ACCESSING HH AT THE HL-LHC

Rafael Teixeira de Lima [SLAC],

on behalf of the ATLAS and CMS Collaborations

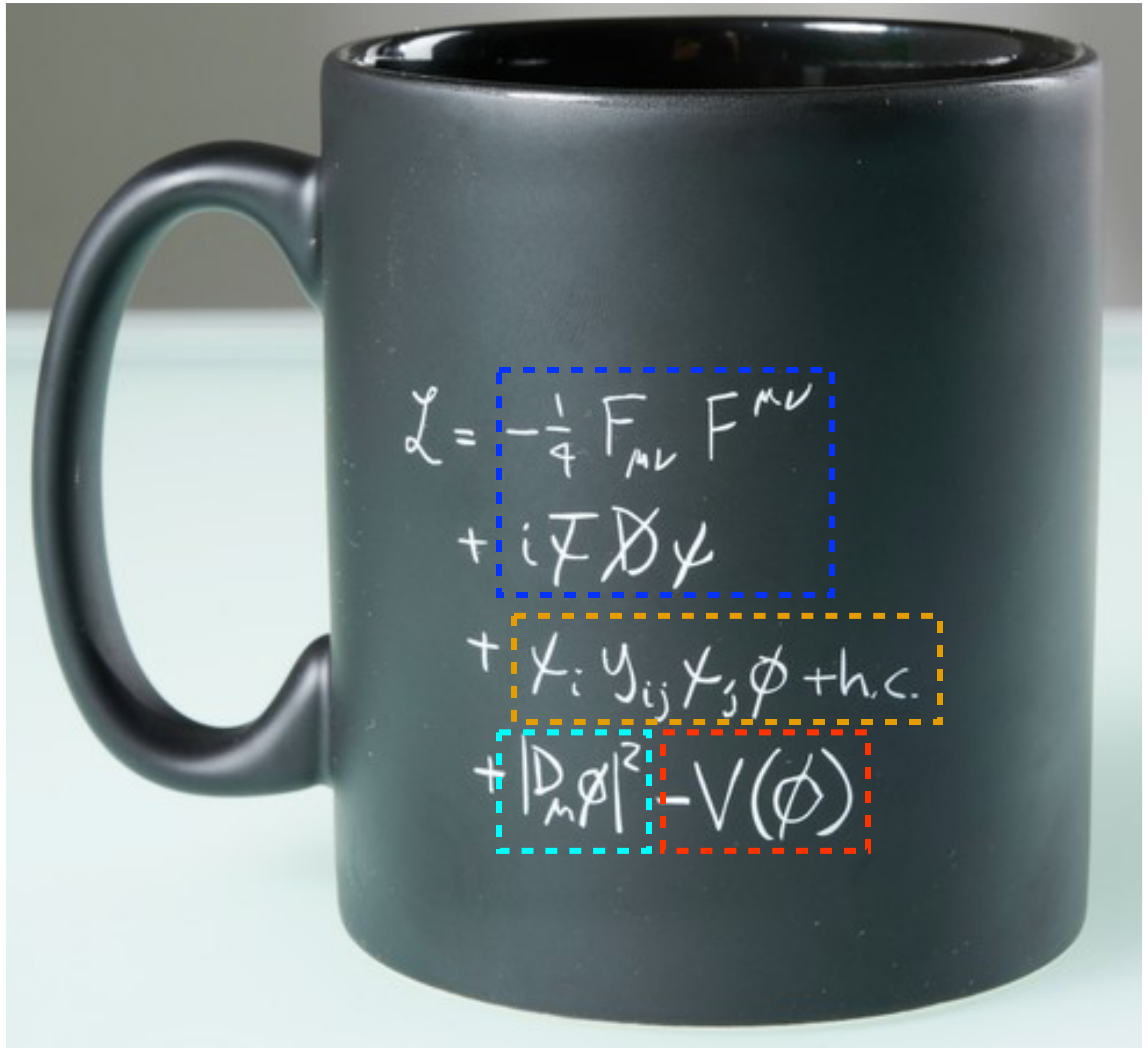
LHCP 2020

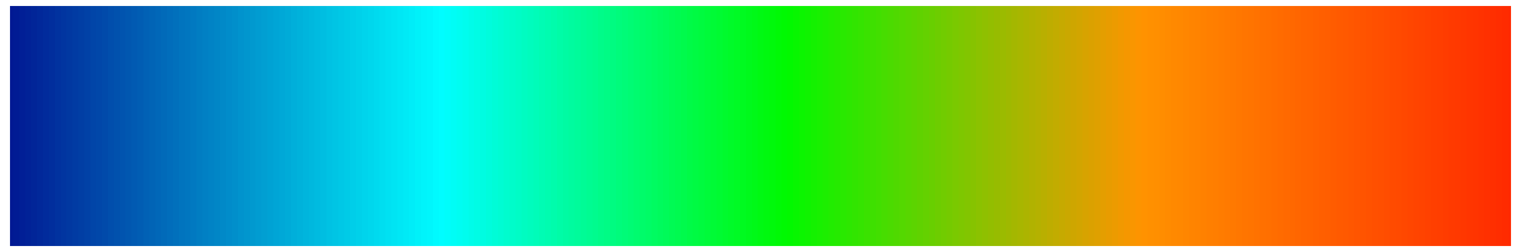
May 26, 2020

SLAC

*View from Zamansky tower (Jussieu), July 16 2018

Why HH?





Knowledge   Assumption

Adapted from G. Salam

Higgs potential: least explored region of SM!

- EWK physics well understood (so far?)
- Higgs couplings to EWK bosons observed and extensively studied
- Higgs Yukawa couplings to 3rd generation observed to follow SM (bb, tt, ττ)

But could be the key to unlock BSM physics!

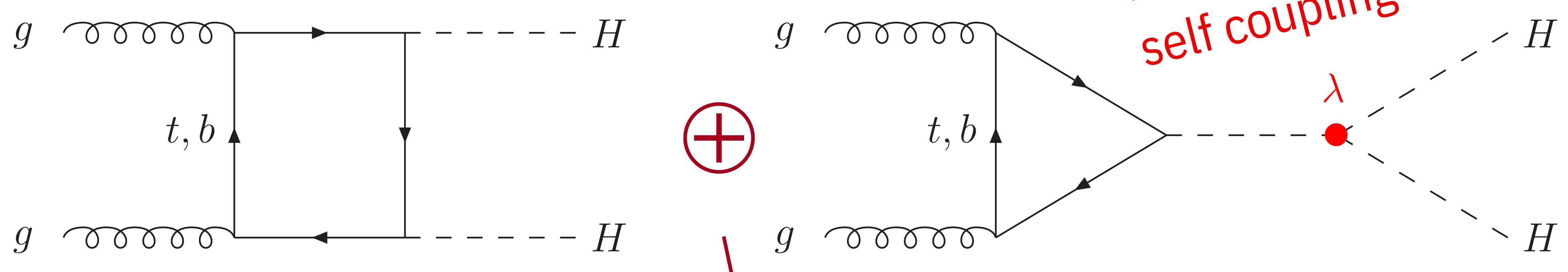
- Cosmological inflation, EWPT & Baryogenesis, Compositeness, 2HDM, etc…
  Strong BSM potential to modify Higgs self coupling λ

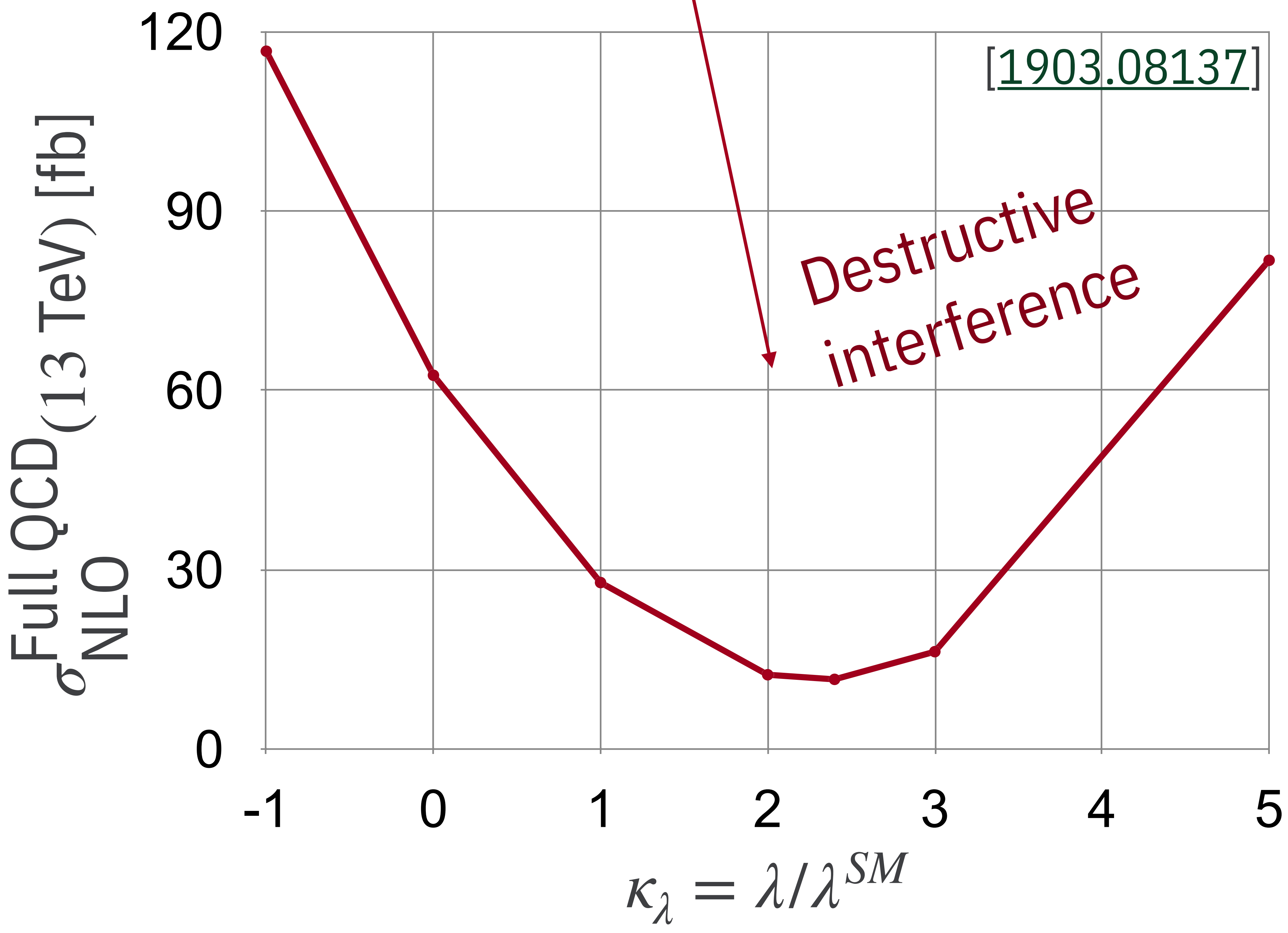
Only directly accessible through HH production!

ACCESSING **HH AT THE LHC**

Main production mode:
gluon-fusion

Directly dependence on self coupling





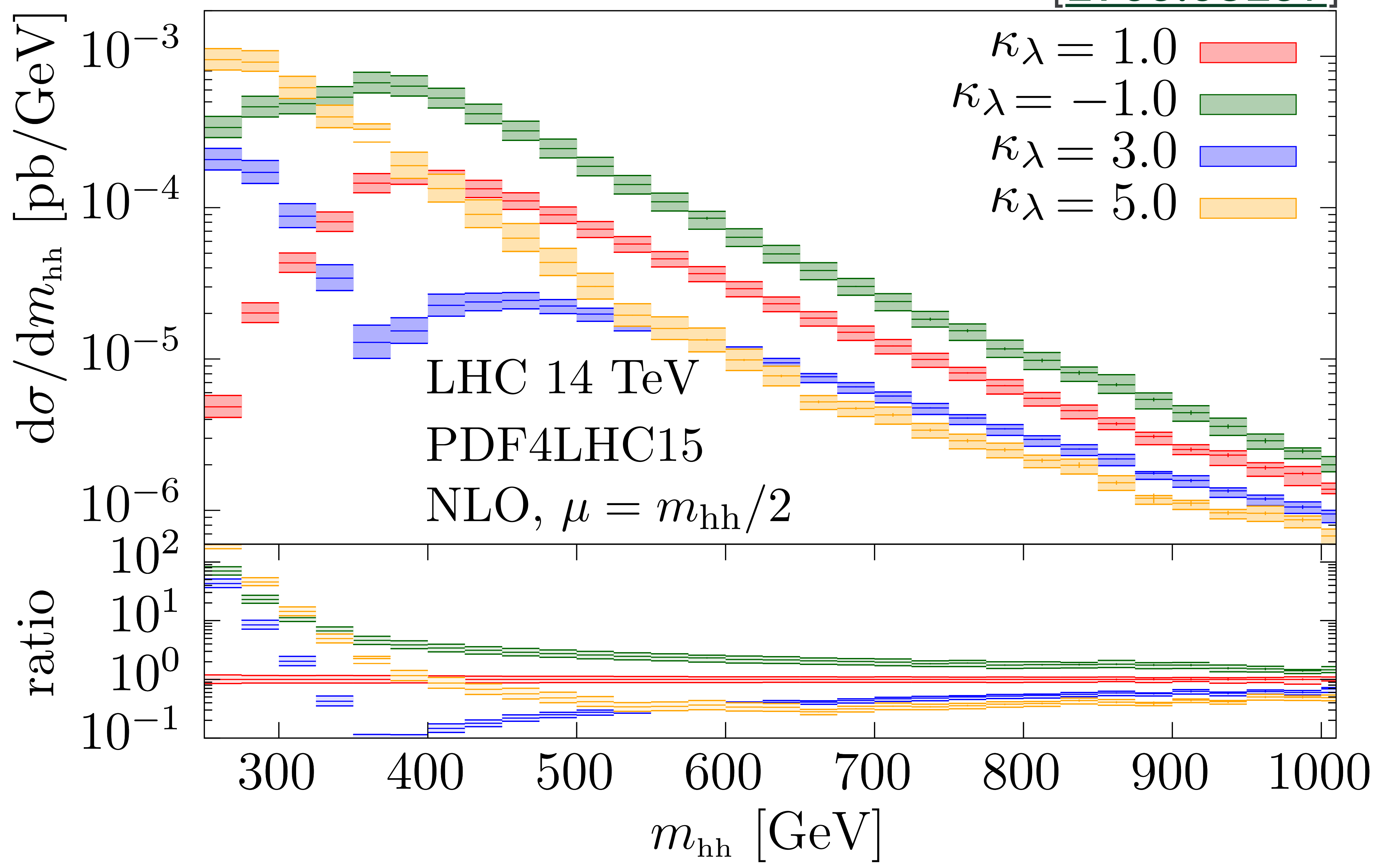
Interesting but rare...

