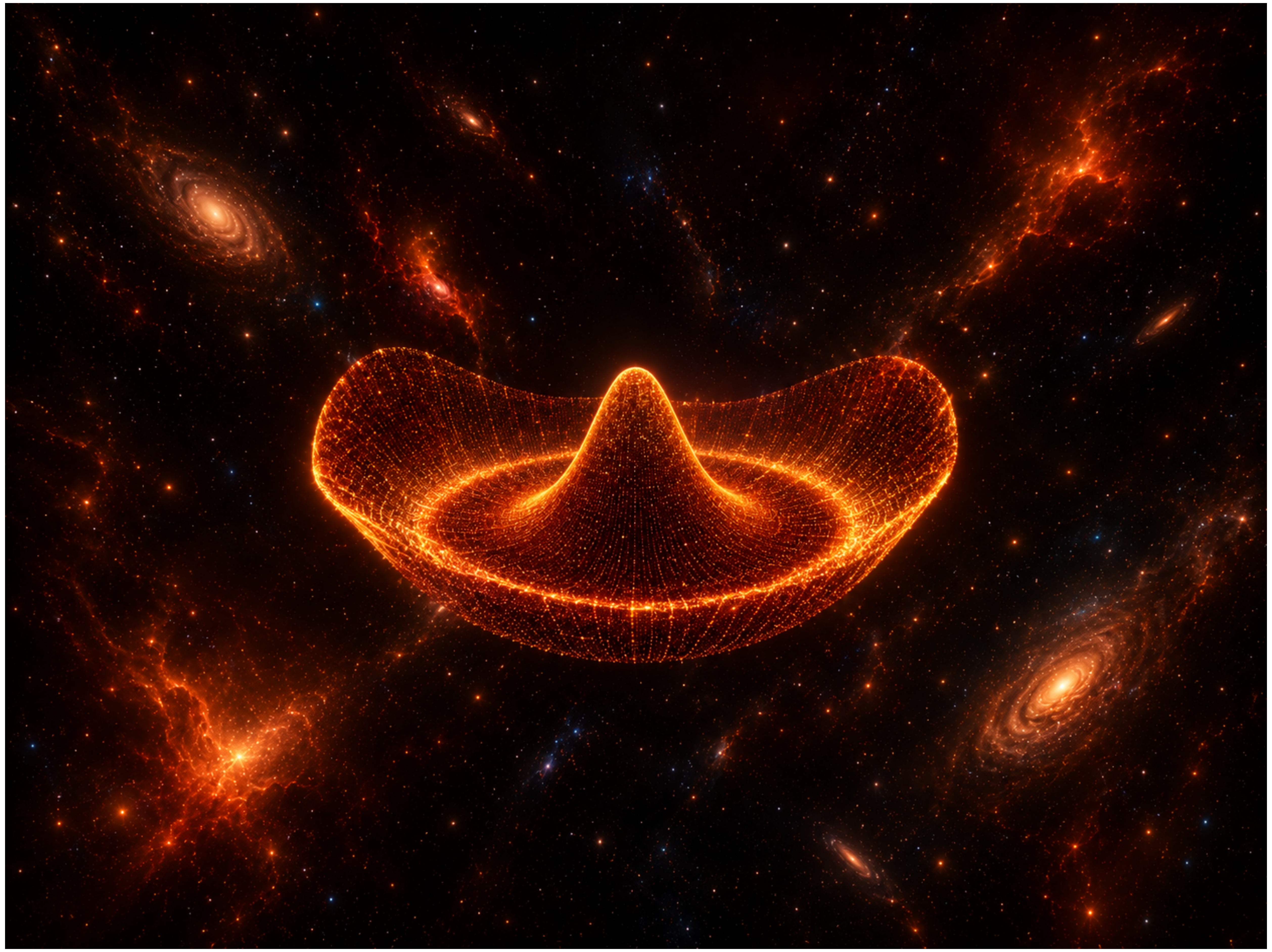
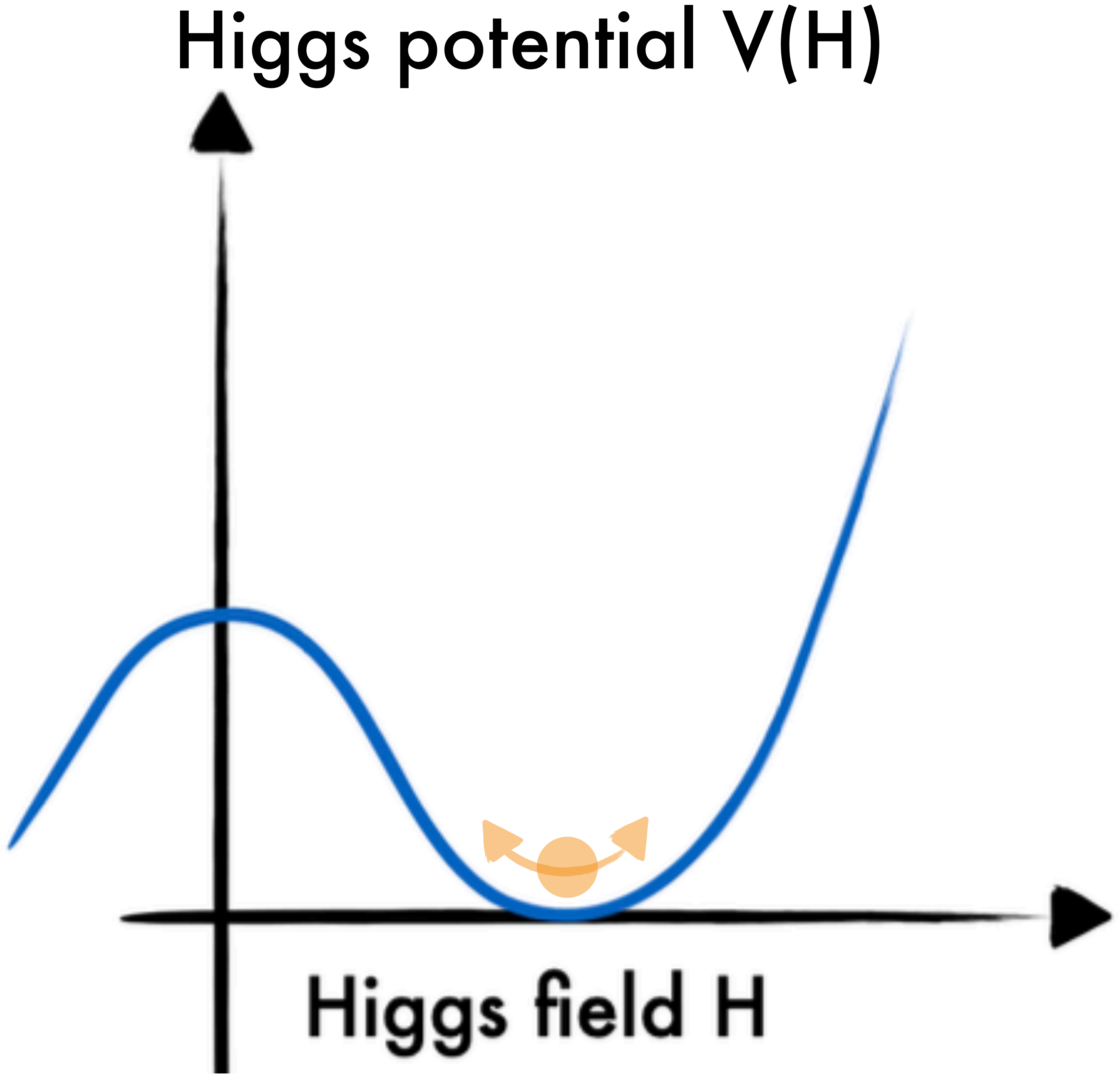
Probing the Higgs potential through Higgs boson pair production

Marko Stamenkovic (Brown University)

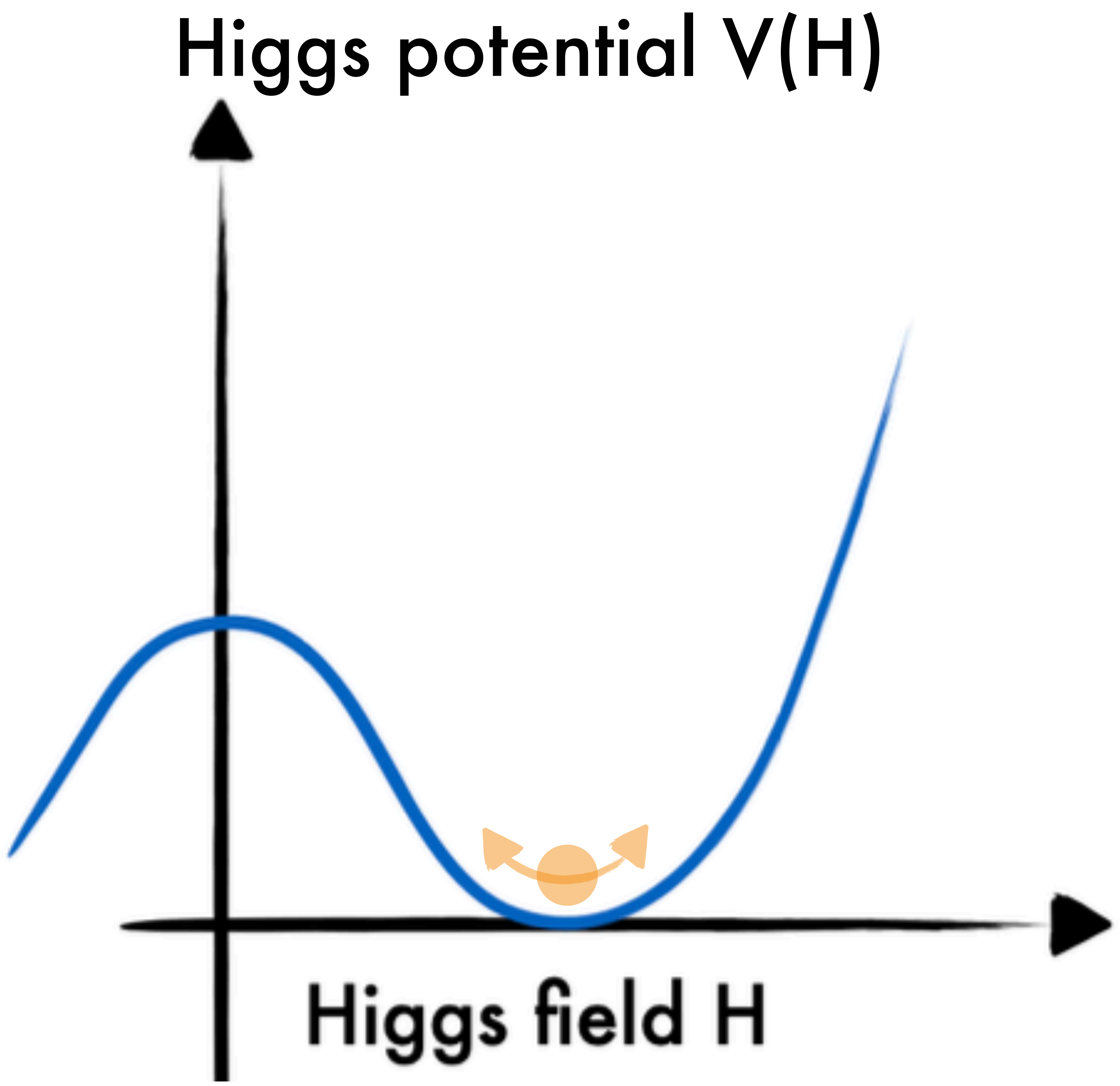
Les Rencontres de Noirmoutier
2nd of June 2026



Scientific landscape: Higgs potential



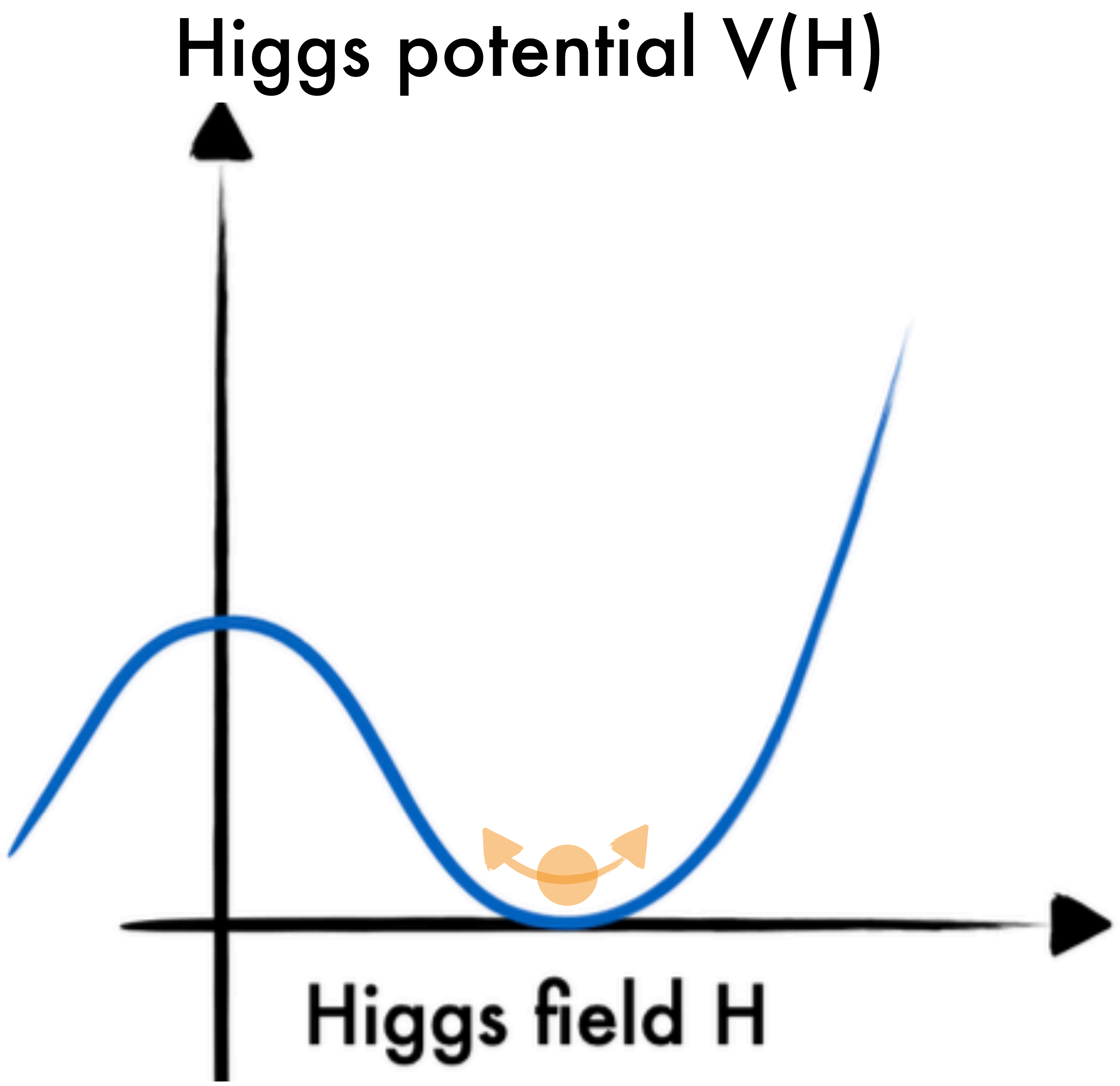
Scientific landscape: Higgs potential



Higgs potential: decides what **"empty space" means**

- Selects the electroweak vacuum: $vev \approx 246$ GeV
- Gives mass to the W and Z bosons
- Converts *Yukawa couplings* into fermion masses and flavor structure
- Shapes the electroweak phase transition in the early Universe

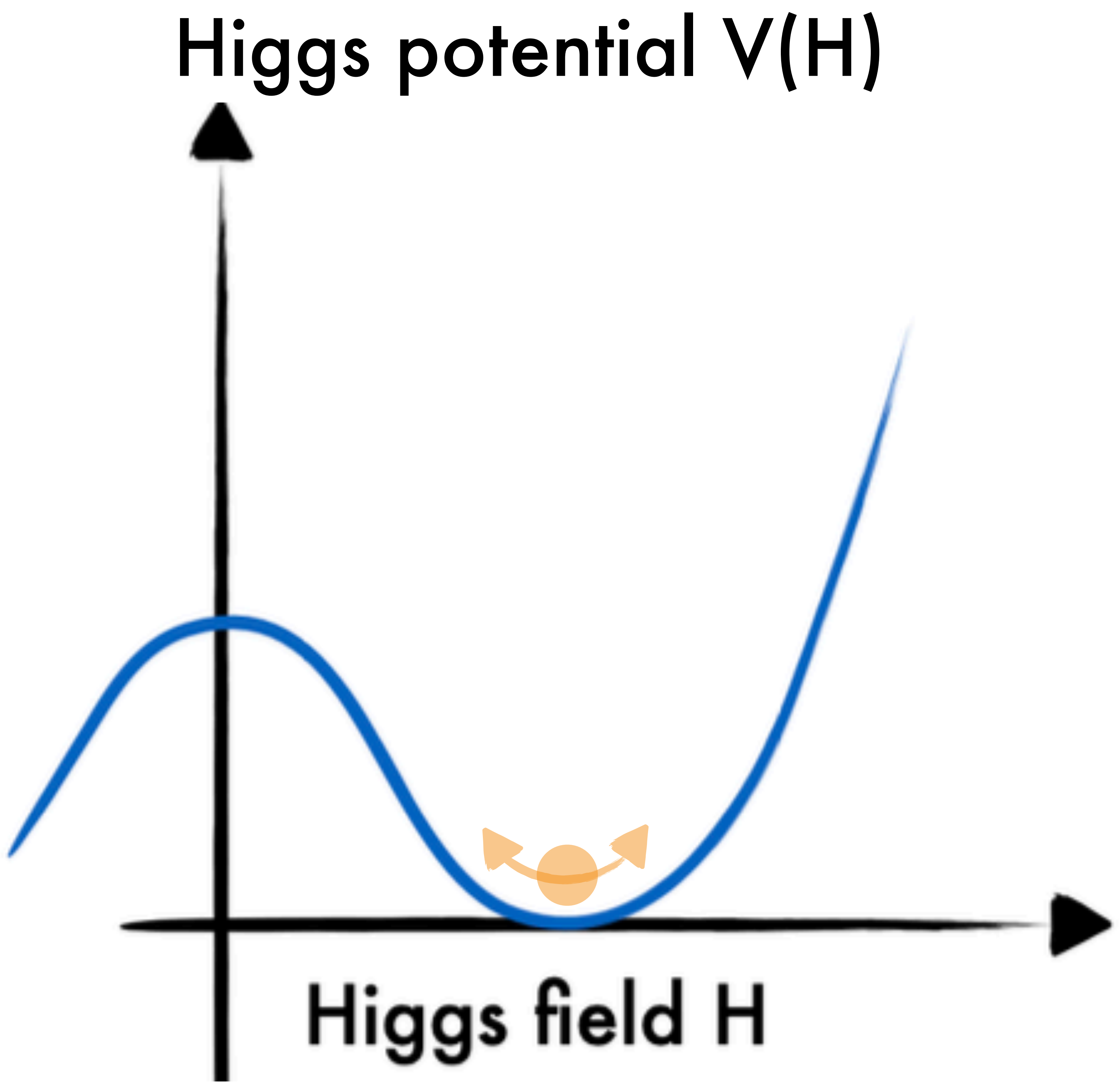
Scientific landscape: Higgs potential



But it **fails** to **describe**:

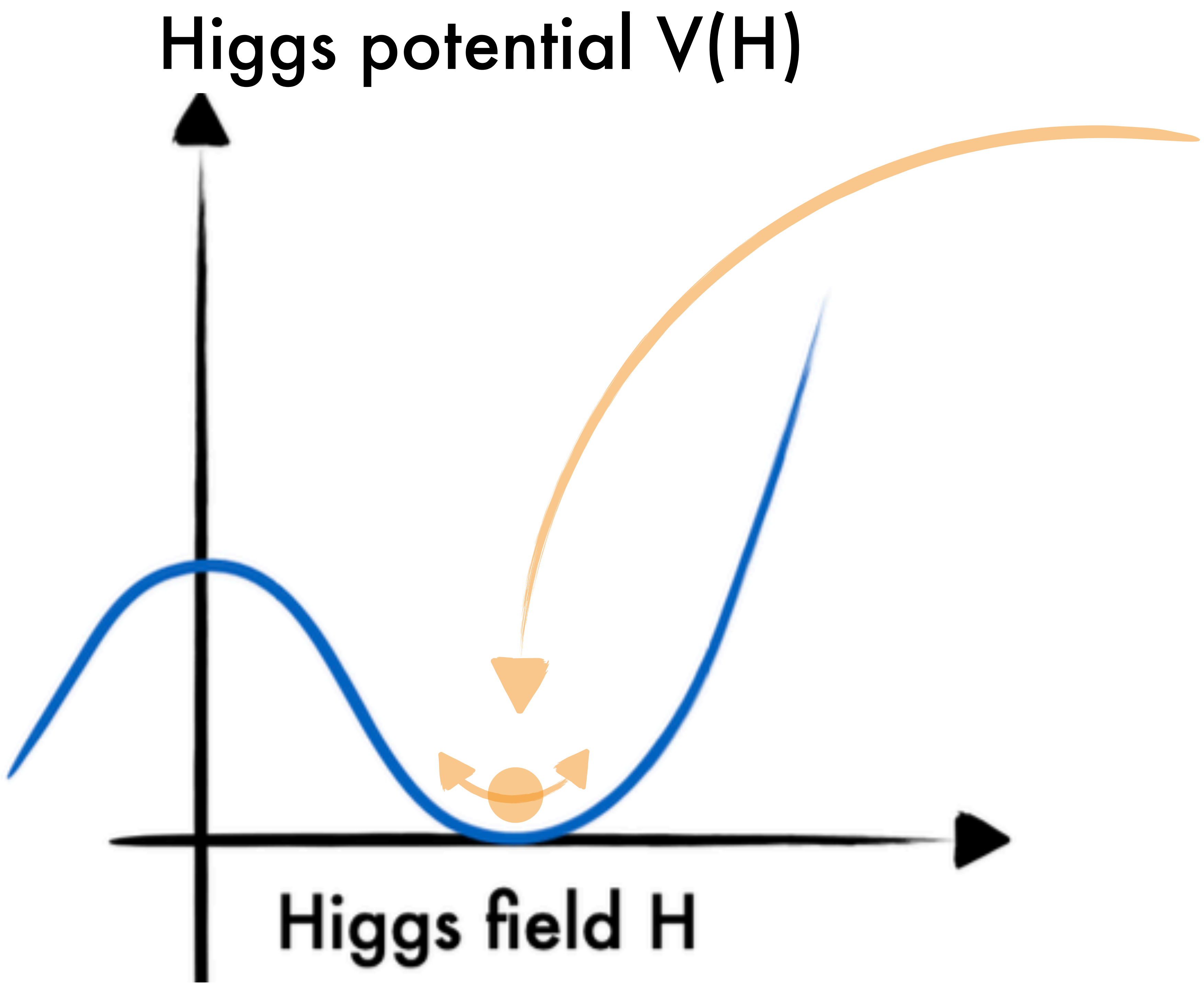
- **Dark energy** / the vacuum-energy problem
- **Dark matter**
- **Baryogenesis** and the **matter–antimatter asymmetry**
- **Neutrino masses**
- The **origin** of the **Yukawa/flavor pattern**

Scientific landscape: Higgs potential



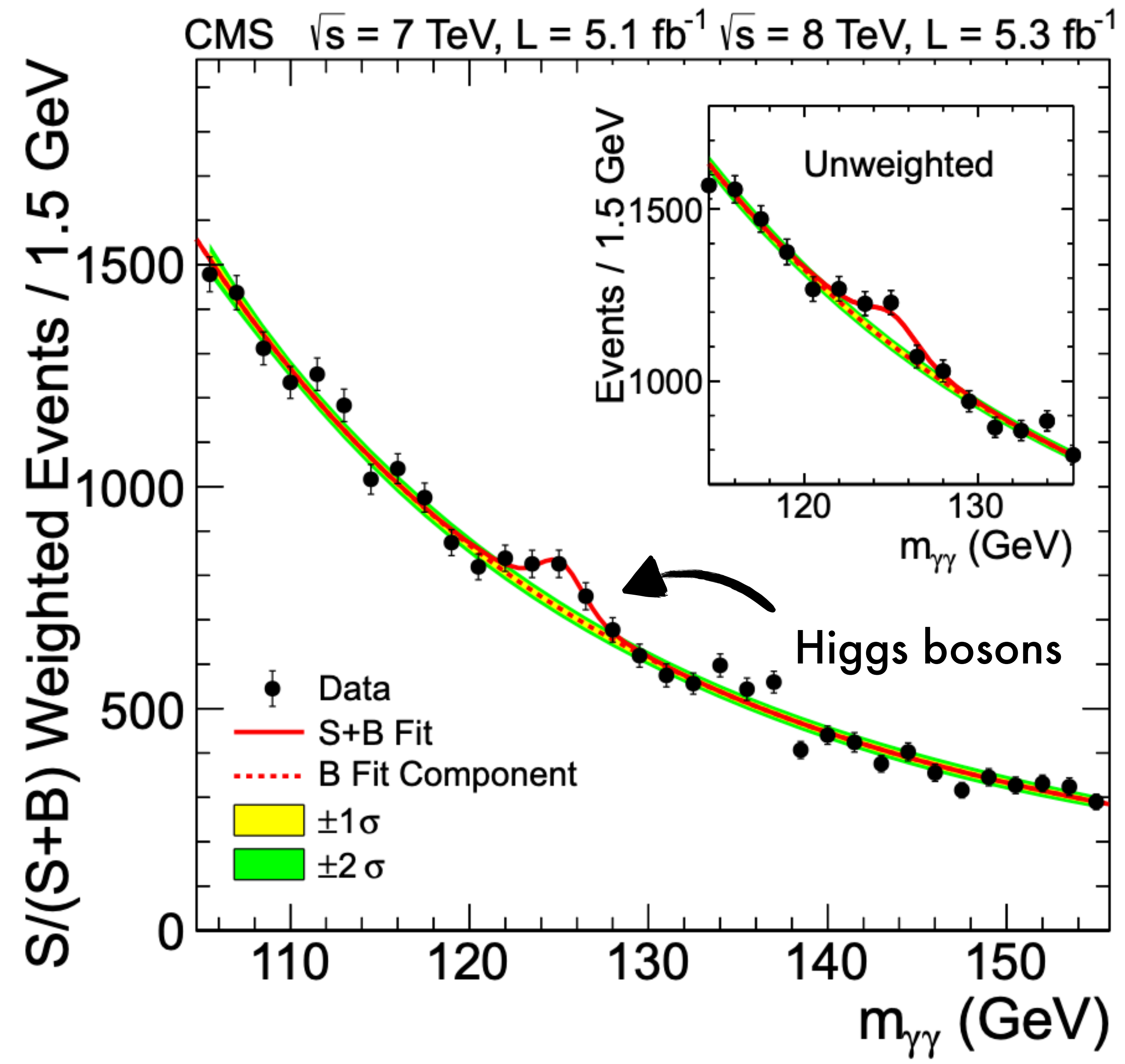
At the core of the question *"Why is there something rather than nothing?"*

Scientific landscape: Higgs potential



$H \to b\bar{b}$
$H \to c\bar{c}$
ttH
$H \to \gamma\gamma$
$H \to ZZ$
$H \to WW$
$H \to \tau\tau$
$H \to \mu\mu$

$H \to \gamma\gamma$



Higgs potential: decides what **“empty space” means**

- Selects the electroweak vacuum: $vev \approx 246$ GeV
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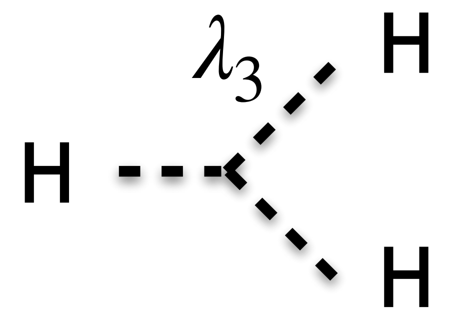
- Higgs boson: discovered in 2012 → probes the minima of the Higgs potential

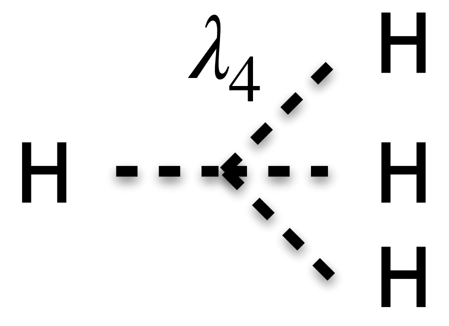
The LHC discovered the Higgs boson

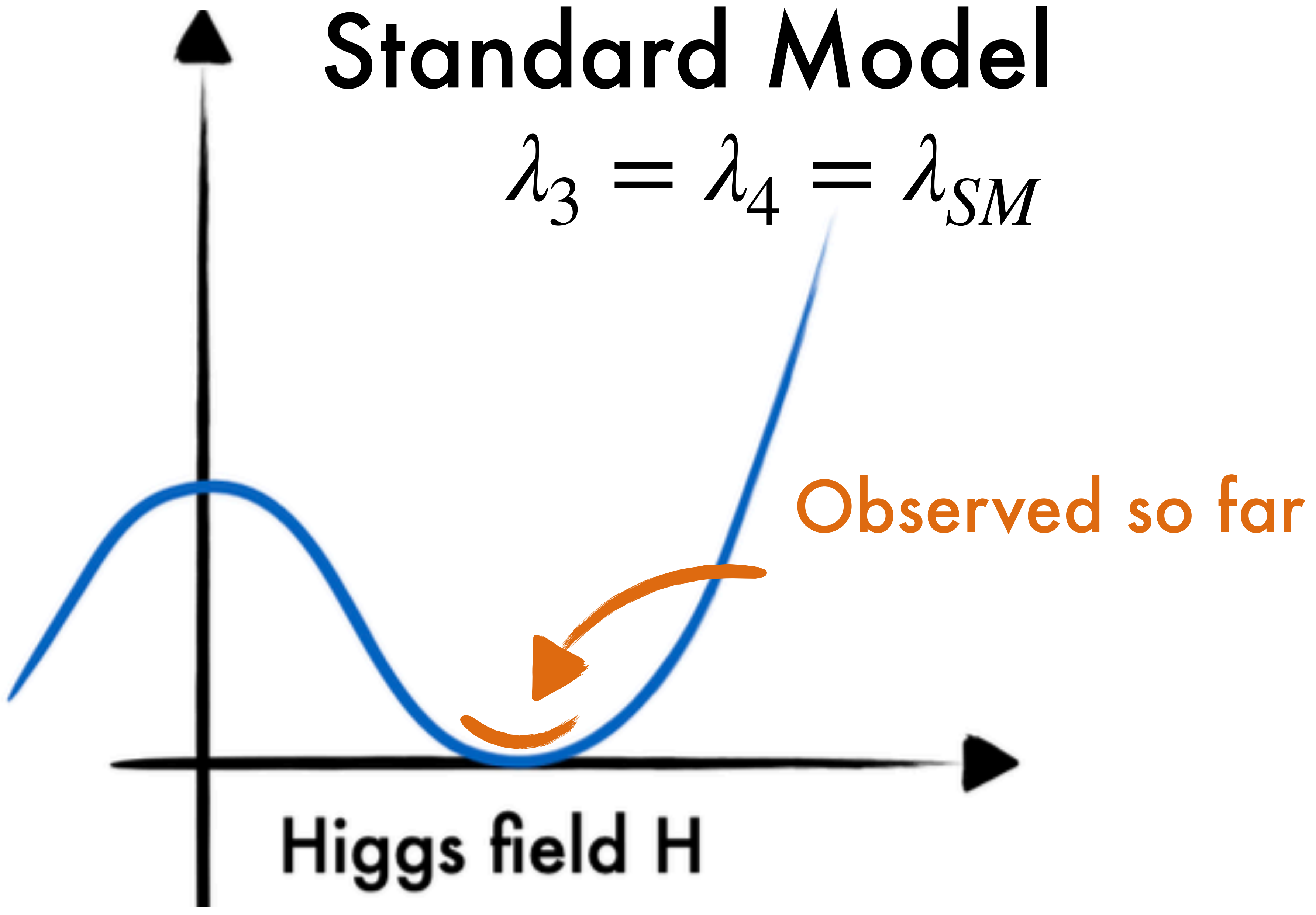
but it **did not discover the Higgs potential**

Measuring the Higgs potential

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

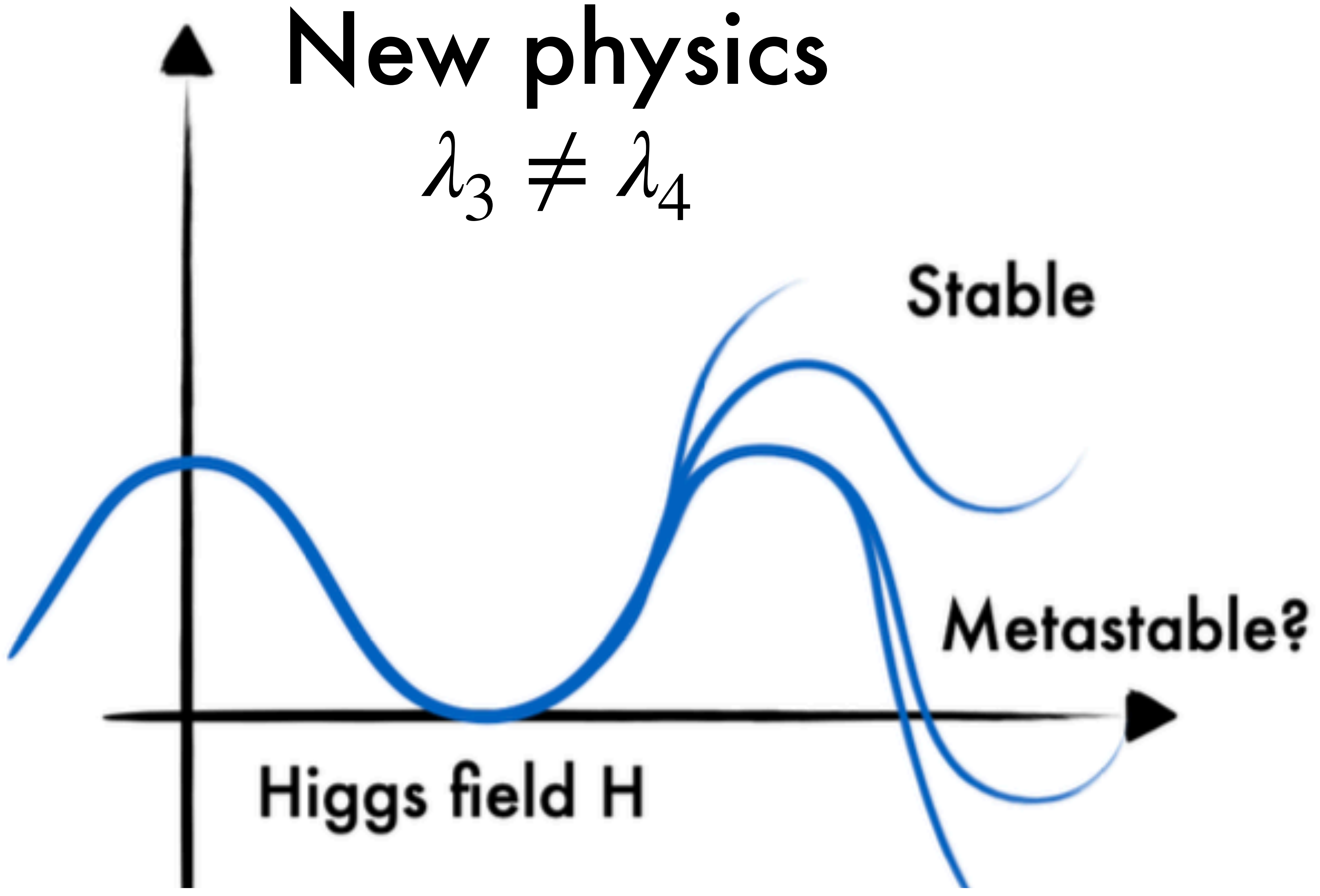






Standard Model

$\lambda_3 = \lambda_4 = \lambda_{SM}$

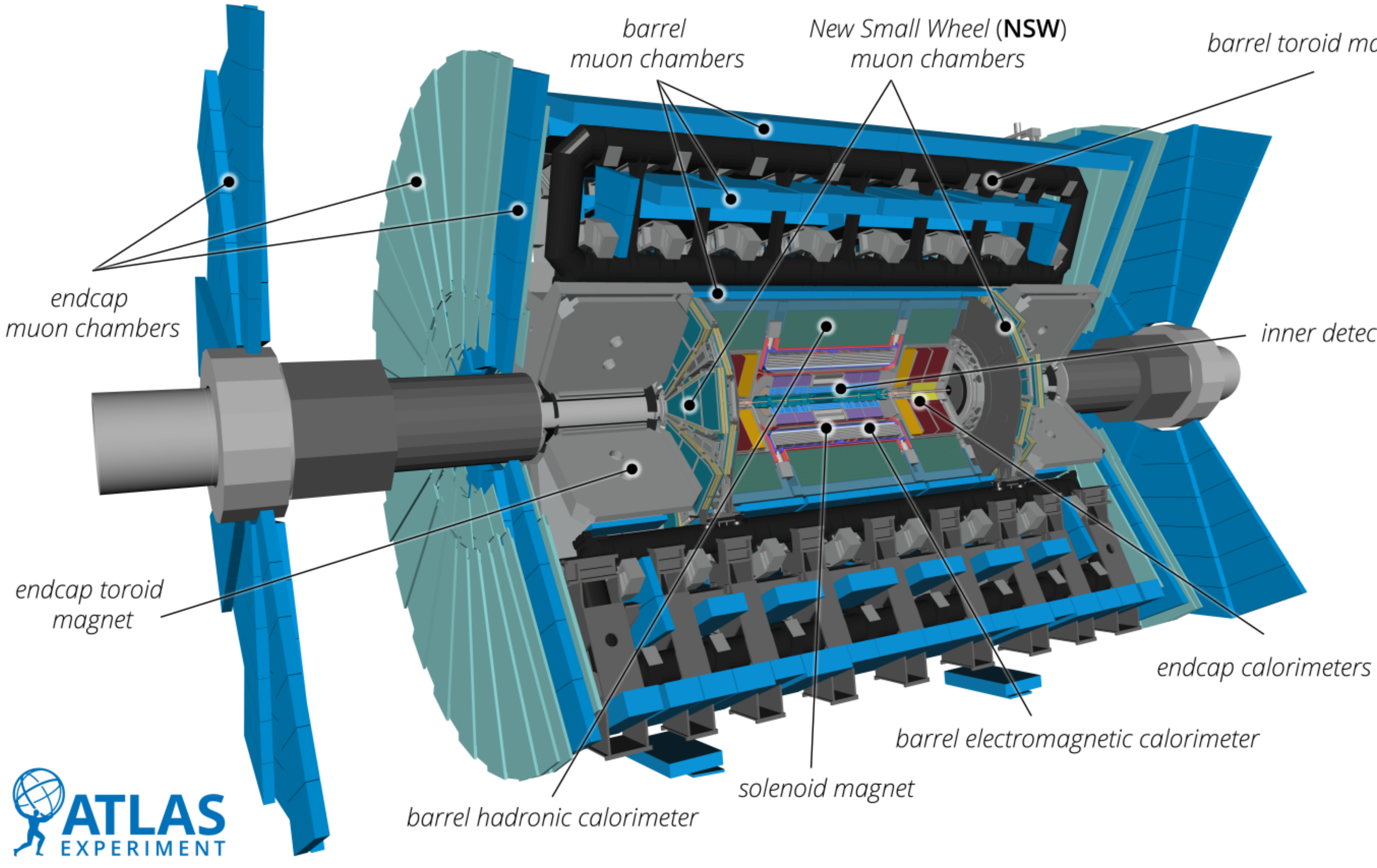


New physics

$\lambda_3 \neq \lambda_4$

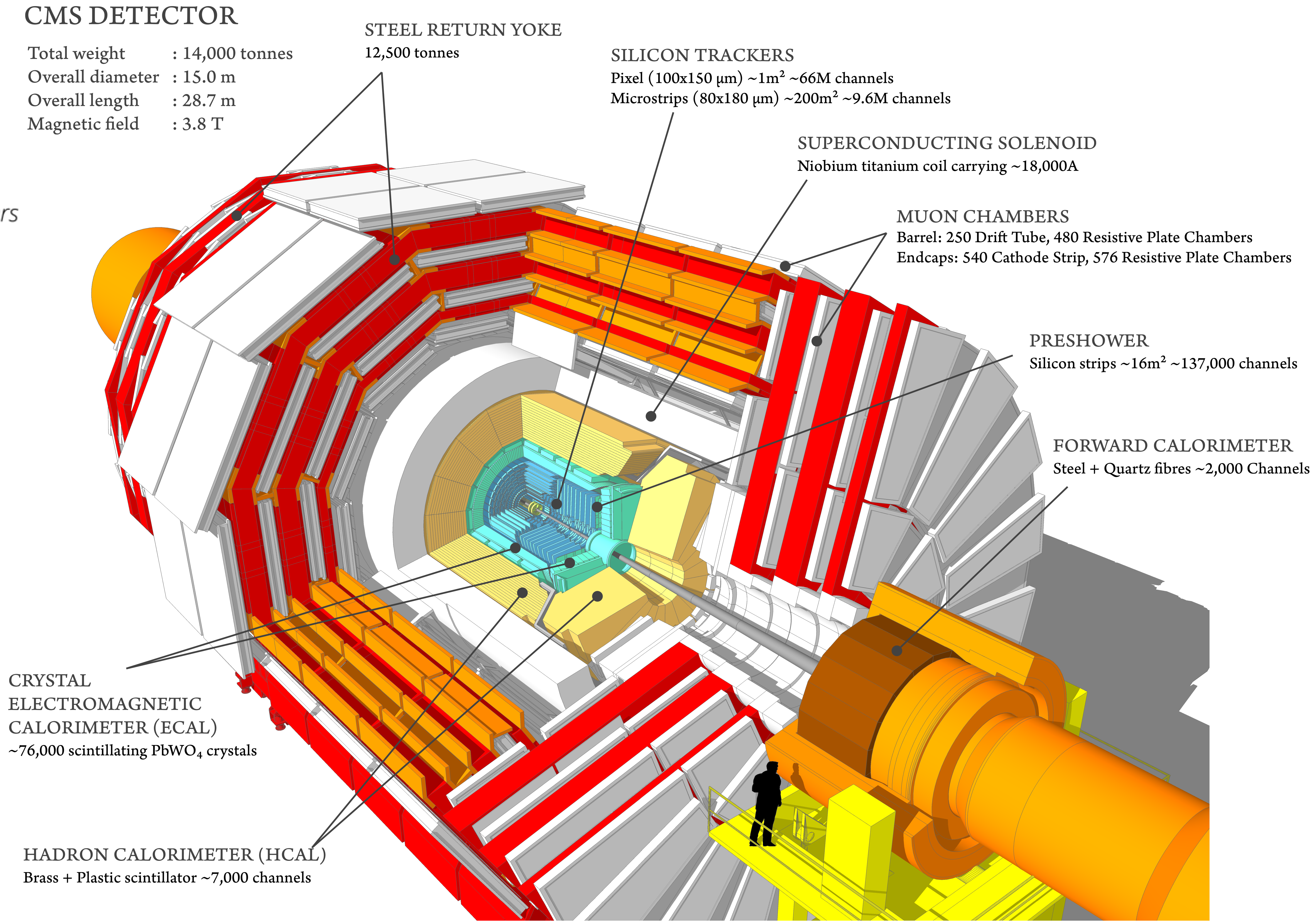
Experimental probe of the Higgs potential at the LHC → Measure **HH** and **HHH** production!

ATLAS and CMS experiments



Two general purpose detectors:

- Layered detectors with different technologies
  - Tracker → Calorimeter → Muon system



Infer particles from debris for multi-Higgs:

- Reconstruct quarks / photons / leptons
- Triggers to record interesting events
- Machine learning: identification of particles

ATLAS and CMS HH and HHH searches

Major challenges

Major challenges

Small cross-sections

Events produced by end of 2026

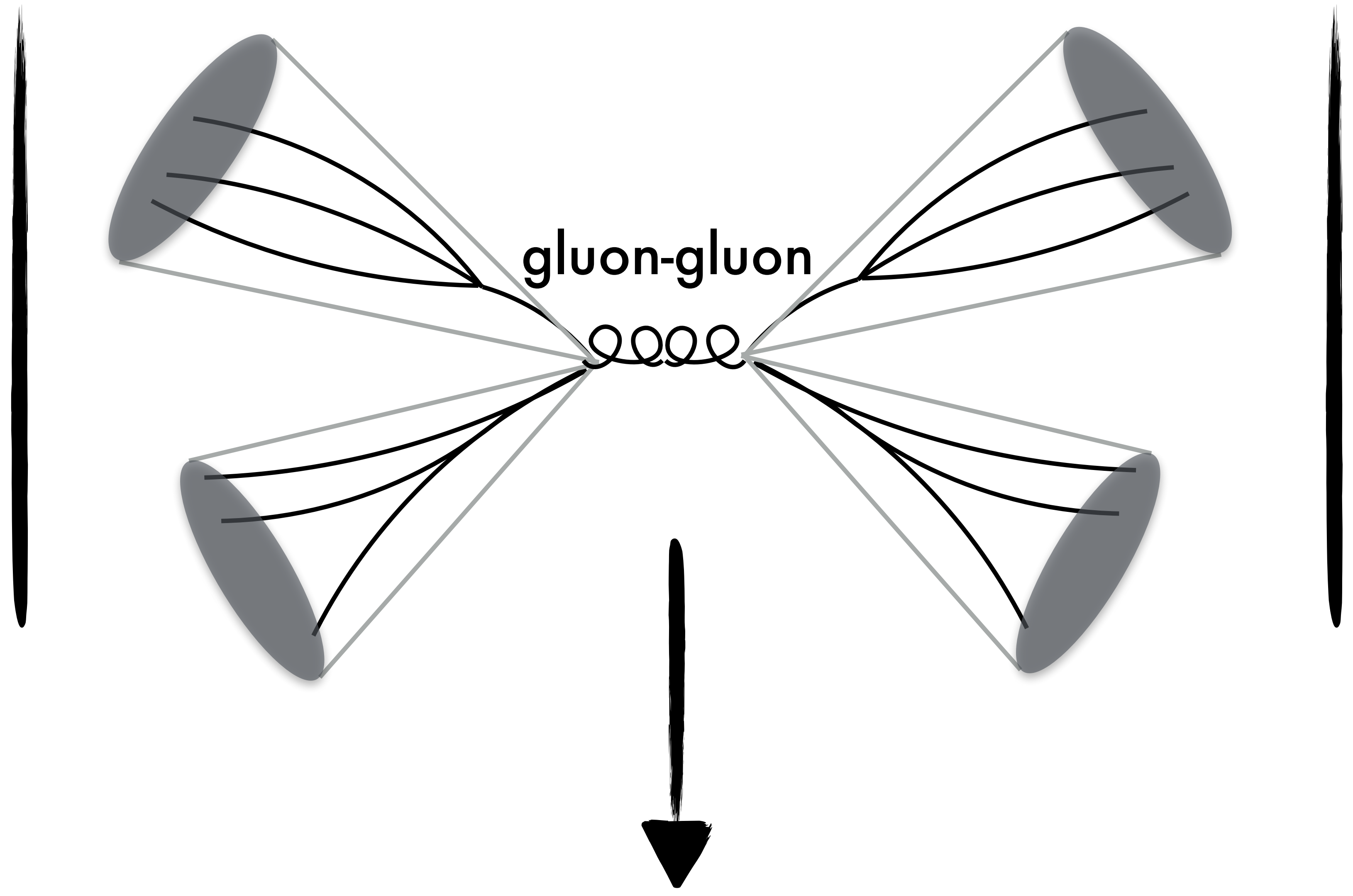
HH: **15 000** events
HHH: **50** events

Rare signal

1. Rare processes: about HH is **300x rarer** than single H production, HHH 300x rarer than HH

Major challenges

Standard Model background

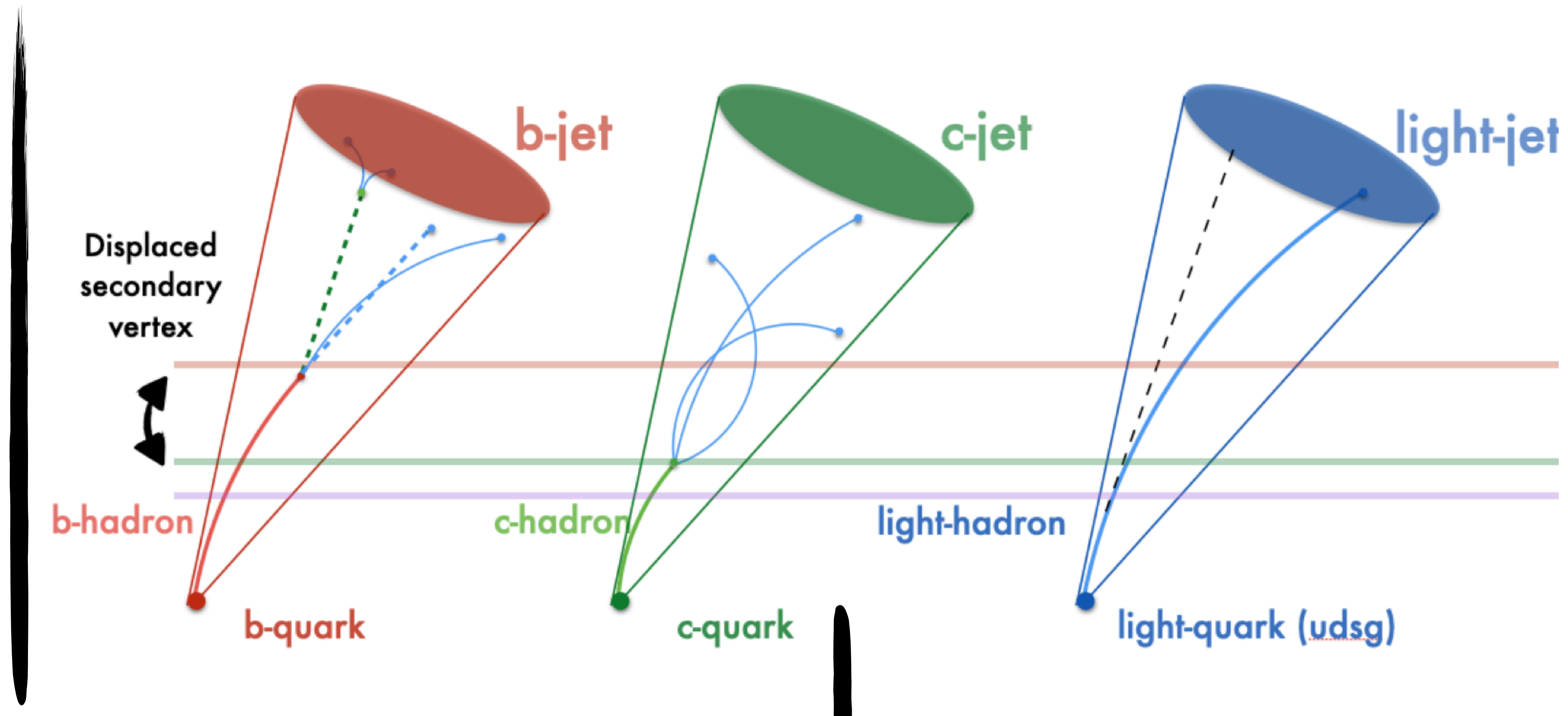


Large combinatorial background

2. Very large background contamination from Standard Model gluons decaying to quarks
   - For **every HH event** produced, about **60 million gluon events produced**

Major challenges

Flavor tag and trigger



Event selection → loss of signal

3.Event selection: quark flavor identification and data acquisition filters (triggers): **reduce signal**!

