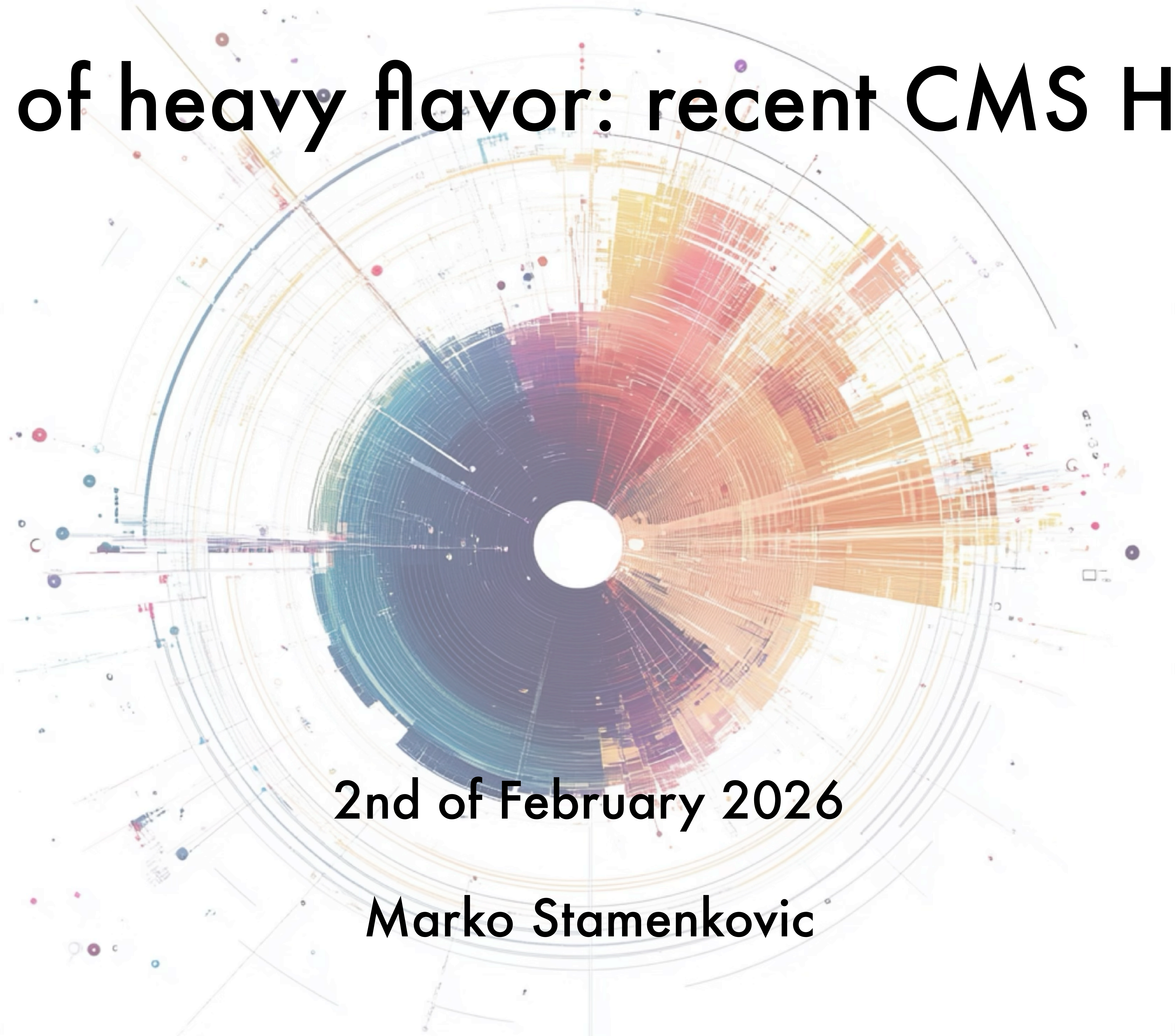
The decade of heavy flavor: recent CMS H-bb/cc results



2nd of February 2026

Marko Stamenkovic

Leon Lederman: Nobel prize in 1988

- Discovered 2 generation of neutrinos
- *Didn't discover the charm quark 3x*
- Discovered the bottom quark

“First comes the observation, then comes the measurement”

I. Rabi to L. Lederman, quoted in Lederman’s Nobel lecture in 1988

"First comes the observation, then comes the measurement"

I. Rabi to L. Lederman, quoted in Lederman's Nobel lecture in 1988

Observation

- Opens a new field
- Qualitative
- Something is possible

Measurement

- Subsequent
- Quantitative
- More precise

“First comes the observation, then comes the measurement”

I. Rabi to L. Lederman, quoted in Lederman’s Nobel lecture in 1988

Observation

- Opens a new field
- Qualitative
- Something is possible

At the LHC:

2-3σ physicist: excited to exclude Standard Model

Measurement

- Subsequent
- Quantitative
- More precise

At the LHC:

$5^{*}\sigma$ physicist: excited to measure Standard Model

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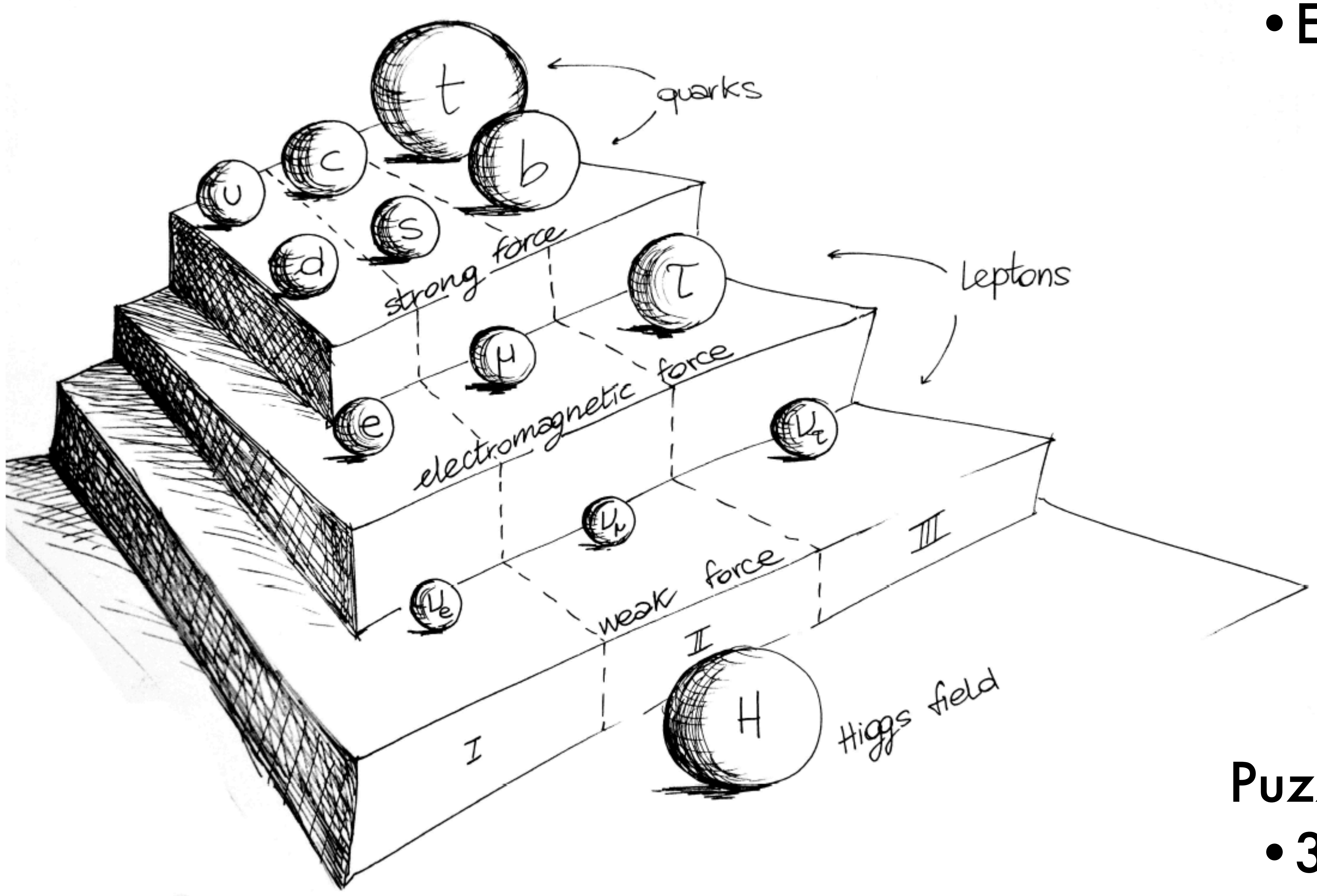
*Disclaimer: valid only in gaussian regime, if no background in your analysis, analogy doesn’t hold

