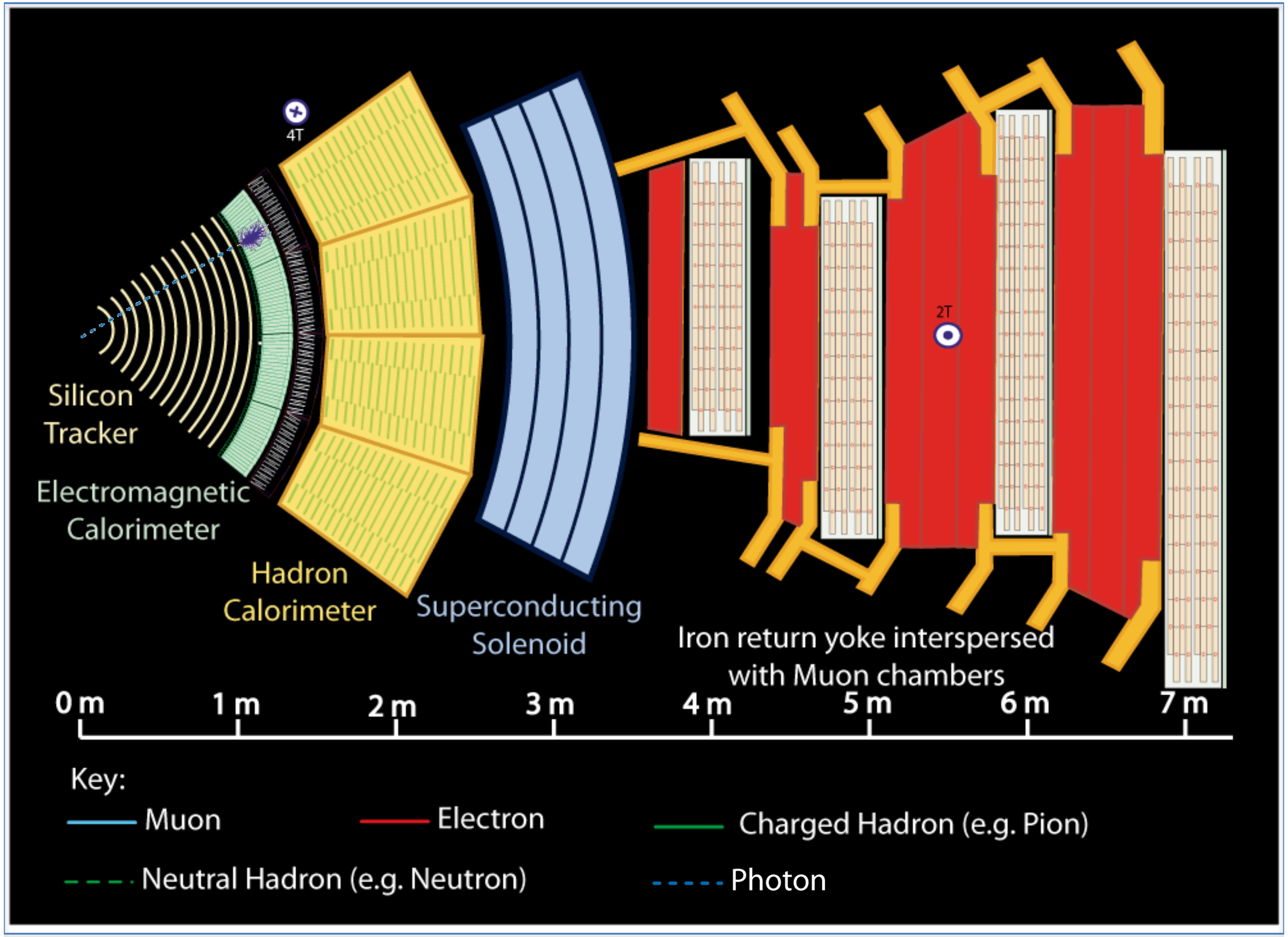
How CMS detects particles



How CMS detects particles



How CMS detects particles



PAS-FTR-15-002
PAS-FTR-16-002

Double Higgs at HL-LHC. Projections

CMS upgrade:

