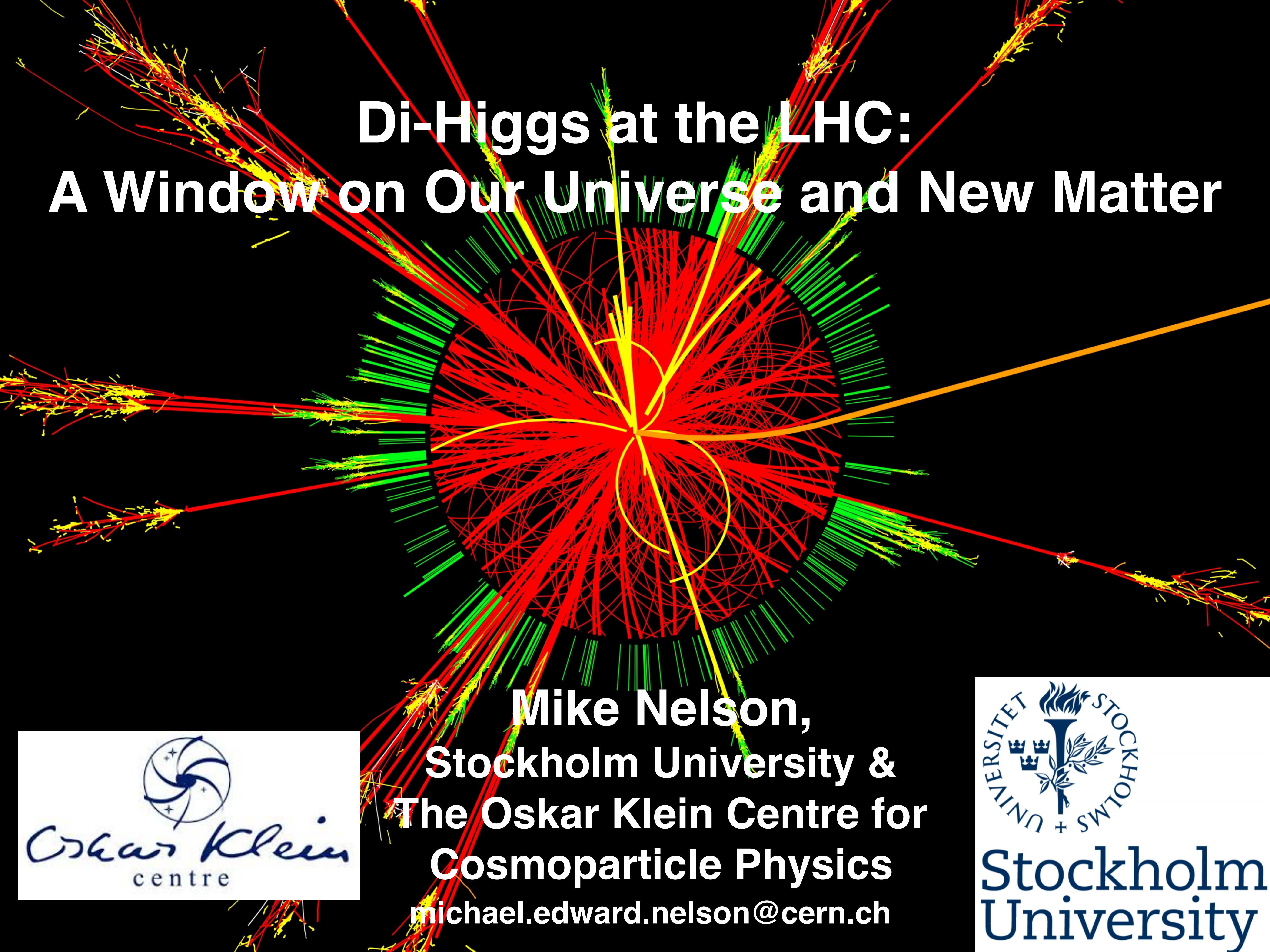
Di-Higgs at the LHC: A Window on Our Universe and New Matter



Mike Nelson,

Stockholm University &

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Physics is Hard

Physics is Hard

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What is the nature of dark matter ?

Physics is Hard

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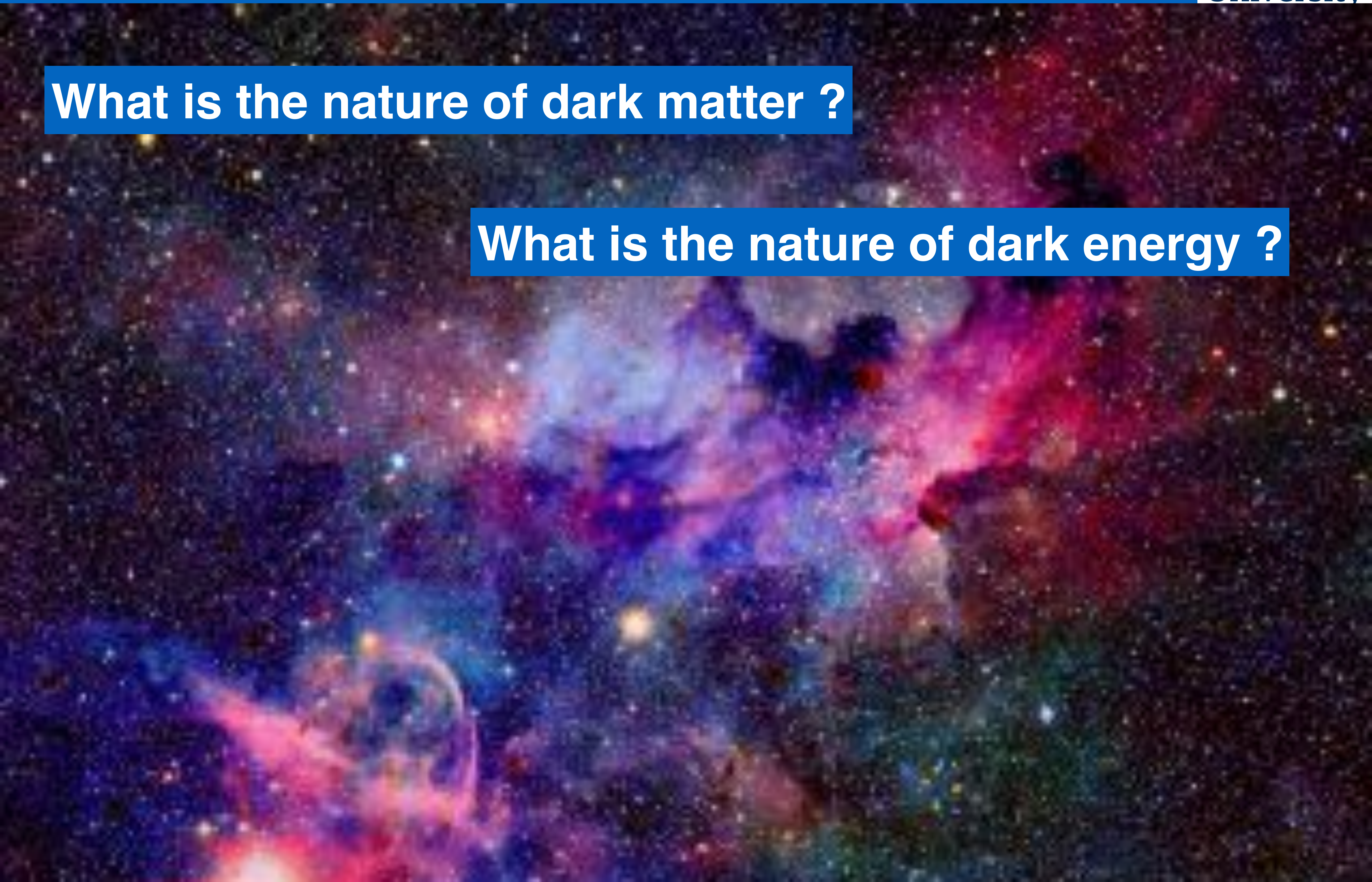
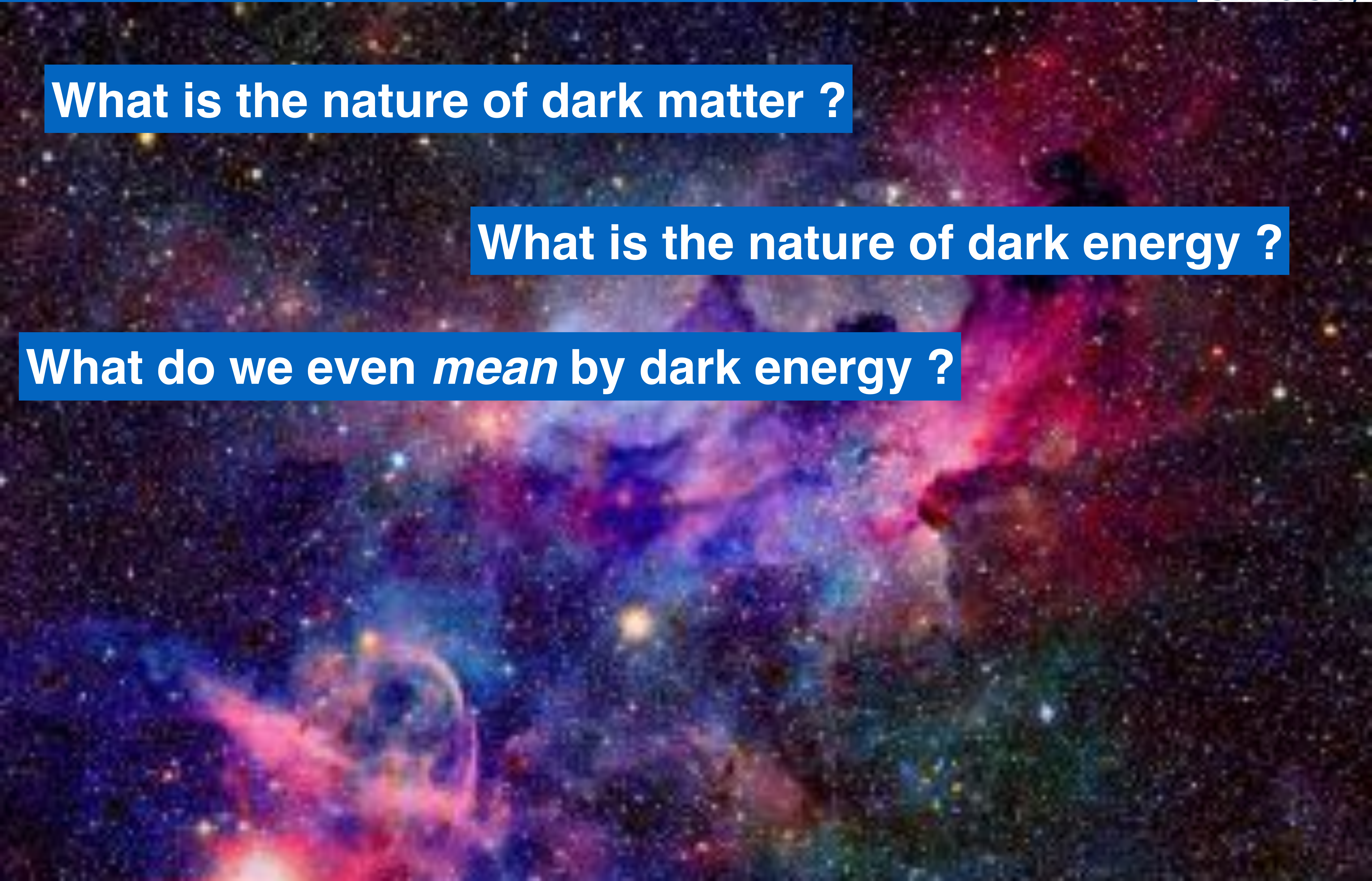


Physics is Hard

What is the nature of dark matter ?

What is the nature of dark energy ?

What do we even *mean* by dark energy ?



Physics is Hard

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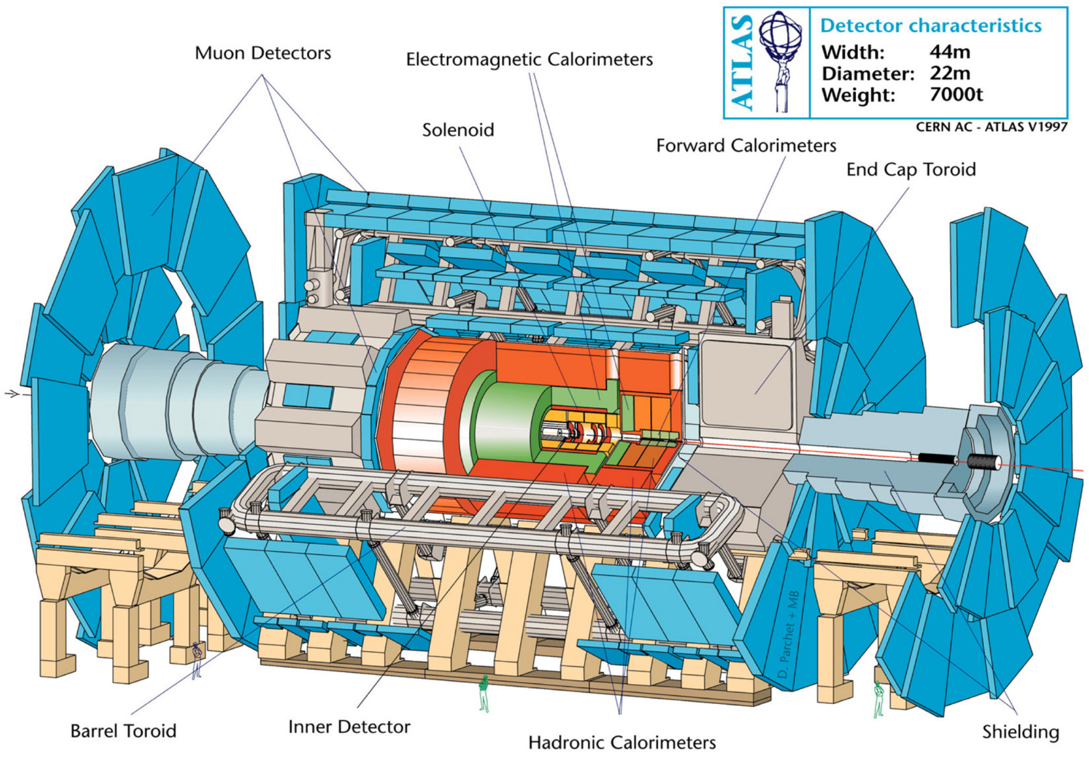
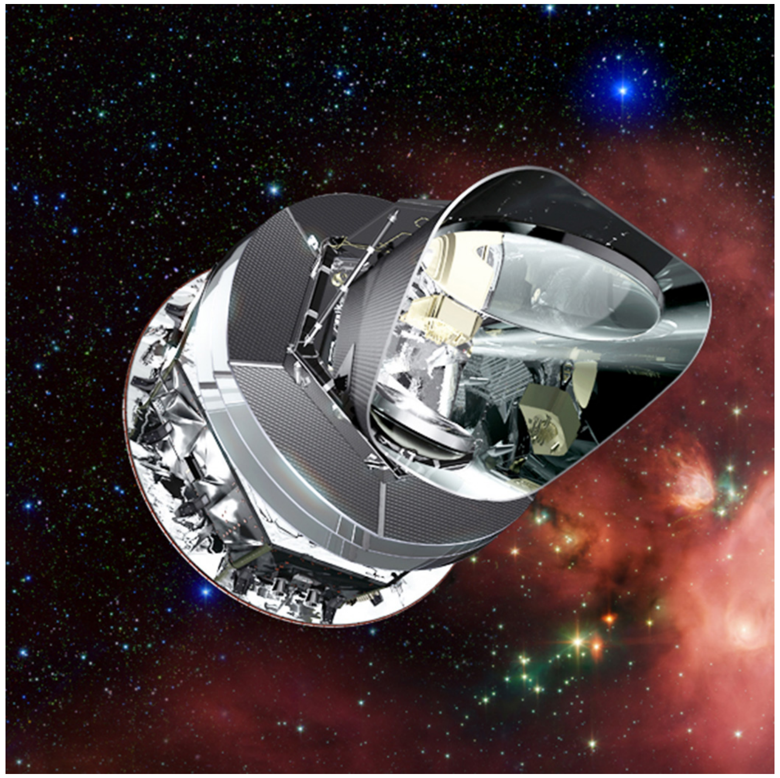
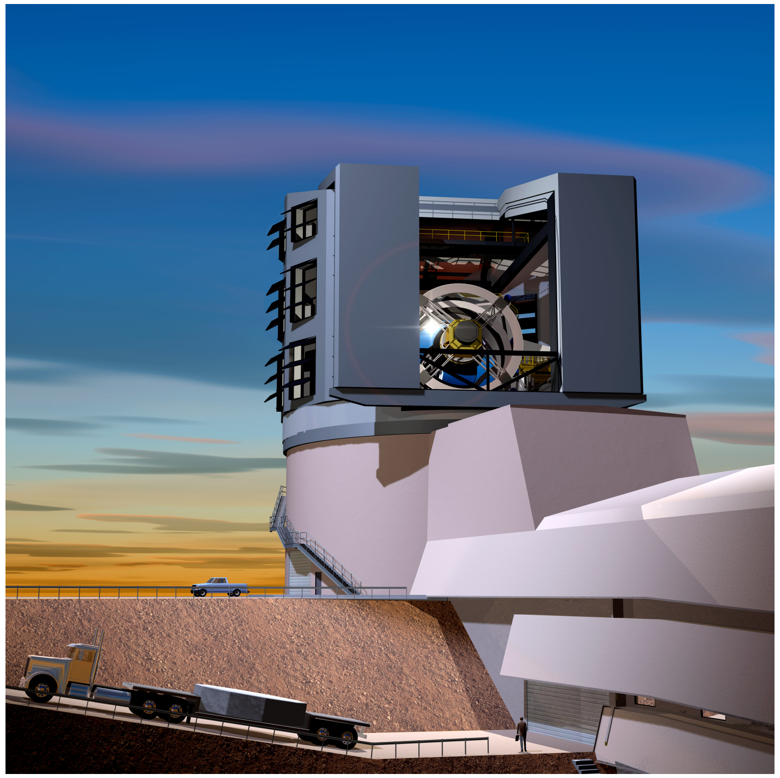
How are these questions connected ?

Particle Physics ☞ Cosmology

- We are entering an era of **precision cosmology** and **precision particle physics experiments**.



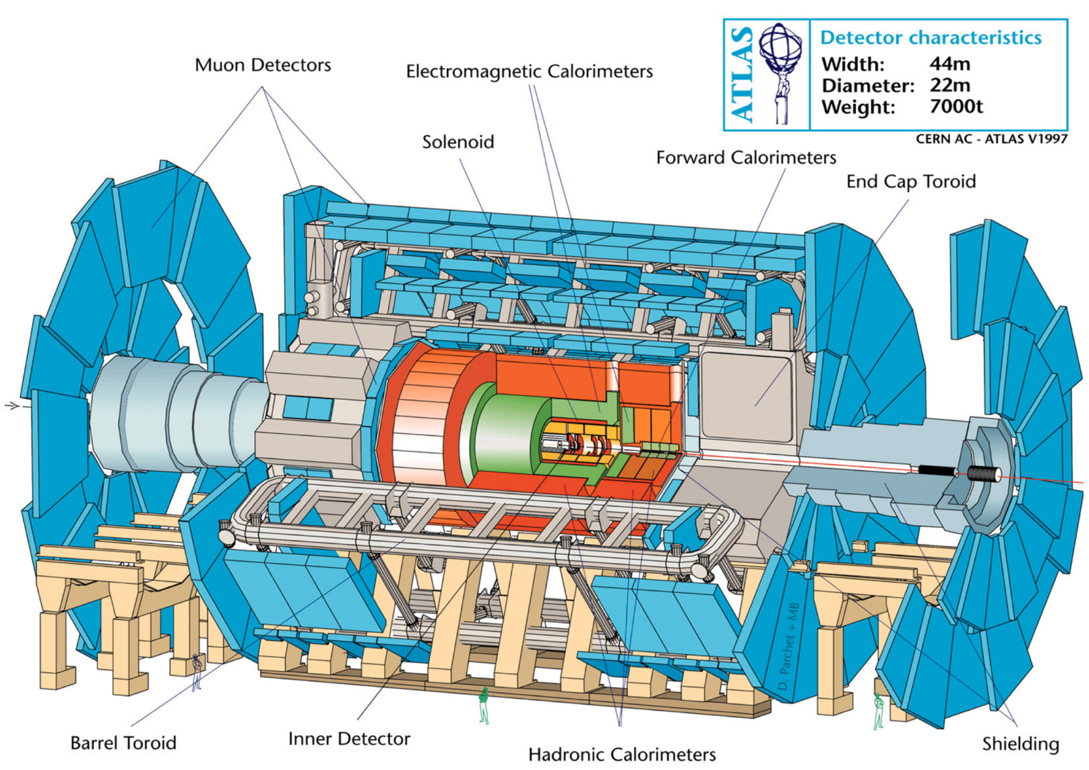



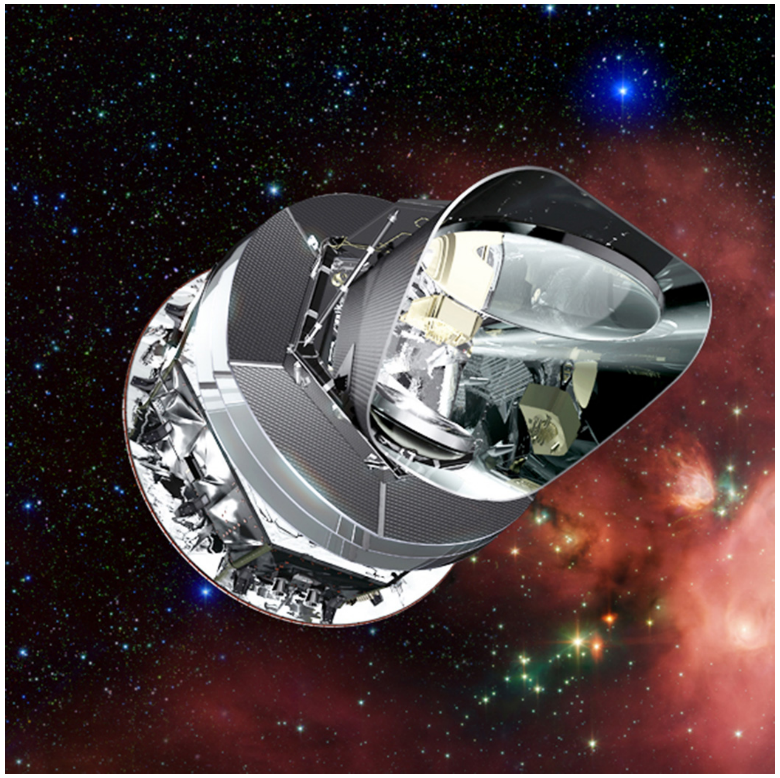
Particle Physics ☞ Cosmology

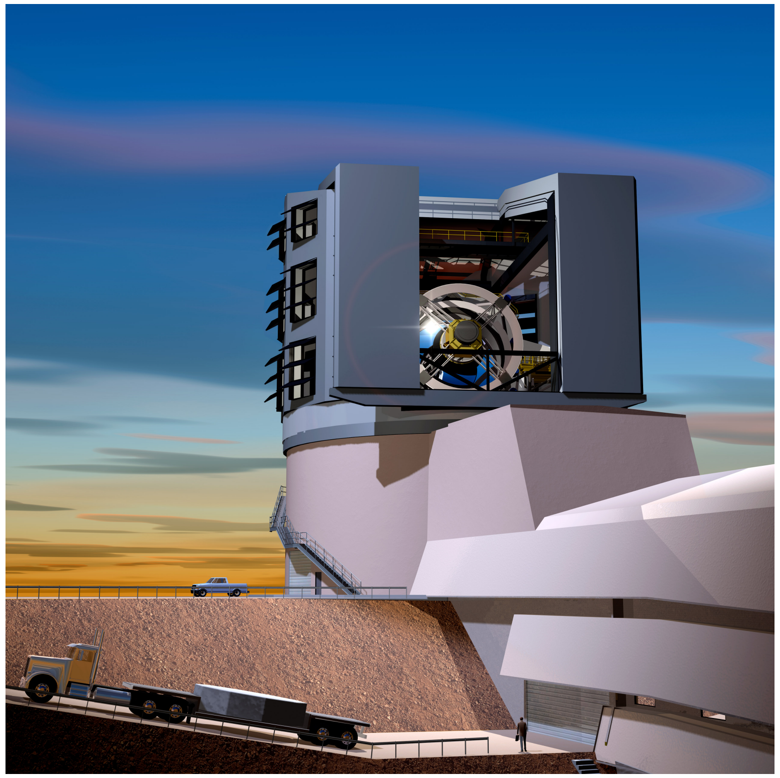
- We are entering an era of **precision cosmology** and **precision particle physics experiments**.

- We need to:

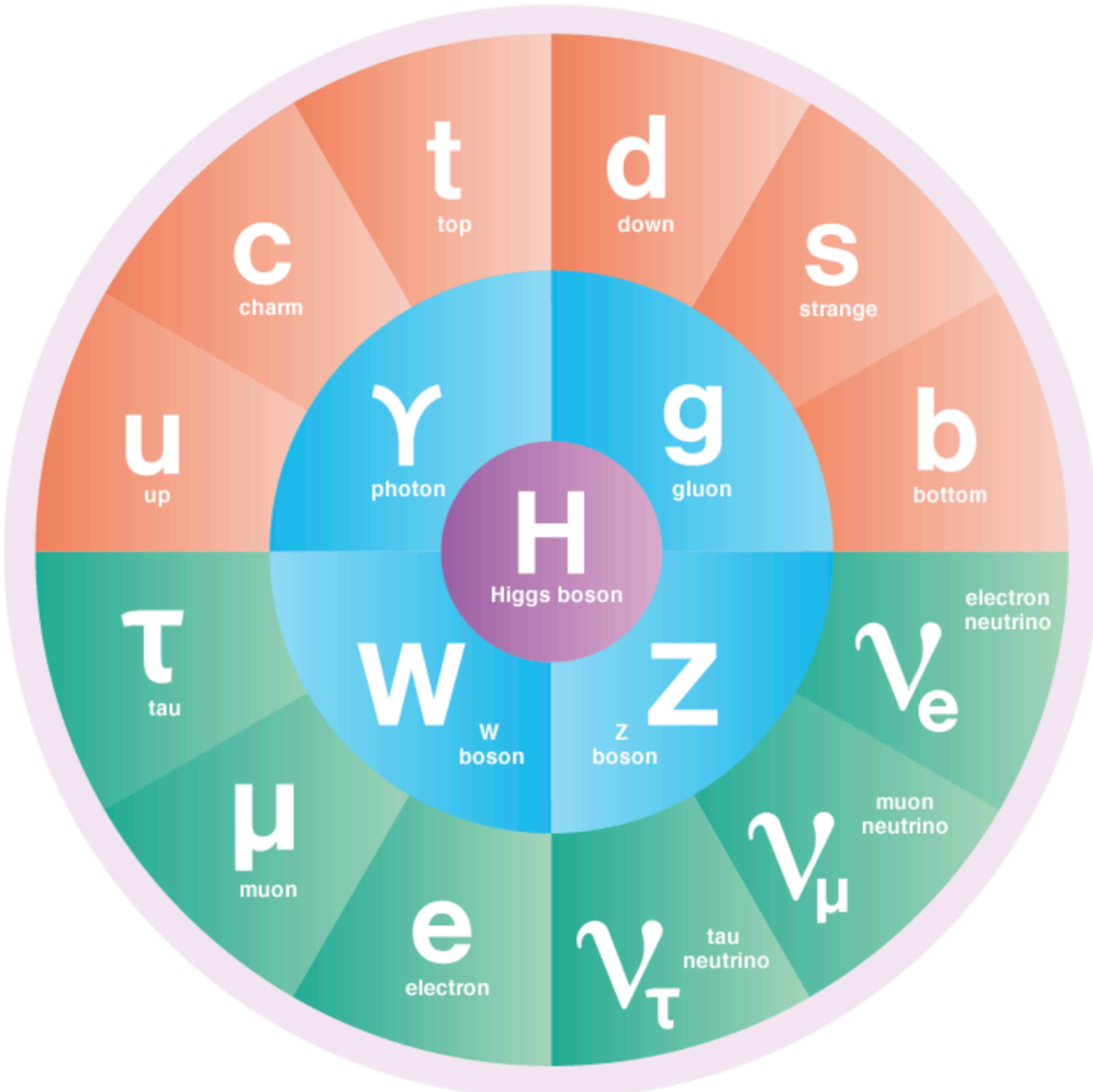
  - Take advantage of that (I, for one, think we're doing at great job here).
  - **Establish** and **develop** connections. Where do we start ?







The Standard Model of Particle Physics

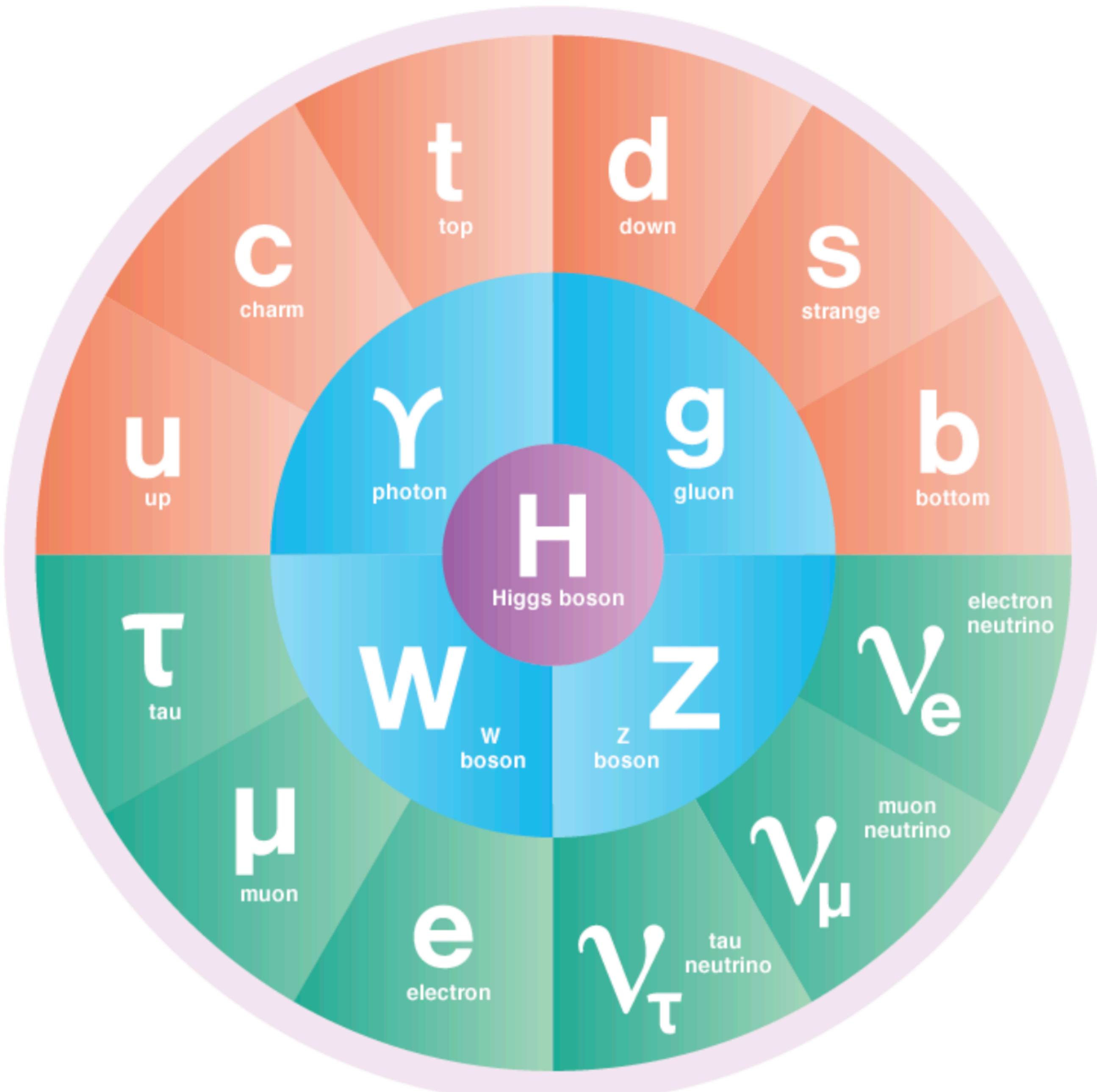


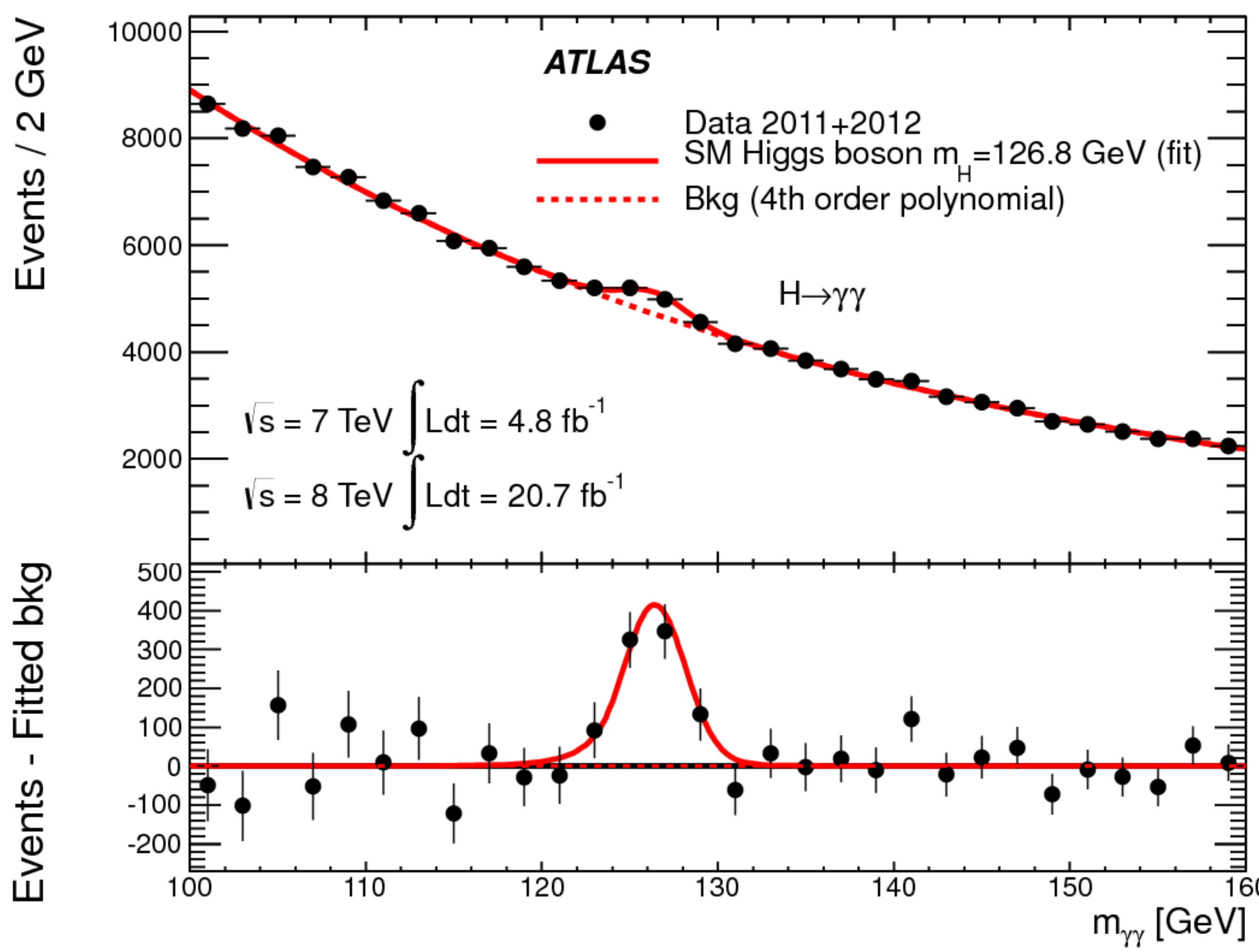
- Six flavours of **quark**.
- Six (**leptons + neutrinos**).
- Four **gauge bosons**.
- **The Higgs Boson** … a fundamental (?) scalar (?)