State-of-the-art Higgs physics

The Standard Model of particle physics



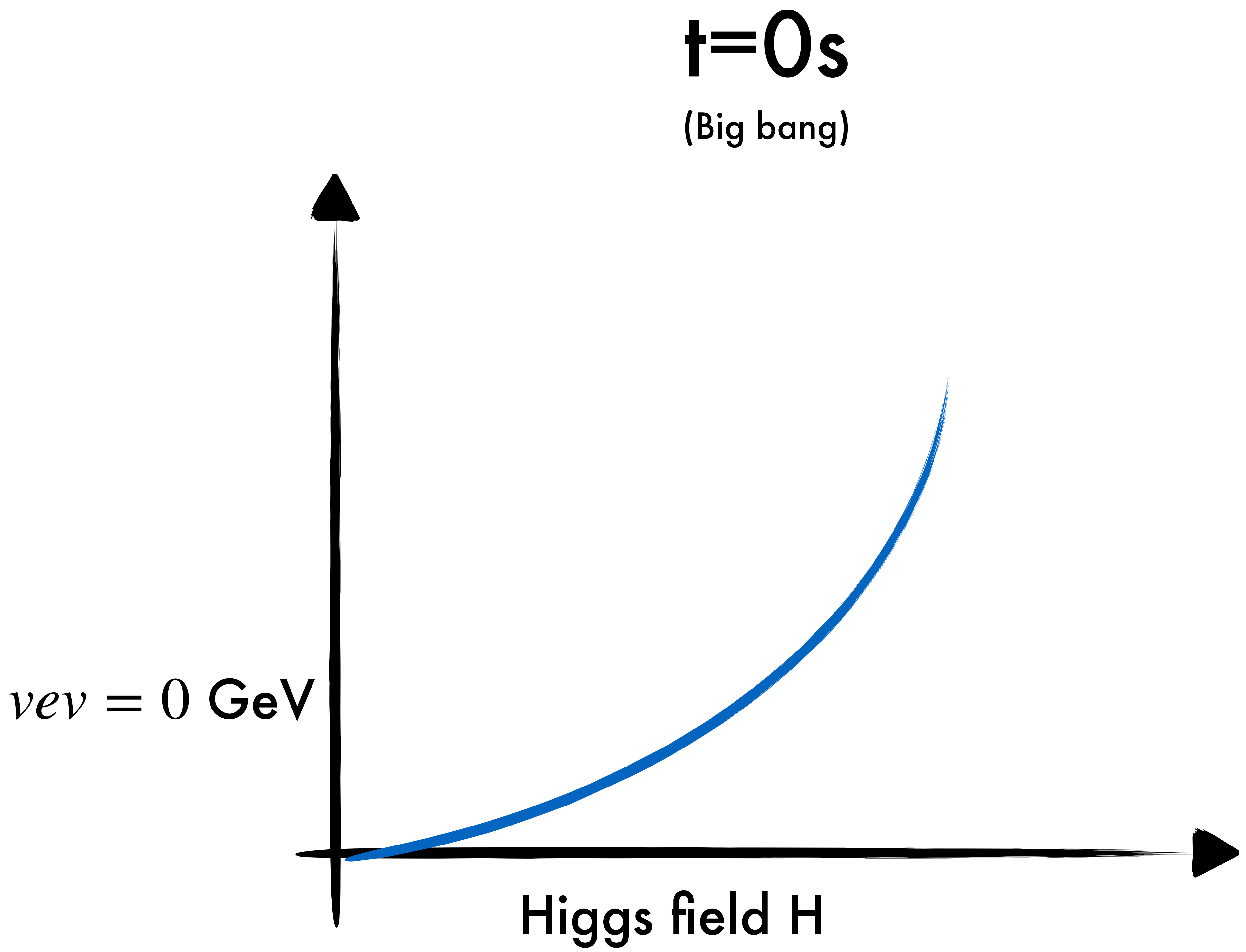
Flavor and mass pattern:

- Elementary particles:
  - Fermions: composing matter
    - 6 quarks: t, b, c, s, u, d
    - 6 leptons: $\tau, \nu_\tau, \mu, \nu_\mu, e, \nu_e$
  - Bosons: mediating interactions
    - 2 mass-less vector bosons: γ, g
    - 2 massive vector bosons: W, Z
    - 1 scalar massive boson: H

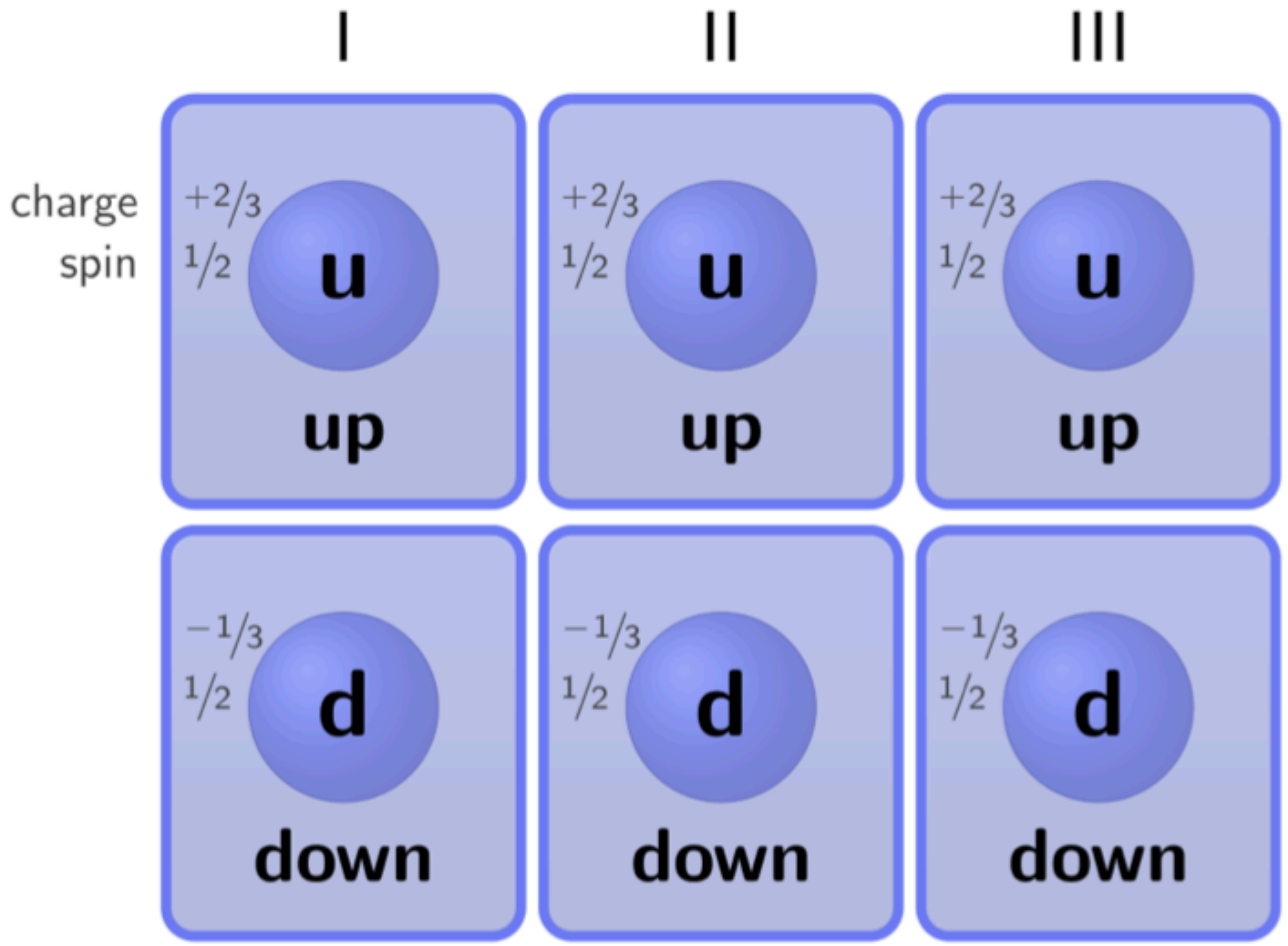
Puzzling patterns:

- 3 generations of particles?
  - *"Heavier copies"*
- Top quark is 400'000x heavier than electron
- Mass and flavor of particles are intrinsically linked
- All these questions somehow tied to the Higgs field

At the very beginning: 3 generations of particles



3 generations of massless particles



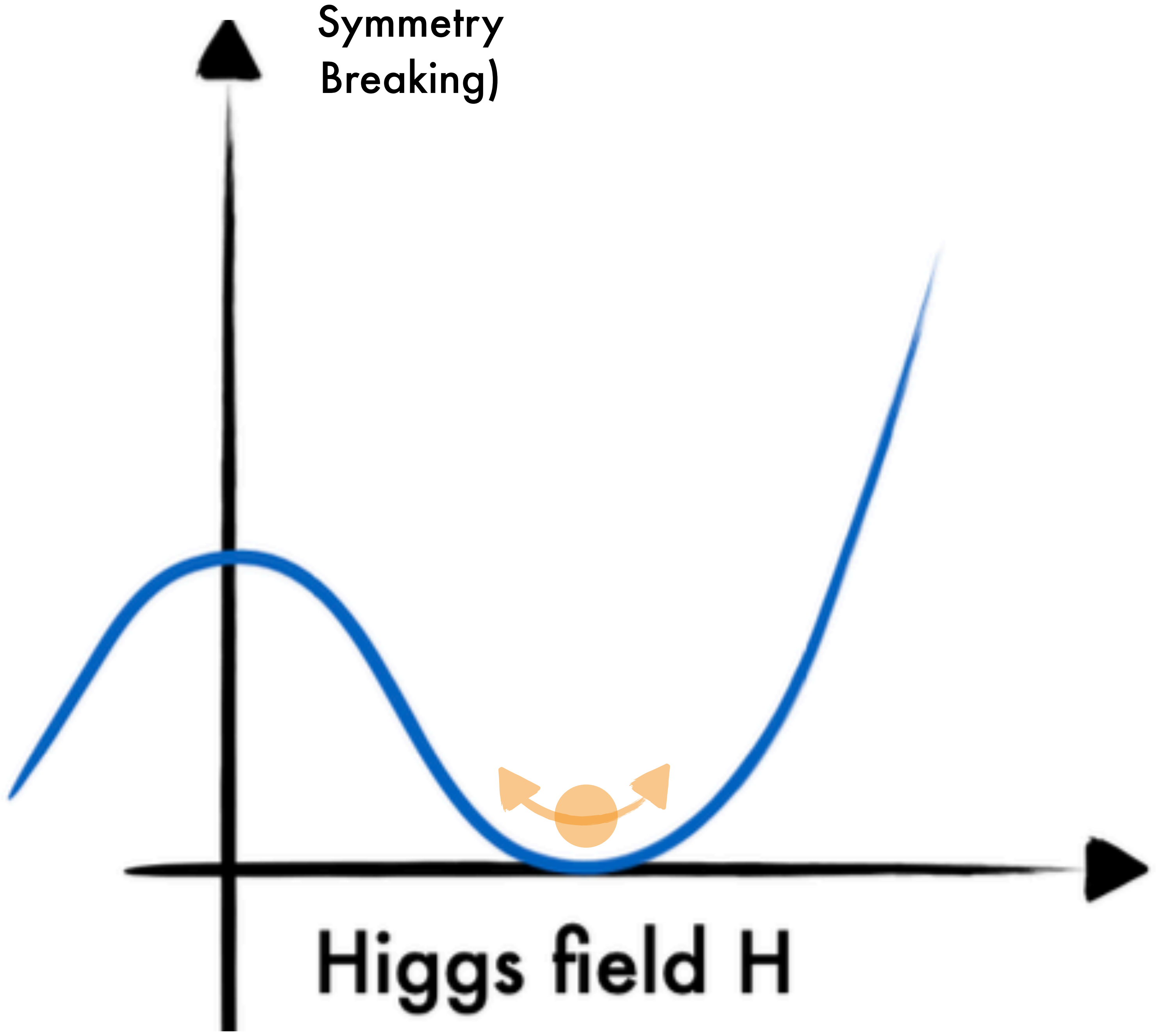
At the very beginning of the universe: 3 generations of particles

- 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

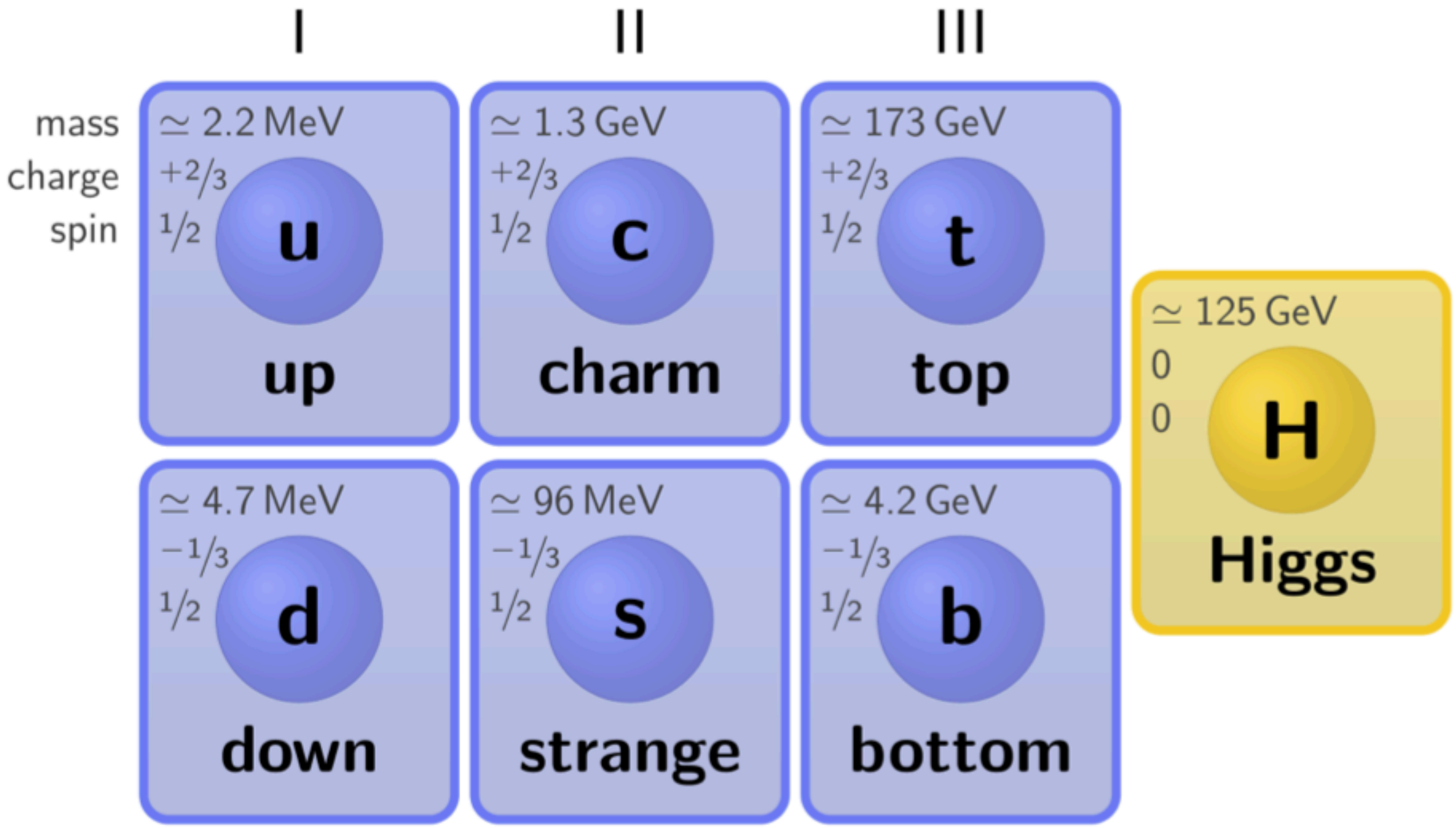
Electroweak symmetry breaking

$t=10^{-12}$s

(Electroweak Symmetry Breaking)