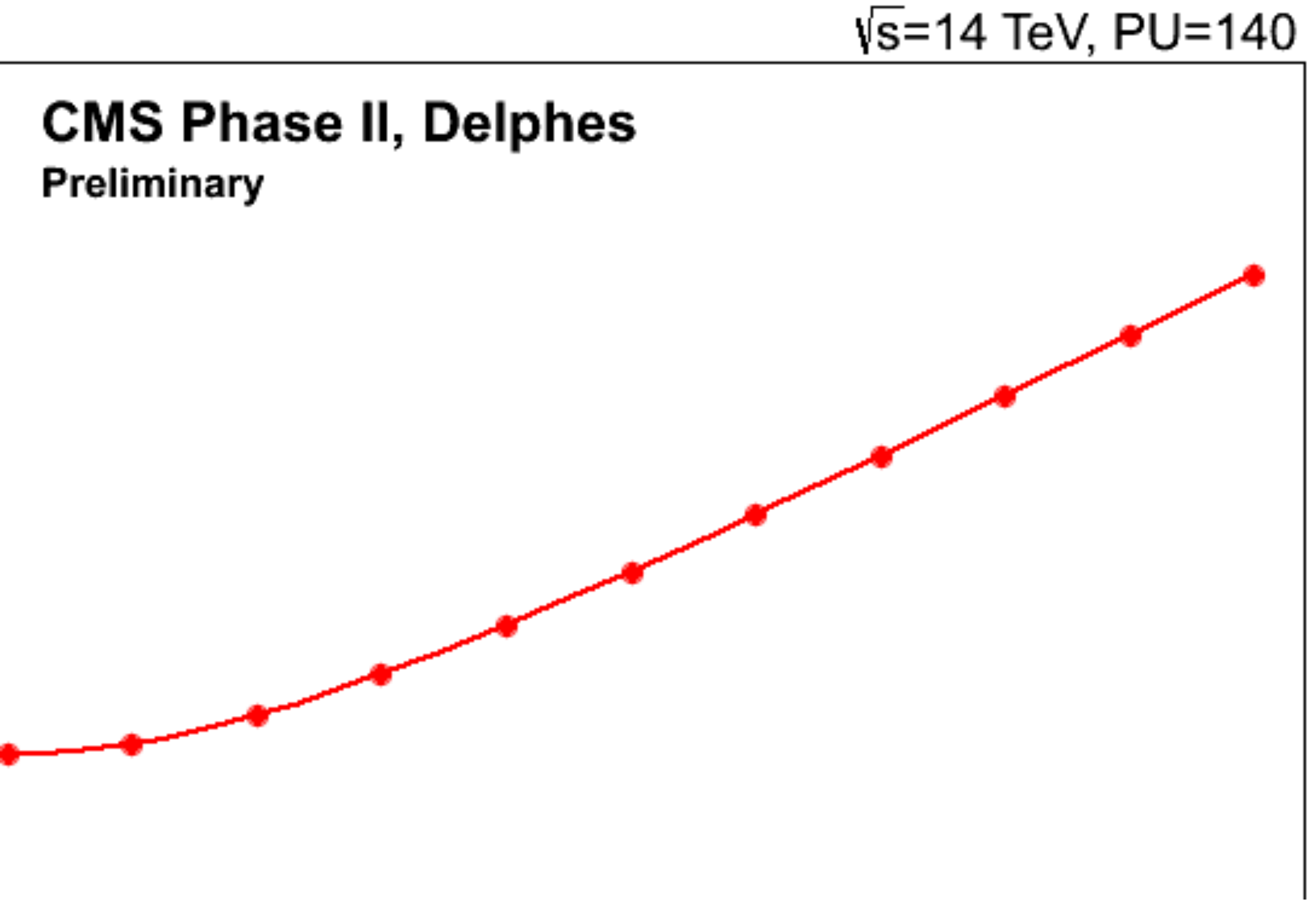
track-trigger Dedicated

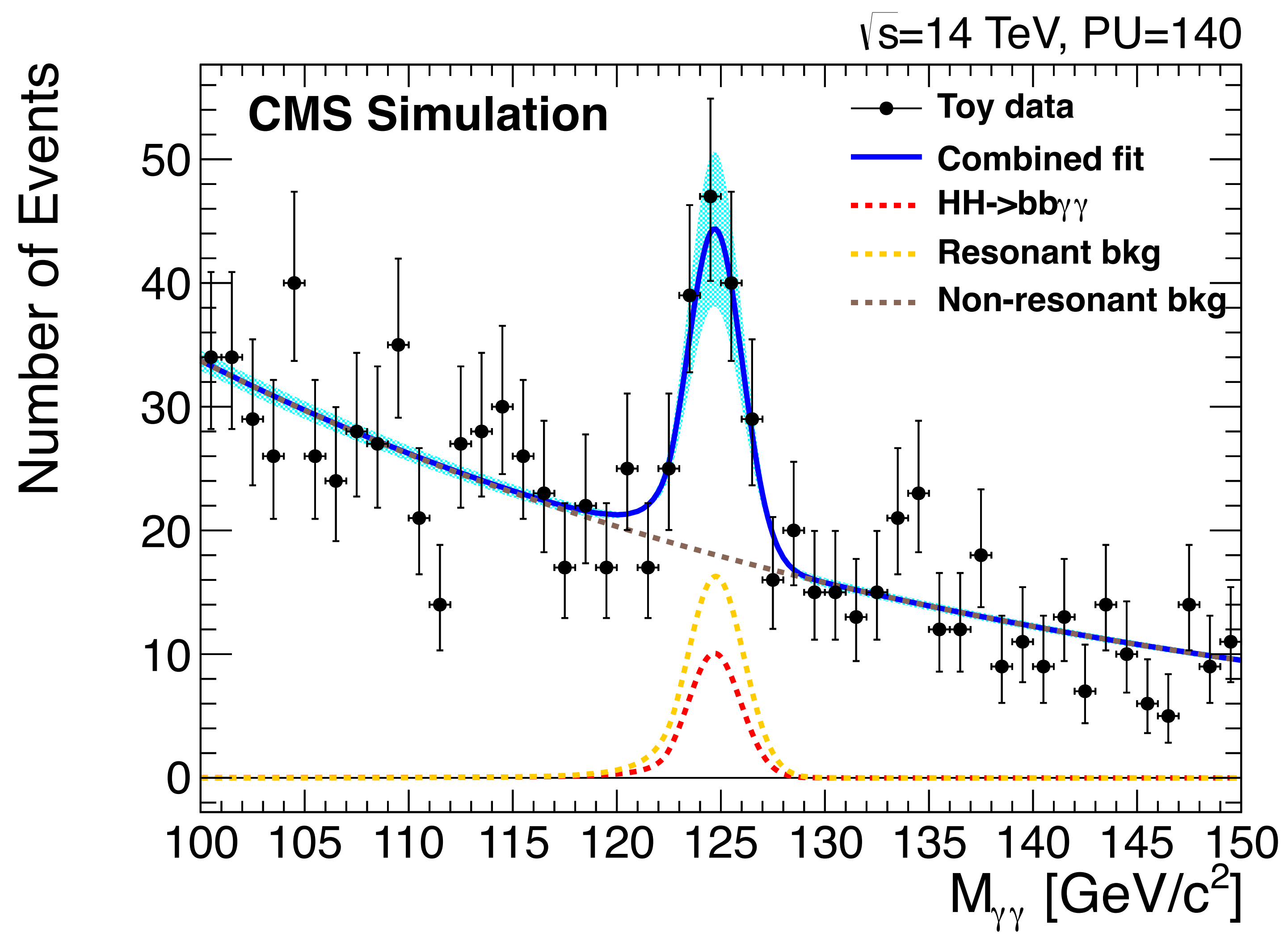
tronics bbγγ, bbτ

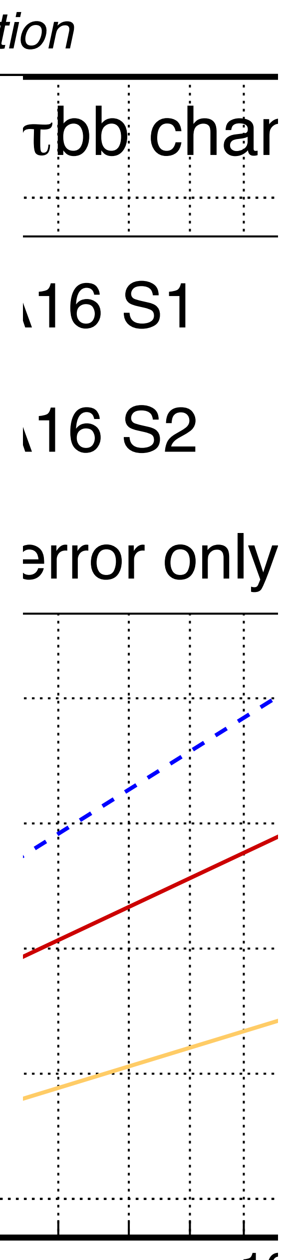
h granularity) ~50% prec

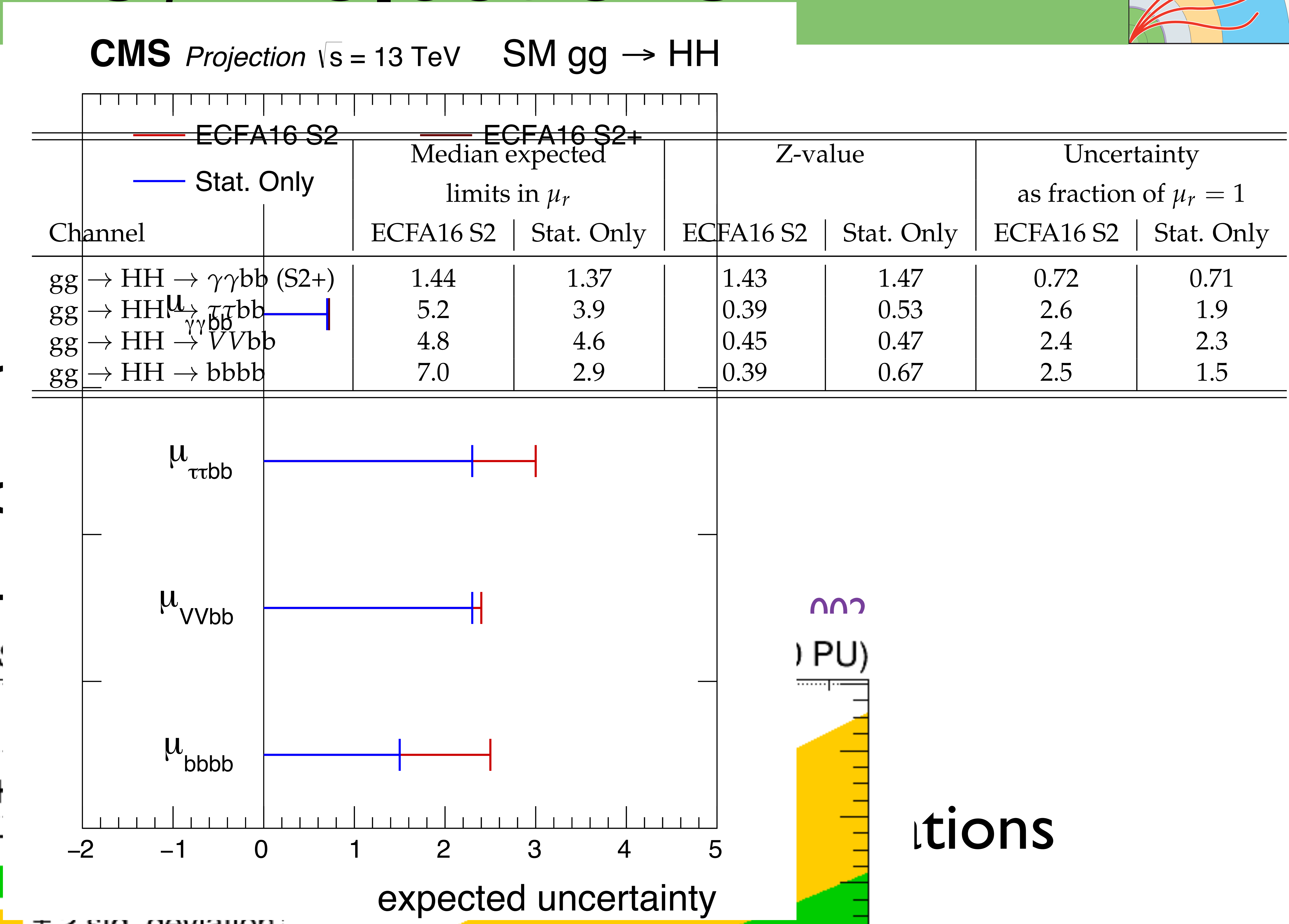