[1803.02463]

$$\sigma^{\text{FTApprox}}_{NNLO}(\text{SM}) = 31.05\ \text{fb}$$

$\kappa_\lambda = \lambda/\lambda^{SM}$ also dictates signal kinematics:

[1903.08137]



For more details, see D. Guerrero on Thurs.

HH Current Status (1)

Results based on 27 - 36 fb-1

[As summarized in HH White Paper]

Search channel	Collaboration	95% CL Upper Limit observed	95% CL Upper Limit expected
$b\bar{b}b\bar{b}$	ATLAS [PAPER]	13	21
	CMS [PAPER]	75	37
$b\bar{b}\gamma\gamma$	ATLAS [PAPER]	20	26
	CMS [PAPER]	24	19
$b\bar{b}\tau^+\tau^-$	ATLAS [PAPER]	12	15
	CMS [PAPER]	32	25
$b\bar{b}VV^*$ $(\ell\nu\ell\nu)$ *	ATLAS [PAPER]	40	29
	CMS [PAPER]	79	89
$b\bar{b}WW^*$ $(\ell\nu qq)$	ATLAS [PAPER]	305	305
	CMS	–	–
$WW^*\gamma\gamma$	ATLAS [PAPER]	230	160
	CMS	–	–
WW^*WW^*	ATLAS [PAPER]	160	120
	CMS	–	–
Combined	ATLAS [PAPER]	6.9	10
	CMS [PAPER]	22	13

CMS strongest ($b\bar{b}\gamma\gamma$, CMS: 24 / 19)

ATLAS strongest ($b\bar{b}\tau^+\tau^-$, ATLAS: 12 / 15)

* 140 fb-1, not in combination

ATLAS and CMS Expected Upper Limits ~10 x SM

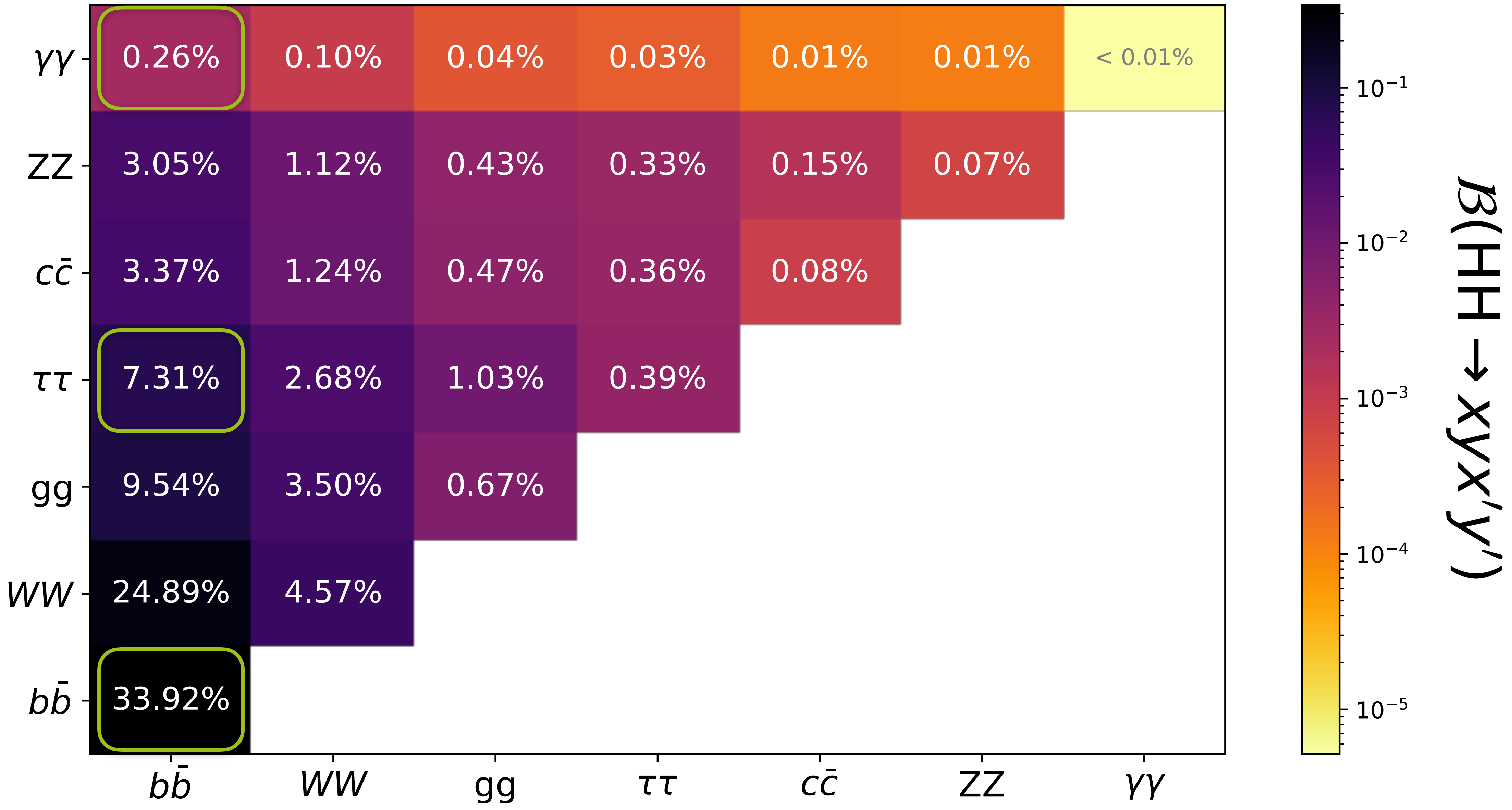
Same most sensitive channels in ATLAS and CMS: $HH \to b\bar{b}b\bar{b}$ (4b), $b\bar{b}\tau^+\tau^-$, and $b\bar{b}\gamma\gamma$

- Complementary channels:

  $4b$ (high mass region, $M_{HH} \gtrsim 400$ GeV),

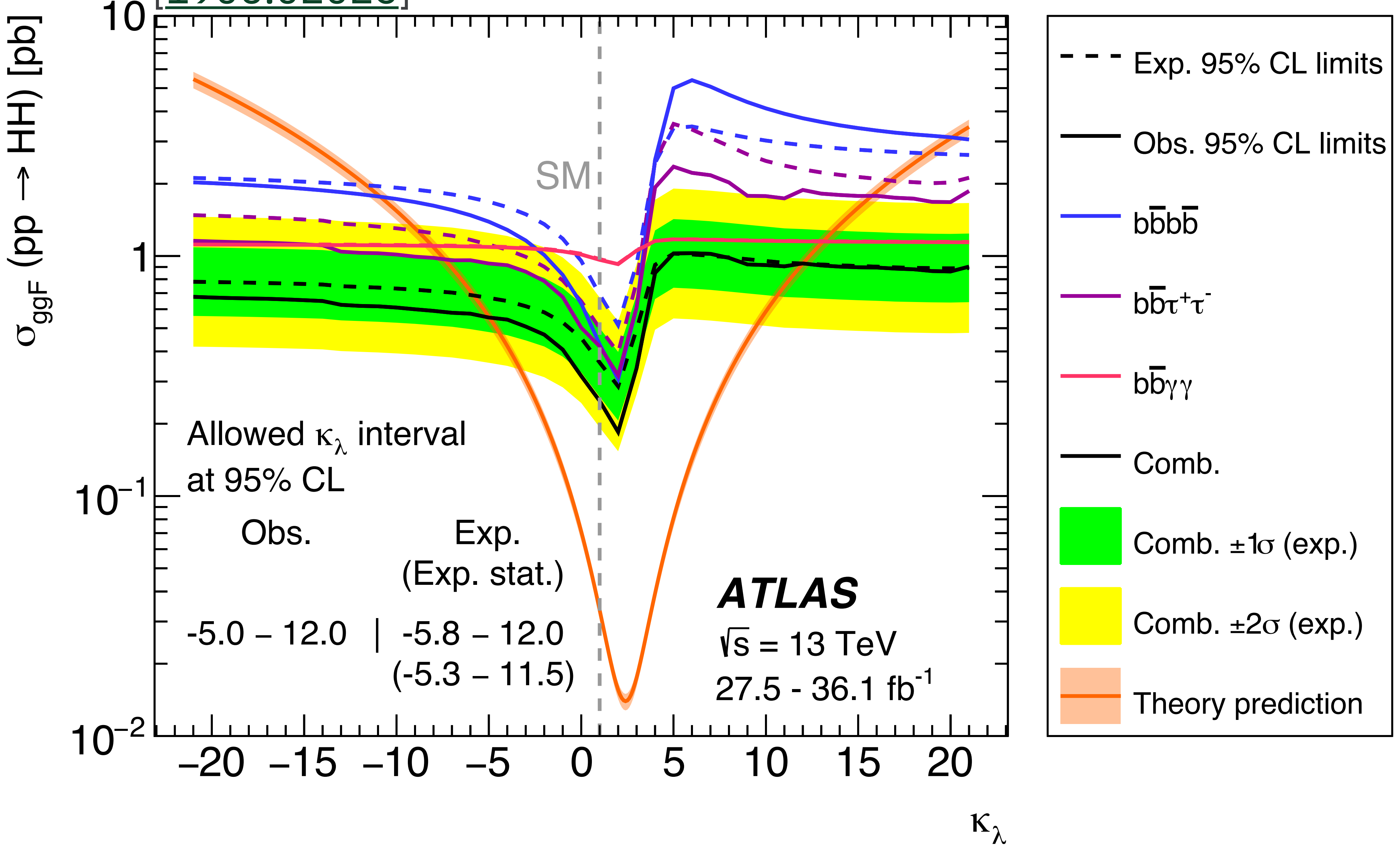
  $b\bar{b}\gamma\gamma$ (low mass region, $M_{HH} \lesssim 400$ GeV)

  $b\bar{b}\tau^+\tau^-$ (intermediate mass region, $M_{HH} \approx 400$ GeV)



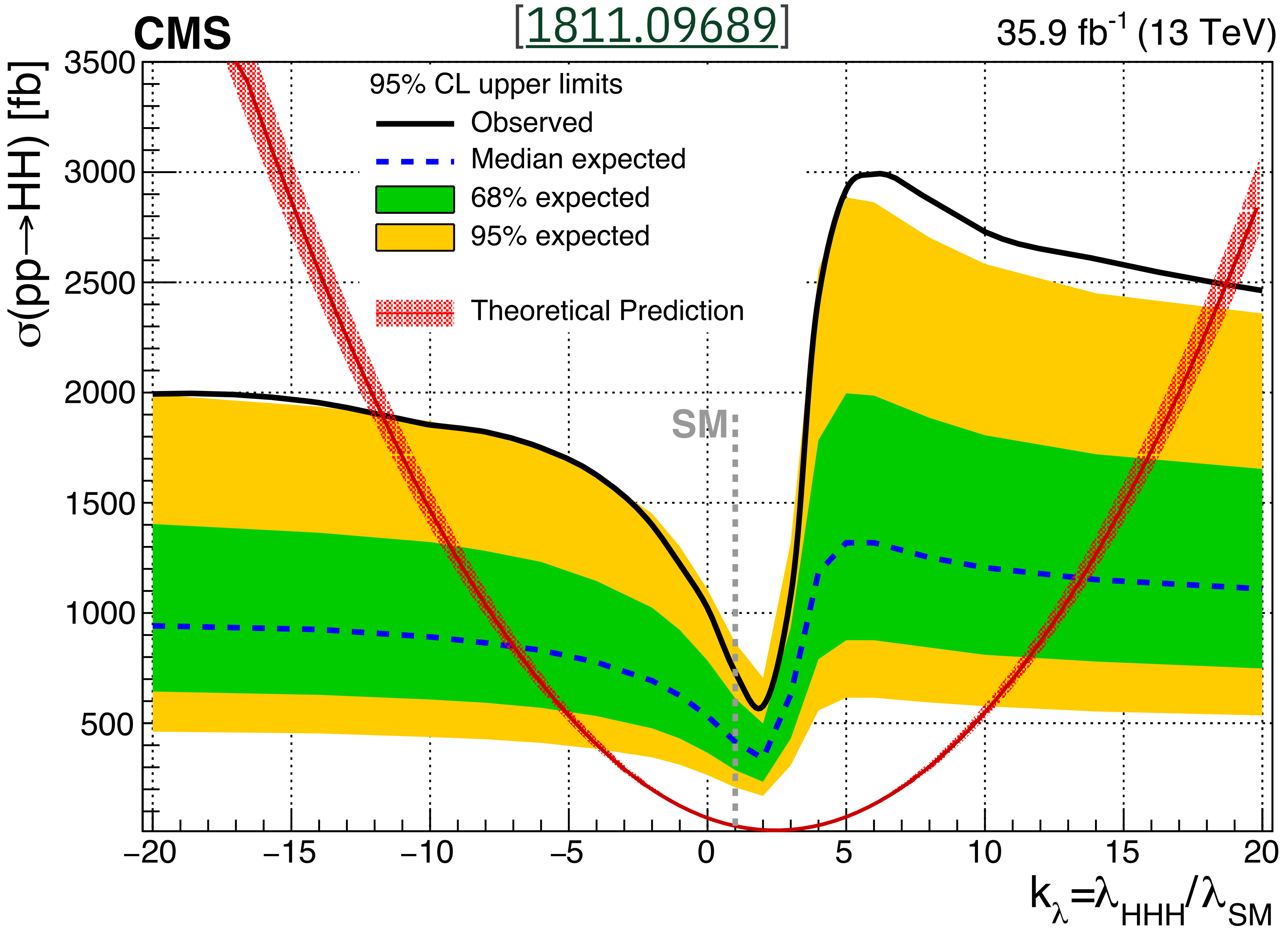
HH Current Status (2)

[1906.02025]



$-5.0\,(-5.8) < \kappa_\lambda < 12.0\,(12.0)$ Observed (Expected)

[1811.09689]



$-11.8\,(-7.1) < \kappa_\lambda < 18.8\,(13.6)$ Observed (Expected)

Analyses sensitivities vary strongly with κ_λ

- Signal kinematics and thus acceptance are κ_λ dependent!