3 generations of massive particles + Higgs boson

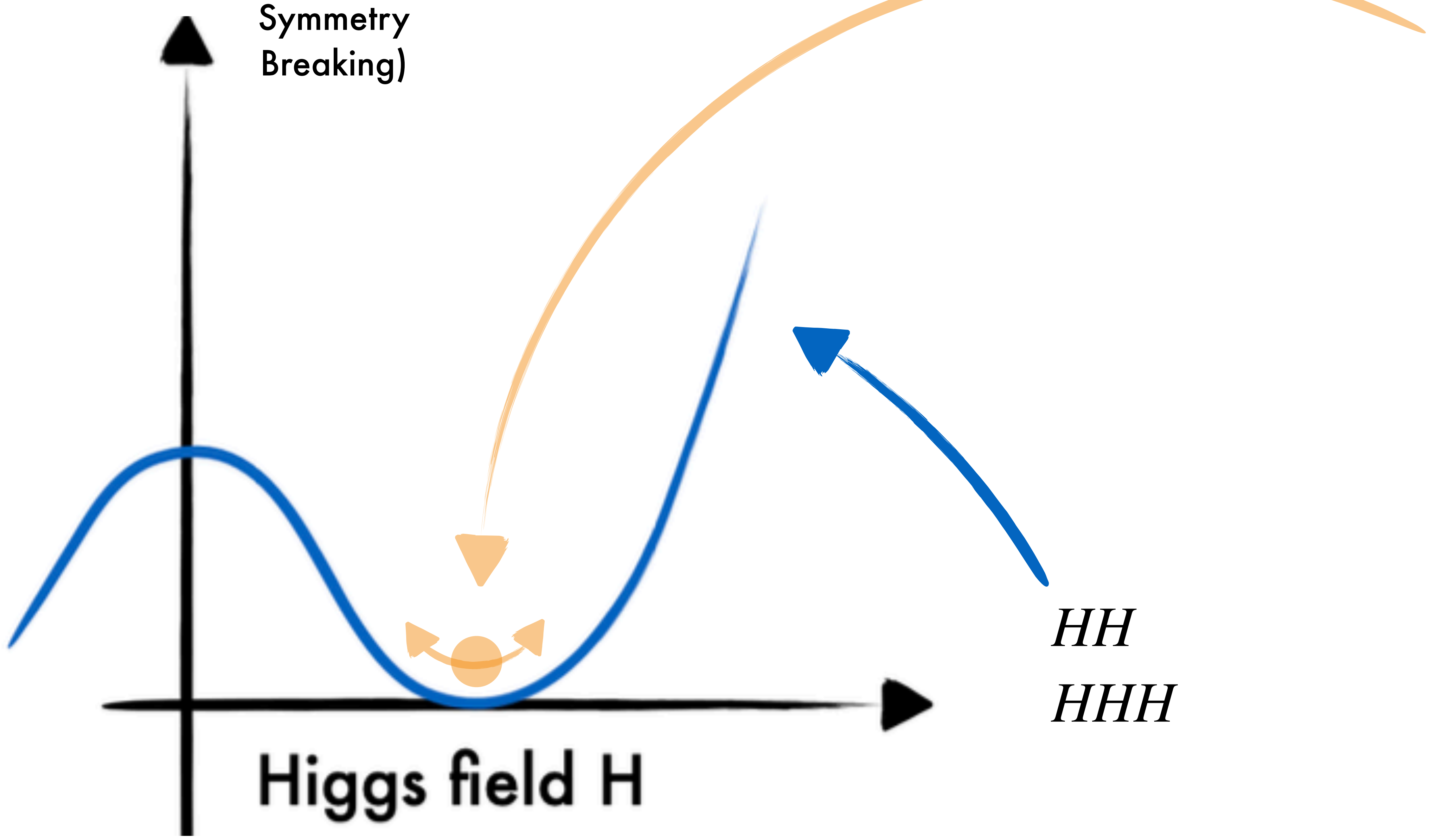


	I	II	III	
mass charge spin	≃ 2.2 MeV +2/3 1/2 **u** **up**	≃ 1.3 GeV +2/3 1/2 **c** **charm**	≃ 173 GeV +2/3 1/2 **t** **top**	≃ 125 GeV 0 0 **H** **Higgs**
	≃ 4.7 MeV −1/3 1/2 **d** **down**	≃ 96 MeV −1/3 1/2 **s** **strange**	≃ 4.2 GeV −1/3 1/2 **b** **bottom**	

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)

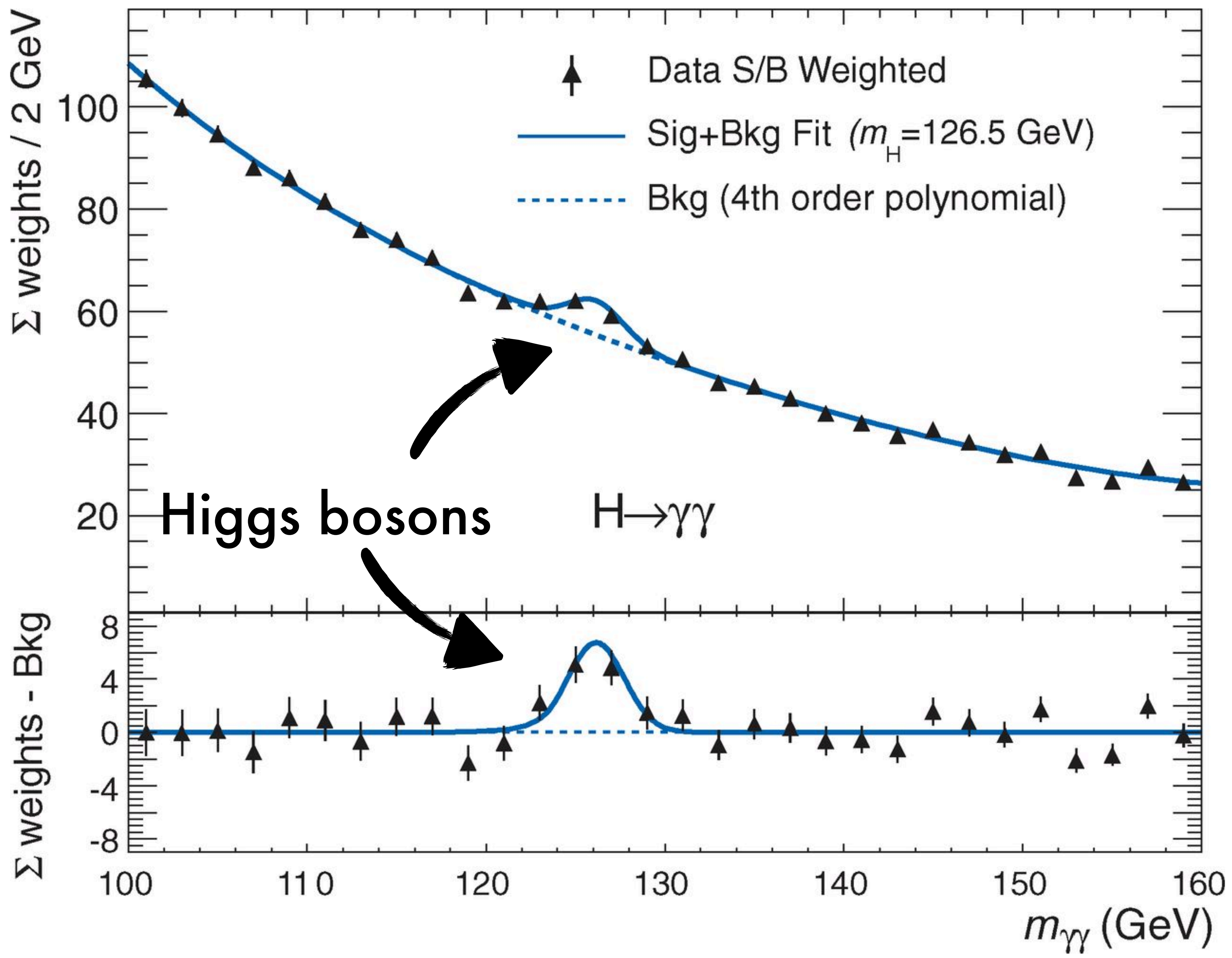
$H \to b\bar{b}$
$H \to c\bar{c}$
ttH
$H \to \gamma\gamma$
$H \to ZZ$
$H \to WW$
$H \to \tau\tau$
$H \to \mu\mu$