The Higgs: Why do we care ?

1) It has a mass of ~125 GeV

- Higgs boson **discovered** during Run 1 of the LHC.

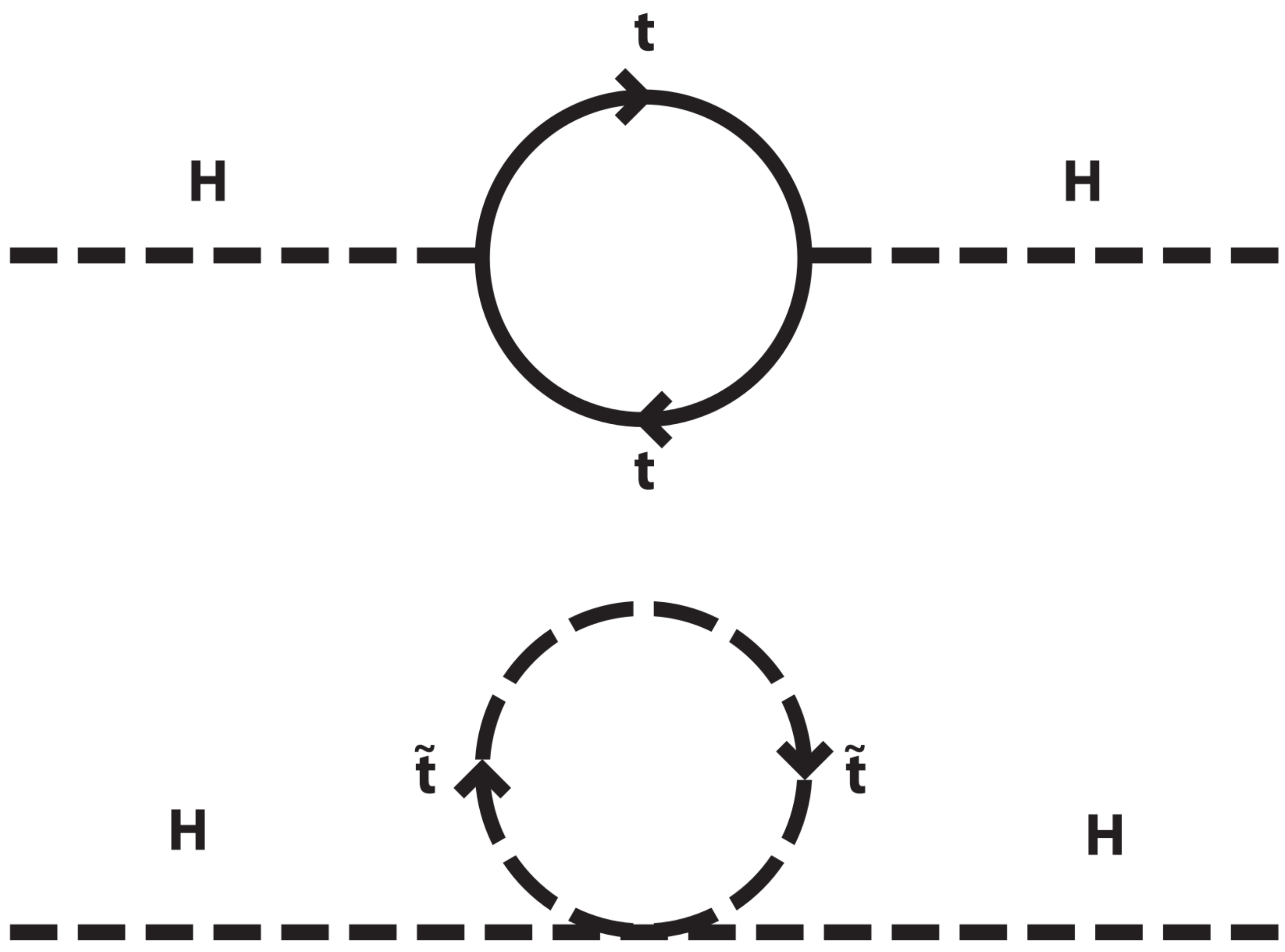




From arXiv:1207.7214

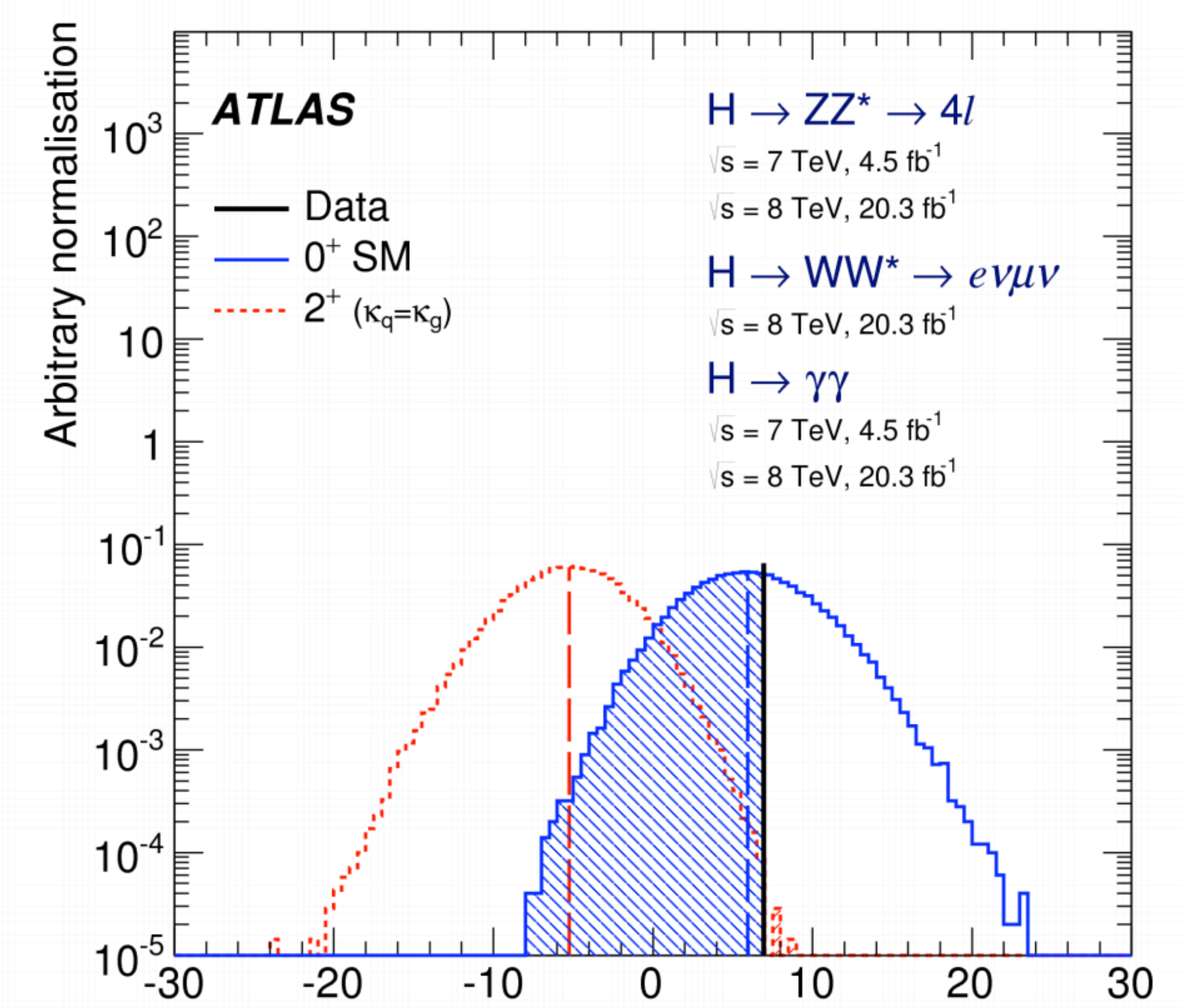
2) It connects the SM to BSM

- Higgs mass explained by popular beyond Standard Model (BSM) theories like Supersymmetry … **SPECIAL !**

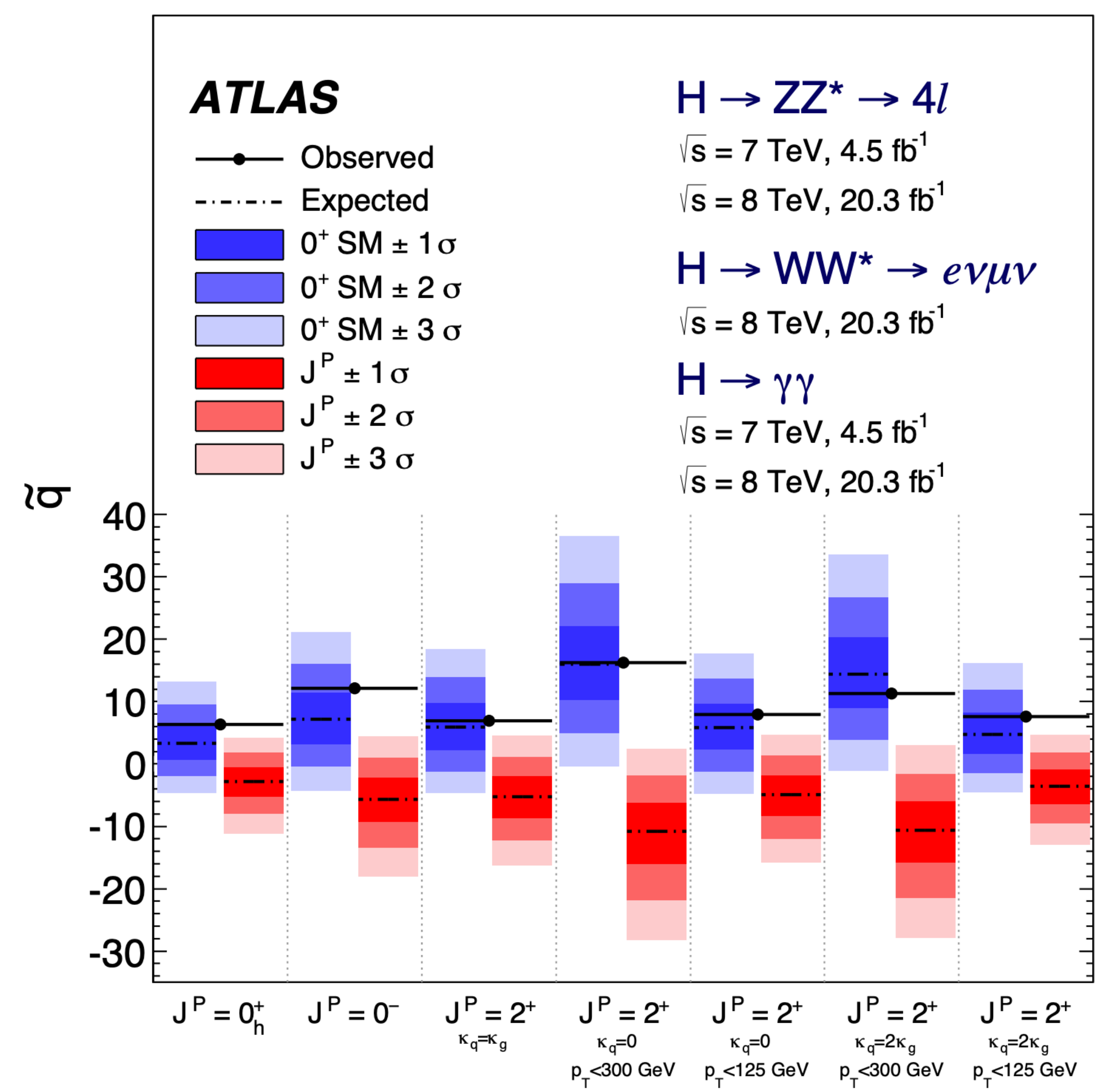


3) It's a scalar

- The only experimentally verified **scalar** … **SPECIAL !**

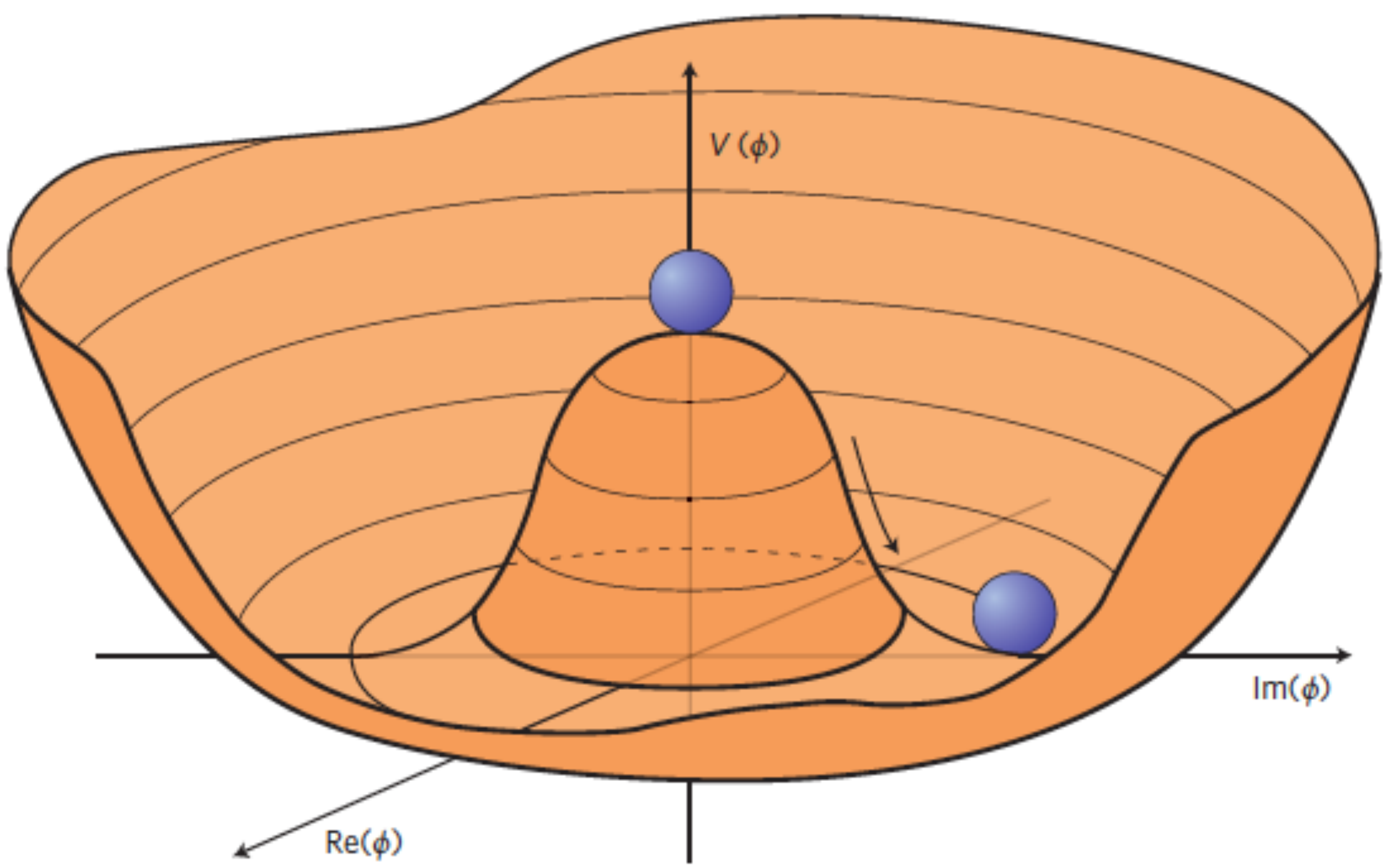


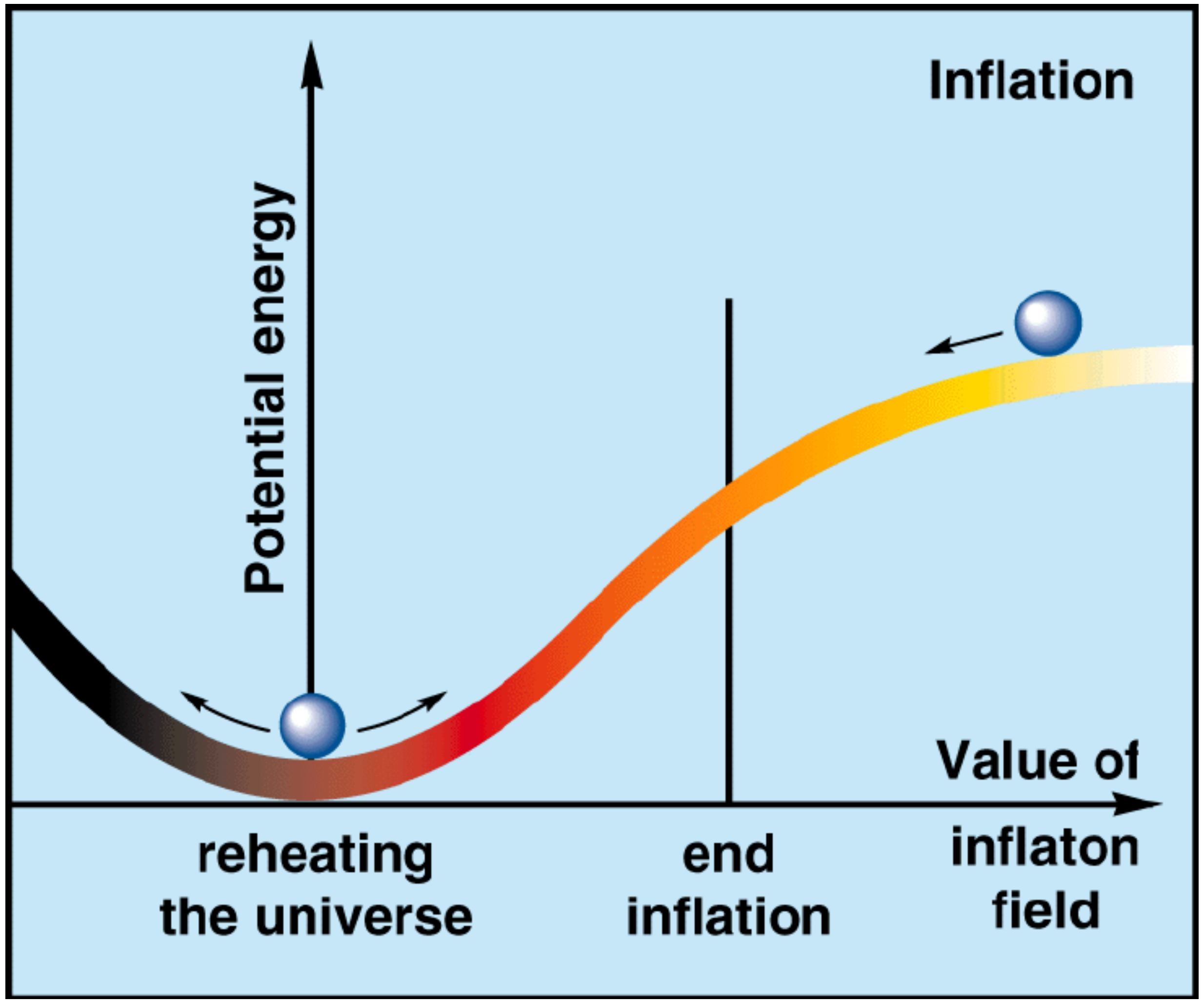
$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\rm SM}, \hat{\hat{\mu}}_{J^P_{\rm SM}}, \hat{\hat{\theta}}_{J^P_{\rm SM}})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$



4) It connects to cosmology

- Can construct models connecting the **Higgs potential to inflation**.
- If **Higgs-like scalar = inflaton** => could drive the early expansion of the universe.

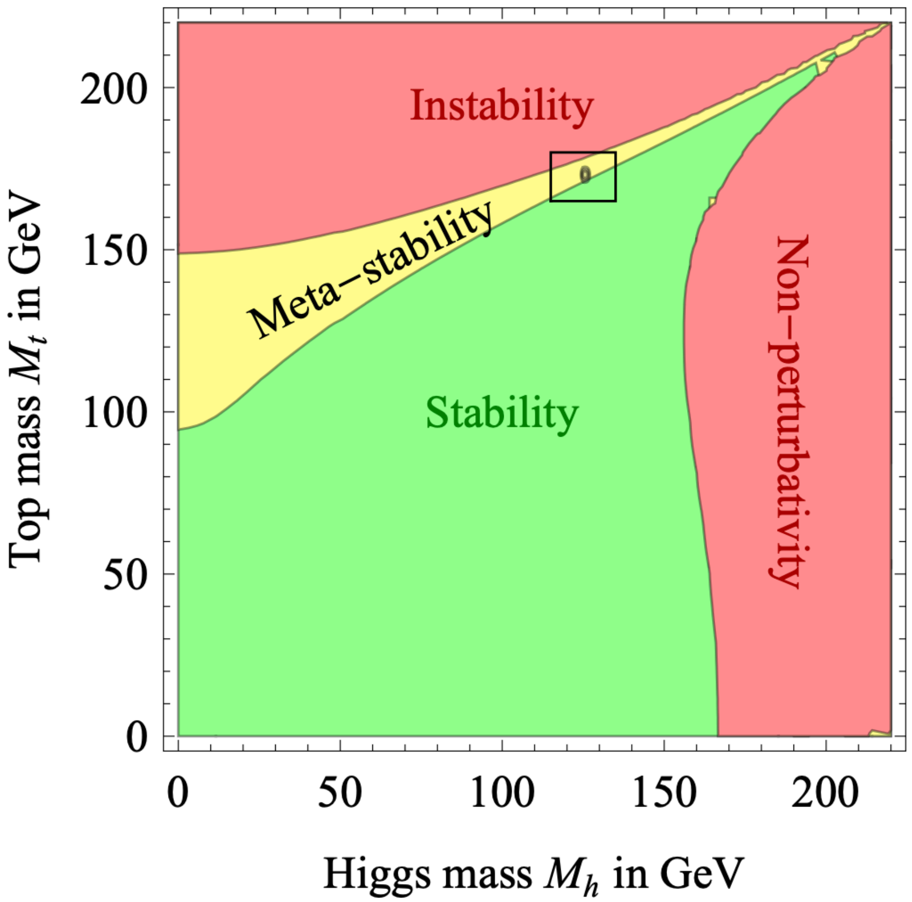


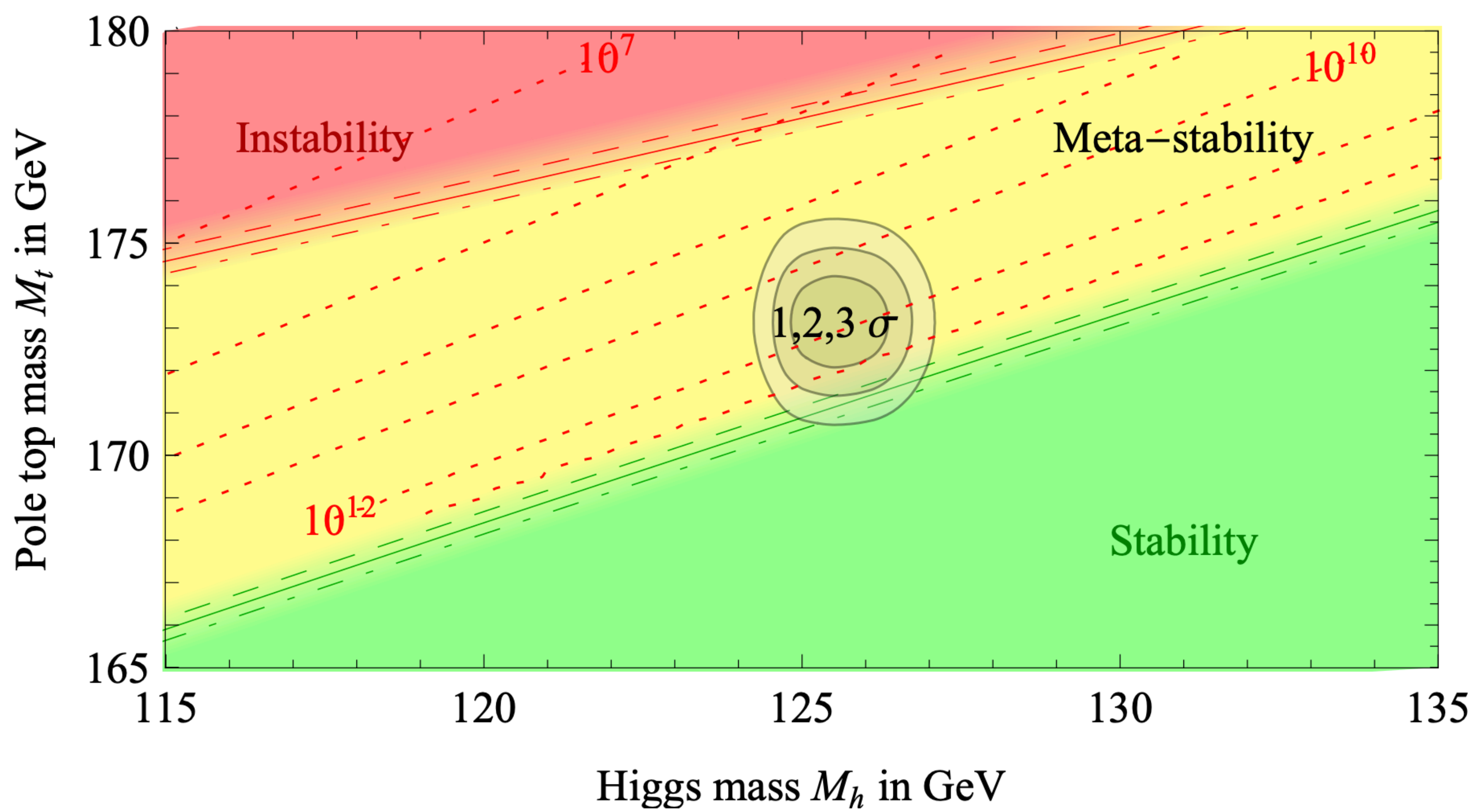


- We need to understand the **global shape of the Higgs potential**.

4) It connects to cosmology

- The **mass of the Higgs** is intimately related to the **stability of our universe**.





- We need a detailed understanding the **electroweak symmetry breaking in the early universe**.

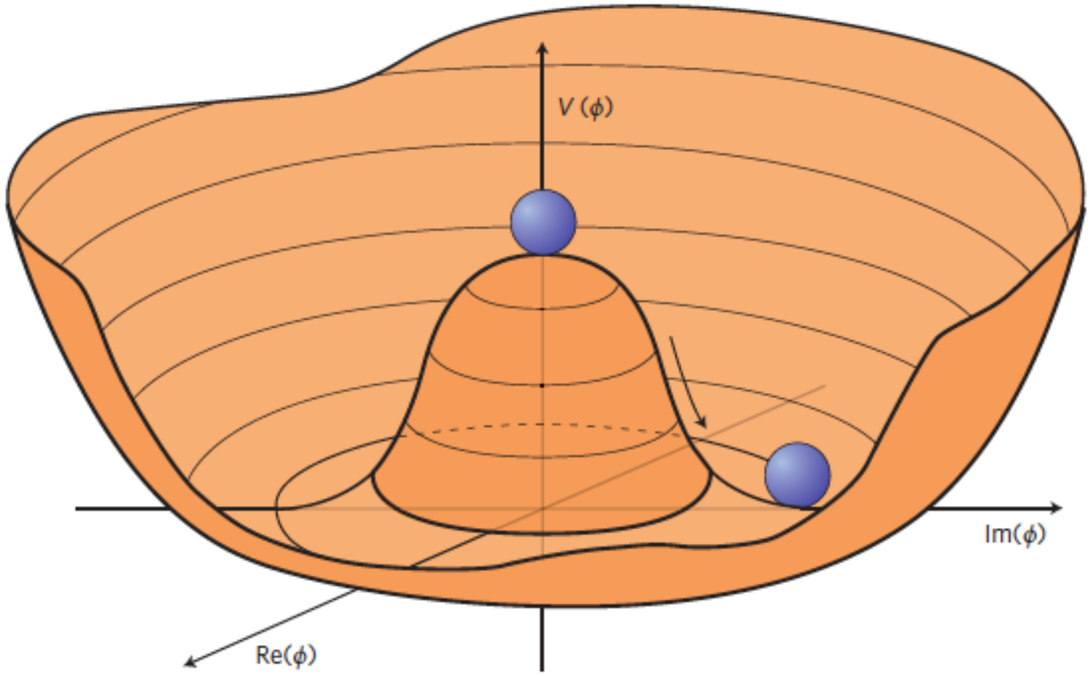
- Again, this comes from understanding the **global shape of the Higgs potential**.

Let’s talk about the Higgs potential …

The Global Higgs Potential

- Q: How can one probe the **global** shape of the **Higgs potential** ?