Major challenges

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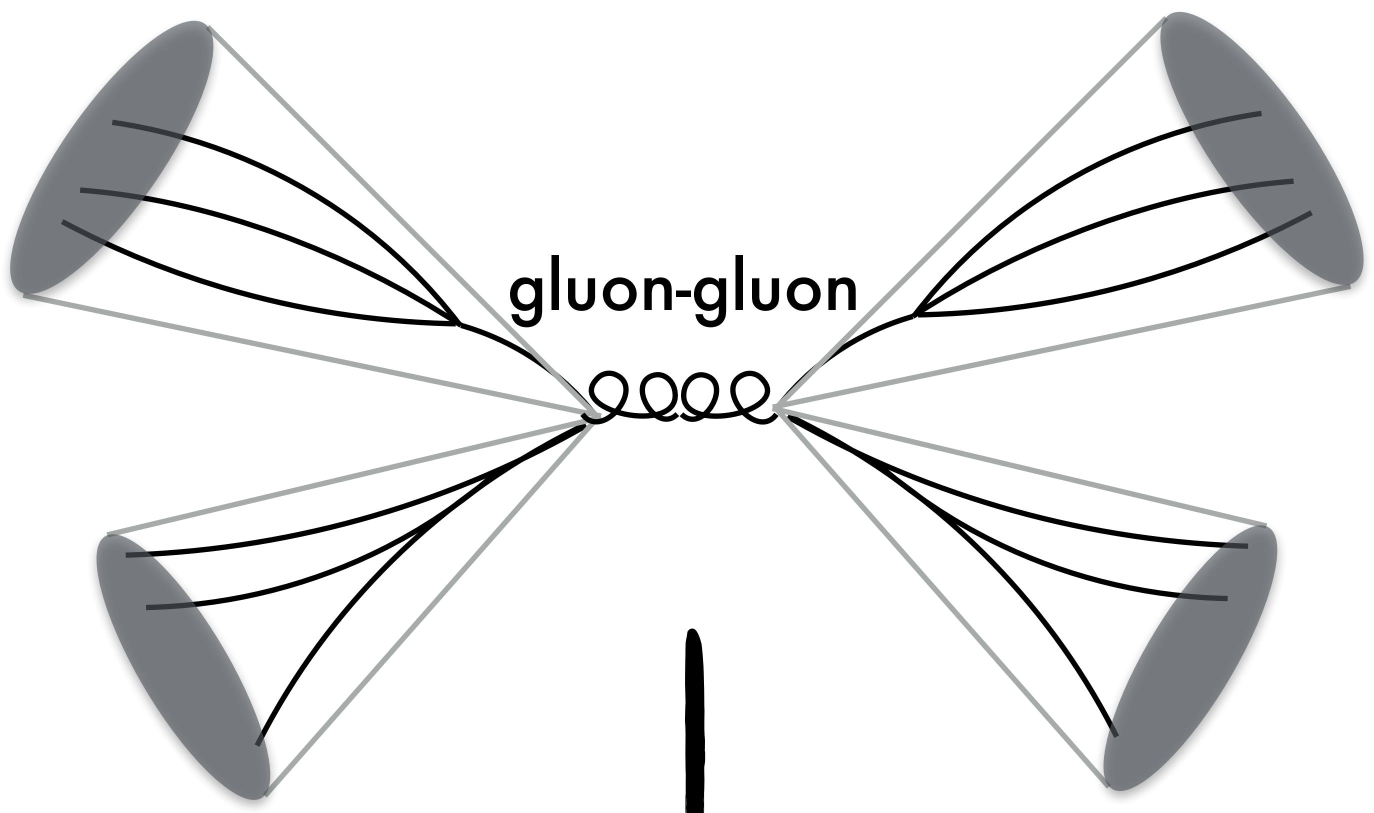
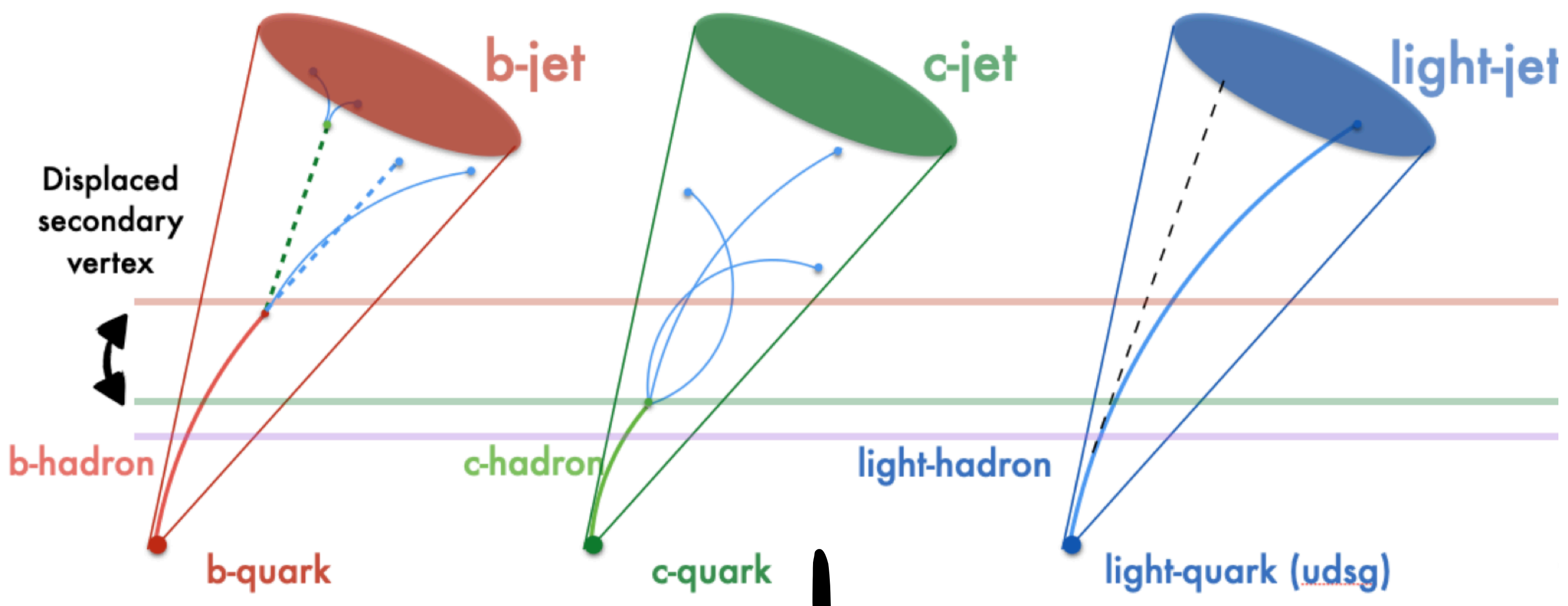
Rare signal

Standard Model background



Large combinatorial background

Flavor tag and trigger



Event selection → loss of signal

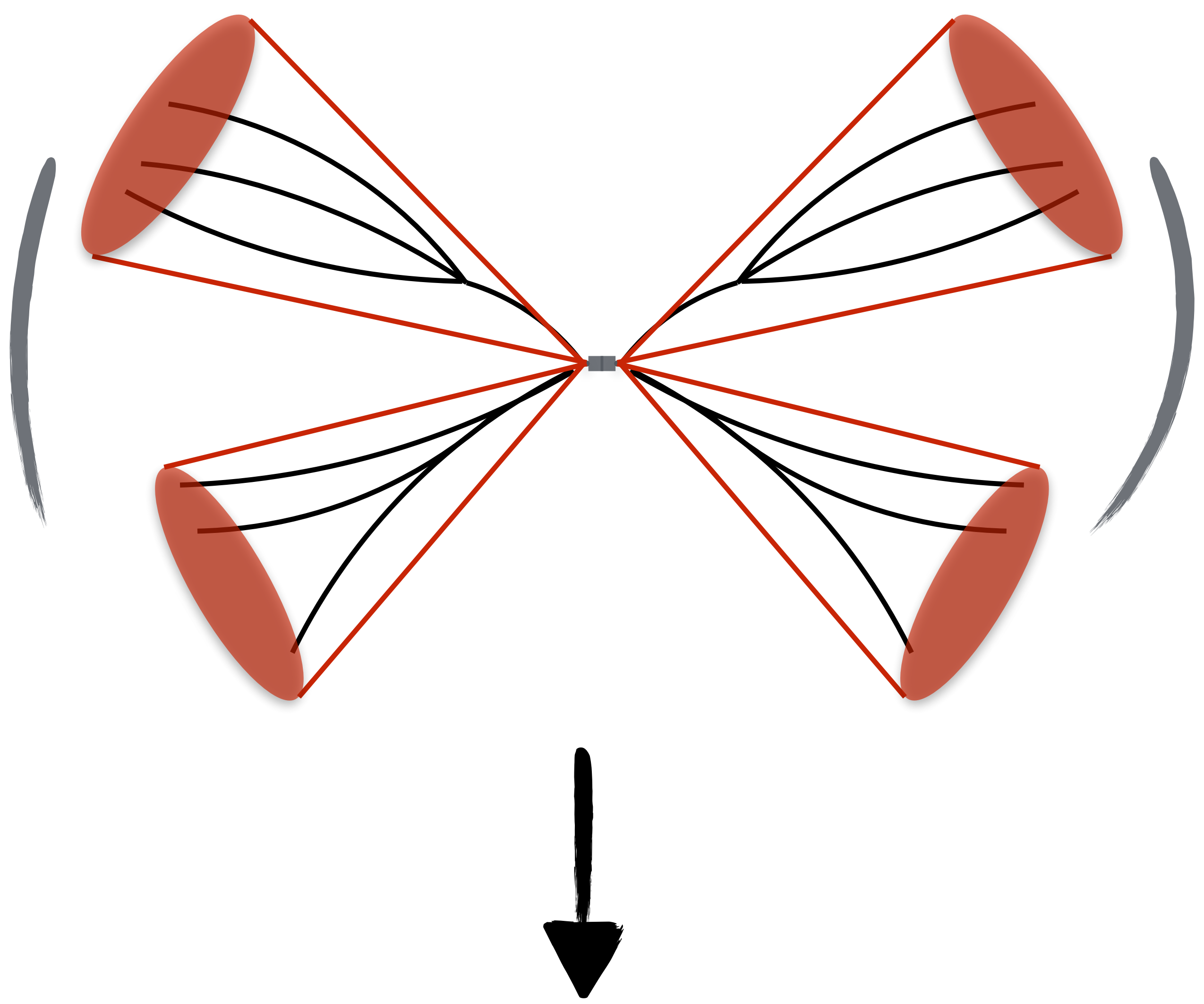
1. Rare processes: about HH is 300x rarer than single H production, HHH 300x rarer than HH

2. Very large background contamination from Standard Model gluons decaying to quarks
    - For every HH event produced, about 60 million gluon events produced

3. Event selection: quark flavor identification and data acquisition filters (triggers): reduce signal!

HH: the three *silver* channels

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

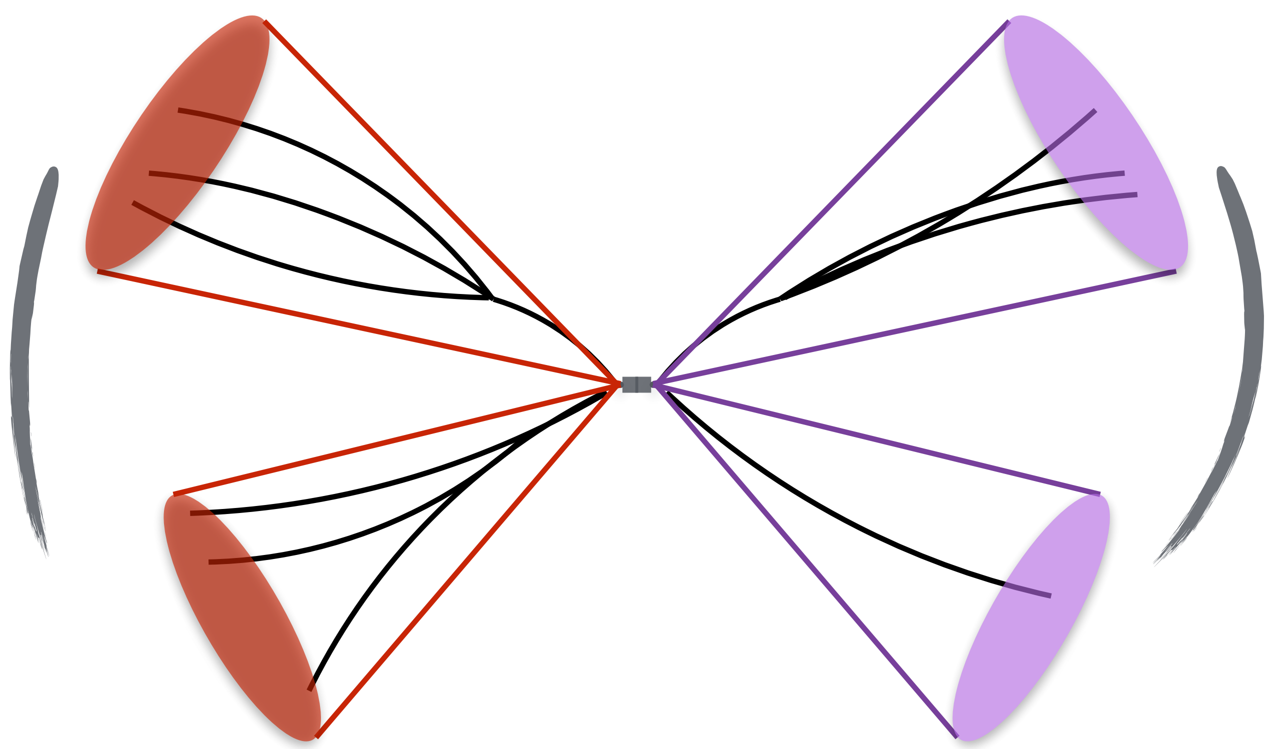


$Prob(HH \to b\bar{b}b\bar{b})$ = 34%

Large signal but large background

Heavily relies on b-jet identification

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

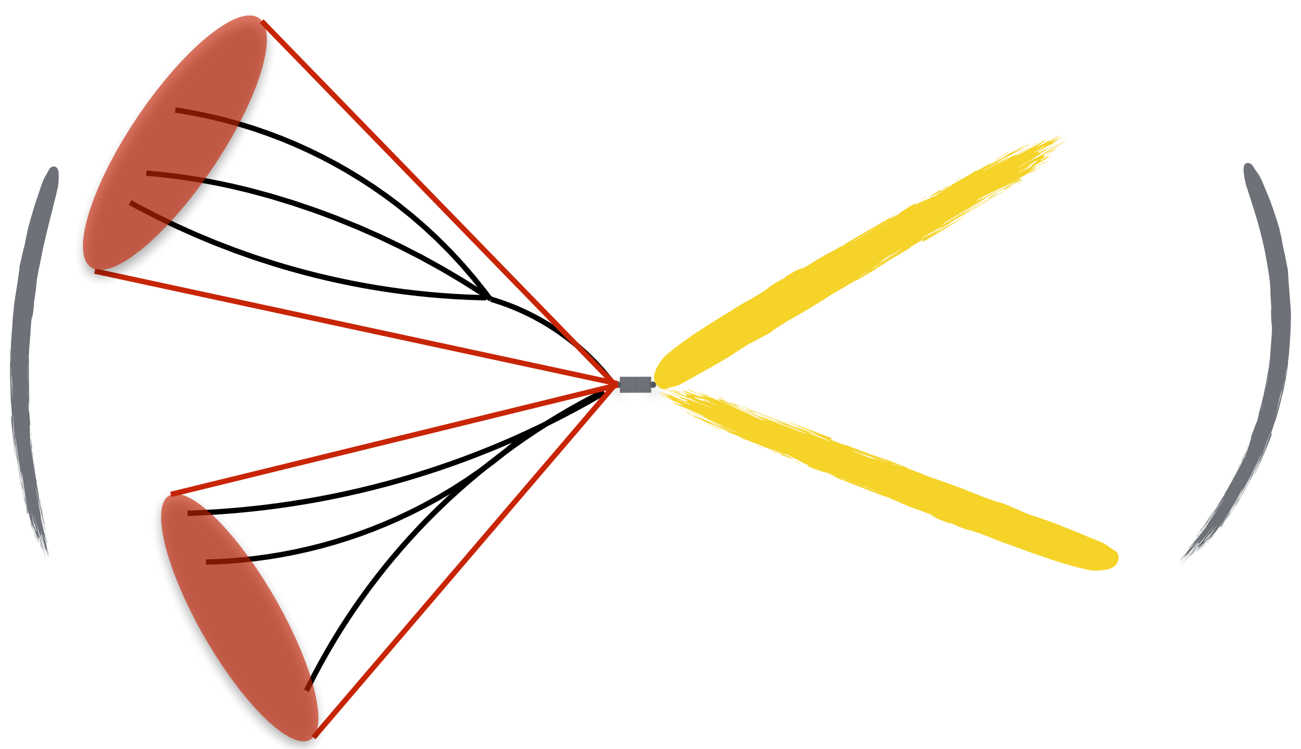


$Prob(HH \to b\bar{b}\tau^+\tau^-)$ = 7%

Sizable signal, lower background

Relies on both b-jet and τ tagging

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



$Prob(HH \to b\bar{b}\gamma\gamma)$ = 0.3%

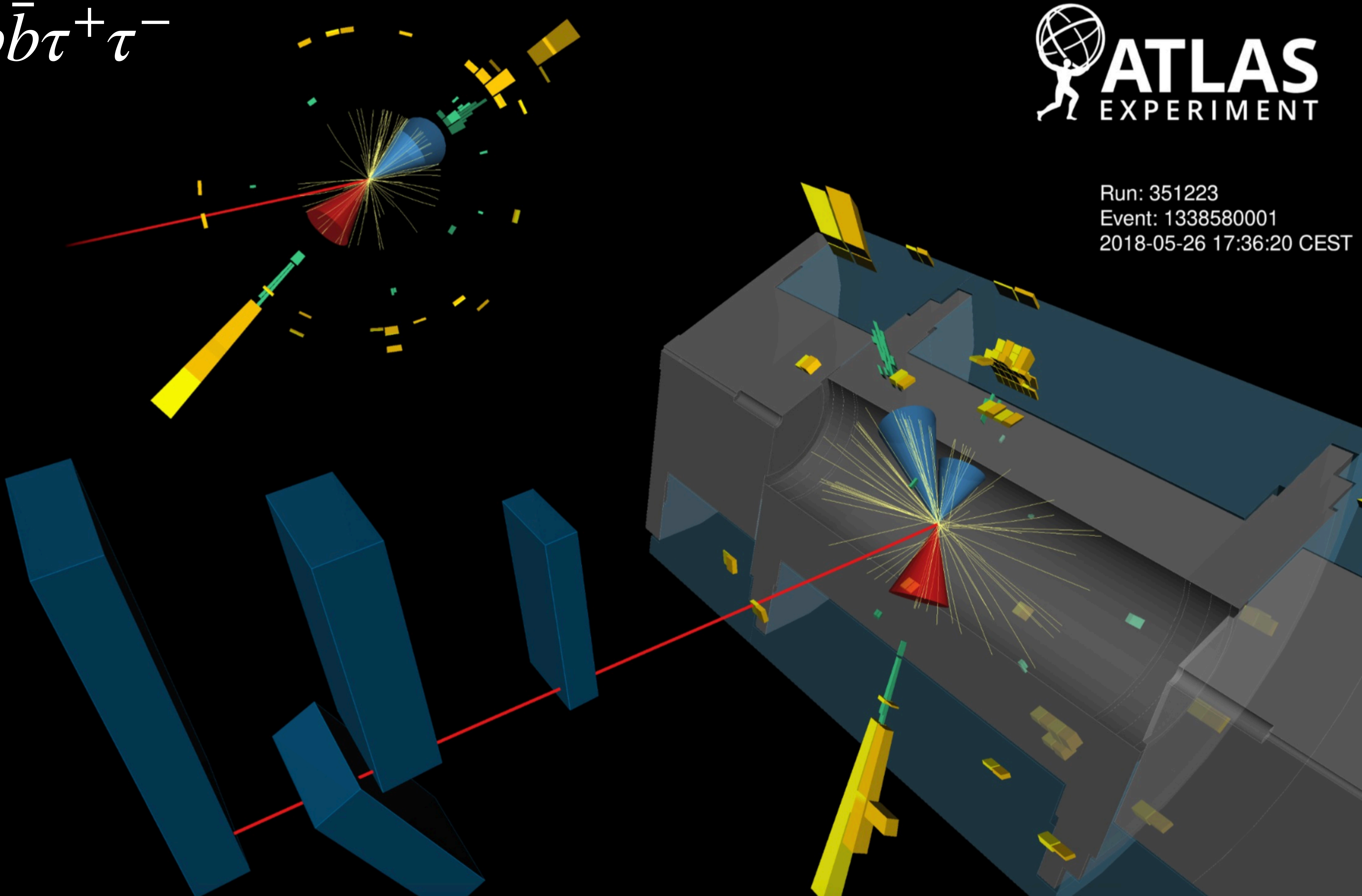
Very low signal, low background

Very clean di-photon signature

CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-13 16:51:13.749568 GMT
Run / Event / LS: 278803 / 465417690 / 259

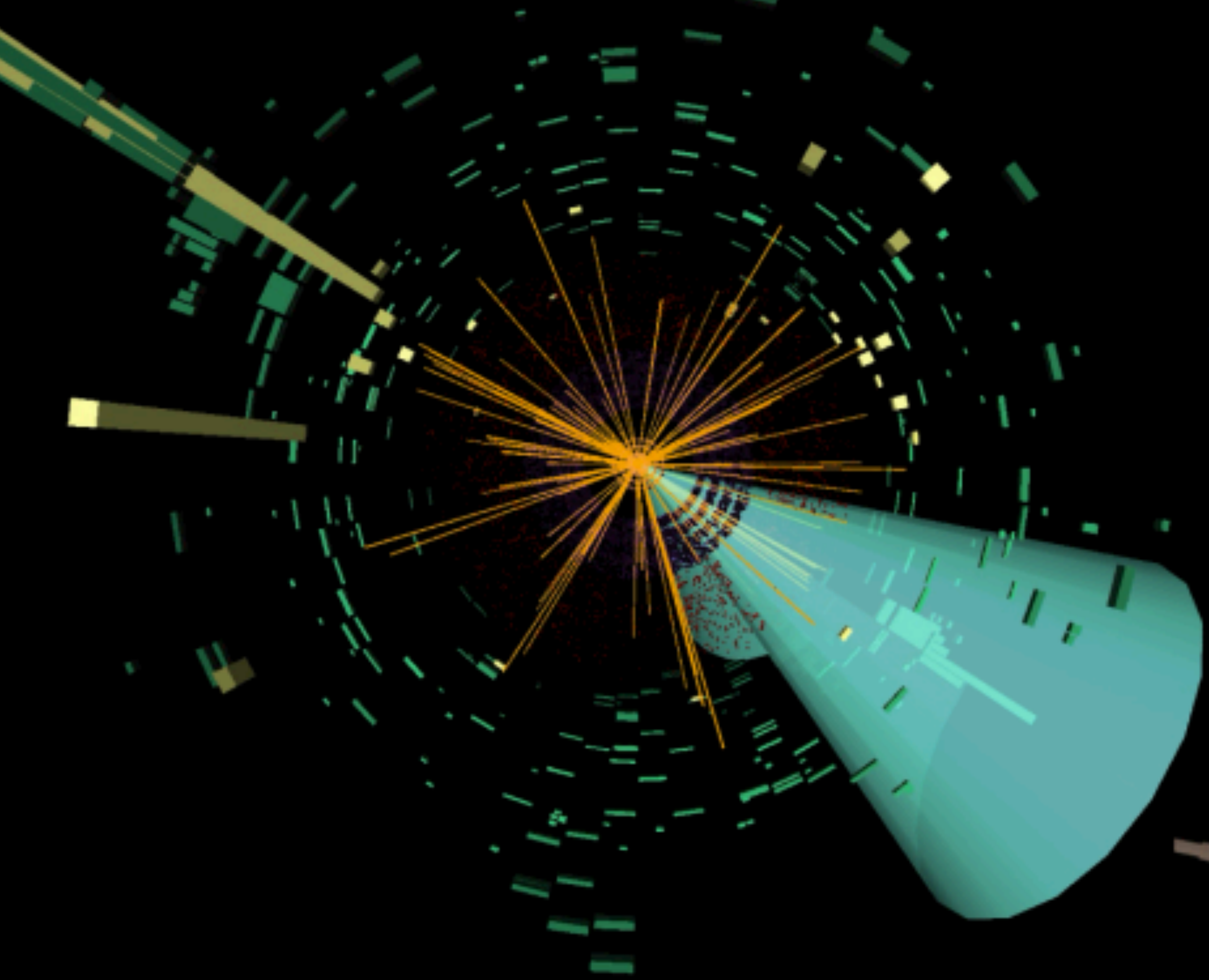
$HH \to b\bar{b}b\bar{b}$

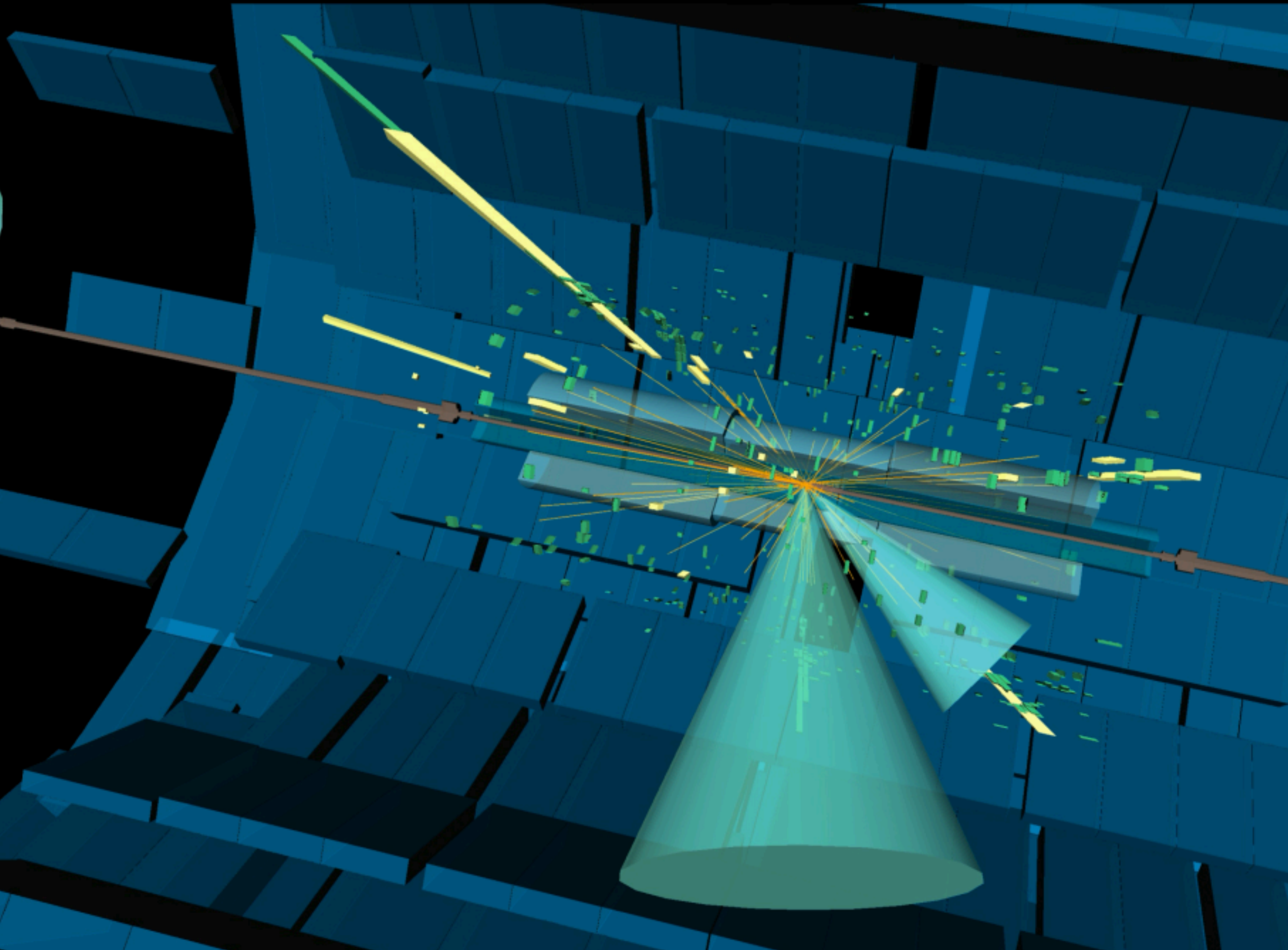
$$HH \to b\bar{b}\tau^+\tau^-$$



Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST

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





ATLAS EXPERIMENT

Run: 482747

Event: 990703589

2024-08-17 15:42:18 CEST

Sensitivities using Run 2 (2015 - 2018)

arxiv.2602.23991

Limits on cross-section $\mu = \sigma/\sigma_{SM} @ 95\,\%$	ATLAS		CMS	
	Observed	Expected	Observed	Expected
$HH \to b\bar{b}b\bar{b}$	5.4	8.1	7.0	**4.3**
$HH \to b\bar{b}\tau^+\tau^-$	5.8	**3.3**	3.5	5.4
$HH \to b\bar{b}\gamma\gamma$	4.1	**5.2**	8.7	5.7

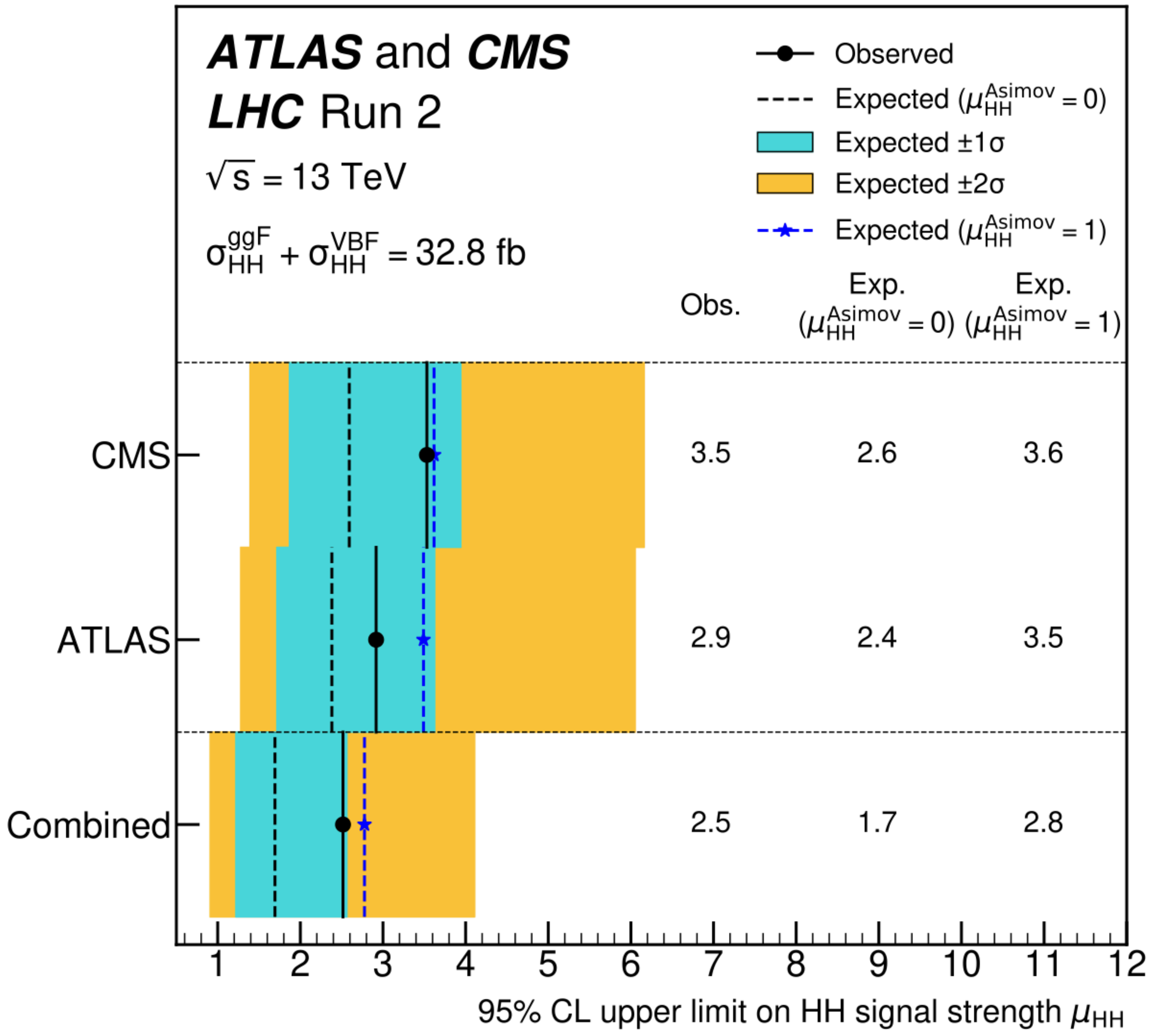
ATLAS and CMS: similar sensitivities across both experiments

- CMS drives sensitivity in $HH \to b\bar{b}b\bar{b}$ exploiting $H \to b\bar{b}$ taggers in high momentum topologies
- ATLAS drives sensitivity in $HH \to b\bar{b}\tau^+\tau^-$ thanks to better acceptance in triggers
- Similar sensitivities for $HH \to b\bar{b}\gamma\gamma$
- Overall: limits of the order of 3-5x the prediction of the Standard Model → not discovered yet!

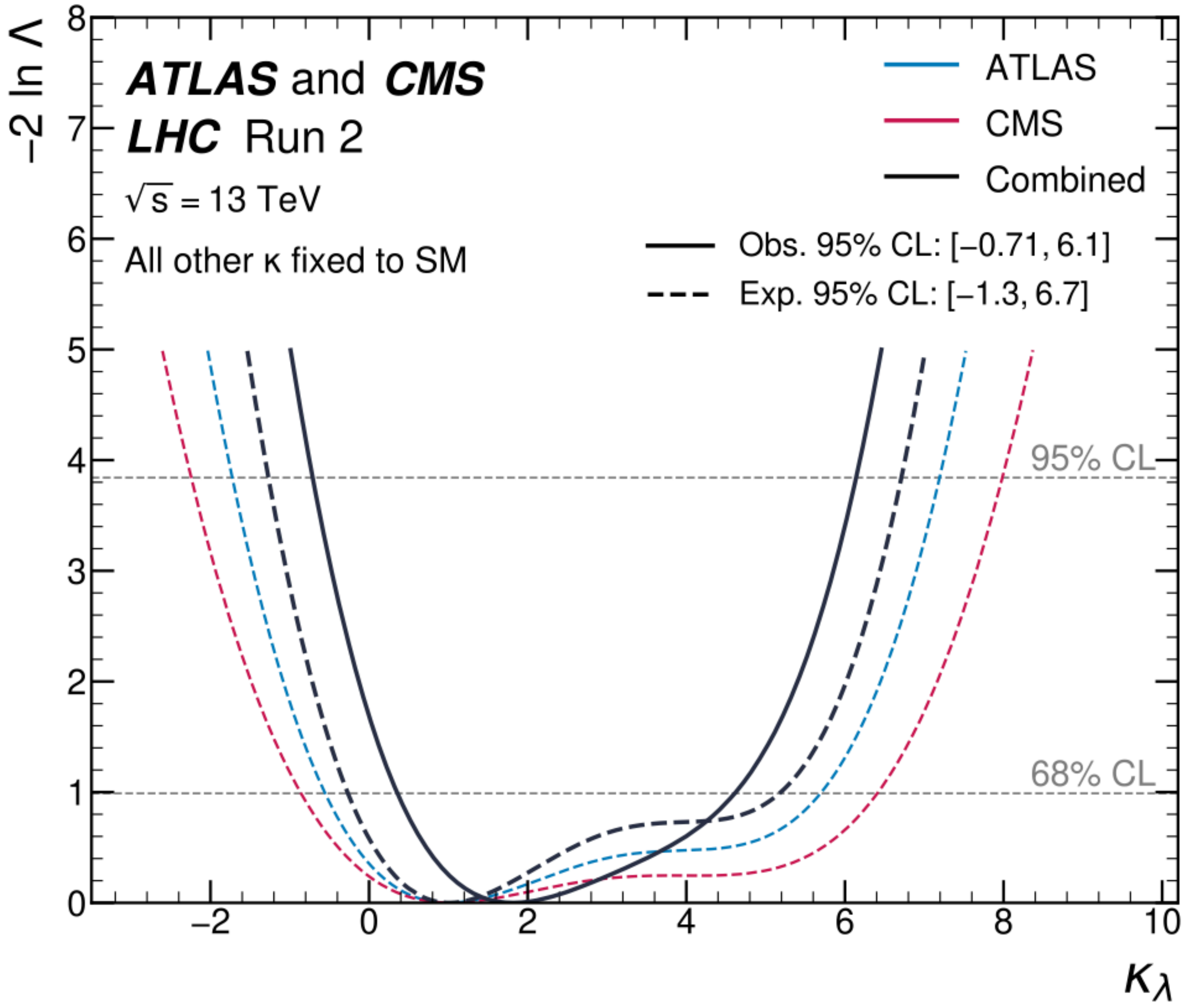
ATLAS and CMS combination

arxiv.2602.23991

Limit on Standard Model cross-section



Interpretation on tri-linear coupling modifier κ_{λ_3}



Combined sensitivity: exclude cross-sections higher than 2.5 x SM prediction

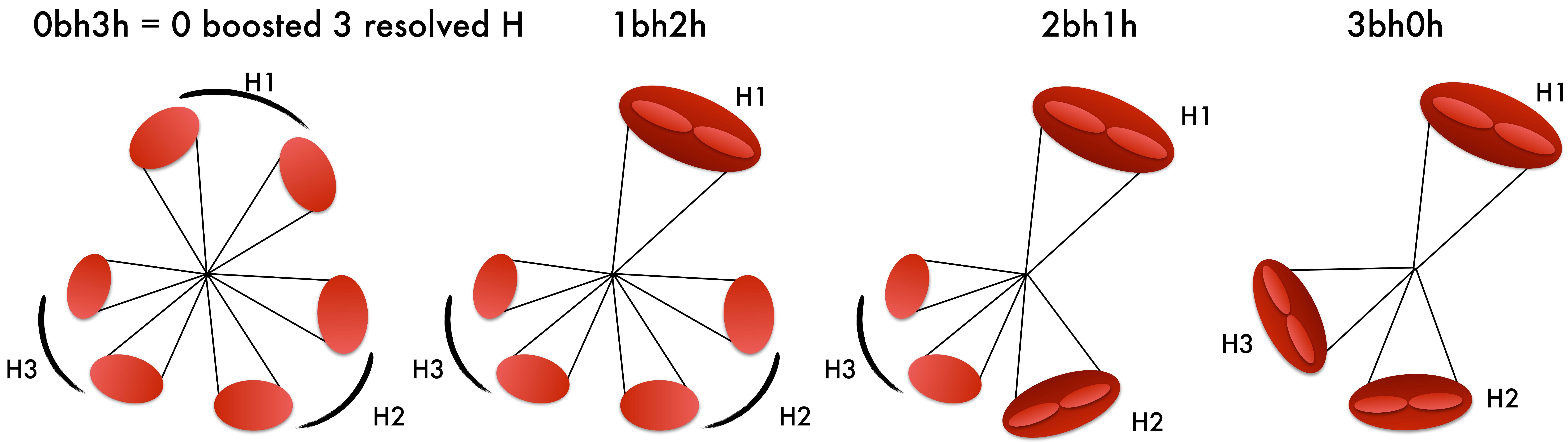
- Corresponding to $\approx 1.3\sigma$ sensitivity → more data + new tools needed for evidence (3σ)
- Constraining the Higgs self-coupling $\kappa_{\lambda_3} = \lambda_3/\lambda_3^{SM}$ **between [-0.6, 6]**
  - Stringent probe of the trilinear Higgs self-coupling!

CMS Experiment at the LHC, CERN
Data recorded: 2018-Aug-14 16:10:00.900096 GMT
Run / Event / LS: 321283 / 304117084 / 212

$HHH \rightarrow b\bar{b}b\bar{b}b\bar{b}$

Non-resonant $HHH \rightarrow 6b$

CMS-PAS-HIG-24-012
Phys. Rev. D 111, 032006



3 events produced in Run 2, up to 60 events by the end of the HL-LHC

HHH6b: rich experimental topology

- Resolved Higgs: reconstructed from 2 small-radius jets
- Boosted Higgs: reconstructed from one large-radius jets
- Complex mixing, dependent on momentum of the Higgs candidates

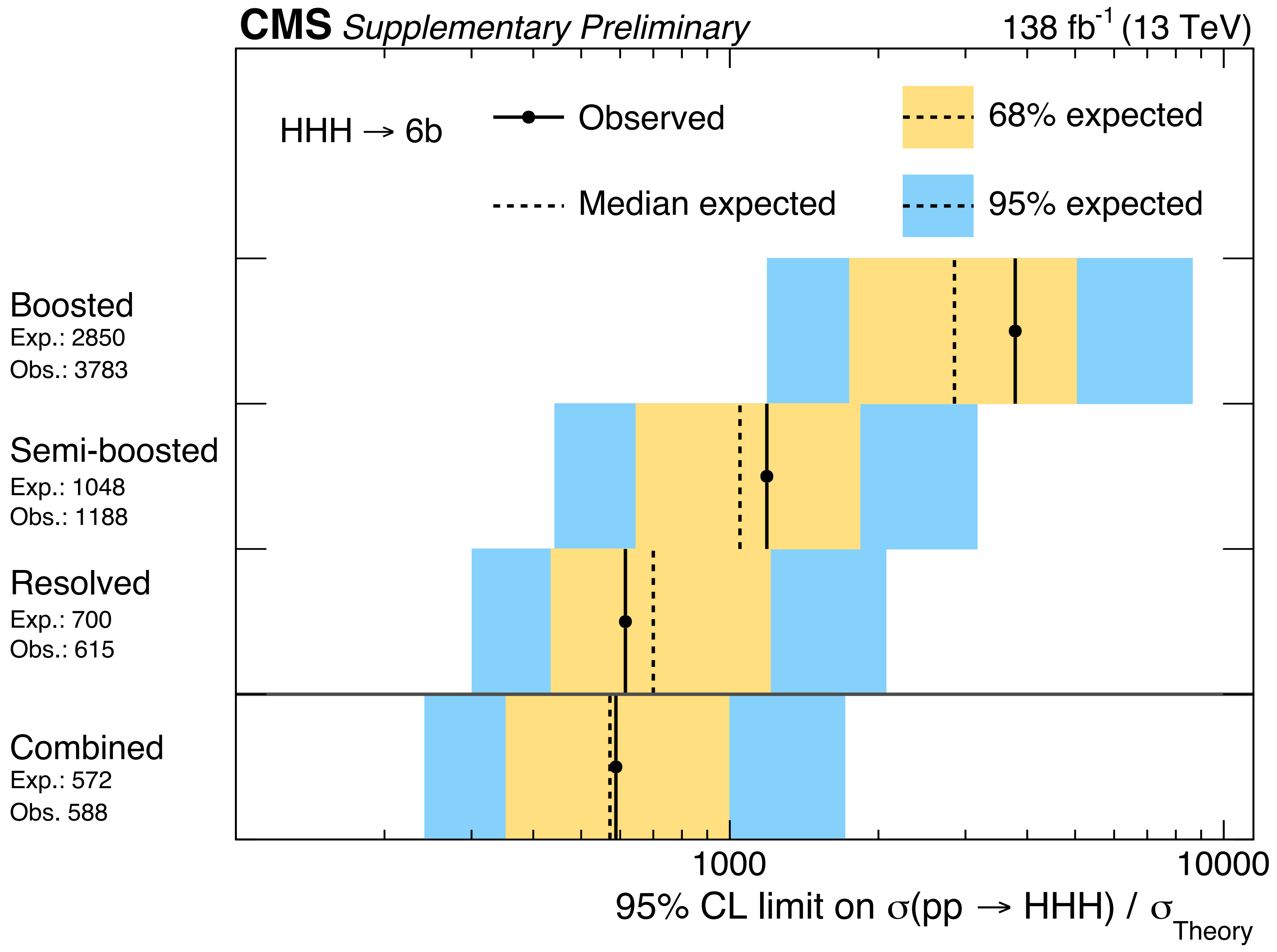
Rare process, but backgrounds faking 3 Higgs boson masses is also rare!

- Probe the trilinear λ_3 and quartic λ_4 couplings: *can we measure it at the HL-LHC?*

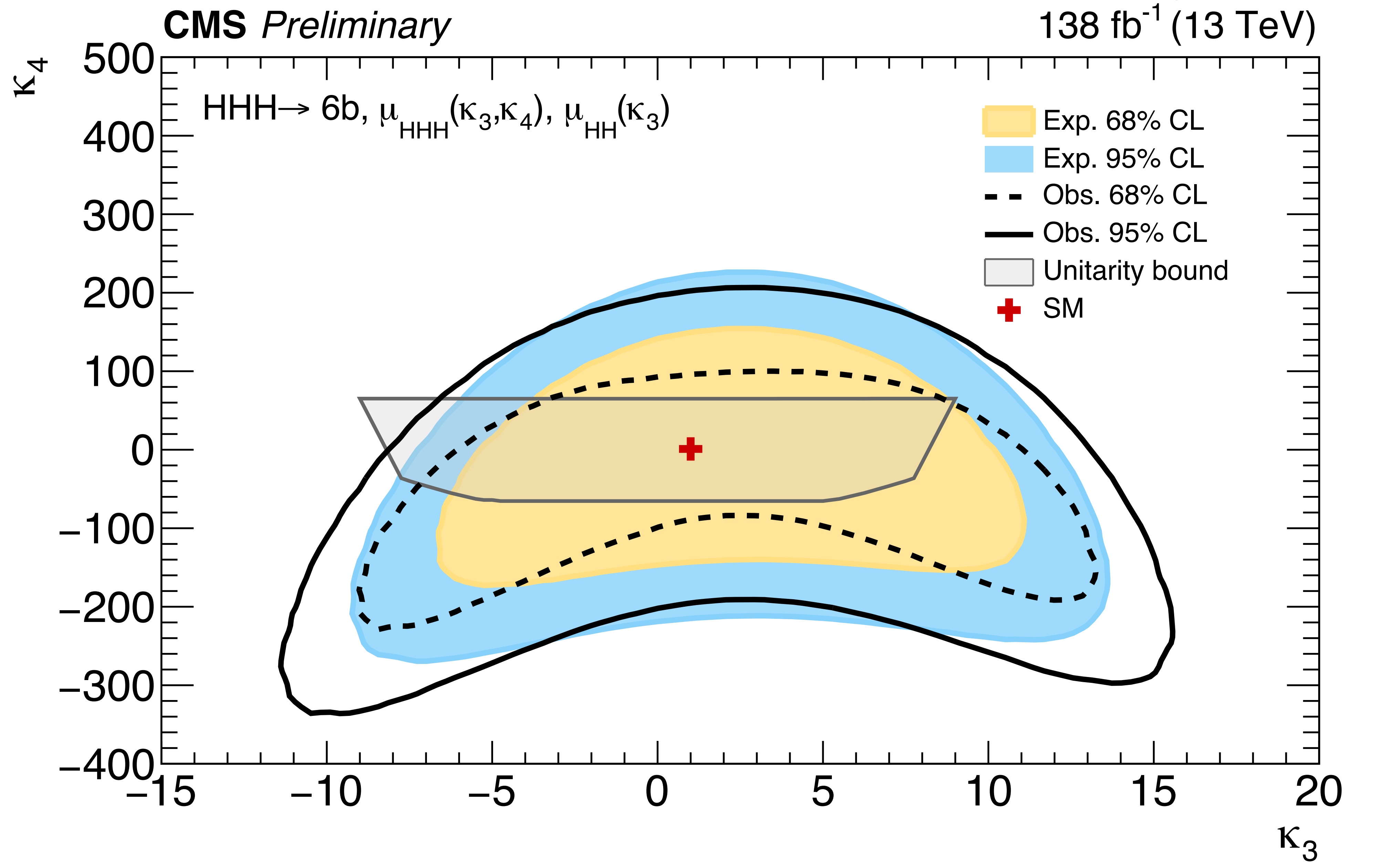
Non-resonant $HHH \rightarrow 6b$

CMS-PAS-HIG-24-012
Phys. Rev. D 111, 032006

Limit on Standard Model cross-section



Interpretation on coupling modifier κ_{λ_3} and κ_{λ_4}



CMS result: observed (expected) limit of $\mu < 588\ (572)$ x the SM at 95% CL

- ATLAS: $\mu < 750\ (750)$ focusing on resolved topologies with 6 b-jets
- One of the most challenging process ever targeted at the LHC!

Interpretation: effects of κ_3 and κ_4 on HHH and κ_3 on HH

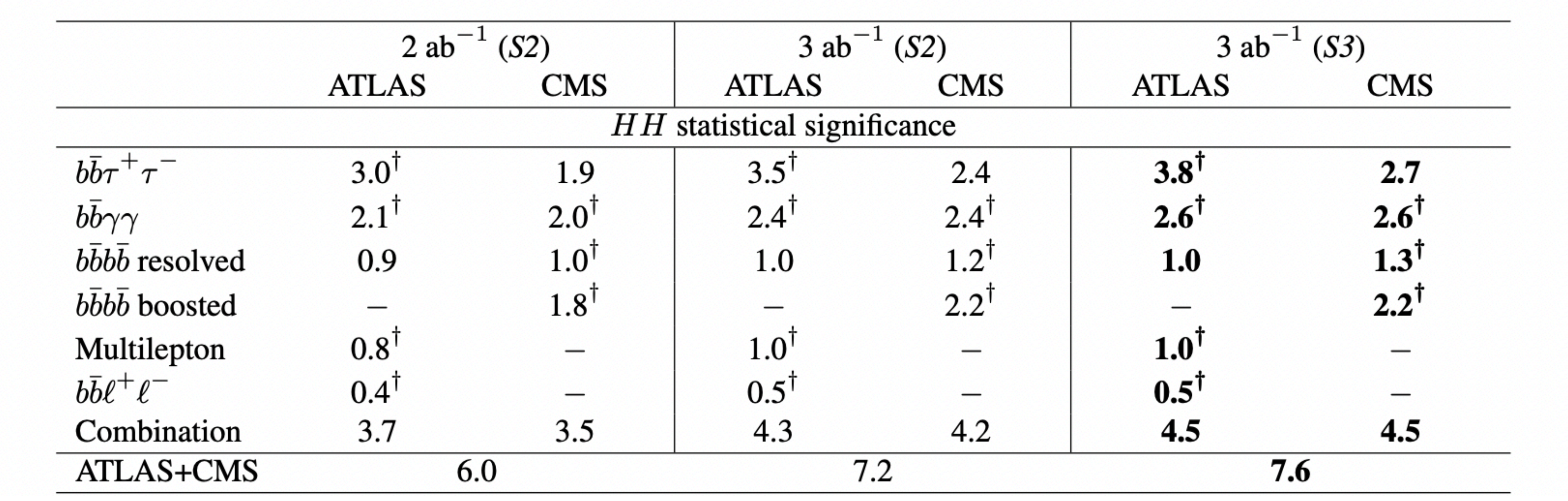
- Deviations constrained to $-7 < \kappa_3 < 12$ and $-190 < \kappa_4 < 190$

First experimental step into probing the quartic coupling!

2026 European Strategy update

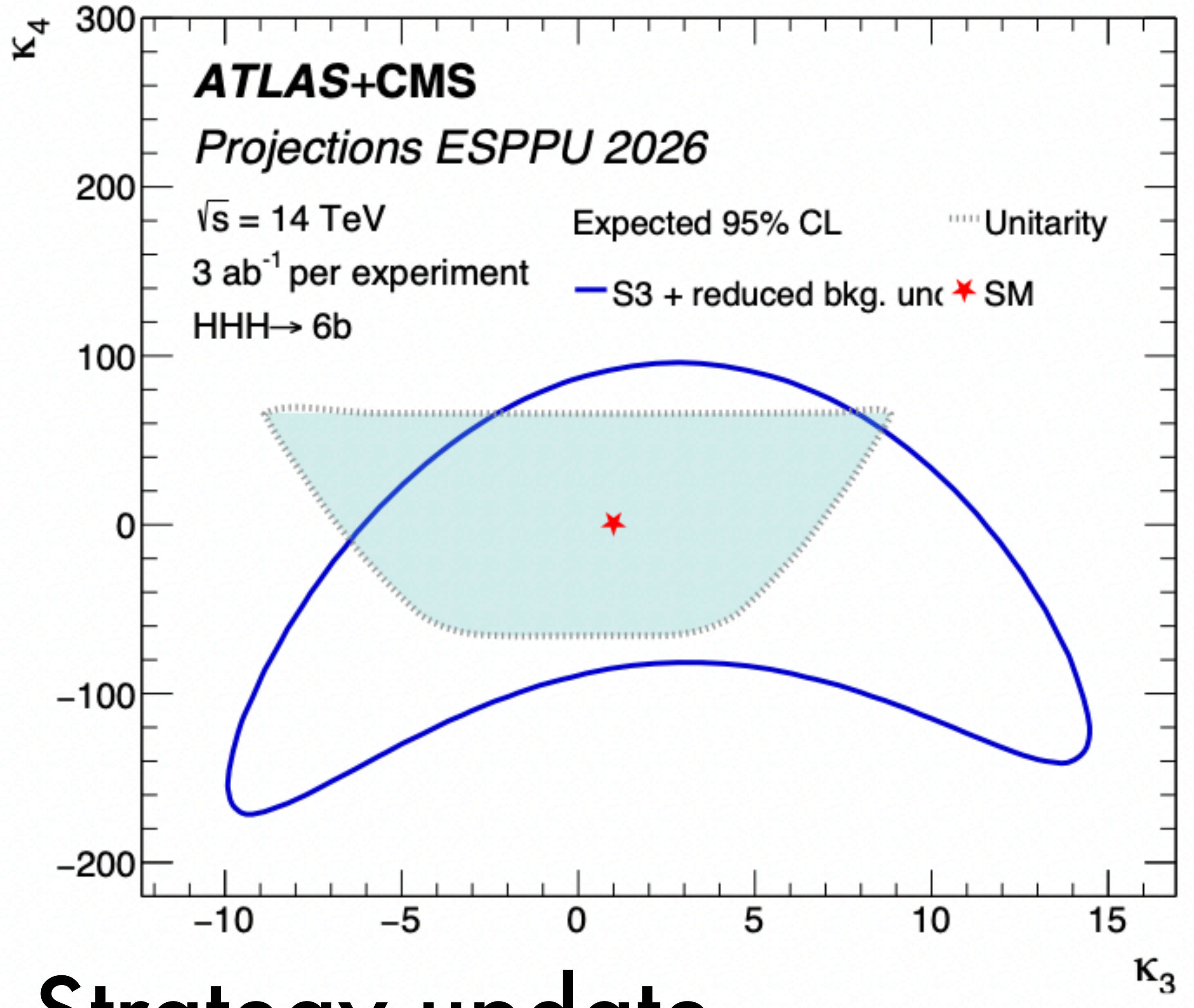
arXiv:2504.00672

HL-LHC projections: HH



	$2\ \text{ab}^{-1}$ (*S2*)		$3\ \text{ab}^{-1}$ (*S2*)		$3\ \text{ab}^{-1}$ (*S3*)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
	HH statistical significance					
$b\bar{b}\tau^+\tau^-$	$3.0^{\dagger}$	1.9	$3.5^{\dagger}$	2.4	**$3.8^{\dagger}$**	**2.7**
$b\bar{b}\gamma\gamma$	$2.1^{\dagger}$	$2.0^{\dagger}$	$2.4^{\dagger}$	$2.4^{\dagger}$	**$2.6^{\dagger}$**	**$2.6^{\dagger}$**
$b\bar{b}b\bar{b}$ resolved	0.9	$1.0^{\dagger}$	1.0	$1.2^{\dagger}$	**1.0**	**$1.3^{\dagger}$**
$b\bar{b}b\bar{b}$ boosted	–	$1.8^{\dagger}$	–	$2.2^{\dagger}$	–	**$2.2^{\dagger}$**
Multilepton	$0.8^{\dagger}$	–	$1.0^{\dagger}$	–	**$1.0^{\dagger}$**	–
$b\bar{b}\ell^+\ell^-$	$0.4^{\dagger}$	–	$0.5^{\dagger}$	–	**$0.5^{\dagger}$**	–
Combination	3.7	3.5	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	6.0		7.2		**7.6**	

HL-LHC projections: HHH



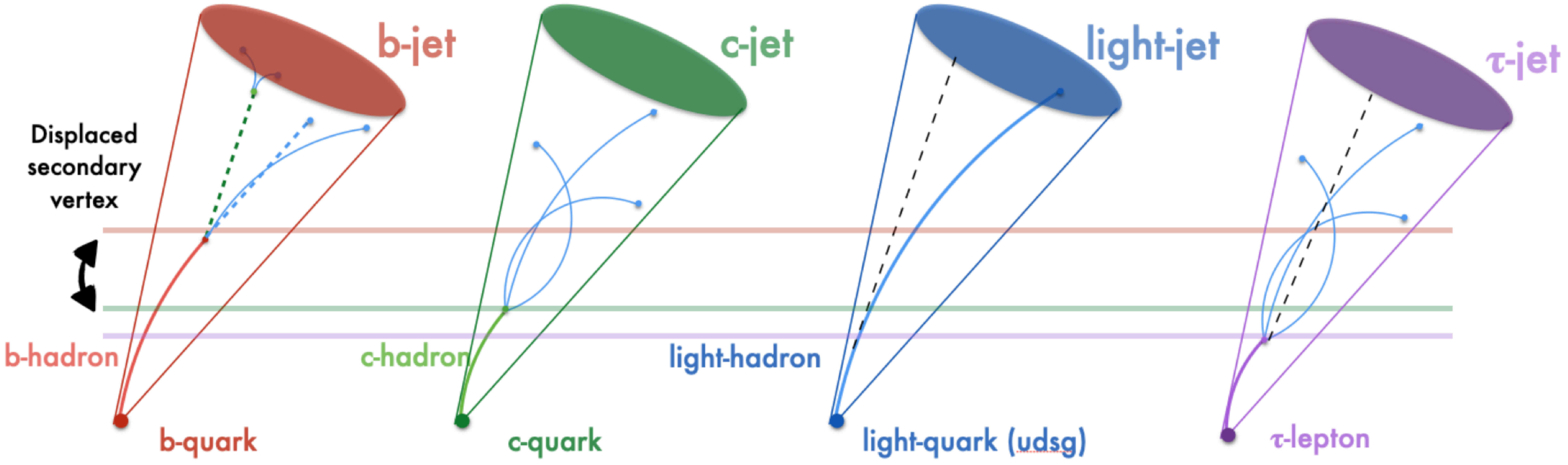
HH and HHH included as priorities in the 2026 European Strategy update

- Based on Run 2 results:
  - First **evidence of HH** process (30% precision): by **2040**
  - Combining ATLAS + CMS results with HL-LHC data (in 2045+): 20% precision
  - HHH: considered beyond reach of HL-LHC

Increased data sets and new tools are necessary to **accelerate discoveries**!