HH
HHH

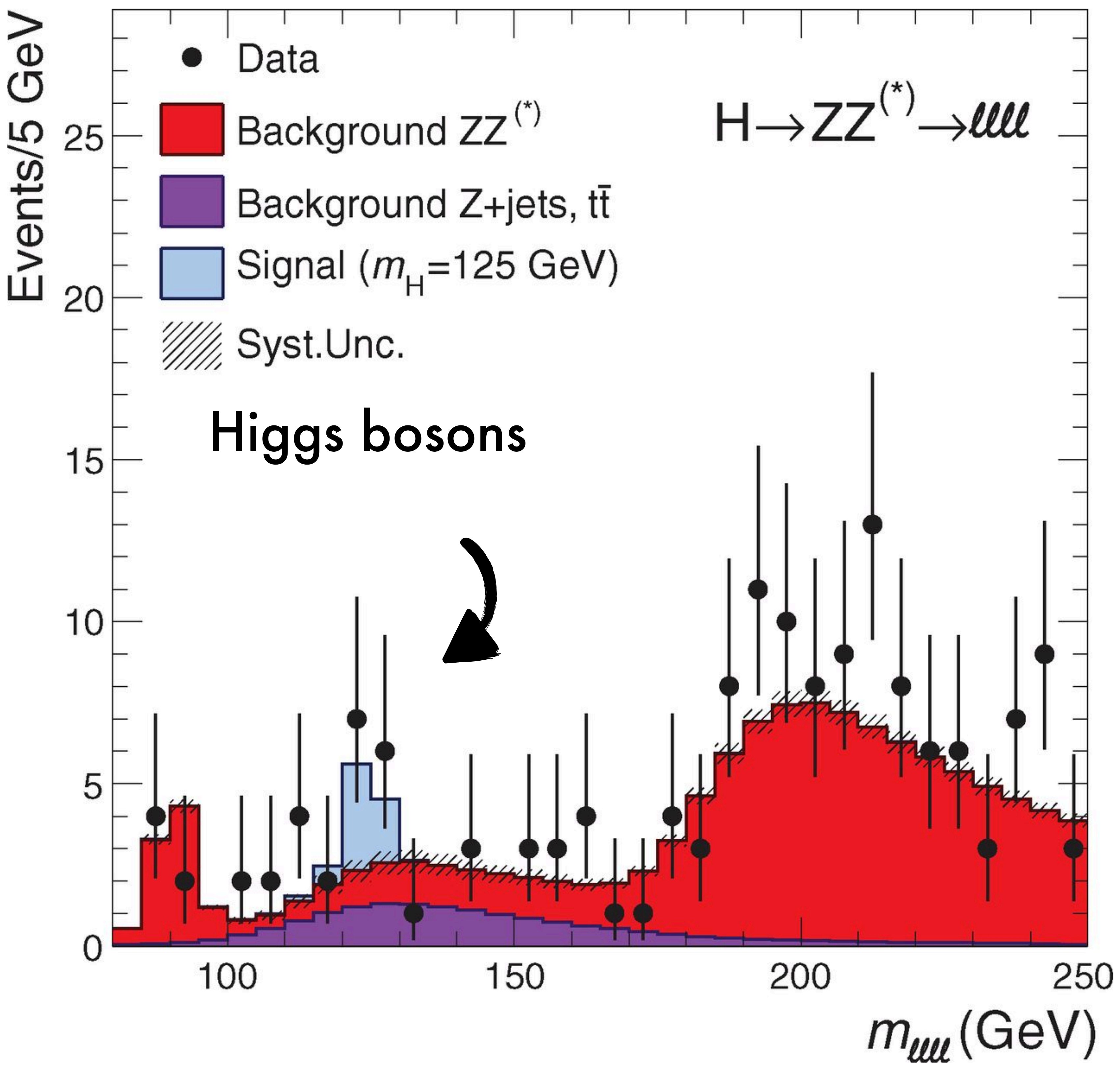
Probing electro-weak symmetry breaking at the LHC: two complementary ways

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



Higgs bosons



Higgs bosons

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

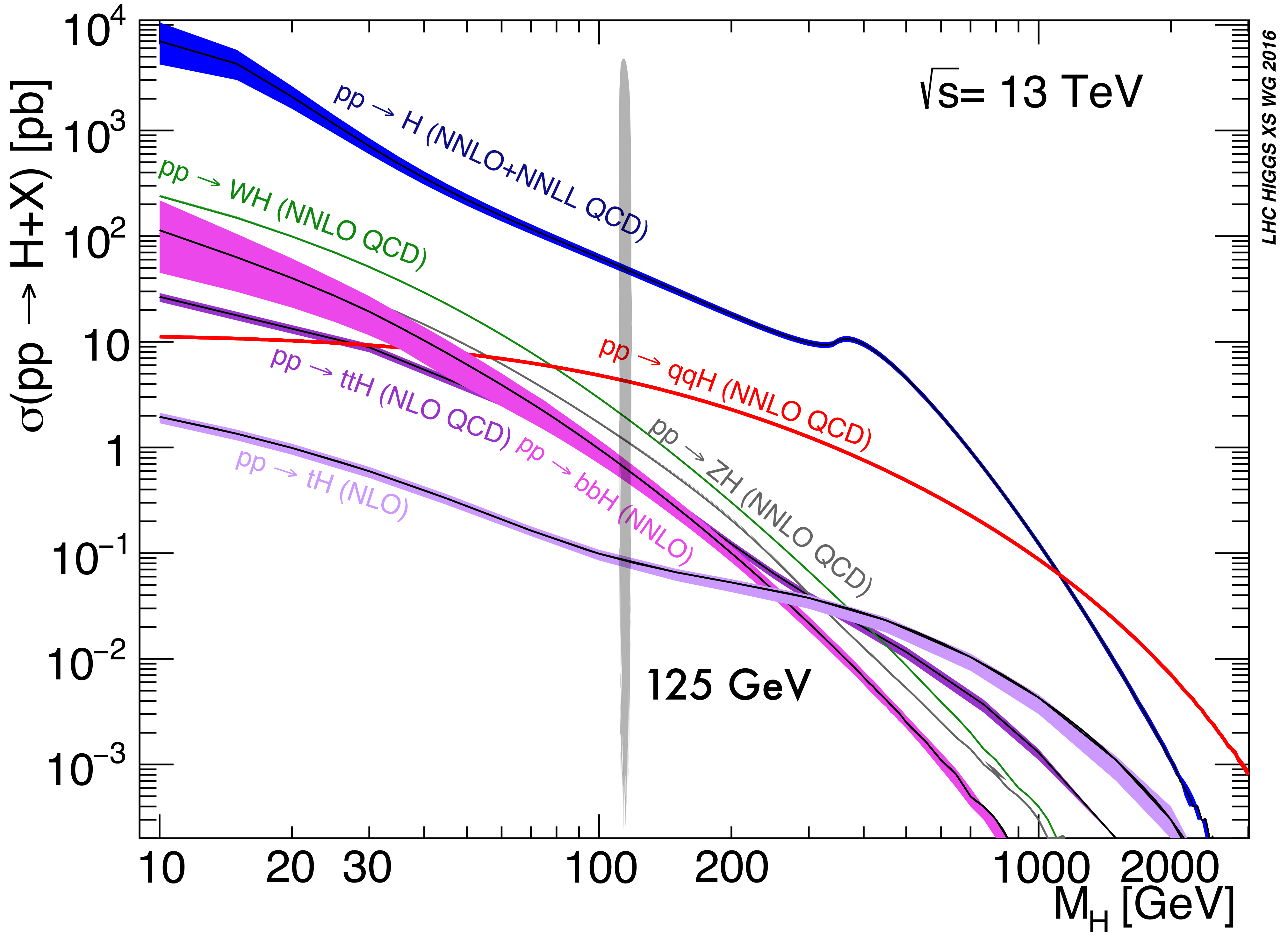
- Only fundamental particle with spin-0 (scalar) observed
- Higgs mass measured to be 125 GeV

