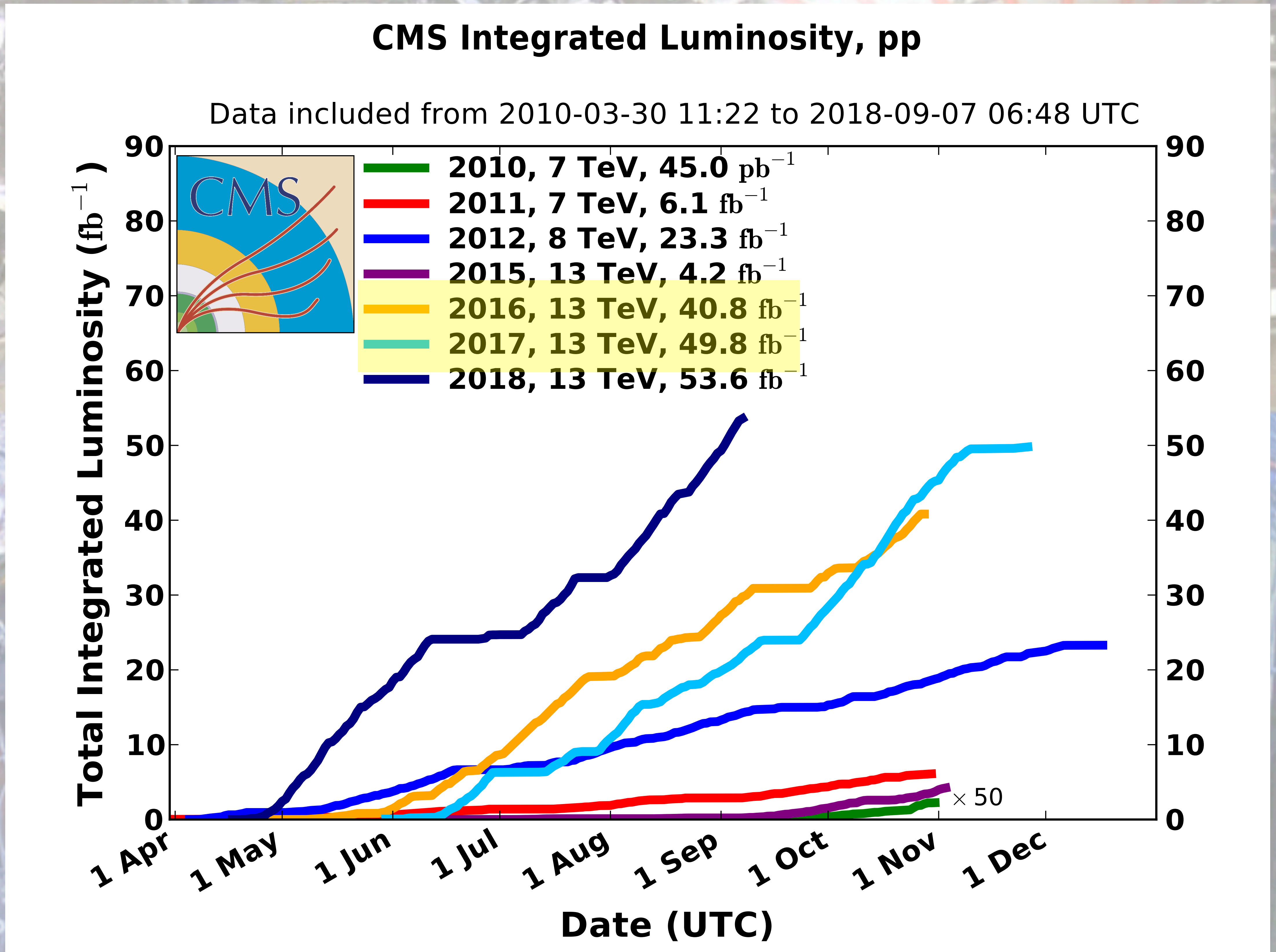
Double Higgs Production at Colliders Workshop
4-8 September 2018 , FNAL

Experimental Summary

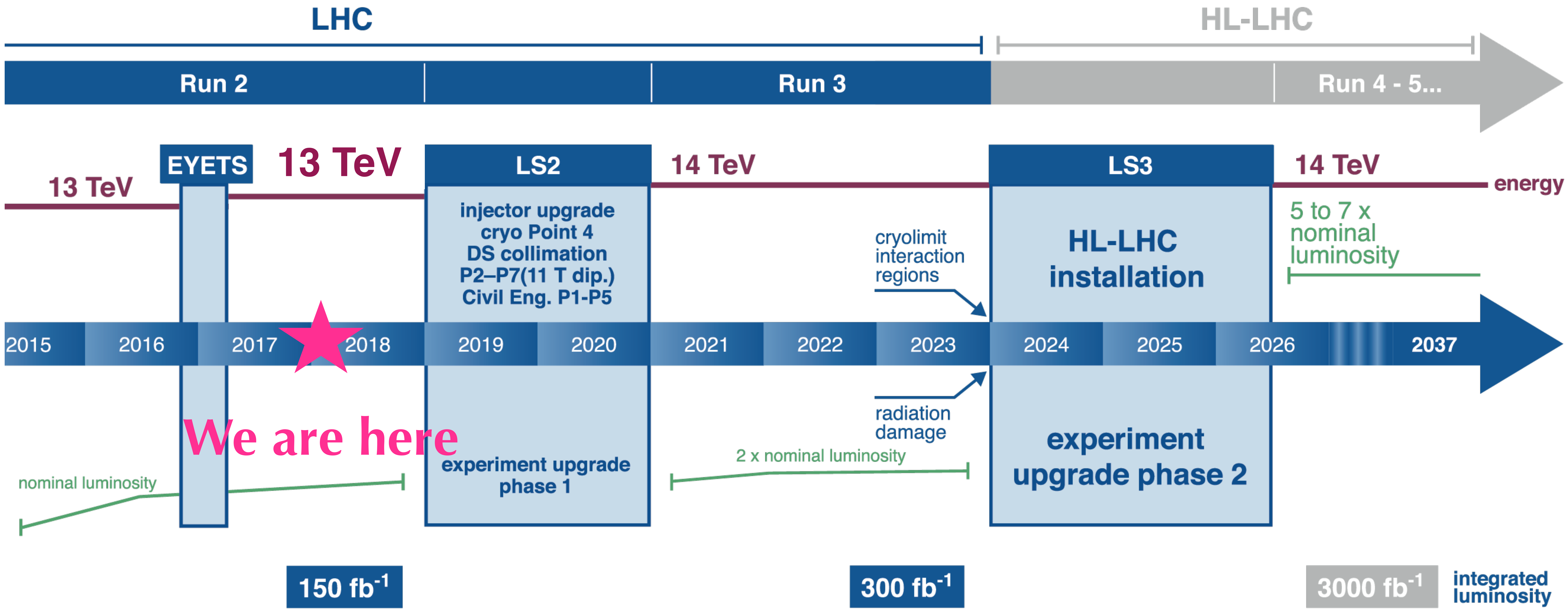
thanks to all the participants for the fruitful discussions
and the sessions conveners for their inputs!

LHC is performing extremely well
~140/fb delivered at 13 TeV to

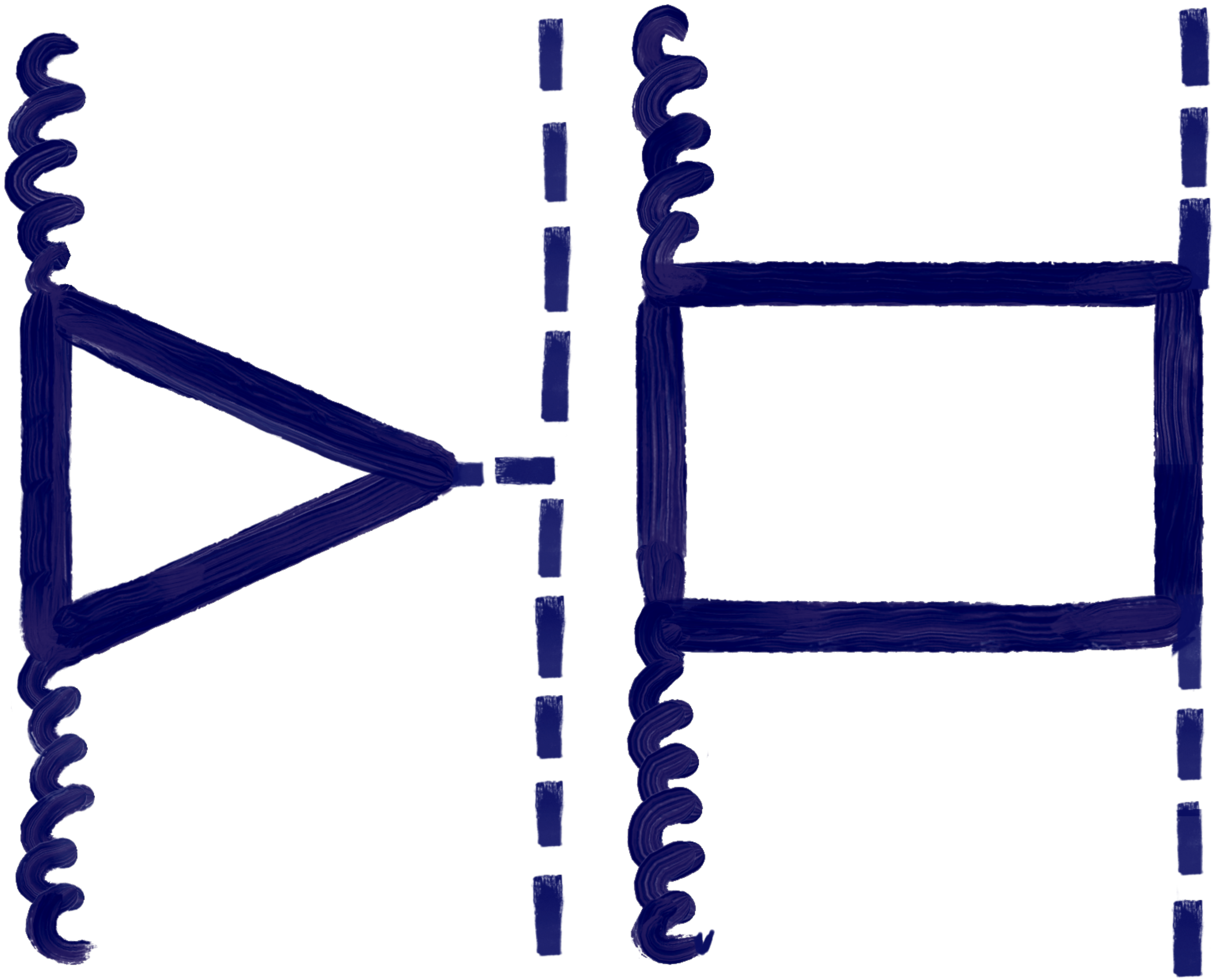
ATLAS EXPERIMENT CMS



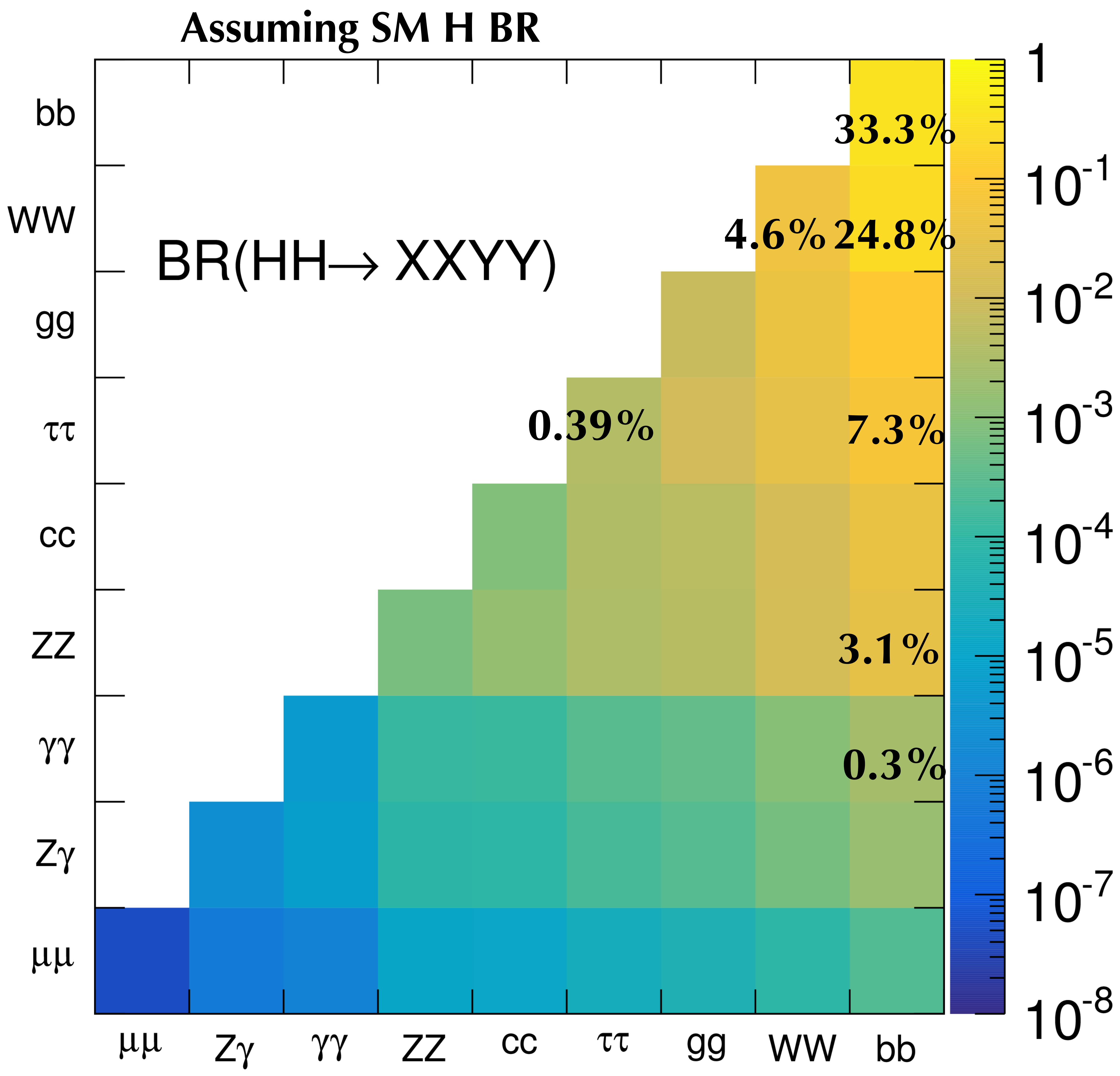
LHC → HL-LHC



HL-LHC will enable precision measurements of H properties (couplings, self-couplings,…) and to probe the existence of very rare new physics processes



HH, a variety of final states



Complementarity of the channels

H($b\bar{b}$)

highest BR: larger statistics

high b-tag efficiency and low fake rate

multi-light jets background is highly reduced

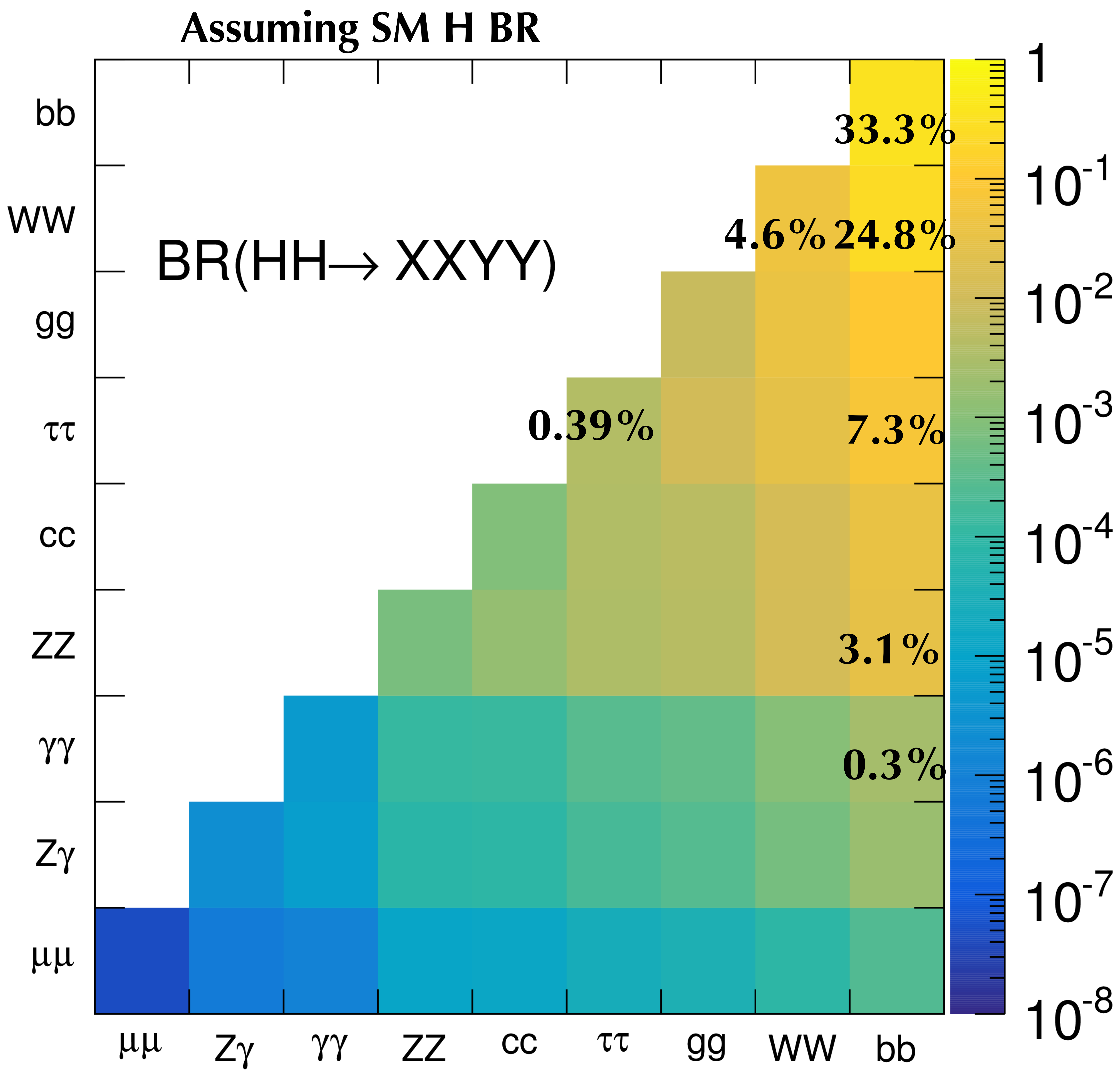
H(γγ)

simple topology

excellent mass resolution

Limited by small BR

HH, a variety of final states



Complementarity of the channels

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highest BR: larger statistics

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H(γγ)

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excellent mass resolution

Limited by small BR

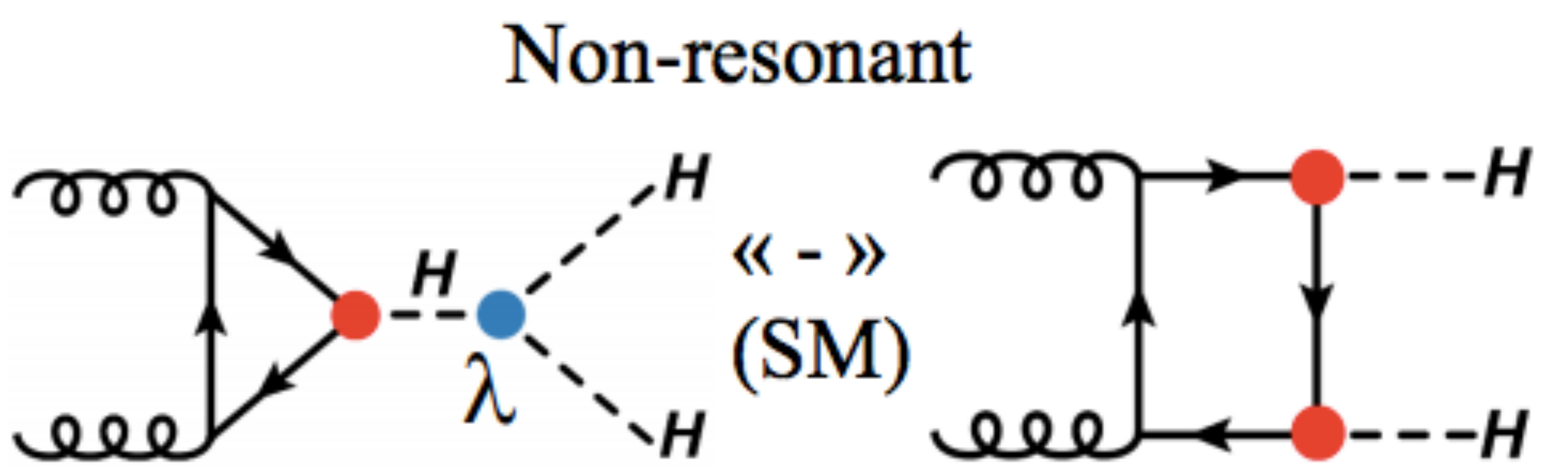
We are exploiting several possible combinations including all the possible final states…

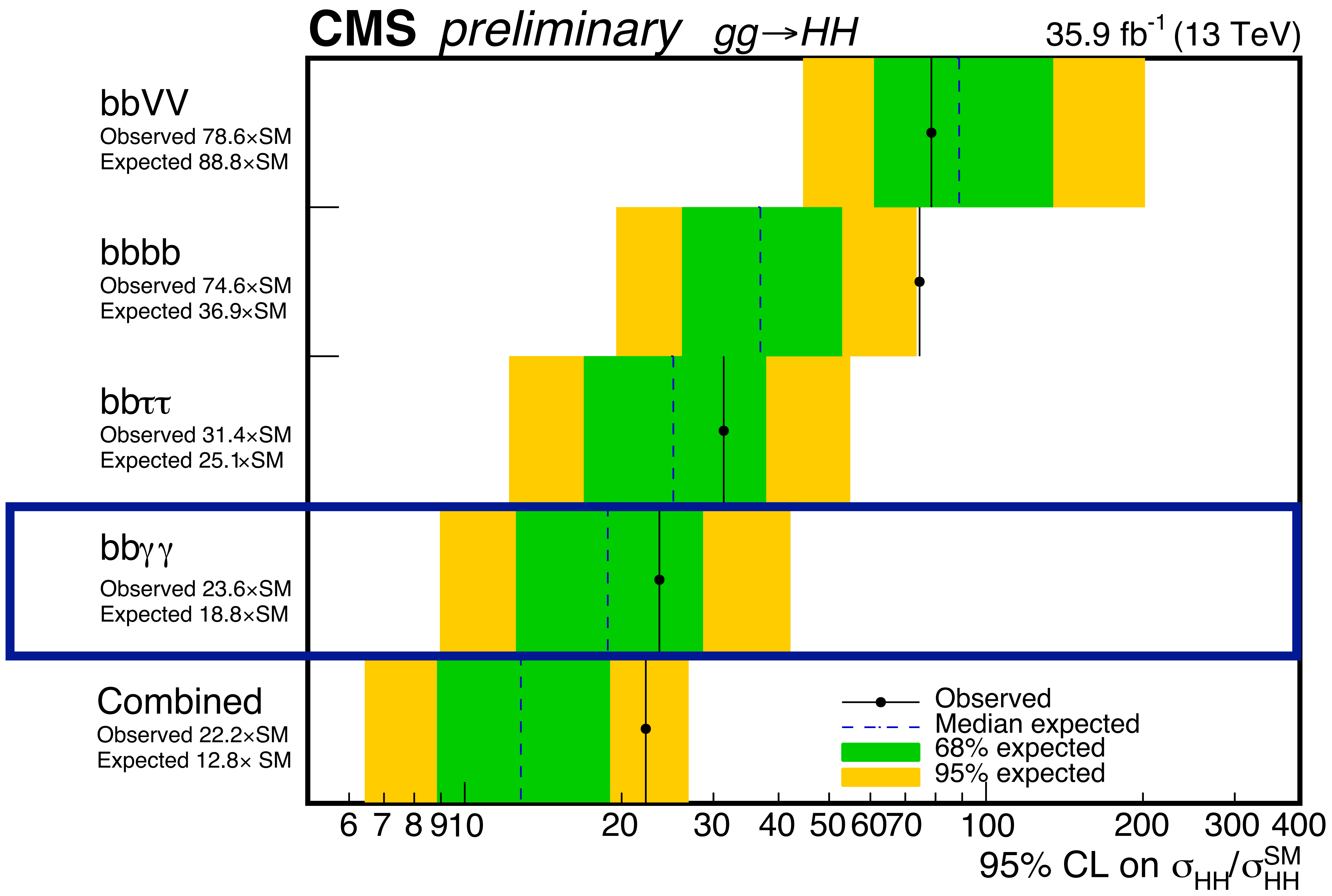
Summary^2

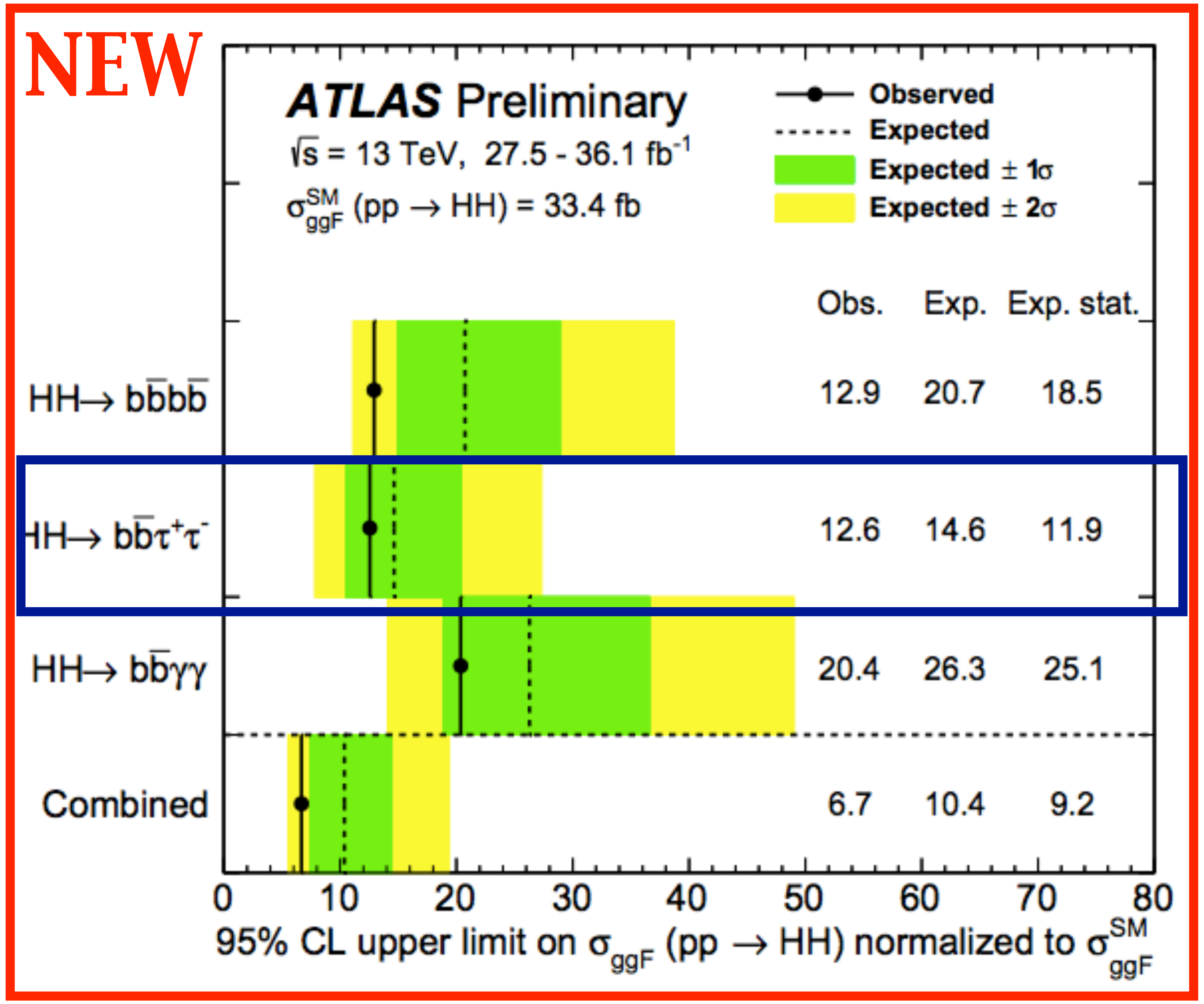
Non Resonant HH

Similar sensitivity from several channels to SM HH production

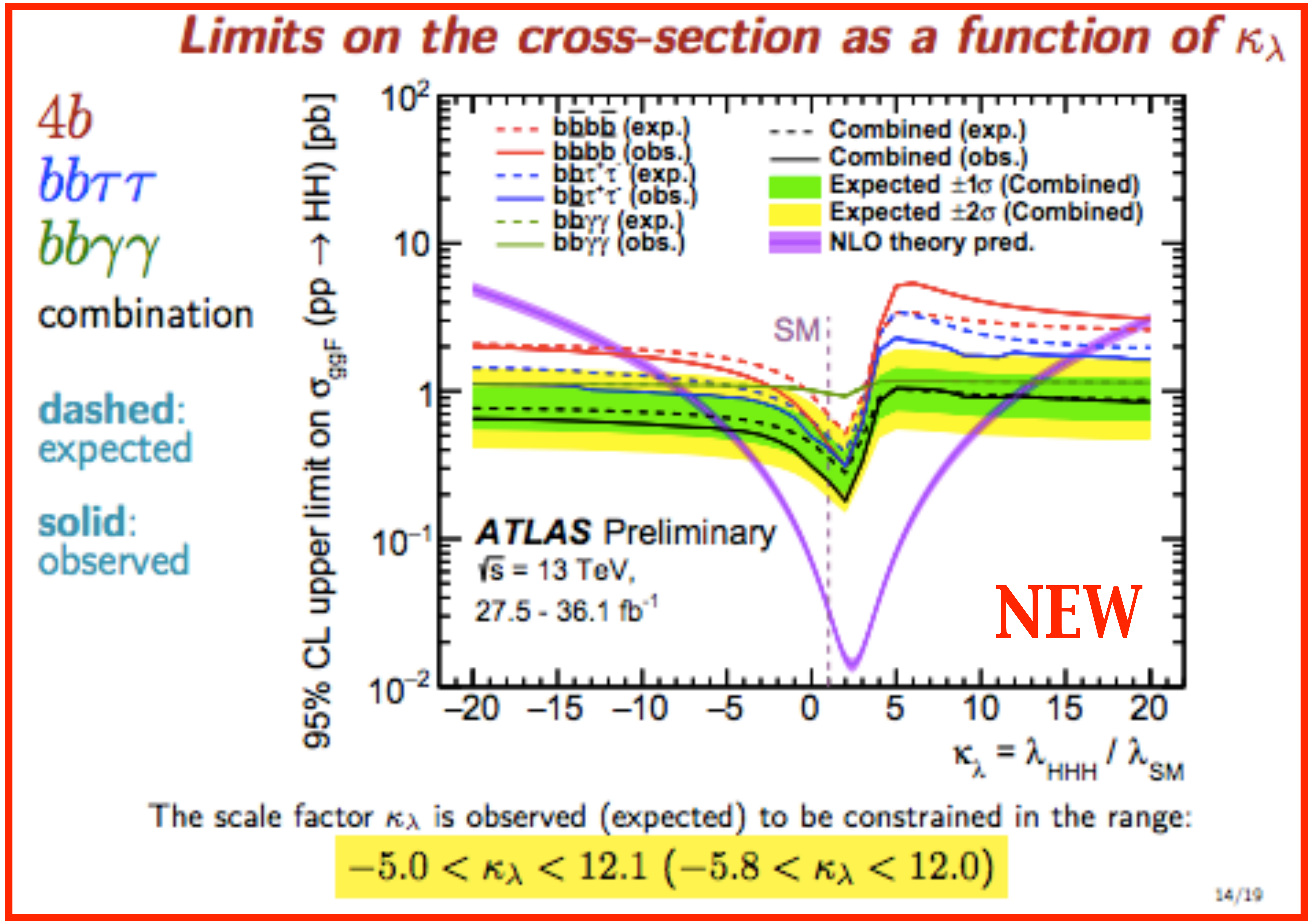
- SM production limits reach less than **20 x SM**
- Best channels are $b\bar{b}\tau\tau$ (ATLAS) and $b\bar{b}\gamma\gamma$ (CMS)

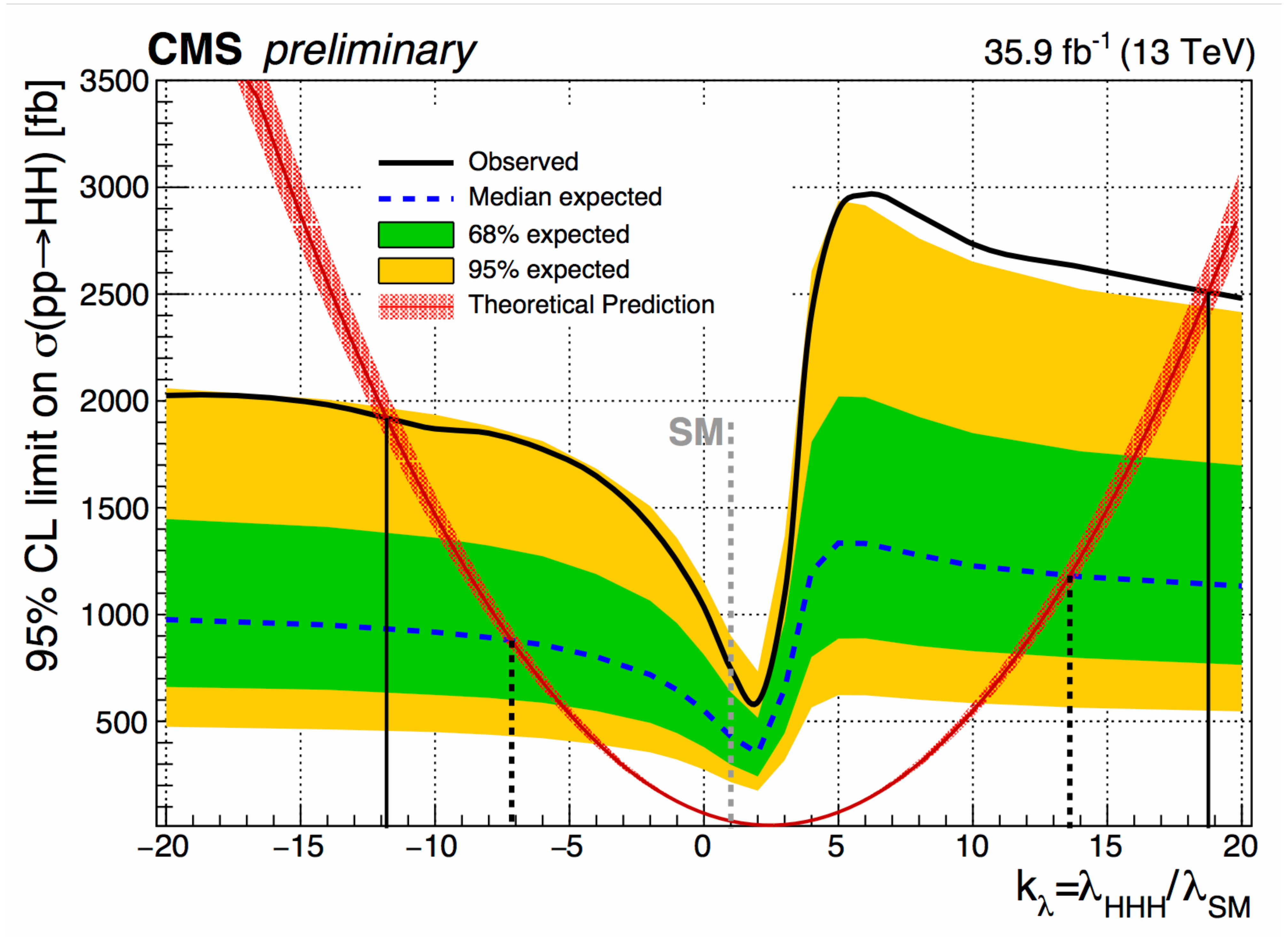






Constraints on k_λ

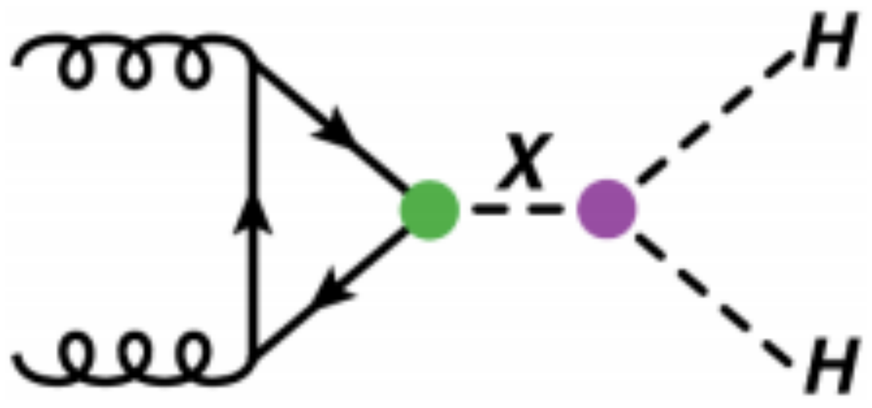




$\kappa_\lambda \in [-11.8, 18.8]$ assuming SM top-H coupling

Resonant HH Summary

Resonant



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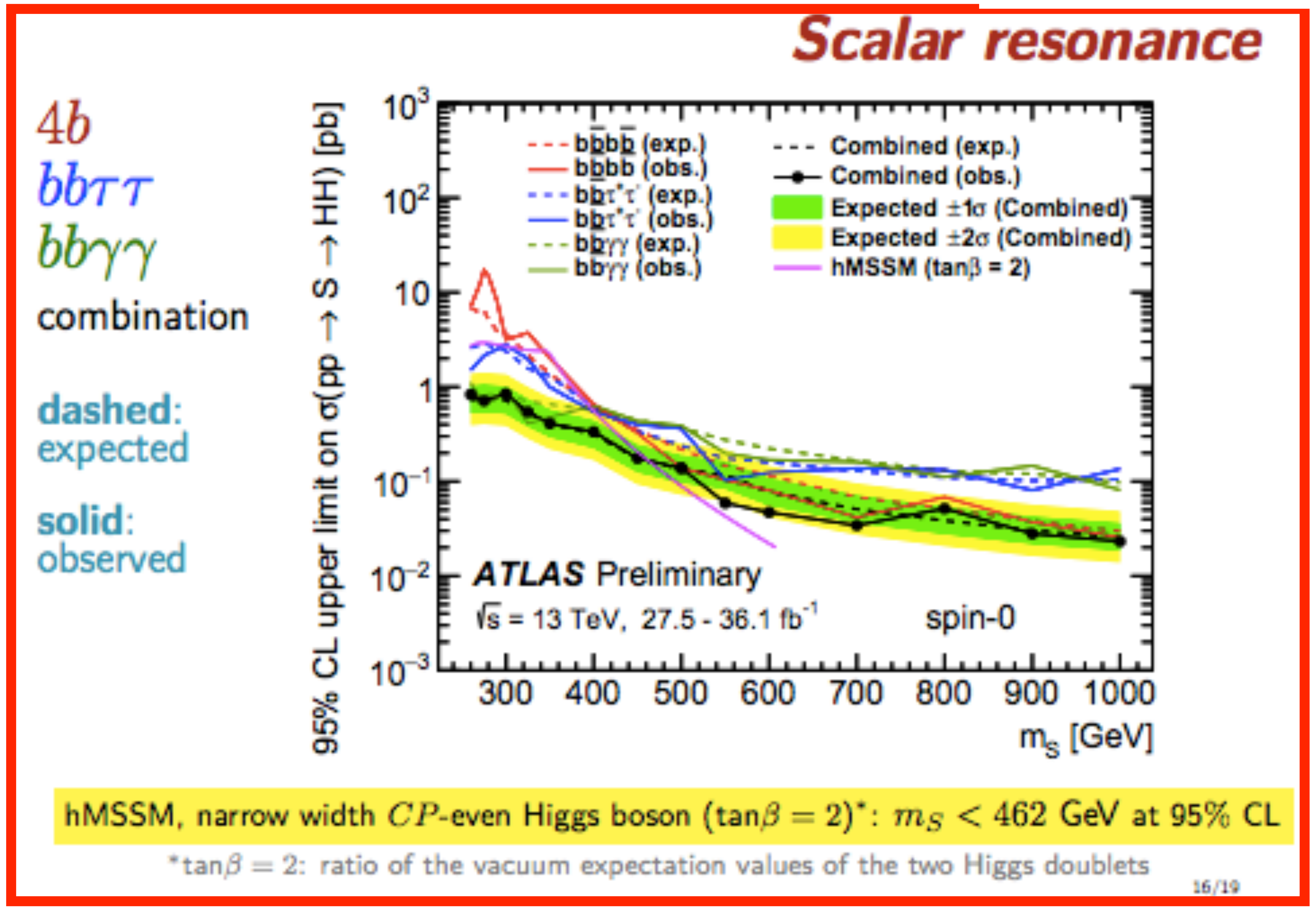
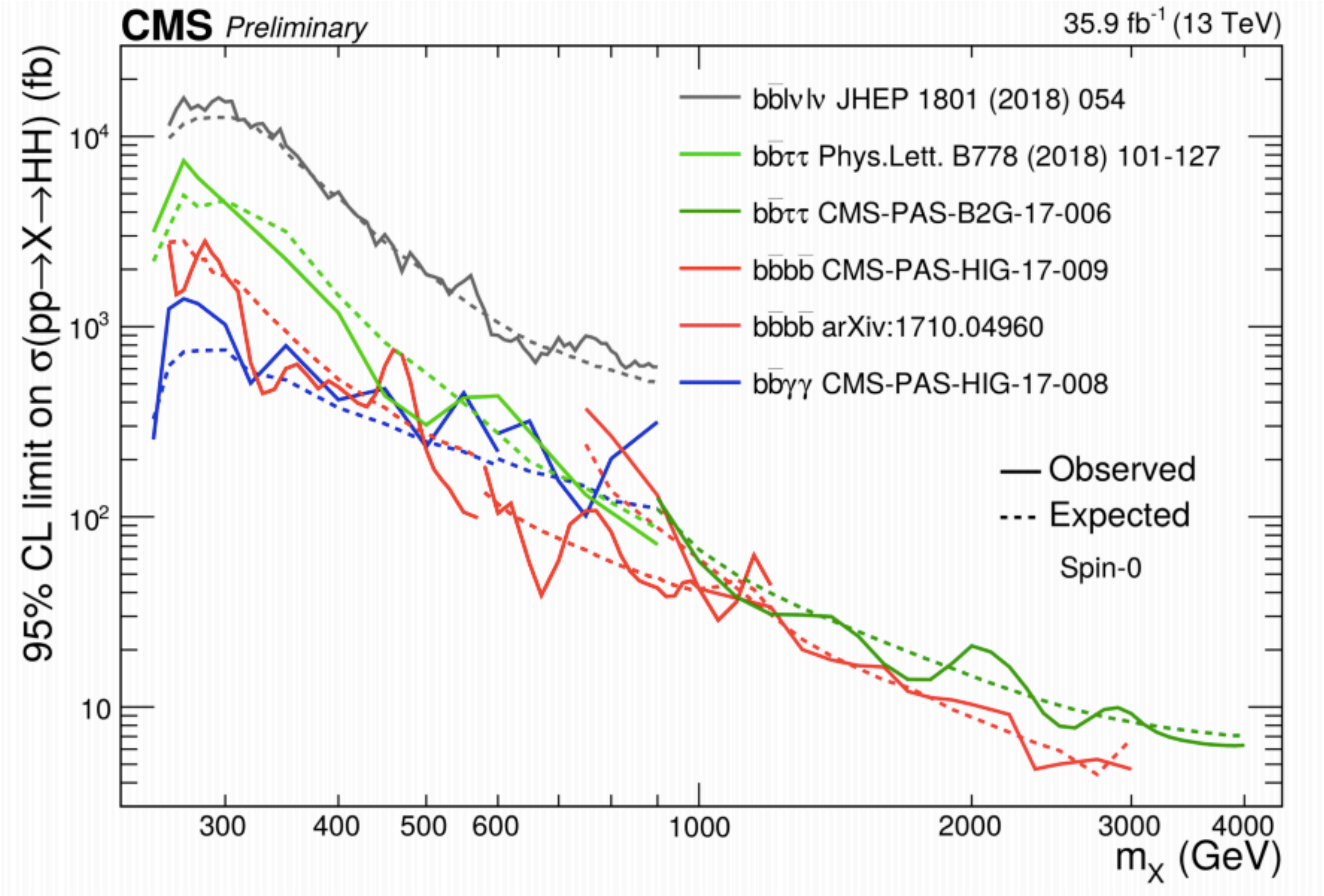




