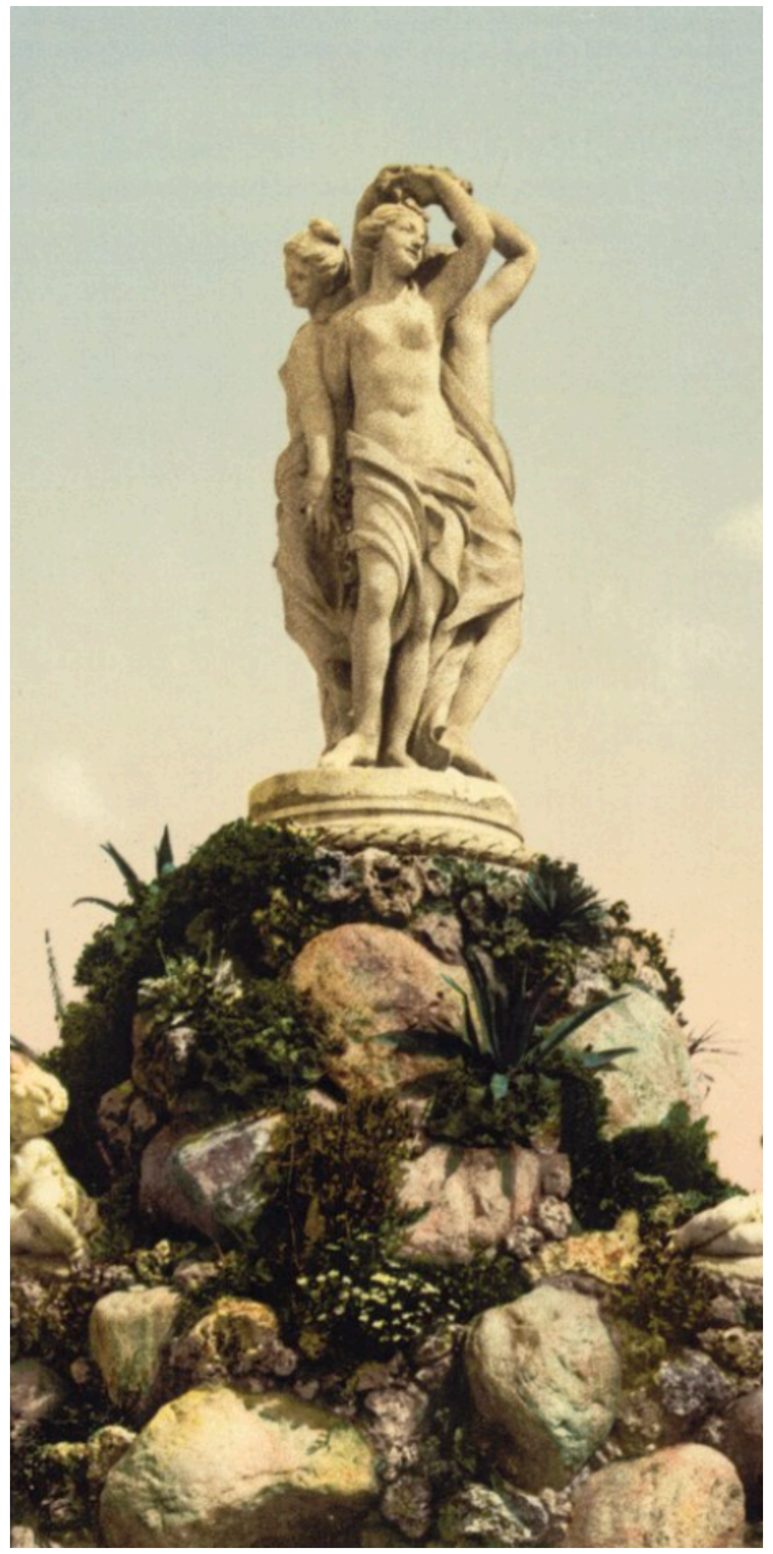
Triple Higgs production at the LHC and ATLAS results

Carlo Pandini

25/11/2025

IRN Terascale, Montpellier

Les Trois Grâces à Montpellier …



… les Trois Higgs au LHC ?

ATLAS EXPERIMENT

LPSC GRENOBLE | MODANE

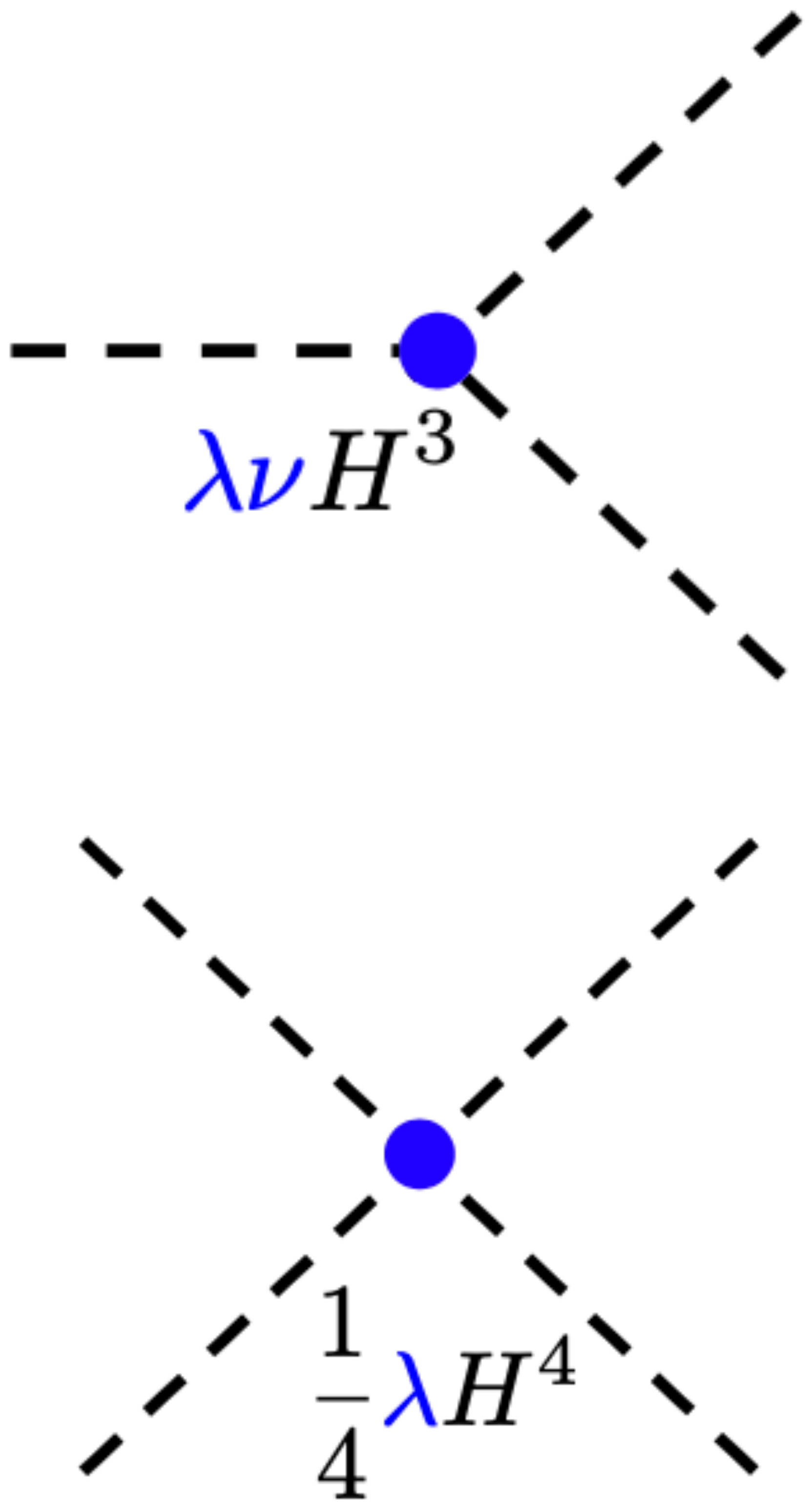
Brief phenomenology of SM HHH

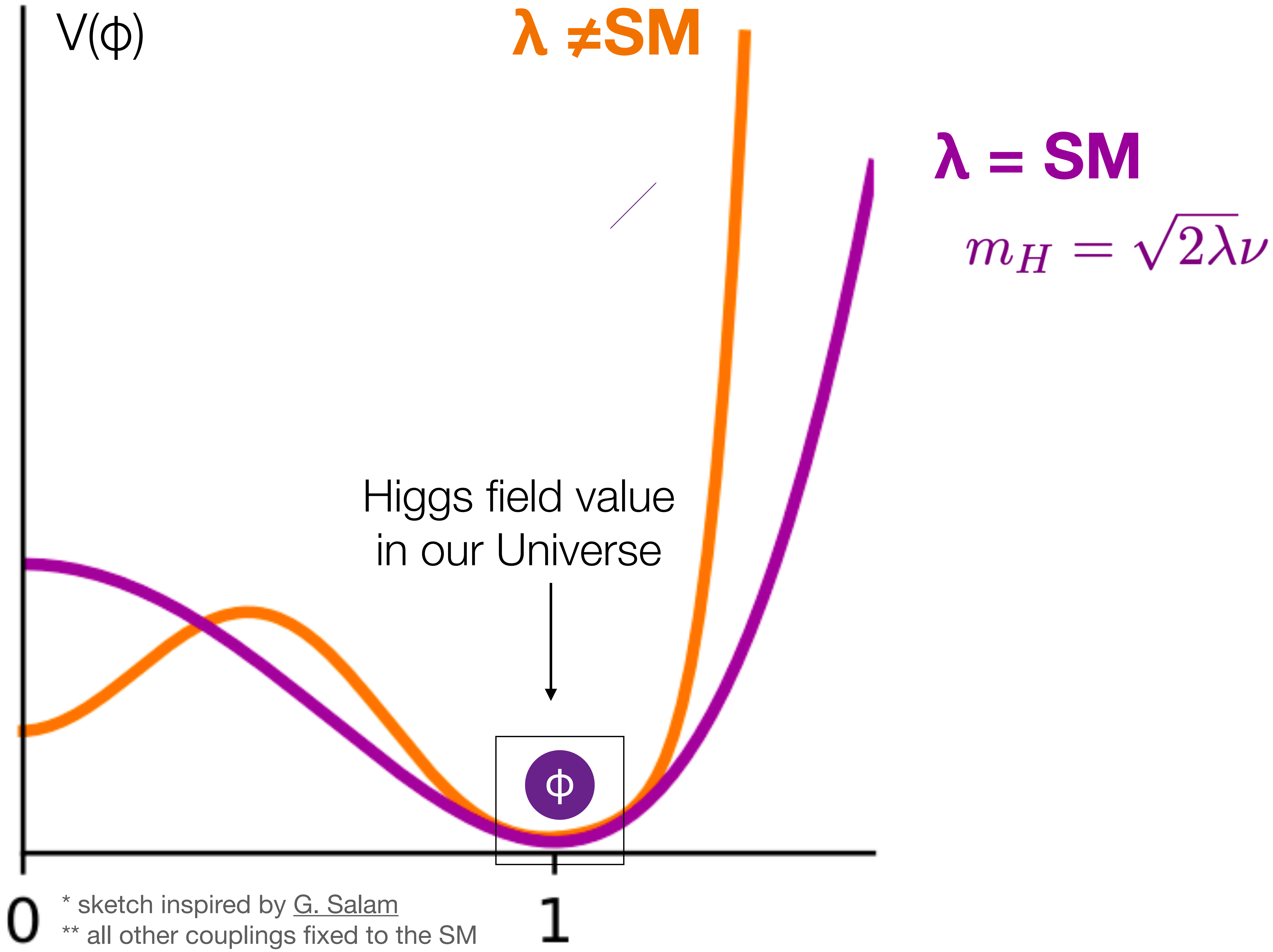
ATLAS Run-2 Results

HL-LHC Prospects & CMS comparison

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^4$$

Higgs self-interactions





* sketch inspired by G. Salam
** all other couplings fixed to the SM

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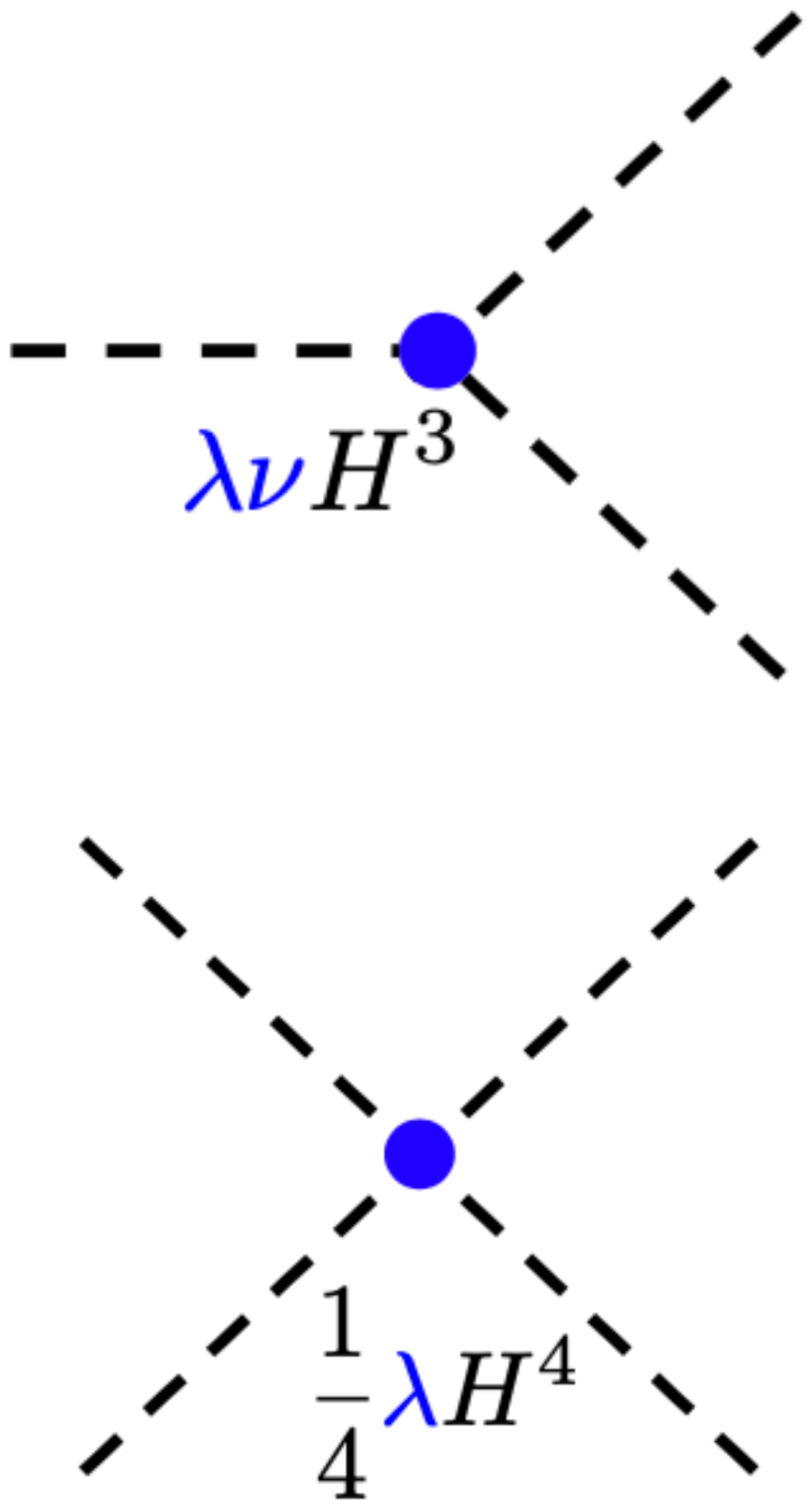

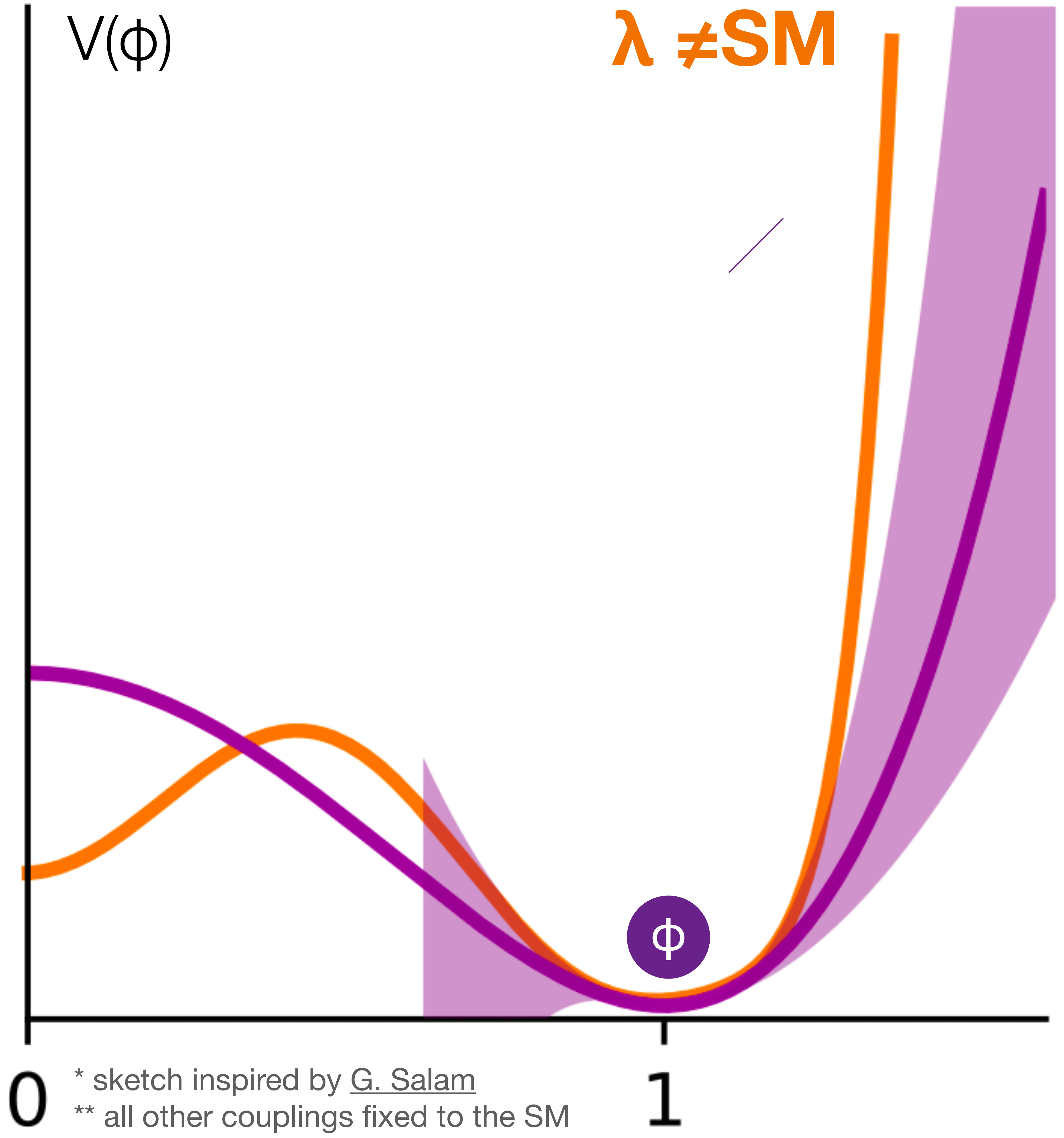

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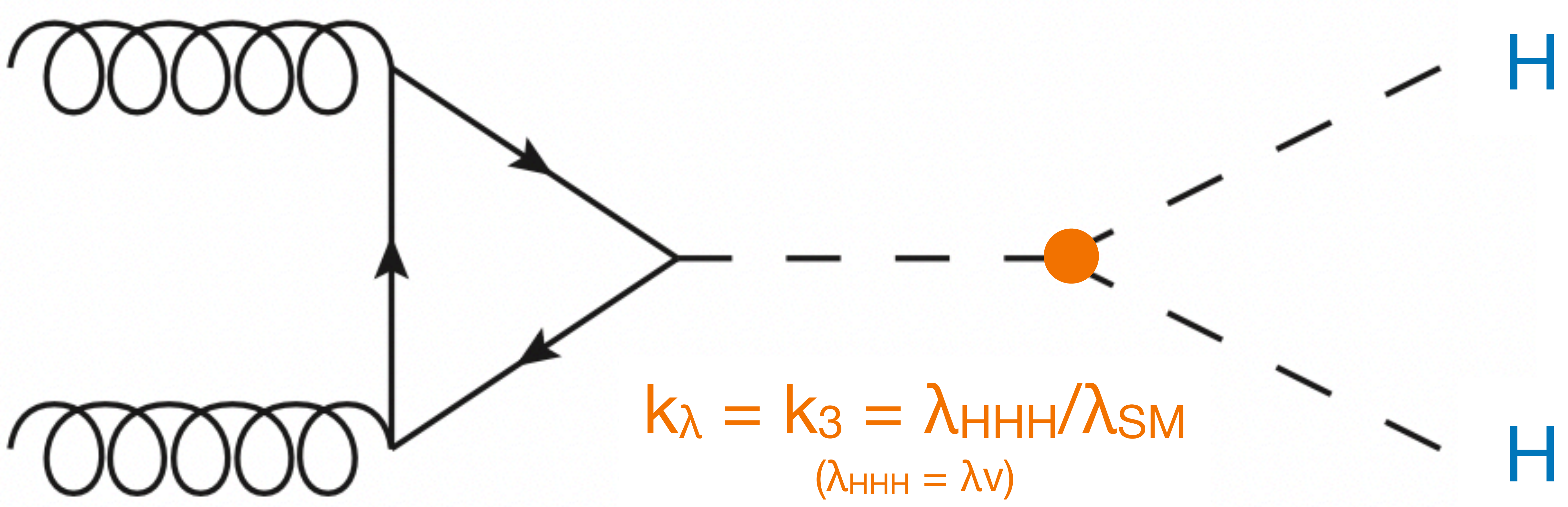
Current experimental knowledge

-0.7 < λ/SM < 6.1

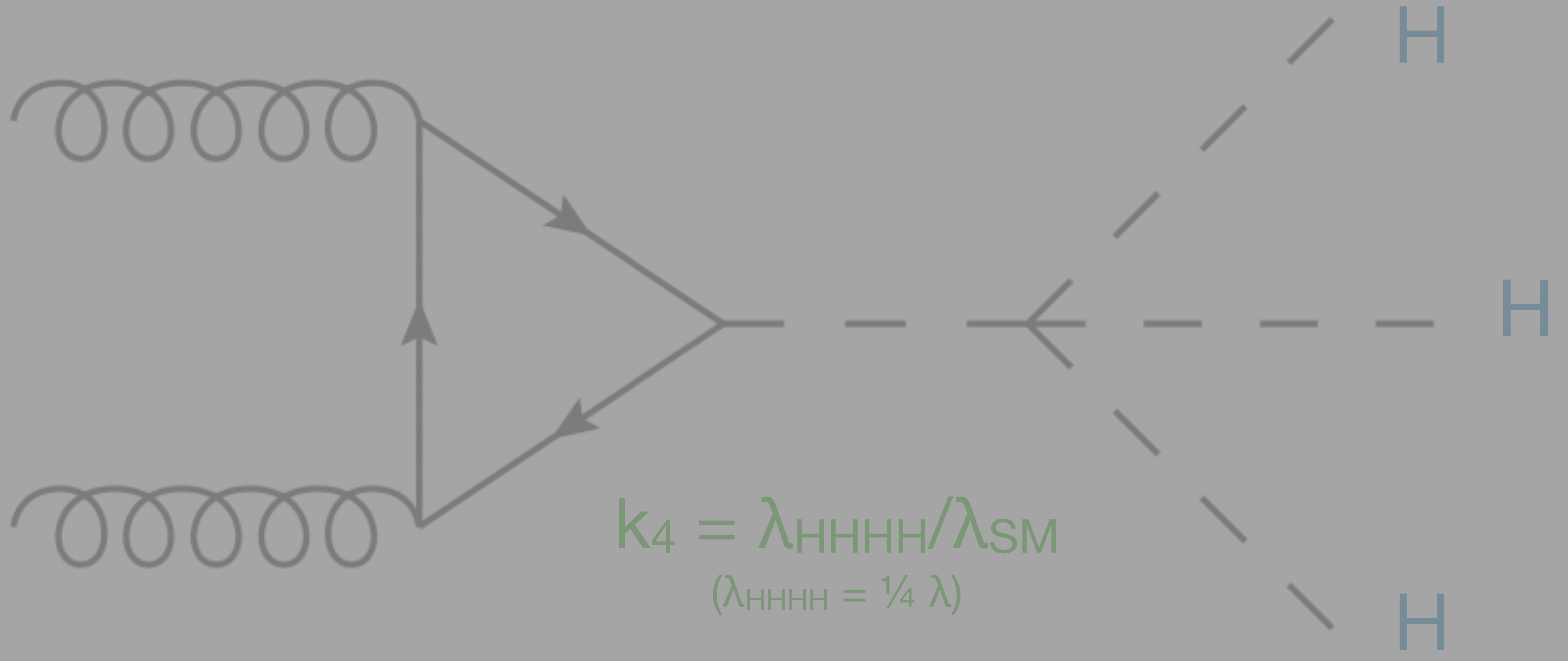
from ATLAS+CMS Run-2 combined results ATLAS-CONF-2025-012

How do we measure Higgs self-coupling at the LHC?



Double-Higgs (HH) production:

- σ_{HH}~31fb at 13TeV
- sensitive to trilinear self-coupling
- deep physics program in ATLAS and CMS to measure HH production: SM possibly in reach at the end of LHC Run-3



Triple Higgs (HHH) production:

- σ_{HHH}~0.08fb at 13TeV:

  →O(10) events at LHC Run-2

  →O(2) events after HHH(→6b) decays

  →comparison: O(1300) events in HH(→4b) for an exclusion limit at ~5·SM

- sensitive to quartic self-coupling

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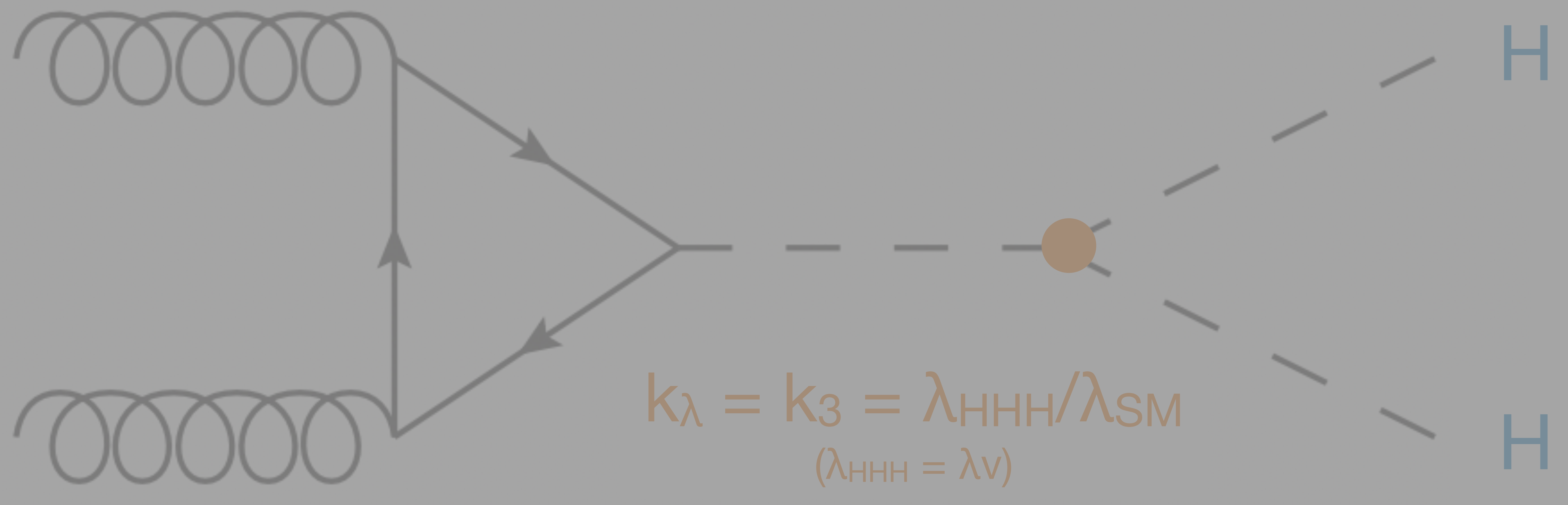

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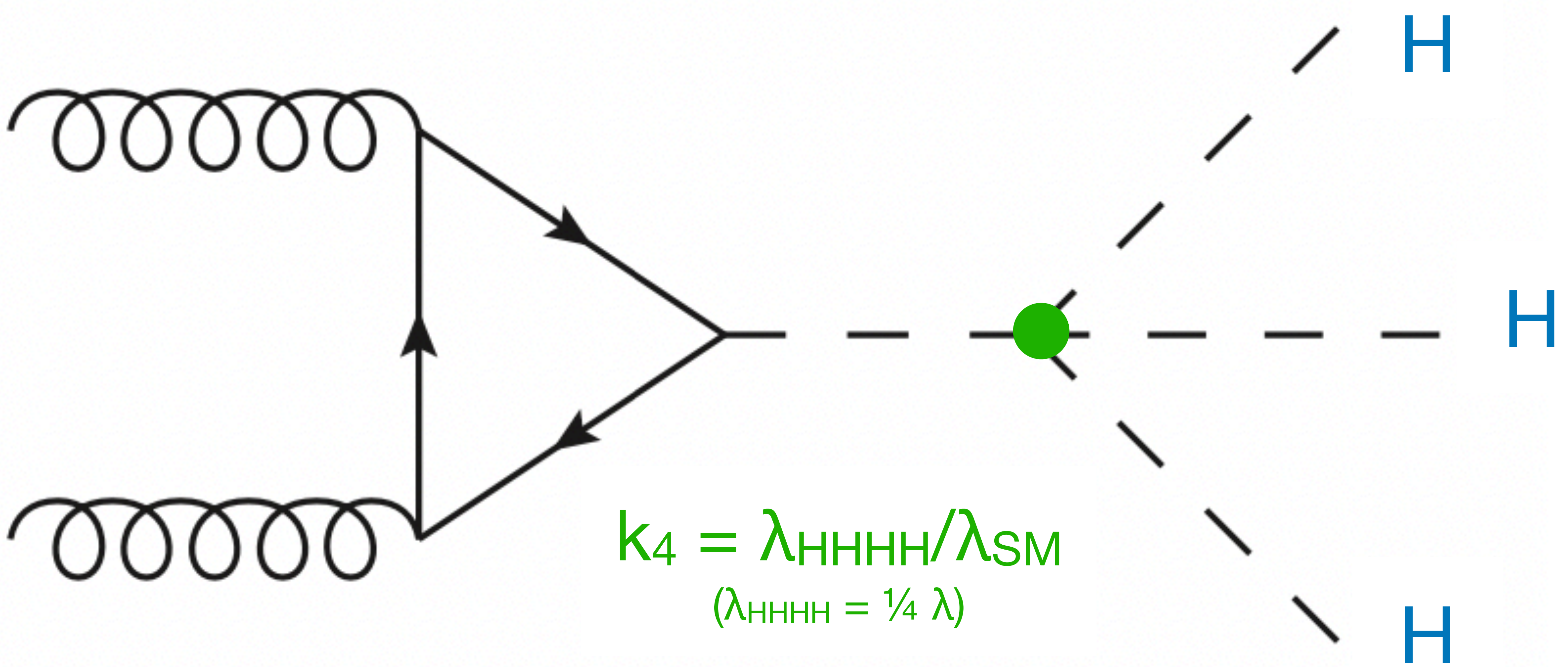

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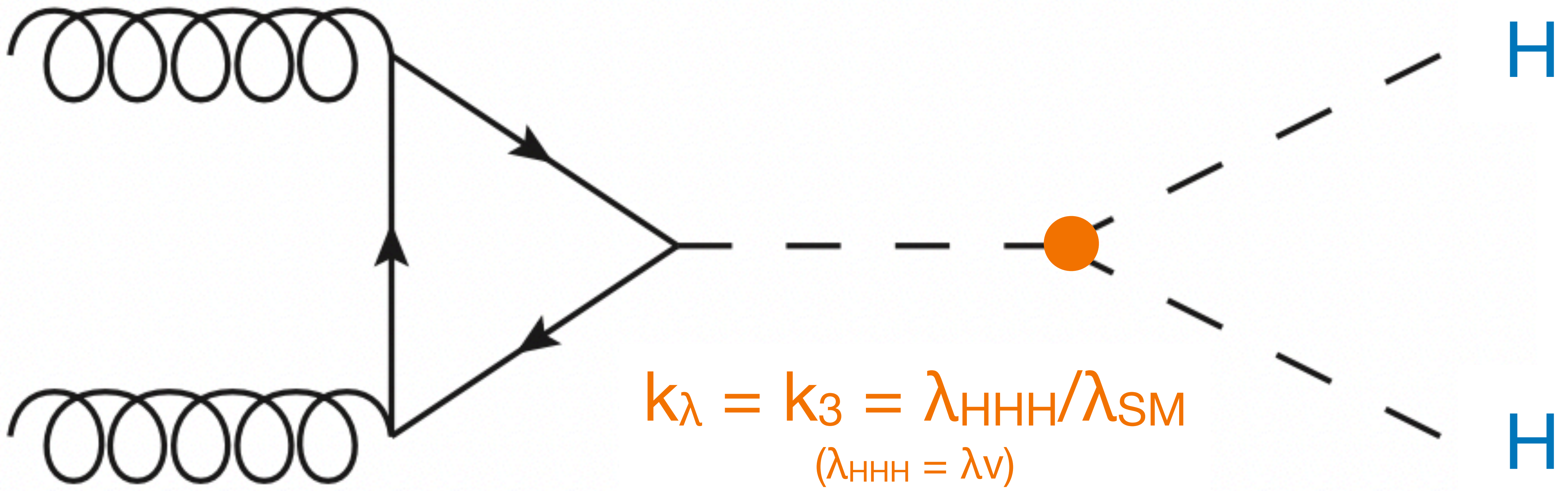

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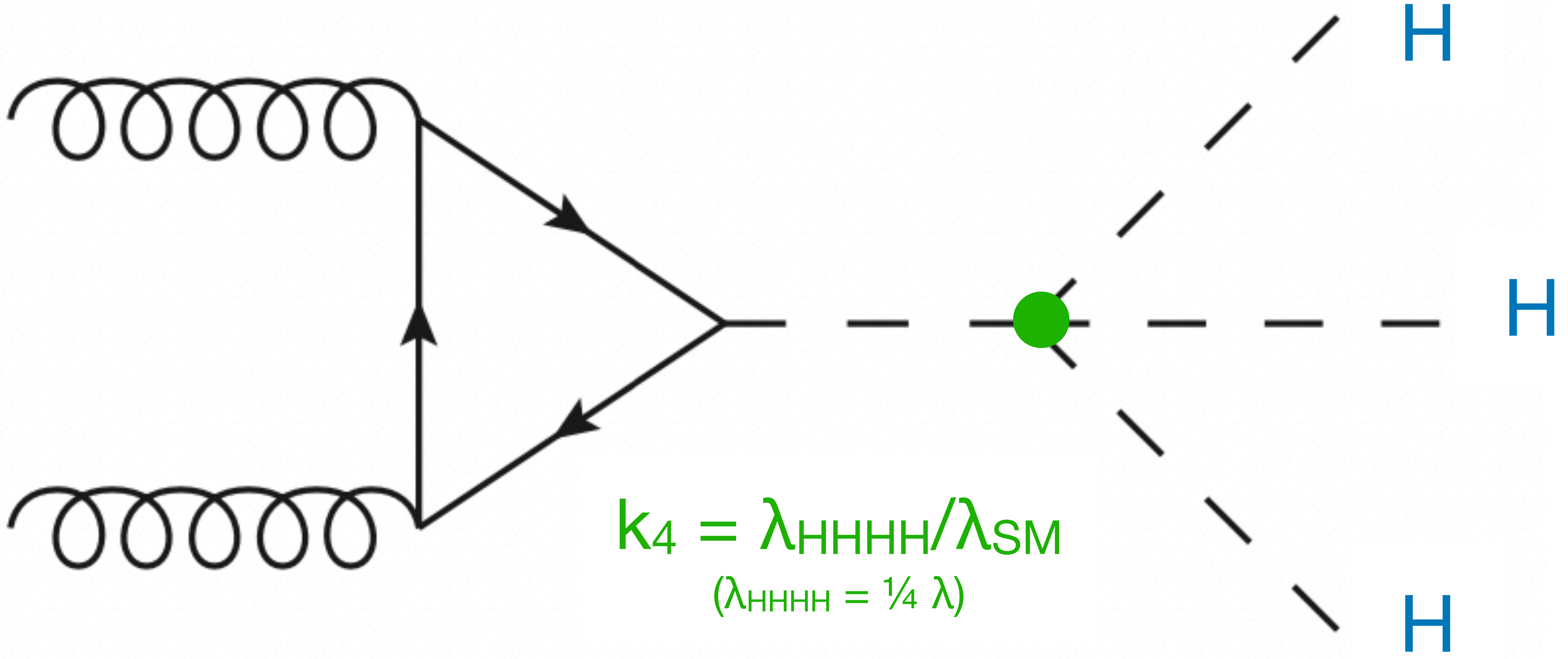

