Hadronic *HH*

Limitations and Potential Improvements

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PITT PACC Workshop: LHC physics for Run 3

Outline

Why *HH* ?
Why hadronic *HH* ?

Experimental Challenges:
- Trigger
- Background Modeling

Themes from organizers:
- How do we design future analyses to fully utilize a doubled dataset, beyond statistics ?
- What lessons have been learned from Run 2 analyses ? How do we apply them to Run 3?
- What new SM measurements would you like to see ?
- How would you like to see measurements improved beyond the current state-of-the-art?
- How might we benefit the most by using new triggers or trigger techniques?
- How can novel ideas from ML be utilized in the analysis of data?

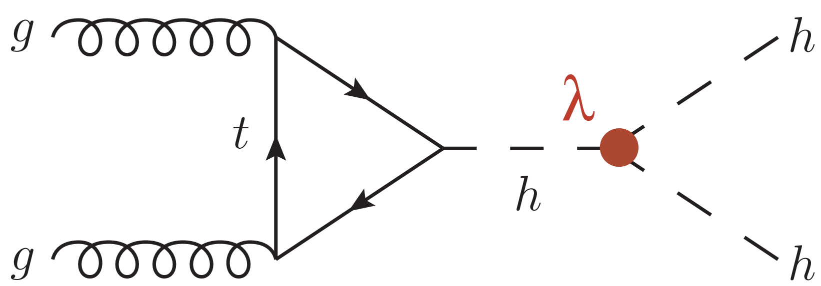
Emphasis on answering these.
Focus on what could be improved / Differences in approach.

Why *HH* ?

HH production interesting because sensitive to λ

Measuring λ important because it probes the shape of the Higgs potential

Shape of potential gives relationship between λ and m_H and *v*



HH Small in Standard Model.

$$\sigma_{HH} \sim 10^{-3}\sigma_H$$

Just seeing HH is hard … ***real goal is to constrain λ***

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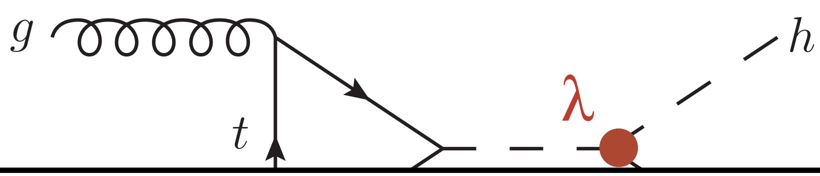

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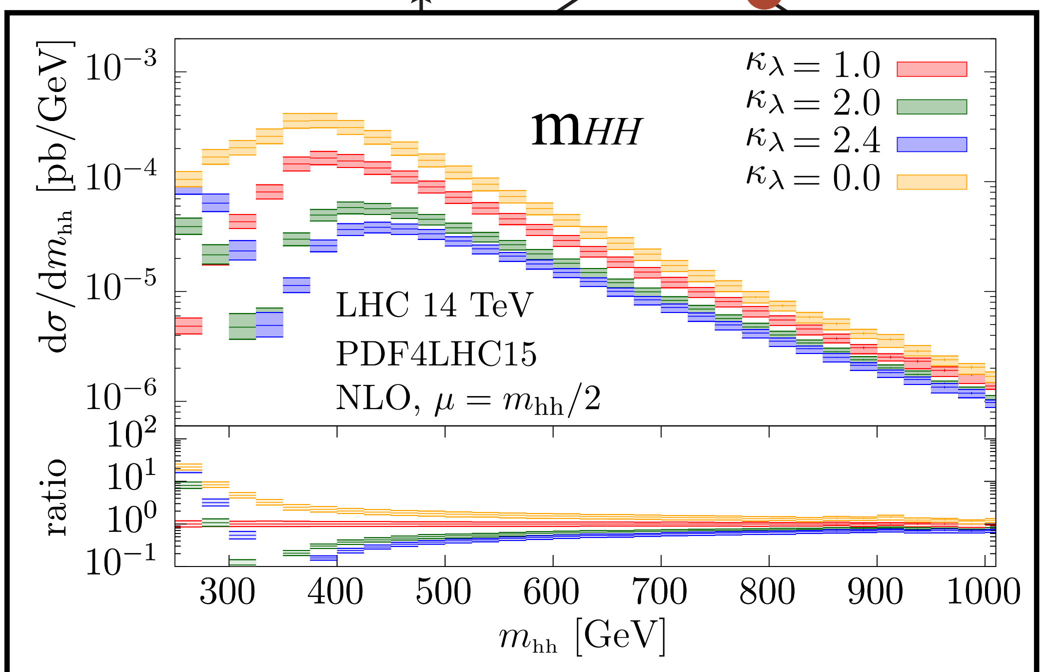

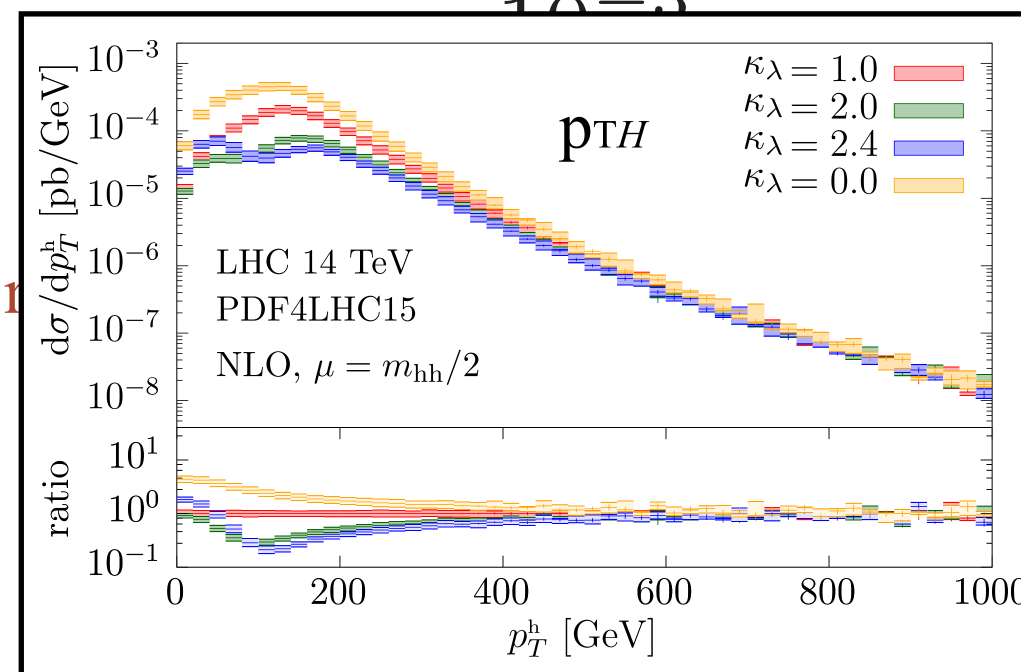

https://arxiv.org/abs/1910.00012

Why *HH* ?

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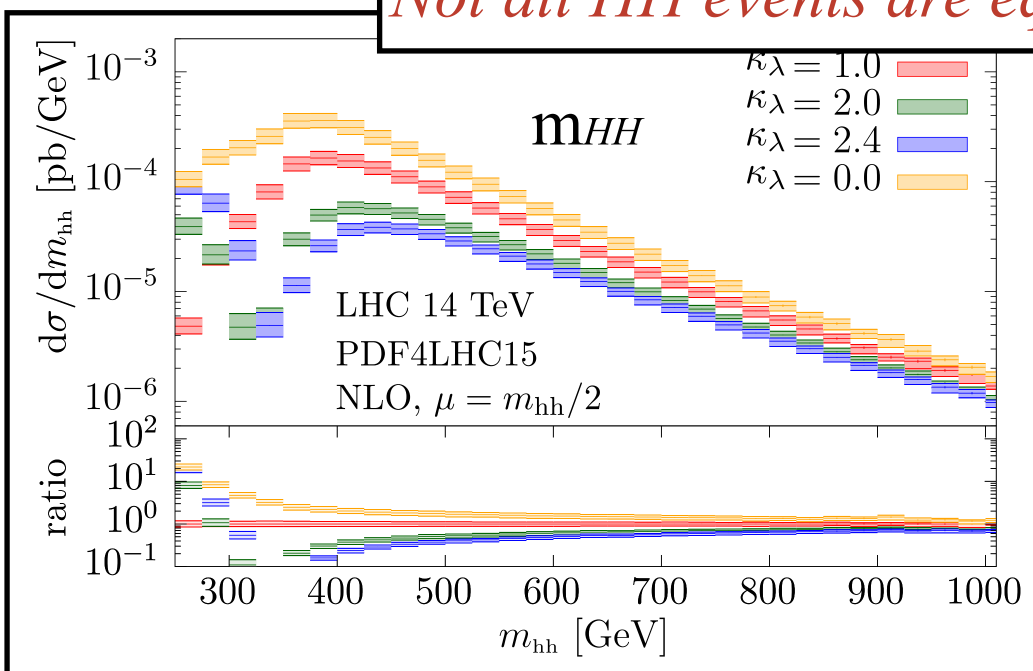
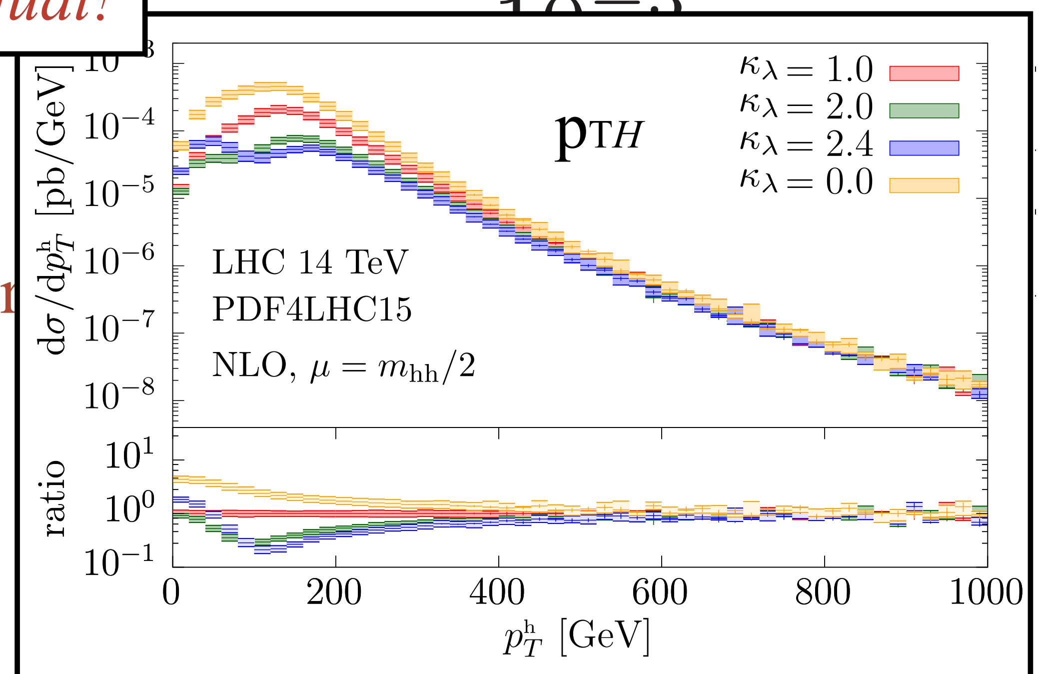
Shape of potential gives relationship between λ and m_H and *v*

HH Small in Standard Model.

Not all HH events are equal!





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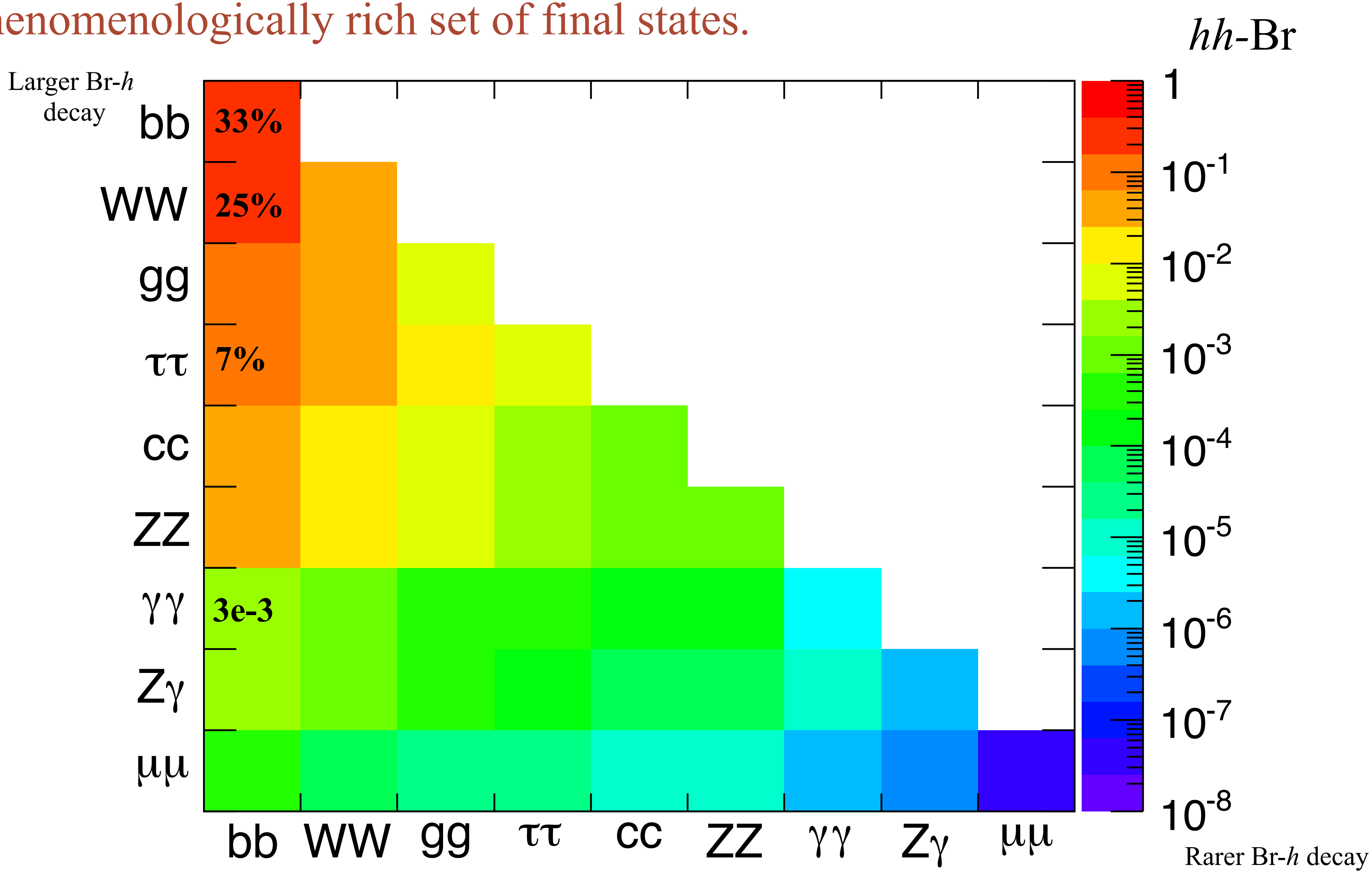
Why Hadronic *HH* ?

Phenomenologically rich set of final states.



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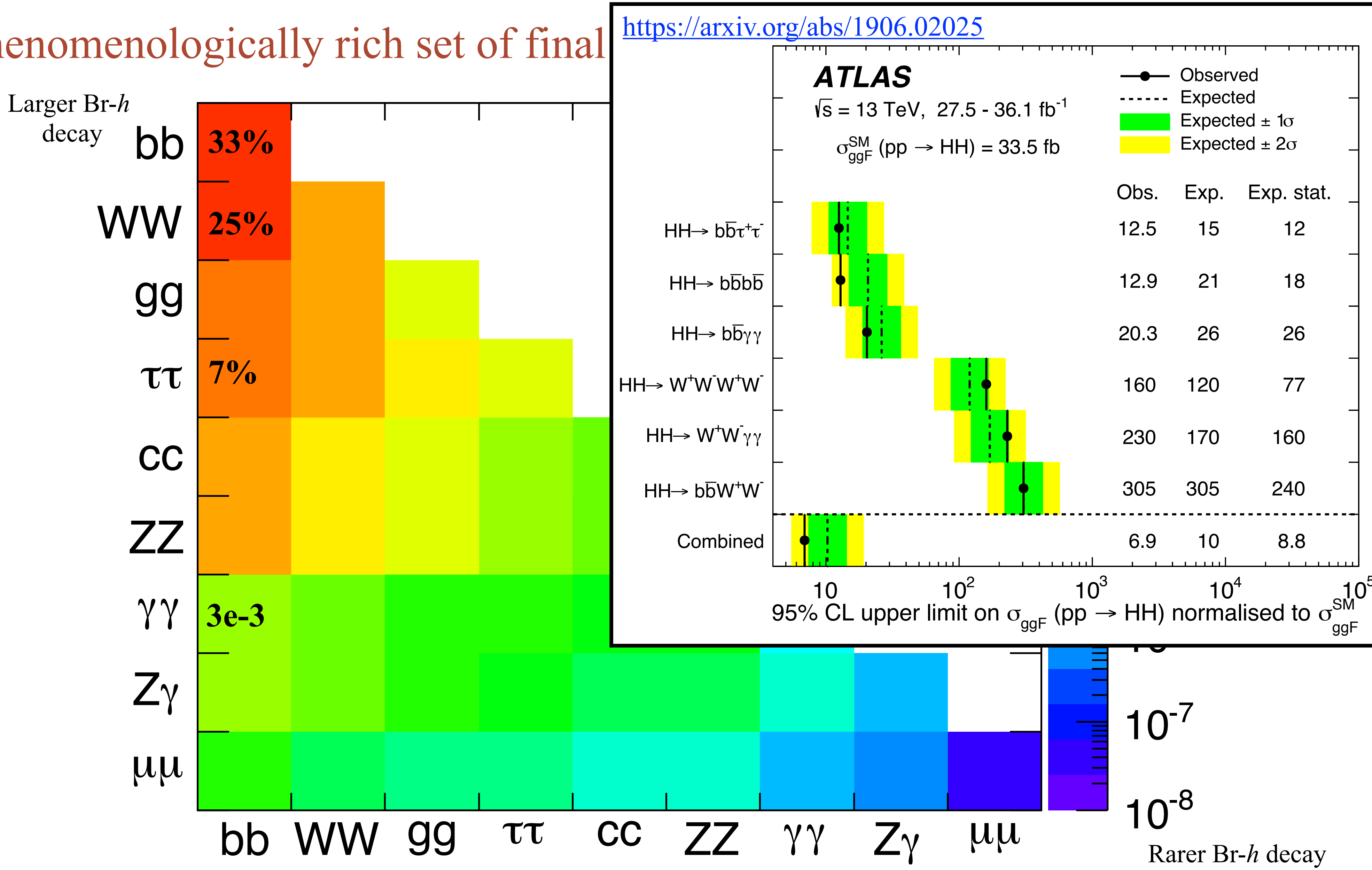

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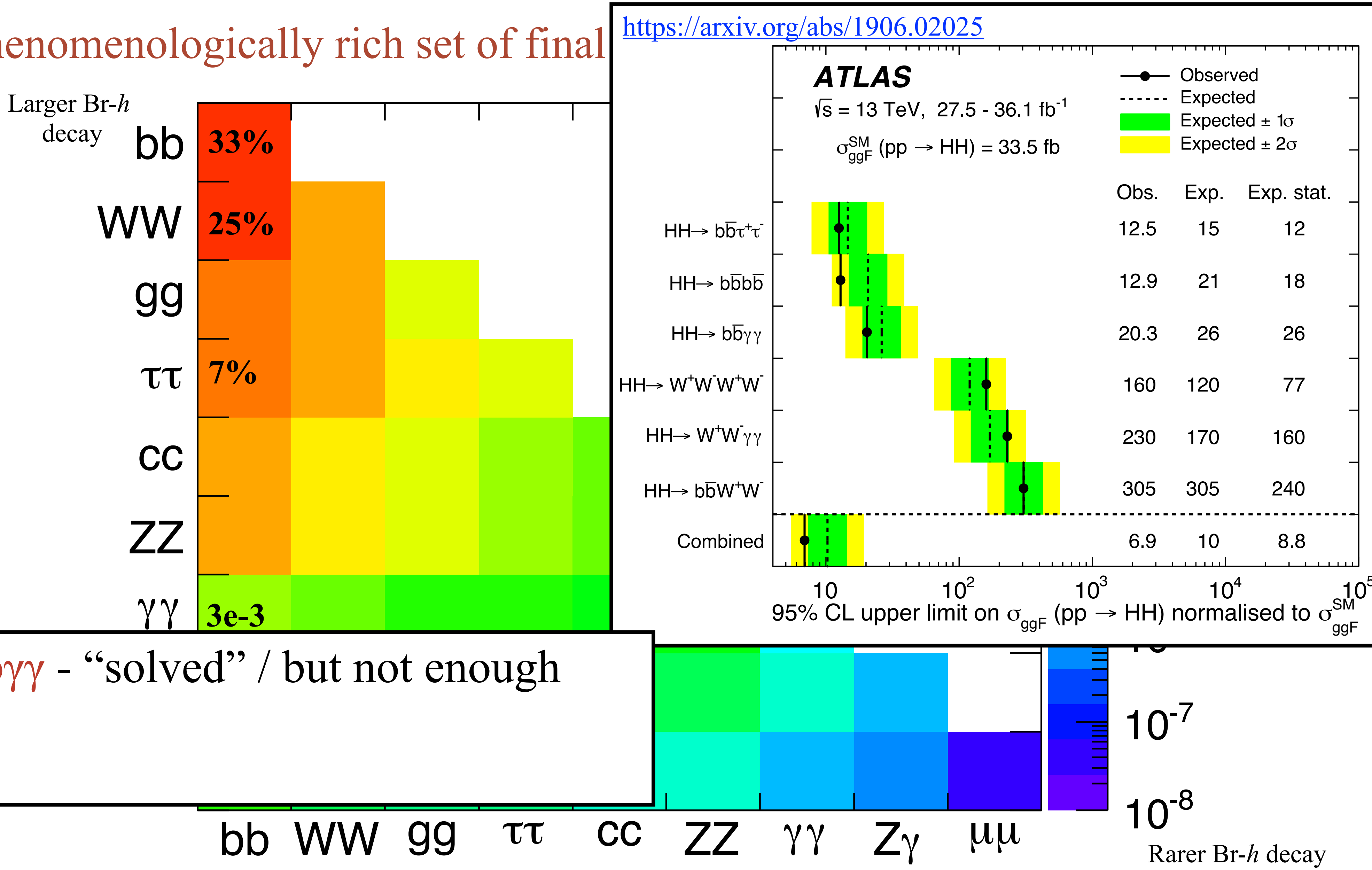
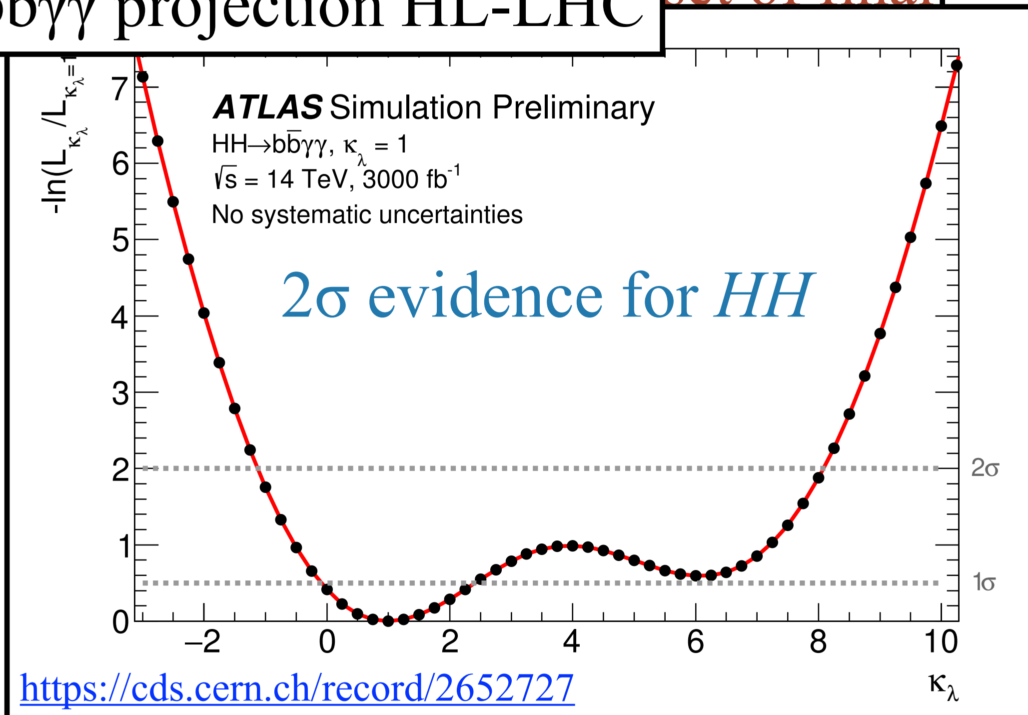


bbγγ - "solved" / but not enough

Why Hadronic *HH* ?