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$



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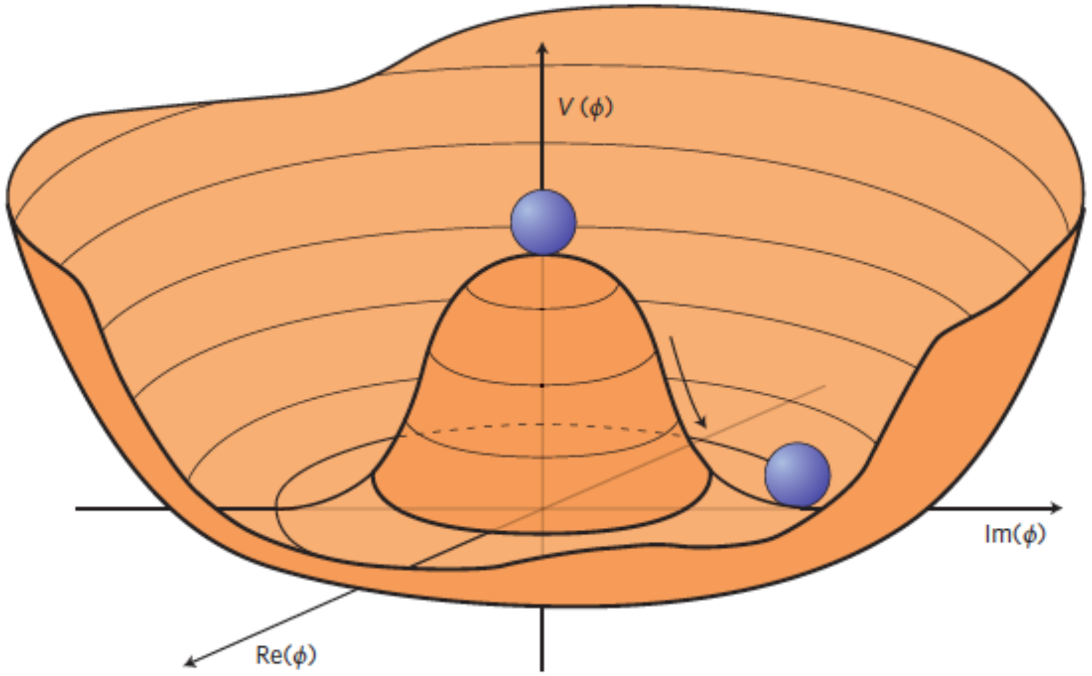

Perturb minimum, *v*, by amount *h* $V(\phi) \rightarrow V(v+h)$

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

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

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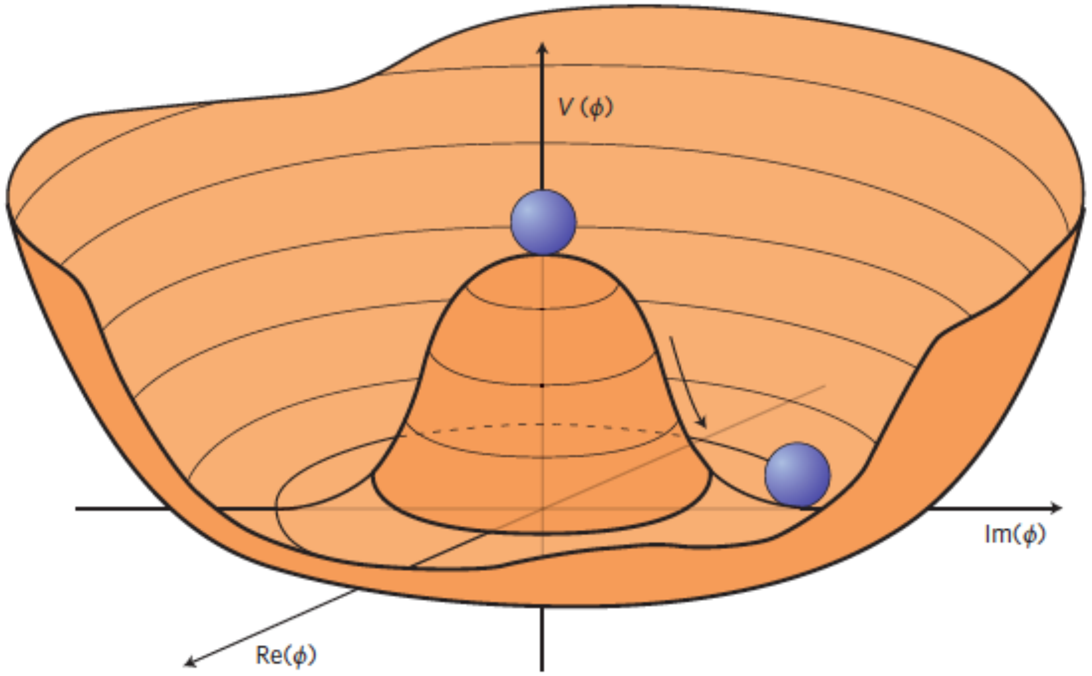

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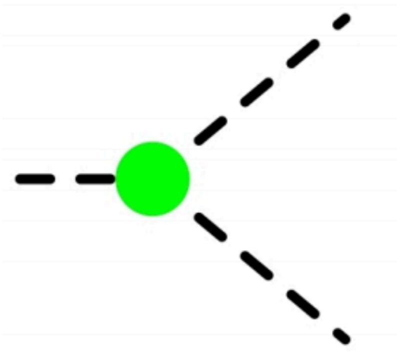
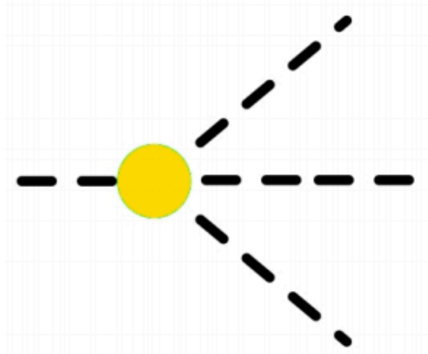
Higgs mass *HH* production *HHH* production





Test the SM predictions:

$$v = \frac{\mu}{\sqrt{\lambda}} = 246\,\mathrm{GeV}$$

$$\lambda = \frac{m_h^2}{2v^2} \approx 0.13$$

Cosmological implications !

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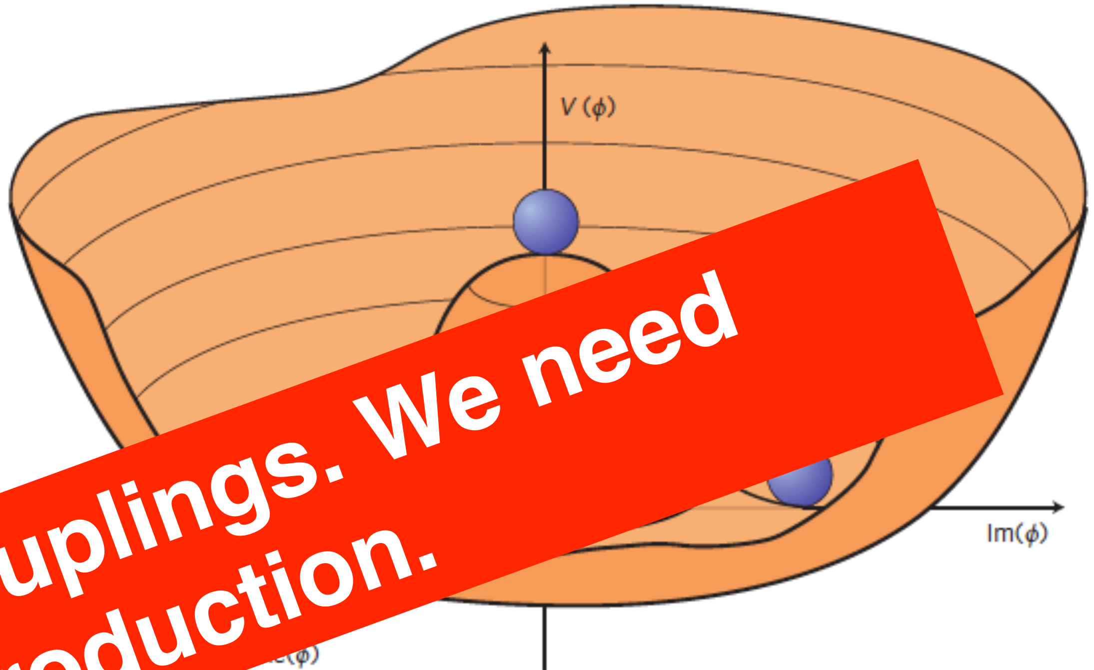

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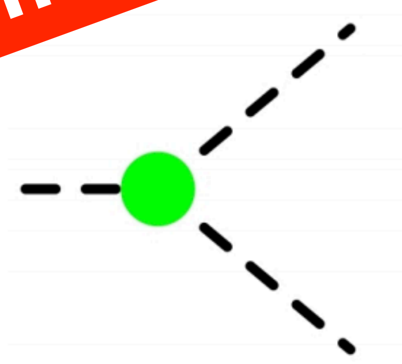
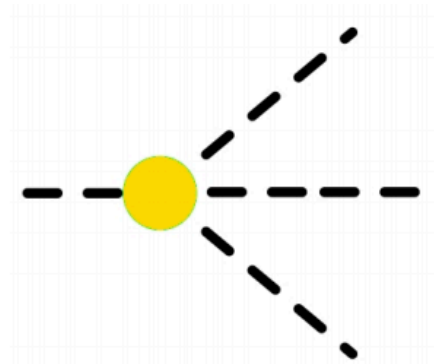
A: Investigating multi-Higgs couplings. We need to measure di-Higgs production.

Hi… …tion



HHH production



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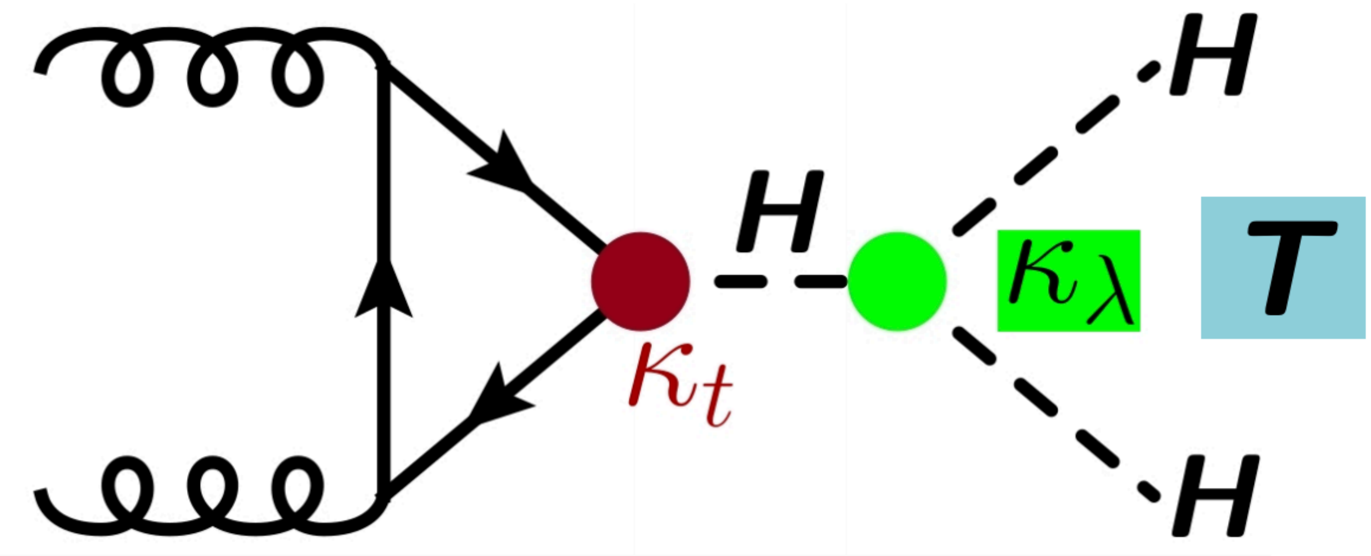
Cosmological implications !

Measuring the Higgs Self-Coupling

- Can measure *HH* production at the LHC, hence **constrain the self-coupling**.
- Start with the highest cross-section production process, **gluon-gluon fusion (*gg*F)**.

(using scale factors: $\kappa_t = g_{t\bar{t}H}/g^{SM}_{t\bar{t}H}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$)



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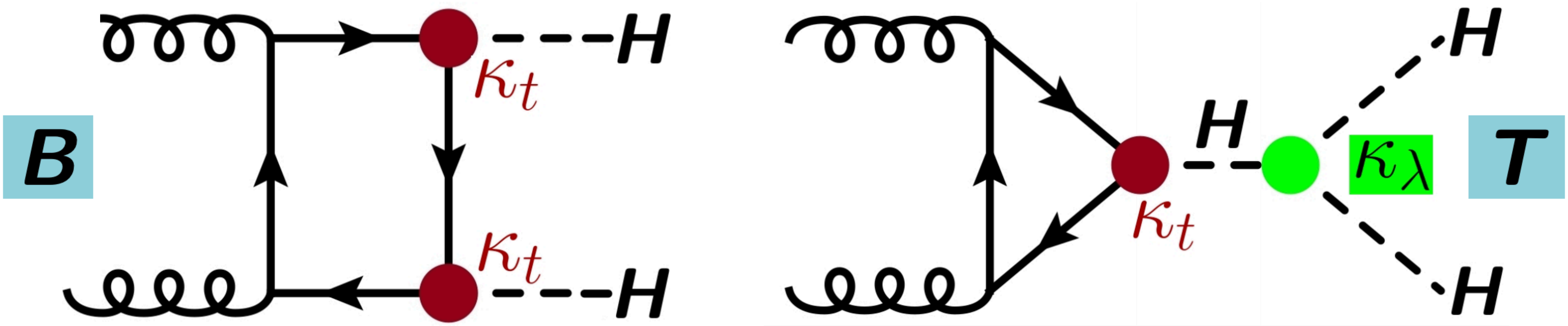
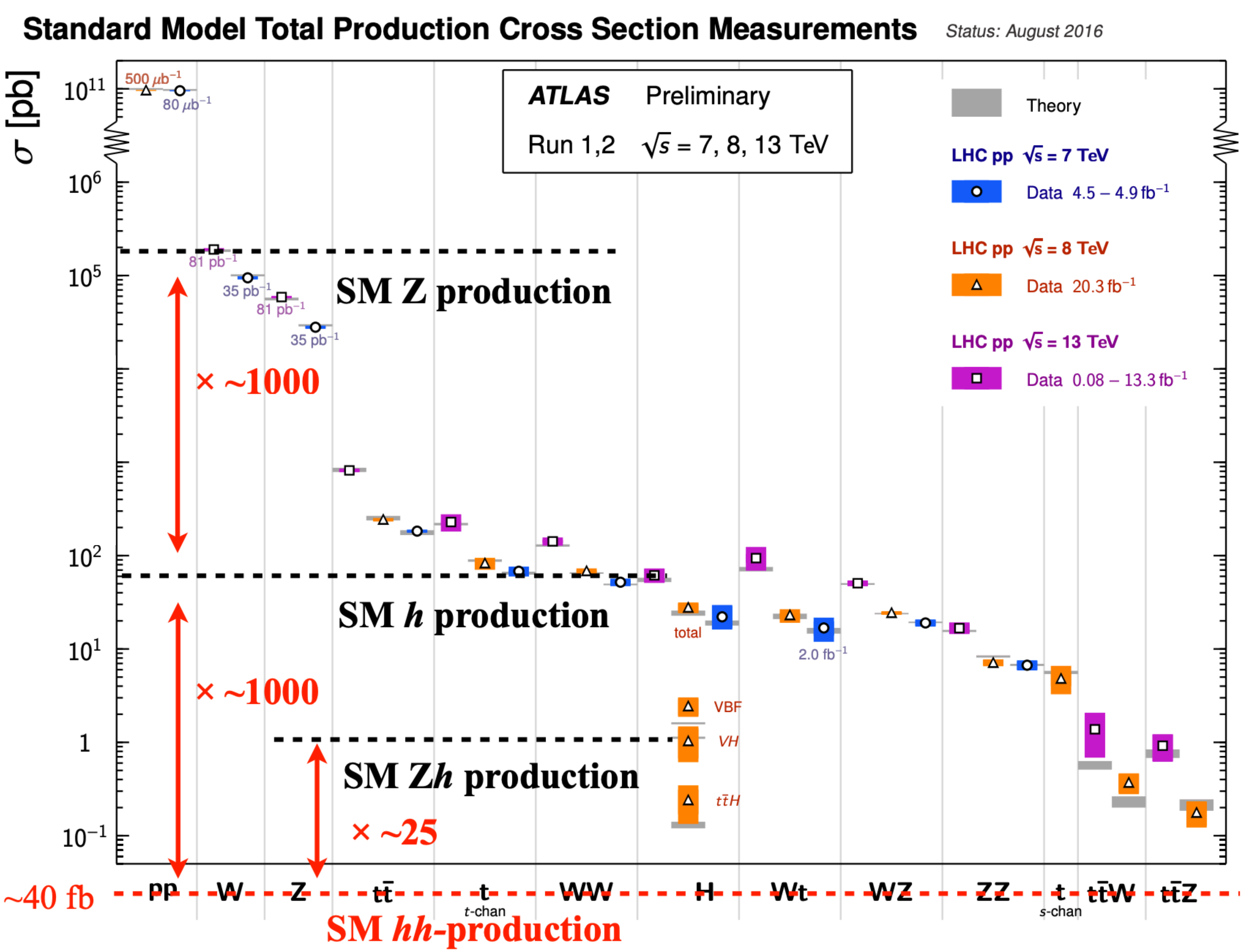


Destructive interference

=> **small cross-section for *HH* production !**

Measuring the Higgs Self-Coupling

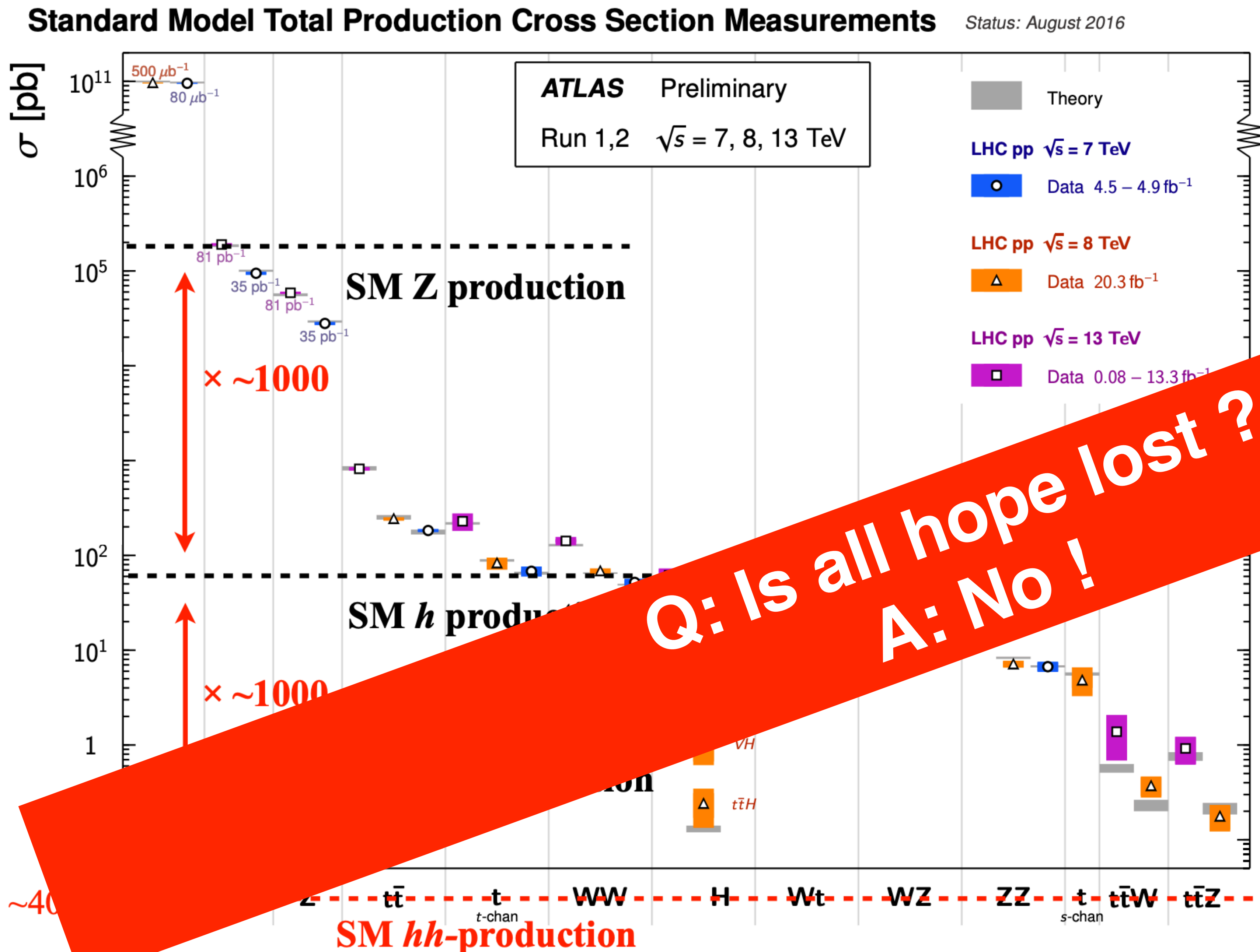


Production mode	Cross section (14 TeV)
ggF-*hh*	~ 40 fb
VBF-*hh*	~2 fb
V-*hh*	~ 1 fb
tt-*hh*	~ 1 fb

arXiv:1212.5581

*From J. Alison

Measuring the Higgs Self-Coupling



	~ 40 fb
VBF-*hh*	~2 fb
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tt-*hh*	~ 1 fb

arXiv:1212.5581

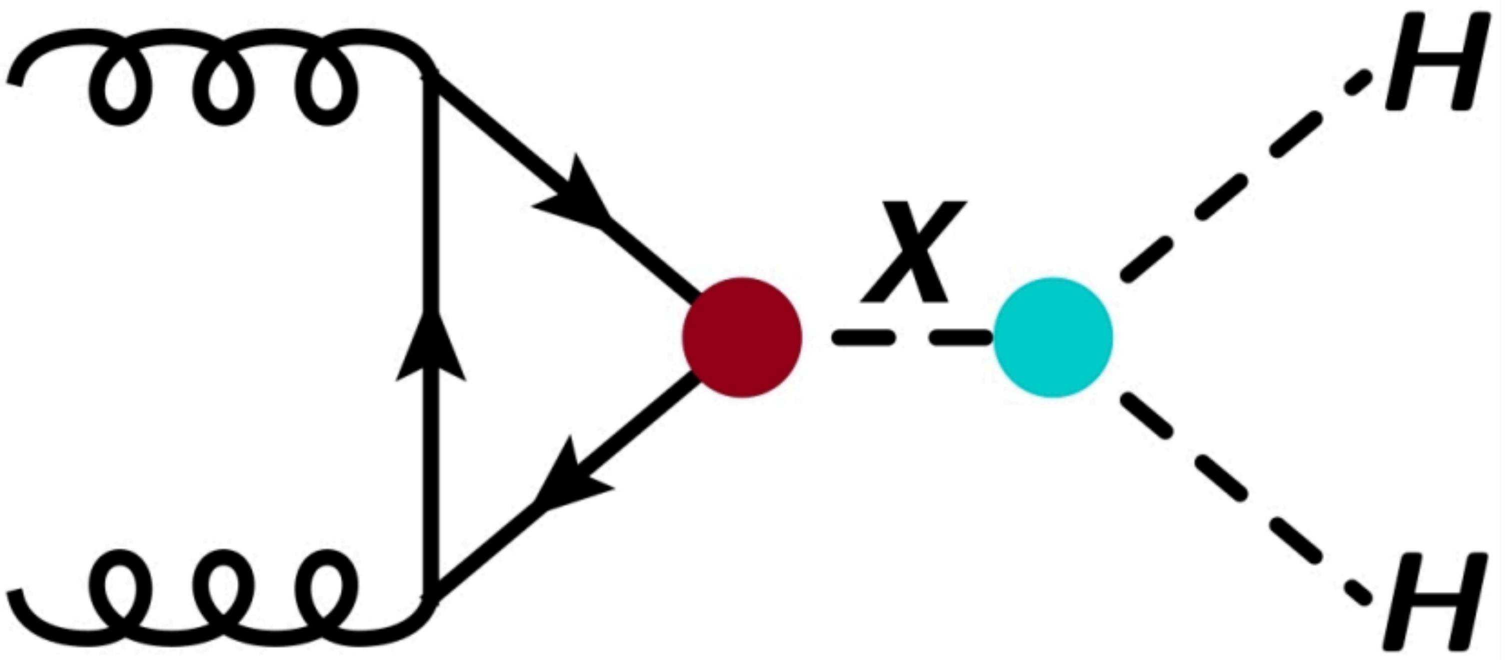
Q: Is all hope lost ?
A: No !

*From J. Alison

How might New Physics Manifest in HH Production ?

Searching for New Matter: Resonant

- One can use *HH* to search for new matter which modifies the Higgs self-coupling and **enhances the *HH* cross-section => $\sigma_{HH} / \sigma_{HH}^{SM} > 1$**.



***X* = New Matter**

e.g. Spin-0: *X* = *S*, a new scalar

e.g. Spin-2 *X* = *G*, Randall-Sundrum graviton

- Different models and different *X*-masses allow for **different sizes of enhancement** to the cross-section.

Searching for New Matter: Non-Resonant

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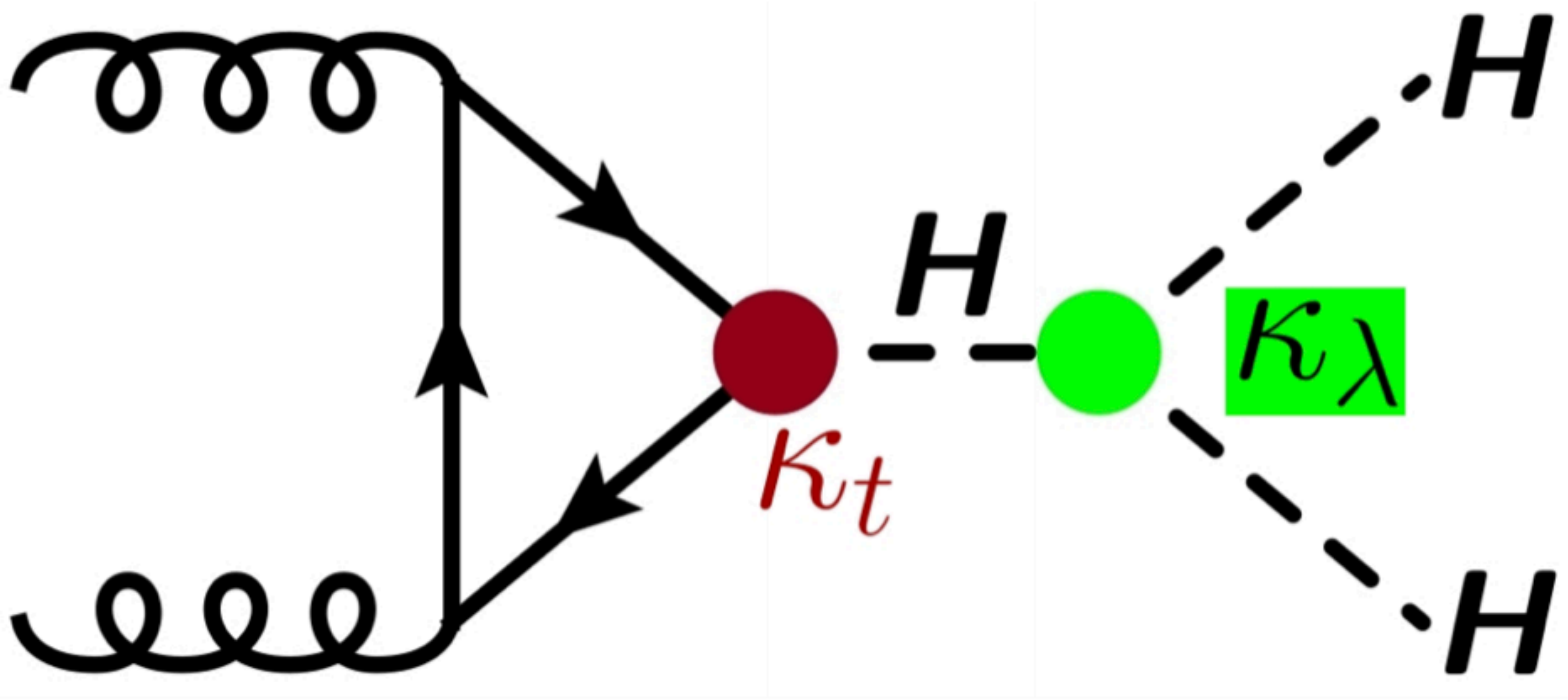
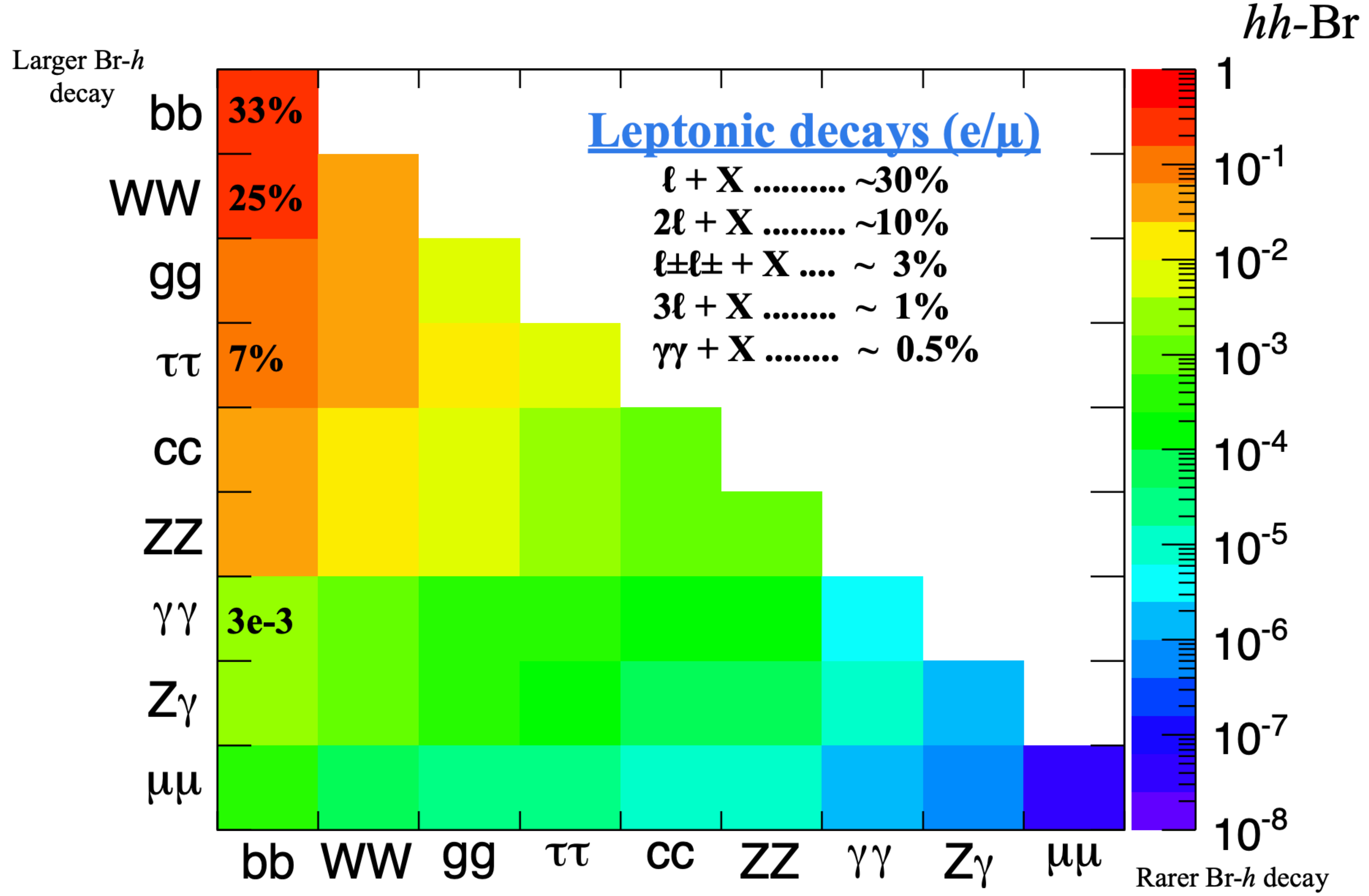
- Generic **non-resonant enhancement** is possibly in many BSM models, such as composite Higgs and Little Higgs scenarios.
- Can get significant enhancements to the self-coupling.



- Look for **enhanced κ_λ** or **activation of new vertices**.
- Also motivates an **EFT approach** to Higgs physics.

Which channels ?