Driving innovations - from H to HH to HHH:
Technological **revolutions** at the LHC in Run 3

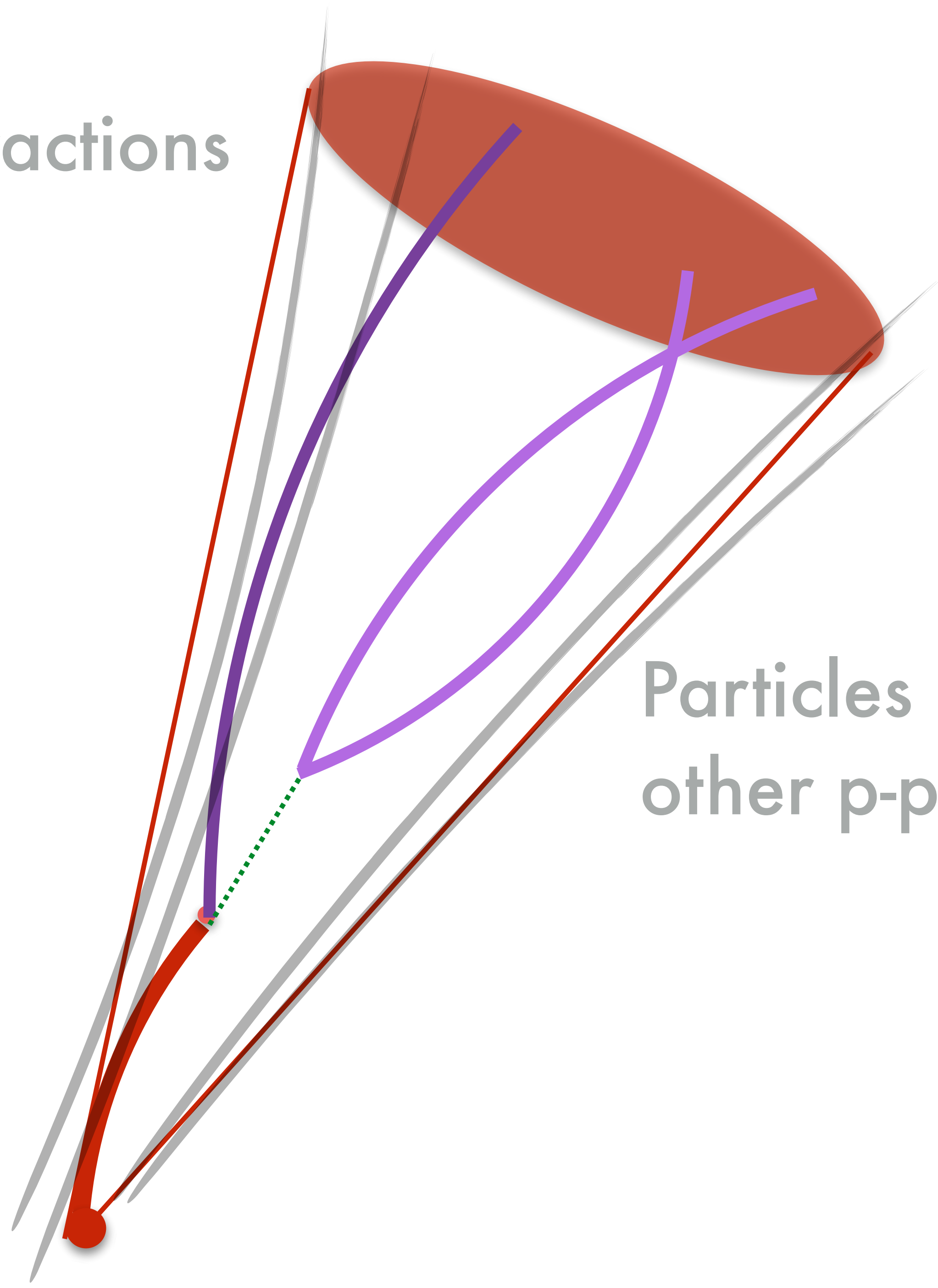
Flavor tagging concept



Until 2022: concept to identify heavy hadrons - lifetime and displacement

- Hadrons decay via W transition, top transitions are suppressed due to very large mass
  - $b \rightarrow c$ and $c \rightarrow s$ transitions, longer lifetime for b-hadron than c-hadrons
  - Identification algorithms **heavily relied on secondary vertices reconstruction**
    - Usage of machine learning algorithms with higher-level reconstructed variables
  - In general, **easier** to **identify b-jets** than **c-jets** due to physics properties of b-hadrons

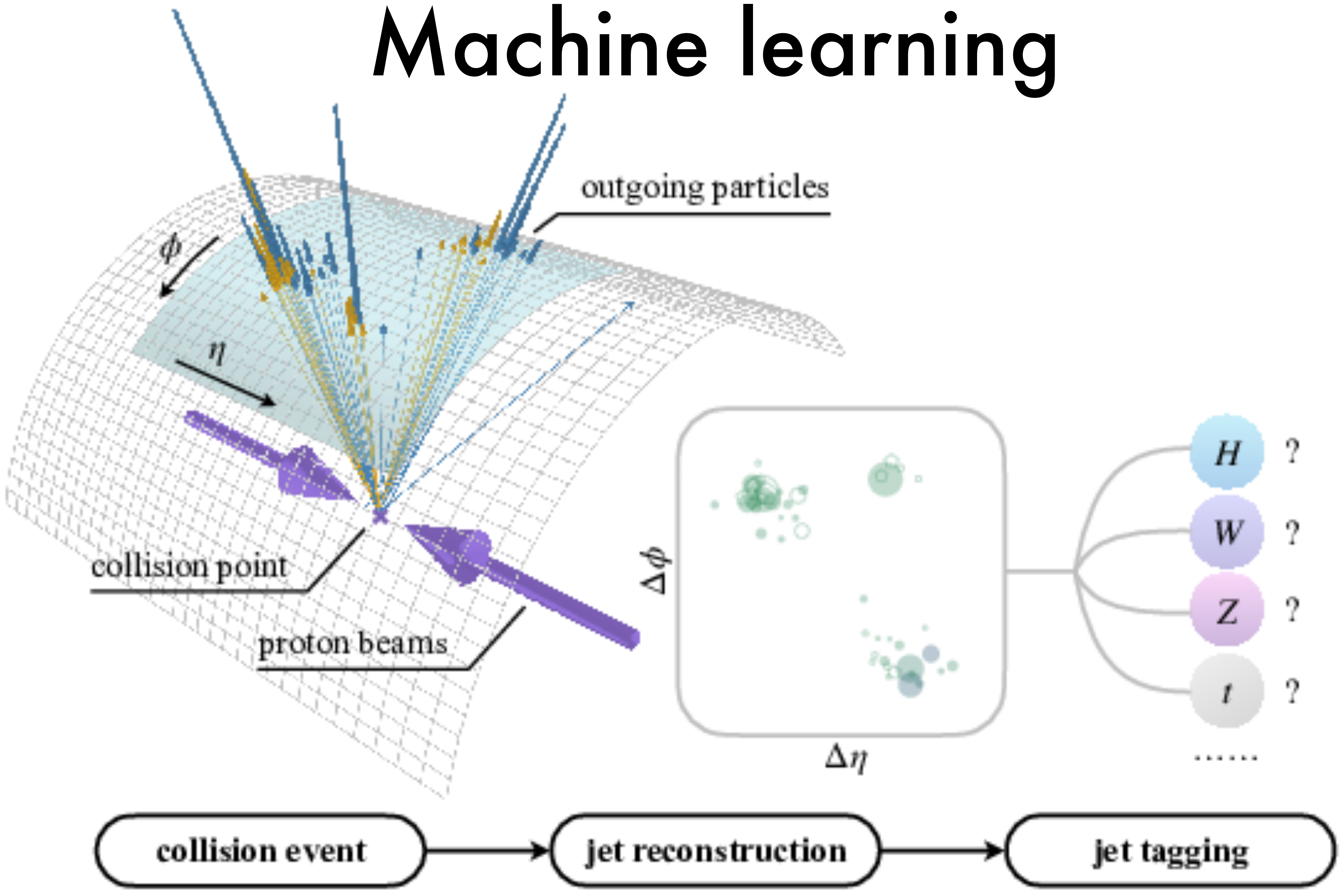
Paradigm shift for Run 3 and Run 2 re-analysis



Particles from
other p-p interactions

Particles from
other p-p interactions

Machine learning

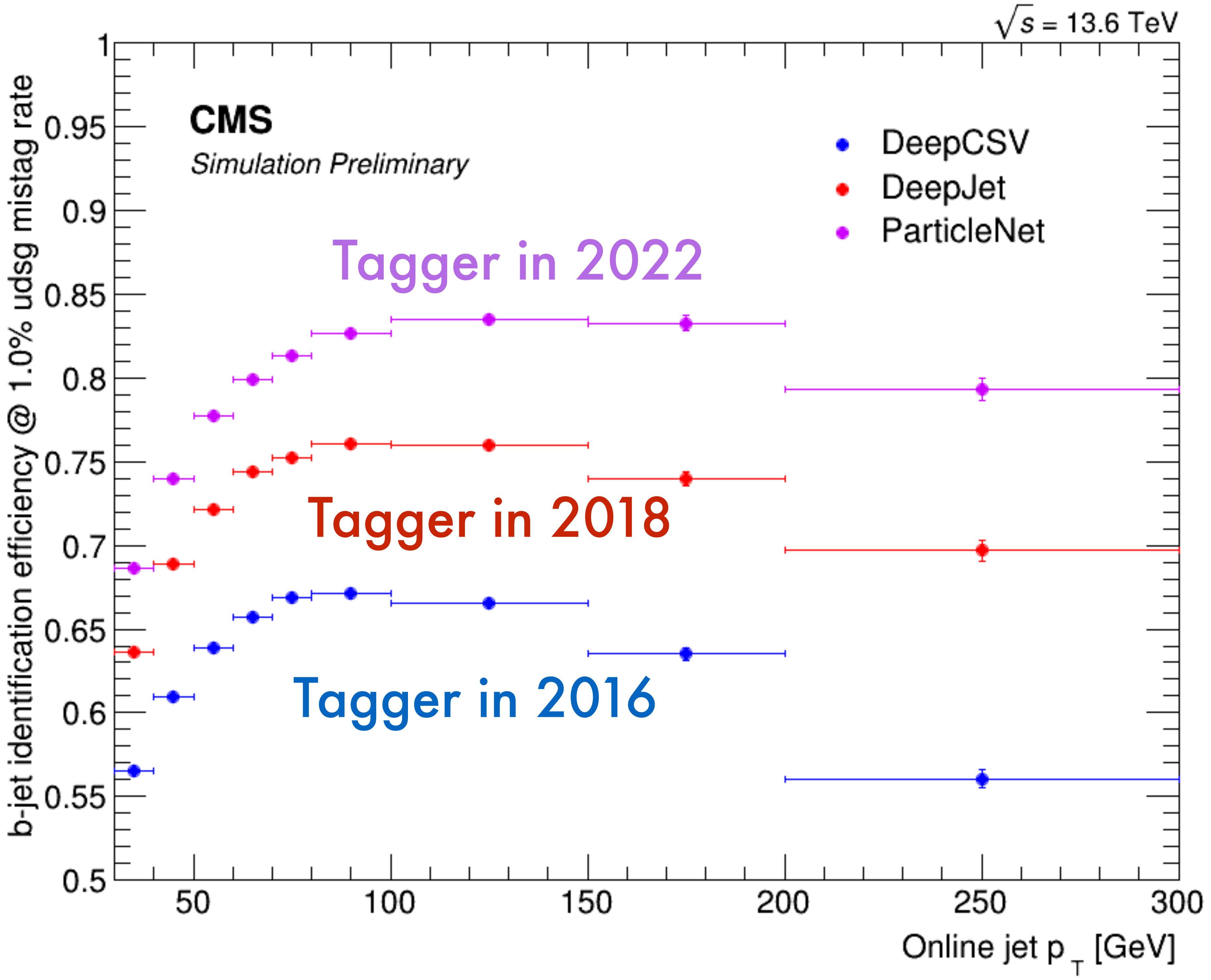


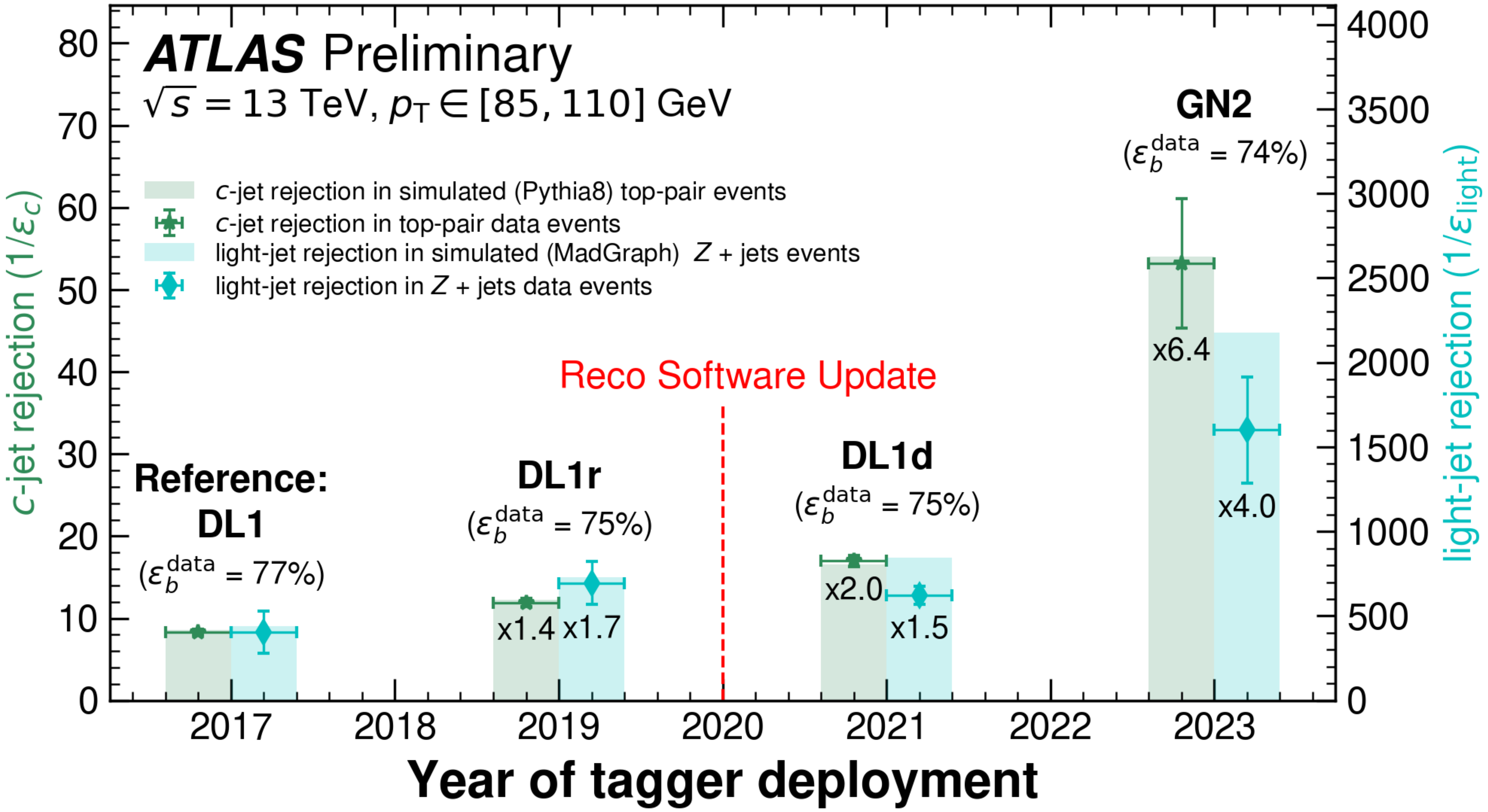
Advances in machine learning and computing (GPUs)

- Instead of relying on secondary vertices, use **all charged and neutral particles**
- Train algorithms to predict flavor of a jet using tens and hundreds of particles in jet
  - Momenta, position, angular separation, secondary vertices…

Paradigm shift for Run 3: flavor tagging

CMS DP-2023/021
ATLAS FTAG-2023-07
Nature Communications volume 17





Performance of b-jet identification at fixed 1% mis-identification rate for other flavors

- 2016: ≈65%, 2018: ≈75%, 2022: ≈85%
- More than **30% improvement on same jets** in 6 years **just using better tools**!

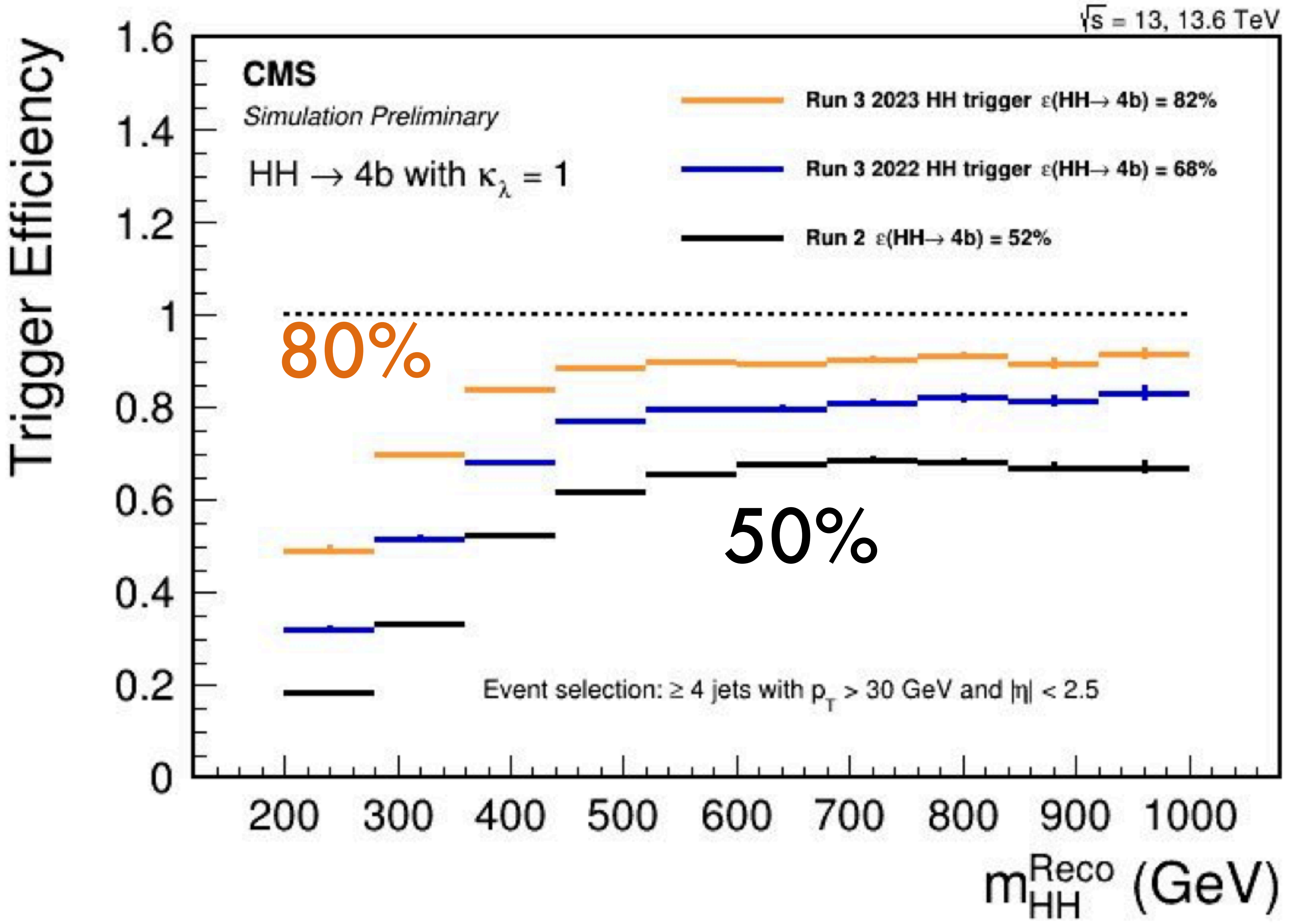
At fixed b-jet tagging efficiency: **improvements** of **factor 4-6** in **background rejection**!

Same detector, same jets, better algorithms: enormous gains without building a new collider!

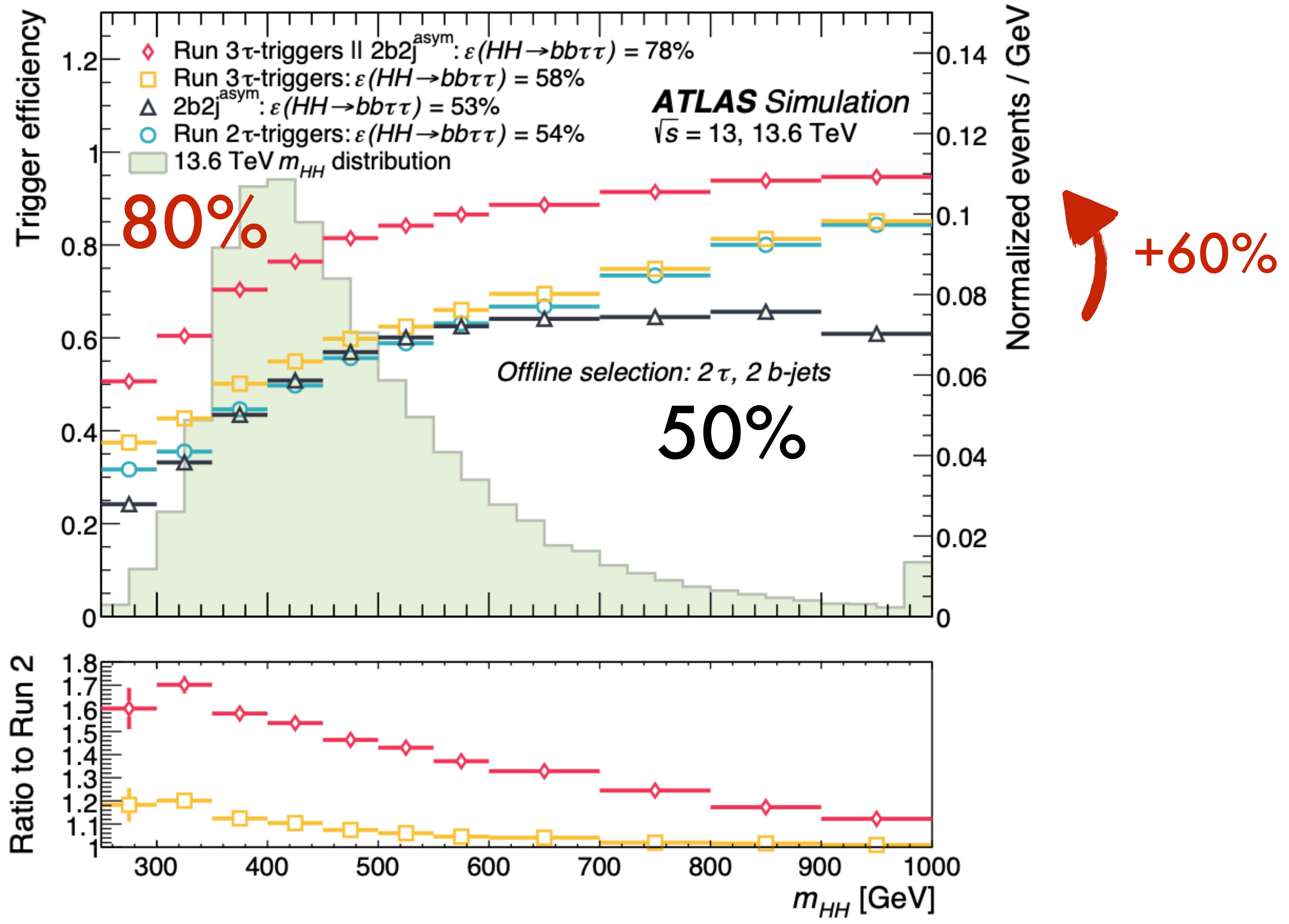
New triggers for multi-Higgs production

CMS DP-2023/021
CMS DP-2023/050
JINST, 20, 2025

$HH \rightarrow 4b$



$HH \rightarrow 2b2\tau$



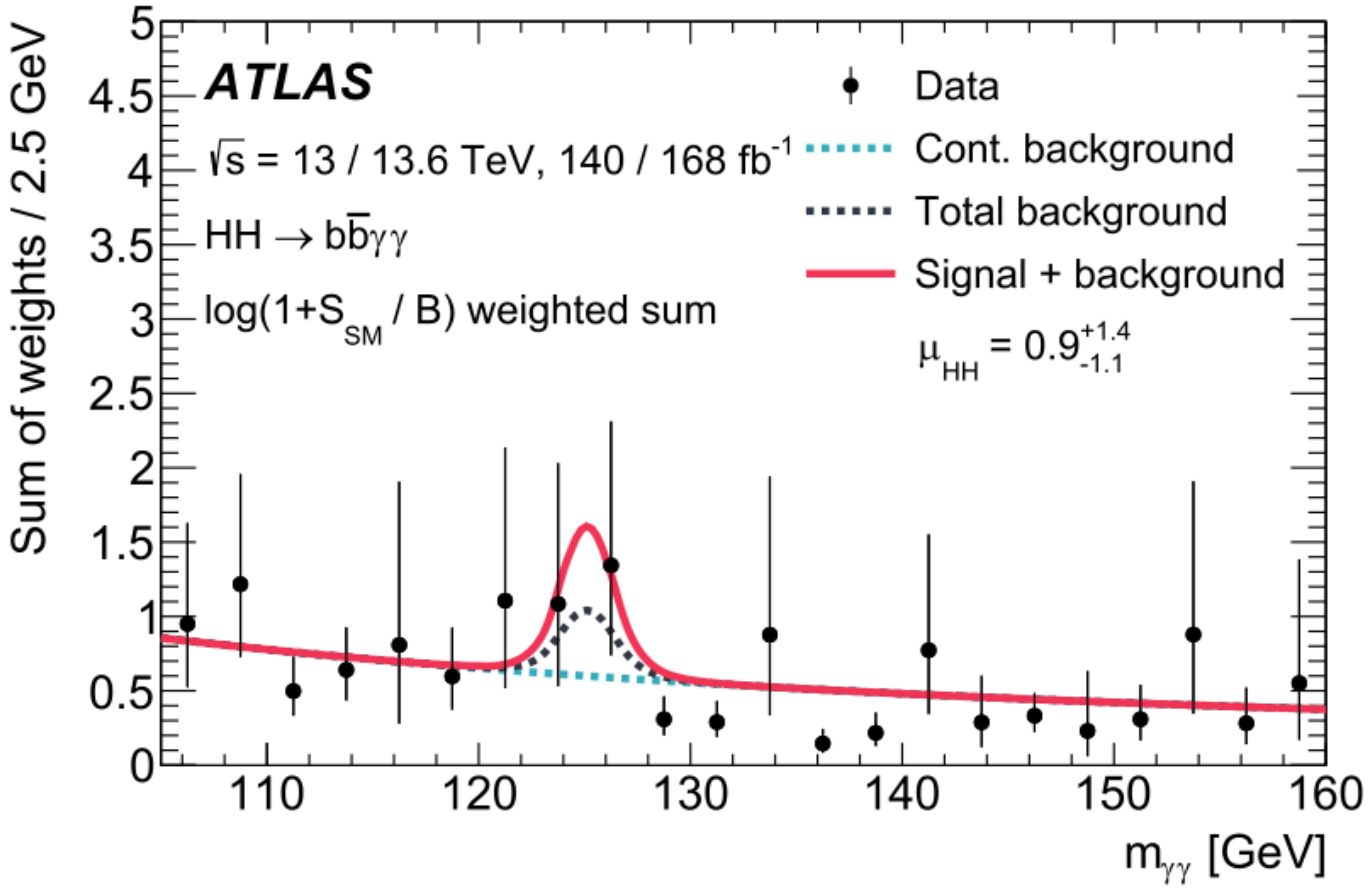
New flavor tagger + extensive usage of CPU and GPU farms at trigger

- Allows large increase in the number of multi-Higgs events recorded!
- In 2018: only recording 50% of $HH \rightarrow 4b$ and of $HH \rightarrow 2b2\tau_h$ events
  - HH events are already hard to produce, we recorded only a small fraction of them
- In Run 3: from 50% to 80, relative improvement of **60%!**

ATLAS and CMS Run 3 HH

Phys. Lett. B 876 (2026) 140280
arxiv:2604.27044

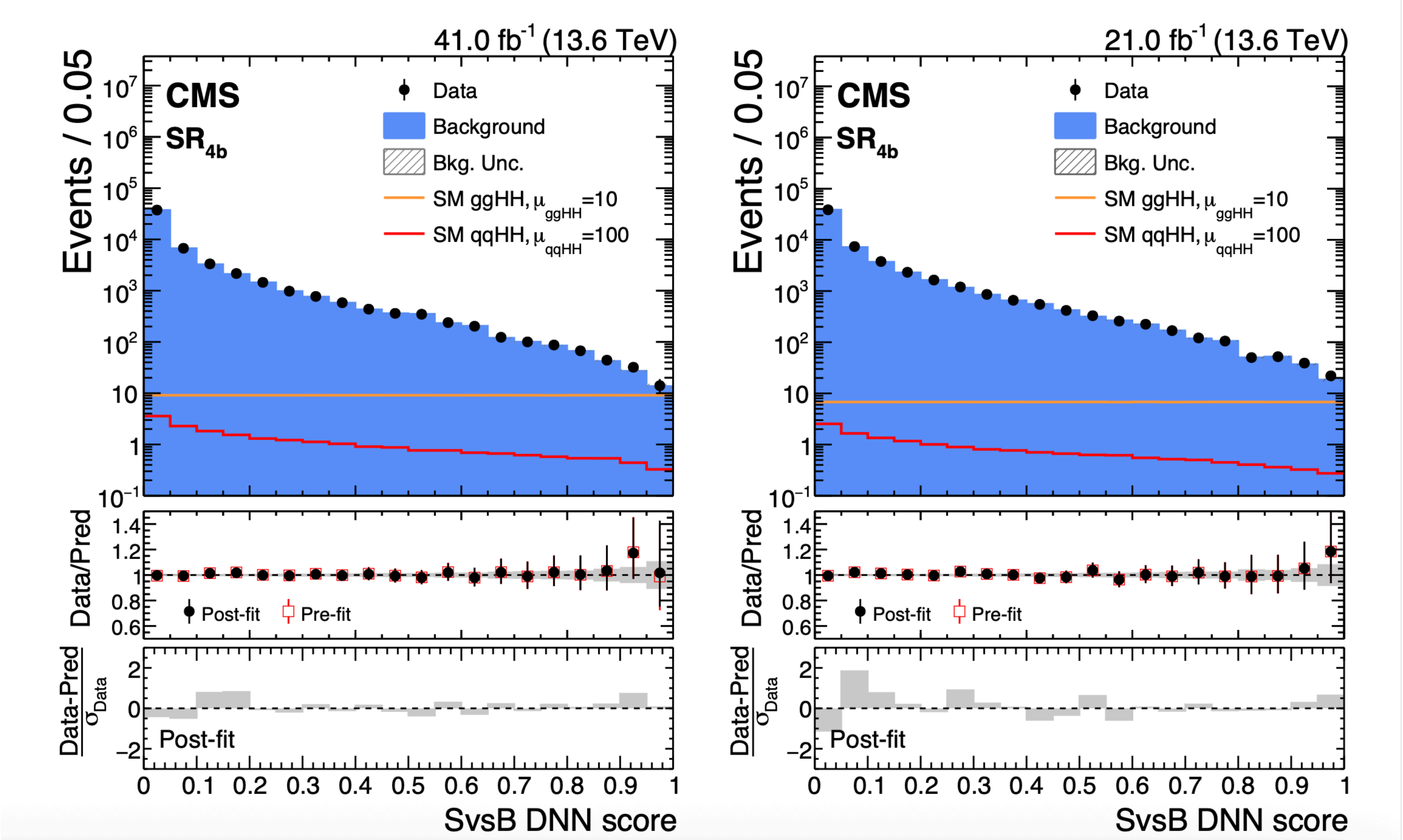
ATLAS $HH \to b\bar{b}\gamma\gamma$



Using data from 2016 to 2024:

- Limit **< 2.6x SM (** $\approx 1\sigma$**)**

CMS $HH \to b\bar{b}b\bar{b}$



Using data from 2016 to 2023:

- Limit **< 2.8x SM (** $\approx 1\sigma$**)**

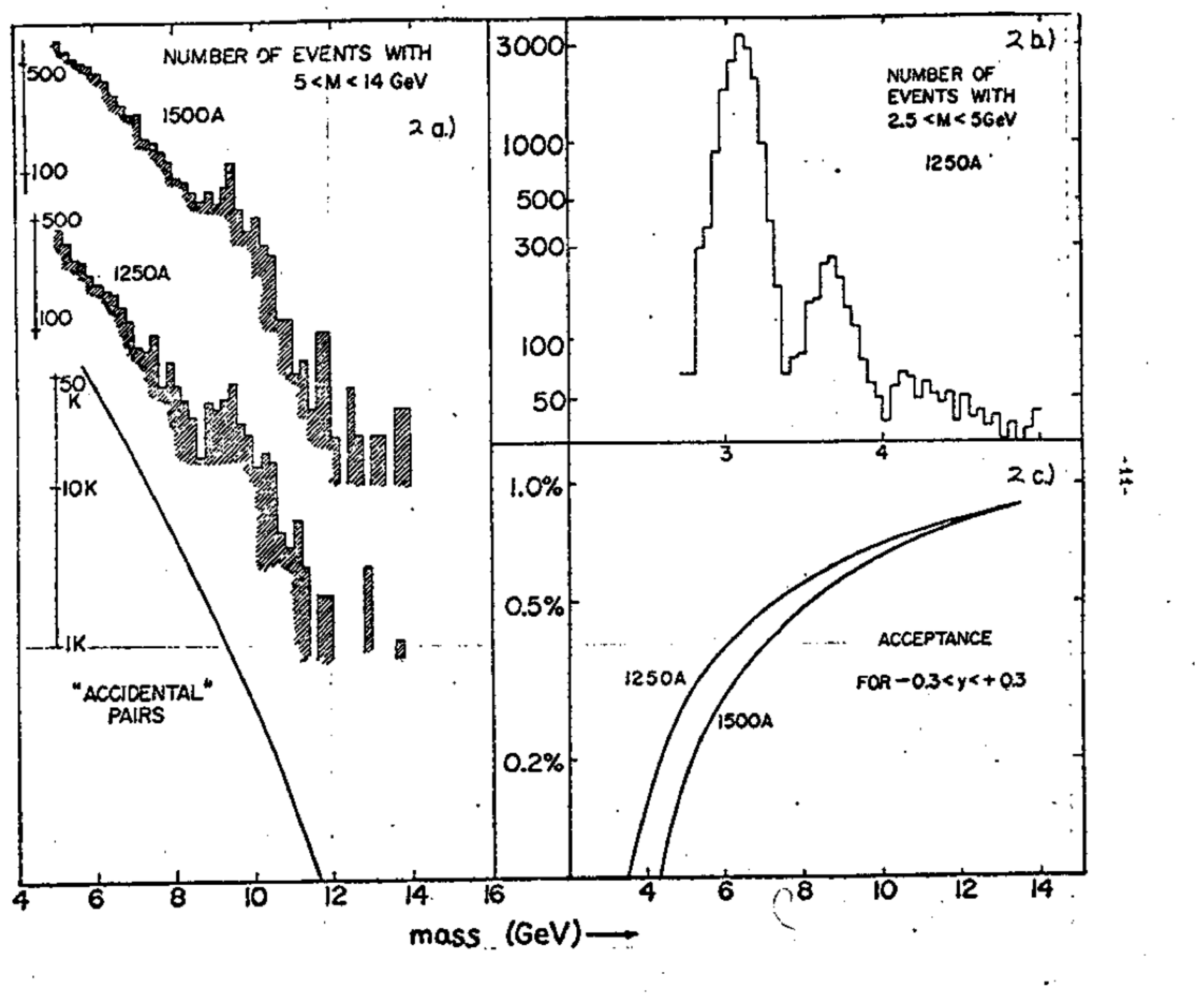
New tools and triggers applied to ATLAS and CMS data:

- Single channels now as sensitive as Run 2 combinations!
- Factor **2x improvements by optimizing how detector is used!**
- Extraordinary developments in LHC physics in the last 5 years! → More results soon!

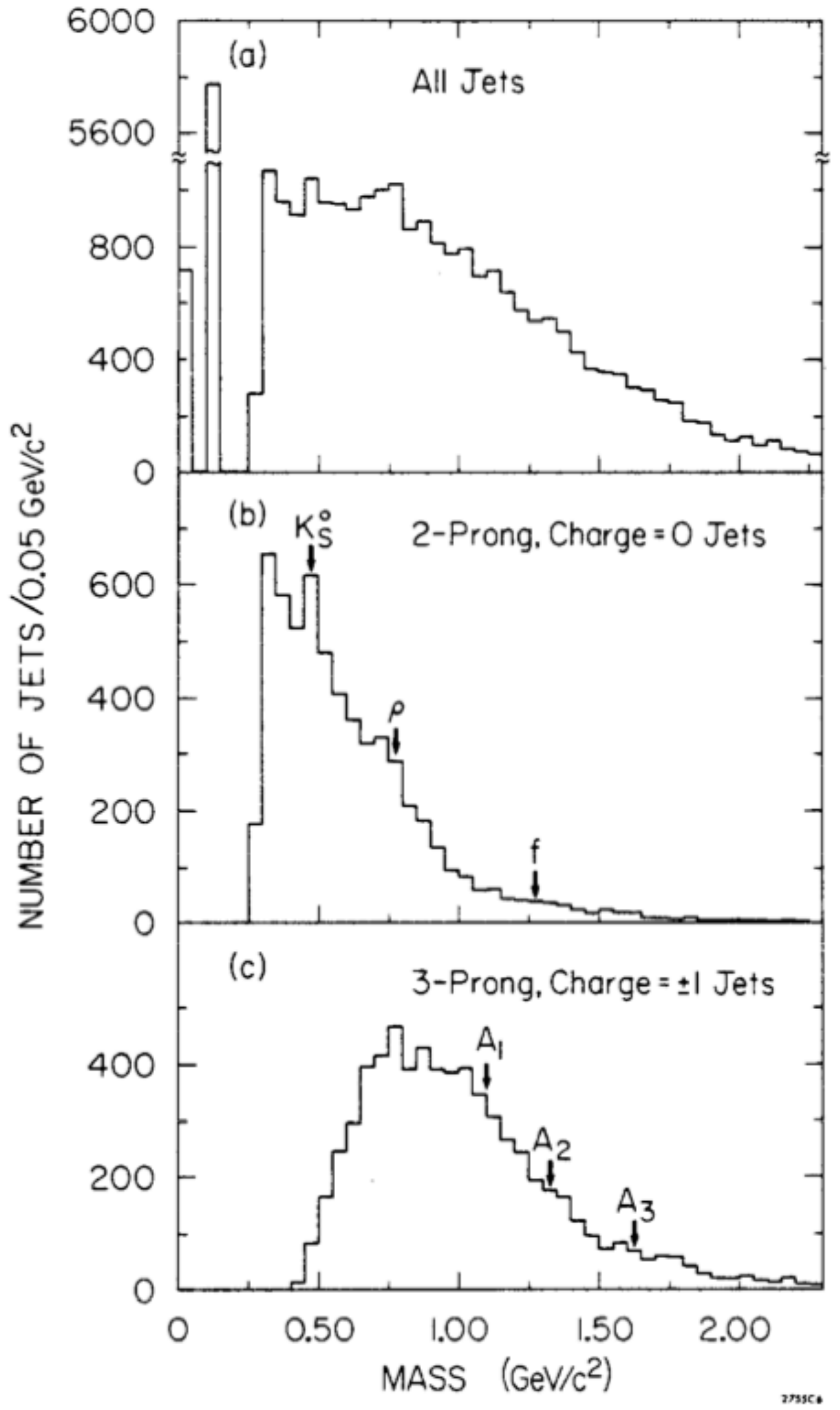
Increasing the discovery potential: jet-charge tagger

Jet charge tagging

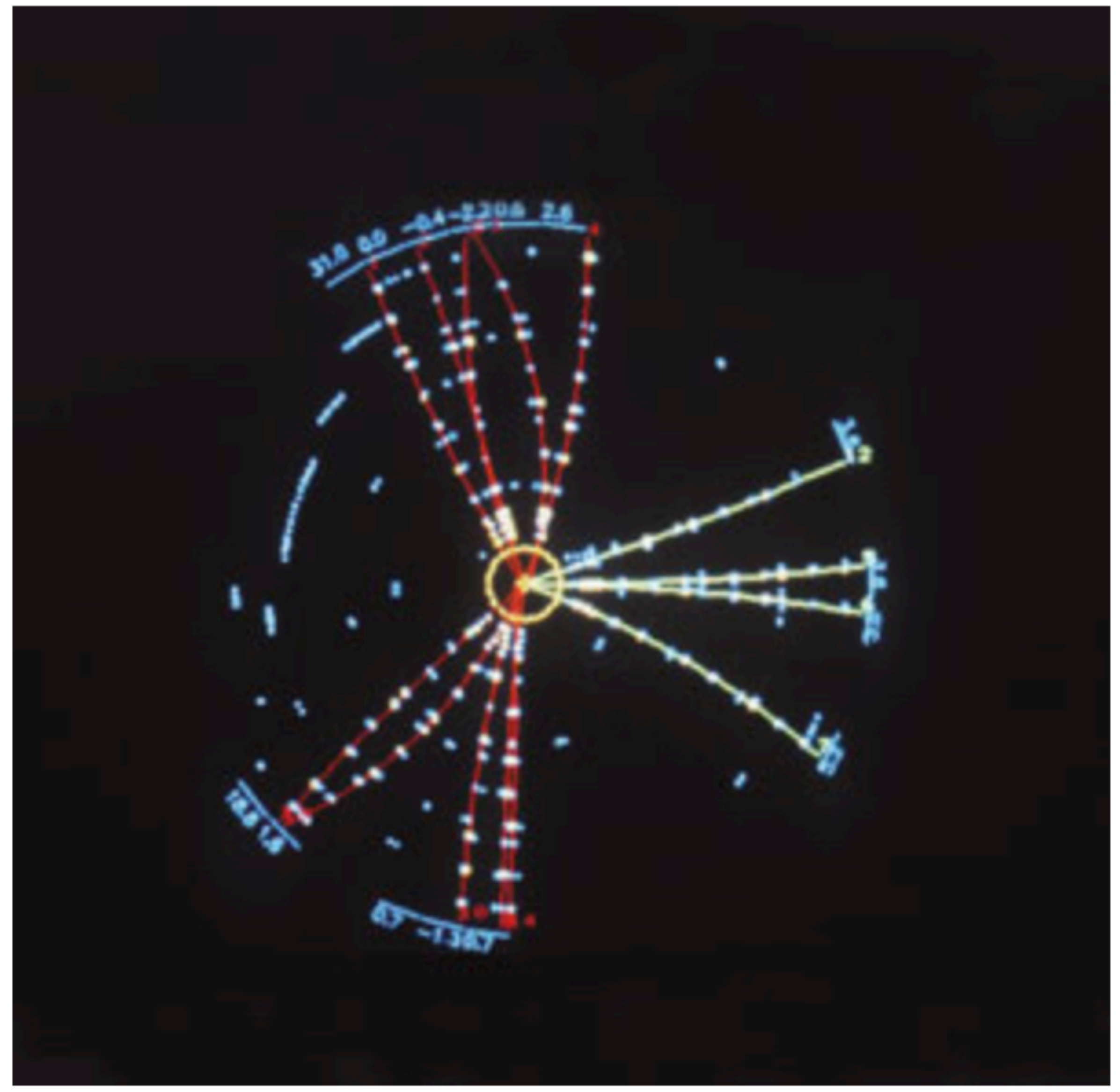
1977 b-quark discovery at Fermilab



1975 jet discovery at SLAC



1979 gluon discovery at DESY

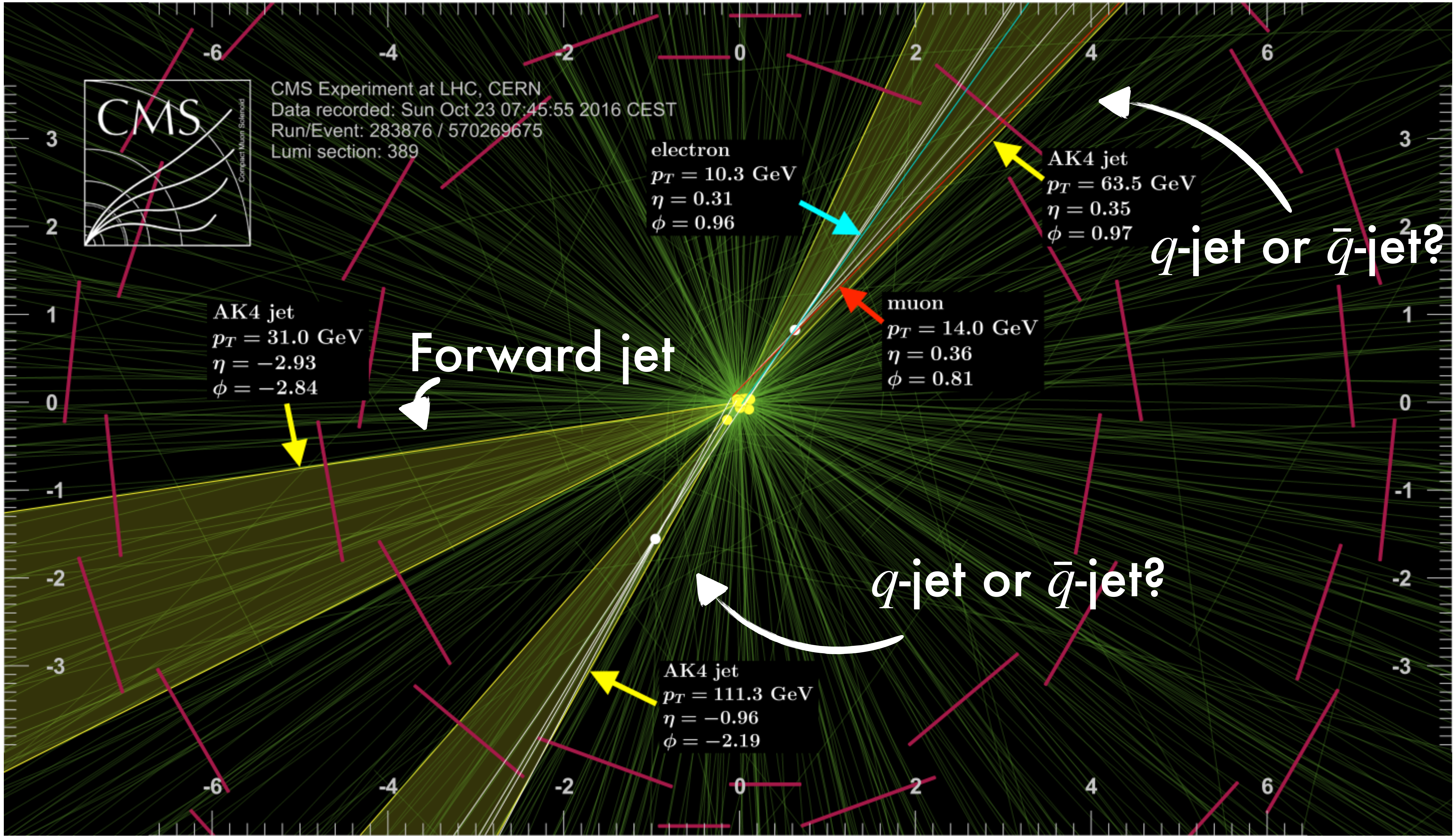


About 50 years after the **b-quark** and **jet discoveries**:

- ATLAS and CMS: blind to **sign of the electric charge of quarks**
  - We don't know how to **separate** jets originating from **quarks** and **anti-quarks**
  - Intrinsic signal property currently not used, decays conserve the electric charge!

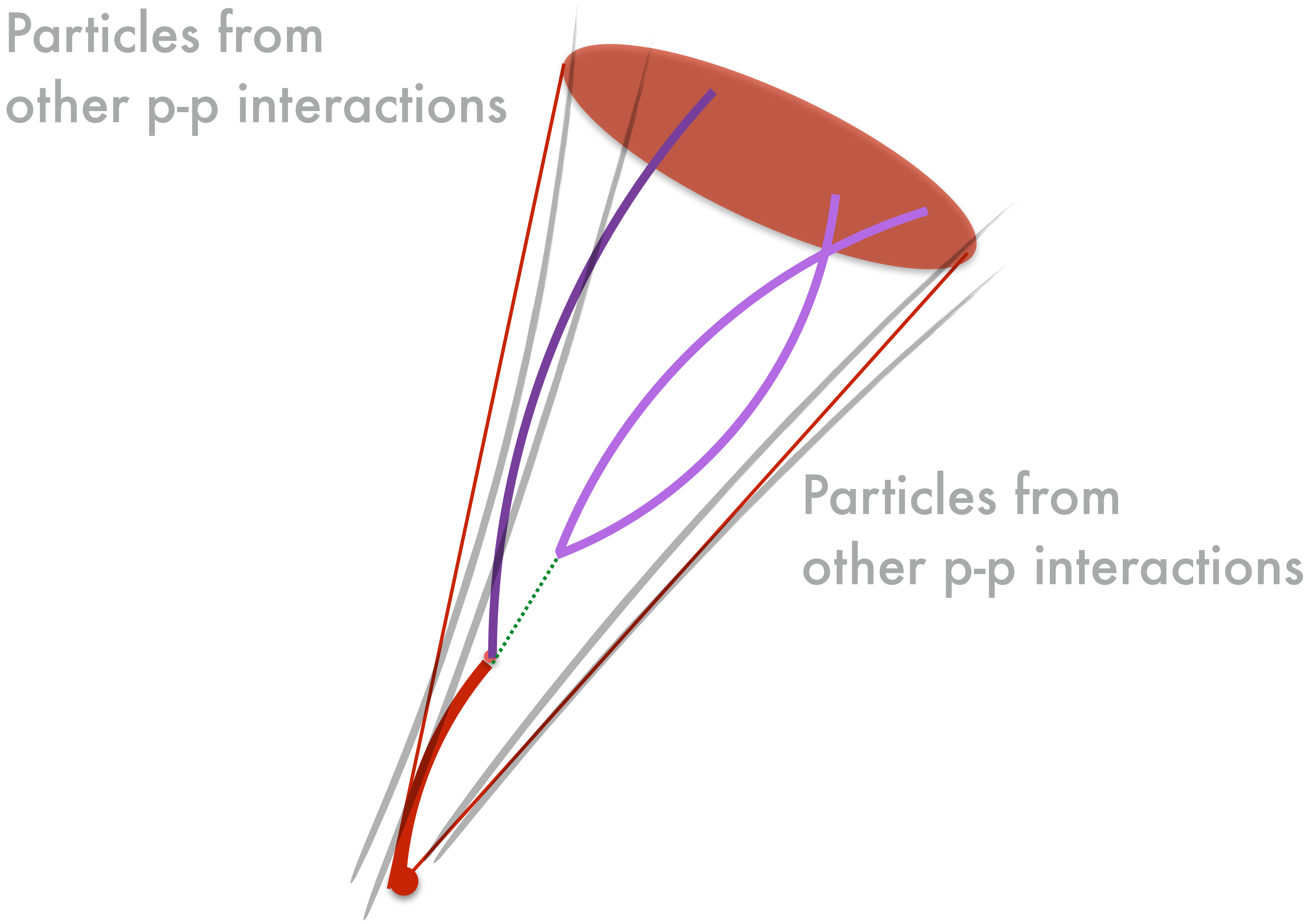
Why is this not used in ATLAS and CMS?

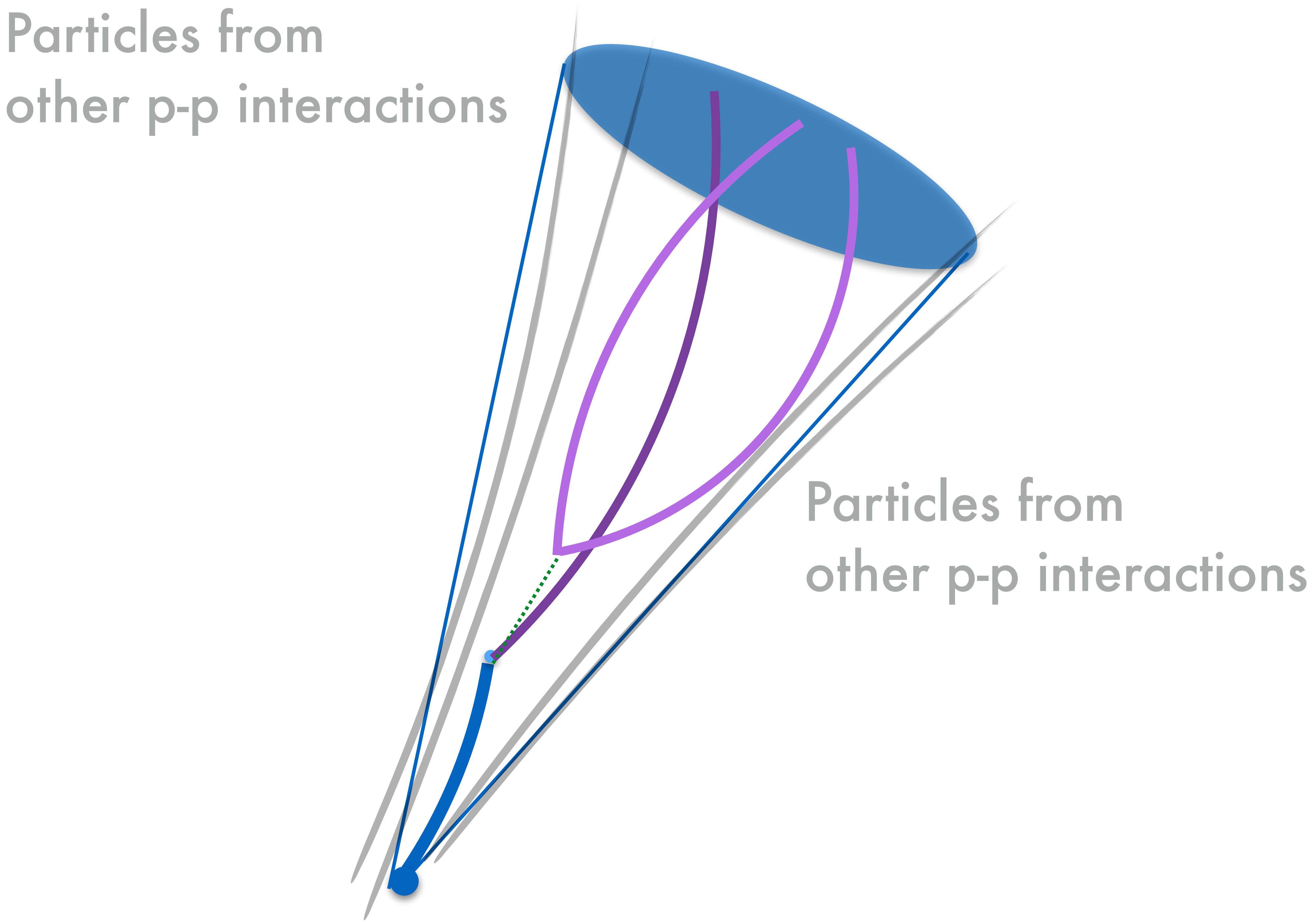
Why is this not used in ATLAS and CMS?