bbγγ projection HL-LHC

set of final



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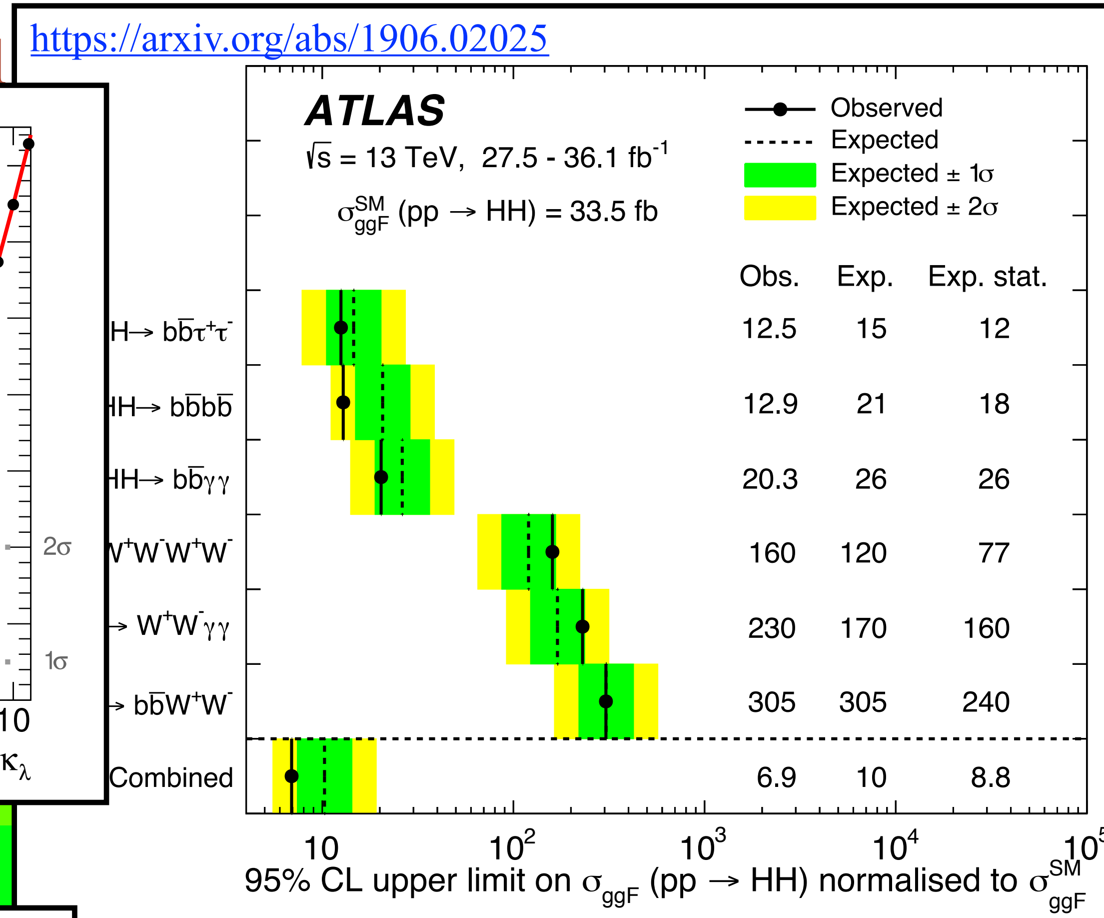

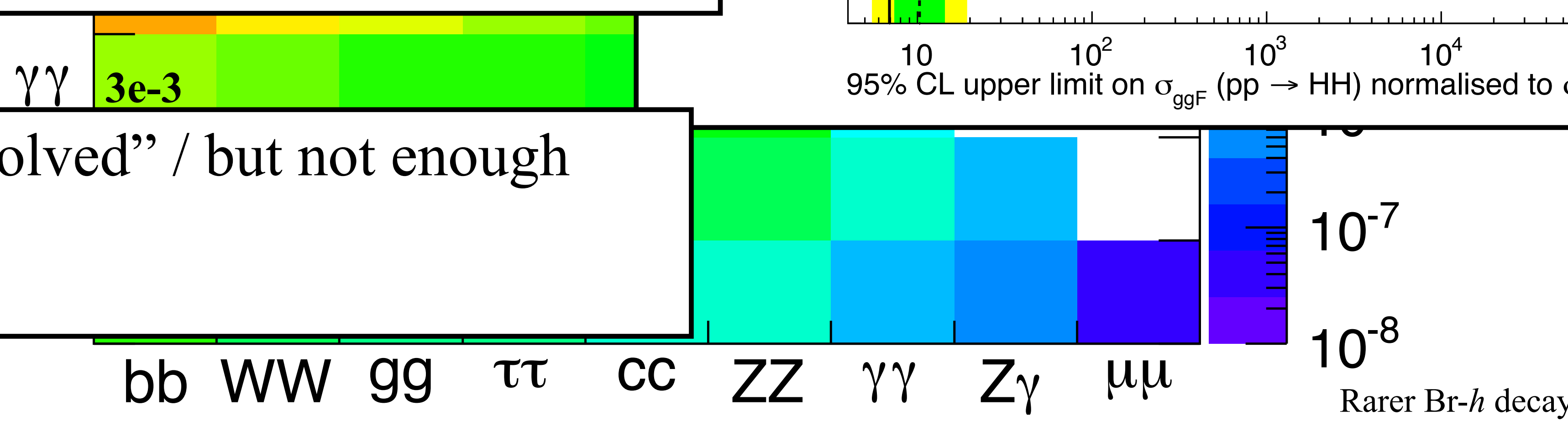

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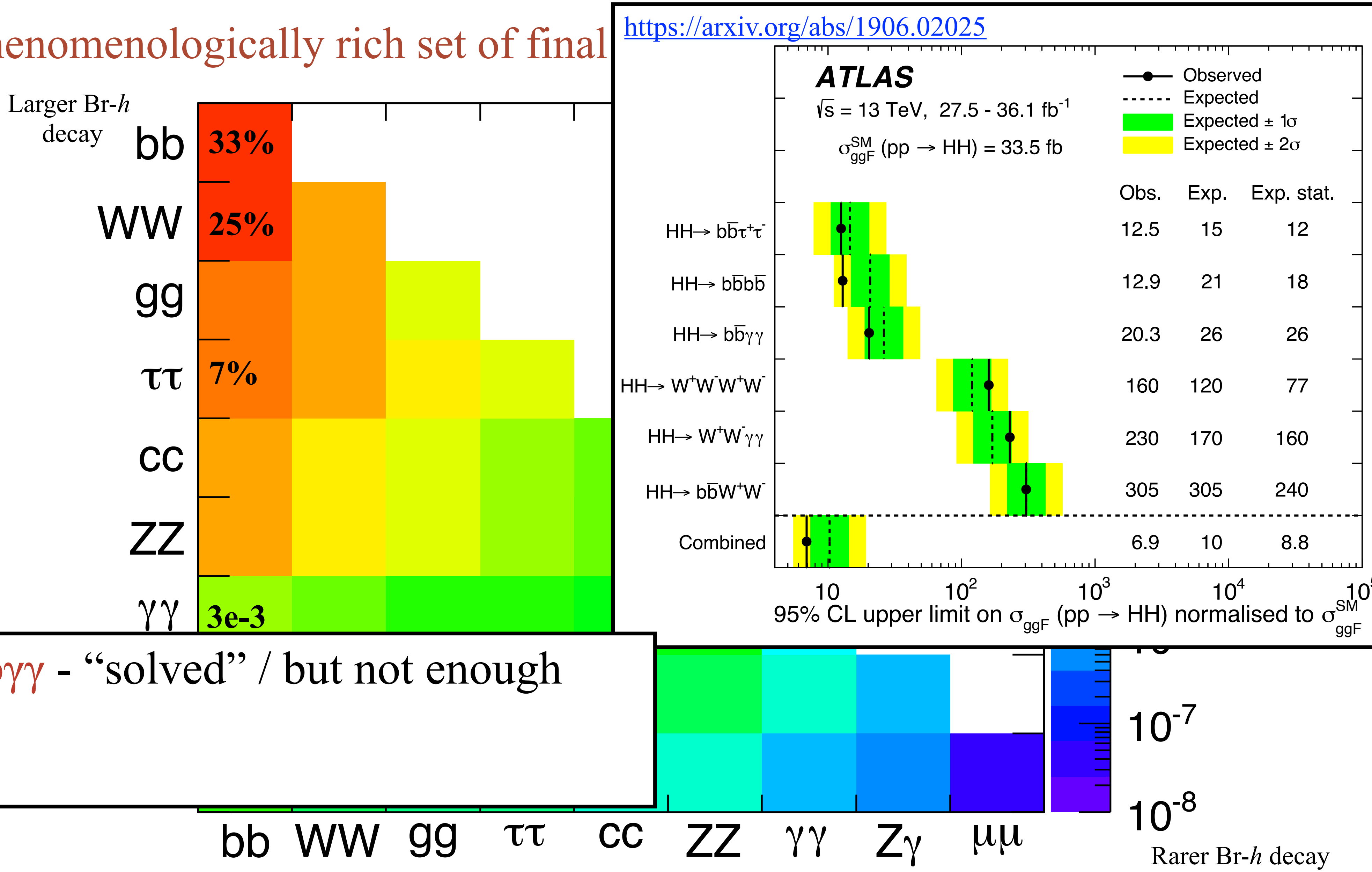

$bb\gamma\gamma$ - "solved" / but not enough

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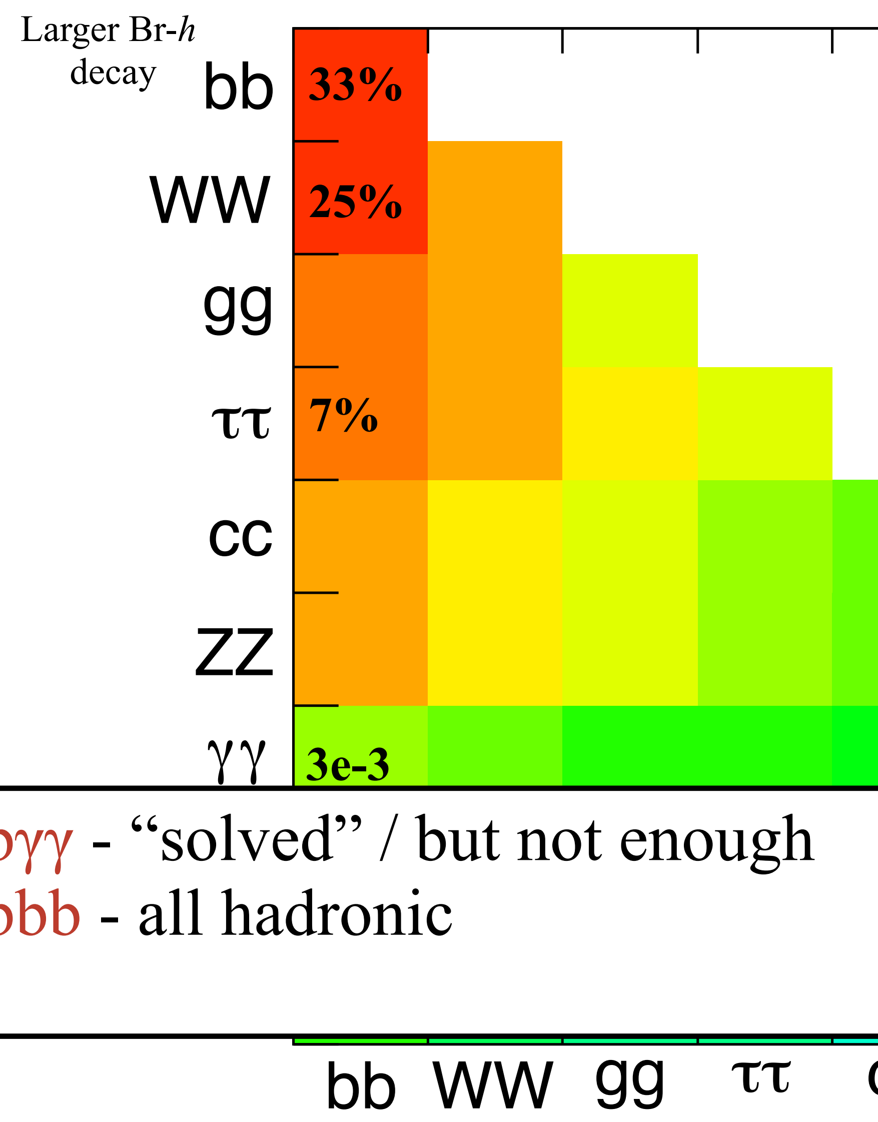

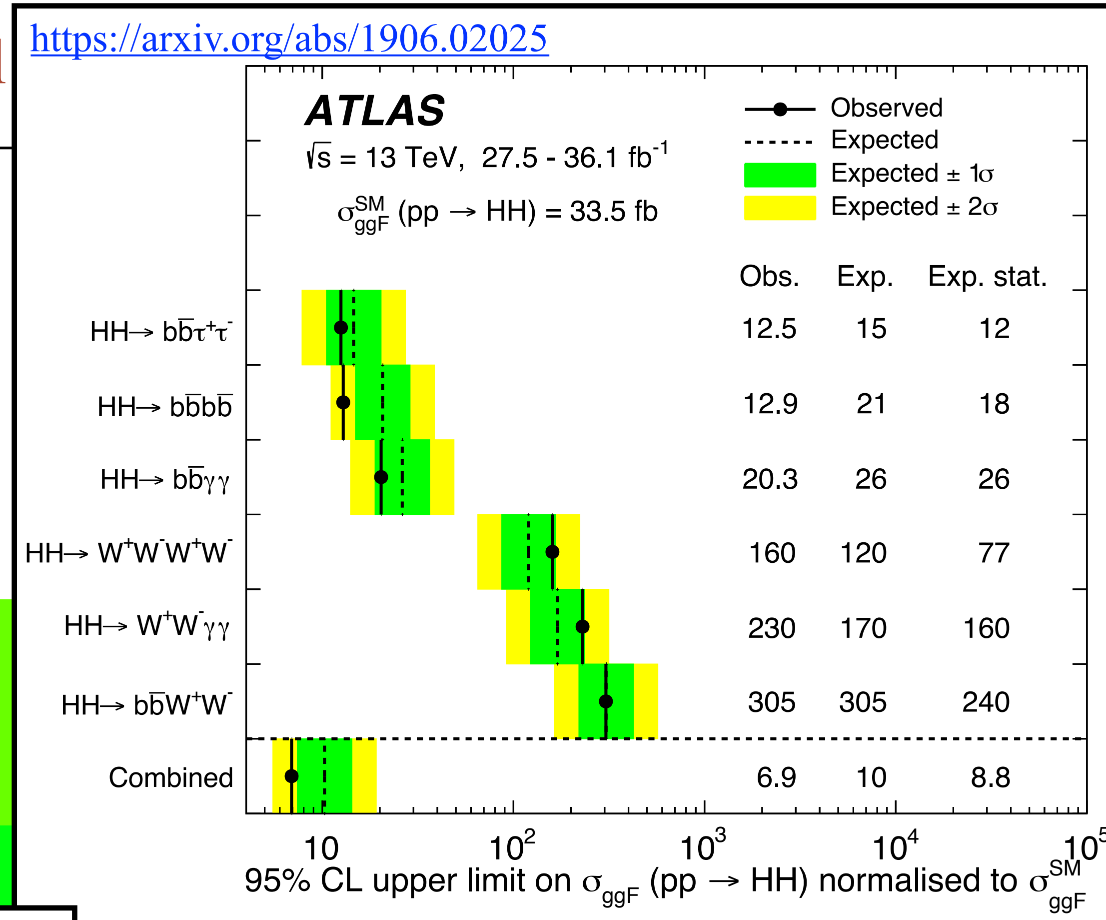

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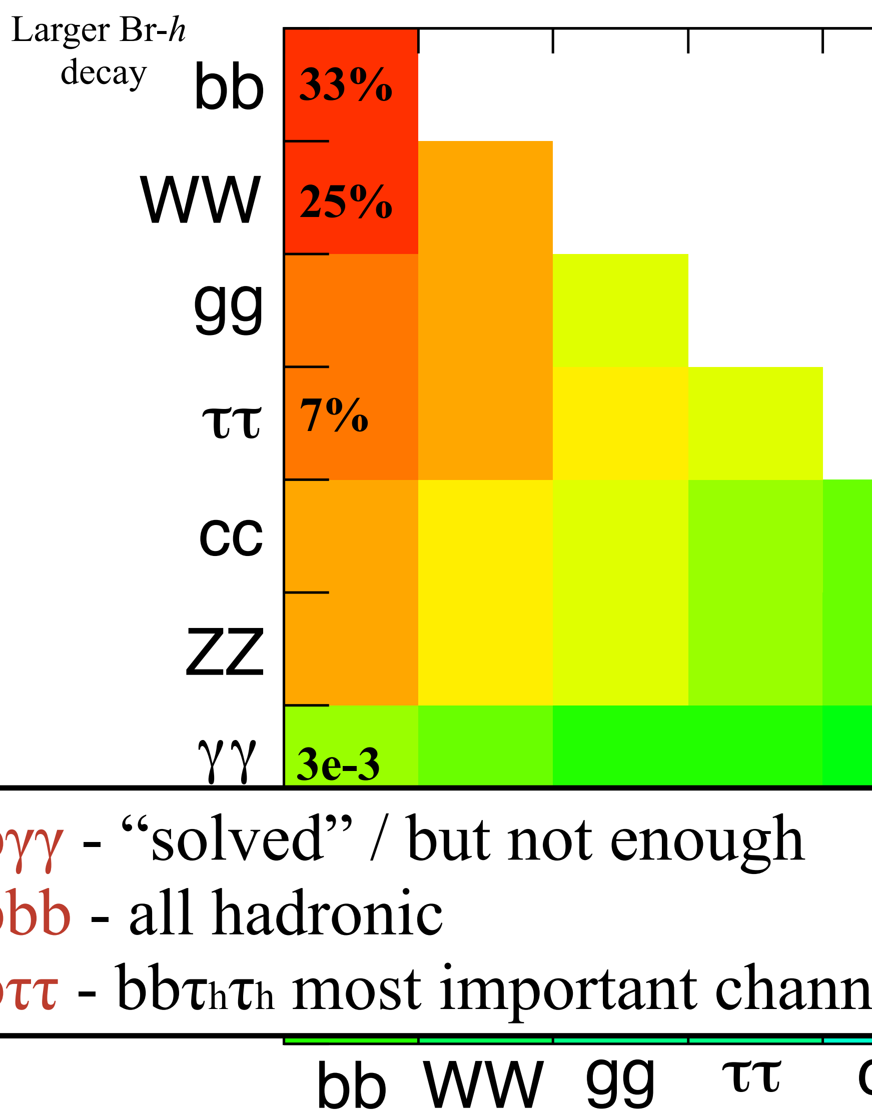

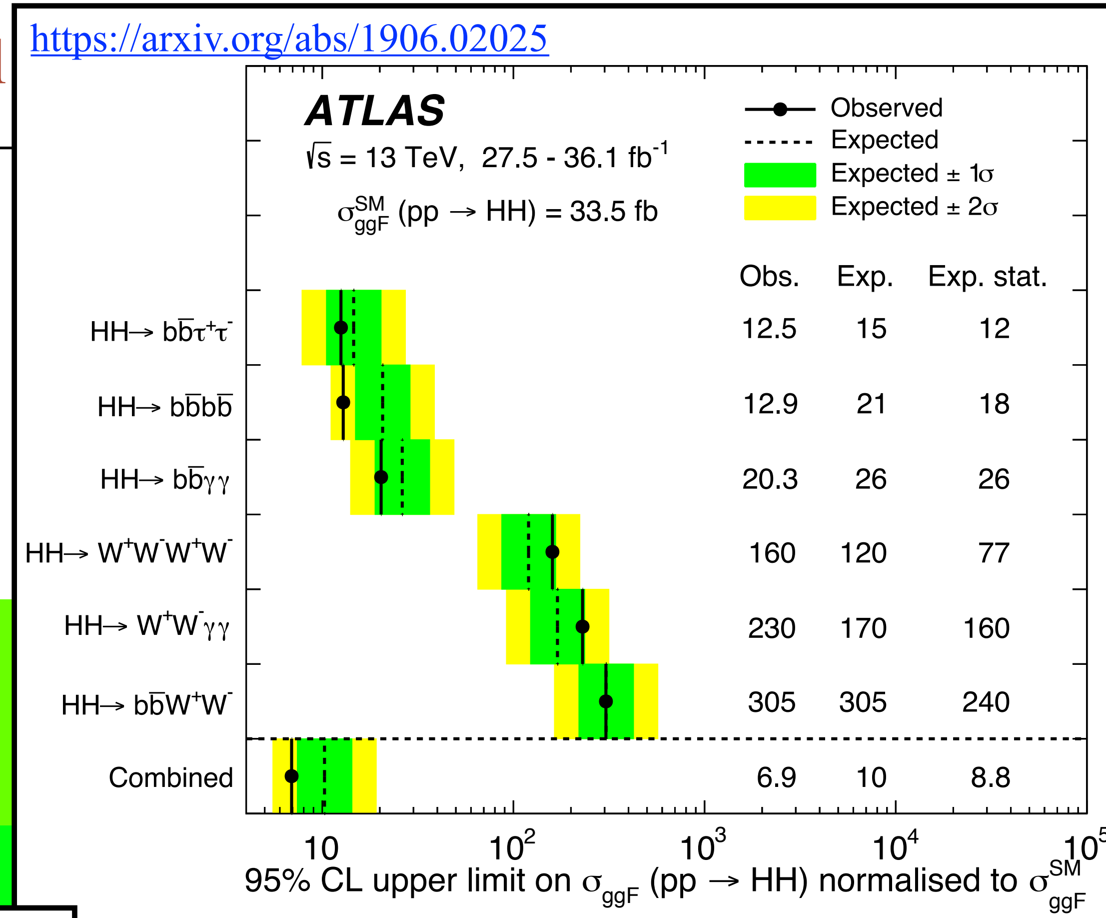

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bbττ - $bb\tau_h\tau_h$ most important channel

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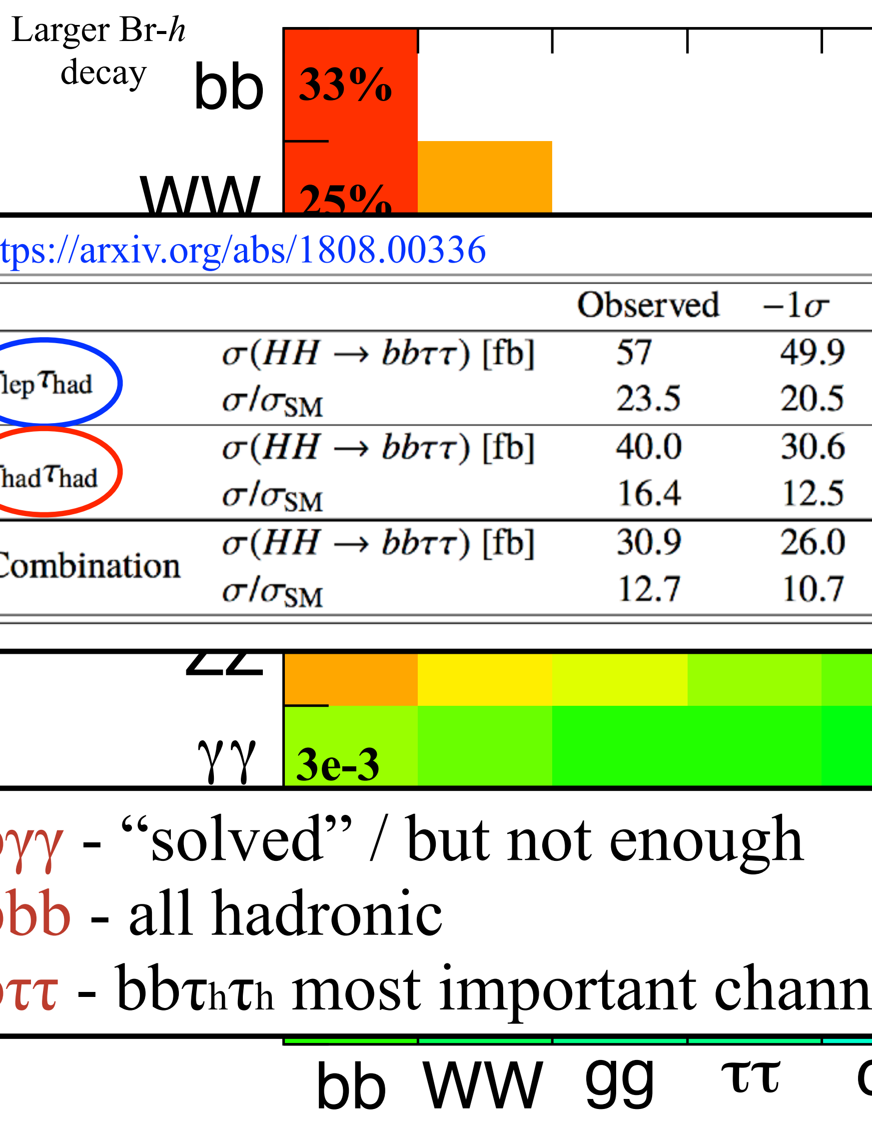