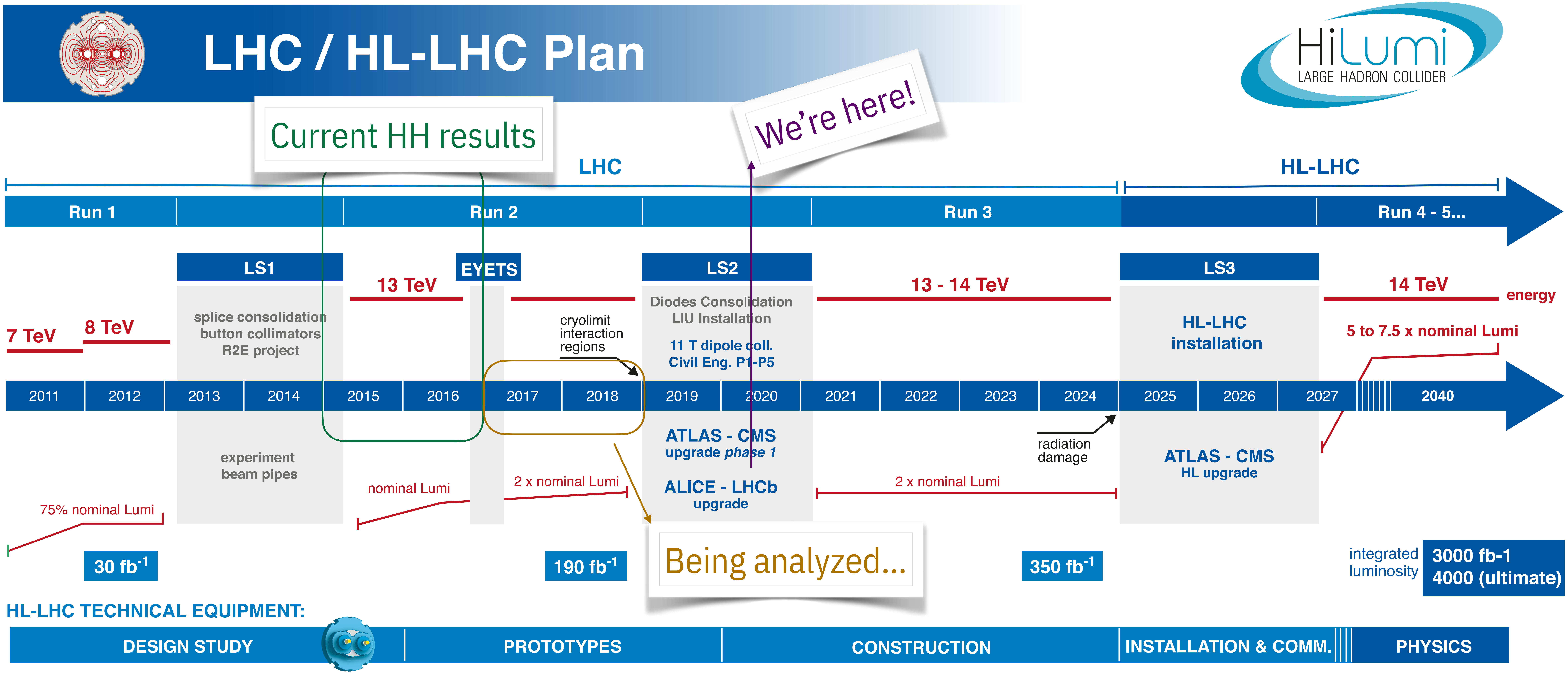
Need more data!

Unfortunately, still not close to SM sensitivity…

HIGH-LUMINOSITY LHC

Review of ATLAS HL-LHC Upgrades (LHCP 2020)

Review of CMS HL-LHC Upgrades (LHCP 2020)



Current HH results use ~ 1% of expected full HL-LHC dataset!

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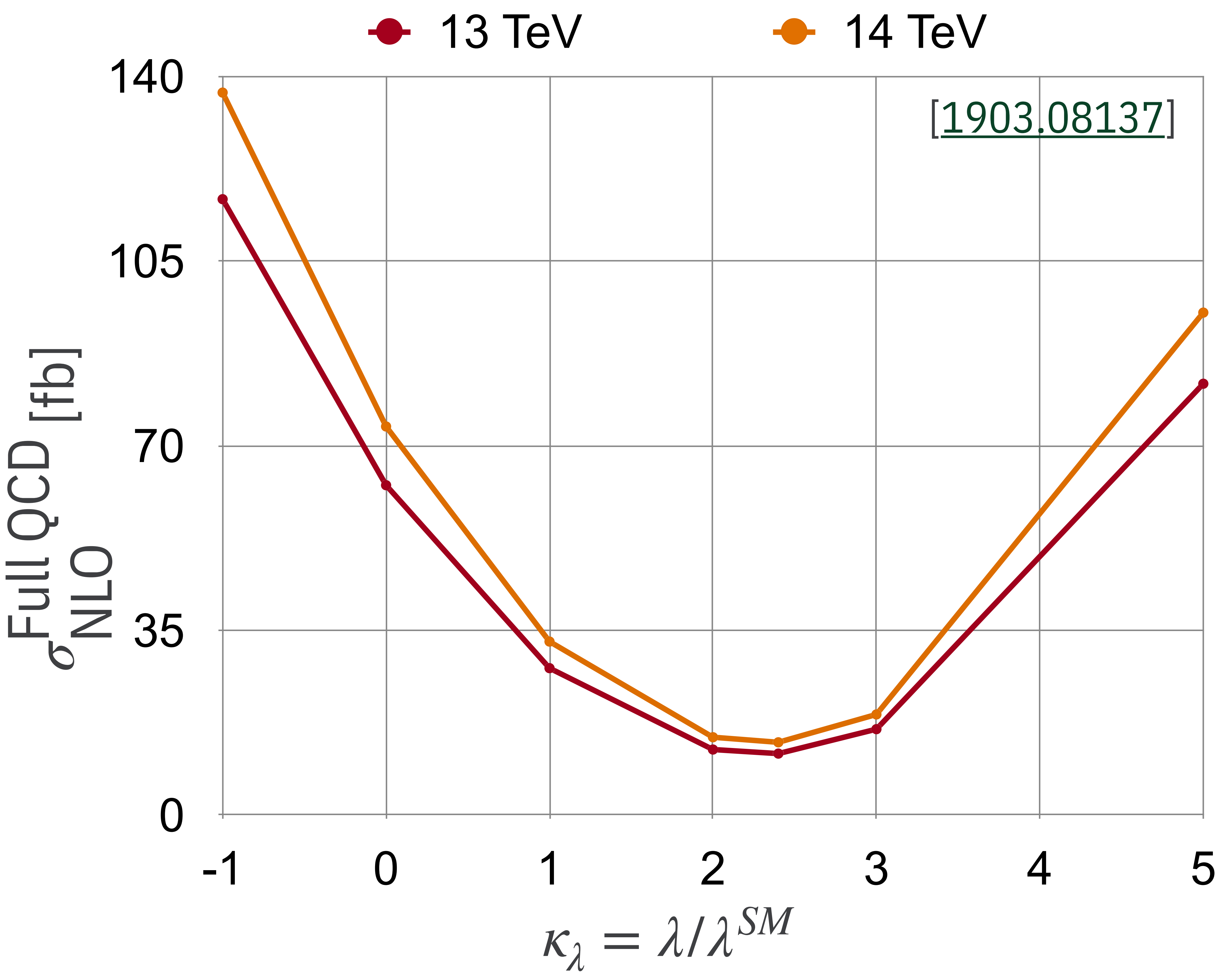
HH @ HL-LHC

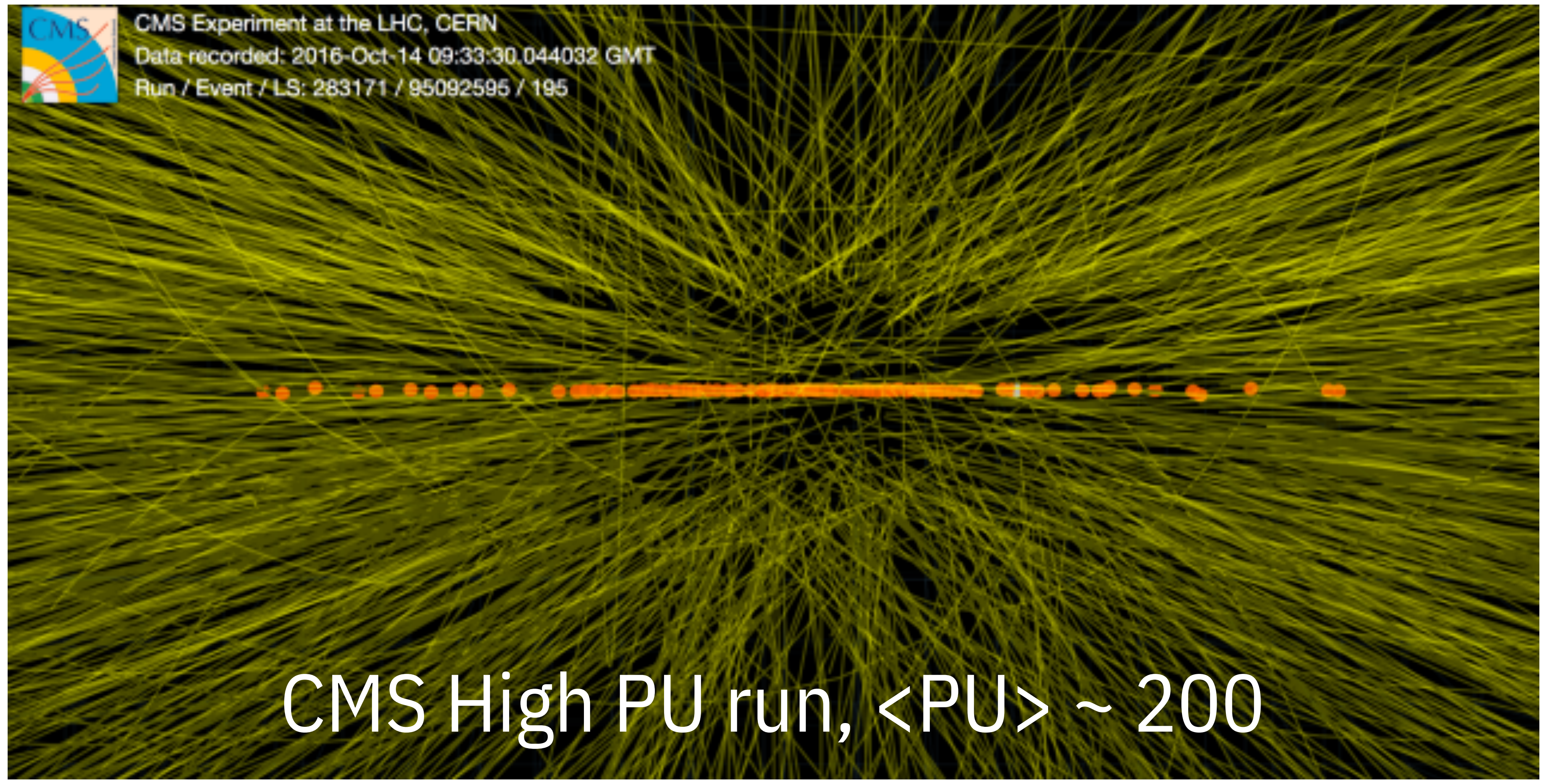


~20% larger cross section, but much more difficult environment!

- Higher PU → lower sensitivity to κ_λ variations (low M_{HH})

Need LHC experiments upgrades to cope with challenges!

[CDS]



HH HL-LHC Prospects: **Strategies**

How to assess HH sensitivity at HL-LHC? Different strategies!