Our experimental tools

Michael Kagan

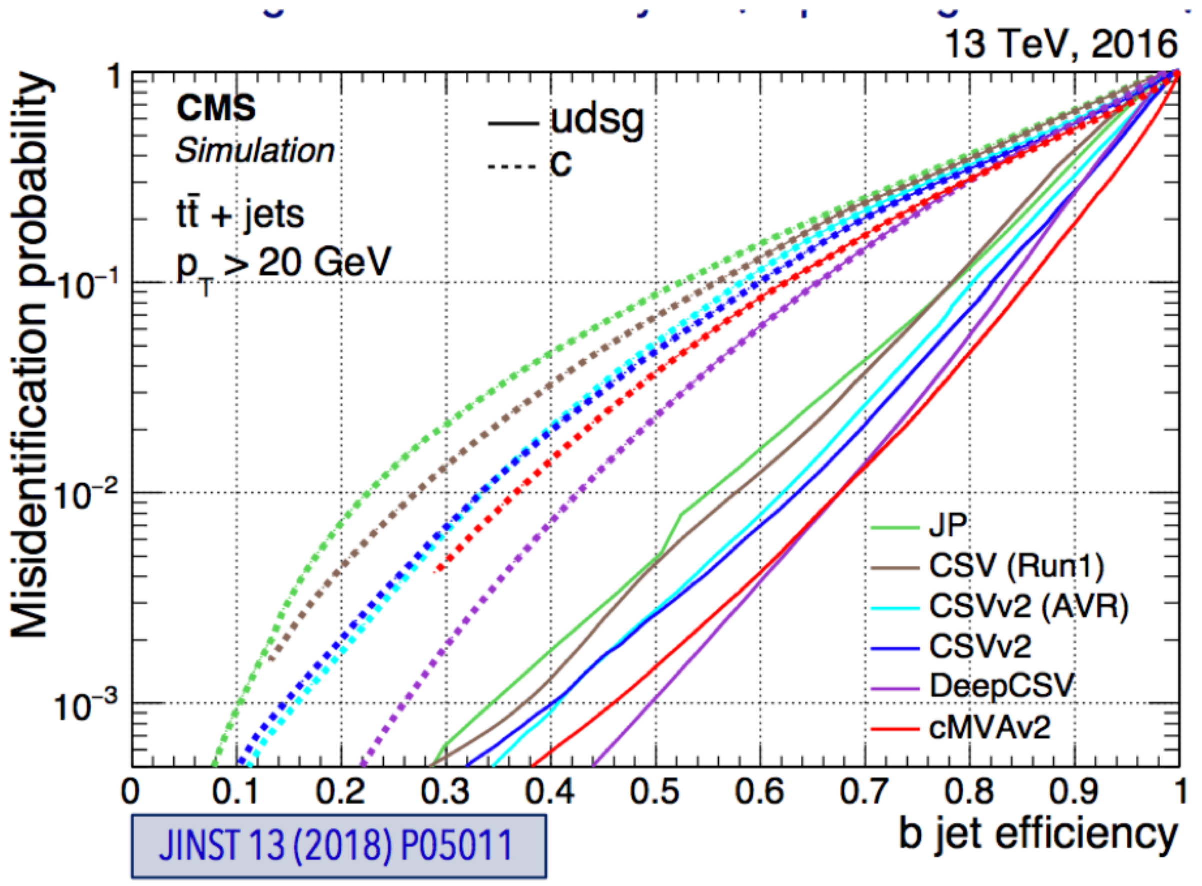
B-Tagging

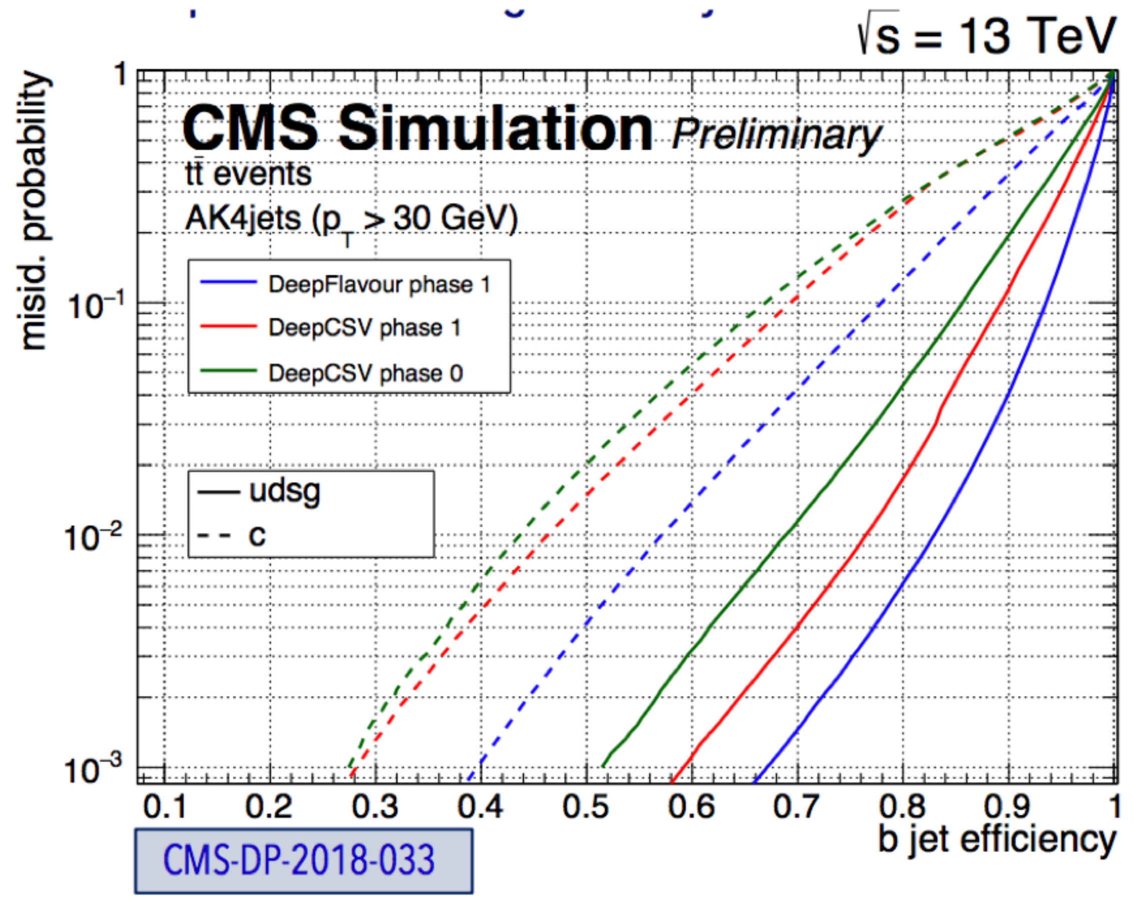
- State of the art performance from combining several low level impact parameter and secondary vertexing algorithms

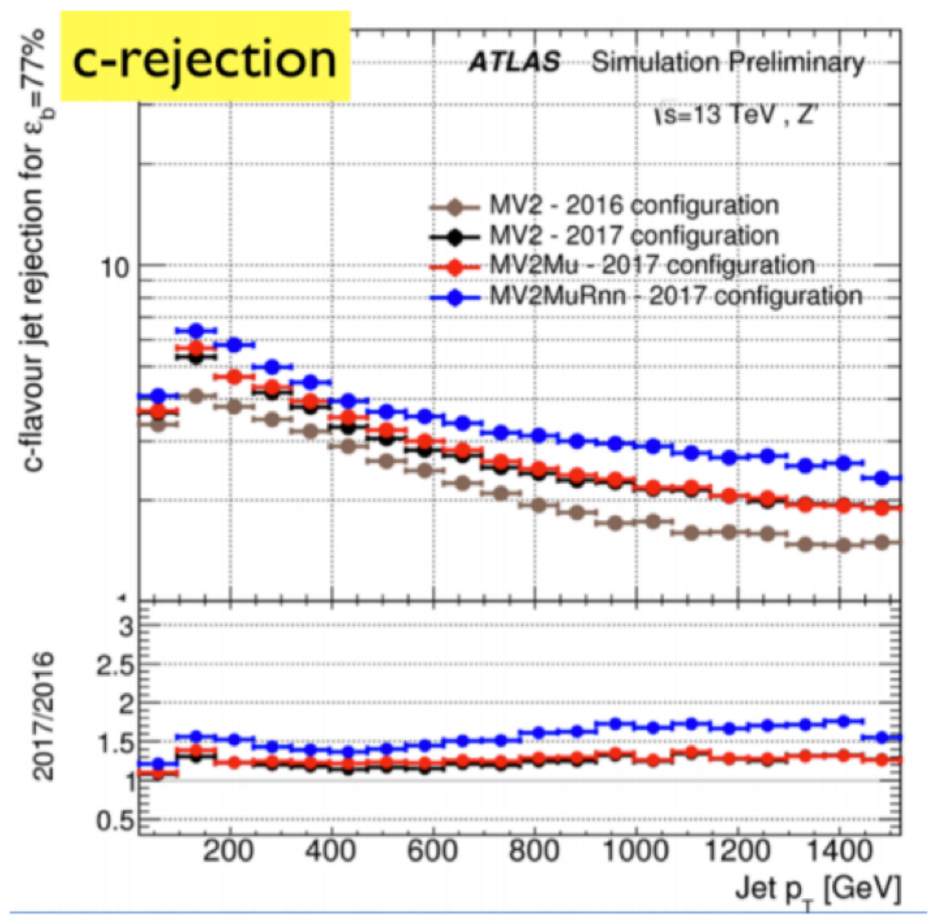
- Some differences in algorithms between experiments, and in pixel detectors, leads to differing performance

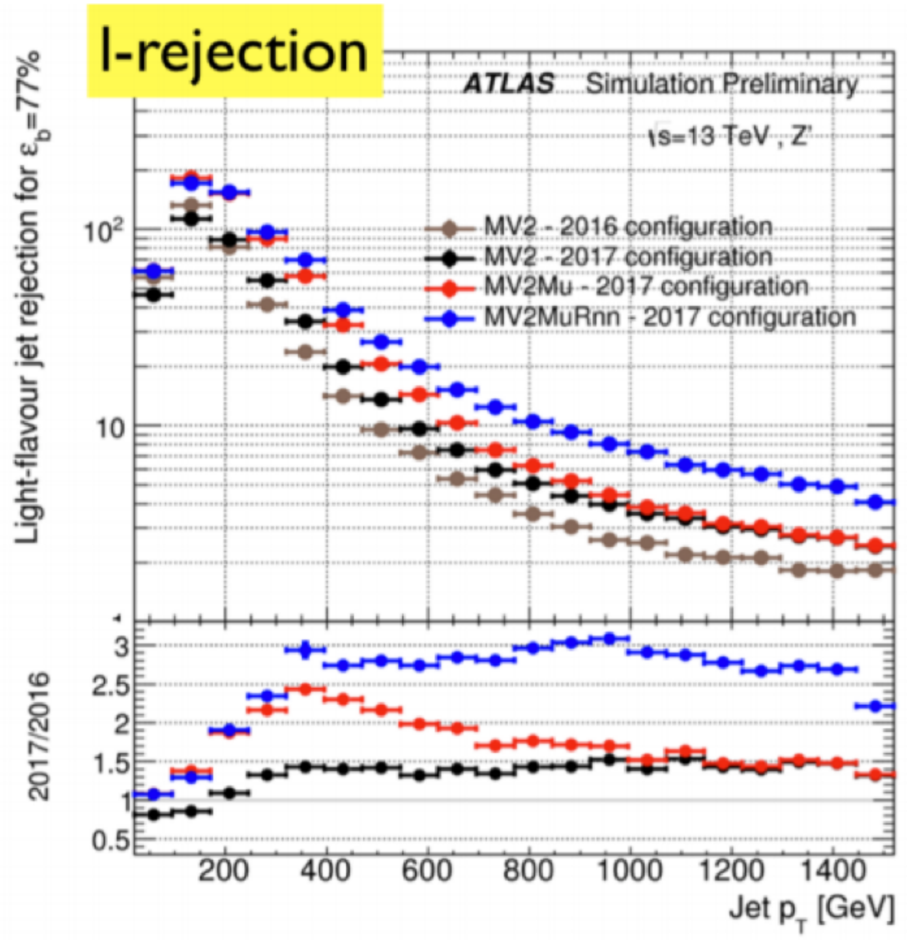
- A direct comparison based on public plots with the same truth labeling and same jet selection is still needed.

- Significant algorithm development, based heavily on applications for ML algorithms, is underway

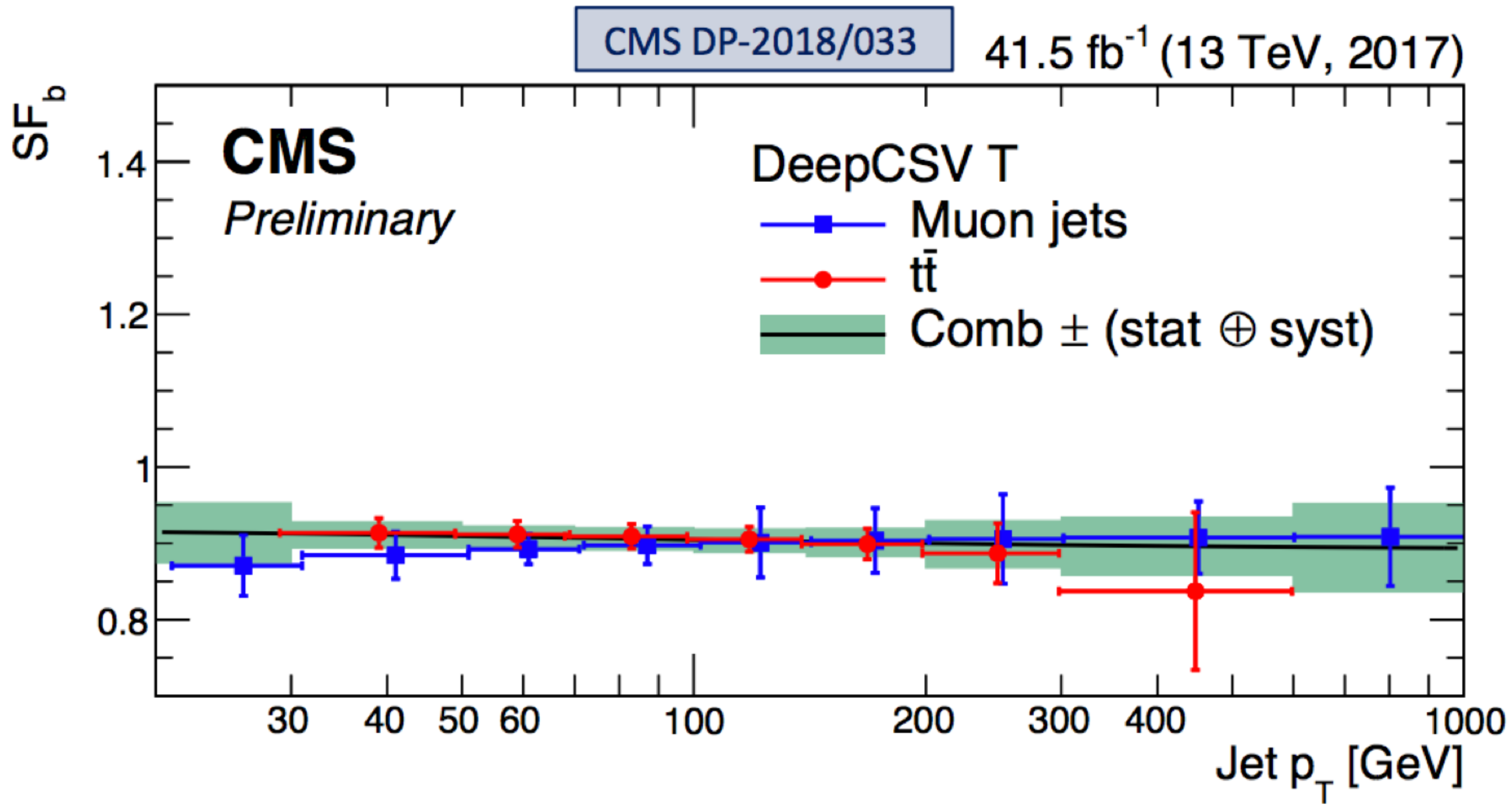


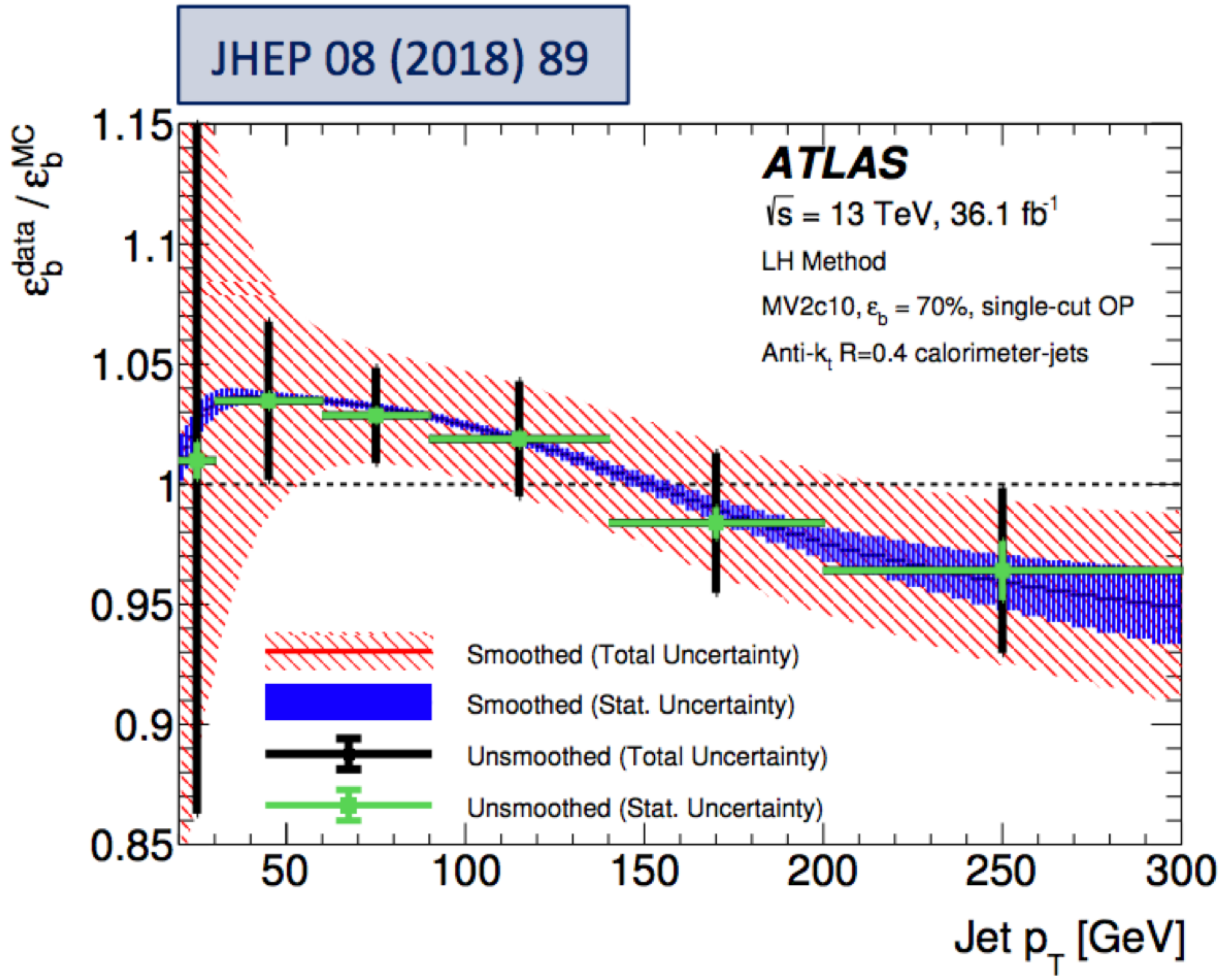






- Calibrations for current taggers will understood, often with few percent level uncertainties
  - Includes calibrations for bottom, charm, and light jets

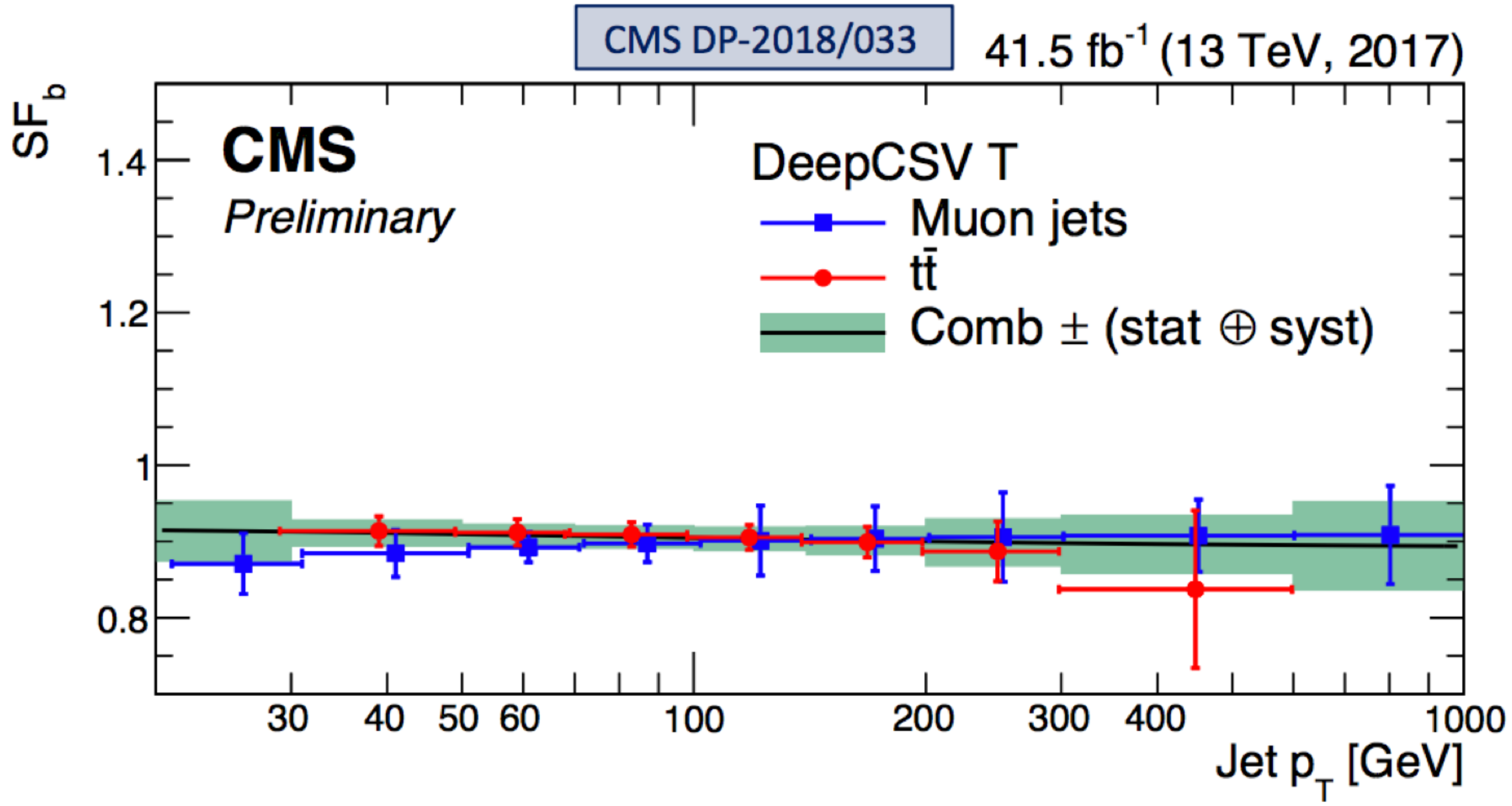




- Calibrations for current taggers will understood, often with few percent level uncertainties
  - Includes calibrations for bottom, charm, and light jets

With more advanced ML approaches, it will require more careful validation of MC prediction (if moving to raw observables)

CMS DP-2018/033



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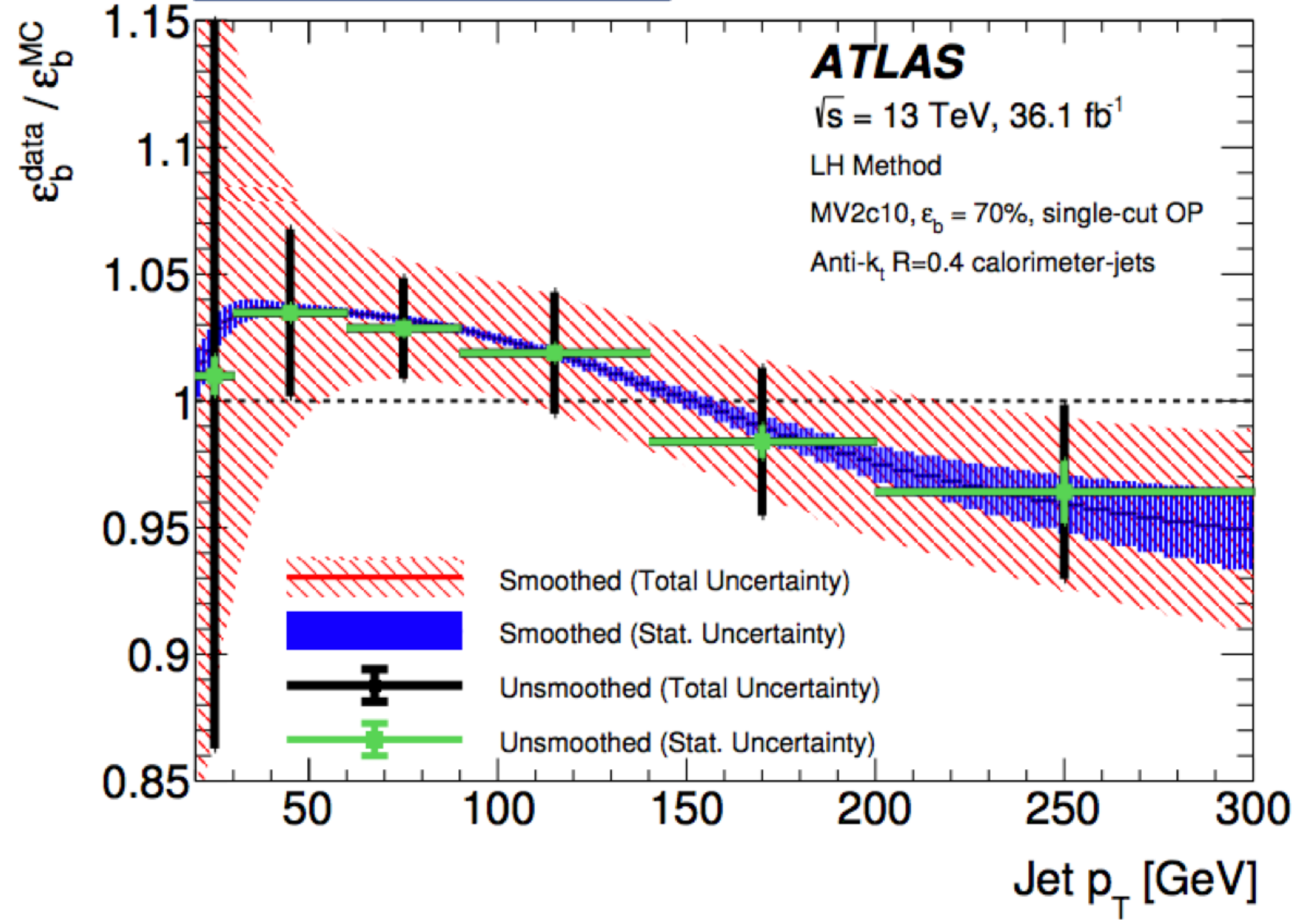
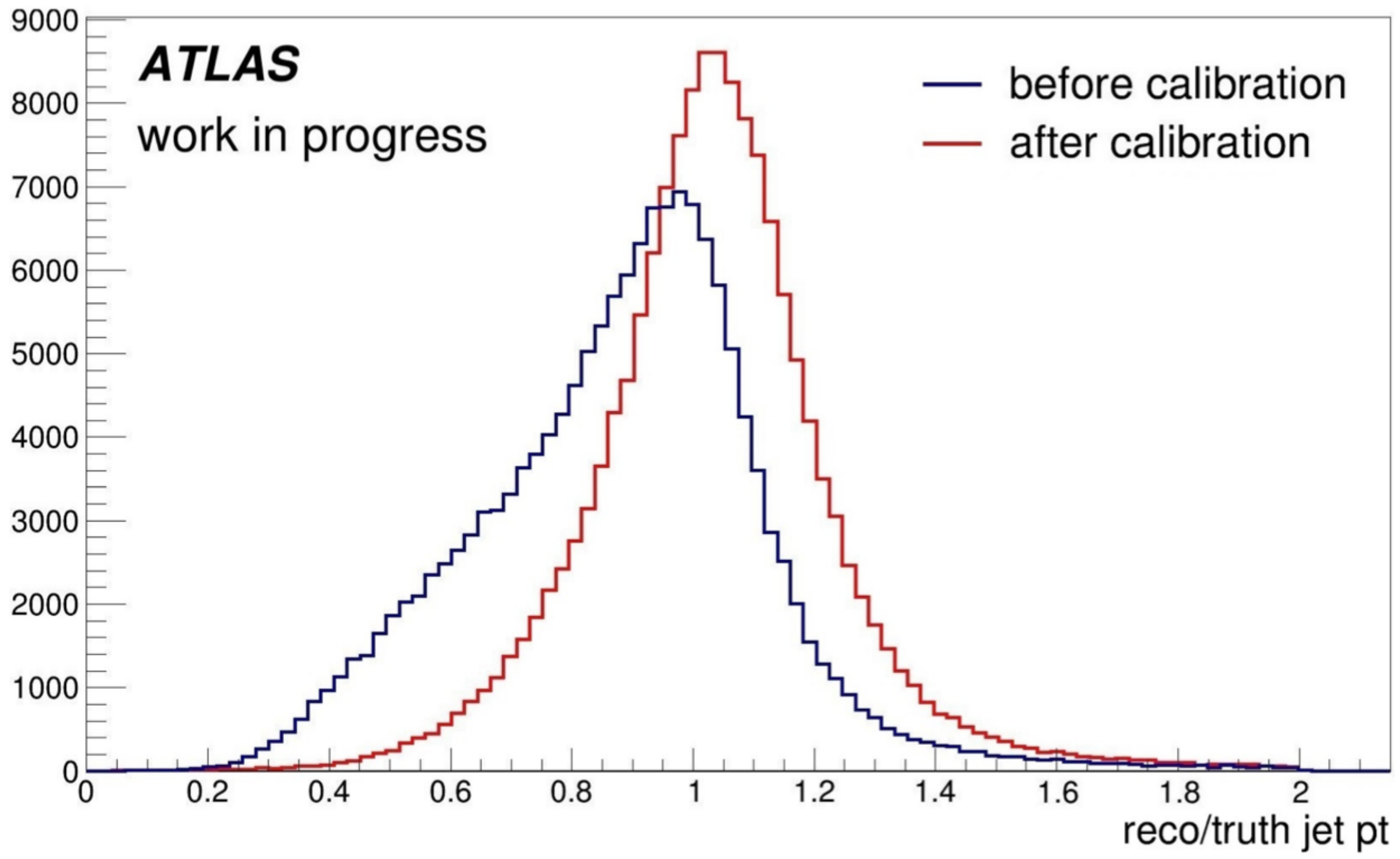
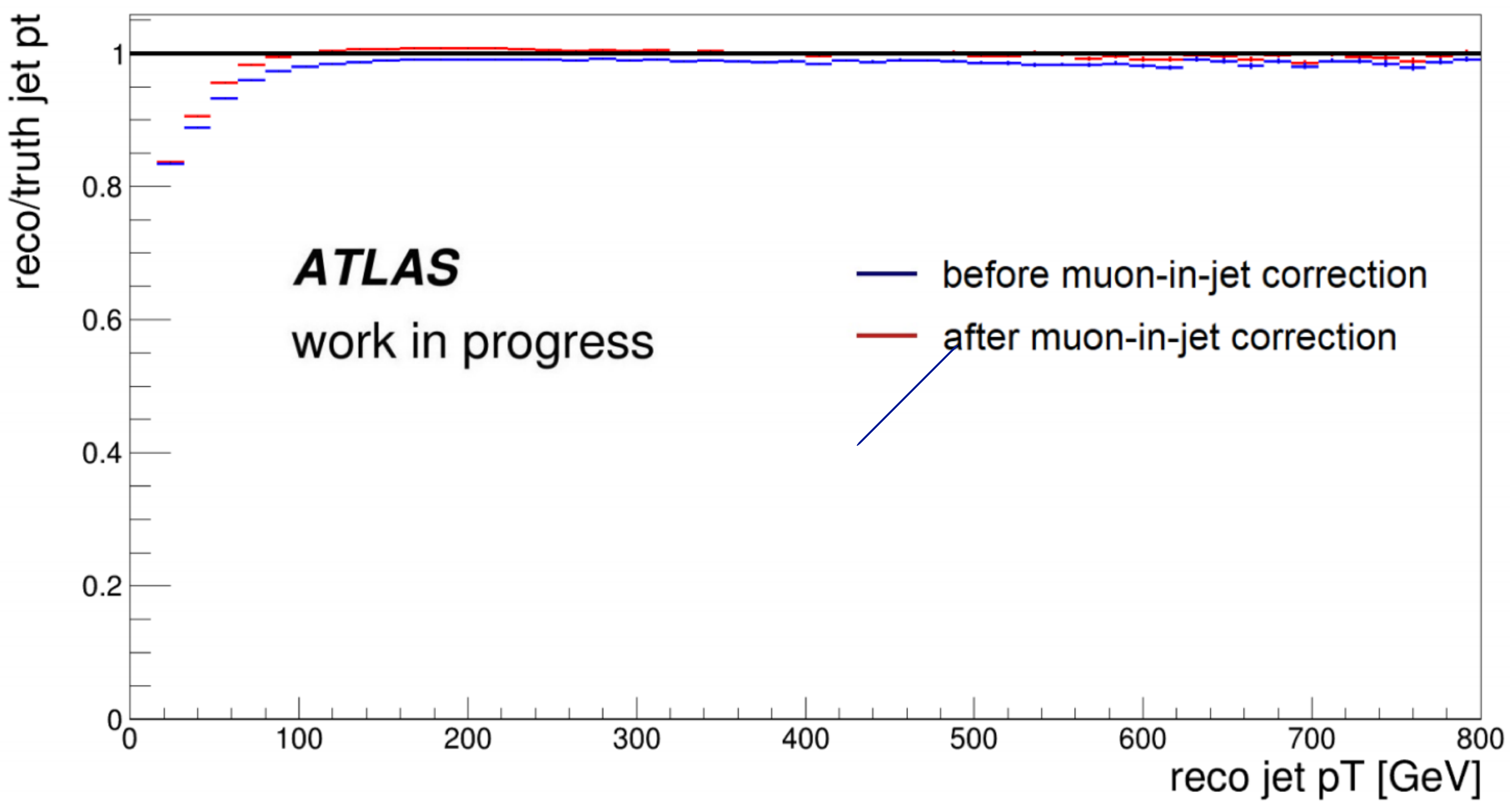


B-jet Energy Regressions

- Raw measurement → Standard Calibration → Muon correction





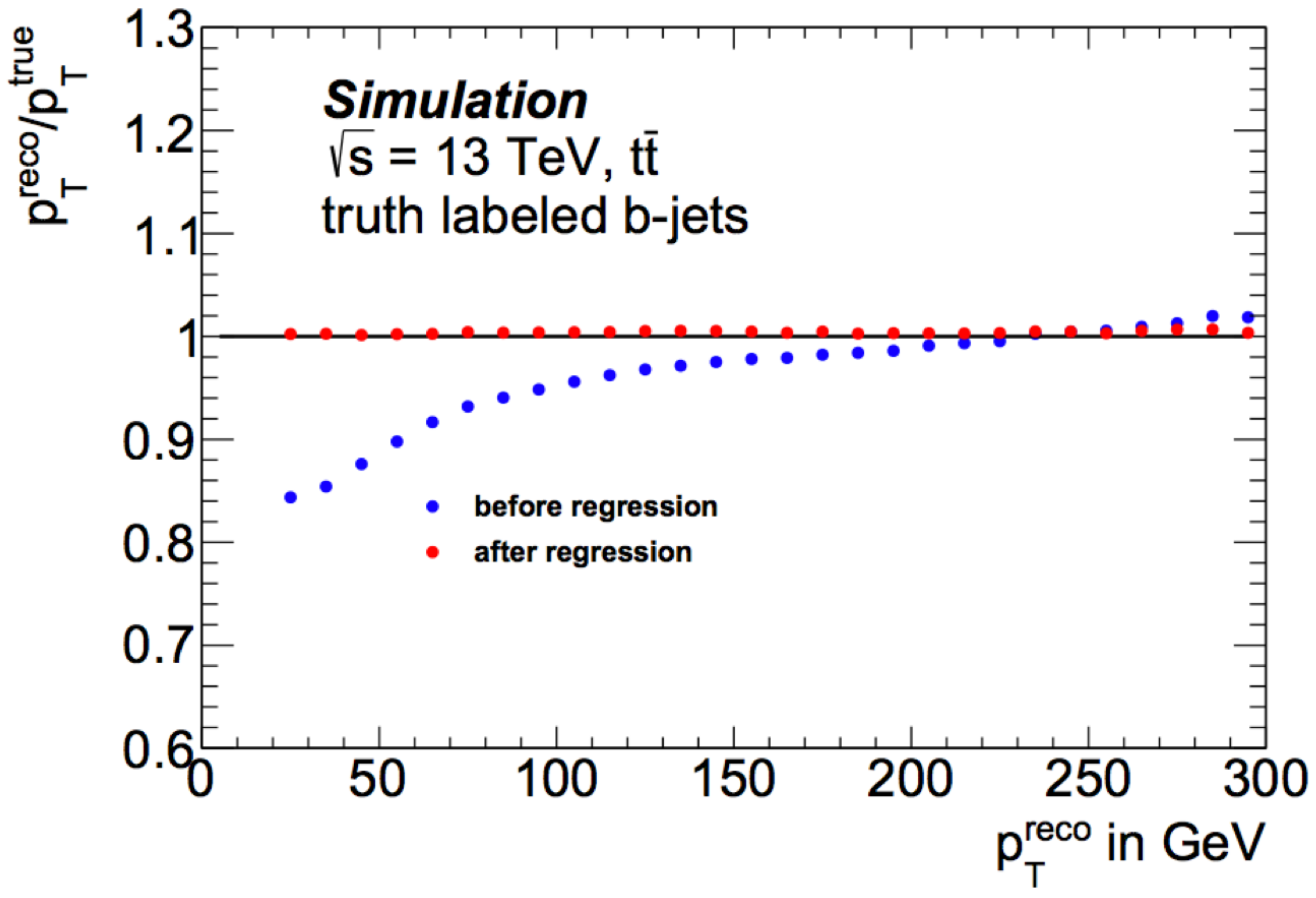
- What's missing?
  - Neutrino energy not accounted for
  - B-jet fragmentation is different from light quarks, could we benefit from b-flavor specific calibration?