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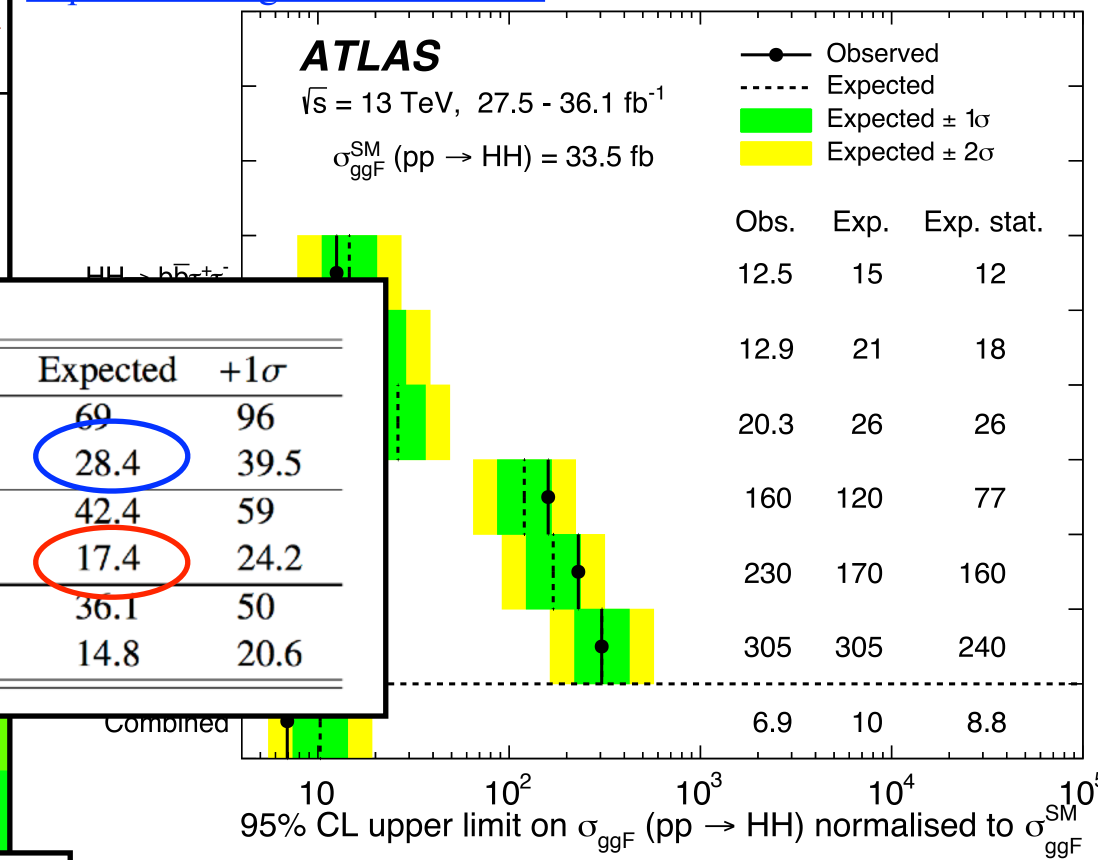

https://arxiv.org/abs/1808.00336

		Observed	-1σ	Expected	$+1\sigma$
$\tau_{lep}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	σ/σ_{SM}	23.5	20.5	28.4	39.5
$\tau_{had}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	σ/σ_{SM}	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	σ/σ_{SM}	12.7	10.7	14.8	20.6

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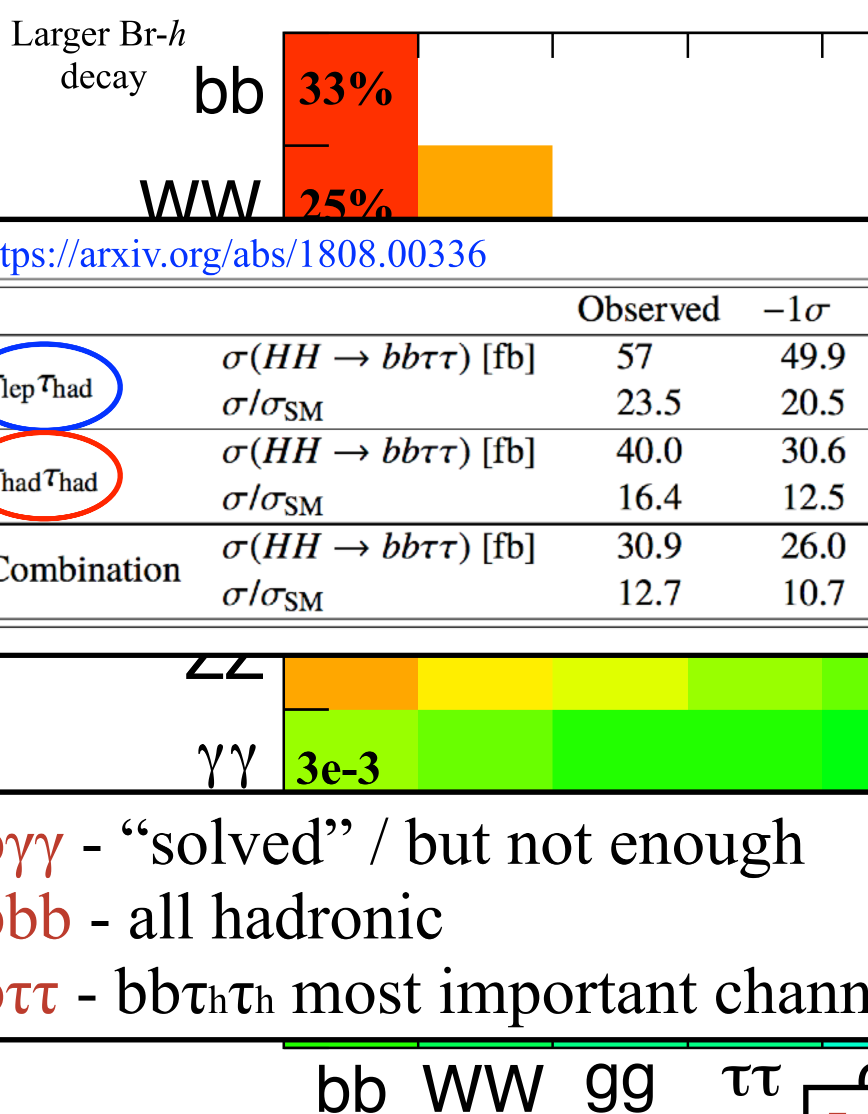

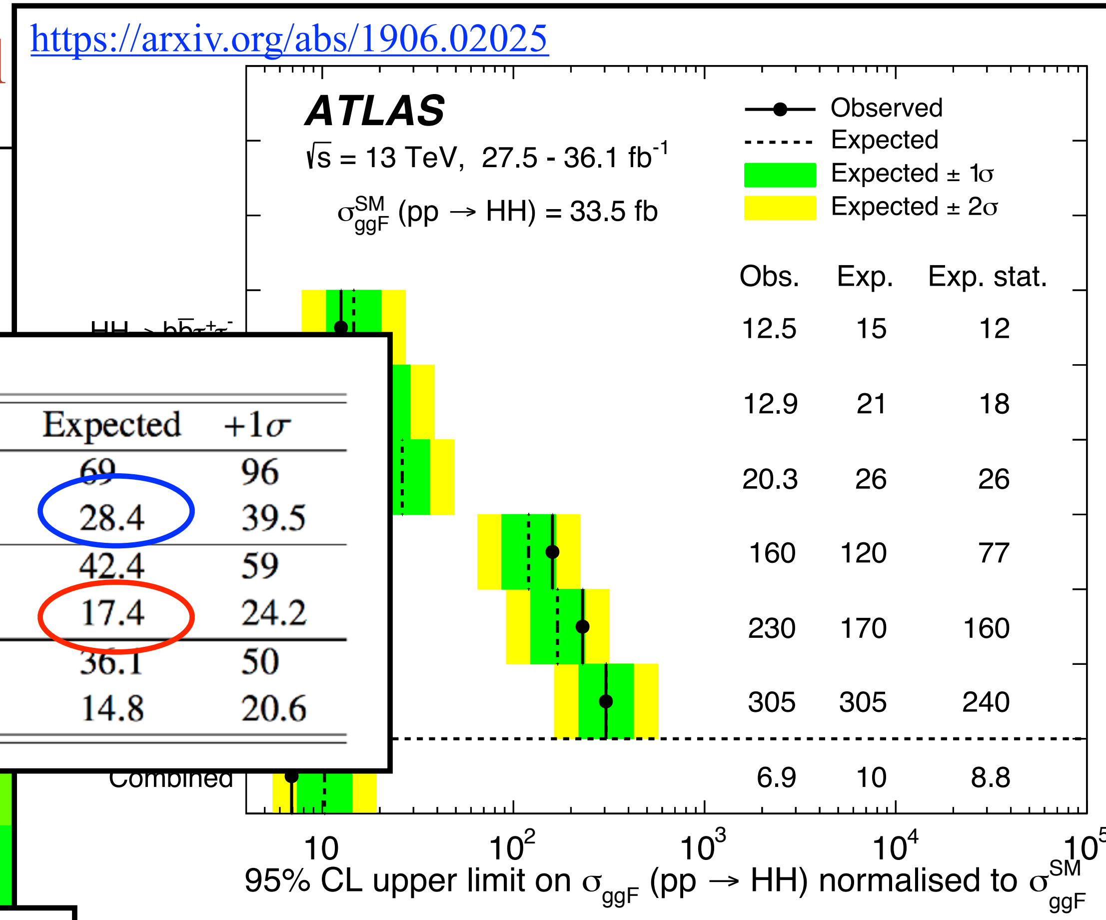

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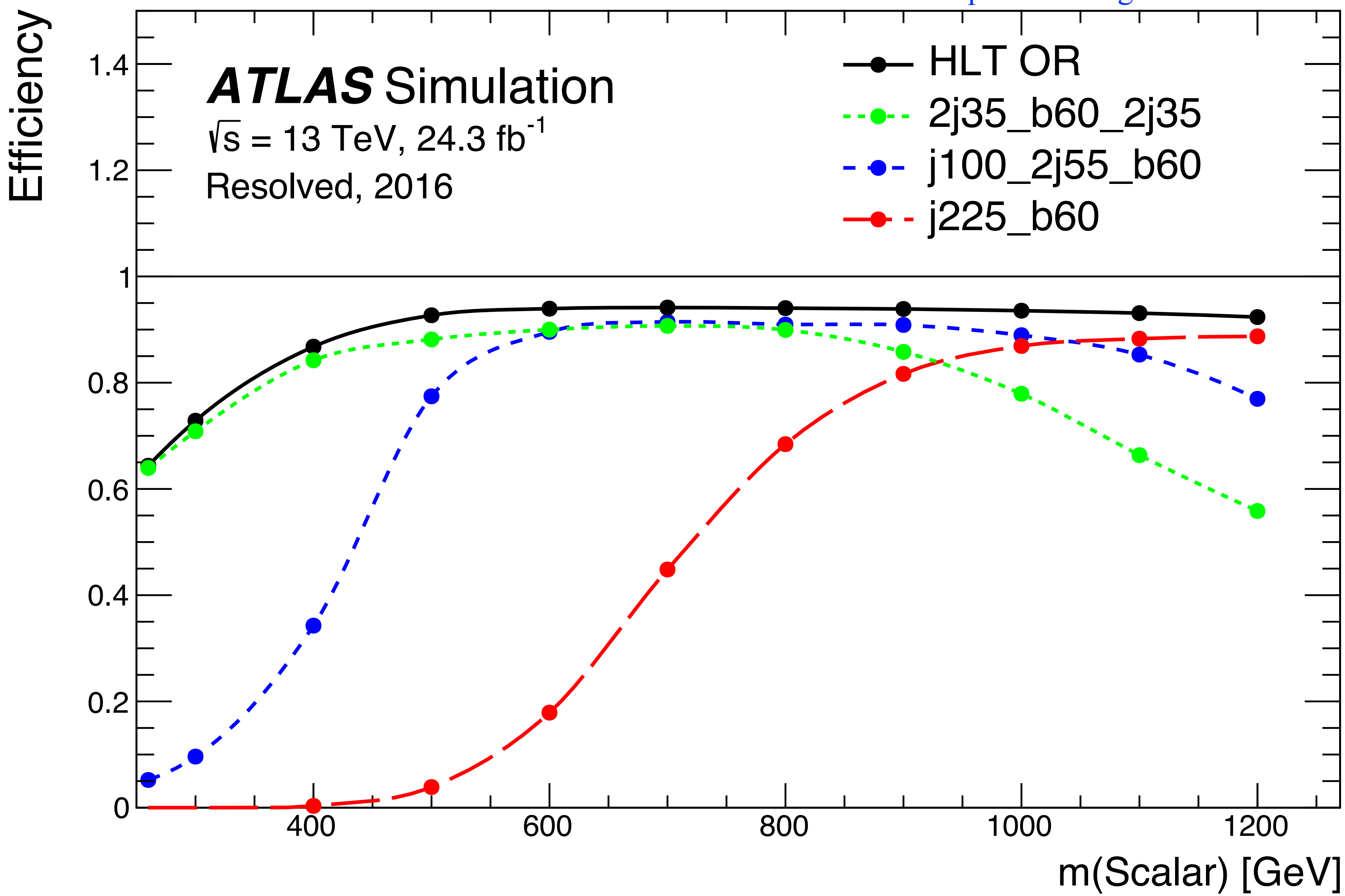
In following, will focus on 4b and $bb\tau_h\tau_h$

Trigger

Major experimental challenge in 4b and $bb\tau_h\tau_h$

4b Triggers

https://arxiv.org/abs/1804.06174



ε wrt to signal region

4b Triggers 2016

Trigger	L1 Seed	L1 Rate	HLT Rate
4j35 (2 b-tags) (ATLAS)	4×J15	~3.5 kHz	~60 Hz
4j45 (3 b-tags) (CMS)	4xJ50 HT300	~2.5 kHz ~9 kHz	~30 Hz

(Rates scaled to $\mathcal{L} = 1.2 \times 10^{34} cm^{-2} s^{-1}$)

4b Triggers 2016

Trigger	L1 Seed		
4j35 (2 b-tags) (ATLAS)	4×J15		
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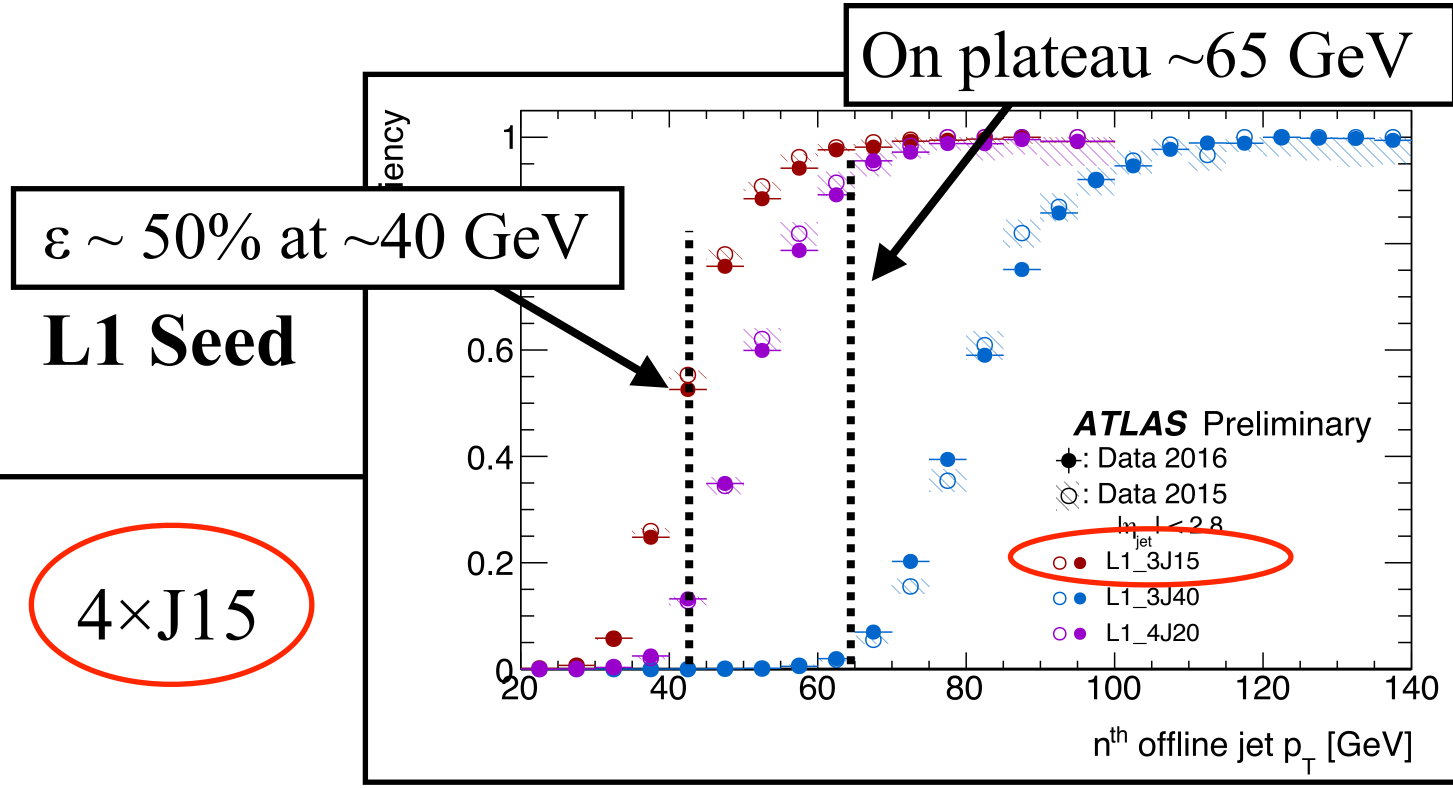

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https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetTriggerPublicResults

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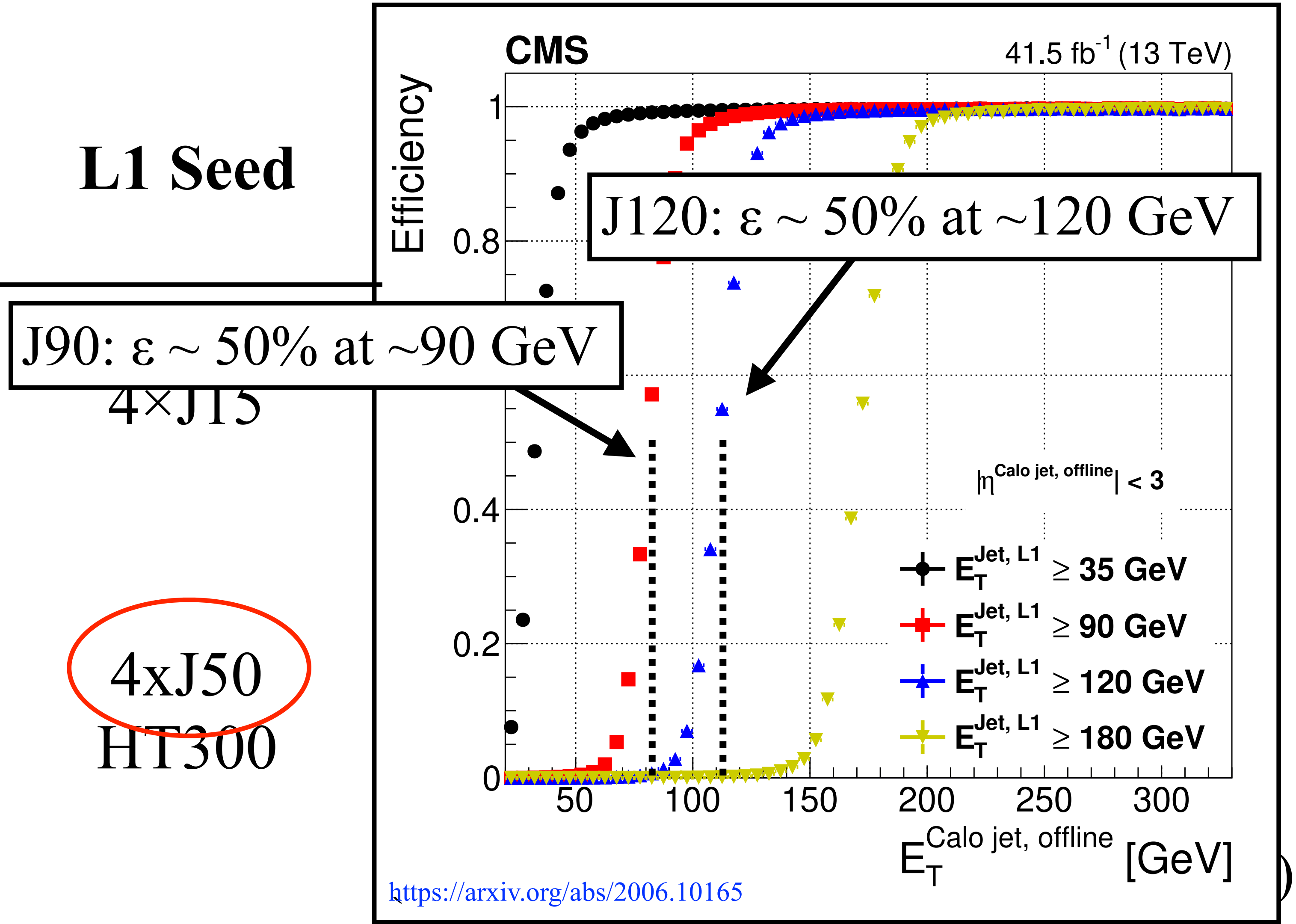


(Rates scaled to $\mathcal{L} = 1.2 \times 10^{34} cm^{-2} s^{-1}$)

4b Triggers 2016

Trigger	L1 Seed	L1 Rate	HLT Rate
4j35 (2 b-tags) (ATLAS)	4×J40*	~3 kHz	~40 Hz
4j45 (3 b-tags) (CMS)	4xJ50 HT300	~2.5 kHz ~9 kHz	~30 Hz

* quoted at ε ~ 50%

(Rates scaled to $\mathcal{L} = 1.2 \times 10^{34} cm^{-2} s^{-1}$)

4b Triggers 2017

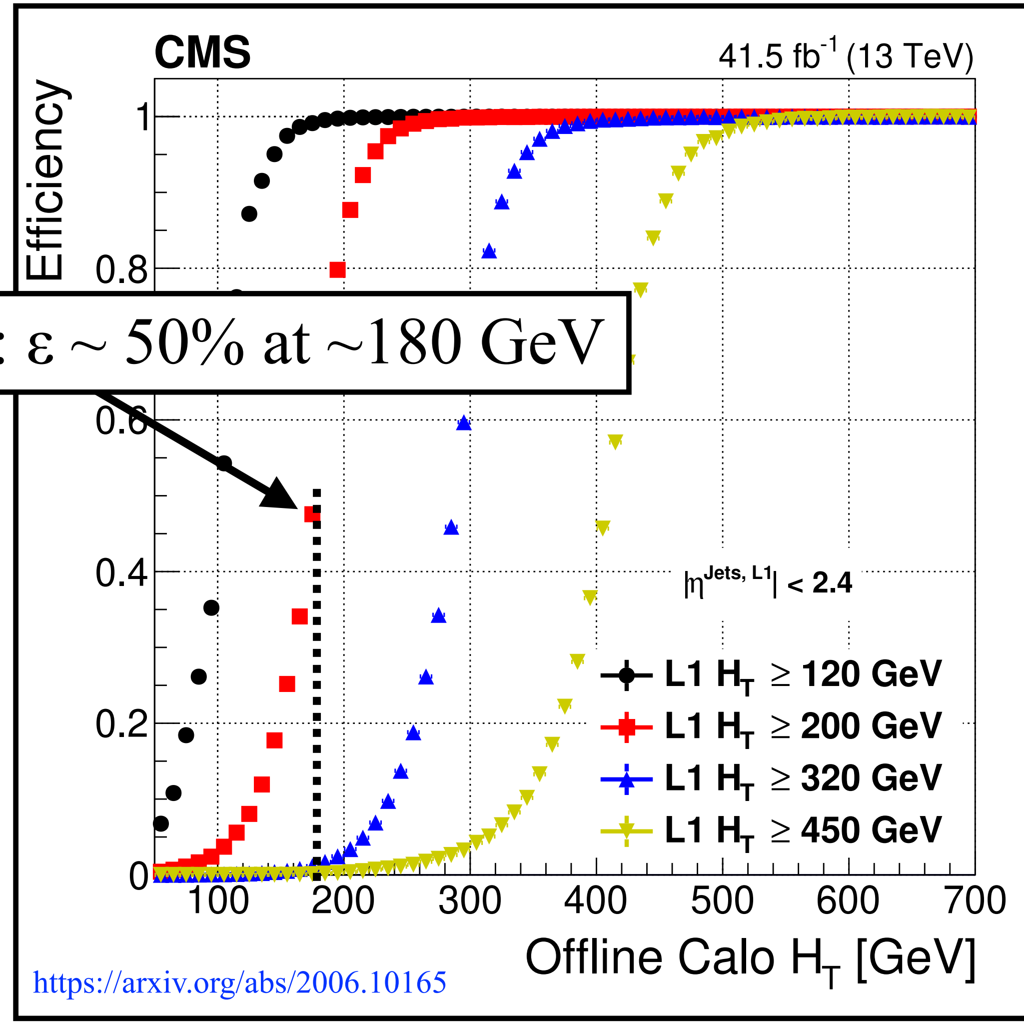
Trigger	L1 Seed	L1 Rate	HLT Rate
4j35 (2 b-tags) (ATLAS)	4×J40*	~3.2 kHz	~13 Hz
HT300 + 4j + 3b (75,60,45,40) (CMS)	HT280 + J70/55/40/35 4×J60	~10 kHz ~1 kHz	~10 Hz