Distinguishing quarks from anti-quarks in jets: extremely challenging task in data

Why is this not used in ATLAS and CMS?





Believed **impossible** to do efficiently at high luminosity proton-proton colliders:

- Large variety of hadron decays: $B^- \to D^0\pi^-$ is one of the largest decay mode and only 0.5% of all B^-
- Contamination from additional particles produced in secondary proton-proton interactions
- Algorithmic limitations resulting in performance of 50-60% on CMS data, restricted to high rate process!

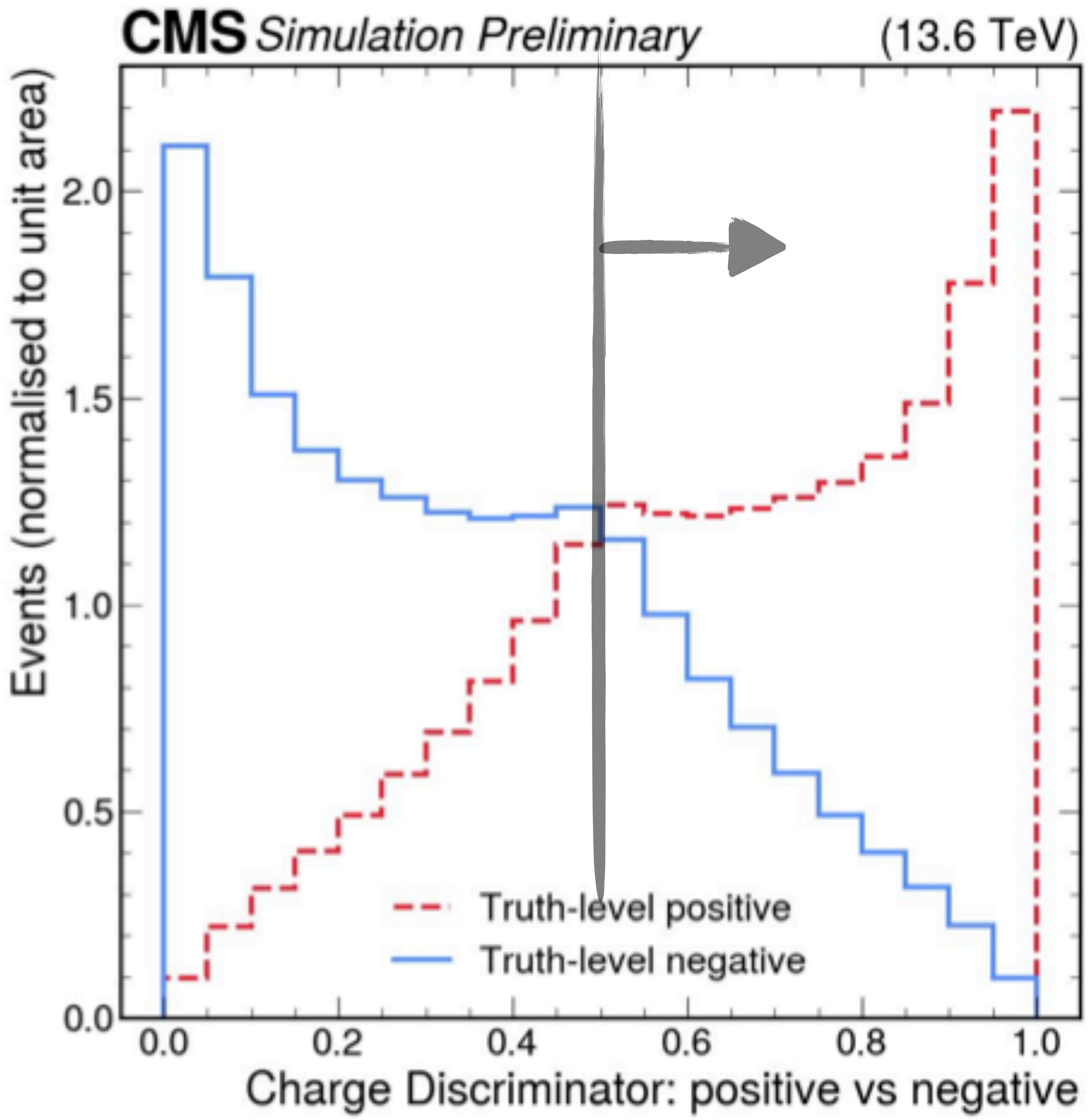
Timely: algorithms applied to b- and c-jet tagging improved performance by x10 to 100!

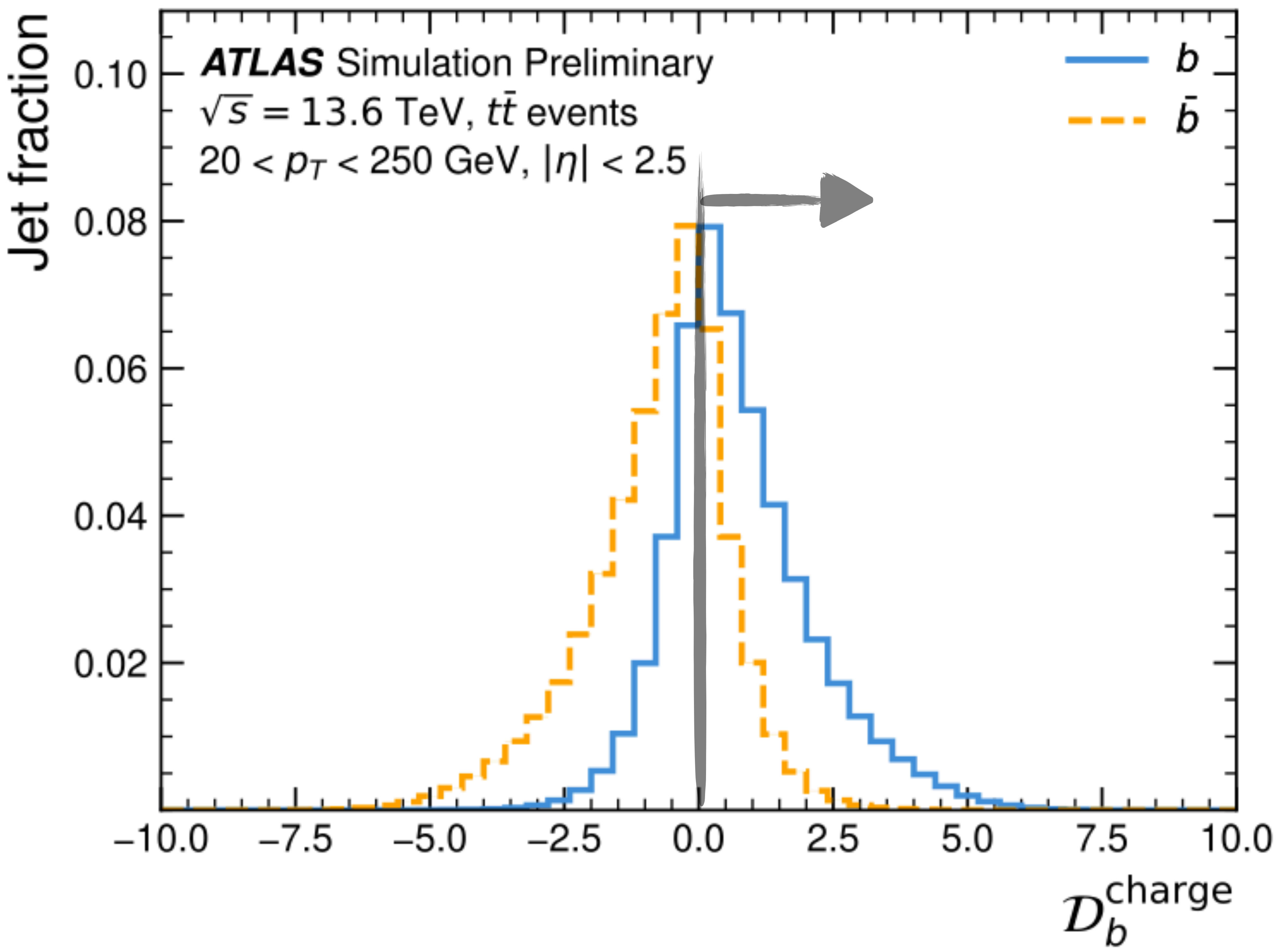
- Same tools can be extended to jet-charge identification!

Jet-charge taggers in ATLAS and CMS

DP-2025-071

ATL-PHYS-PUB-2026-005





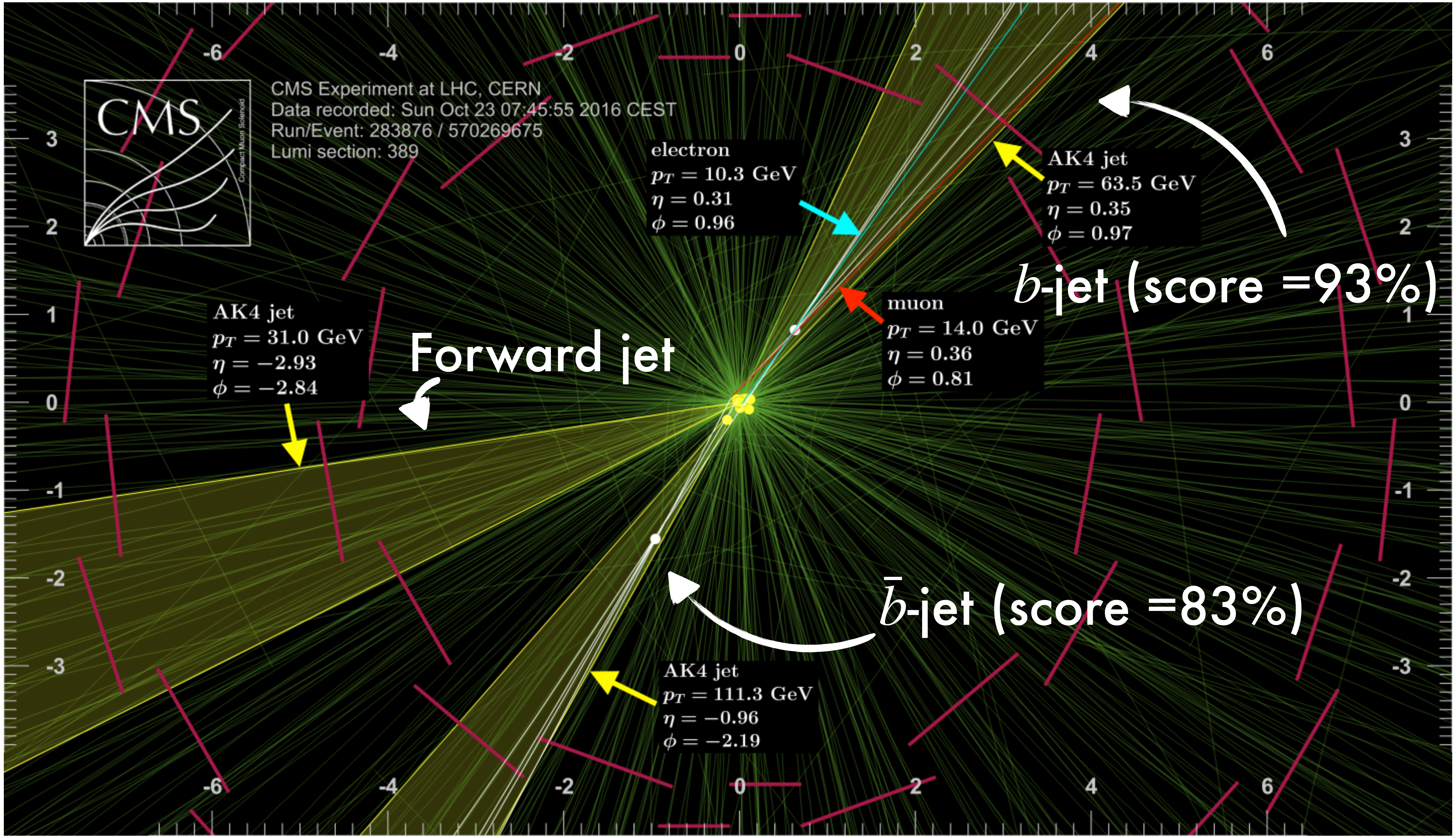
Since late 2025: ATLAS and CMS capable of distinguishing quarks from anti-quarks in jets!

- Performance: comparable to the best jet-charge taggers developed at electron-positron machines

Profound impact on the entire physics program of ATLAS and CMS:

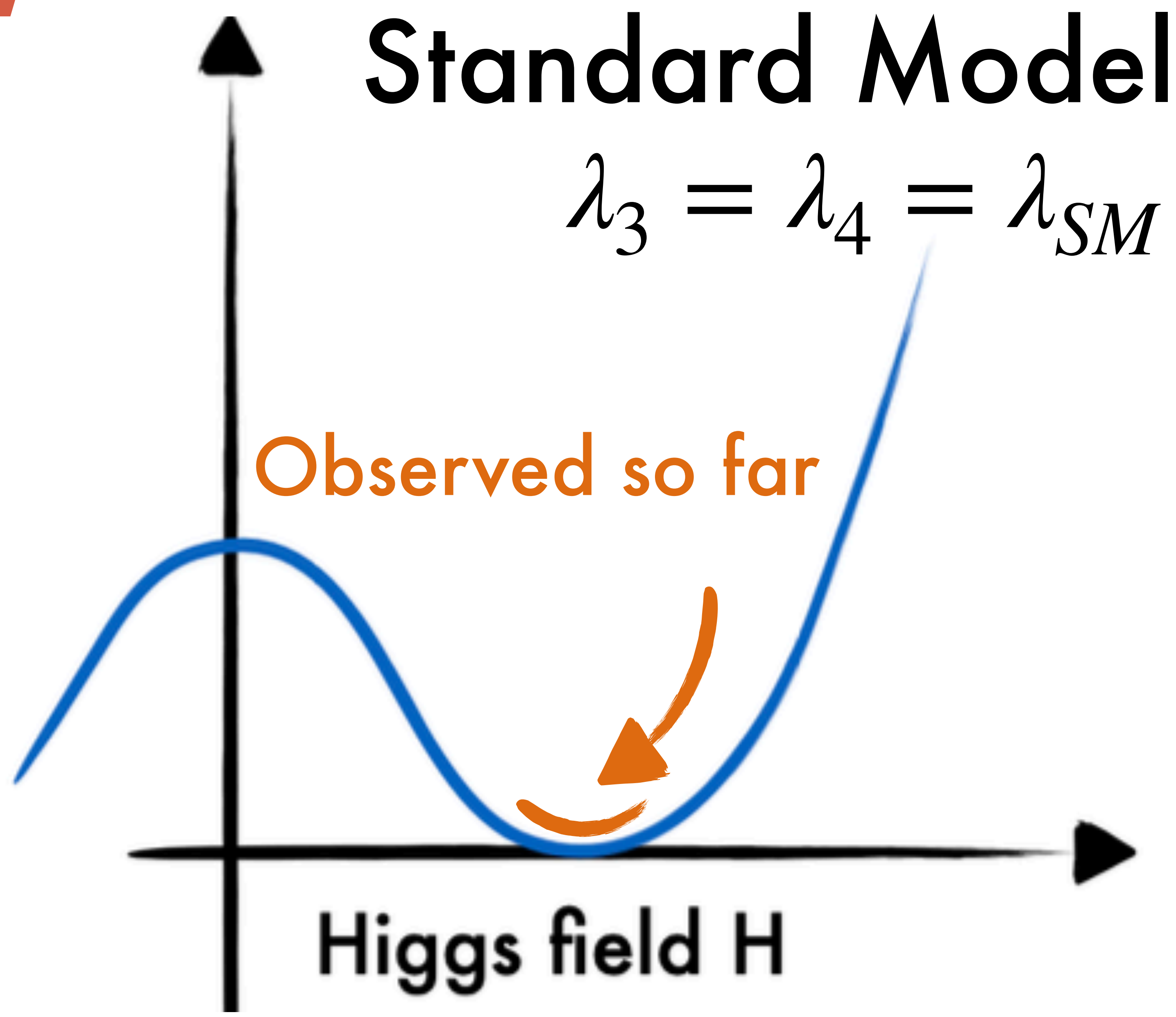
- About 50% of analyses use b-tagging → expect same impact from jet-charge taggers!

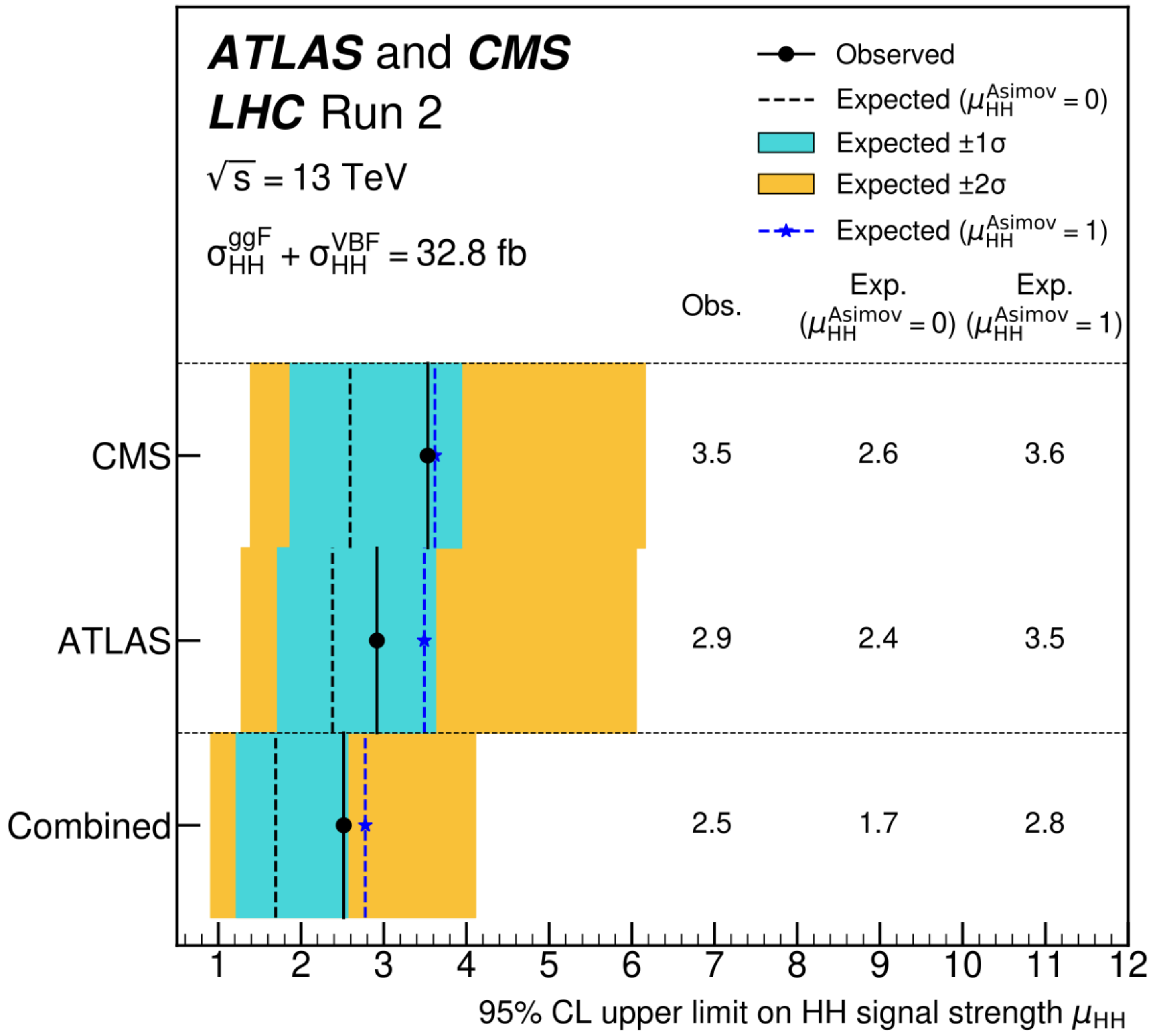
Jet-charge tagger on data

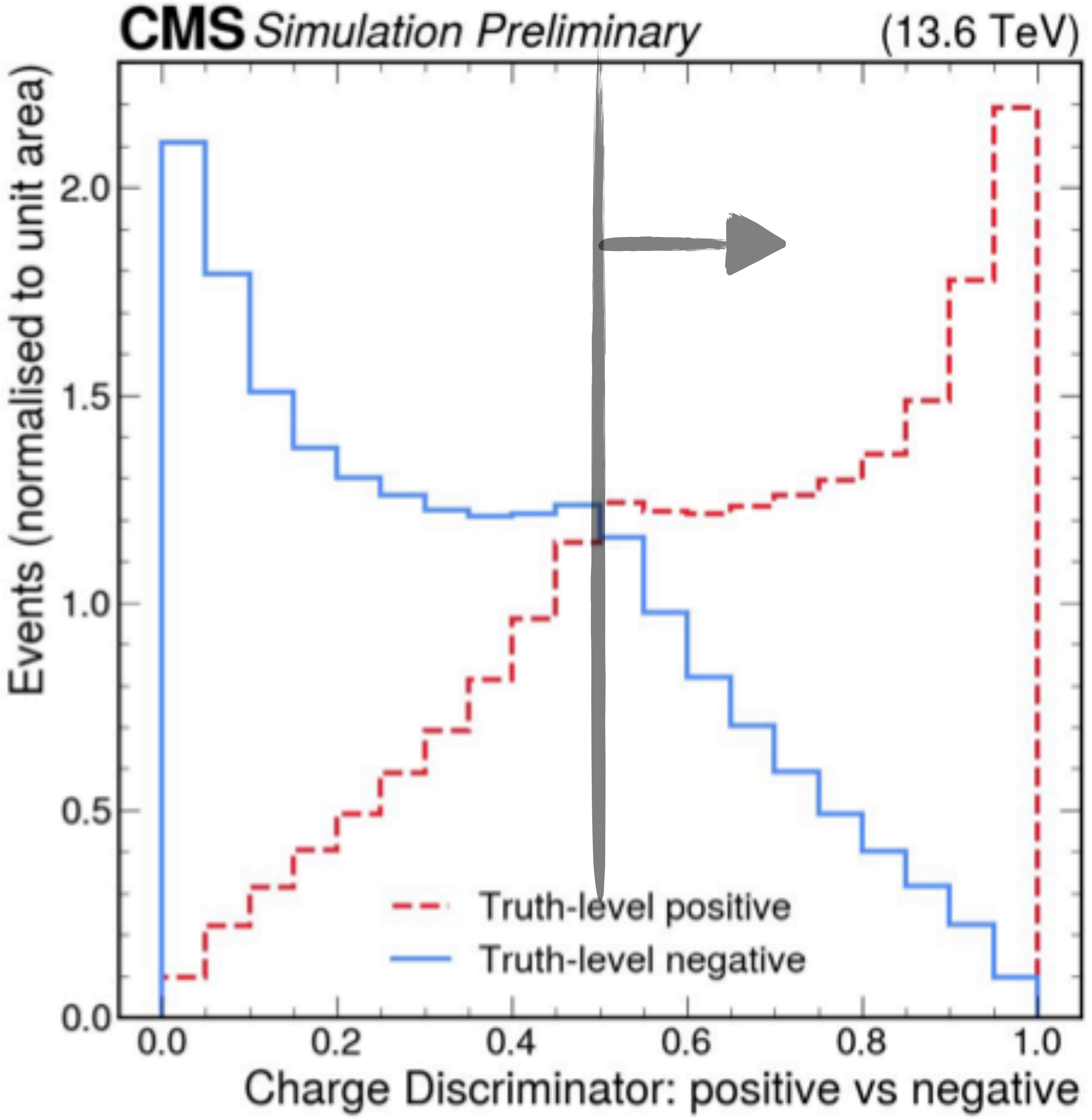


For the very first time, distinguish b- from $\bar{b}$-jets in the detector!

Summary







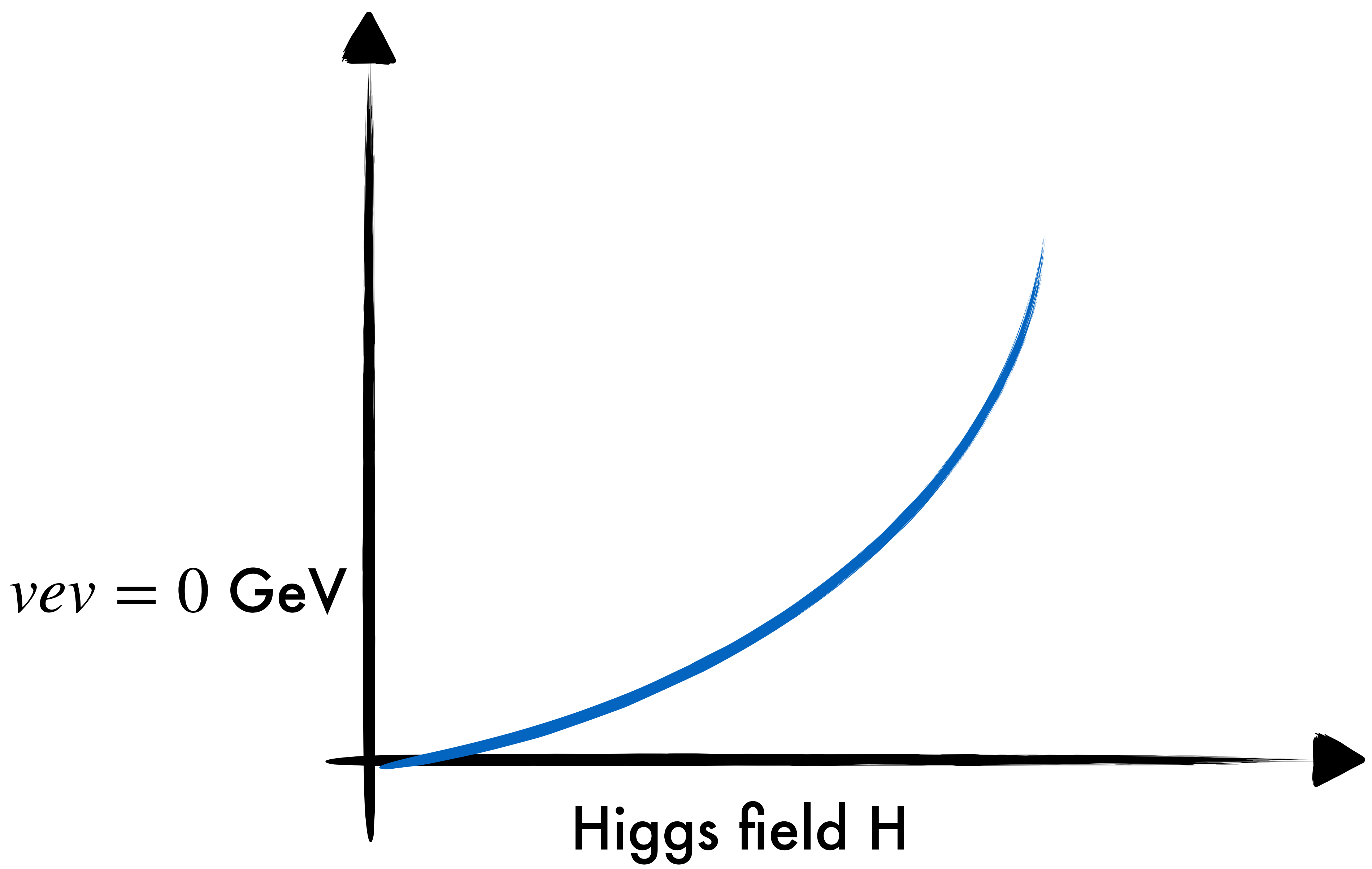
Higgs potential: at the core of the question "Why is there something rather than nothing?"

ATLAS and CMS program: targeting HH and HHH to answer this question
- In doing so, improve existing tools and develop new technologies
- In turn, accelerates the discovery potential of the LHC

Higgs boson plays a key role in the future of particle physics!

Back-up

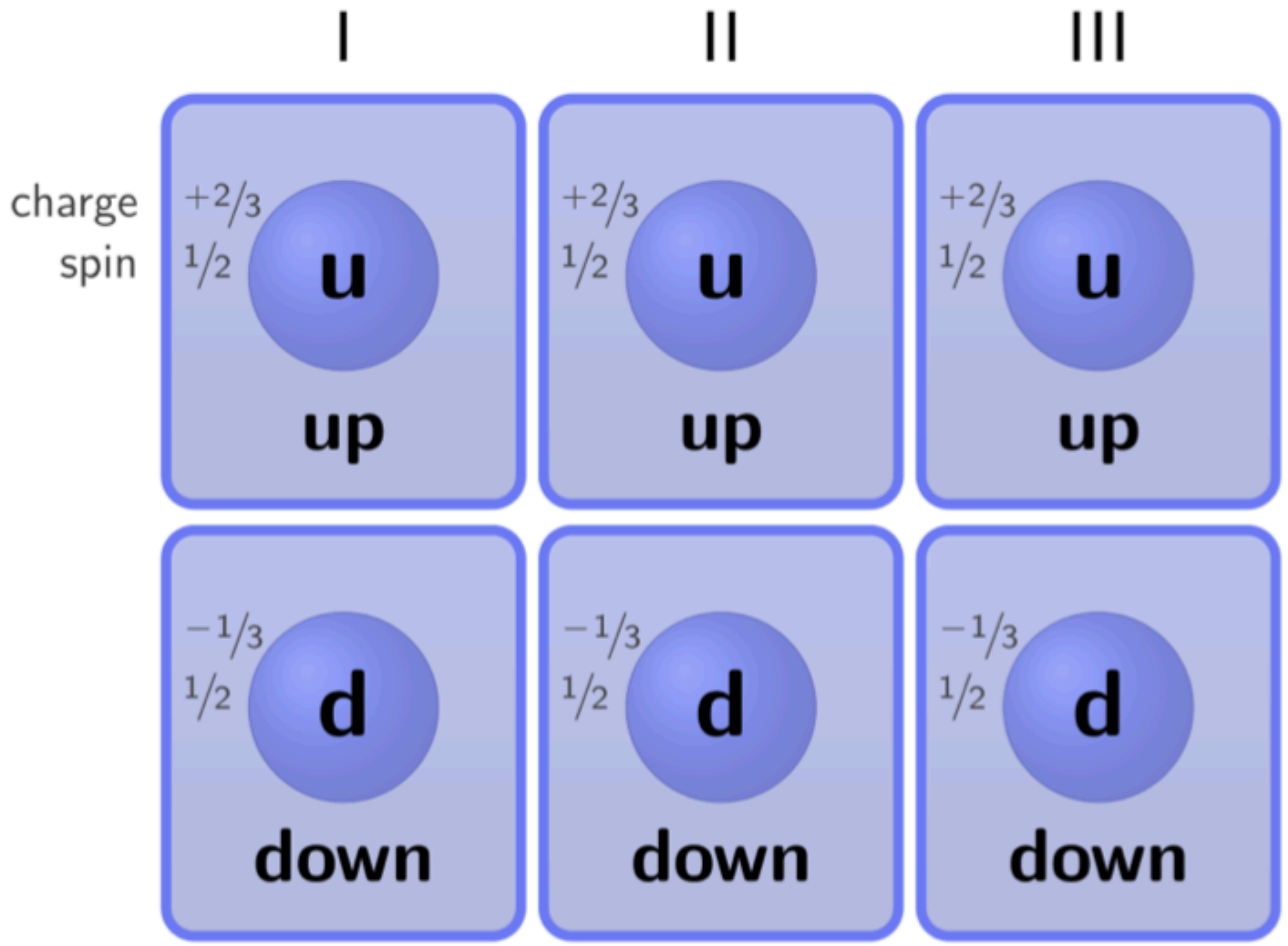
At the very beginning: 3 generations of particles



t=0s

(Big bang)

3 generations of massless particles



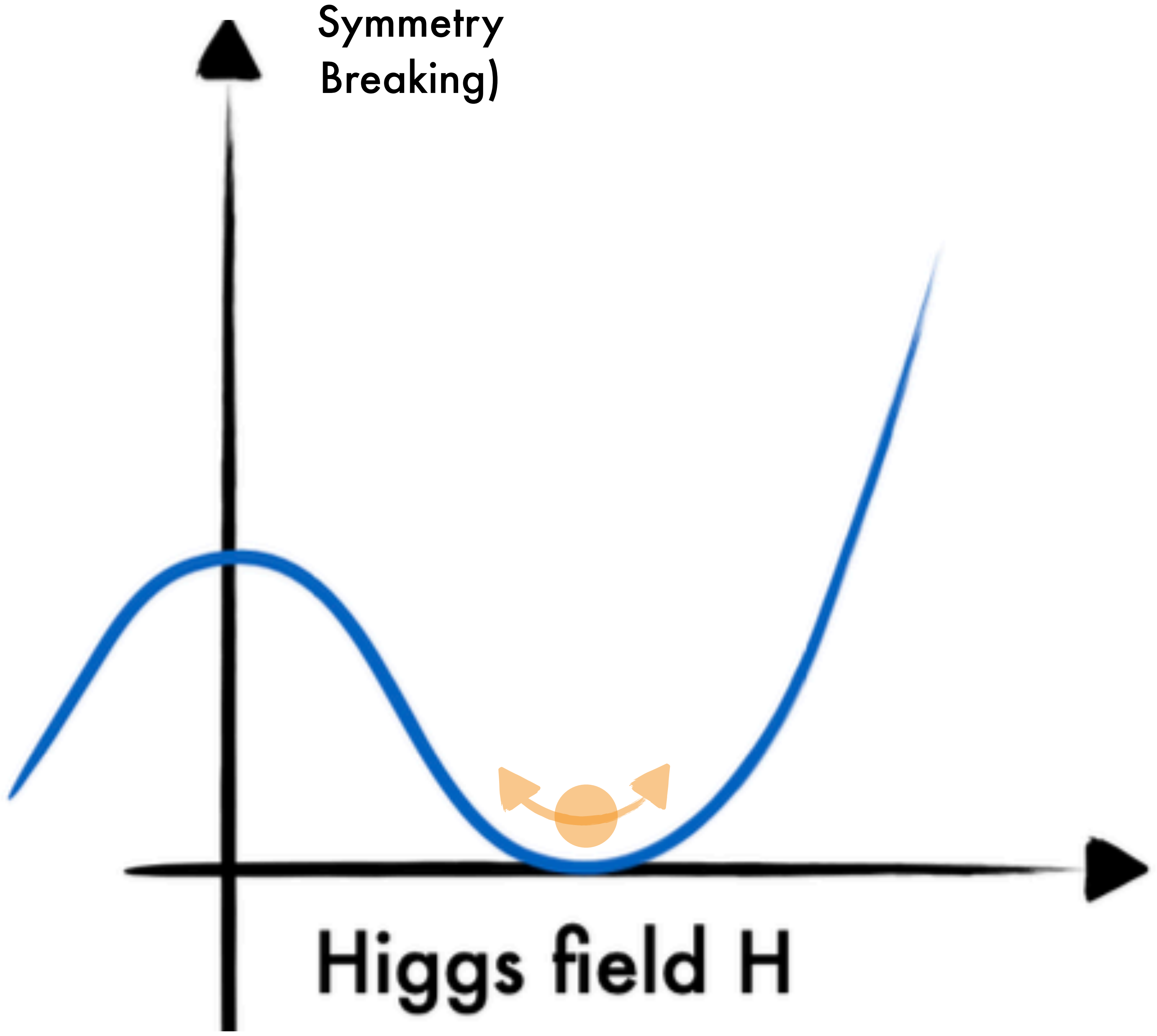
At the very beginning of the universe: 3 generations of particles

- Massless particles, separated in up and down type for quarks
- Same properties across the different generations per type
- Very different from the Universe we live in

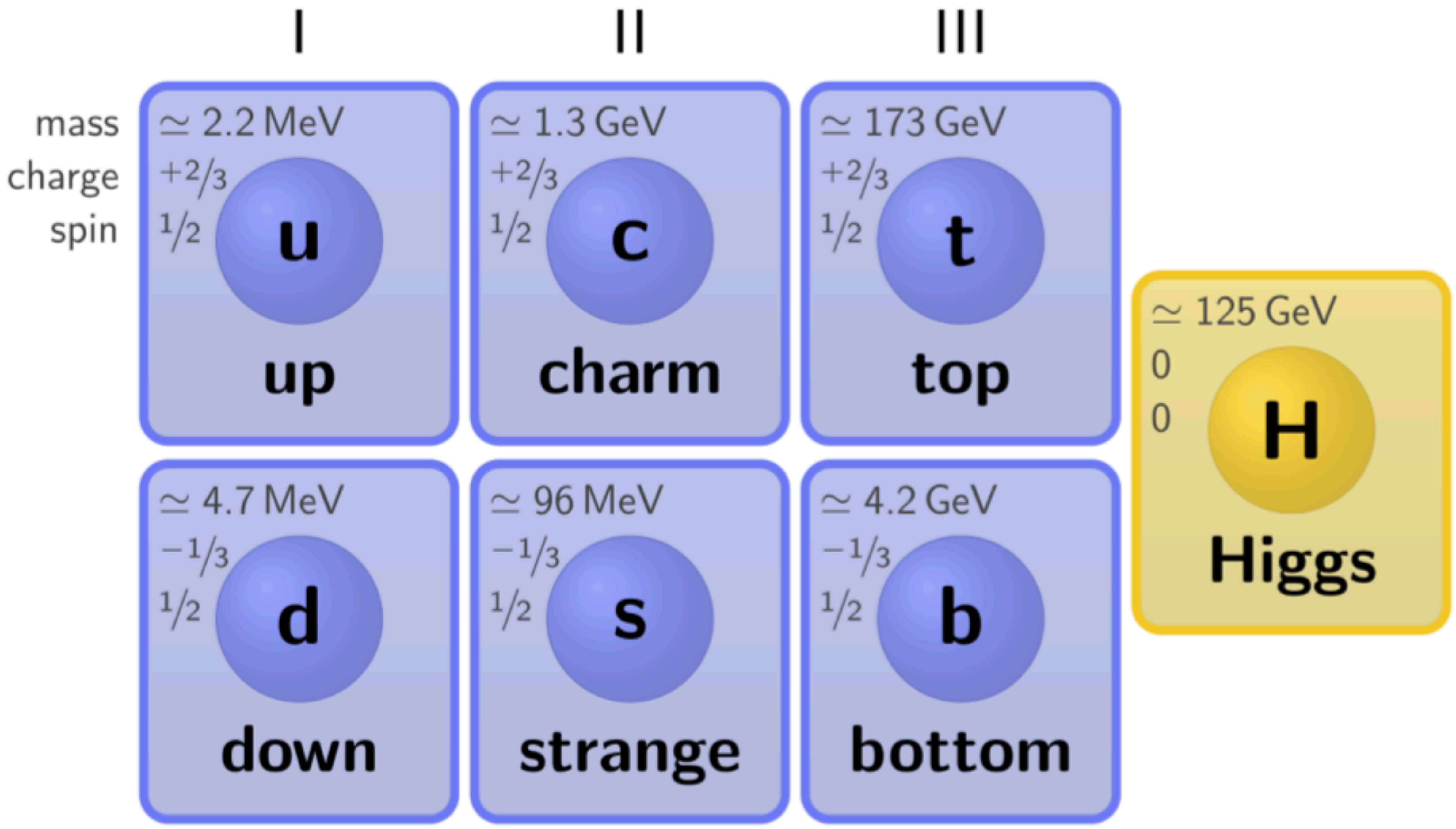
Electroweak symmetry breaking

t=10^{-12}s

(Electroweak Symmetry Breaking)



3 generations of massive particles + Higgs boson

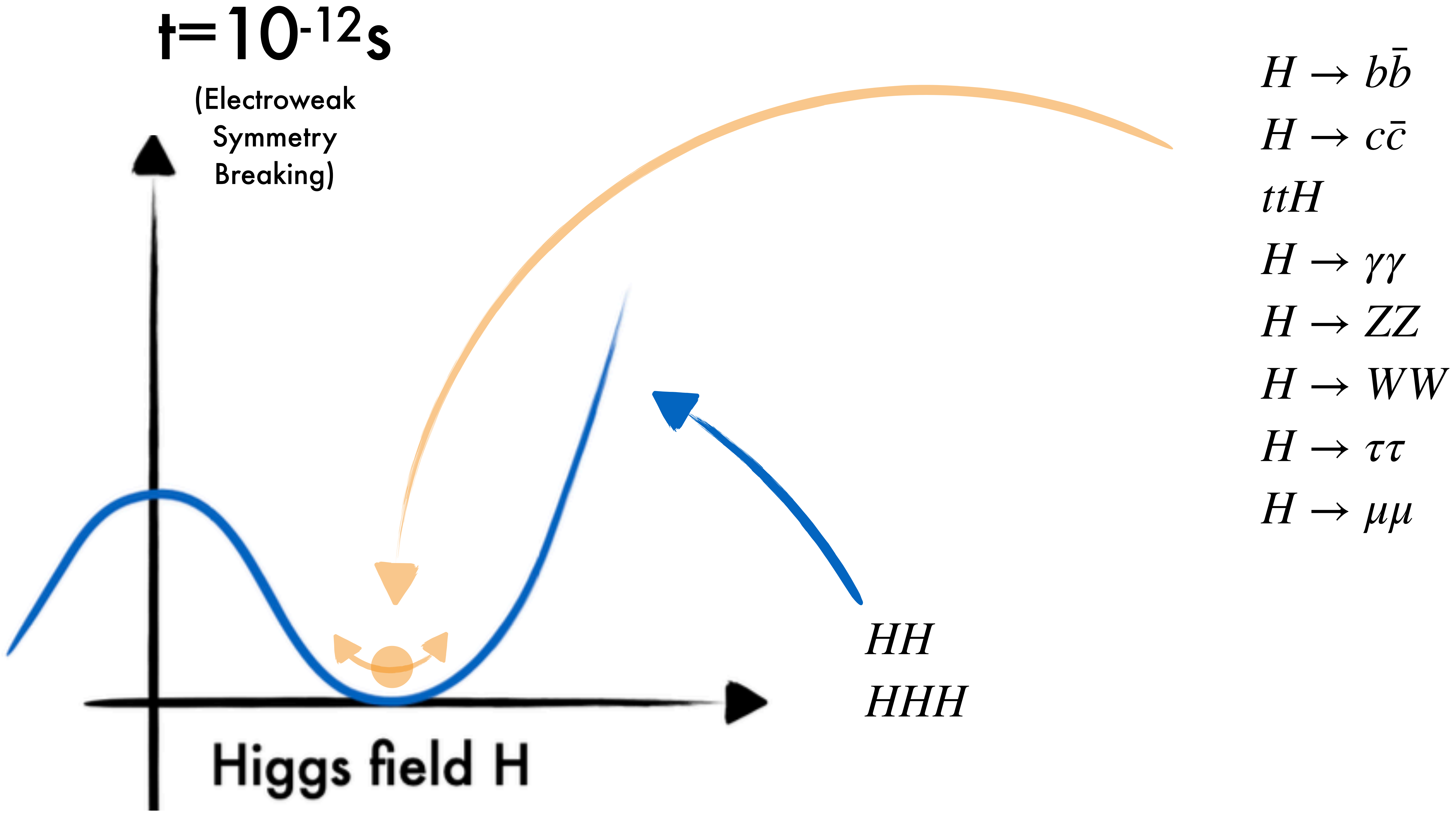


	I	II	III	
mass charge spin	≃ 2.2 MeV +2/3 1/2 **u** **up**	≃ 1.3 GeV +2/3 1/2 **c** **charm**	≃ 173 GeV +2/3 1/2 **t** **top**	≃ 125 GeV 0 0 **H** **Higgs**
	≃ 4.7 MeV −1/3 1/2 **d** **down**	≃ 96 MeV −1/3 1/2 **s** **strange**	≃ 4.2 GeV −1/3 1/2 **b** **bottom**	

Electroweak symmetry breaking: Higgs field acquires non-zero minima

- Three generations of particles acquire mass (proportional to the vacuum expectation value)
- W and Z bosons acquire mass
- Massive Higgs boson: interacting proportionally to the masses of the particles
- Explains almost all the interactions we’ve measured so far!

Rich phenomenology to test it experimentally



$t=10^{-12}s$

(Electroweak Symmetry Breaking)

$H \rightarrow b\bar{b}$

$H \rightarrow c\bar{c}$

ttH

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ$

$H \rightarrow WW$

$H \rightarrow \tau\tau$

$H \rightarrow \mu\mu$

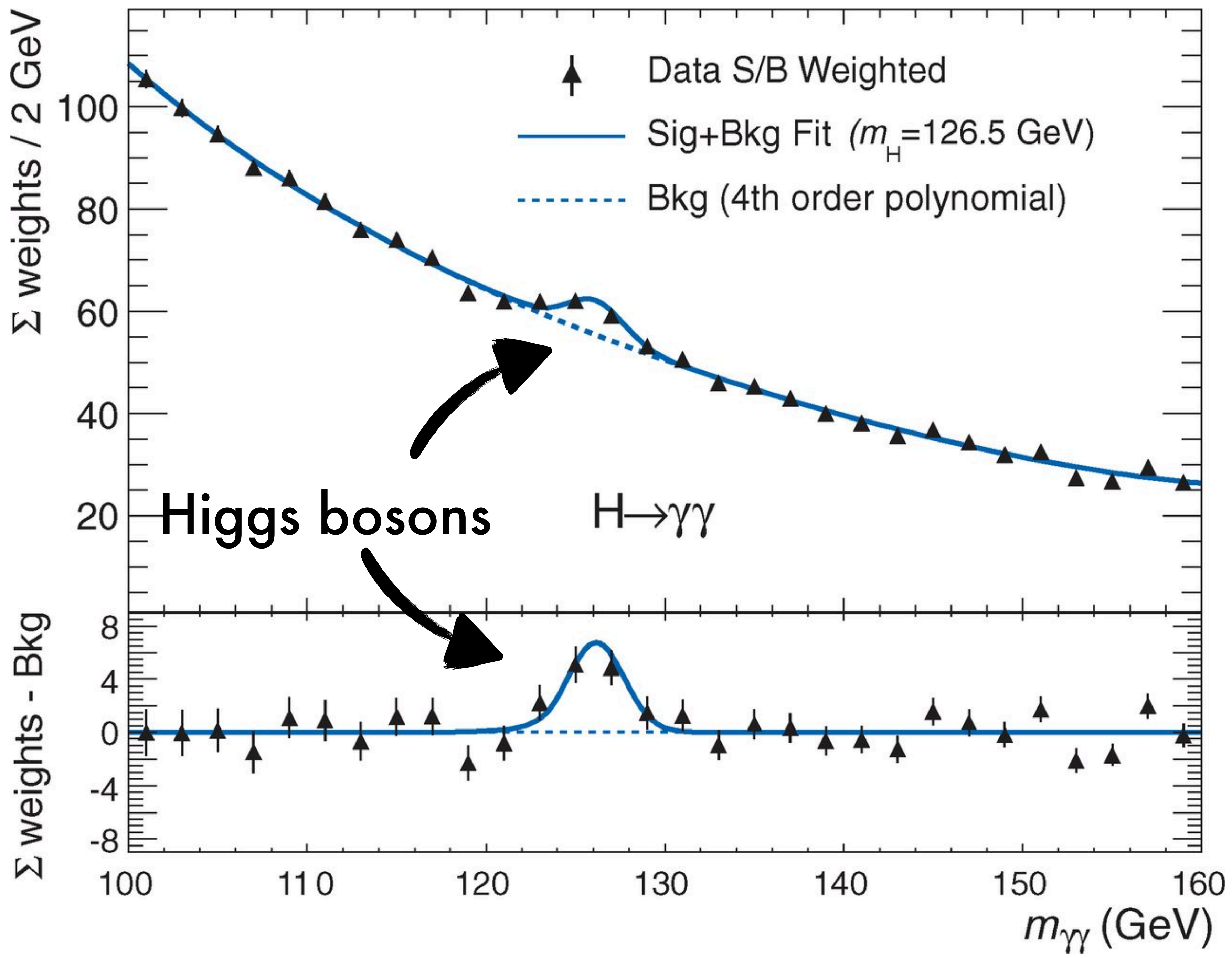
HH

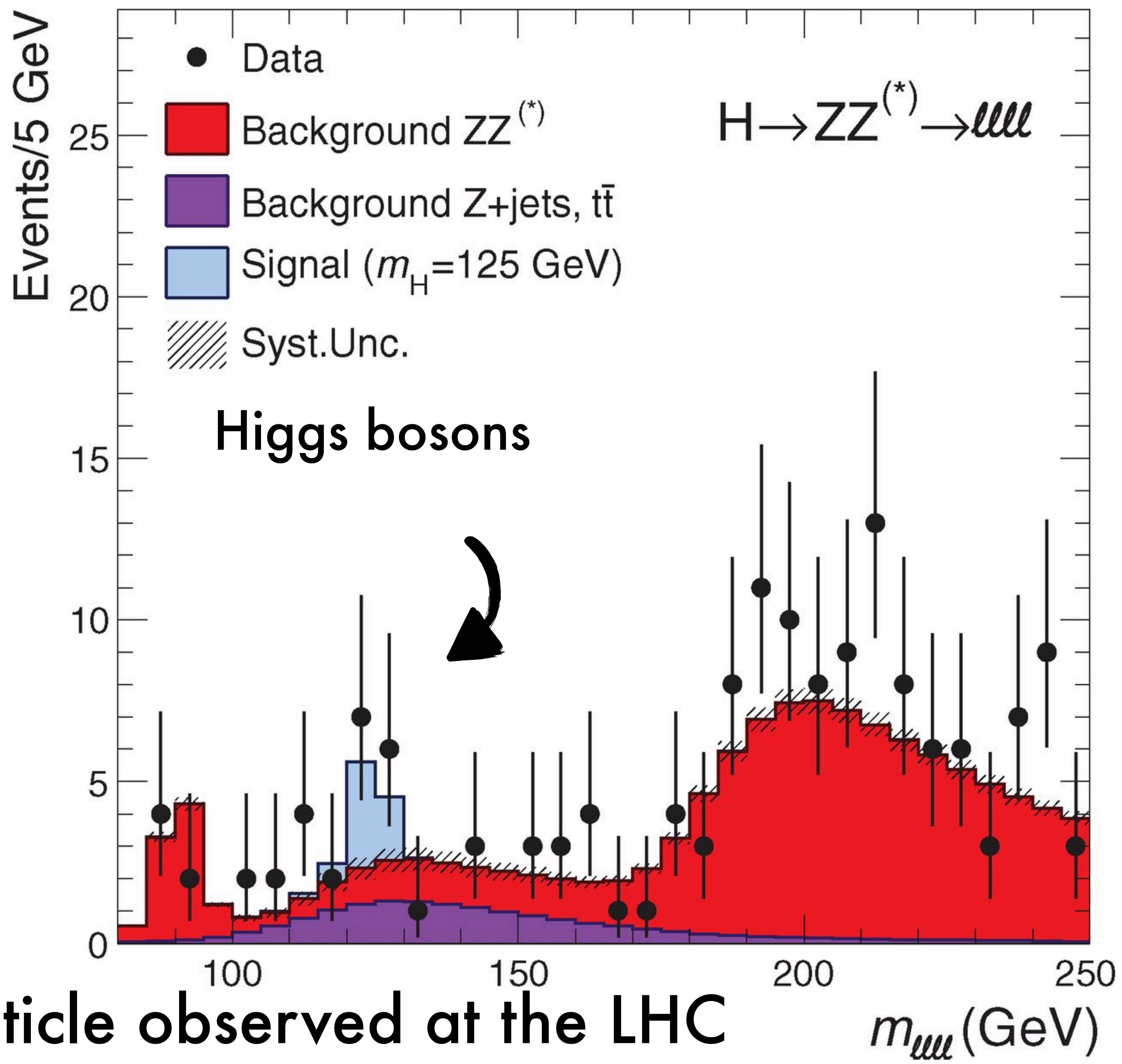
HHH

Probing electro-weak symmetry breaking at the LHC: two complementary ways

1. Measure **Higgs coupling to other particles**: test **the minima of the potential**
2. Measure **Higgs self-interaction**: test **the shape of the potential**

Higgs boson





Discovered in 2012, Higgs boson is a new fundamental particle observed at the LHC