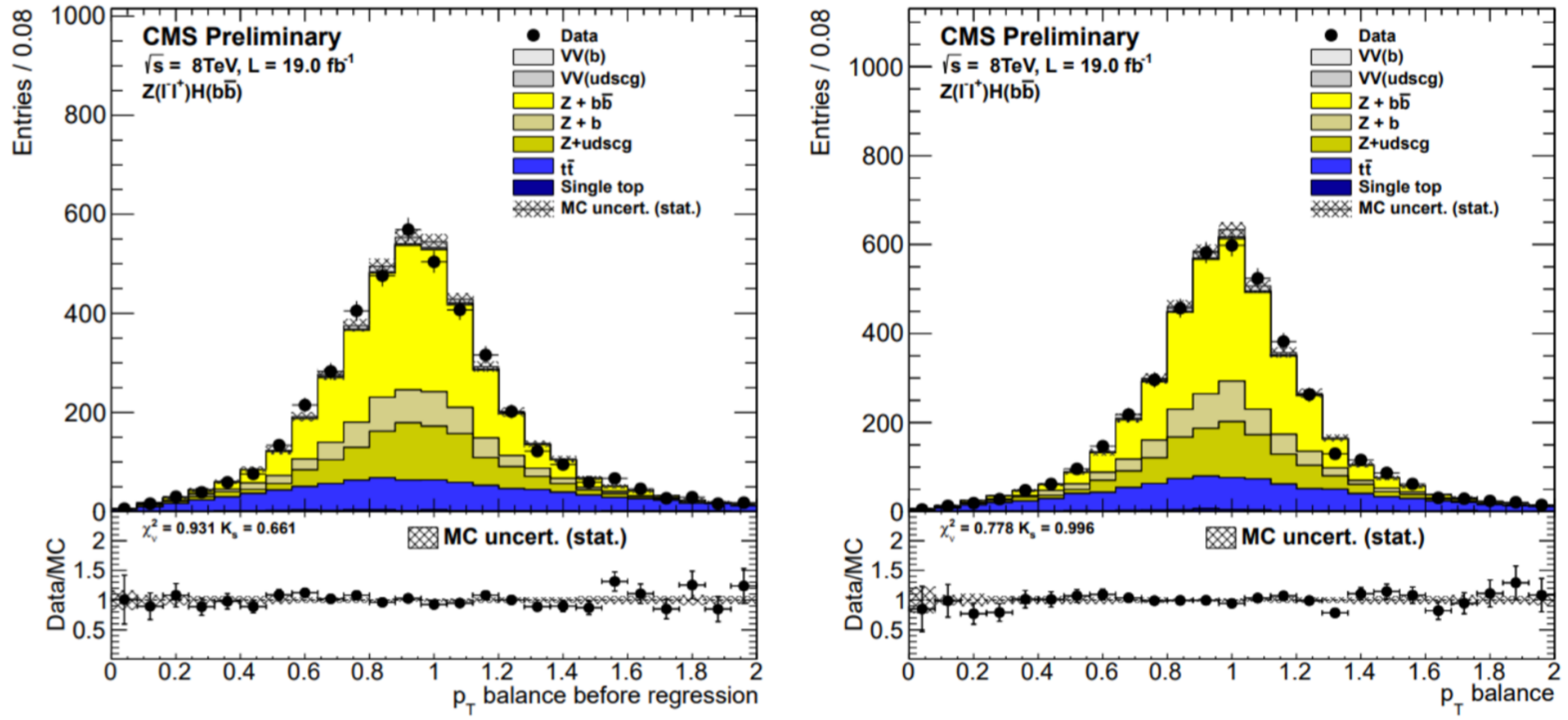
BR 35% b → l + ν + X

B-jet Energy Regressions

- Additional corrections can be applied
  - Standard correction, correct p_T on average
  - MVA based approached for improved scale and resolution

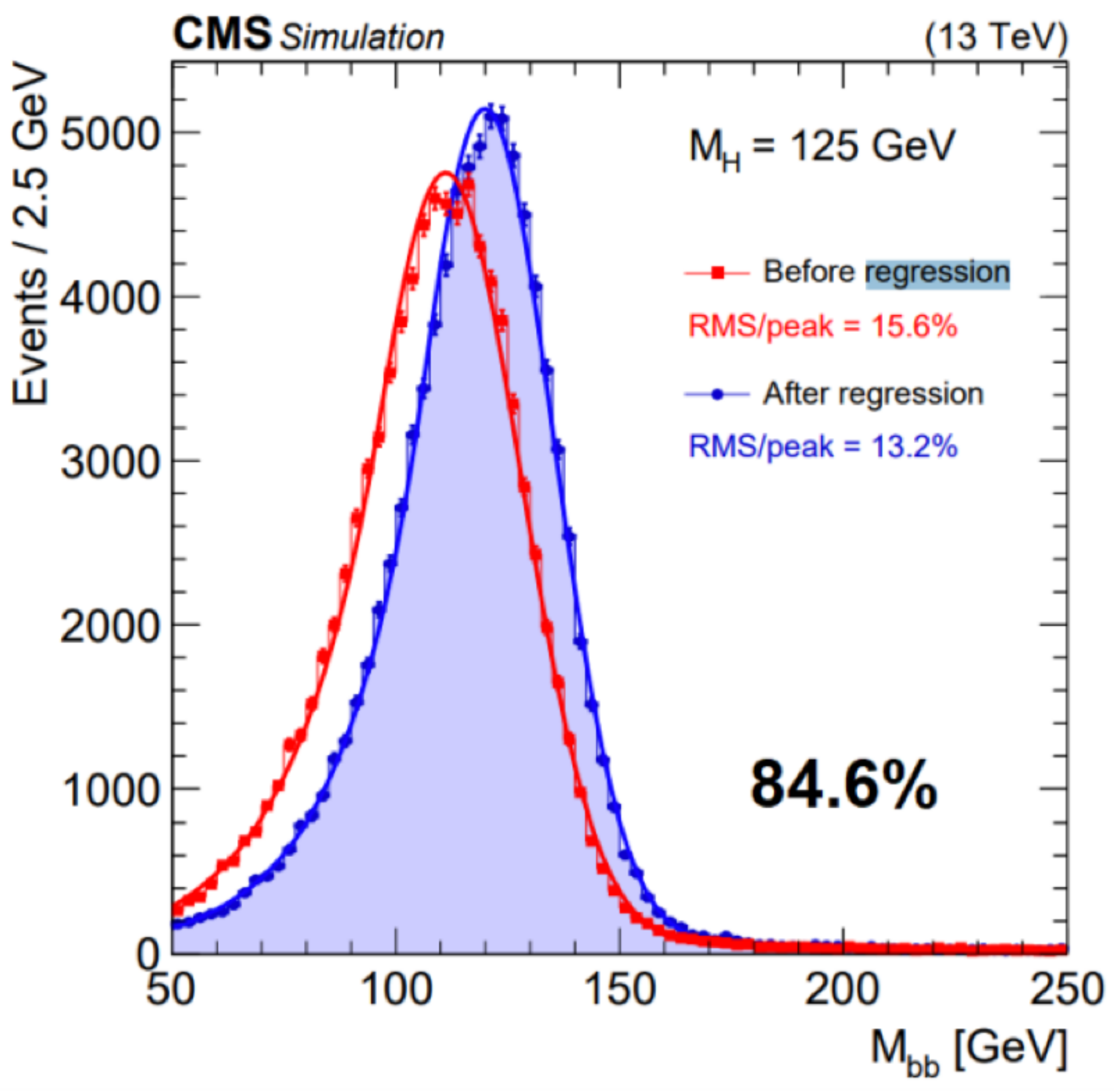
CERN-THESIS-2014-161





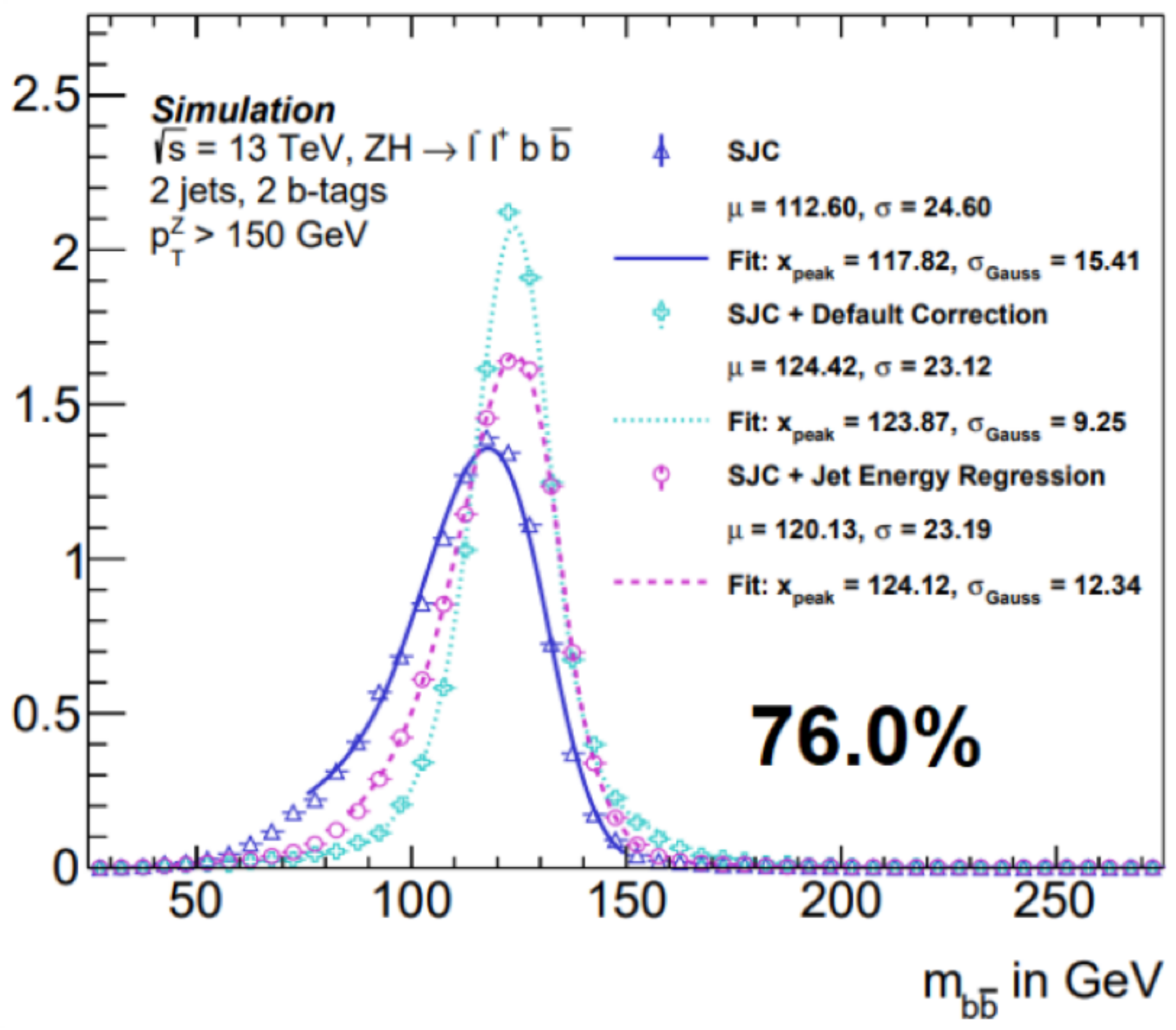
	Data w/o regression	Data w regression	MC w/o regression	MC w regression
Constant	517.1 ± 13.3	579.5 ± 14.8	535.5 ± 8.2	586.4 ± 8.8
μ	0.929 ± 0.008	0.985 ± 0.005	0.938 ± 0.004	0.981 ± 0.003
σ	0.226 ± 0.010	0.192 ± 0.007	0.205 ± 0.005	0.189 ± 0.004

CERN-THESIS-2014-161

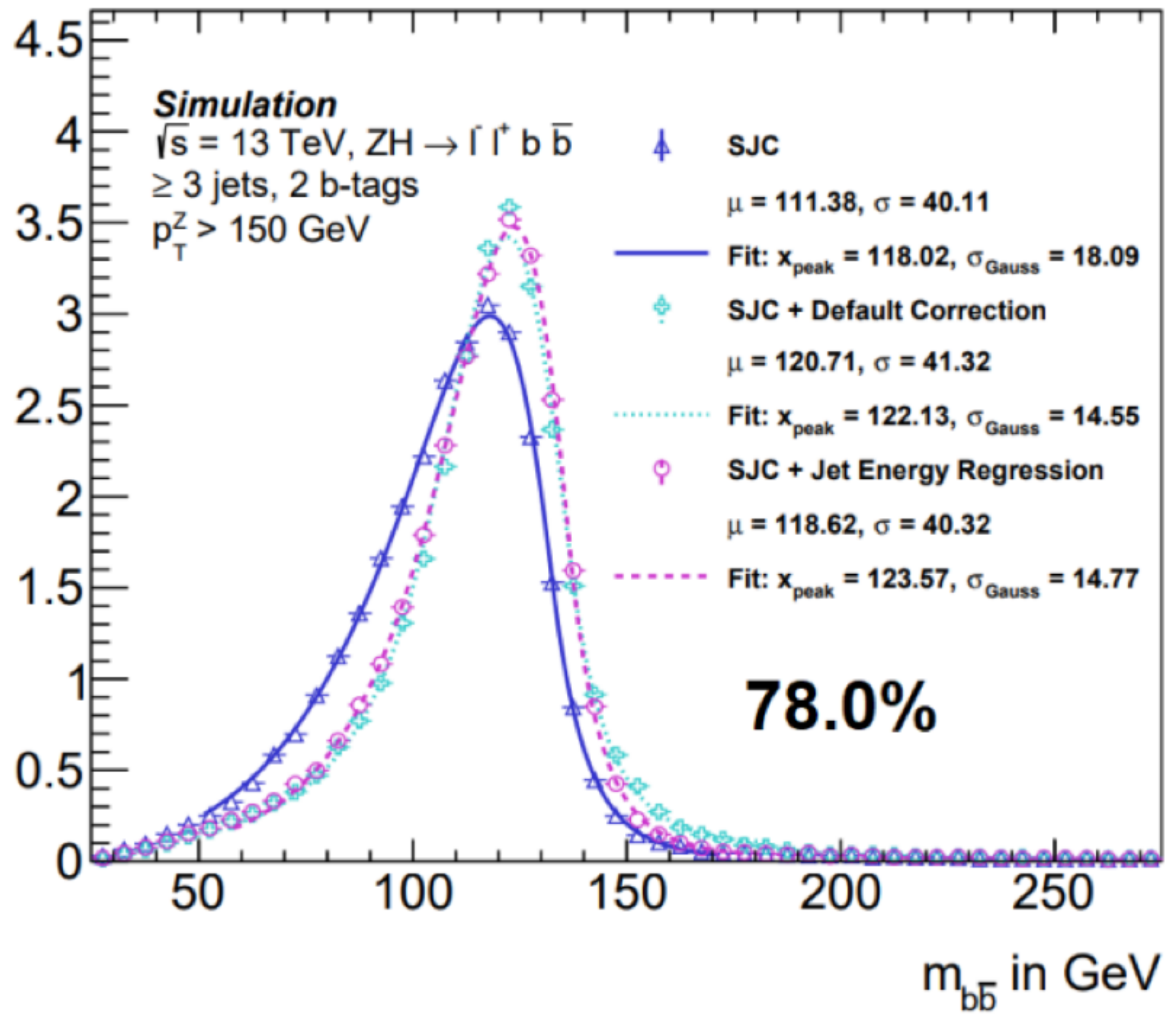


1709.07497

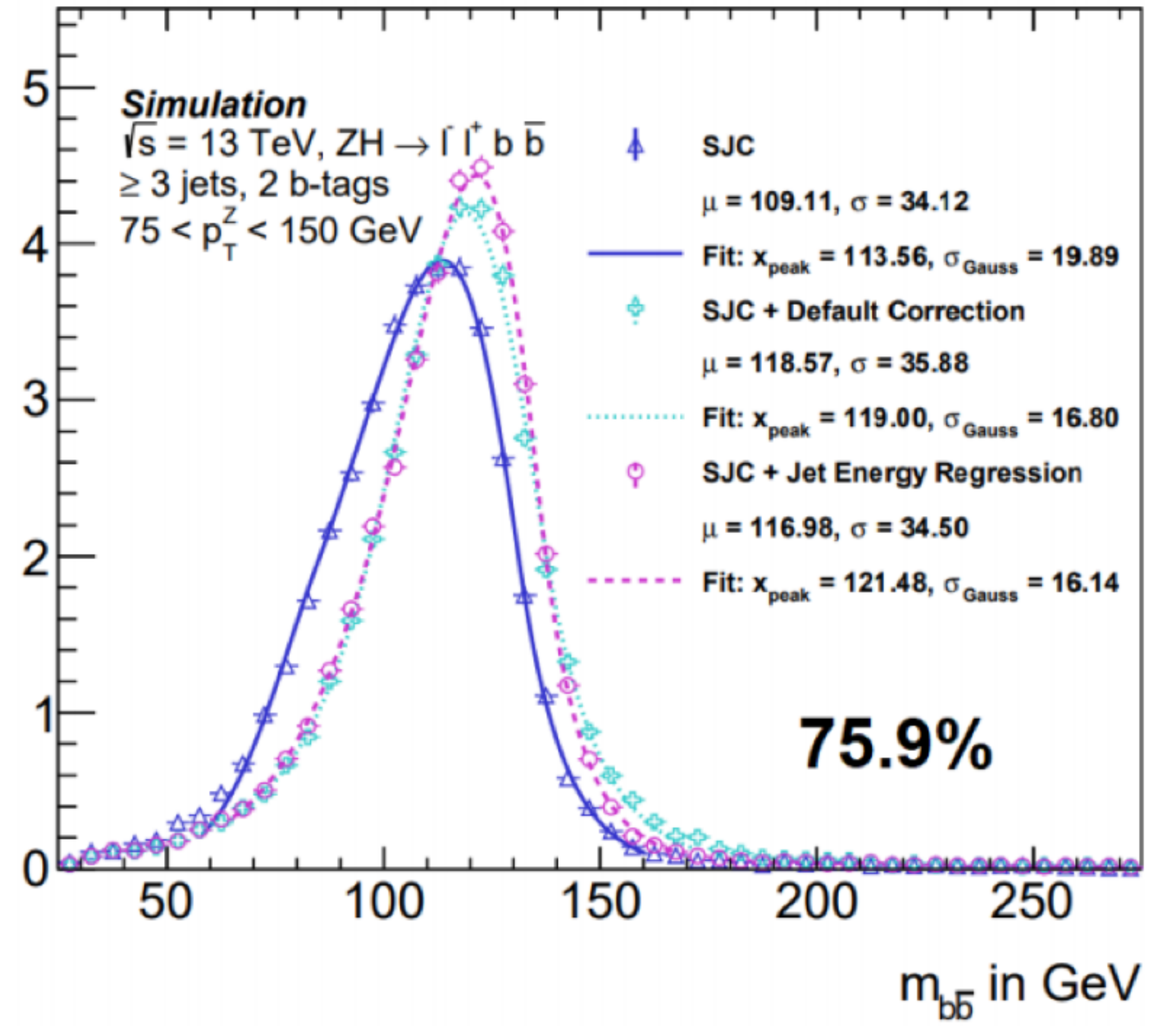
$2l, 2j, p_T^Z > 150$ GeV



$2l, > 2j, p_T^Z > 150$ GeV



75 GeV $< p_T^Z <$ 150 GeV



- Both experiments see compatible improvements in m_{bb} resolution.
- In case of ATLAS the regression does not show an advantage over PtReco. Default jet correction performs better due to kinematic fit in $2l, 2j$ channel.

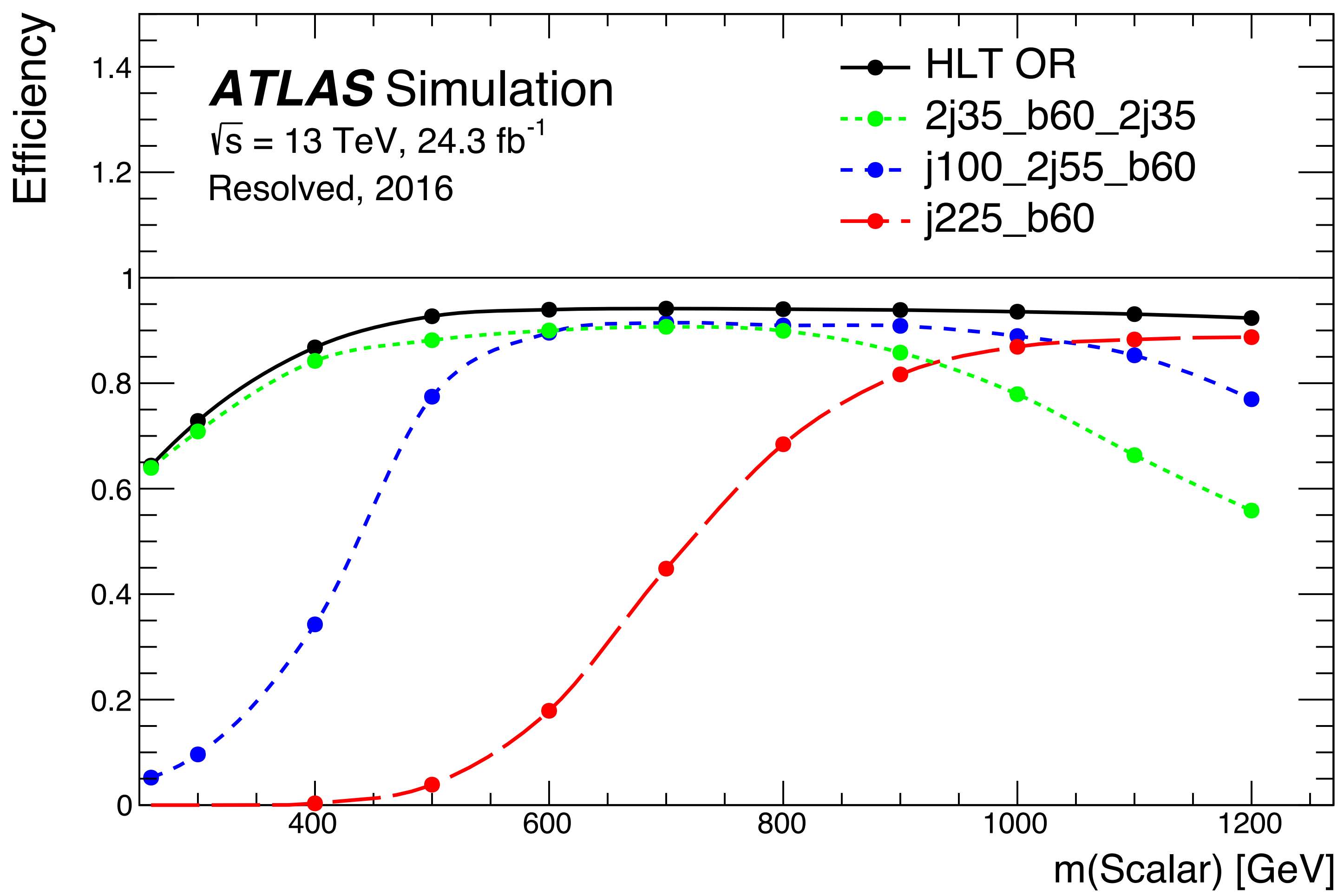
- Larger improvements from MVA approaches seen on CMS. **_HIG-18-016 (1808.08242) uses DNN and more info_**

$H(b\bar{b})H(b\bar{b})$

David Wardrope, Caterina Vernieri

Online b-tagging (John Alison)

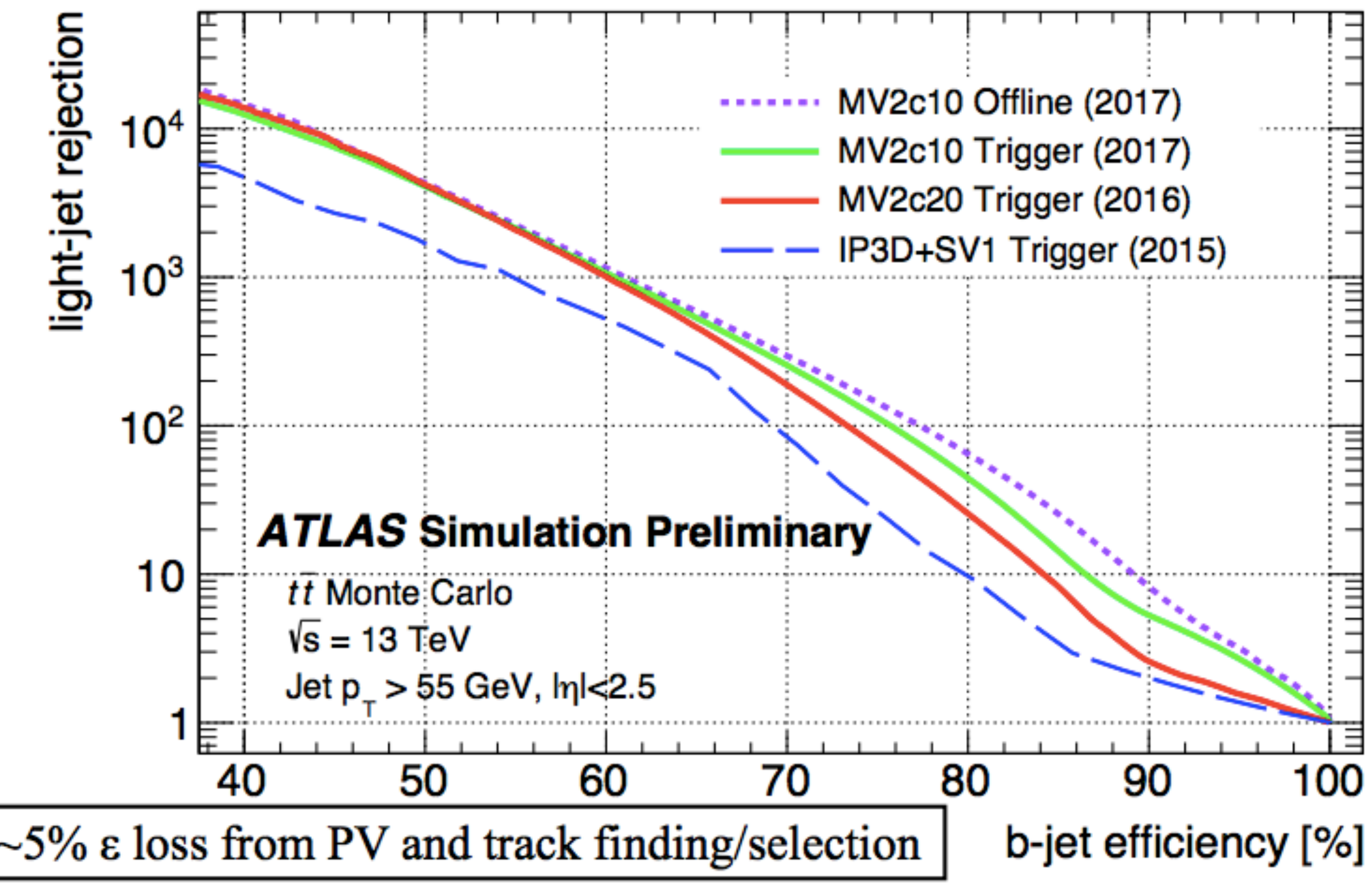
- b-jet triggers are most complicated LHC trigger paths
  - Need jet reconstruction, vertexing, tracking, b-tagging
- Acceptance × efficiency constrained by:
  - L1 rate: (only calorimeter info for decision)
  - CPU resources available in HLT (and output rate)

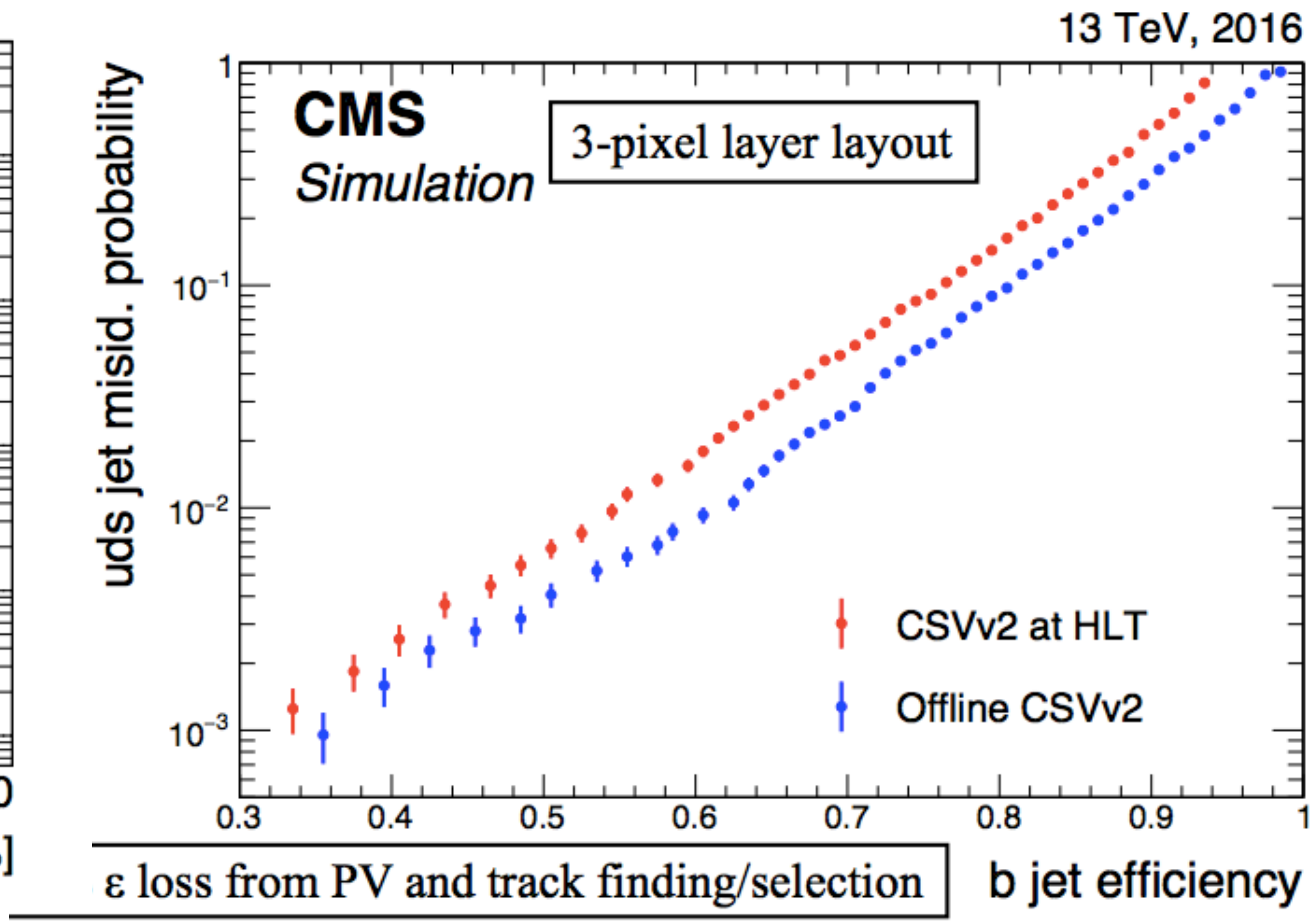


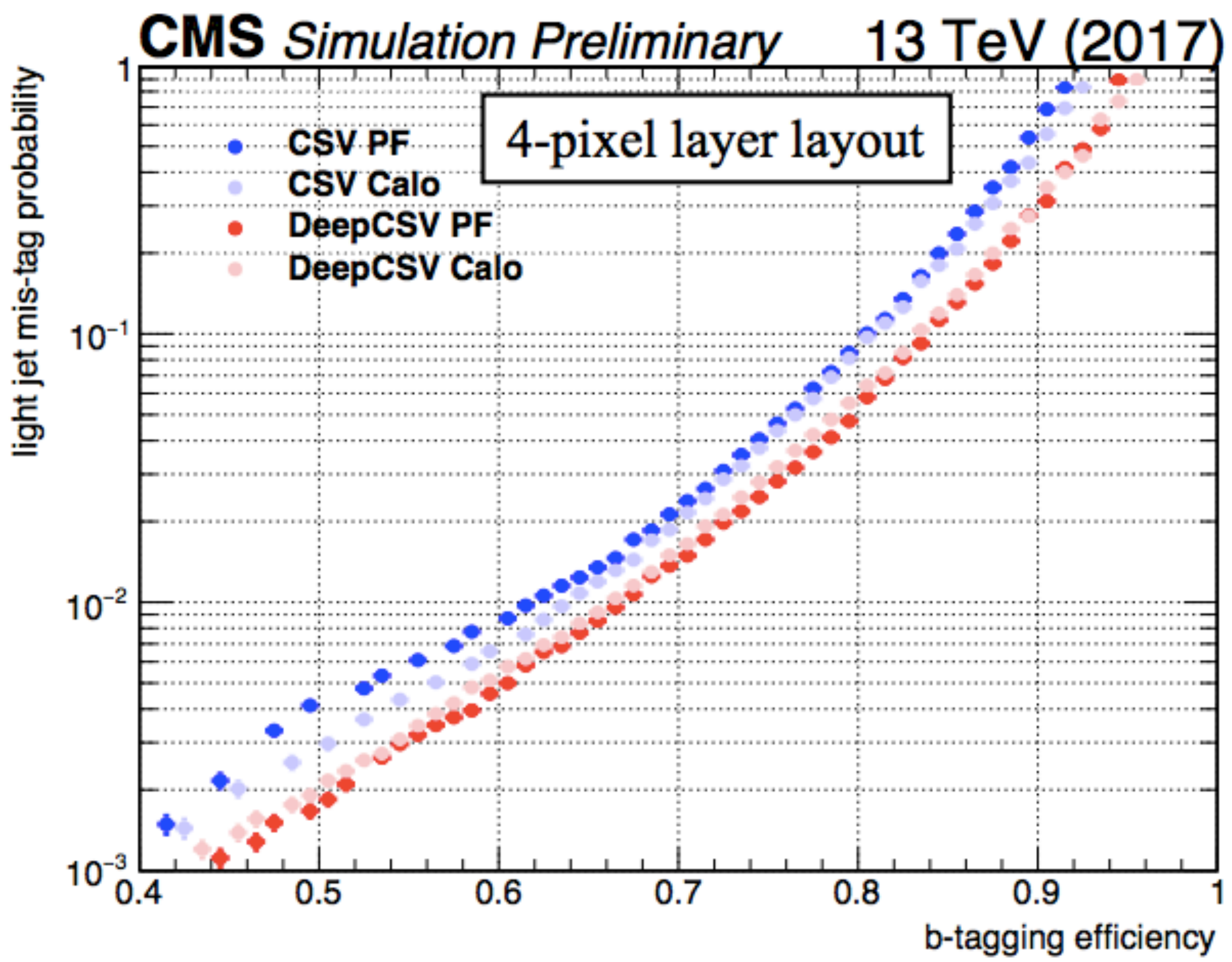
- Trigger places limits on HH→bbbb analysis in both ATLAS and CMS
  - Limitations even more serious at HL-LHC
- ATLAS has 2 b-jet trigger paths for improved low m_{HH} sensitivity
  - Enables background model with normalisation from 2-tag control sample
- CMS requires at least 3 b-jets to pass trigger
  - Reduces efficiency, motivates hemisphere background model

David Wardrope 2

b-tagging Online vs Offline







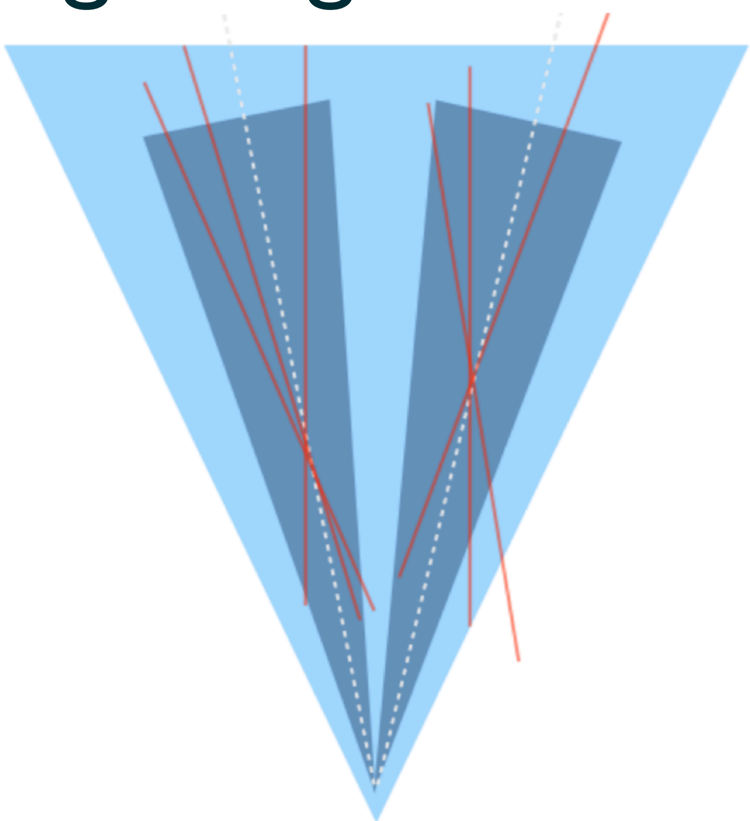
Identifying Boosted H→bb (Michael Kagan)

High p_T Higgs boson reconstruction gives access to

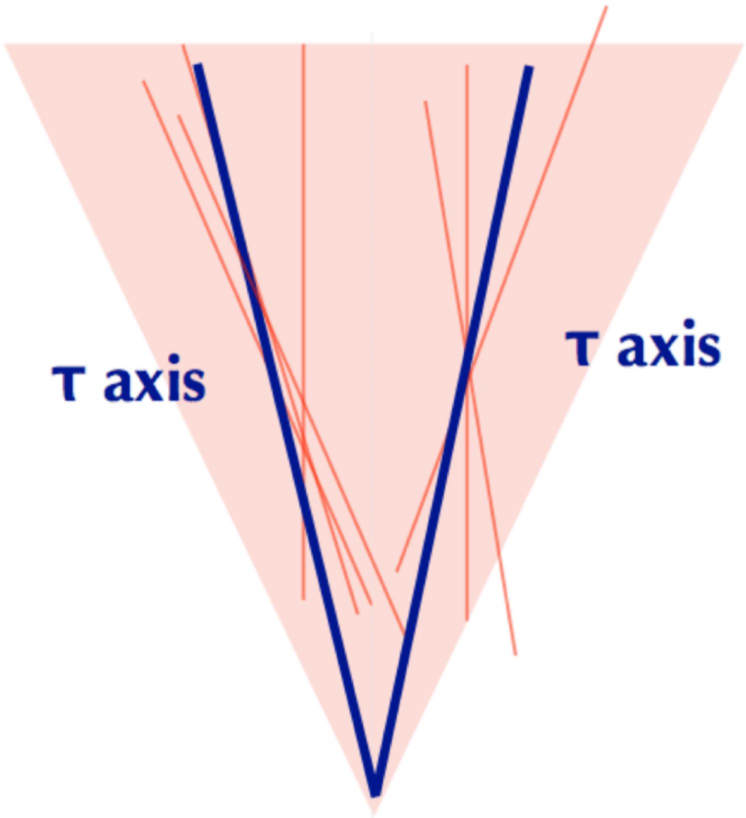
- high-mass resonances
- m_{HH} tails from non-resonant signals

Higgs boson kinematics reconstructed using large-R jets, identification relies on dedicated b-tagging algorithms

ATLAS b-tag using R=0.2 trackjets



CMS use exclusive-k_T subjet axis to used **to sort information** related to the sec vertexes & tracking



Methods to calibrate/validate these methods becoming well-established

New methods are in the work

David Wardrope 3

Multijet background is dominant:

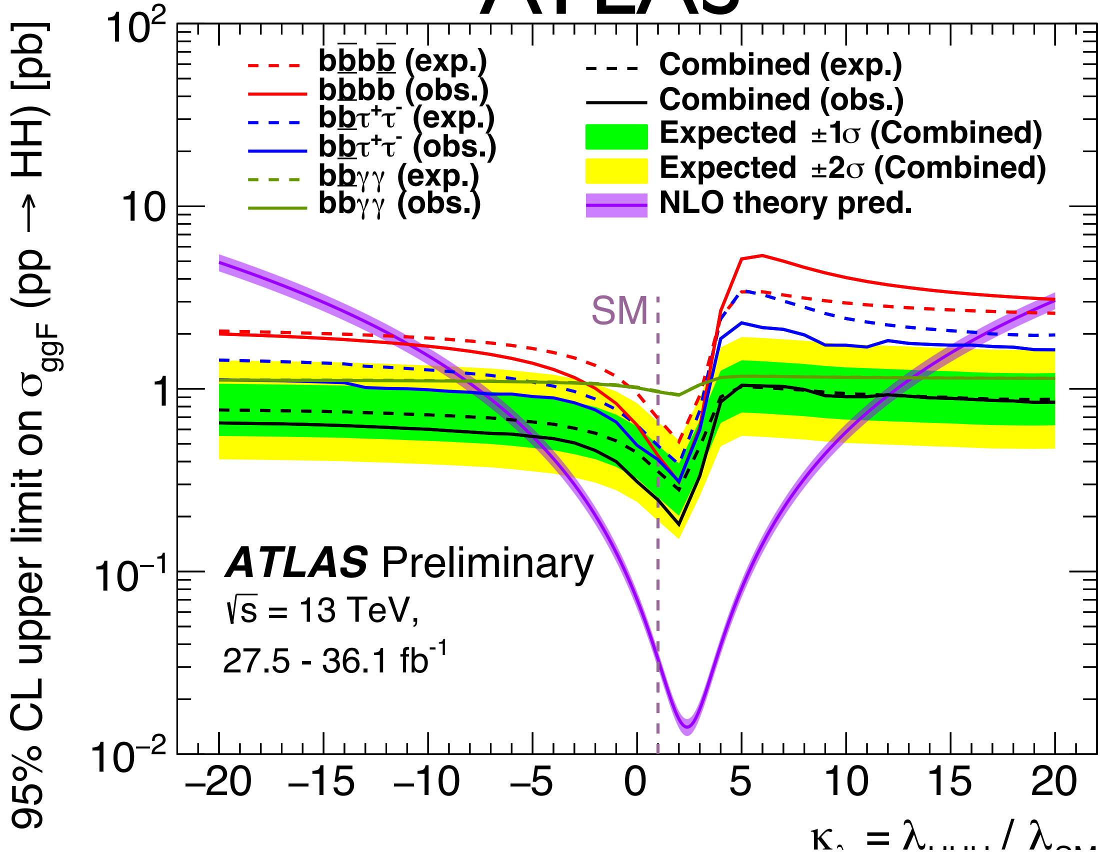
Data-driven background estimates : bump-hunt, anti-tag reweighting, hemisphere mixing

With more data, **systematics uncertainties** related to the data-driven backgrounds will become more dominant

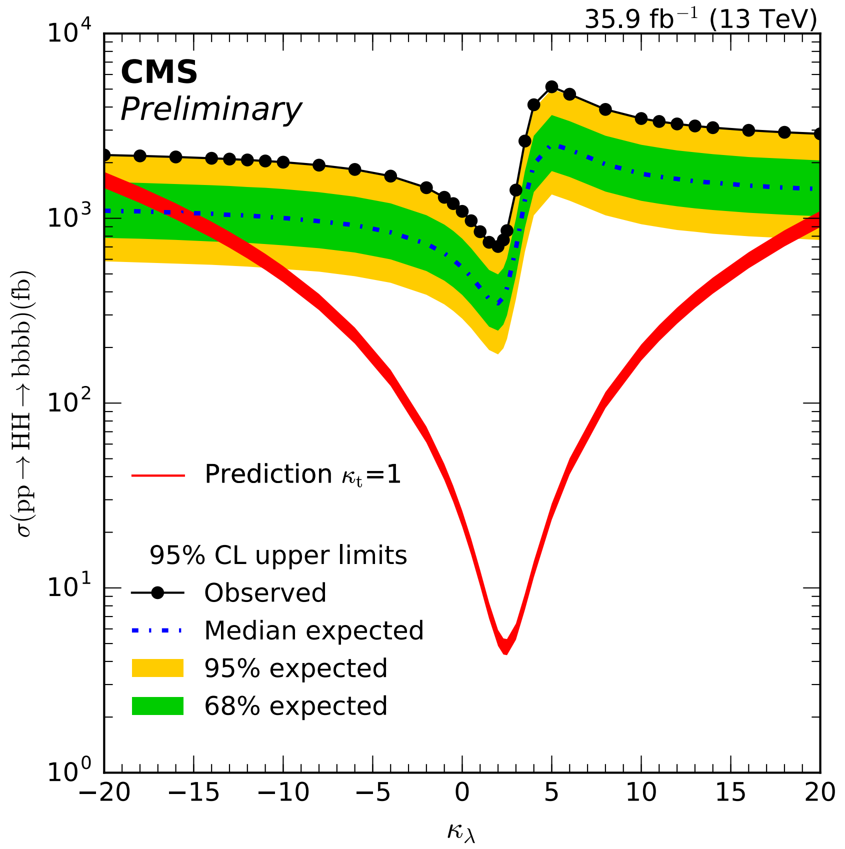
Can we get a better simulation for this?