- We need to consider the **most sensitive channels** when searching for $H(\rightarrow ab)H(\rightarrow cd)$ production. Driven by two important factors:
  - **Branching fraction**
  - **Complexity of final states**



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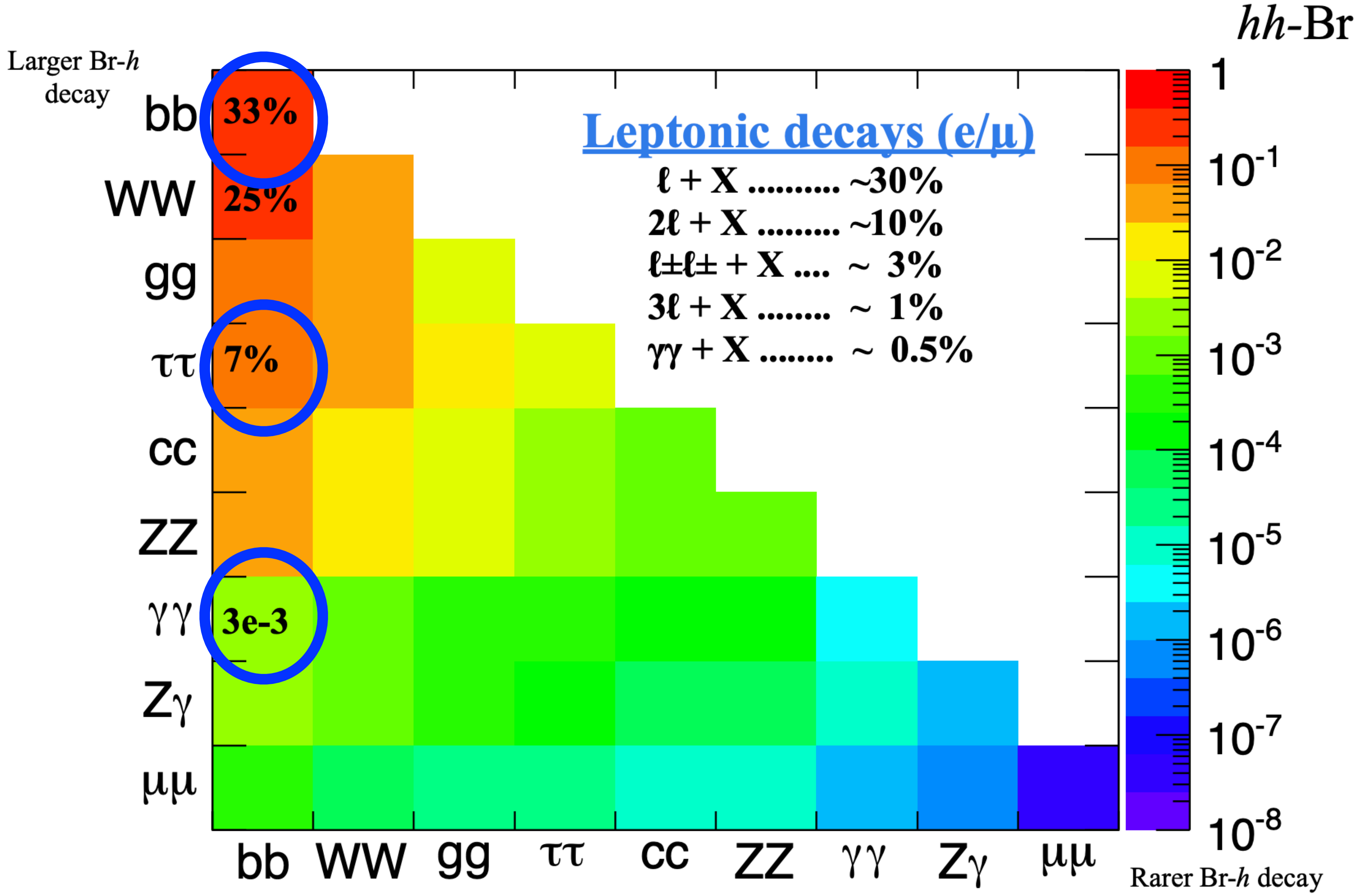

Looking for *HH* at ATLAS

The ATLAS Experiment @ CERN

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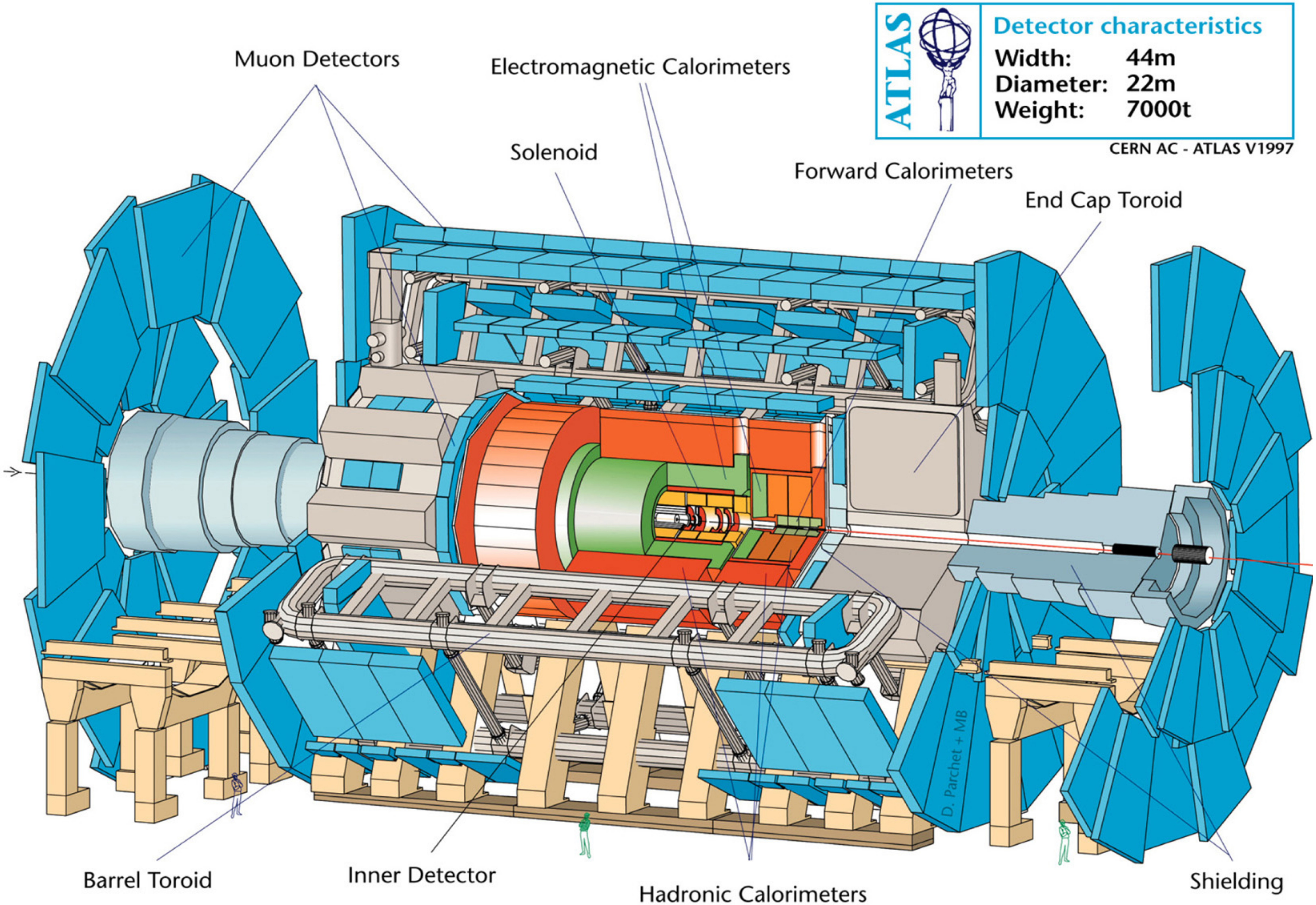
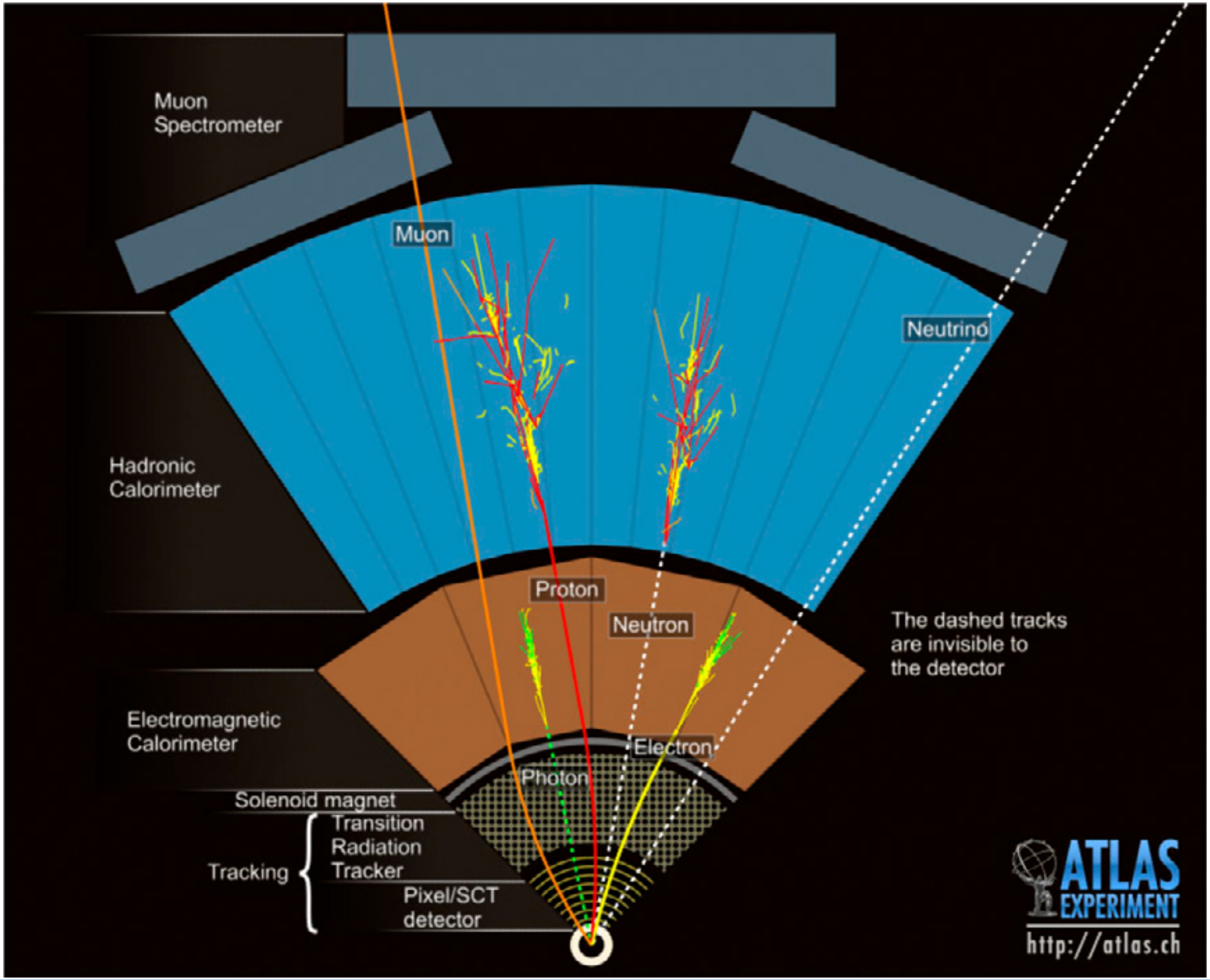
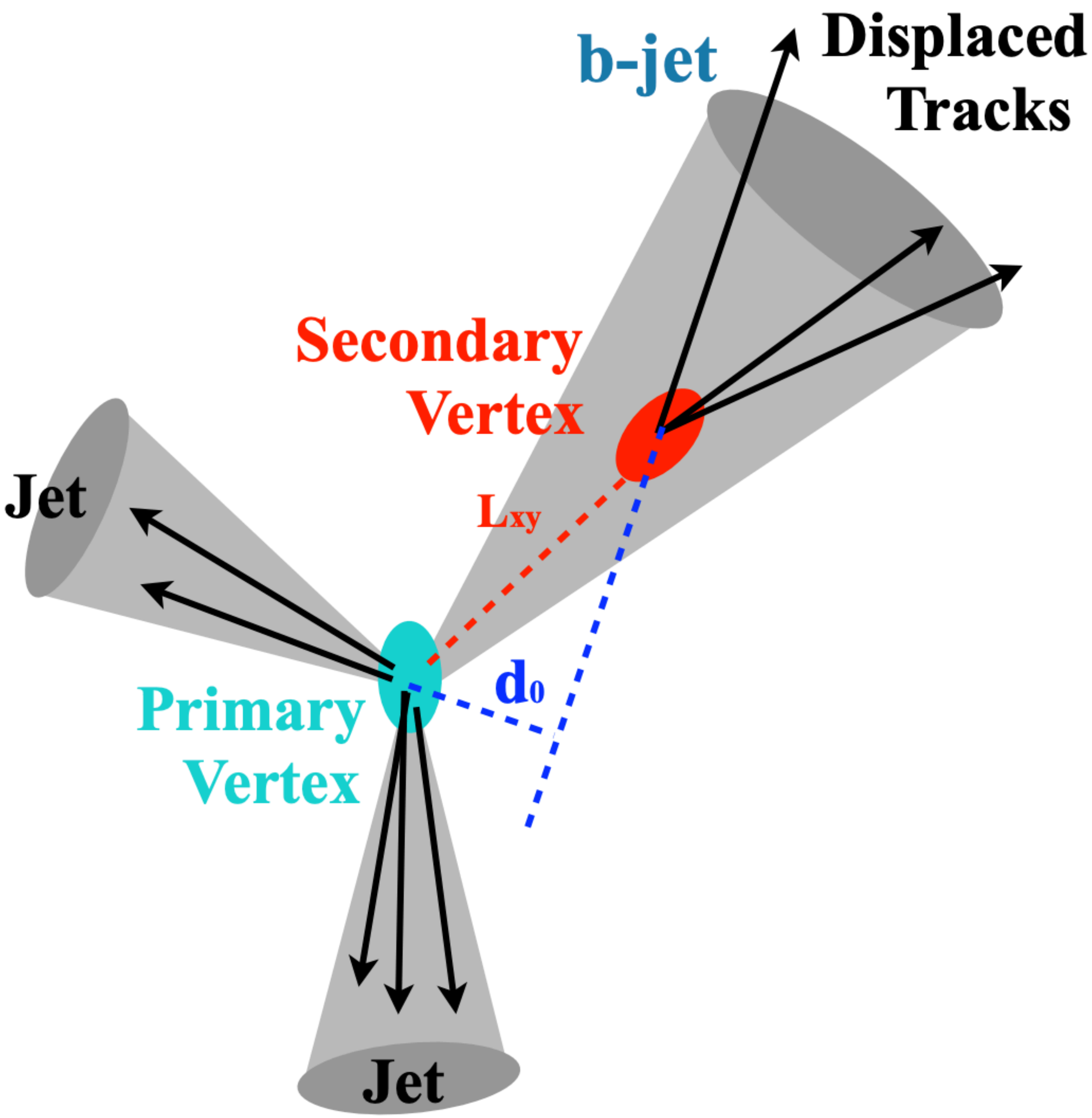


A Slice of ATLAS



B-jet Identification



- **Large branching fraction of $H \rightarrow bb$** makes *b*-tagging essential in di-Higgs searches.
- **Exploit the relatively long lifetime of *B*-hadrons** => *b*-decay displaced from the interaction point.
- Displacement identified using **tracking** and **secondary vertices**.
- Build multivariate discriminants from this low-level information to "tag" *b*-jets.

Trigger Challenges

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- Interesting physics is incredibly rare and we cannot save all events from LHC collisions to disk. **Two-part trigger system**:

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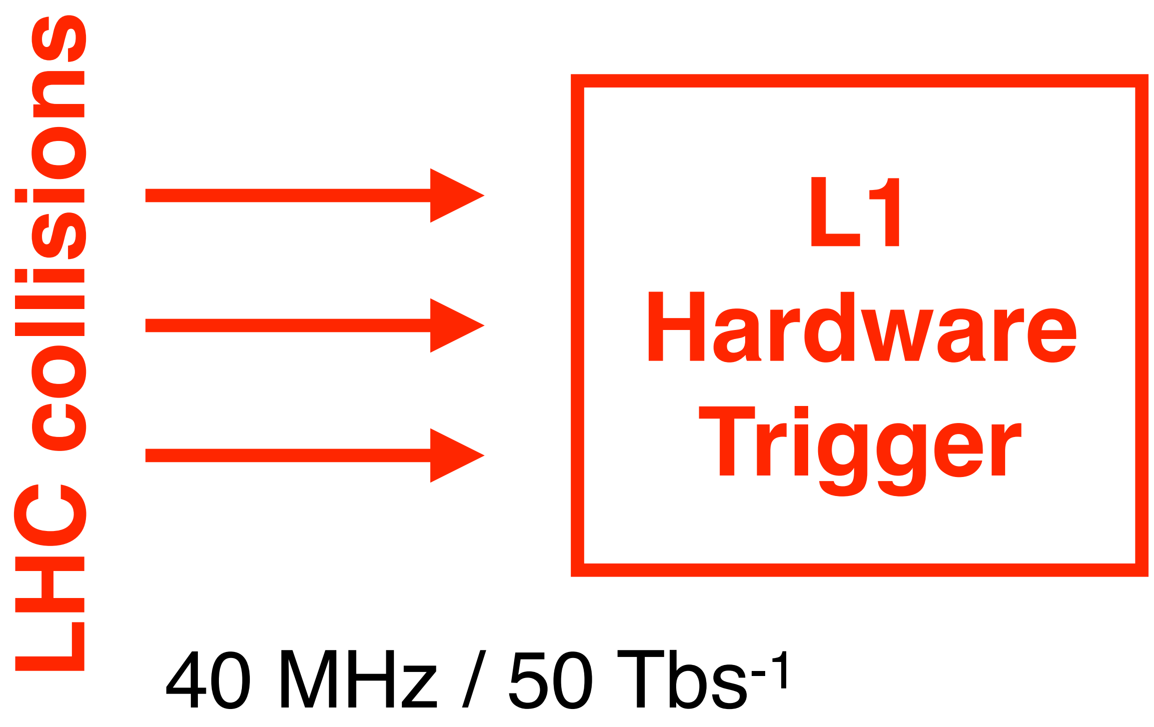

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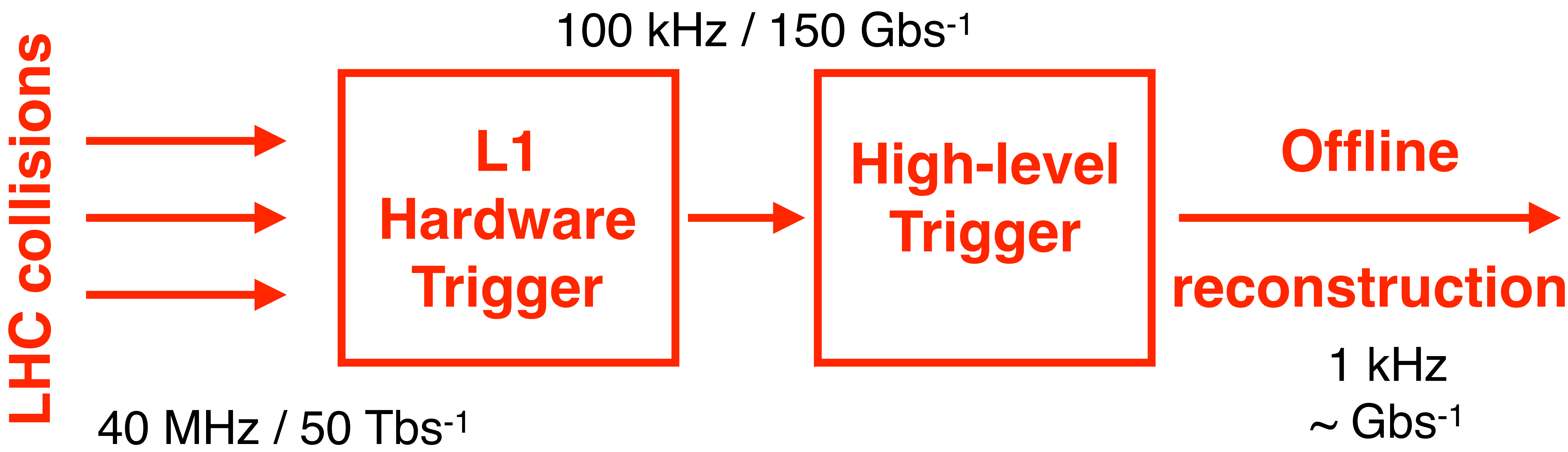


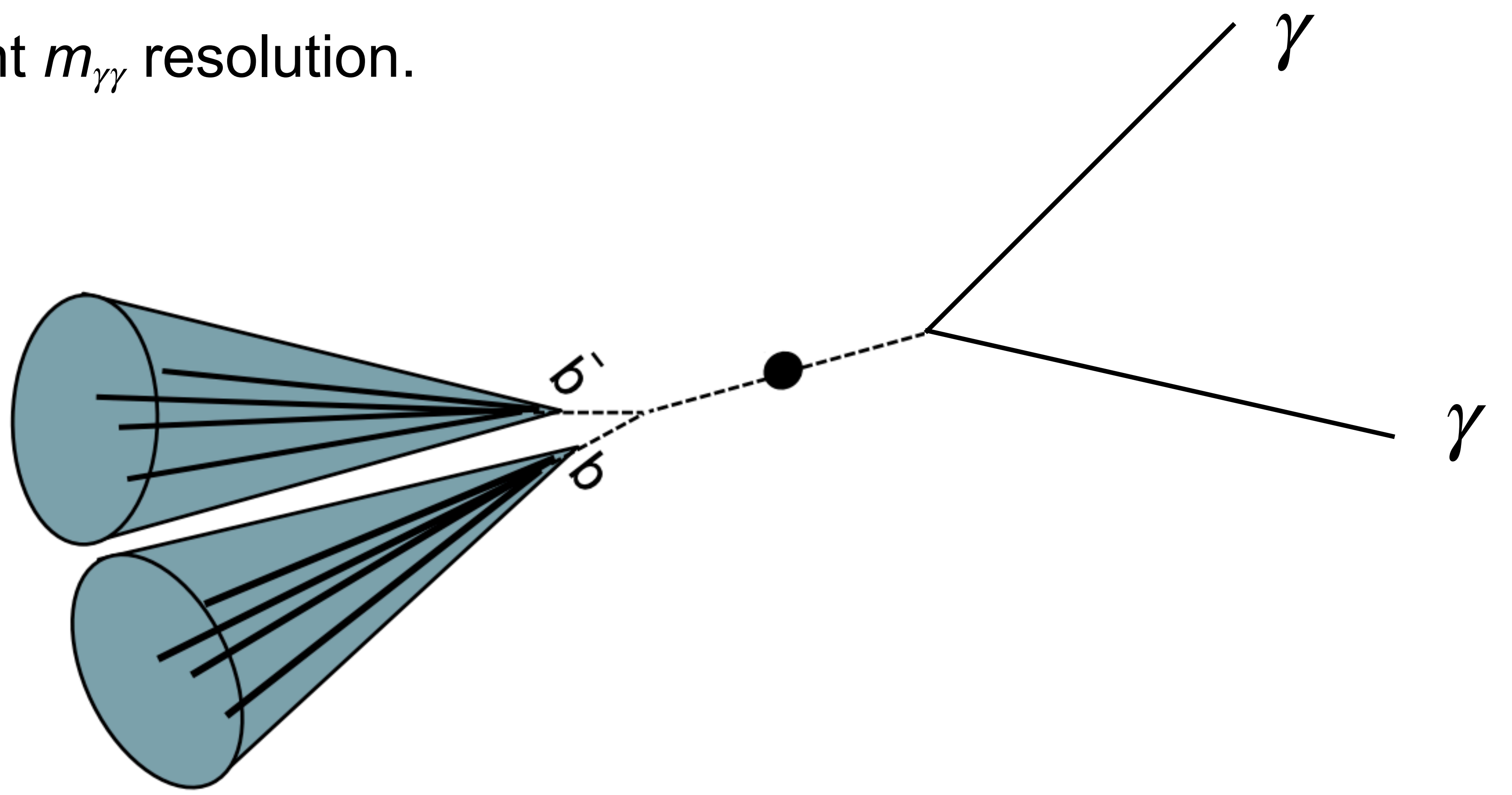
- We rely on tracking at the HLT for *b*-tagging, which is **very CPU intensive**. **This will get worse with more luminosity**. We need to be smarter with tracking in future.

- The dream: tracking and tagging **at L1**.

$HH \rightarrow bb\gamma\gamma$ @ 36 fb^{-1}

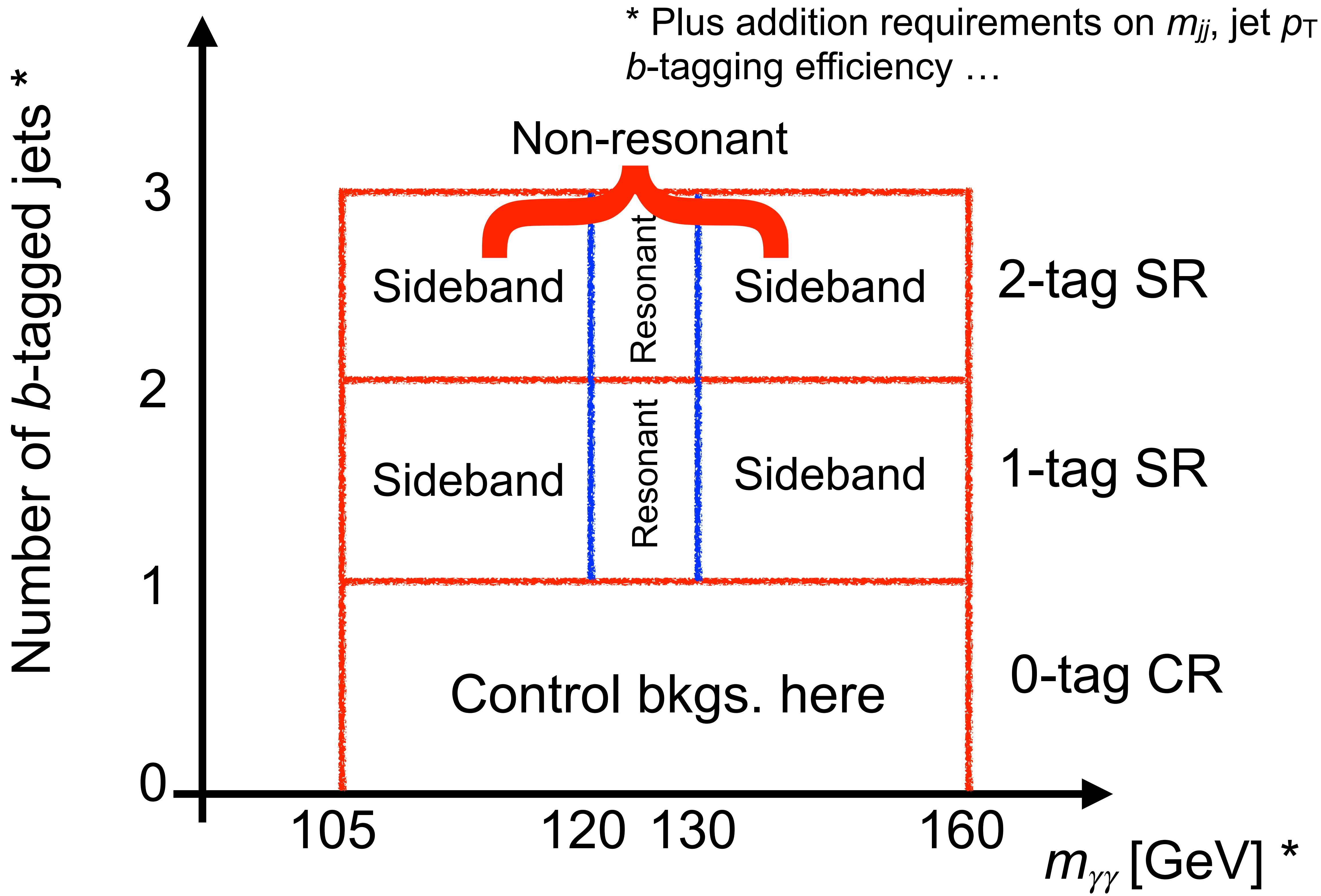
$bb\gamma\gamma$ channel

- Small branching fraction, but **very clean background and clean trigger on the γ.**
- Excellent $m_{\gamma\gamma}$ resolution.



- Require 2 b-tagged jets and two γ:
  - **Non-resonant**: m_{bb} and $m_{\gamma\gamma}$ reconstructed around the Higgs mass.
  - **Resonant**: reconstruct the full $m_{bb\gamma\gamma}$ system and scan for resonances.

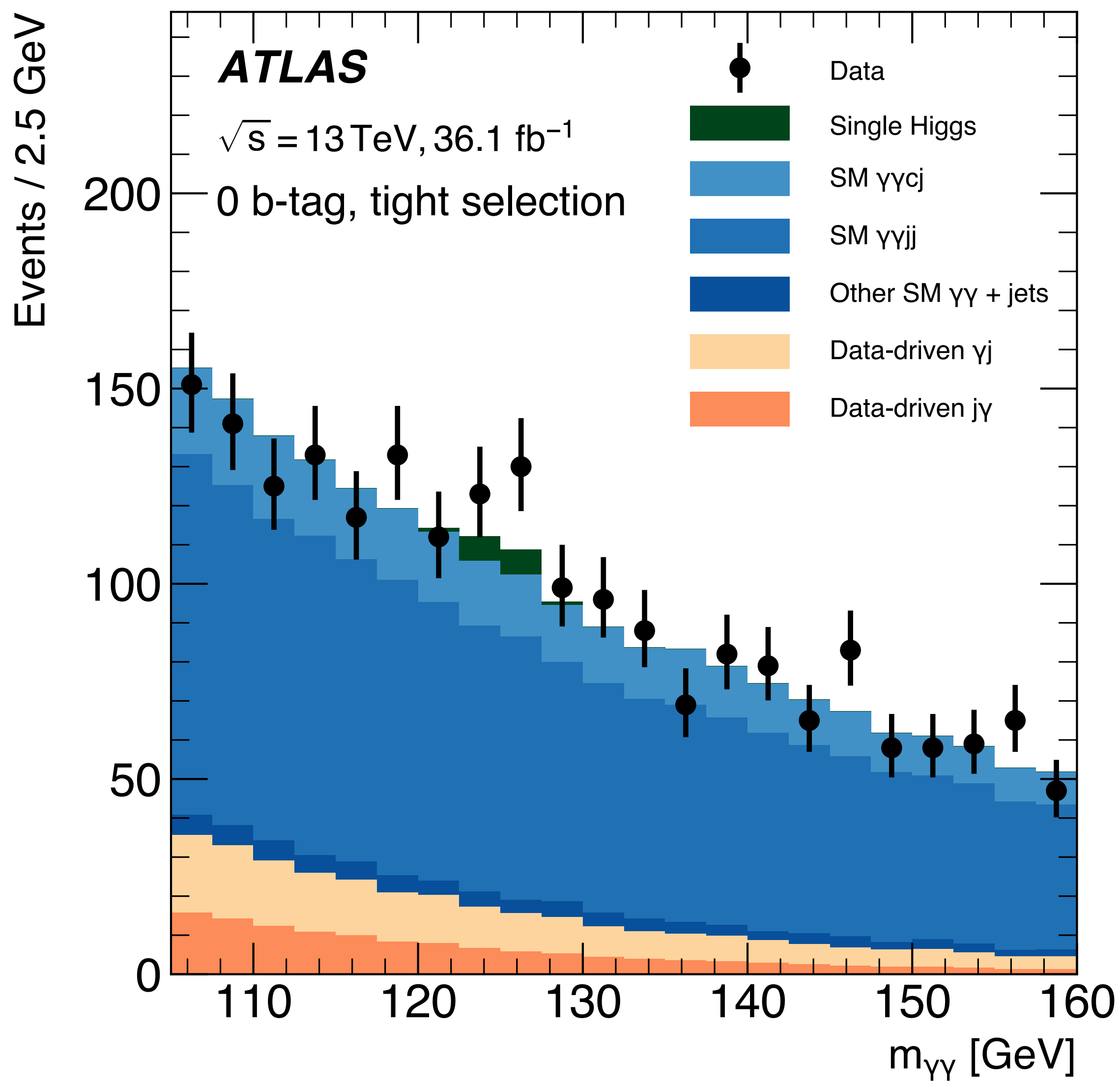
bb$\gamma\gamma$ Regions



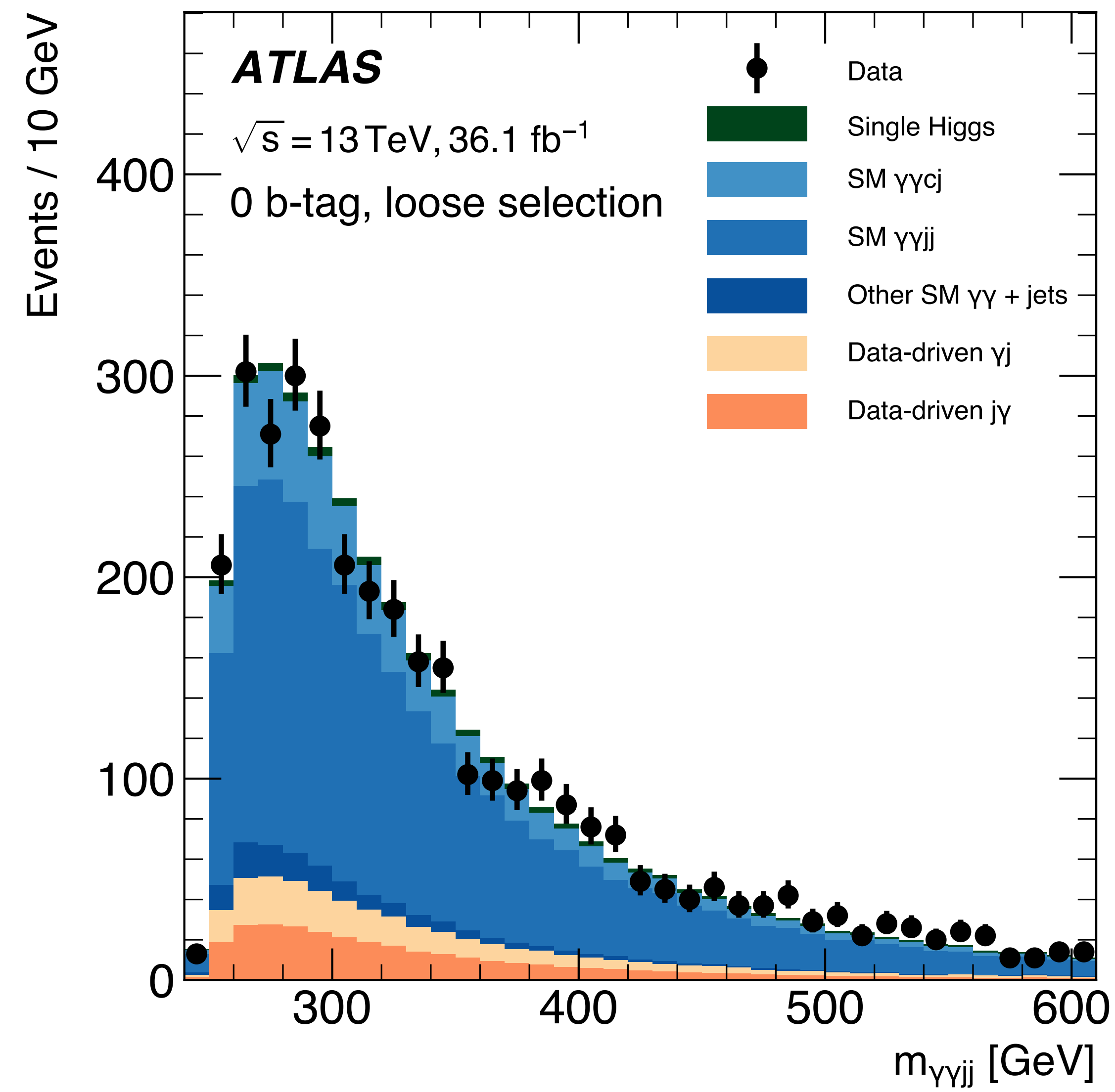
bbγγ channel

- Establish **0-tag regions** (with loose and tight jet p_T requirements) where the γ+jet background is estimated from data and data/MC corrections to $m_{\gamma\gamma}$ are extracted and applied to the **1- and 2-tag signal regions**.