- **Extrapolating current Run 2 results**
  - *Assumption:* object performance not degraded due to higher PU (detector upgrades), Run 2 detector uncertainties
  - Pessimistic: No new analysis strategies from larger dataset; expect better e/μ triggers in HL-LHC;…
  - Optimistic: Multijet/tau trigger performances

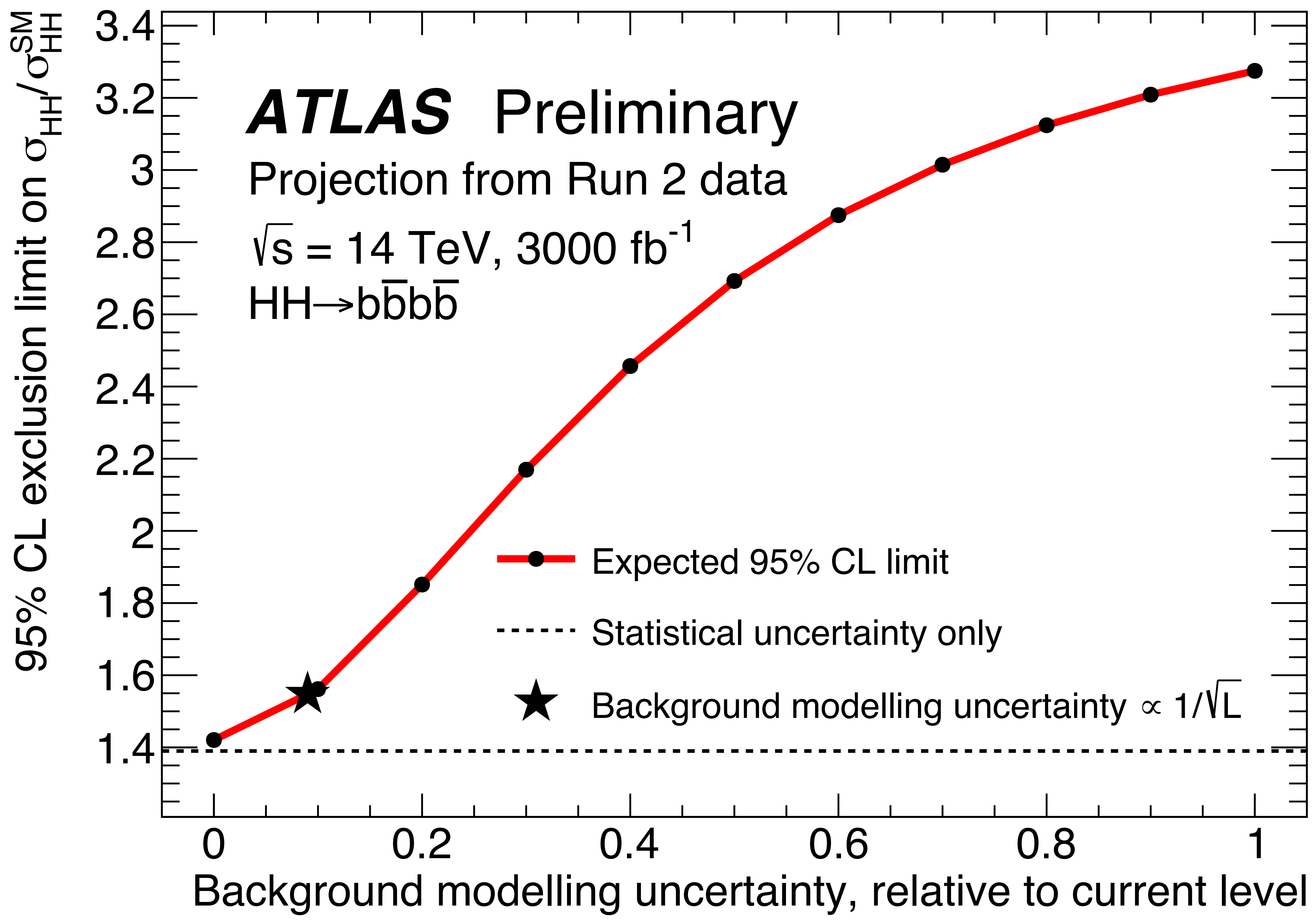
- **Devising new analyses/strategies to cope with larger dataset in new conditions**
  - *Parametrized detector response* according to expected HL-LHC upgraded simulation performances, improved detector acceptance (e.g., tracker coverage)
  - Pessimistic: Object reconstruction algorithms not highly optimized for HL-LHC, can be better!
  - Optimistic: Significant improvements from ML-based techniques with large datasets (for example)

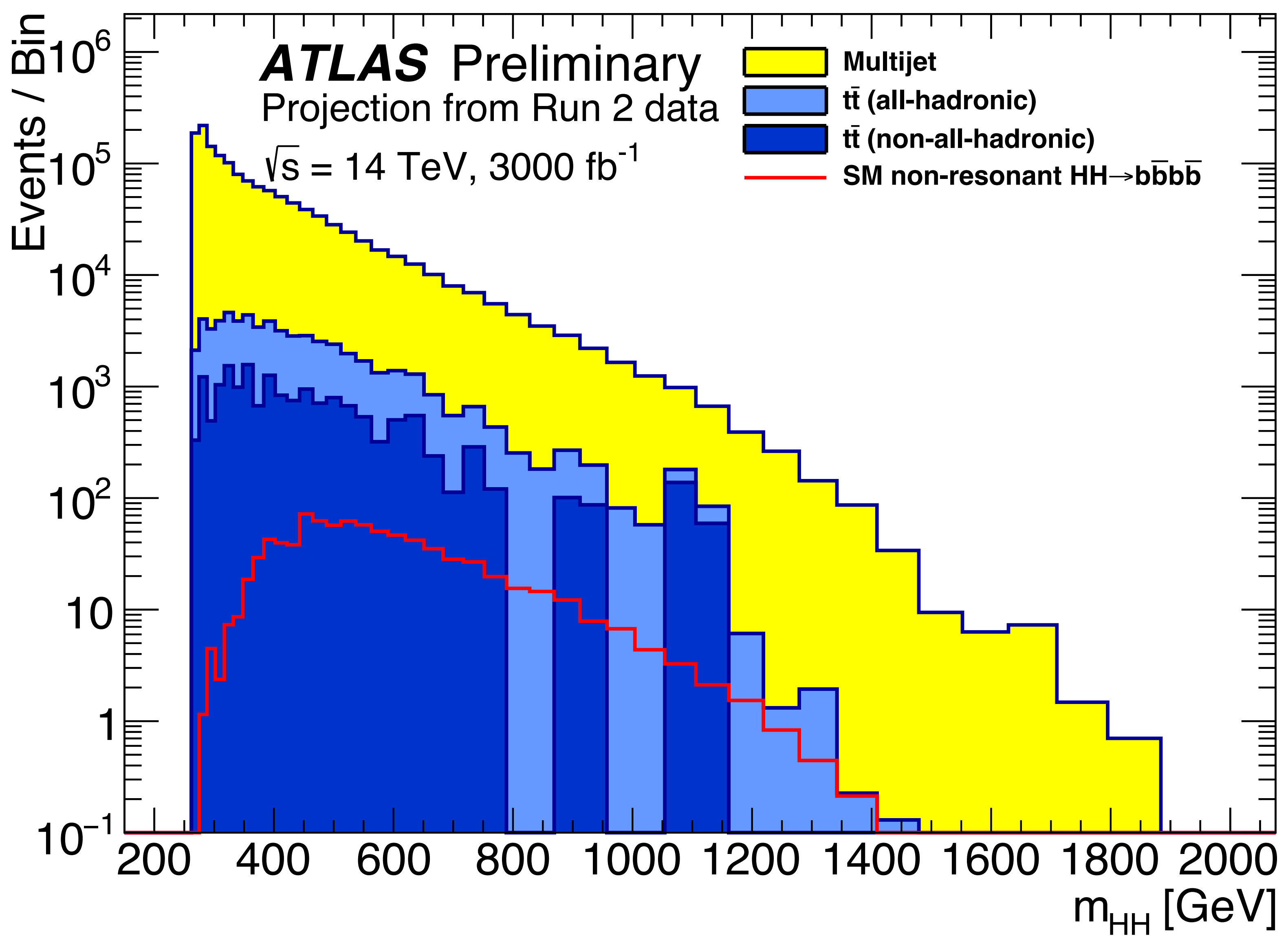
HH@HL-LHC: **ATLAS** (1)

[ATL-PHYS-PUB-2018-053]

$HH \rightarrow b\bar{b}b\bar{b}$ analysis

- Extrapolated from *early* Run 2 analysis
- Multijets (main background) estimated with data
  - Pessimistic background estimation uncertainty
  - Sensitivity vs background uncertainty assumptions studied





Final discriminant with data-driven (multijet) and MC-based ($t\bar{t}$) backgrounds

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HH@HL-LHC: **ATLAS** (2)

[ATL-PHYS-PUB-2018-053]

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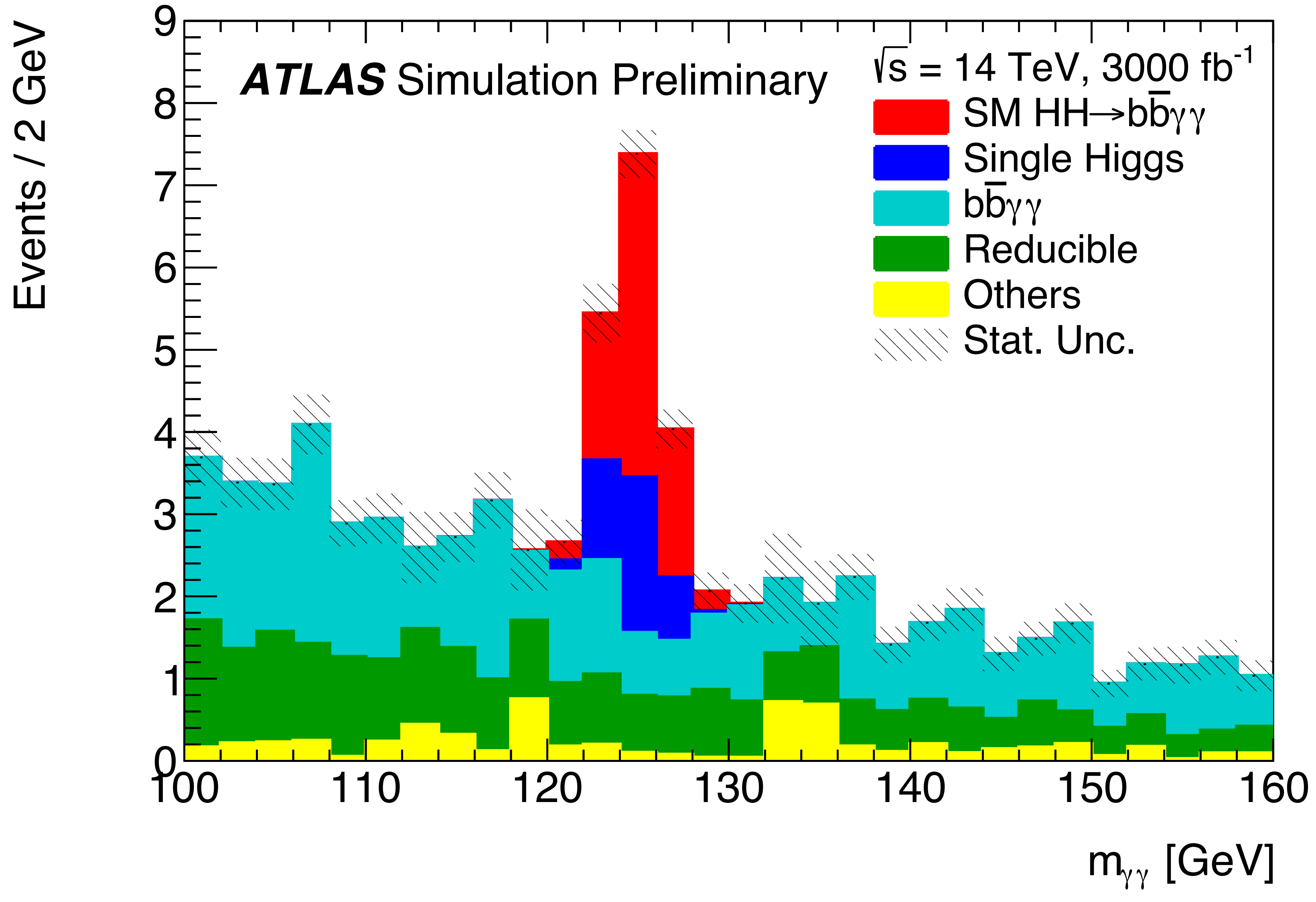
$HH \to b\bar{b}\gamma\gamma$ analysis

- New analysis on parametrized performance simulation
- BDT to discriminate [$\gamma\gamma$+multijet+SM single Higgs] and signal
- Fit on M_{HH} bins w/ window selection on $M_{\gamma\gamma}$