Non-resonant Results (Jana Schaarschmidt, Andres Tiko)

ATLAS



CMS



σ/σ_{SM}:

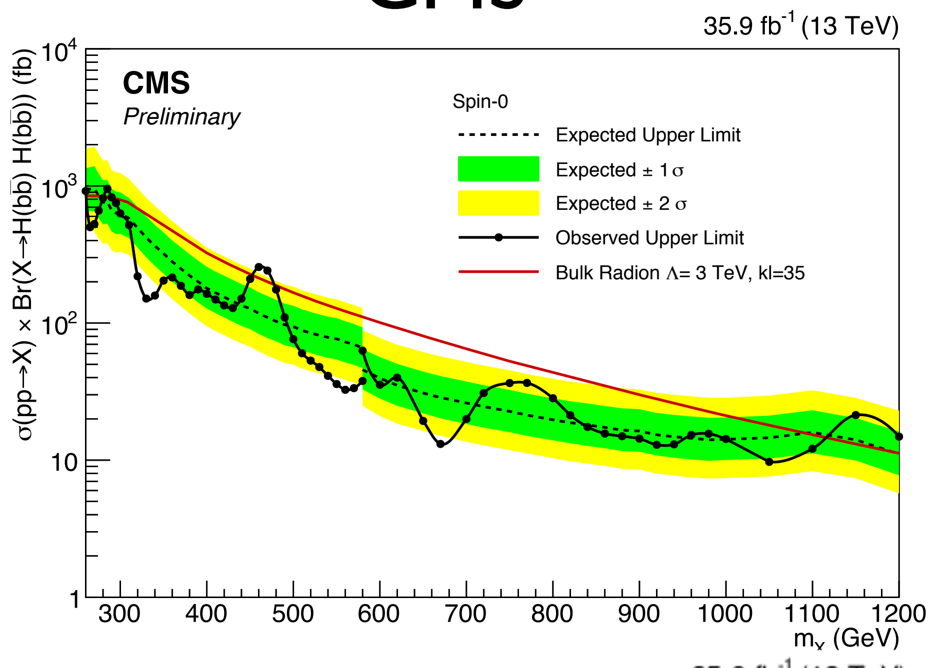
Observed	−2σ	−1σ	Expected	+1σ	+2σ
13.0	11.1	14.9	20.7	30.0	43.5

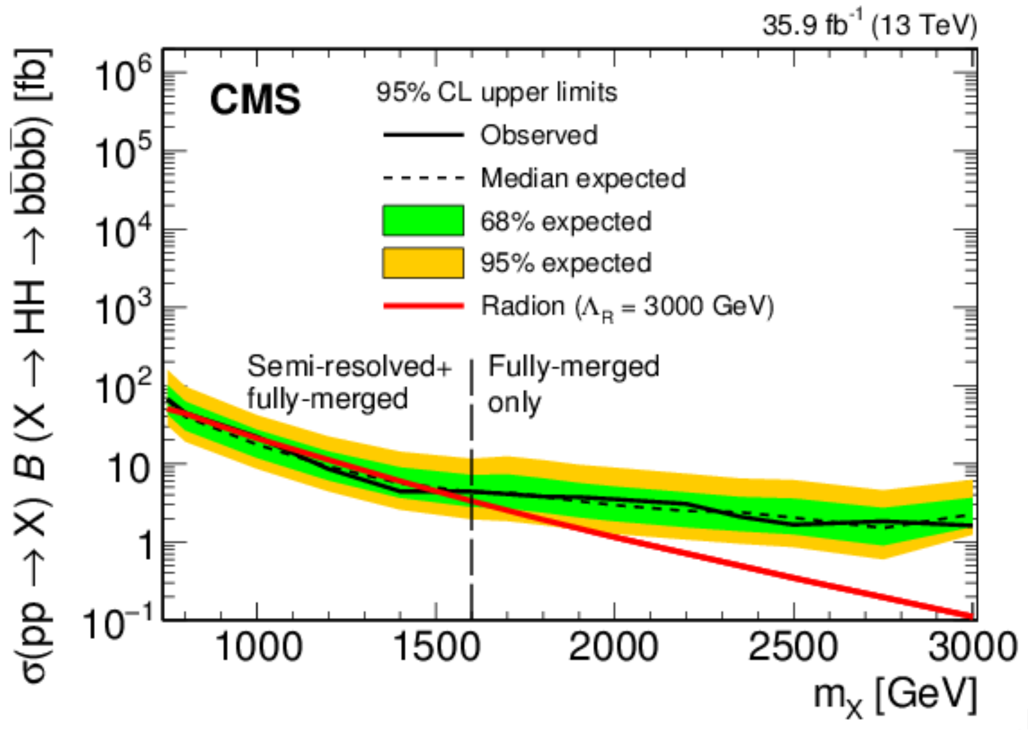
Observed	−2σ	−1σ	Expected	+1σ	+2σ
74.5	19.5	26.2	36.9	52.9	73.4

ATLAS sensitivity ~2× than CMS analysis

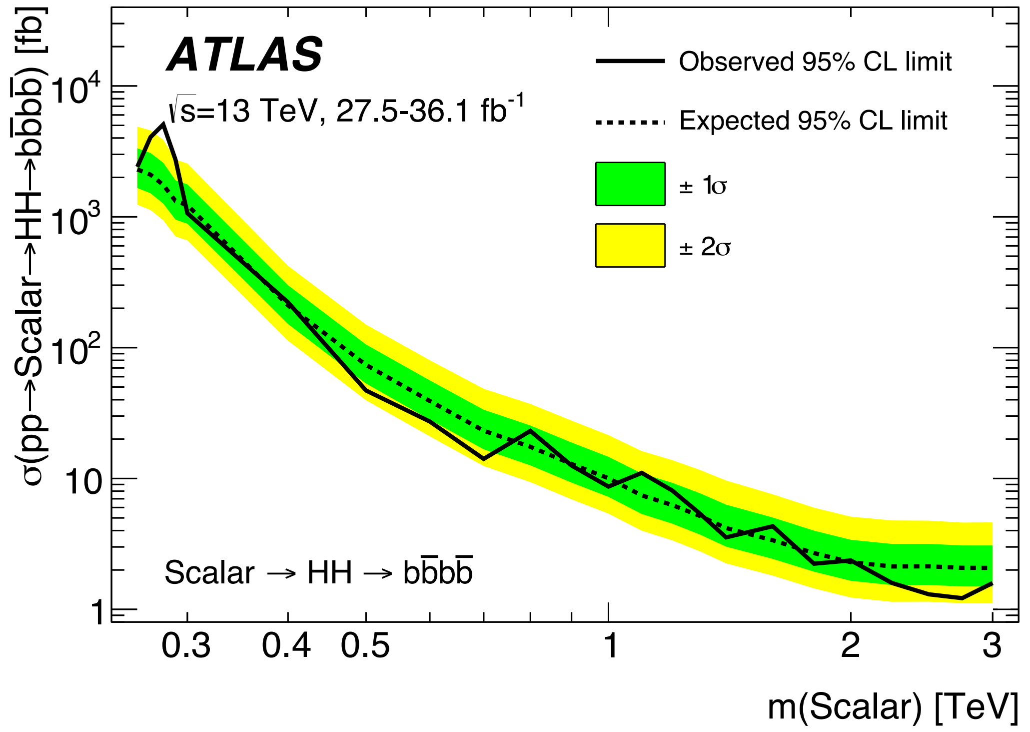
Resonant Results (Jana Schaarschmidt, Andres Tiko)

CMS





ATLAS



Resonant results are broadly comparable

David Wardrope 4

vid Wardrope 5

CMS 2+1 has non-resonant interpreation, but not orthogonal to the resolved …

for some benchmark similar sensitivity to the resolved

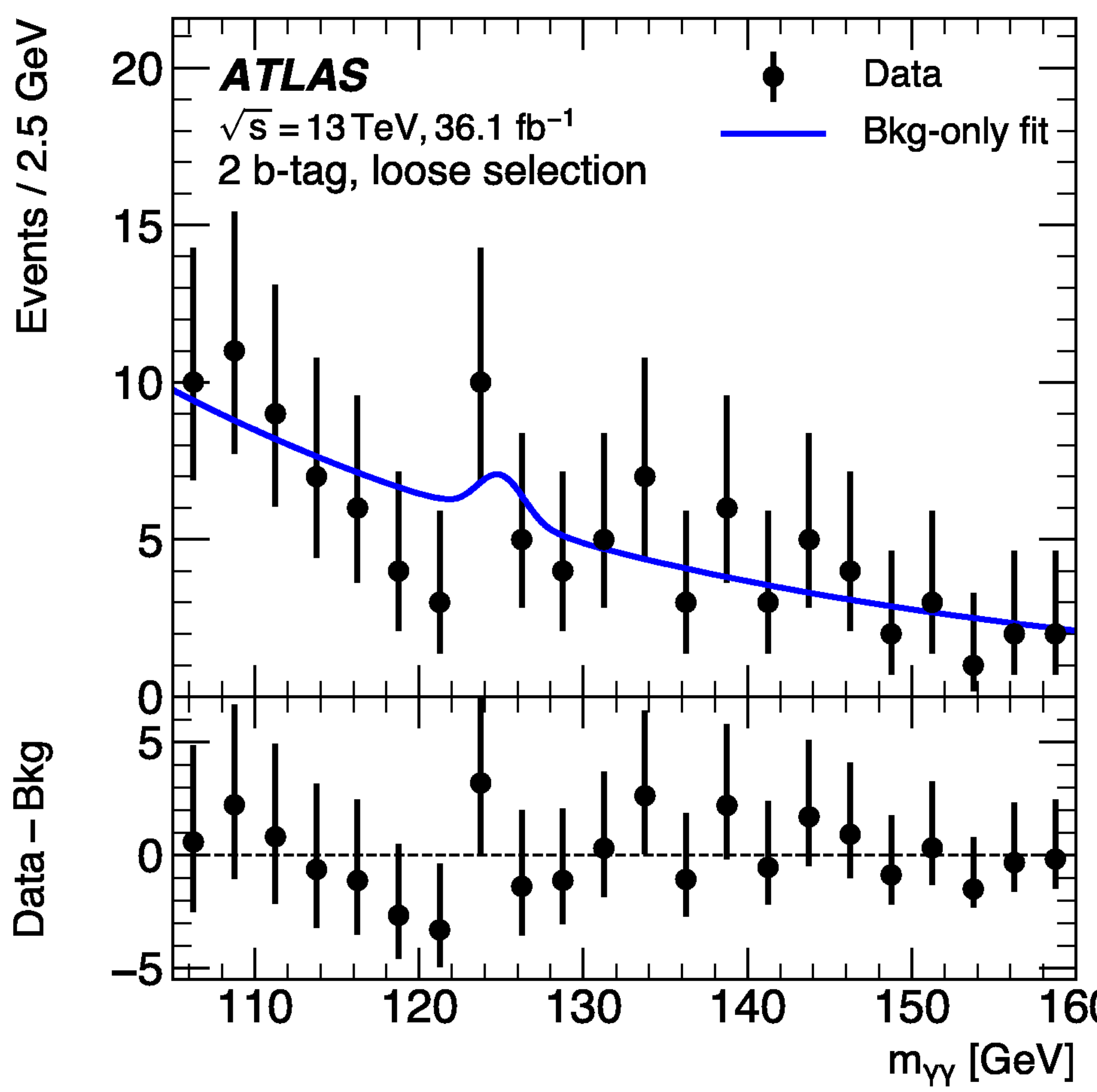
$H(b\bar{b})H(\gamma\gamma)$

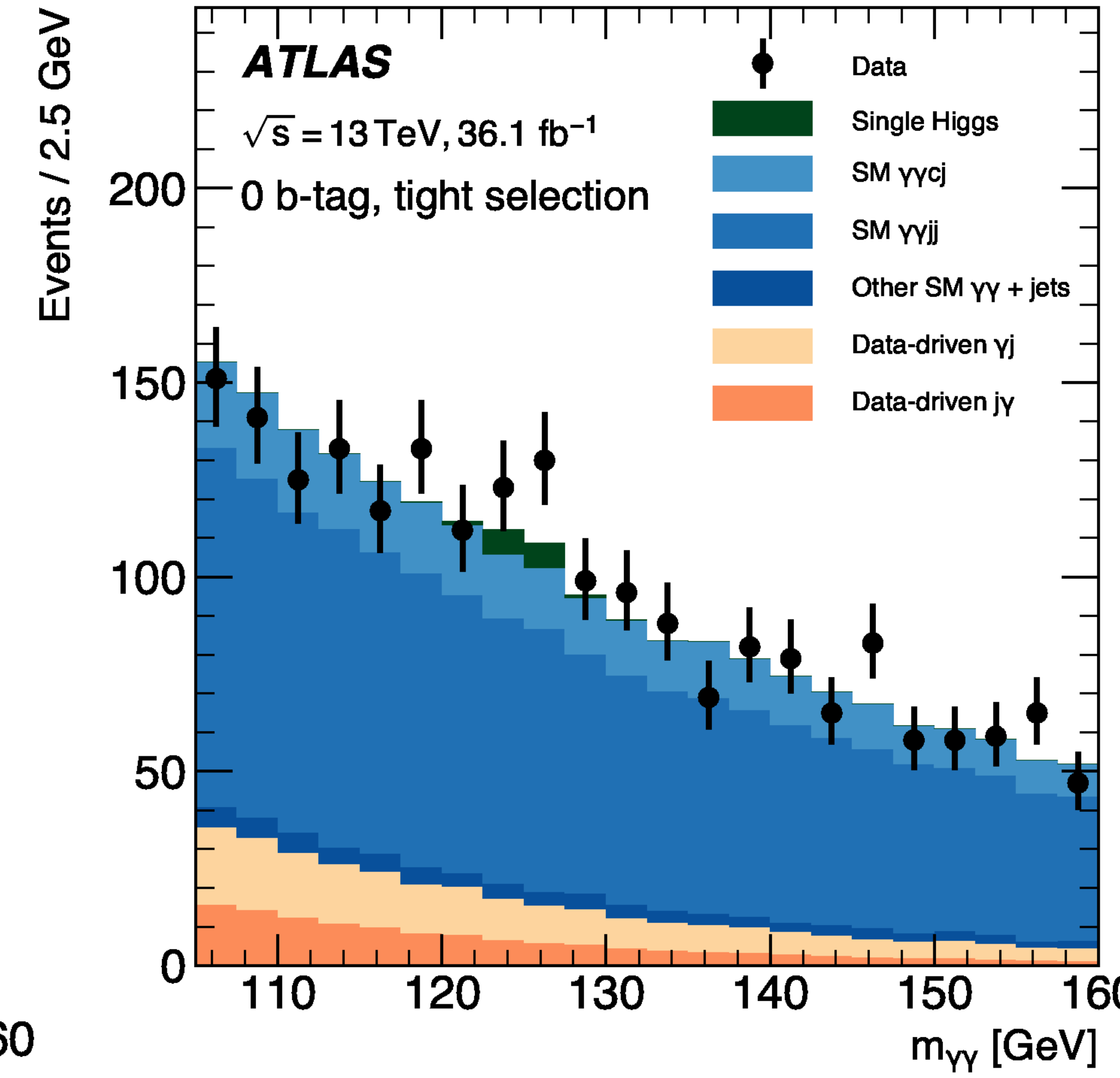
Francesco Micheli, James Robinson

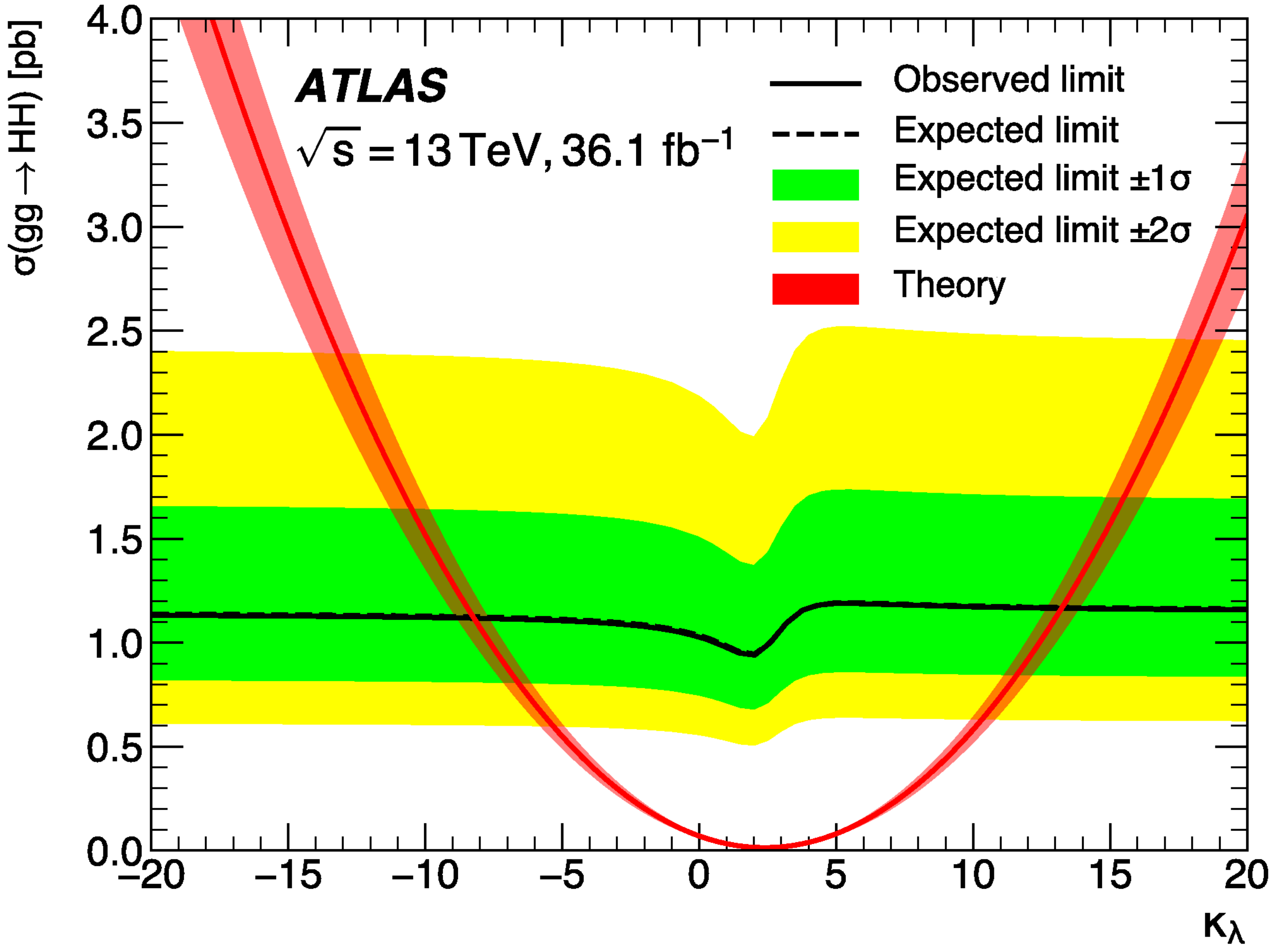
ATLAS experimental: non-resonant

- Fit $m_{\gamma\gamma}$: resonant signal on top of continuum background
- SM $\gamma\gamma$+jets: MC re-weighted to data (shape + normalization) in 0-tag CR.
- Jets faking photons from fully data-driven 2x2D method
- ***Data-driven***: use MC only to decide which fit function to use - bias in function choice taken as a systematic

Dominant contribution to ATLAS κ_λ sensitivity



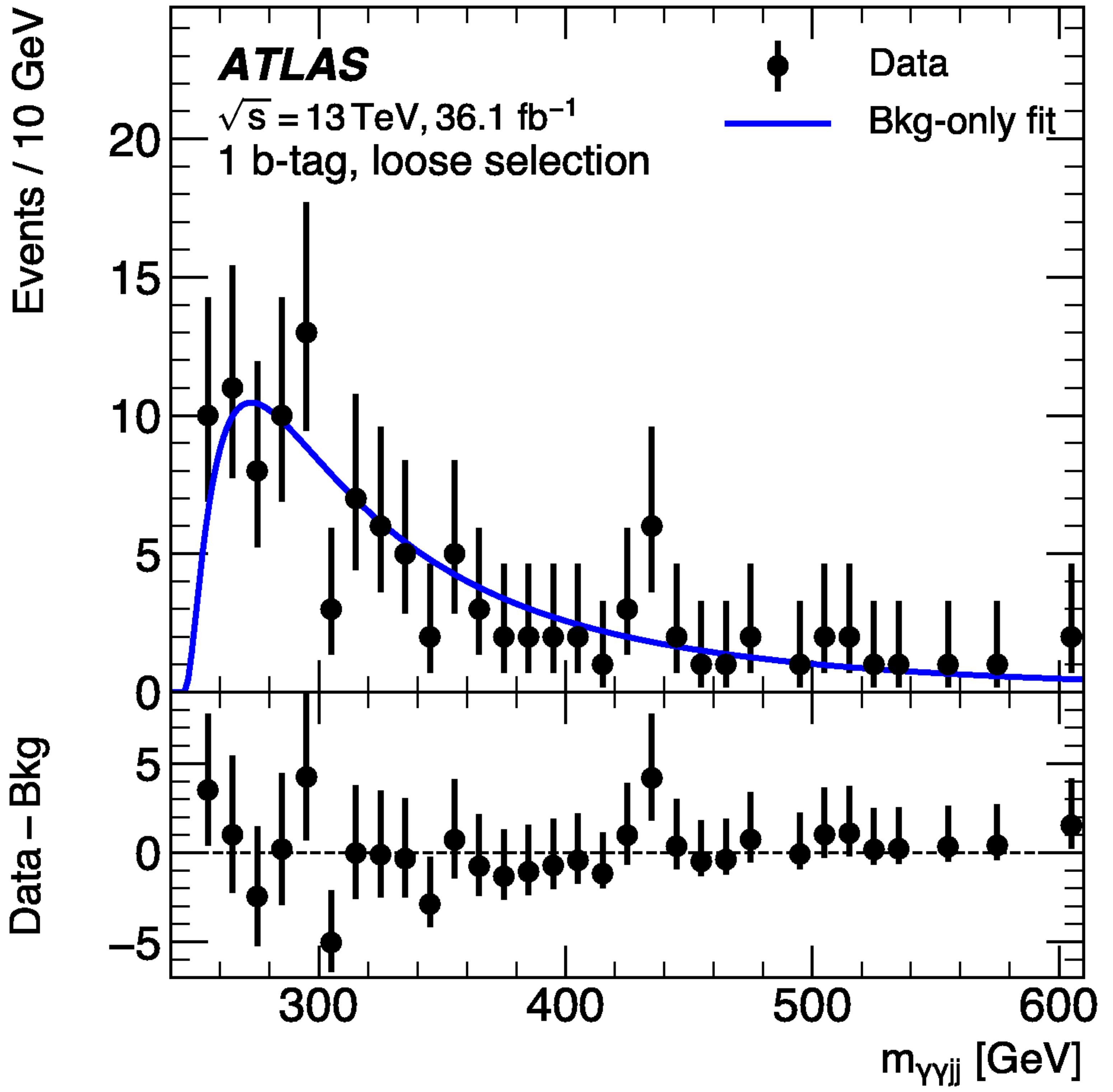


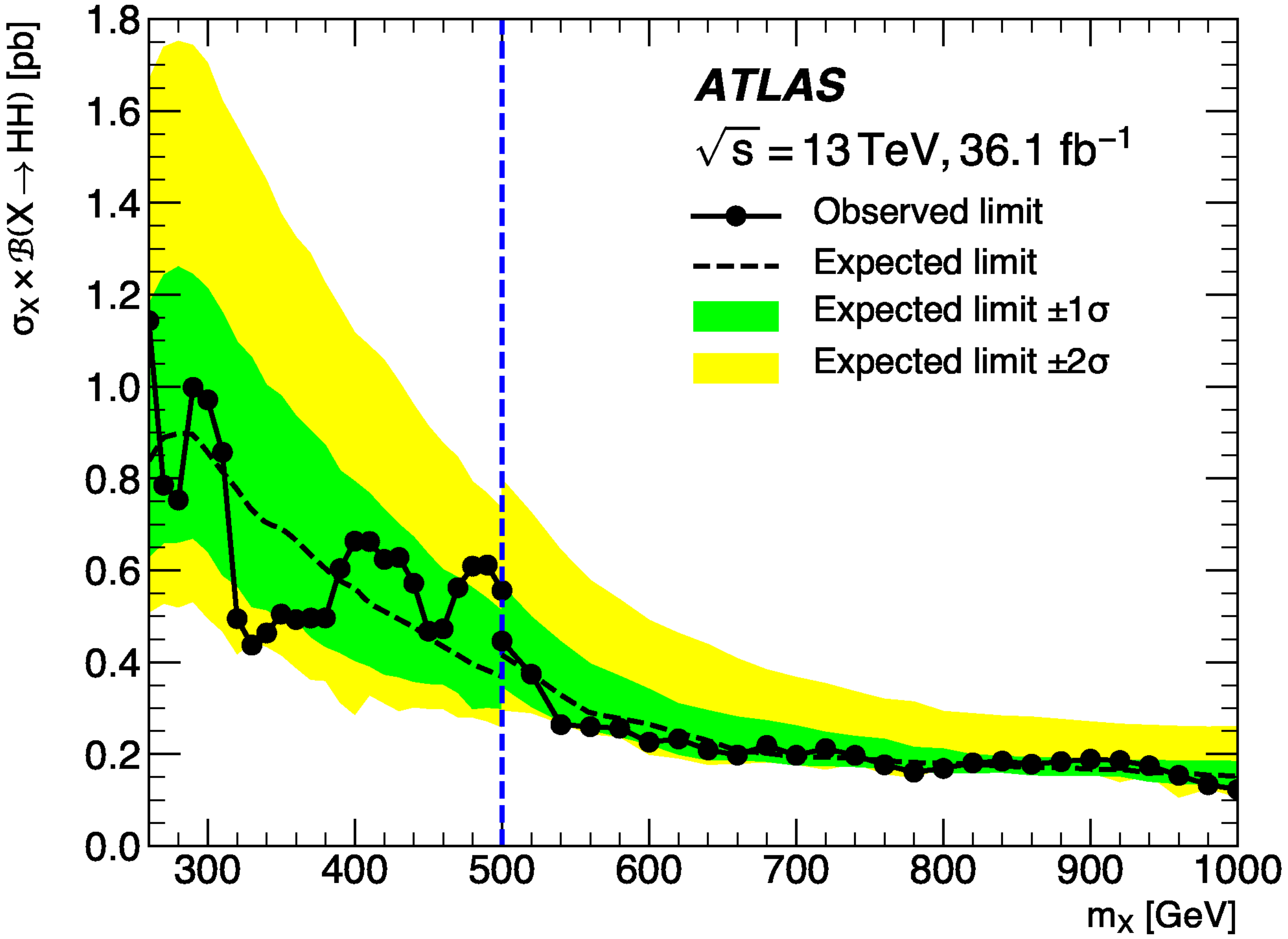


ATLAS experimental: resonant

Fit $m_{\gamma\gamma jj}$ constructed after scaling jj 4-vector to have $m_{jj} = m_H$

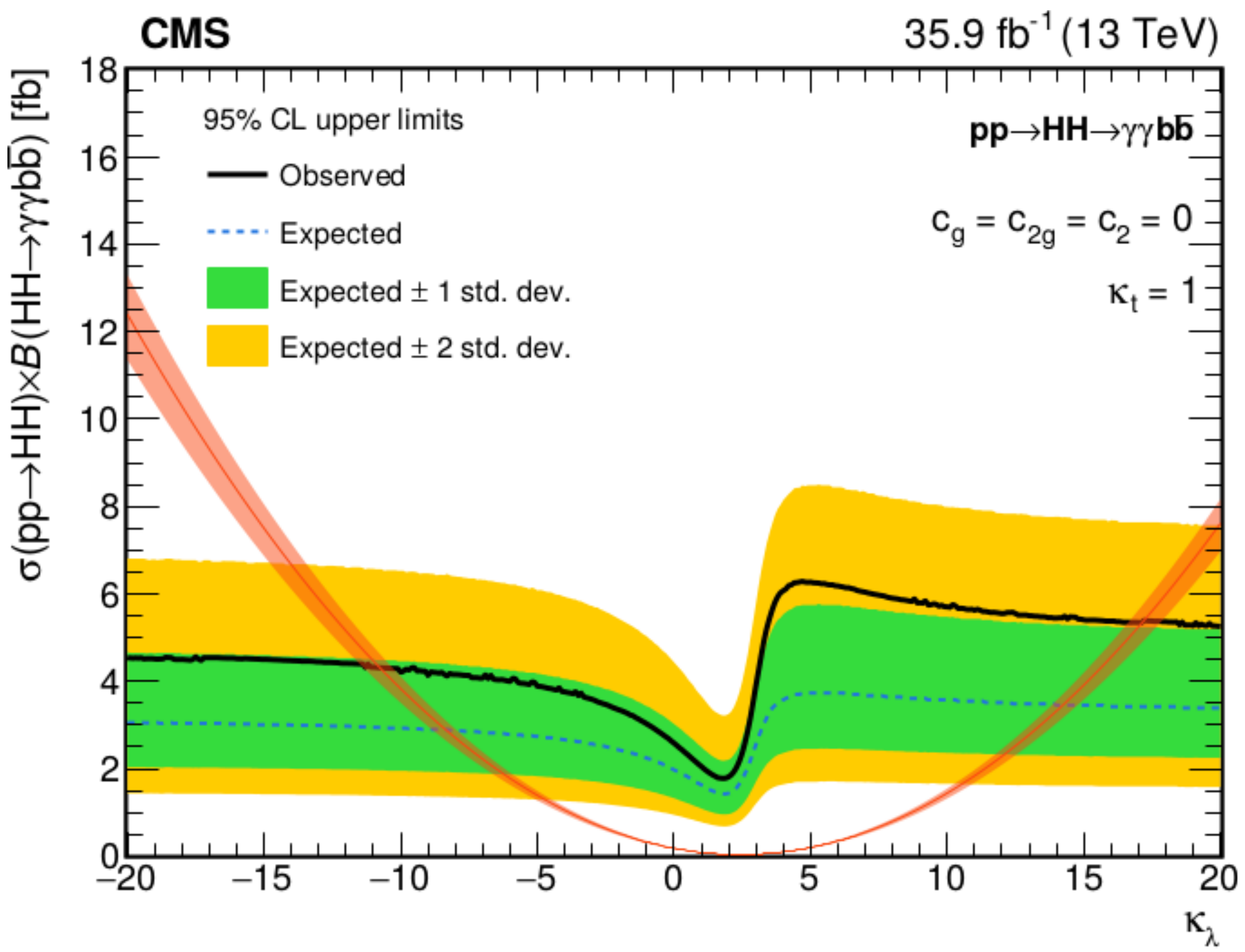
Interference between BSM HH and SM HH considered to be negligible and **ignored**





CMS experimental summary

- Tight object selection to reduce background from fakes:
  - Photon selection similar to H(γγ), regression for b-jets to improve m_{bb} resolution
- **MVA classification** using kinematic variables:
  - Resonant/nonResonant, low/High mass optimized separately
- **2D fit** to $\mathbf{m_{\gamma\gamma}}$ and $\mathbf{m_{bb}}$ to derive limits



Most sensitive channel:

Dominating $\boldsymbol{\kappa}_\lambda$ scan

Dominant channel for resonant at low mass

Follow-uPs and action Items

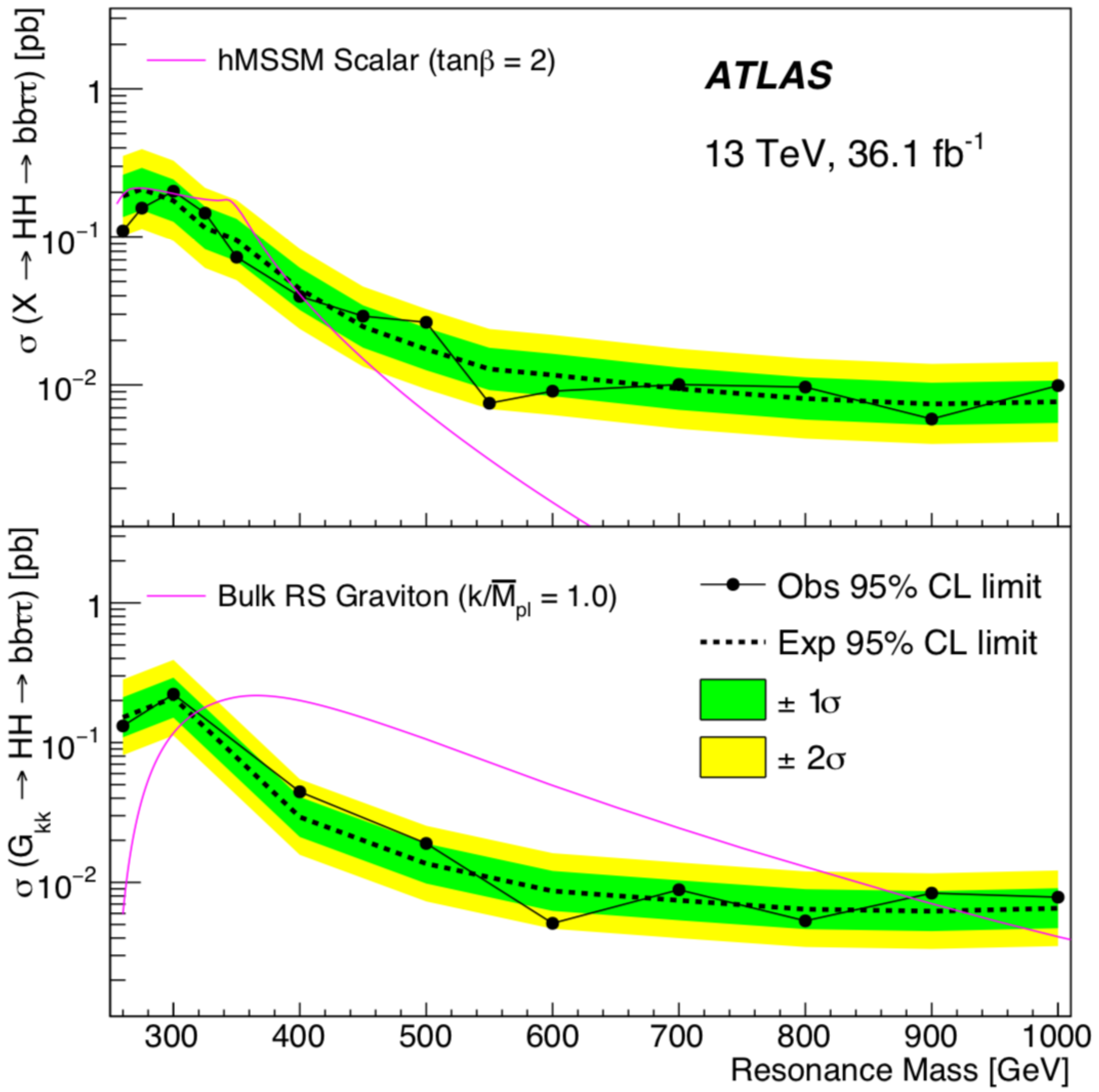
- **More general approach**:
  - For this channel, **relax the mass window on bb pair** (~60-250 GeV) to test exotic models ($X \rightarrow h(125)Y$) could be doable without huge effort
    - ML approach for bump hunting could help
  - Better integration with **single Higgs** measurements and wider interpretations
- Improvements on **b-jet reconstruction** are foreseen
- **Updates on projections** will come soon:
  - Photon resolution to be treated carefully in these estimates

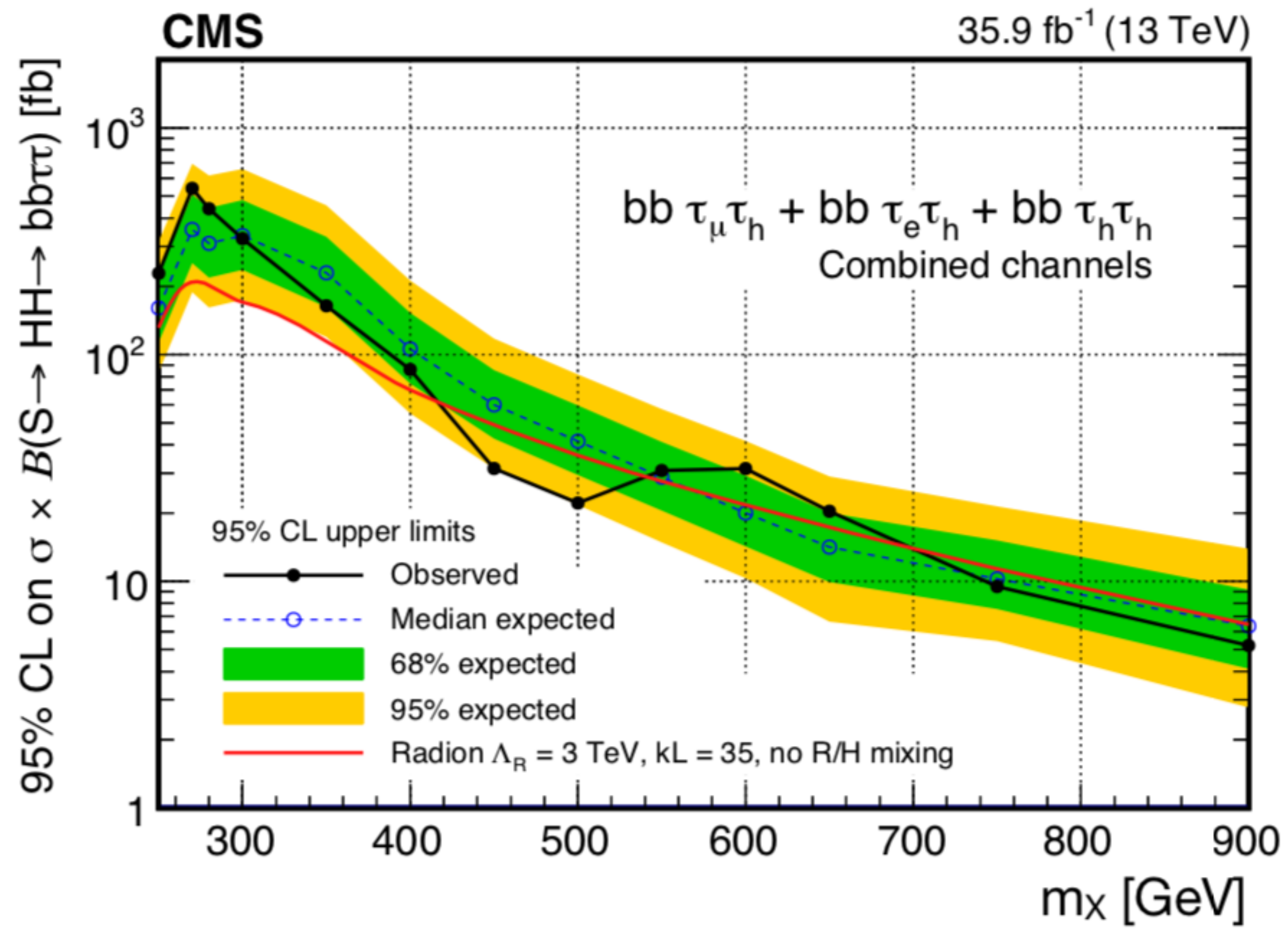
$H(b\bar{b})H(\tau\tau)$

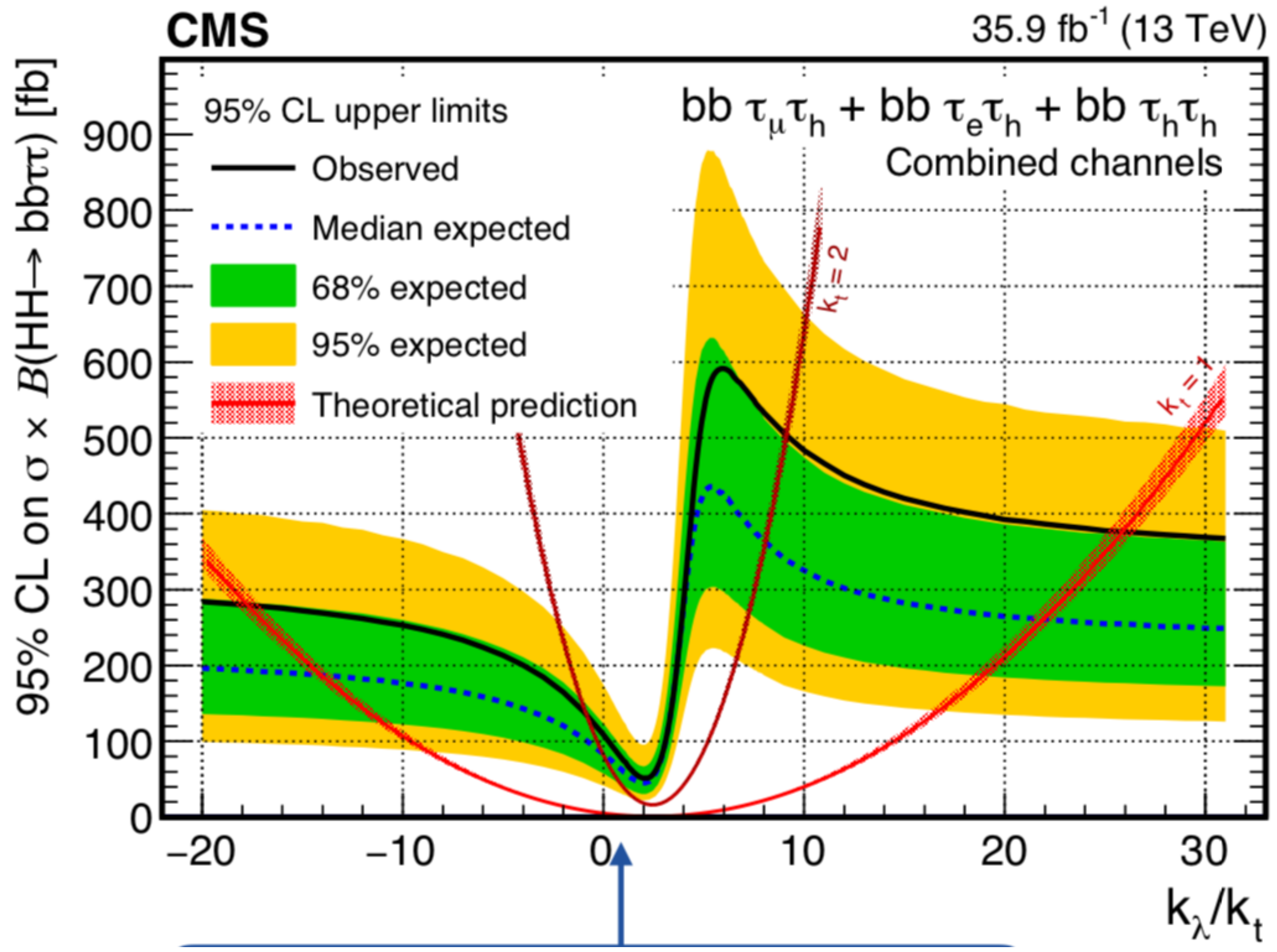
Luca Cadamuro, Katharine Leney

Results

	Expected	Observed
ATLAS	14.8	12.7
CMS	25	30







Analysis Strategies

CMS uses also **boosted** events (and semi-resolved events) to improve sensitivity (for non-resonant too)

1 b-tag category adds 10% to sensitivity in CMS.

Multivariate techniques help but require attention:

- How can we be sure that backgrounds are well modelled in high BDT region.
- Training lots of different BDTs for different scenarios is computational expensive.
- Parameterized NN's should be investigated by both experiments.
- Re-weighting BDT inputs is possible means you need to validate everything again (more work), and leads to more fluctuations.
- Interesting to open up the BDTs to see what cuts are being applied.

Both experiments confirm each others results when comparing cut-based and MVA analyses.