* quoted at ε ~ 50%

(Rates scaled to $\mathcal{L} = 1.7 \times 10^{34} cm^{-2} s^{-1}$)

4b Triggers 2017

Trigger	L1 Seed
4j35 (2 b-tags) (ATLAS)	4×J40*
HT300 + 4j + 3b (75,60,45,40) (CMS)	HT280 + J70/55/40/35 4×J60



J200: ε ~ 50% at ~180 GeV

* quoted at ε ~ 50%

(Rates scaled to $\mathcal{L} = 1.7 \times 10^{34} cm^{-2} s^{-1}$)

4b Triggers 2017

Trigger	L1 Seed	L1 Rate	HLT Rate
4j35 (2 b-tags) (ATLAS)	4×J40*	~3.2 kHz	~13 Hz
HT300 + 4j + 3b (75,60,45,40) (CMS)	HT260* + J70/55/40/35 4×J60	~10 kHz ~1 kHz	~10 Hz

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4b Triggers 2018

Trigger	L1 Seed	L1 Rate	HLT Rate
4j35 (2 b-tags) (ATLAS)	4×J40*	~3.2 kHz	~15 Hz
HT330 + 4j + 3b (75,60,45,40) (CMS)	HT300* + J70/55/40/35	~2.2 kHz	~12 Hz

* quoted at ε ~ 50%

(Rates scaled to $\mathcal{L} = 2.0 \times 10^{34} cm^{-2} s^{-1}$)

4b Triggers 2018

Trigger	L1 Seed	L1 Rate	HLT Rate
4j35 (2 b-tags) (ATLAS)	4×J40*	~3.2 kHz	~15 Hz
HT3 (75			

CPU for tracking was a major constraint

One of the primary limitations in the trigger is HLT CPU usage

b-jet triggers are among largest user of HLT CPU

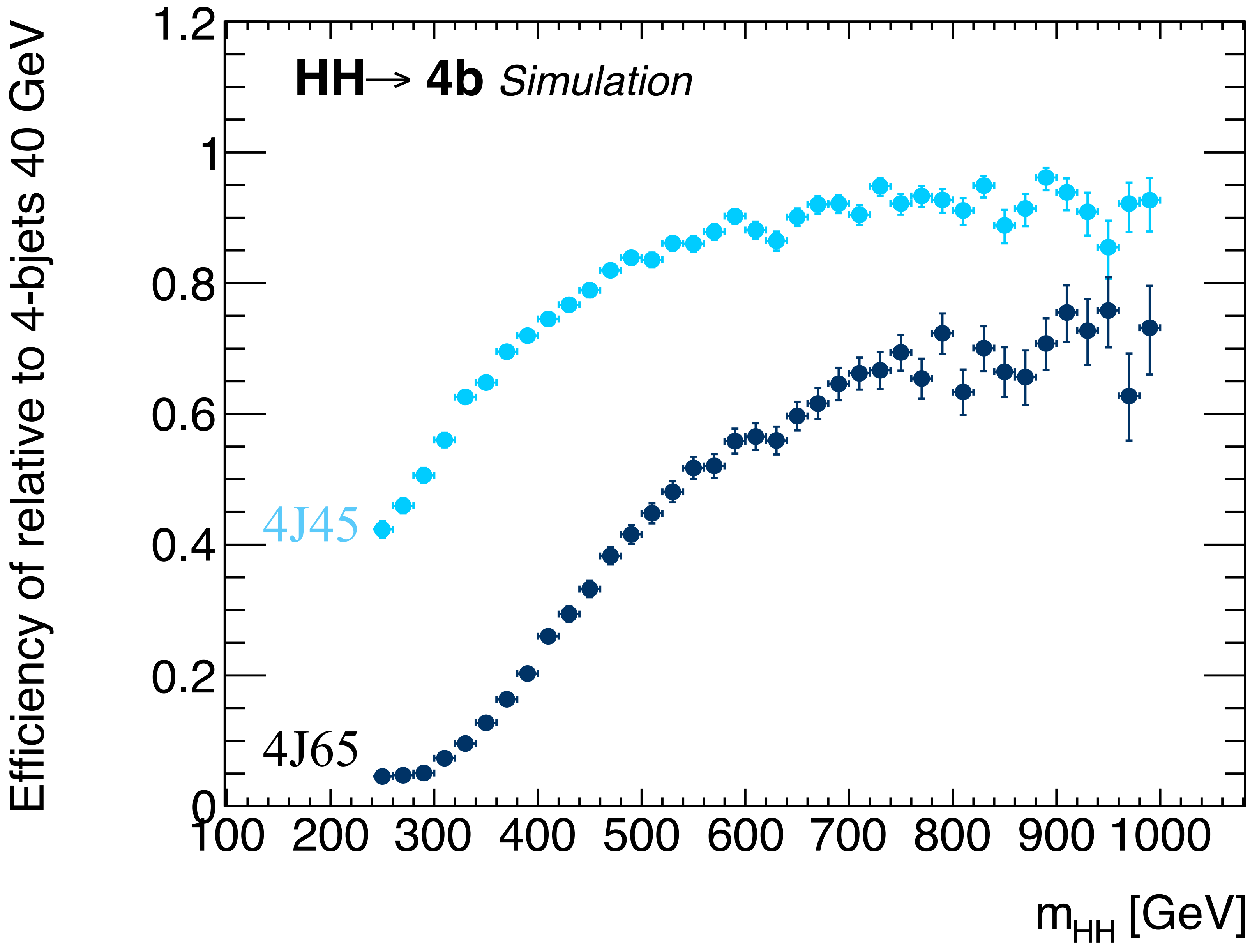
Several major campaigns to reduce b-jet trigger CPU usage:

Implement 2-step tracking / PV finding: trk PT 1 GeV → 5 GeV

* quoted at ε ~ 50%

(Rates scaled to $\mathcal{L} = 2.0 \times 10$ cm s)

4b Trigger Acceptance



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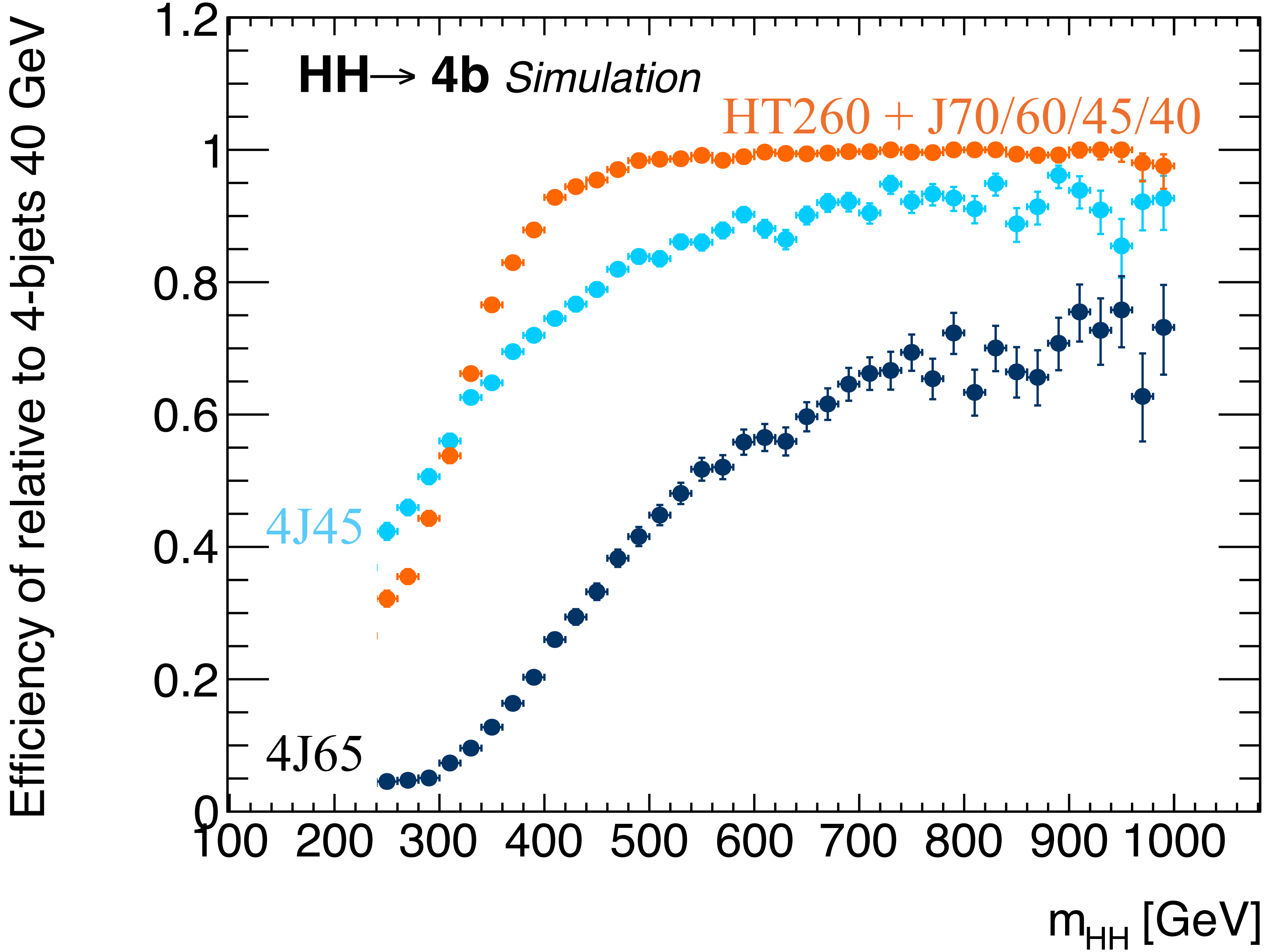

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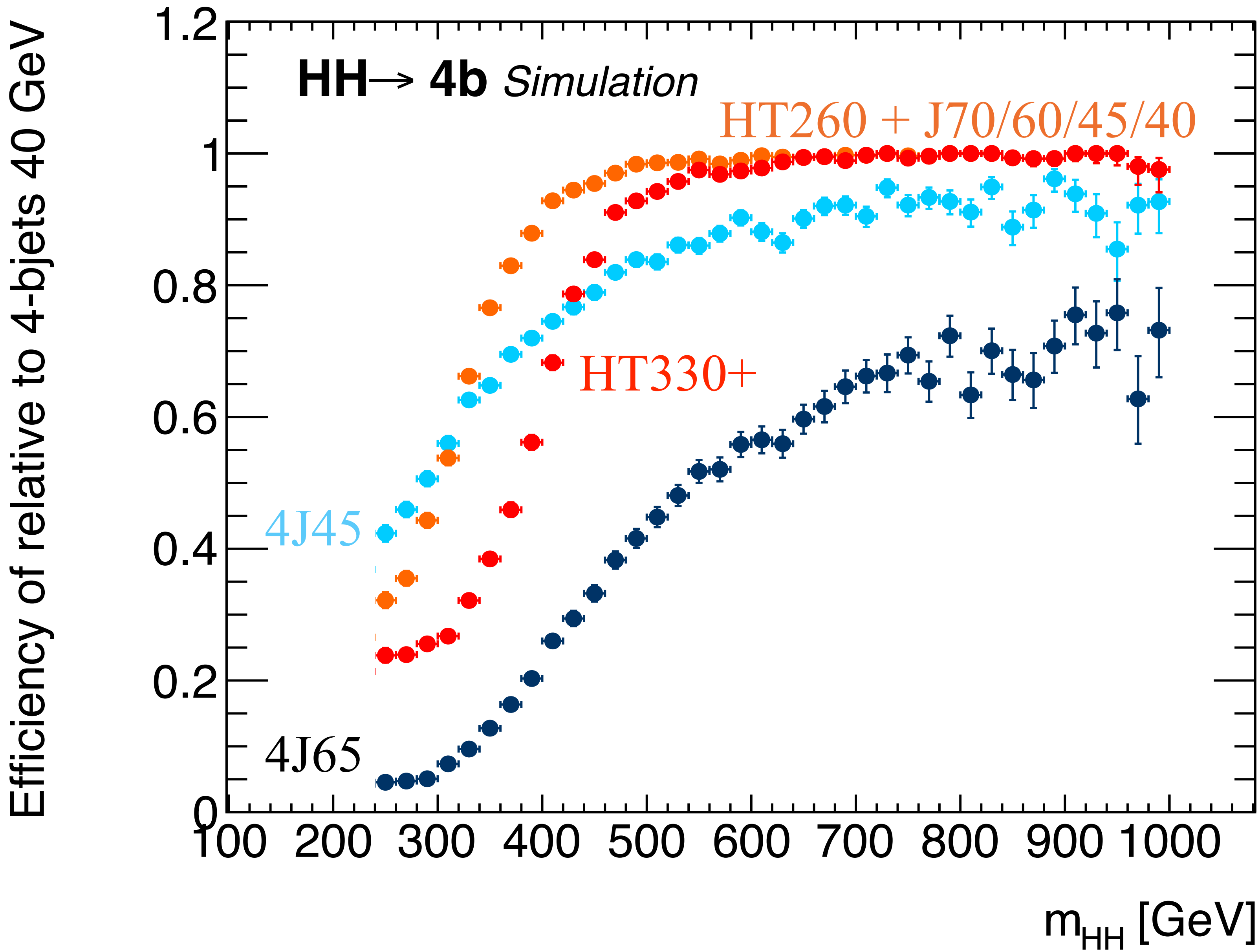

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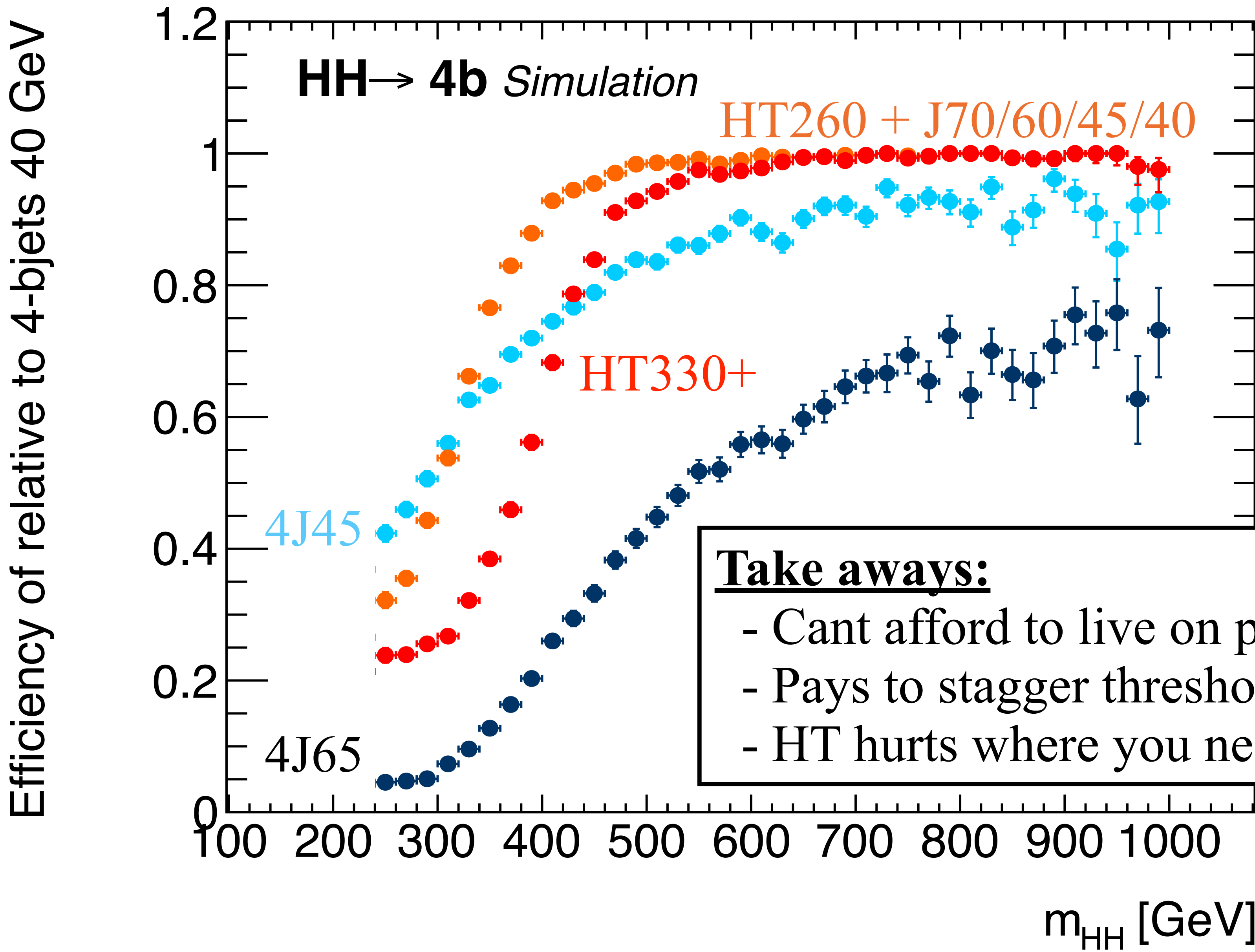

<u>Take aways:</u>

- Cant afford to live on plateau
- Pays to stagger thresholds
- HT hurts where you need it most

bbττ Triggers 2016

Trigger	L1 Seed	L1 Rate	HLT Rate
2τ + j 35/25 + 80 (ATLAS)	τ20(i) τ12(i) +J25	~6 kHz	~35 Hz
2τ 35 (CMS)	2×τ30(i)	~12 kHz	~40 Hz

(Rates scaled to $\mathcal{L} = 1.2 \times 10^{34} cm^{-2} s^{-1}$)

bbττ Triggers 2016

Trigger	L1 Seed	L1 Rate	HLT Rate
2τ + j 35/25 + 80 (ATLAS)	τ35(i) τ20(i) +J50*	~6 kHz	~35 Hz
2τ 35 (CMS)	2×τ30(i)	~12 kHz	~40 Hz

* quoted at ε ~ 50%

(Rates scaled to $\mathcal{L} = 1.2 \times 10^{34} cm^{-2} s^{-1}$)

bbττ Triggers 2017

Trigger	L1 Seed	L1 Rate	HLT Rate
2τ + j 35/25 + 80 (ATLAS)	τ35(i) τ20(i) +J50*	~5 kHz	~60 Hz
2τ 35 (CMS)	2×τ32(i)	~10 kHz	~50 Hz

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(Rates scaled to $\mathcal{L} = 1.7 \times 10^{34} cm^{-2} s^{-1}$)

bbττ Triggers 2018

Trigger	L1 Seed	L1 Rate	HLT Rate
2τ + j **35/25 + 80** **(ATLAS)**	τ35(i) τ20(i) +J50*	~6 kHz	~90 Hz
2τ 35 **(CMS)**	2×τ32(i)	~17 kHz	~60 Hz

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(Rates scaled to $\mathcal{L} = 2.0 \times 10^{34} cm^{-2} s^{-1}$)

bbττ Trigger Acceptance

Neither experiment discusses the impact of the trigger on the Run 2 analyses

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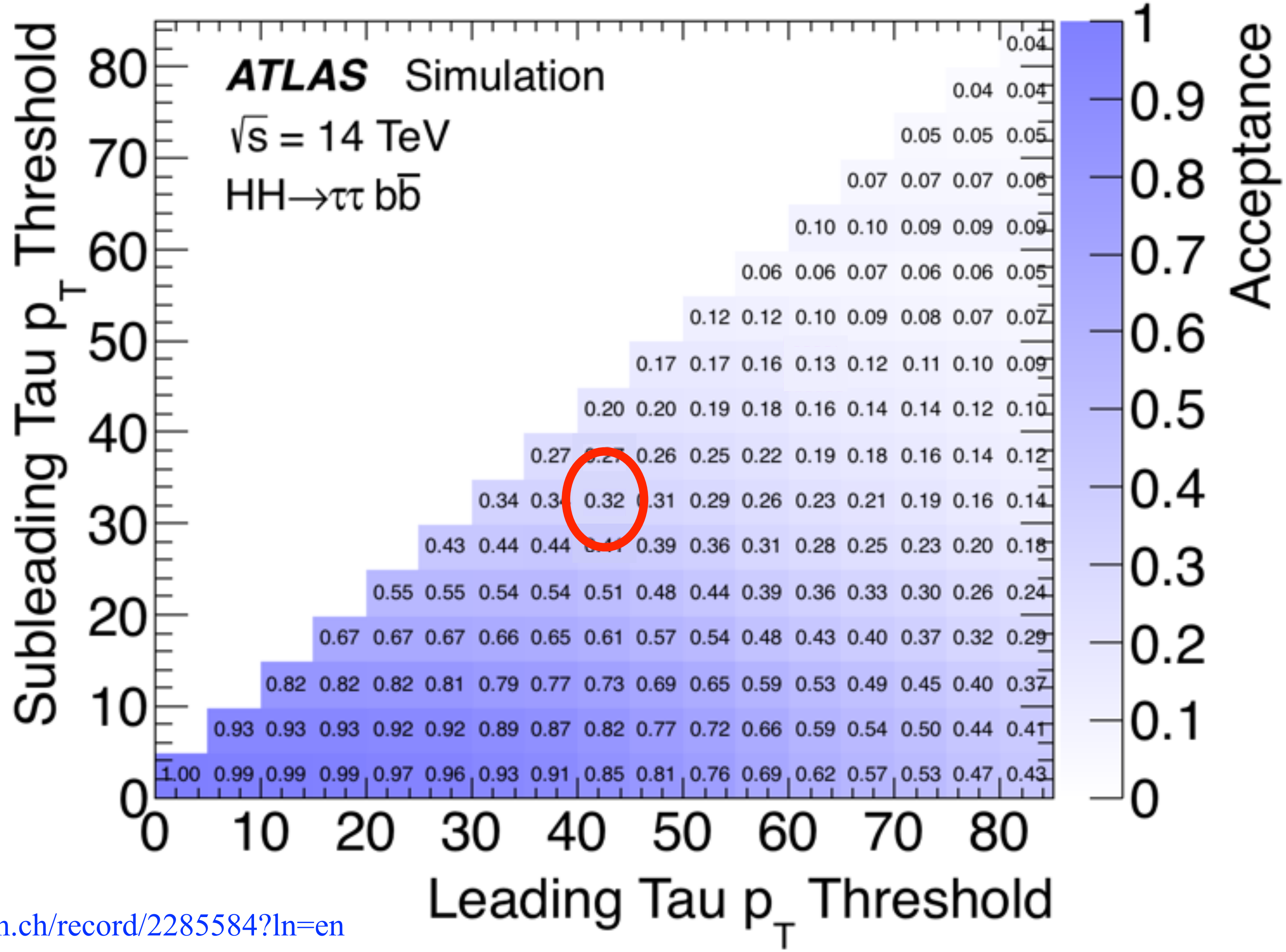

https://cds.cern.ch/record/2285584?ln=en

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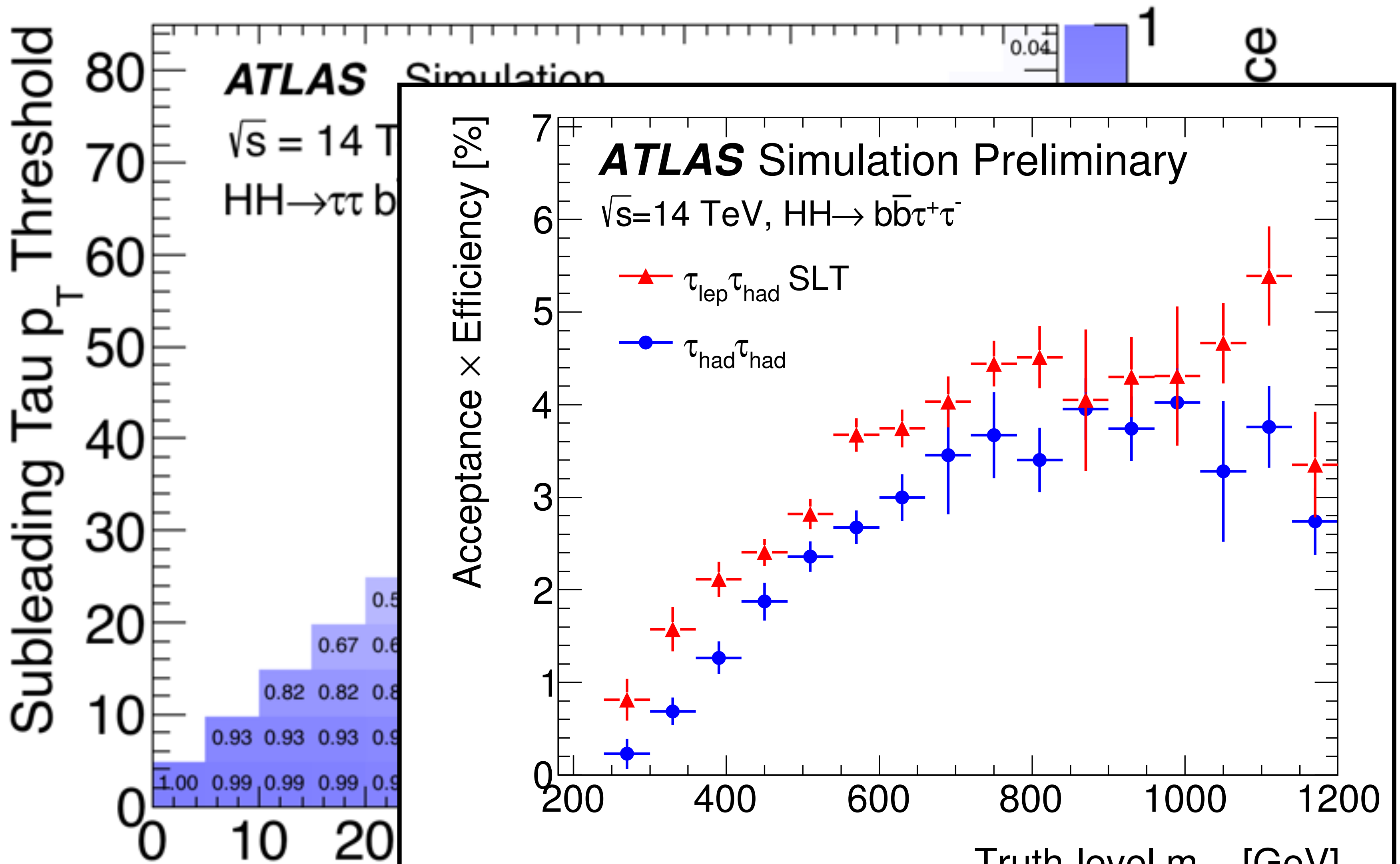