Non-resonant



Resonant



$bb\gamma\gamma$ channel

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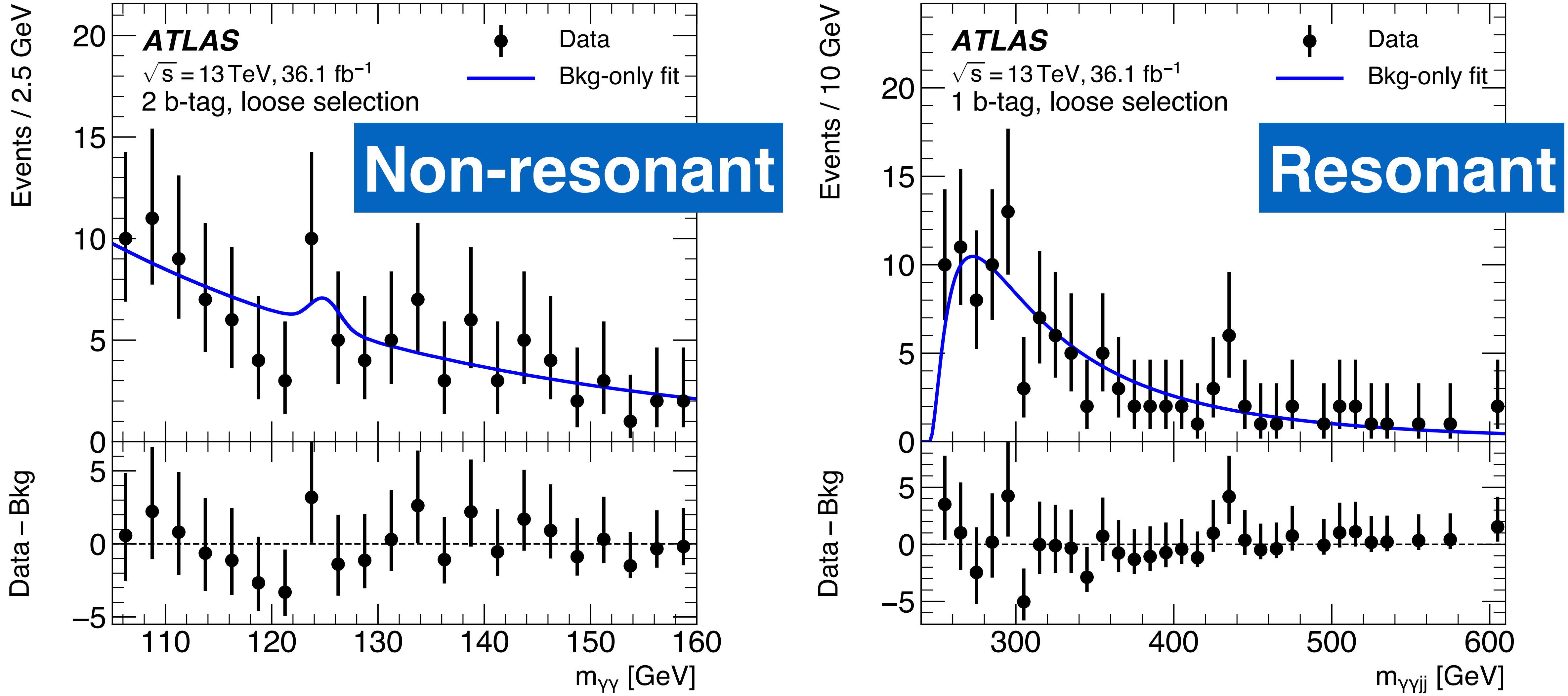
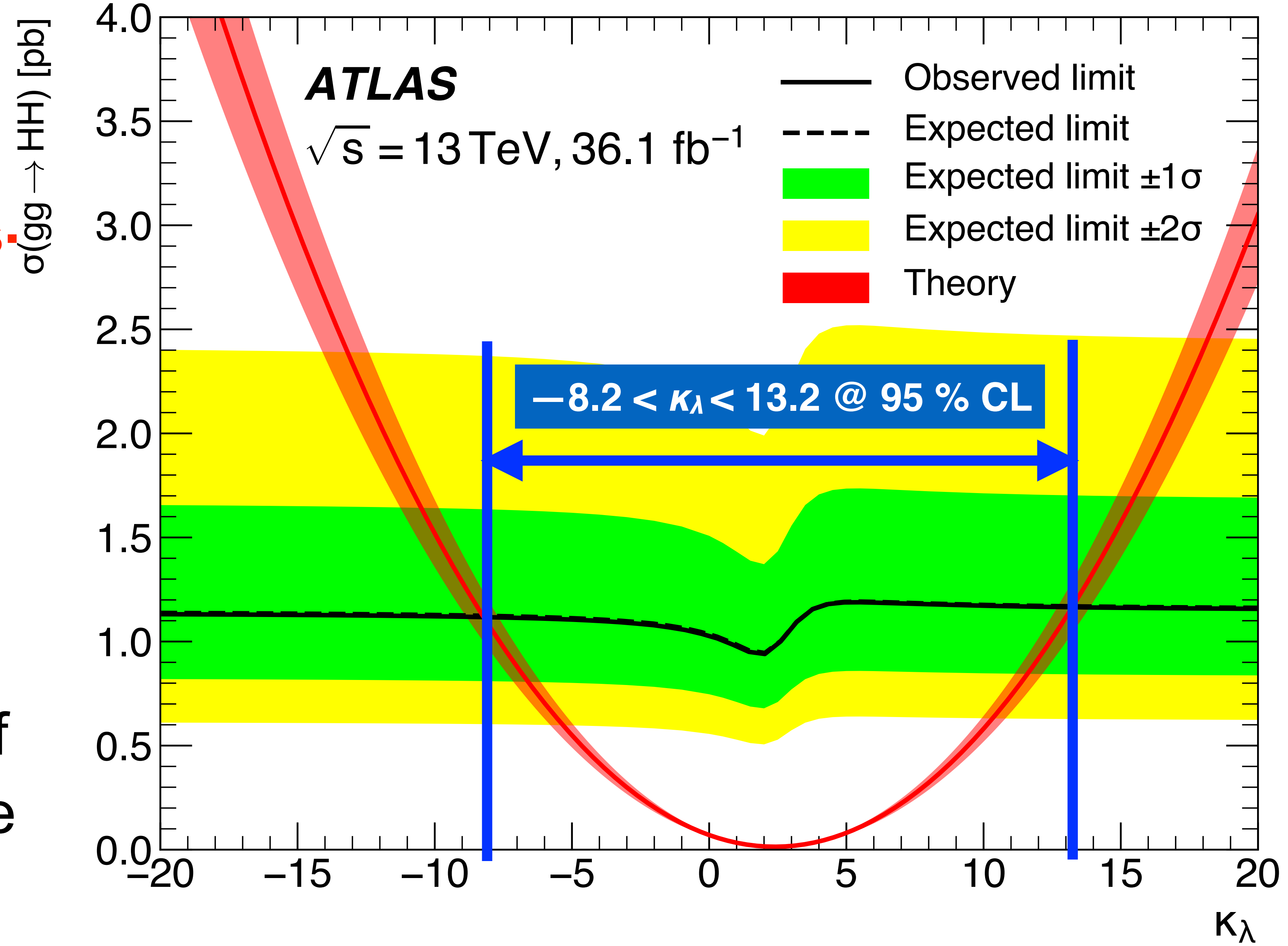


- Example search regions in both the resonant and non-resonant channels.
- **Results are statistically limited at 36 fb^{-1}**. Full run 2 analysis in progress.
- Use **non-resonant search** to set an upper limit on *HH* production from *gg*F, and the **resonant** to set an upper limit on the cross-section for e.g heavy scalar production.

Constraining κ_λ

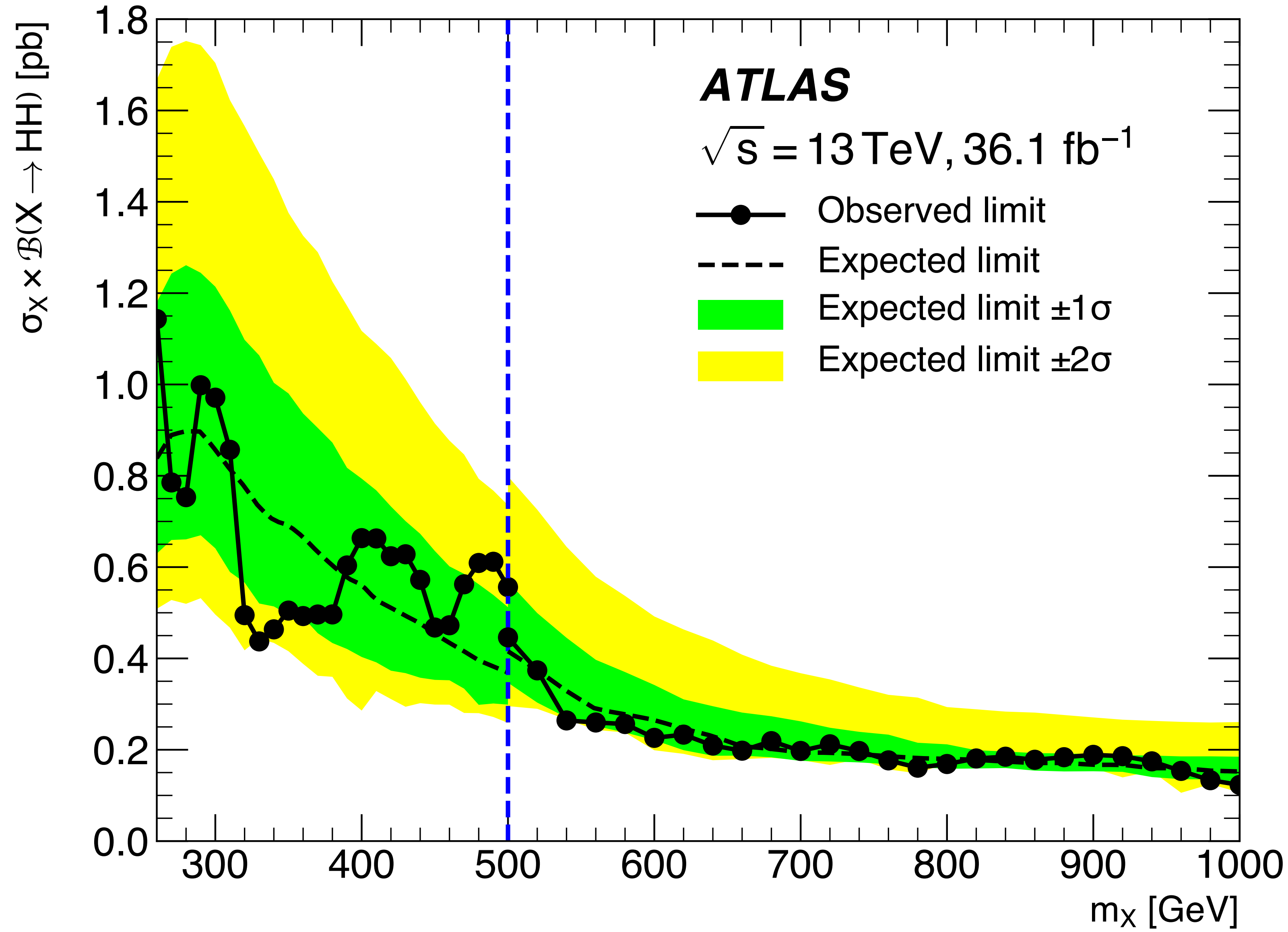
- **Set limits on both the Higgs self-coupling and the *gg*F production cross-section for non-resonant *HH*.**
- $bb\gamma\gamma$ sets stringent constraints on κ_λ.
- Upper limits on the mass of $X \rightarrow HH(bb\gamma\gamma)$ set using the resonant channel.



	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg \rightarrow HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

Constraining New Matter

- Set limits on both the Higgs self-coupling and the *gg*F production cross-section for non-resonant *HH*.
- $bb\gamma\gamma$ sets stringent constraints on κ_λ.
- **Upper limits on the mass of $X \rightarrow HH(bb\gamma\gamma)$ set using the resonant channel.**



	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\rightarrow HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

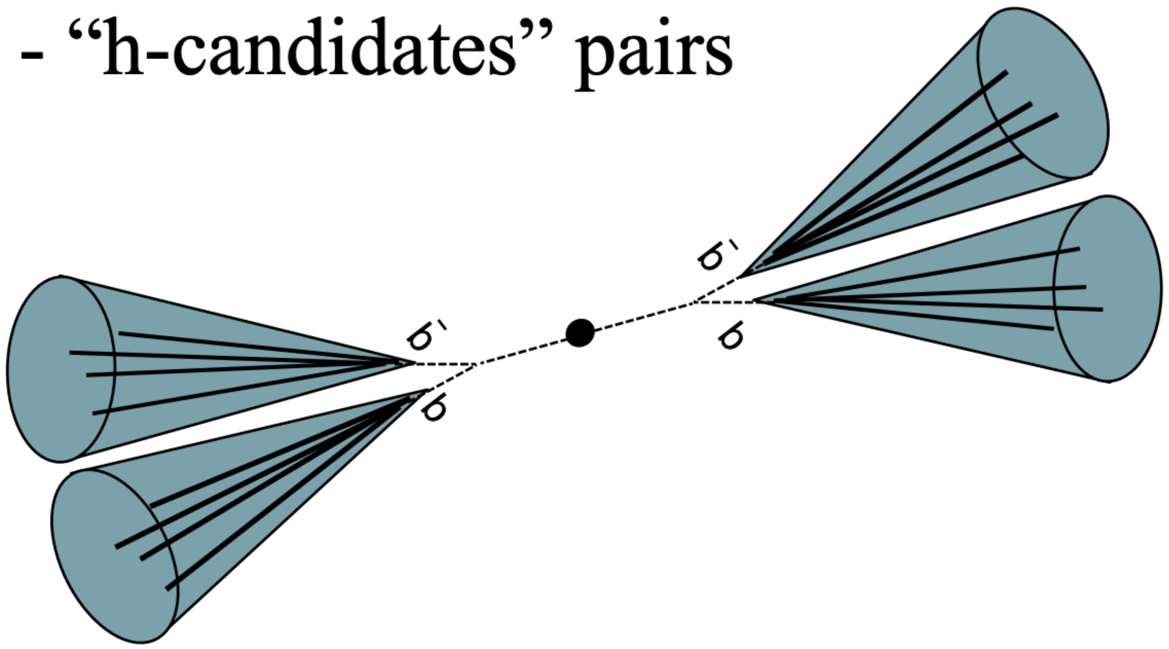
$HH \to bbbb$ and $HH \to bb\tau\tau$ @ 36 fb^{-1}

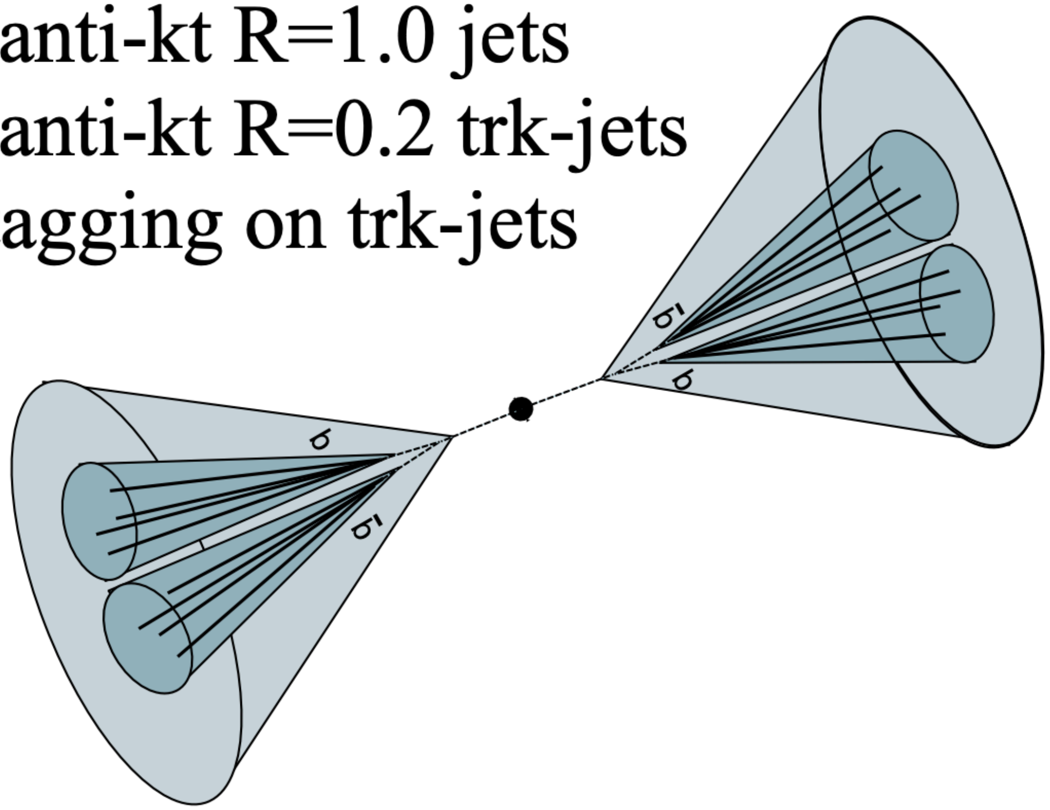
bbbb channel

- *bbbb* uses a **combination of small and large-radius jets** to target highly-boosted resonant production.

Resolved Analysis:
- 4 btagged anti-kt 0.4 jets
- "h-candidates" pairs

Boosted Analysis:
- 2 anti-kt R=1.0 jets
- 4 anti-kt R=0.2 trk-jets
- btagging on trk-jets





X→hh low mass ≤ 1 TeV
non-resonant search

X→hh high mass ≥ 1 TeV

*From J. Alison

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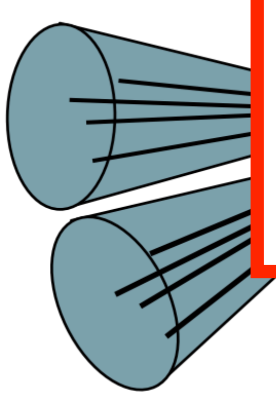
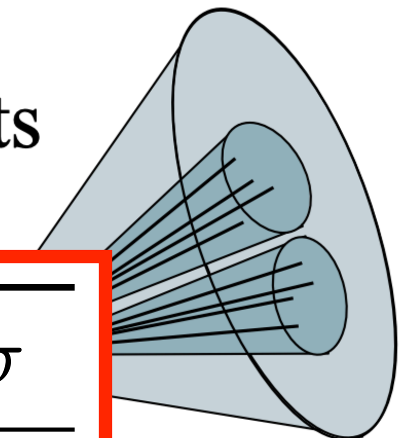


Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
12.9	11.1	14.9	20.7	30.0	43.6



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$bb\tau\tau$ channel

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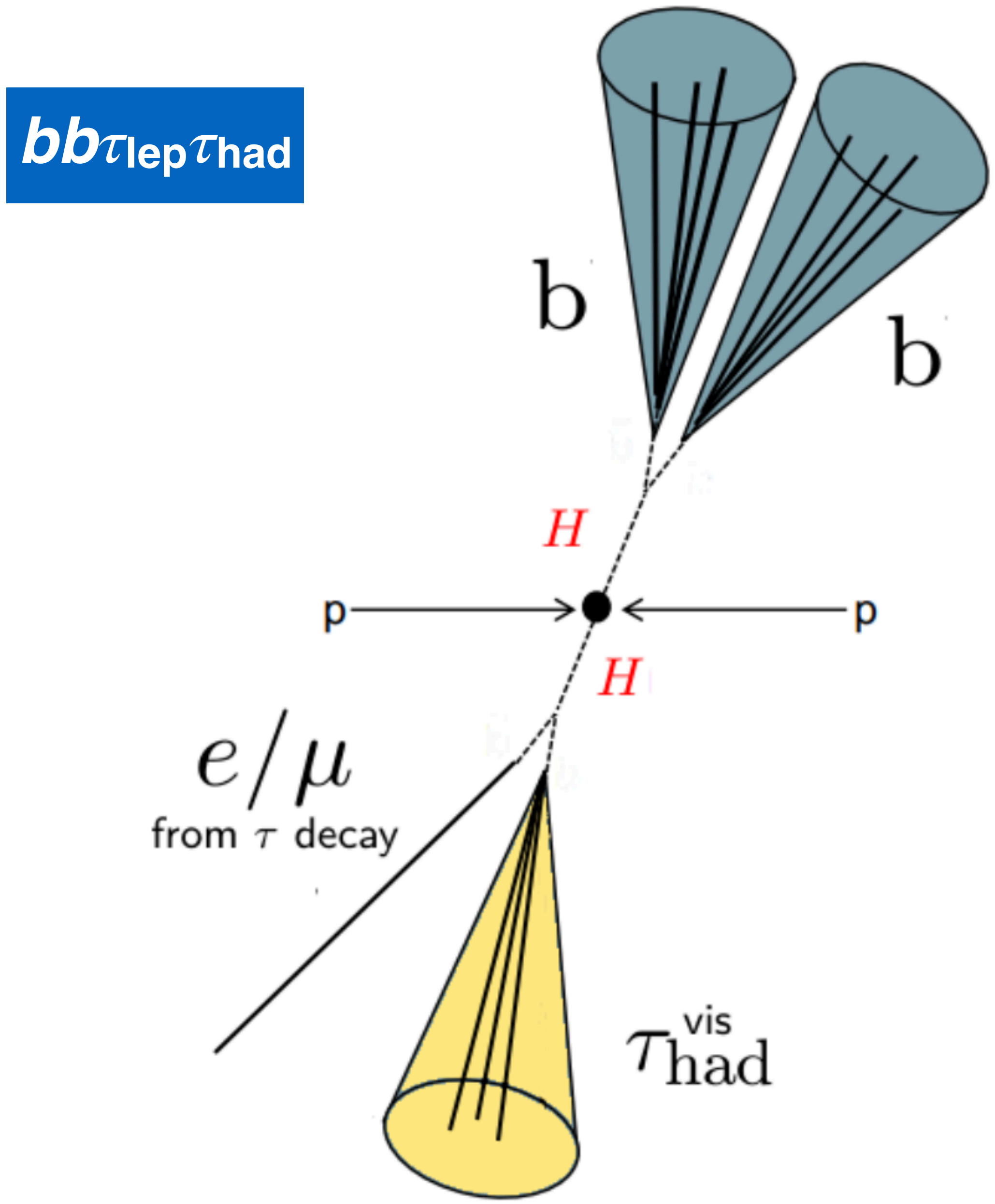
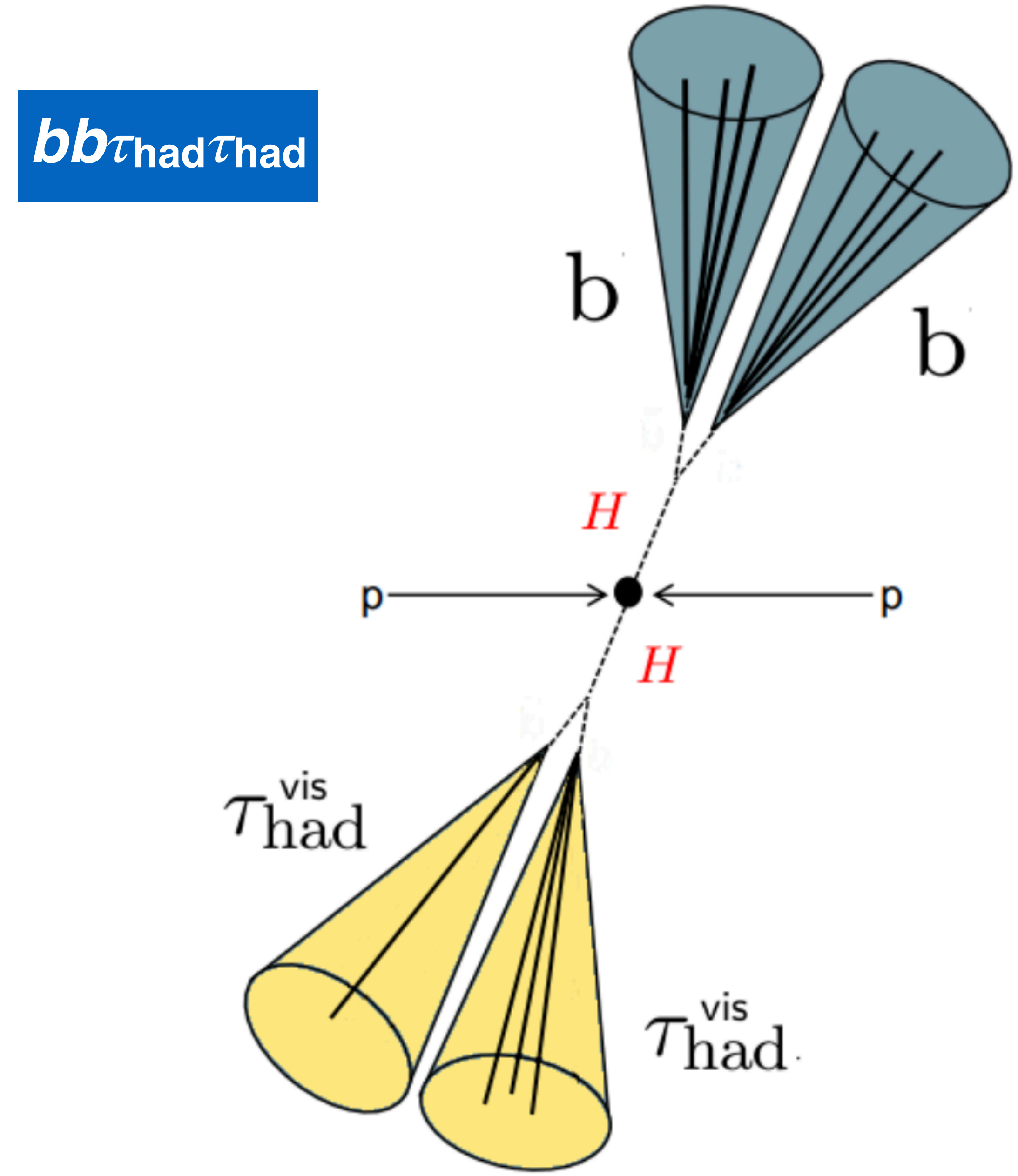


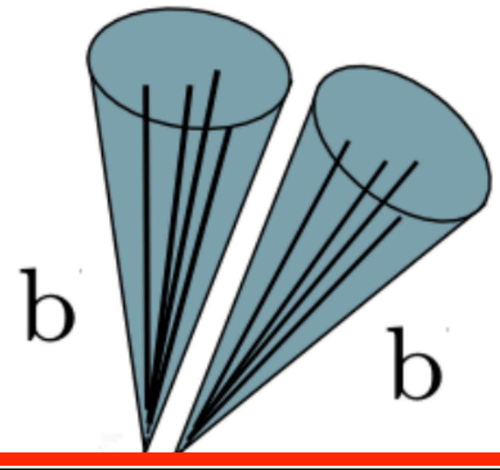


- Single lepton triggering on events, with exactly two *b*-tagged jets and a "missing mass" > 60 GeV.

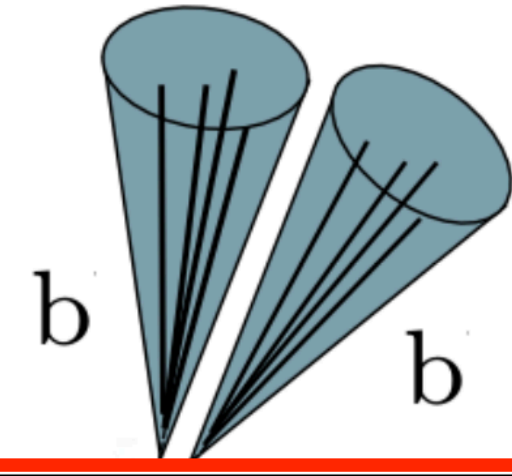
From arXiv:1808.00336

$bb\tau\tau$ channel

$bb\tau_{lep}\tau_{had}$



$bb\tau_{had}\tau_{had}$



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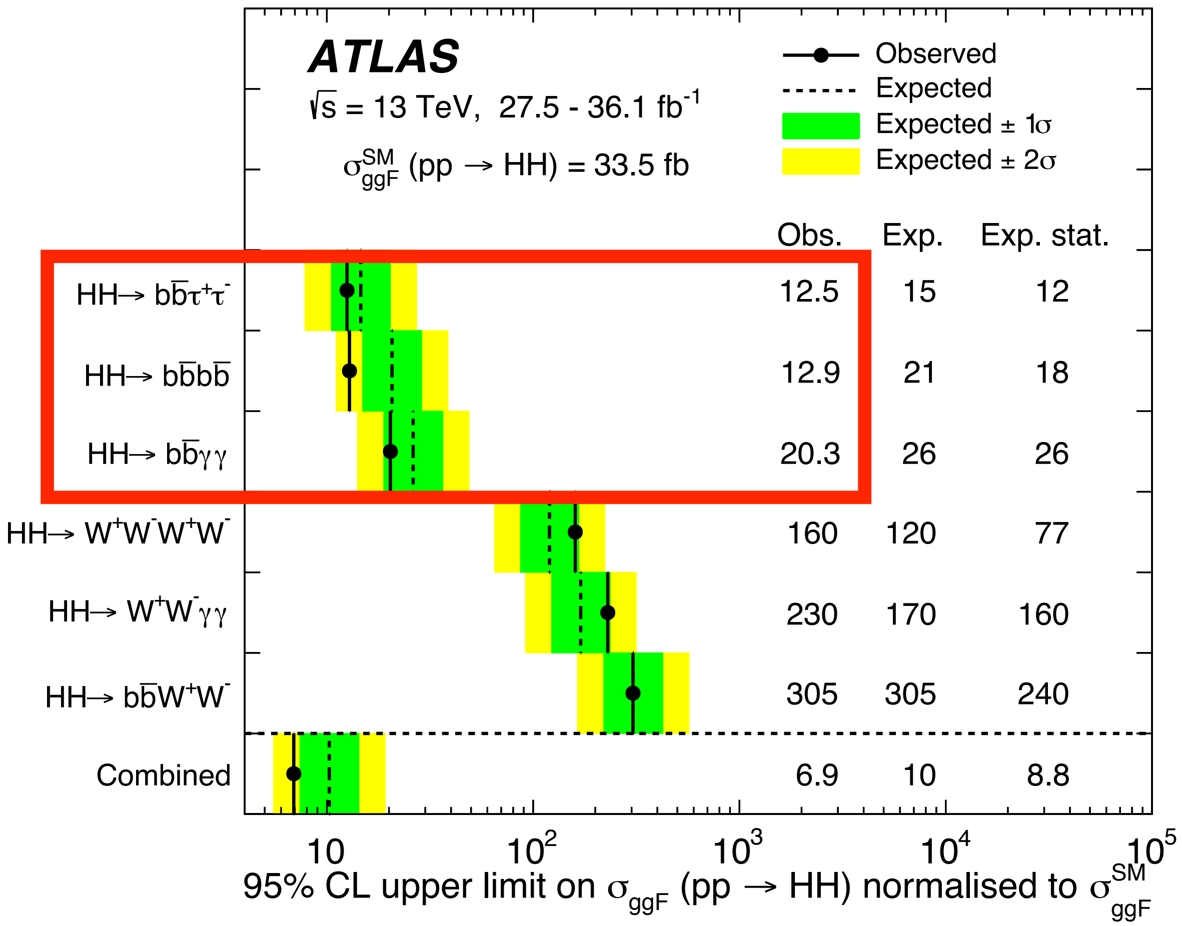
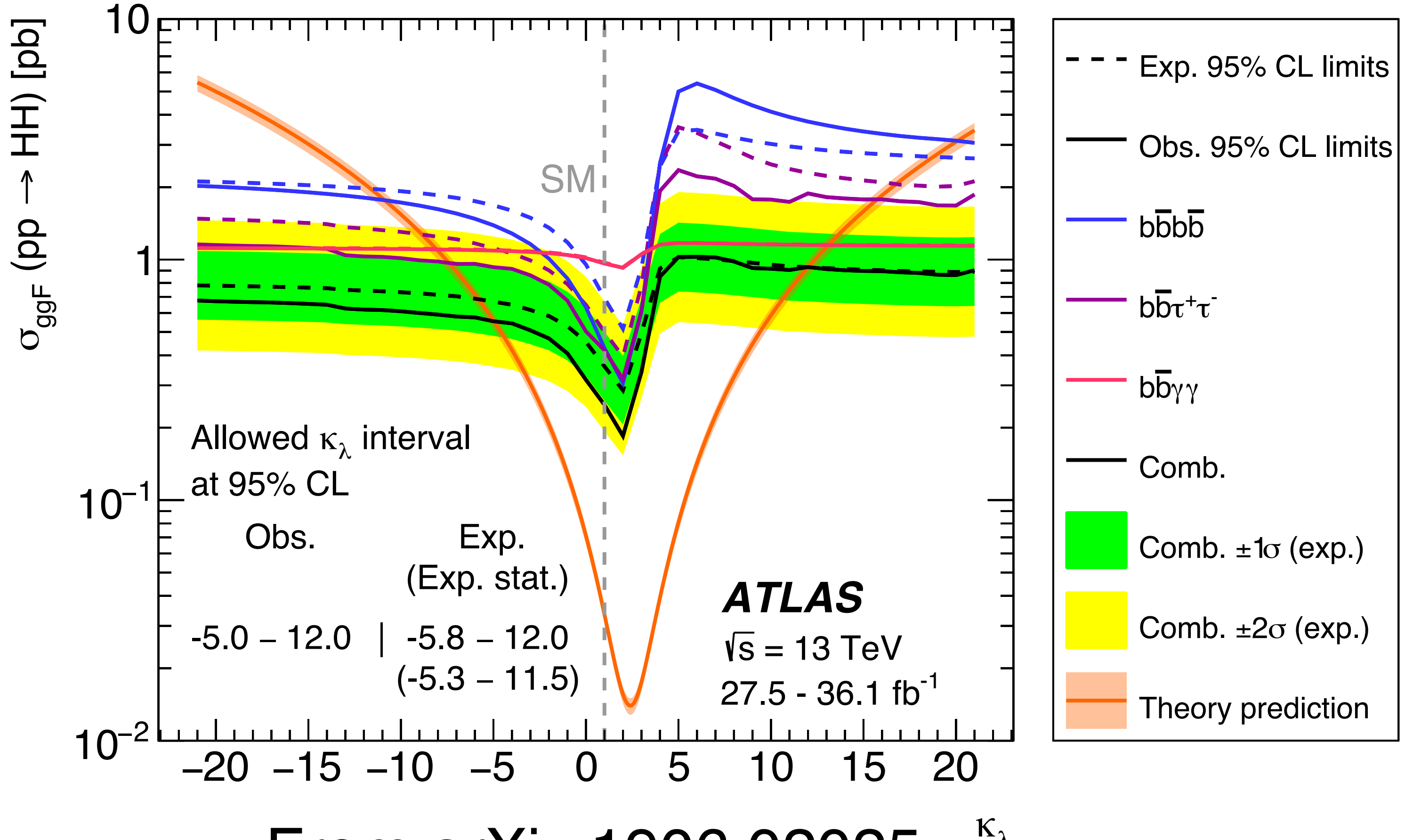
HH Combinations