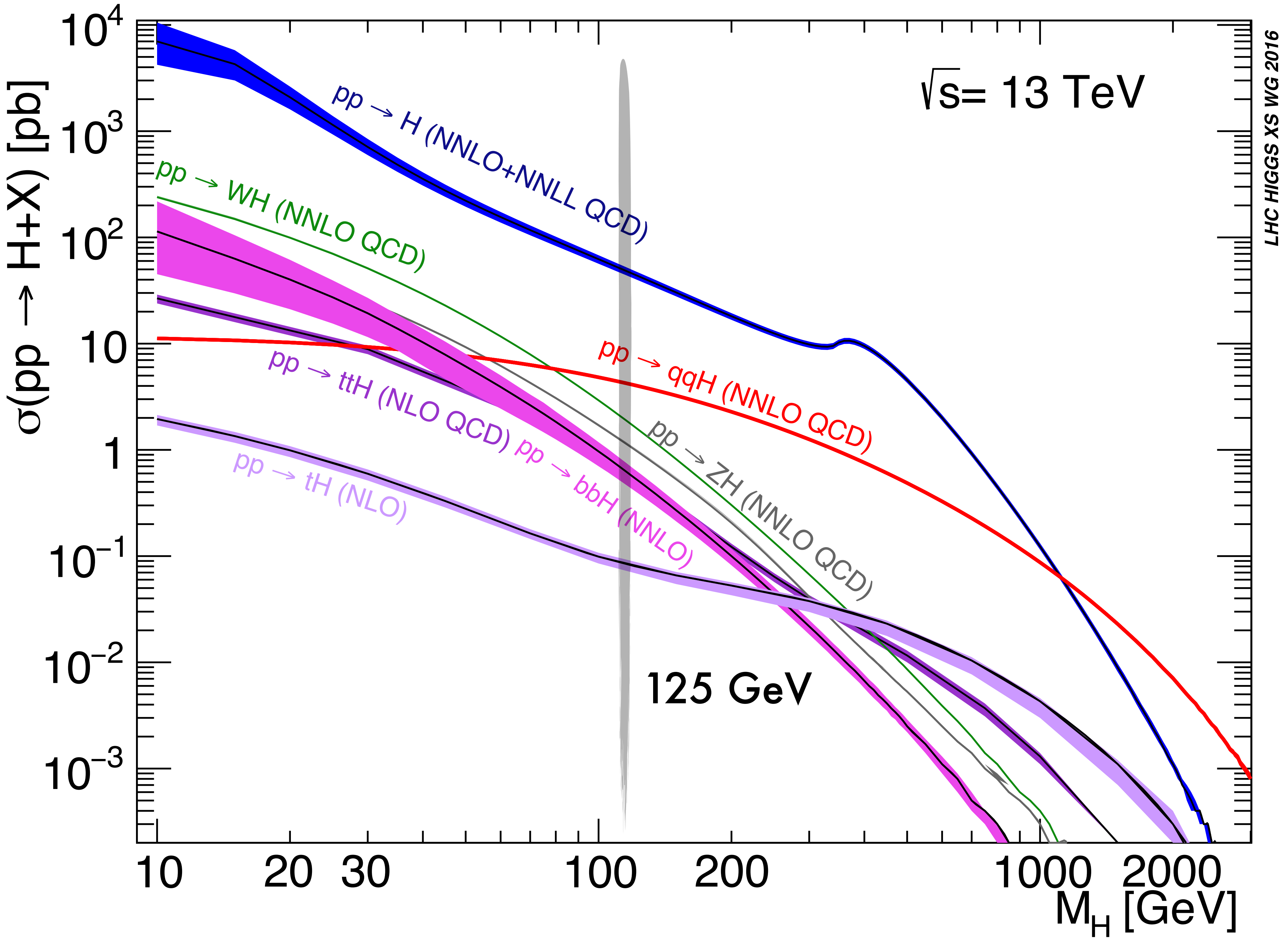
- Only fundamental particle with spin-0 (scalar) observed
- Higgs mass measured to be 125 GeV

Possible deviation in Standard Model prediction = new physics

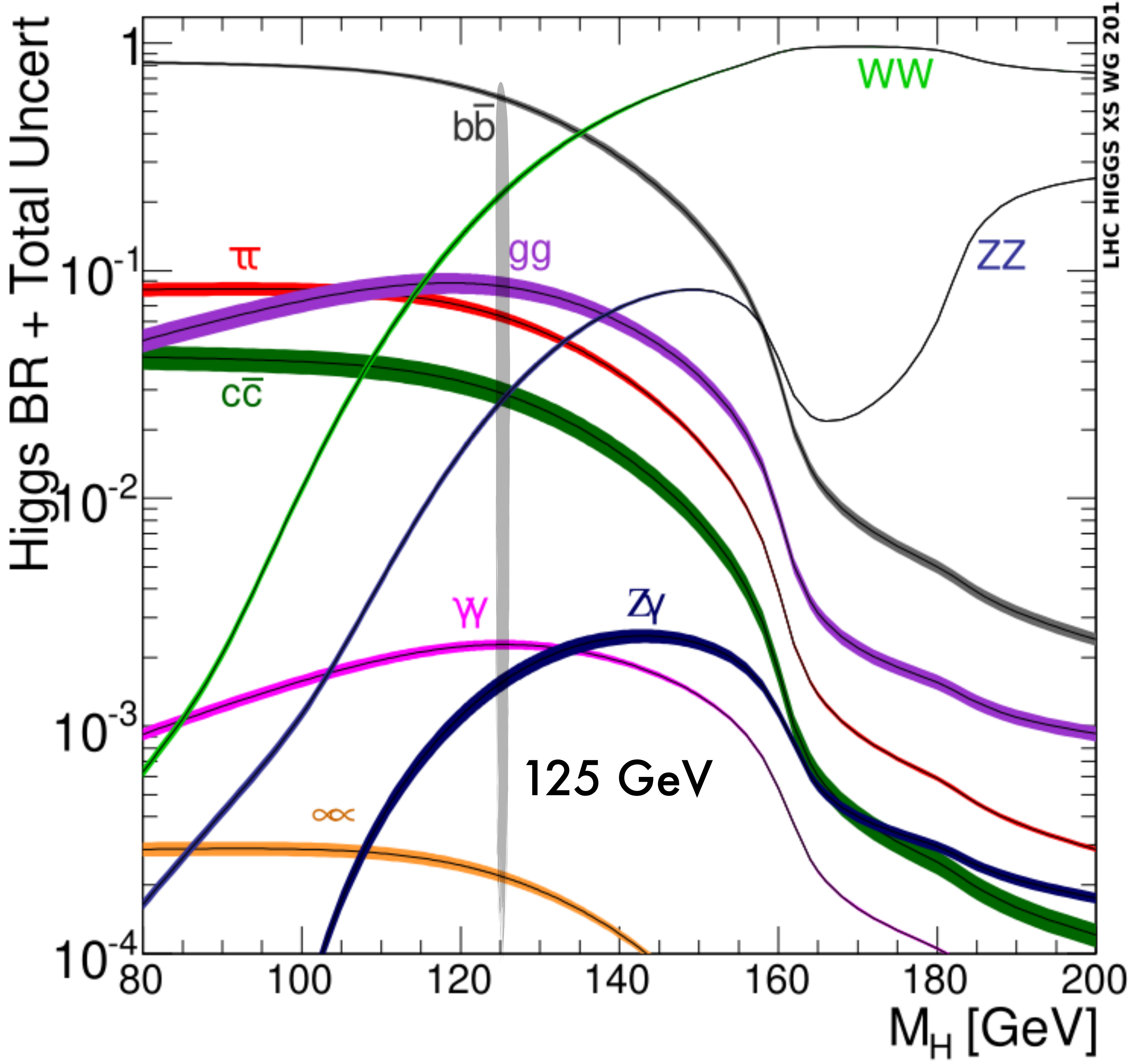
- Compositeness, extra dimensions, extended scalars …
- Possible ties to baryogenesis, matter-antimatter asymmetry, cosmology, …
- “Why is there something rather than nothing?” - R. Wallny quoting Leibniz

Higgs boson production and decay at ATLAS and CMS

Production cross-section



Decay branching ratio



Fundamental scalar particle → mass measured to be 125 GeV in 2012

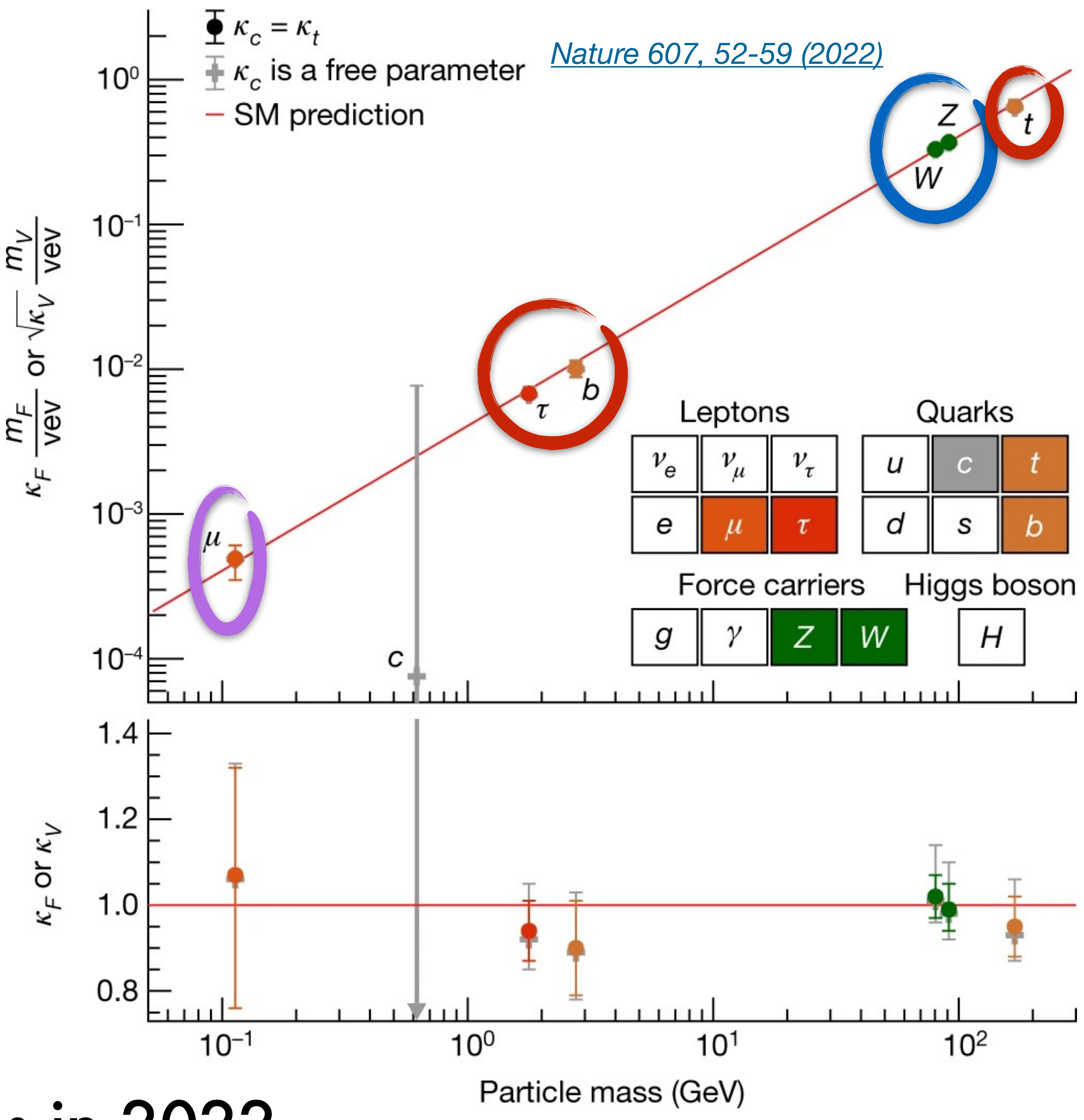
- Determines the kinematic properties, from production to decay rate
- At the LHC: more than **14.6 million Higgs bosons** produced
    - Main decay mode: **60% to a pair of b-quarks**: $H \rightarrow b\bar{b}$

Between 2010 and 2020:

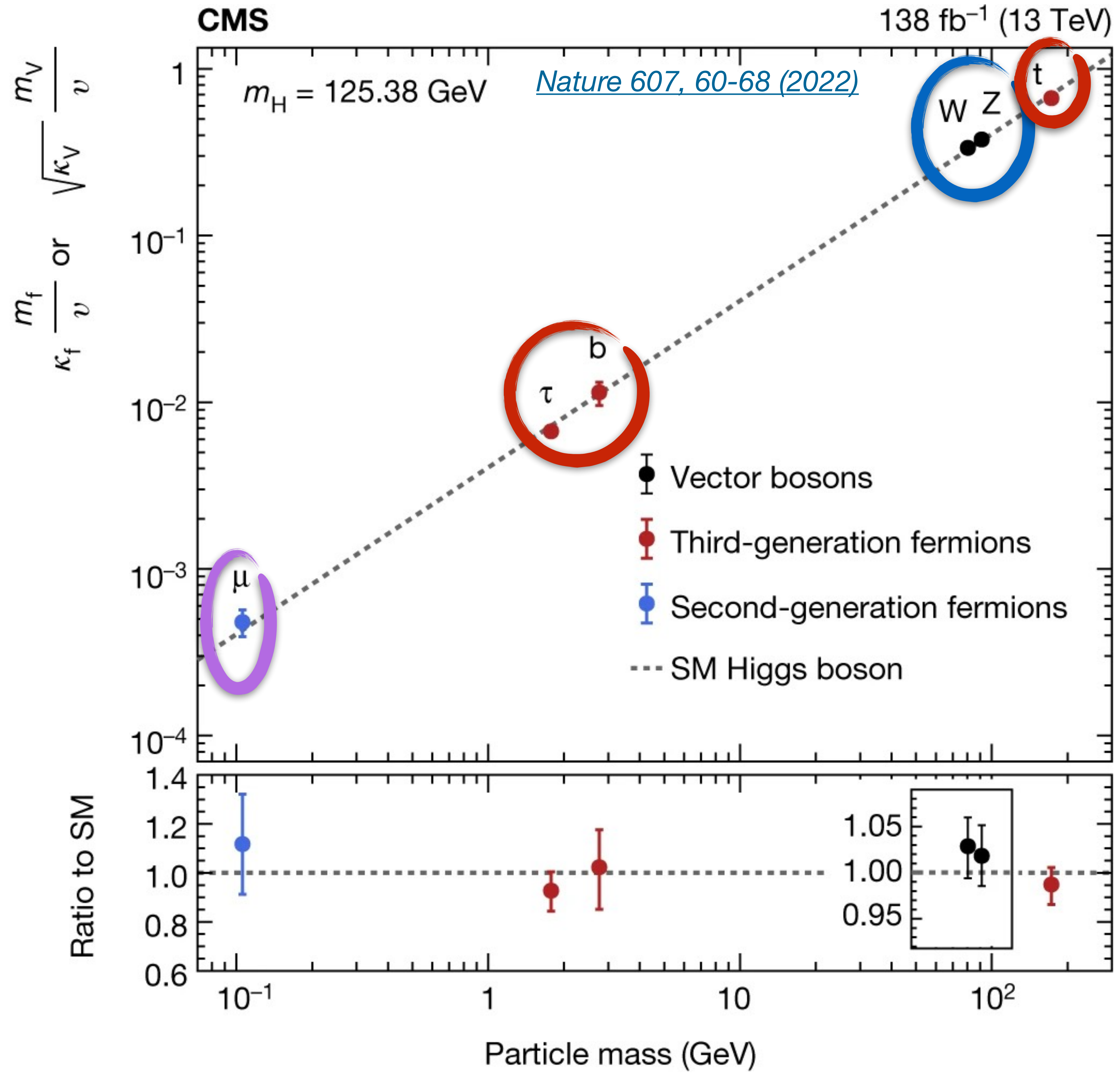
- Great decade to be a 5σ physicist, **new collider, new detector** and the **right Higgs mass!**

Experimental results

ATLAS Higgs coupling



CMS Higgs coupling



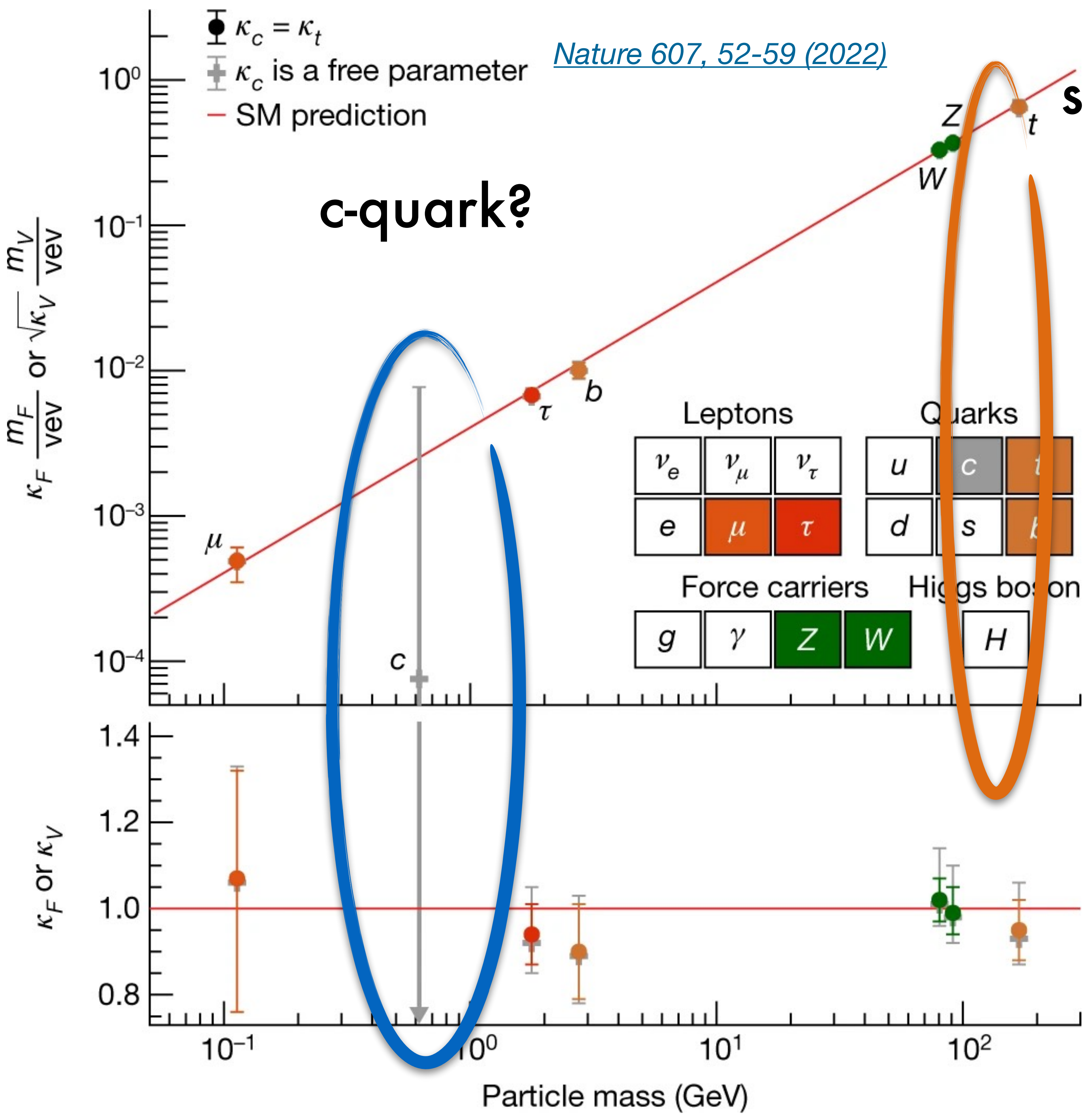
Status in 2022

- Precision on Higgs coupling: > 5 sigma (= < 20% precision)
- Vector bosons: W and Z
- 3rd generation fermions: top, bottom and tau
- About 30%-40% precision on the coupling to muons

All measurement so far found in agreement with the Standard Model

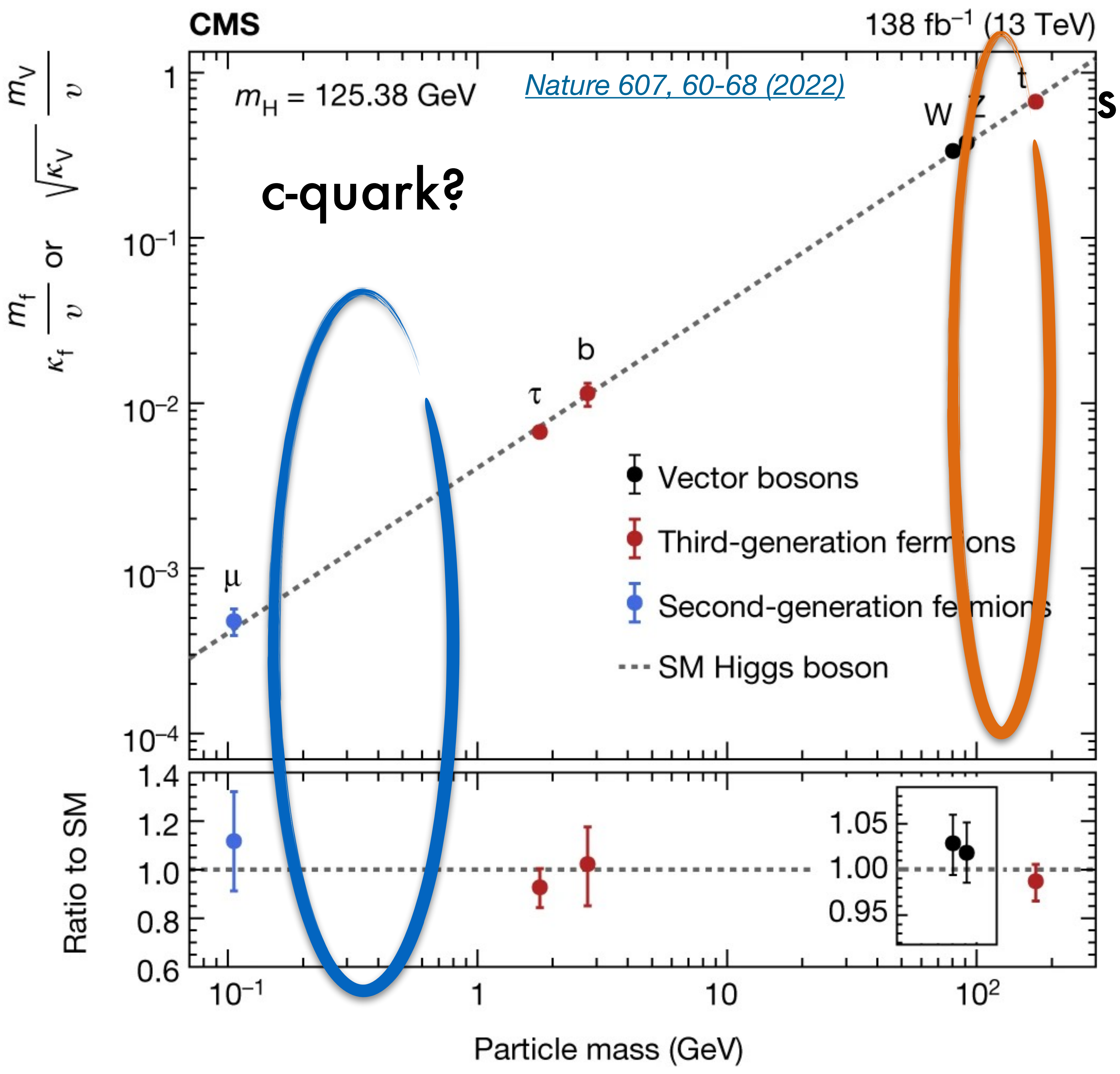
Experimental results

ATLAS Higgs coupling



Higgs self-coupling?

CMS Higgs coupling



Higgs self-coupling?

Born too late to be a 5σ physicist:

- Higgs to charm coupling: VHcc result 31x SM for ATLAS (10x SM now), 8x SM for CMS
  - Inclusion of the Higgs-charm coupling in the Higgs coupling interpretation by ATLAS!
- Higgs self-coupling: HH results 2.5 x SM for both ATLAS and CMS

Challenging measurements to perform at the LHC, rare processes with large backgrounds

The LHC discovered the Higgs boson

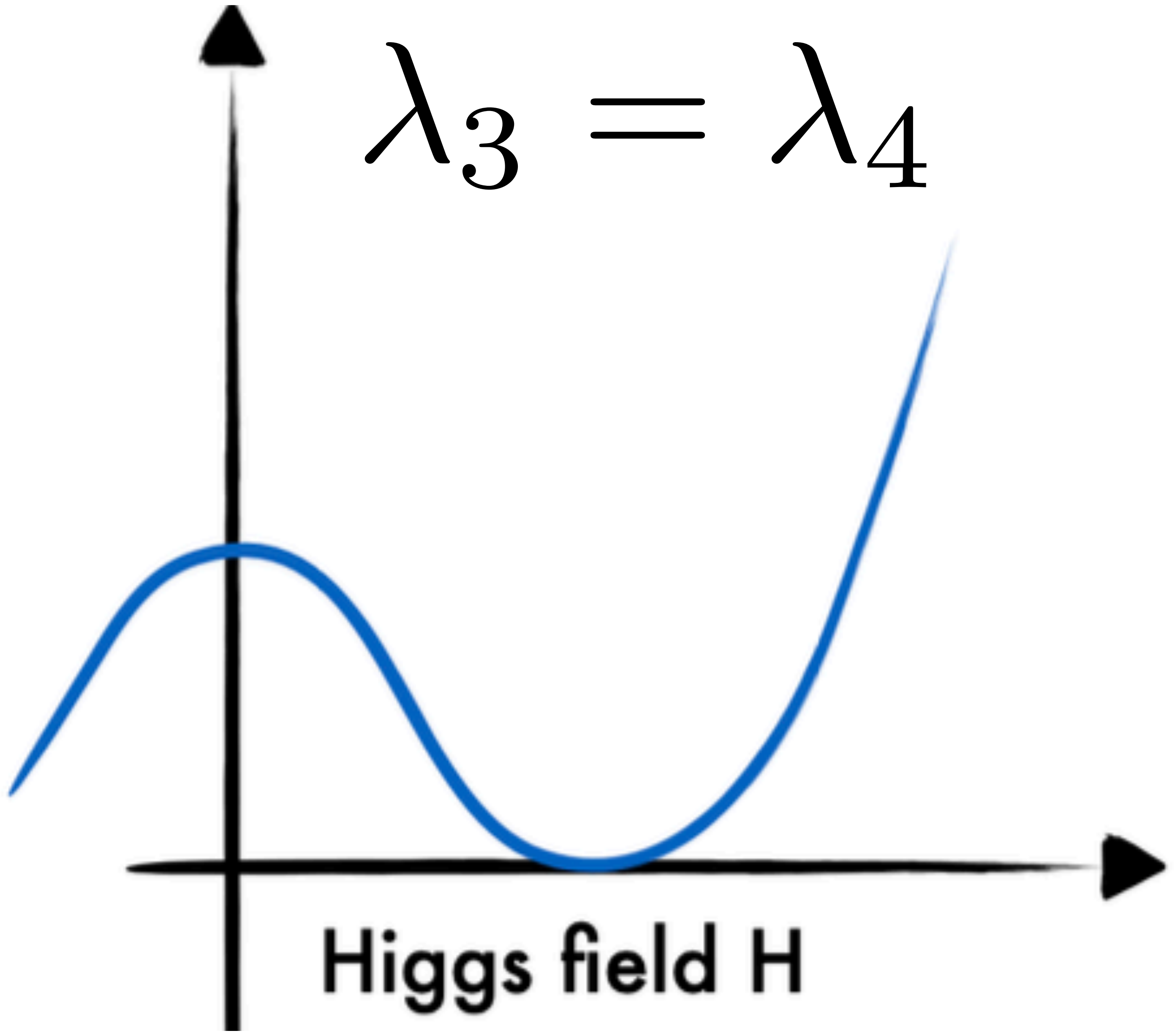
but it **did not discover the Higgs potential**

Measuring the Higgs potential

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

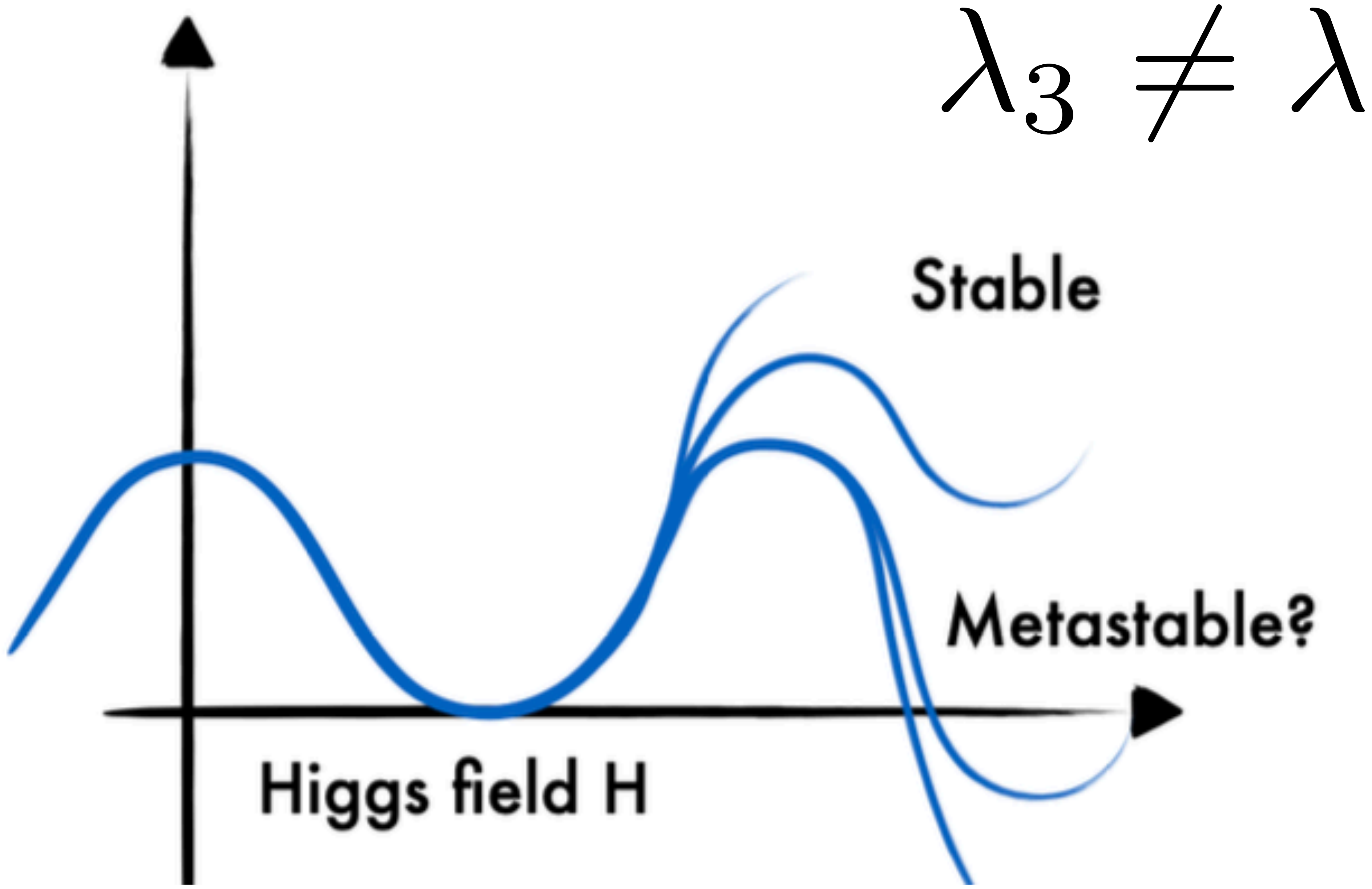
Standard Model

$$\lambda_3 = \lambda_4$$



New physics

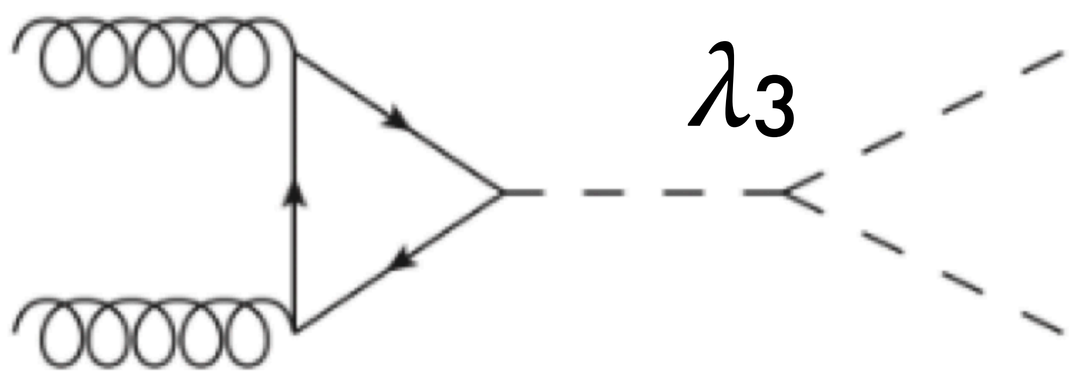
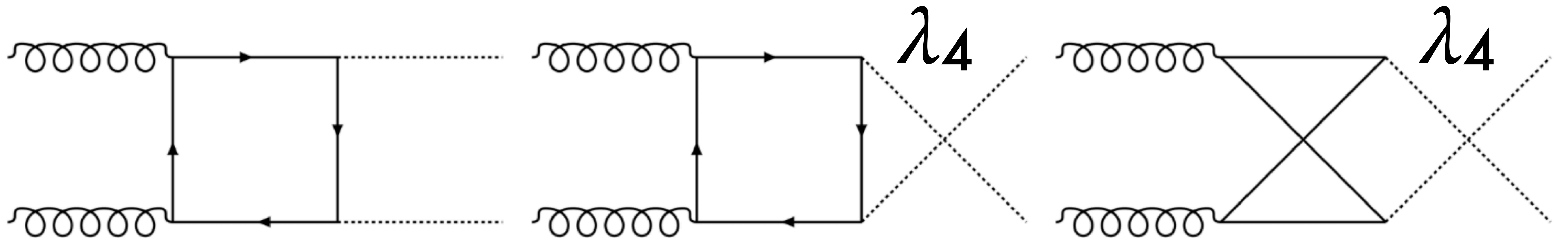
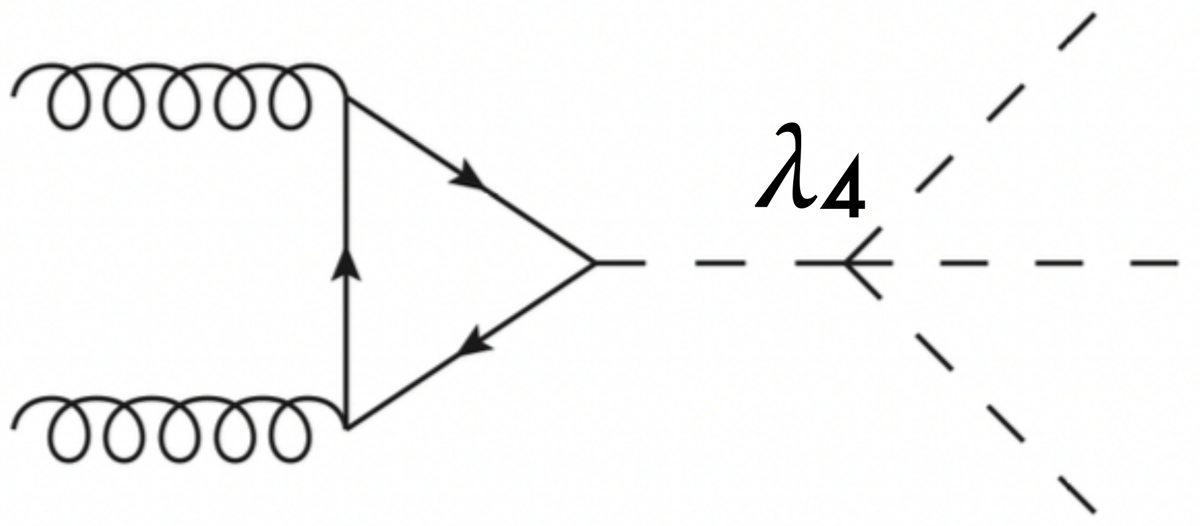
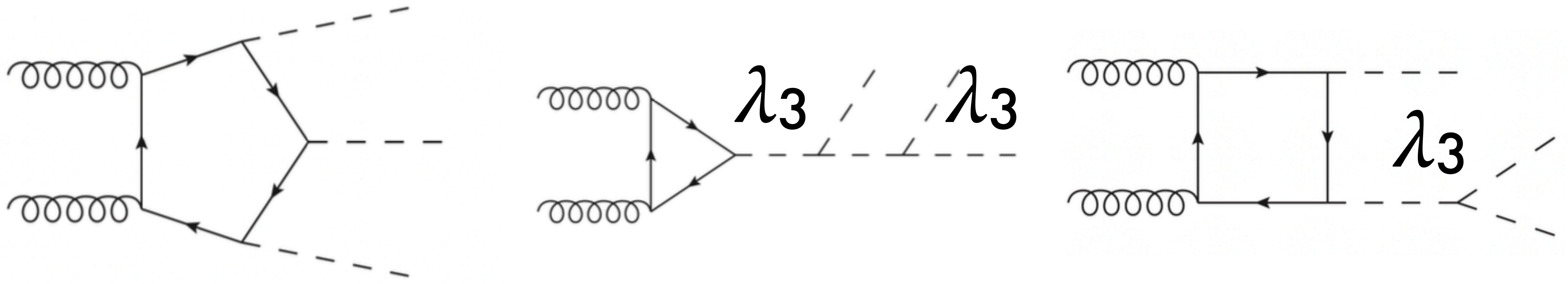
$$\lambda_3 \neq \lambda_4$$



In the Standard Model: $\lambda_3 = \lambda_4$

- Not given for a fact, needs to be measured
- New physics can affect the shape of the Higgs potential → large consequences for the Universe

Probing self-interaction di-Higgs and triple Higgs

	Signal	Irreducible background with Higgs bosons
Di-Higgs		
Triple Higgs		

Probing the Higgs self-coupling possible through di-Higgs and triple Higgs measurements:

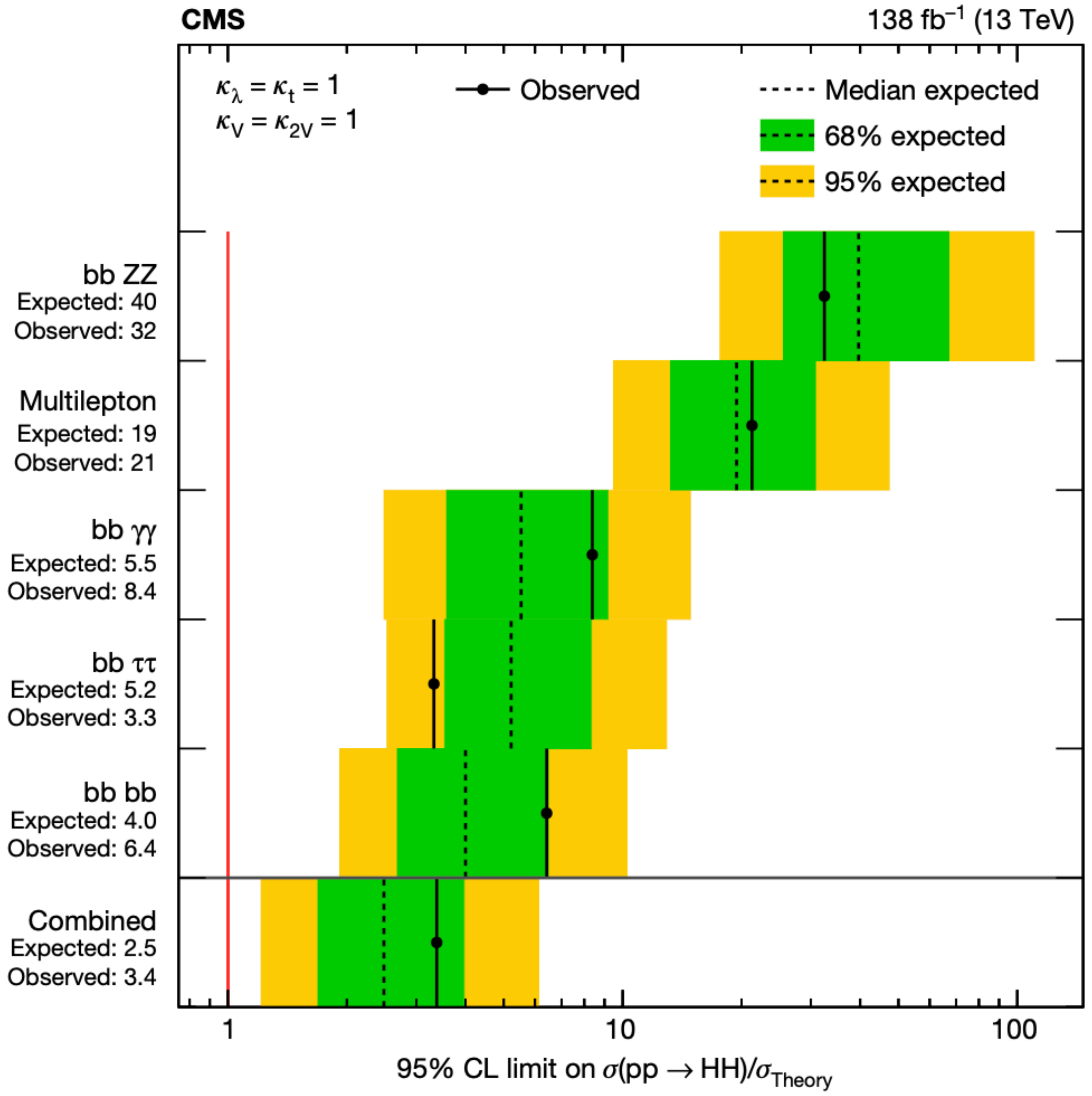
- Di-Higgs: nearly exclusively sensitive to λ_3 coupling (very small contribution from λ_4)
- Triple Higgs: sensitive to both λ_3 and λ_4 coupling

→ Full determination of the Higgs potential only possible through combined measurement!

HH is at the centre of ATLAS and CMS physics program, HHH is novel and recently explored

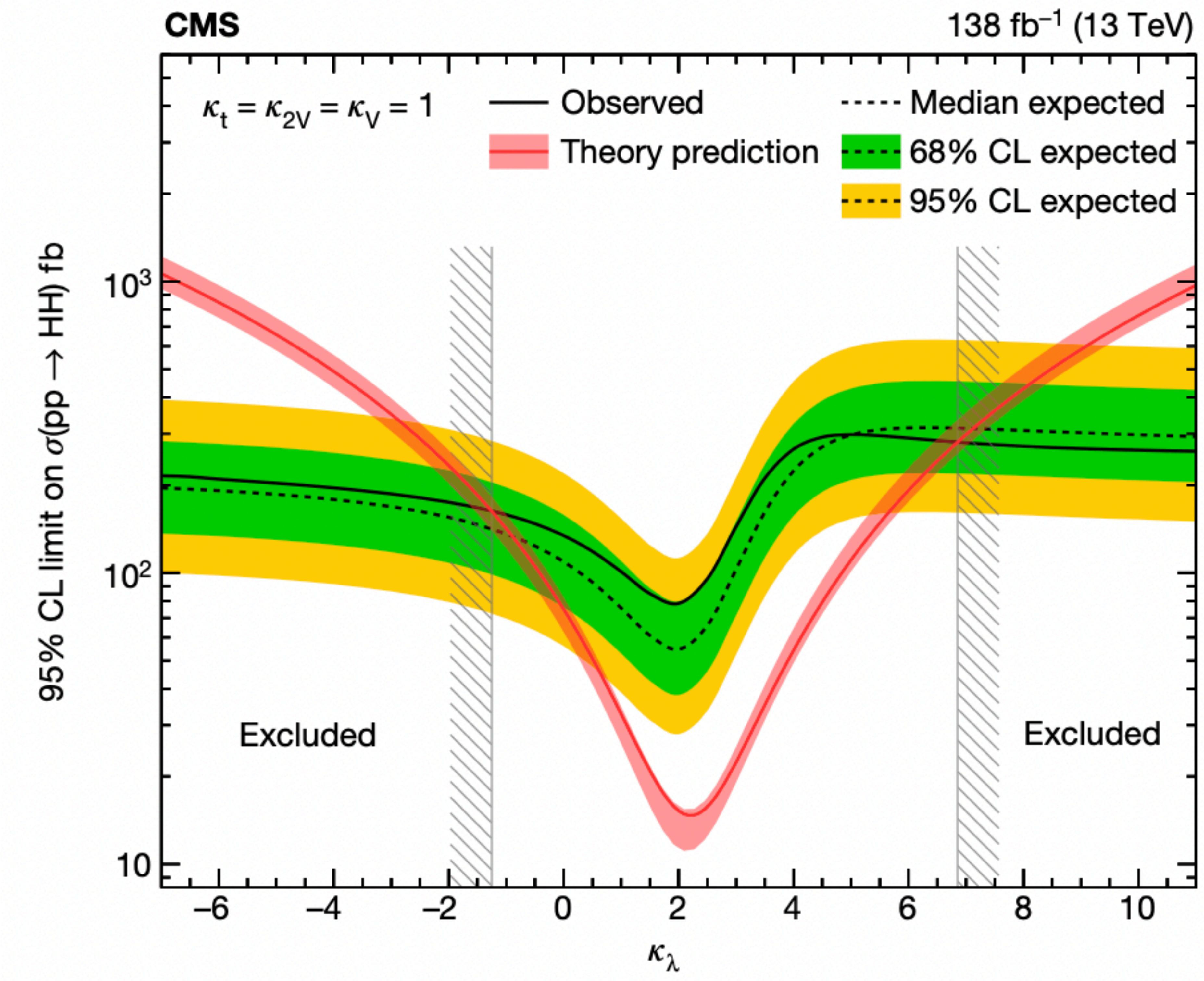
HH as probe of the Higgs potential

Limit on signal strength



Expected: μHH < 2.5 x SM @ 95% CL
Observed: μHH < 3.4 x SM @ 95% CL

κ_λ interpretation



Expected at 95%: $-0.9 < \kappa_\lambda < 7.1$
Observed at 95%: $-1.2 < \kappa_\lambda < 6.5$

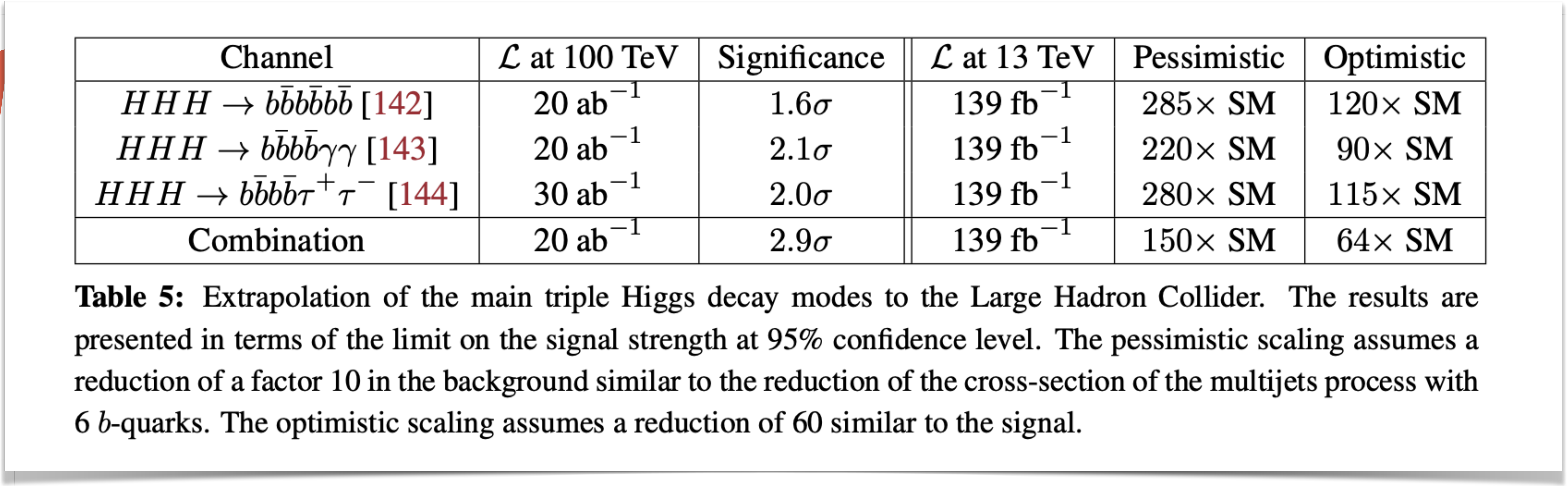
HH combination: three *silver channels* **HH4b**, **HH2b2tau** and **HH2b2y**

- Combination of HH4b boosted and resolved drives with 20% better sensitivity
- Similar results from ATLAS once combined

HHH as the quartic coupling frontier

Non-resonant *HHH*

HHH whitepaper : non resonant HHH extrapolations



Channel	$\mathcal{L}$ at 100 TeV	Significance	$\mathcal{L}$ at 13 TeV	Pessimistic	Optimistic
$HHH \to b\bar{b}b\bar{b}b\bar{b}$ [142]	20 ab^{-1}	1.6σ	139 fb^{-1}	285× SM	120× SM
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$ [143]	20 ab^{-1}	2.1σ	139 fb^{-1}	220× SM	90× SM
$HHH \to b\bar{b}b\bar{b}\tau^{+}\tau^{-}$ [144]	30 ab^{-1}	2.0σ	139 fb^{-1}	280× SM	115× SM
Combination	20 ab^{-1}	2.9σ	139 fb^{-1}	150× SM	64× SM

Table 5: Extrapolation of the main triple Higgs decay modes to the Large Hadron Collider. The results are presented in terms of the limit on the signal strength at 95% confidence level. The pessimistic scaling assumes a reduction of a factor 10 in the background similar to the reduction of the cross-section of the multijets process with 6 b-quarks. The optimistic scaling assumes a reduction of 60 similar to the signal.

Theory papers on HHH at FCC-hh

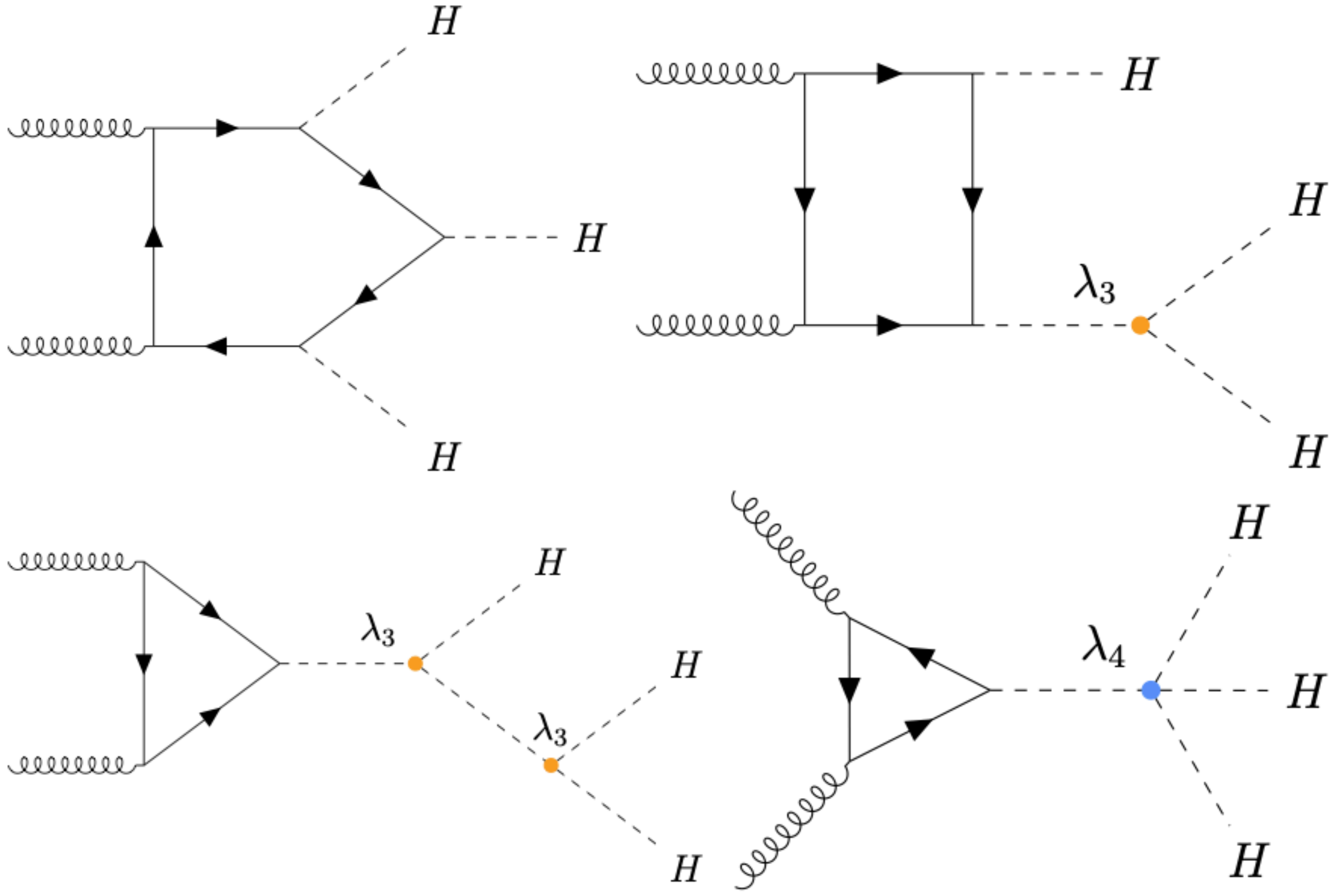
- Assuming 20 ab-1 and simplistic analysis strategies: achieve 3 sigma observation
- Extrapolation from FCC-hh to LHC: assuming cross-section scaling
  - Small cross-section: **0.1 fb** at the LHC
  - Achieve 100x SM with Run 2 → check with real data and analysis techniques!