Extrapolat

@ 7.5 kHz





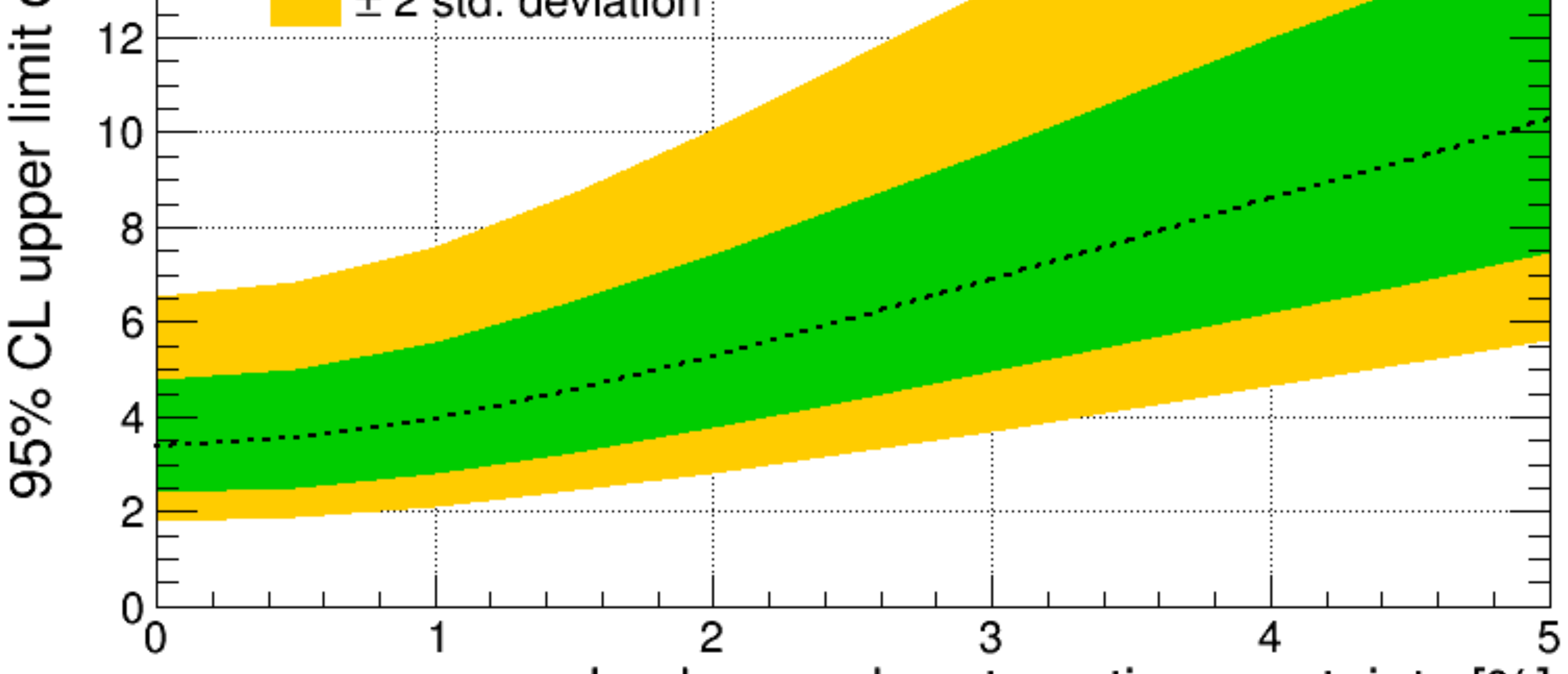




Channel	Median expected limits in μ_r ECFA16 S2	Median expected limits in μ_r Stat. Only	Z-value ECFA16 S2	Z-value Stat. Only	Uncertainty as fraction of $\mu_r = 1$ ECFA16 S2	Uncertainty as fraction of $\mu_r = 1$ Stat. Only
gg → HH → γγbb (S2+)	1.44	1.37	1.43	1.47	0.72	0.71
gg → HH → ττbb	5.2	3.9	0.39	0.53	2.6	1.9
gg → HH → VVbb	4.8	4.6	0.45	0.47	2.4	2.3
gg → HH → bbbb	7.0	2.9	0.39	0.67	2.5	1.5