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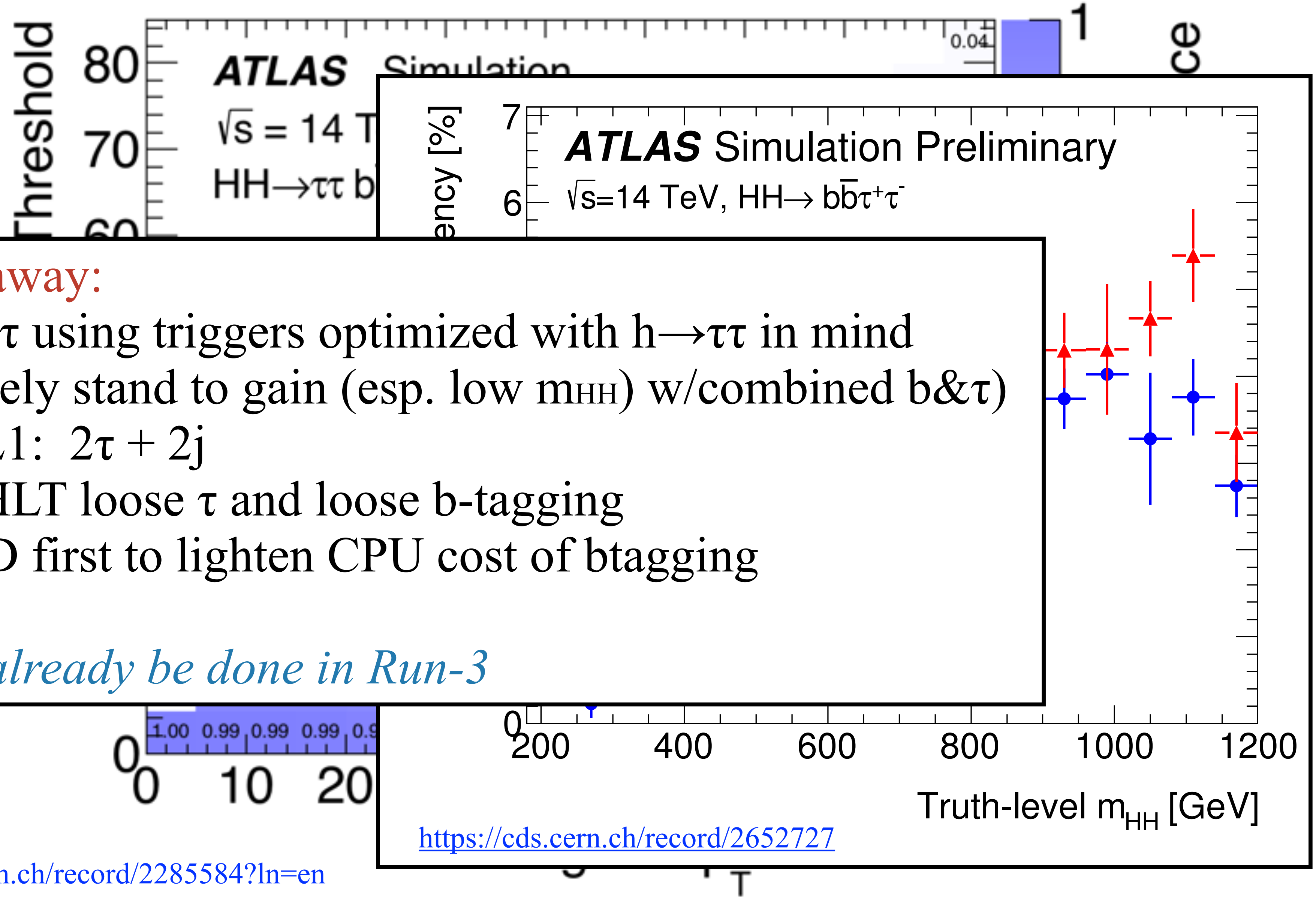


Take away:

- bbττ using triggers optimized with h→ττ in mind
- Likely stand to gain (esp. low m_{HH}) w/combined b&τ)
  - L1: 2τ + 2j
  - HLT loose τ and loose b-tagging
- τ-ID first to lighten CPU cost of btagging

Can already be done in Run-3

https://cds.cern.ch/record/2652727

https://cds.cern.ch/record/2285584?ln=en

Trigger Upgrades

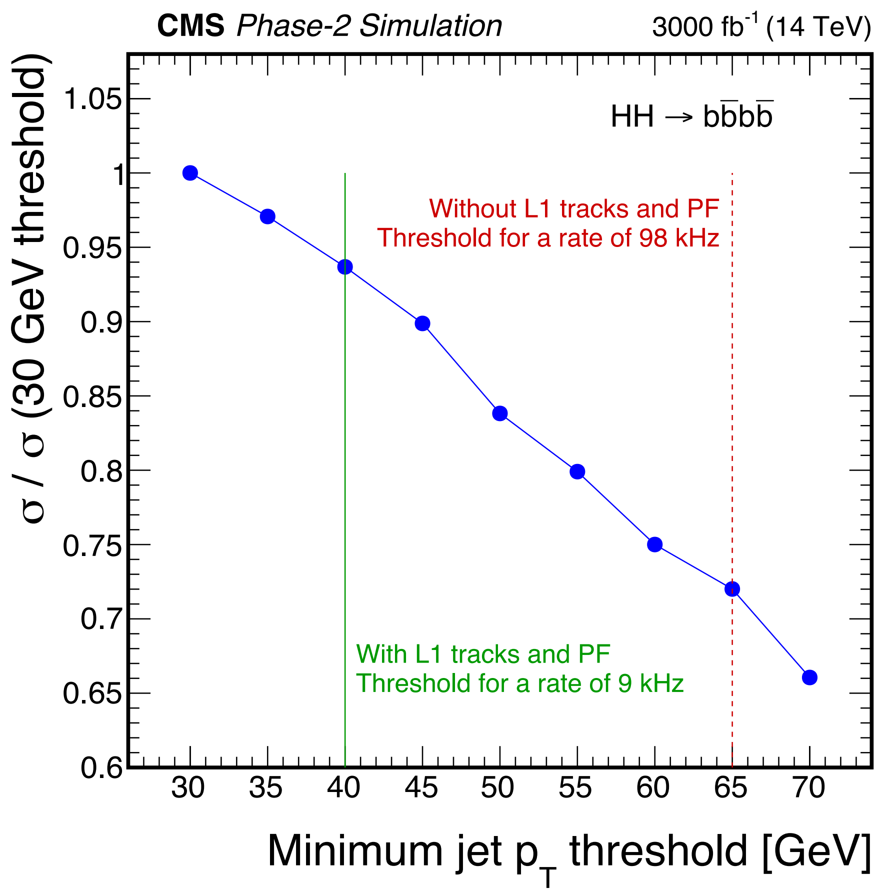
Upgrades critical to hadronic HH *In many cases driving specs*

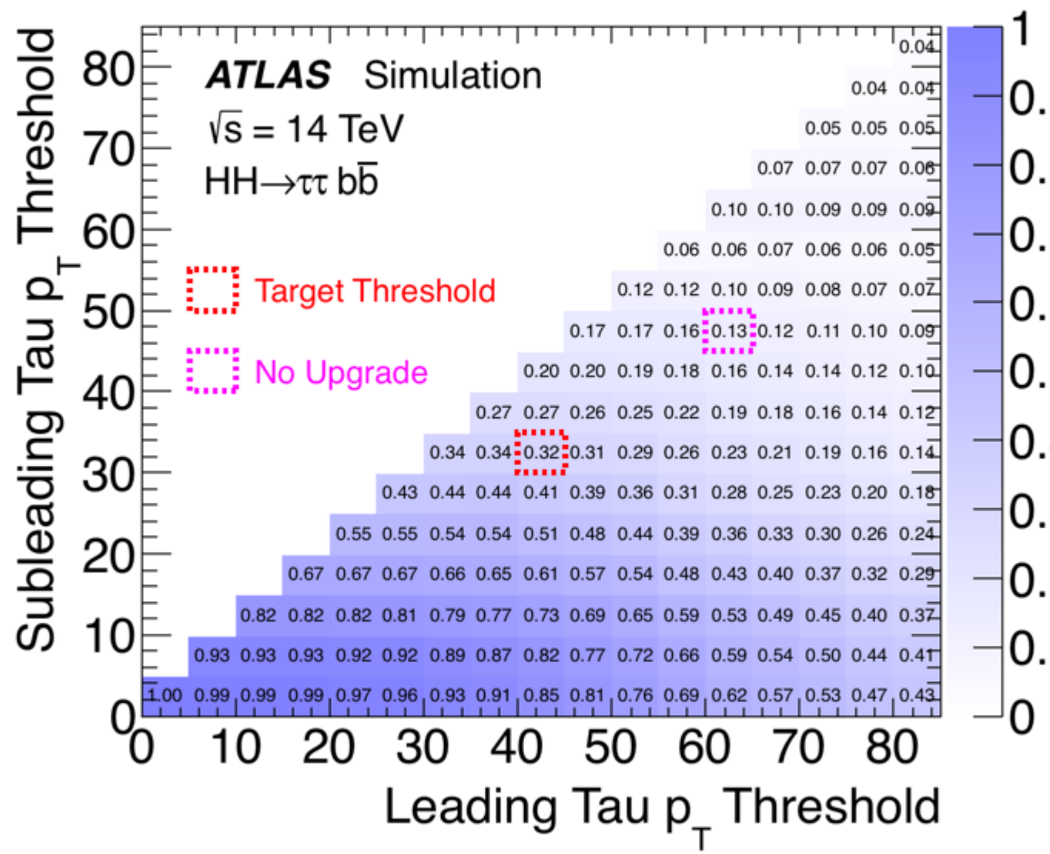
Keys: L1 jet thresholds / CPU b-tagging

<u>Run-3</u>: Better L1 jets / GPU tracking mitigate CPU cost

<u>Phase-2:</u> Tracking in trigger (40 MHz @ CMS)

http://cds.cern.ch/record/2714892





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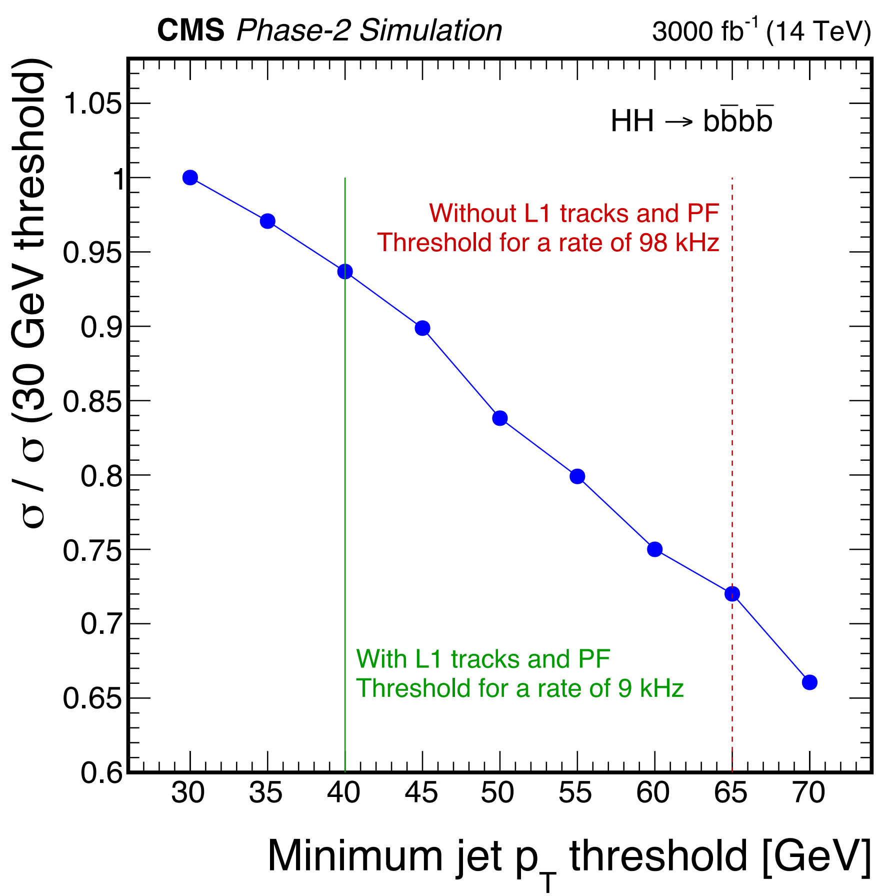
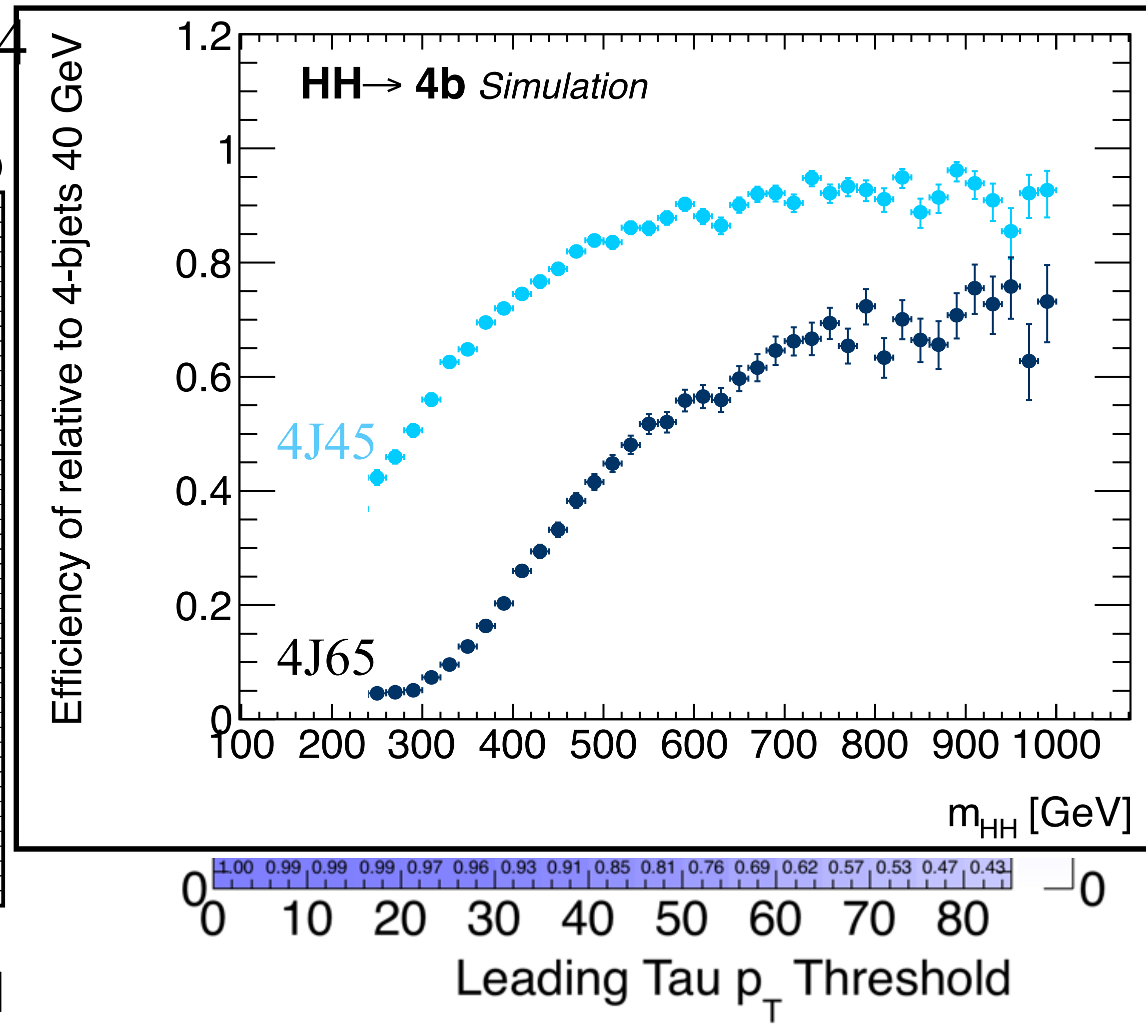




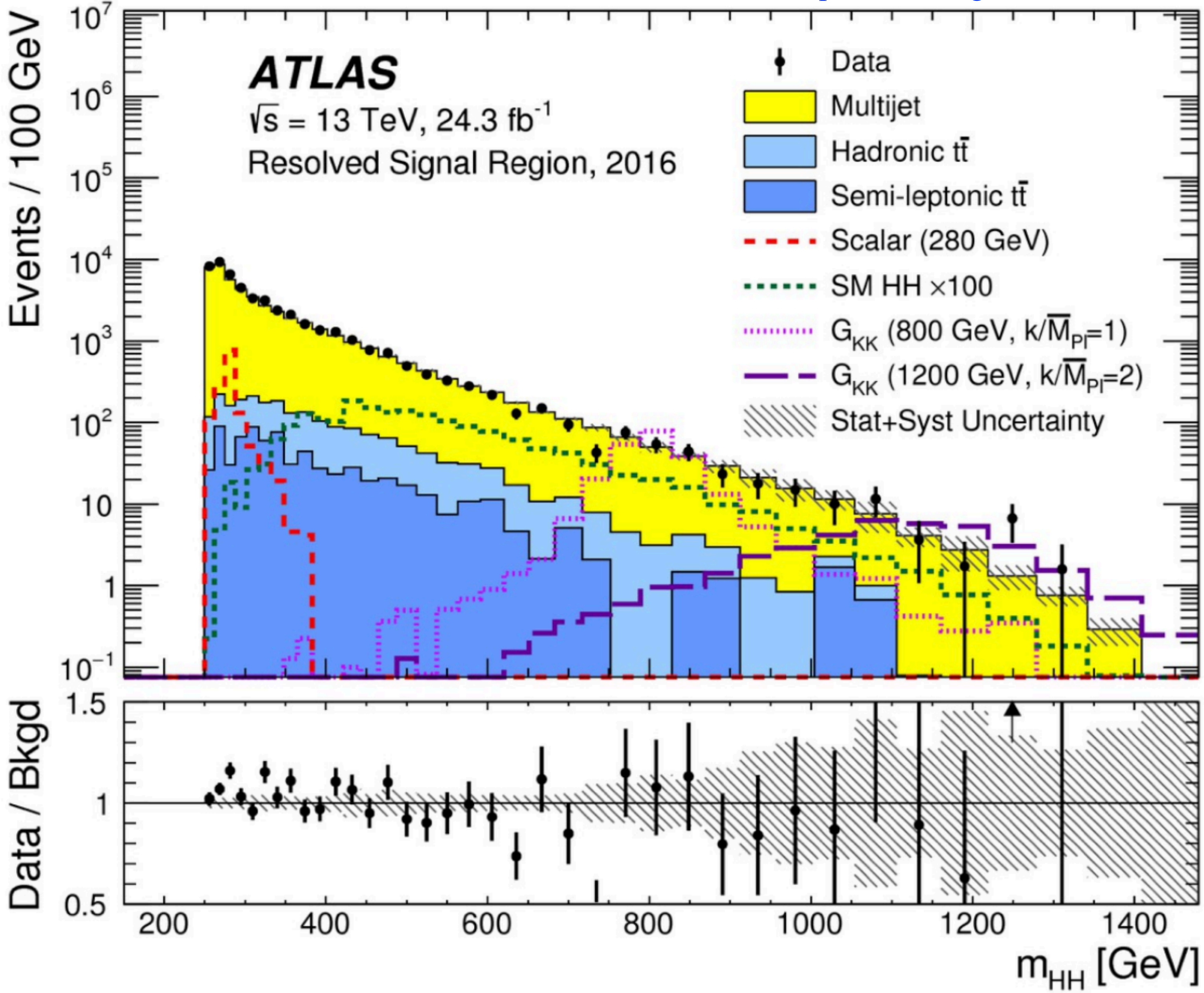
Backgrounds

The other big challenge in 4b and bbττ

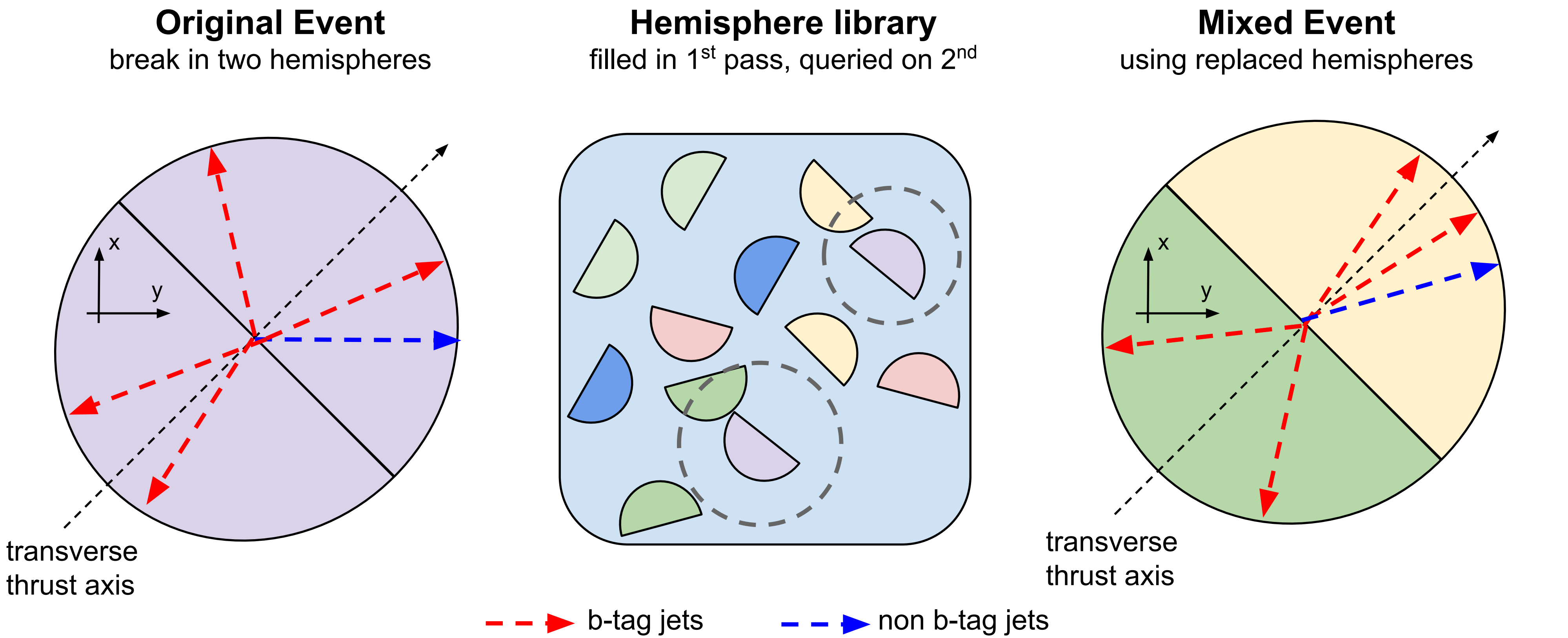
Will focus on 4b.
  Same comments apply (to a lesser extent) to bbττ.