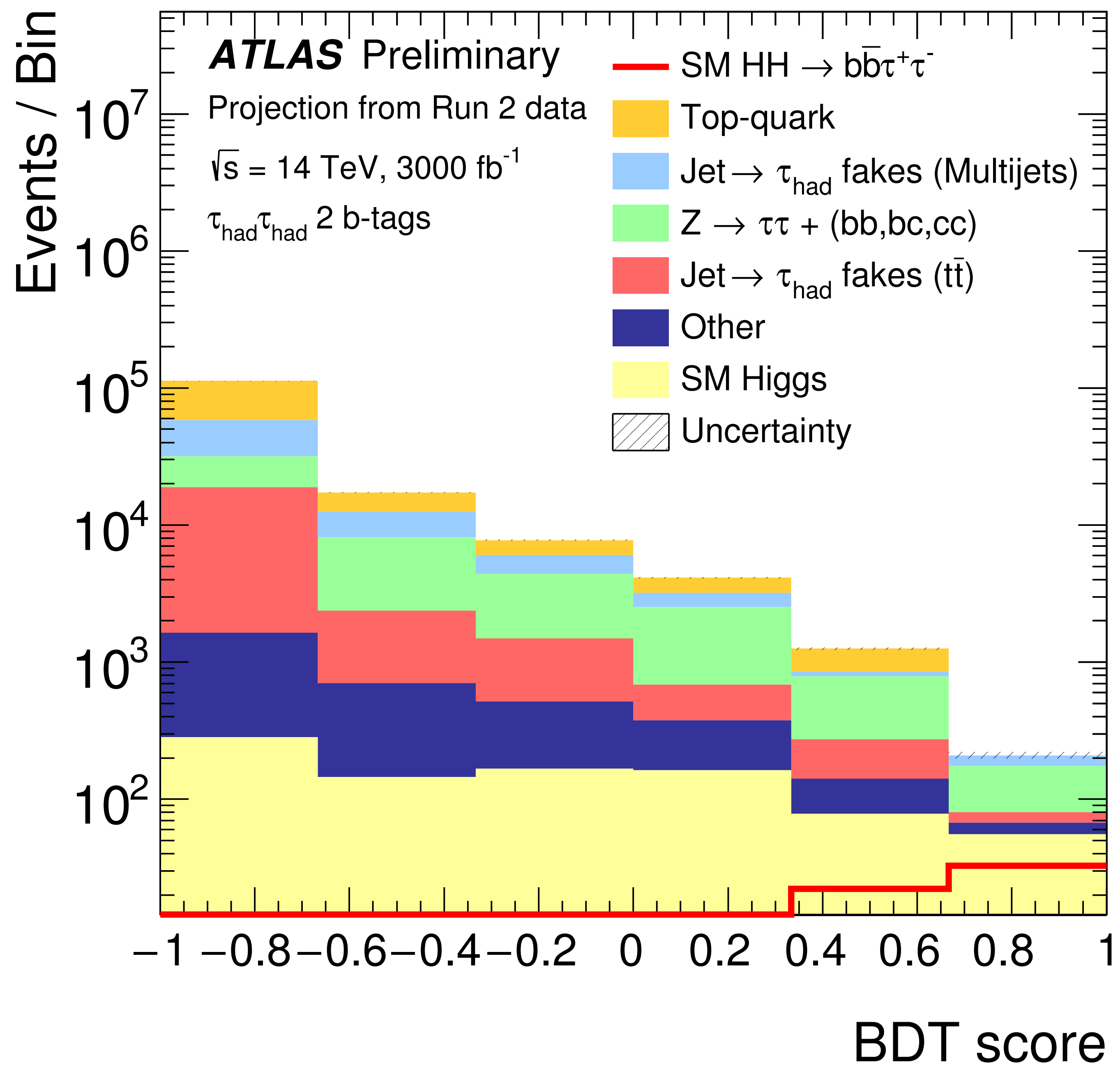


Continuous and resonant (single Higgs) MC-based background and signal distributions in $M_{\gamma\gamma}$

$HH \to b\bar{b}\tau^+\tau^-$ analysis

- Extrapolated from *early* Run 2 analysis
- BDT to discriminate signal and background in $\tau_h\tau_h$ category, and $e\tau_h + \mu\tau_h$ categories
- Norm. uncertainty largely reduced for backgrounds constrained in data (statistical)
- Sensitive to MC statistical precision - considered separately

Most sensitive category ($\tau_h\tau_h$) final discriminant (BDT)

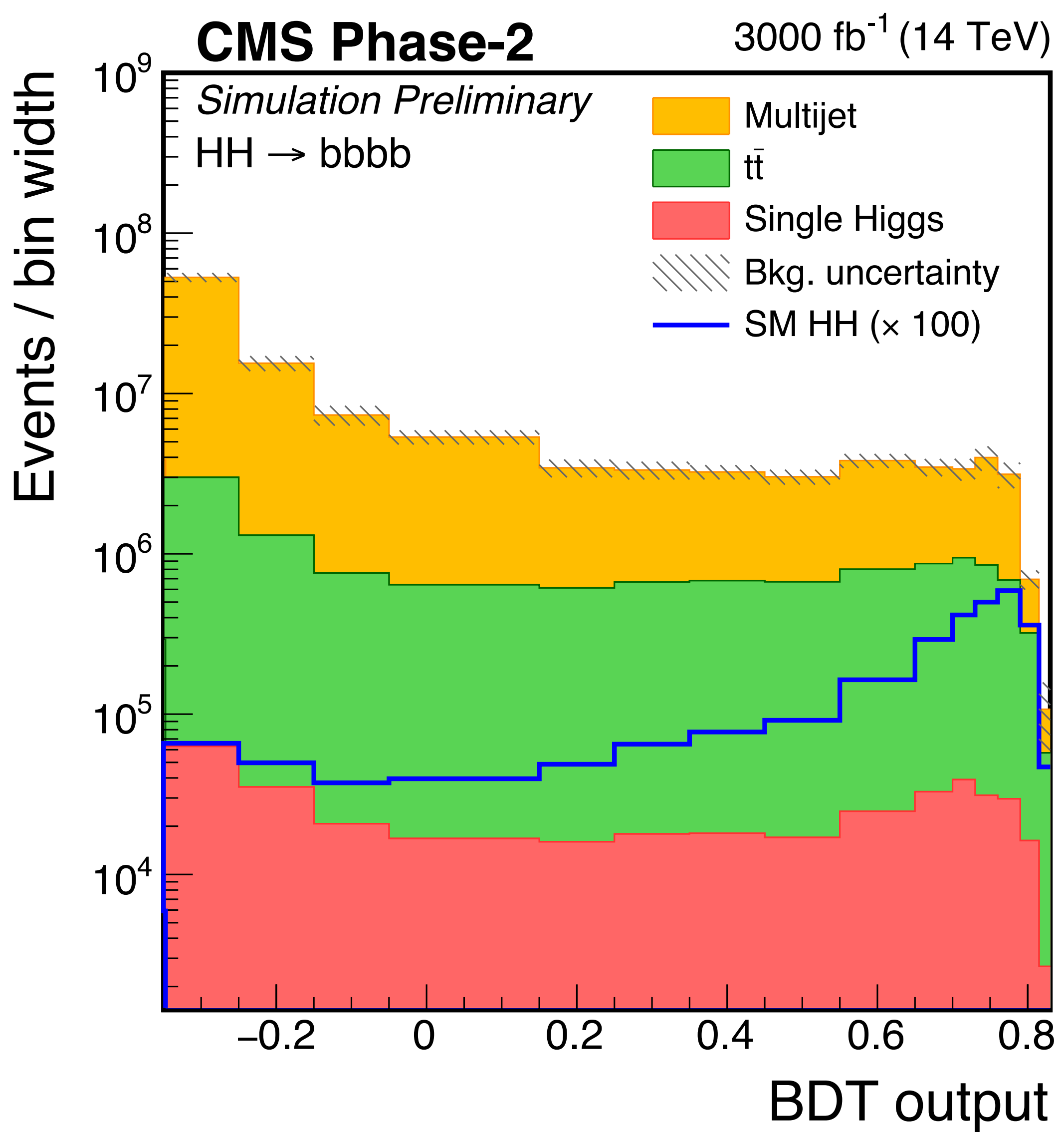


HH@HL-LHC: **CMS** (1)

[CMS-PAS-FTR-18-019]

$HH \rightarrow b\bar{b}b\bar{b}$ analysis

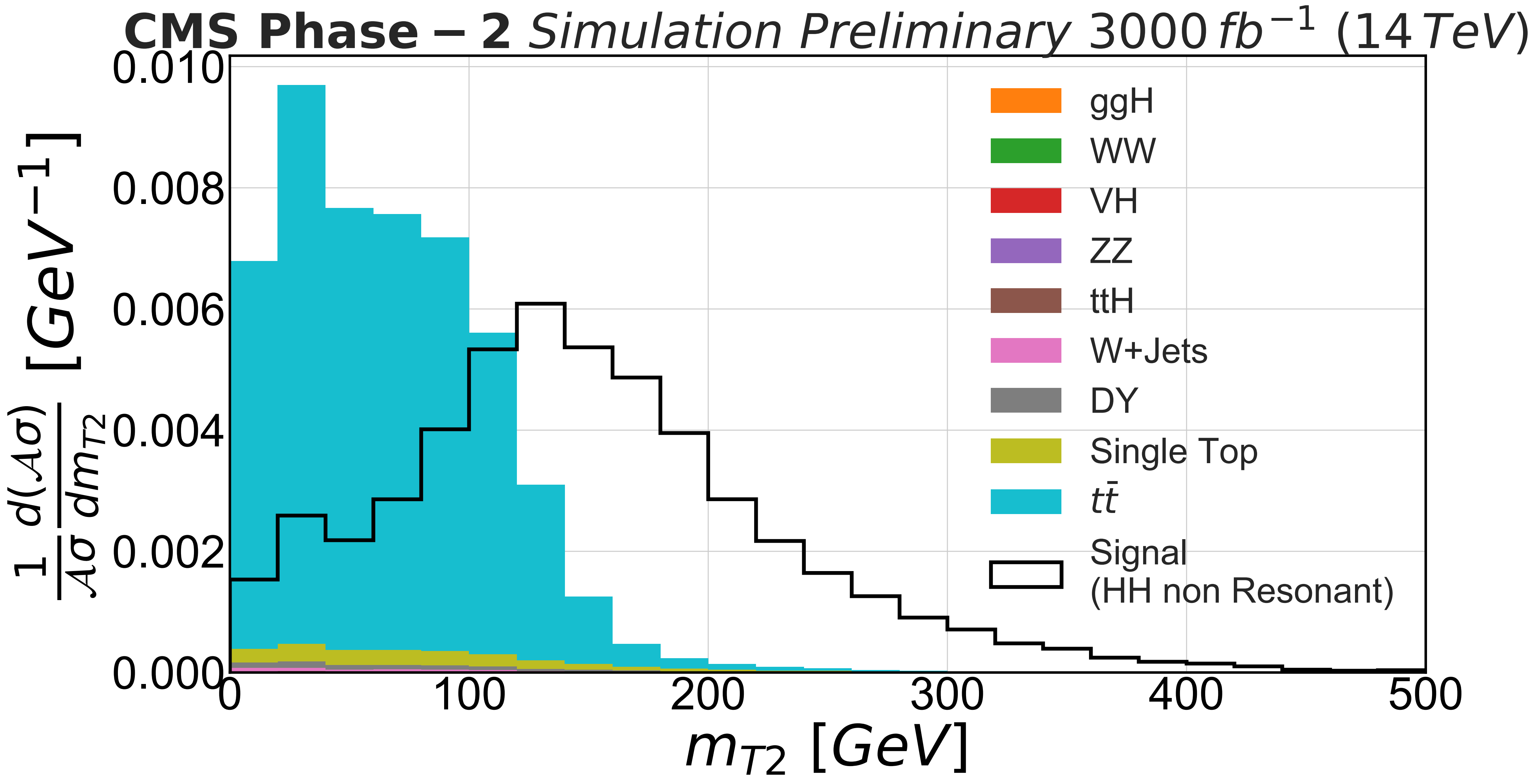
- Analysis on parametrized detector simulation (DEPLHES)
- Complimentary topologies:
  - *Resolved*: BDT-based, SM and κλ constraints
  - *Boosted*: large-R jet based, EFT interpretation (high M_{HH})



Resolved analysis final discriminant (BDT-based), with MC-based background components

$HH \rightarrow b\bar{b}\tau^+\tau^-$ analysis

- Dedicated DELPHES analysis
- Neural network used to discriminate signal and background in $\tau_h\tau_h$, $e\tau_h$ and $\mu\tau_h$ categories



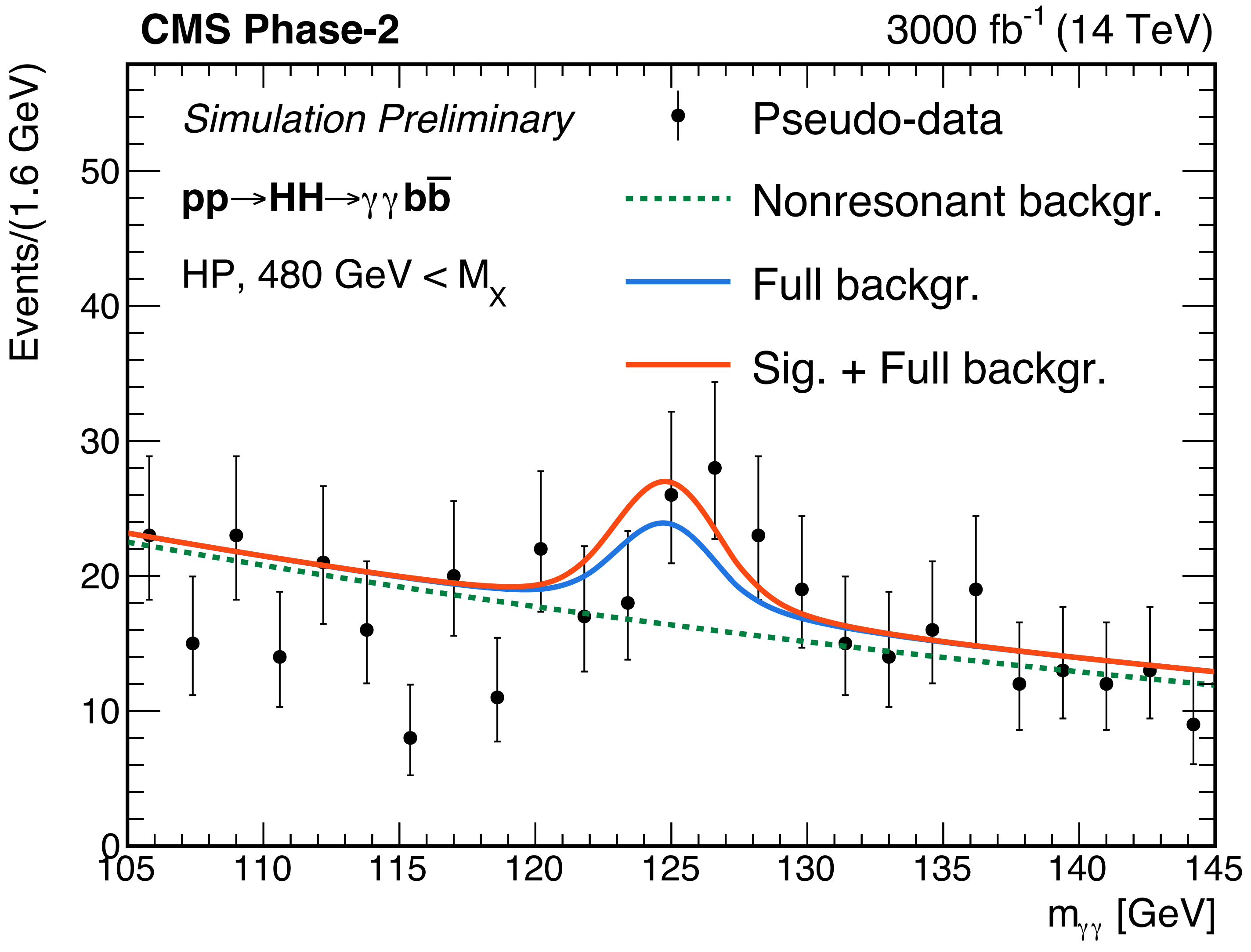
Example distribution of discriminating variable in $\mu\tau_h$ neural network