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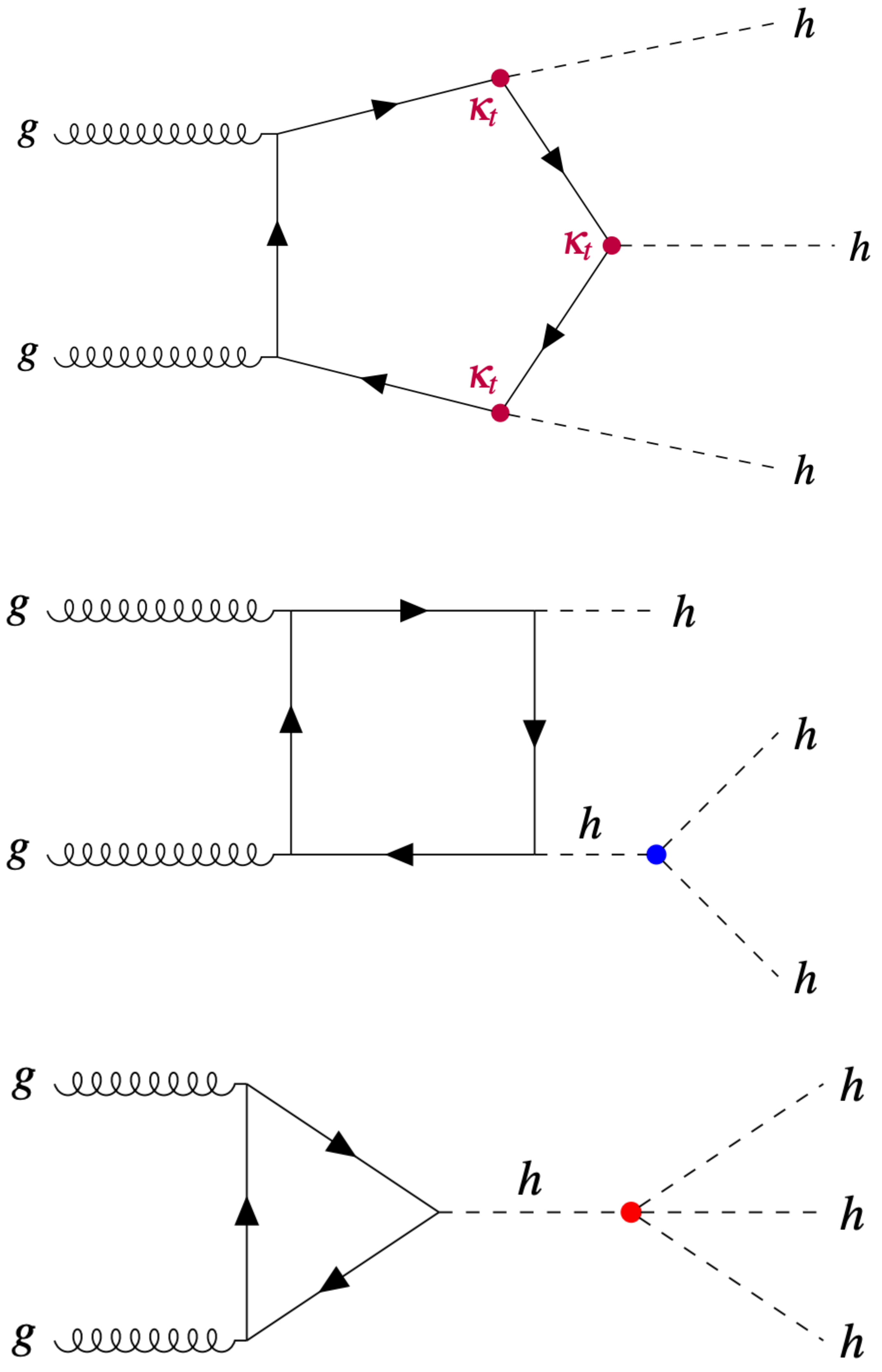
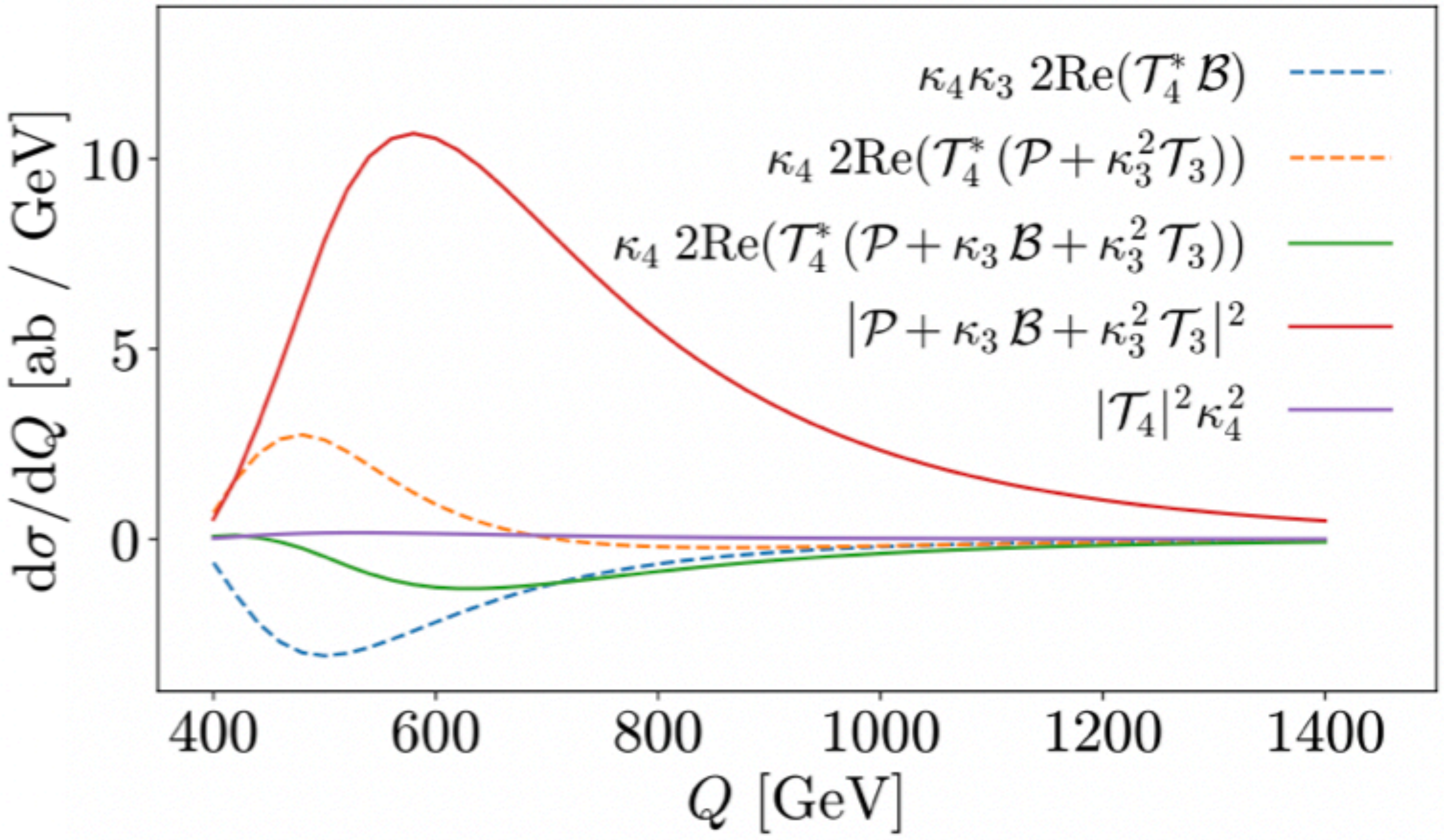
Focus of today's presentation !

Triple-Higgs production in the Standard Model

HHH production at the LHC is sensitive to several Higgs coupling parameters
(through interfering diagrams)



de Florian, Fabre, Mazzitelli



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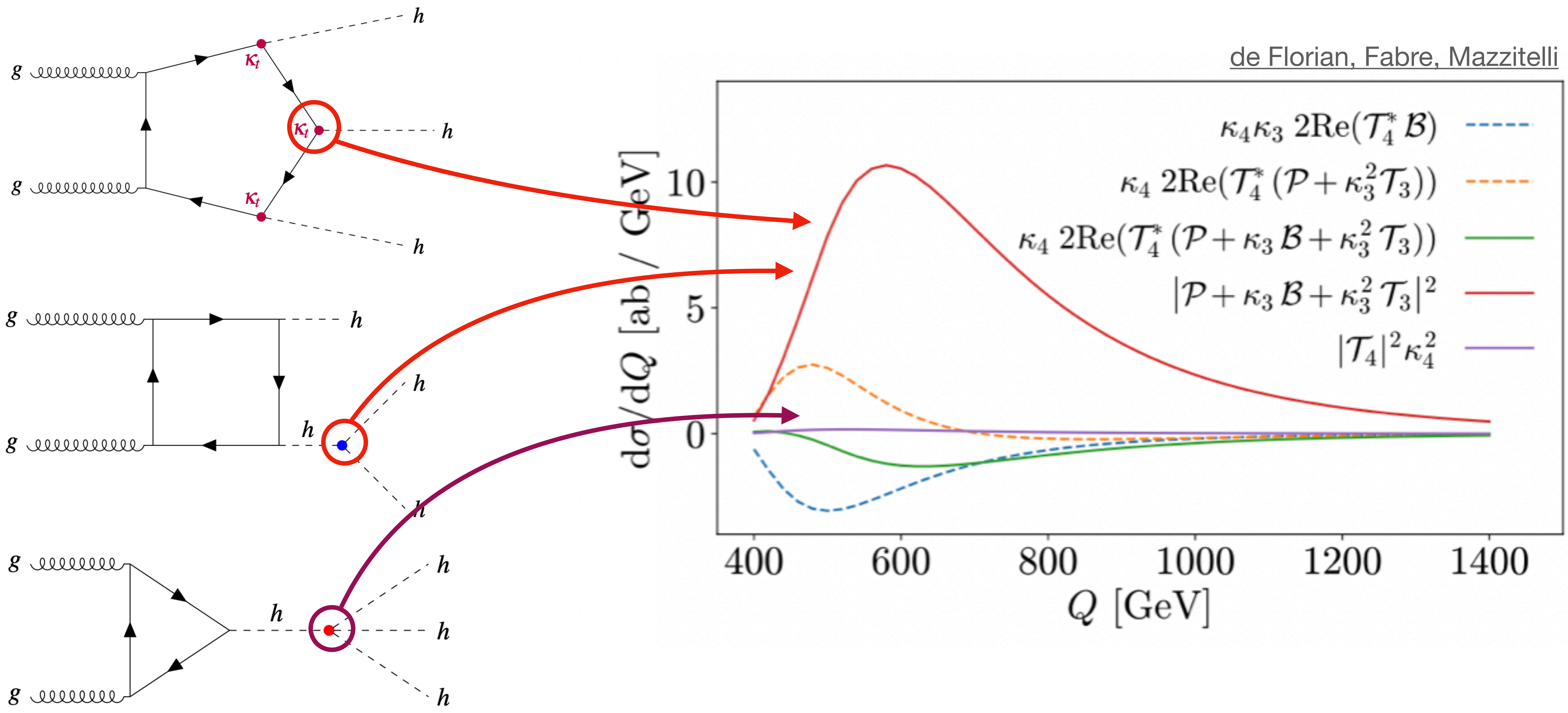

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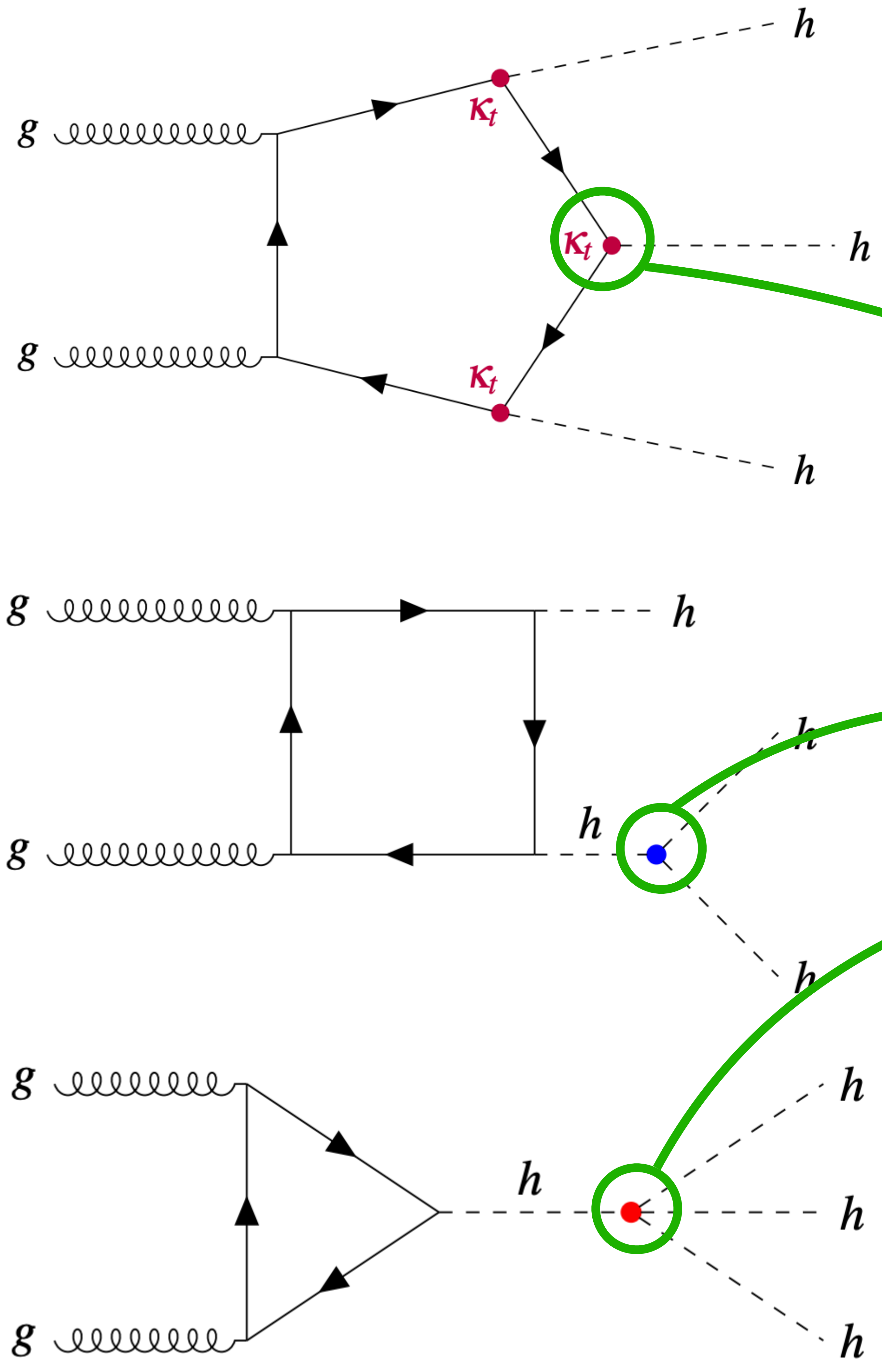

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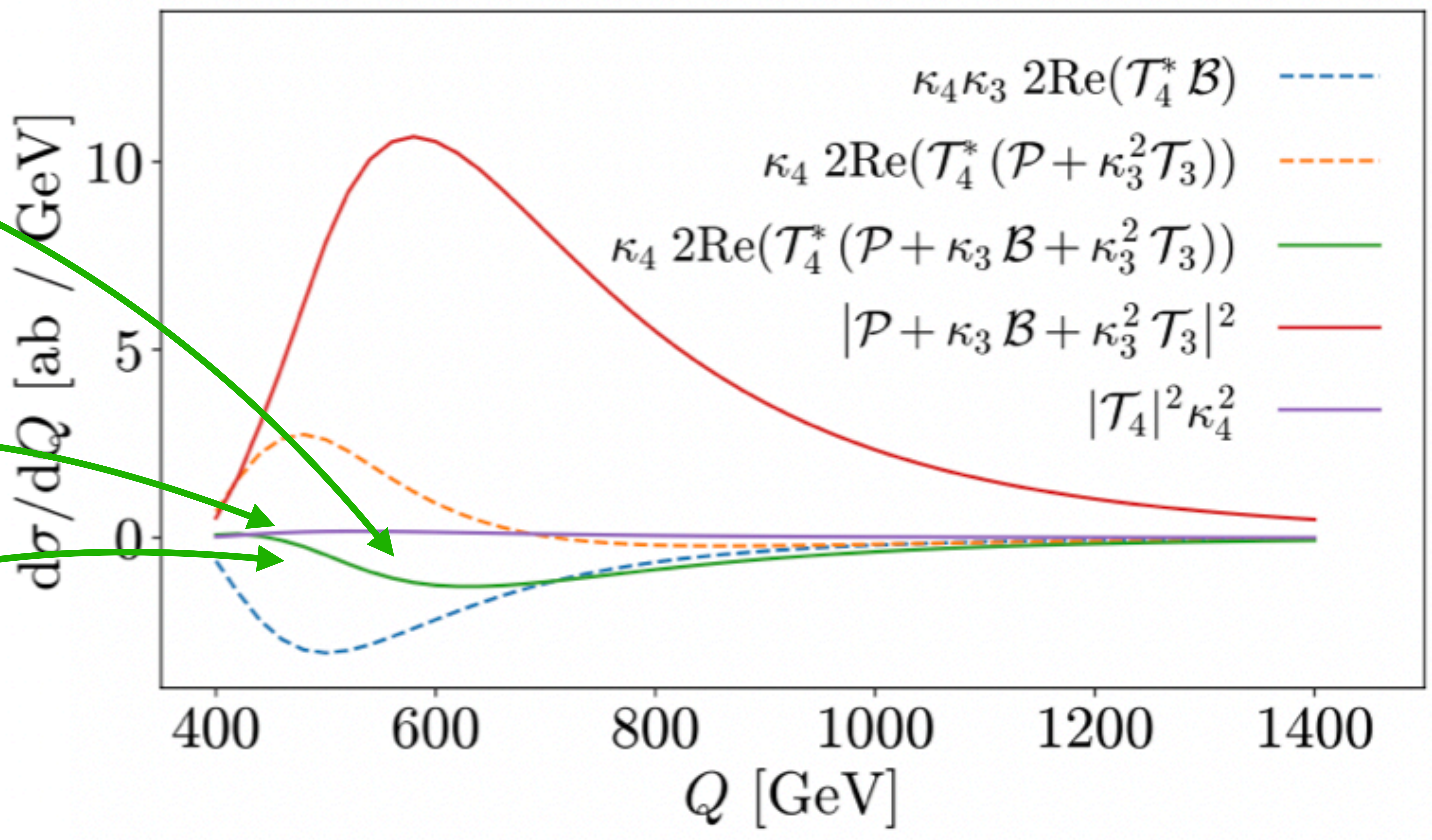

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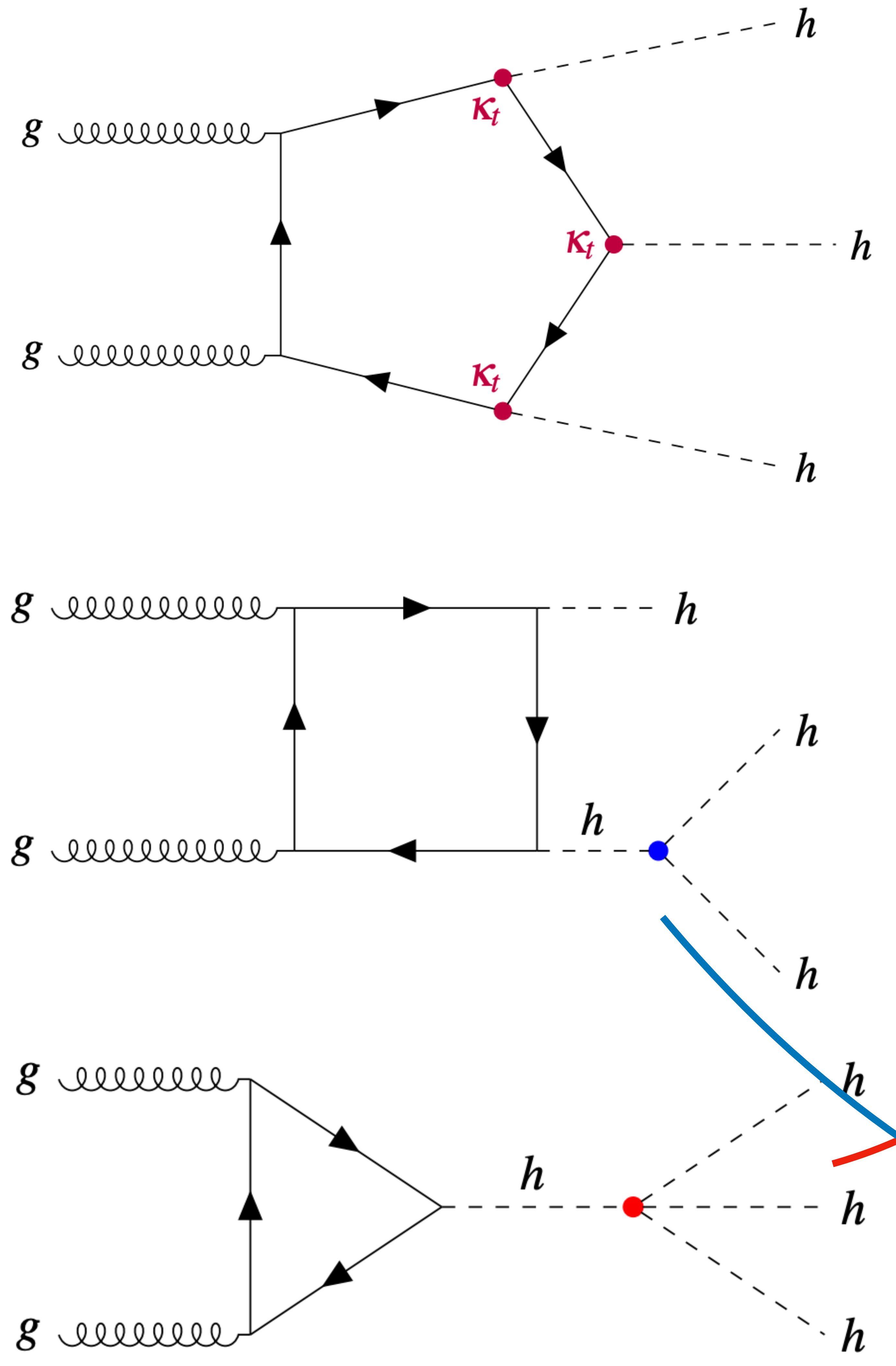
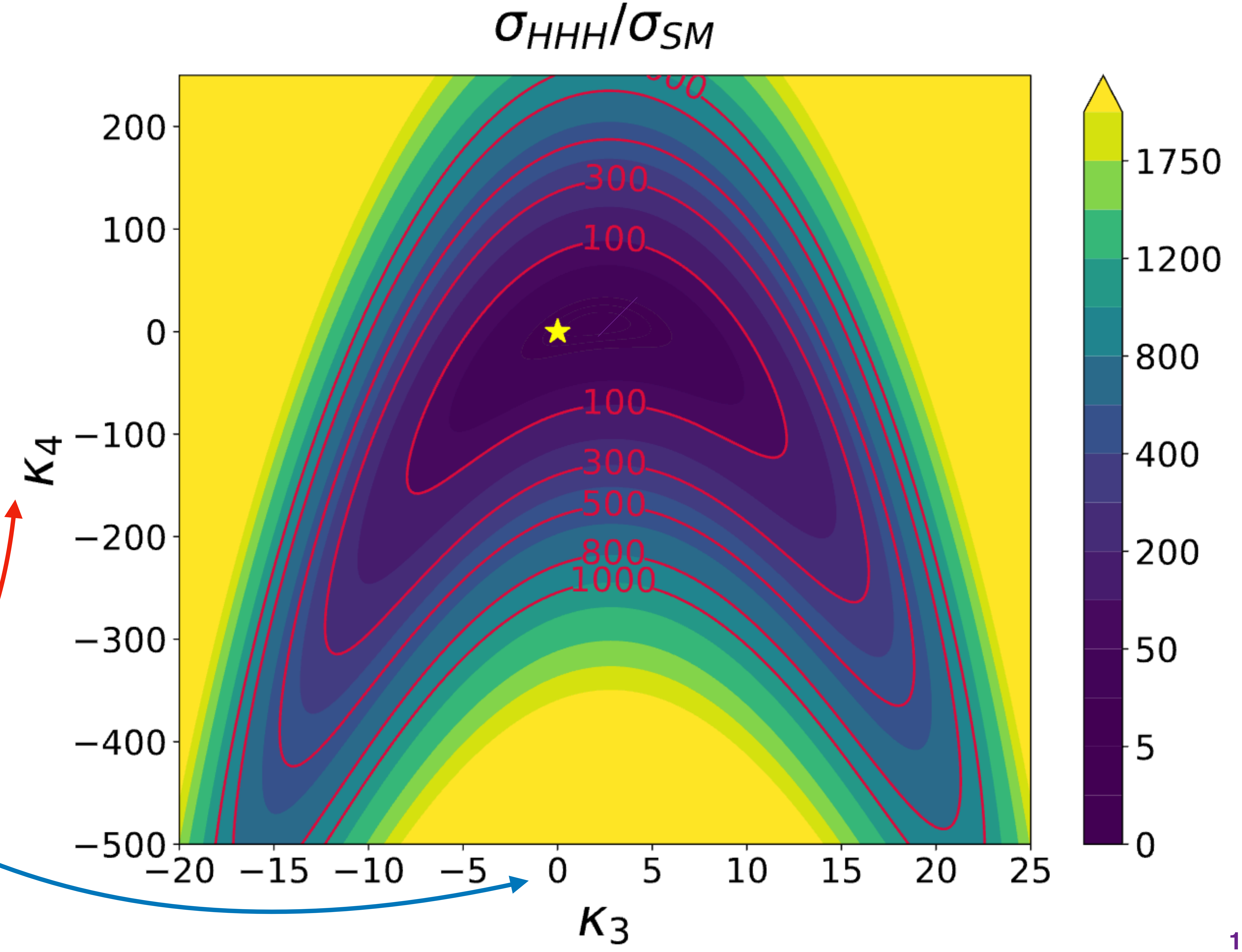
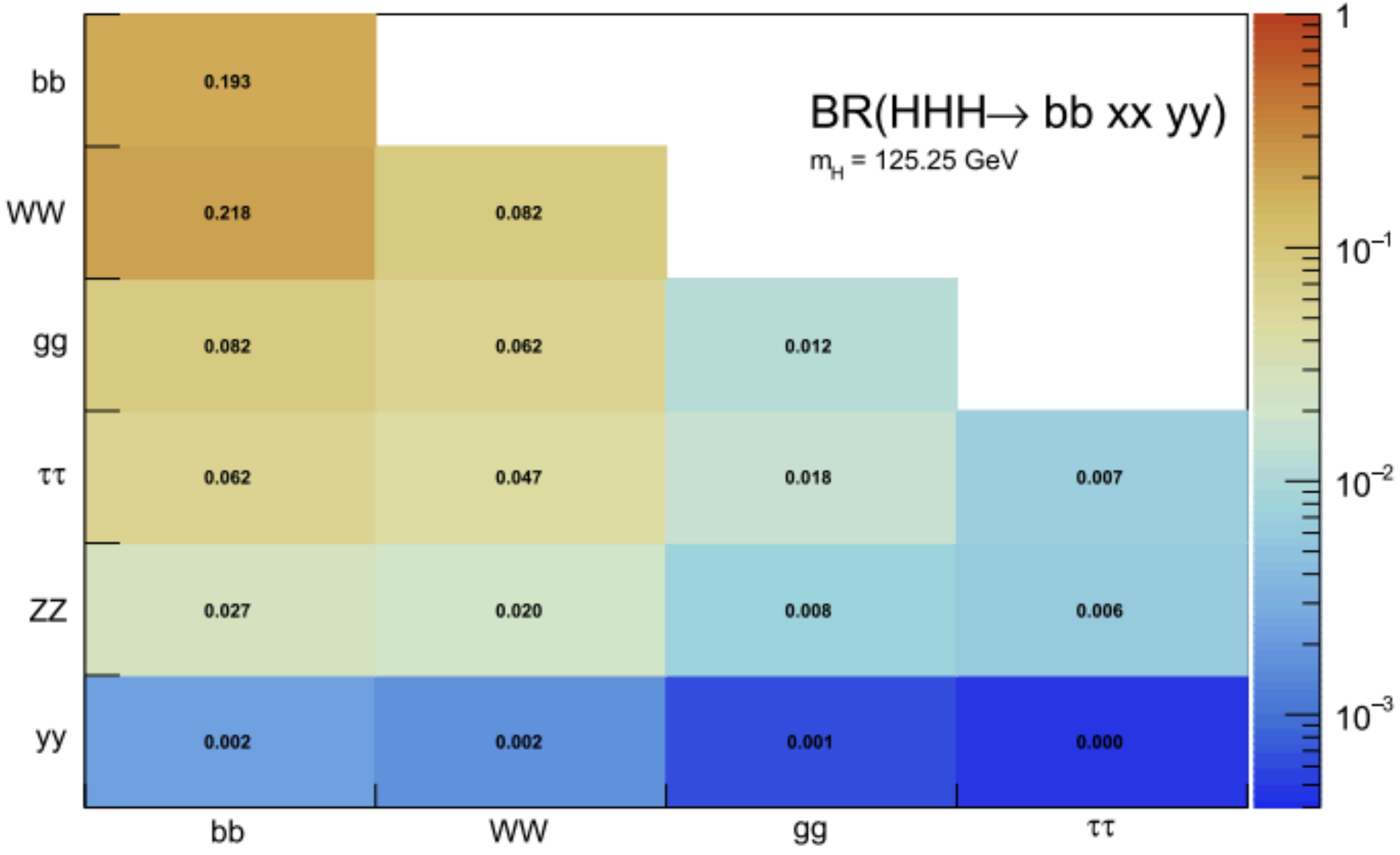




ATLAS Run-2 Results

HHH experimental analysis

Very small σ_{HHH} (~0.08 fb) - BR's important to determine viable experimental channels



- HHH(→6b) ~ O(20%)
- HHH(→4b2W) ~ O(20%) (+W decays)
- HHH(→4b2τ) ~ O(6%)
- HHH(→4b2γ) ~ O(0.2%)

In ATLAS focus on HHH(→6b) to maximise statistics.

CMS already explored smaller channels (4b2γ) as well.

HHH experimental analysis

Phys. Rev. D 111 (2025) 032006

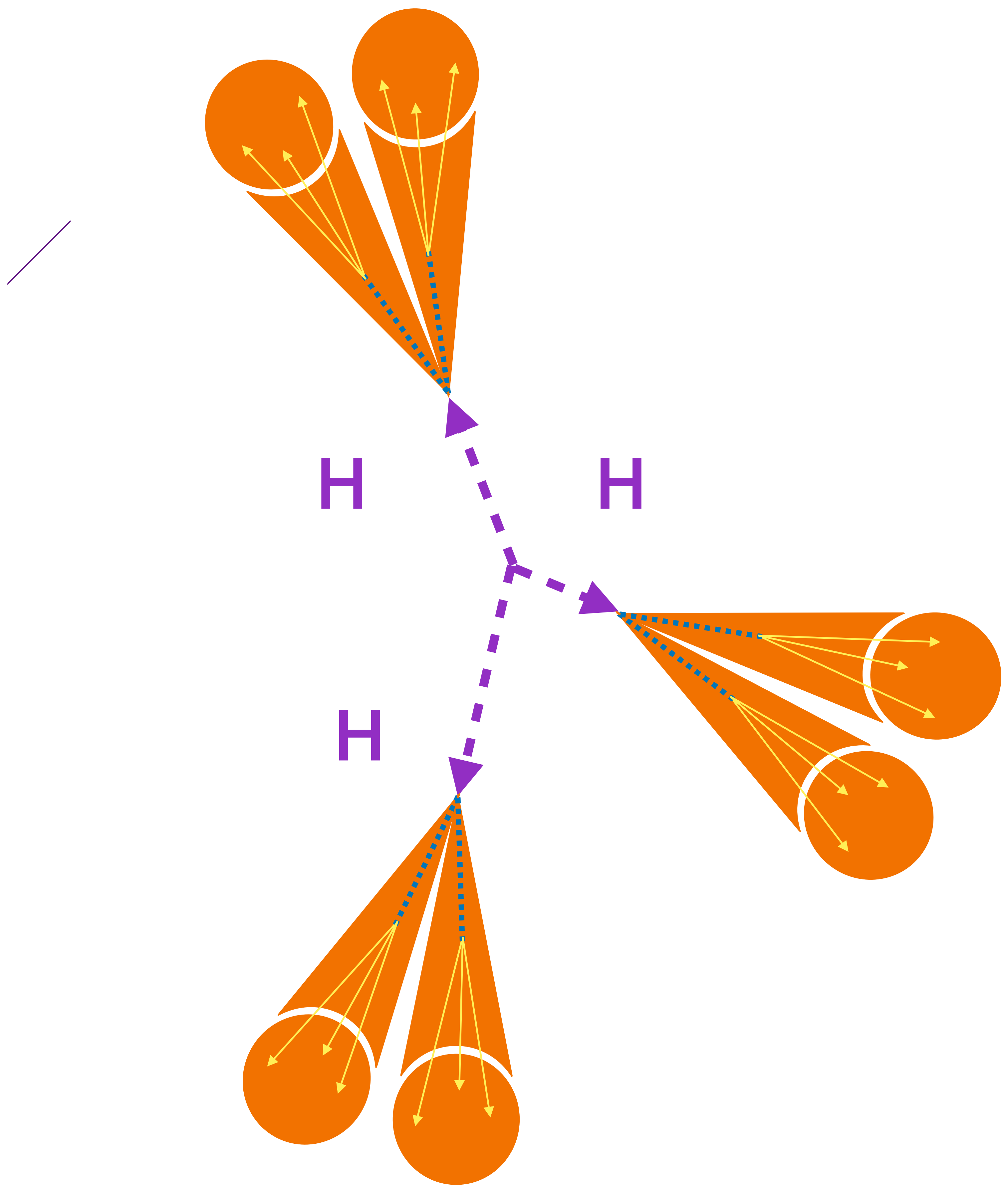
Challenges

Very small σ_{HHH} (~0.08 fb) → H(bb) decay for maximum statistics → **6 bottom-quark jet final state**

- large QCD background
- 6 bottom-jets pairing

Relatively simple analysis selection:

- combination of b-jet triggers across full Run-2 (2b2j, 3b1j)
- at least **6-jets (40 GeV)**, at least 4 b-jets (**DL1d 77%**)
- **4 b-jets**: validation region
- **5 b-jets**: background extrapolation region
- **6 b-jets**: signal region



… relatively busy final state !