4b Background

https://arxiv.org/abs/1804.06174



Background Model

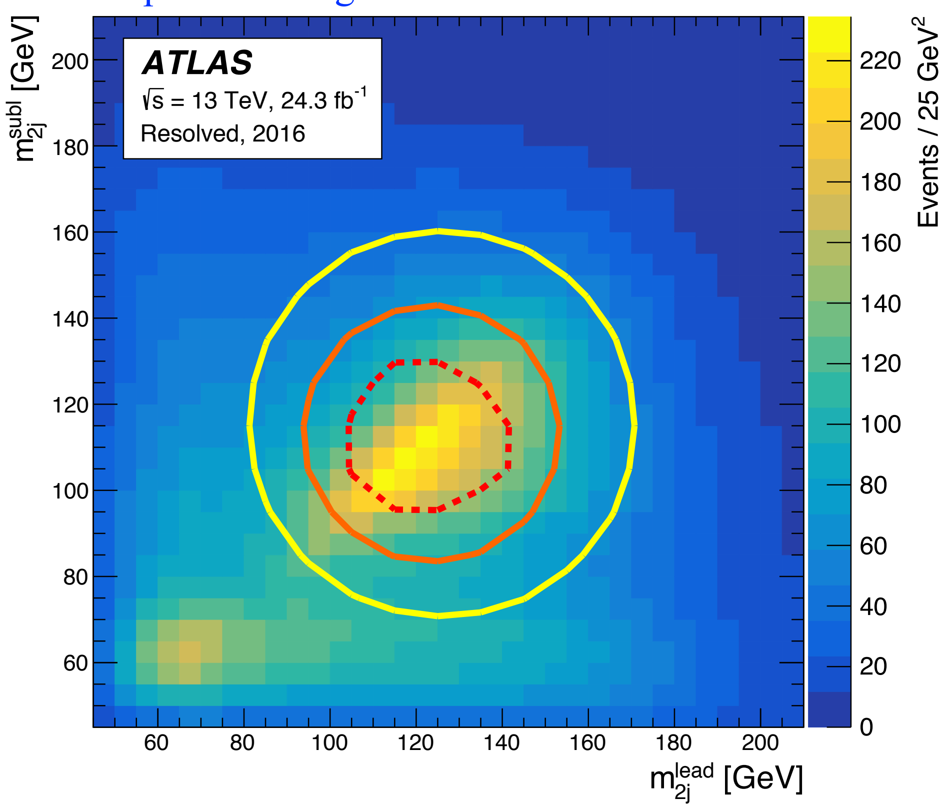


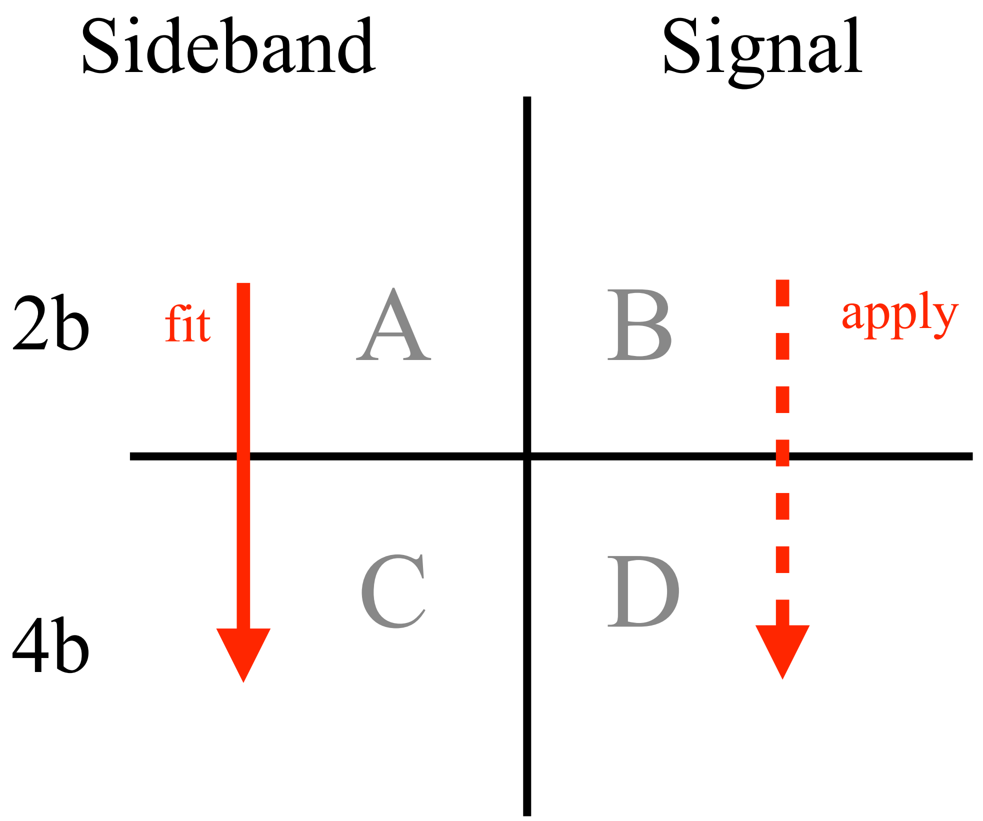
https://arxiv.org/abs/1712.02538

Background Model

Use 2b events to model 4b background
Correct 2b→4b kinematics with ABCD

https://arxiv.org/abs/1804.06174

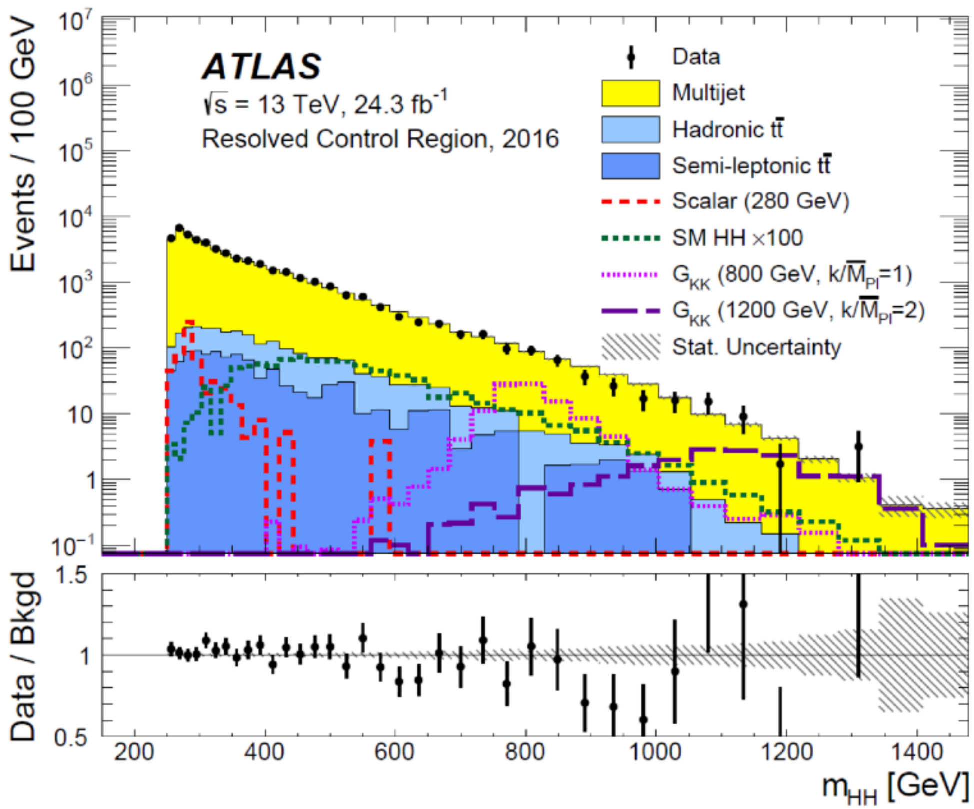




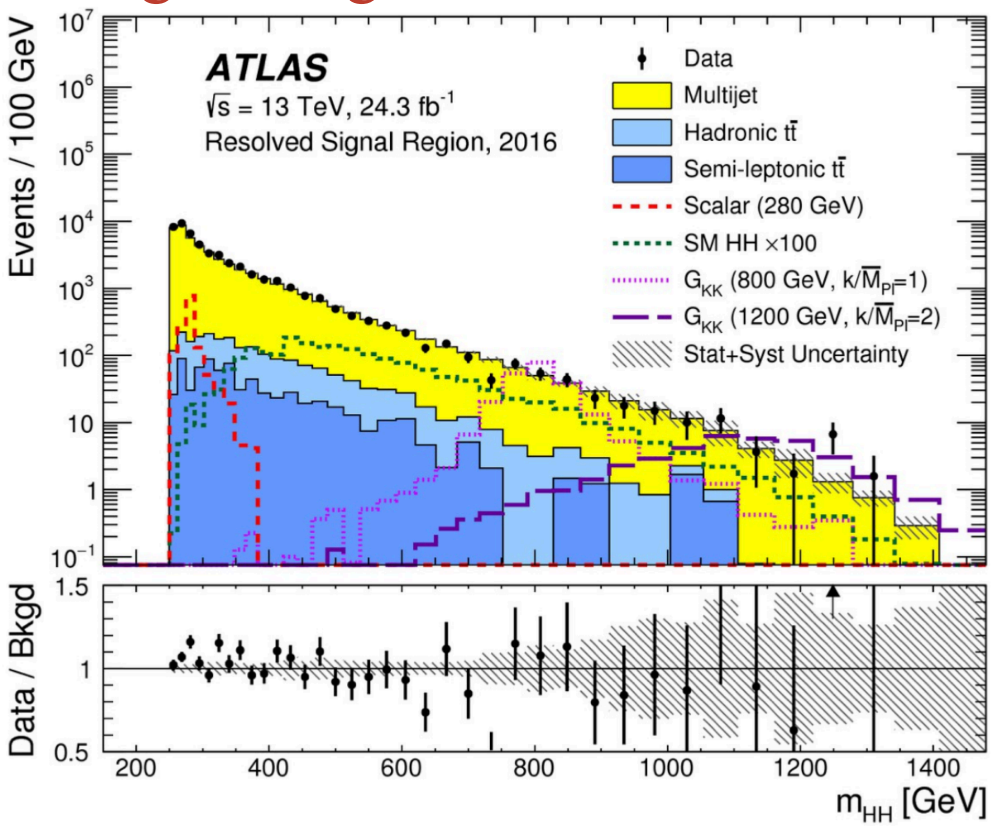
$$4b \text{ background} = \left(\frac{C}{A}\right) \times B.$$

Background Validation

Control Region



Signal Region



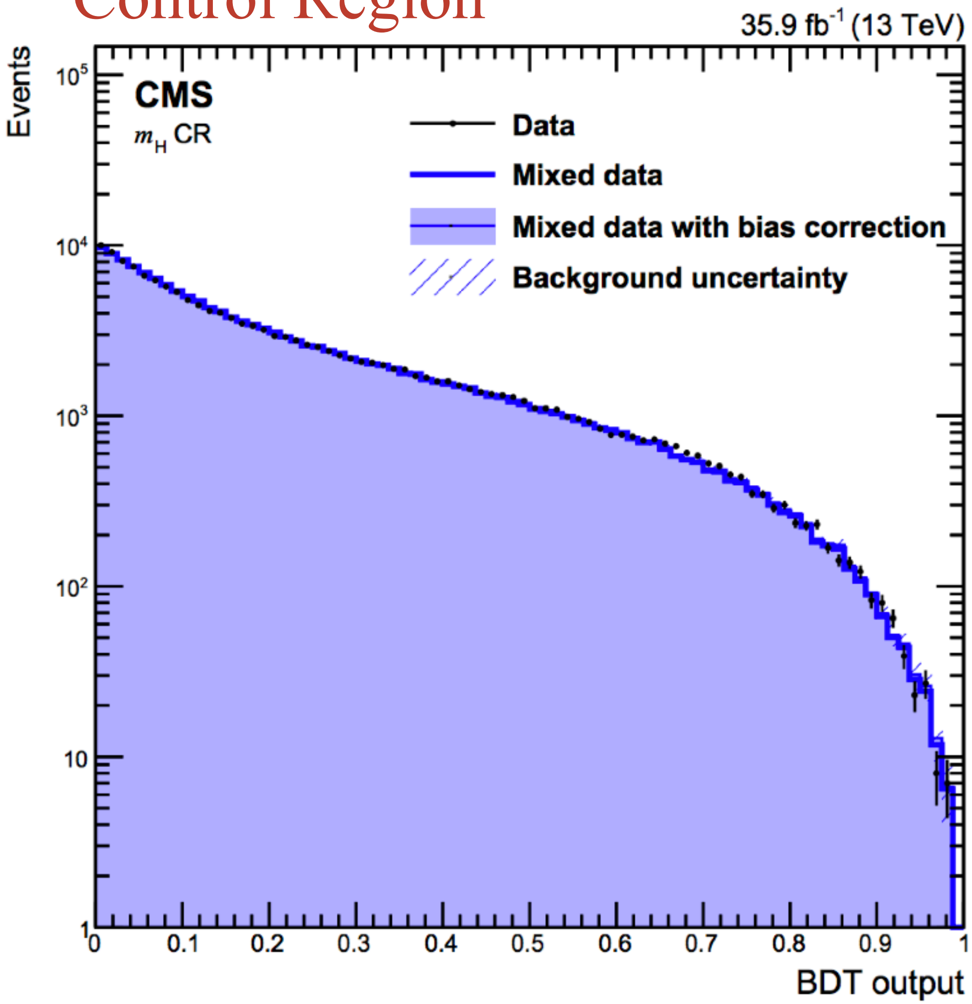
Reasonable check of modeling in the variable used to set limits.

https://arxiv.org/abs/1804.06174

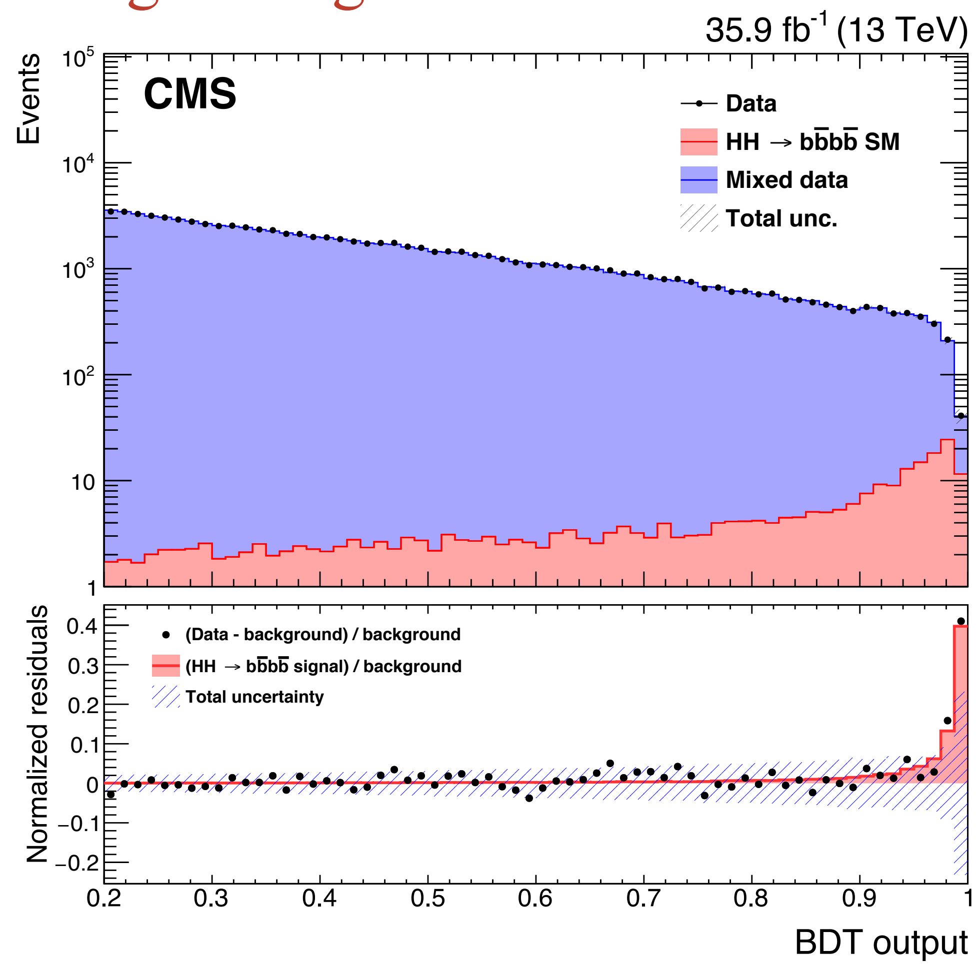
Background Validation

Validation becomes much harder when analyses become more sophisticated

Control Region



Signal Region

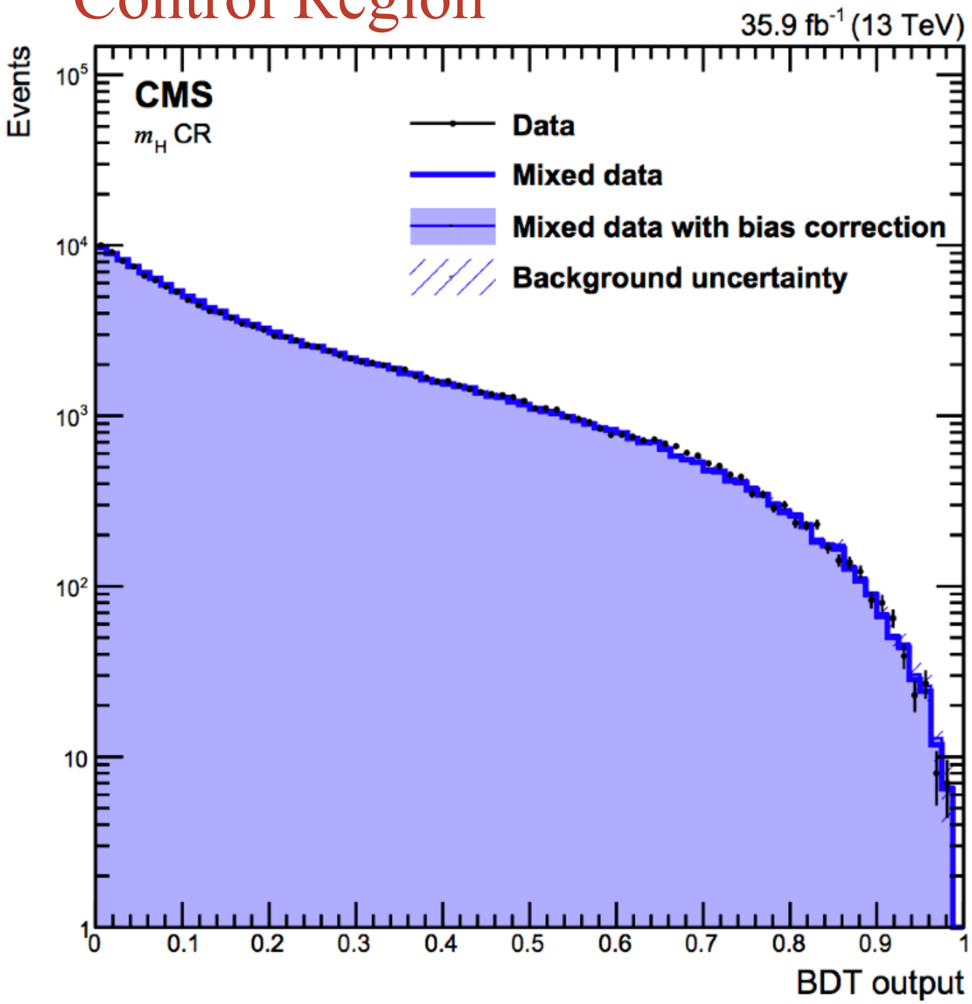


https://arxiv.org/abs/1810.11854

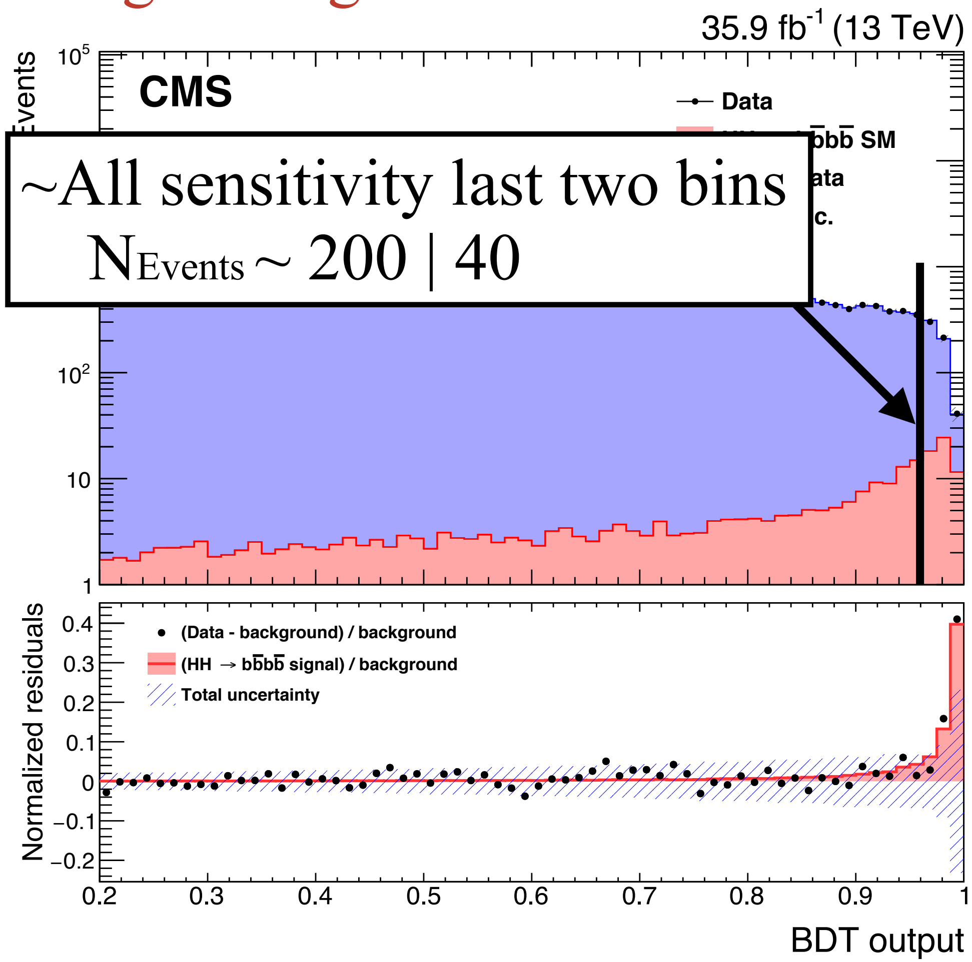
Background Validation

Validation becomes much harder when analyses become more sophisticated

Control Region



Signal Region



~All sensitivity last two bins
N_{Events} ~ 200 | 40

https://arxiv.org/abs/1810.11854

Background Validation

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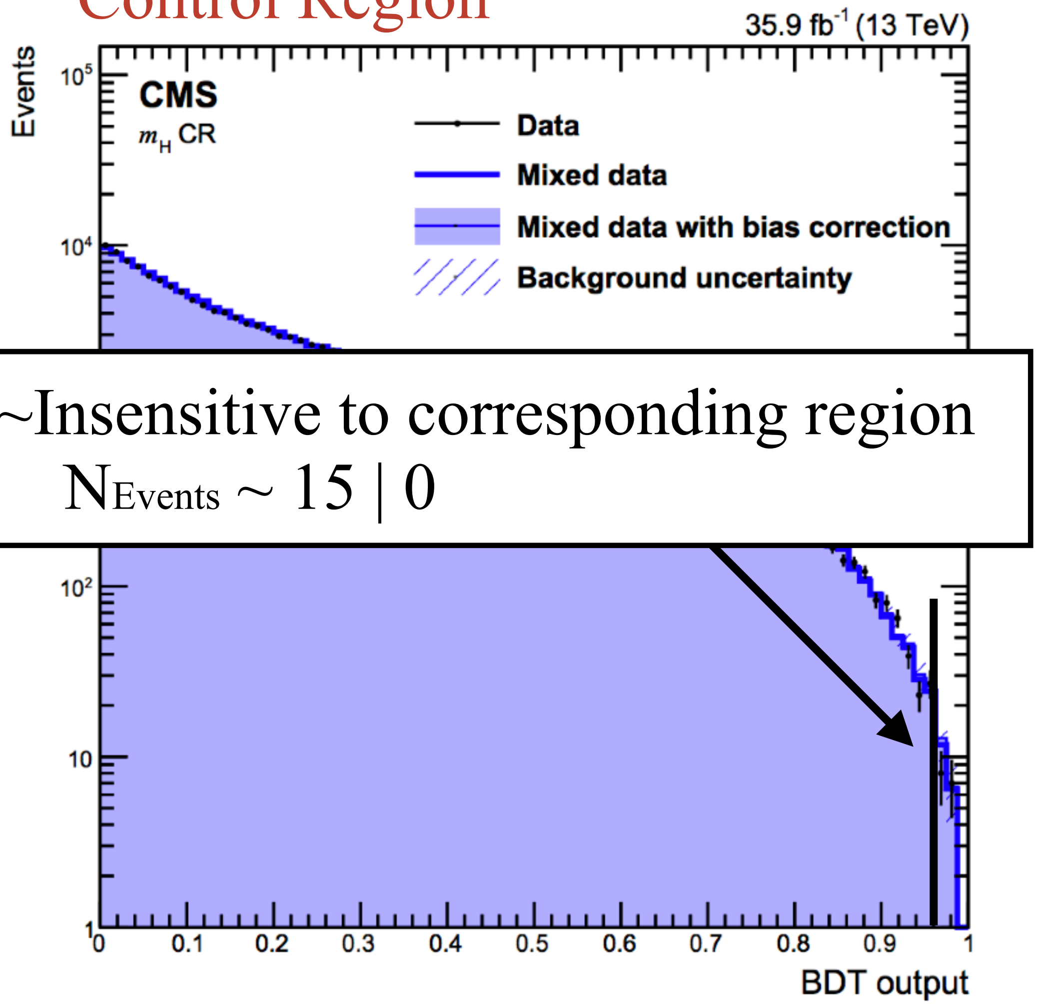
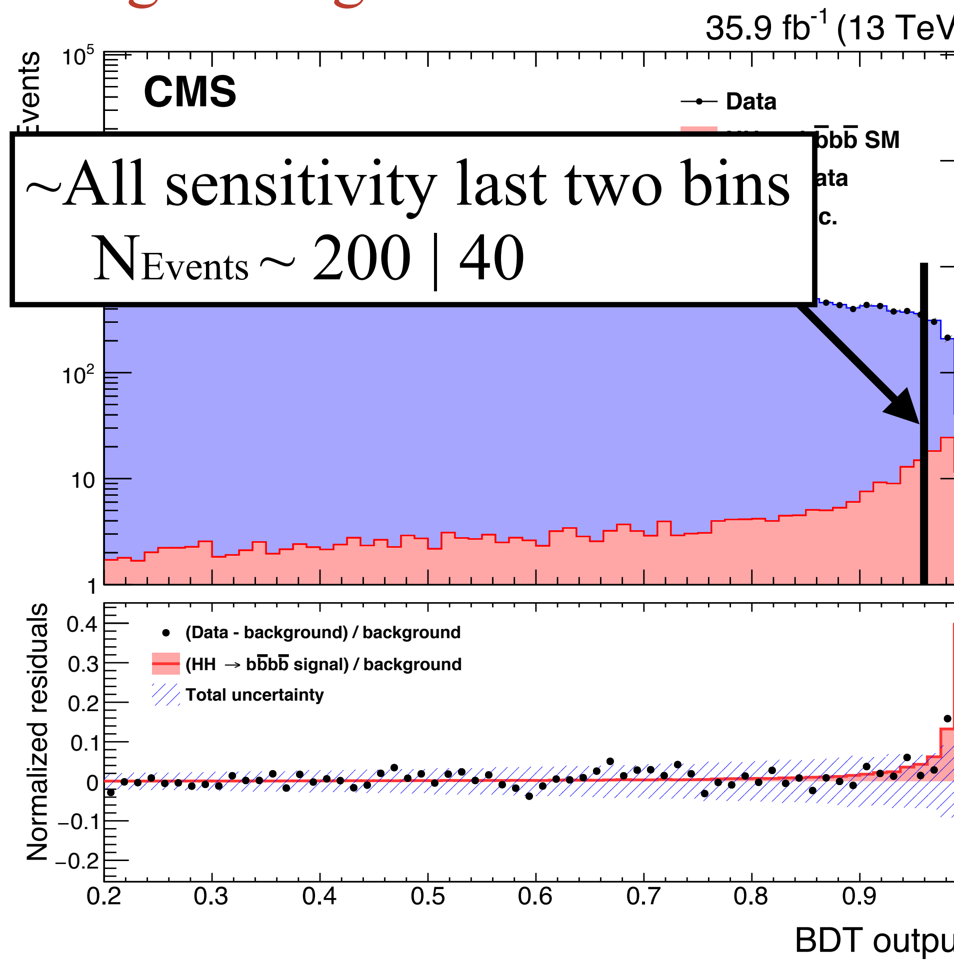
Control Region