Non resonant $HHH \to 4b2\gamma$

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

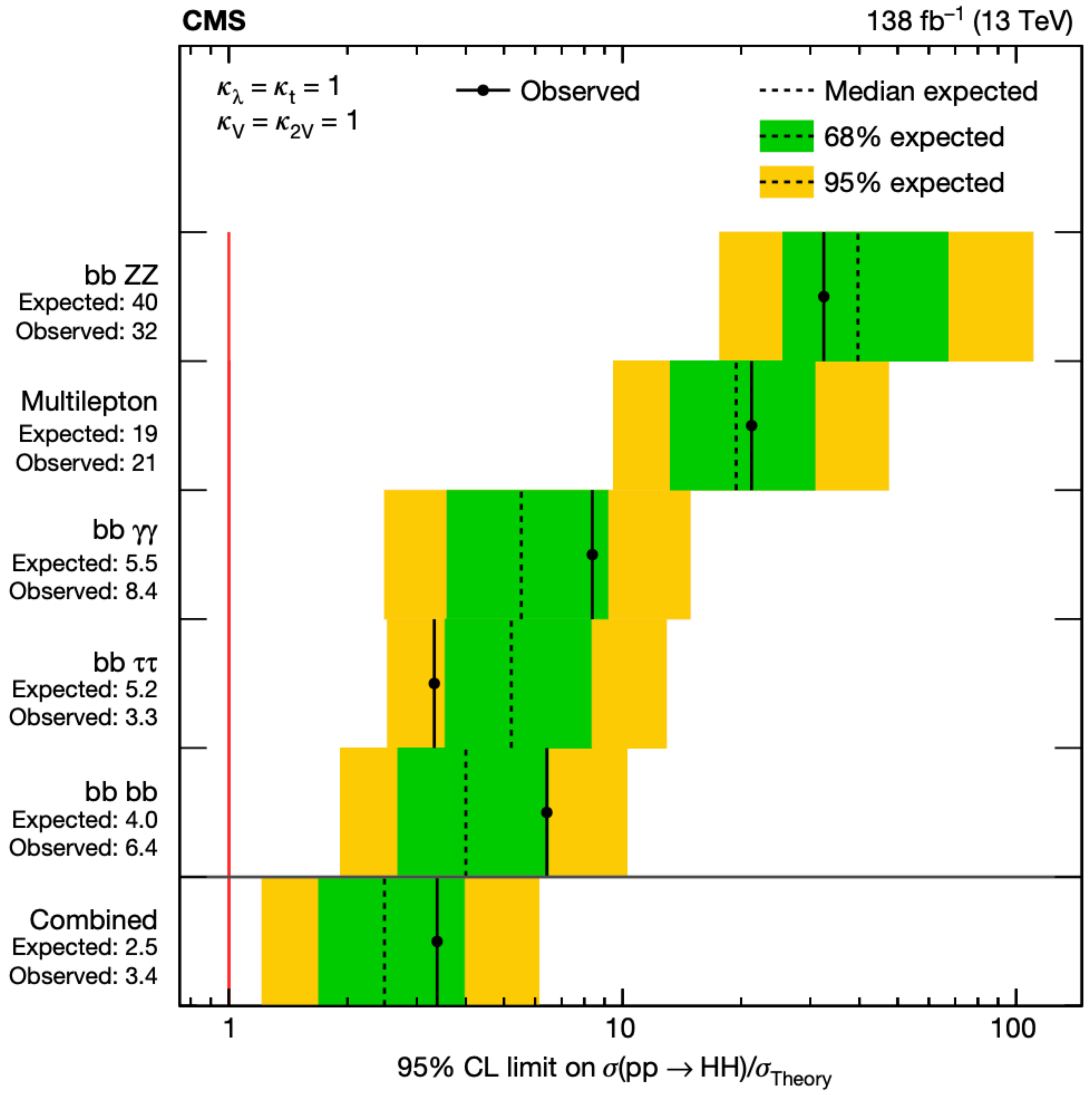
CMS-PAS-HIG-24-015

HHH production



HH signal strength limits

$HH \rightarrow 2b2\gamma$



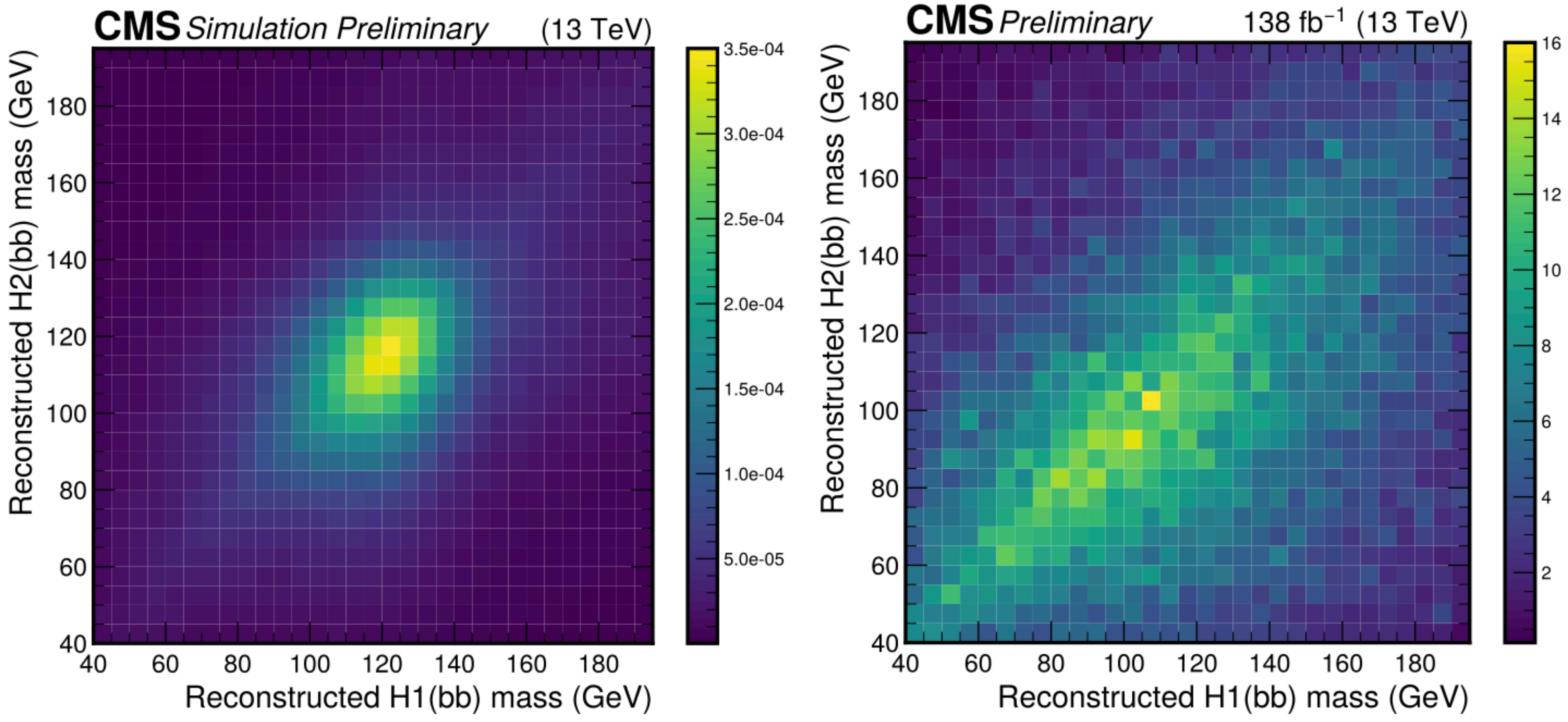
In HH: $2b2\gamma$ is one of the most sensitive channels

- Natural extension to investigate $HHH \rightarrow 4b2\gamma$
- However challenging:
  - $\sigma_{HHH} = 0.1$ fb about 14 events in Run 2
  - $BR(HHH \rightarrow 4b2\gamma) = 0.2\,\% \rightarrow$ Probing for enhanced trilinear and quartic couplings!
  - Non-resonant $\gamma\gamma$ + jets and resonant background H+X ($ttH \rightarrow \gamma\gamma$, ...)
- Advantage: fit in $m_{\gamma\gamma}$ distribution benefitting from high energy resolution (a few GeV opposed to 10-15GeV for Hbb)

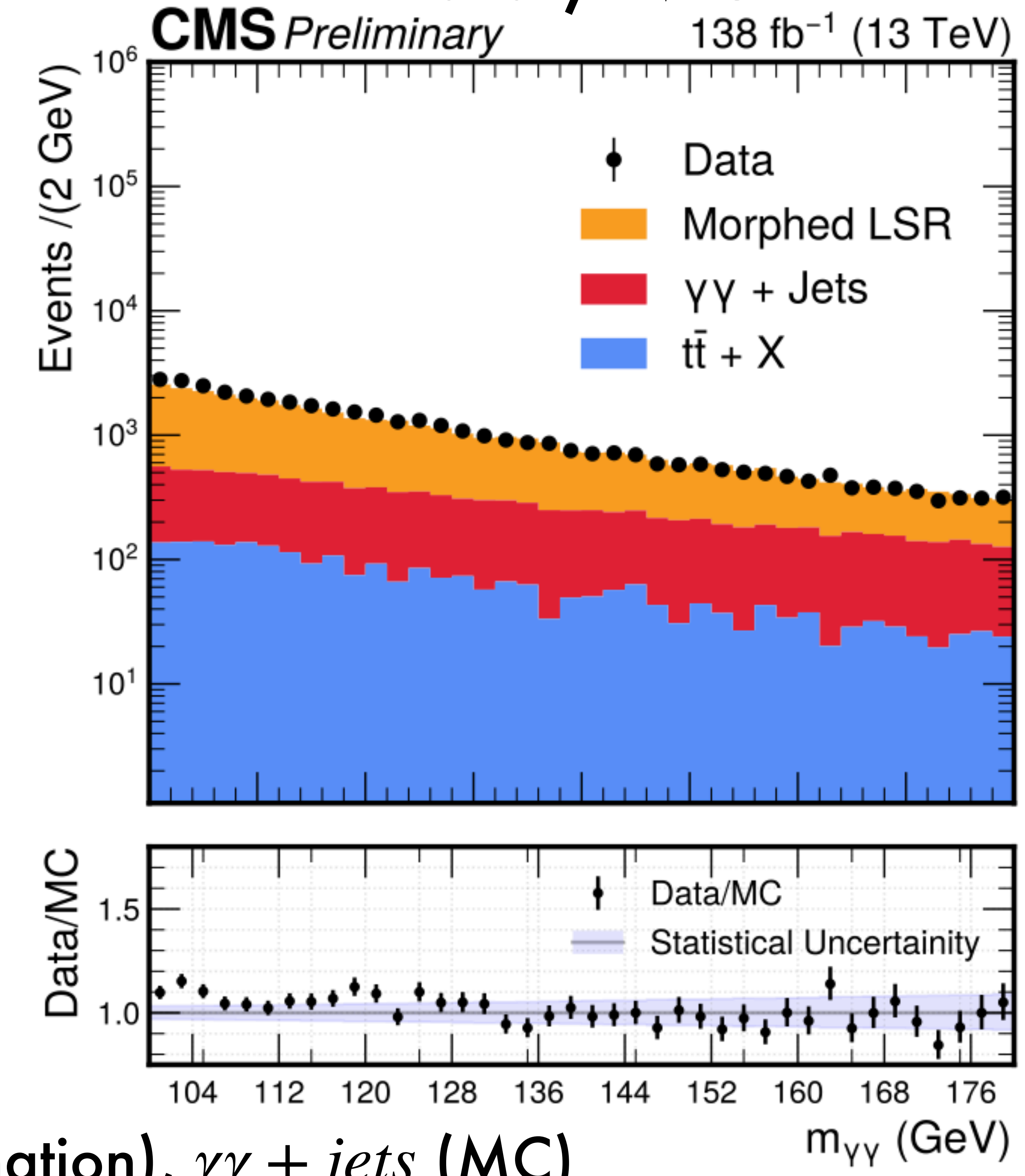
Non-resonant $HHH \rightarrow 4b2\gamma$

CMS-PAS-HIG-24-015

Pairing algorithms for 4b



Data / MC



Trigger: di-photon trigger developed for $H \rightarrow \gamma\gamma$, about 70% acceptance

- Non-resonant: $\gamma + jets$ and QCD (faking photons, modeled with data-driven estimation), $\gamma\gamma + jets$ (MC)
- Resonant: H+X using MC

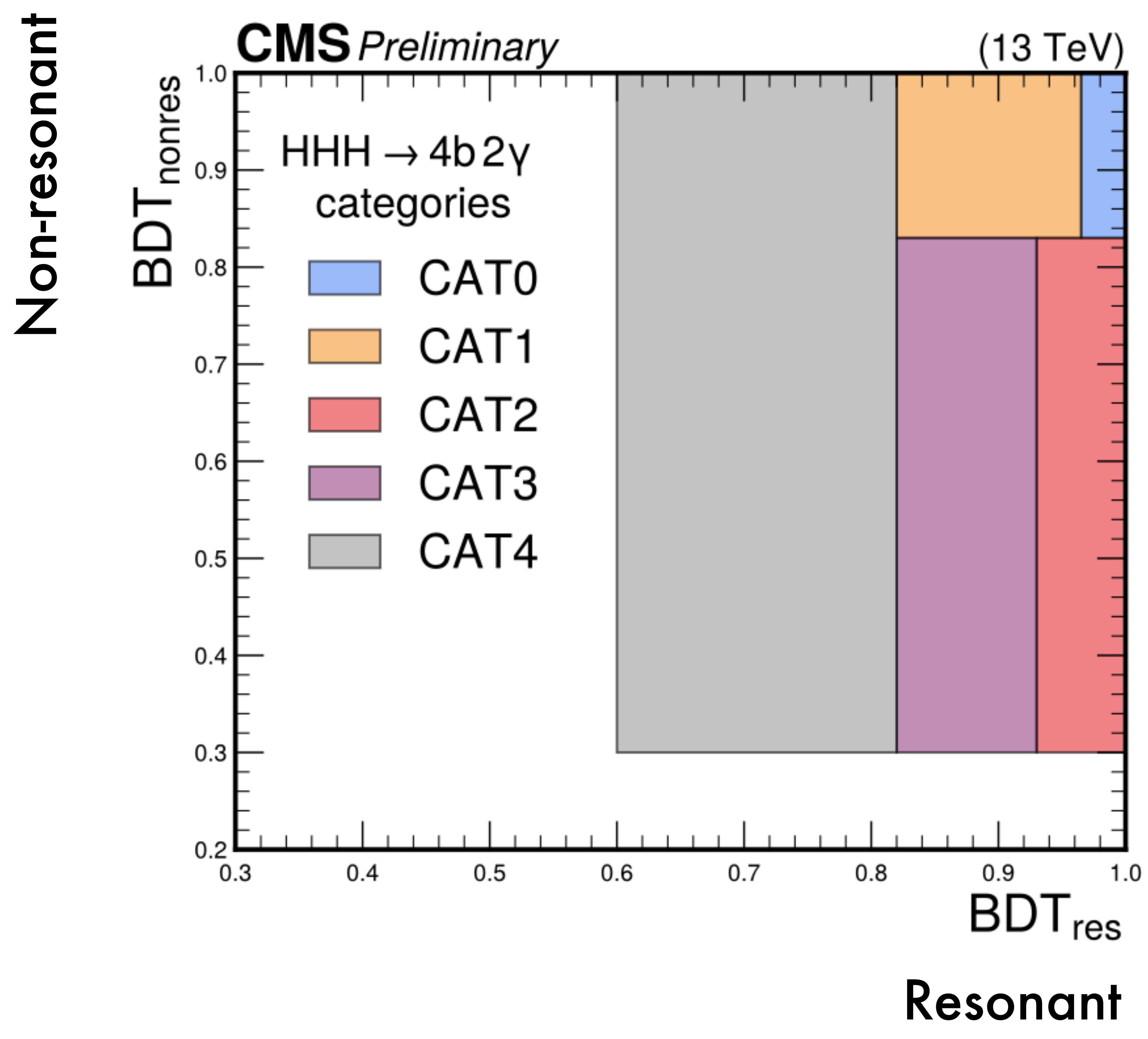
Focus on fully resolved analysis, pairing of the 4b candidates: exploiting HH4b methods minimizing $D_{HH} = |m_{H_1} - 1.05 \times m_{H_2}|$

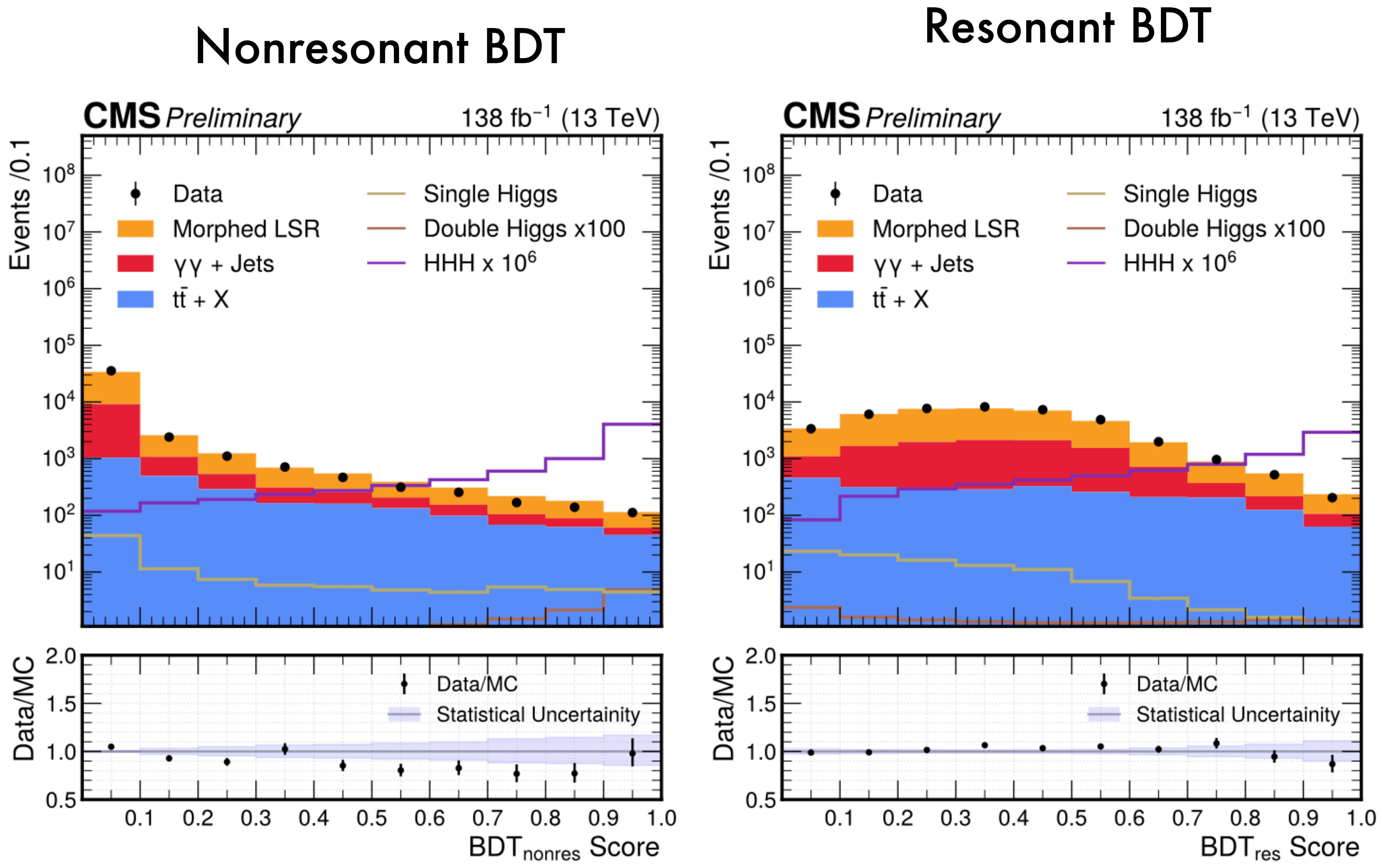
- Accuracy, about 75% (softer Higgs kinematic than in HH4b)

Overall, signal efficiency is about 60% before machine learning optimization

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

CMS-PAS-HIG-24-015





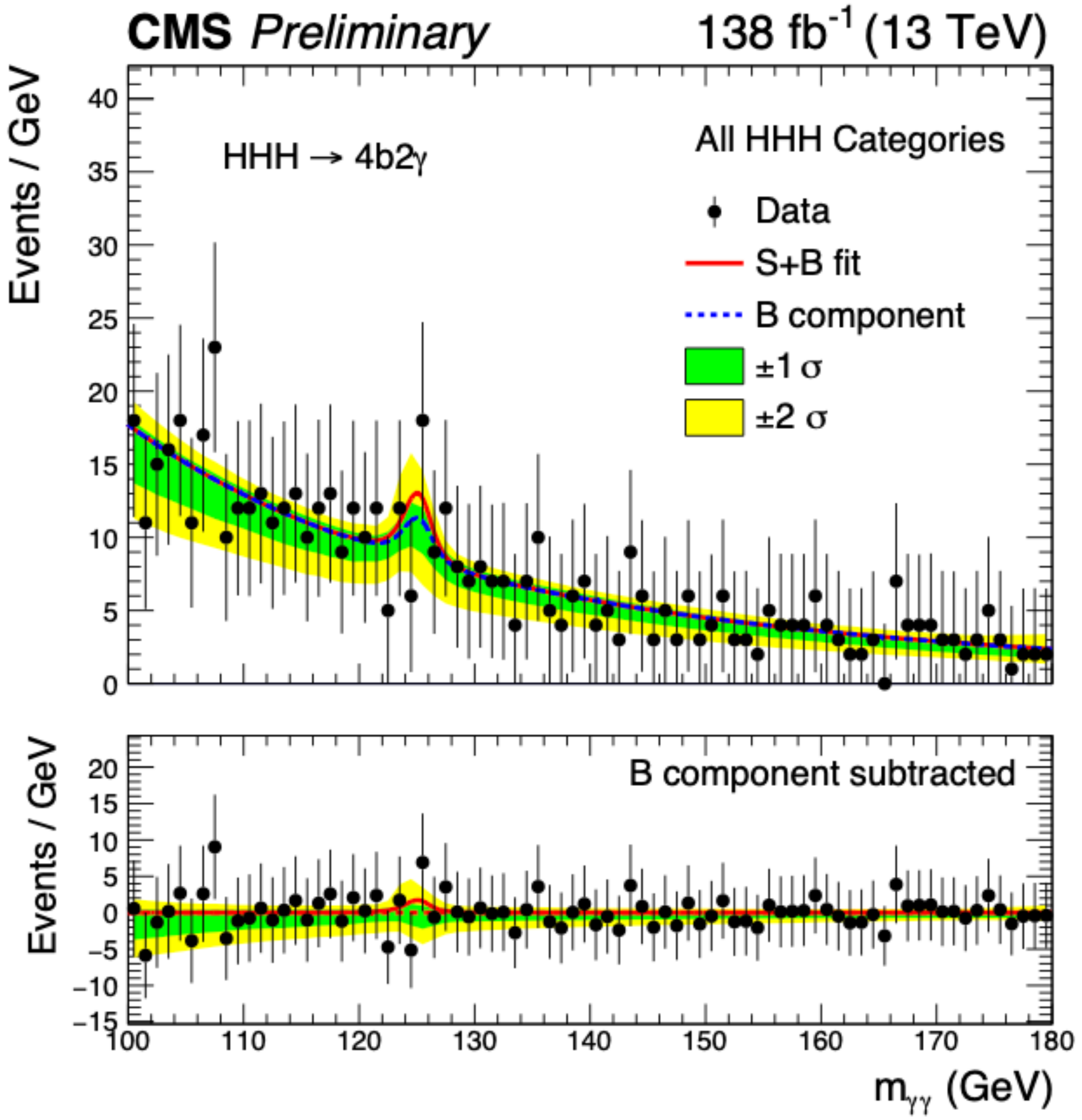
Two boosted decision trees trained:

- Inputs: photon identification, b-tagging score, kinematic variables of final states, geometric variables
- Signal vs non-resonant background
- Signal vs resonant background
- 5 analyses categories optimized for sensitivity built on 2D selection

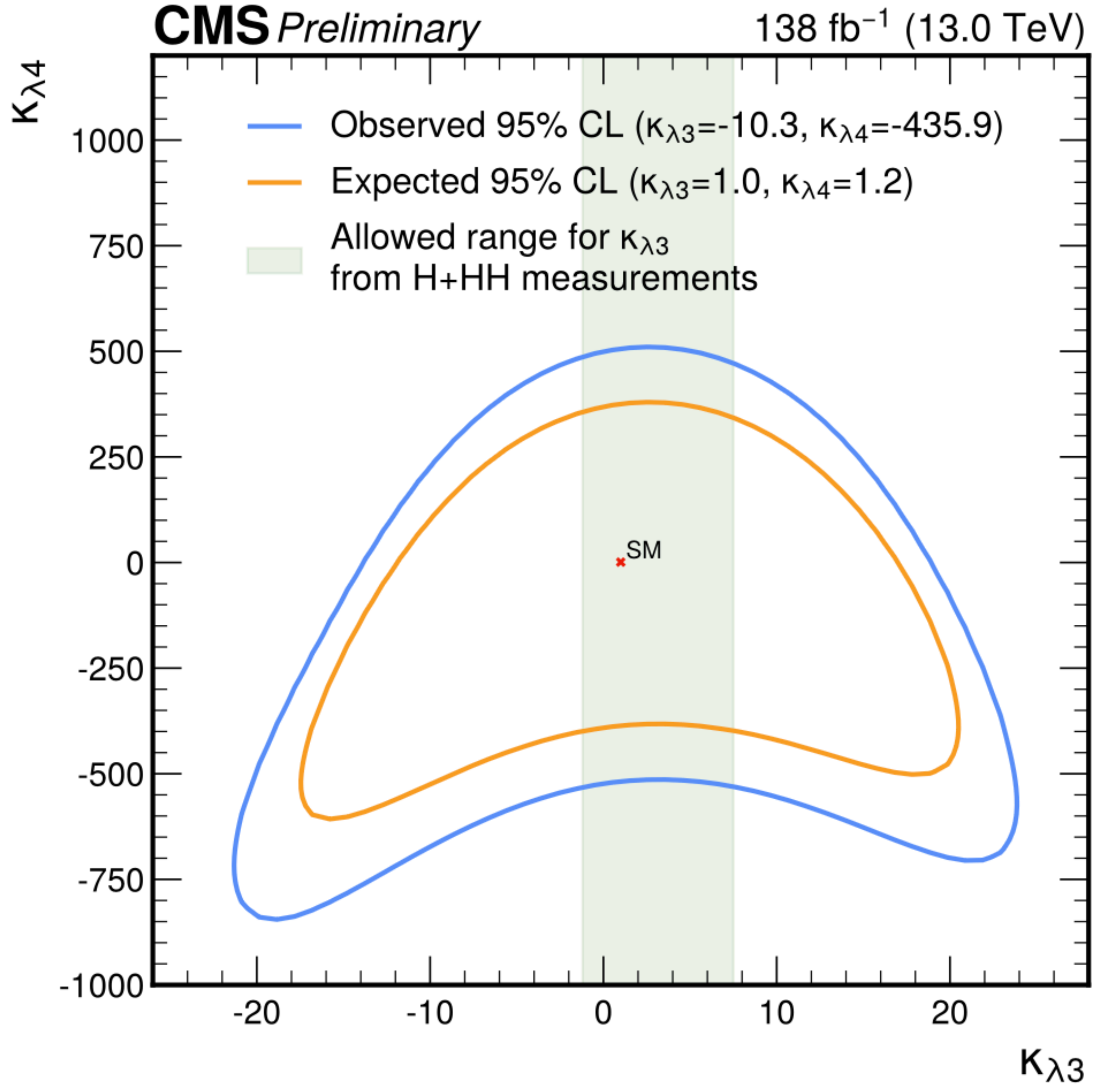
Non-resonant $HHH \to 4b2\gamma$

CMS-PAS-HIG-24-015

Fit to the data



(κ_3, κ_4) scan



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

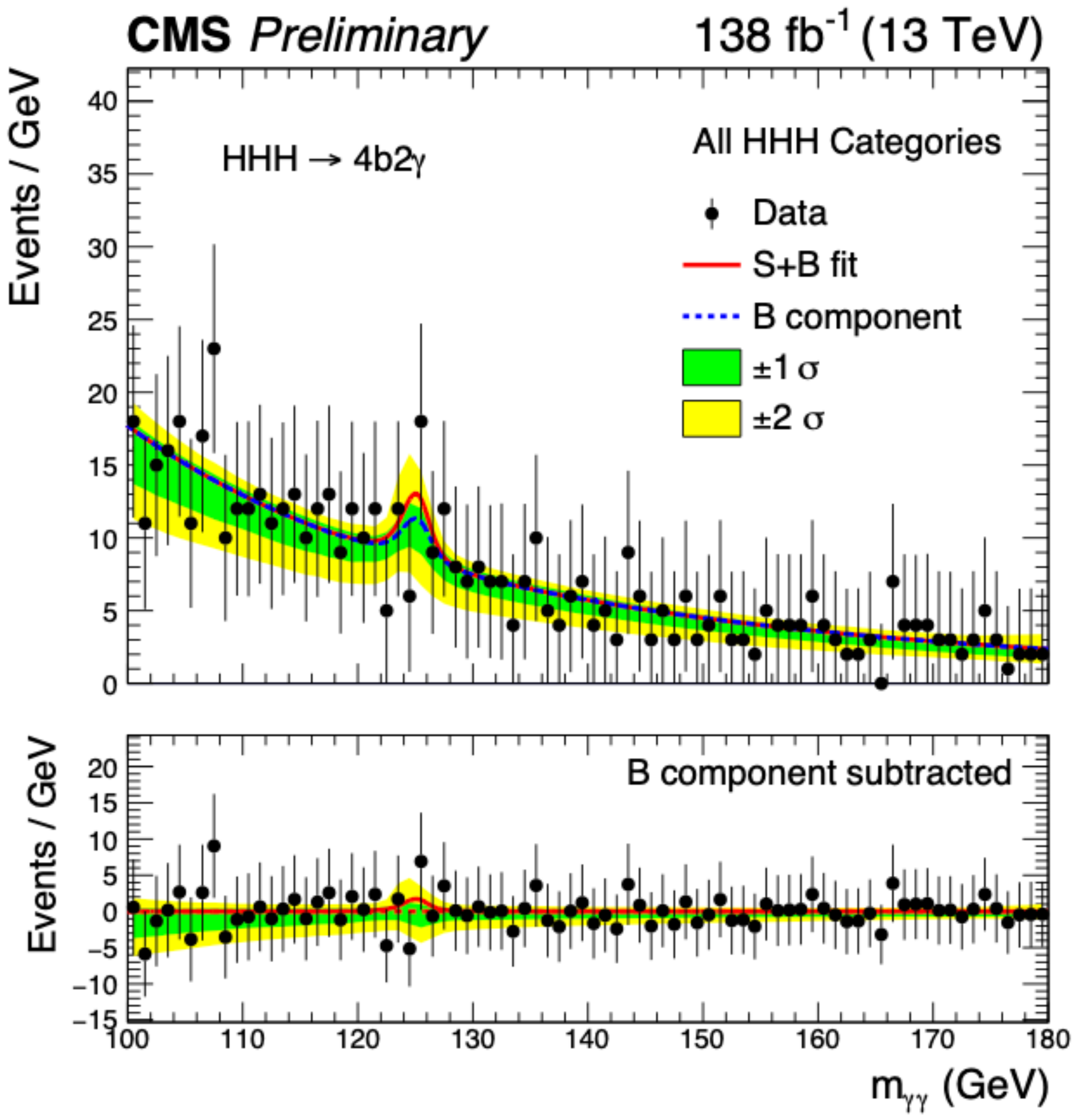
- Slight excess observed in data (within 1 sigma)
- Challenging channel, large background and low cross-section
- Selection acceptance, trigger, pairing, tagging, …

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

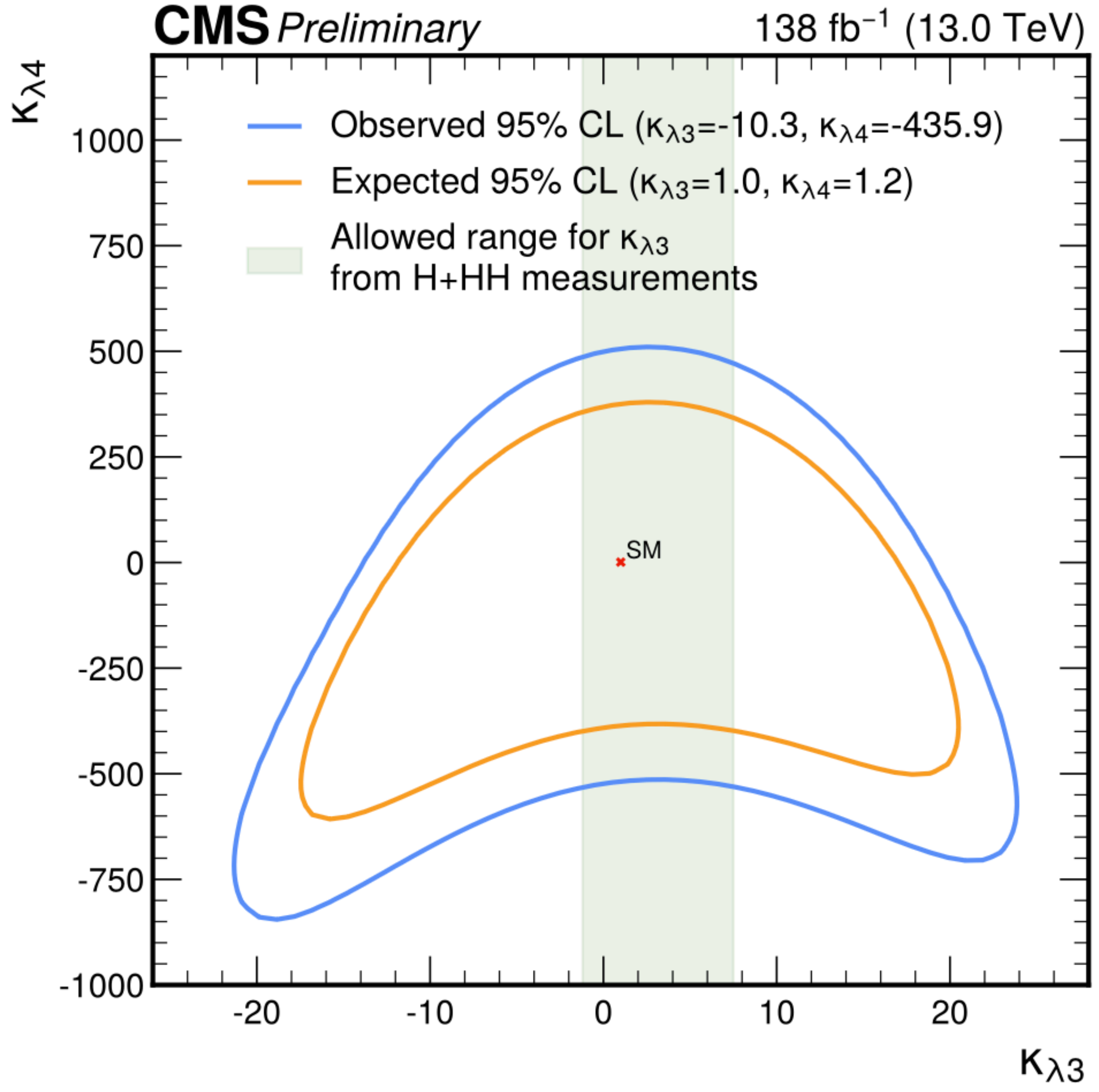
Non-resonant $HHH \to 4b2\gamma$

CMS-PAS-HIG-24-015

Fit to the data



(κ_3, κ_4) scan



Slight excess observed (within 1 sigma)

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

- Challenging channel, large background and low cross-section
- Selection acceptance, trigger, pairing, tagging, …

Interpretation:

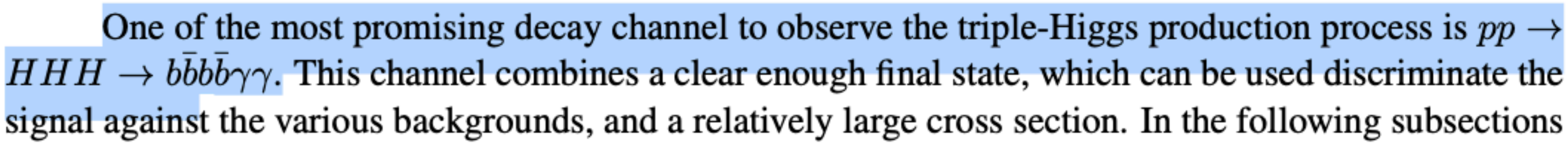
- 1D: $-16 < \kappa_3 < 20$ and $-397 < \kappa_4 < 405$ as well as 2D scan

Compared to 2023 estimate
Pessimistic: 220x SM with Run 2
Extrapolated from FCC-hh
Off by factor 10…
FCC projection: don't include fakes!
$\gamma + jets$ +QCD + $t\bar{t} + jets/\gamma/\gamma\gamma$
is also a background…

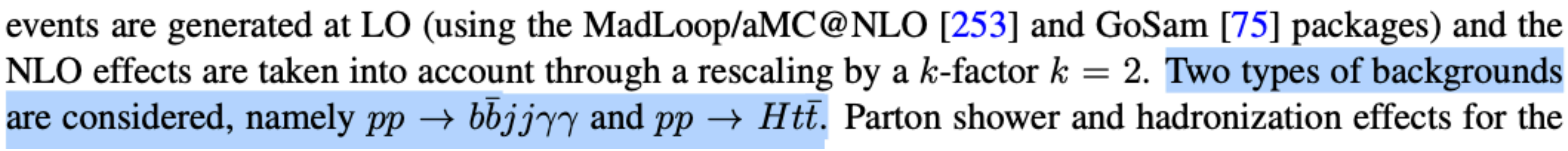
Non-resonant $HHH \to 4b2\gamma$

CMS-PAS-HIG-24-015

FCC projection

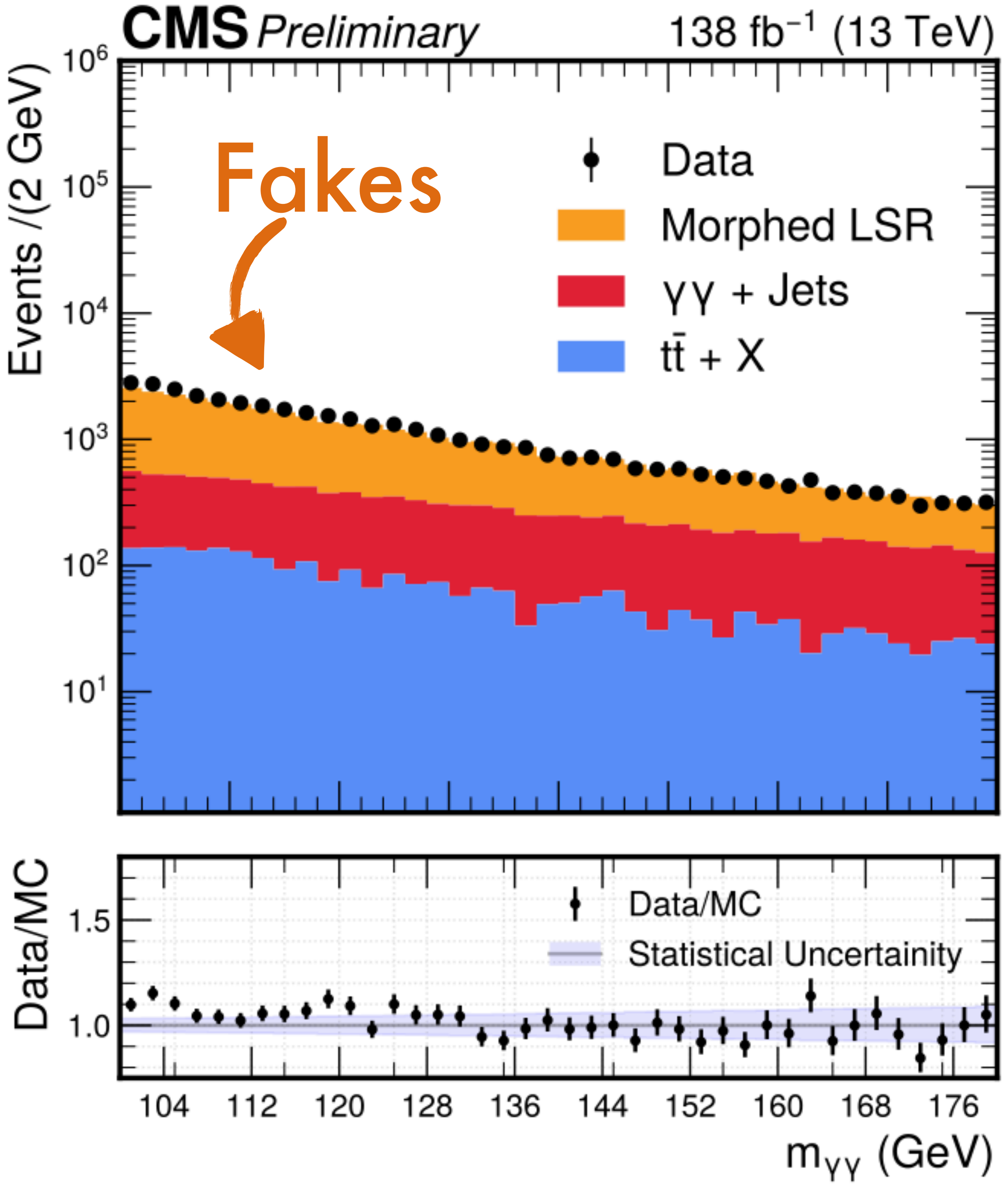


One of the most promising decay channel to observe the triple-Higgs production process is $pp \to HHH \to b\bar{b}b\bar{b}\gamma\gamma$. This channel combines a clear enough final state, which can be used discriminate the signal against the various backgrounds, and a relatively large cross section. In the following subsections



events are generated at LO (using the MadLoop/aMC@NLO [253] and GoSam [75] packages) and the NLO effects are taken into account through a rescaling by a k-factor $k = 2$. Two types of backgrounds are considered, namely $pp \to b\bar{b}jj\gamma\gamma$ and $pp \to Ht\bar{t}$. Parton shower and hadronization effects for the

Data / MC



Large scientific value: fakes and combinatorial backgrounds challenging for HHH!

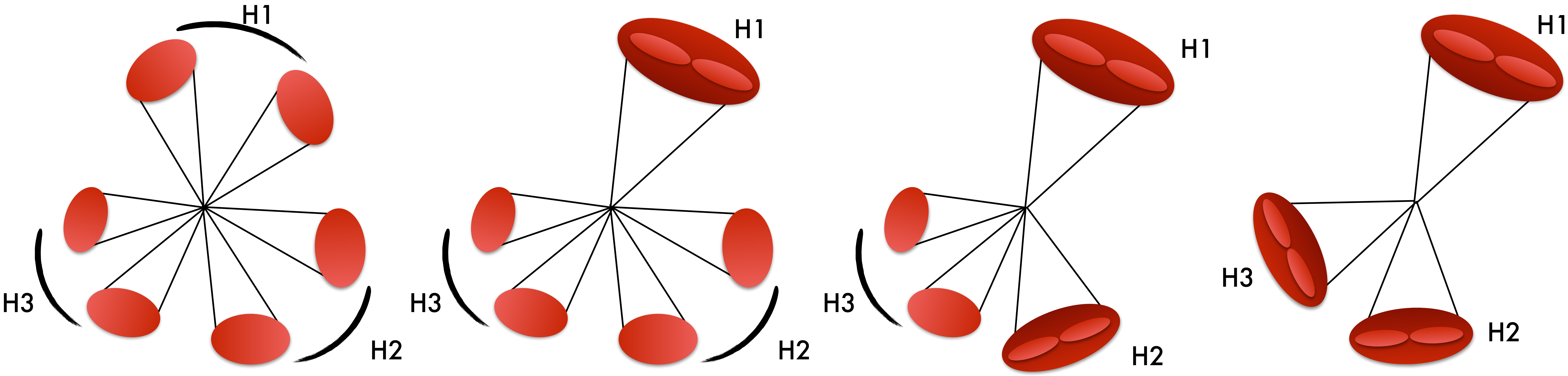
- **We are still in the process of determining the golden channels for HHH!**

Non resonant $HHH \rightarrow 6b$

Non-resonant $HHH \rightarrow 6b$

CMS-PAS-HIG-24-012

0bh3h = 0 boosted 3 resolved H 1bh2h 2bh1h 3bh0h



3 events produced in Run 2, up to 60 events by the end of the HL-LHC

HHH6b: rich experimental topology

- Resolved Higgs: reconstructed from 2 small-radius jets
- Boosted Higgs: reconstructed from one large-radius jets
- Complex mixing, dependent on momentum of the Higgs candidates

Rare process, but backgrounds faking 3 Higgs boson masses is also rare!

- Probe the trilinear λ_3 and quartic λ_4 couplings: *can we measure it at the HL-LHC?*

Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012

Number of reconstructible Higgs in **2 AK4 (small radius jets)**

Reconstructible Higgs in **AK8 (large radius jets)**

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

0Higgs → 1.3%

1Higgs → 19.7%

2Higgs → 52%

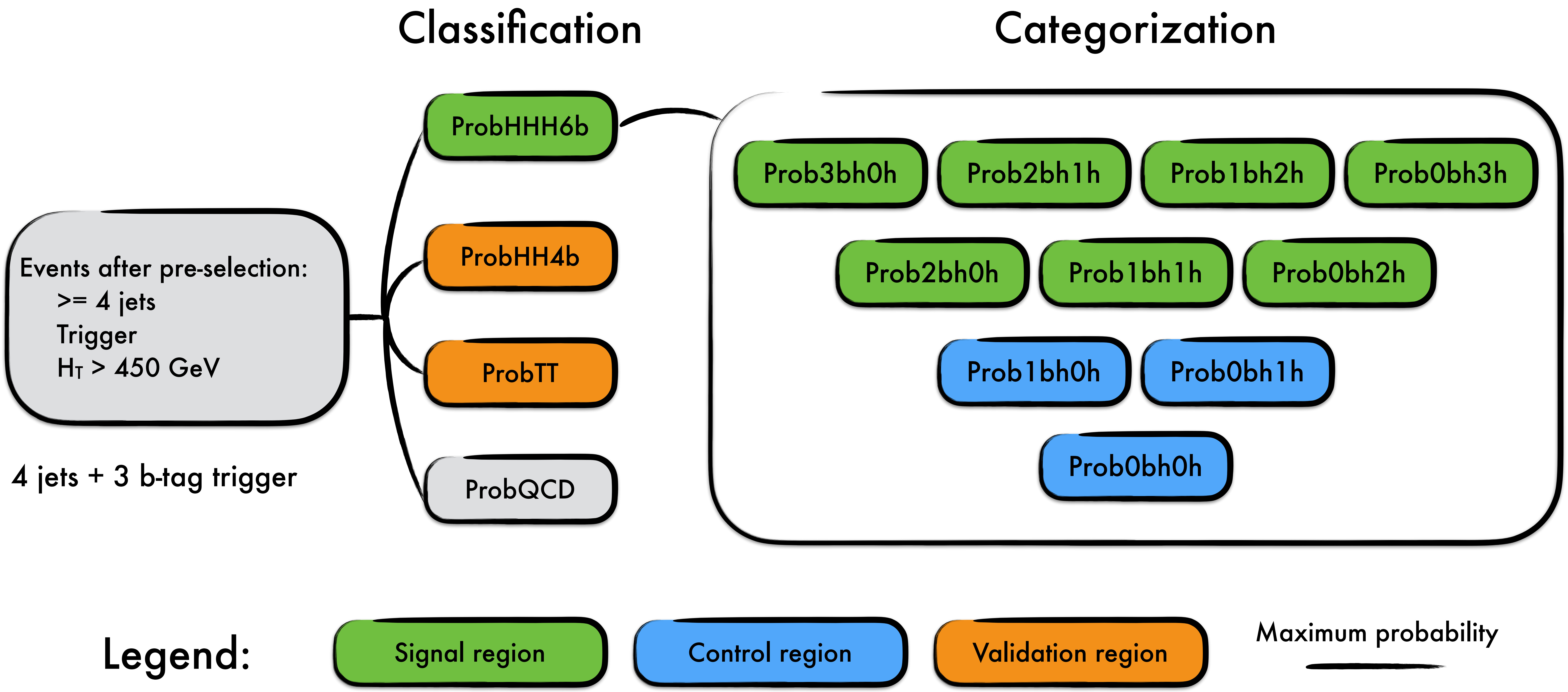
3Higgs → **27%**

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

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

Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012



Classification

Categorization

Events after pre-selection:
>= 4 jets
Trigger
$H_T > 450$ GeV

4 jets + 3 b-tag trigger

ProbHHH6b
ProbHH4b
ProbTT
ProbQCD

Prob3bh0h
Prob2bh1h
Prob1bh2h
Prob0bh3h
Prob2bh0h
Prob1bh1h
Prob0bh2h
Prob1bh0h
Prob0bh1h
Prob0bh0h

Legend:
Signal region
Control region
Validation region
Maximum probability

Dominant background: QCD (95%) and ttbar (5%)

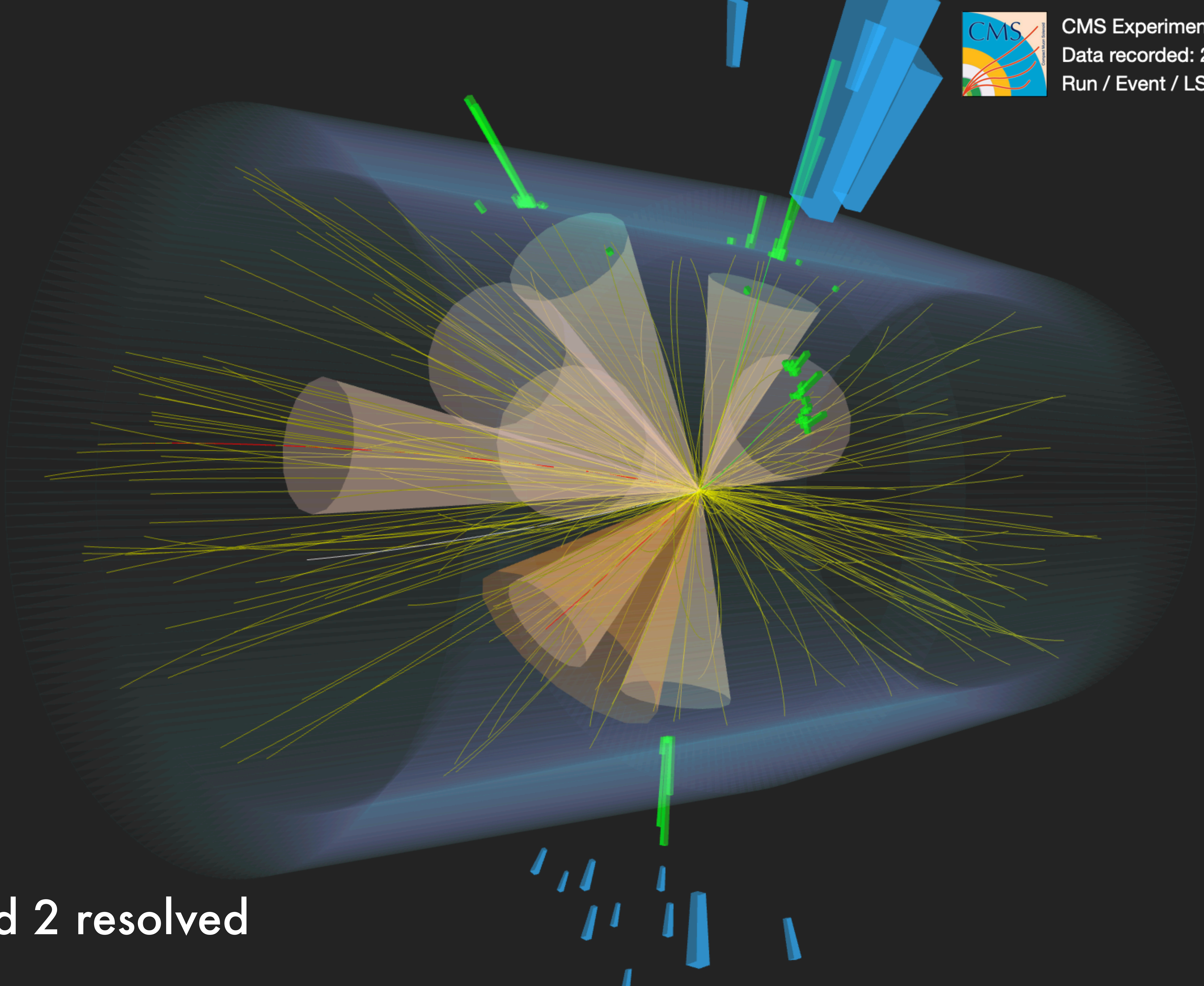
Train two machine learning networks (attention network) used

- Multi-classifier: **HHH6b** vs **HH4b** vs **QCD** vs **ttbar** → Effectively vetoing HH4b events
  - Use HH4b-like events to validate background model, use ttbar node to validate Data / MC
- Multi-categorization: trained on HHH6b and HH4b **predict categories** based on truth matching


CMS Experiment at the LHC, CERN
Data recorded: 2018-Jul-23 02:33:00.203520 GMT
Run / Event / LS: 320065 / 1074081512 / 679

3 boosted 0 resolved

2 boosted 1 resolved



CMS Experiment at the LHC, CERN
Data recorded: 2018-Jul-23 02:33:00.203520 GMT
Run / Event / LS: 320065 / 1074081512 / 679

1 boosted 2 resolved

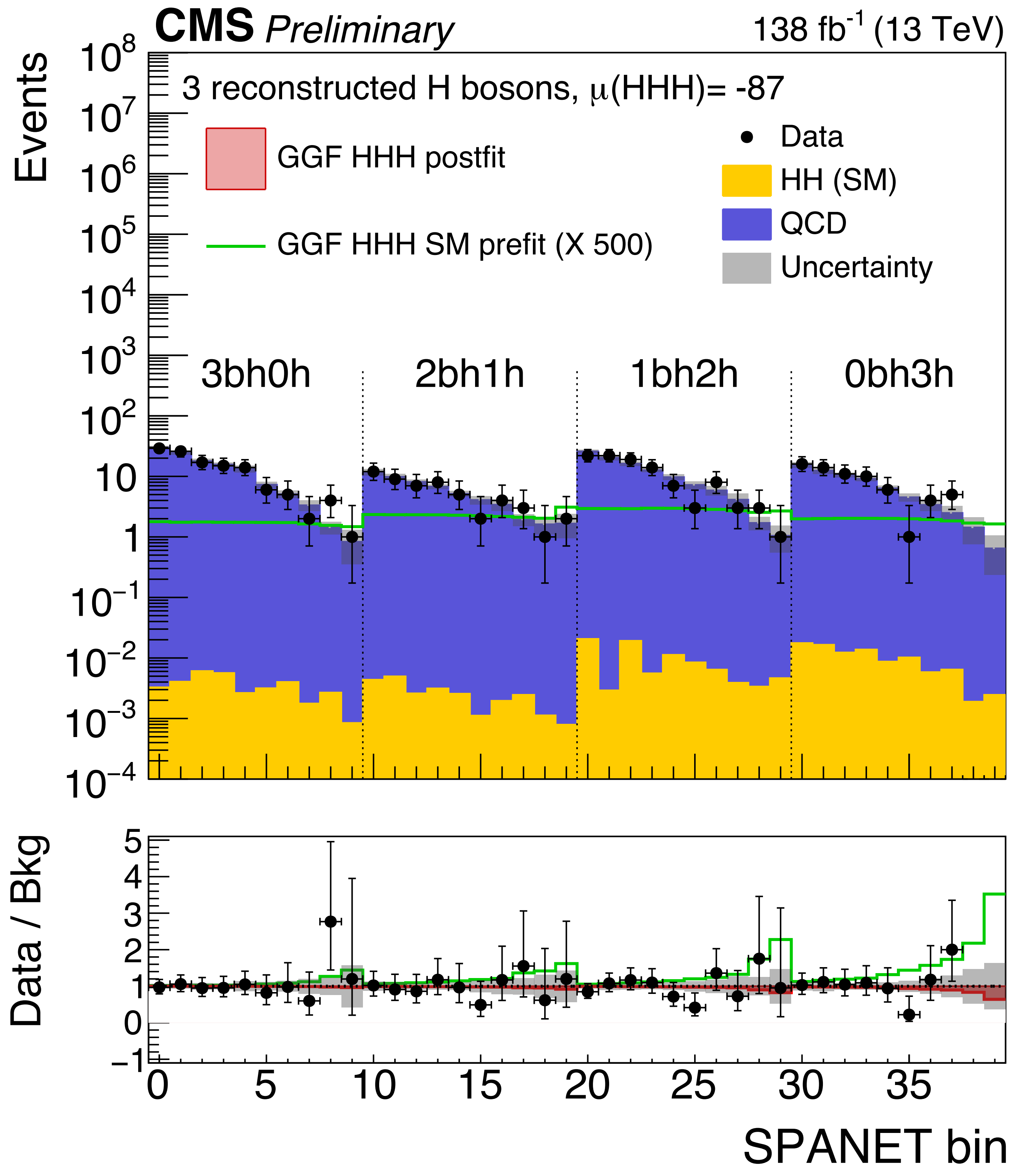
0 boosted 3 resolved

CMS Experiment at the LHC, CERN
Data recorded: 2018-Jul-23 02:25:45.572928 GMT
Run / Event / LS: 320065 / 1043813170 / 660