Signal strength, $\sigma_{HH}/\sigma_{HH}^{SM}$



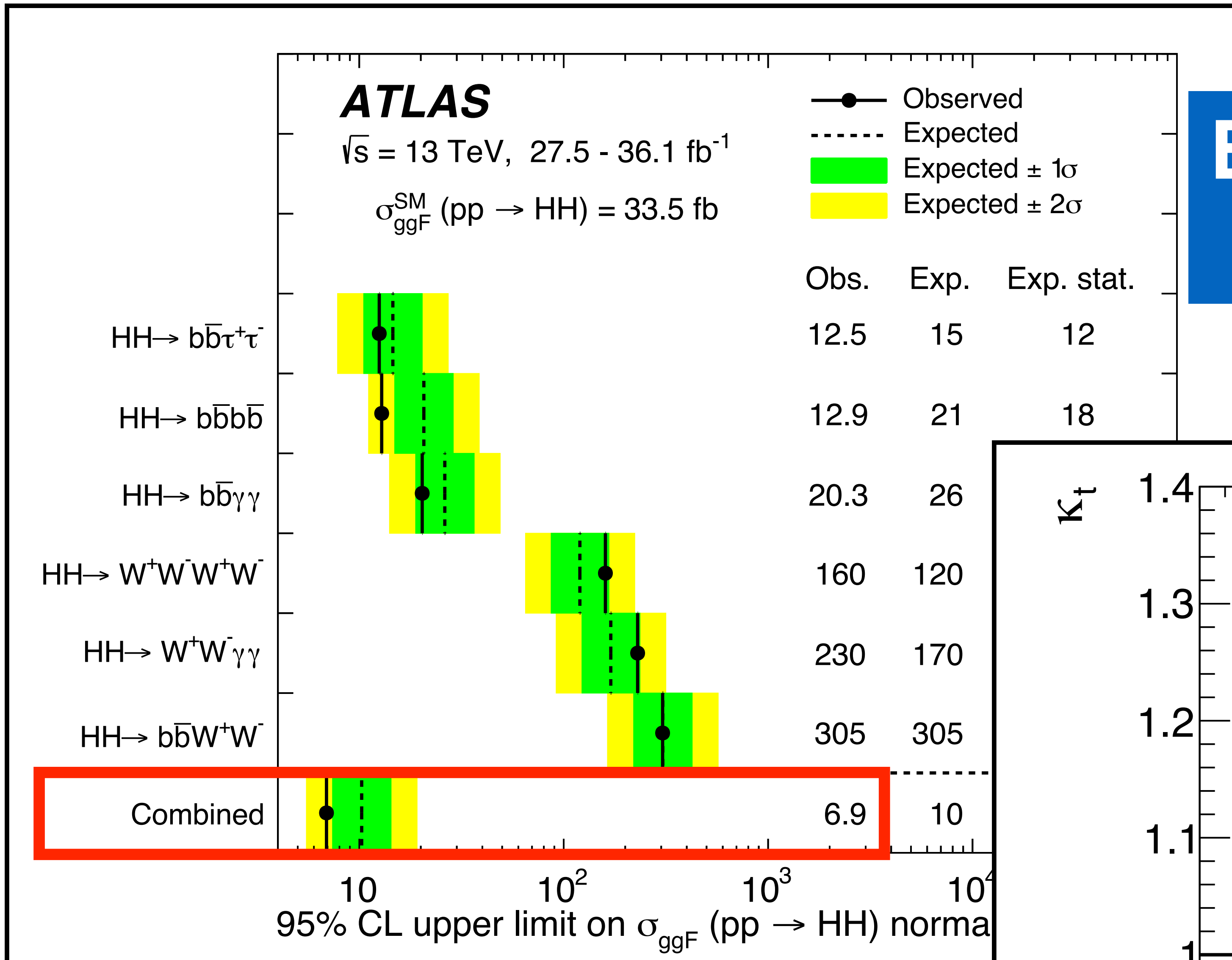
κ_λ scan



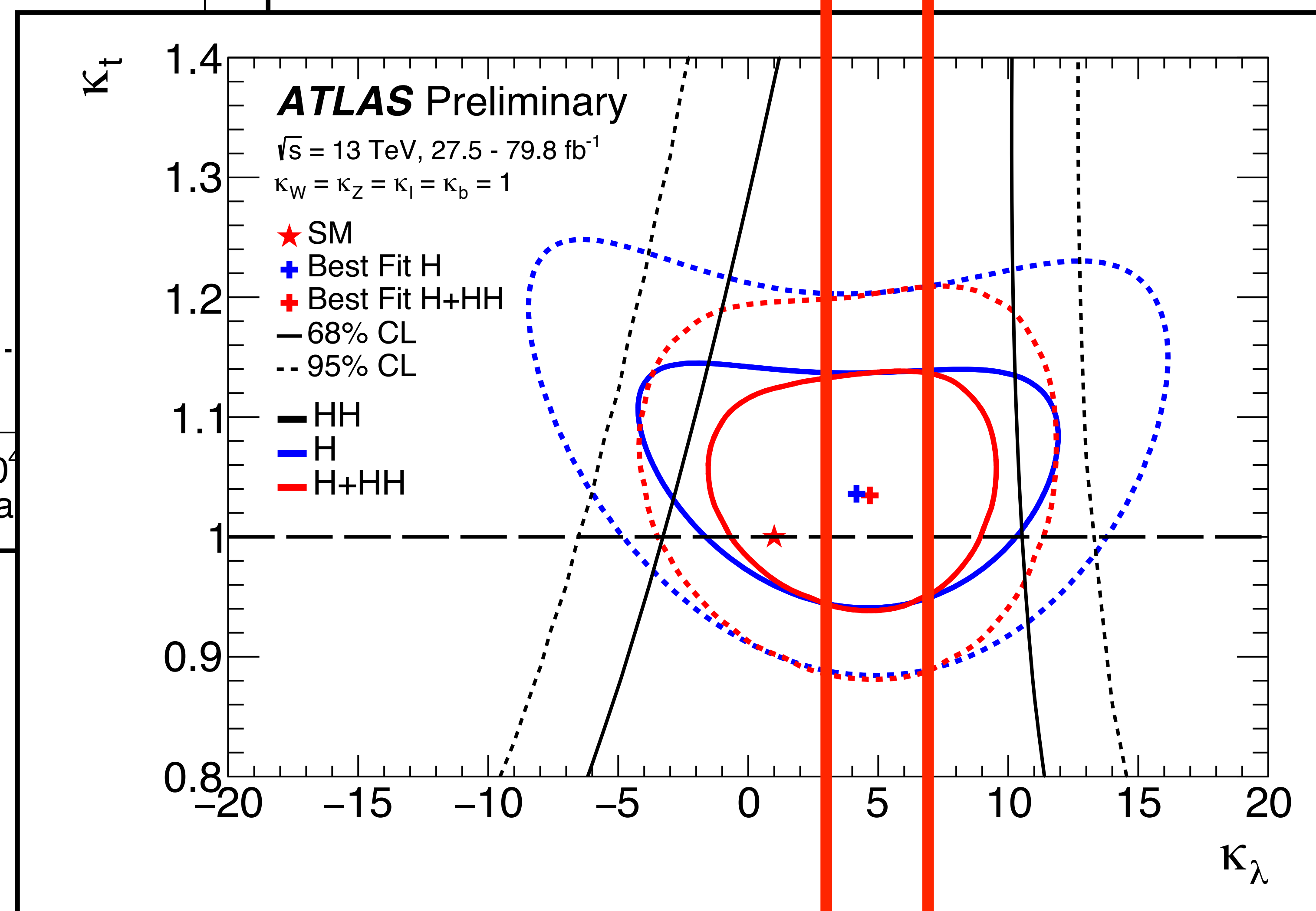
From arXiv:1906.02025

- *bbττ, bbγγ, bbbb* provide the most sensitive limits on the cross-section of non-resonant *HH* production.
- **Combine *bbττ, bbγγ, bbbb*** in a 2015+2016 limit of **—5.0 < κ_λ < 12.0**.

HH Combinations

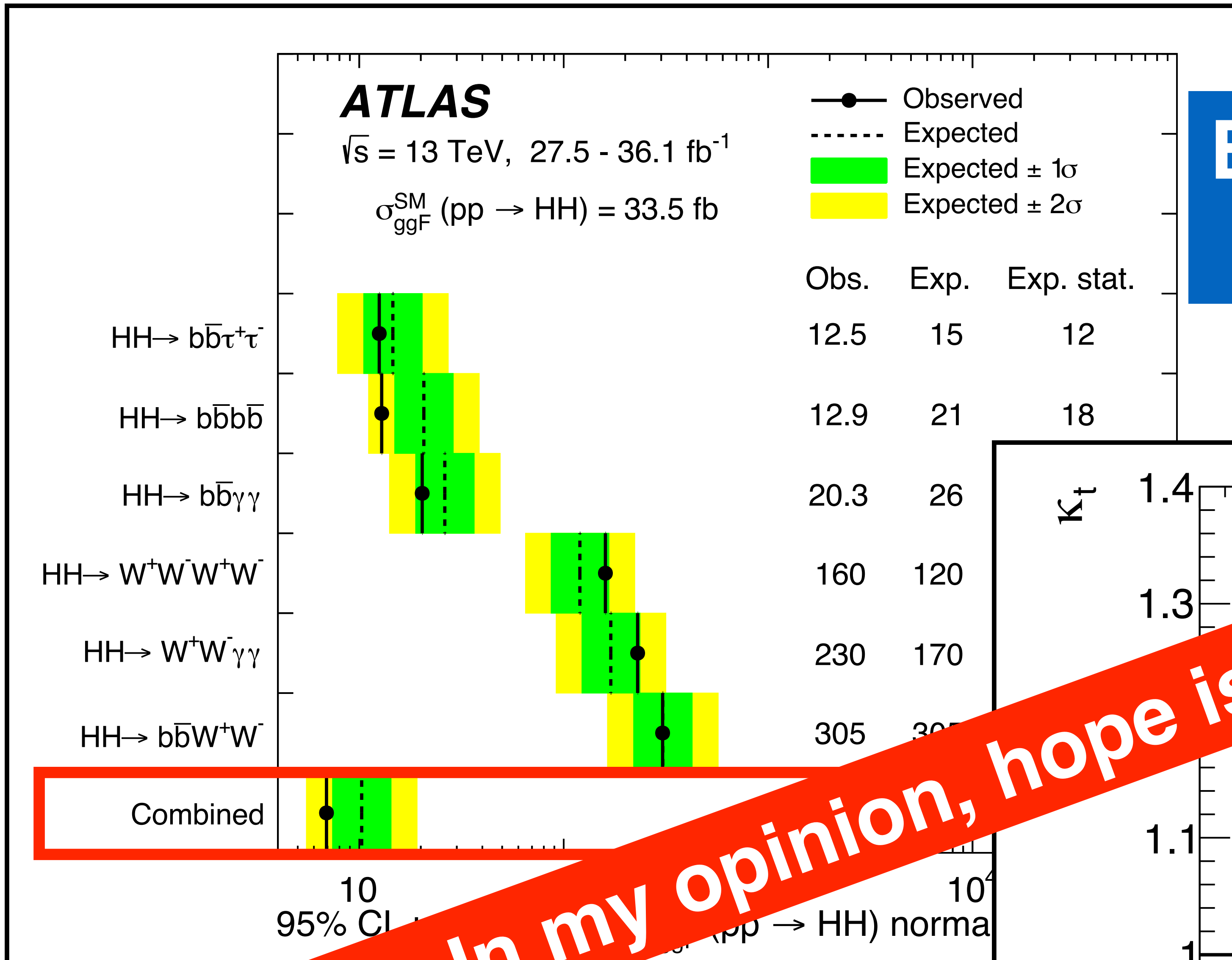


Best fit *H+HH* combination:
$\kappa_\lambda = 4.7$



Combined upper limit
$\sigma_{HH} \;/\; \sigma_{HH}^{SM} < 6.9$

HH Combinations



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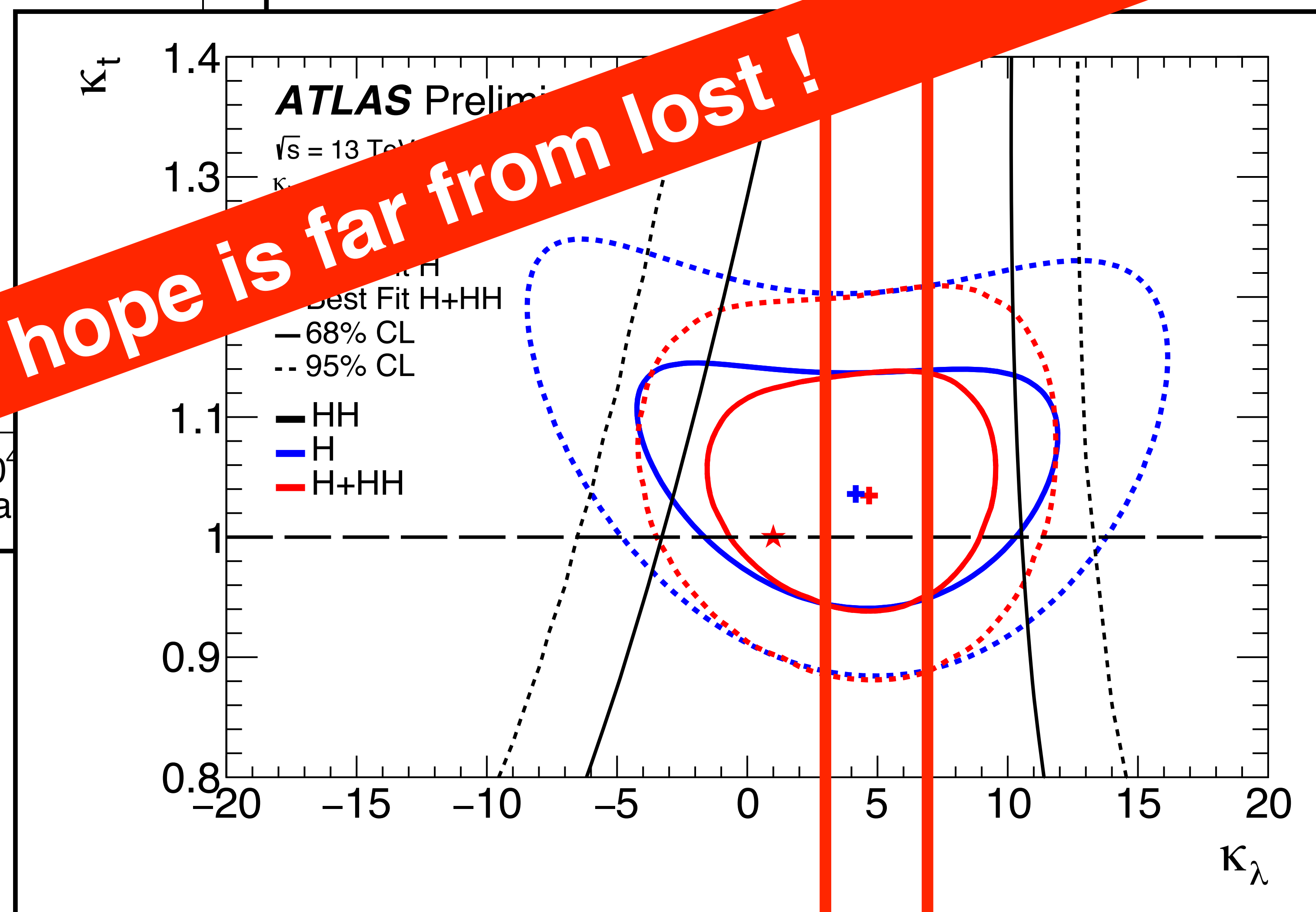

In my opinion, hope is far from lost !

Combined upper limit
σ_{HH} / σ_{HH}^{SM} < 6.9

Future Prospects

An optimistic illustration ? …

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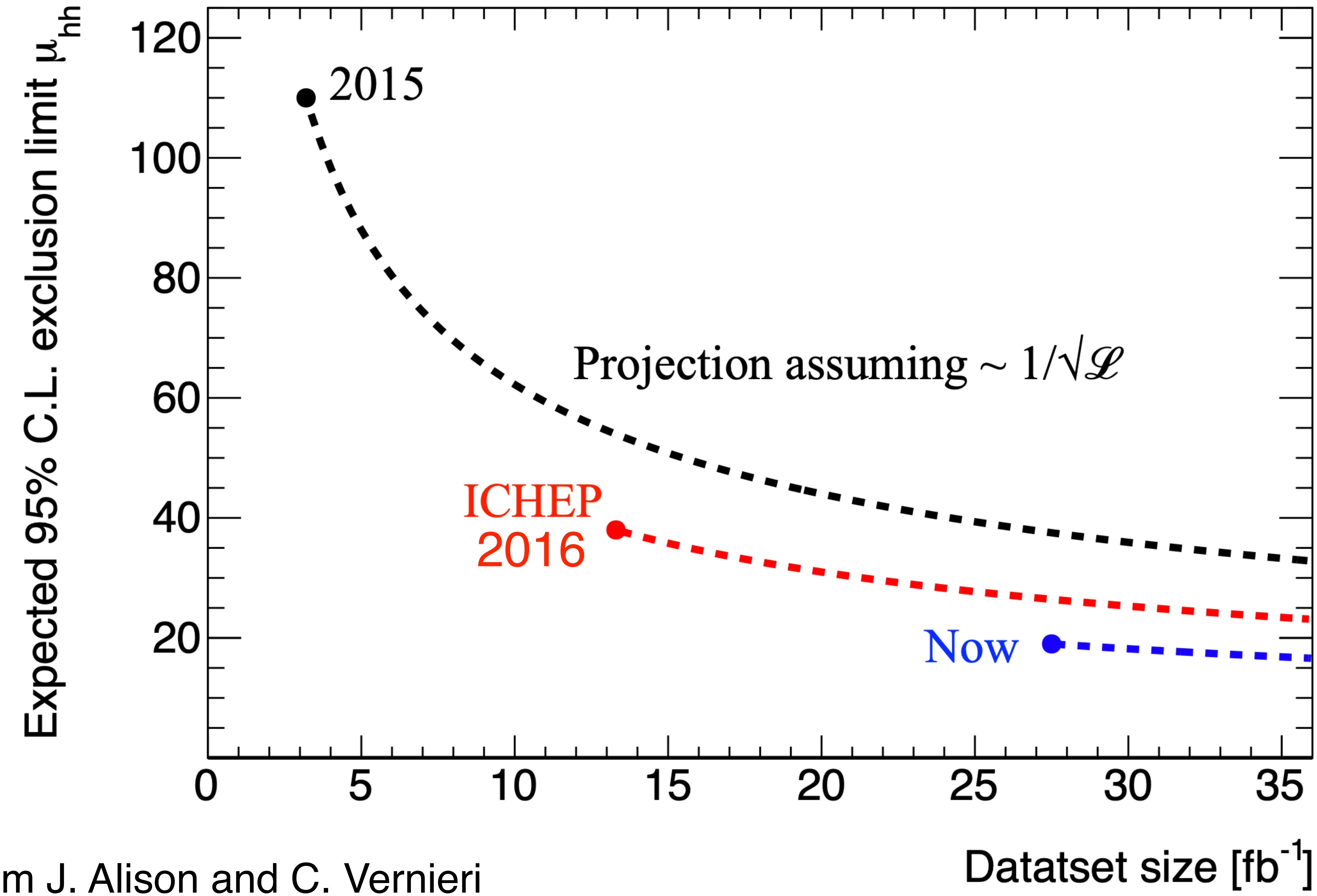
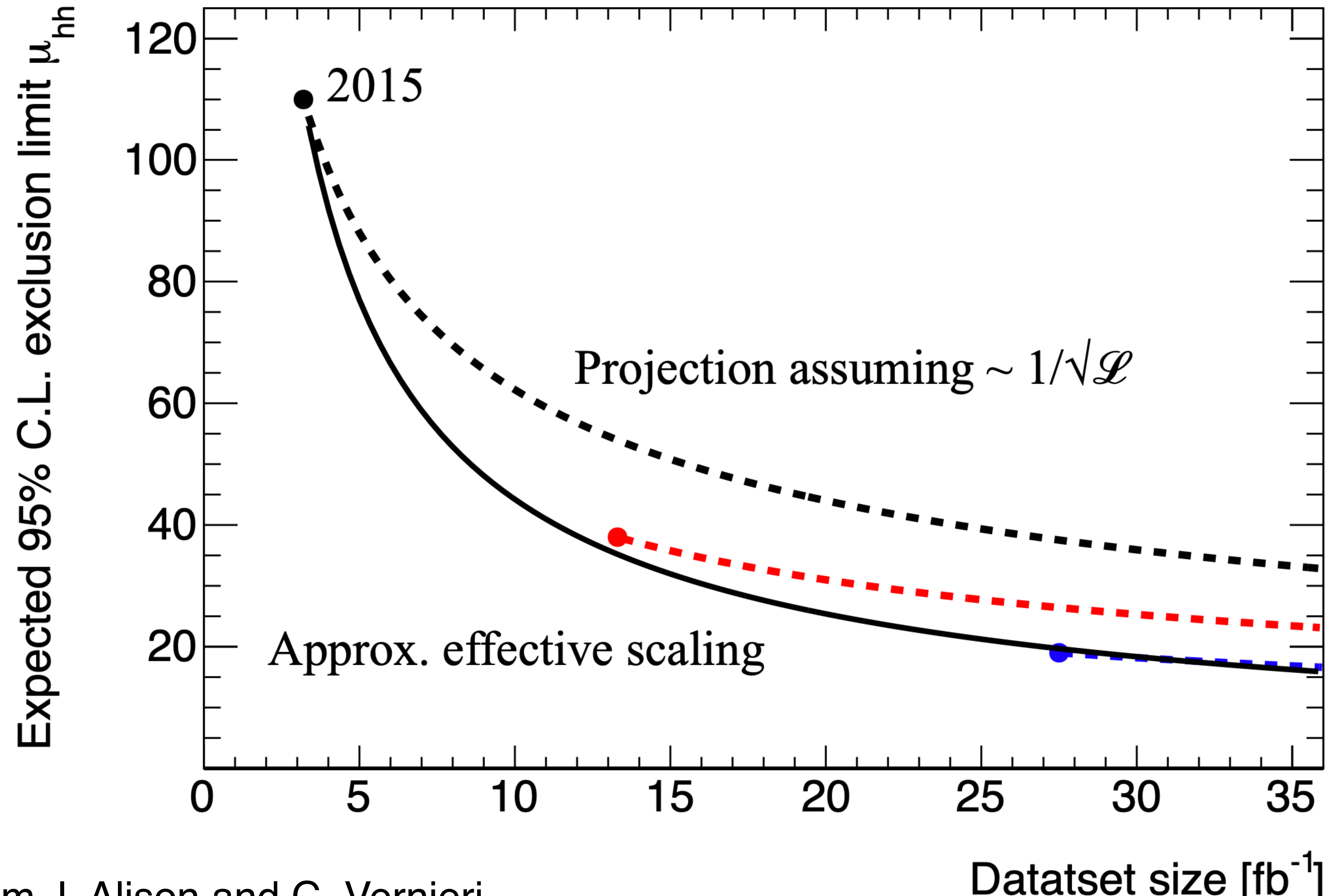


*From J. Alison and C. Vernieri

An optimistic illustration ? …



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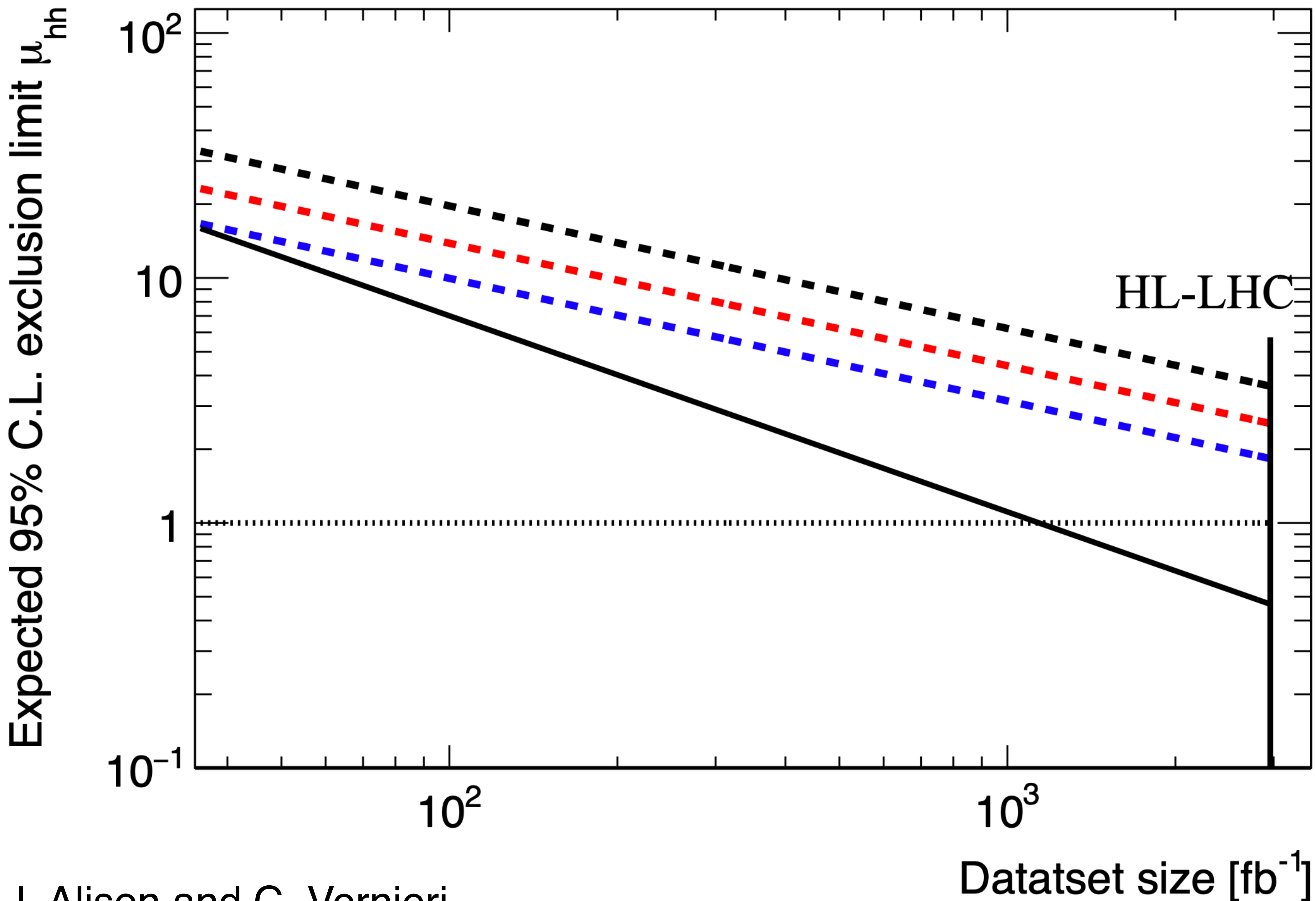
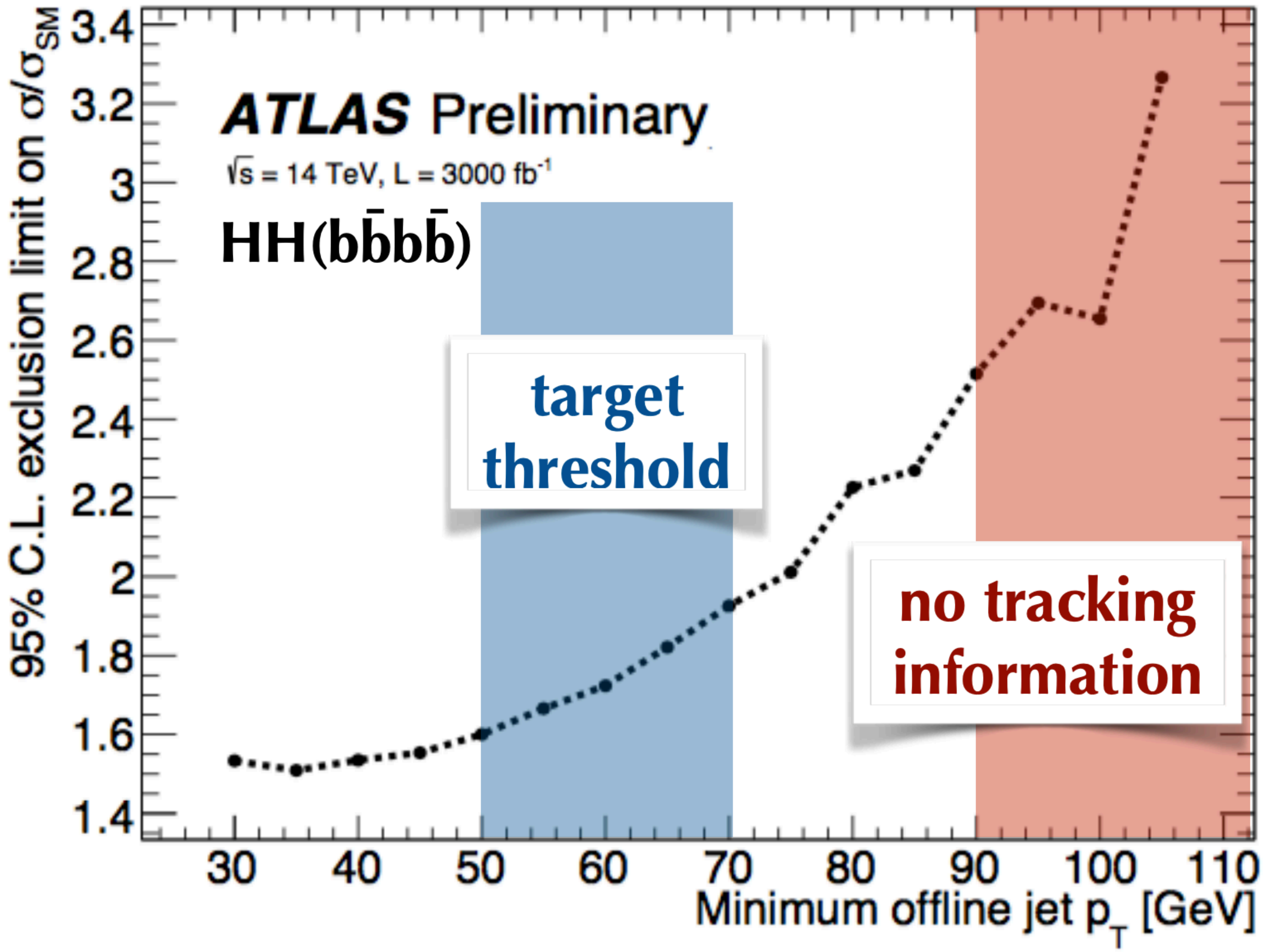


*From J. Alison and C. Vernieri

A closing example



- **Tracking information at the trigger level** will be crucial to discovering *HH* at the LHC.