Possible deviation in Standard Model prediction = new physics

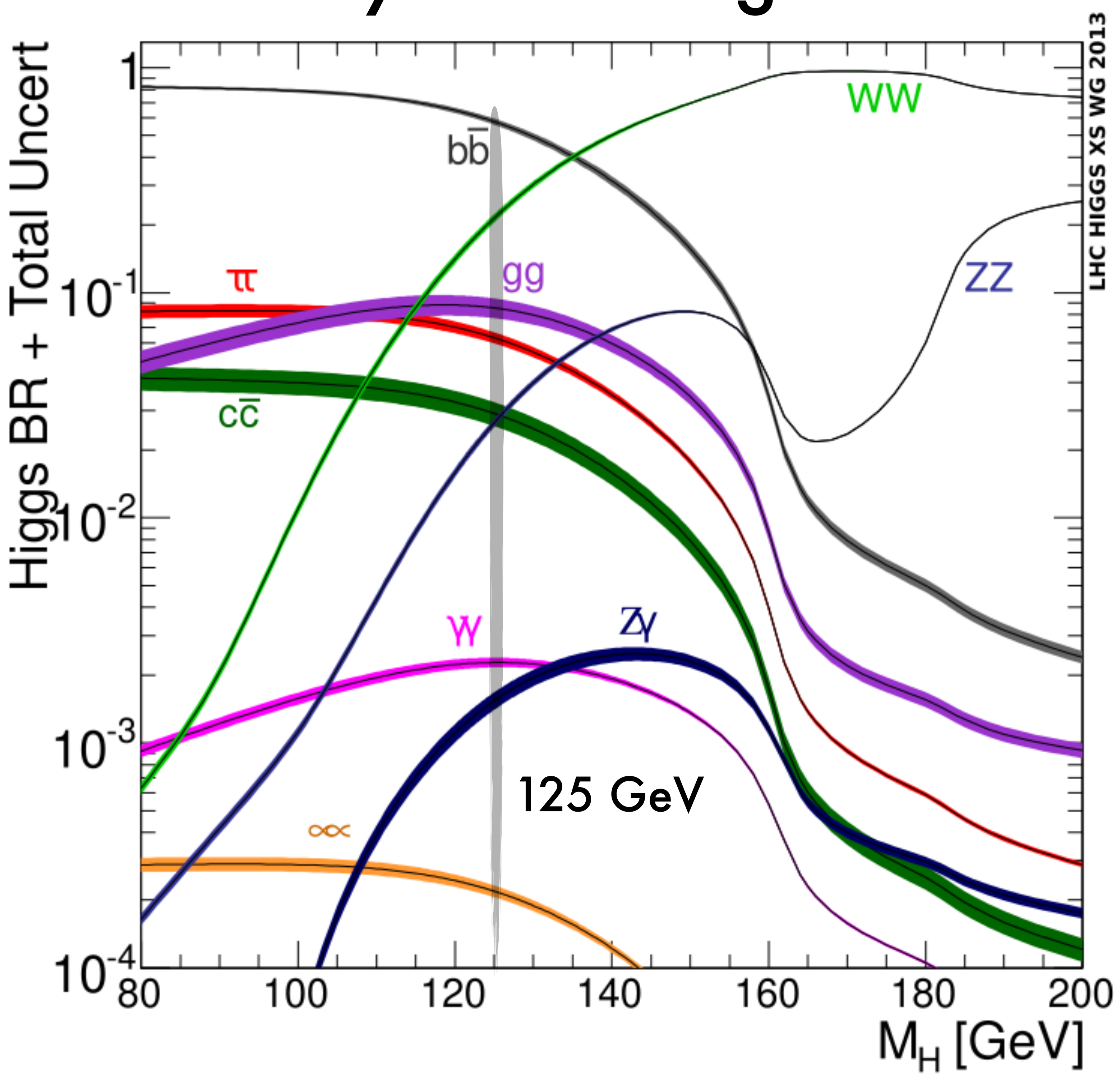
- Compositeness, extra dimensions, extended scalars ...

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

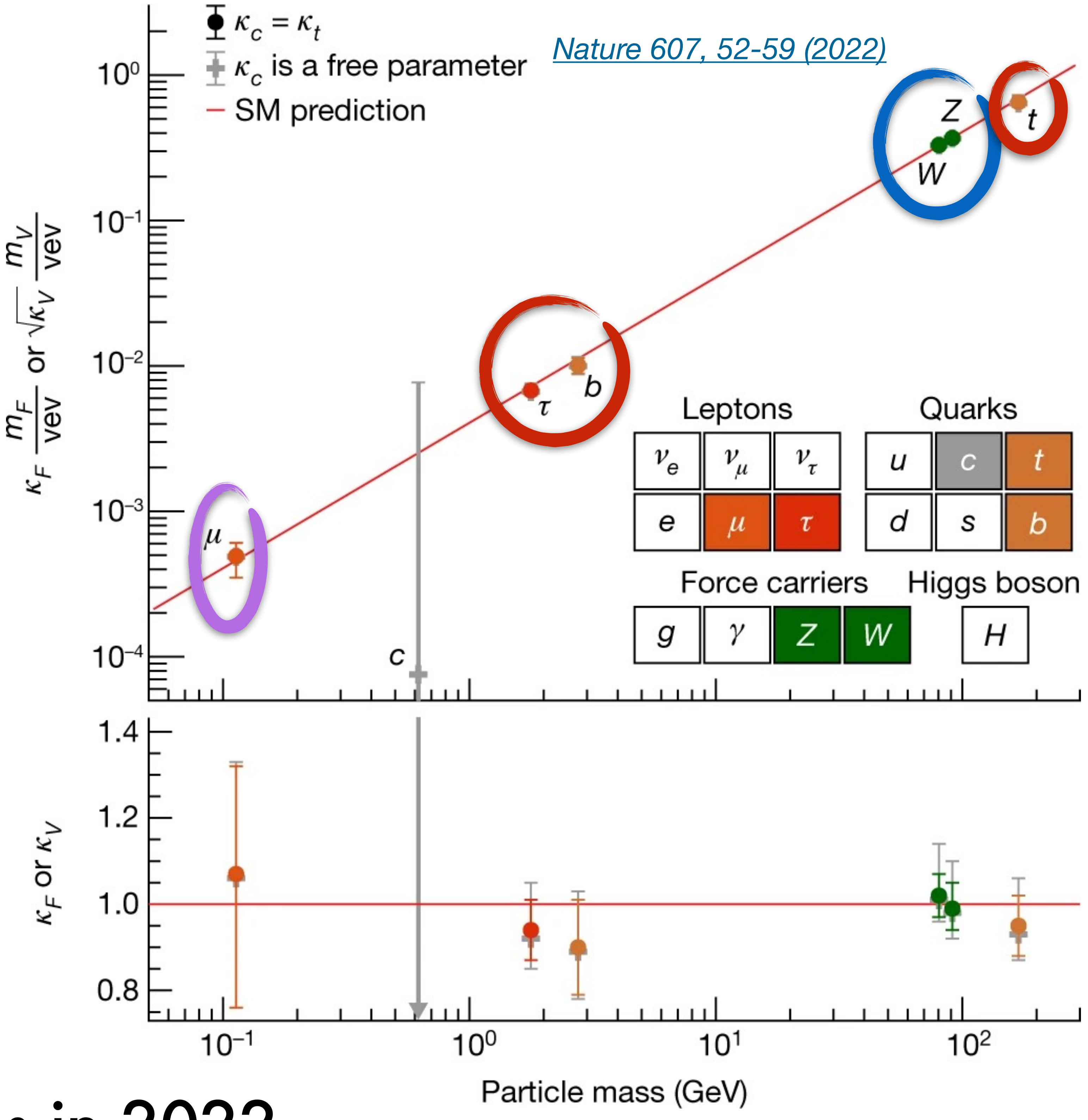
- Determines the kinematic properties, from production to decay rate
- At the LHC: more than **14.6 million Higgs bosons** produced
    - Main decay mode: **60% to a pair of b-quarks**: $H \rightarrow b\bar{b}$