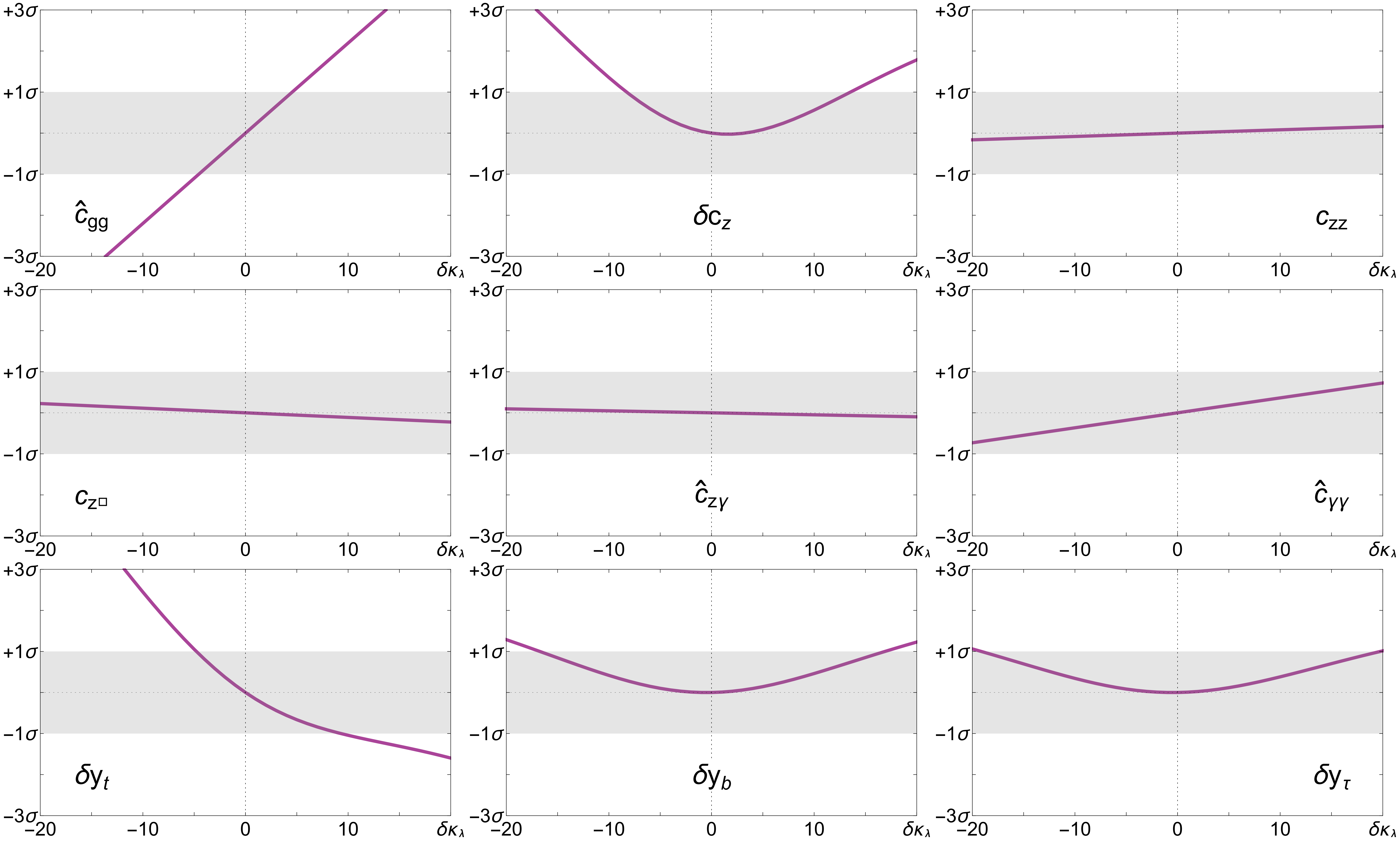
002

PU)