HHH experimental analysis

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for maximum statistics

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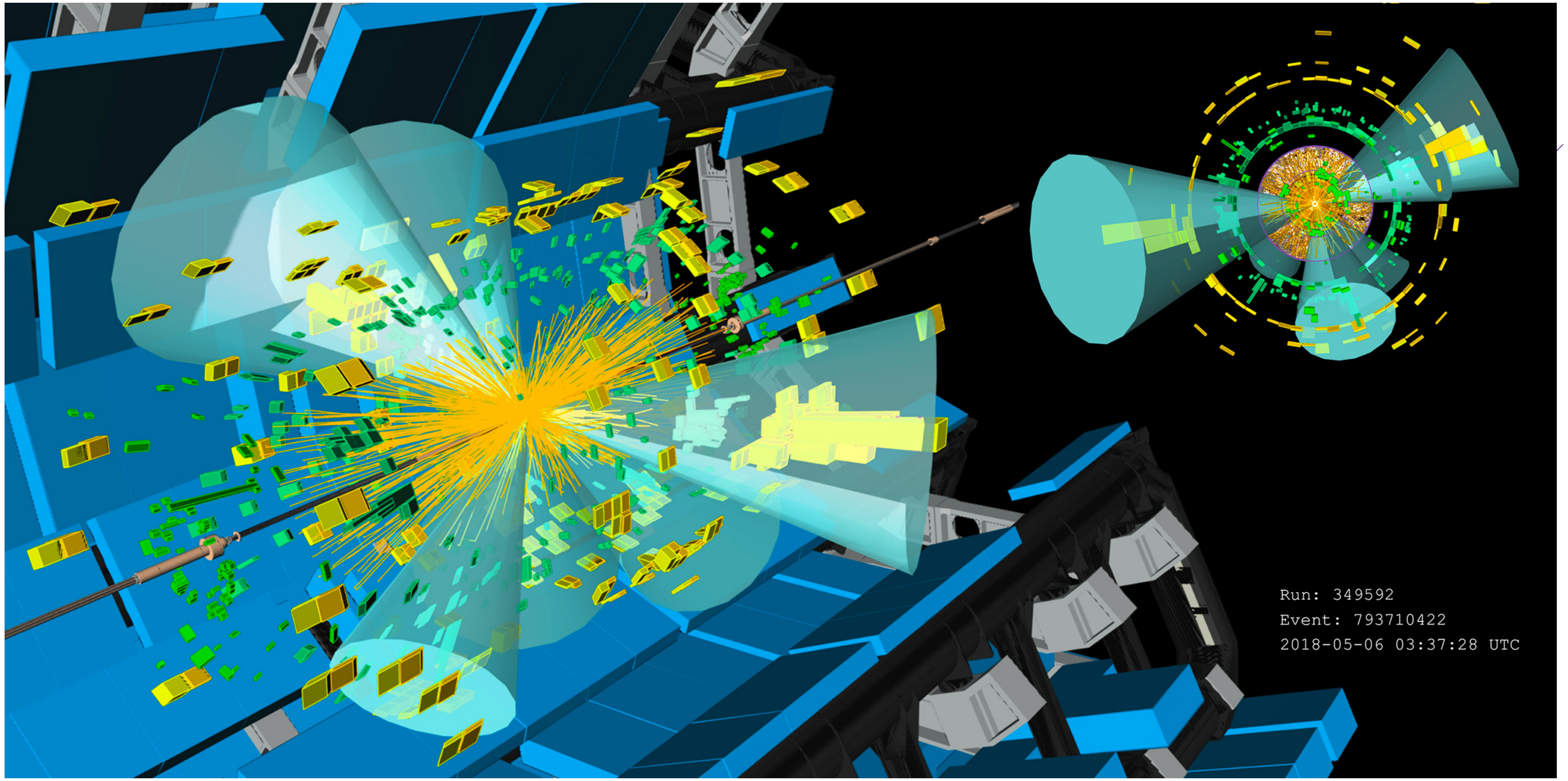
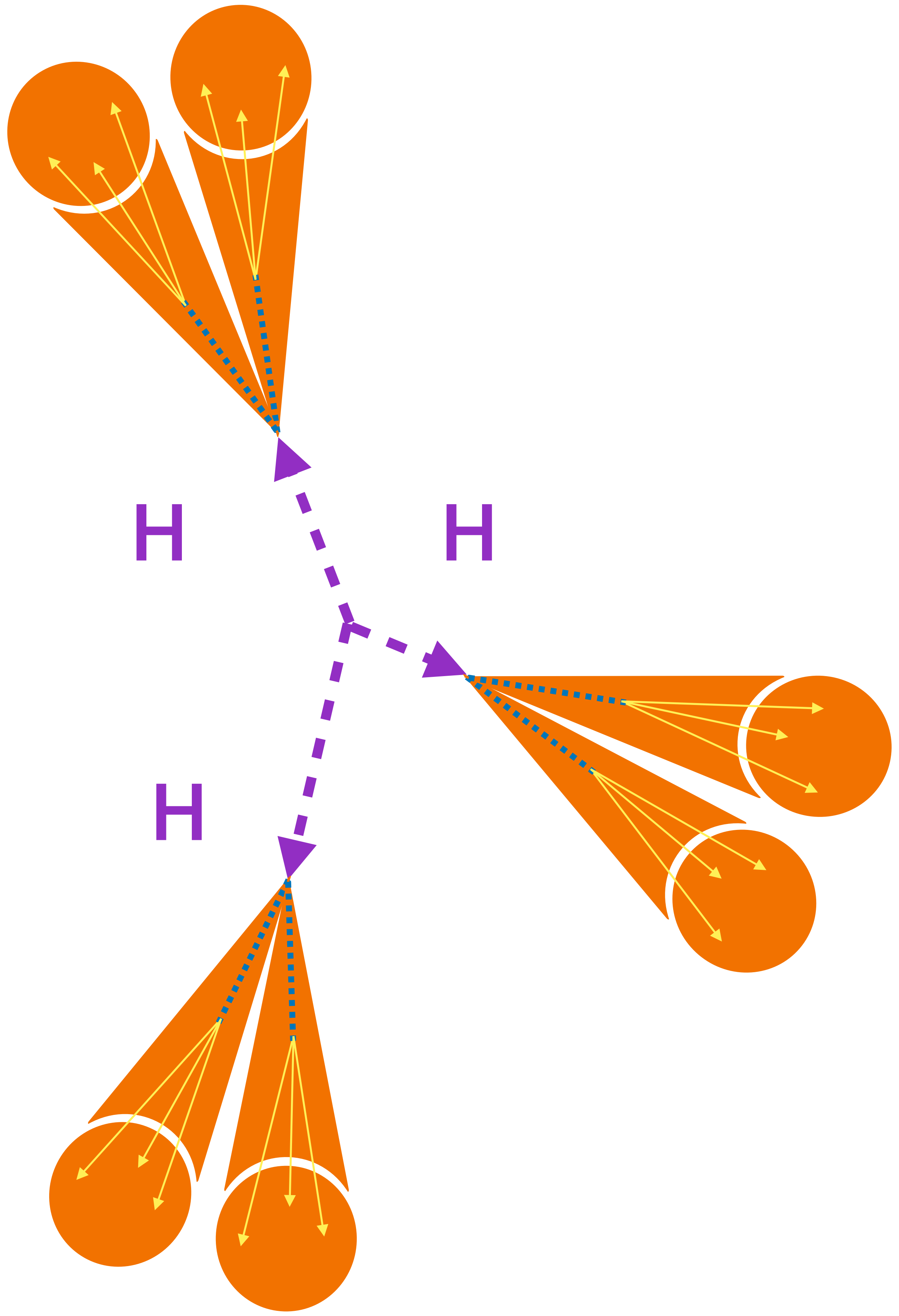




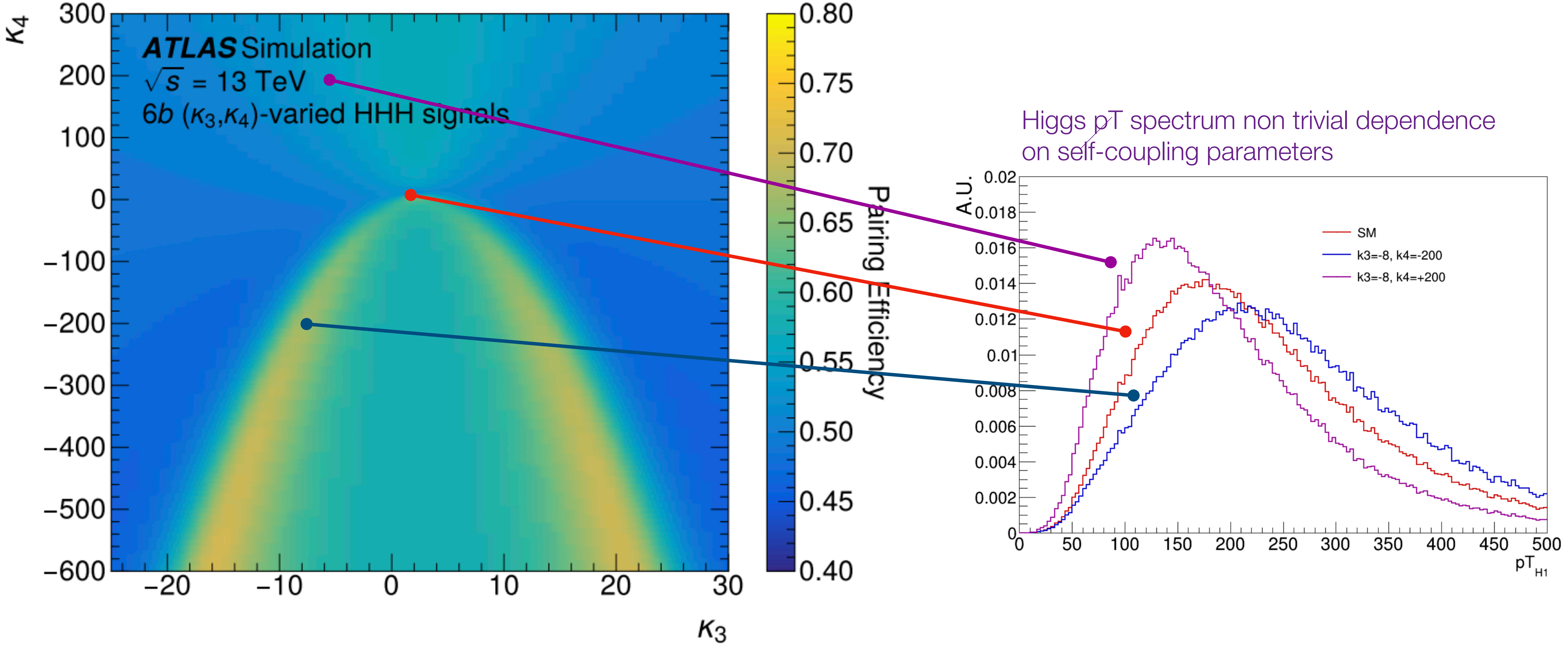
HHH experimental analysis

Jet pairing: how often do we reconstruct the correct Higgs candidate from (bb) pairs?

→ reconstruct (bb) pair consistent with Higgs mass ~ 125GeV [efficiency ~ 60% for SM]

$$|m_{H1} - 120\,\mathrm{GeV}| + |m_{H2} - 115\,\mathrm{GeV}| + |m_{H3} - 110\,\mathrm{GeV}|$$

Higgs pT spectrum non trivial dependence on self-coupling parameters



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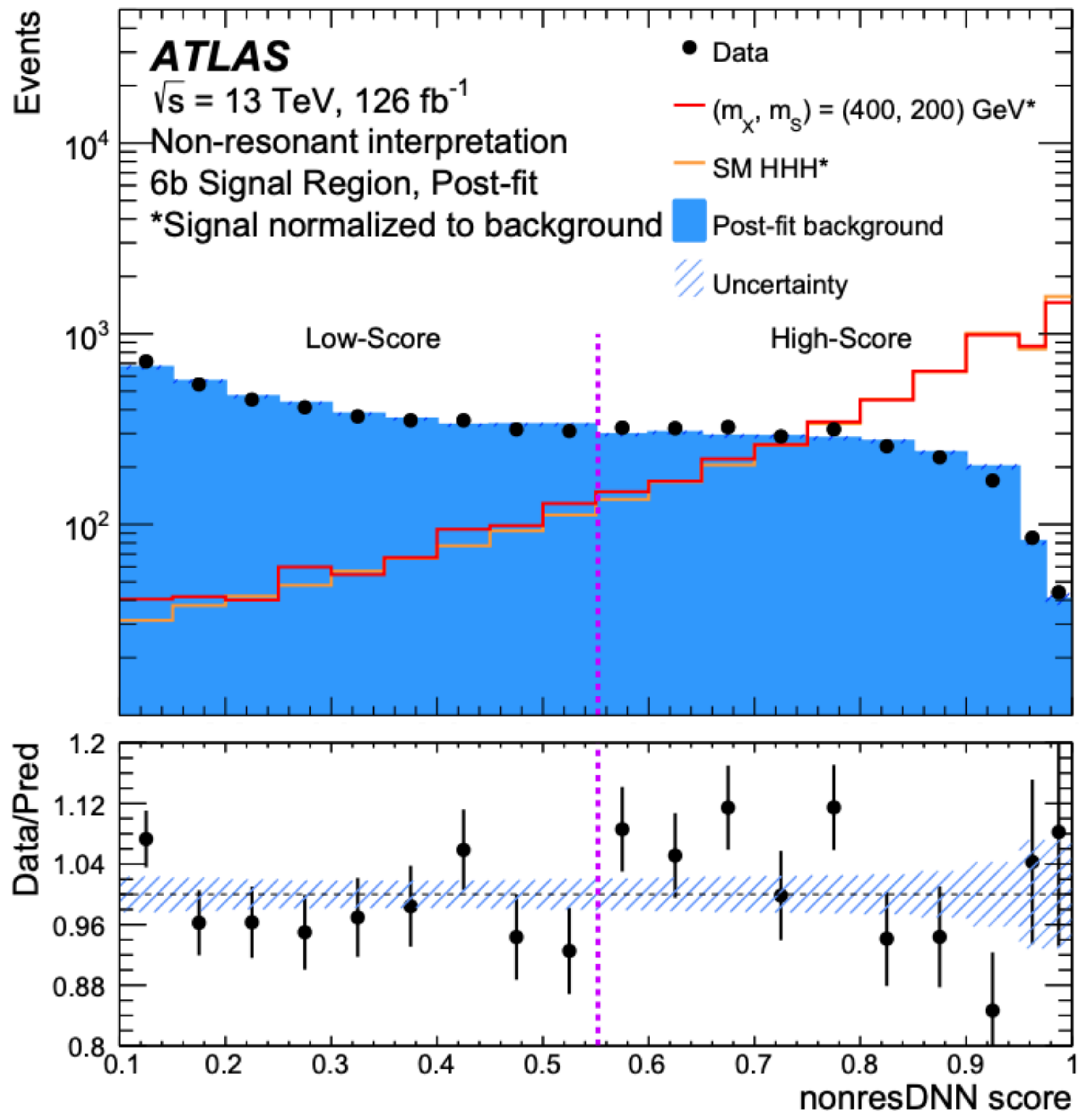
MVA: how do we distinguish the signal from the background?

→ DNN approach combining variables (with minimal correlation with b-tagging information)

Variable	Definition	nonres	res	heavyres
m_H-radius	Euclidean distance between the event and the pairing center (120, 115, 110) GeV in the (m_{H1}, m_{H2}, m_{H3}) volume.	✓		✓
m_{H1}	Reconstructed mass of the highest p_T Higgs boson candidate.	✓		✓
RMS(m_{jj})	Root-mean-squared (RMS) of the invariant mass of all possible jet pairs that can form a Higgs boson candidate.	✓		✓
RMS(ΔR_{jj})	RMS of the angular separation between all possible jet pairs that can form a Higgs boson candidate.	✓	✓	✓
RMS(η)	RMS of the pseudo-rapidity of the Higgs boson candidates.	✓		✓
Skewness ΔA_{jj}	Skewness of $\cosh(\Delta\eta_{ik}) - \cos(\Delta\phi_{ik})$, where i, k are all possible jet pairs that can form a Higgs boson candidate.		✓	
H_T^{6j}	Scalar sum of the p_T of the 6 jets selected to reconstruct the 3 Higgs boson candidates.		✓	
$\cos\theta$	In the (m_{H1}, m_{H2}, m_{H3}) coordinate system, θ is the angle between the vector from the origin to the event's reconstructed mass of the Higgs boson candidates, and the vector from the origin to (120, 115, 110) GeV.		✓	
Aplanarity$_{6j}$	The fraction of p_T from the 6 jets selected to reconstruct the 3 Higgs boson candidates lying outside the plane formed by the 2 highest p_T jets.	✓	✓	✓
Sphericity$_{6j}$	Isotropy of the momenta of the 6 jets selected to reconstruct the 3 Higgs boson candidates.		✓	
Transverse Sphericity$_{6j}$	Isotropy of the p_T of the 6 jets used for Higgs reconstruction, within the $x - y$ plane.	✓		
Sphericity	Isotropy of the momenta of all jets in the event.			✓
$\eta - m_{HHH}$ fraction	$\frac{\sum_{i,k} 2p_T^i * p_T^k * (\cosh(\Delta\eta(ik))-1)}{m_{HHH}^2}$ where i, k are all possible jet pairs that can form a Higgs boson candidate, and m_{HHH} is the reconstructed tri-Higgs invariant mass.		✓	
ΔR_{H1}	Angular separation between the jets paired to form the highest p_T Higgs boson candidate.	✓	✓	✓
ΔR_{H2}	Angular separation between the jets paired to form the second-highest p_T Higgs boson candidate.	✓	✓	✓
ΔR_{H3}	Angular separation between the jets paired to form the lowest p_T Higgs boson candidate.	✓	✓	✓

Trained on 5b-data as background



HHH experimental analysis

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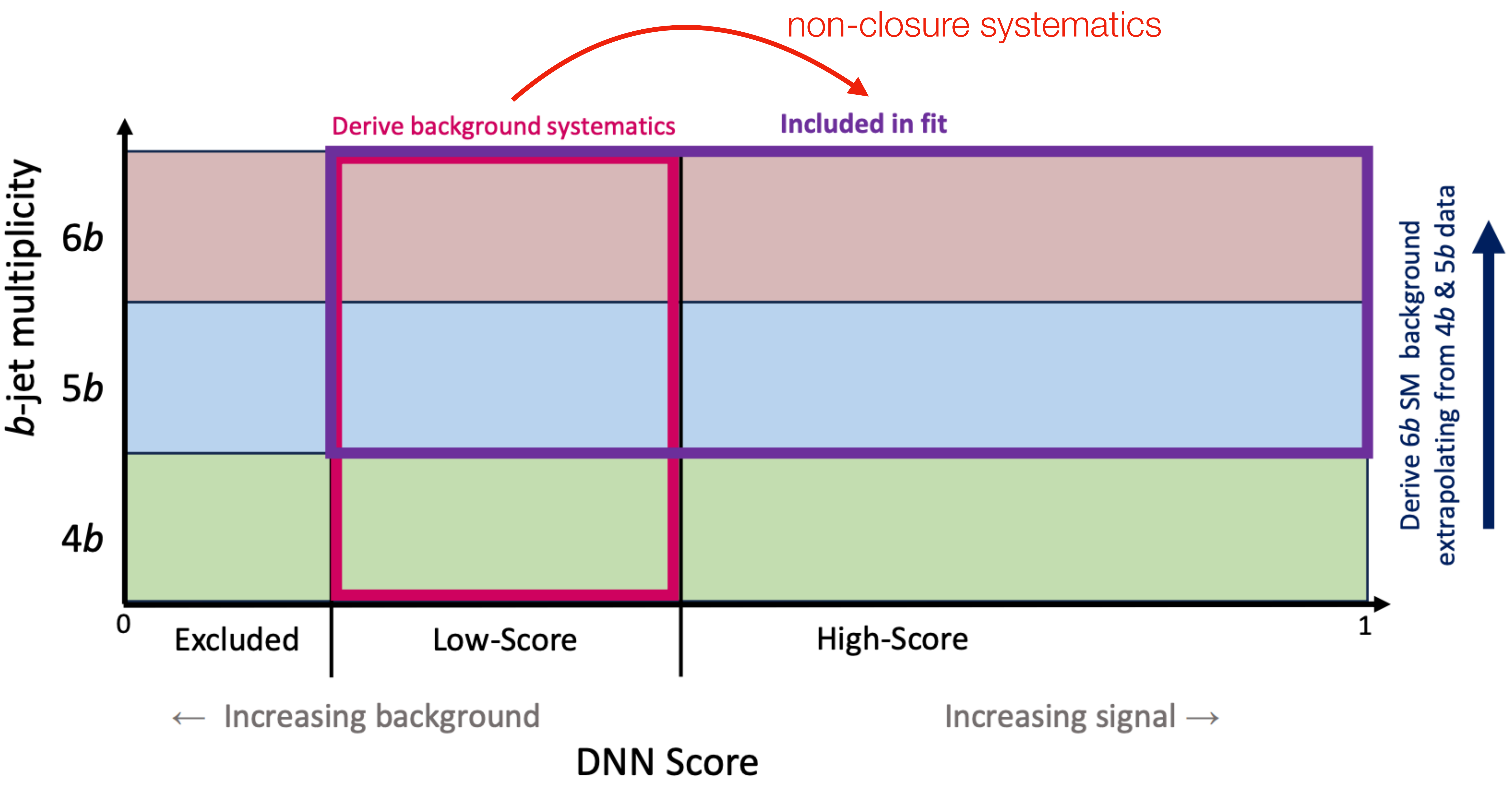
Background modeling: QCD multi-jet multi-b background fully data-driven

→ extrapolation from low-DNN and low-#b-tag regions to fully control the bkg shape and yield

Key assumption: QCD modeling similar for 4b, 5b, 6b events



- [**5b**] data reweighted to [**6b**] data yield
- shape correction from [**4b**/**5b**]

Binned DNN distribution fitted in the final fit: [**5b**] + [**6b**] regions in the profile likelihood

HHH experimental analysis

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Extrapolating in #b-tags means that the figure of merit for good modeling is $D = R_{6b/5b}/R_{5b/4b}$

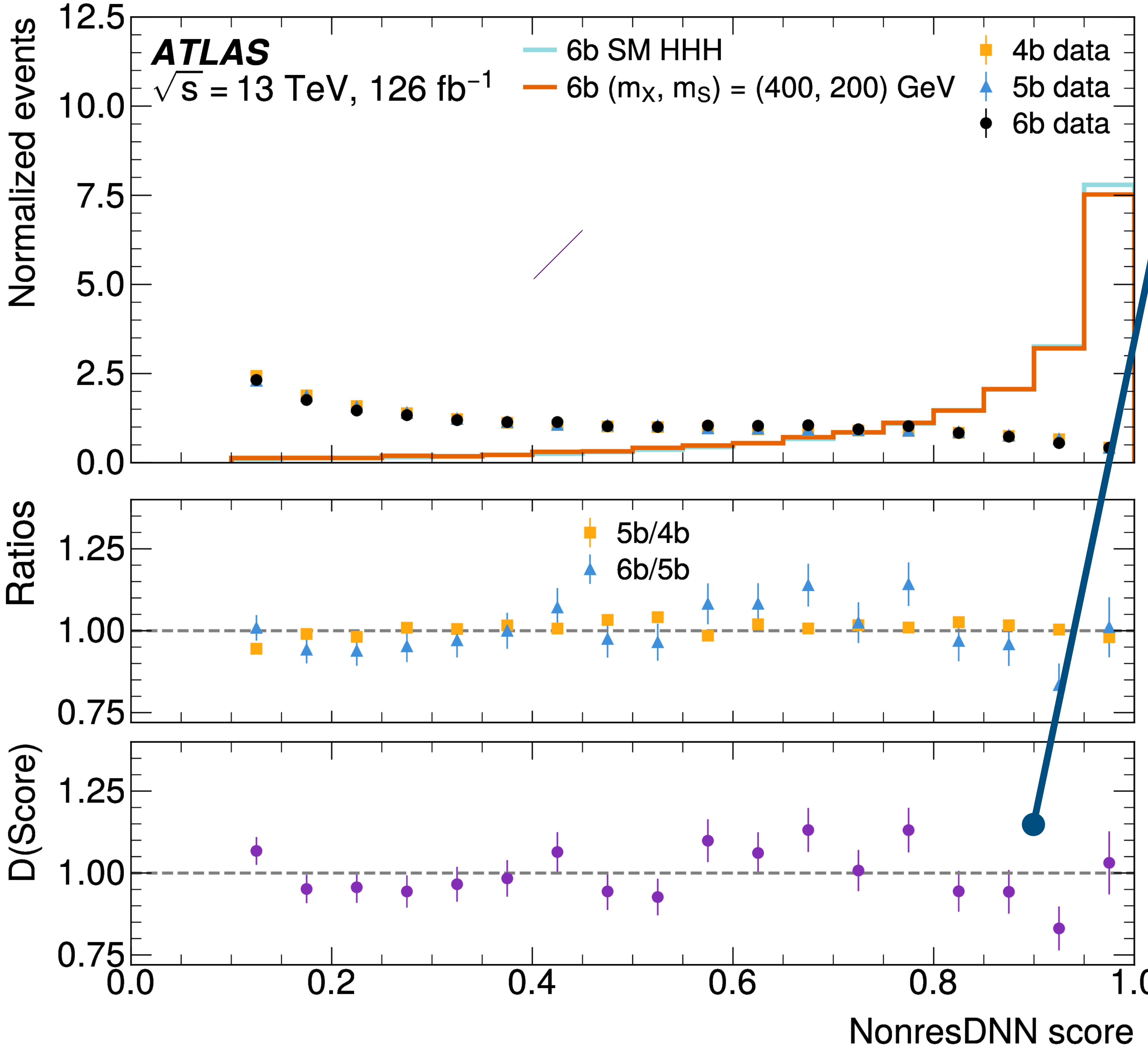
Low DNN-score region: **non-closure in the double ratio D** taken as systematics (accounted for 3 different uncorrelated variables)

$$\frac{D^{\text{low score}}_{6b/5b/4b}(\text{input variable})_j}{D^{\text{low score}}_{6b/5b/4b}}$$

The assumption is relaxed to:

Deviations or the double-ratio D from ~1 are similar in the low- and high-score regions

(DNN decorrelated from b-tag information)



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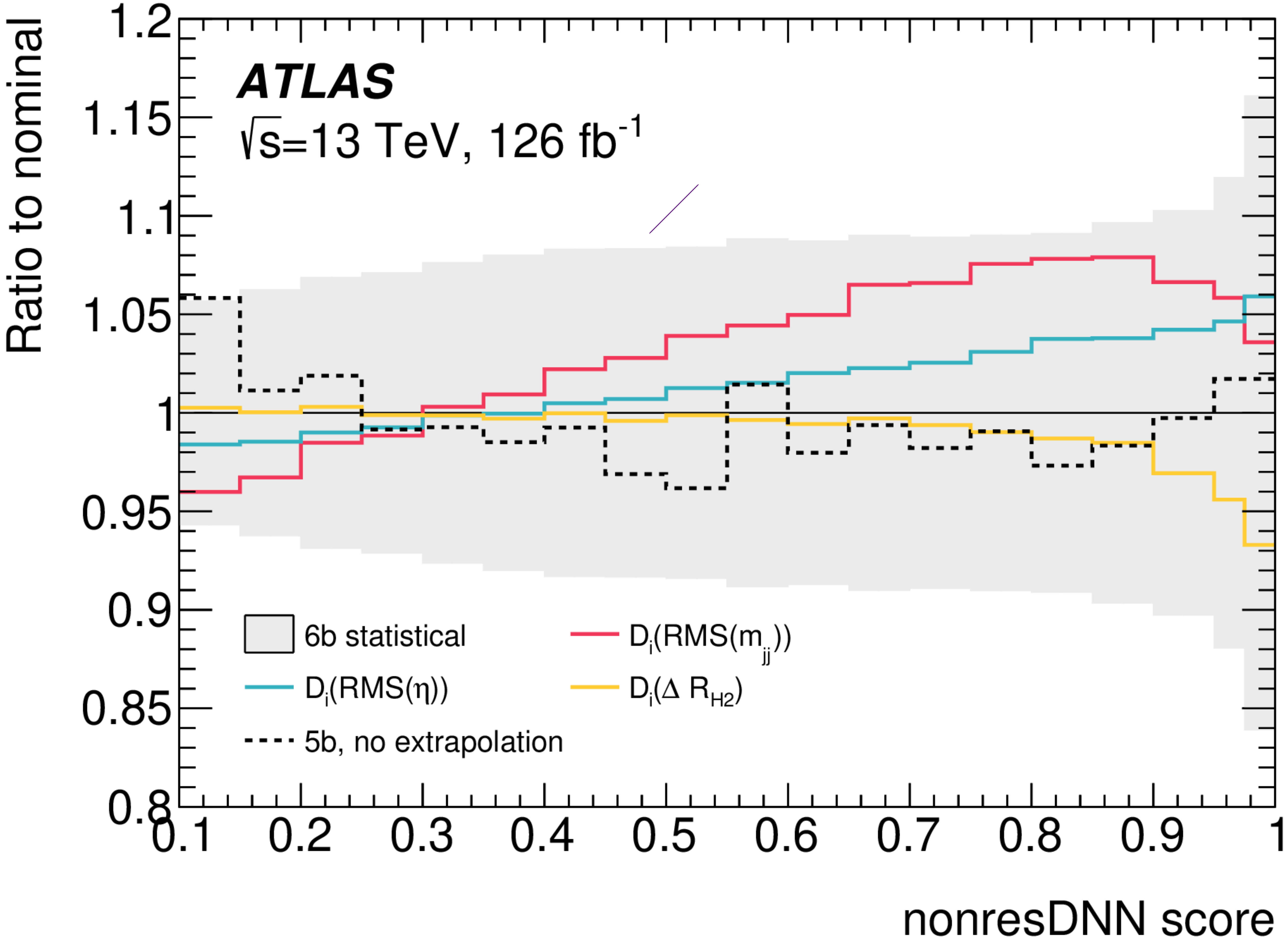
These shape uncertainties are profiled in the fit, essentially contributing to the data-driven background model in the 4-5-6b extrapolation



HHH ATLAS Run-2 results

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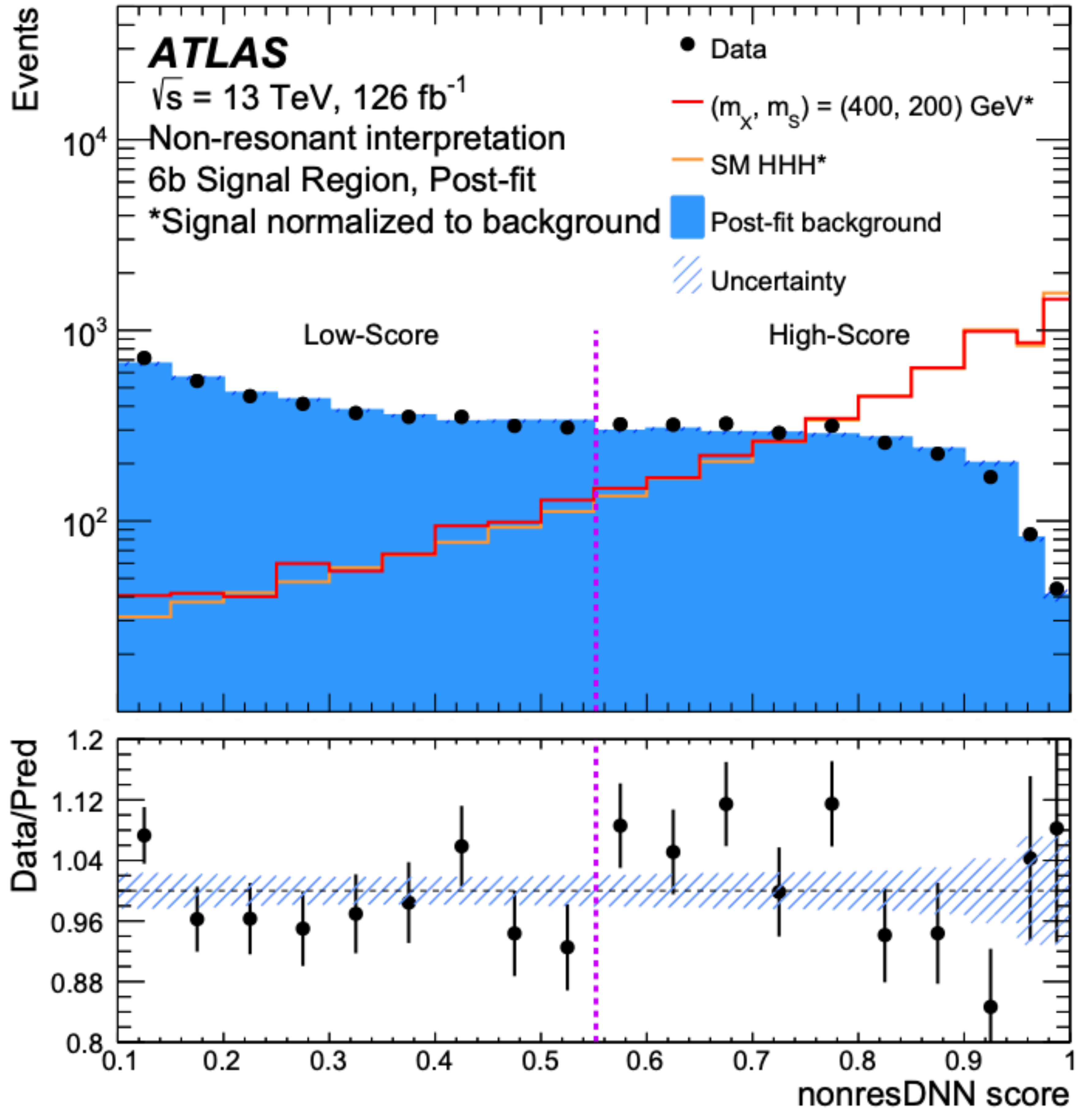
$\mu_{HHH} < 750$

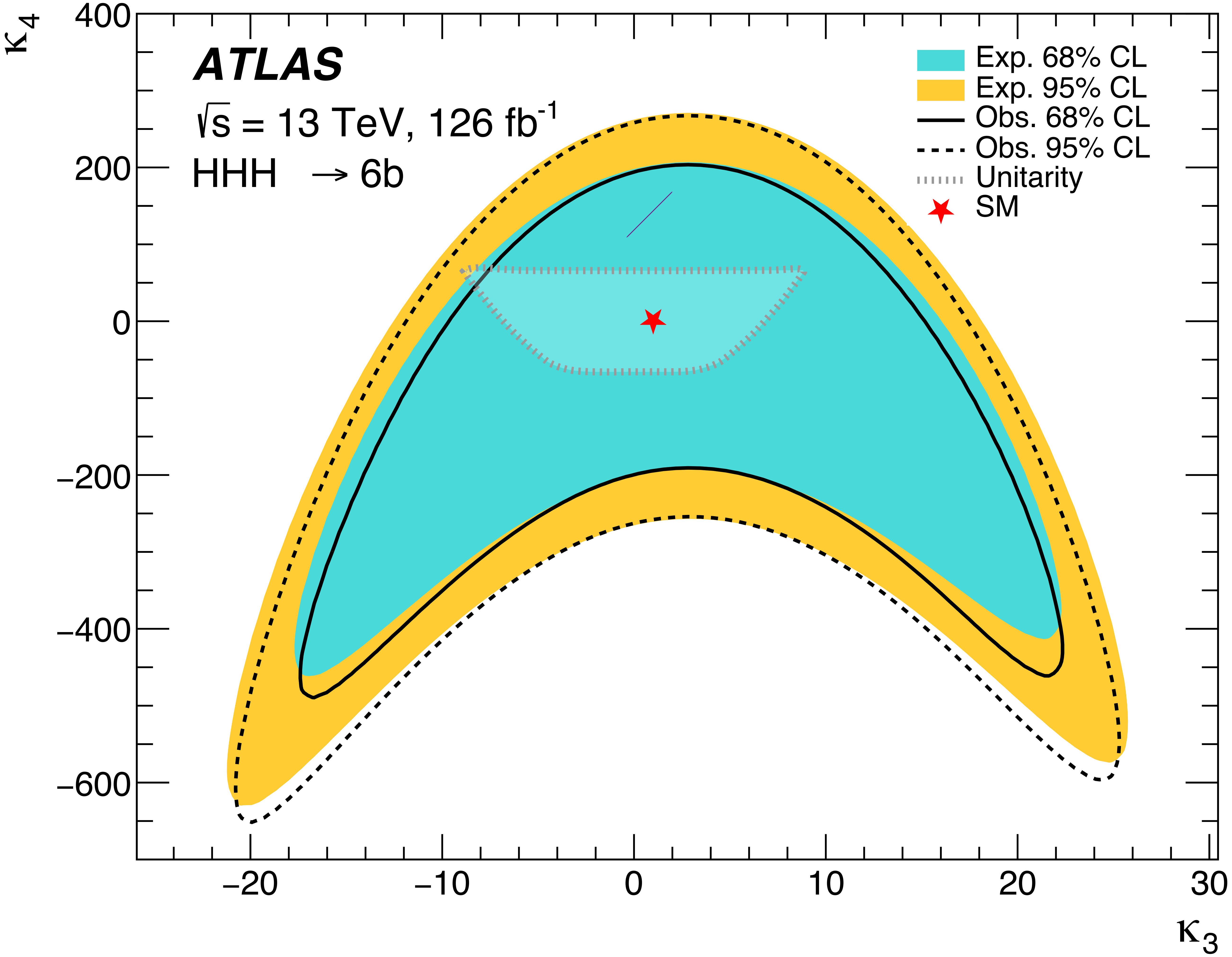
$\sigma_{HHH} < 59$ fb [$\sigma_{HHH}^{SM} \sim 0.08$ fb]

fully dominated by available data statistics

$-11 < k_3 < 17$ (k_4=1)

$-230 < k_4 < 240$ (k_3=1)