Between 2010 and 2020:

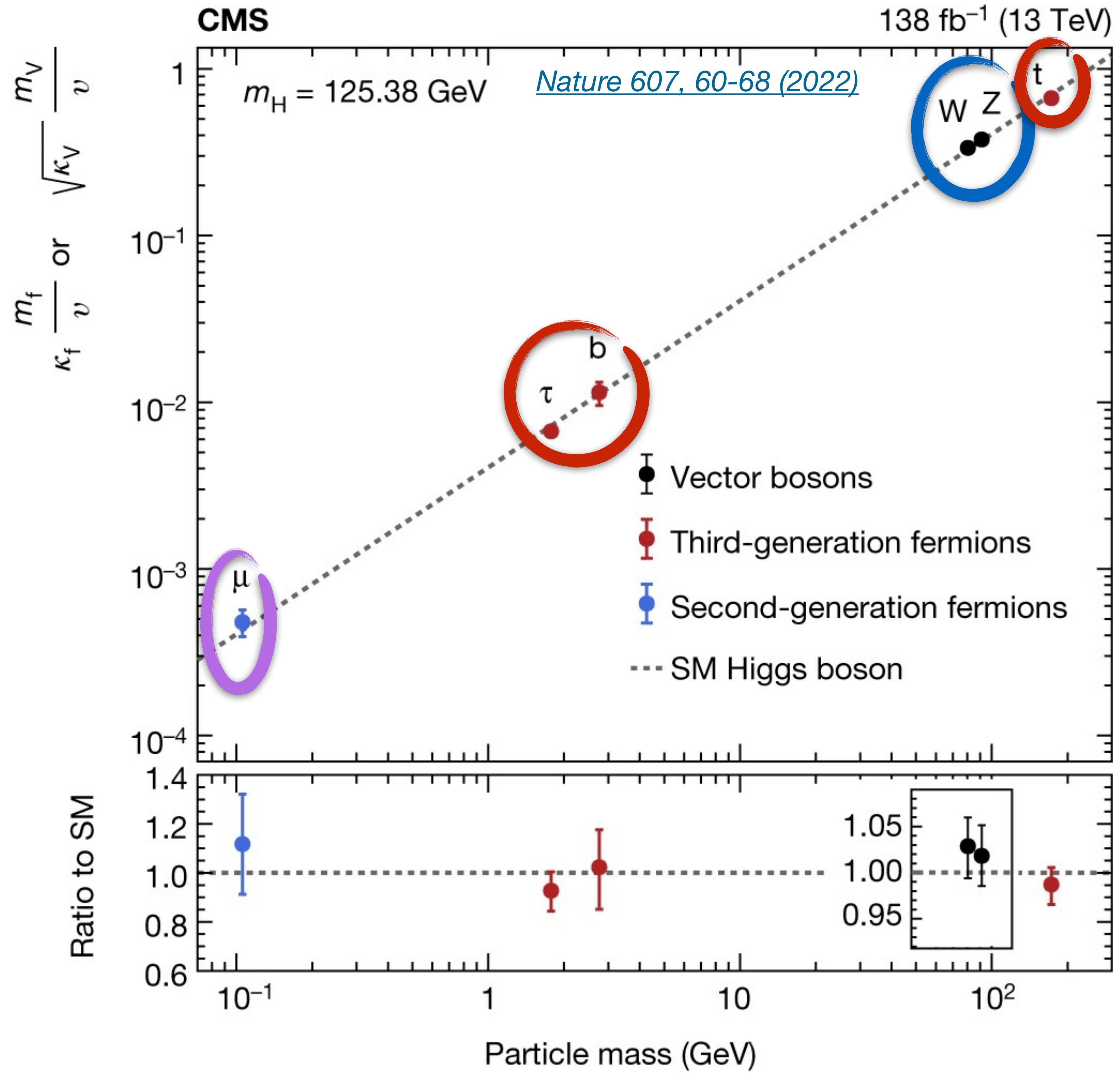
- Great decade to be a 5σ physicist, **new collider, new detector** and the **right Higgs mass!**

Experimental results

ATLAS Higgs coupling


Nature 607, 52-59 (2022)

CMS Higgs coupling


Nature 607, 60-68 (2022)