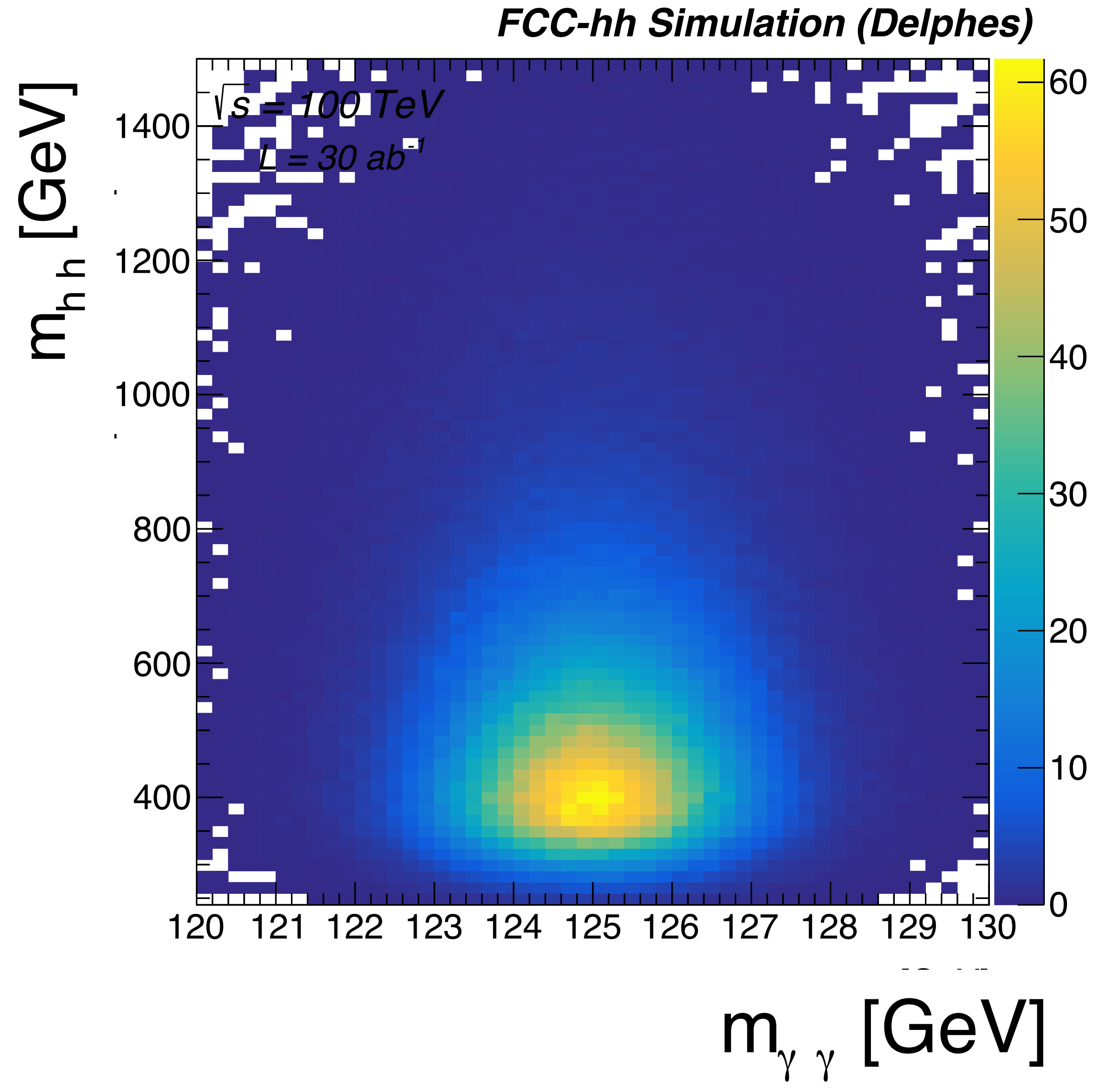
tions

Flat direction in the global fit