HHH ATLAS Run-2 results: TRSM interpretation

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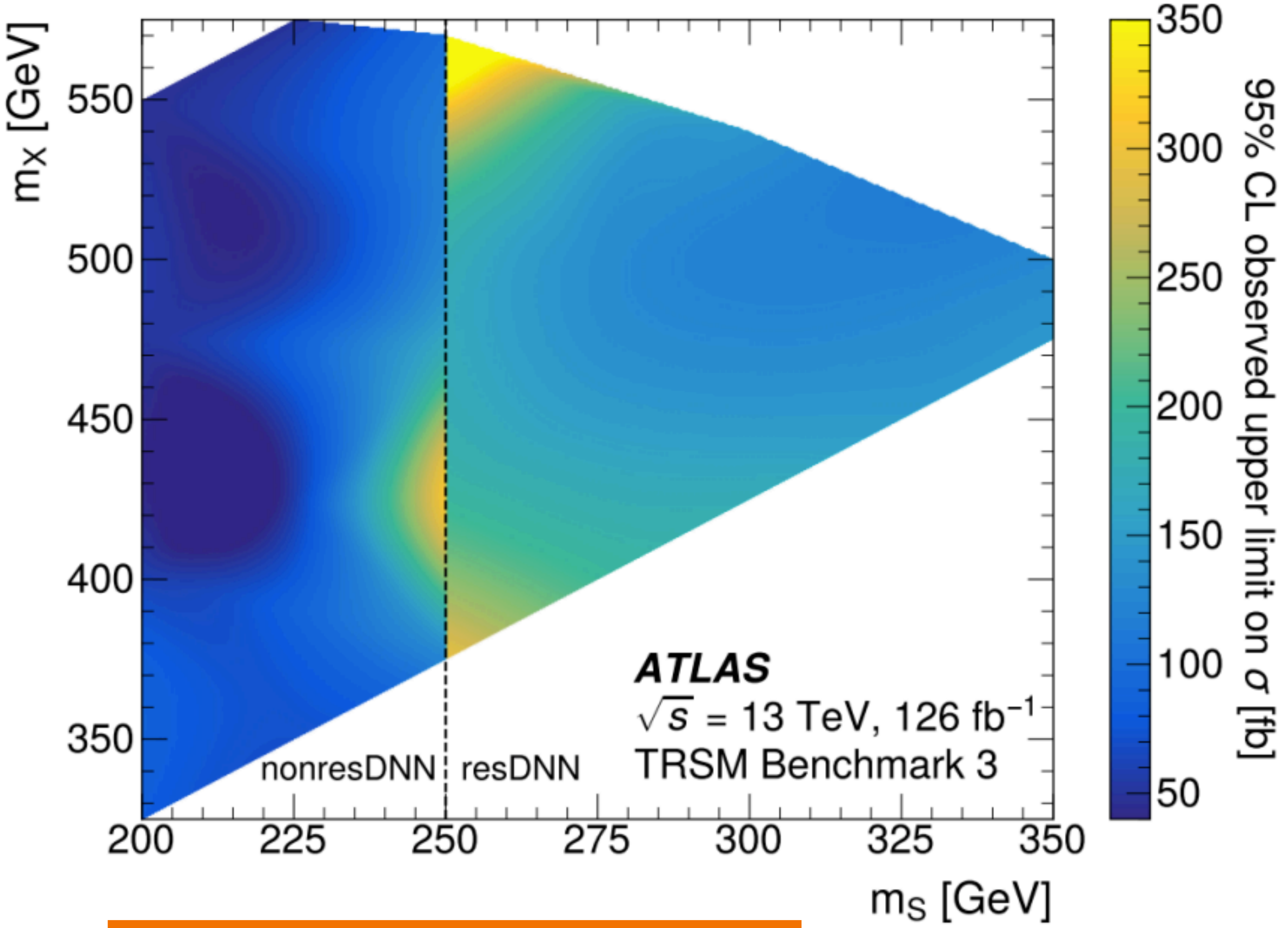
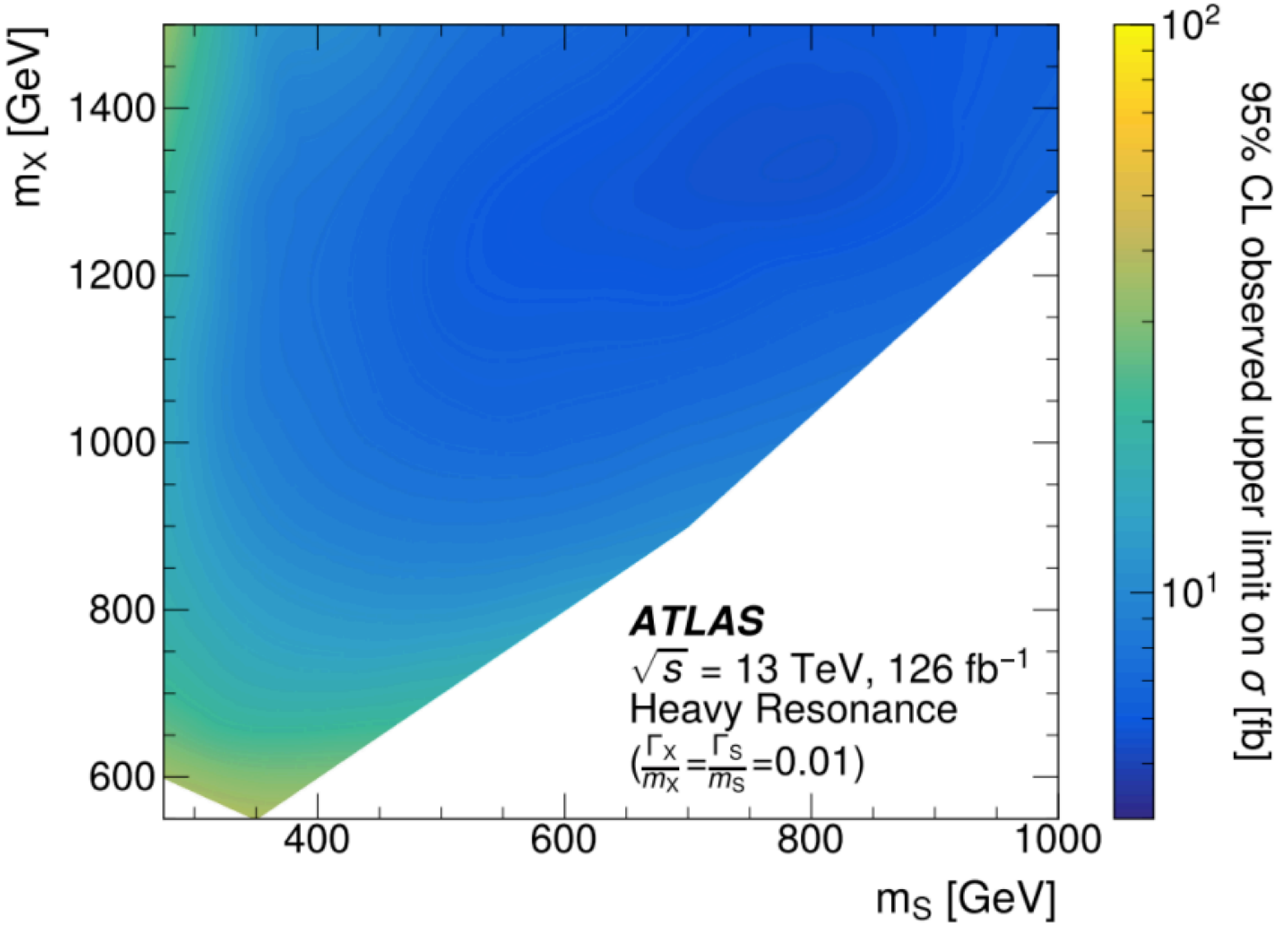
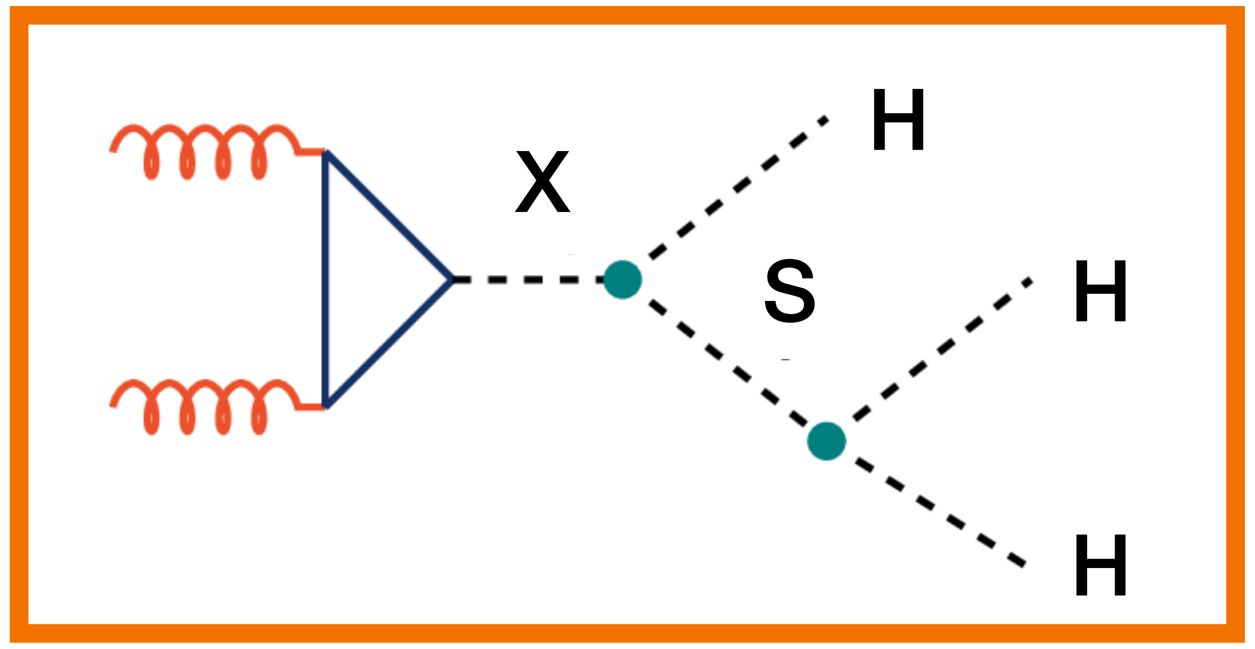
Results in the HHH(6b) final state can be translated to limits to TRSM and generic heavy resonance models: DNN approach re-optimised for different signal models





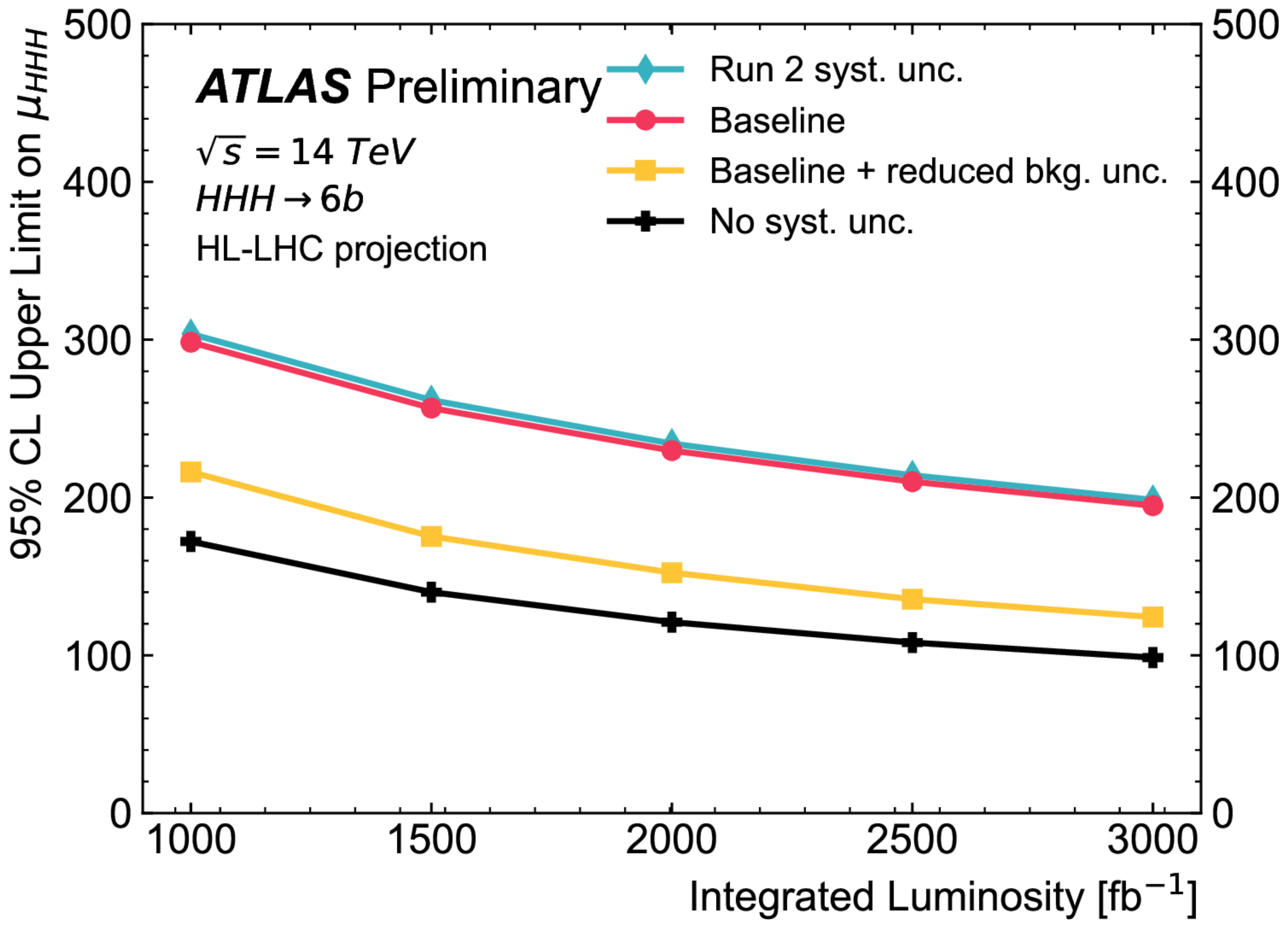


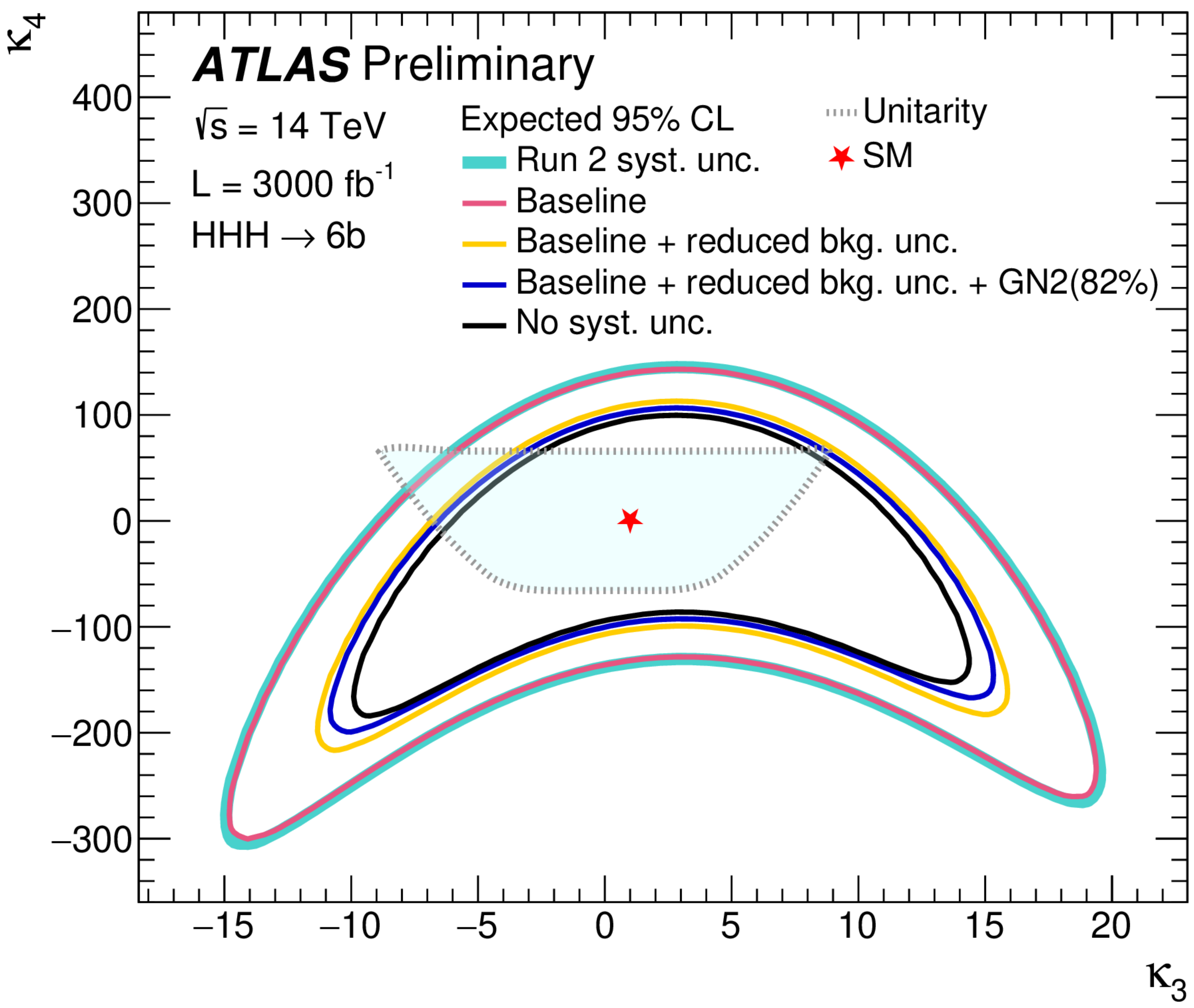
- TRSM Benchmark Point 3: $m_H \leq m_S < m_X$
  pert. bounds: 325< $\mathbf{m_X}$ <575GeV; 200< $\mathbf{m_S}$ <350GeV
- Generic heavy resonance : only resonant diagram from TRSM BP3
  500< $\mathbf{m_X}$ <1500GeV; 275< $\mathbf{m_S}$ <1000GeV

HL-LHC Prospects

HL-LHC Projections

SM HHH limited by small cross-section and low statistics: O(10 times) more data at HL-LHC





- same systematics as in Run-2 analysis
- halved b-tagging and theory systematics
- + data-driven bkg syst. scaling with luminosity
- + 5% extra b-tagging efficiency (fixed bkg rejection)

HL-LHC Projections

ATL-PHYS-PUB-2025-003

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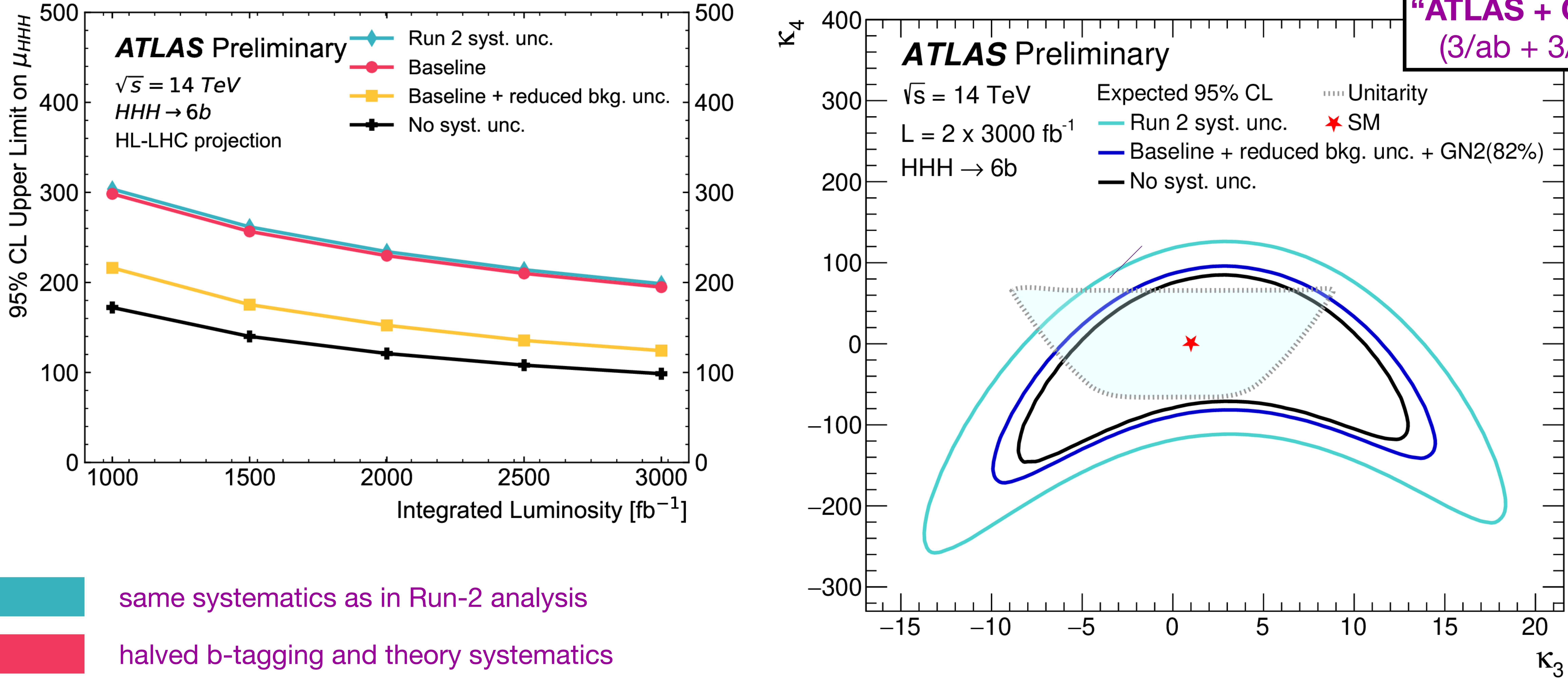

"ATLAS + CMS"
(3/ab + 3/ab)

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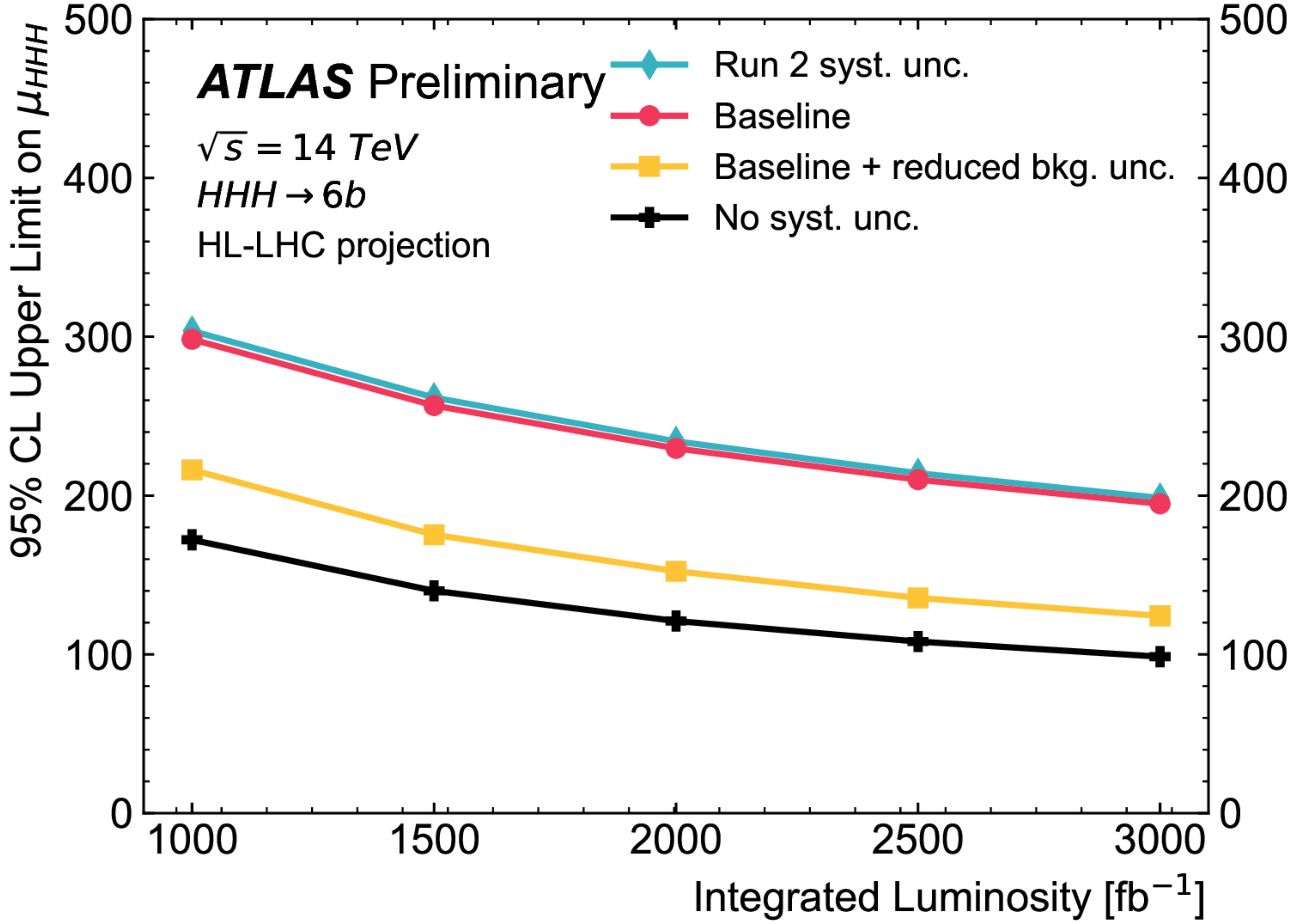

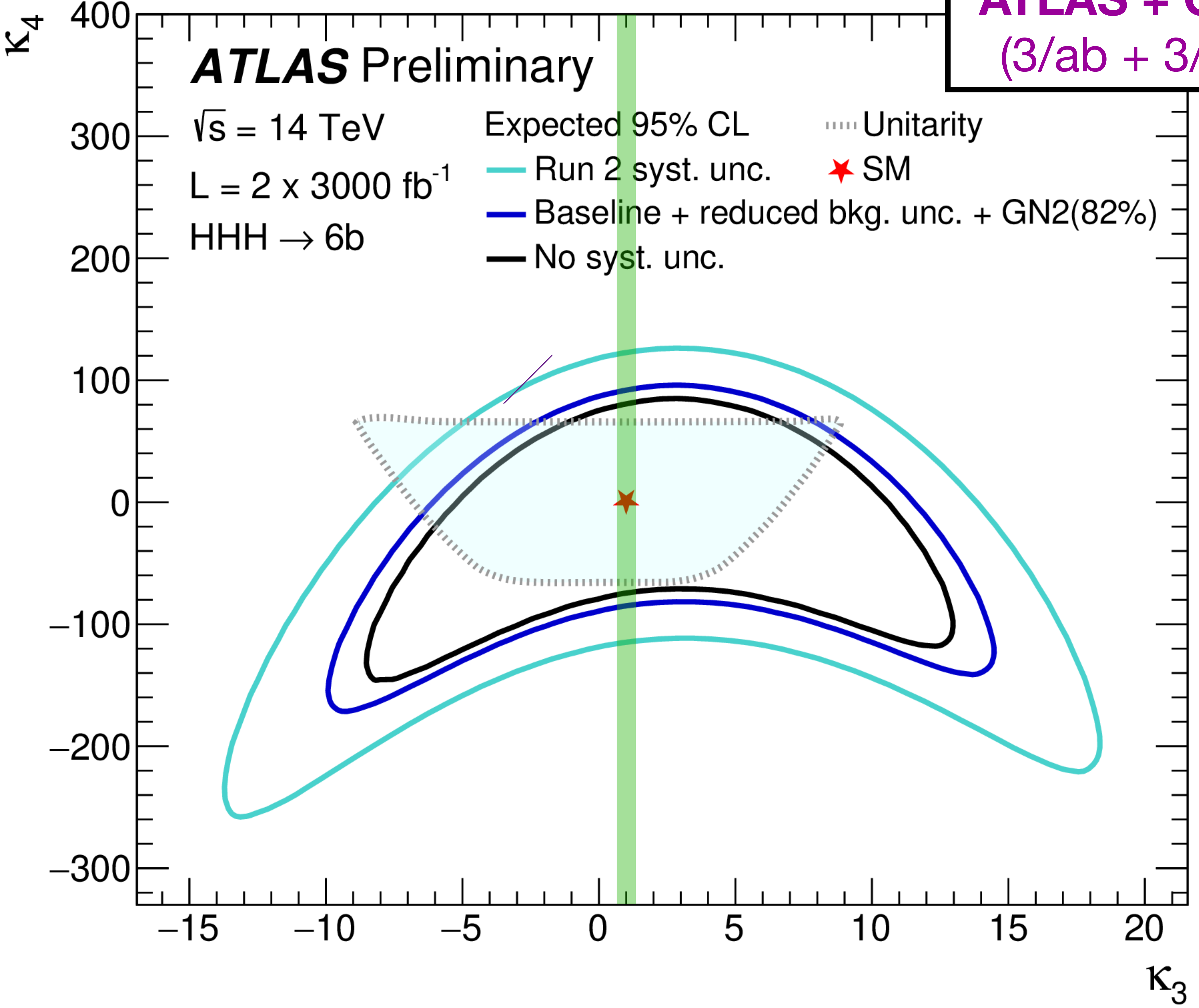

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O(30%) k_3 expected precision from HH at HL-LHC

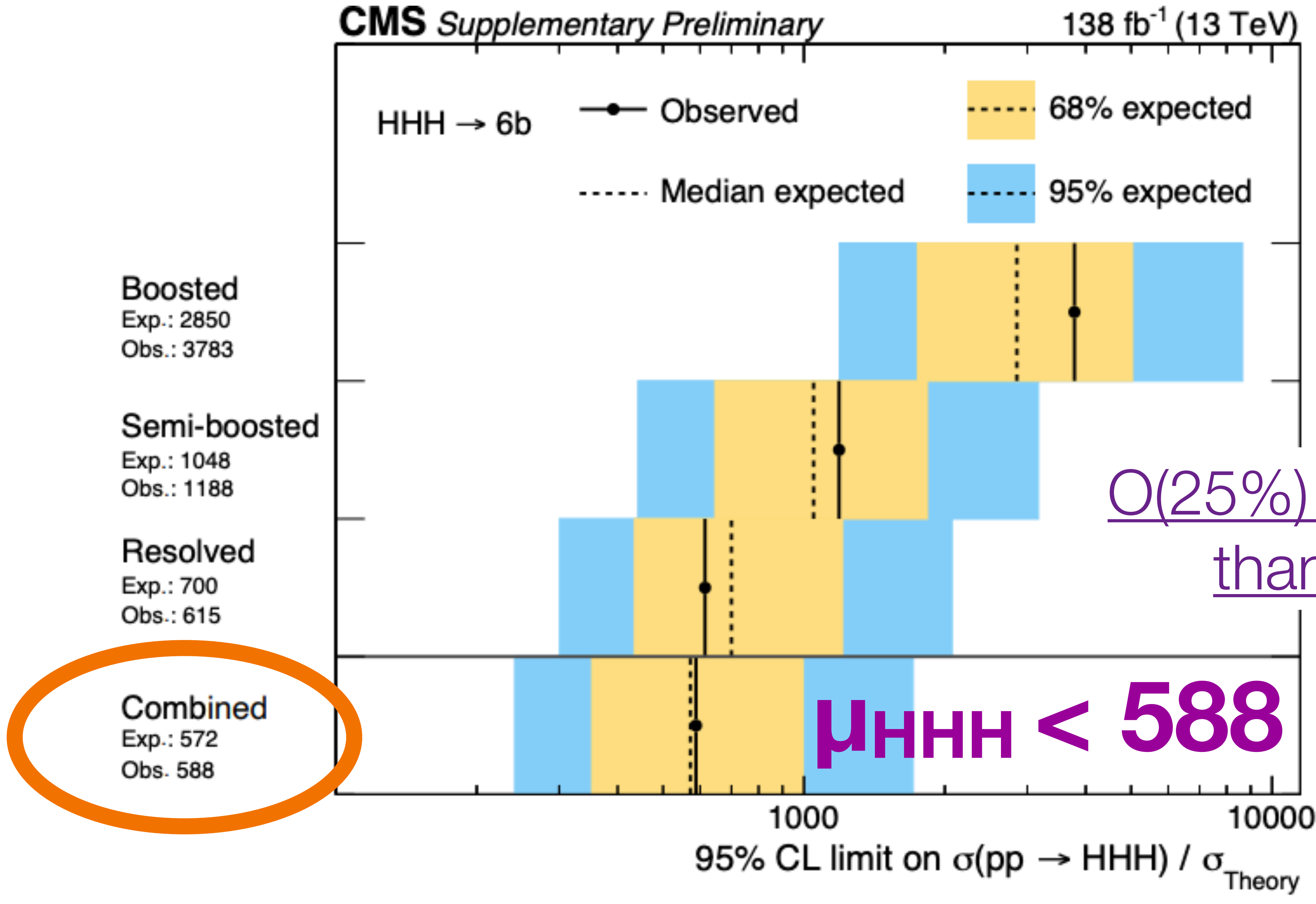
k_4 unitarity bounds for (k_3=1) **around (-65, 65)**

CMS results & other channels

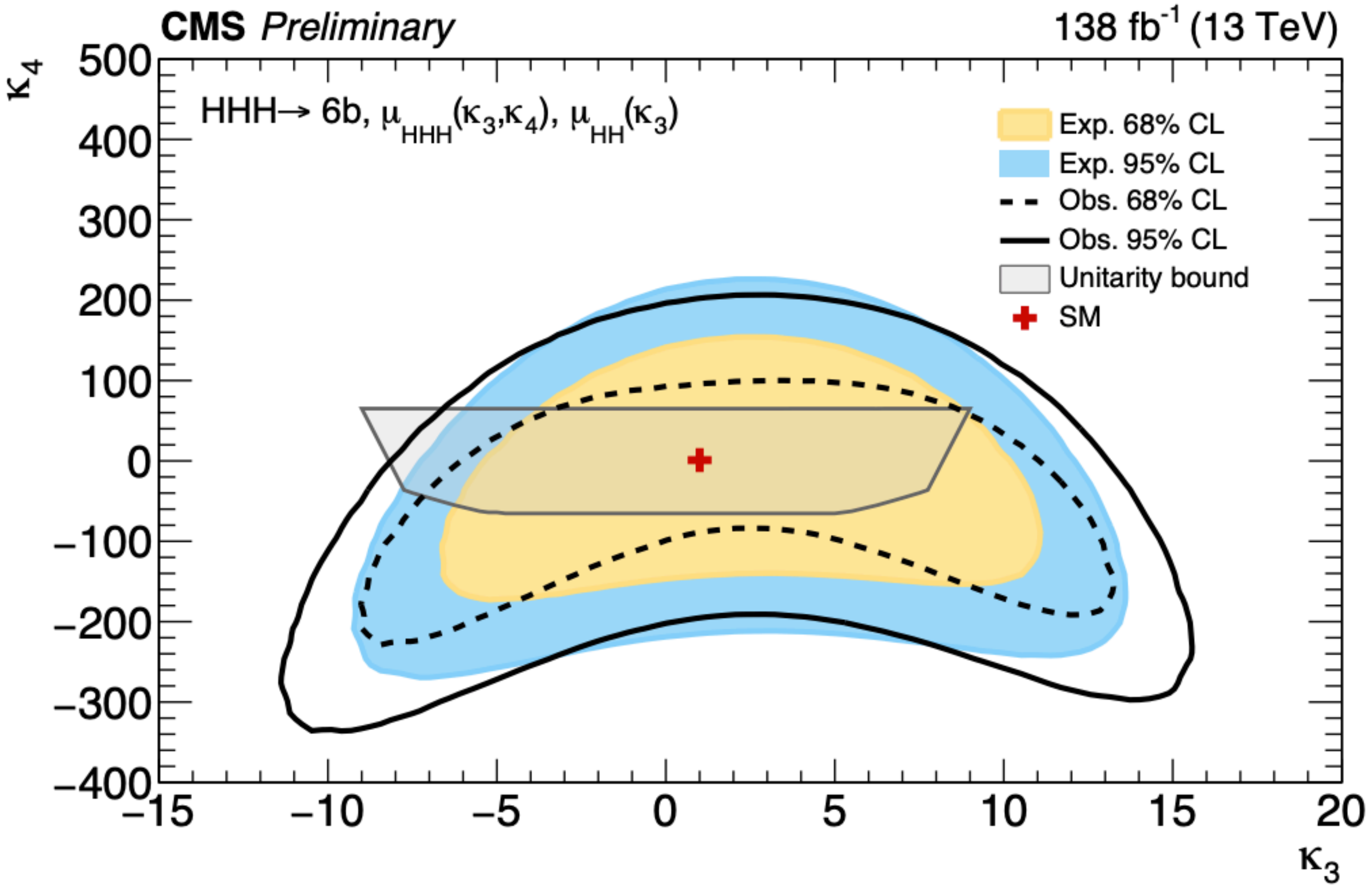
CMS PAS HIG-24-012

Recent CMS results for the HHH(6b) final state:

- including boosted and semi-boosted topologies, one or more H reconstructed as large-R jets
  → O(20%) improvement
- including events with <3 reconstructed Higgs (impact of limited b-tagging acceptance)
  → O(18%) improvement



O(25%) better limits than ATLAS



Constraints on the self-coupling plane:

- HH processes included as background, with k3 dependency
  → strong impact on k's constraints !
  (missing from ATLAS results)
- Difficult to model HH(k3,k4) yet

Conclusions & Outlook

First triple-Higgs experimental search from ATLAS in the 6 b-jets final state

- Limits still very far from SM (~750xSM)
- Sensitivity to trilinear and (uniquely) quartic self-coupling, some complementarity with HH
- Probing TRSM / heavy scalar BSM models

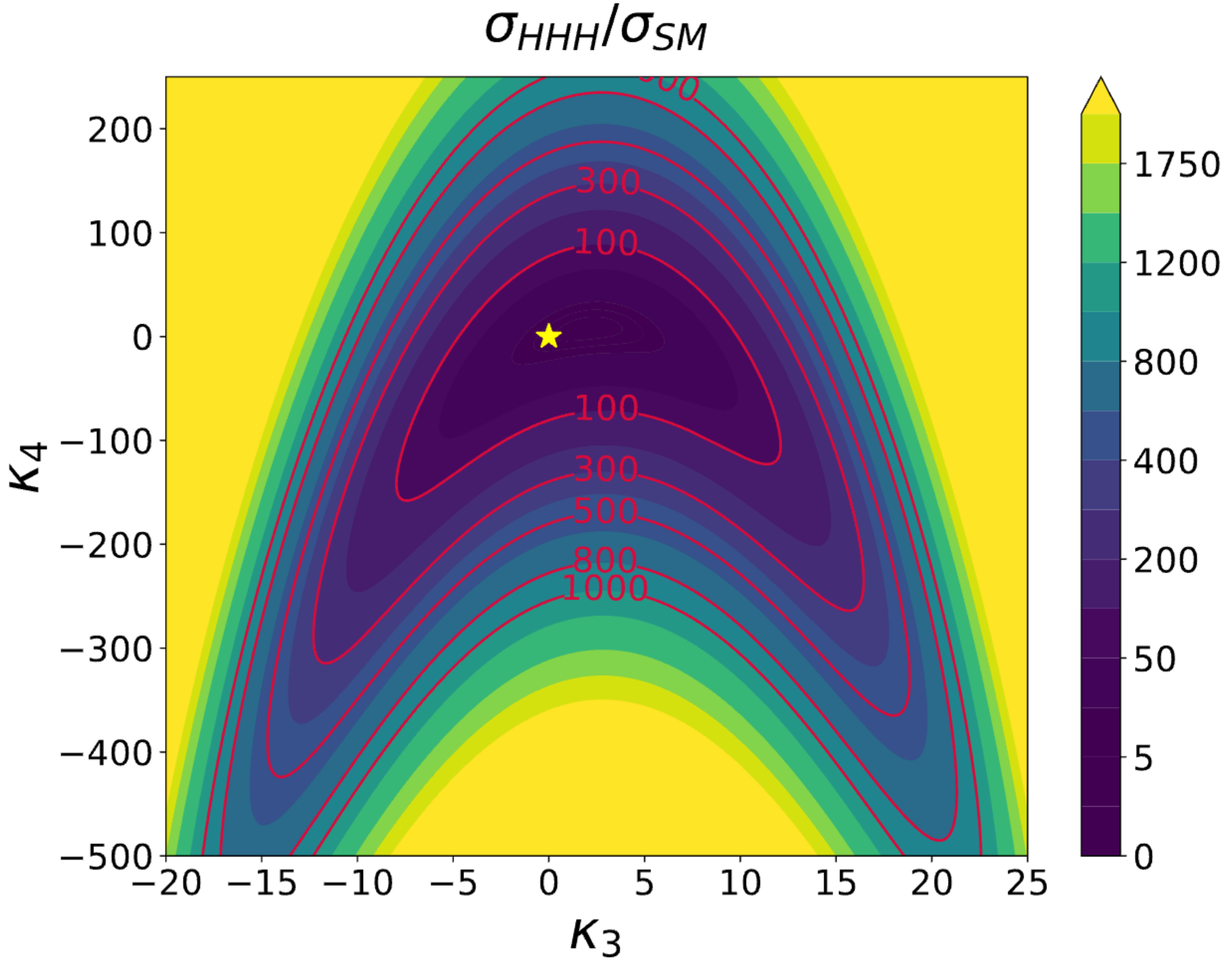
Clearly this is a physics target yet far from Standard Model sensitivity, yet some interest growing in the experimental community.