~Insensitive to corresponding region
N_{Events} ~ 15 | 0

Signal Region



~All sensitivity last two bins
N_{Events} ~ 200 | 40

https://arxiv.org/abs/1810.11854

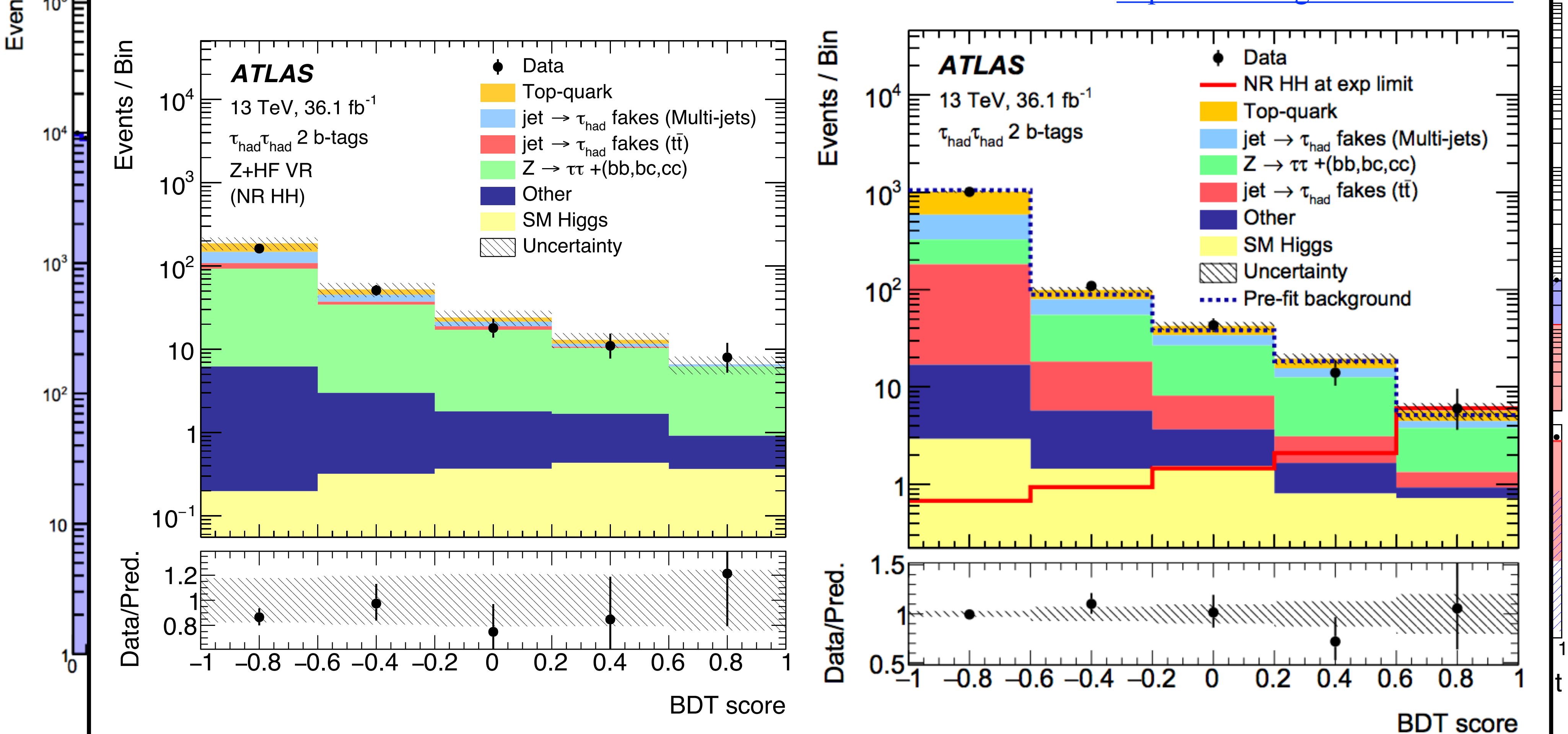
Background Validation

Validation becomes much harder when analyses become more sophisticated

C

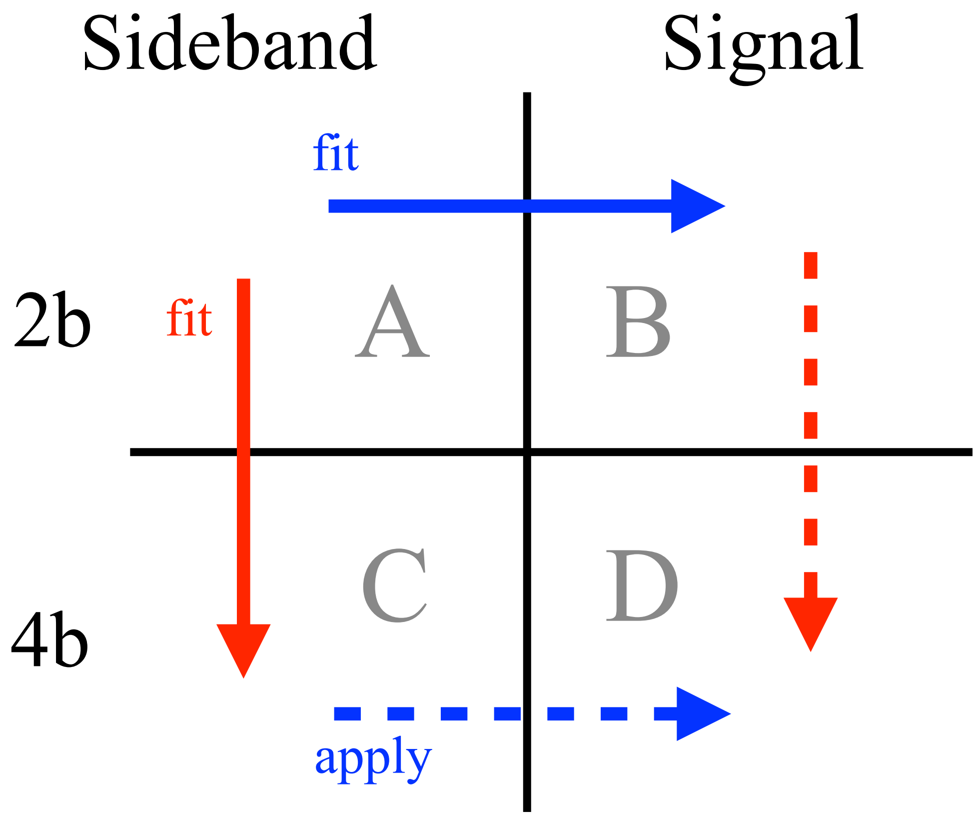
Similar concern (lesser extent) in bbττ

https://arxiv.org/abs/1808.00336



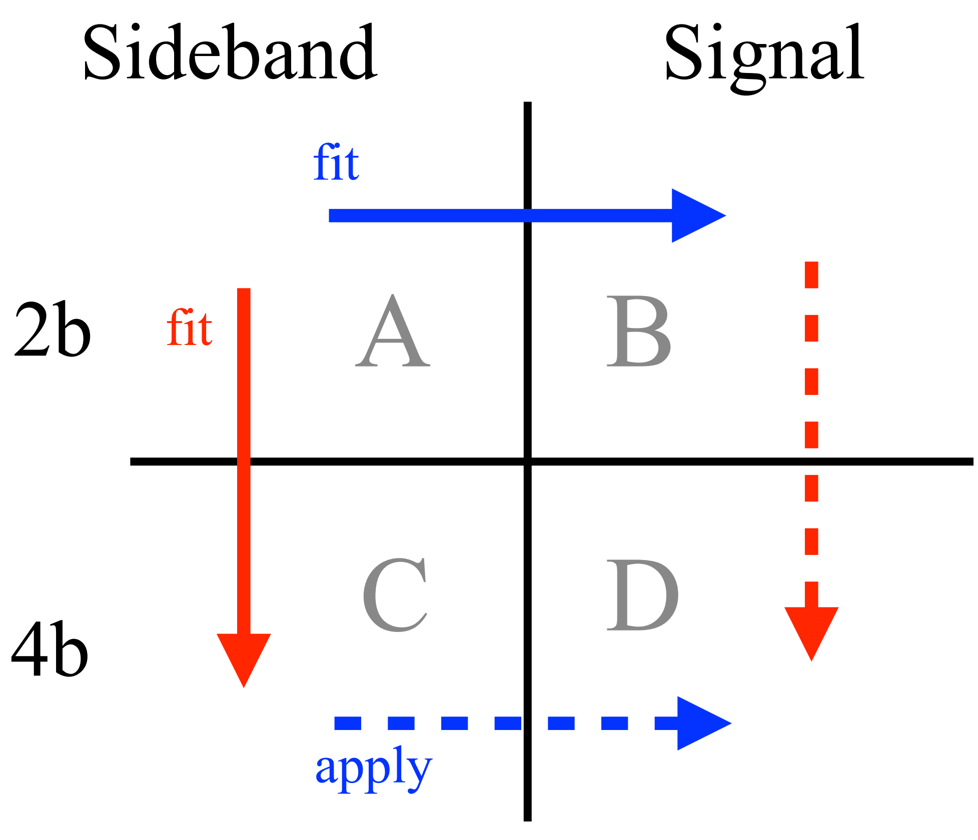
https://arxiv.org/pdf/1810.11854.pdf

Potential Improvements

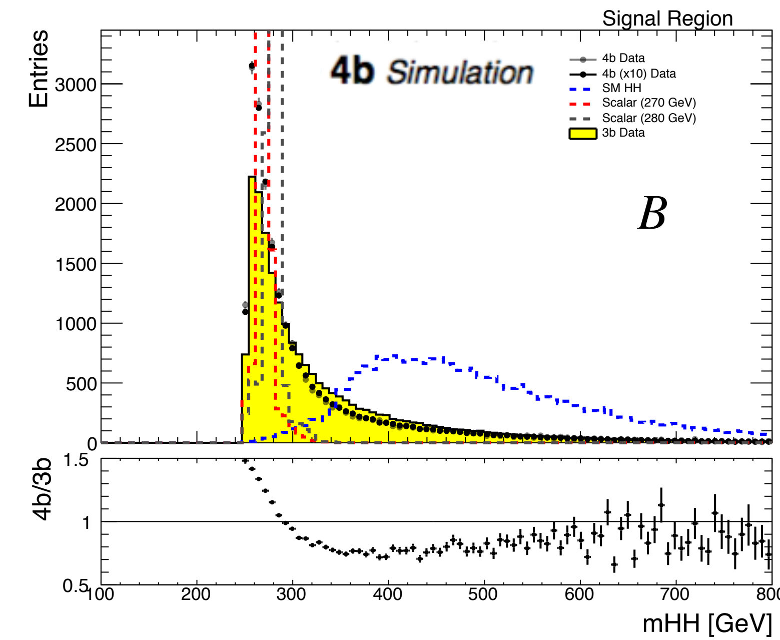


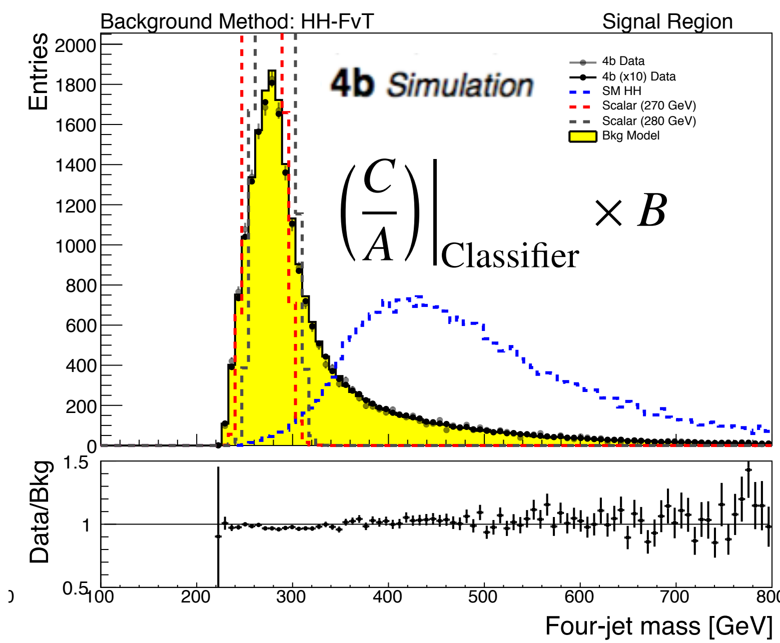
$$\left(\frac{C}{A}\right)\Bigg|_{\text{Classifier}} \times B \quad \stackrel{?}{=} \quad \left(\frac{B}{A}\right)\Bigg|_{\text{OT}} \times C,$$

Potential Improvements

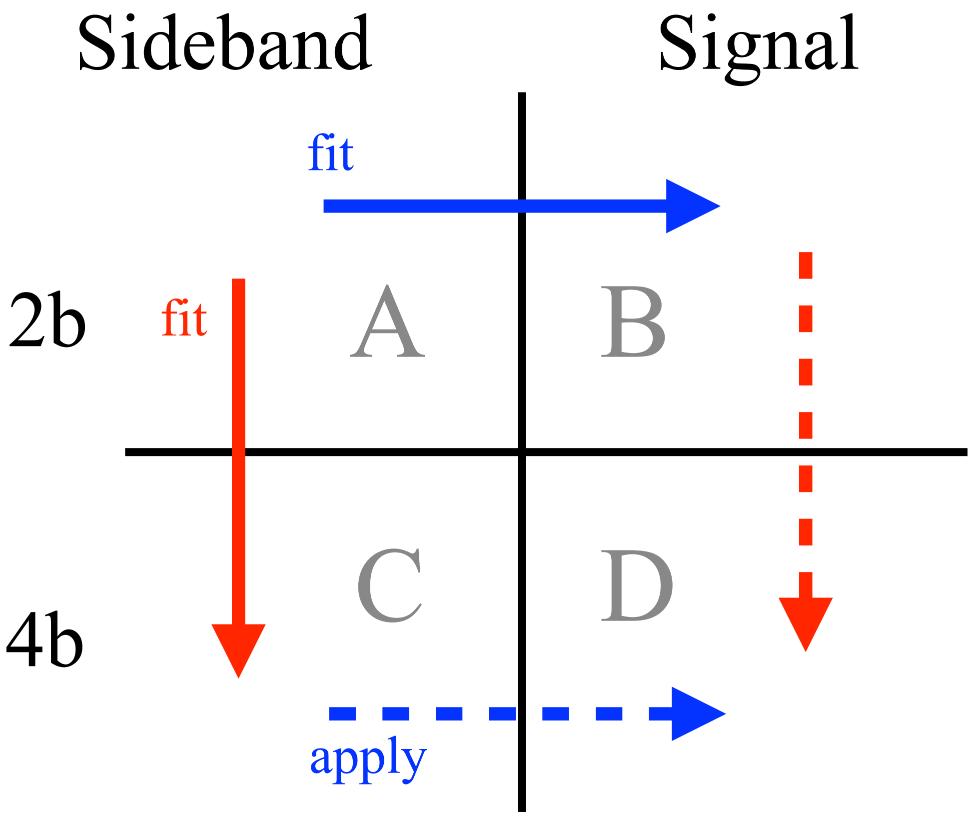


$$\left(\frac{C}{A}\right)\Bigg|_{\text{Classifier}} \times B \stackrel{?}{=} \left(\frac{B}{A}\right)\Bigg|_{\text{OT}} \times C,$$

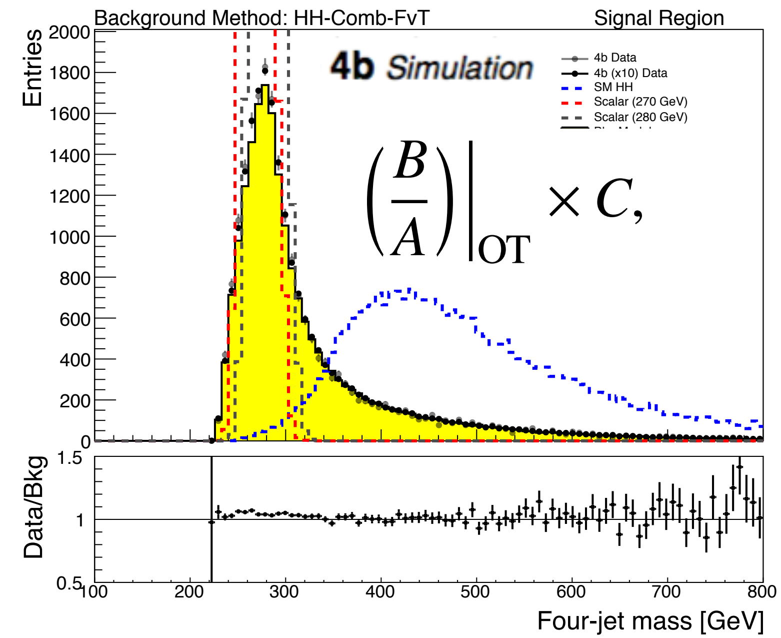


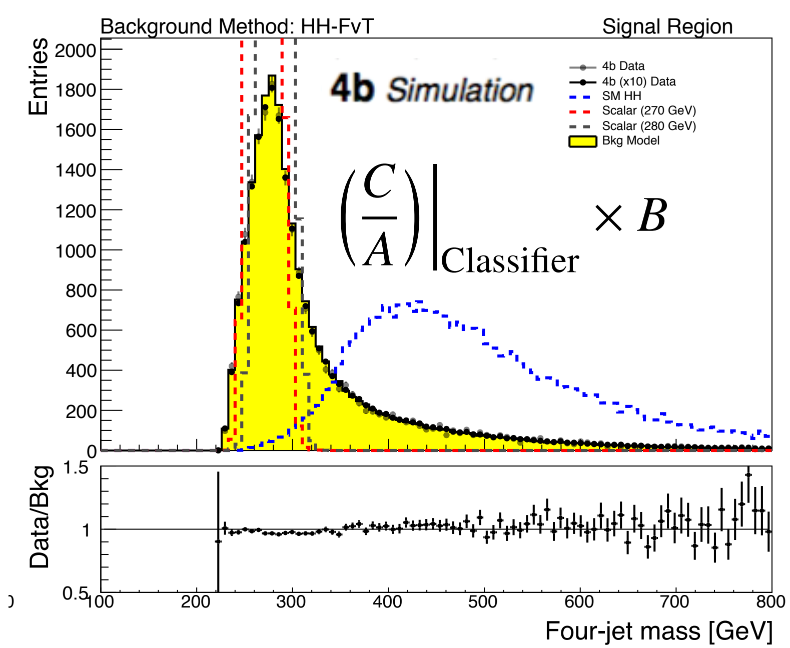


Potential Improvements

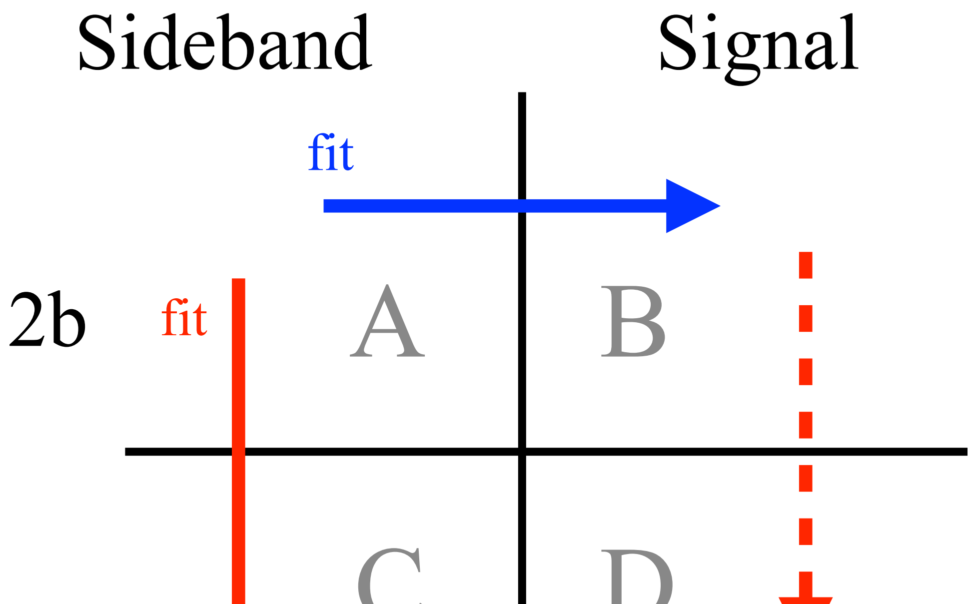


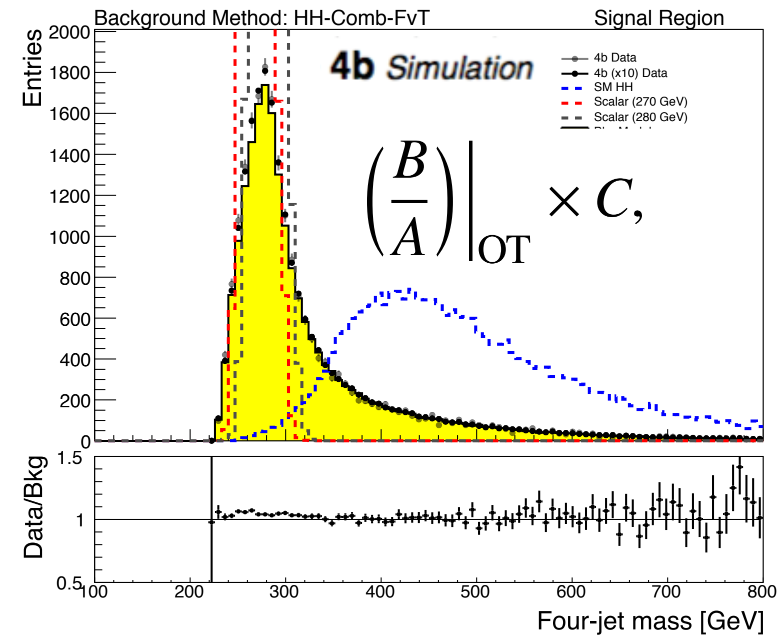
$$\left(\frac{C}{A}\right)\bigg|_{\text{Classifier}} \times B \quad \stackrel{?}{=} \quad \left(\frac{B}{A}\right)\bigg|_{\text{OT}} \times C,$$