HH@HL-LHC: **CMS** (2)

[CMS-PAS-FTR-18-019]

$HH \to b\bar{b}\gamma\gamma$ analysis

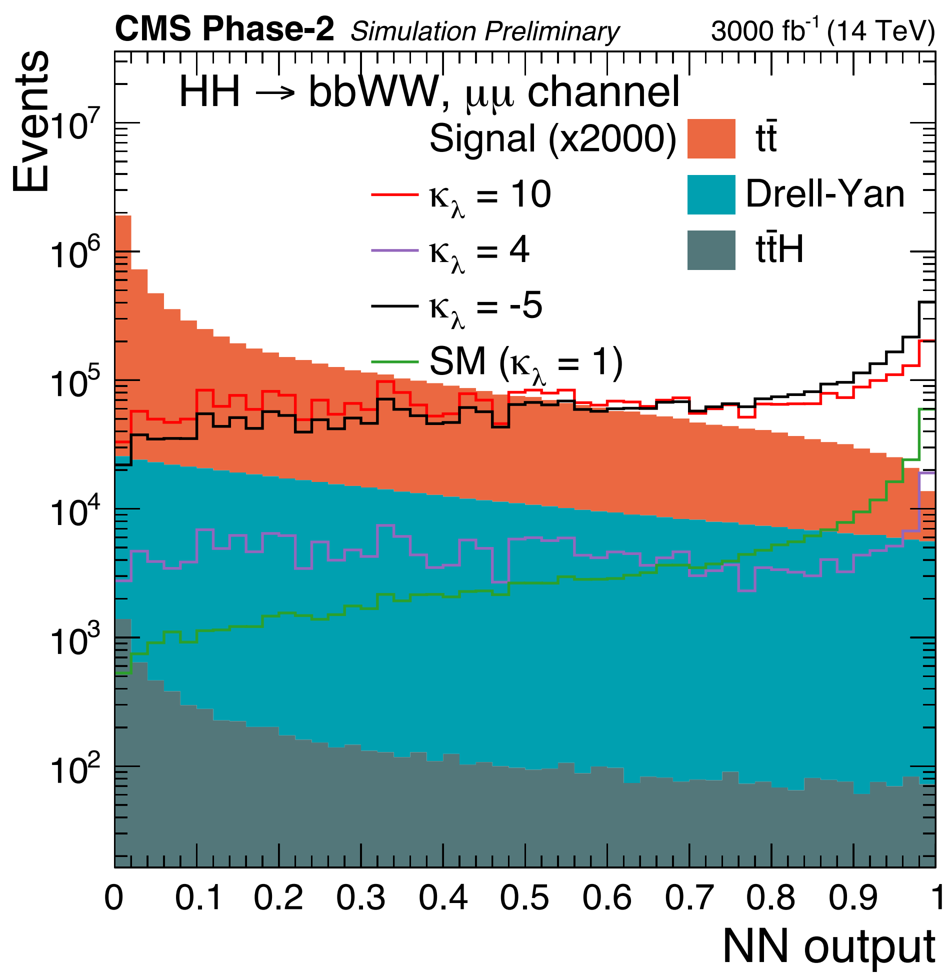
- Dedicated DELPHES analysis
- BDT-based $t\bar{t}H$ mitigation; BDT for signal-purity categories
- Extra categorization on M_{HH} (sensitivity to both SM and κ_λ variations, solving κ_λ degeneracy)

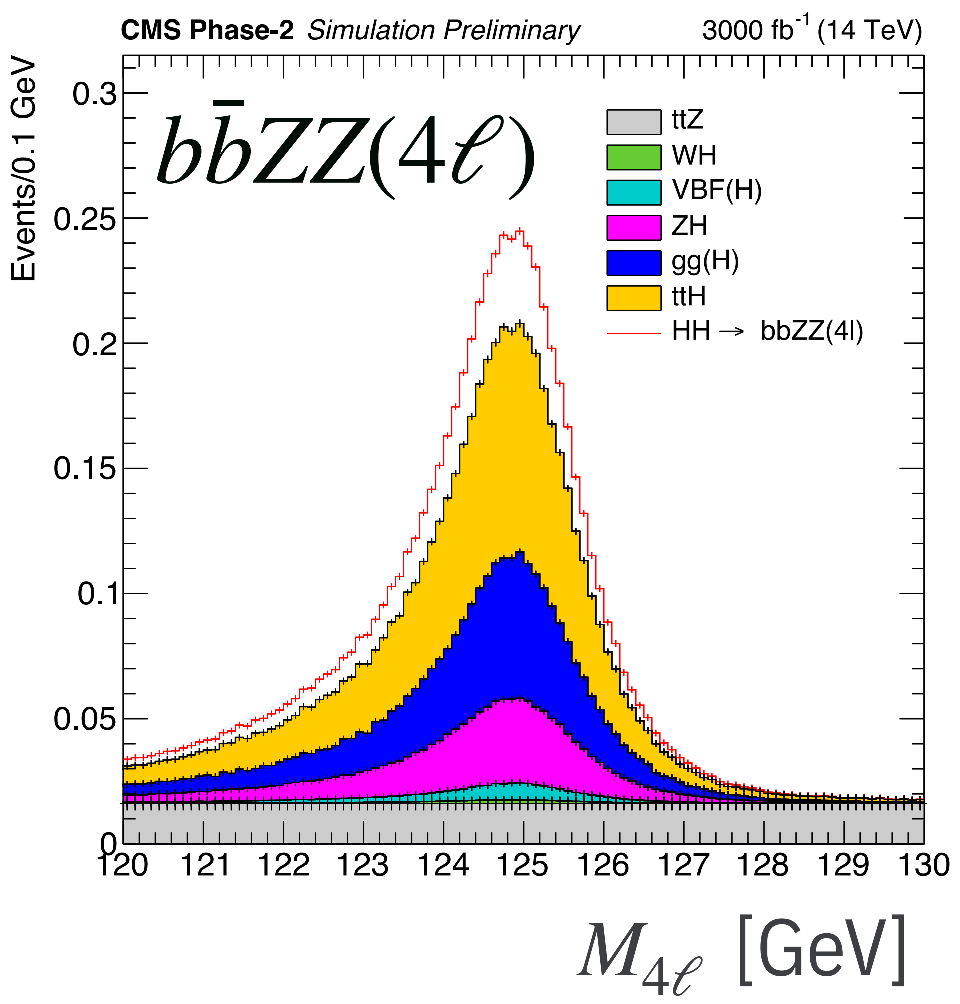


Pseudodata generated from Asimov fit to MC signal and background distributions

Other Channels:

- $HH \to b\bar{b}WW(\ell\nu\ell\nu)$:
  - (DELPHES) Based on neural network discriminants
- $HH \to b\bar{b}ZZ(4\ell)$:
  - Very low stats, single Higgs and $t\bar{t}Z$ as only backgrounds
- Less sensitive but contribute to combination





RESULTS: **SM HH CROSS SECTION**

[ATL-PHYS-PUB-2018-053]

[CMS-PAS-FTR-18-019]

SM HH Signal Significances	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau^+\tau^-$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV^*$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4\ell)$	-	0.37	-	0.37
Combination	3.5	2.8	3.0	2.6
	4.5		4.0	

Roughly ~3σ sensitivity from each experiment!

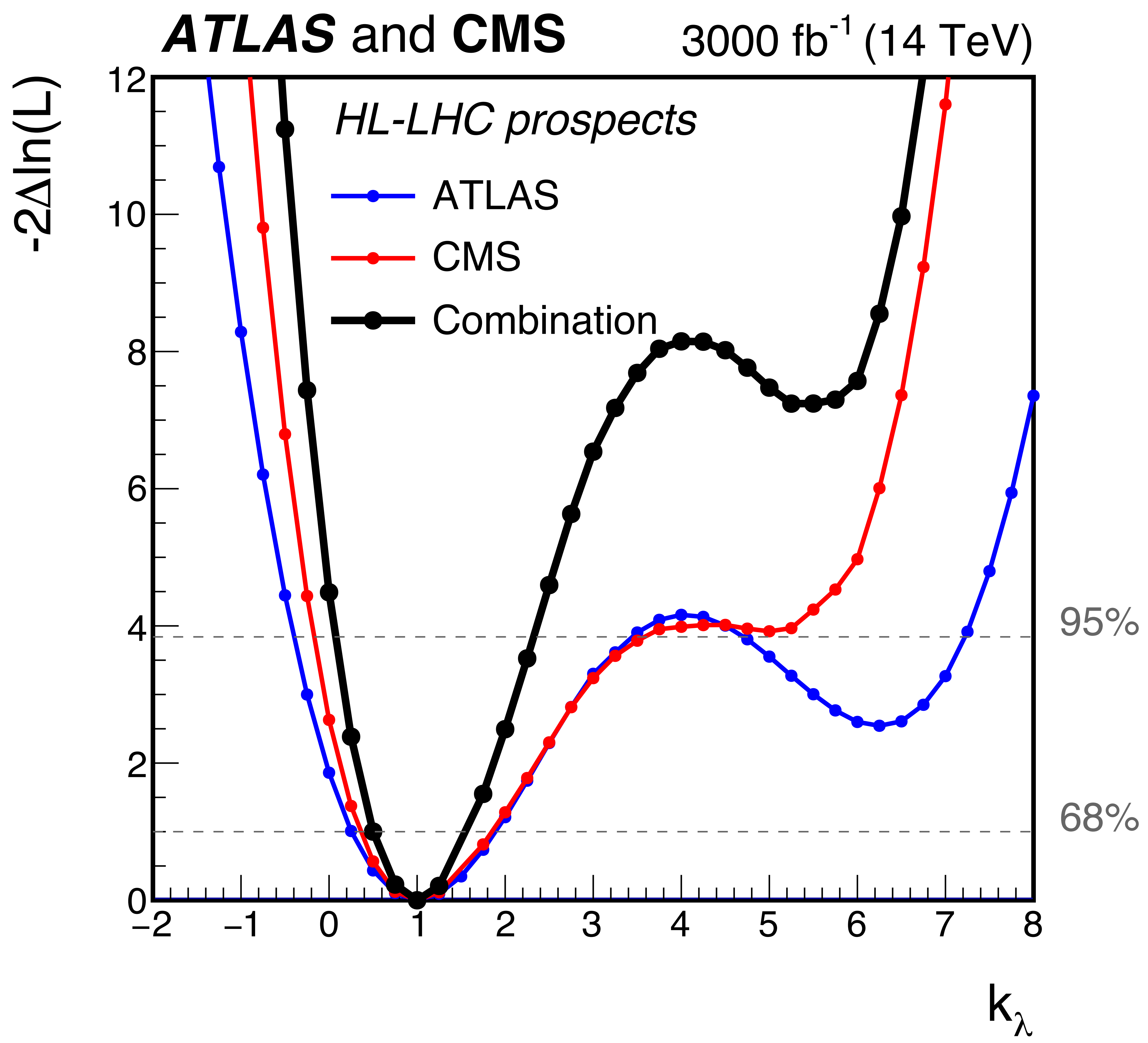
Simple ATLAS+CMS combination:
~4σ sensitivity to SM HH