Refining analysis techniques (see CMS) and exploring other channels (4b2τ), possibly interesting results already at HL-LHC?

**Pas de Trois Grâces à Dubrovnik jusqu'à présent*

Thank you for your attention !

HHH cross-section dependency on Higgs self-coupling: the details



$$\frac{\sigma(c_3,d_4)_{hhh}}{\sigma(\mathrm{SM})_{hhh}} - 1 = 0.0309 \times c_3^4 - 0.2079 \times c_3^3 + 0.0407 \times c_3^2 d_4 + 0.7384 \times c_3^2 + 0.0156 \times d_4^2 - 0.1450 \times c_3 d_4 - 0.1078 \times d_4 - 0.6887 \times c_3 \,.$$

In this formula:
$c_3 = k_3 - 1$
$c_4 = k_4 - 1$

Standard Model → $k_3 = k_4 = 1$

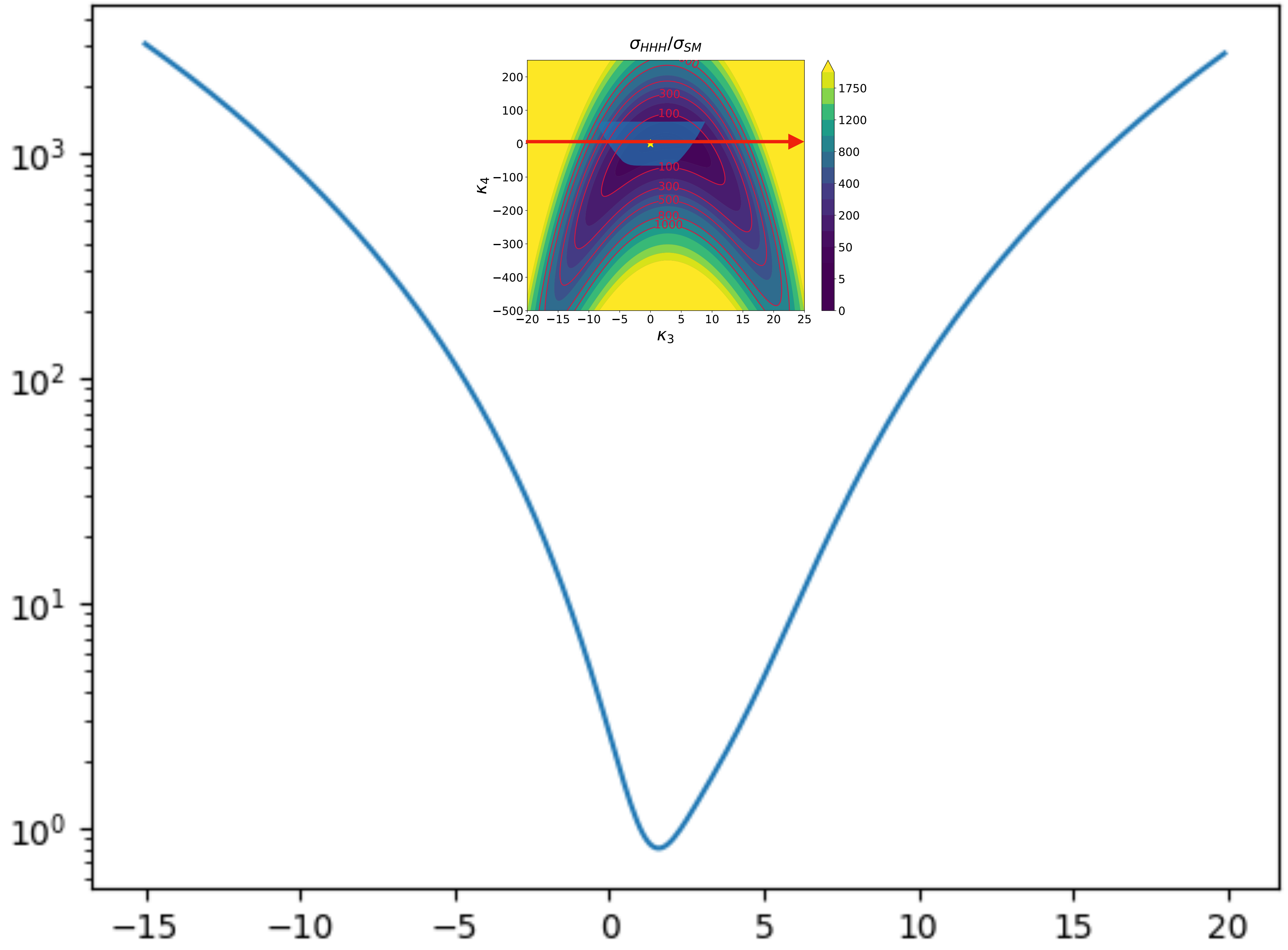
$XS_{min}(k_3, k_4)$ → k_3 ~2, k_4 ~8

$XS_{min}(k_3, k_4=1)$ → k_3 ~1.6

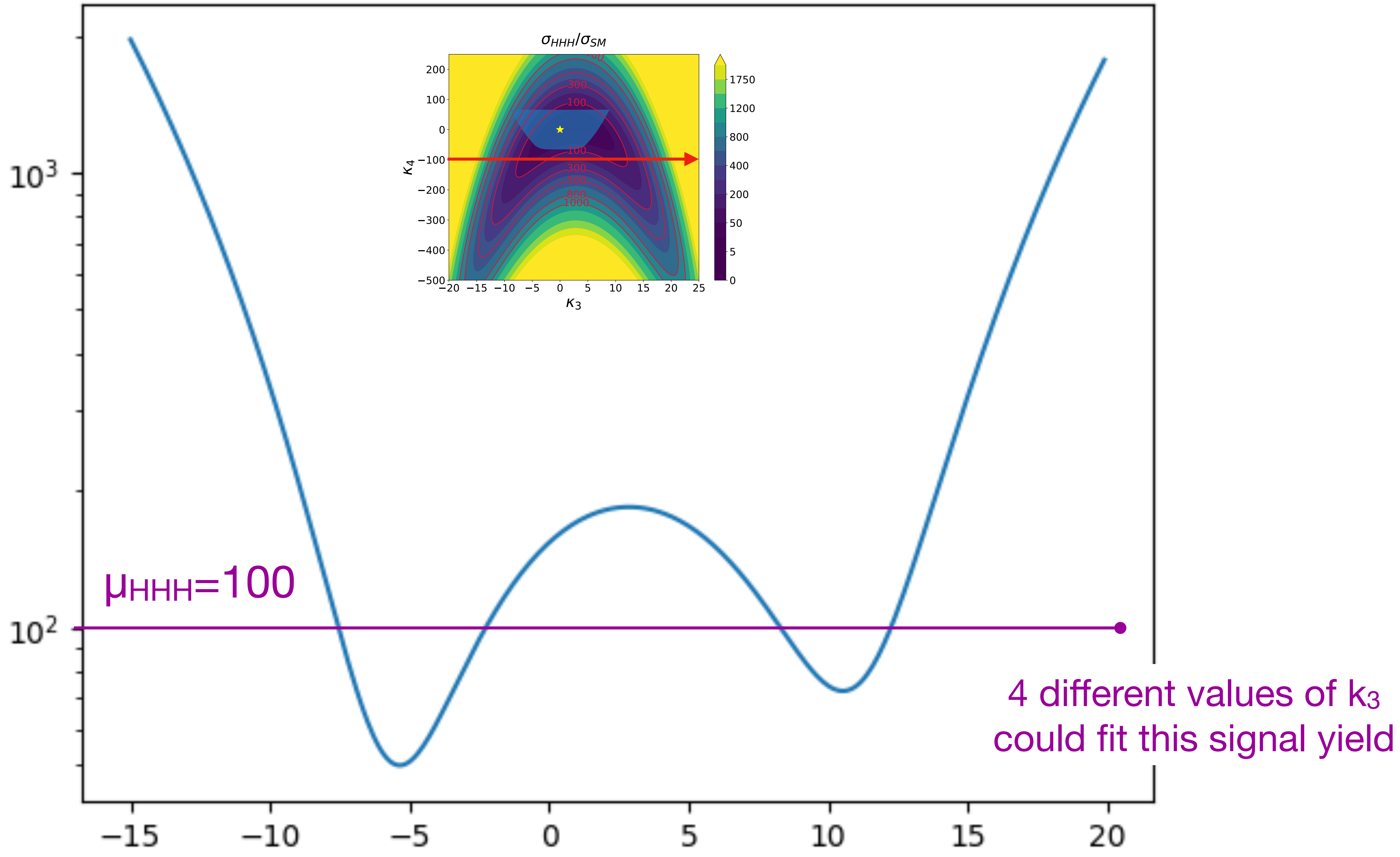
$XS_{min}(k_3=1, k_4)$ → k_4 ~4.5

This complex dependency makes measuring the k_3 and k_4 parameters non trivial

$\sigma_{HHH}(k_3, \mathbf{k_4=1})/\sigma_{HHH}(SM)$

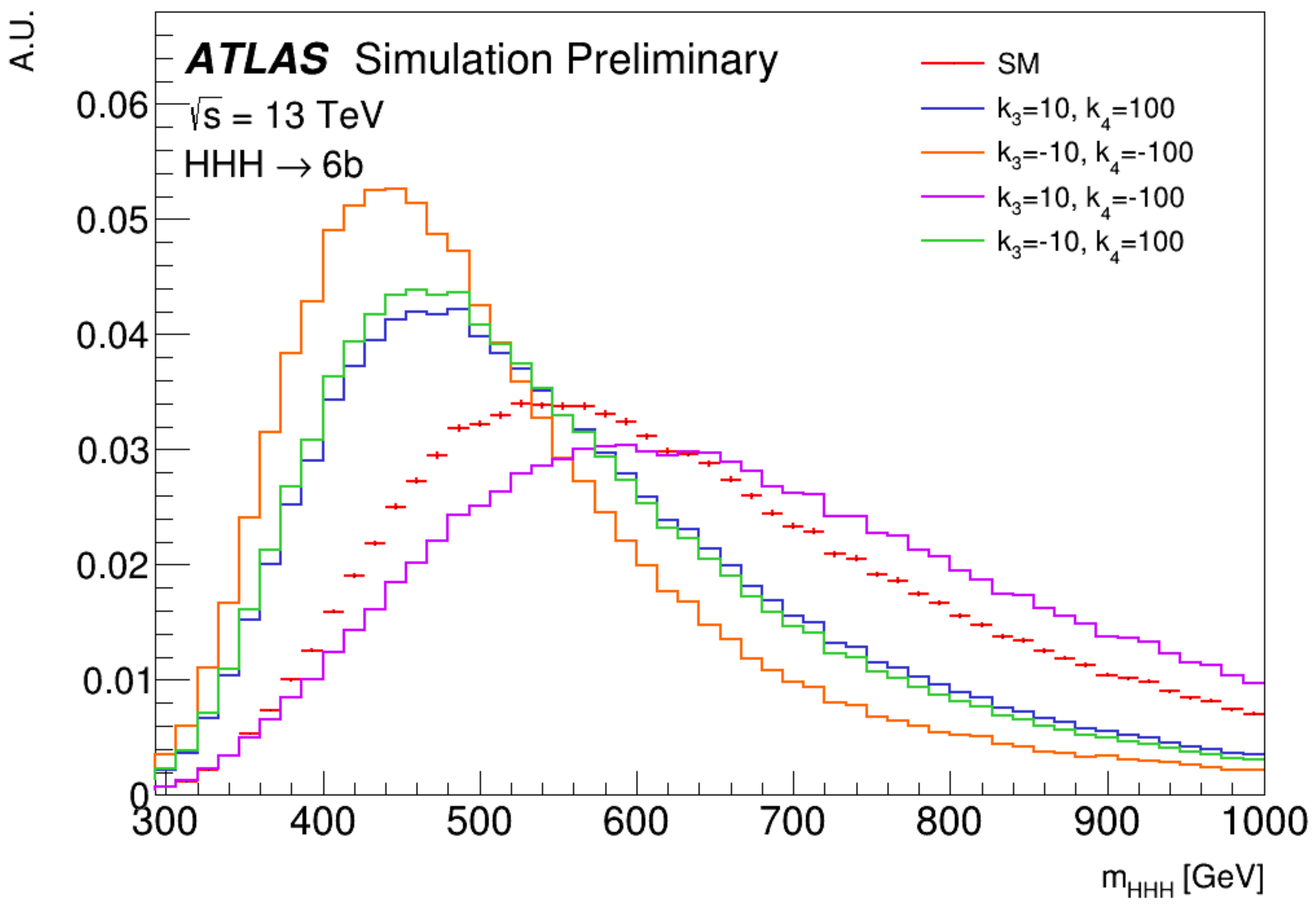


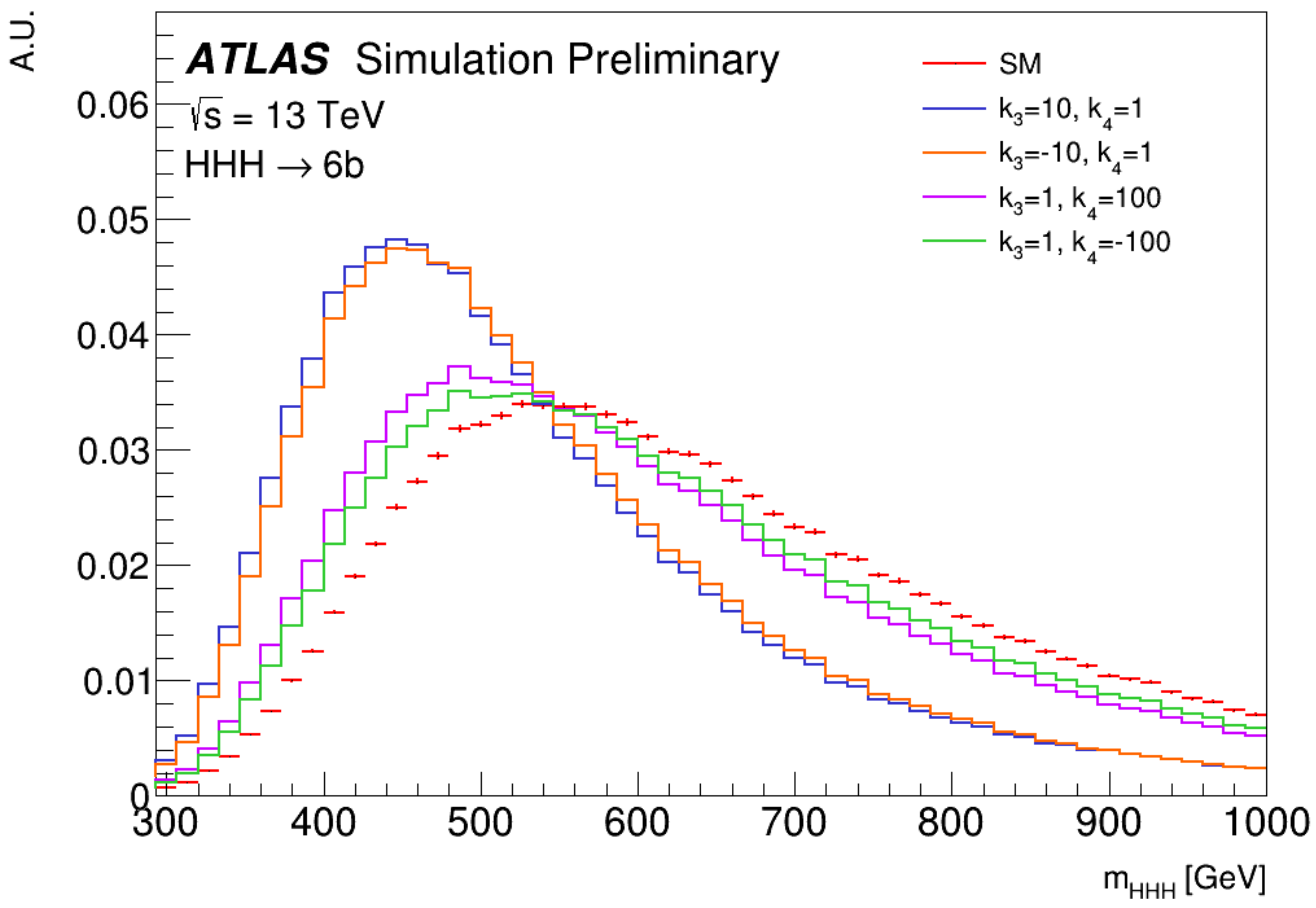
$\sigma_{HHH}(k_3, \mathbf{k_4=-100})/\sigma_{HHH}(SM)$



Our signal scaling with a non-linear function of k_3 and k_4 can create degeneracies if we only rely on the signal-yield and cross-section information: Higgs kinematics can help

Impact of coupling variations on HHH kinematics:





$X \to SH \to HHH \to 6b$

The first ever search of this topology at the LHC!

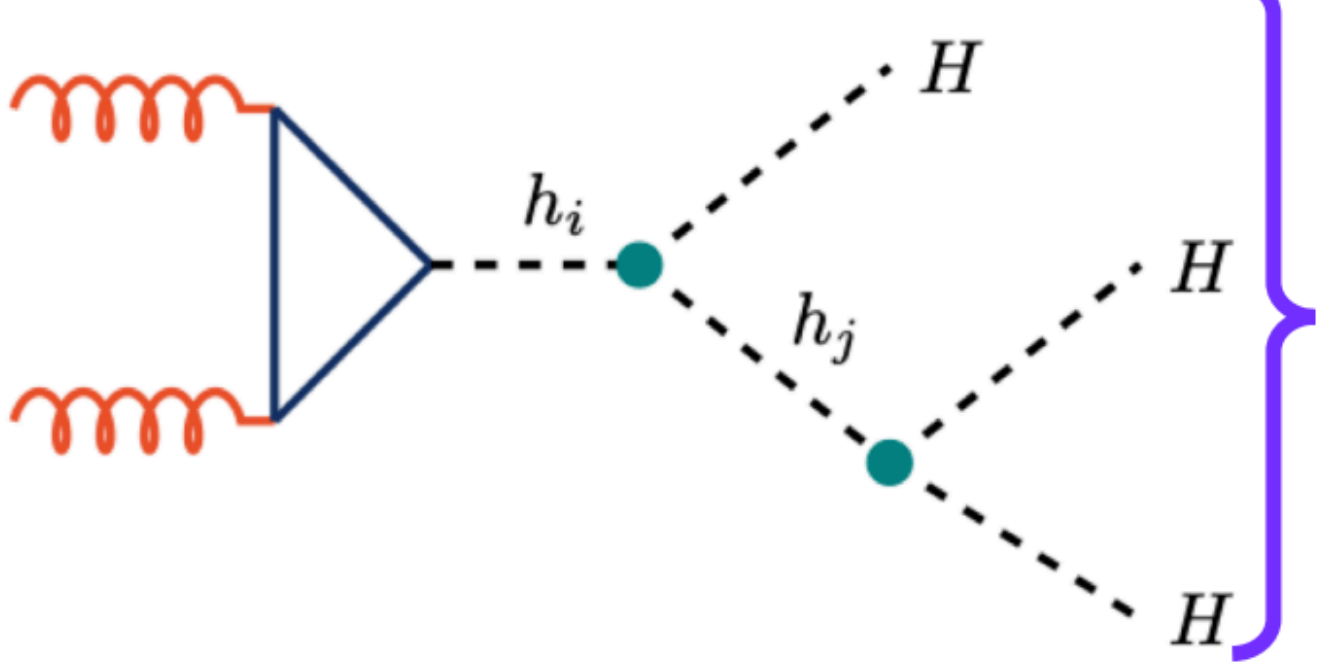
[CERN-EP-2024-285]

Searching for heavy scalars in TRSM

- $325 < m_X < 575$ GeV
- $200 < m_S < 350$ GeV

& generic heavy resonance

- $500 < m_X < 1500$ GeV
- $275 < m_S < 1000$ GeV



New!

6 small-radius *b*-tagged jets from Higgs boson decay

Large # combinatorics: C(6, 2) = 15

- Mass-based method, minimising:

$$|m_{H1} - 120\ \text{GeV}| + |m_{H2} - 115\ \text{GeV}| + |m_{H3} - 110\ \text{GeV}|$$

TRSM HHH production

Resonant – S on-shell ($m_S > 2\ m_H$)

Low m_{HHH}

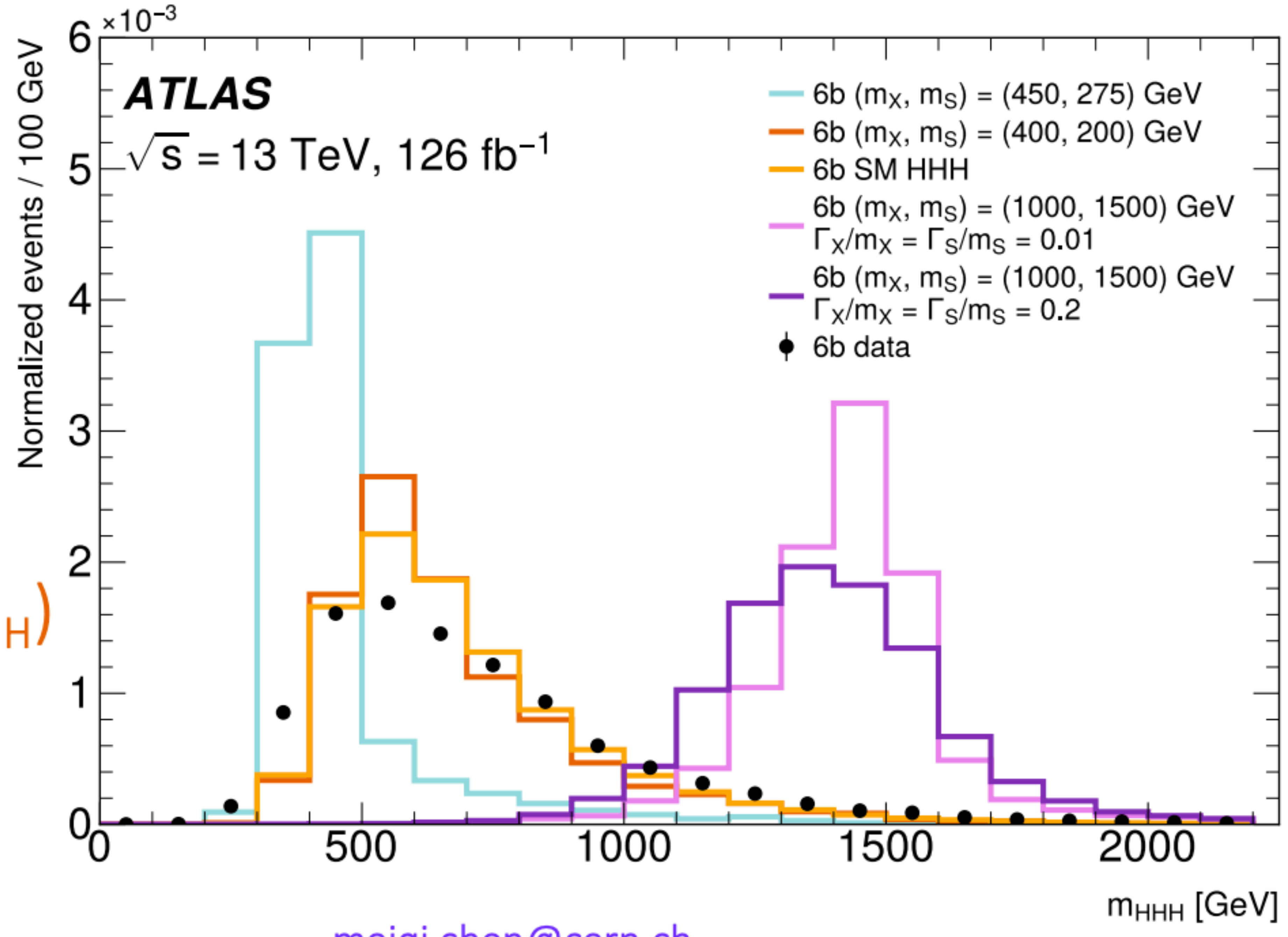
→ low p_T, overlapping *b*-jets

→ more challenging jet pairing

Non-resonant – S off-shell ($m_S \leq 2\ m_H$)

Higher m_{HHH}

More akin to SM HHH production



Heavy resonant production

Highest m_{HHH}

→ boosted, collimated *b*-jets

→ less ambiguity in jet pairing

Slides from Maggie Chen

meiqi.chen@cern.ch

$X \rightarrow SH \rightarrow HHH \rightarrow 6b$

The first ever search of this topology at the LHC!

[CERN-EP-2024-285]

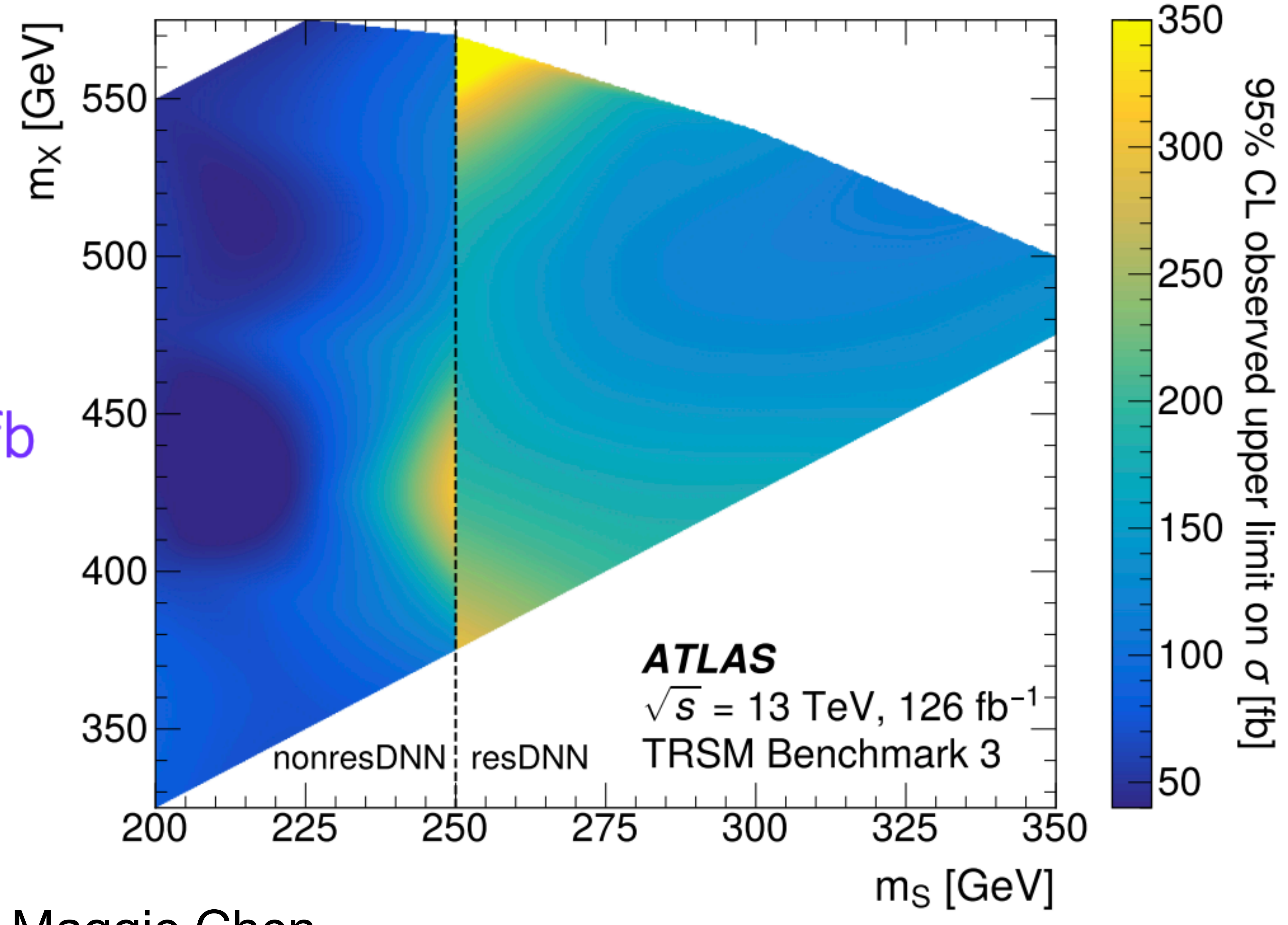
No significant evidence of BSM signals observed

Non-resonant interpretation: constraints placed on the trilinear & quartic Higgs self-coupling modifiers κ_3, κ_4 (see Bill Balunas' talk on non-resonant HH)

Obs. upper limits on

$\sigma_{TRSM}(X \rightarrow SH \rightarrow HHH \rightarrow 6b)$

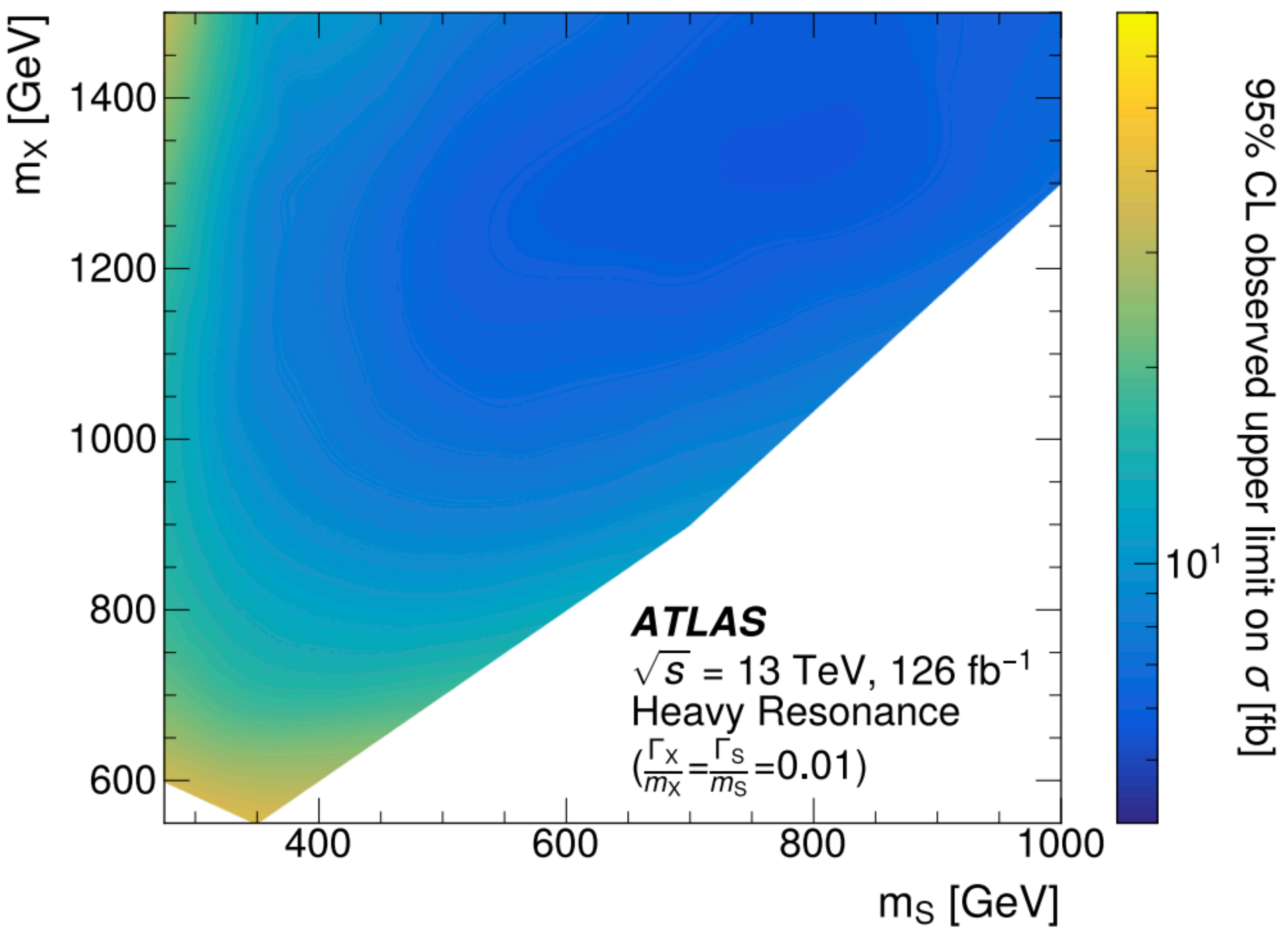
48 – 310 fb



$\sigma_{Heavy\ resonance}(X \rightarrow SH \rightarrow HHH \rightarrow 6b)$

5.7 – 38 fb

New!