A closing example

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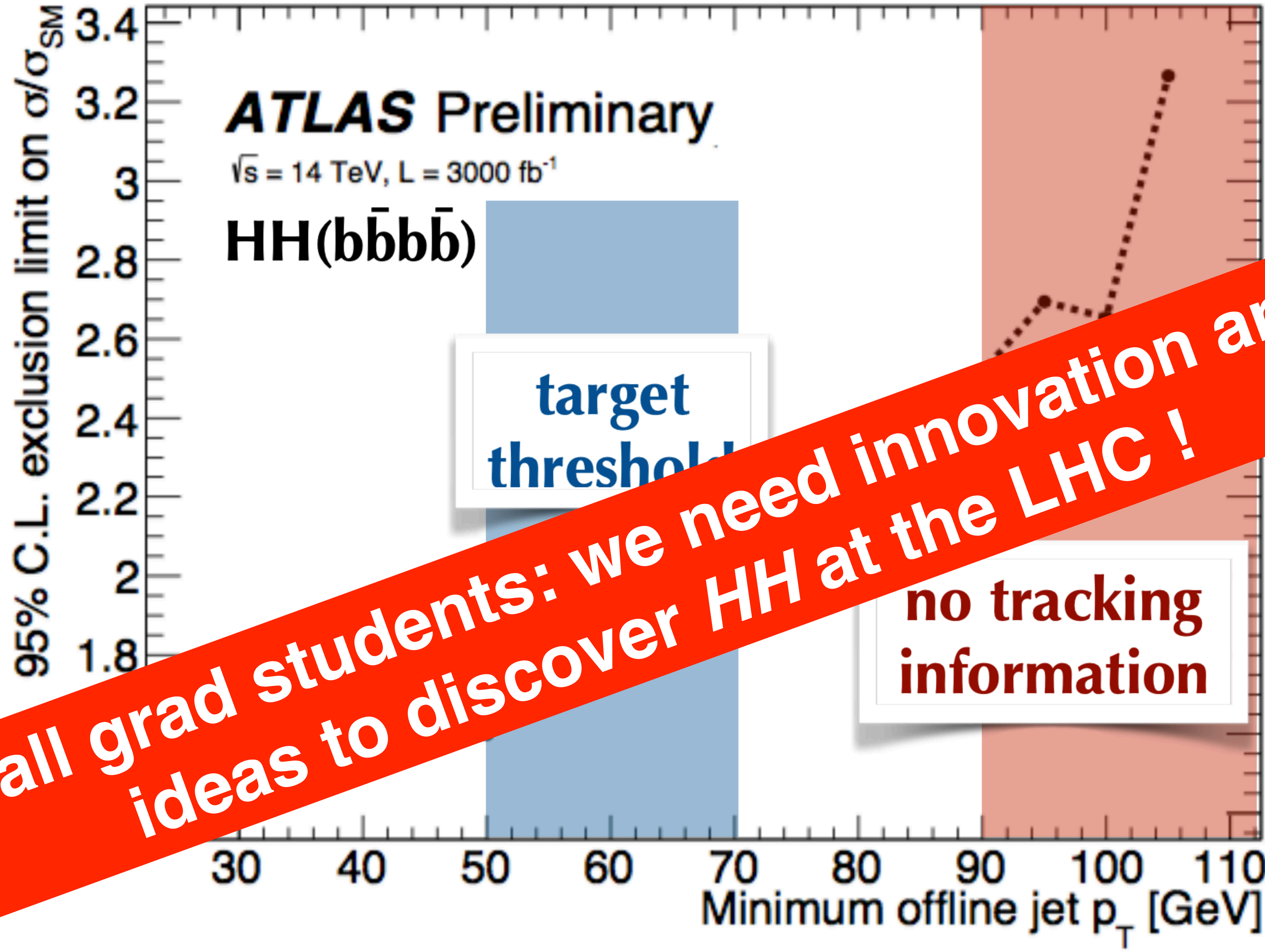

Calling all grad students: we need innovation and fresh ideas to discover *HH* at the LHC !

- **Tracking information at the trigger level** will be crucial to discovering *HH* at the LHC.

Summary

- **Breakthroughs in fundamental physics rely on establishing connections** => particle physics and cosmology of EWSB.

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- **Breakthroughs in fundamental physics rely on establishing connections** => particle physics and cosmology of EWSB.
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- At ATLAS we are pushing the boundaries of innovation and making **large gains in *HH* sensitivity**, even without the full run 2 dataset.

Summary

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- **Breakthroughs in fundamental physics rely on establishing connections** => particle physics and cosmology of EWSB.
- *HH* production allows us to probe the **global shape of the Higgs potential** for the first time. Powerful implications for EWSB and inflation.
- At ATLAS we are pushing the boundaries of innovation and making **large gains in *HH* sensitivity**, even without the full run 2 dataset.
- Prospects for discovery at (or even before ?) the HL-LHC are promising, but we **need bright ideas and innovation**.
- I think we live in very exciting times for *HH* prospects. **Come join the fun !**

Thank you !

Backup

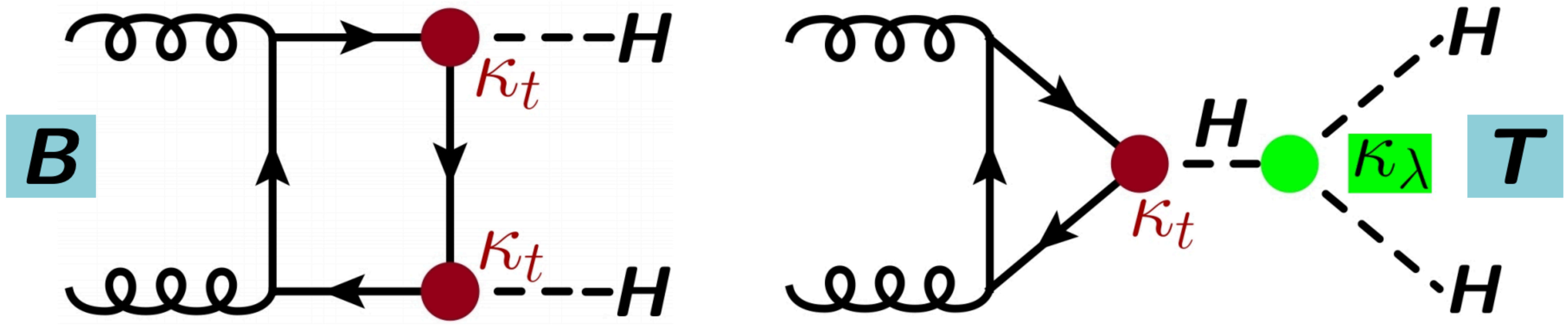
Varying κ_λ

HH production modified

True to all orders *in QCD*

*From P. Bokan

(using scale factors: $\kappa_t = g_{t\bar{t}H}/g_{t\bar{t}H}^{SM}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$)



$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

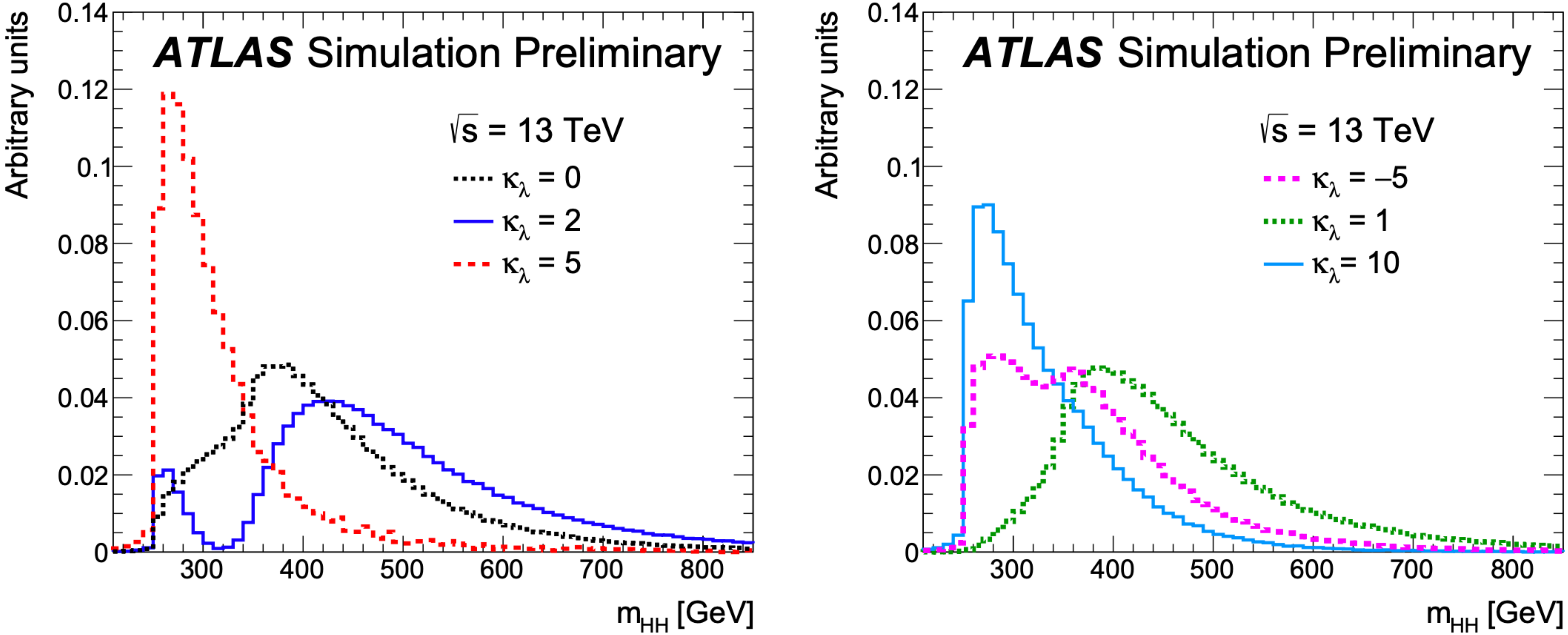
$$A(1,0) = B \qquad A(1,1) = B + T \qquad A(1,2) = B + 2T$$

Express $|B|^2$, $|T|^2$ and $(BT^* + TB^*)$ in terms of $|A(1,0)|^2$, $|A(1,1)|^2$ and $|A(1,2)|^2$, which leads to:

$$|A(\kappa_t, \kappa_\lambda)|^2 = a(\kappa_t, \kappa_\lambda)|A(1,0)|^2 + b(\kappa_t, \kappa_\lambda)|A(1,1)|^2 + c(\kappa_t, \kappa_\lambda)|A(1,2)|^2$$

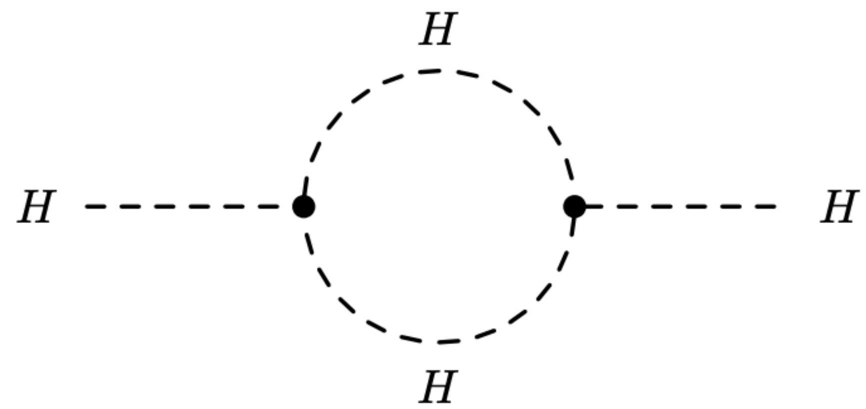
Any $(\kappa_t, \kappa_\lambda)$ combination at LO can be obtained from a **linear combination** of some 3 $(\kappa_t \neq 0, \kappa_\lambda)$ samples!

m_{HH} for Different κ_λ

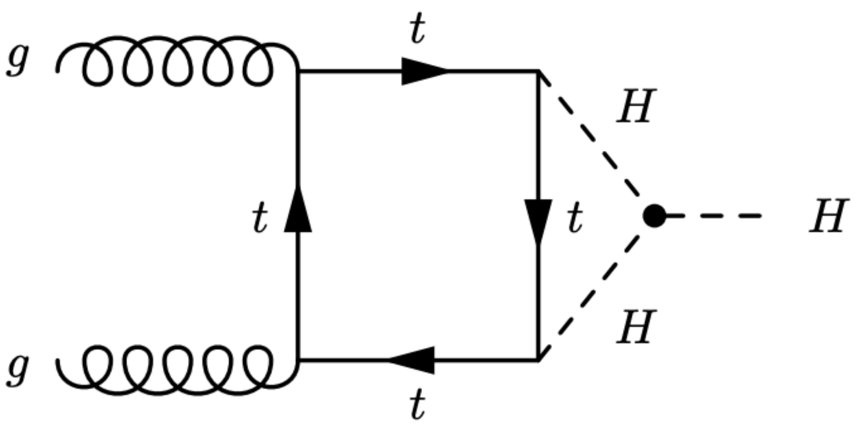


- Get **different interference effects across m_{HH}**, particularly for $\kappa_\lambda = 2$.
- m_{HH} and p_T^{HH} can be dramatically modified.

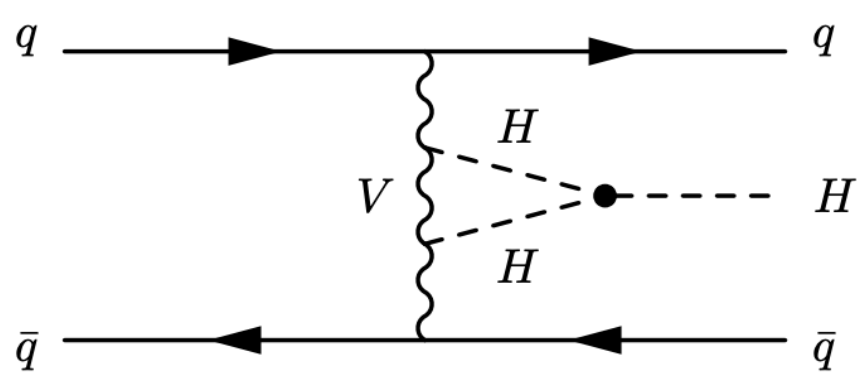
NLO EW enhancements on κ_λ



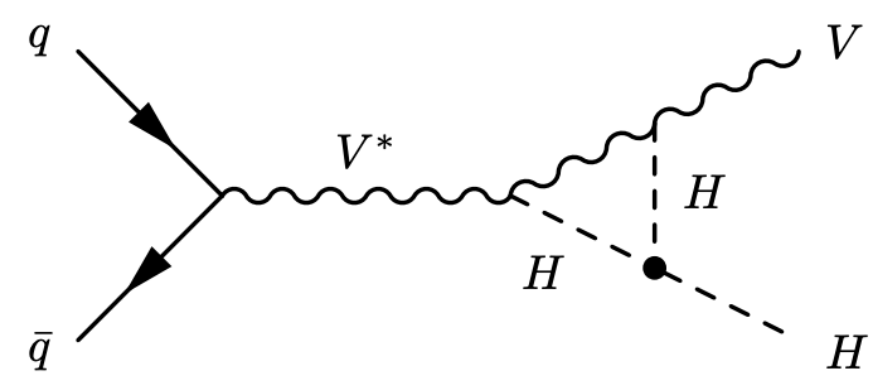
(a)



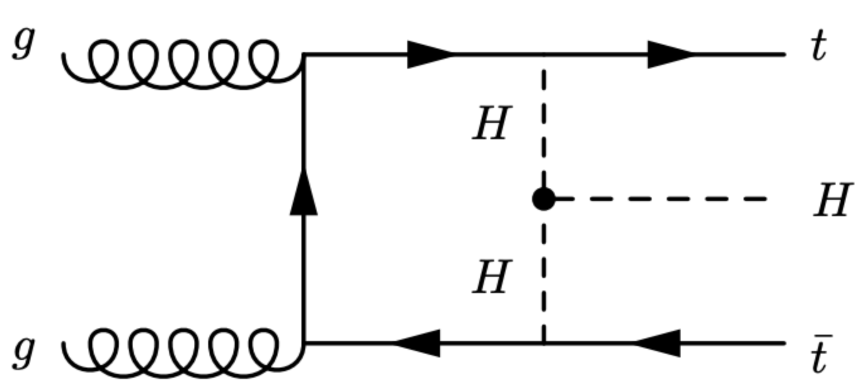
(b)



(c)



(d)



(e)

Non-resonant and Resonant Regions

	Non-resonant			
	1-tag		2-tag	
	Loose	Tight	Loose	Tight
$m_{\gamma\gamma}$ range [GeV]	105–160	105–160	105–160	105–160
Jet b-tagging WPs used	60% + BDT	60% + BDT	70%	70%
Leading jet p_T [GeV]	>40	>100	>40	>100
Subleading jet p_T [GeV]	>25	>105	>25	>30
m_{jj} range [GeV]	80–140	90–140	80–140	90–140

	Resonant			
	1-tag		2-tag	
	Loose	Tight	Loose	Tight
$m_{\gamma\gamma}$ range [GeV]	120.39–129.79	120.79–129.39	120.39–129.79	120.79–129.39
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$bb\gamma\gamma$ Systematic Uncertainties

Source of systematic uncertainty		% effect relative to nominal in the 2-tag (1-tag) category							
		Non-resonant analysis				Resonant analysis: BSM HH			
		SM HH signal		Single-H bkg		Loose selection		Tight selection	
Luminosity		±2.1	(±2.1)	±2.1	(± 2.1)	±2.1	(±2.1)	±2.1	(±2.1)
Trigger		±0.4	(±0.4)	±0.4	(± 0.4)	±0.4	(±0.4)	±0.4	(±0.4)
Pile-up modelling		±3.2	(±1.3)	±2.0	(± 0.8)	±4.0	(±4.2)	±4.0	(±3.8)
Photon	identification	±2.5	(±2.4)	±1.7	(± 1.8)	±2.6	(±2.6)	±2.5	(±2.5)
	isolation	±0.8	(±0.8)	±0.8	(± 0.8)	±0.8	(±0.8)	±0.9	(±0.9)
	energy resolution	-		-		±1.0	(±1.3)	±1.8	(±1.2)
	energy scale	-		-		±0.9	(±3.0)	±0.9	(±2.4)
Jet	energy resolution	±1.5	(±2.2)	±2.9	(± 6.4)	±7.5	(±8.5)	±6.4	(±6.4)
	energy scale	±2.9	(±2.7)	±7.8	(± 5.6)	±3.0	(±3.3)	±2.3	(±3.4)
Flavour tagging	b-jets	±2.4	(±2.5)	±2.3	(± 1.4)	±3.4	(±2.6)	±2.5	(±2.6)
	c-jets	±0.1	(±1.0)	±1.8	(±11.6)	-		-	
	light-jets	<0.1	(±5.0)	±1.6	(± 2.2)	-		-	
Theory	PDF+α_S	±2.3	(±2.3)	±3.1	(± 3.3)	n/a		n/a	
	Scale	+4.3	(+4.3)	+4.9	(+ 5.3)	n/a		n/a	
		−6.0	(−6.0)	+7.0	(+ 8.0)	n/a		n/a	
	EFT	±5.0	(±5.0)	n/a		n/a		n/a	

bbγγ Yields

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	1-tag		2-tag	
	Loose selection	Tight selection	Loose selection	Tight selection
Continuum background	117.5 ±4.7	15.7 ±1.6	21.0 ± 2.0	3.74 ± 0.78
SM single-Higgs-boson background	5.51 ±0.10	2.20 ±0.05	1.63 ± 0.04	0.56 ± 0.02
Total background	123.0 ±4.7	17.9 ±1.6	22.6 ± 2.0	4.30 ± 0.79
SM Higgs boson pair signal	0.219±0.006	0.120±0.004	0.305± 0.007	0.175± 0.005
Data	125	19	21	3

bbbb channel

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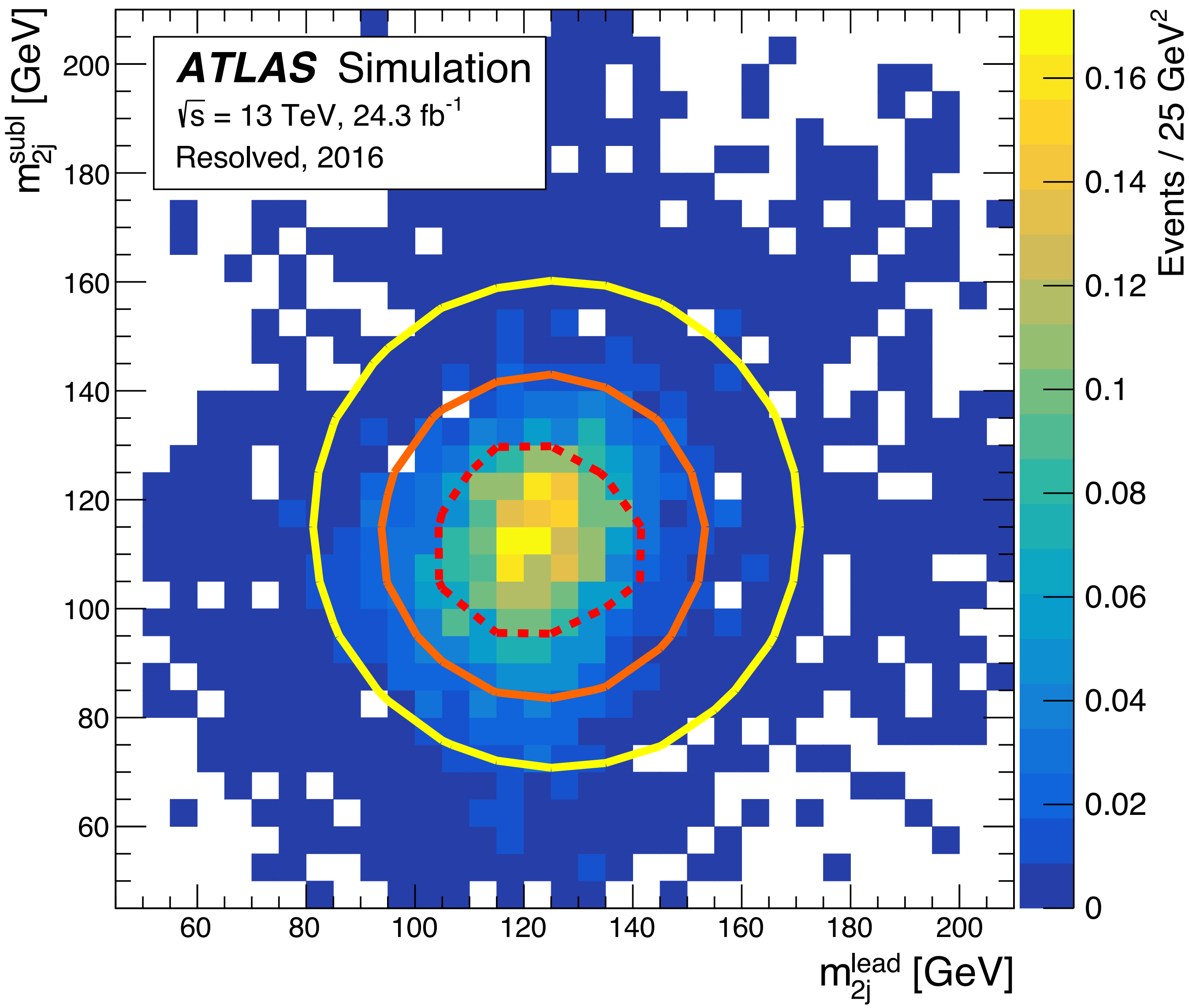
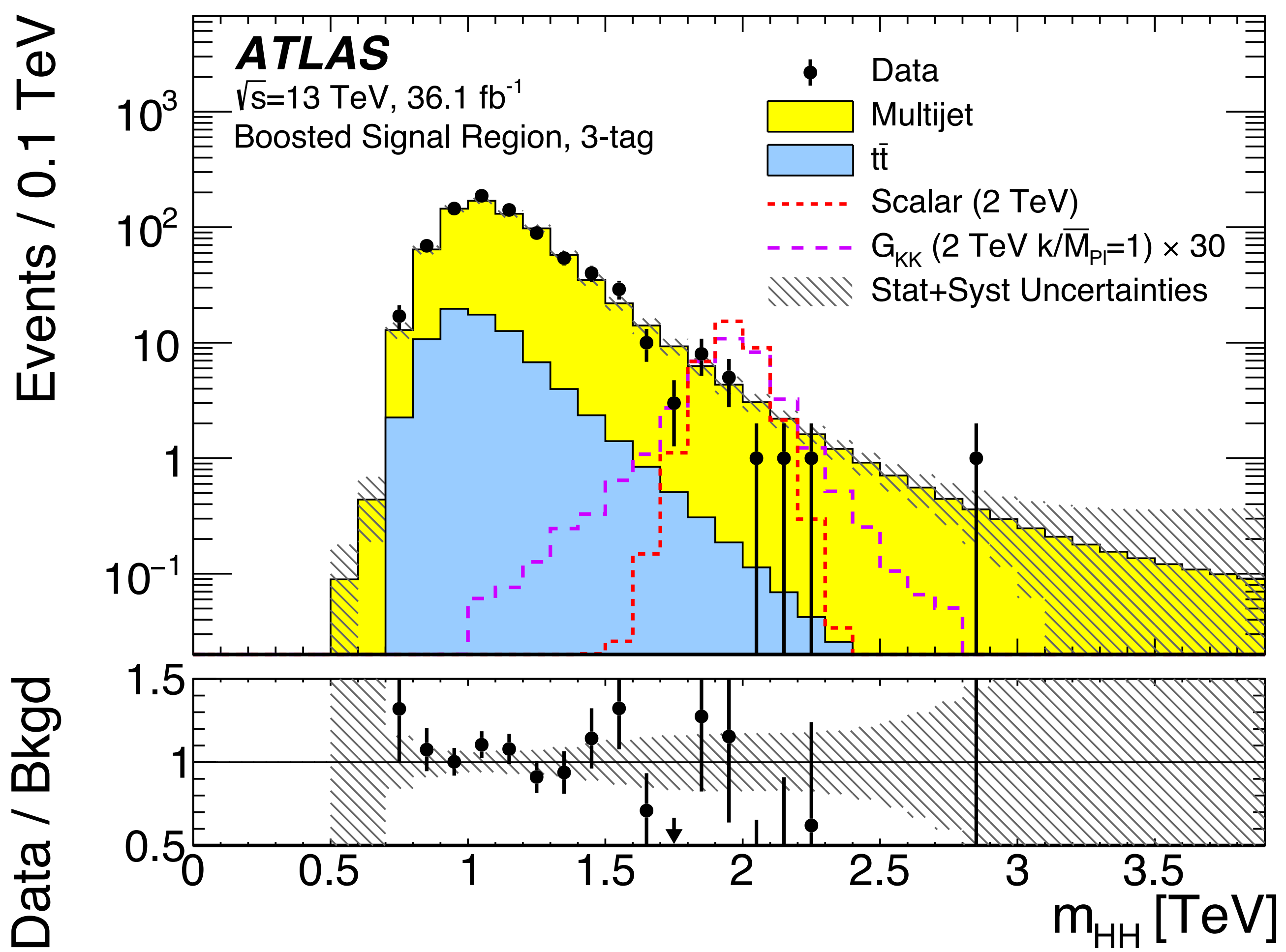
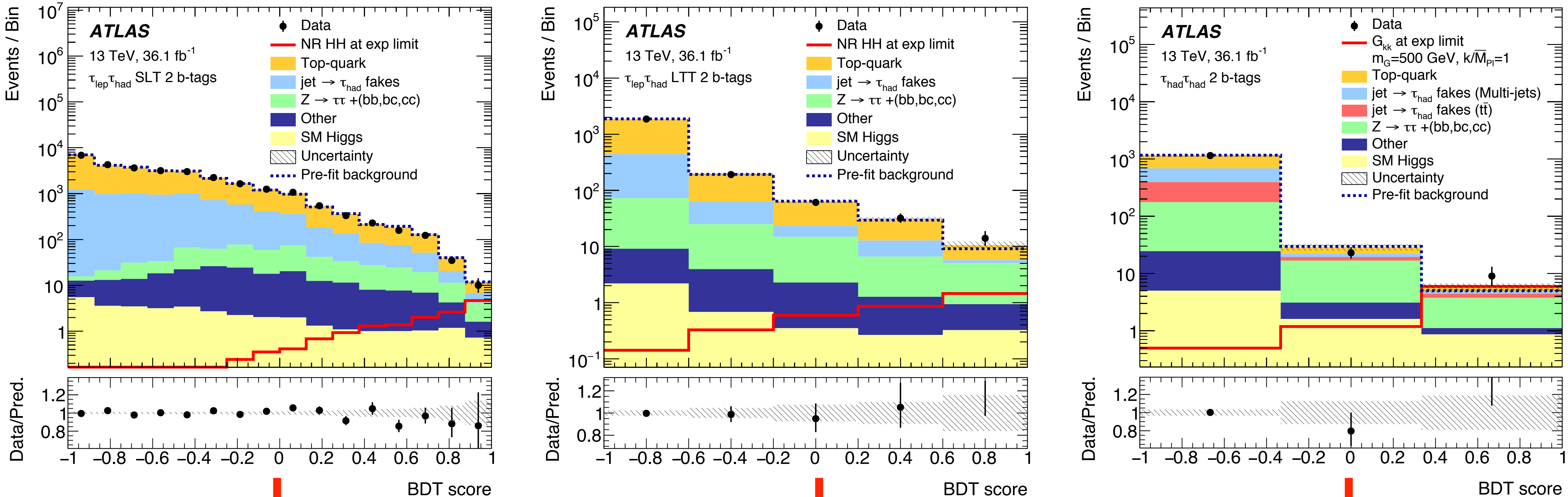
Resolved



Boosted



$HH \rightarrow bb\tau\tau$



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	σ/σ_{SM}	23.5	20.5	28.4	39.5
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$bb\tau\tau$ channel

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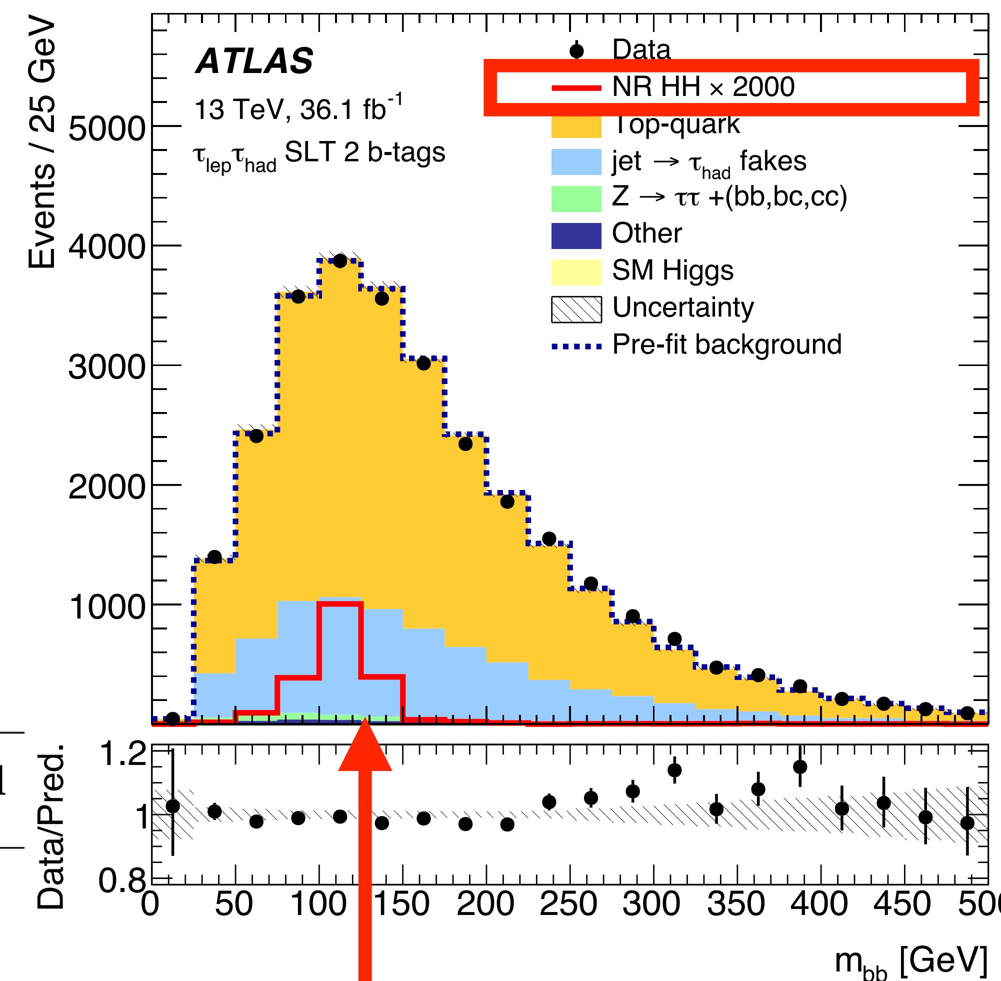
- Major analysis tool is the **Boosted Decision Tree** algorithm.
- Takes **different combinations of 11 kinematic variables** in the difference lep-had and had-had channels.