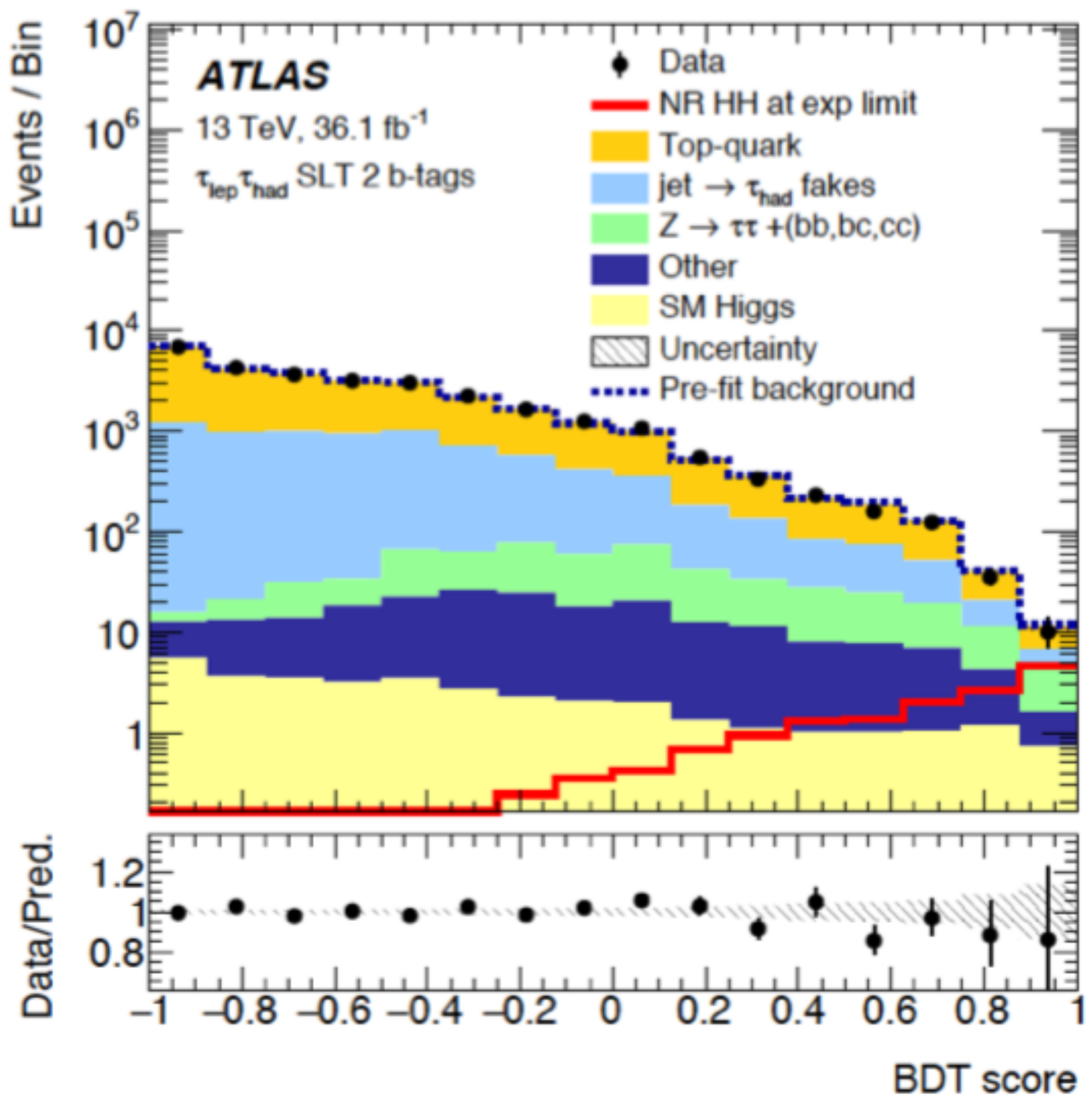
Using multivariate discriminants as final fitted value give optimal analysis sensitivity.

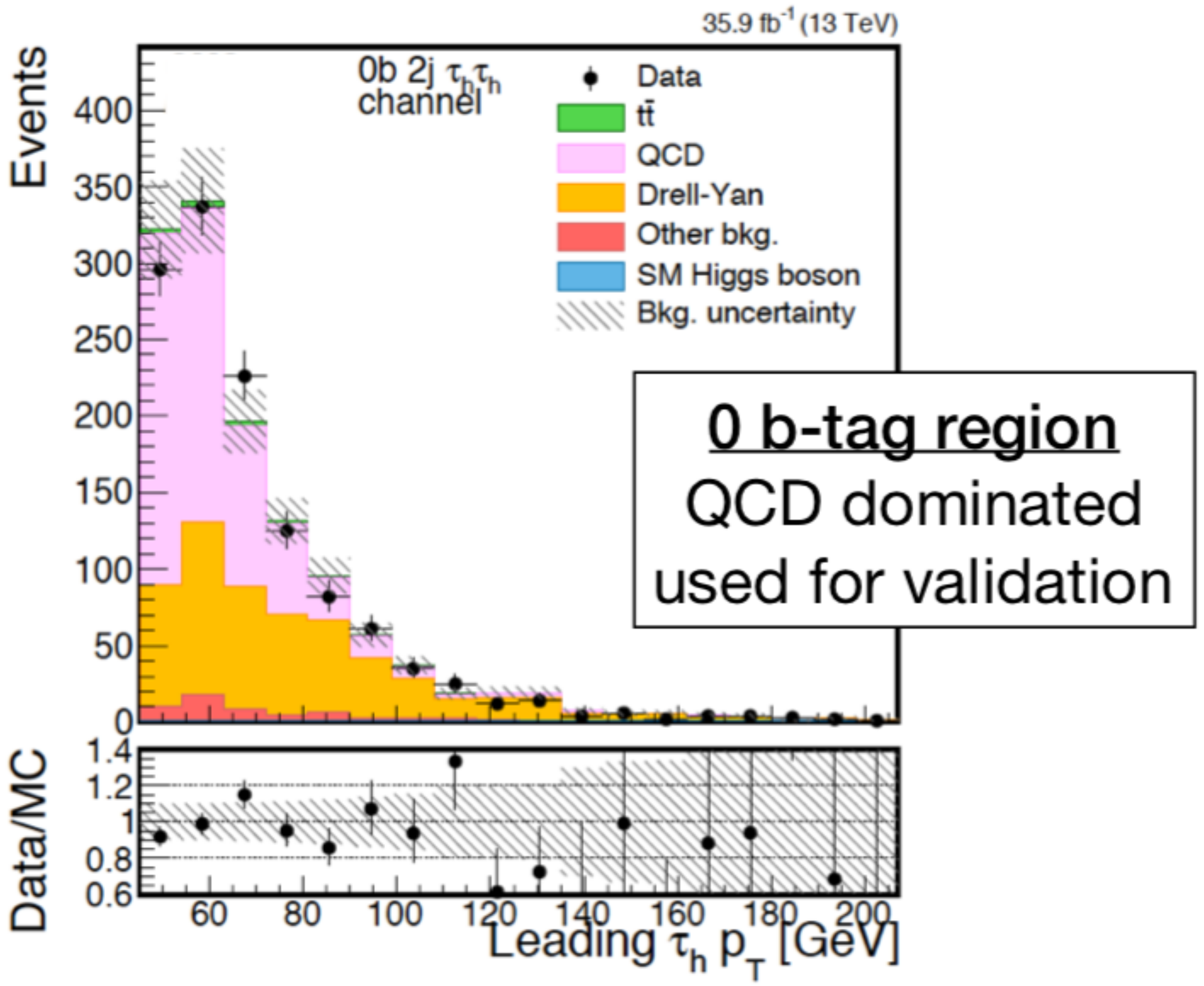
Background Estimates

Main difference in the estimation of fake-τ_h backgrounds.
<u>CMS:</u> Inclusive fake-factors to estimate multi-jet backgrounds (tt estimated from MC)
<u>ATLAS:</u> Parameterized fake factors for treatment of fake-τ_h from multi-jet

- Fake-rate method to correct MC for tt with fake-τ_h

Despite different approaches, both experiments model fake-τ_h backgrounds well.





Triggers

CMS relies only di-τ and single lepton triggers.

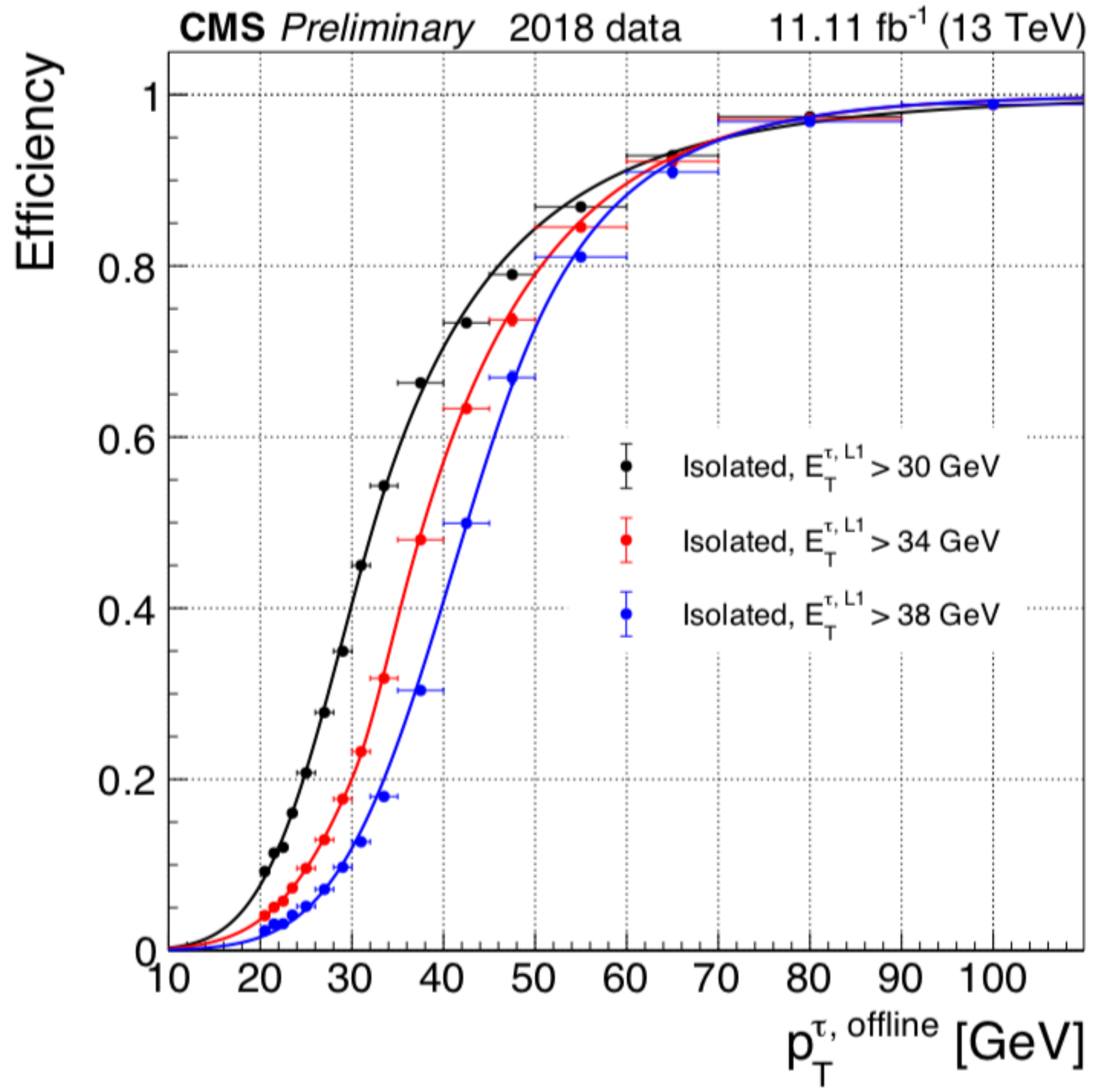
ATLAS includes single tau and lepton+τ triggers, and requires an additional jet to reduce rate of di-τ and lepton+τ items.

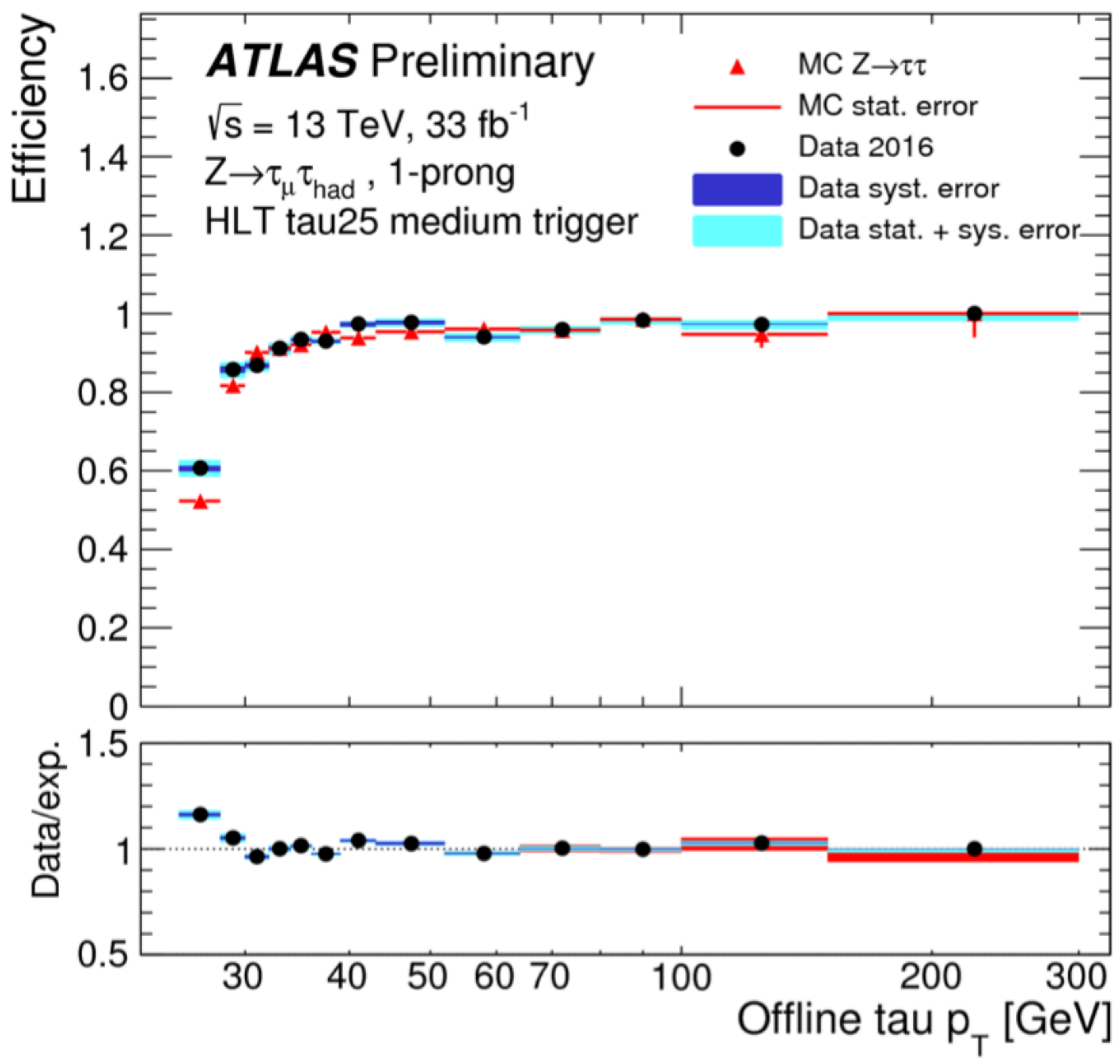
Despite different approaches, overall acceptance seems similar between experiments.

<u>Main challenges are keeping rates low at L1</u>

Both experiments have upgrades which can be utilized to keep H($b\bar{b}$)H(ττ) acceptance high.

CMS is using dedicated VBF triggers. ATLAS has functionality to select VBF signatures at L1 but not fully exploited.





Future

Both experiments plan to include VBF channels for next round.

- Need to check modeling of jet multiplicities.
- Understand gluon-fusion contamination when evaluating anomalous couplings with enhanced VBF?

Can embedding techniques reduce uncertainties on Z+jets backgrounds?

ATLAS	CMS
Include 1 b-tag category.	Move toward fitting MVA output.
Include boosted events.	Extend MVA to all channels.

$H(b\bar{b})H(VV)$

Rami Kamalieddin, Suyog Shrestha, Kuver Sinha

ATLAS bbWW*: Status

G. Palacino

Preliminary results shown in H(b$\bar{b}$)H(lνqq) channel using 36/fb data: Counting experiment, dominated by tt and multijet backgrounds

Non-resonant production

$\sigma(pp\ !\ \ HH) < 10\ \ 10^{+4.1}_{-2.8}$ pb at 95% CL

- Current non-resonant di-Higgs production limit is ~300 x σ_{SM}

ATLAS bbWW*: Plans

J. Veatch

- bbWW* has ongoing studies in 0, 1, and 2 lepton channels
- 0 lepton channel sensitive to both bbWW and bbZZ, targeting high mass resonance –fat jet and jet image techniques
- In 1 lepton channel, improvement through better trigger strategy, reduced backgrounds and systematics being investigated
- 2 lepton channel sensitive to low-mass and non-resonance; Though not yet public, significant improvement expected
- Plan to combine all these channels for full Run2 data

CMS $H(b\bar{b})H(l\nu l\nu)$

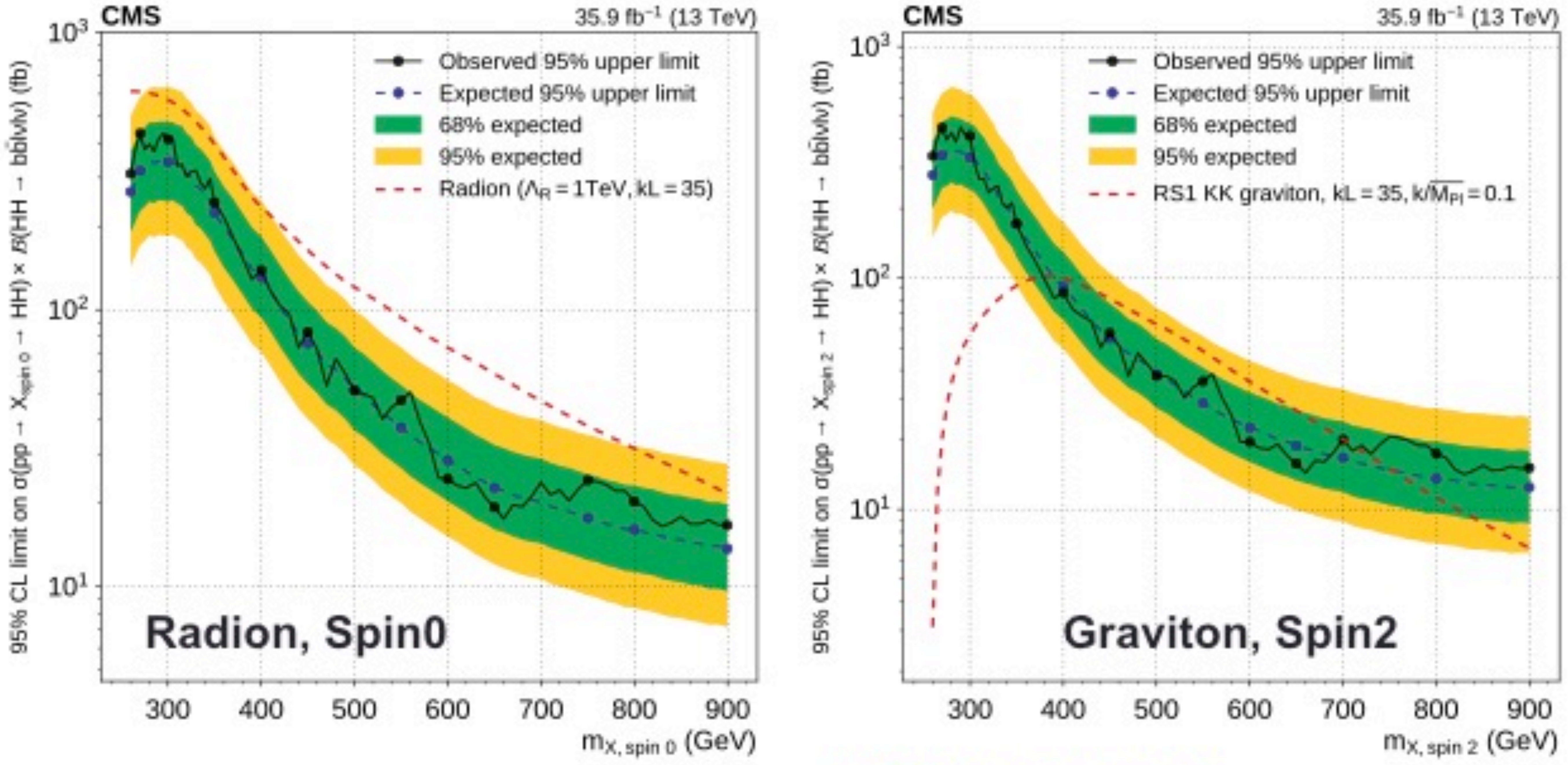
T. Huang

36/fb analysis: DNN with several kinematic variables input, more sensitive than ATLAS 1lepton result

- With SM HH hypothesis, 2016 CMS data excludes σxBr(HH->bblvlv) above 72fb at 95% confidence level

  95% C.L. upper limit on signal strength σ/σ_{SM} : Observed = 79 and Expected $= 89^{+46}_{-28}$

  Stringent limits could be expected by combing other channels



JHEP01(2018)054

CMS H($b\bar{b}$)H(VV) Plans

A. Hortiangtham

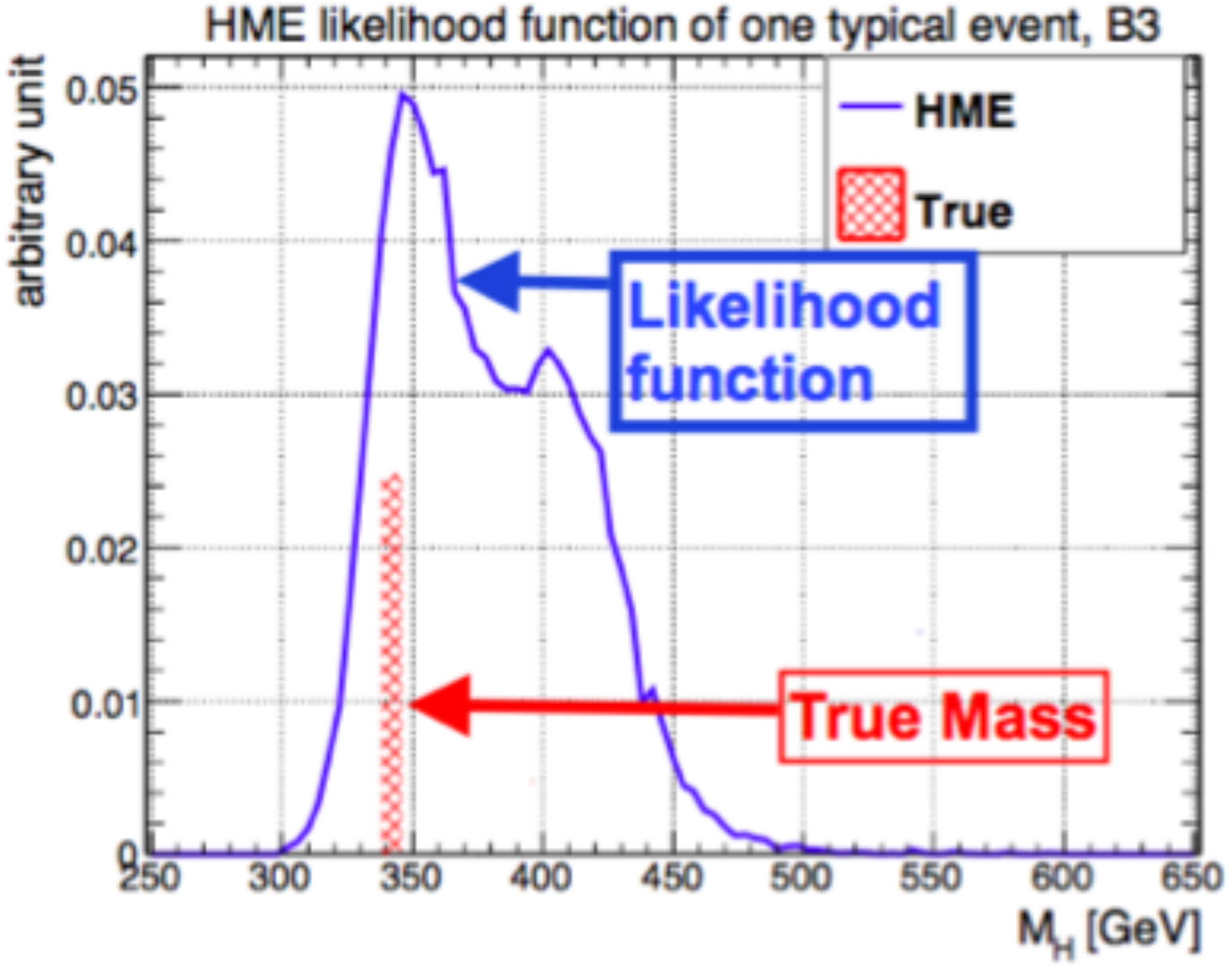
R&D started also for targeted bbZZ analysis

- HH $\rightarrow$ bb2l2ν
- HH $\rightarrow$ bb2l2q
- HH $\rightarrow$ bb4l

New techniques such as HME being studied for event reconstruction – initial results promising

- Construct the likelihood function of each event via the random generations of η and ϕ of one neutrino
- The most probable mass in likelihood function is taken as the estimator of heavy resonance in each event
- All estimators reconstruct a narrow shape of the resonance, for each signal benchmark

Phys. Rev. D 96, 035007



T. Huang

Heavy Mass Estimator

Other signatures

Christian Veelken, Yaquan Fang

arXiv: 1606.01674

Three decay modes without bb studied by ATLAS and CMS:

- WW$\gamma\gamma$ (BR=9.8 10^{-4}) ATLAS
- WWWW (BR=4.6 10^{-2}) ATLAS
- $\tau\tau\tau\tau$ (BR=4.0 10^{-3}) CMS

WW$\gamma\gamma$ and WWWW channels provide sensitivity to Higgs-like scalars S

Current sensitivity (non-resonant production):

- WW$\gamma\gamma$ 160 x SM
- WWWW 110 x SM
- $\tau\tau\tau\tau$ - (current analysis concentrates on resonant signal)

➔ Currently factor 5-10 less sensitivity compared to most sensitive channels (bbbb, bb$\tau\tau$, bb$\gamma\gamma$)

Too early to draw conclusions, however:

- Analysis effort has started very recently and is still ramping-up
- Many potential improvements currently still in the queue

ATLAS H(WW)H(WW)

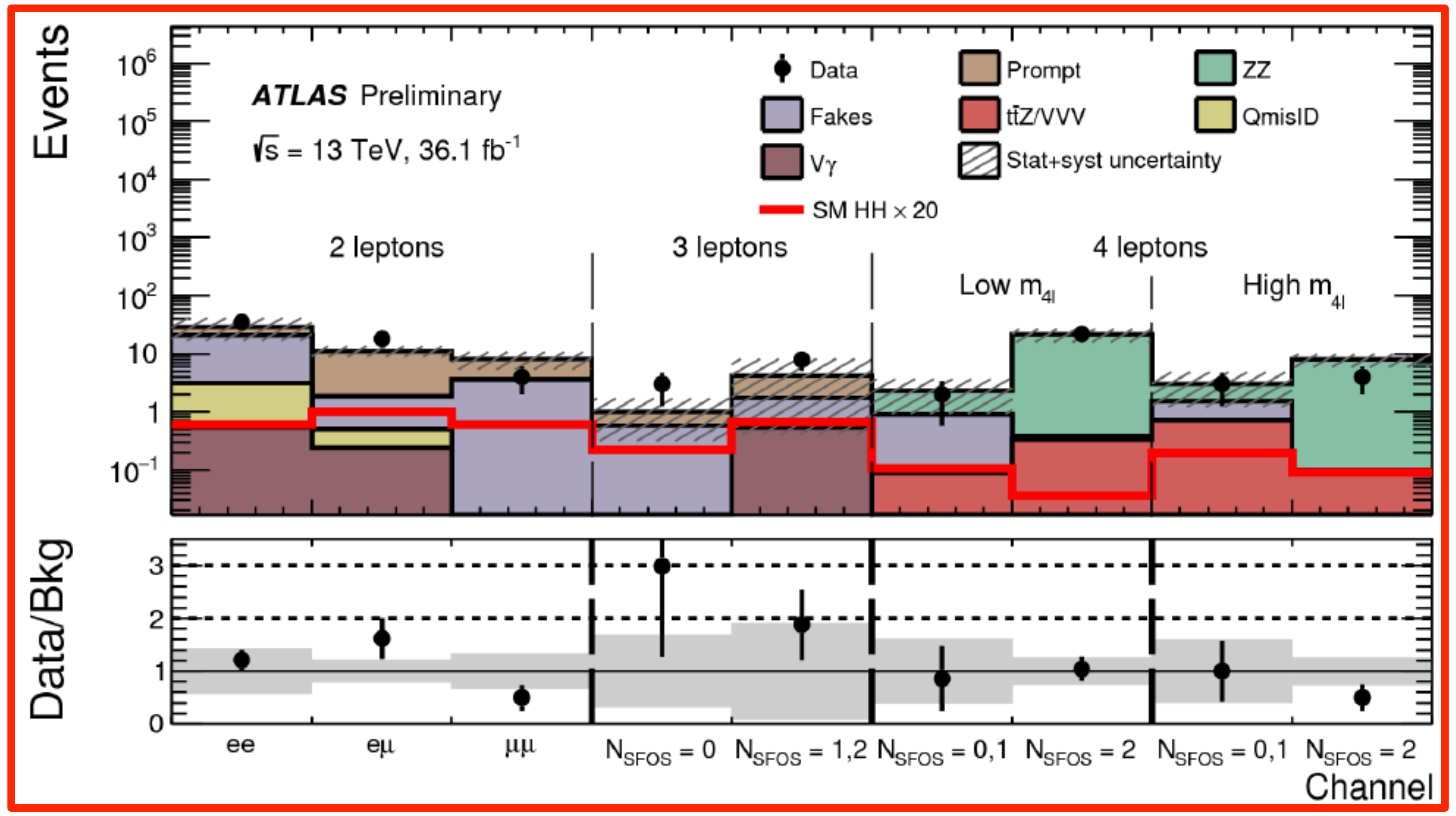
Liang Li

Analysis covers 2 lepton (same charge), 3 lepton and 4 lepton channels

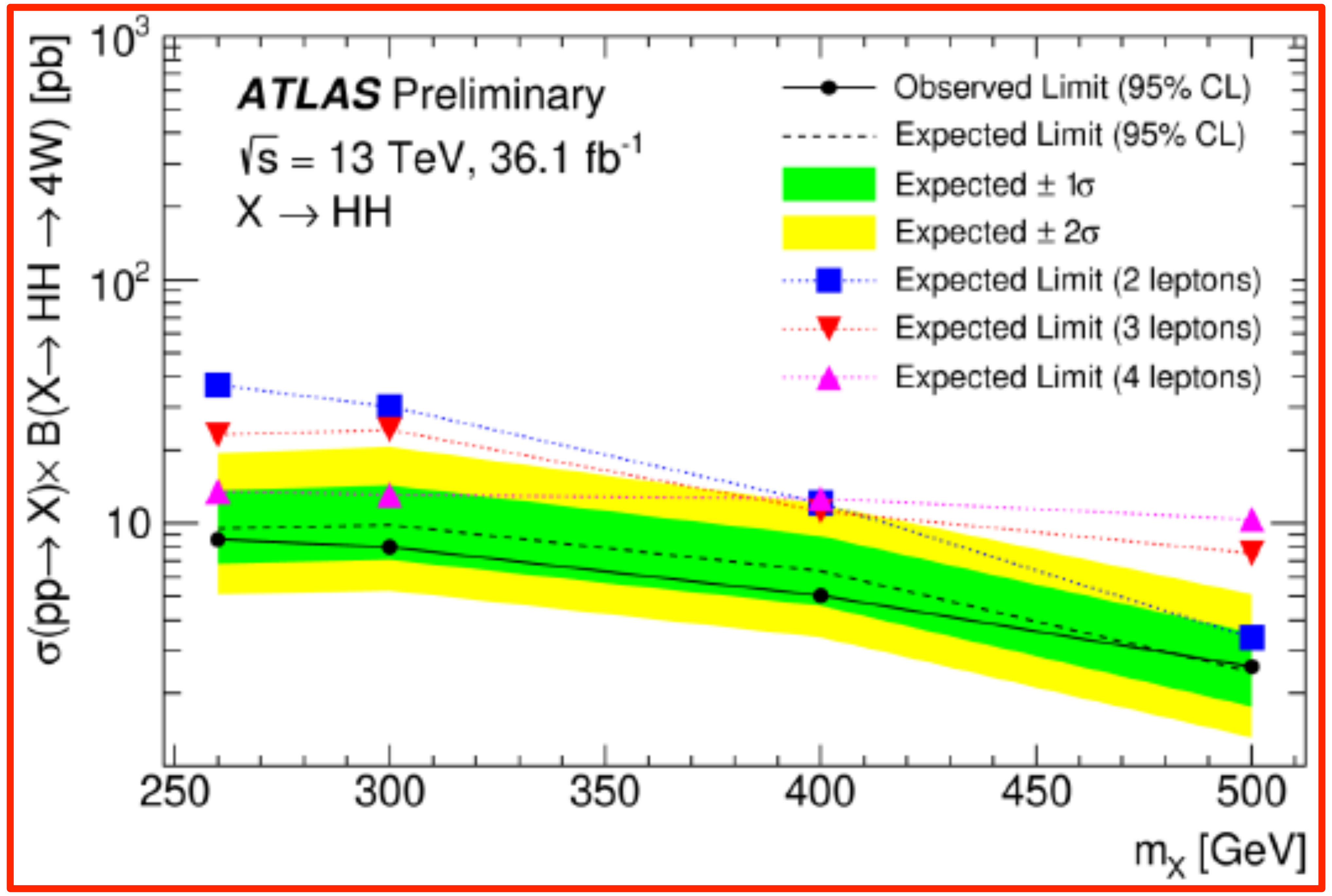
Cut&count used for signal extraction

Sensitivity lower compared to most sensitive bbττ channel, but many significant improvements are in the queue:

- Switch from cut&count to MVA-based signal extraction
- Add more variables to enhance signal/ background separation
- Add 1 lepton+boosted hadronic W channel



NEW



Maosen Zhou

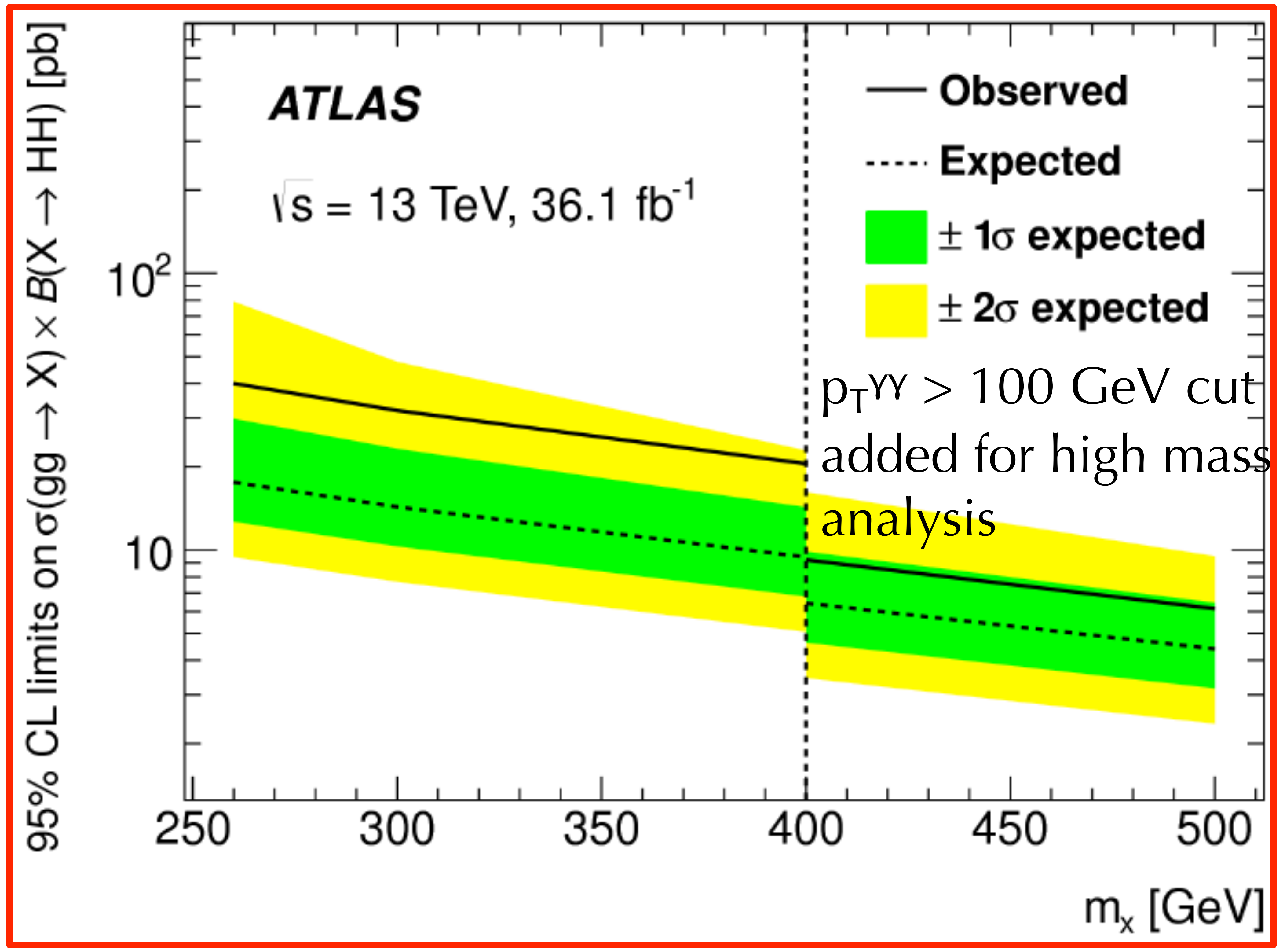
ATLAS H(WW)H(γγ)

Analysis performed in lepton + 2 jet channel

<u>Sensitivity at present limited by small signal yield, but expected to scale well with luminosity</u>

Many significant improvements are in the queue:

- Optimize signal extraction with MVA
- Add dilepton channel
- Add 1 lepton+boosted hadronic W channel
- Categorize events in $p_T^{\gamma\gamma}$



NEW

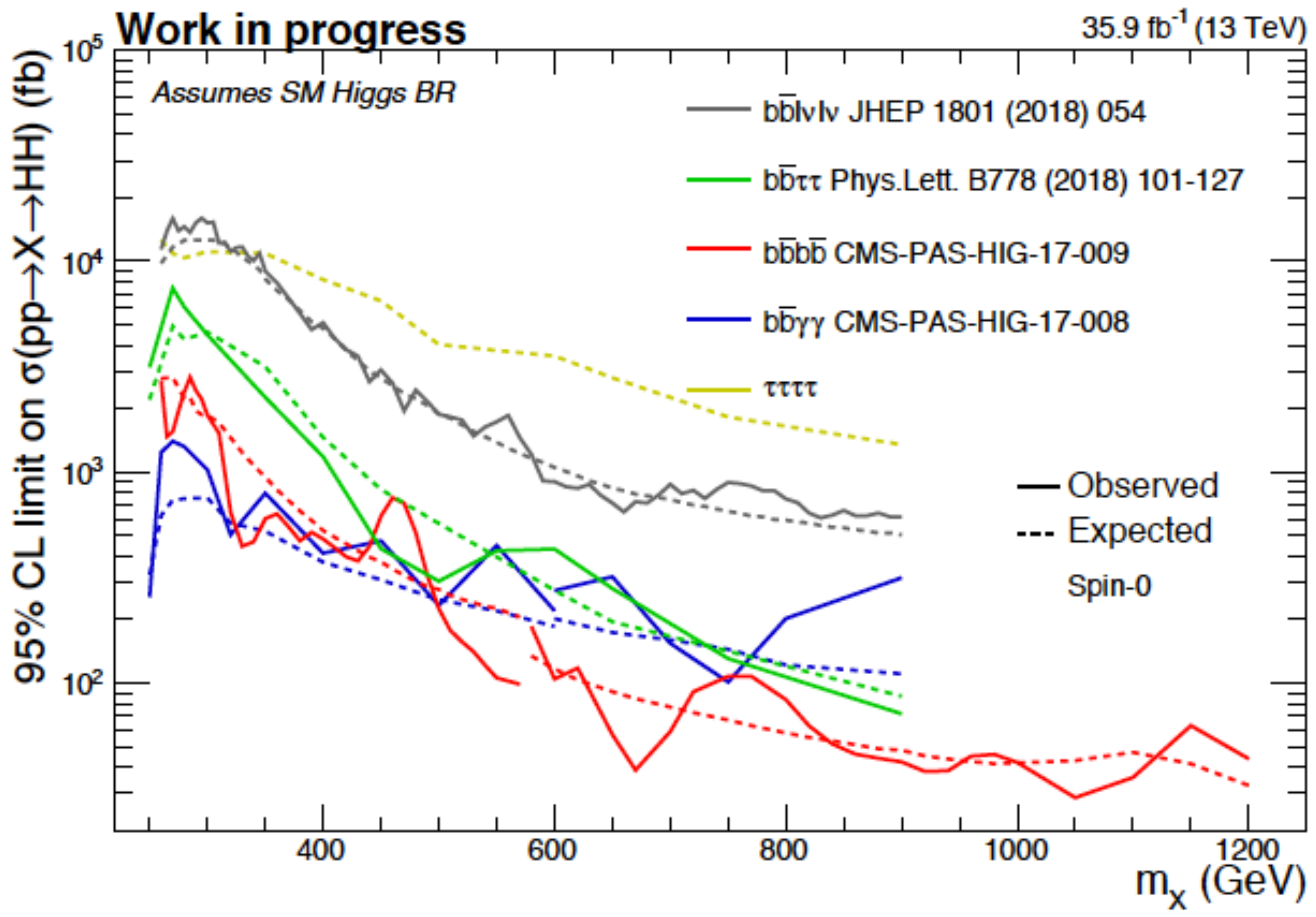
Saswati Nandan

CMS H(ττ)H(ττ)

Analysis currently concentrating on resonant production

Only the **ττττ** to 2l + 2τ_h channel included in analysis so far

Events analyzed in 6 event categories based on lepton flavor (ee, **μμ**, e**μ**) and charge (same charge, opposite charge)



Analysis does not yet consider signal contribution from H(WW)H(**ττ**) and H(WW)H(WW)

<u>In particular sensitivity of same charge categories limited by small signal yield</u>

➔ expected to scale well with luminosity

Potential for significant sensitivity improvements:

- Add 1 lepton + 3 τ_h, 4τ_h, 3 lepton + 1τ_h, and 4 lepton channels
- Reconstruct HH mass with SVFit algorithm
- Consider adding 2 lepton (same charge) and 3 lepton + jets channels also

More on the combination

Arnaud Ferrari, Maxime Gouzevitch

Not so much about combination, three topics were addressed:

- Interferences in HH searches
- Interpolations and interpretations in BSM non-resonant HH (ggF)
- VBF generation and benchmarks

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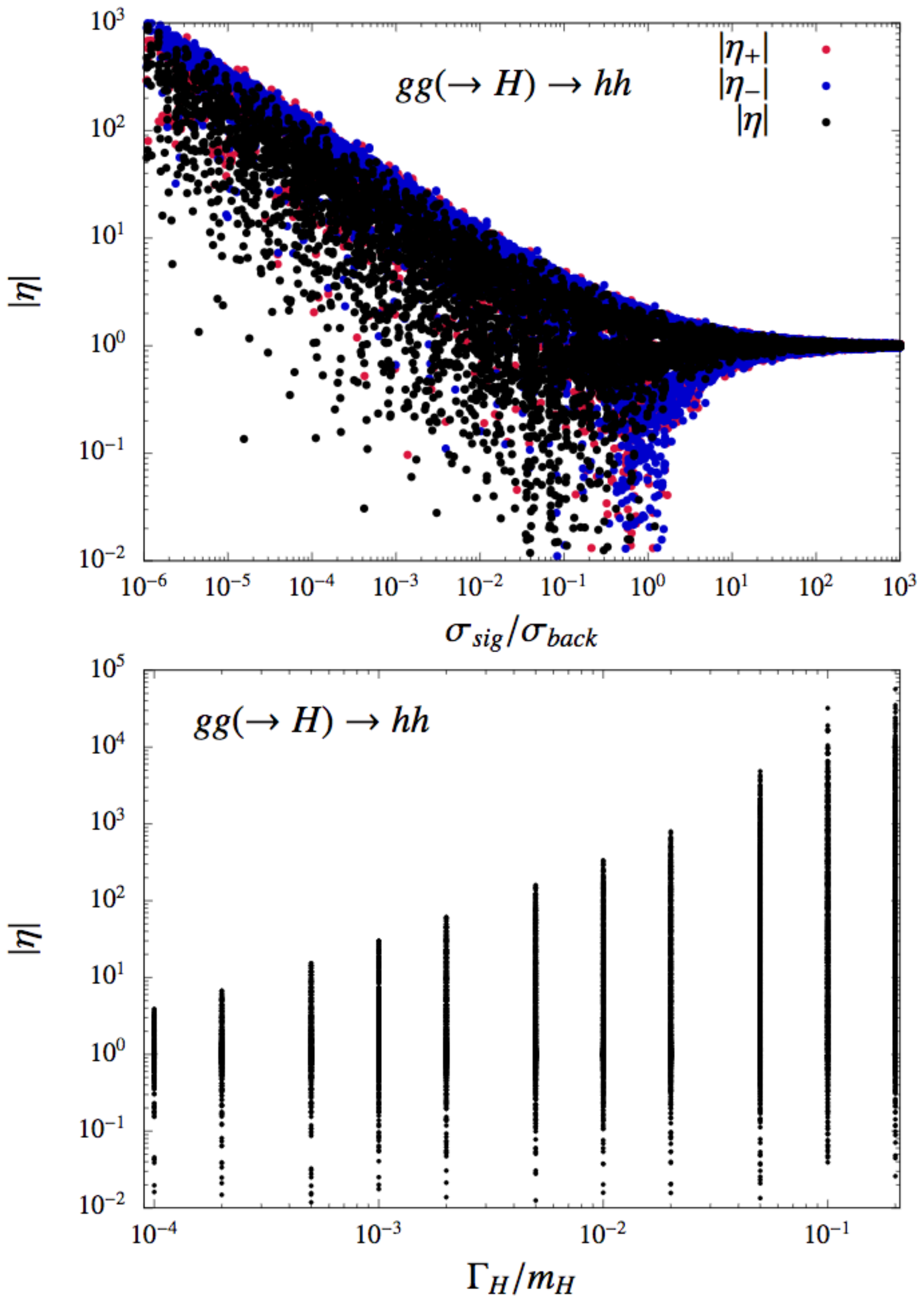
Experimental Signatures: Combination and other common topics

A. Ferrari, M. Gouzevitch

Interferences in HH searches

Interference effects (η) depend on Γ/m but also on the signal over background cross-sections, where signal = BSM resonant HH and background = SM non-resonant HH. Can be large if $\sigma_{sig}/\sigma_{back}$ is very small.