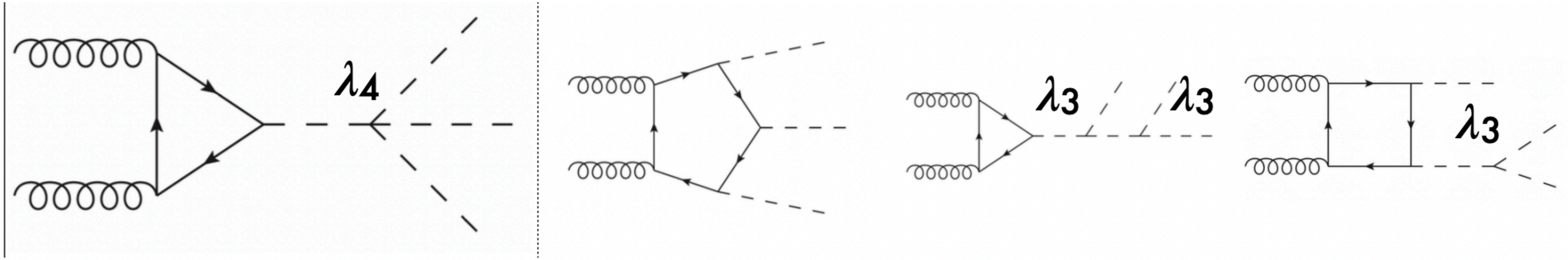


Slides from Maggie Chen

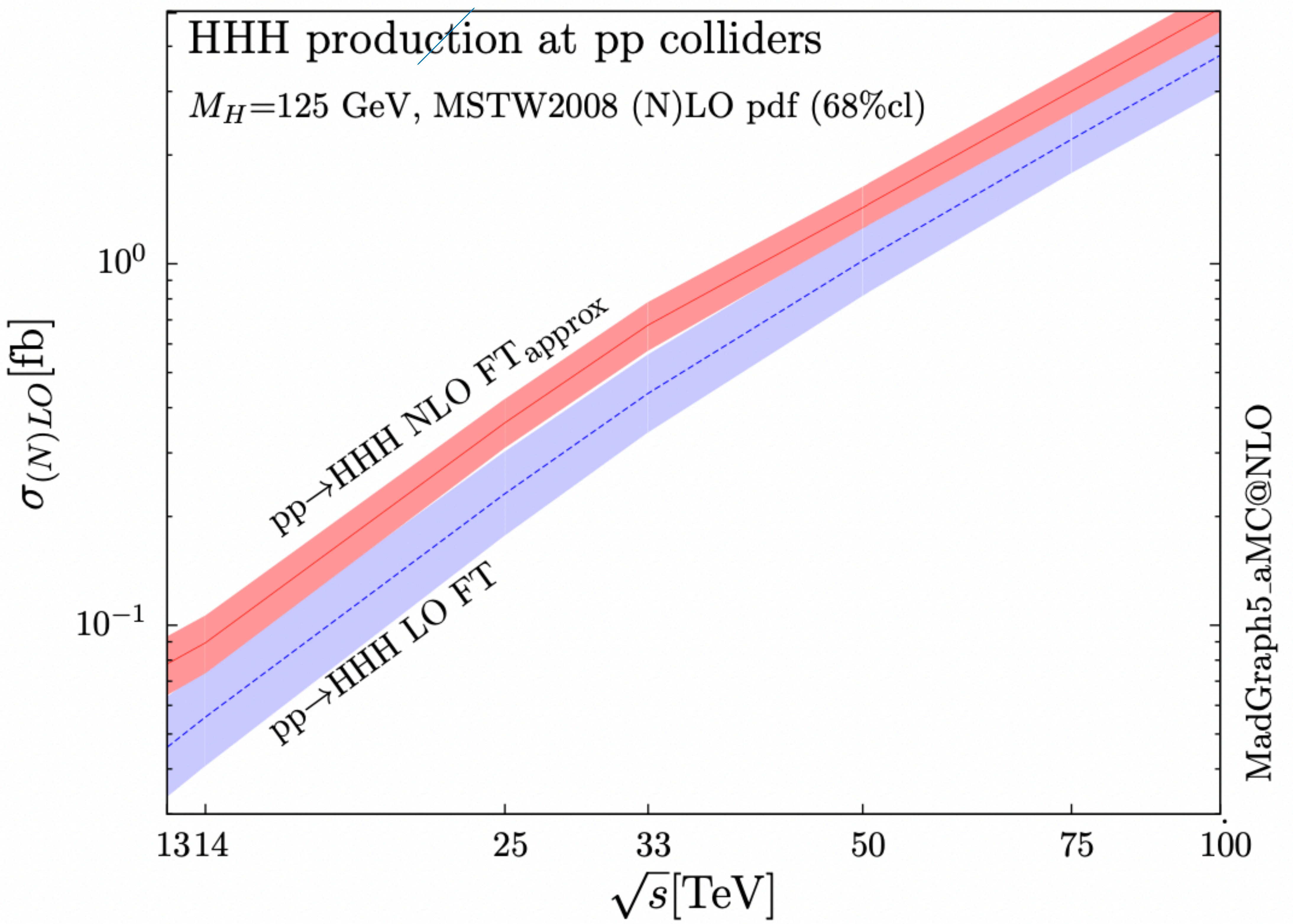
HHH signal phenomenology

back-up

Triple Higgs

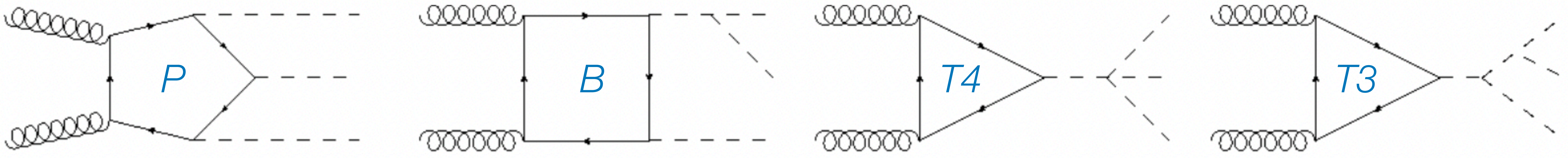


$\sigma(HHH)$ [fb]	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33$ TeV	$\sqrt{s} = 100$ TeV
LO FT	$0.0557\ ^{+34.5+2.5\%}_{-24.0-2.7\%}$	$0.438\ ^{+26.8+1.5\%}_{+20.0-2.0\%}$	$3.78\ ^{+24.1+0.9\%}_{-18.7-1.7\%}$
NLO $\mathrm{FT_{approx}}$	$0.0894^{+16.5+2.5\%}_{-14.6-3.2\%}$	$0.677\ ^{+14.5+1.4\%}_{-13.4-1.7\%}$	$5.09\ ^{+13.5+1.0\%}_{-12.7-1.3\%}$

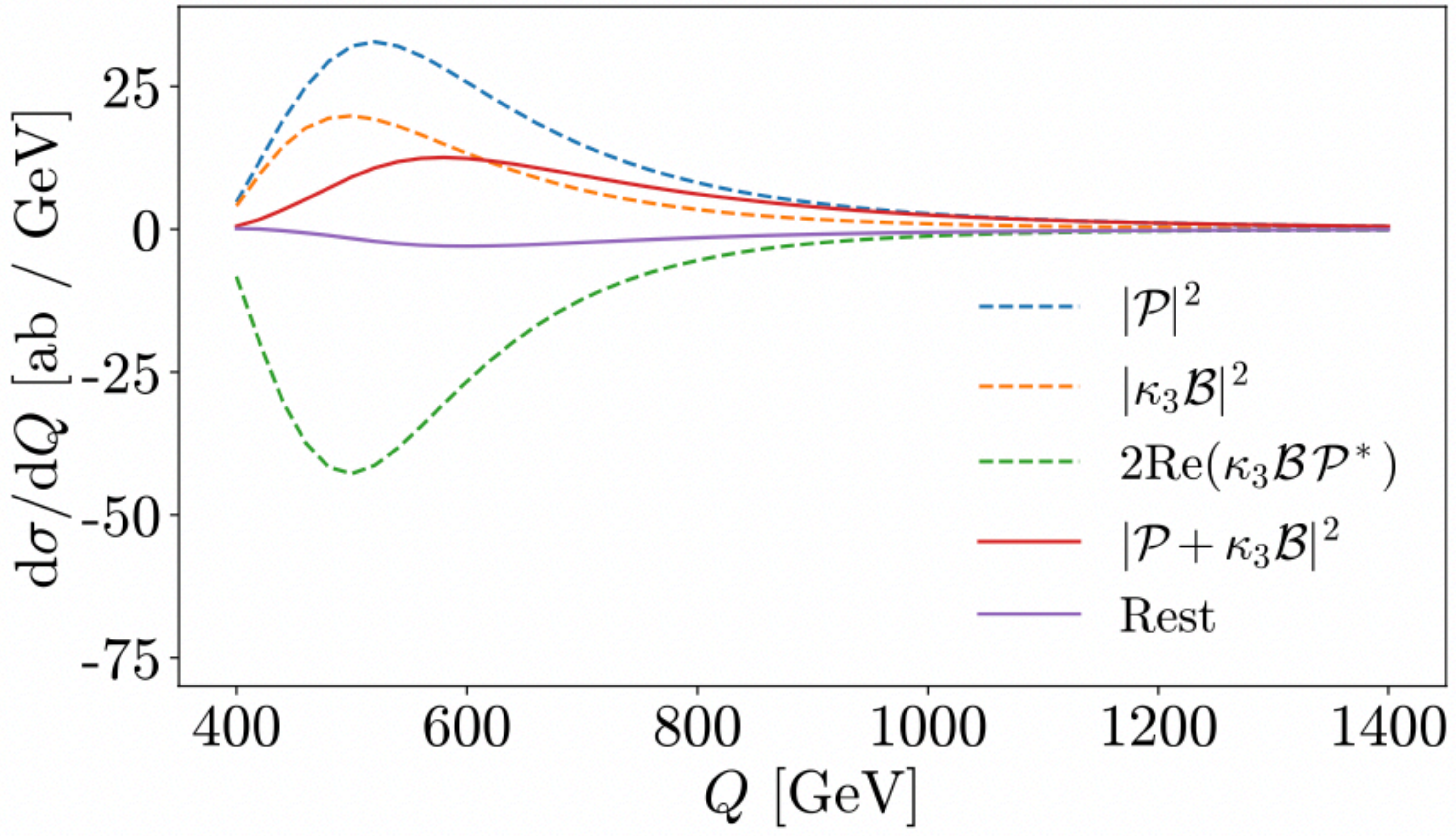


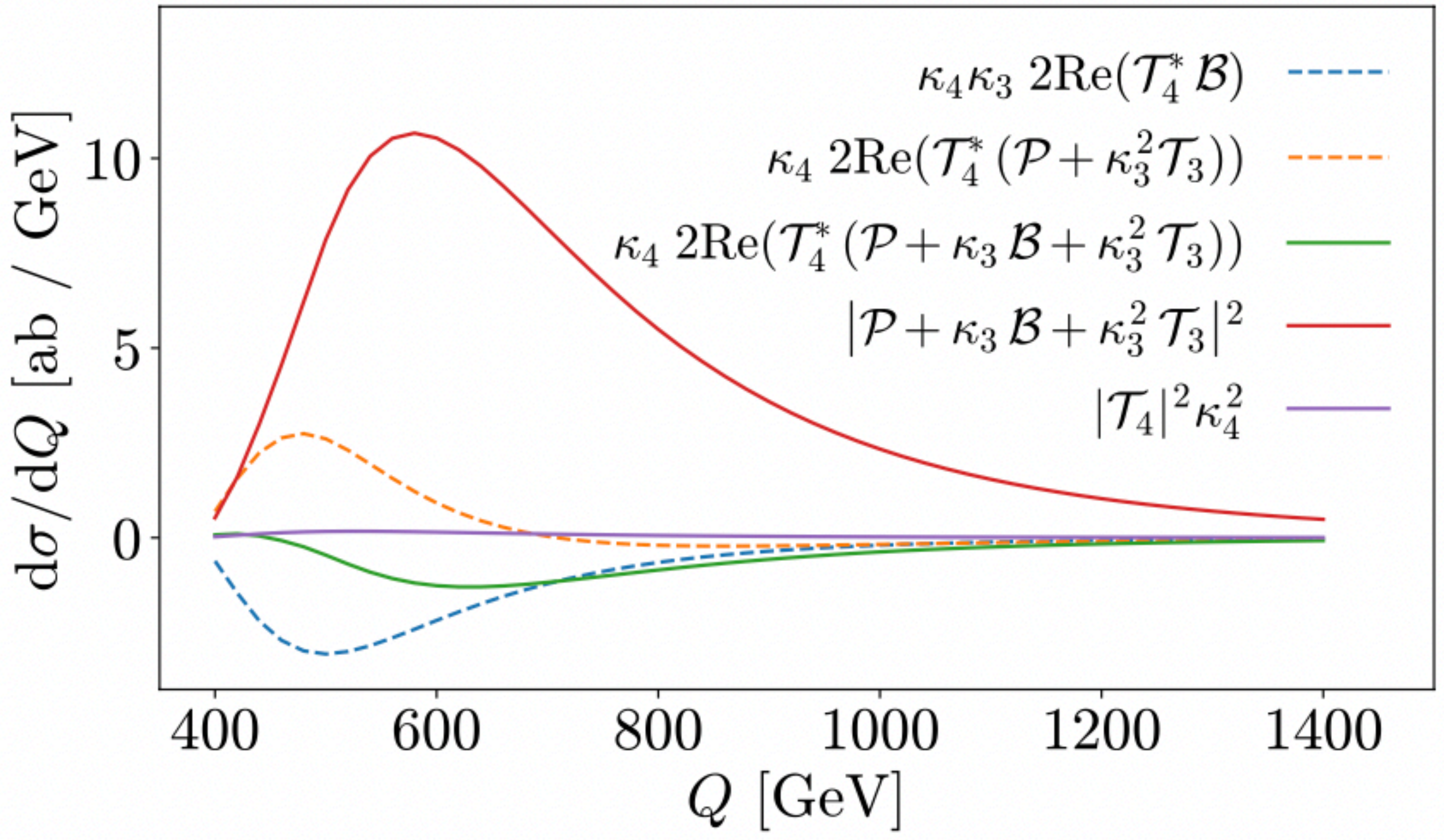
HHH signal phenomenology

back-up

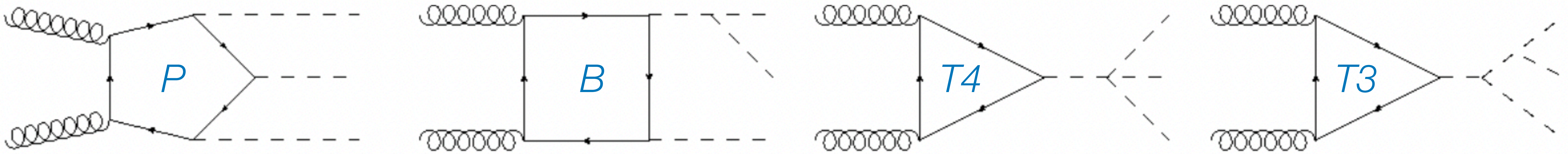


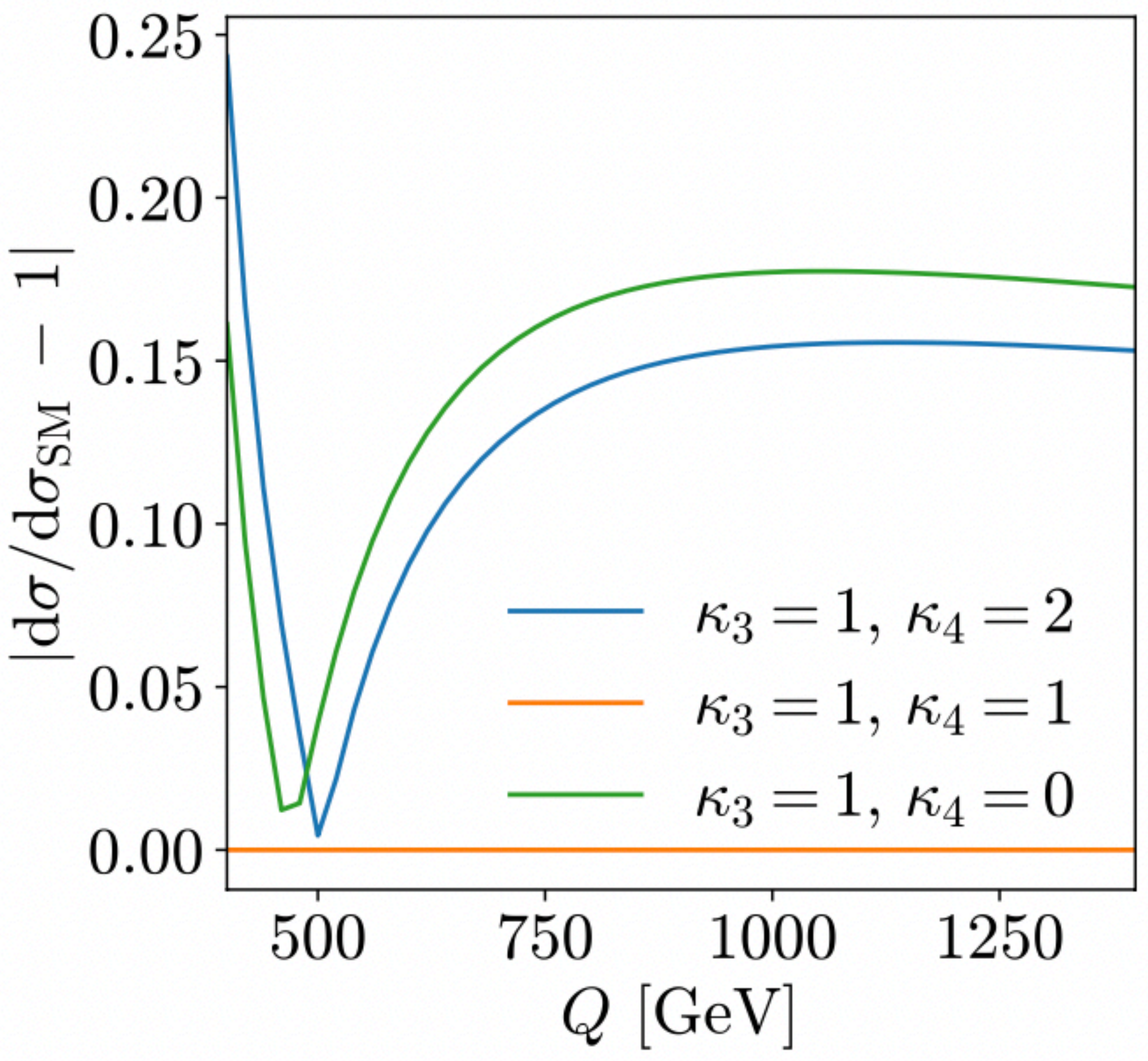
$$\mathcal{M} = \mathcal{P} + \kappa_3\,\mathcal{B} + \kappa_3^2\,\mathcal{T}_3 + \kappa_4\,\mathcal{T}_4.$$

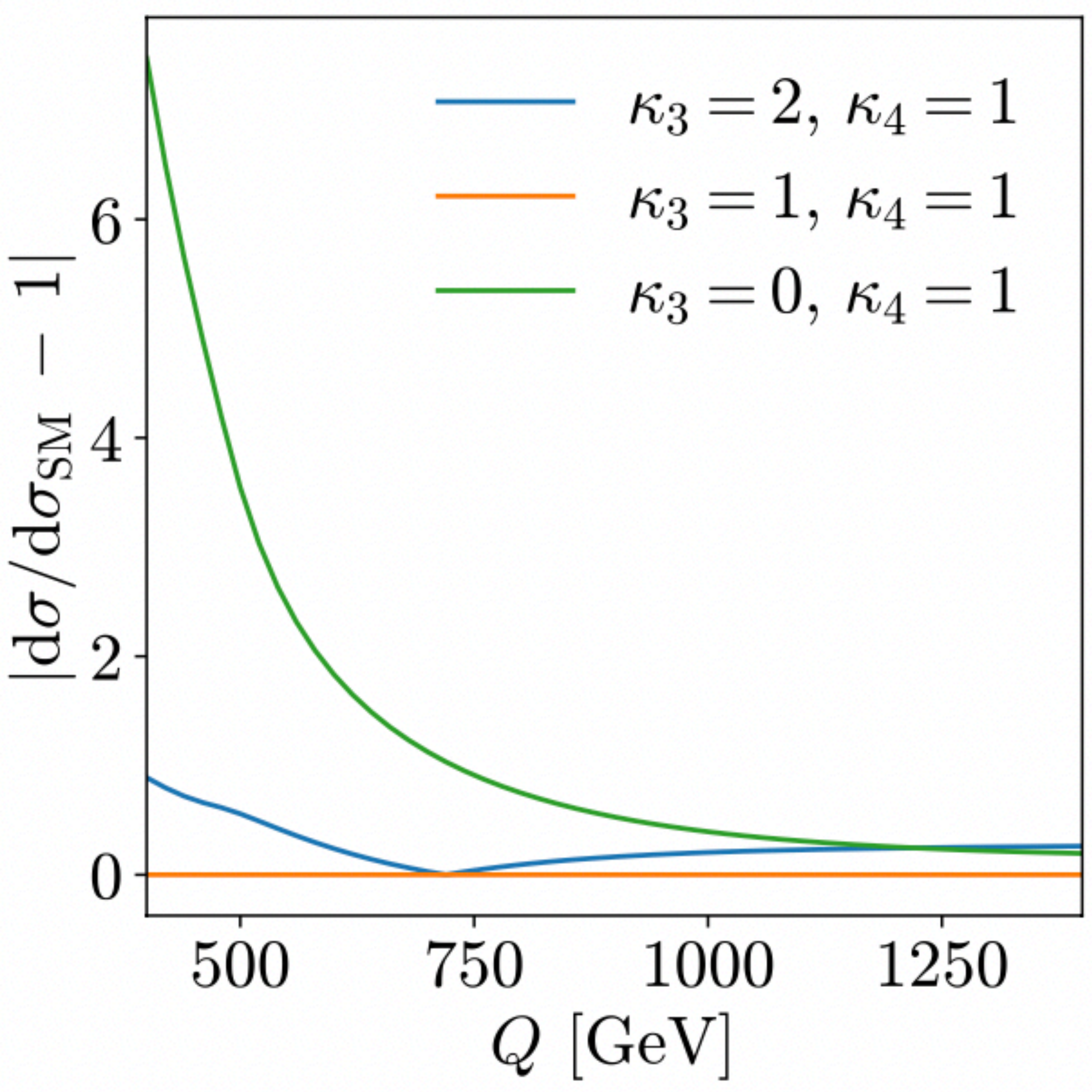


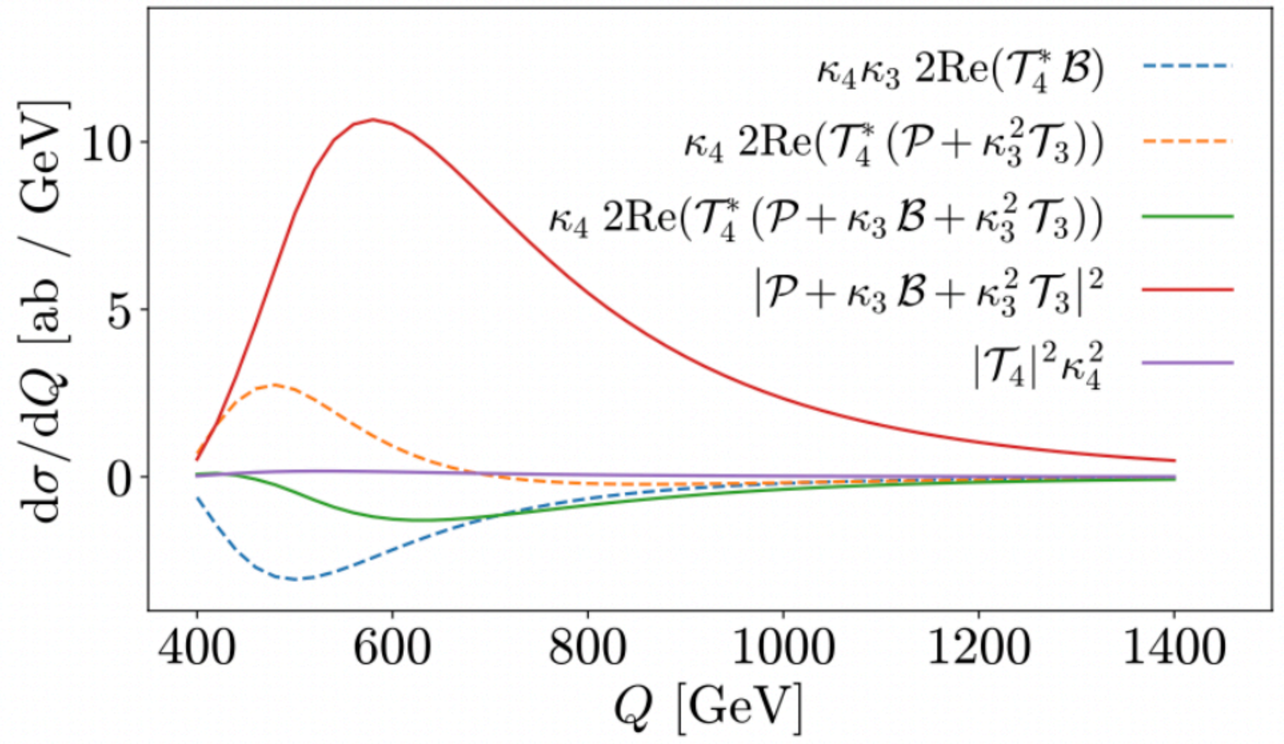


HHH signal phenomenology







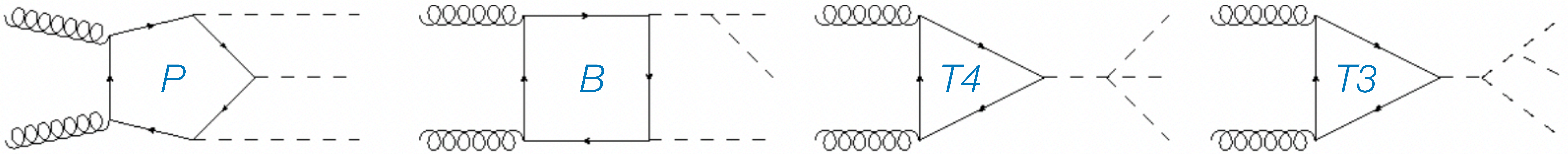


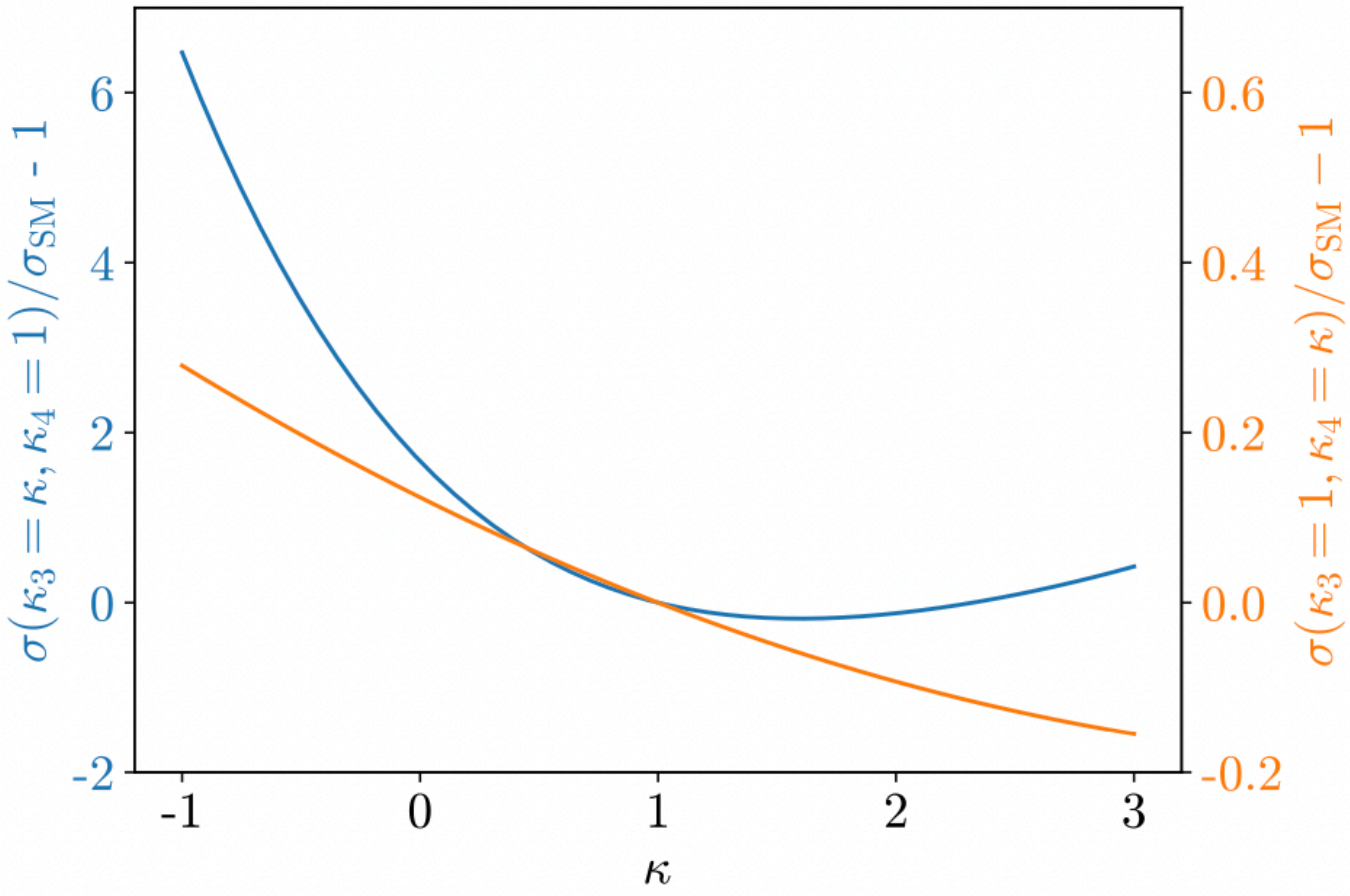
quartic sensitivity when P and B are smallest:
production threshold (low mHHH) and high tails (large mHHH)

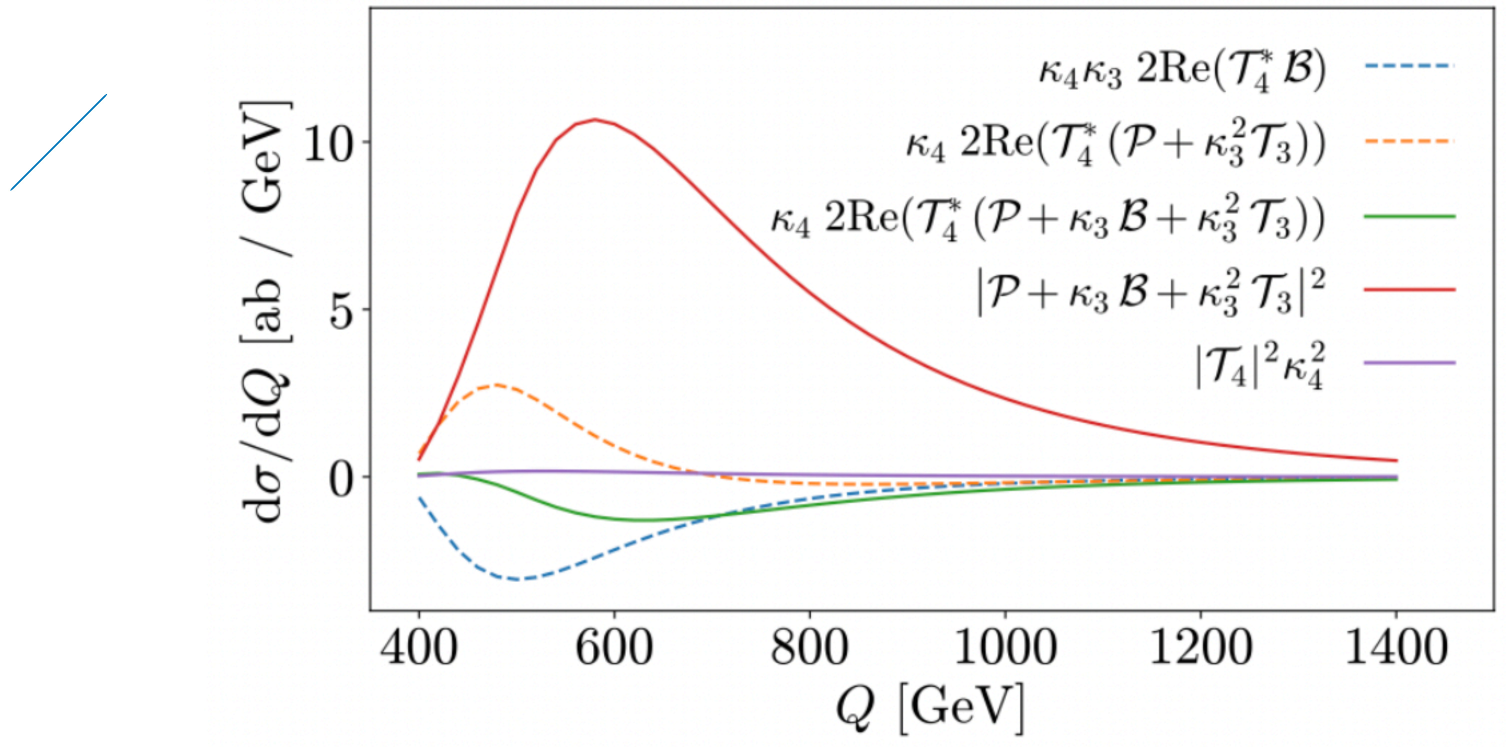
trilinear sensitivity rather large

thanks to spoiling of the cancellation effects

HHH signal phenomenology





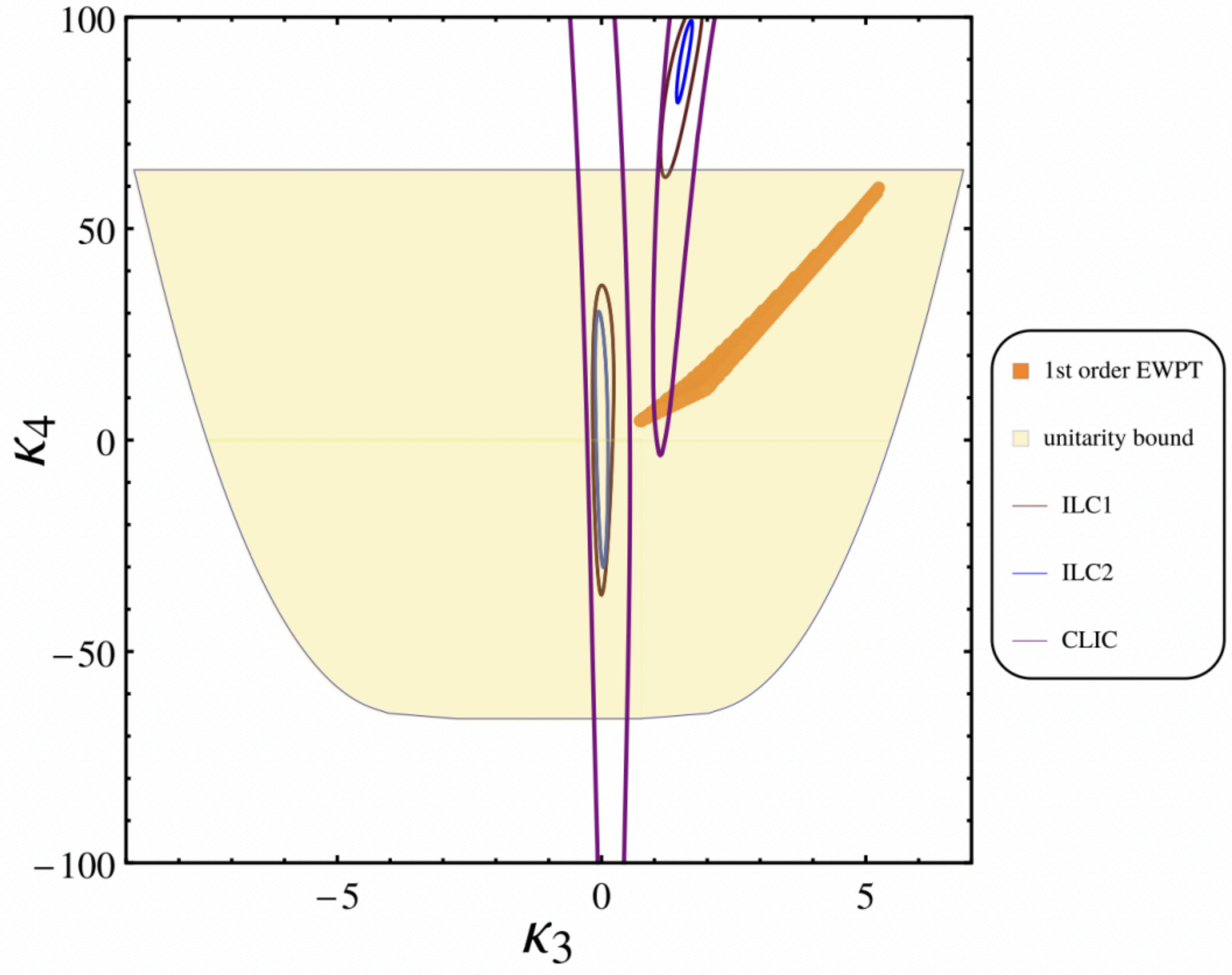


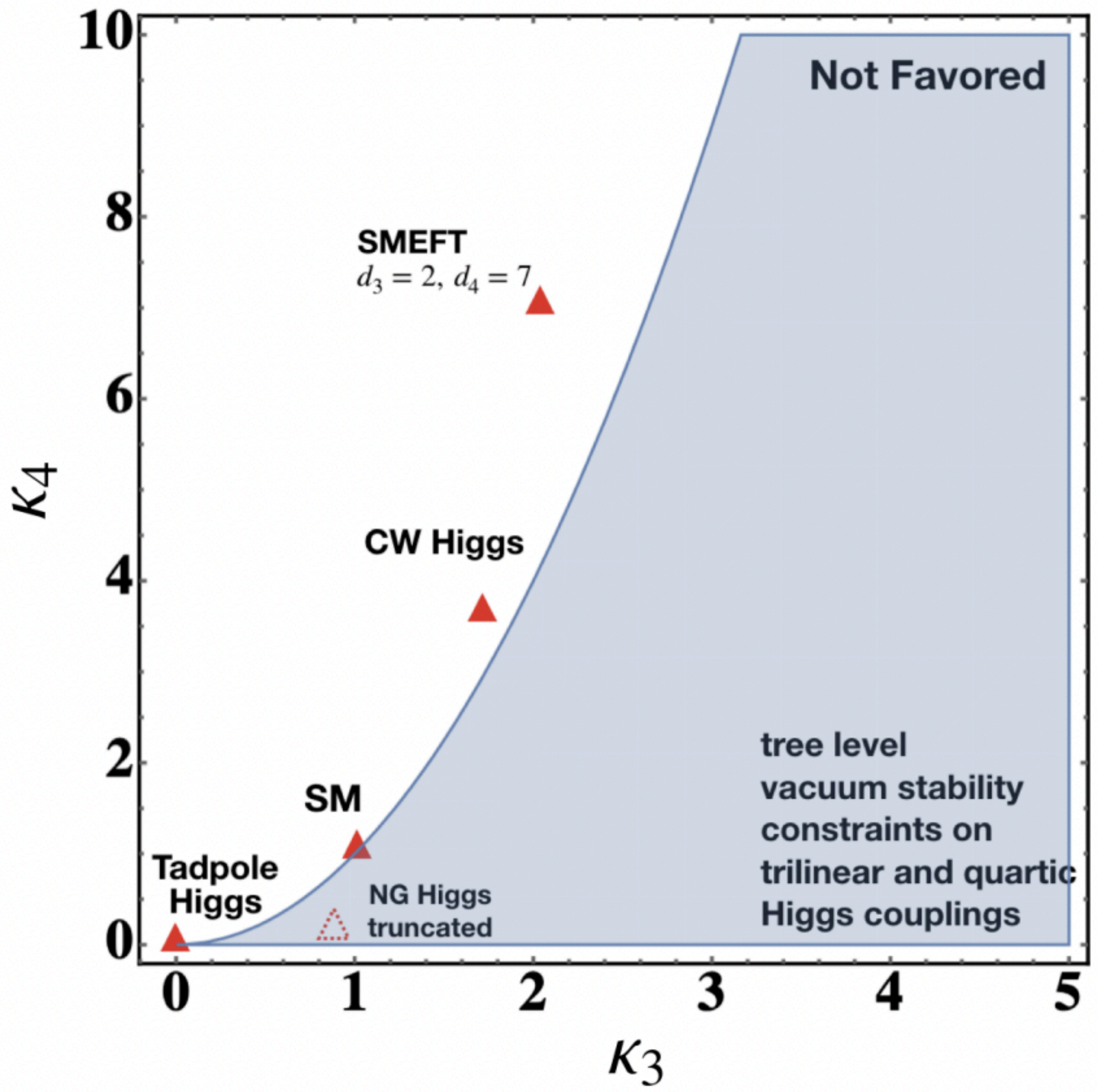
quartic sensitivity when P and B are smallest:
production threshold (low mHHH) and high tails (large mHHH)