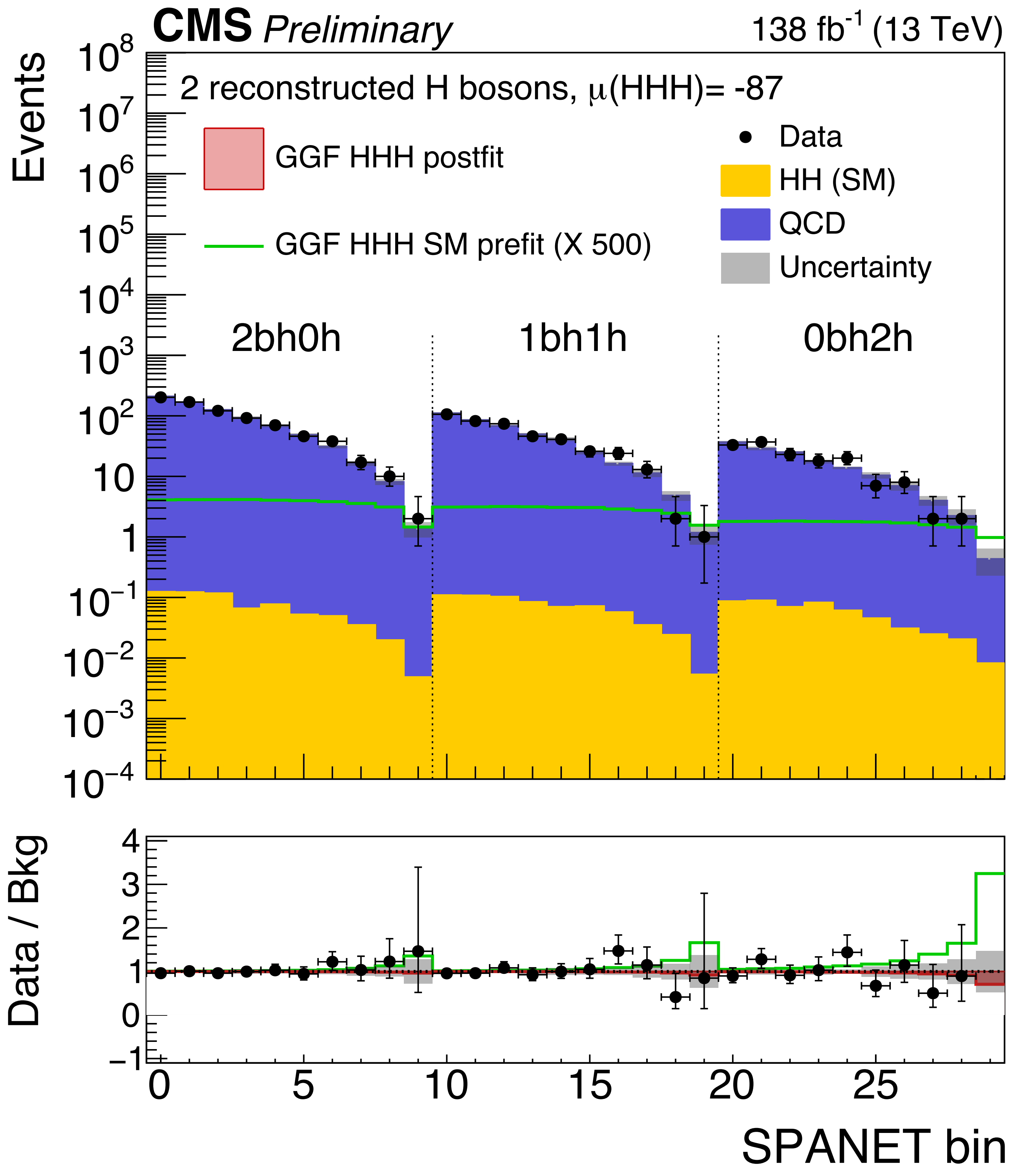
Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012

3 reconstructed Higgs bosons



2 reconstructed Higgs bosons



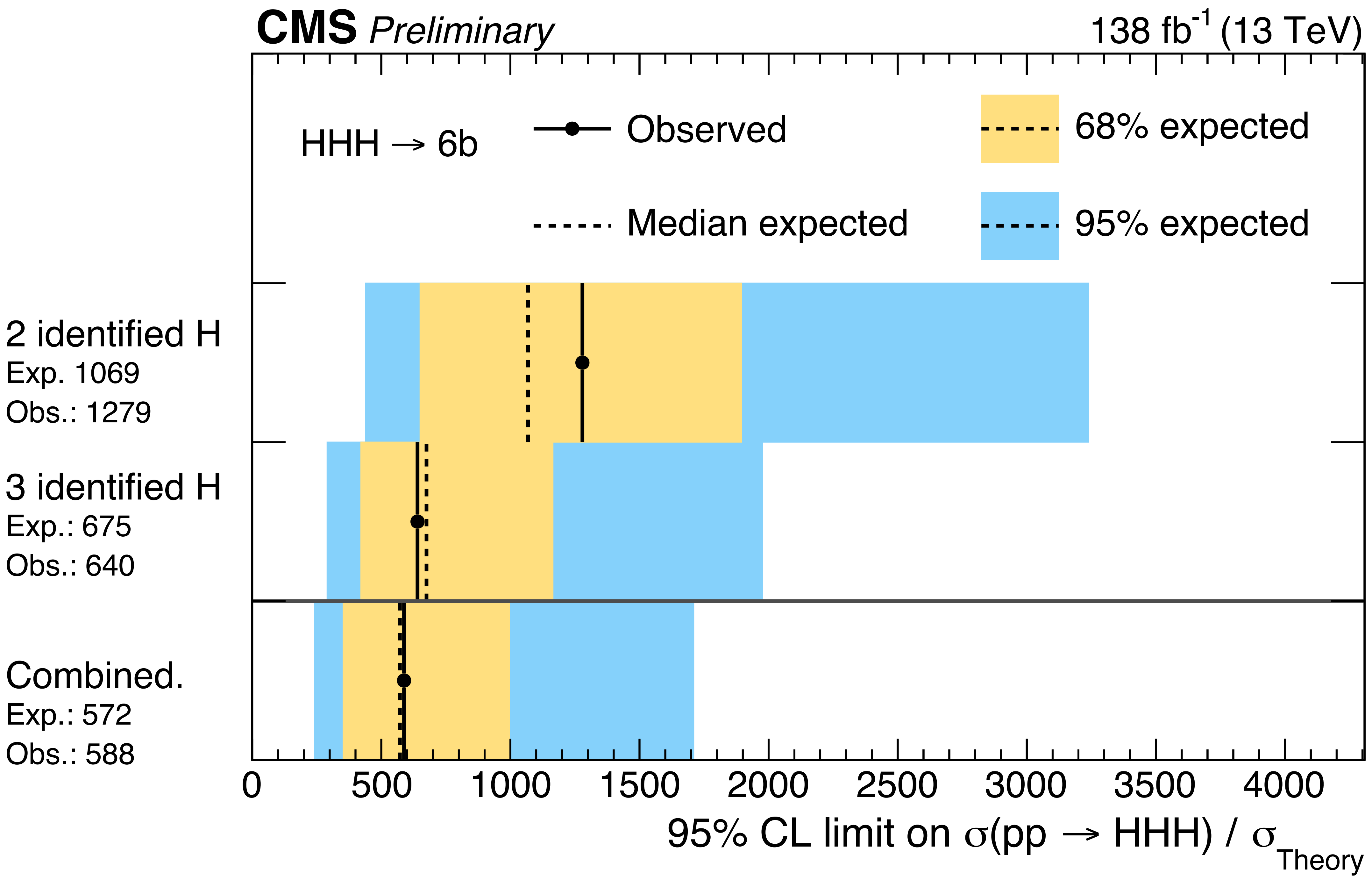
Background modeling: data driven approach due to overwhelming QCD

- Jet-flavor embedding: event failing HHH and HH selections are used
- Sampling flavor tagging information from data SR and replace it in failed region
- Perform prediction of machine learning algorithm on artificial data set to get background model
  - Extensively validated on HH4b-like events, QCD MC… Additional shape uncertainty derived from CR assigned

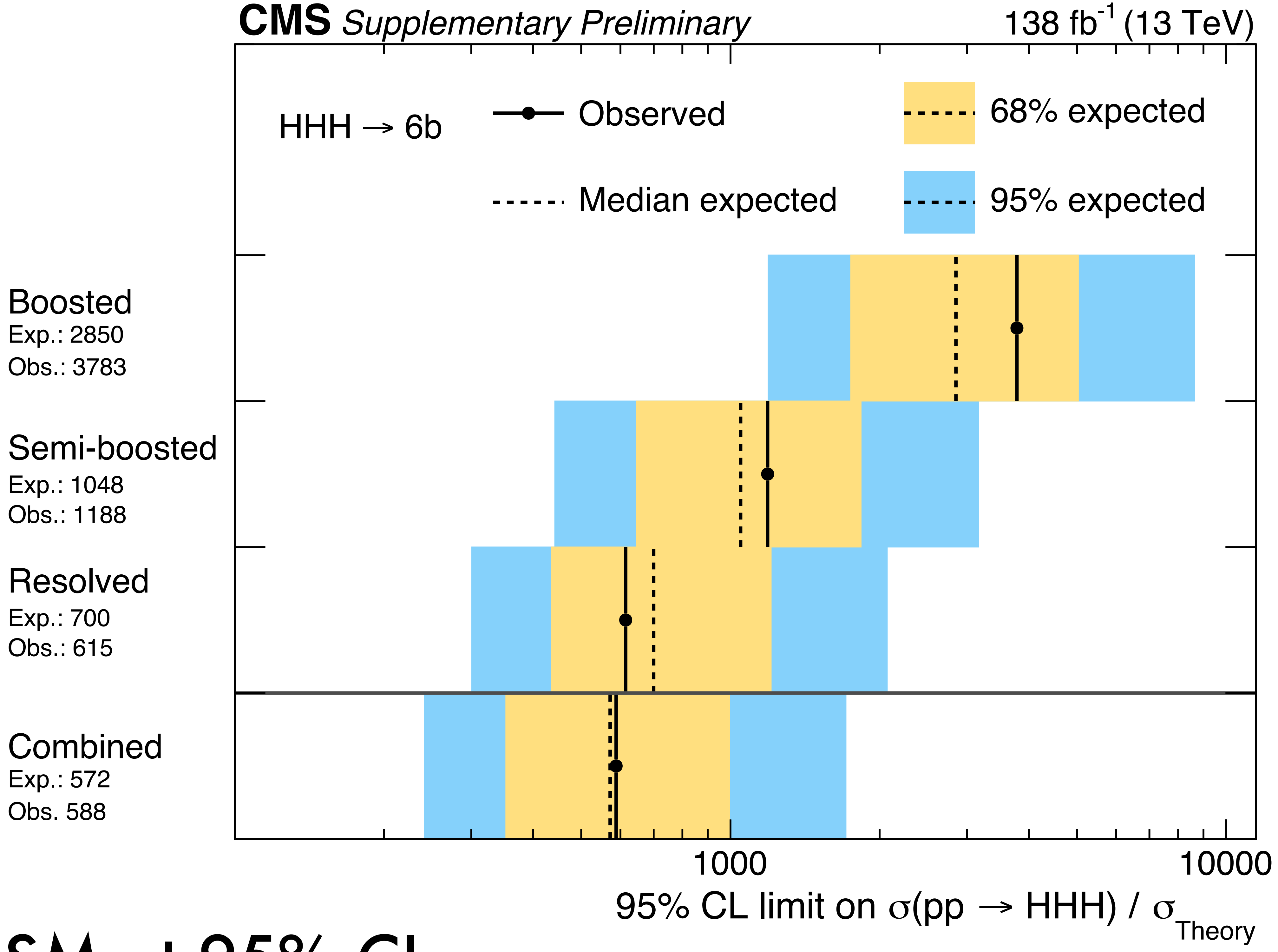
Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012

Categories breakdown



Topology breakdown

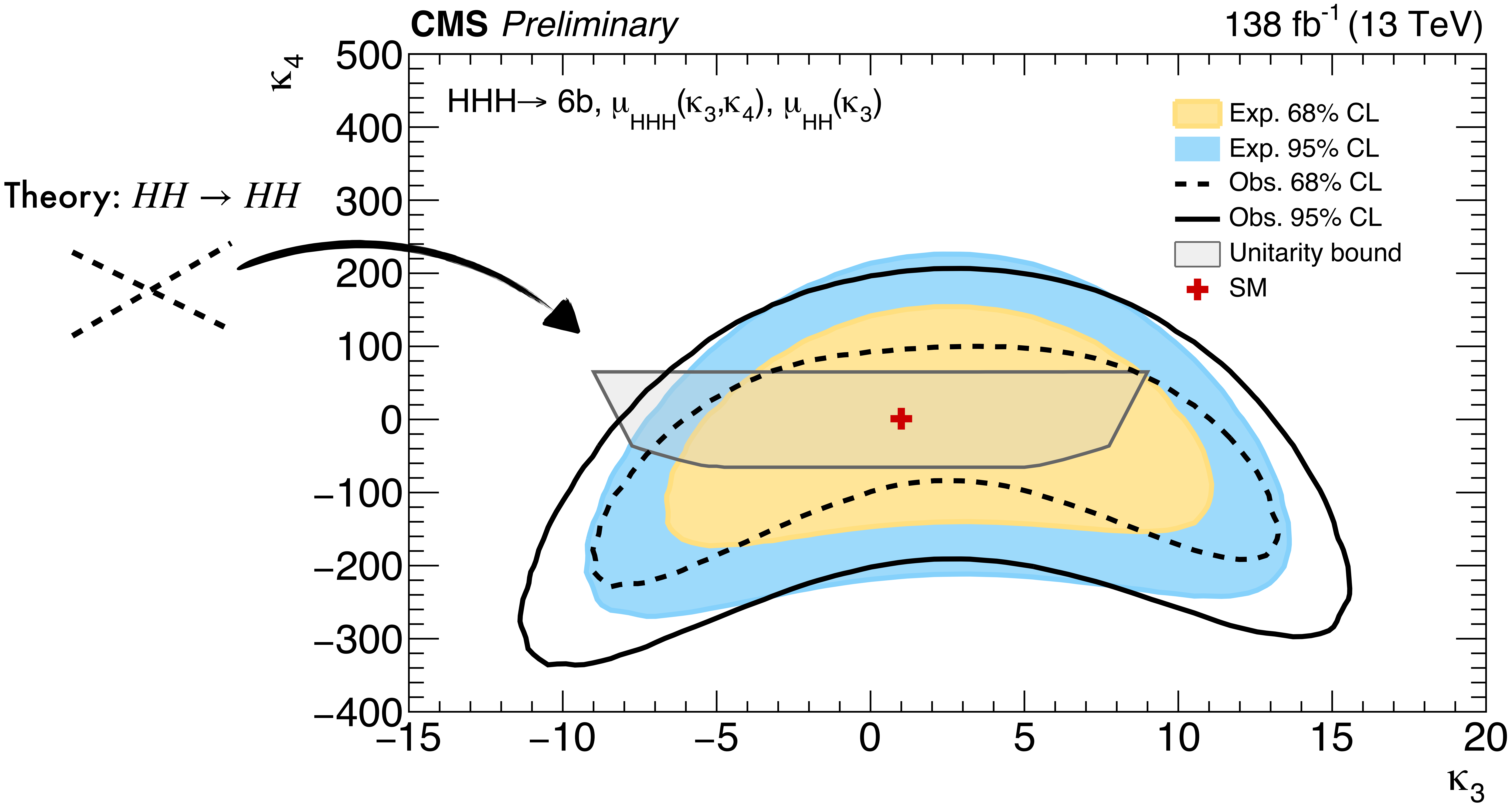


Result: observed (expected) limit of $\mu < 588\ (572)$ x the SM at 95% CL

- 3 reconstructed Higgs category drives the sensitivity
  - **+18% sensitivity** achieved thanks to **2Higgs categories**!
- Resolved categories drive the sensitivity
  - **+20% sensitivity** achieved thanks to **semi-boosted and boosted categories**!
- About 25-30% better than ATLAS, benefitting from semi-boosted and boosted categories!
  - ATLAS: resolved analysis only with $750 \times SM$, compatible with CMS resolved-only

Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012


Theory: $HH \to HH$

Interpretation: normalization effects of κ_3 and κ_4 on HHH and κ_3 on HH

- Deviations constrained to $-7 < \kappa_3 < 12$ and $-190 < \kappa_4 < 190$

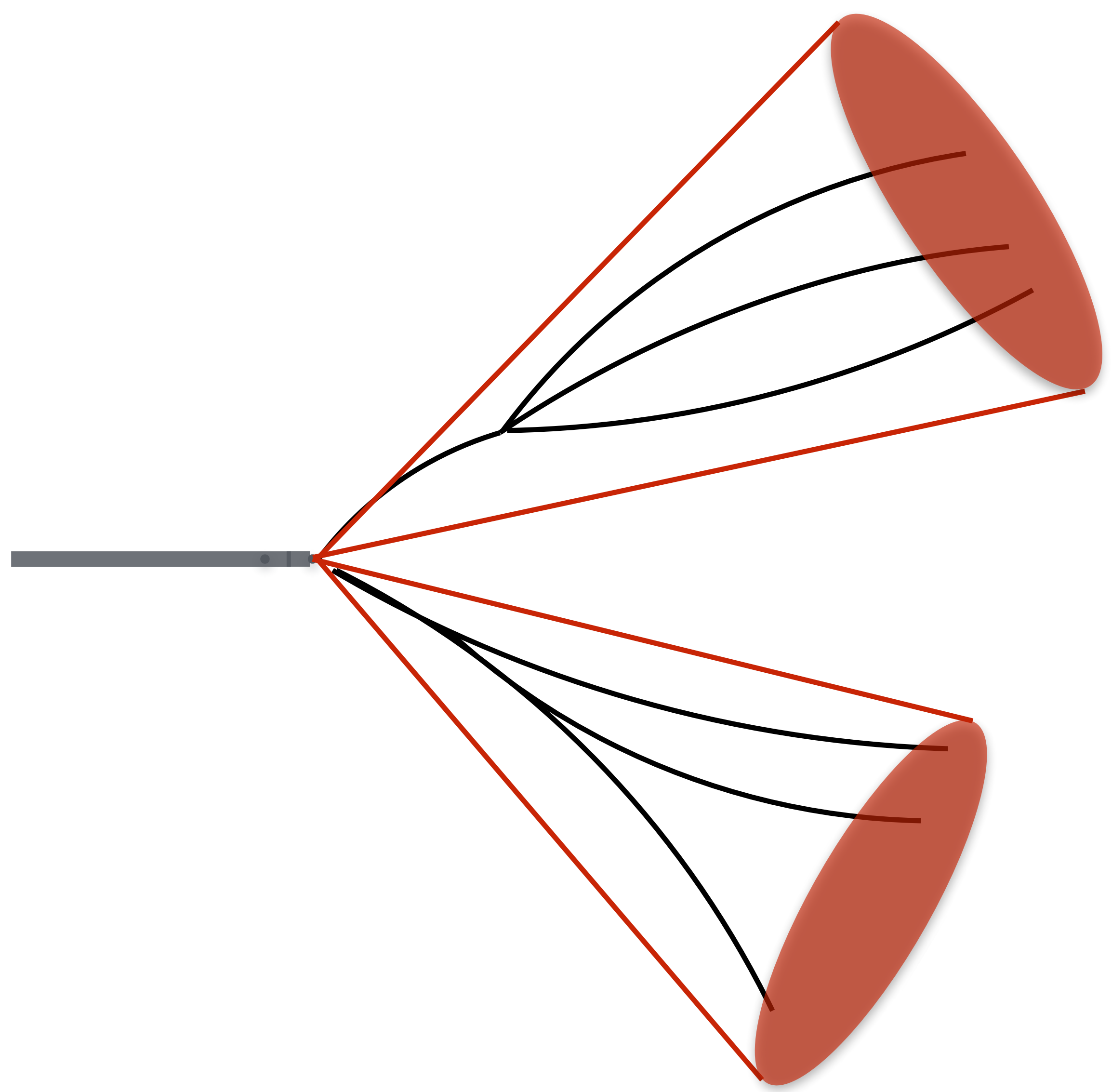
First exclusion of (κ_3, κ_4) at 95% CL in region **probing perturbative unitarity bounds**!

Revolutions since Run 2: flavor tagging and trigger

Flavor tagging

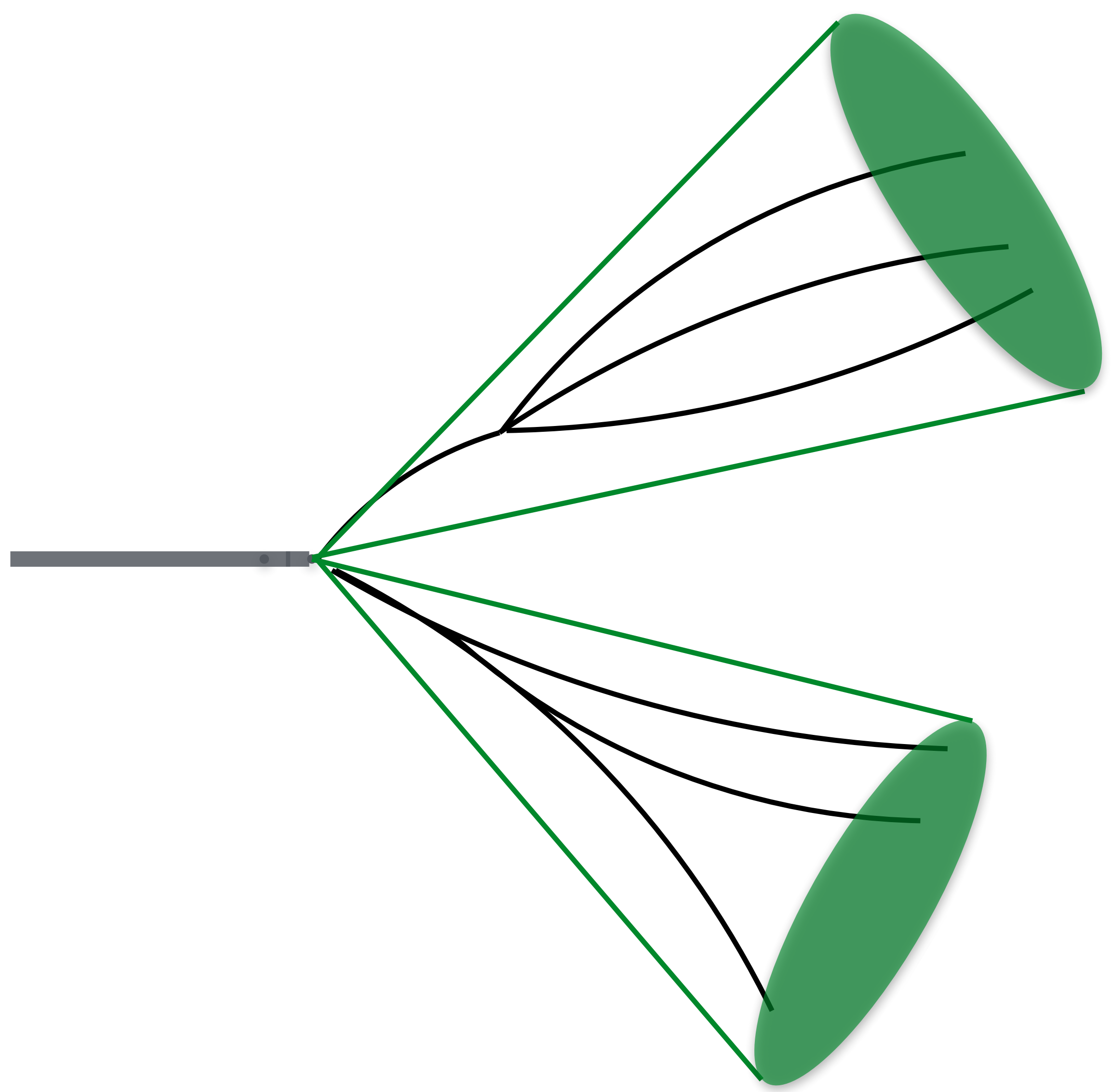
Higgs decays to heavy flavor quarks

$H \rightarrow b\bar{b}$



60% of Higgs bosons decay to b-quarks

$H \rightarrow c\bar{c}$

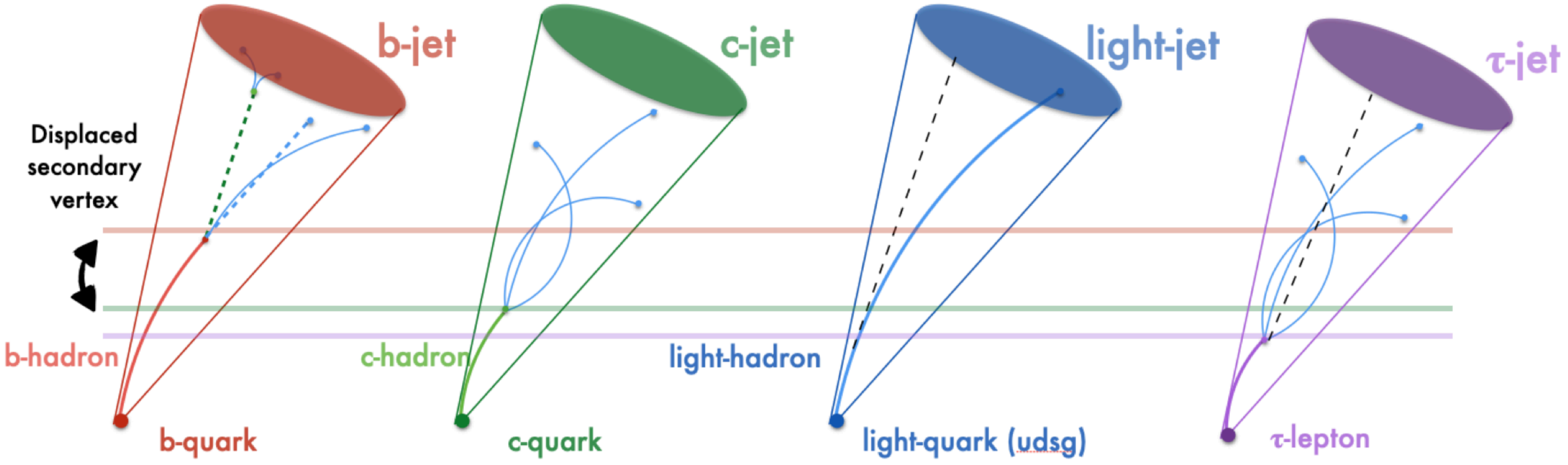


3% of Higgs bosons decay to c-quarks

Major challenge: Higgs predominantly decays to heavy flavor b- and c-quarks

- Quark hadronize and decay in the detector to form jets
- Need to infer the flavor of the quark from the decay final states!
- Measuring most of the Higgs bosons requires precise identification of b- and c-jets!

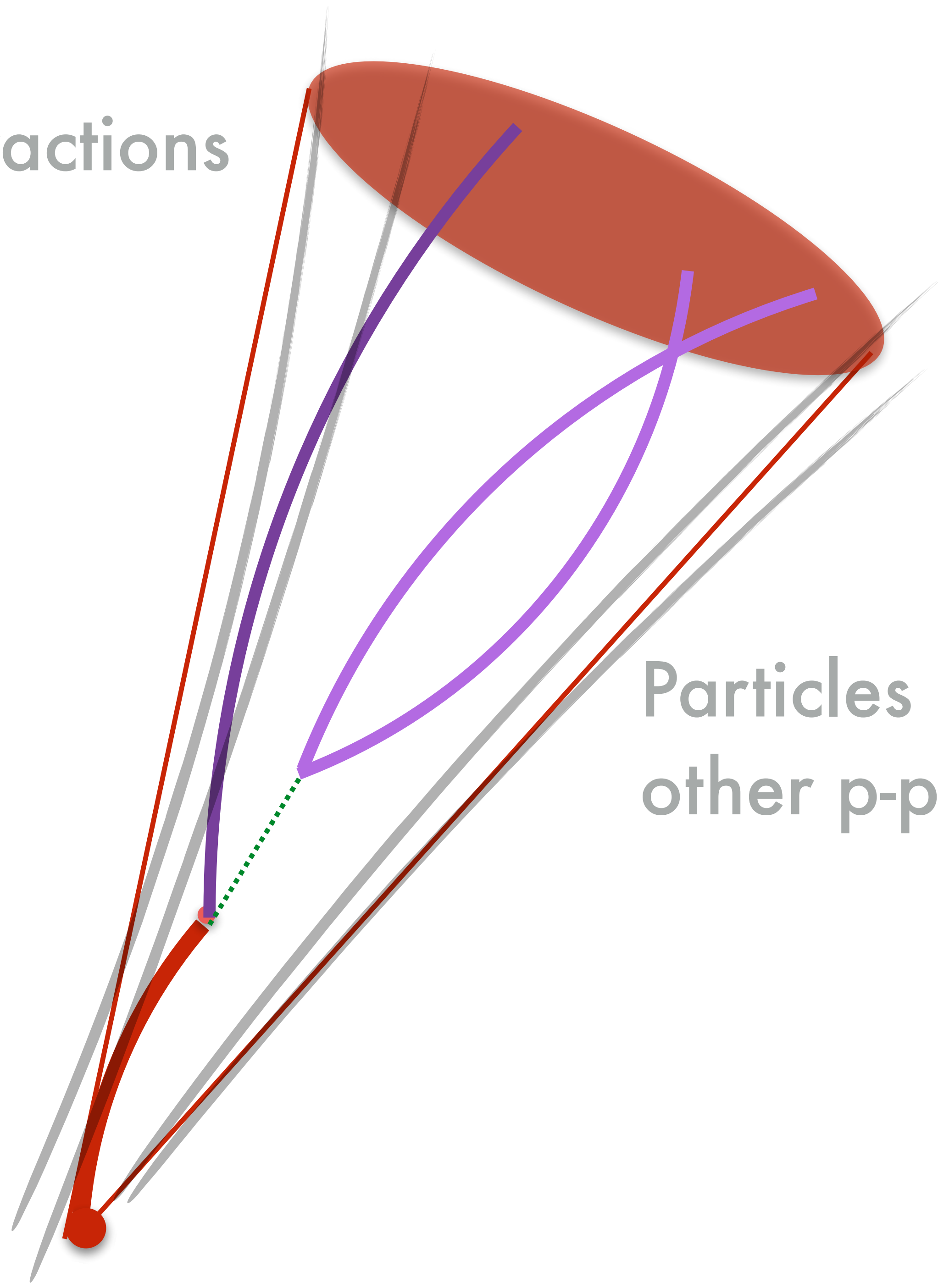
Flavor tagging concept



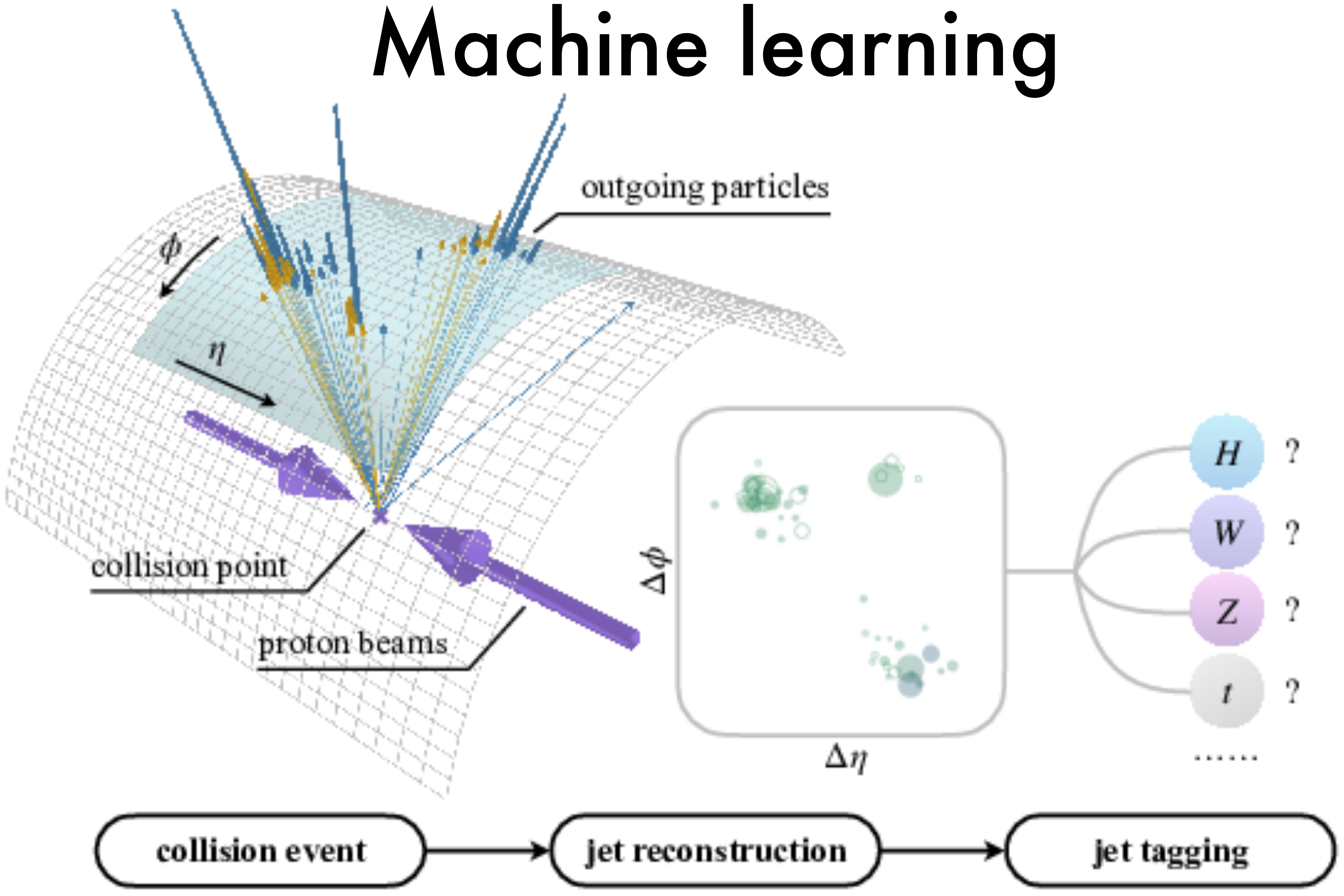
By 2022: concept to identify heavy hadrons - lifetime and displacement

- Hadrons decay via W transition, top transitions are suppressed due to vey large mass
  - $b \rightarrow c$ and $c \rightarrow s$ transitions, longer lifetime for b-hadron than c-hadrons
  - Identification algorithms **heavily relied on secondary vertices reconstruction**
    - Usage of machine learning algorithms with higher-level reconstructed variables
  - In general, **easier** to **identify b-jets** than **c-jets** due to physics properties of b-hadrons

Paradigm shift for Run 3 and Run 2 re-analysis



Machine learning

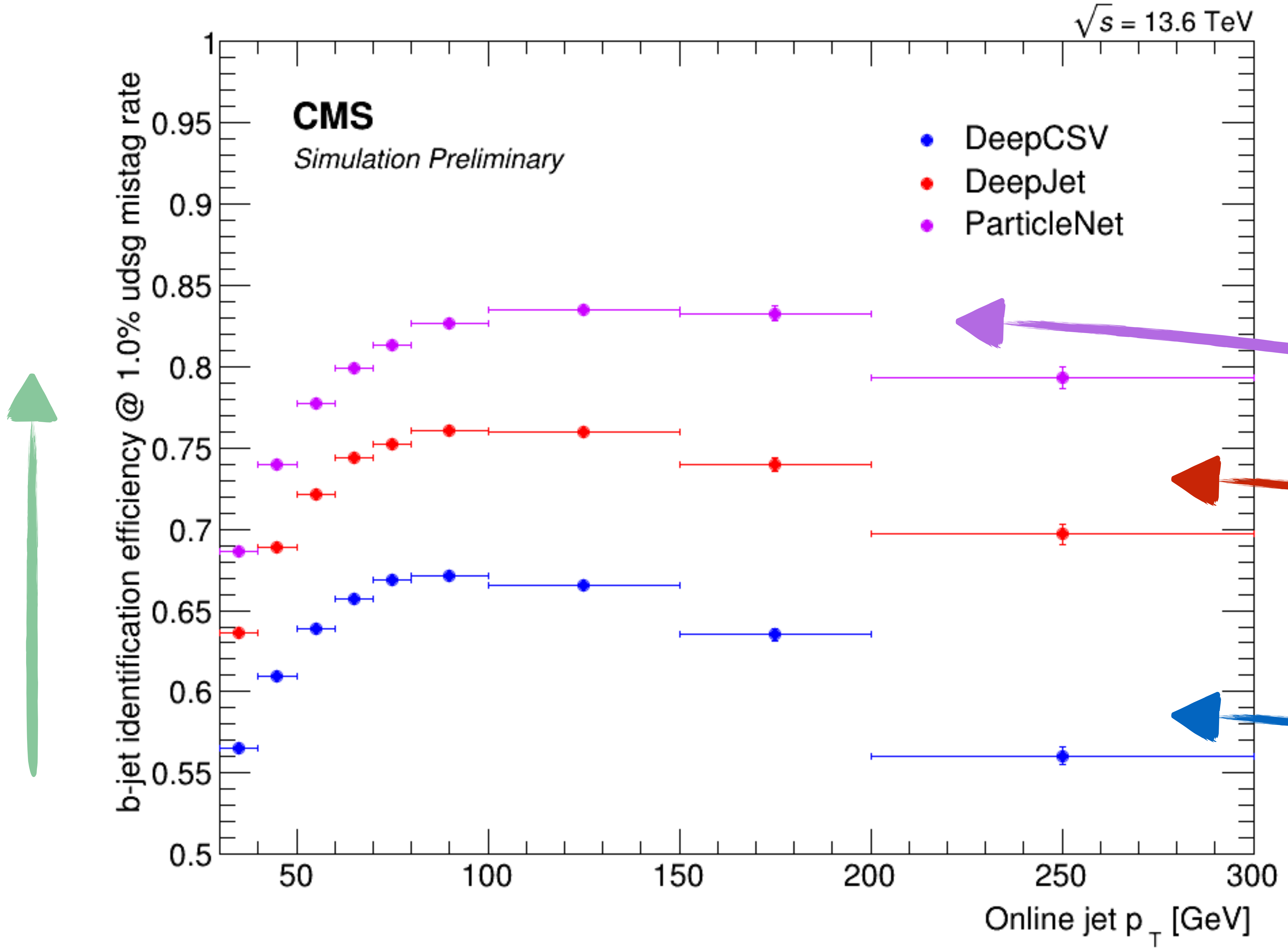


Advances in machine learning and computing (GPUs)

- Instead of relying on secondary vertices, use **all charged and neutral particles**
- Train algorithms to predict flavor of a jet using tens and hundreds of particles in jet
  - Momenta, position, angular separation, secondary vertices...

Paradigm shift for Run 3

CMS DP-2023/021



Tagger in 2022

Tagger in 2018

Tagger in 2016

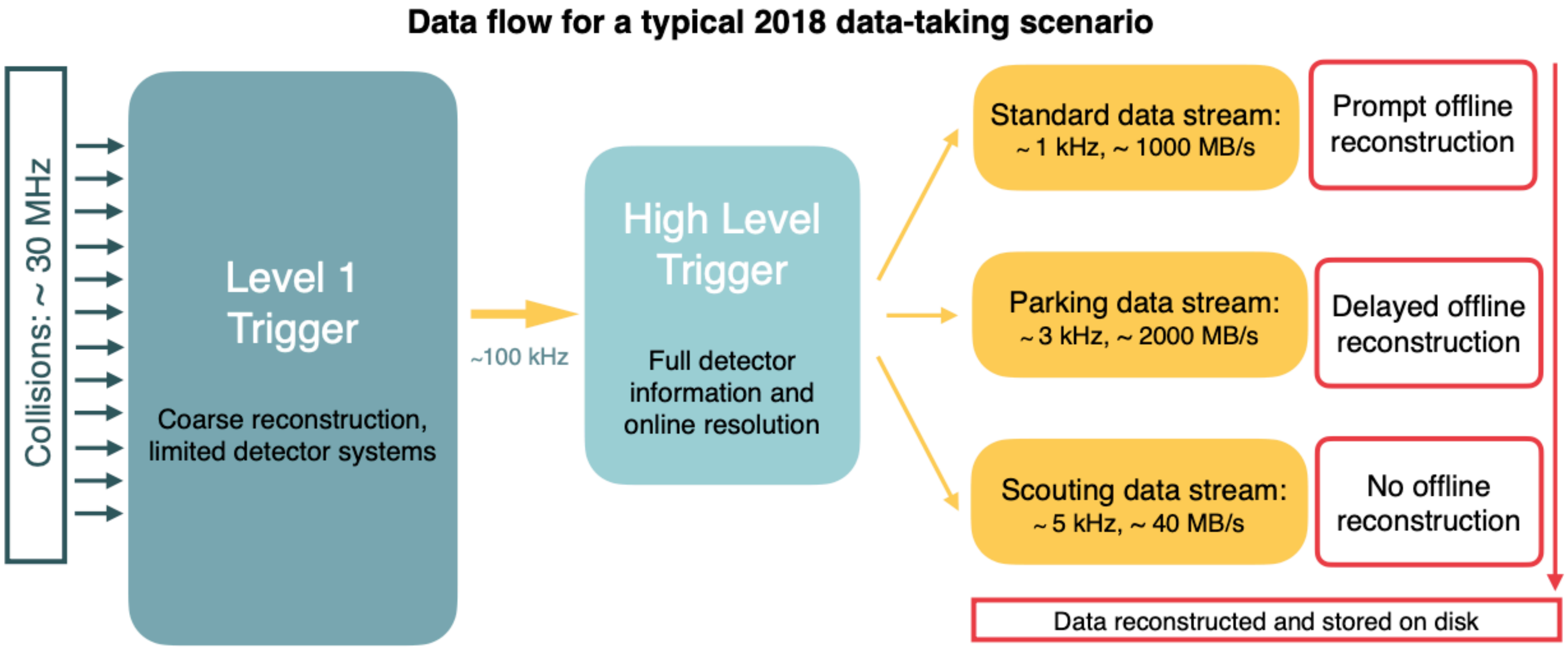
Performance of b-jet identification at fixed 1% mis-identification rate for other flavors

- 2016: ≈65%
- 2018: ≈75%
- 2022: ≈85% more than **30% improvement on same jets** in 6 years **just using better tools**!

Trigger

Data acquisition in CMS

arXiv:2403.16134


Data flow for a typical 2018 data-taking scenario

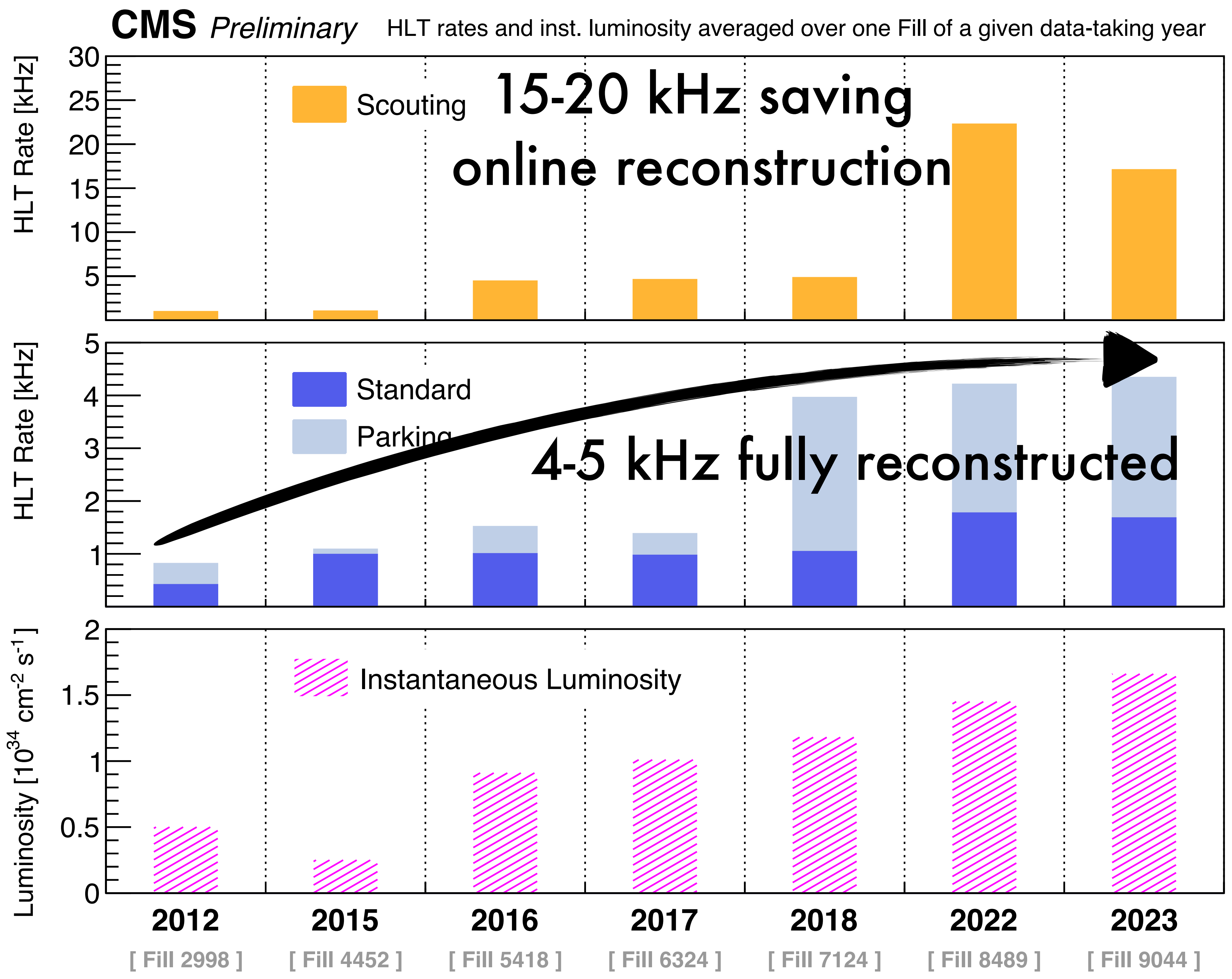
Data acquisition in 2018 and Run 3 (2022 - 2026):

- LHC produces **40 MHz bunch crossings** with **pp-collisions at 33 MHz**
  - Can't technically store that much information, 1 event is about 2 MB
- L1 trigger: reduces rate to **100 kHz (2018) to 110 kHz (Run 3)**
  → Relying on calorimeter and muon system
- HLT: 3 different strategies:
  - Prompt stream (**1 kHz**) / parking stream (**3 kHz**) / scouting stream (5 kHz)

Run 3 HLT rates

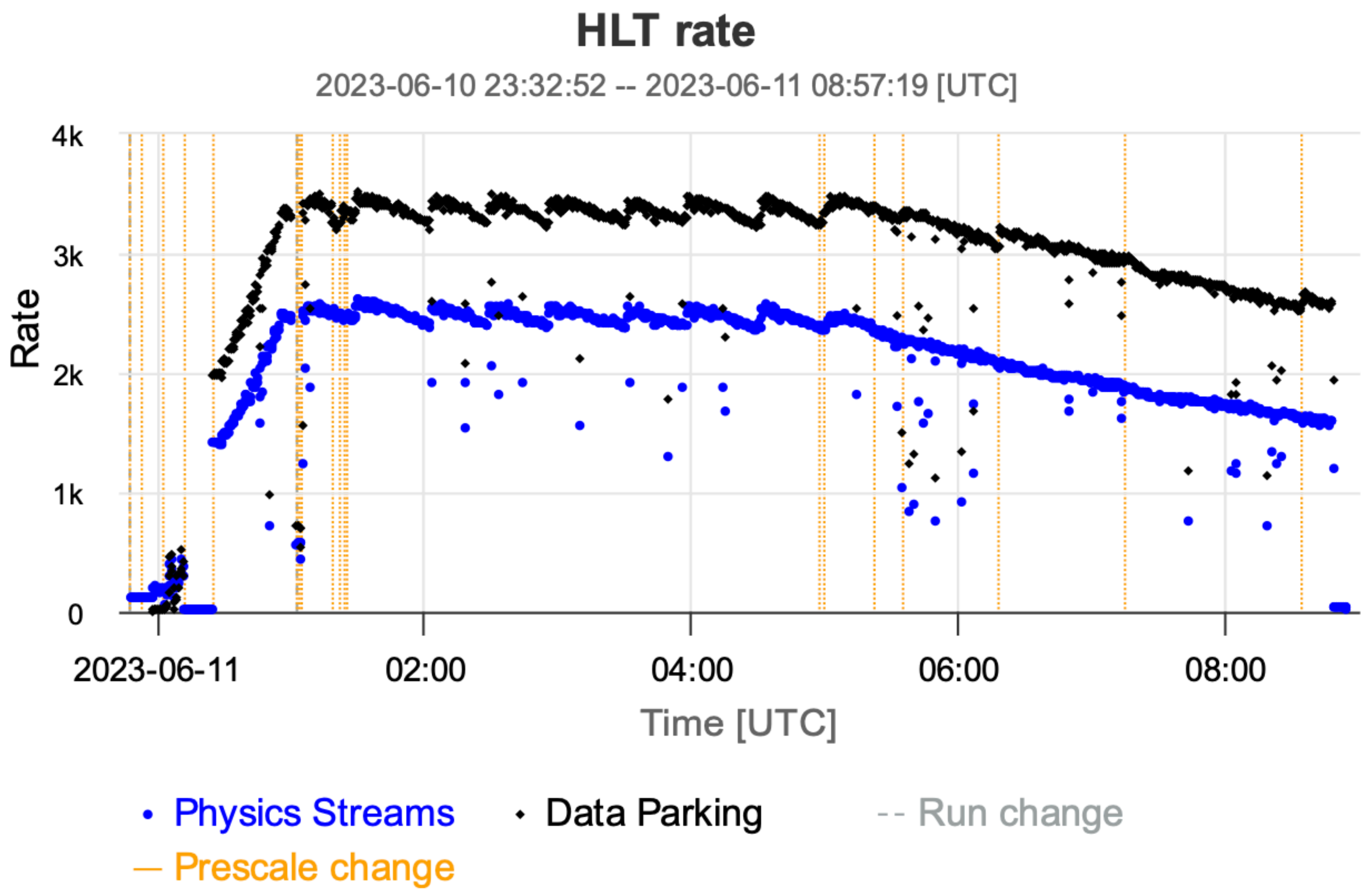
CMS-DP-2024/012

arXiv:2403.16134



15-20 kHz saving online reconstruction

4-5 kHz fully reconstructed



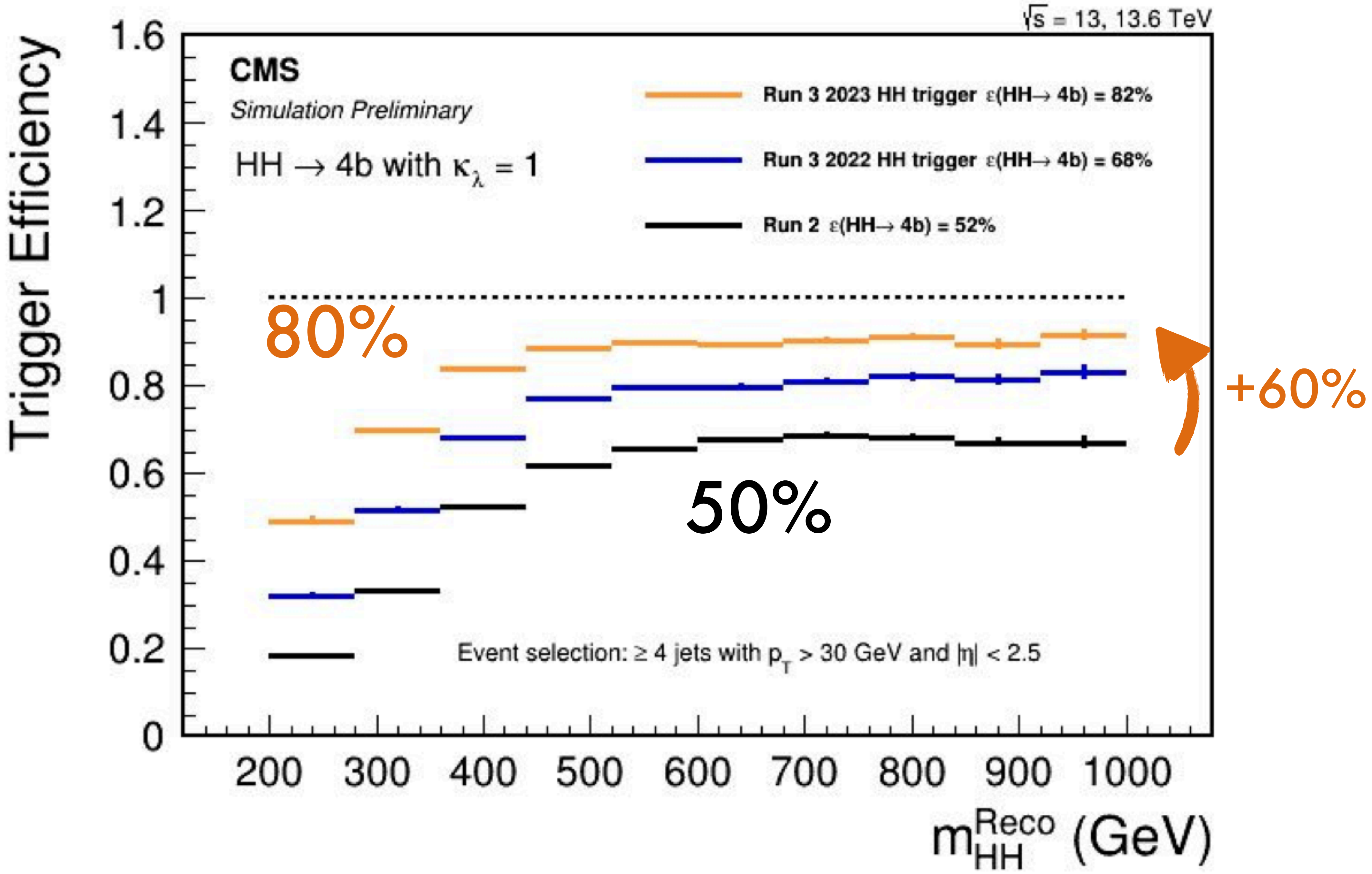
Extraordinary increase in computing capacities:

- In 2012: prompt rate and parking rate about 0.3 kHz each for total of 0.6 kHz
- In 2023: prompt rate about 2 kHz and parking rate about 3 kHz for total of 5-6 kHz
- Increase of a factor **5-10x in number of events saved to disk**
- Increase storage capacity to write events / extensive usage of CPUs and GPUs to trigger
- In 2023: CMS dedicated **7% of total HLT budget** to HH and HHH searches!