Marcela presented a model with additional singlets: $gg \to S \to HH$ and SM HH can interfere:

- Real parts of the interference $\Rightarrow$ shift of the mass peak;
- Imaginaryparts of the interference $\Rightarrow$ peak or dip structure at the mass peak $\Rightarrow$ effective change of the cross-section.

Searches should consider this on-shell constructive interference. At large m_S, the increase of the mass reach can be important (40% on the cross-section, a few 100 GeV on the mass reach at HL-LHC).

To do for experiments: consider models with both resonant and non-resonant HH in the searches. In such cases, probe the interference!

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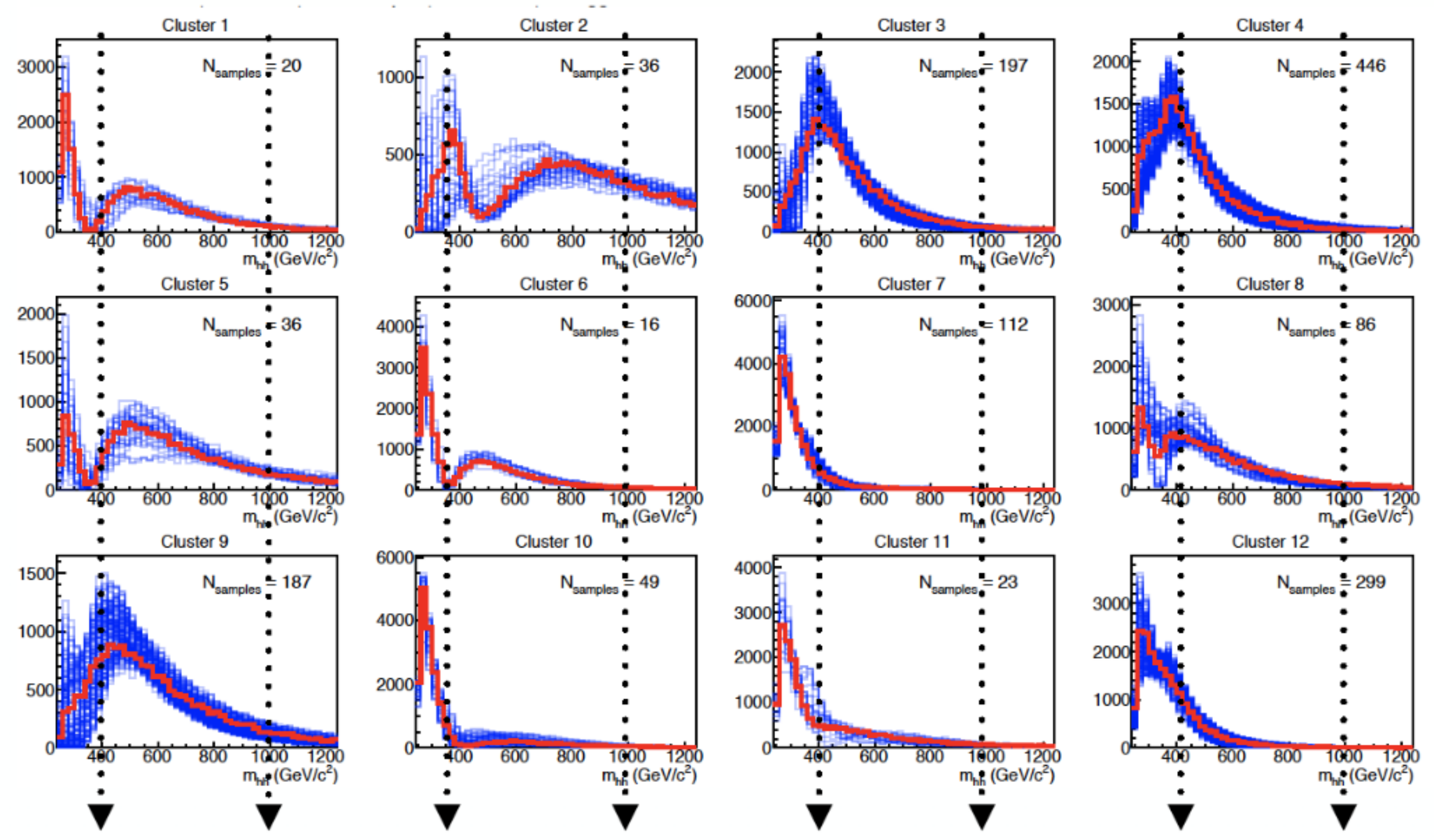
Experimental Signatures: Combination and other common topics

A. Ferrari, M. Gouzevitch

Interpolations and interpretations in BSM non-resonant HH (ggF)

From a 5D parameter space, one defines 12 shape benchmarks. The distributions of benchmarks usually enclose simply connected regions of couplings. Within the precision of the methods, similar shapes at LO and NLO.

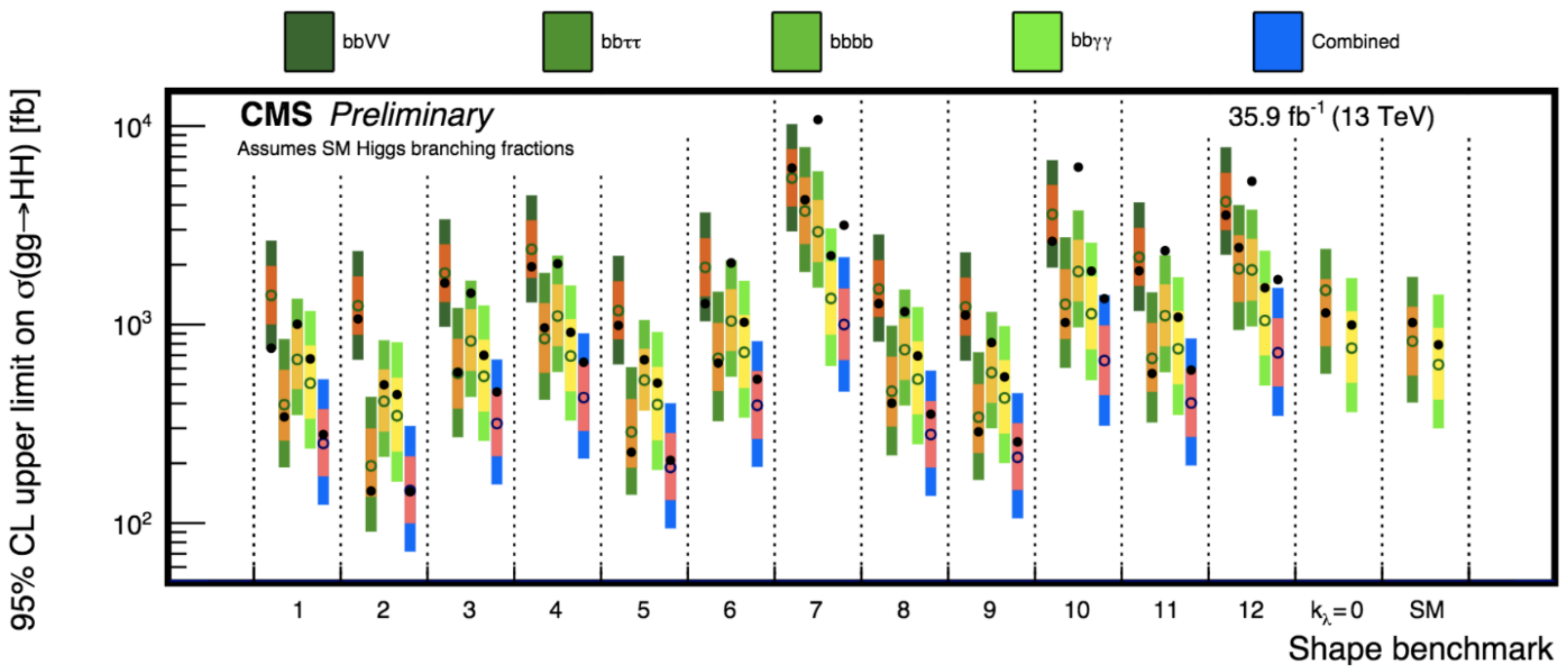


Mhh = 400, 1000, 400, 1000, 400, 1000, 400, 1000, GeV

Red: the benchmark
Blue: the other samples in the cluster

The benchmarks are part of the LHCXSWG YR4

Used by CMS for interpretations, but ATLAS only probed the self-coupling variation. Needs harmonisation!!!



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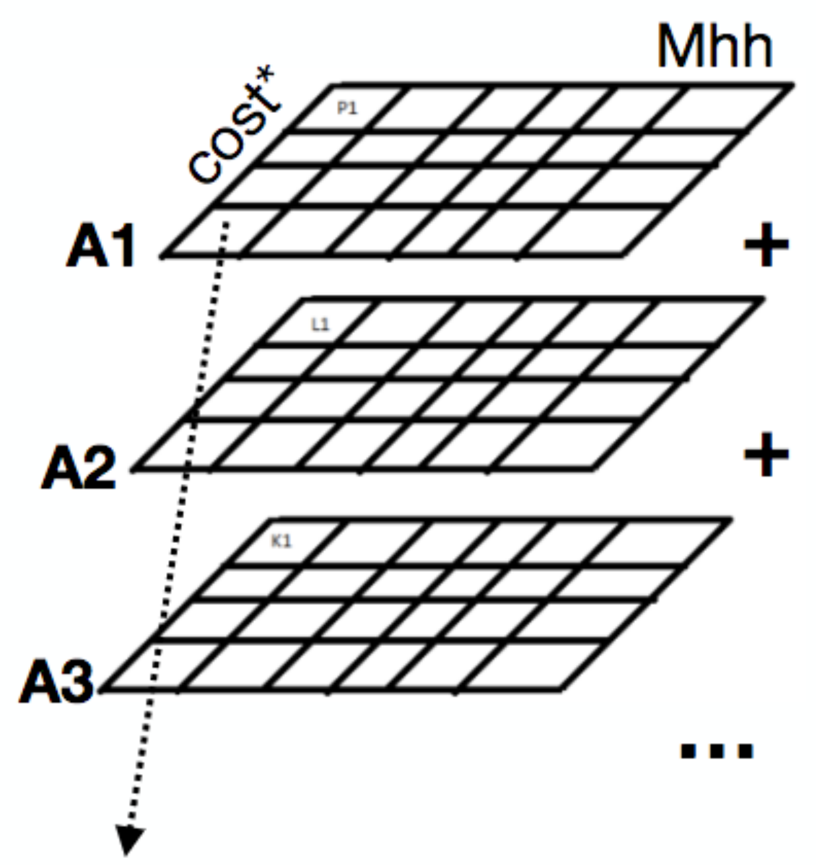
Experimental Signatures: Combination and other common topics

A. Ferrari, M. Gouzevitch

Interpolations and interpretations in BSM non-resonant HH (ggF)

5D amplitude decomposition: 15 coefficients at LO $\rightarrow$ how to use them when making BSM interpretations? Needs harmonisation!!!



$$R_{hh} \equiv \frac{\sigma_{hh}}{\sigma_{hh}^{SM}}$$

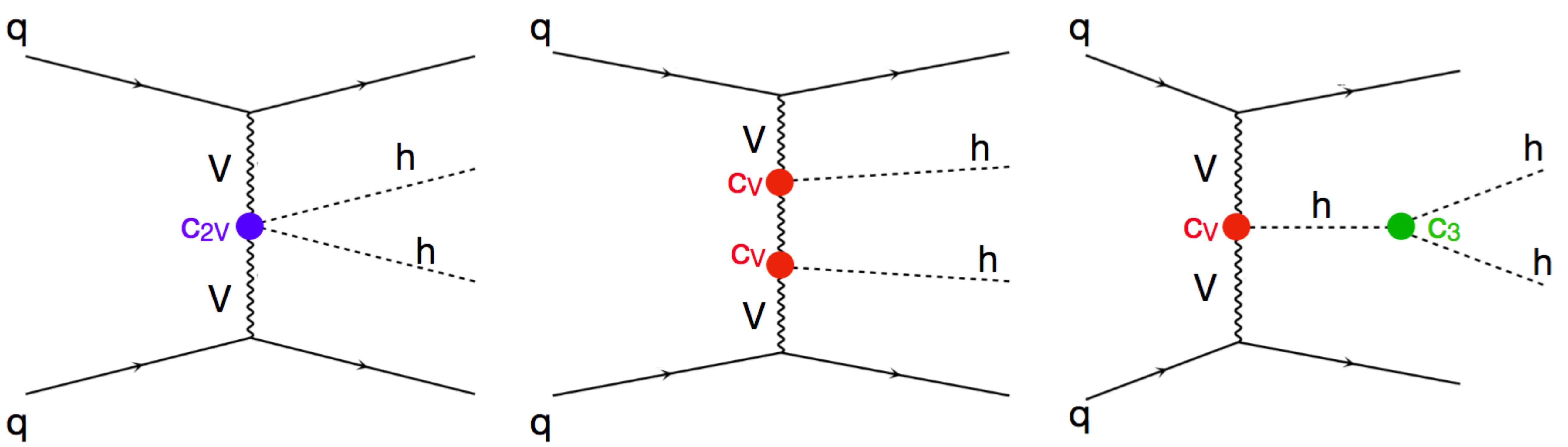
$$= A_1\,\kappa_t^4 + A_2\,c_2^2 + (A_3\,\kappa_t^2 + A_4\,c_g^2)\,\kappa_\lambda^2 + A_5\,c_{2g}^2 + (A_6\,c_2 + A_7\,\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+ (A_8\,\kappa_t\kappa_\lambda + A_9\,c_g\kappa_\lambda)c_2 + A_{10}\,c_2c_{2g} + (A_{11}\,c_g\kappa_\lambda + A_{12}\,c_{2g})\,\kappa_t^2$$
$$+ (A_{13}\,\kappa_\lambda c_g + A_{14}\,c_{2g})\,\kappa_t\kappa_\lambda + A_{15}\,c_g c_{2g}\kappa_\lambda$$

Those coefficients can also be viewed as differential

	Reweighing event by event using representative matrix of events (e.g. the shape benchmarks)	Treating the parts of the cross section as different samples to be combined
Pros	All the generated event statistics has positive weights = Maximal use of MC stats	More intuitive for setting limits on parameters given the statistical tools available on experiments
Cons	To set limits on parameters one must adapt a framework for doing limits on from scans/ shape morphings	Part of the generated MC stats. may have negative weights, according with the point Some weights can be large.
	CMS analyses has been doing up to now	ATLAS has been doing up to now

The method of defining shape benchmarks for HH non-resonant searches allows to compute limits on any preferred combination of anomalous Higgs couplings. ATLAS and CMS need to uniform the method of BSM scan for a combination. The very same shape extrapolation methods can be used for VBH HH production, too :)

VBF HH production and benchmarks



- VBF production has a small cross-section wrt ggF but two high-pT forward jets that provide a clean signature.
- VBF categories have never been explicitly implemented in searches.
- Three couplings (c2v, cv and c3) to probe with VBF $\Rightarrow$ access to the c2v (VVHH) coupling $\Rightarrow$ additional tests of the SM.
- Large variations of the cross-section with c2v... and no constraints yet!

$c_3 \equiv \lambda/\lambda_{SM}$	c_{2V}	c_V
1	1	1
1	0	1
1	0.5	1
1	1.5	1
1	2	1
0	1	1
2	1	1
1	1	0
0	1	0
1	0	0
1	0	0.5

ATLAS has a set of coupling variations $\Rightarrow$ a discussion with CMS is needed!
One could even use a shape benchmark approach to scan BSM couplings.

Future …

Nicola De Filippis, …

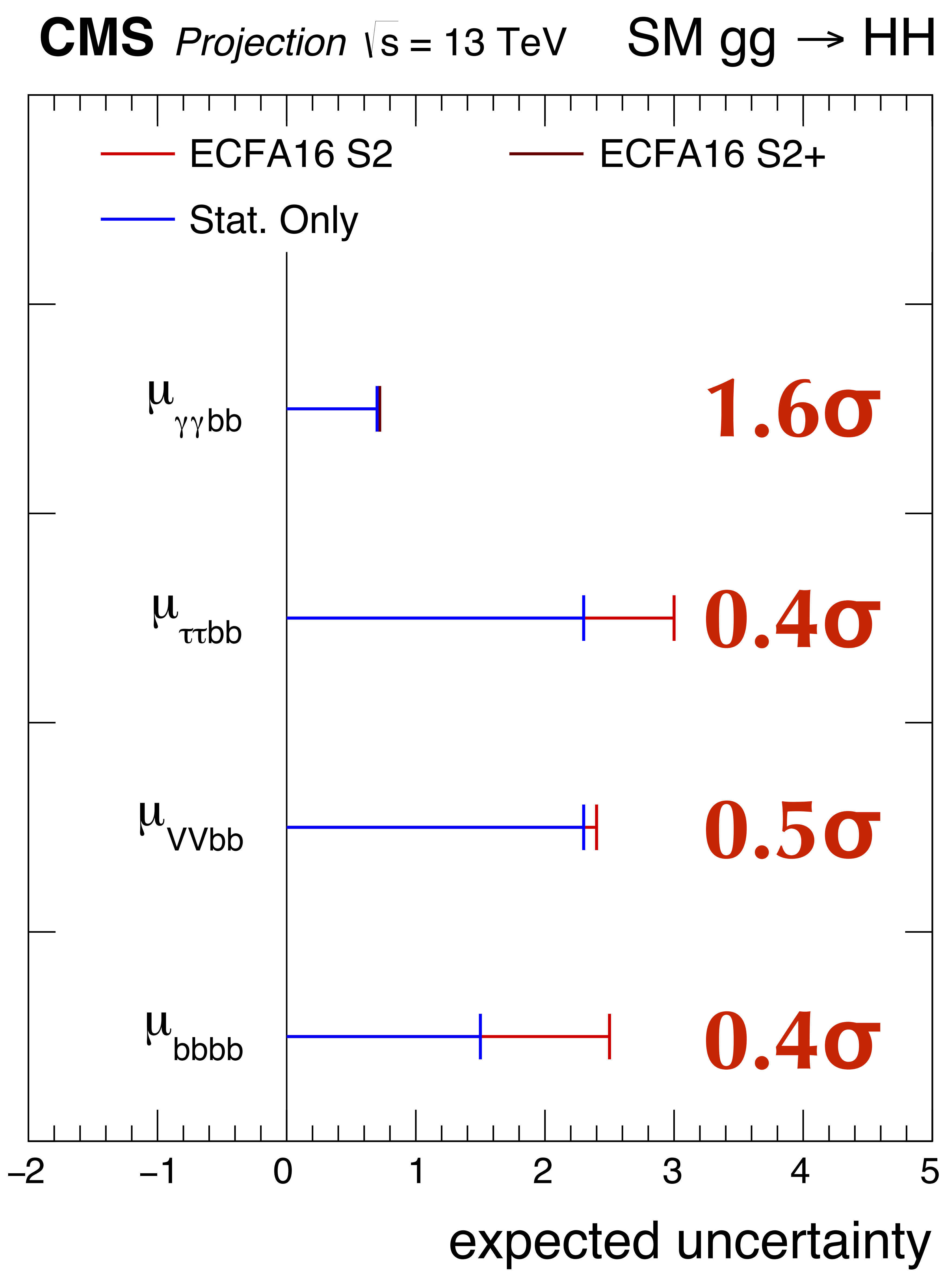
CMS-FTR-16-002
CMS-TDR-17-001

Projections for HL-LHC

Extrapolation from Run II to HL-LHC (3000 fb^{-1})

- based on 2015 data, about 2.3-2.7fb^{-1}
- Different scenarios:
  - **No systematics**
  - **ECFA16 S2** reduced theory uncertainties and reduced systematics
  - **ECFA16 S2 +** including future detector performance

This is overly pessimistic



HL-LHC projections and YR status by S. Gori

Channel	CMS	ATLAS
$HH \rightarrow bbbb$	$Z(\sigma_{HH}(SM))=0.39\ \sigma$ CMS PAS FTR-16-002	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L. ATLAS-TDR-030
$HH \rightarrow bb\tau\tau$	1.6 xSM CMS-TDR-019	$0.6\ \sigma$ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L. ATL-PHYS-PUB-2015-046
$HH \rightarrow bb\gamma\gamma$	$1.43\ \sigma$ CMS PAS FTR-16-002	$1.5\ \sigma$ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only) ATLAS-TDR-030
$HH \rightarrow WWbb$	$0.45\ \sigma$ CMS PAS FTR-16-002	
$tt(HH \rightarrow bbbb)$		$0.35\ \sigma$ ATL-PHYS-PUB-2016-023

This is still pessimistic

HL-LHC projections and YR status by S. Gori

a) SM cross section: New recommendation of the LHC Higgs cross section WG https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHH

b) Overview of the CMS effort:
- "Double Higgs measurements and trilinear coupling" development of full analyses based on fast simulation in the five main decay channels under HL-LHC conditions
- "Indirect probes of the trilinear coupling through differential distributions measurements" projected constrains of k_λ from $h \to \gamma\gamma$ differential measurements

c) Overview of the ATLAS effort:
- Analysis mainly based on extrapolation of Run II results (bbbb,bb$\tau\tau$,bb$\gamma\gamma$)
- Studying systematics and triggers in HL-environment
- Interpretations in terms of di-Higgs significance + measurement of k_λ

e) Prospects for HE-LHC: Two theory groups involved in the studies [?] bb$\gamma\gamma$ results available

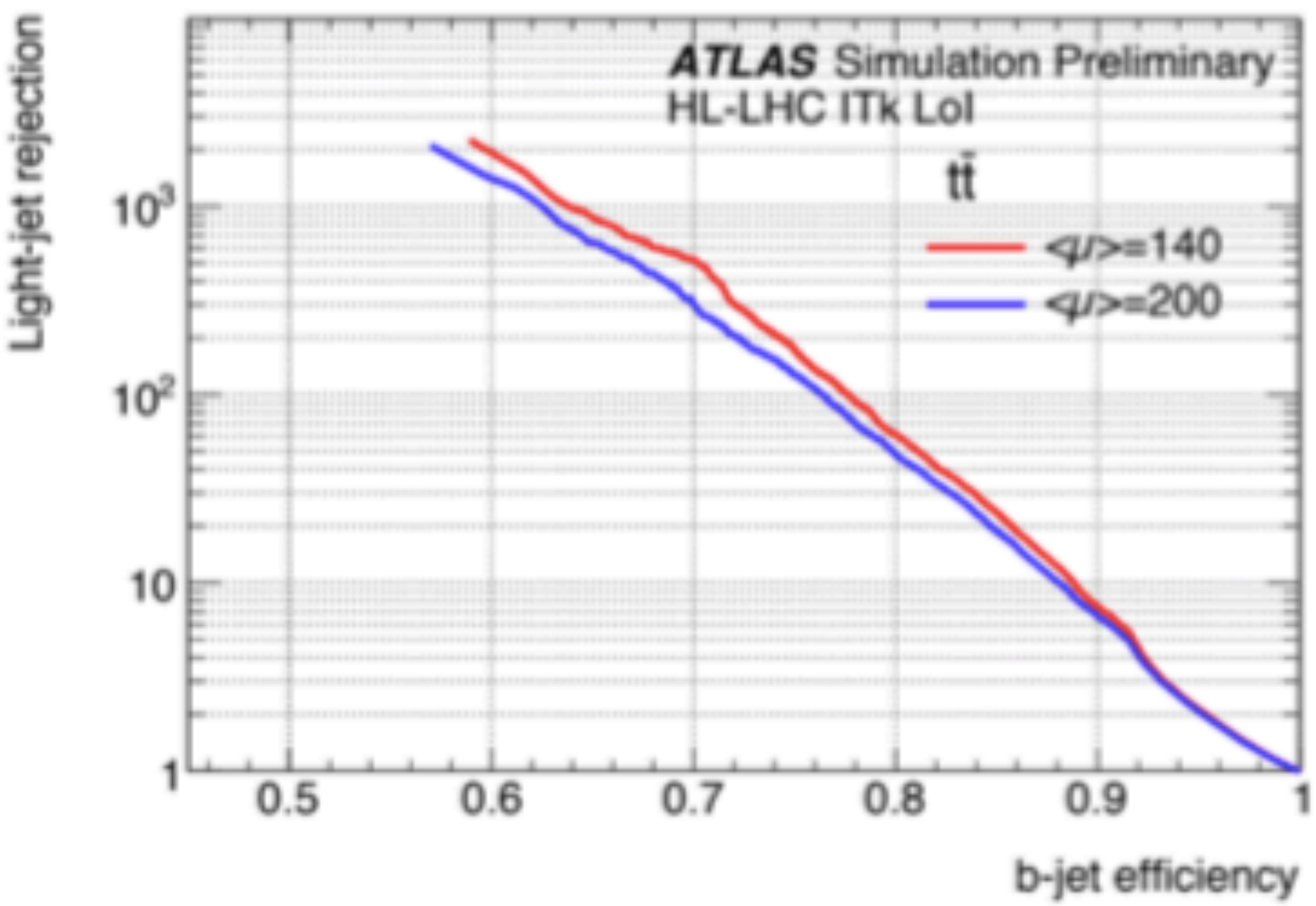
f) Global fits (di-Higgs+single Higgs): EFT fit performed in the 10-dimensional space

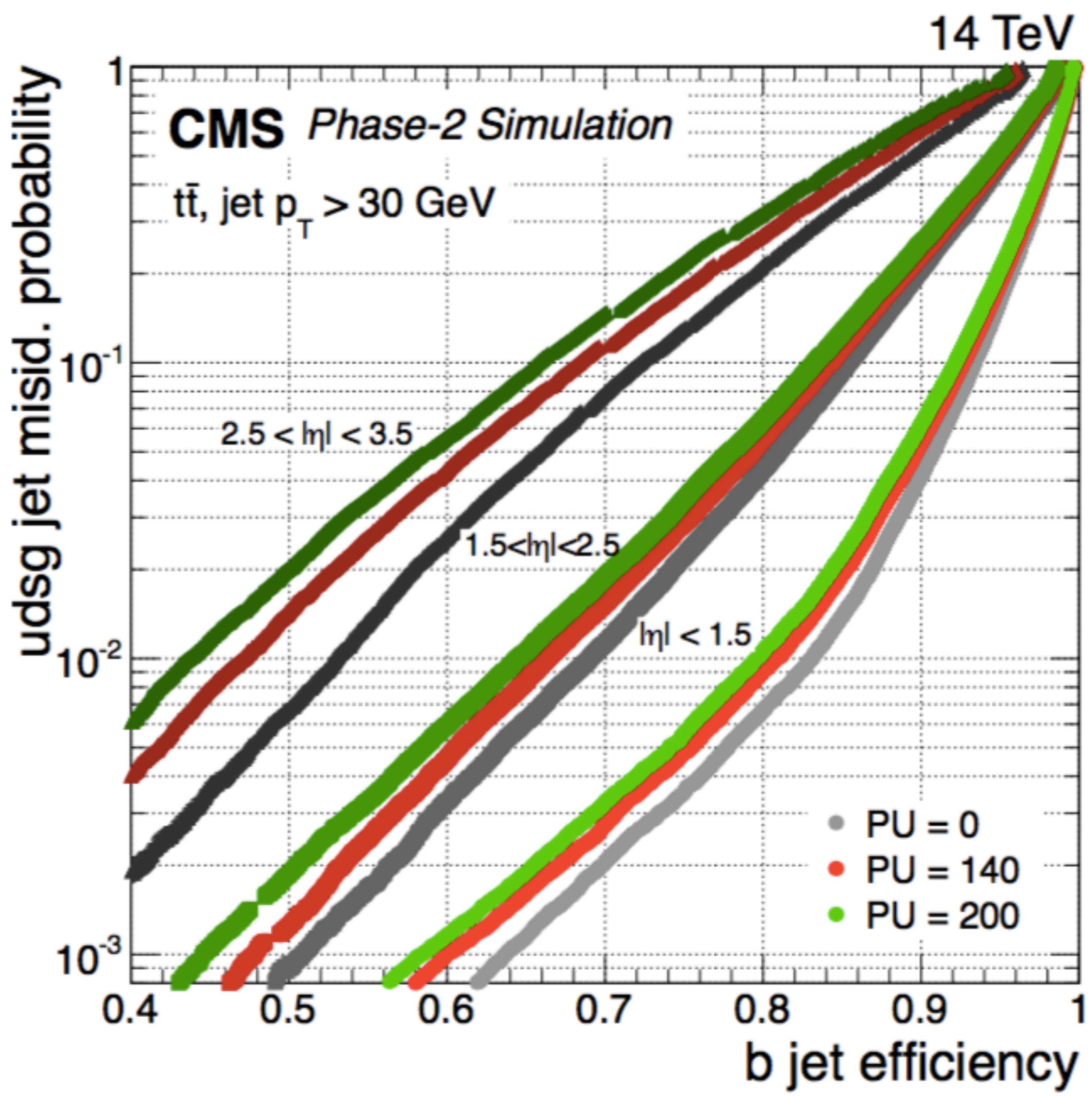
g) New physics models for di-higgs in non linear EFT

b-tagging @ HL-LHC

- ***SM HH discovery is challenging*** but analysis improvements thus far are faster than only luminosity gains
- We will have a **new tracker detector at HL-LHC…**
  - *10% improvement in signal acceptance* for $H(b\bar{b})H(b\bar{b})$ from extended tracker acceptance up to $|\eta| = 4$
  - b-tagging performance will benefit from a more granular detector

ATL-PHYS-PUB-2016-026

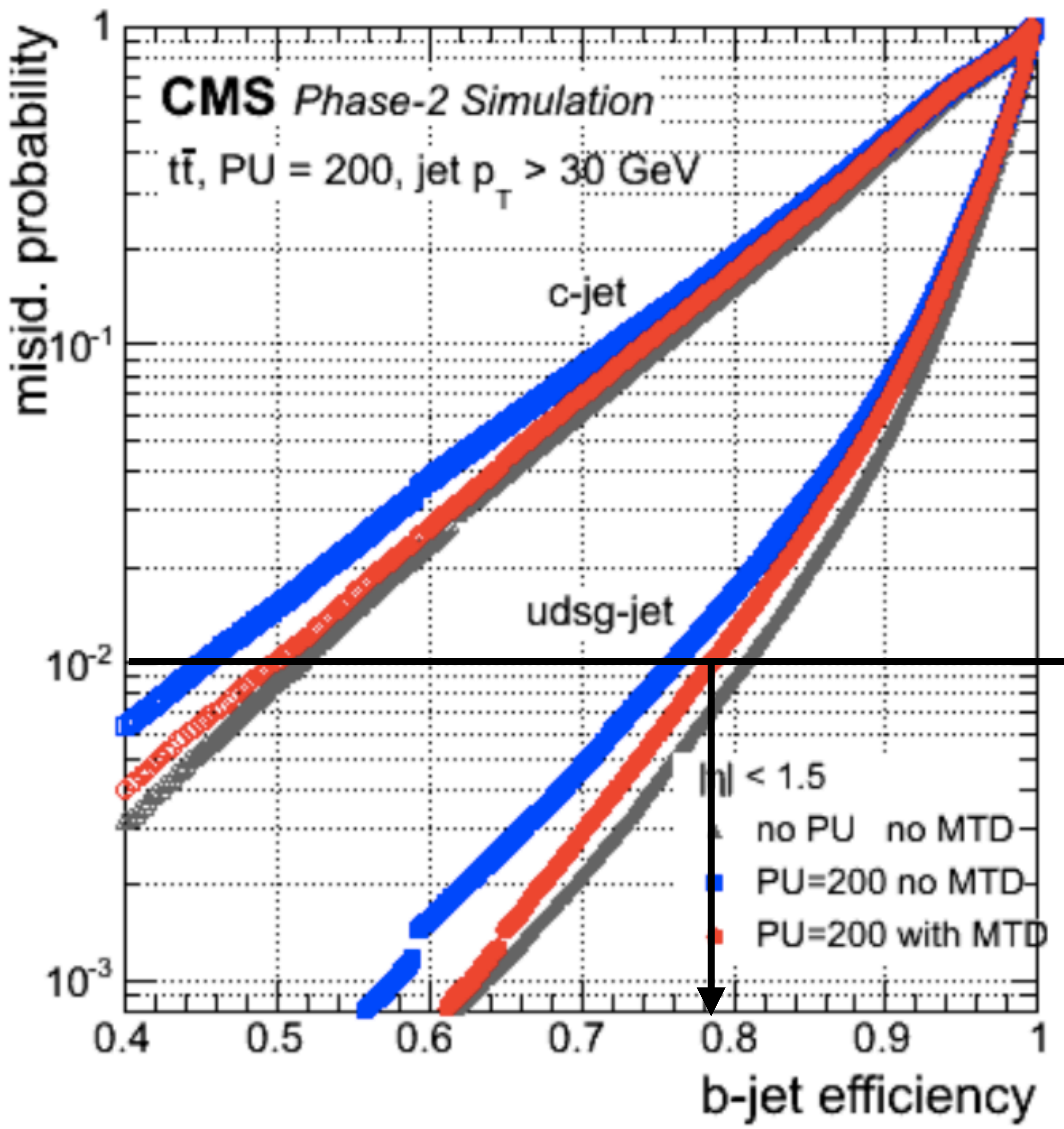


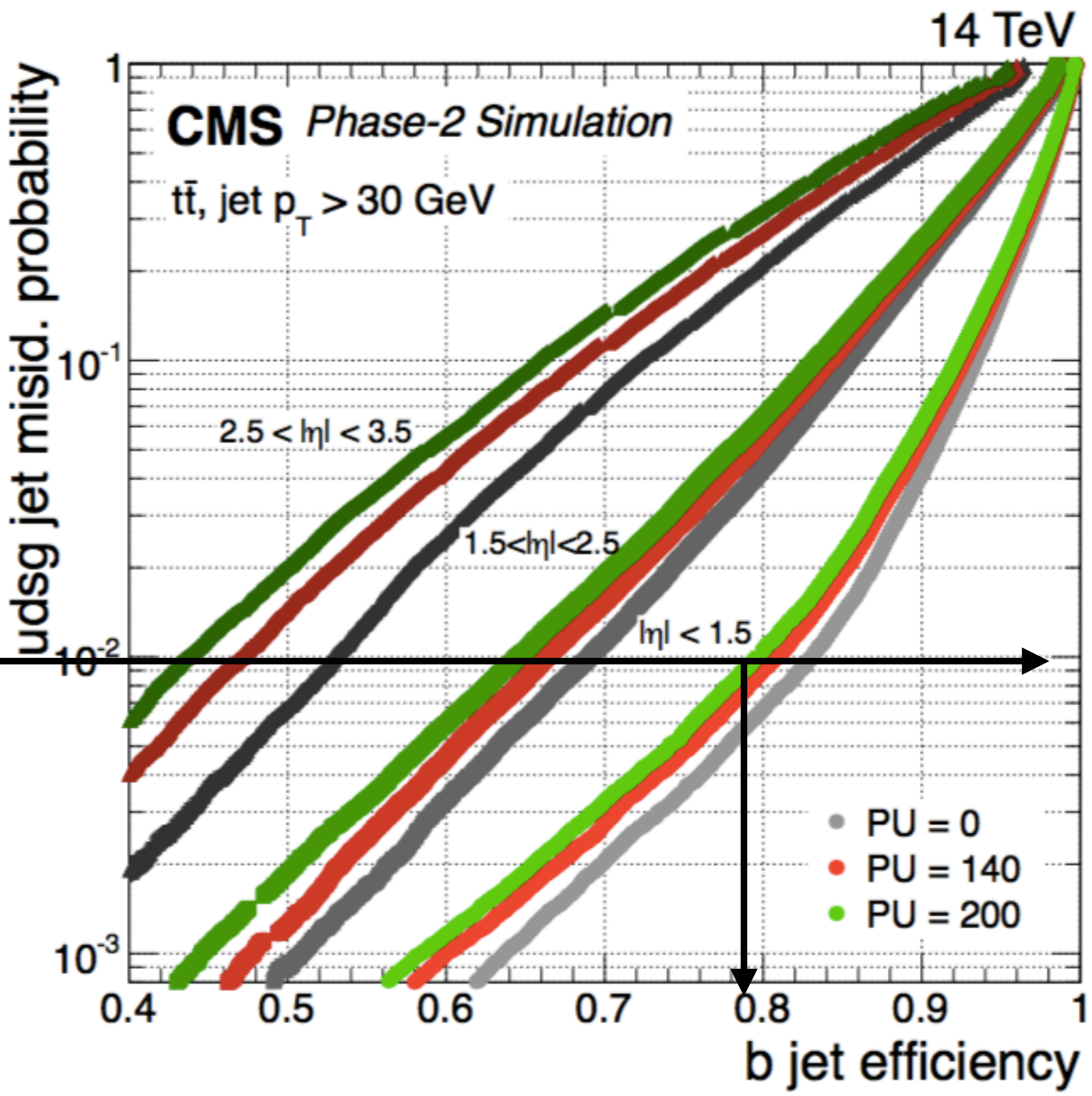


b-tagging with timing

Mip Timing Detector

Channel	Signal increase (%)
HH→ $b\bar{b}\gamma\gamma$	22
HH→ $b\bar{b}b\bar{b}$	18

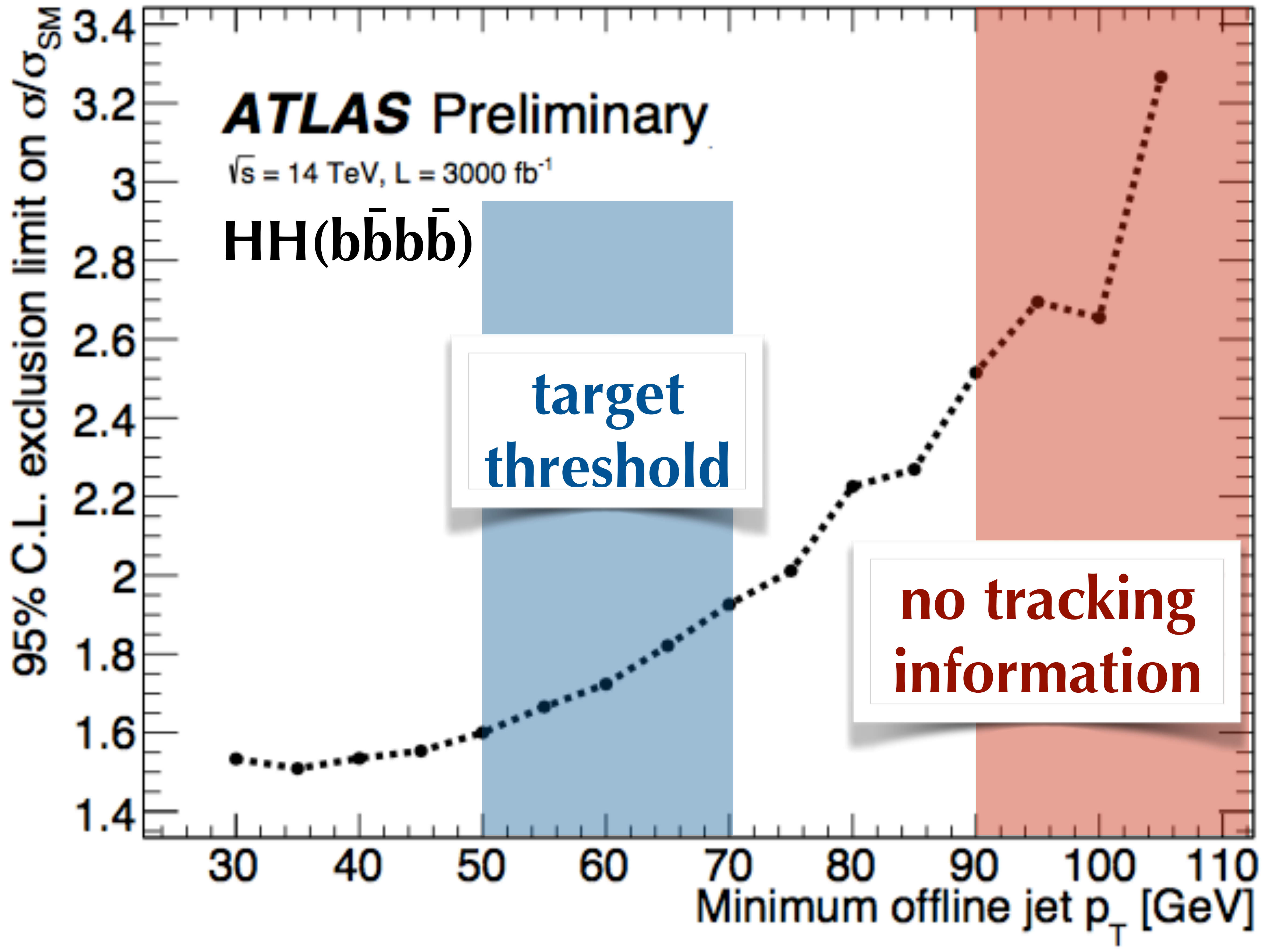




Impact of b-jet triggers at HL-LHC

- The ability of using **tracking information at trigger level** is **crucial** to reach sensitivity to the **SM HH** process
- A no-upgrade scenario would lead to a sensitivity loss of ~ 60% by the increase of jet p_T thresholds

Exploiting b-tagging information at trigger level will play a critical role



One lesson from the past

One lesson from the past

“uncertainty of ± 5 %. on the shape of the $Wb\bar{b}$ background in the $H \to b\bar{b}$ signal region. In conclusion, the extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions for the b-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself.”