trilinear sensitivity rather large

thanks to spoiling of the cancellation effects

Unitarity Bounds



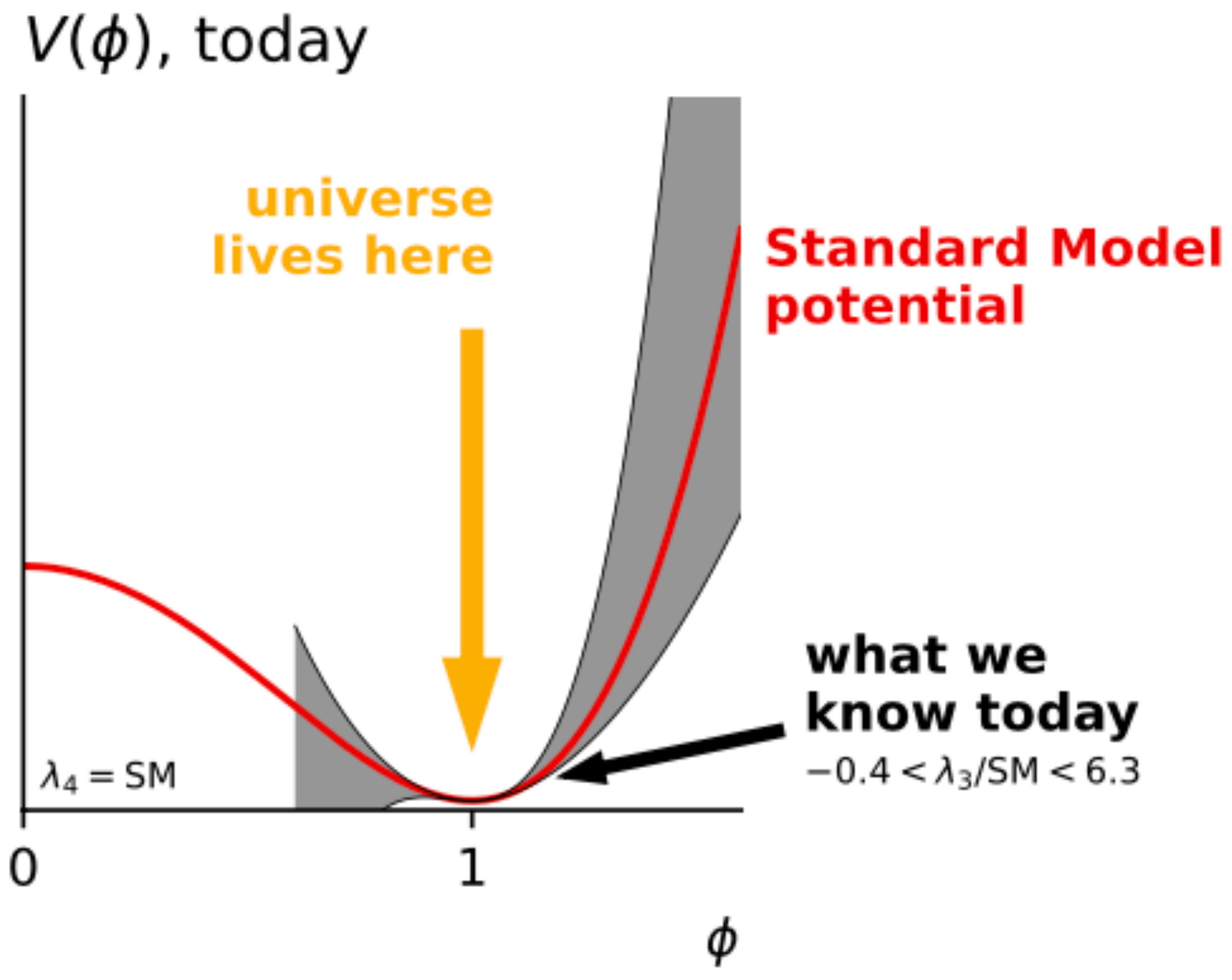


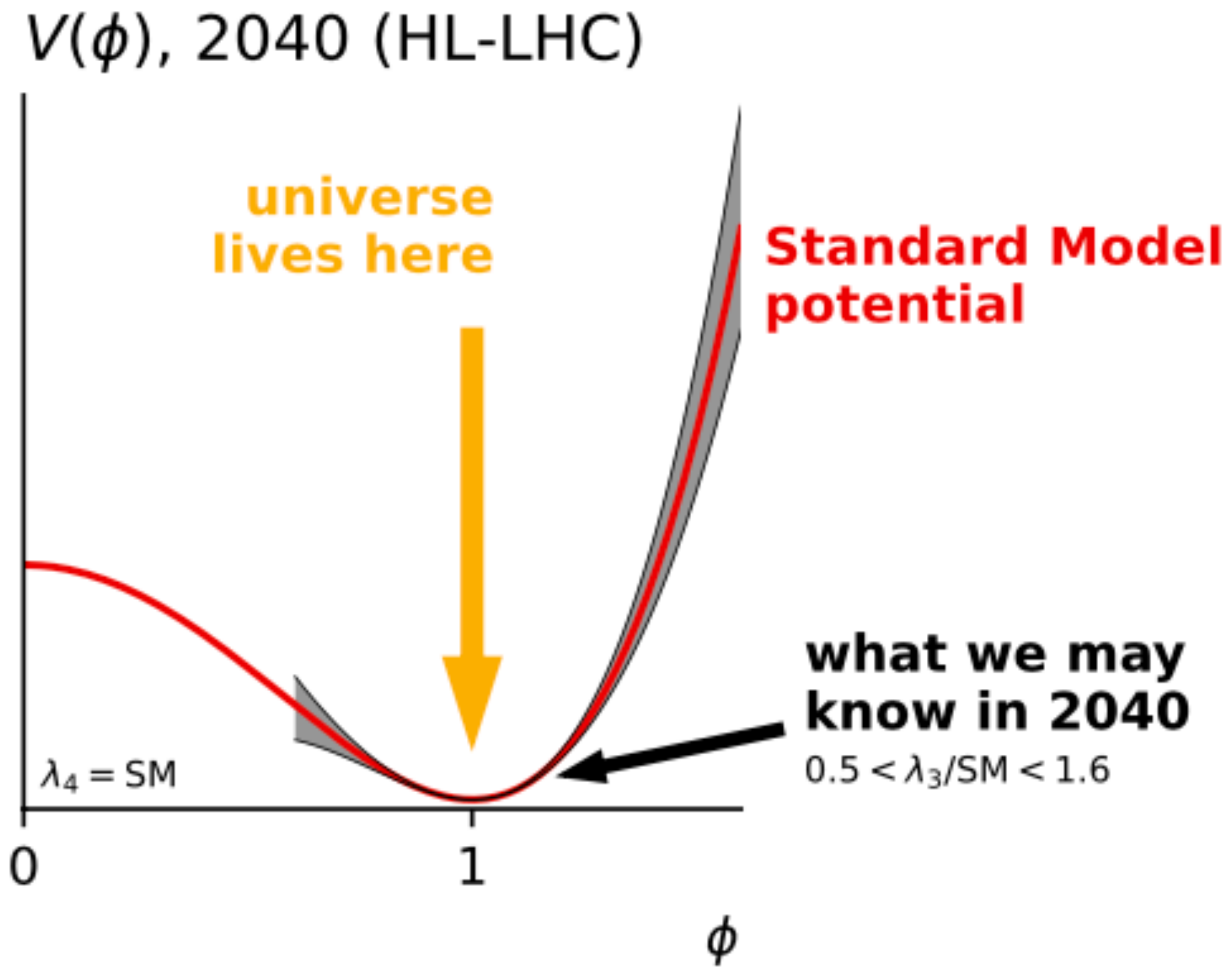
$|\kappa_3\ (= \kappa_\lambda)| \lesssim 6$ from unitarity bounds
[slight dependence on κ_4]

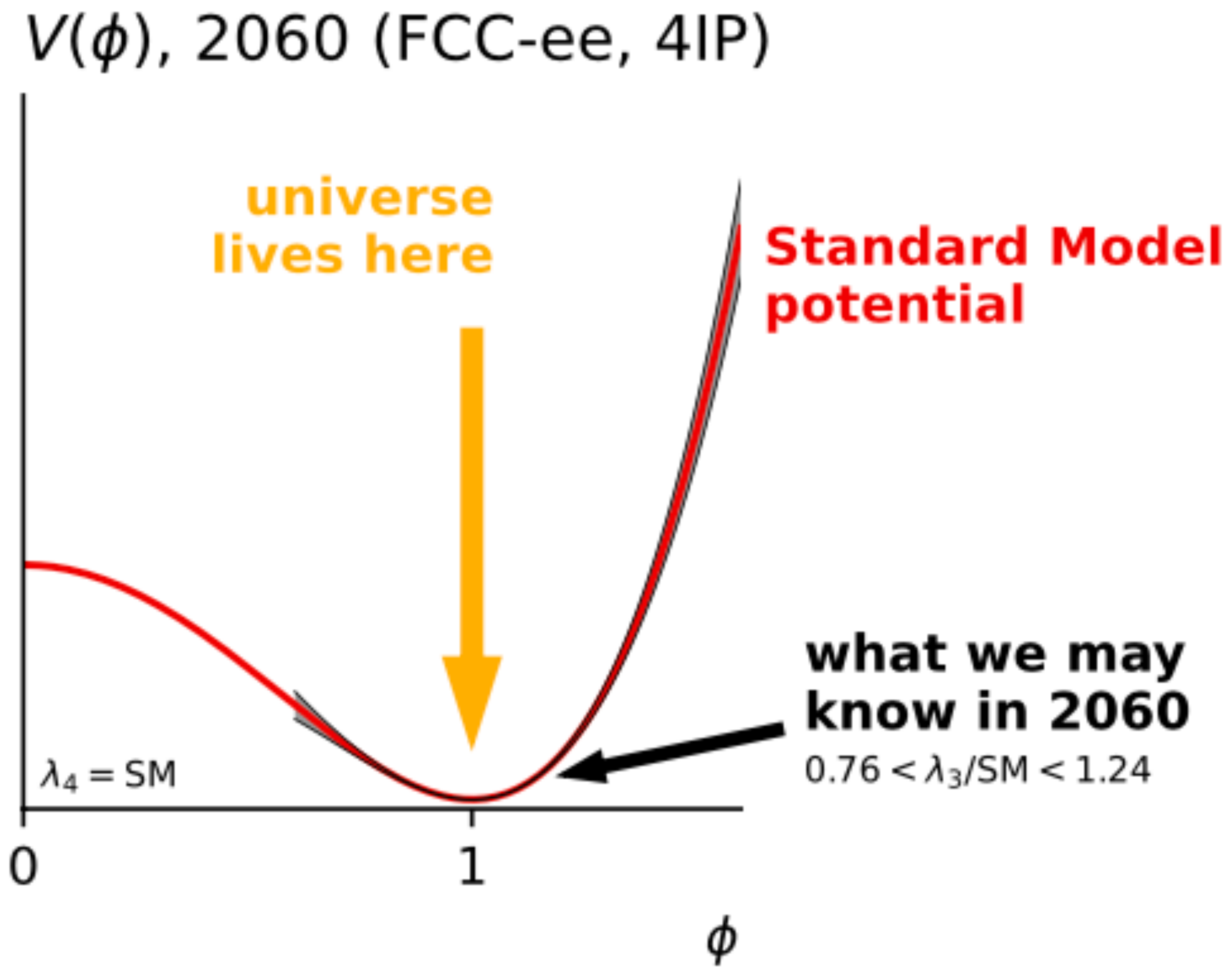
https://arxiv.org/abs/2312.04646

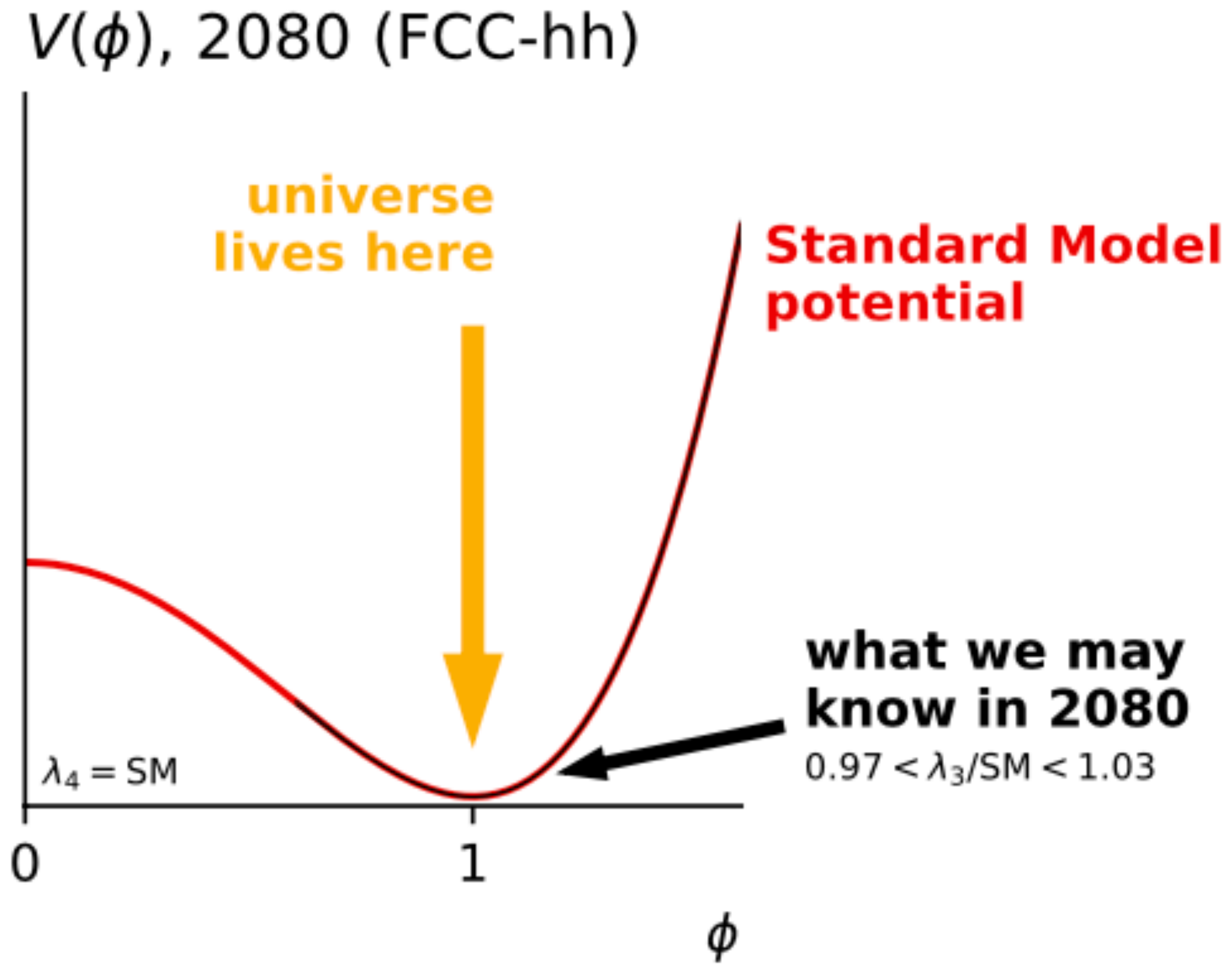
vacuum stability poses conditions on the relationship between κ_3 and κ_4
→ interesting in case we see deviations

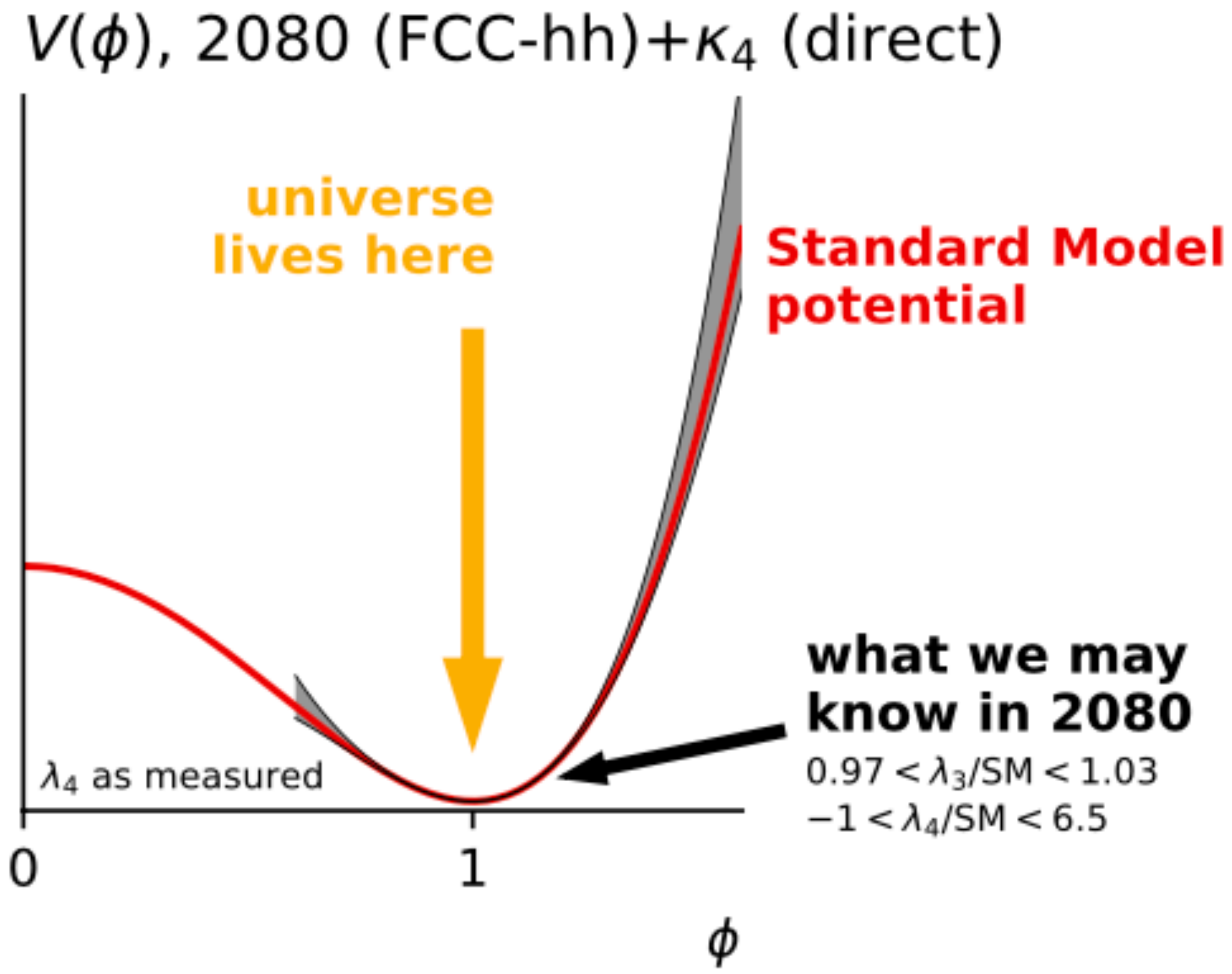
The Higgs Potential





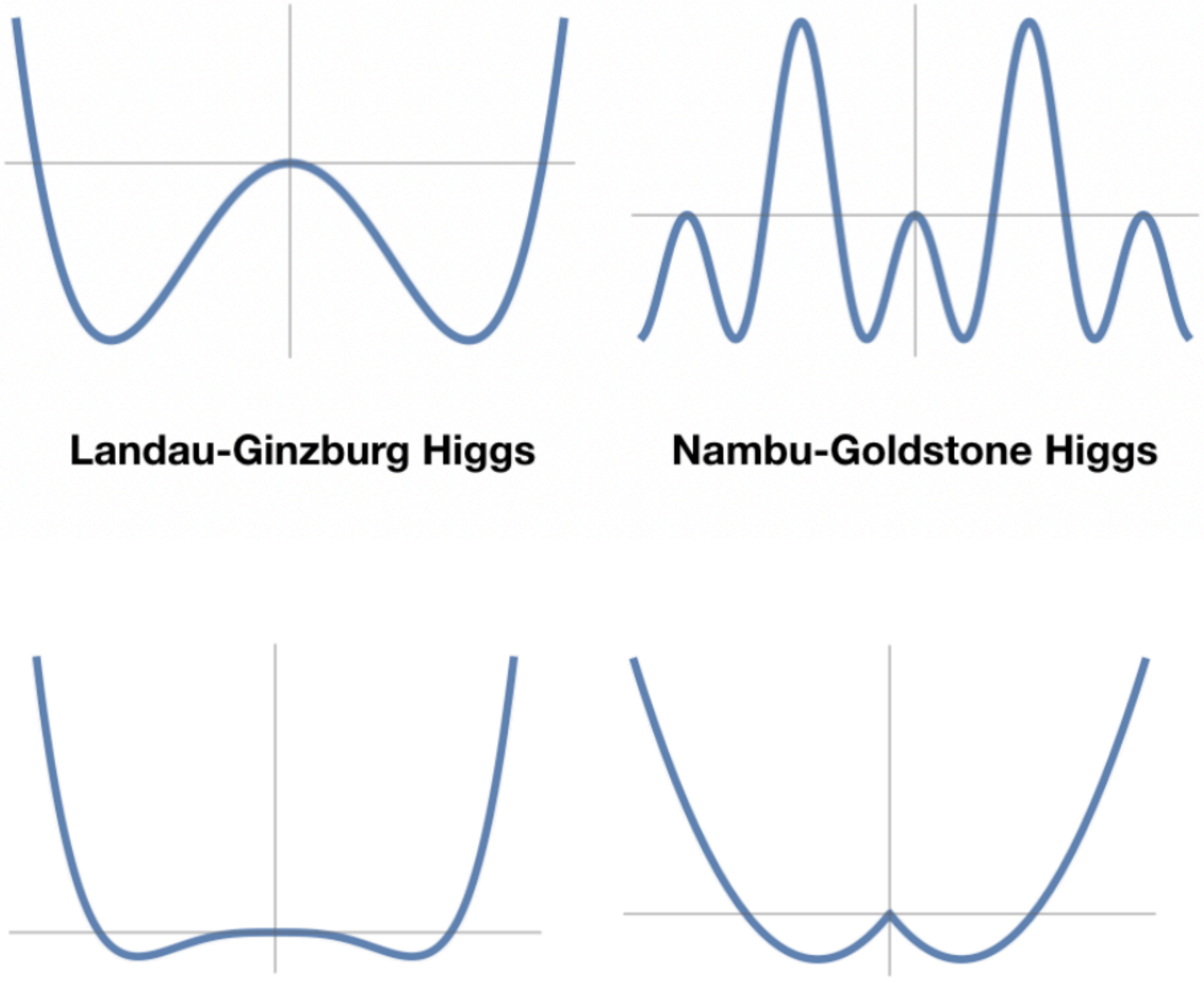






The Higgs Potential

The Higgs Potential in QFT textbooks of the future
(might still be the Standard Model realisation)