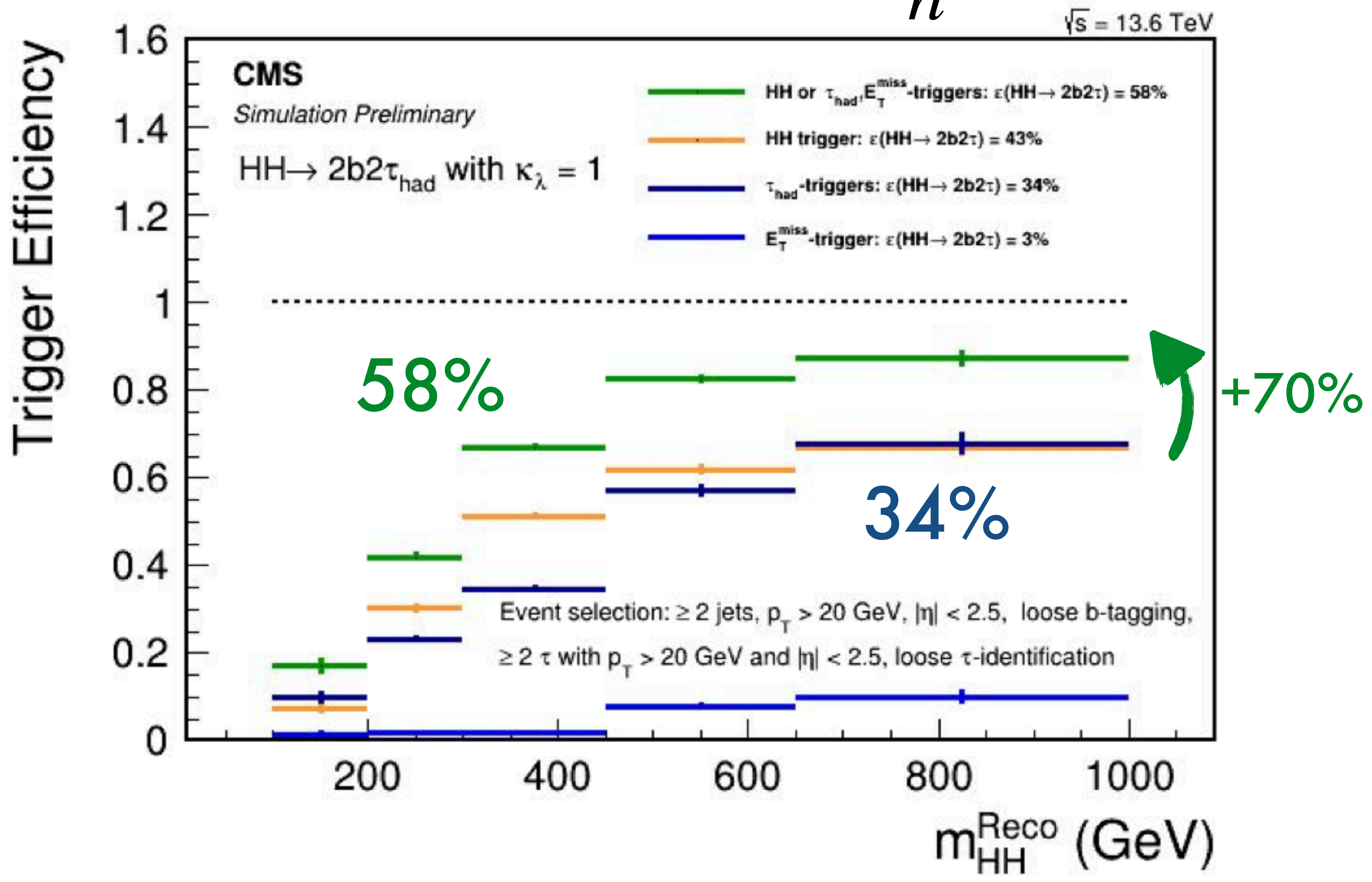
New triggers for multi-Higgs production

CMS DP-2023/021
CMS DP-2023/050

$HH \rightarrow 4b$



$HH \rightarrow 2b2\tau_h$



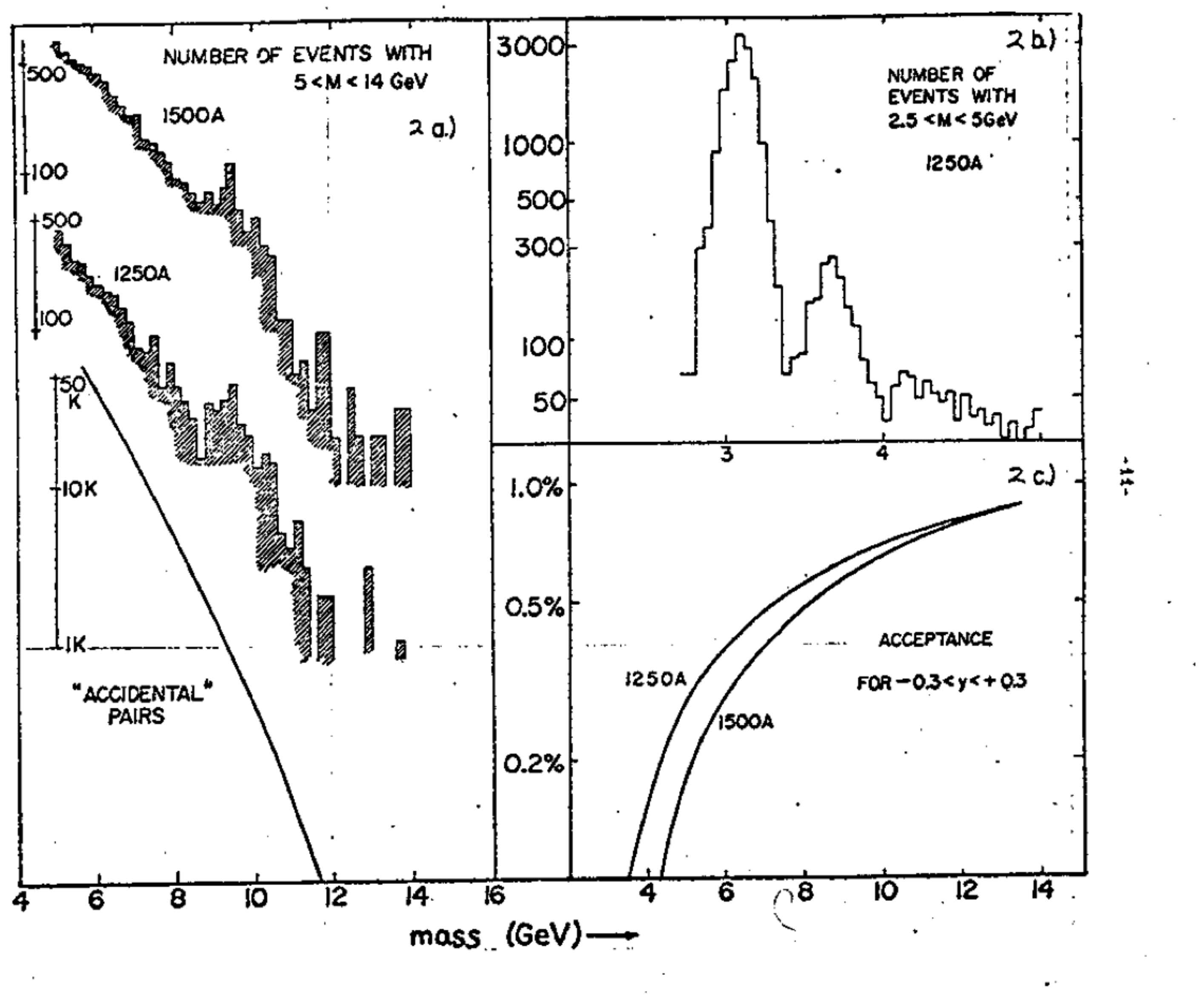
New flavor tagger + extensive usage of CPU and GPU farms at trigger

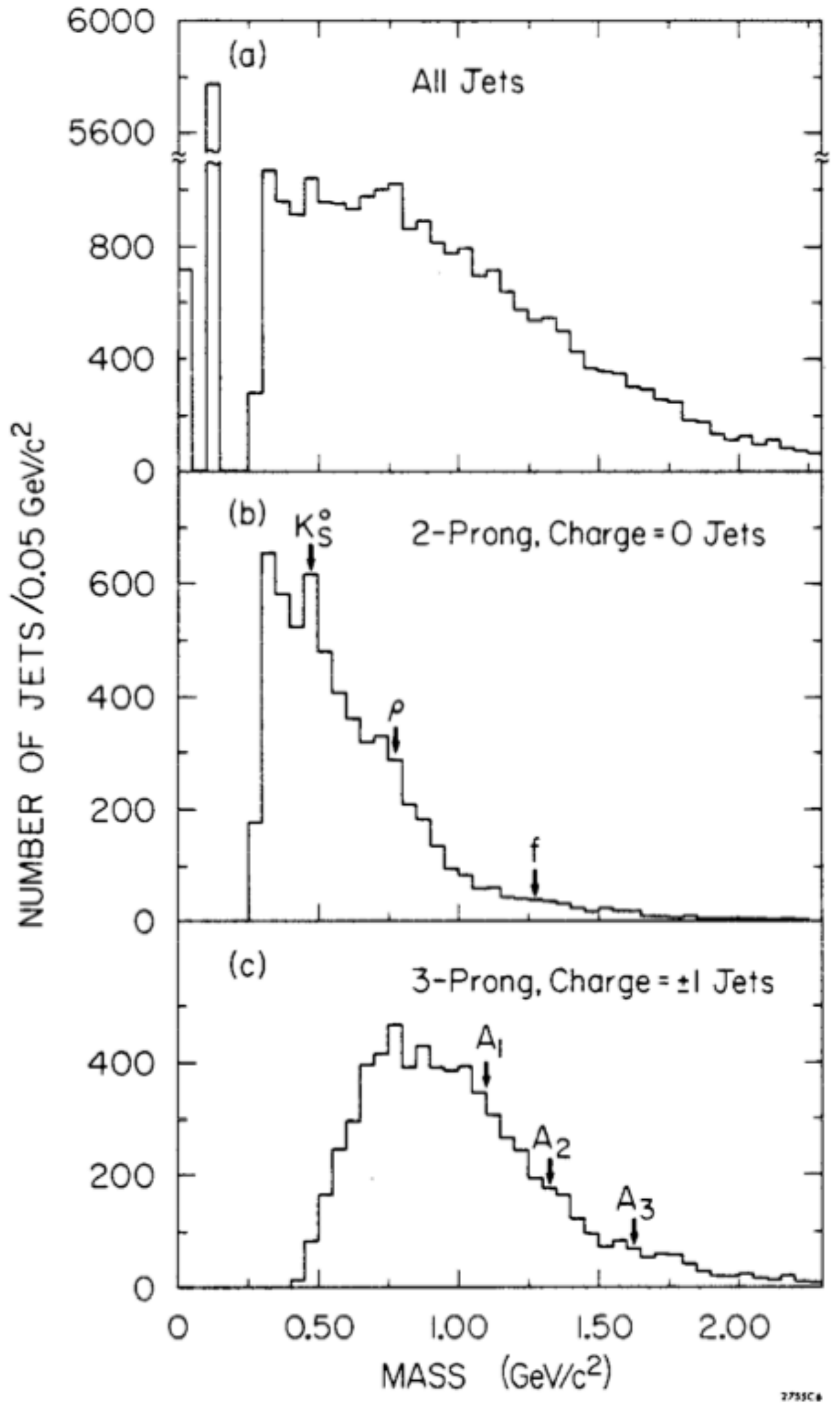
- Allows large increase in the number of multi-Higgs events recorded!
- In 2018: only recording 50% of $HH \rightarrow 4b$ and 34% of $HH \rightarrow 2b2\tau_h$ events
  - HH events are already hard to produce, we recorded only a small faction of them
- In Run 3: increased to **60% and 70% respectively**

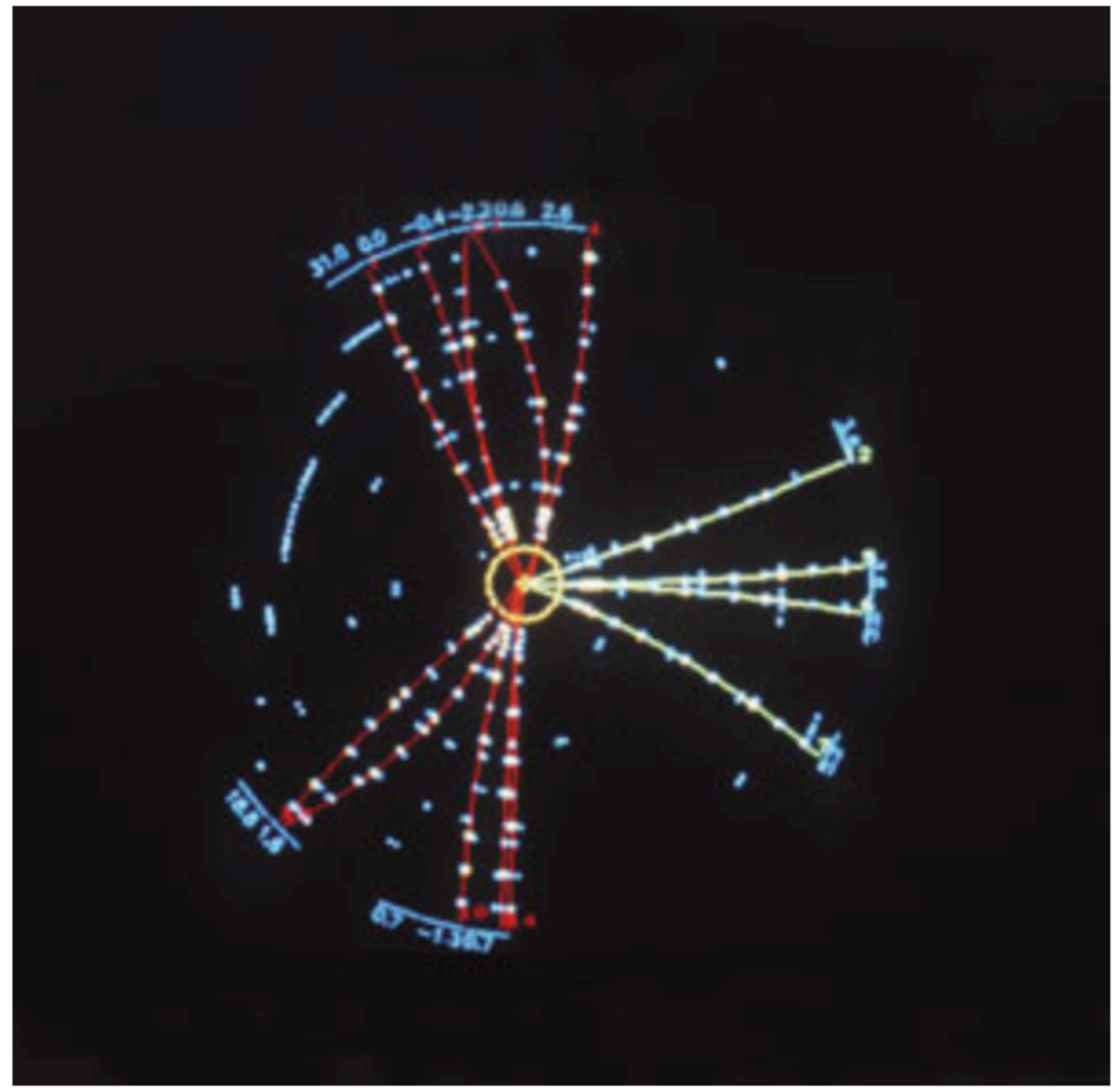
Increasing the discovery potential: jet-charge tagger

Jet charge tagging

1977 b-quark discovery at Fermilab 1975 jet discovery at SLAC 1979 gluon discovery at DESY





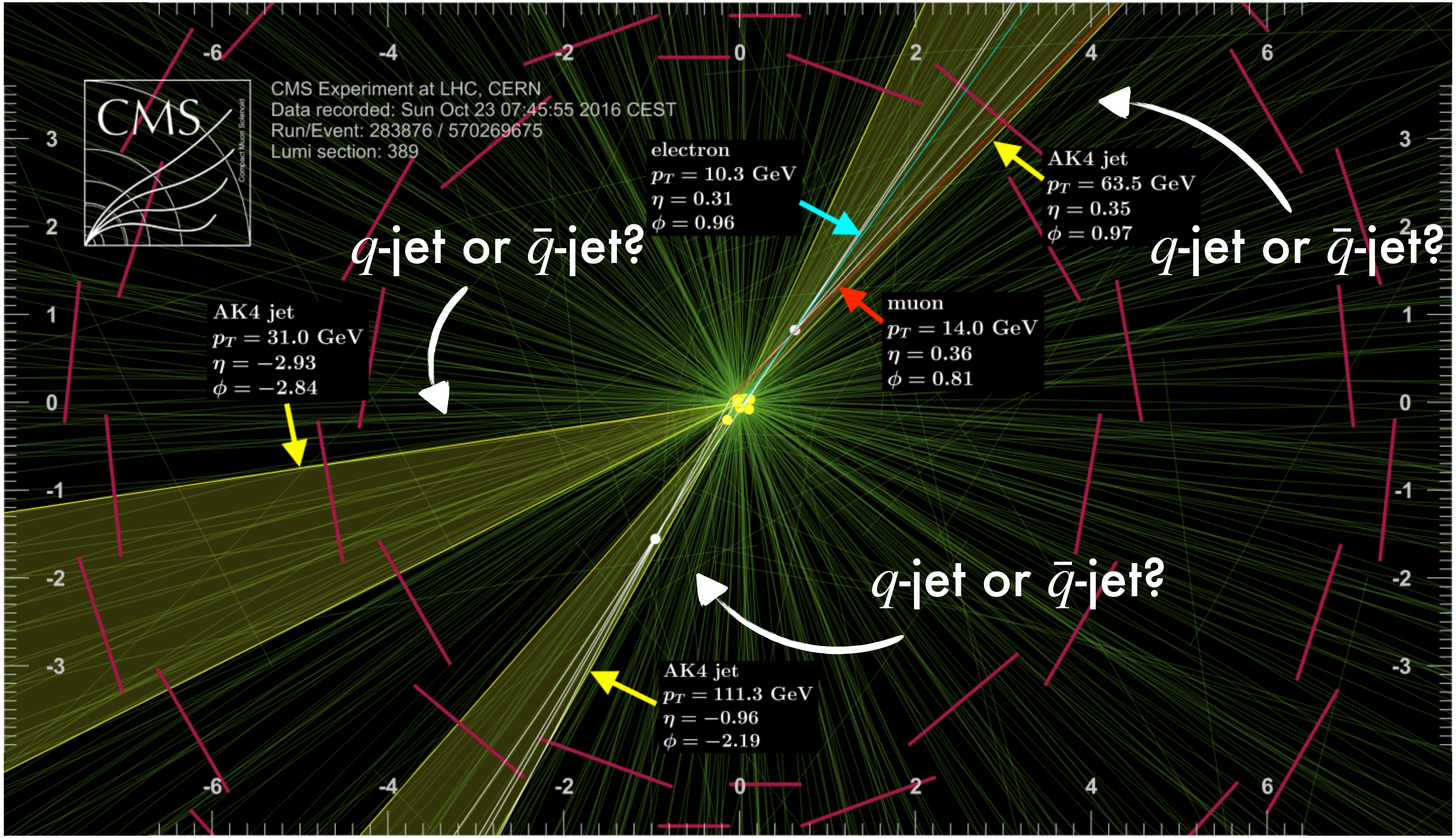


About 50 years after the **b-quark** and **jet discoveries**:

- Still no calibrated access to **sign of electric charge** of quark within jets in ATLAS and CMS!
  - We don’t know how to **separate** jets originating from **quarks** and **anti-quarks**
  - Intrinsic signal property currently not used, decays conserve the electric charge!

Why is this not used in ATLAS and CMS?

Why is this not used in ATLAS and CMS?



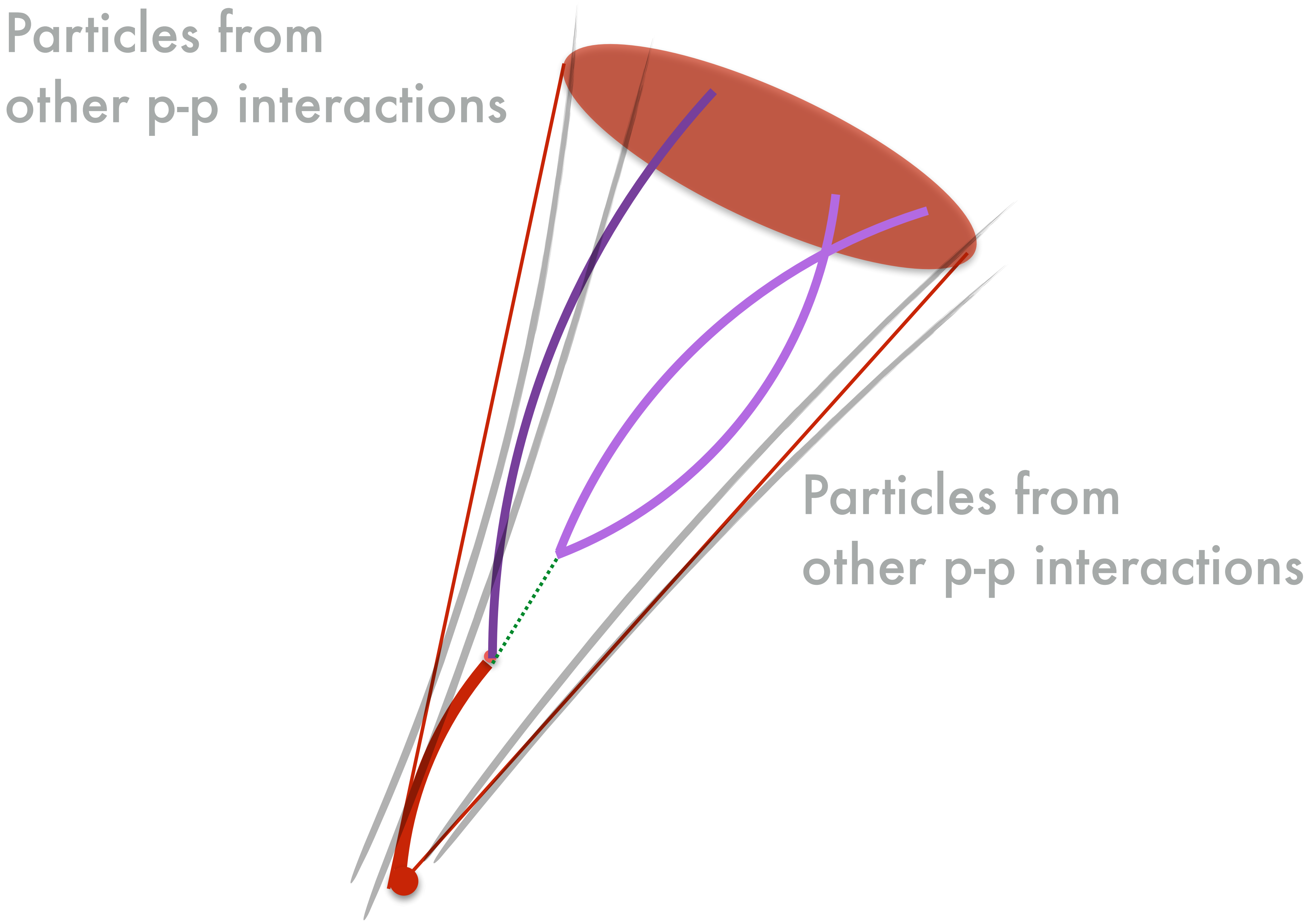
q-jet or $\bar{q}$-jet?

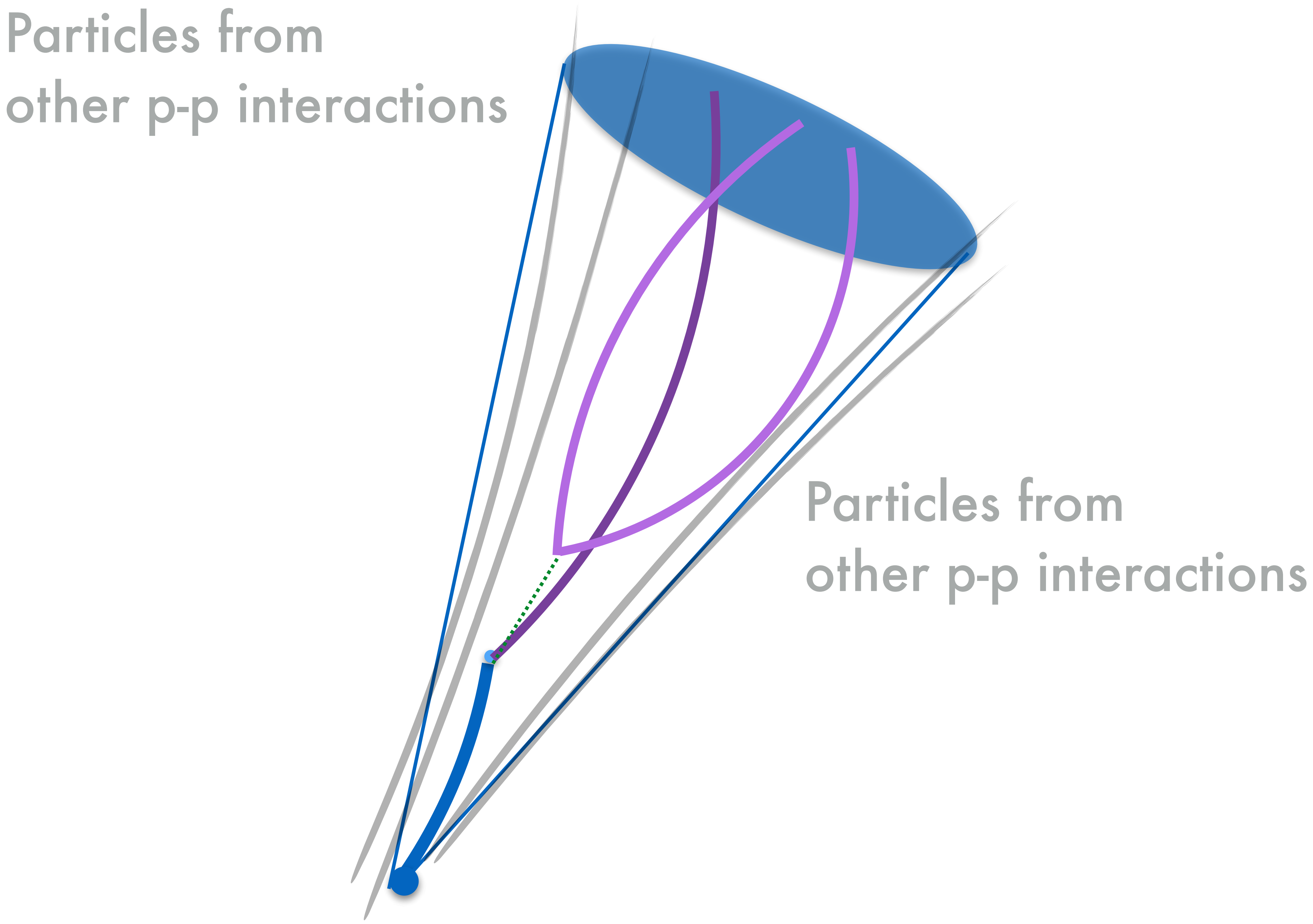
q-jet or $\bar{q}$-jet?

q-jet or $\bar{q}$-jet?

Distinguishing quarks from anti-quarks in jets: extremely challenging task in data

Why is this not used in ATLAS and CMS?





Believed **impossible** to do efficiently at high luminosity proton-proton colliders:

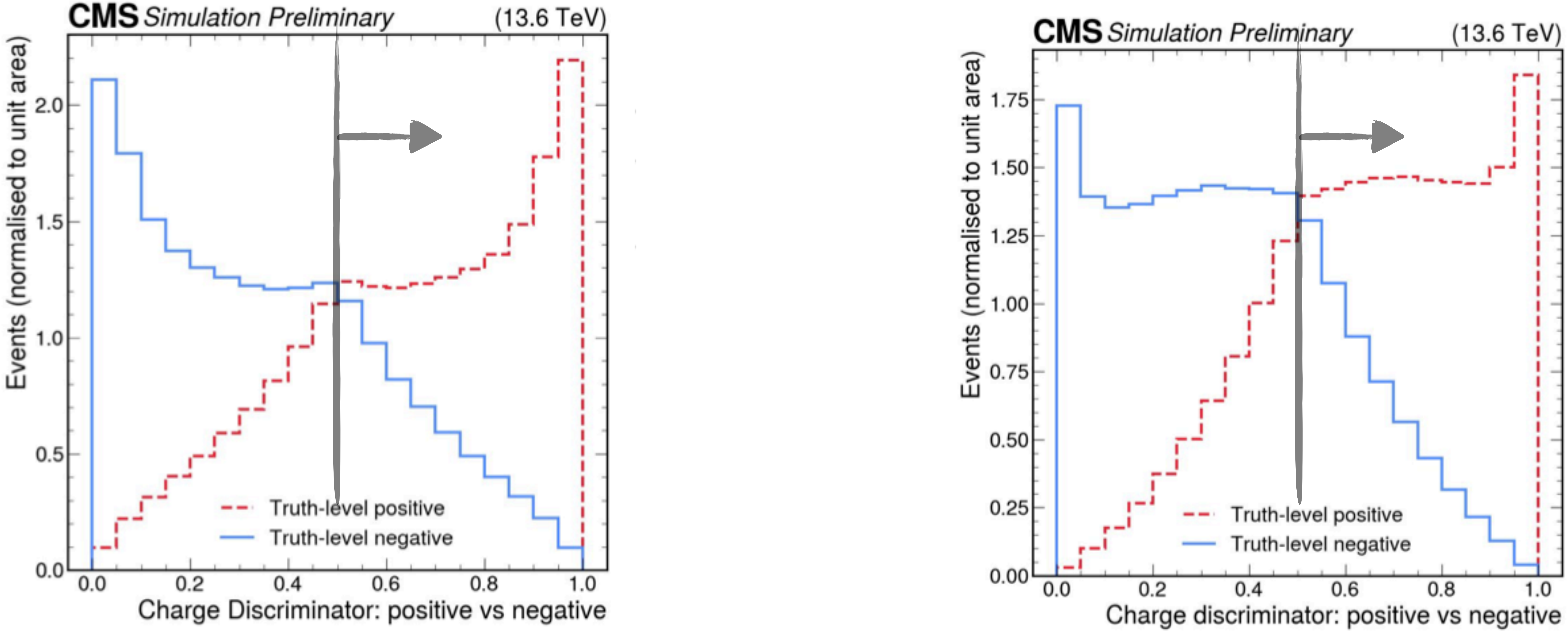
- Large variety of hadron decays: $B^- \to D^0\pi^-$ is one of the largest decay mode and only 0.5% of all B^-
- Contamination from additional particles produced in secondary proton-proton interactions
- Algorithmic limitations resulting in performance of 50-60% on CMS data, restricted to high rate process!

Timely: algorithms applied to b- and c-jet tagging improved performance by x10 to 100!

- Same tools can be extended to jet-charge identification!

Prototype jet-charge tagger

DP-2025-071



Extending flavor tagging to identify the charge $(+, -, 0)$

- Performance: **70%** accuracy on b-jets and **80%** on c-jets
  - Already achieved similar performance to electron-positron state-of-the-art jet-charge tagger

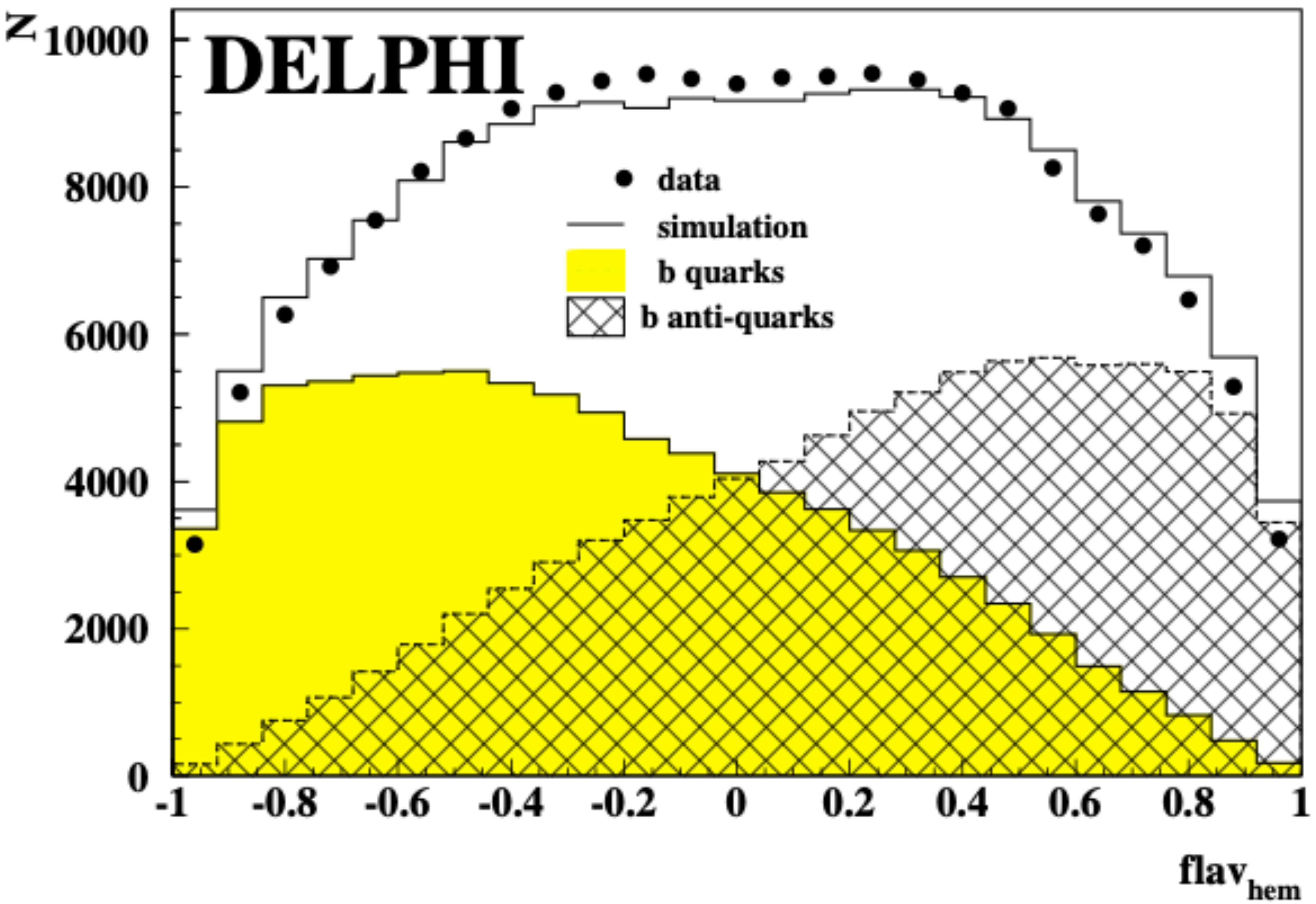
Demonstrates feasibility:

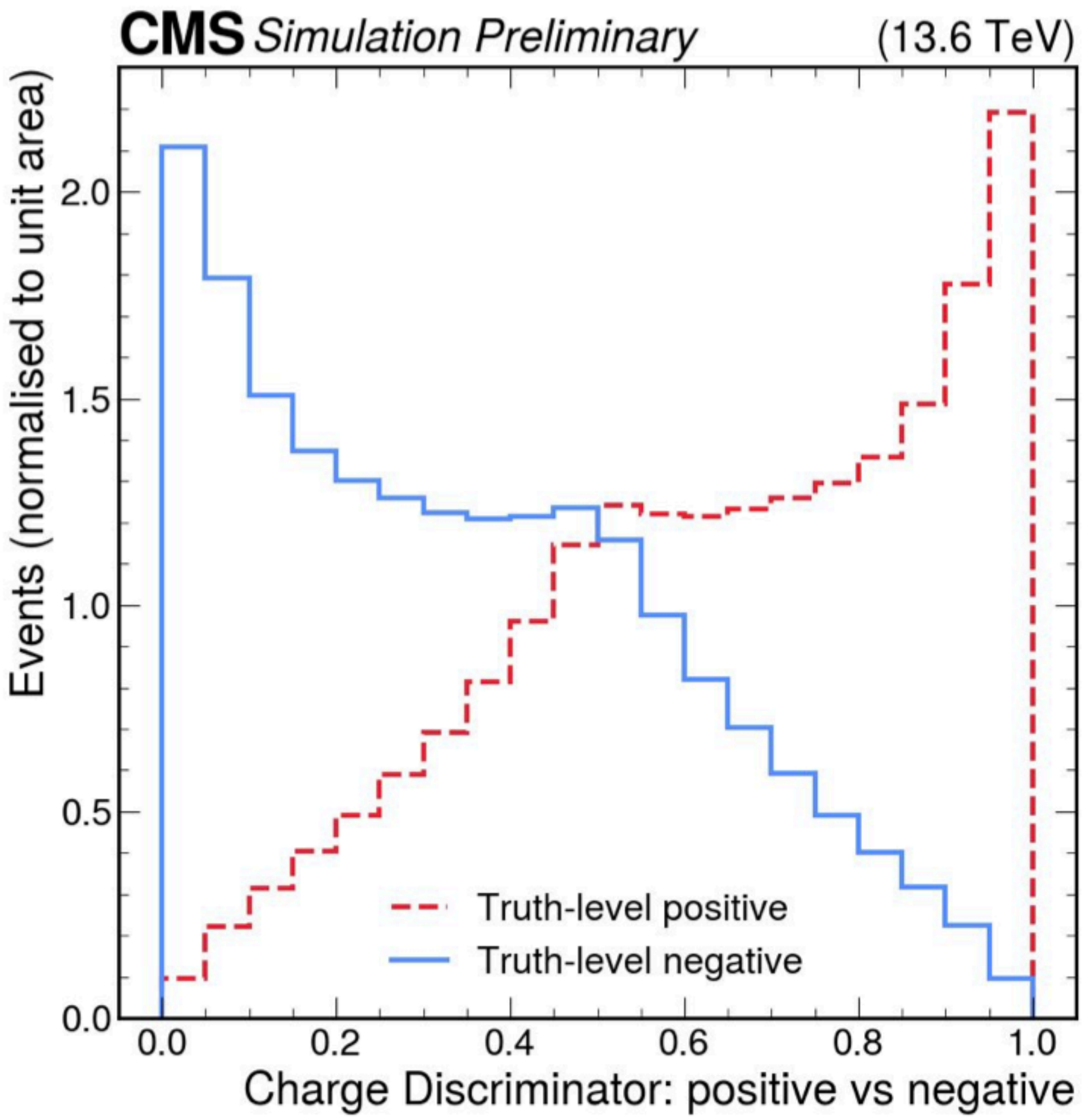
- Improvements in machine learning and physics driven inputs will maximize performance of algorithms!
- If flavor tagging can predict history, this is the **first** and **worst** jet-charge tagger performance in CMS!

DELPHI charge tagger

DP-2025-071

DELPHI

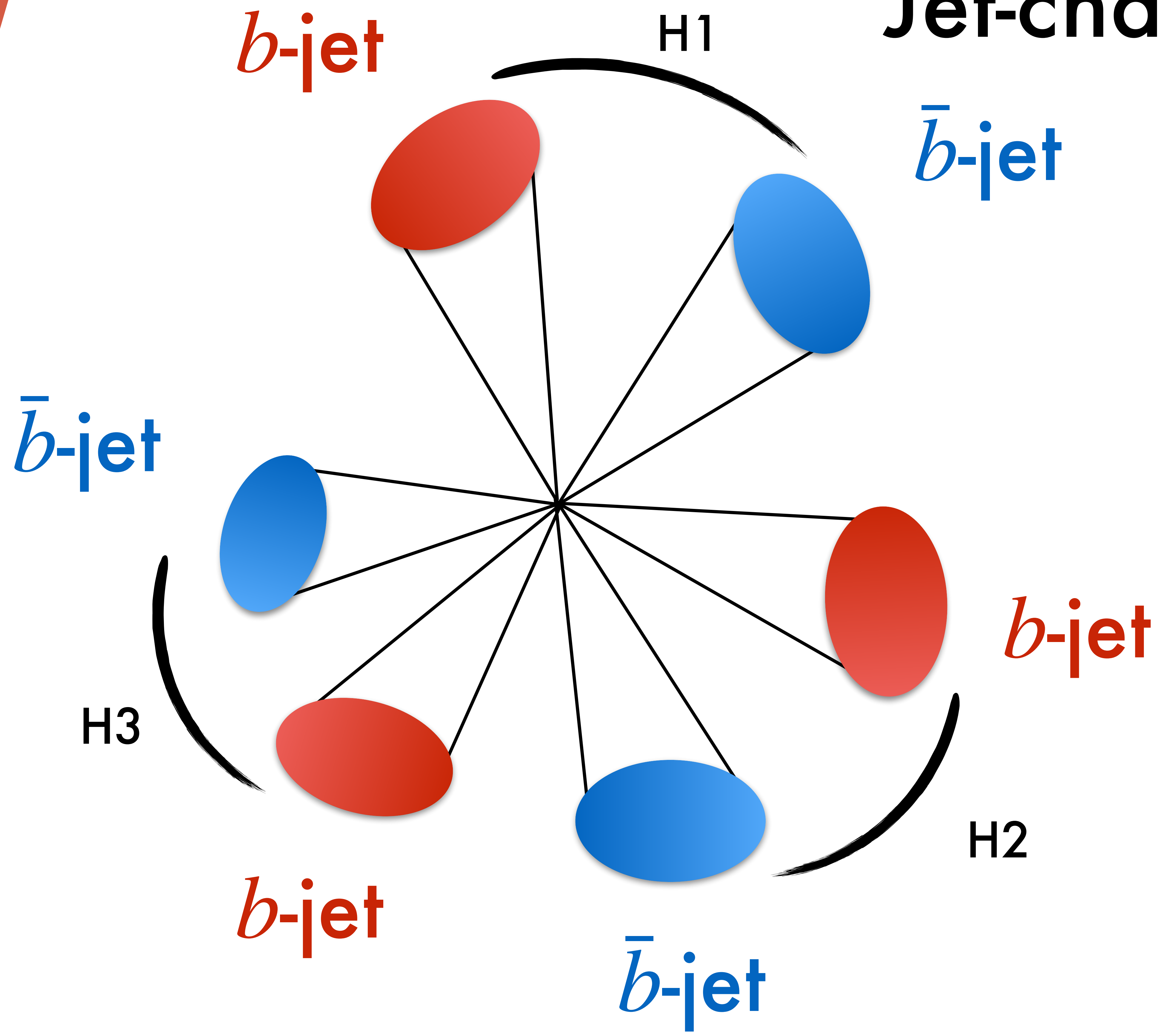




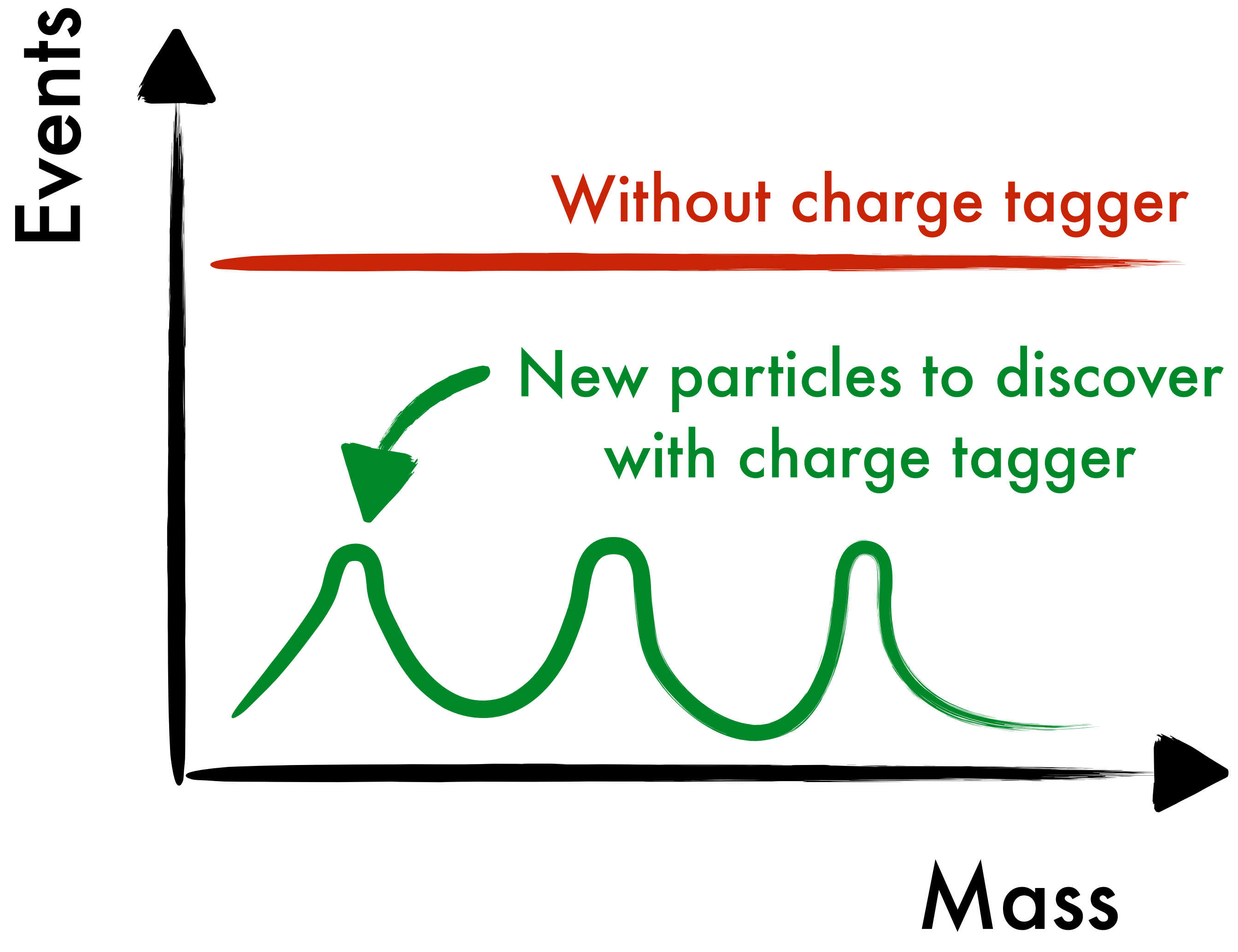
DELPHI: best jet-charge tagger of LEP using DNN on 1994 data

- AUC: 0.75 approximated
- **Similar performance achieved in CMS!**
- Already 25% better than LEP on c-jets vs $\bar{c}$-jets
  - Despite the Cherenkov detector, higher center of mass and better tracker results in better reconstruction

Jet-charge tagging



New physics?



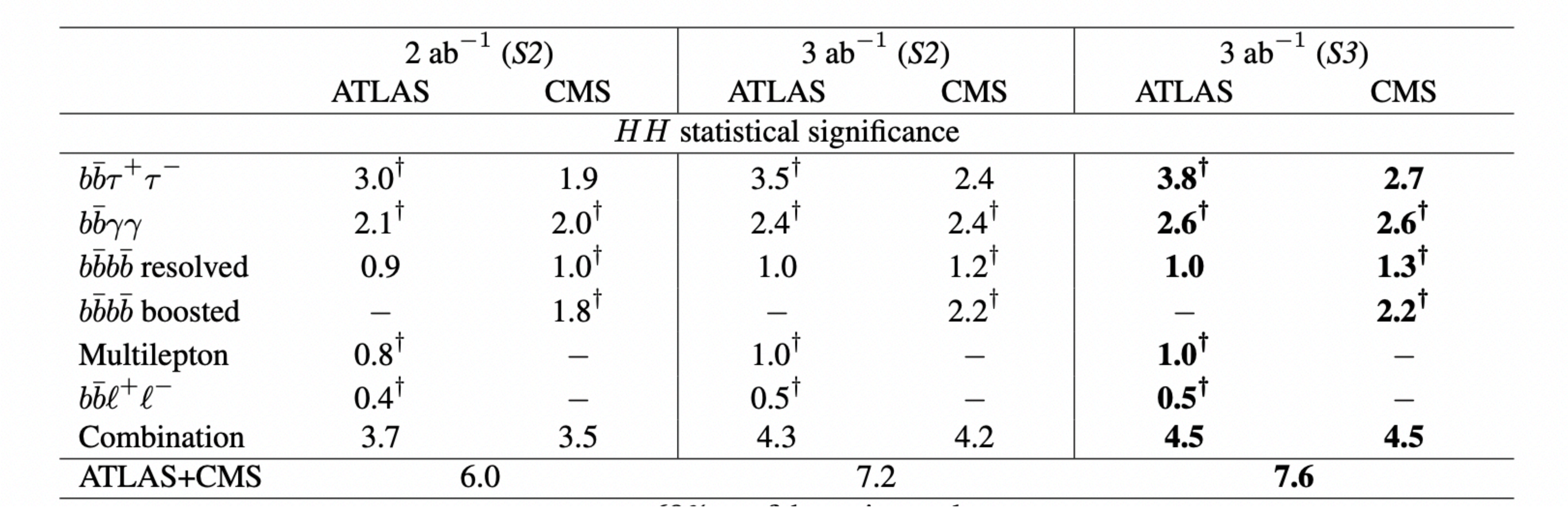
Higgs decays to **b**-quark and **anti-b** quark: currently unused in CMS and HHH
- HHH is extremely challenging, need extraordinary tools to measure it at the LHC

Potential **to very significantly improve HHH6b and HHH4b+X!**

Accelerate the physics program of CMS and **enable potential discoveries**

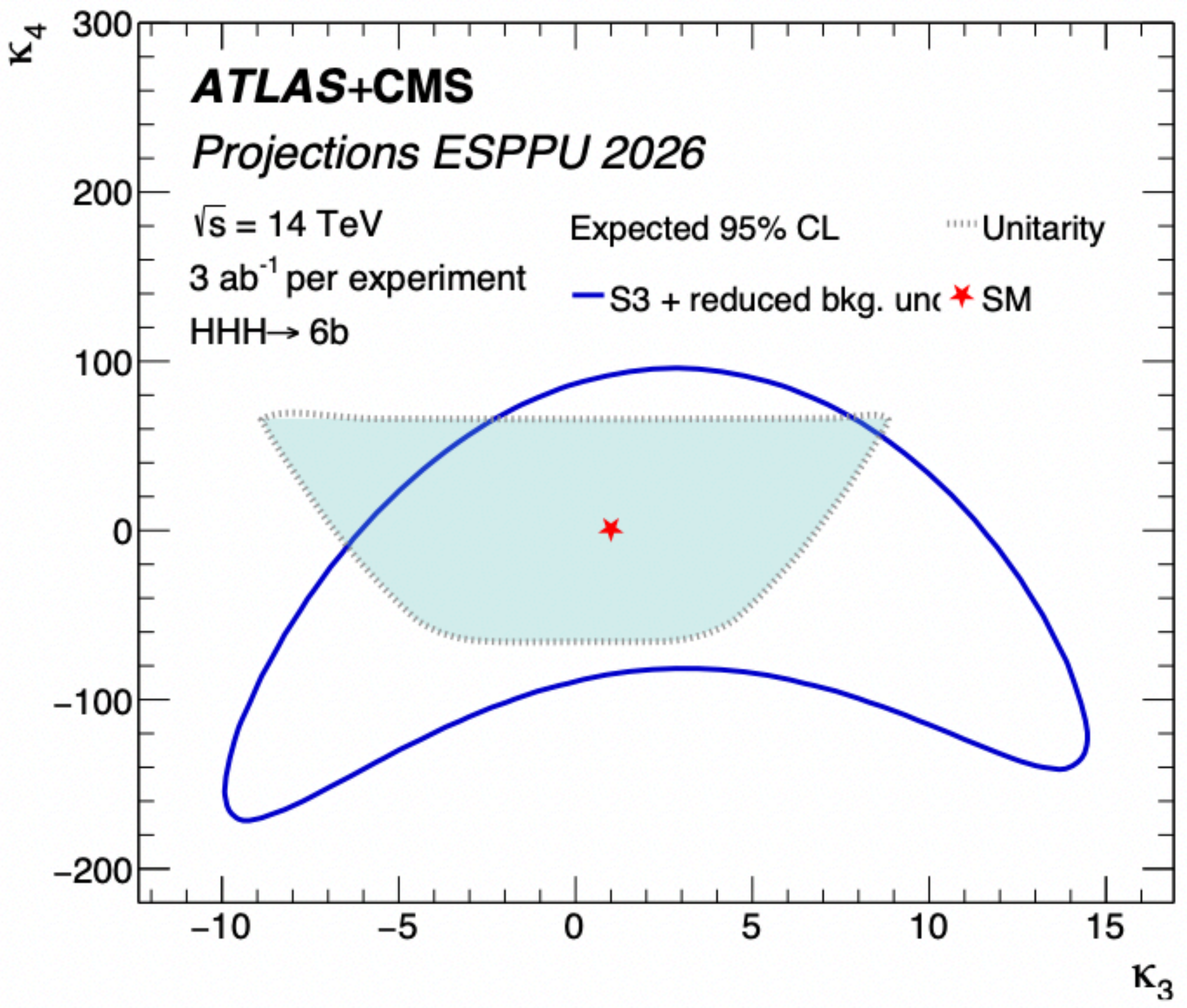
Summary

HL-LHC projections: HH



	2 ab^{-1} ($S2$)		3 ab^{-1} ($S2$)		3 ab^{-1} ($S3$)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
HH statistical significance						
$b\bar{b}\tau^+\tau^-$	$3.0^\dagger$	1.9	$3.5^\dagger$	2.4	**$3.8^\dagger$**	**2.7**
$b\bar{b}\gamma\gamma$	$2.1^\dagger$	$2.0^\dagger$	$2.4^\dagger$	$2.4^\dagger$	**$2.6^\dagger$**	**$2.6^\dagger$**
$b\bar{b}b\bar{b}$ resolved	0.9	$1.0^\dagger$	1.0	$1.2^\dagger$	**1.0**	**$1.3^\dagger$**
$b\bar{b}b\bar{b}$ boosted	–	$1.8^\dagger$	–	$2.2^\dagger$	–	**$2.2^\dagger$**
Multilepton	$0.8^\dagger$	–	$1.0^\dagger$	–	**$1.0^\dagger$**	–
$b\bar{b}\ell^+\ell^-$	$0.4^\dagger$	–	$0.5^\dagger$	–	**$0.5^\dagger$**	–
Combination	3.7	3.5	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	6.0		7.2		**7.6**	

HL-LHC projections: HHH



Exciting new developments in flavor tagging / trigger / charge tagging:

- **HH** and **HHH**: **high priorities** for the **2026 European Strategy Updates**
  - Expected first 3σ **evidence of HH** and about **100x SM HHH by 2040**
  - **New tools will allow to reach these milestones much earlier, potentially with Run 3**

- **HH, HHH** processes can **only be pursued at the LHC, next 10-20 years will be crucial**
- **Great time** to be a 2σ **physicist**!