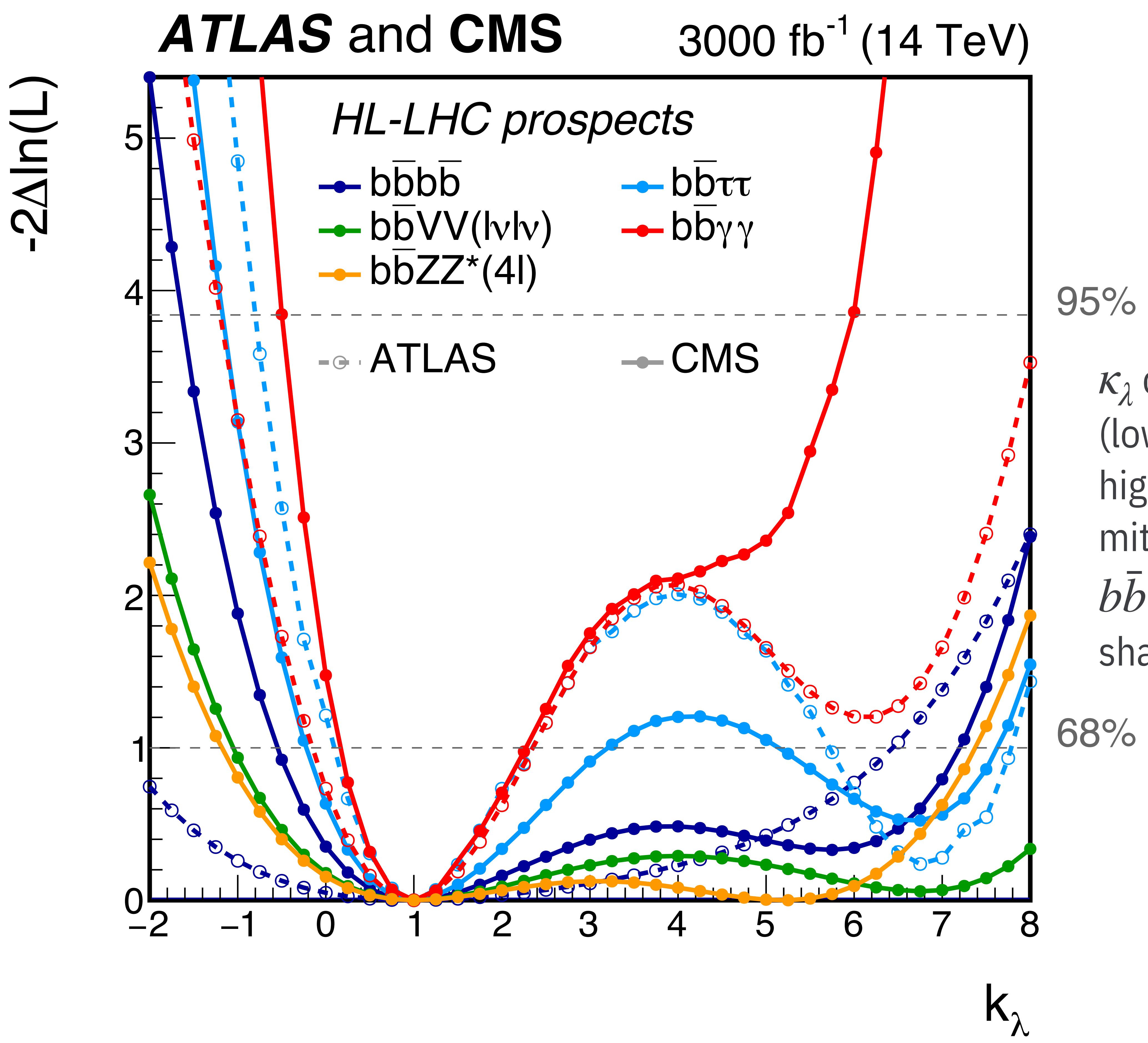
- $b\bar{b}\tau^+\tau^-$ ($b\bar{b}\gamma\gamma$) most sensitive channel in ATLAS (CMS)
- CMS $b\bar{b}VV$ channels with subleading contribution

Combination performed in the context of 1902.00134

RESULTS: κ_λ SENSITIVITY

Combination performed in the context of 1902.00134





κ_λ degeneracy (lower acceptance vs higher cross section) mitigated by CMS $b\bar{b}\gamma\gamma$ exploiting M_{HH} shape!

$b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ leading combination sensitivity: $0.1 \leq \kappa_\lambda \leq 2.3$ @ 95 % CL

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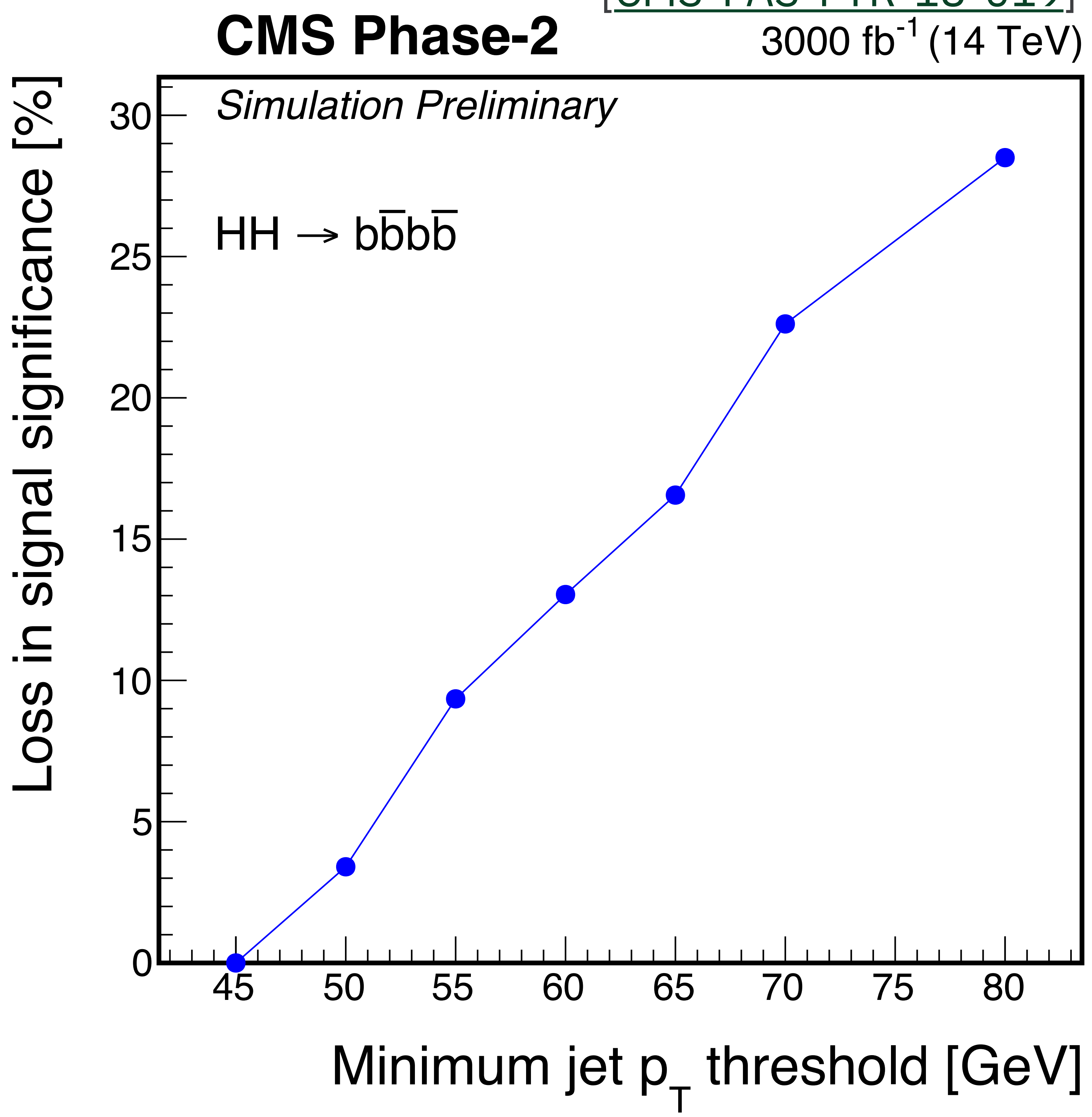
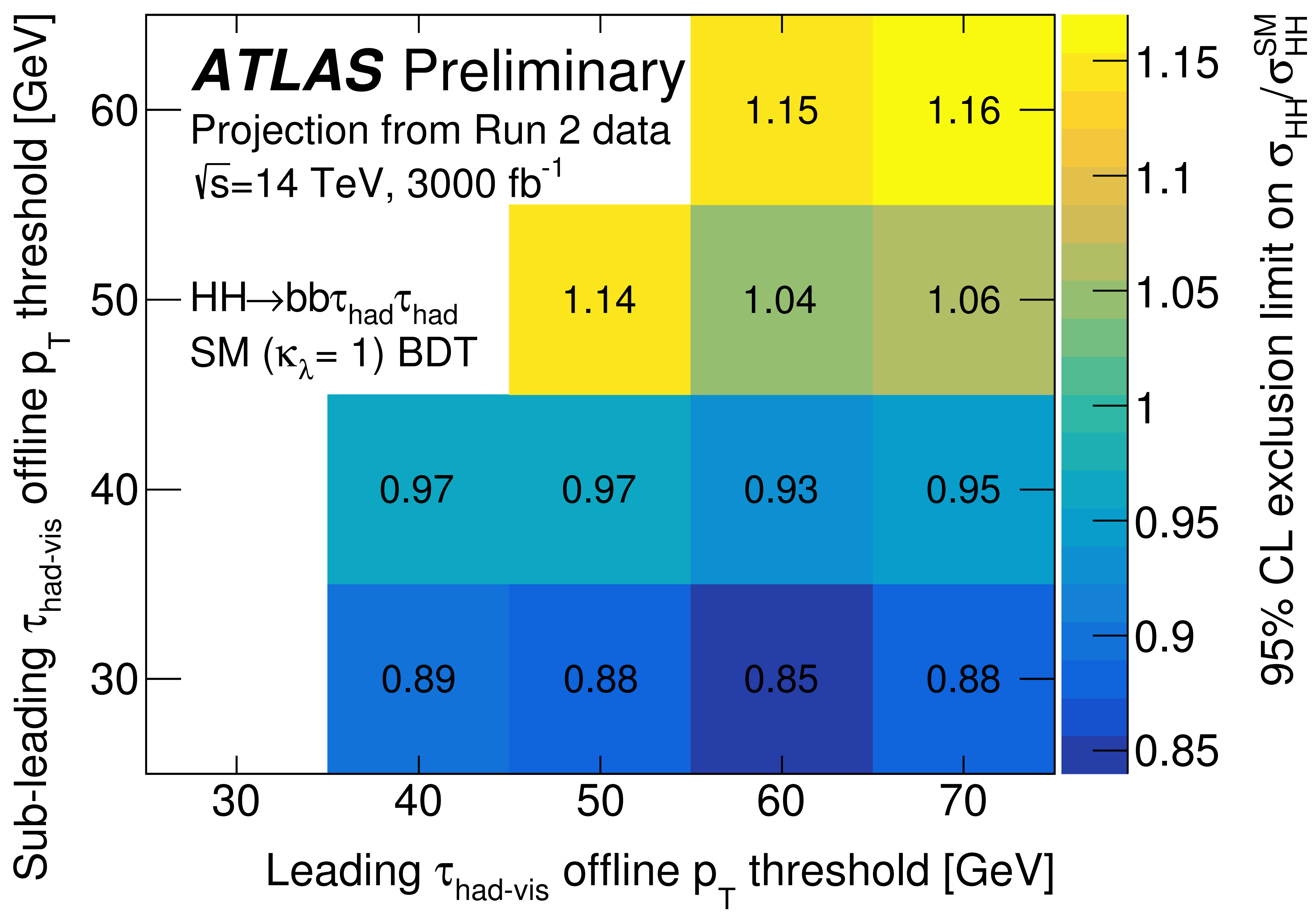
Common Challenges: **Triggers**

[CMS-PAS-FTR-18-019]



[ATL-PHYS-PUB-2018-053]



HL-LHC trigger and DAQ performance extremely important for HH sensitivity!

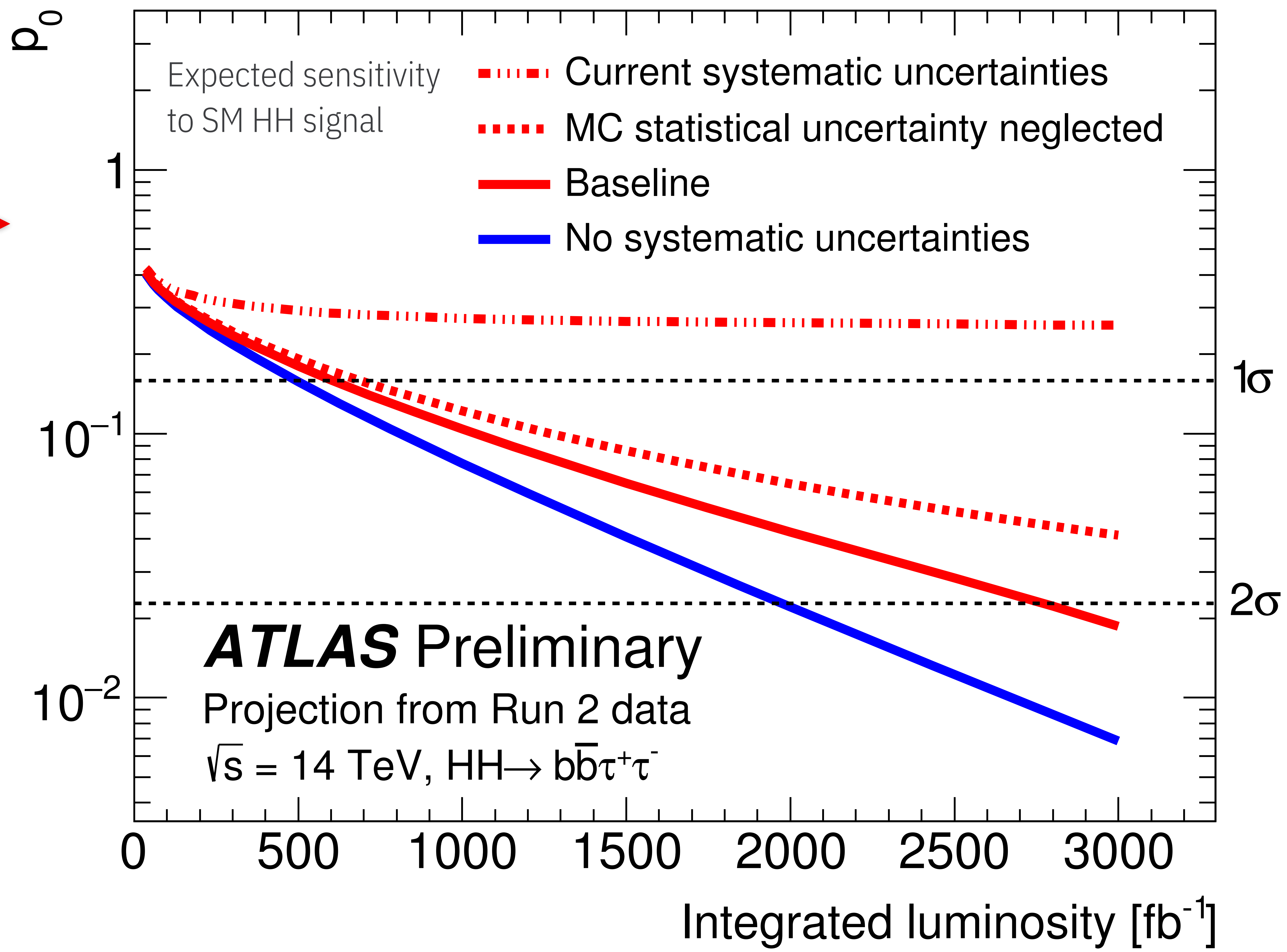
- "Nominal" results assume Run 2-like triggers (optimistic), but performance studied for different scenarios for channels with higher trigger dependencies ($b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$)