— SNOWMASS-2001-P111

“Unfortunately, due to the typically large QCD backgrounds for b jets, it is very difficult to observe this decay. The production modes $t\bar{t}H$ [27, 32, 33] and WH [14, 34] might allow very rough measurements for such a light Higgs, but the statistical significances are quite low and the background uncertainties quite large and their rates probably underestimated; they are definitely high-luminosity measurements.”

— CERN–PH–TH/2004–103

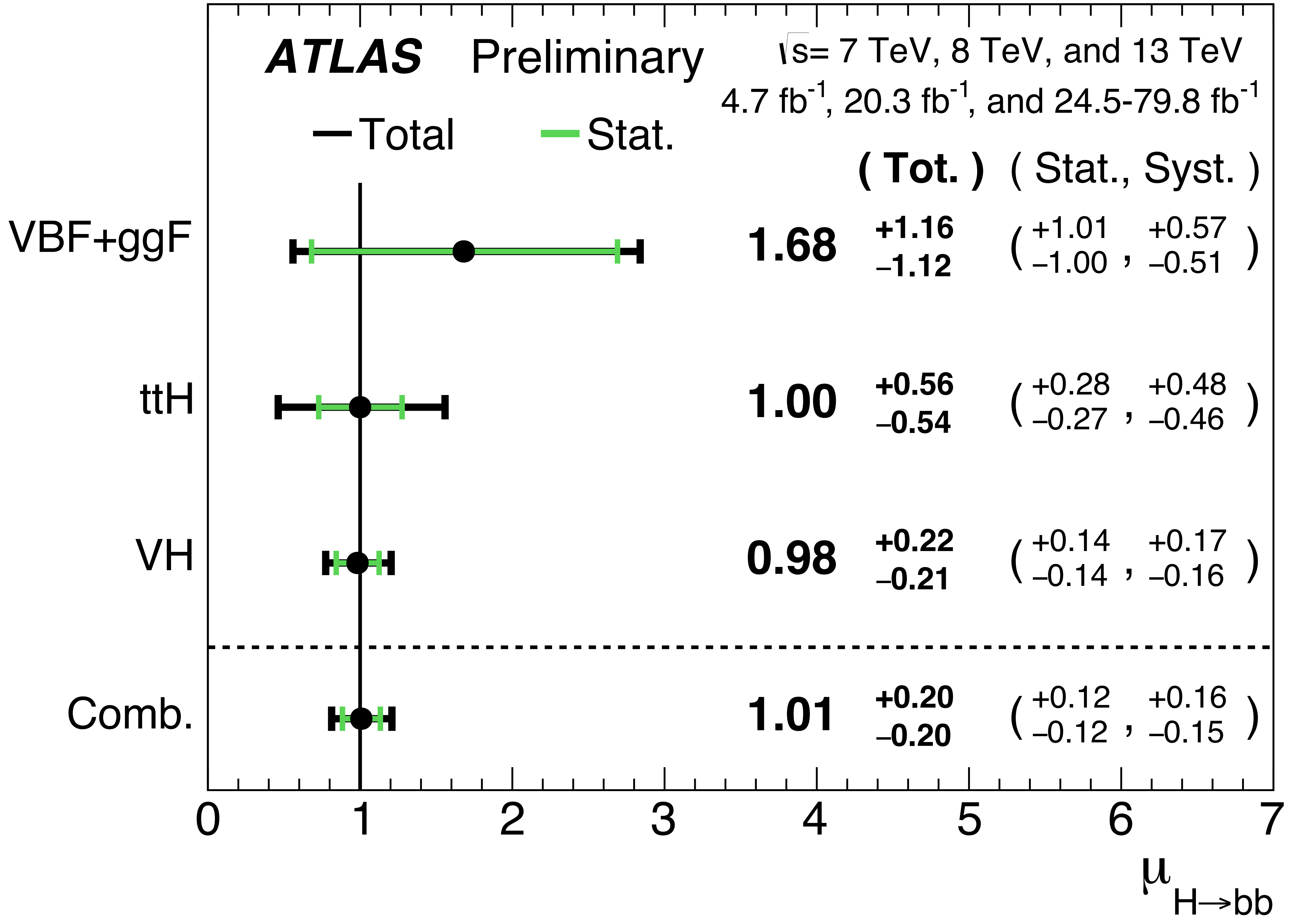
One lesson from the past

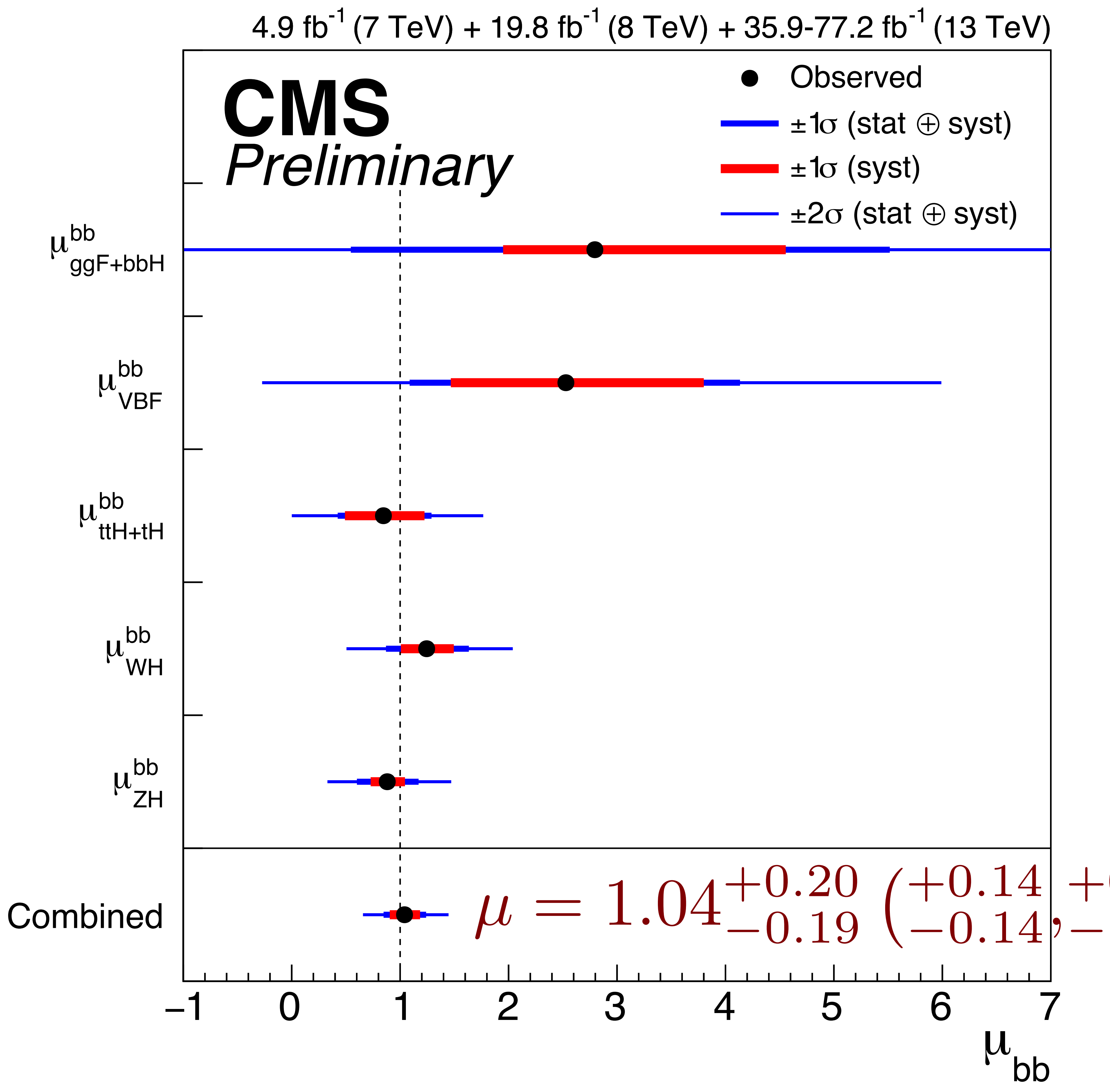
"$H \to b\bar{b}$, which has the largest branching ratio in this mass range. Due to the huge backgrounds from QCD jet production in this decay mode, only the associated production modes have sensitivity. It has been demonstrated that the discovery potential for a Standard Model Higgs boson in the WH production mode at the LHC is marginal.[68,97,98] It is limited by large backgrounds from $Wb\bar{b}$,"

"In addition, the channels $ZH \to \ell\ell b\bar{b}$, $ZH \to \nu\nu b\bar{b}$ and $b\bar{b}H \to b\bar{b}b\bar{b}$ have been suggested in the literature for Higgs boson searches in the $b\bar{b}$ decay mode.[102] For $ZH \to \ell\ell b\bar{b}$ a similar signal-to-background ratio is expected as for the WH channel.[68] The other two have so far not been considered by the LHC collaborations, due to the challenging trigger and background conditions."

— Int. J. Mod. Phys. A 20:2523-2602, 2005

One lesson from the past





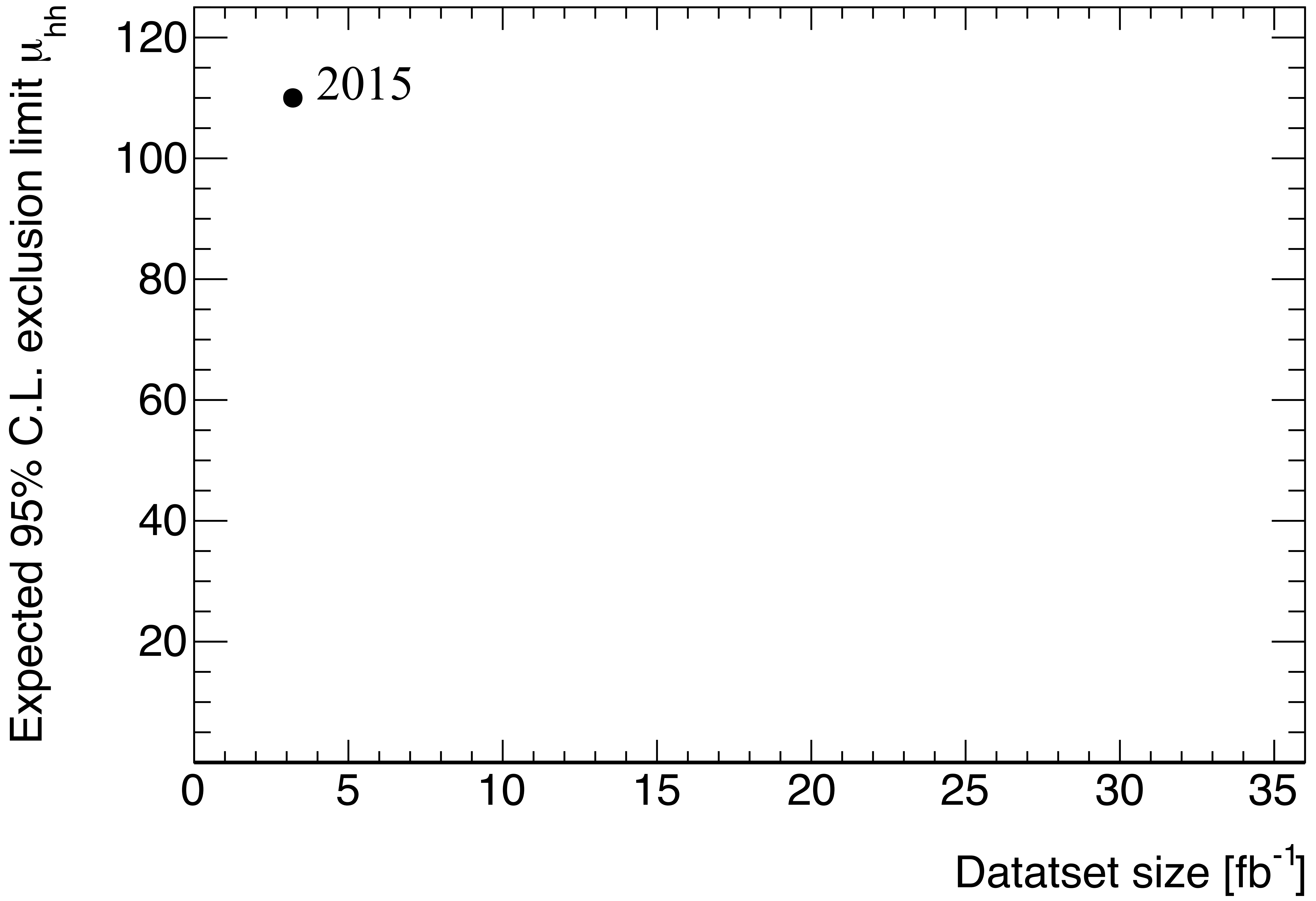
$\mu = 1.04^{+0.20}_{-0.19} \left(^{+0.14}_{-0.14}, ^{+0.14}_{-0.13}\right)$

First observation of H($b\bar{b}$) decay

CMS** Run 1+2: **5.6 σ (5.5 σ exp.)

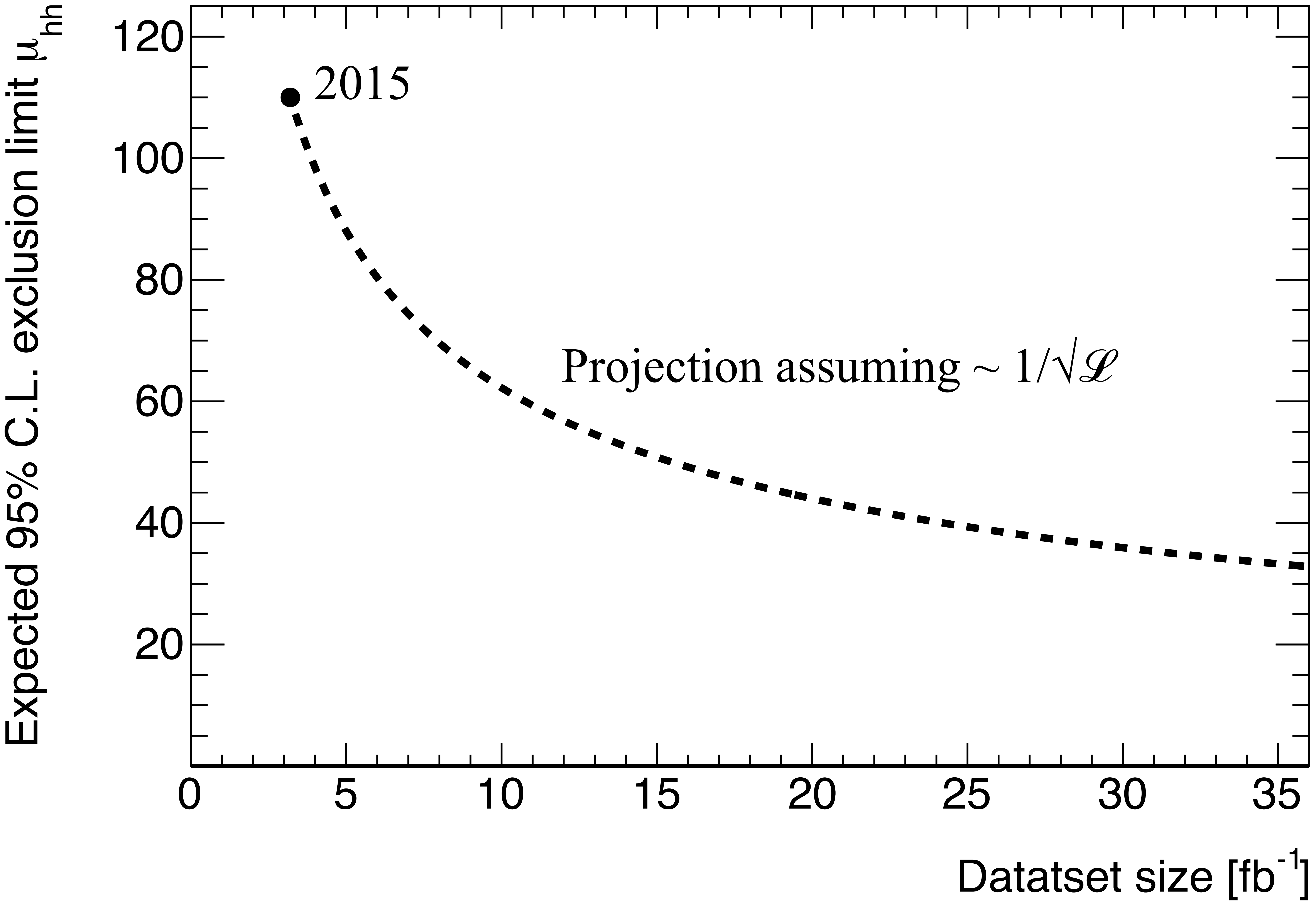
ATLAS** Run 1+2: **5.4 σ (5.5 σ exp.)

J. Alison



Expected 95% C.L. exclusion limit μ_{hh}
120
100
80
60
40
20
2015
0
5
10
15
20
25
30
35
Datatset size [fb^{-1}]

J. Alison



Expected 95% C.L. exclusion limit μ_{hh}
120
100
80
60
40
20
0
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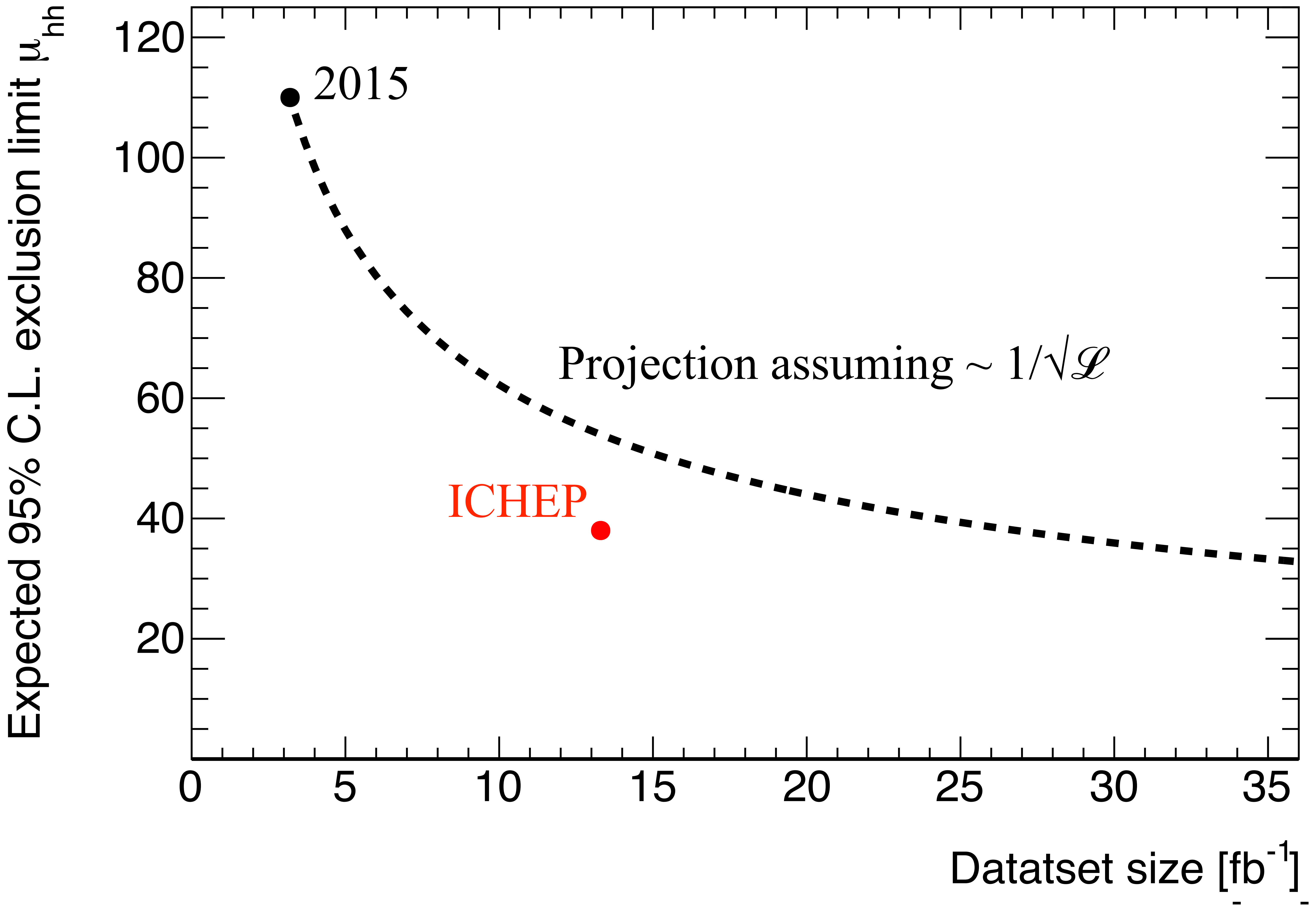
10
15
20
25
30
35
2015
Projection assuming $\sim 1/\sqrt{\mathscr{L}}$
Datatset size [fb^{-1}]

J. Alison



Expected 95% C.L. exclusion limit μ_{hh}
120
100
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0
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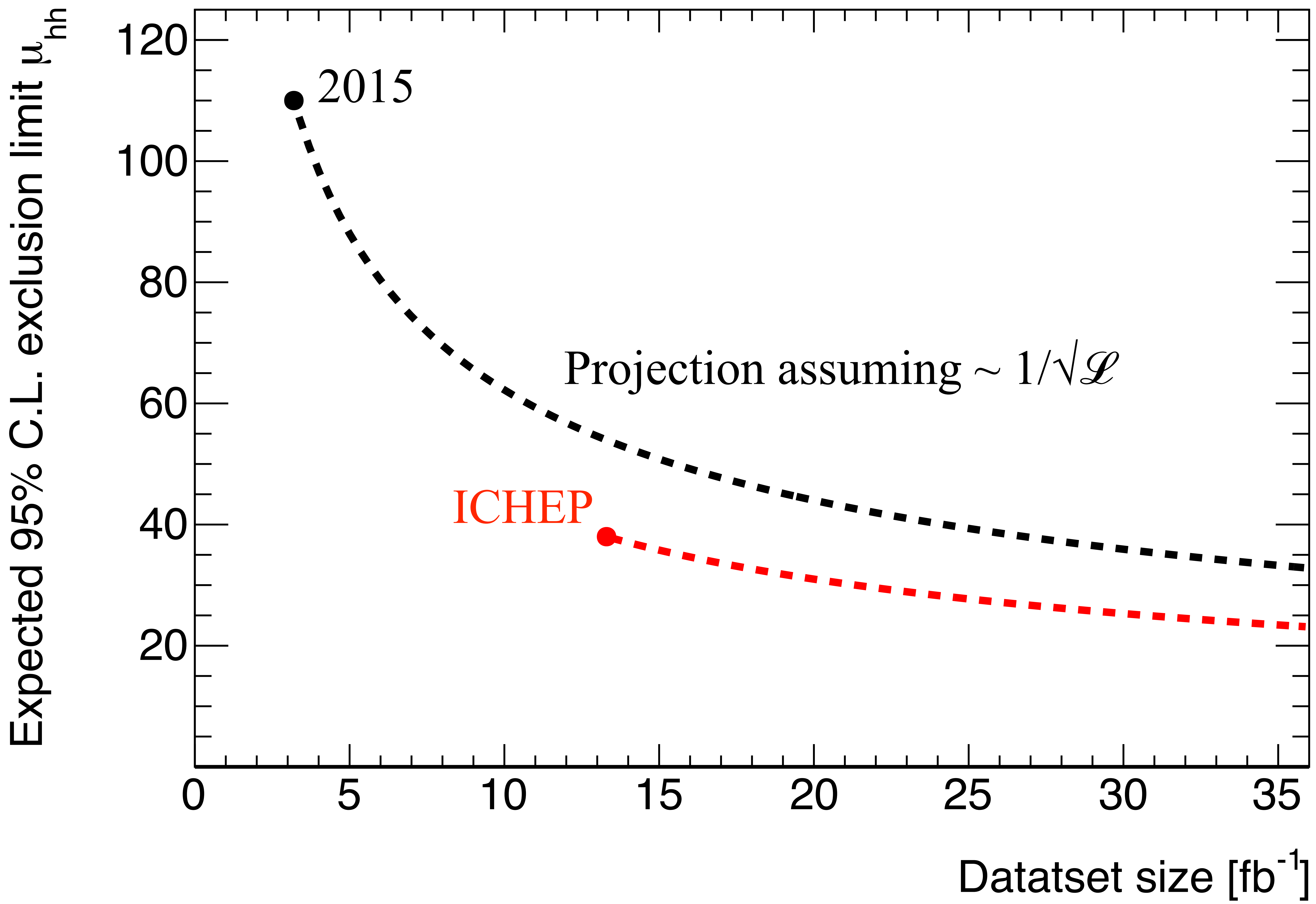
35
2015
Projection assuming ~ $1/\sqrt{\mathscr{L}}$
ICHEP
Datatset size [fb^{-1}]


Expected 95% C.L. exclusion limit μ_{hh}
120
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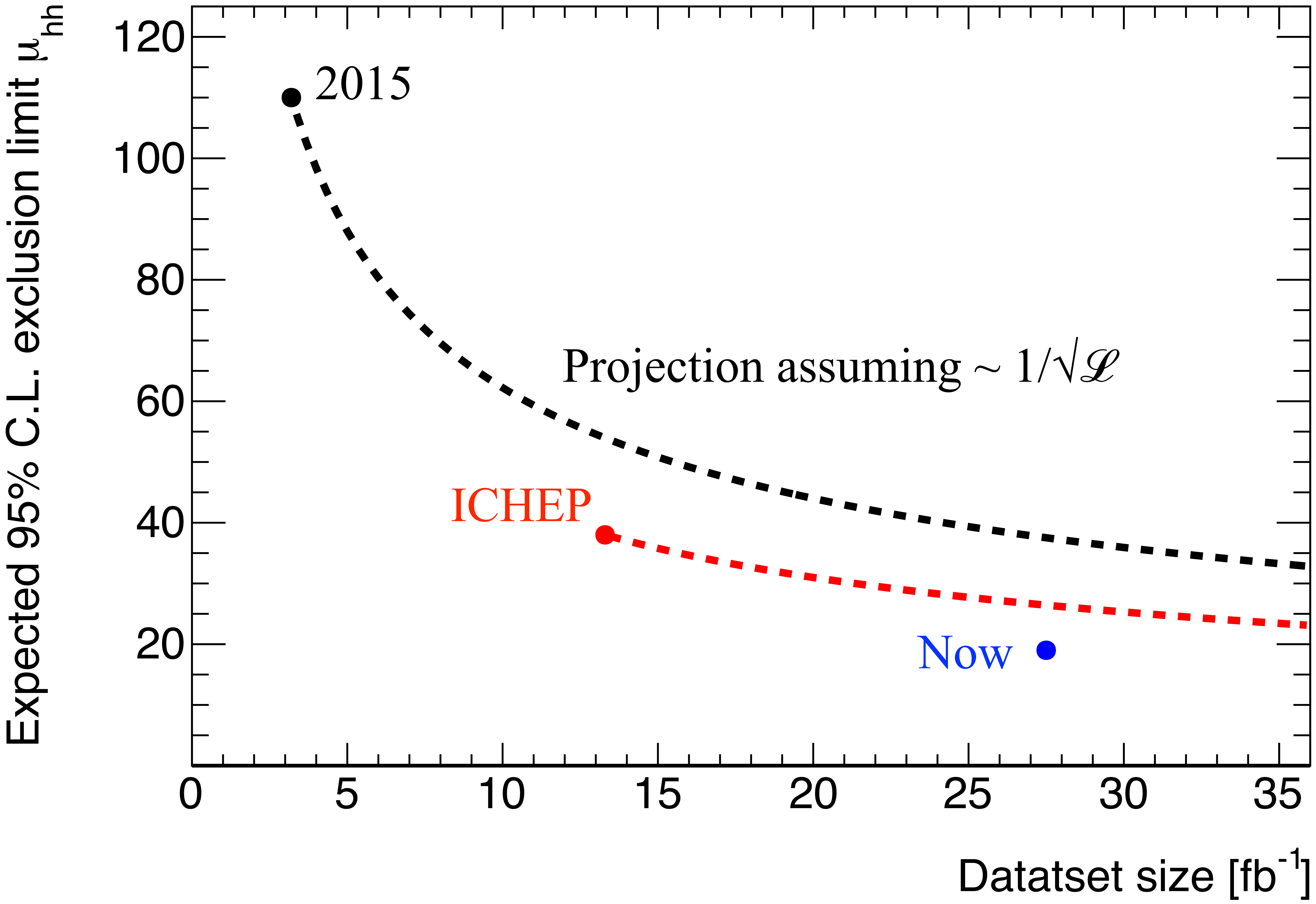
Datatset size [fb^{-1}]
2015
Projection assuming ~ $1/\sqrt{\mathscr{L}}$
ICHEP

J. Alison


Expected 95% C.L. exclusion limit μ_{hh}
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100
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60
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0
5
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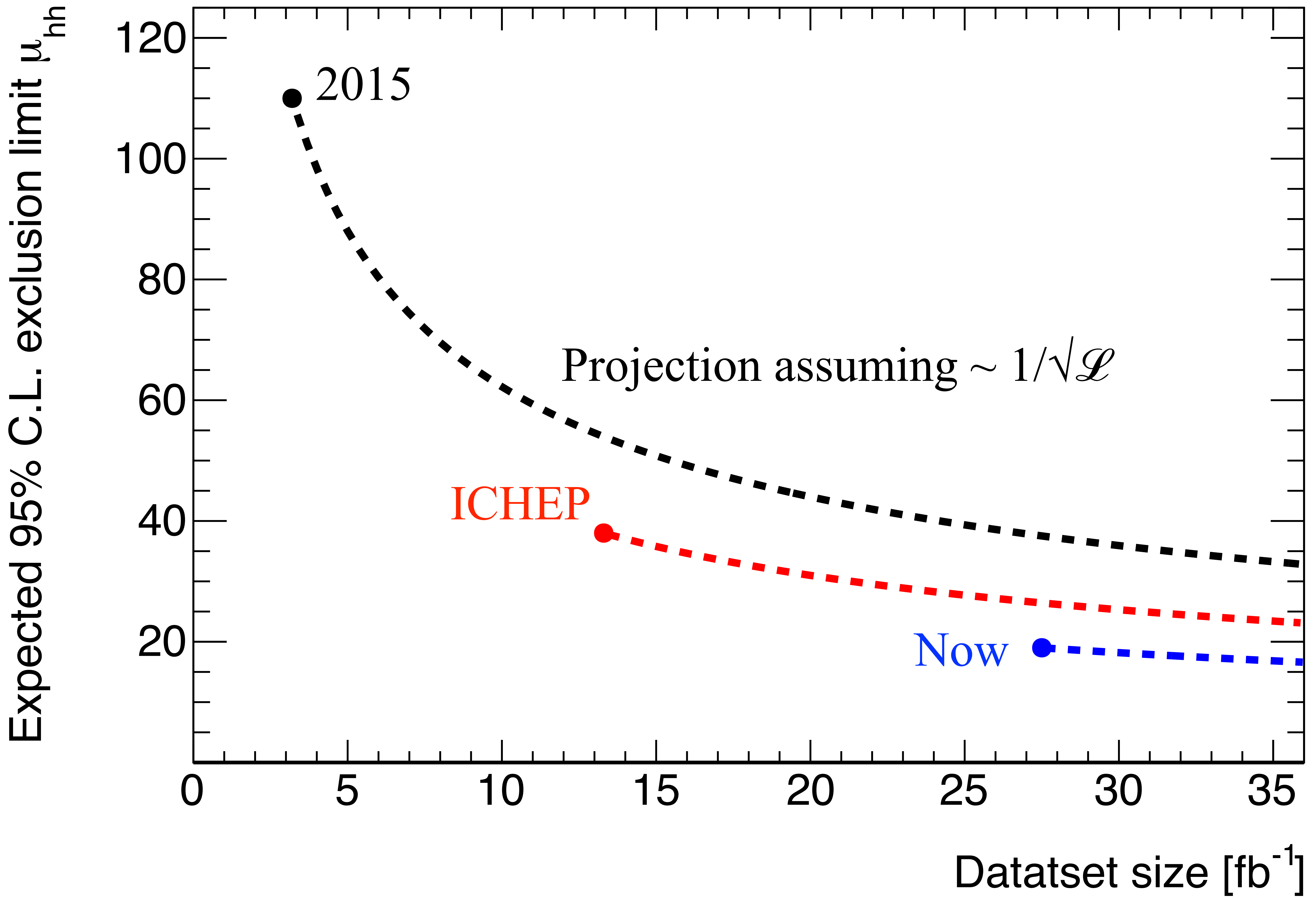
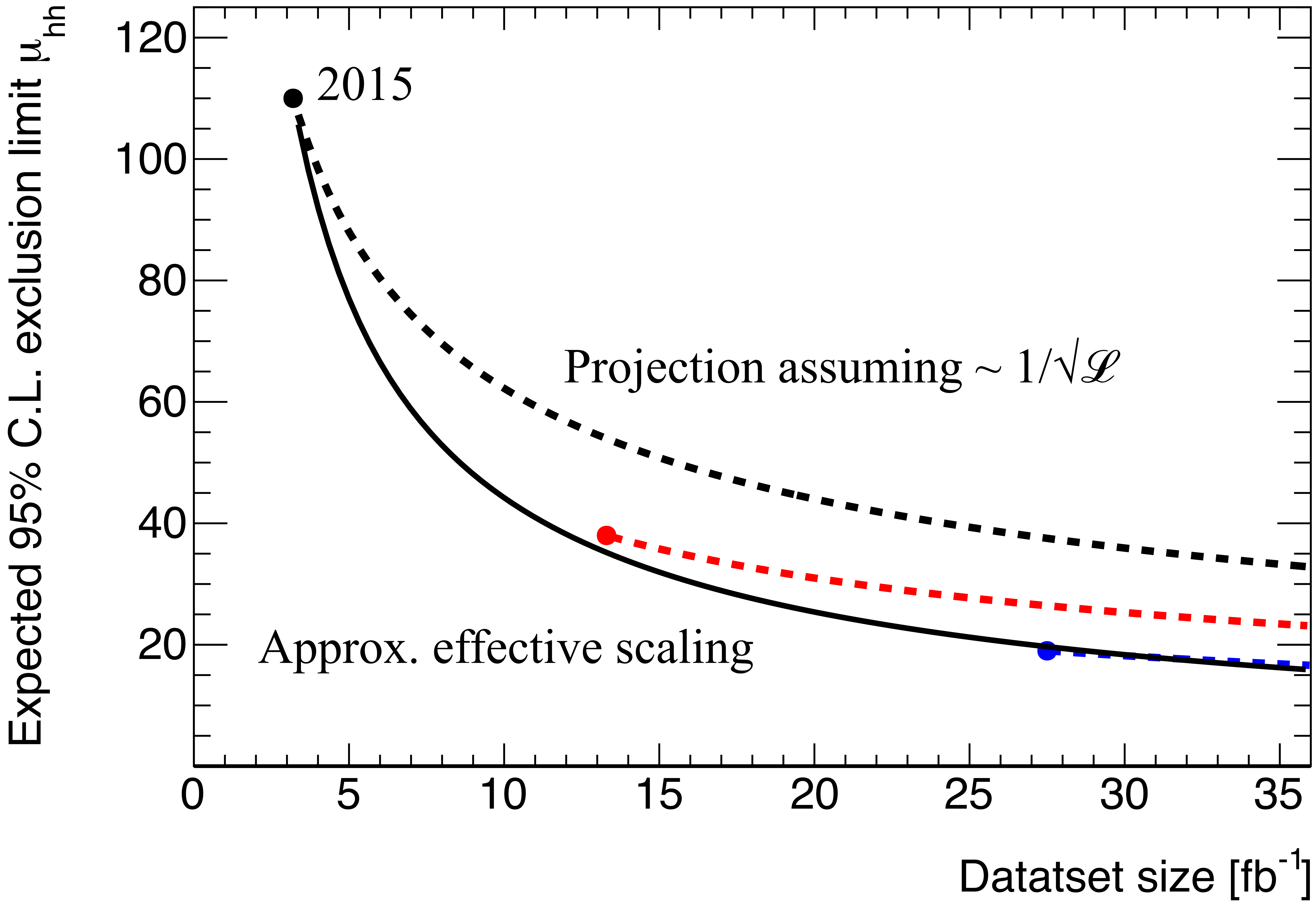
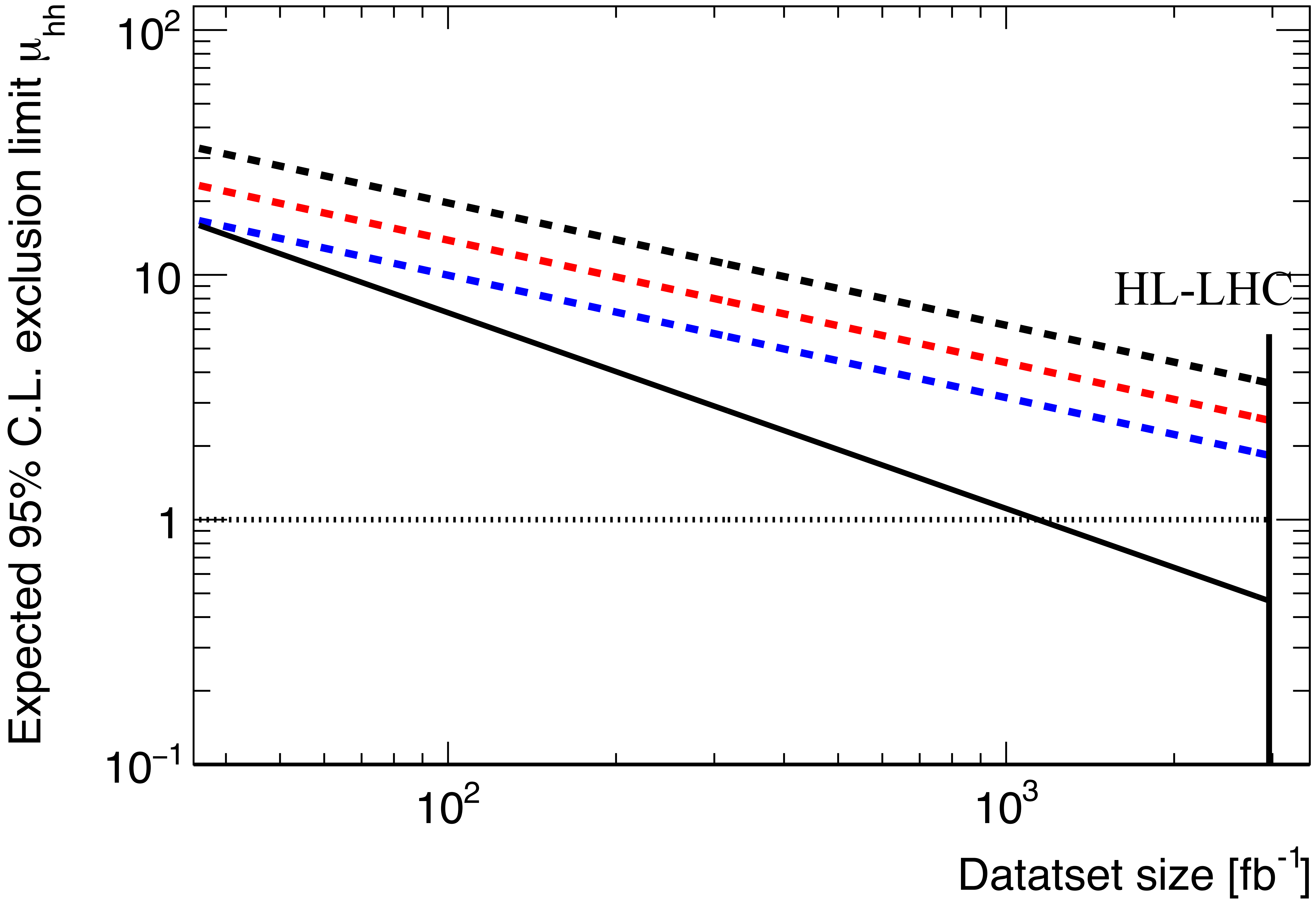
20
25
30
35
2015
Projection assuming ~ $1/\sqrt{\mathscr{L}}$
ICHEP
Now
Datatset size [fb^{-1}]