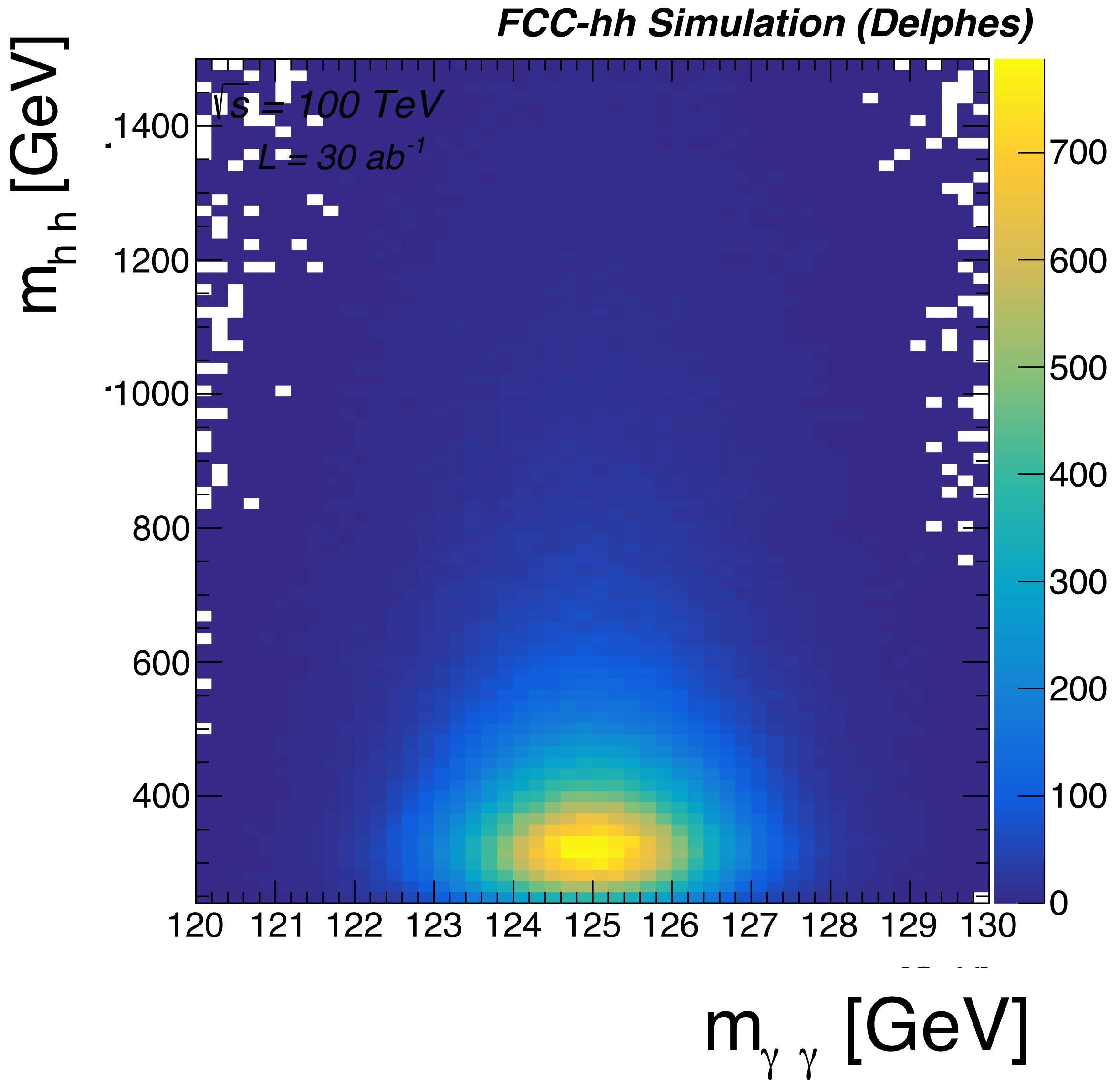


2D shapes (bbgg@FCC)