Common Challenges: **Theory & MC**

MC statistical precision have strong impact on channels such as $b\bar{b}\tau^+\tau^-$

- Nominal extrapolated results decouple MC statistics, but impact quantified

[ATL-PHYS-PUB-2018-053]



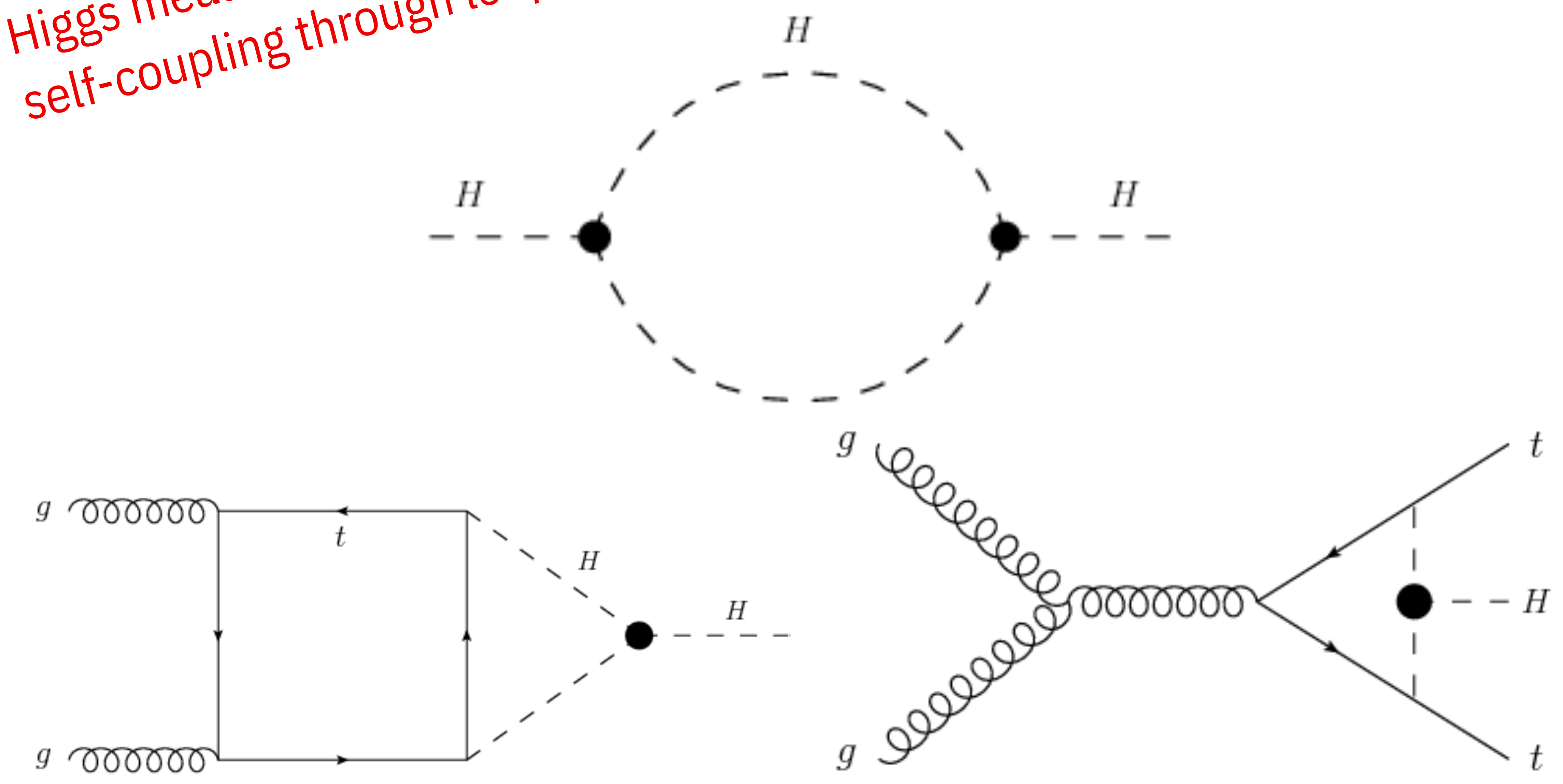
ATLAS+CMS also assume theory uncertainties to be reduced by x2 (calculations improvements)

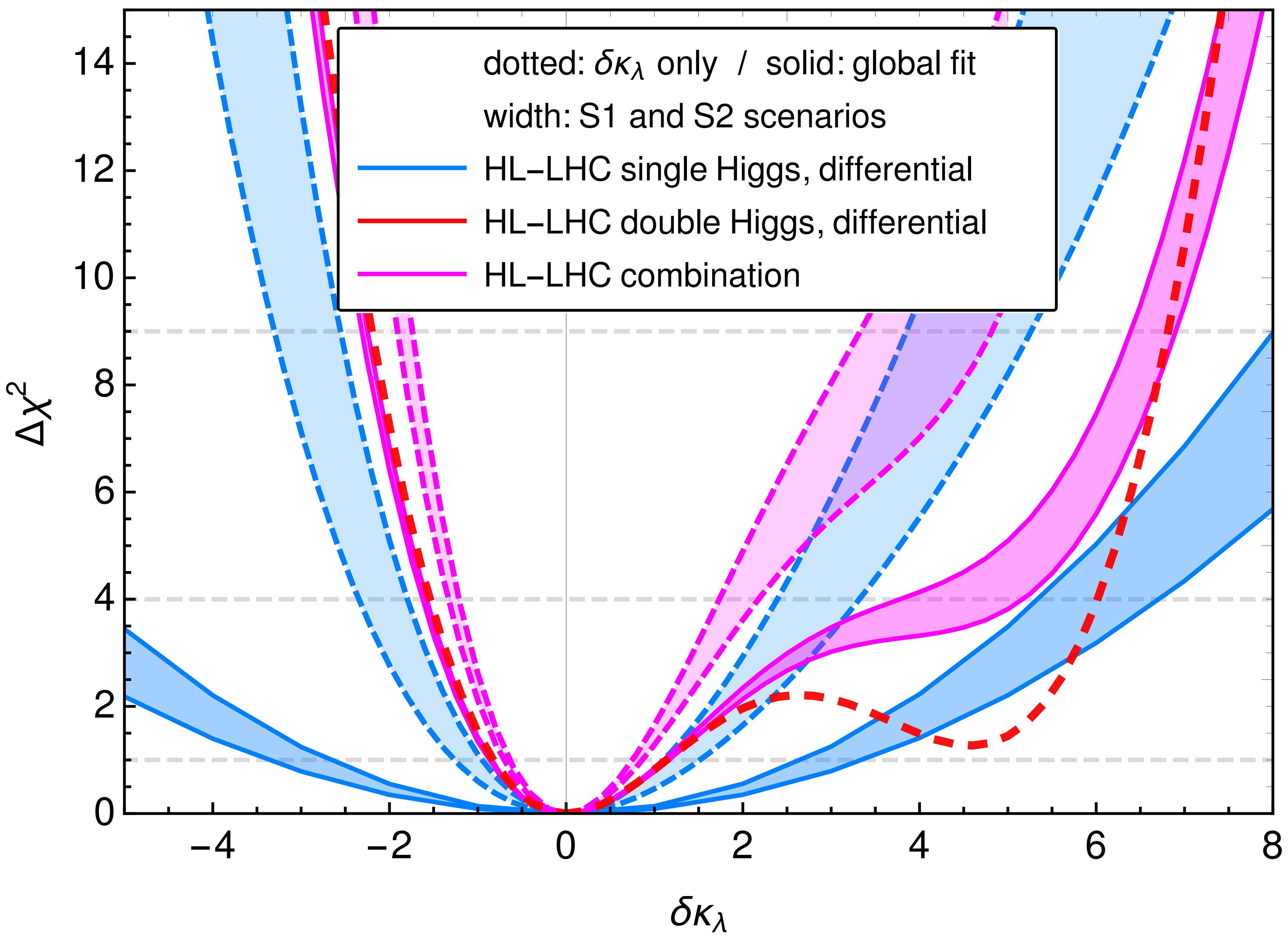
- Important for *constraining single Higgs* backgrounds, particularly for $b\bar{b}\gamma\gamma$
  - Potentially improve single Higgs with constraints directly from data

Beyond Tree-Level

Combination performed in the context of 1902.00134

Higgs measurements sensitive to self-coupling through loops





Combining differential Higgs+HH measurements helps constrain κ_λ

- Especially useful when HH self-coupling measurement becomes sensitive to other Higgs couplings (profile them in single Higgs analyses)

CONCLUSIONS

"Coffee break" discussion after parallel sessions (16:15-16:30):
https://stanford.zoom.us/j/98997054638
(same pwd as current session)

HH production is key to understand the Standard Model

- Still inaccessible with current LHC dataset.

HL-LHC experiments *should* be ideal tools for HH process

- *Current prospects:* ~4σ sensitivity to SM, $0.1 \leq \kappa_\lambda \leq 2.3$ @ $95\,\%$ CL (ATLAS+CMS)
  - Need to ensure HL-LHC detector performances are optimal enough for this result
- ATLAS and CMS HL-LHC trigger systems need to be optimized to ensure discovery!
  - Low energy events are particularly important for constraining κ_λ, but very challenging to trigger under PU 200

Extra:

- Indirect constraints κ_λ (single Higgs measurements) will be important, particularly with 3000 fb^{-1}
- VBF HH can also help unlocking HH physics (e.g., HHVV coupling, c_{2V}) and will be particularly benefited by HL-LHC upgrades (VBF tagging, PU suppression) - *no prospects so far,* first ATLAS Run 2 dedicated analyses out*!*

Backup

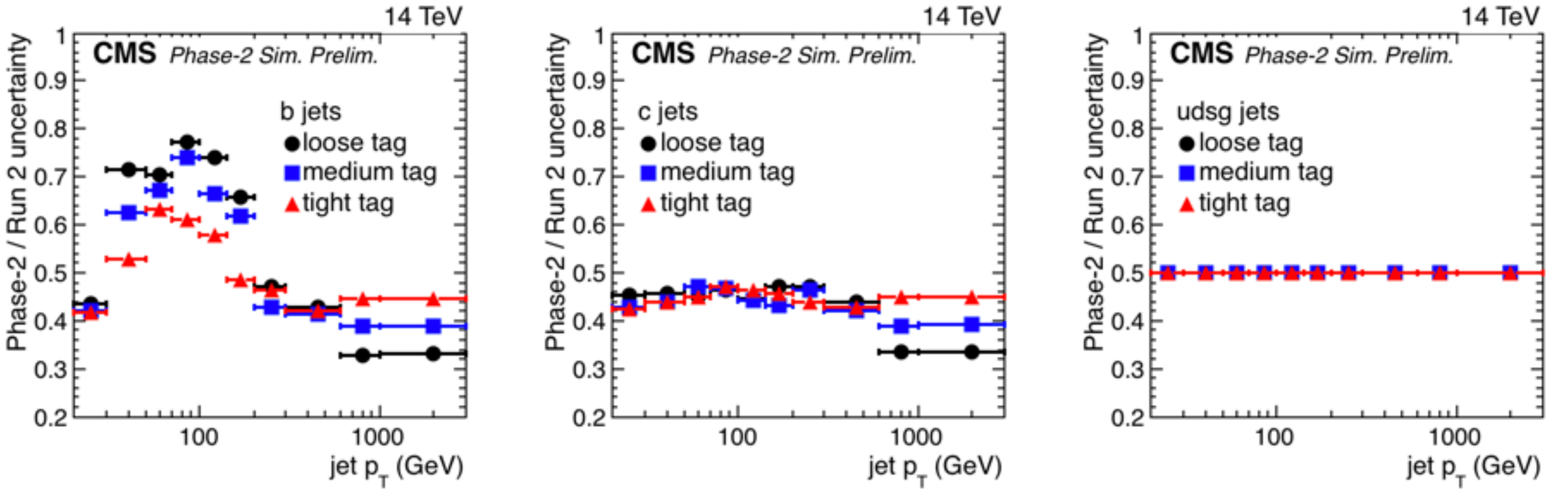
Summary of HL-LHC Uncertainties

Source	Uncertainties
Luminosity	1-1.5%
Muon efficiency (ID, iso)	0.1-0.4%
Electron Efficiency (ID, iso)	0.5%
Tau efficiency (ID, trigger, iso)	5% (if dominant 2.5%)
Photon efficiency (ID, trigger, iso)	2%
Jet Energy Scale	1-2.%
Jet Energy Resolution	1-3%
b-jet tagging efficiency	1%
c-jet tagging efficiency	2%
light jet mis-tag rate	5% (at 10% mis-tag rate)

Summary of the systematic uncertainties used to extrapolate the results at the HL-LHC by ATLAS and CMS

- Kinematic dependencies and the operating points are taken into account when applicable

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics



Assuming b-tagging systematic uncertainties reducing by 2x