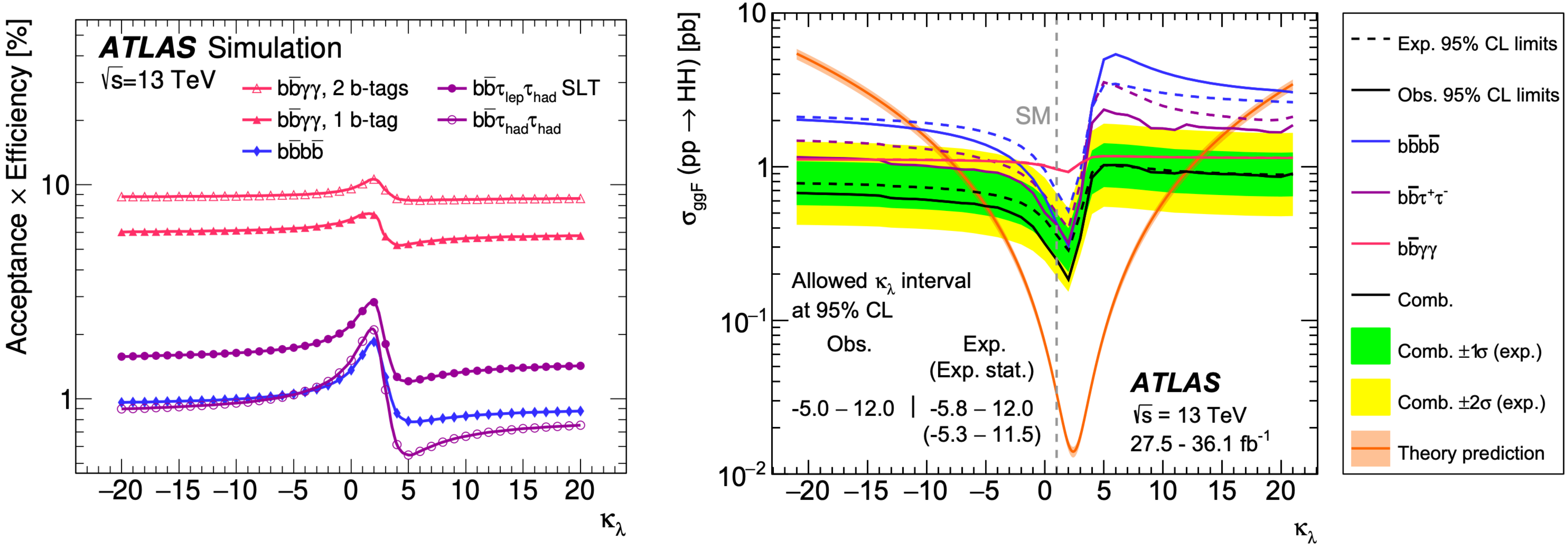


Variable	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel (SLT resonant)	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel (SLT non-resonant & LTT)	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\mathrm{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓		
$E_{\mathrm{T}}^{\mathrm{miss}}$ ϕ centrality	✓		✓
m_{T}^{W}	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_{\mathrm{T}}(\mathrm{lep},\tau_{\mathrm{had\text{-}vis}})$	✓		
Sub-leading b-jet p_{T}	✓		

- Scale of the signal !
- BDT inputs

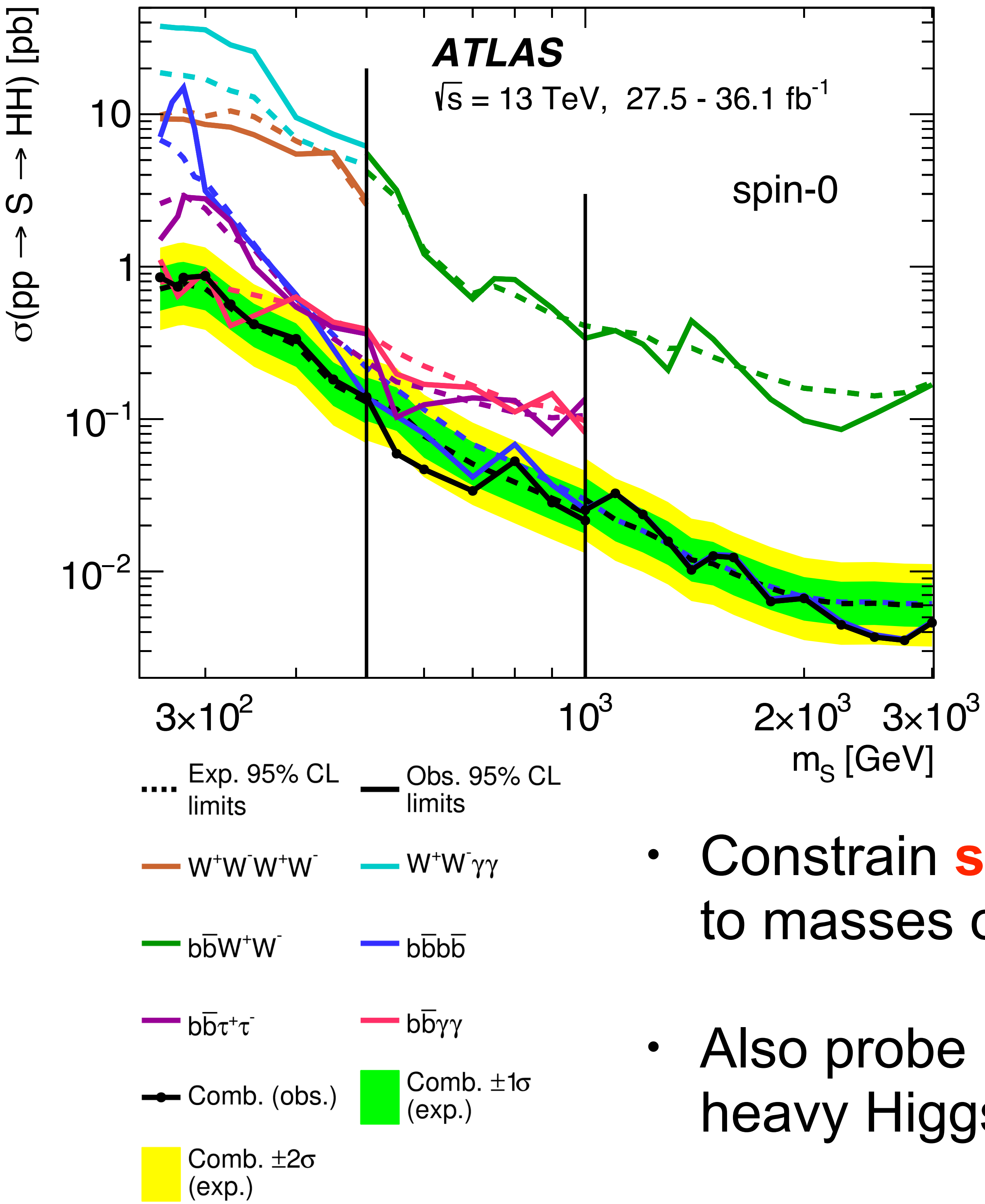
From arXiv:1808.00336

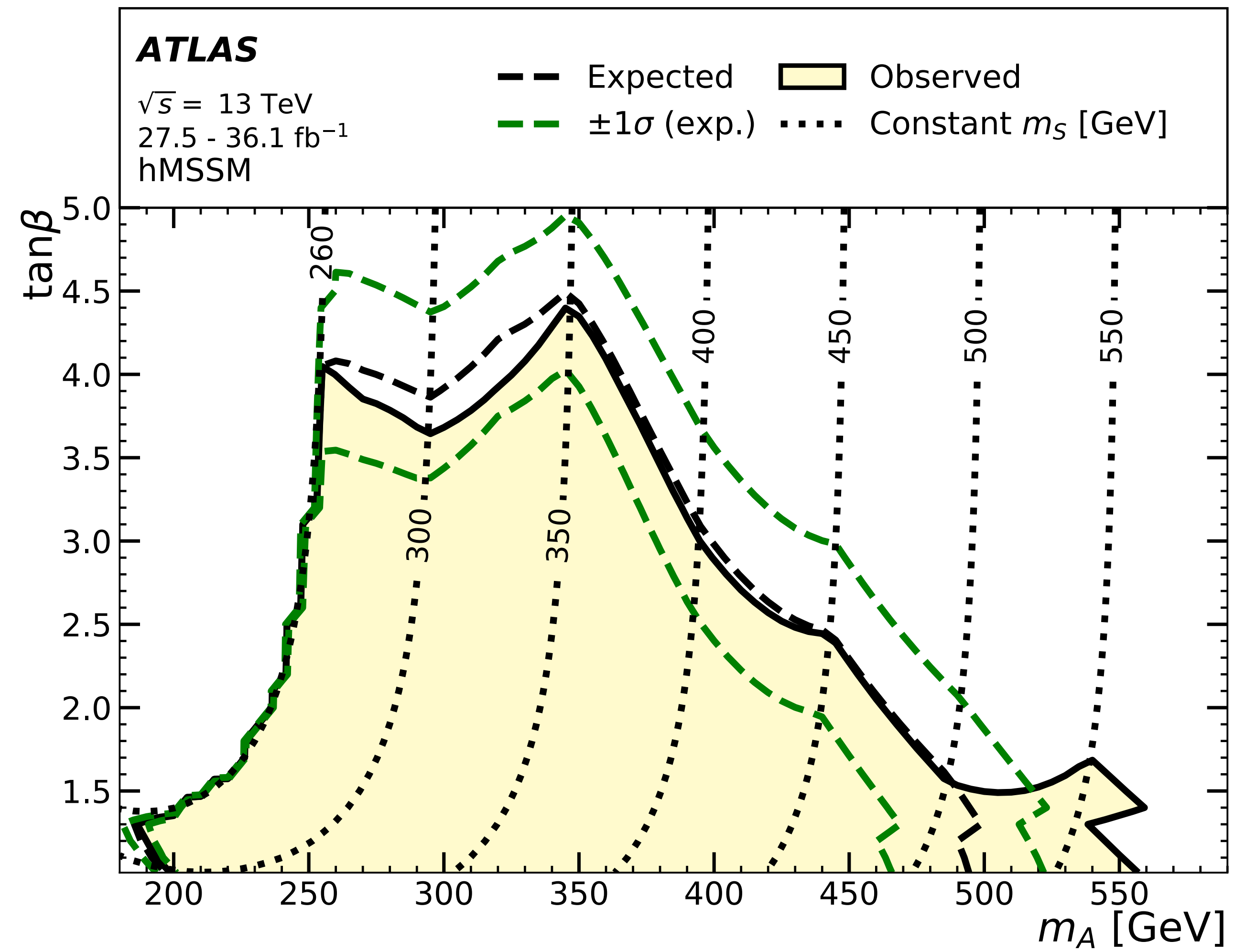
Acceptance x Efficiency



- Different κ_λ obtained using a reweighing of the ggF cross-section.
- Cross-section varies based on the **interference between the dominant triangle and box diagrams**.

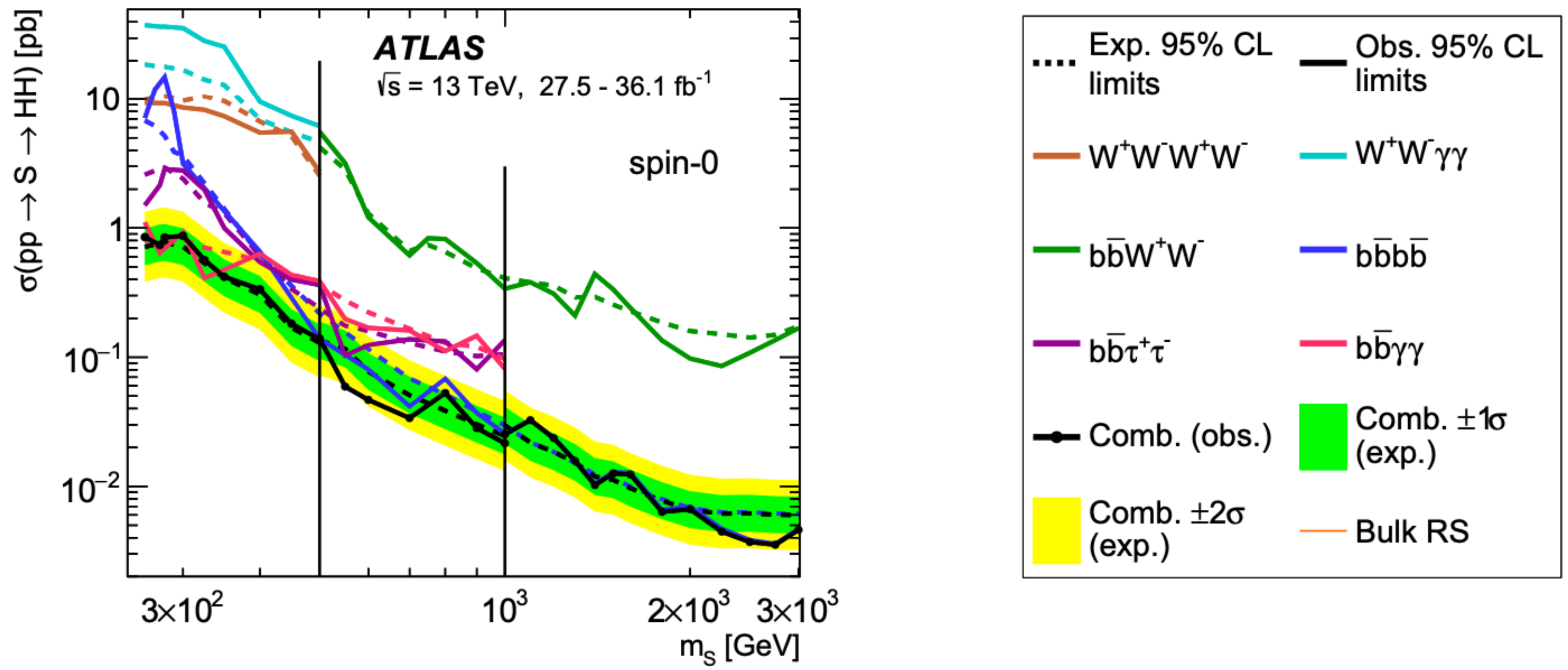
HH Combinations



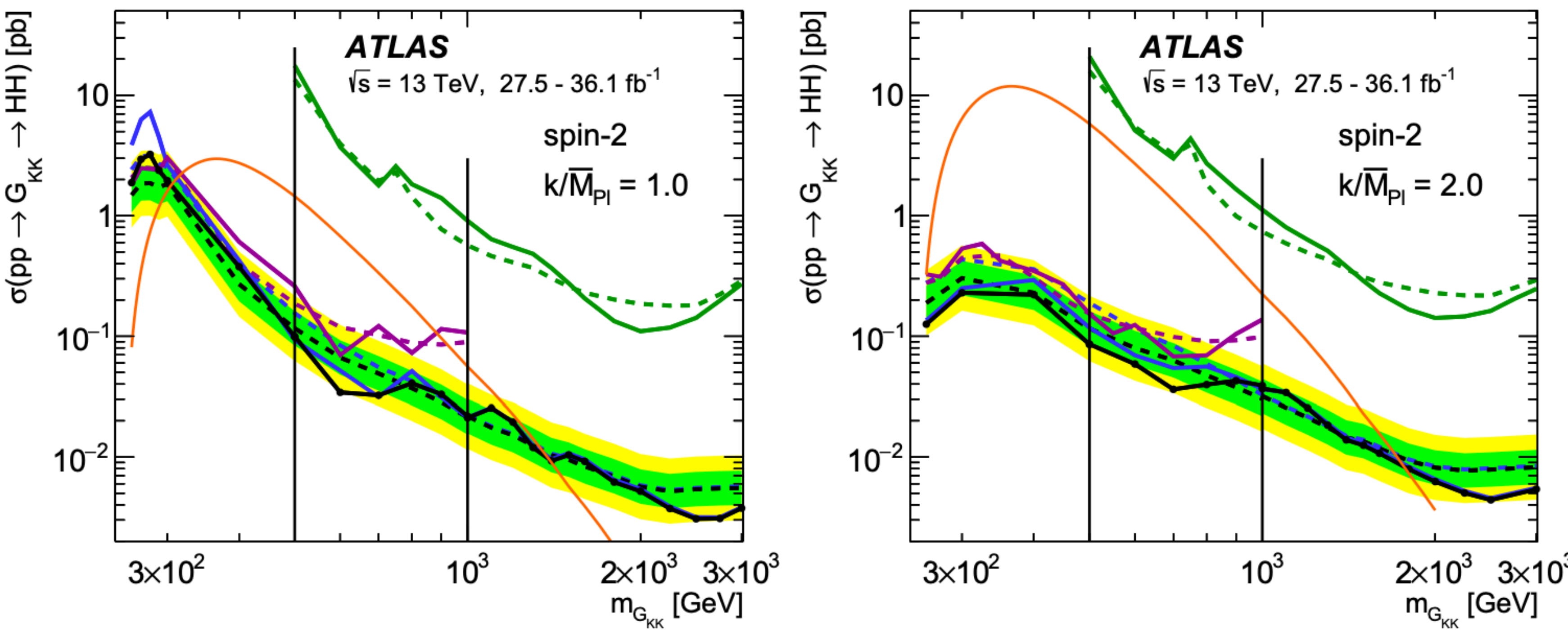


- Constrain **spin-0 and spin-2 resonance models** up to masses of ~ TeV.
- Also probe **hMSSM parameter space**, constraining heavy Higgs mass up to ~ 500 GeV.

HH Combinations



(a)



Inputs to the *H+HH* Global Fit

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (excluding $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau^+\tau^-$	36.1
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$	36.1
$t\bar{t}H$, $H \to$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1

HL-LHC Prospects

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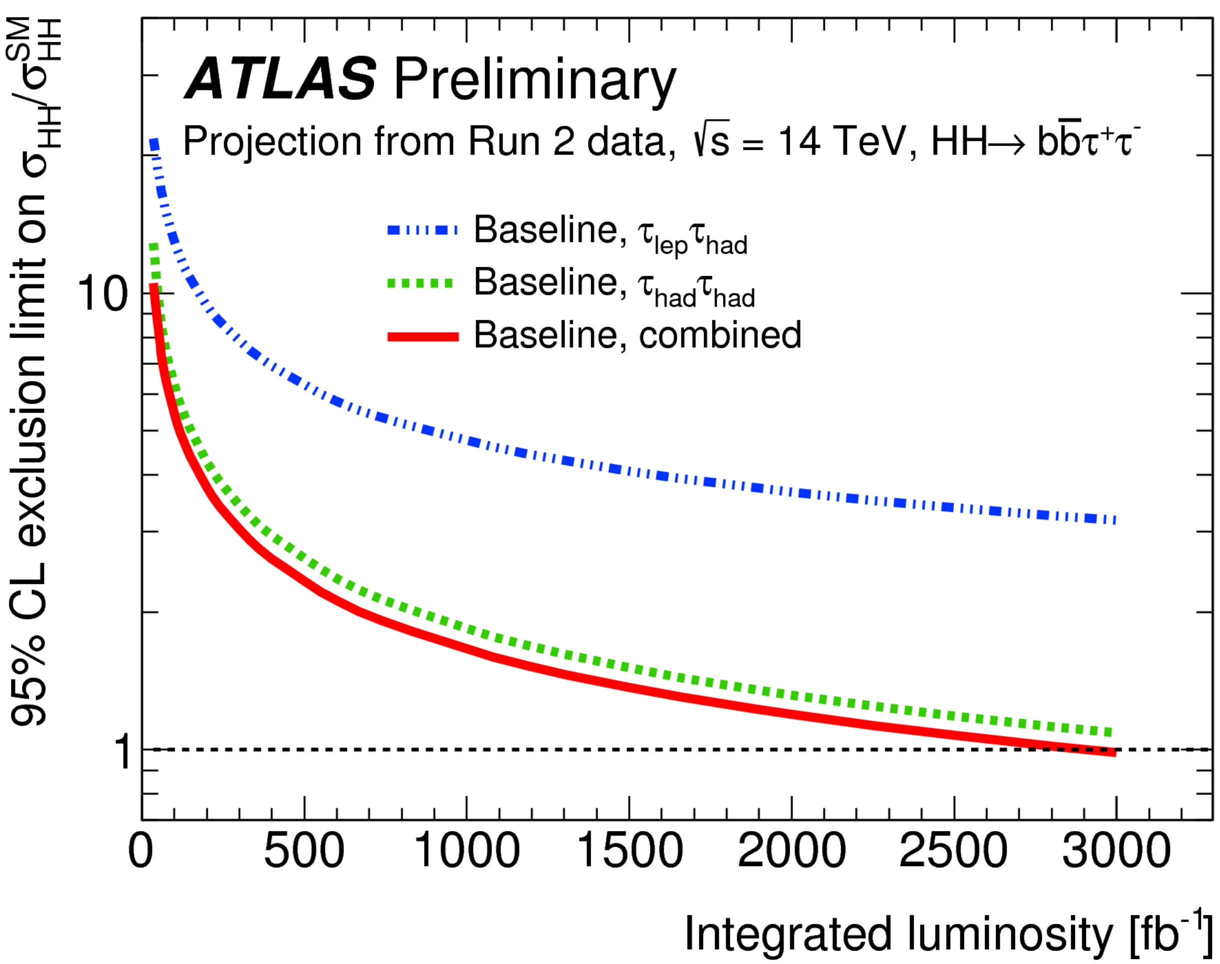
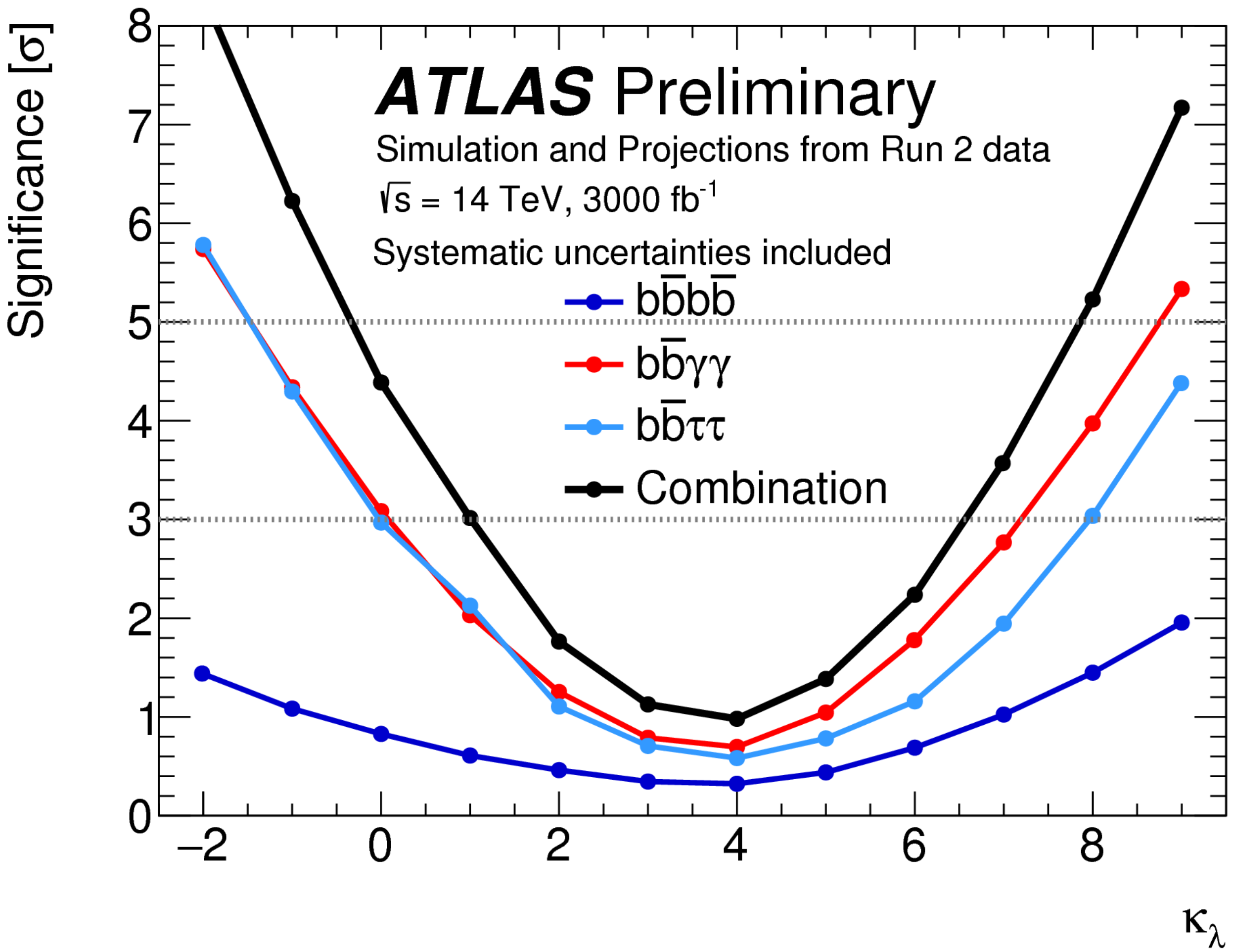
- Extrapolated limits with the HL-LHC could lead to the **5σ discovery of *HH* production**, and a definitive test of the self-coupling in the SM. Further prospects in **ATL-PHYS-PUB-2018-053**.

- Success of discovery dependent on **innovation** and **systematics**.





HL-LHC Prospects

- Extrapolated limits with the HL-LHC could lead to the **5σ discovery of *HH* production**, and a definitive test of the self-coupling in the SM. Further prospects in **ATL-PHYS-PUB-2018-053**.

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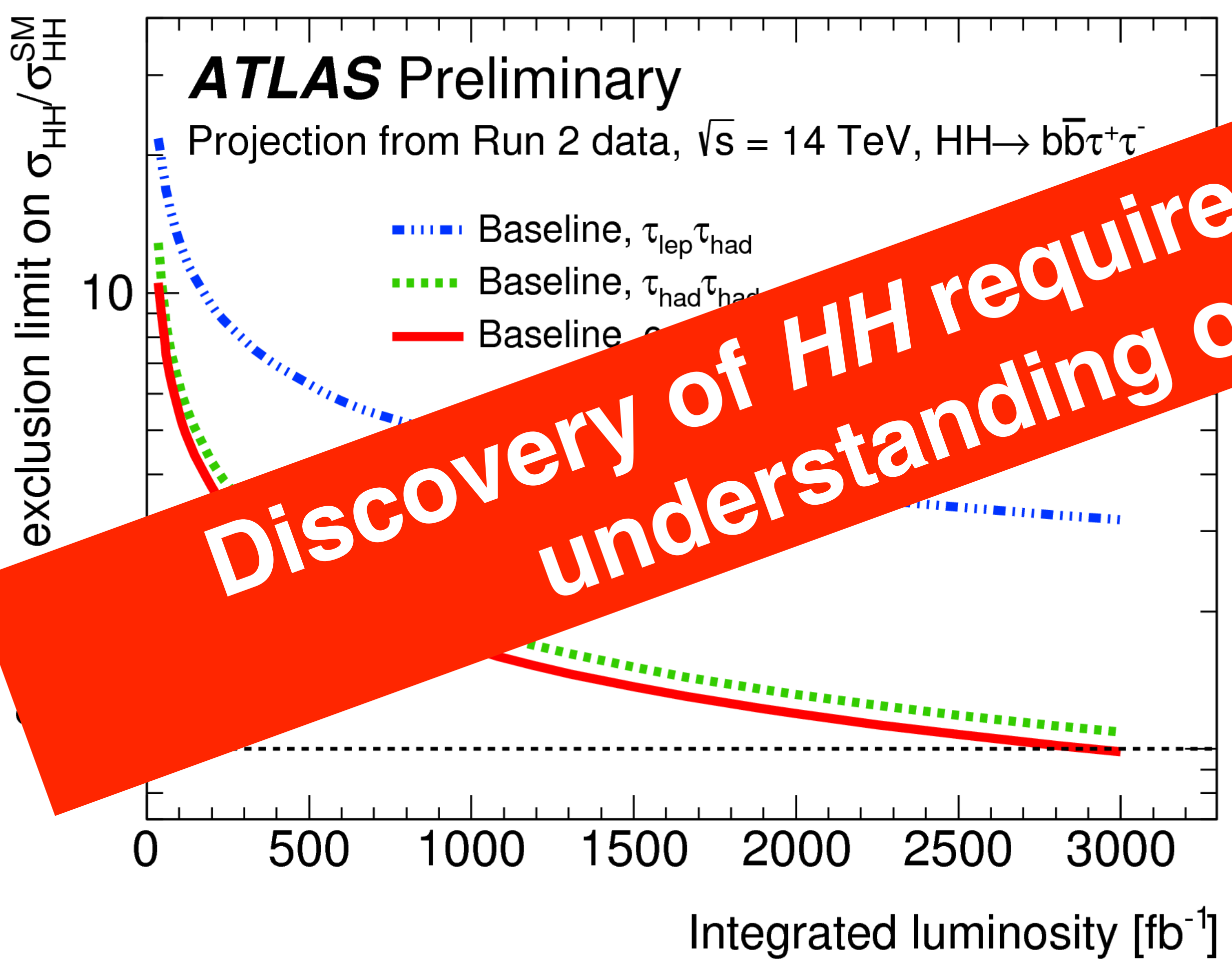
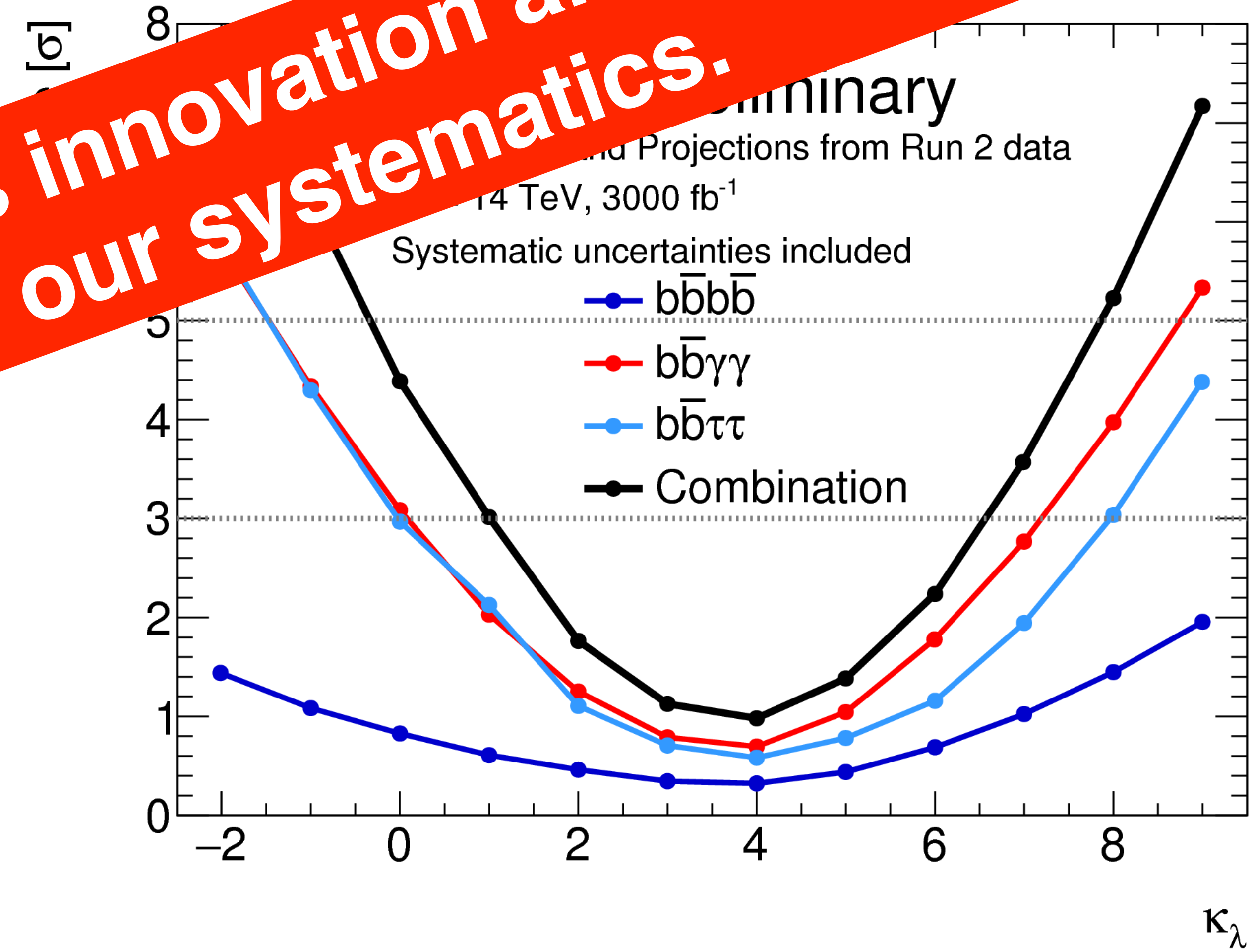
Discovery of *HH* requires innovation and a deep understanding of our systematics.





HL-LHC Prospects: *bbγγ*

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