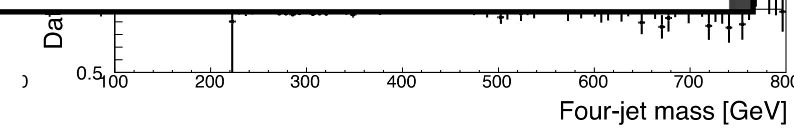




Potential Improvements







https://indico.cern.ch/event/968985/
(paper in preparation)

SM Standard Candles

ZZ and ZH obvious first steps in path to HH

4b:

$$\frac{\sigma(ZZ \to 4b)}{\sigma(HH \to 4b)} \sim \frac{15 \cdot 10^3 \text{ fb } \times 0.15^2}{33 \text{ fb} \times 0.58^2} \sim 30$$

$$\frac{\sigma(ZH \to 4b)}{\sigma(HH \to 4b)} \sim \frac{15 \cdot 10^3 \text{ fb } \times 0.15 \times 0.58}{33 \text{ fb} \times 0.58^2} \sim 7$$

$bb\tau\tau$:

$$\frac{\sigma(ZZ \to bb\tau\tau)}{\sigma(HH \to bb\tau\tau)} \sim 55 \qquad \frac{\sigma(ZH \to bb\tau\tau)}{\sigma(HH \to bb\tau\tau)} \sim 9$$

Good stress test of trigger / background techniques
Known compare with known (measured) signals

Conclusions

Not all *HH* events are equal:

Low m_{HH} worth more, harder to trigger

Hadronic analyses will be key to constraining λ

Trigger:

- Need to live on L1 turn-ons / Avoid H_T if possible
- HLT CPU often biggest limitation

Background modeling:

- Need to validate background in region most relevant
- Exacerbated by sophisticated ML classifier
- Need new approaches to explicitly check underlying assumptions

Measuring *ZZ*/*ZH* in 4b and bbττ serve as ultimate dry-run for *HH*

References

HH Whitepaper: https://arxiv.org/abs/1910.00012

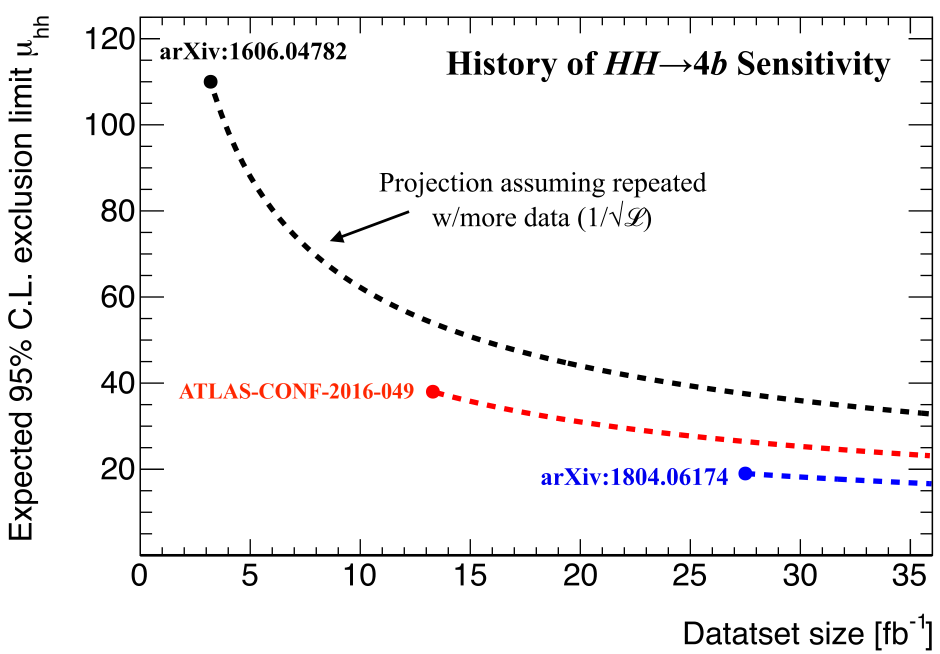
ATLAS

4b: https://arxiv.org/abs/1804.06174
bbττ: https://arxiv.org/abs/1808.00336
HH Combination: https://arxiv.org/abs/1906.02025
Phase 2 HLT TDR: https://cds.cern.ch/record/2285584
HH Projections: https://cds.cern.ch/record/2652727
Jet Trigger: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetTriggerPublicResults

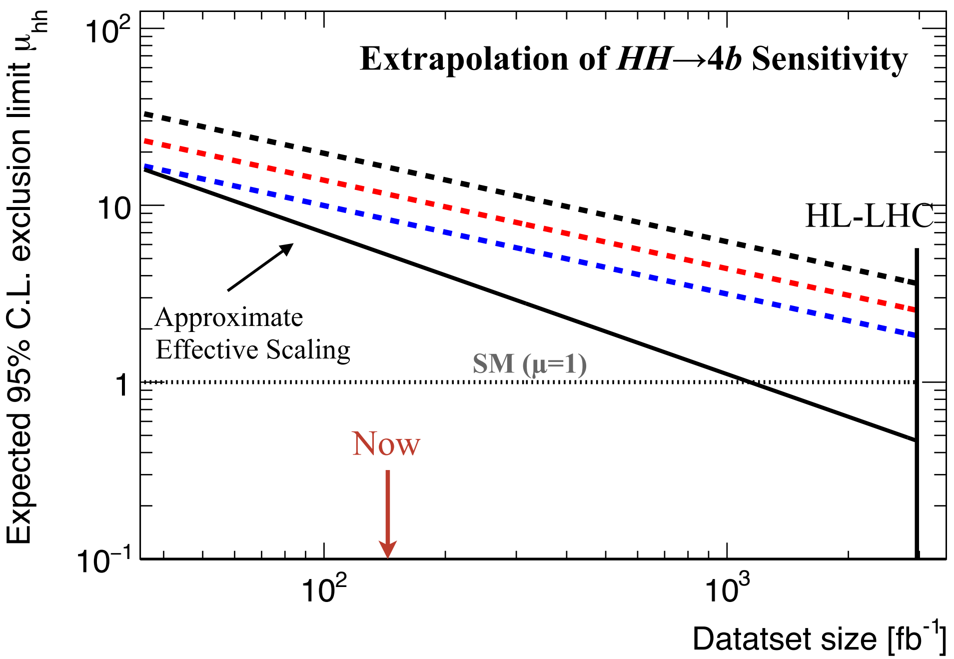
CMS

4b: https://arxiv.org/abs/1810.11854
bbττ: https://arxiv.org/abs/1707.00350
Phase 2 L1 TDR: http://cds.cern.ch/record/2714892
HH combination: https://arxiv.org/abs/1811.09689
L1 Run 2: https://arxiv.org/abs/2006.10165

Backup

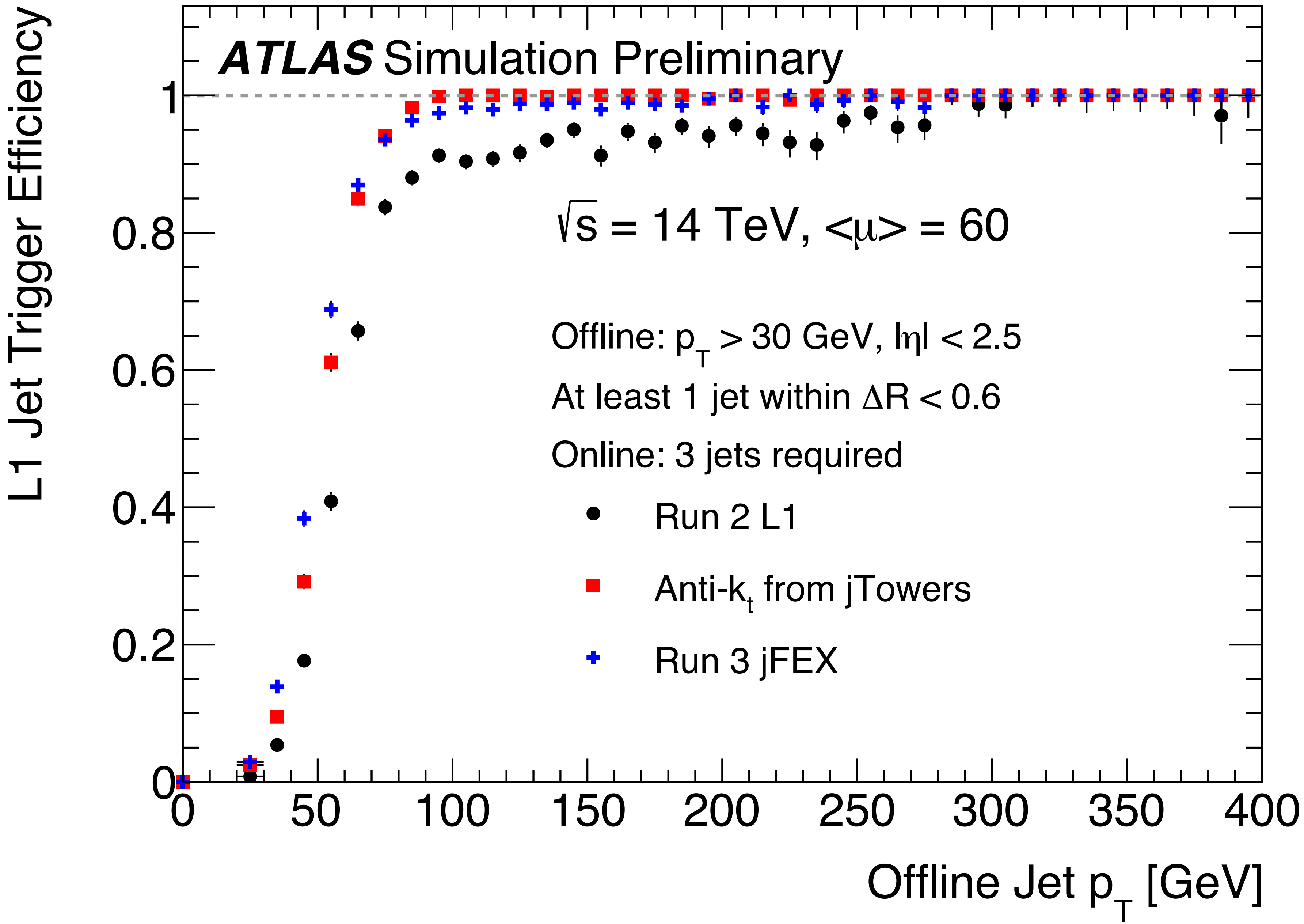


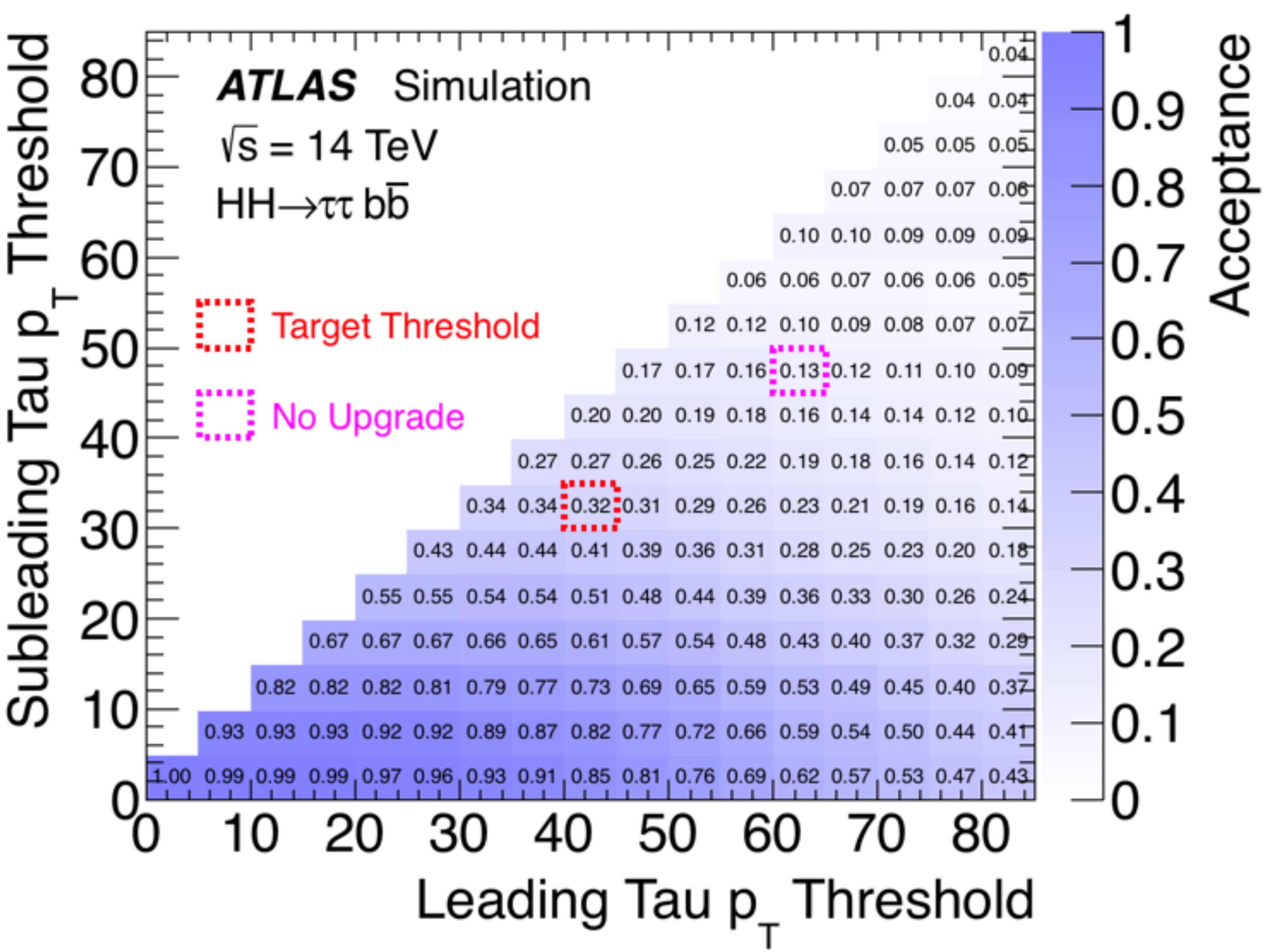
History of $HH\to4b$ Sensitivity
arXiv:1606.04782
Projection assuming repeated
w/more data ($1/\sqrt{\mathscr{L}}$)
ATLAS-CONF-2016-049
arXiv:1804.06174
Expected 95% C.L. exclusion limit μ_{hh}
Datatset size [fb^{-1}]



Extrapolation of $HH\to4b$ Sensitivity
HL-LHC
Approximate
Effective Scaling
SM (μ=1)
Now
Expected 95% C.L. exclusion limit μ_{hh}
Datatset size [fb^{-1}]

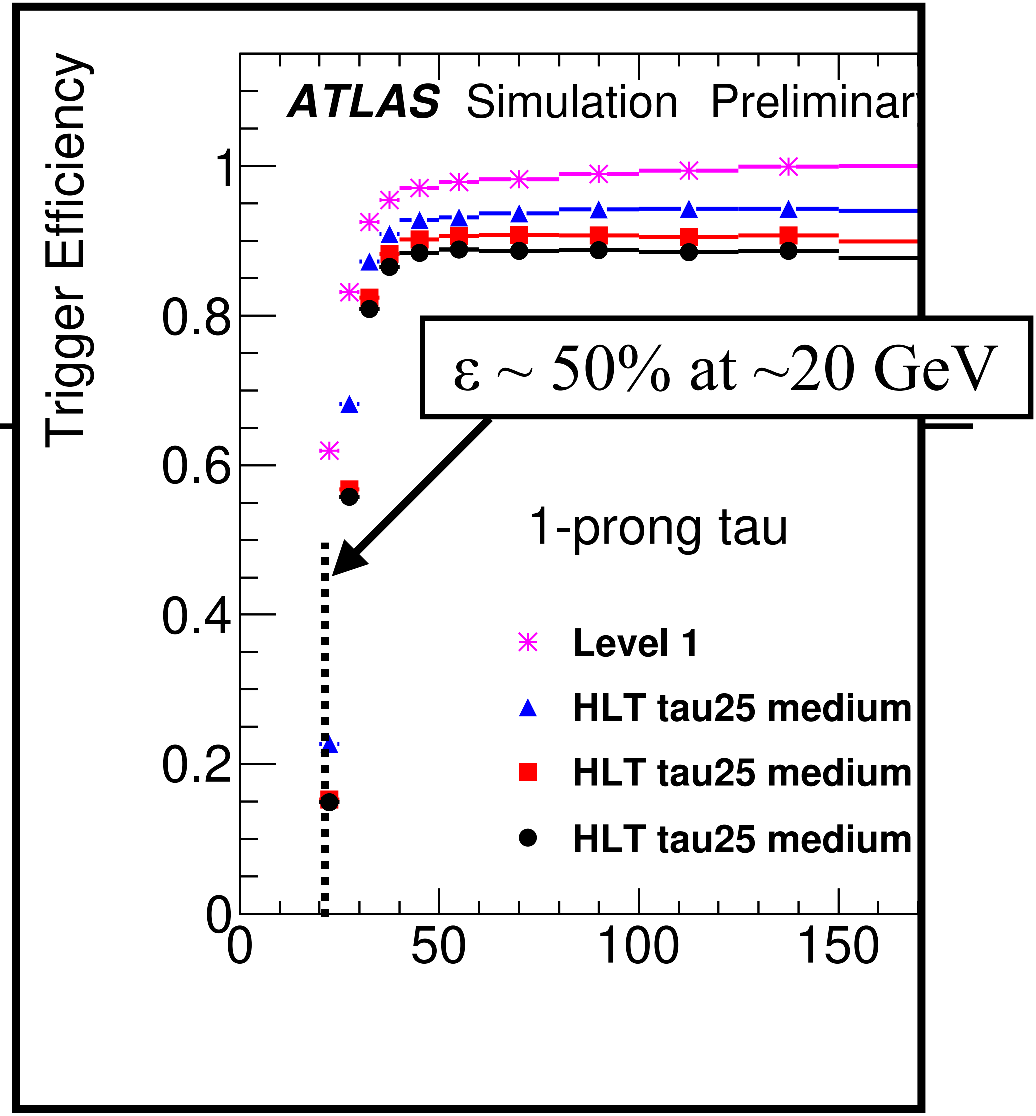
Per-jet efficiency for jets ***with nearby jets***




ATLAS Simulation
√s = 14 TeV
HH→ττ bb̄
Target Threshold
No Upgrade
Subleading Tau p_T Threshold
Leading Tau p_T Threshold
Acceptance
0 10 20 30 40 50 60 70 80
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
0.04
0.04 0.04
0.05 0.05 0.05
0.07 0.07 0.07 0.06
0.10 0.10 0.09 0.09 0.09
0.06 0.06 0.07 0.06 0.06 0.05
0.12 0.12 0.10 0.09 0.08 0.07 0.07
0.17 0.17 0.16 0.13 0.12 0.11 0.10 0.09
0.20 0.20 0.19 0.18 0.16 0.14 0.14 0.12 0.10
0.27 0.27 0.26 0.25 0.22 0.19 0.18 0.16 0.14 0.12
0.34 0.34 0.32 0.31 0.29 0.26 0.23 0.21 0.19 0.16 0.14
0.43 0.44 0.44 0.41 0.39 0.36 0.31 0.28 0.25 0.23 0.20 0.18
0.55 0.55 0.54 0.54 0.51 0.48 0.44 0.39 0.36 0.33 0.30 0.26 0.24
0.67 0.67 0.67 0.66 0.65 0.61 0.57 0.54 0.48 0.43 0.40 0.37 0.32 0.29
0.82 0.82 0.82 0.81 0.79 0.77 0.73 0.69 0.65 0.59 0.53 0.49 0.45 0.40 0.37
0.93 0.93 0.93 0.92 0.92 0.89 0.87 0.82 0.77 0.72 0.66 0.59 0.54 0.50 0.44 0.41
1.00 0.99 0.99 0.99 0.97 0.96 0.93 0.91 0.85 0.81 0.76 0.69 0.62 0.57 0.53 0.47 0.43

bbττ Triggers 2016

Trigger	L1 Seed
2τ + j 35/25 + 80 (ATLAS)	τ20(i) τ12(i) +J25
2τ 35 (CMS)	2×τ30(i)



(Rates scaled to $\mathcal{L} = 1.2 \times 10^{34} cm^{-2} s^{-1}$)

bbττ Triggers 2016

Trigger	L1 Seed
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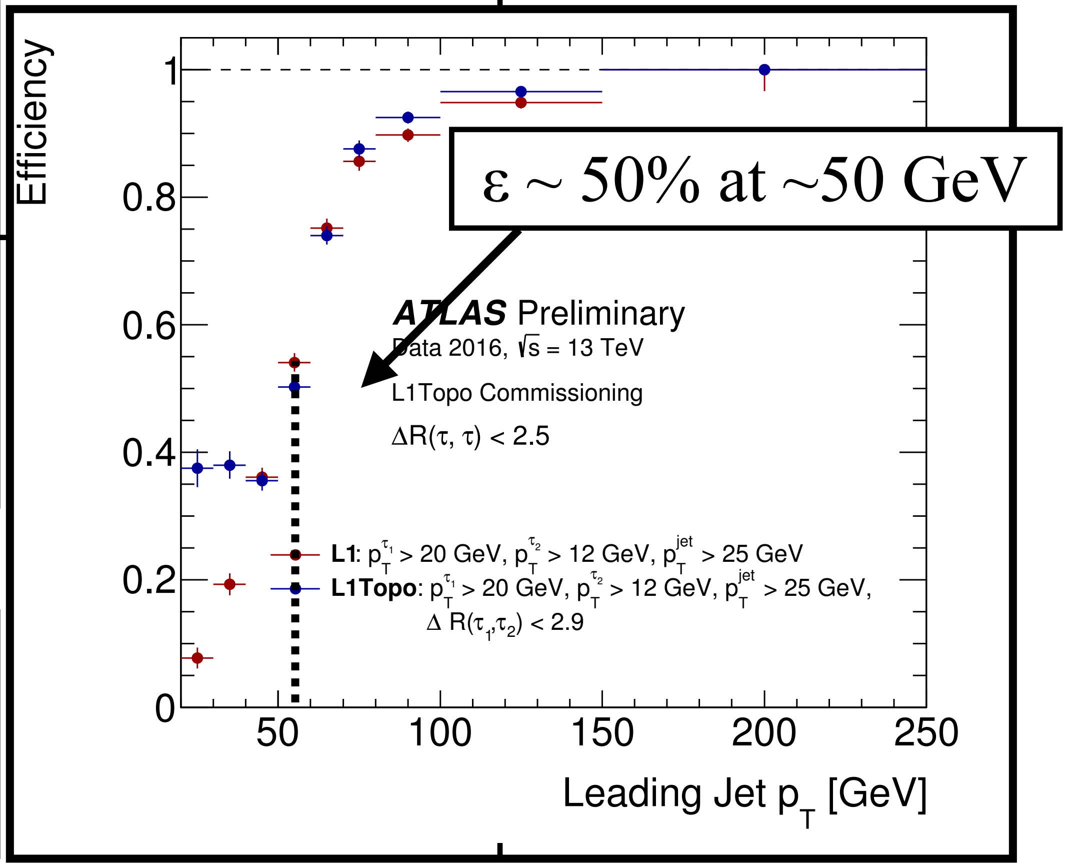
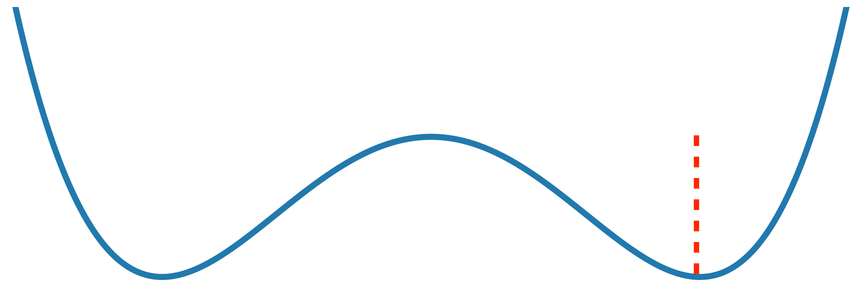


(Rates scaled to $\mathcal{L} = 1.2 \times 10^{34} cm^{-2} s^{-1}$)

hh Production in SM

Higgs potential:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



Expanding about minimum: $V(\phi) \to V(v+h)$

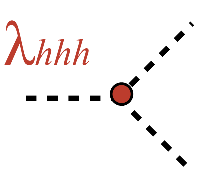
$\frac{\mu}{\sqrt{\lambda}} \equiv v$ 246 GeV

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$

$$= V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

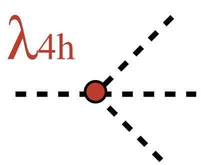
Higgs mass term

λ_{hhh}



hh-production

λ_{4h}



hhh-production

Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

- Shape of potential gives relationship between λ_{hhh} and m_h, v
- Measuring λ_{hhh} important because it probes the shape of the Higgs potential
- *hh* production interesting because it measures λ_{hhh}