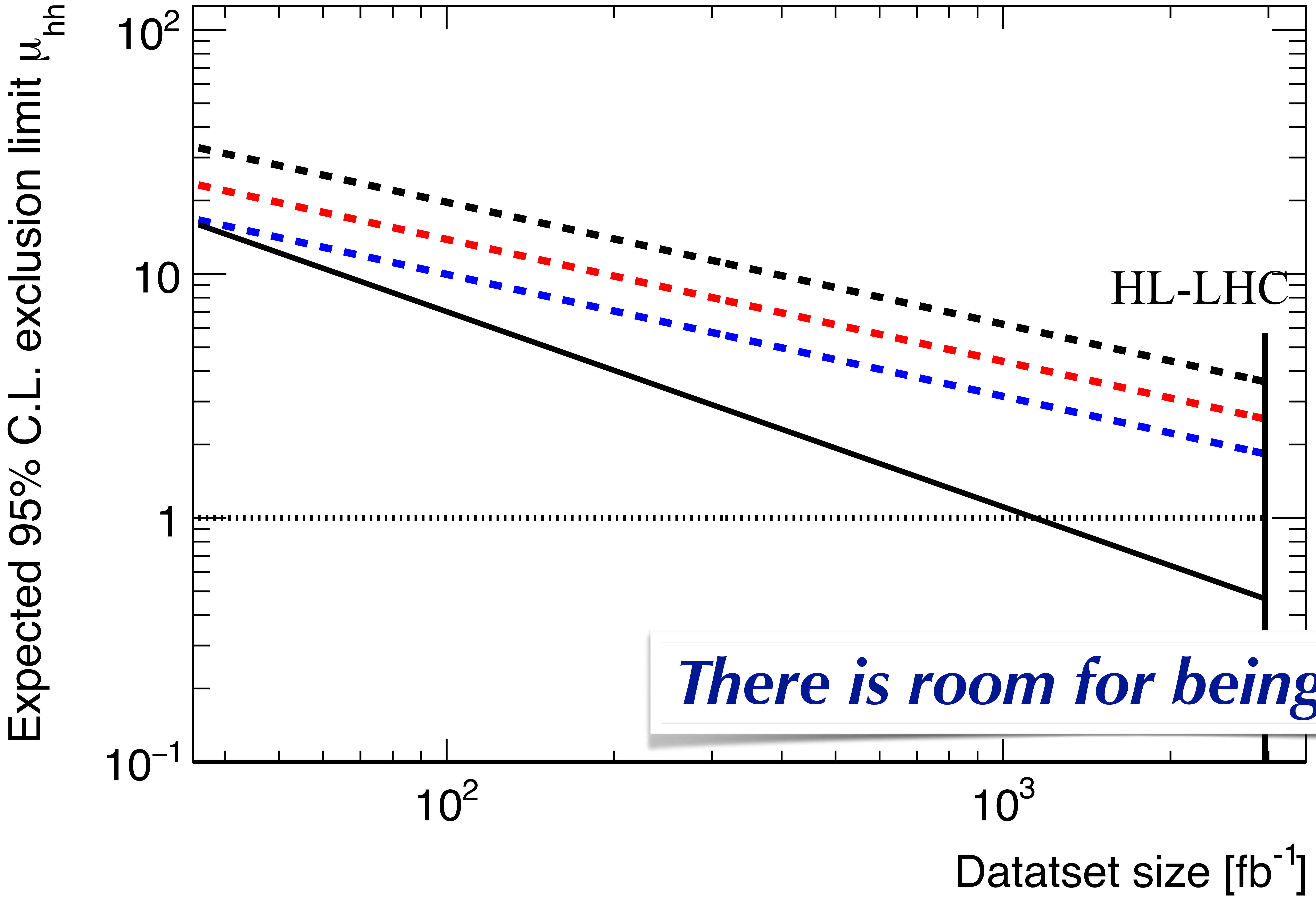


2015
Projection assuming ~ $1/\sqrt{\mathscr{L}}$
ICHEP
Now
Expected 95% C.L. exclusion limit μ_{hh}
Datatset size [fb^{-1}]
0
5
10
15
20
25
30
35
20
40
60
80
100
120



Expected 95% C.L. exclusion limit μ_{hh}
120
100
80
60
40
20
2015
Projection assuming ~ $1/\sqrt{\mathscr{L}}$
Approx. effective scaling
0
5
10
15
20
25
30
35
Datatset size [fb^{-1}]


Expected 95% C.L. exclusion limit μ_{hh}
10^2
10
1
10^{-1}
HL-LHC
10^2
10^3
Datatset size [fb^{-1}]



There is room for being optimistic

Beyond LHC/HL-LHC

FCC/ee

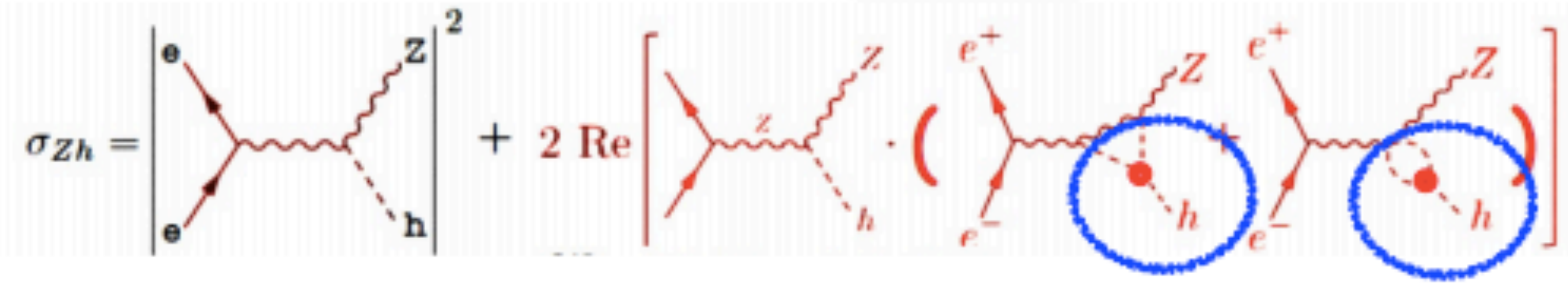
A. Canepa

SELF COUPLING @ FCC-EE (INDIRECT)

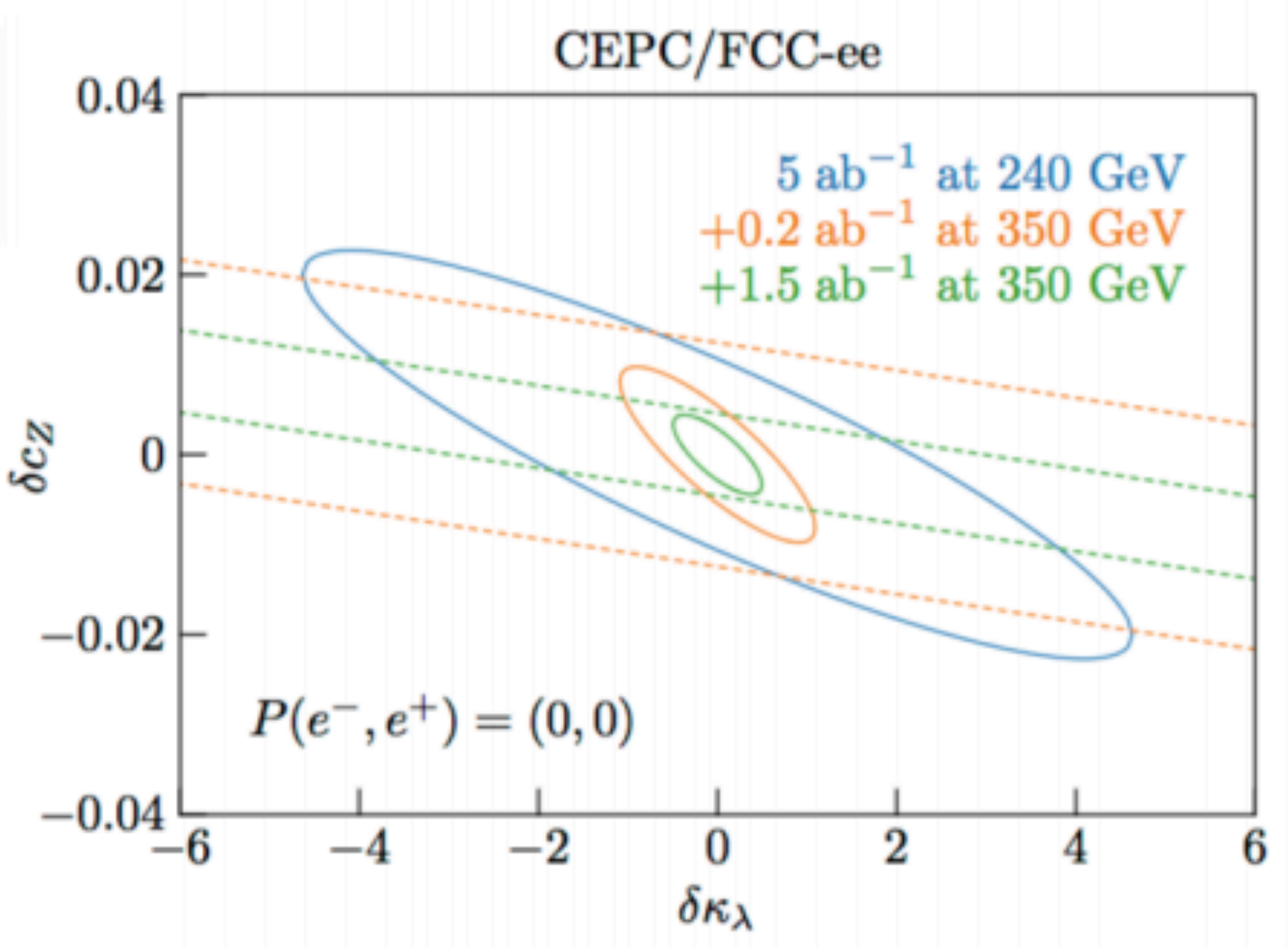
$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

- At FCC-ee, Higgs trilinear indirectly constrained through loop corrections to σ(H+Z)

canepa.key



- Testing possible only thanks to excellent precision on the ZH cross-section measurement
- ~40% precision on trilinear coupling from global fit and combination of 240 and 350 GeV datasets
  - HH cross-section at the HL-LHC ~ 50 fb (150k events) corresponding to an uncertainty on trilinear coupling to ~ 50%



1711.03978, 1701.02663

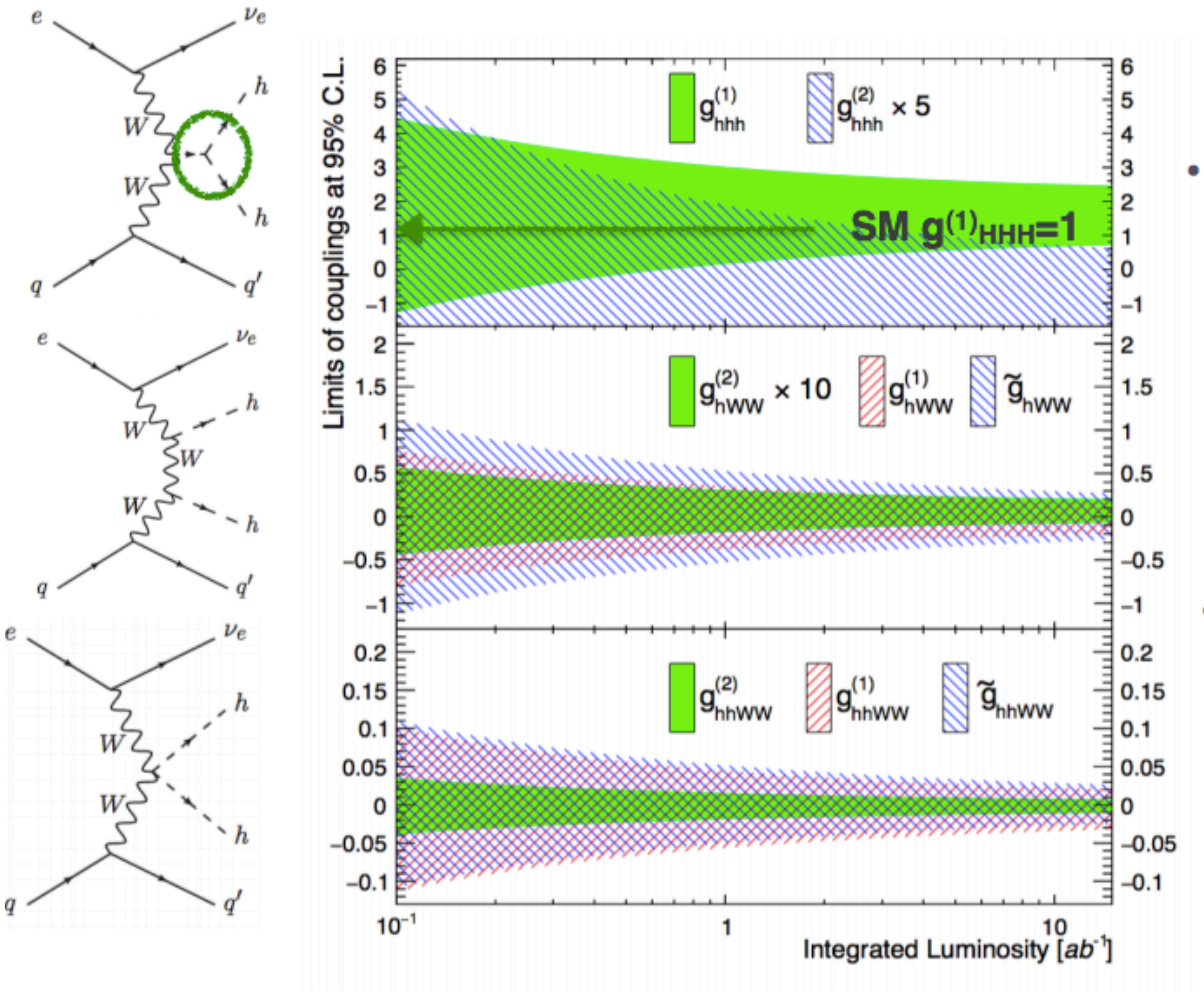
Fermilab

12

FCC/eh

A. Canepa

TRILINEAR COUPLING @ FCC-EH



- **Precision on the trilinear coupling is determined for two electron energy hypotheses, 60 and 120 GeV:**

$$g^{(1)}_{hhh} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}$$

1509.04016

Fermilab

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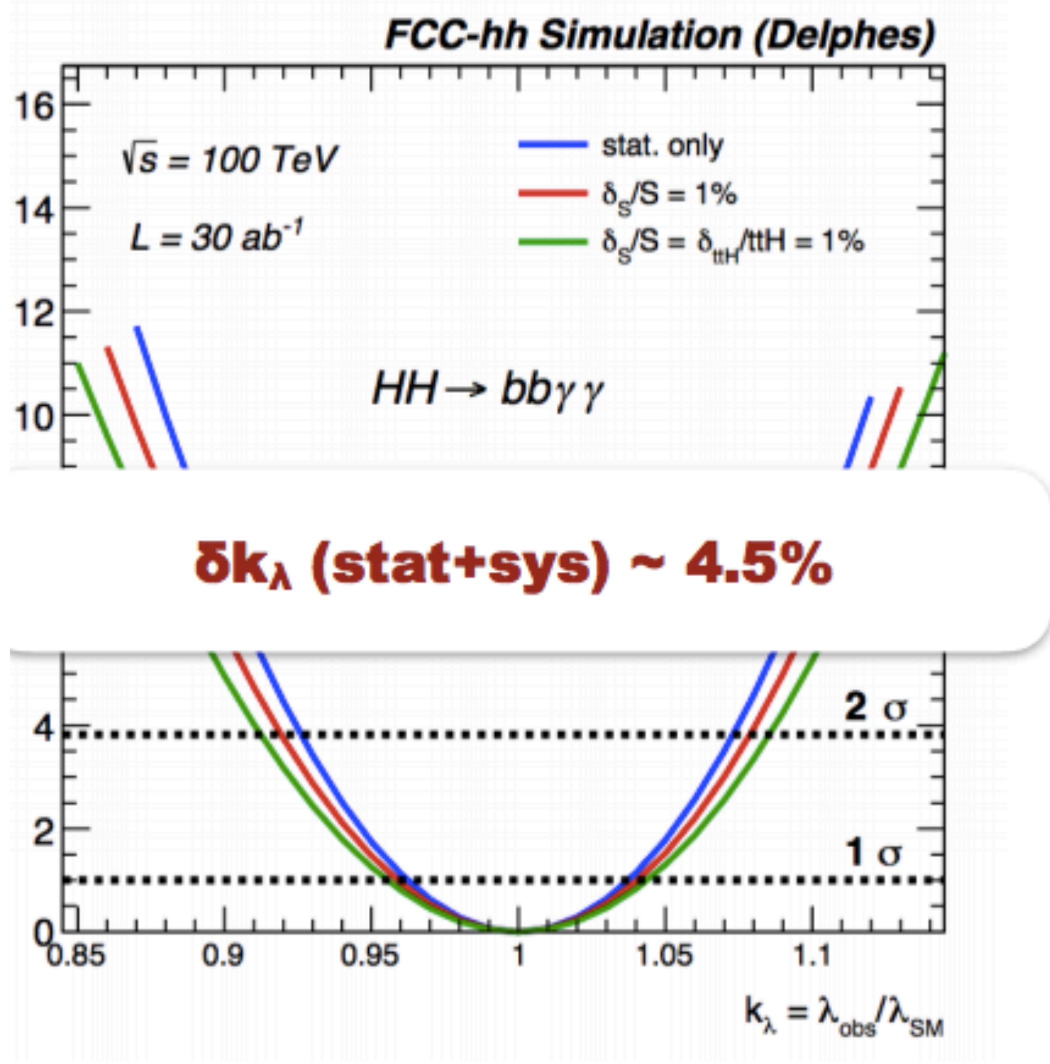
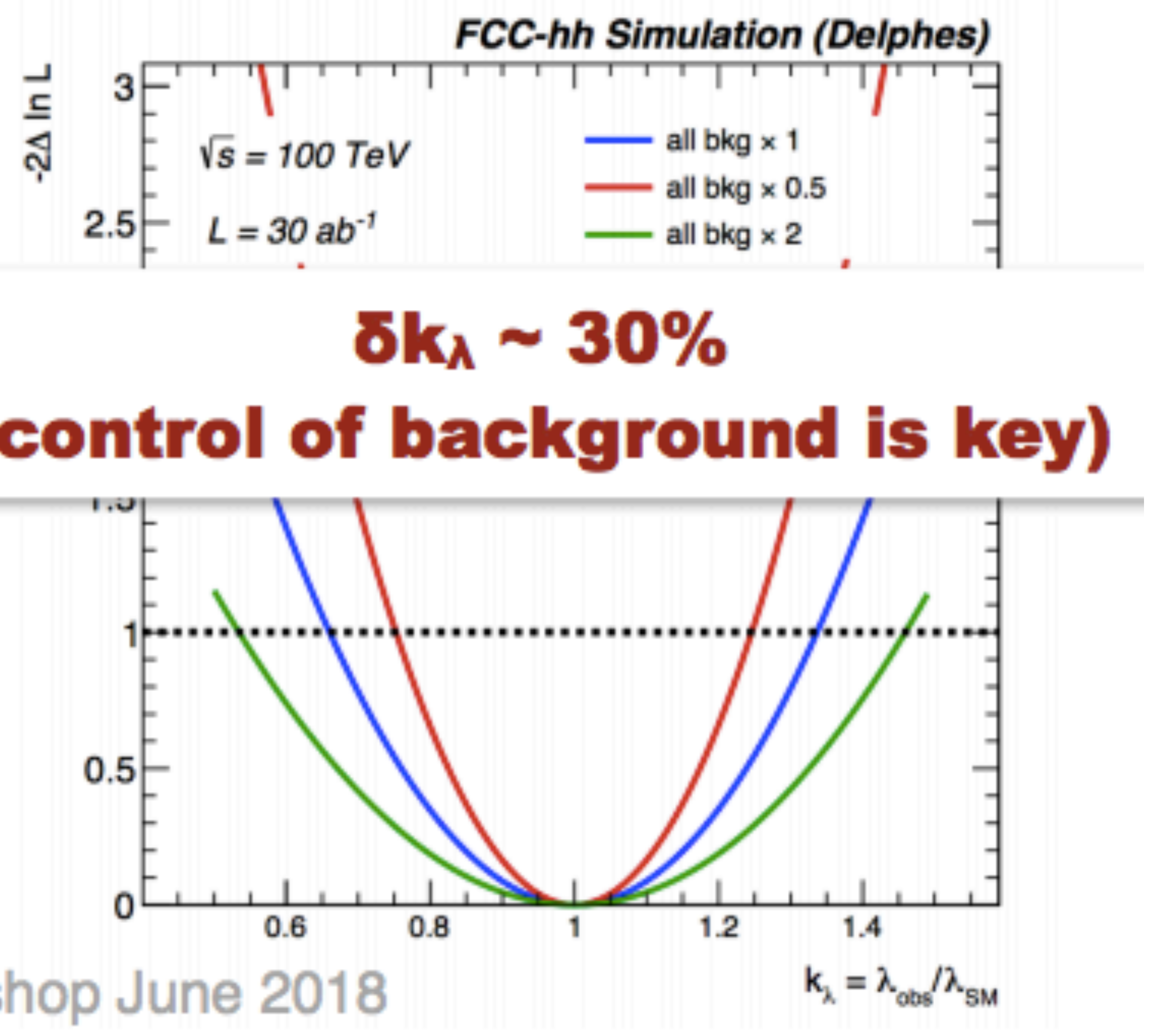
FCC/hh

SELF COUPLING AT FCC-HH

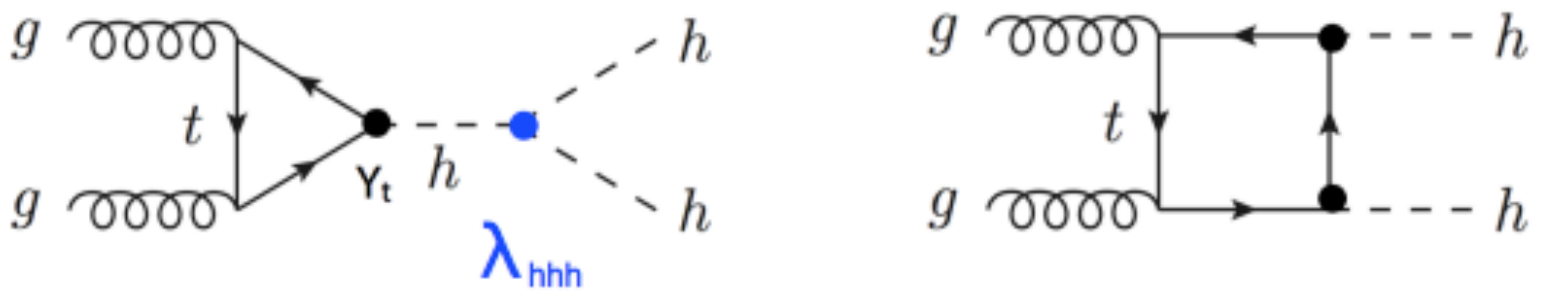


δkλ (stat+sys) ~ 4.5%



δkλ ~ 30%
(control of background is key)

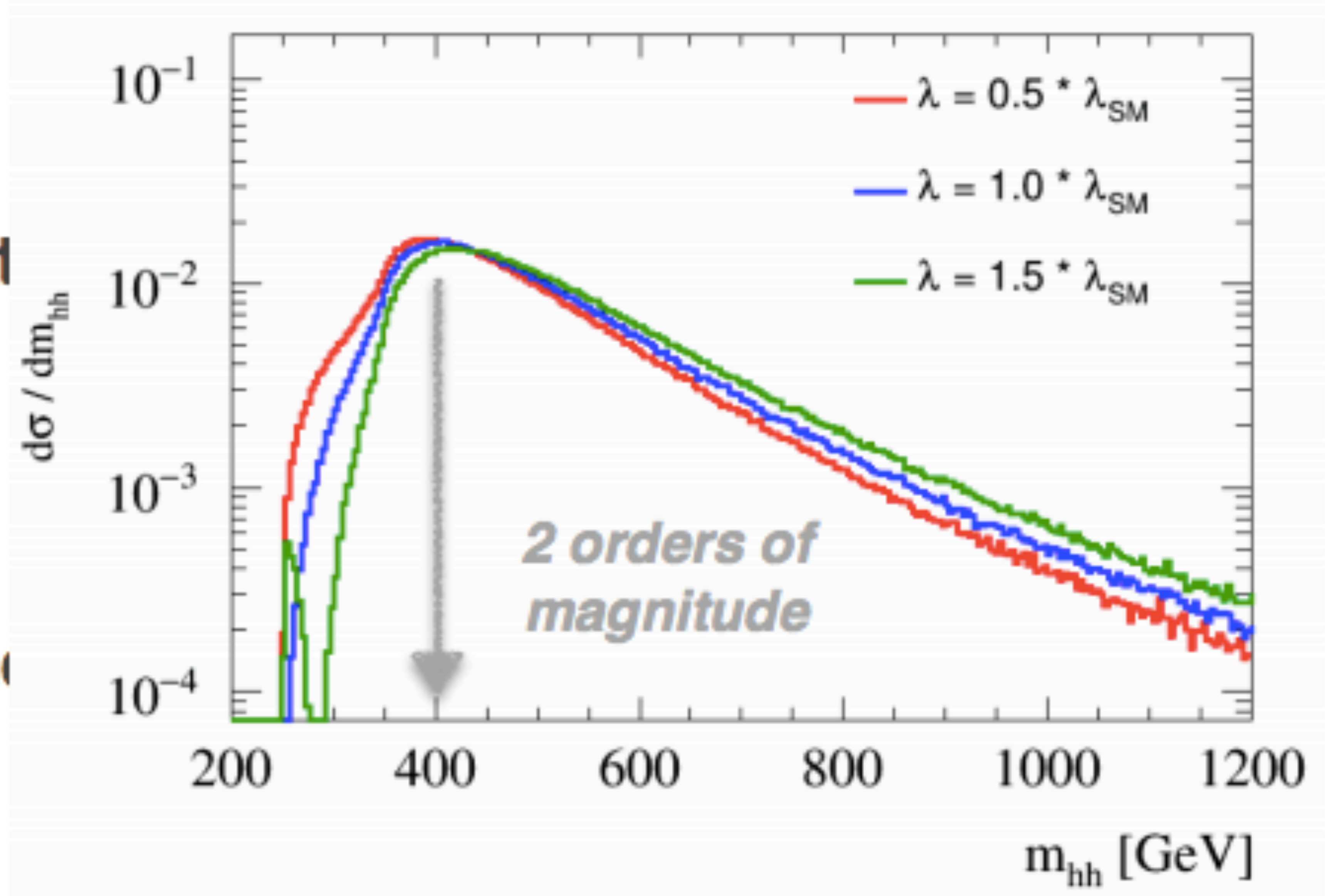
Workshop June 2018



1608.04798

$\sqrt{s}$	LO	B-i. NLO HEFT	NLO FT$_{approx}$	NLO
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$
100 TeV	$731.3^{+20.9\%}_{-15.9\%}$	$1511^{+16.0\%}_{-13.0\%}$	$1220^{+11.9\%}_{-10.7\%}$	$1149^{+10.8\%}_{-10.0\%}$

- With a cross-section ~ 30x HL-LHC and 7x larger dataset, FCC-hh unique opportunity t complete the exploration of the SM Higgs sector
- But challenging search due to negative interference between production modes an significant dependence of rate on m_{HH}



M. Selvaggi, FCC Workshop June 2018

Fermilab

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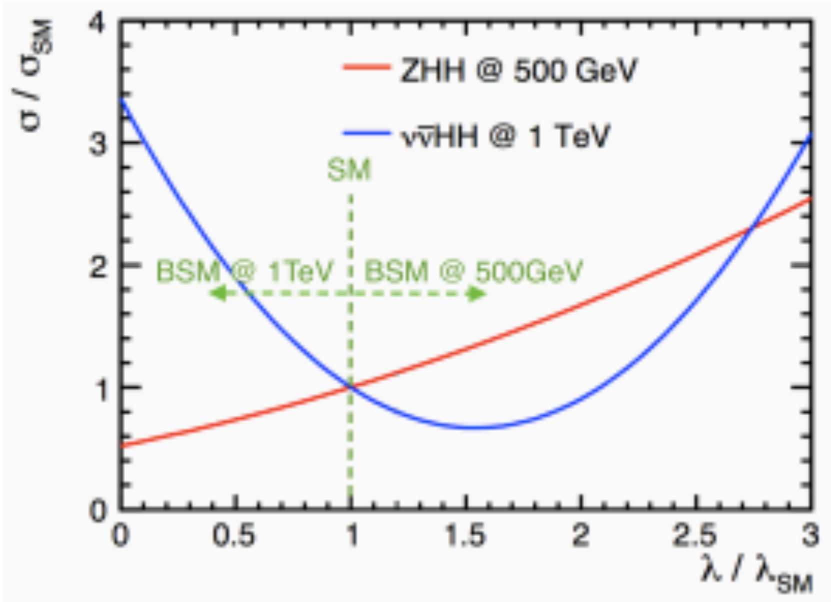
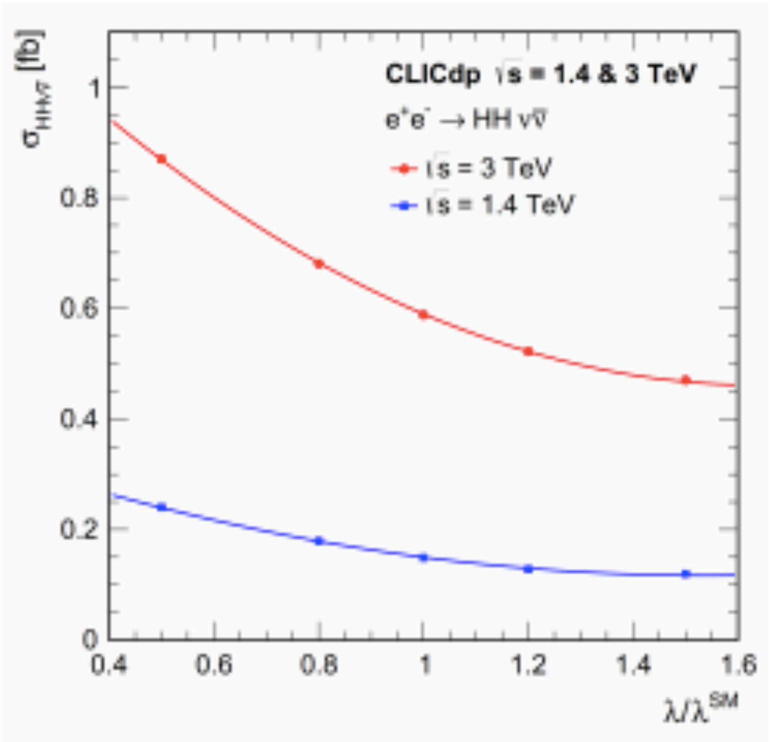
P. Roloff

Linear Colliders

Both CLIC and ILC allow to measure the Higgs-strahlung cross section and extract the total Higgs width in a model-independent manner

- An energy of at least 500 GeV gives access to ttH (best between 800 GeV and 1.5 TeV) and double Higgs production (profits from the highest possible energies)





- **ILC**, $\sqrt{s}$ = 500 GeV, L = 4 ab^{-1}:
$\Delta\lambda/\lambda$ = 27%

DESY-THESIS-2016-027

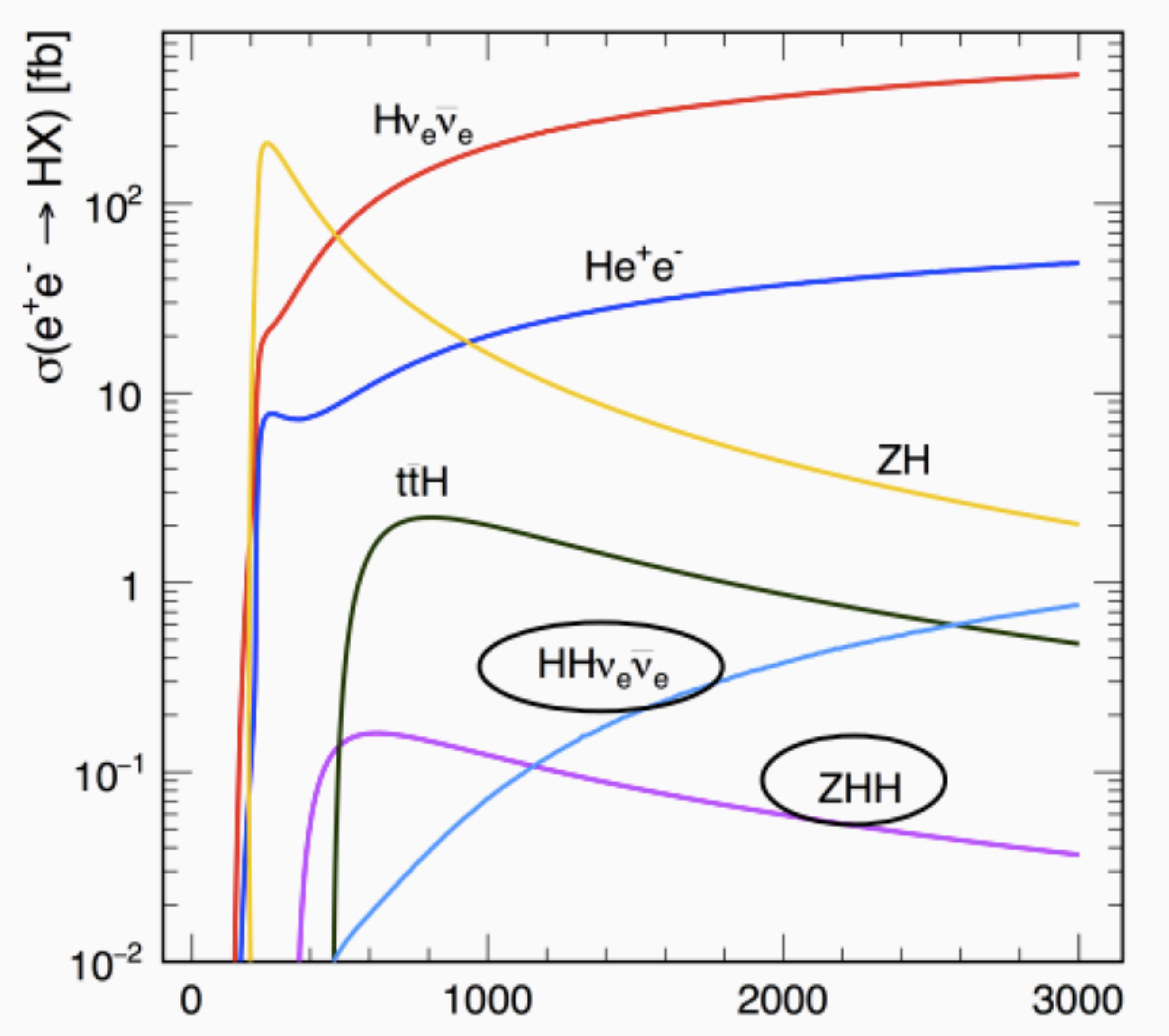
Model-independence demonstrated using EFT framework

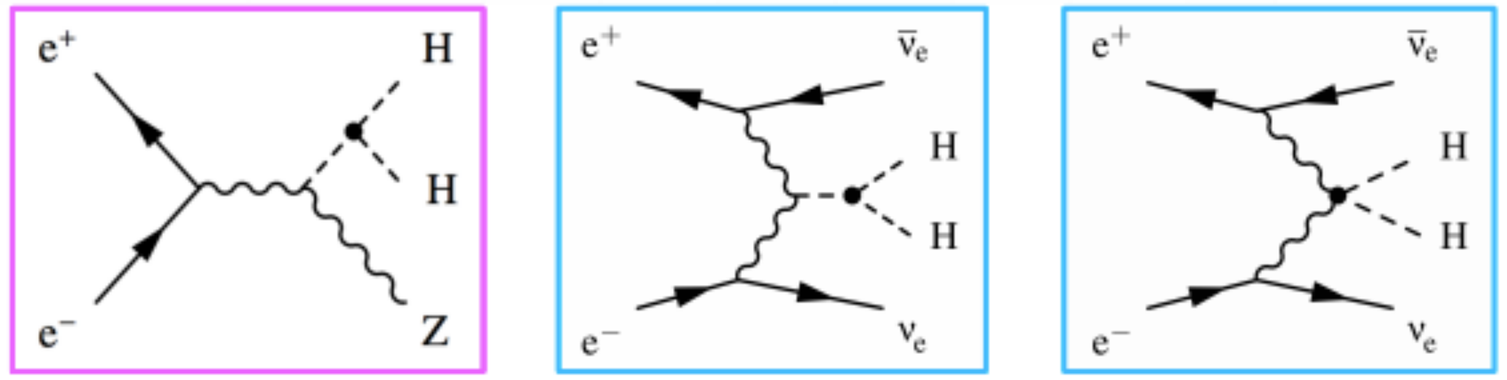
Phys. Rev. D97, 053004 (2018)

- **CLIC**, $\sqrt{s}$ = 1.4 TeV, L = 2.5 ab^{-1}
\+ $\sqrt{s}$ = 3 TeV, L = 5 ab^{-1}: $\Delta\lambda/\lambda$ = 13%

Based on Eur. Phys. J. C 77, 475 (2017)

- **Complementarity of the two production processes:**
$\lambda > \lambda_{SM}$: σ(ZHH) at 500 GeV enhanced
$\lambda < \lambda_{SM}$: $\sigma(HH\nu_e\bar{\nu}_e)$ at high energy enhanced





Outlook

We are approaching SM sensitivity at LHC for **non-resonant HH** production

— several final states investigated, more to come

— new improved analysis techniques

ML is now starting being used in all final states

— more data available (2018 150/fb, 2021 300/fb)

— more ML

— VBF topology is under study

— H+HH fit starts becoming relevant

(note that single H is our irreducible background)

Resonant searches cover the resonances mass range from 250 GeV to 3 TeV

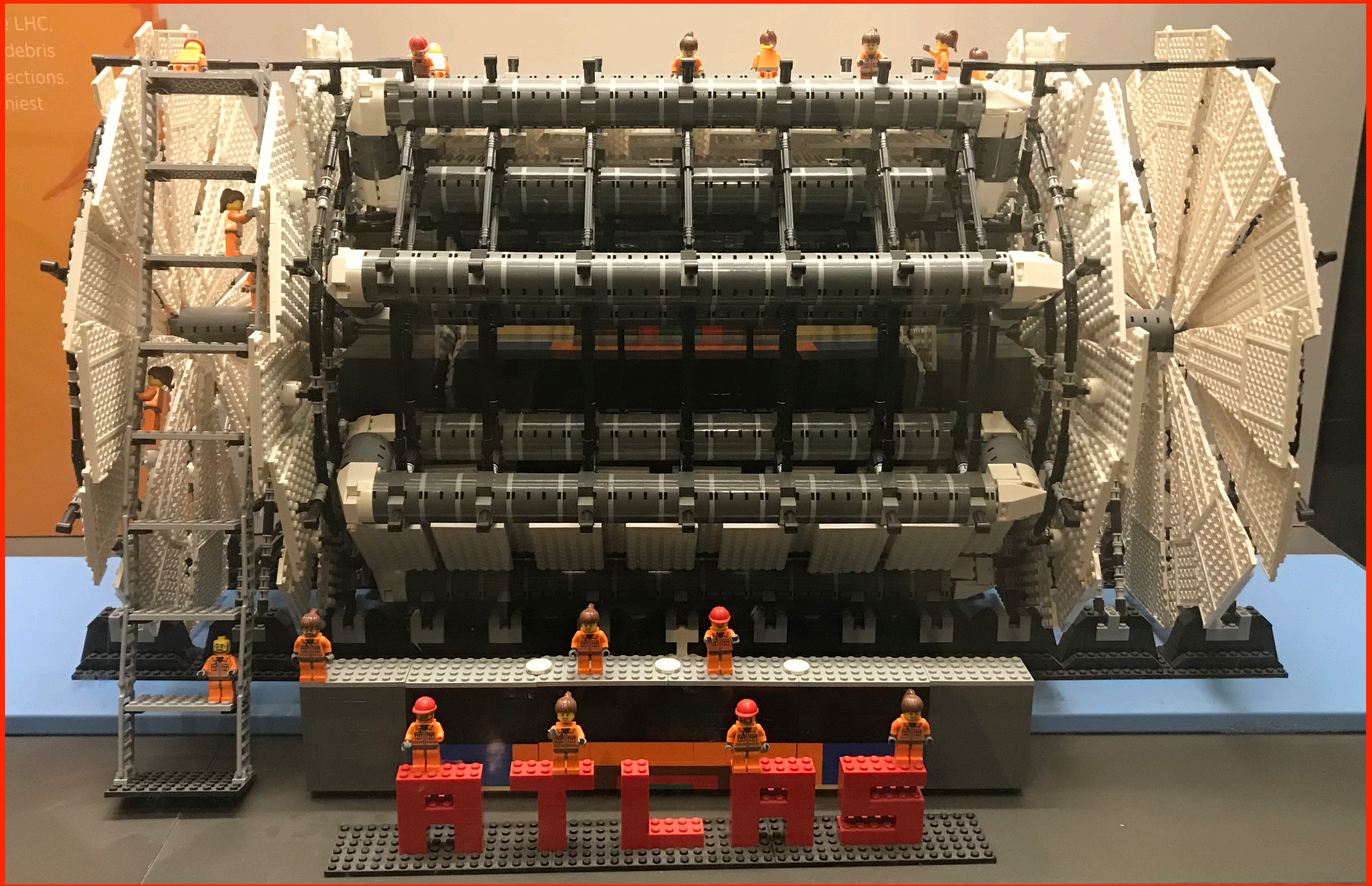
— unexplored phase space include HH+X, H_1H, H_1H_2

At **HL-LHC** we need to ensure we can trigger on HH events :

— b-jets triggers are the main concern

— but improved tracker detectors should yield to increased acceptance (improved b-tagging, VBF topology)

Only analyzed <3% of the final LHC luminosity …**Just the beginning**

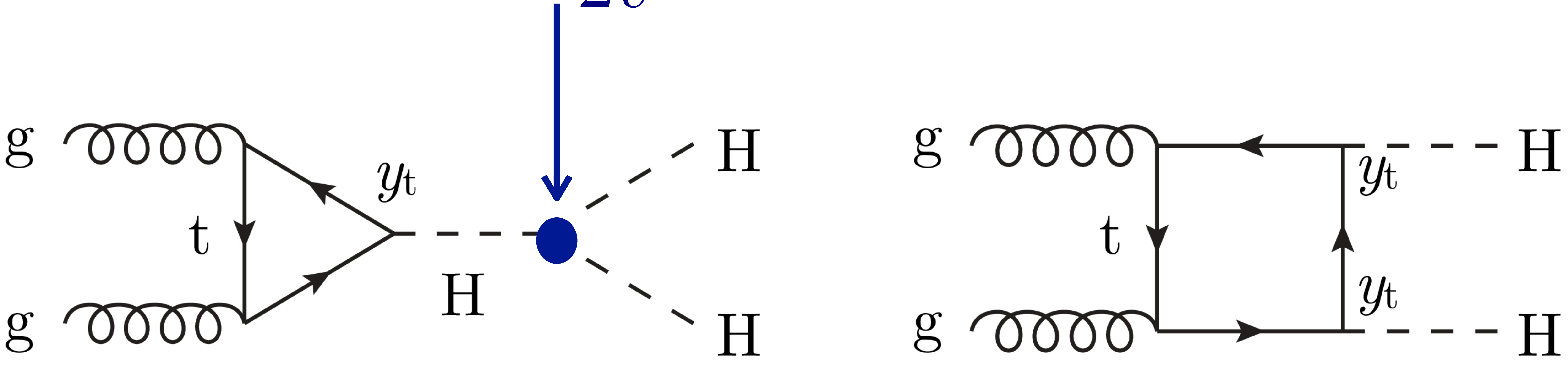


thank you!

di-Higgs in the SM

- The measurement of the Higgs boson **self coupling** is a **fundamental** test of the SM
- SM predicts a **extremely small cross section** for HH production (33.5 fb at 13 TeV)
  - Main production mode is gluon fusion
  - **In the SM:**

$$\lambda_{\mathrm{HHH}} = \frac{m_{\mathrm{H}}^2}{2v^2} = 0.13$$



ArXiv:1610.07922
JHEP04(2016)126

di-Higgs in BSM

Modified in many BSM scenarios

Better than 20% precision on λ_{HHH} [1305.6397] to see a deviation from SM (or less [1505.05488] in NMSSM)

Anomalous Higgs boson couplings

Strong effect on cross-section and m(hh) shape

EFT approach parametrizes new physics (dim 6 operators)

modifications to $\kappa_\lambda = \lambda/\lambda_{SM}$ and $\kappa_t = y_t/y_{t,SM}$

three new interactions: c_2, c_{2g}, c_g