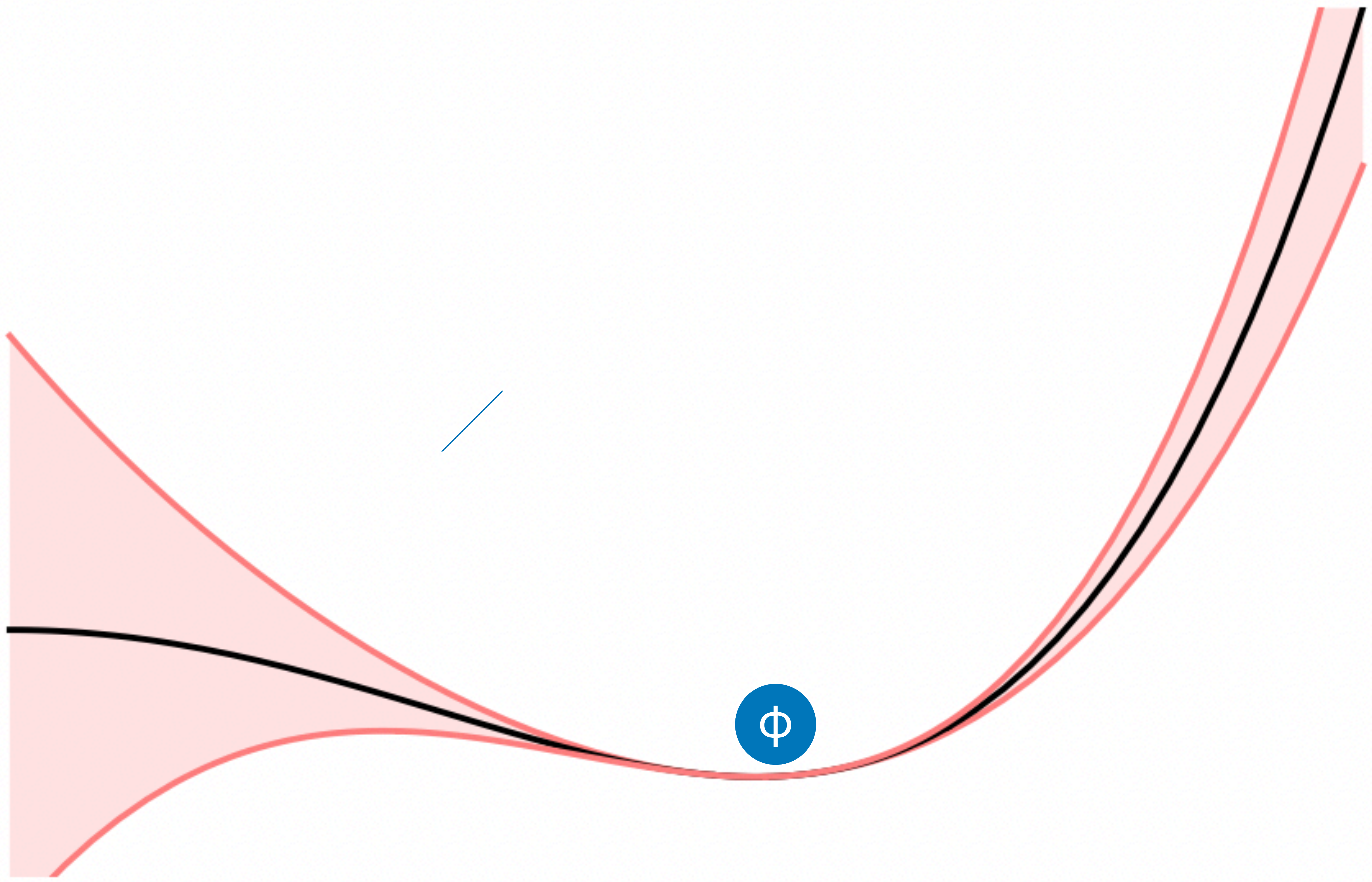


Landau-Ginzburg Higgs

Nambu-Goldstone Higgs

Coleman-Weinberg Higgs

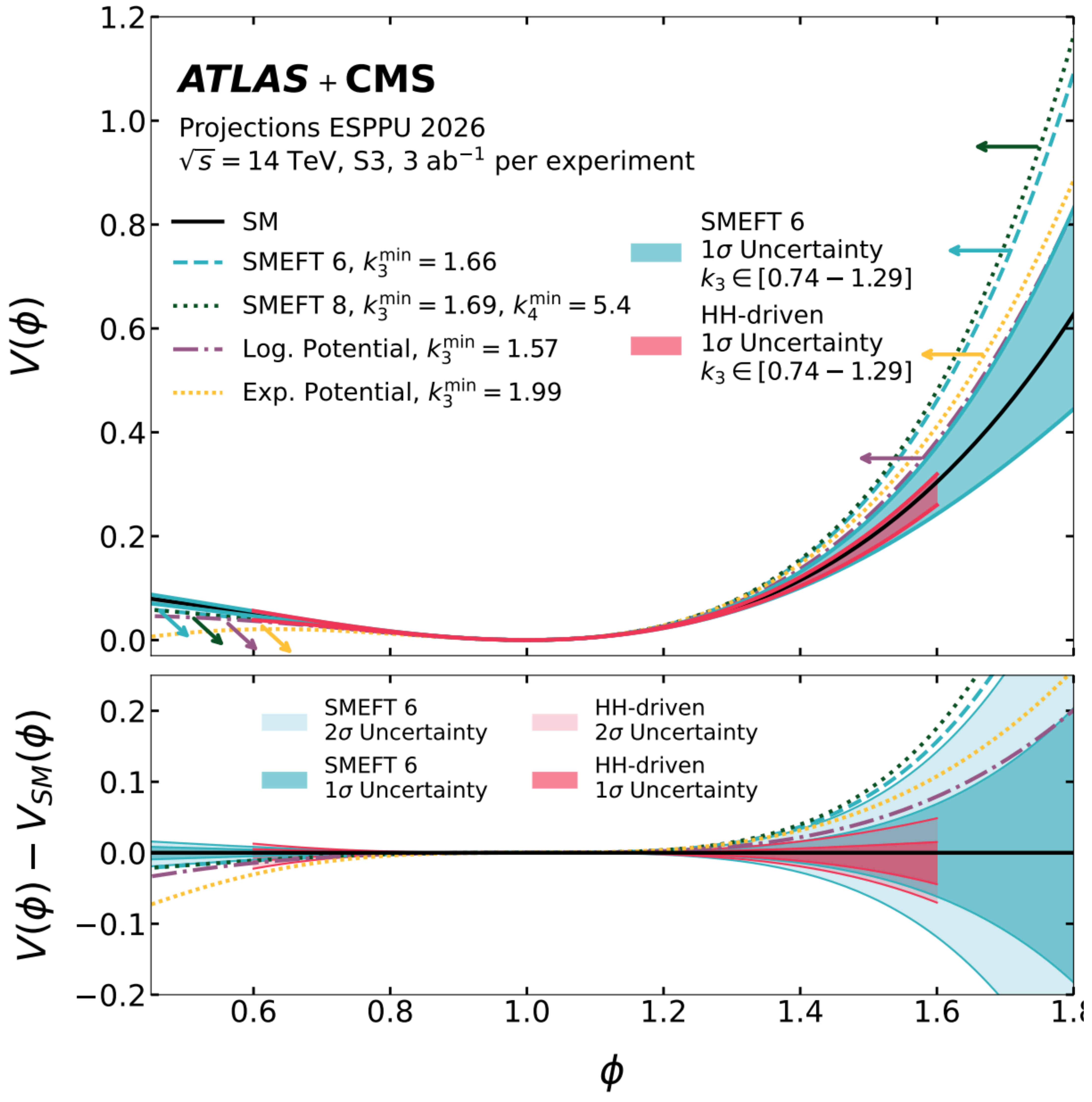
Tadpole-Induced Higgs

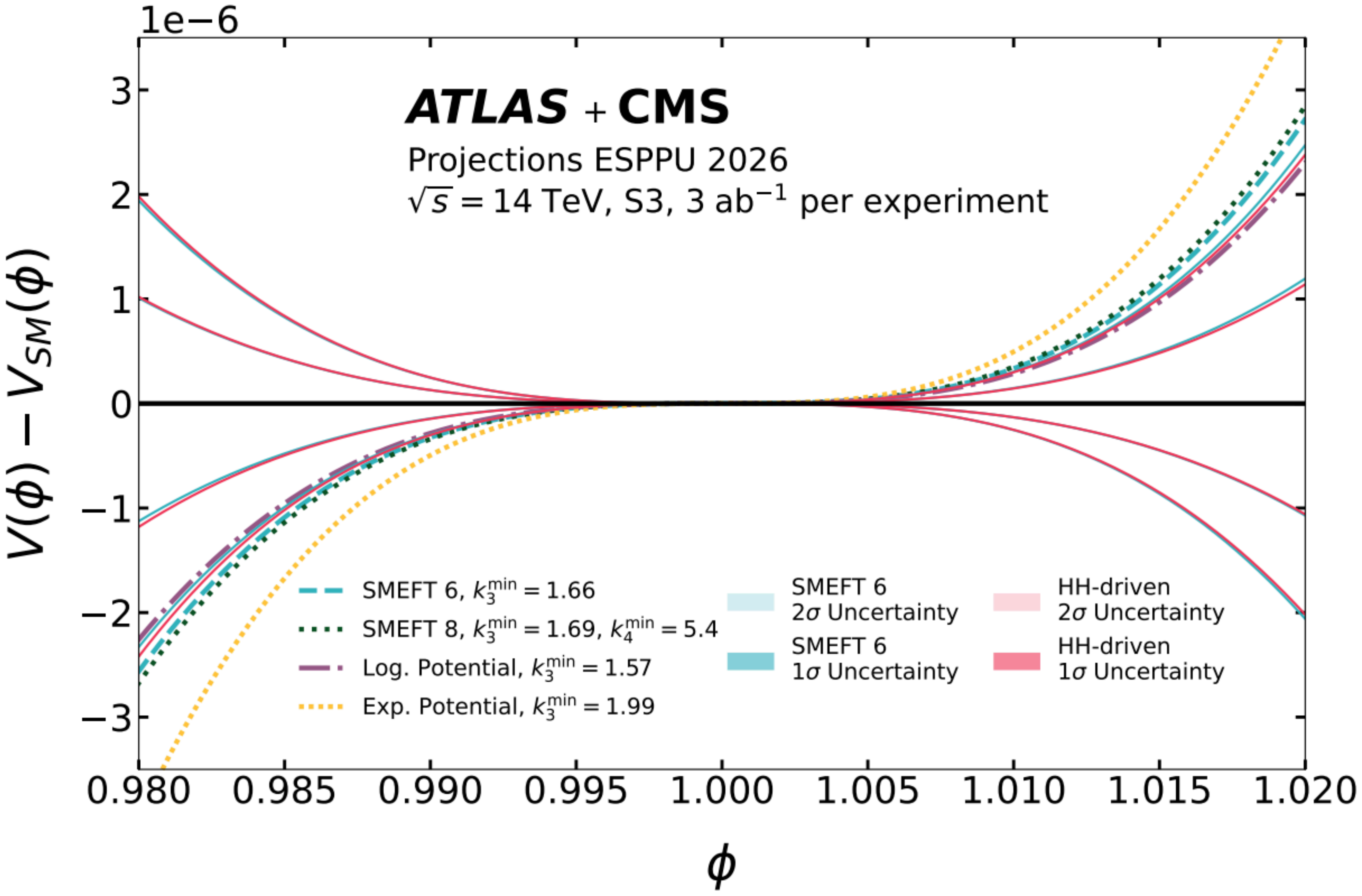


1907.02078

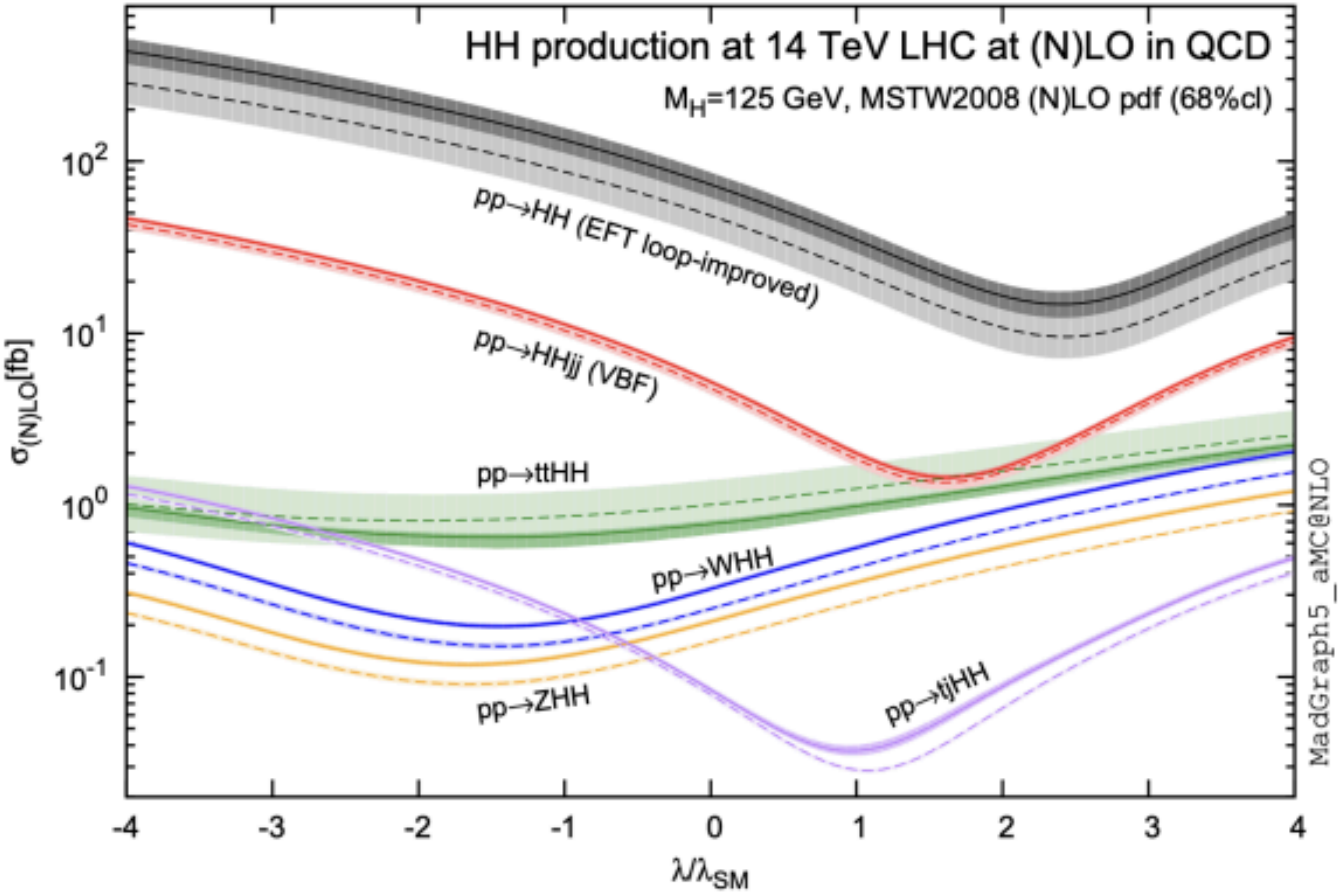
The Higgs Potential

ESU ATLAS & CMS 2025



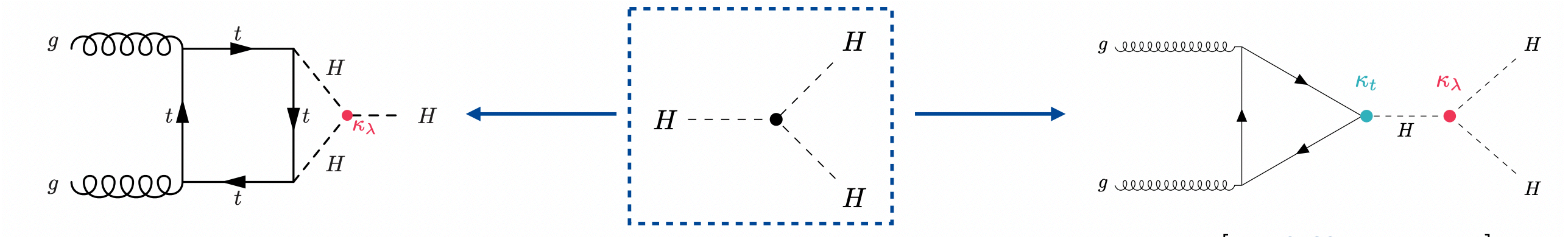


HH signal phenomenology: HH Cross-Section



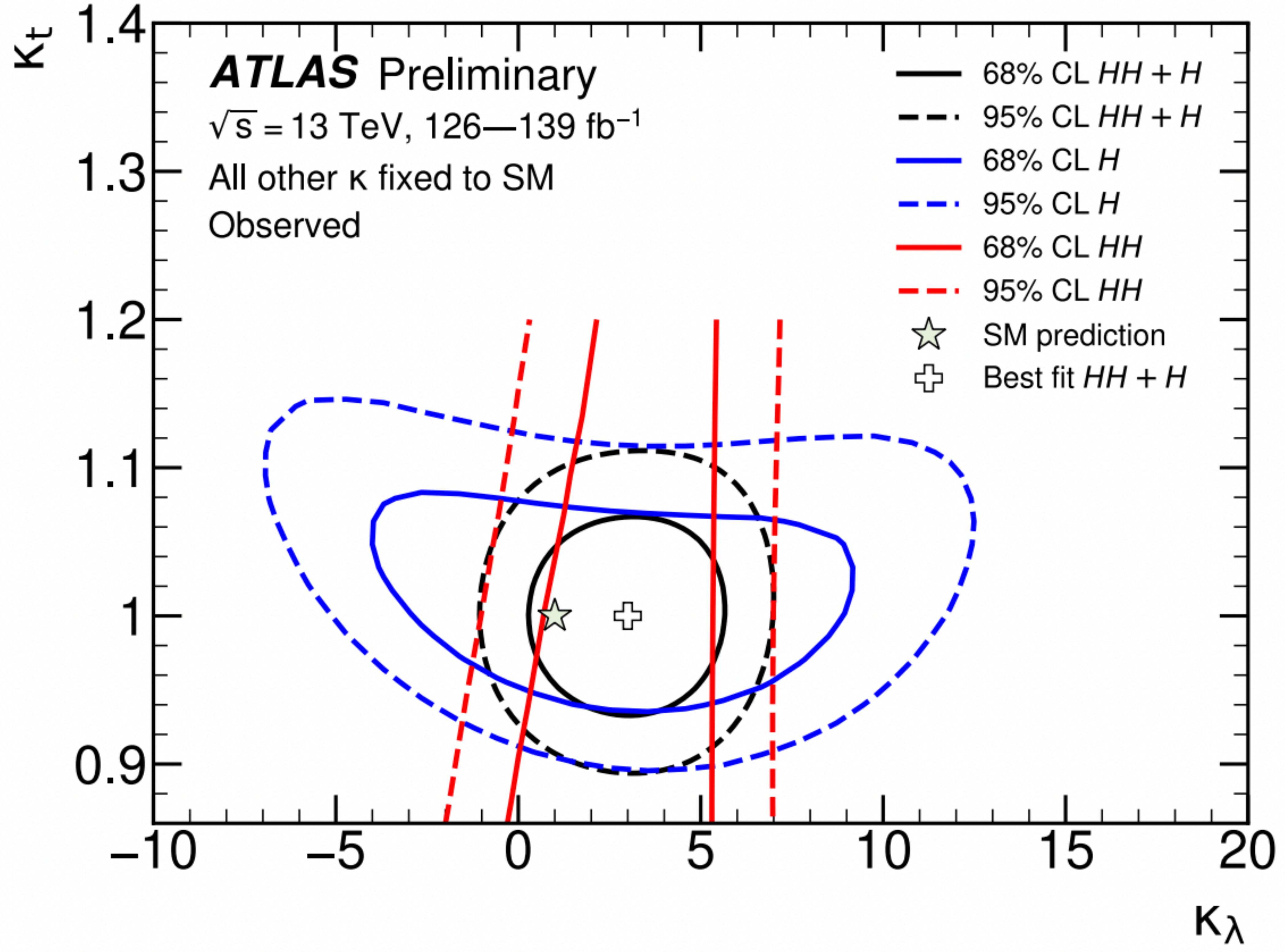
Self-couplings through single-H corrections

back-up



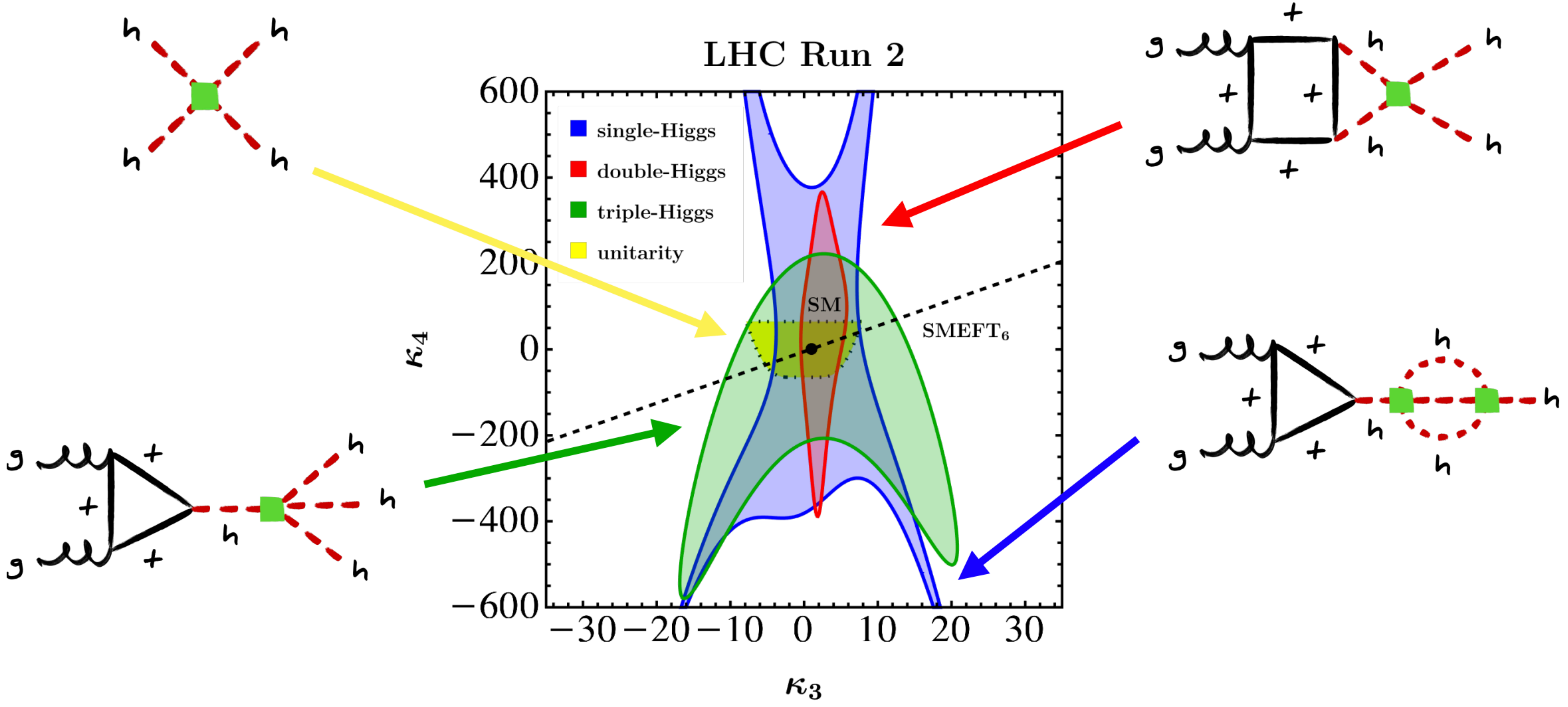
- higher order EW diagrams make single-H boson processes also dependent on the Higgs boson self coupling lambda
- combination of both H and HH (and HHH?) measurements allows to put stringent limits on lambda, while at the same time relaxing assumptions about other Higgs couplings (e.g. top-Higgs couplings in particular)

[ATLAS-CONF-2022-050]



LHC Run 2 analysis

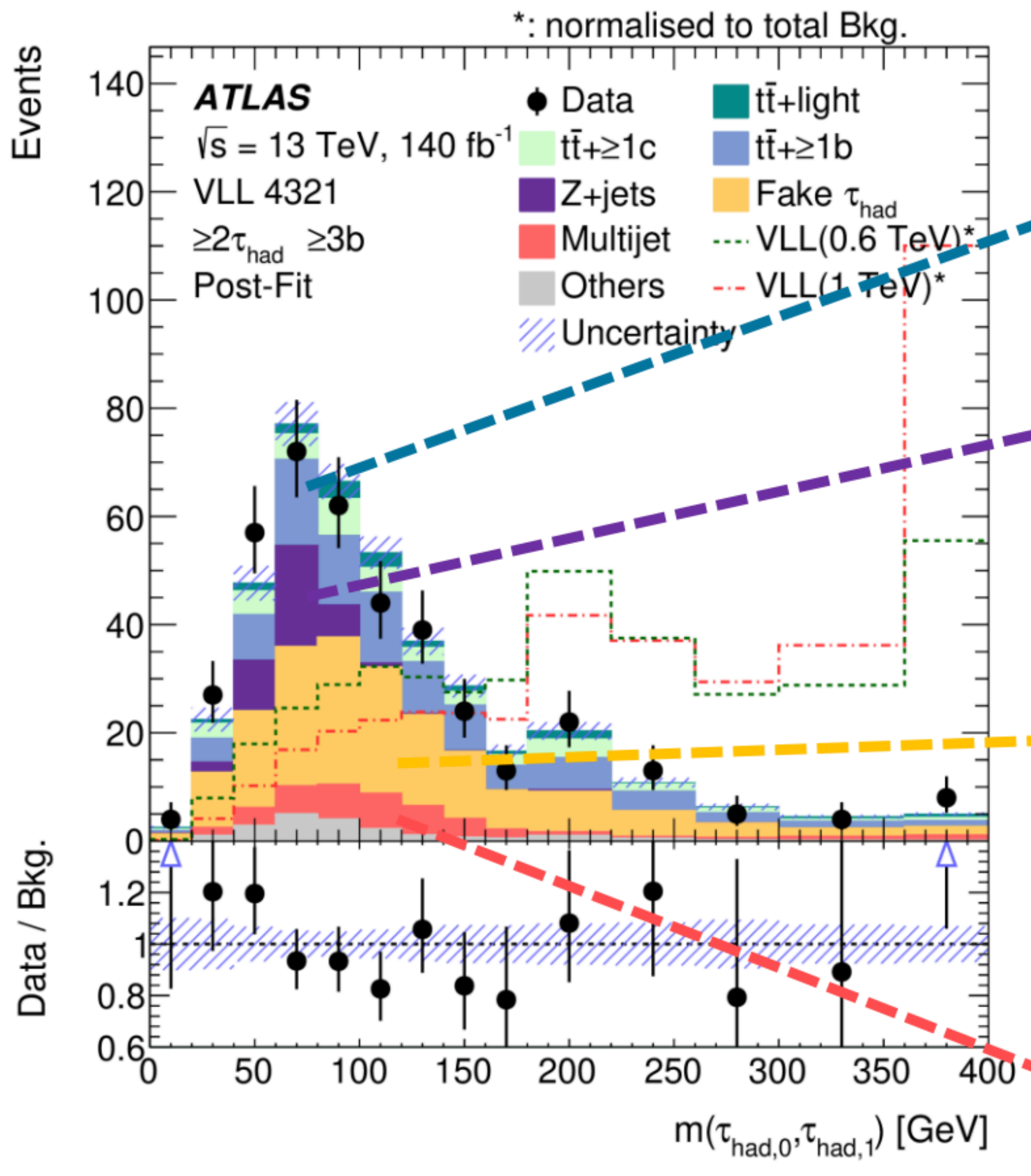
slides from Giulia Zanderighi



[Haisch, Sankar & Zanderighi, 2505.20463; double-Higgs bound from ATLAS, 2406.09971; triple-Higgs bound from ATLAS, 2411.02040]

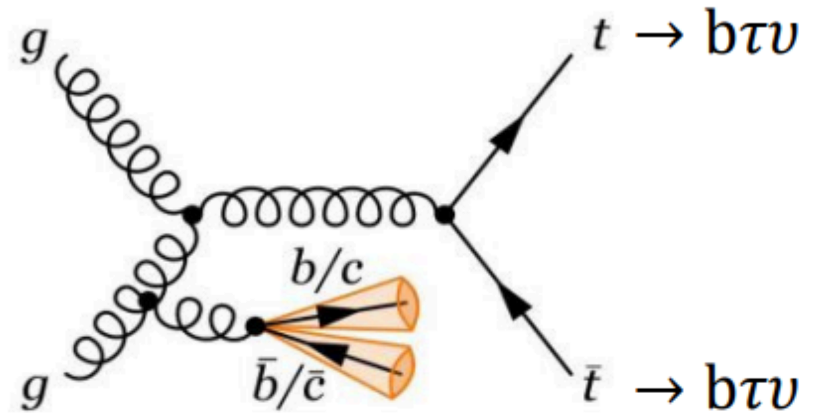
The background estimation

slides from Gabriel Oliveira Corrêa

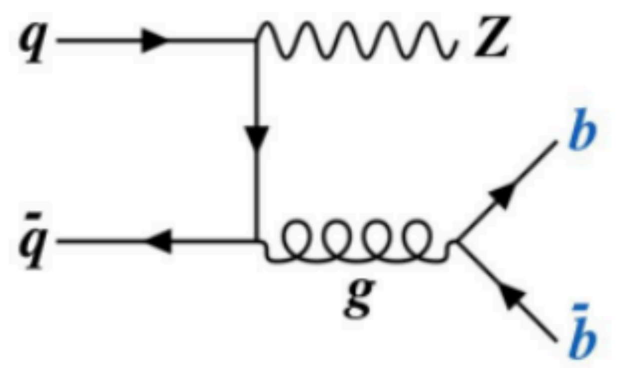


2503.22581

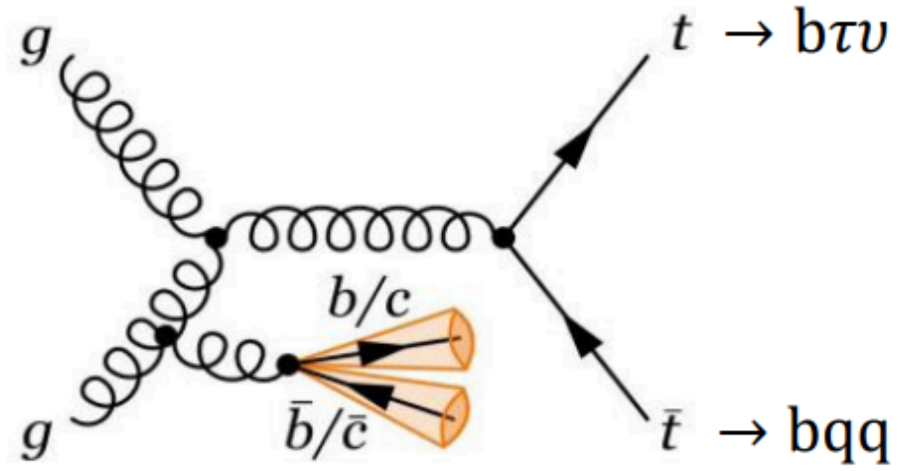
The main background with real hadronic taus is dileptonic $t\bar{t}$ containing extra heavy-flavor jets.



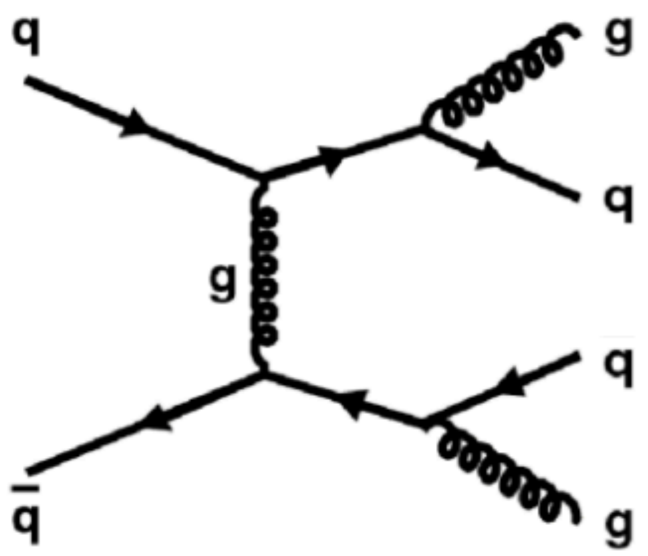
$Z \rightarrow \tau\tau$ with extra heavy-flavor jets also has a sizeable contribution.



The fake hadronic tau background is mostly composed by semi-leptonic $t\bar{t}$ (w/ extra heavy-flavor jets).



The other part of the fake hadronic tau background is composed by QCD multijet background events.

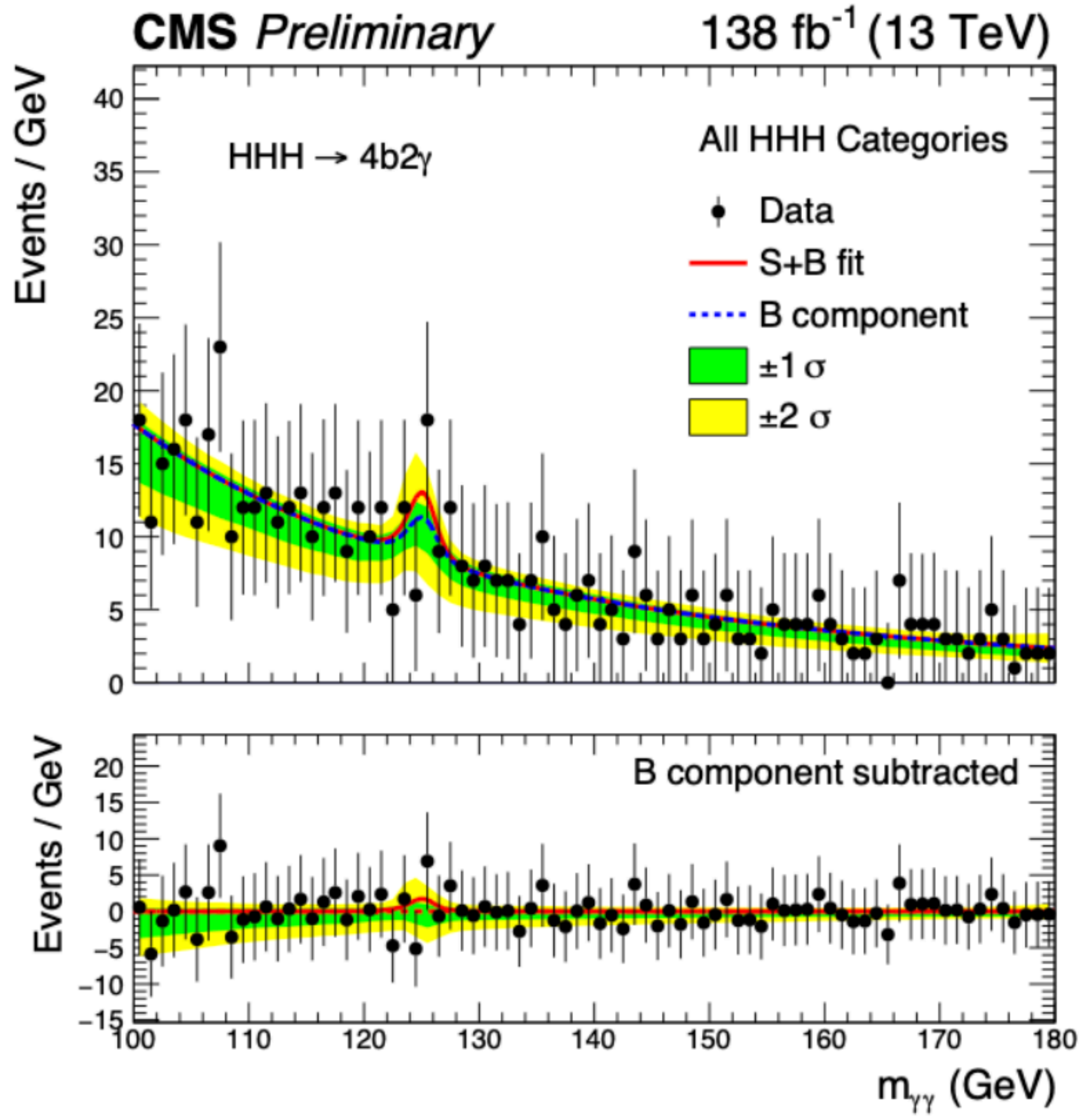


slides from Marko Stamenkovic

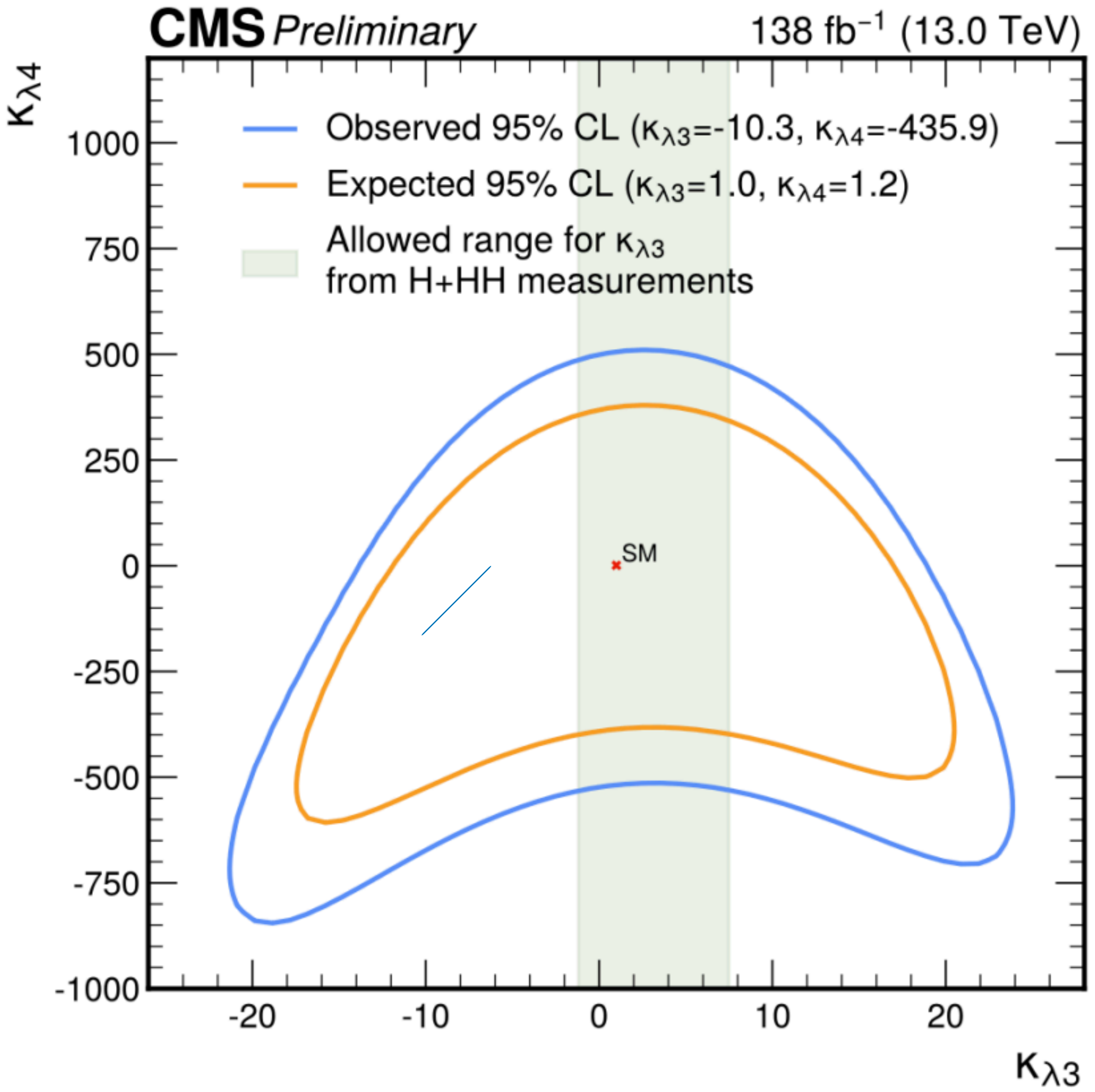
Non-resonant $HHH \rightarrow 4b2\gamma$

CMS-PAS-HIG-24-015

Fit to the data



(κ_3, κ_4) scan



Observed (expected) limit on the signal strength: $\mu < 3400$ (2086) x SM at 95% CL

- **Slight excess observed in data (within 1 sigma)**
- **Challenging channel, large background and low cross-section**
- **Selection acceptance, trigger, pairing, tagging, …**

Interpretation: 1D: $-16 < \kappa_3 < 20$ and $-397 < \kappa_4 < 405$ as well as 2D scan

slides from Marko Stamenkovic

Non-resonant $HHH \rightarrow 6b$

CMS-PAS-HIG-24-012

Number of reconstructible Higgs in **2 AK4** (columns) vs. Reconstructible Higgs in **AK8** (rows)

	0h	1h	2h	3h
3bh	1.7%			
2bh	12.5%	5.9%		
1bh	8.6%	**17.5%**	**7.9%**	
0bh	1.3%	11.1%	**22.0%**	**11.1%**

0Higgs	1Higgs	2Higgs	3Higgs
1.3%	19.7%	52%	**27%**

From MC study matching simulated b-quarks and Higgs bosons to small-and large-radius jets

- **Only 27% of signal events have 3 Higgs** that can be reconstructed in the detector acceptance!
  - Main issue: tracker acceptance needed for b-tagging
  - Most populated regions: resolved Higgs reconstruction

slides from Marko Stamenkovic

Non-resonant $HHH \rightarrow 6b$

CMS-PAS-HIG-24-012

Inputs

AK4 Jets:
pT corr, eta, sin(phi), cos(phi), mass,
PNet@AK4 b-tag discrete score

AK8 jets:
pT, eta, sin(phi), cos(phi), mass,
PNet@AK8 b-tag discrete score

MET, HT +

Up to 45 unique pairs of AK4 jets mass,pT, eta, phi

SPANET

Pairing + classification

Train on signal and background

Prob Multi-H
- ProbHHH6b
- ProbHH4b

ProbQCD / TT...

Perform 2 training with same hyper parameters
Inclusive training and then specific in HHH6b
Network sensitive to number of resolved / boosted events in input samples

SPANET

Categorisation

Train on signal-only HH and HHH

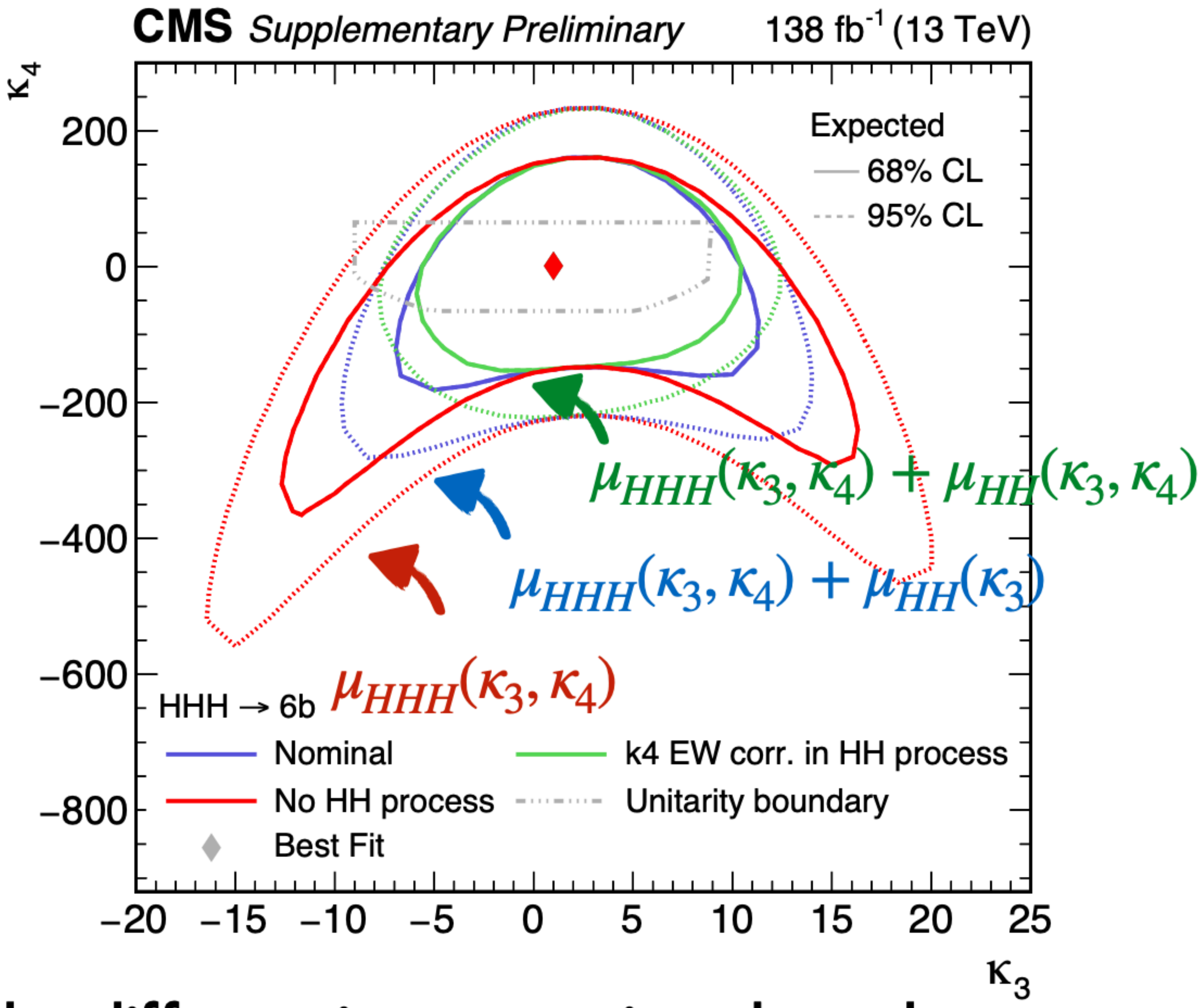
- Prob 3 reconstructible Higgs
- Prob 2 reconstructible Higgs
- Prob 1 reconstructible Higgs
- Prob 0 reconstructible Higgs

slides from Marko Stamenkovic

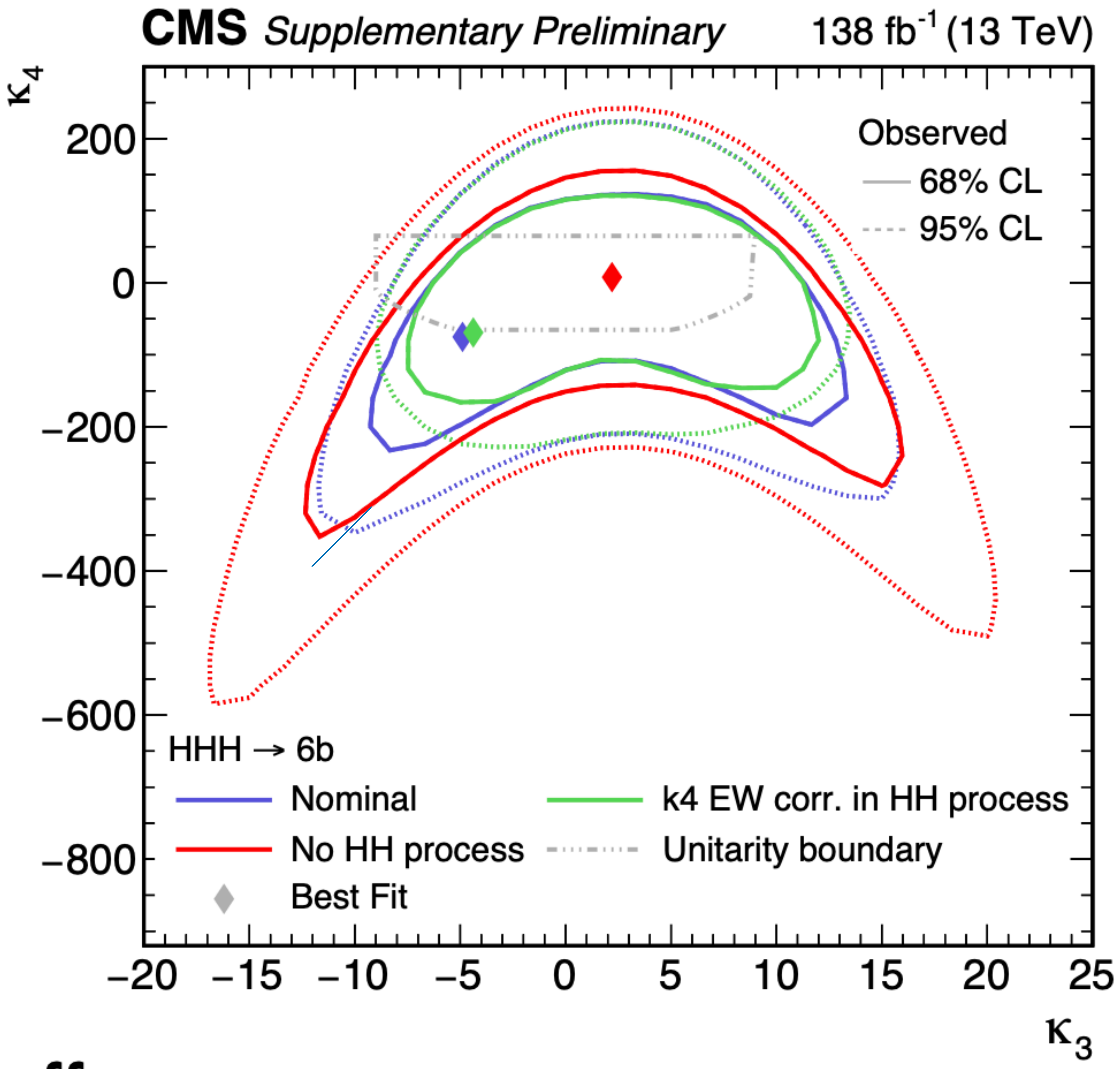
Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012

Expected contours



Observed contours



Study: different interpretations based on normalization effects

- $\mu_{HHH}(\kappa_3, \kappa_4)$ vs $\mu_{HHH}(\kappa_3, \kappa_4) + \mu_{HH}(\kappa_3)$ vs $\mu_{HHH}(\kappa_3, \kappa_4) + \mu_{HH}(\kappa_3, \kappa_4)$
- Using parametrization described in HHH white paper for HHH6b and HH4b
- **Inputs from theorists needed: how to parametrize κ_4 in HH? MC generator?**