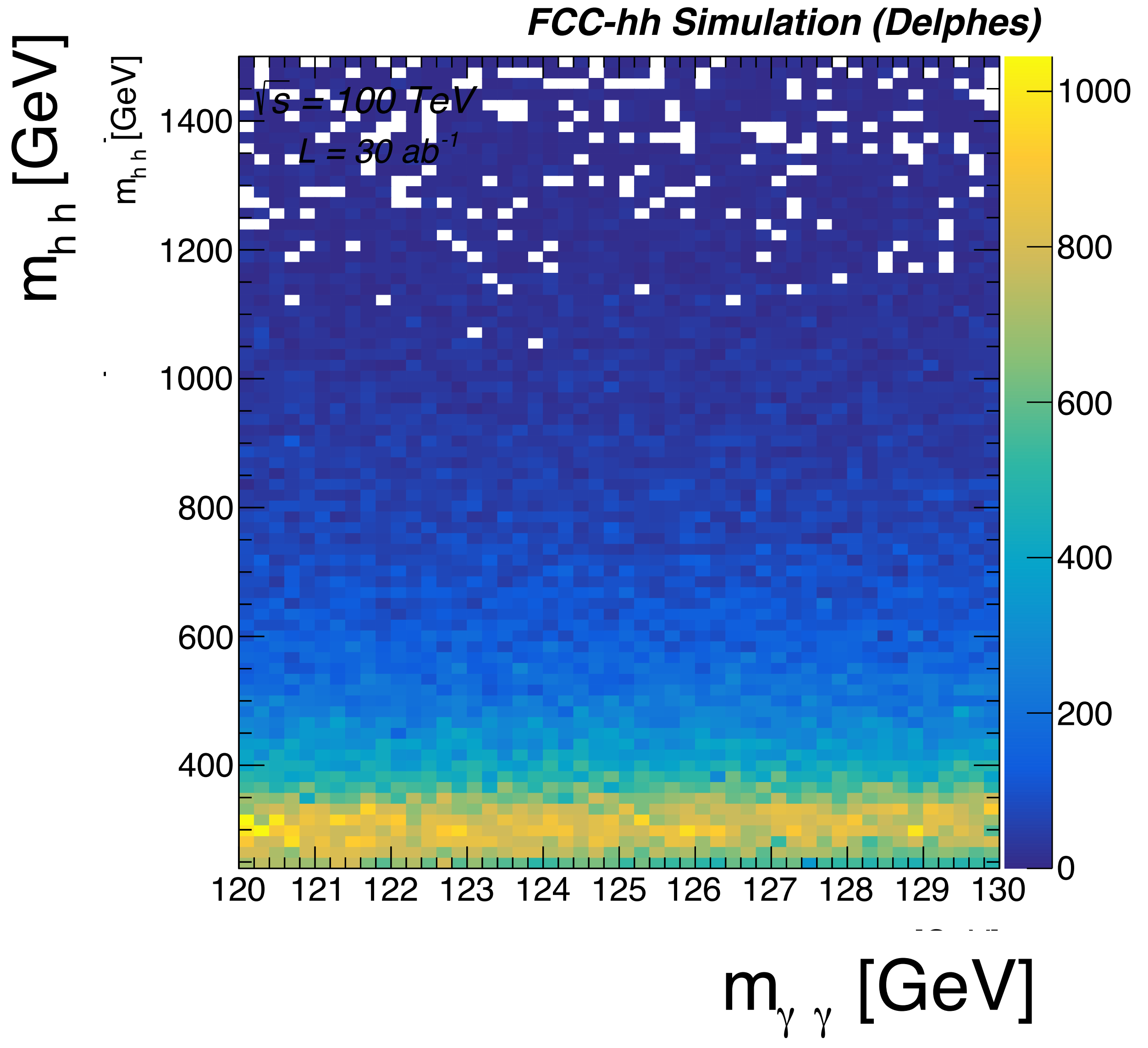
HH



ttH



QCD



- exploit correlations of means in the signal, ex: **$m_{\gamma\gamma}$ vs m_{hh}**
- build **parametric model** in 2D → **$m_{\gamma\gamma}$** : gauss, **m_{hh}**: landau+exp
- perform **2D Likelihood fit** on the **signal strength** and **coupling modifier:**

$$\mu = \sigma_{obs}/\sigma_{SM}$$

$$\kappa_\lambda = \lambda_{obs}/\lambda_{SM}$$