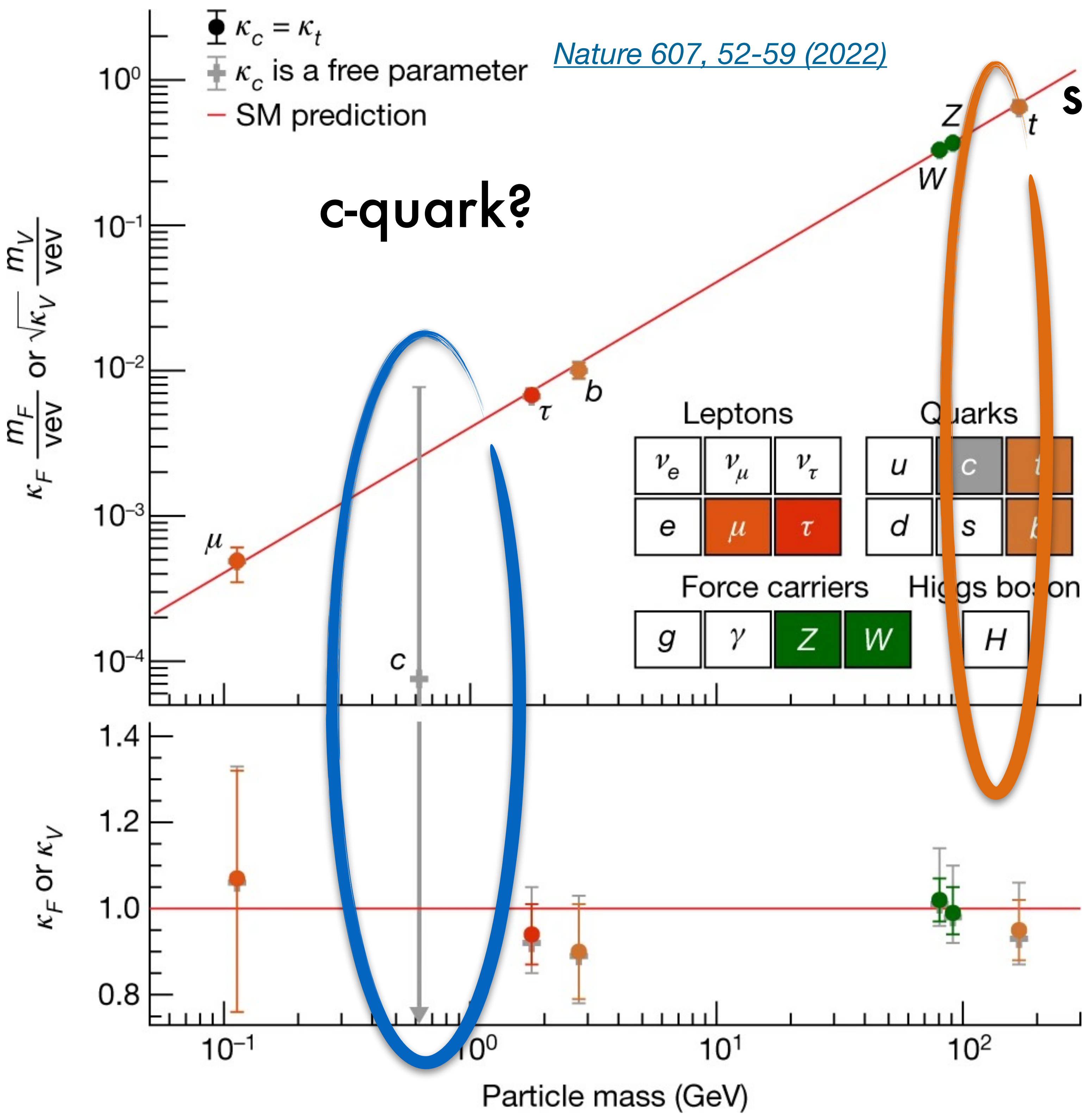
Status in 2022

- 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

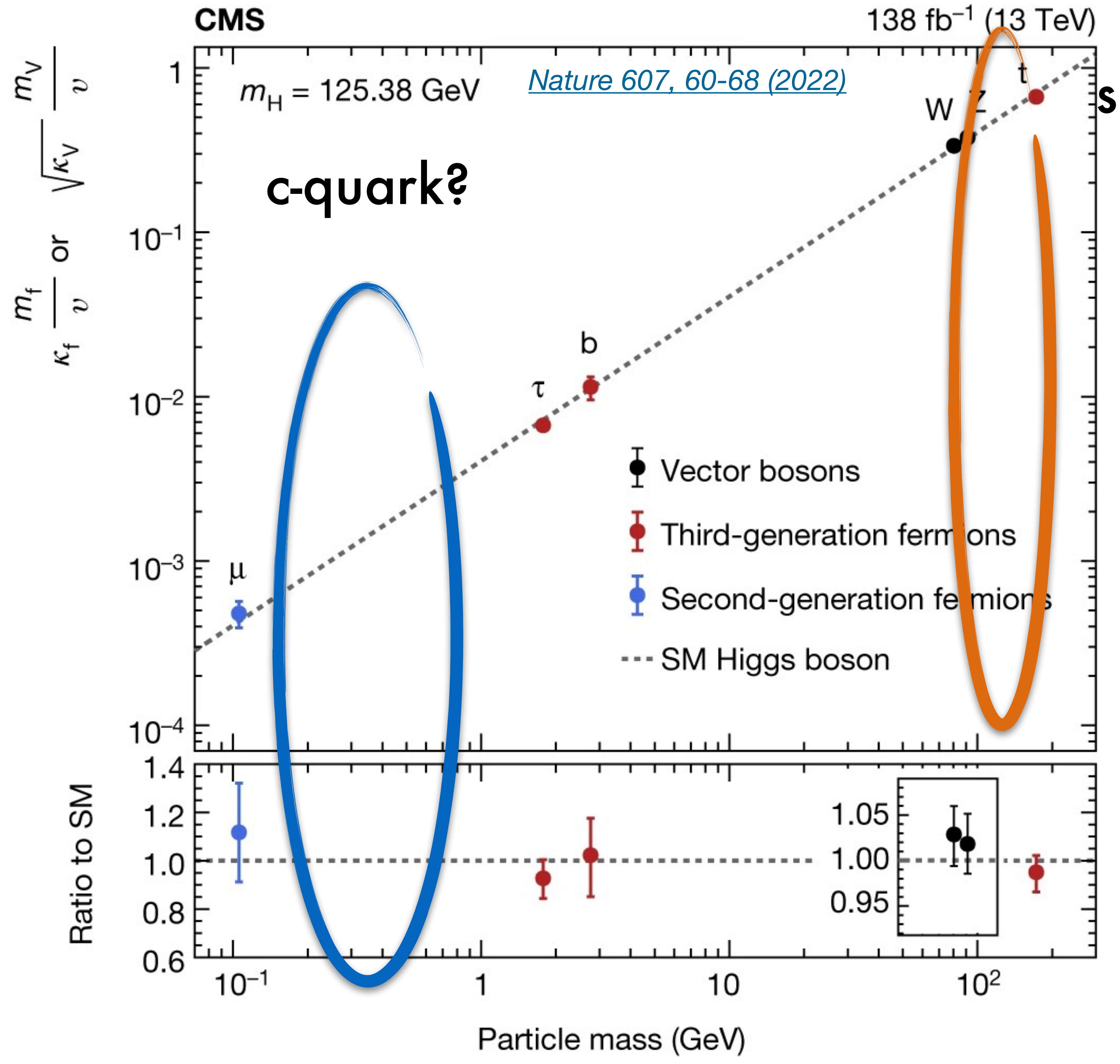


Nature 607, 52-59 (2022)

c-quark?

Higgs self-coupling?

CMS Higgs coupling



Nature 607, 60-68 (2022)

c-quark?

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

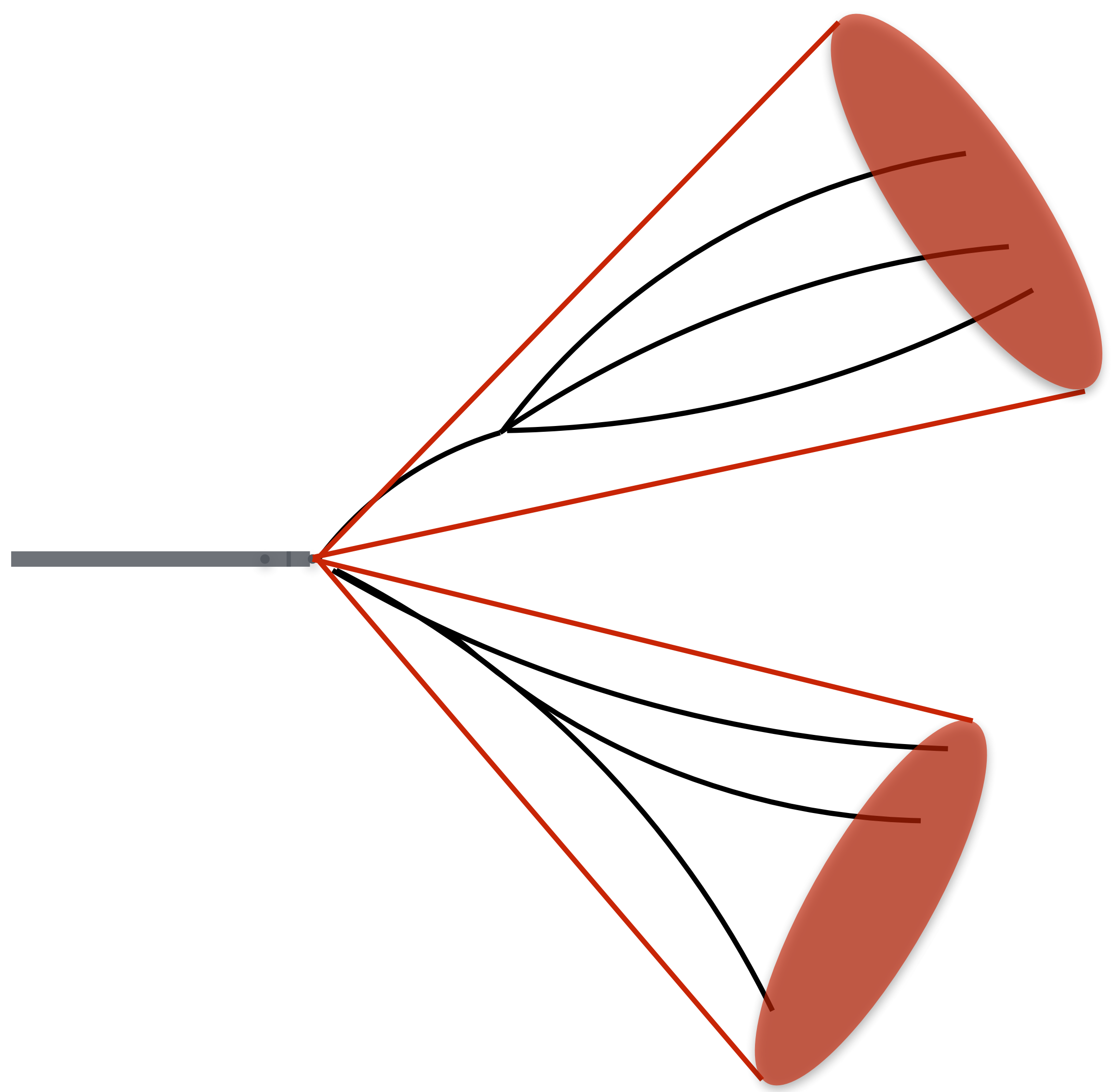
Challenging measurements to perform at the LHC, rare processes with large backgrounds

Revolutions since Run 2: flavor tagging and trigger

Flavor tagging

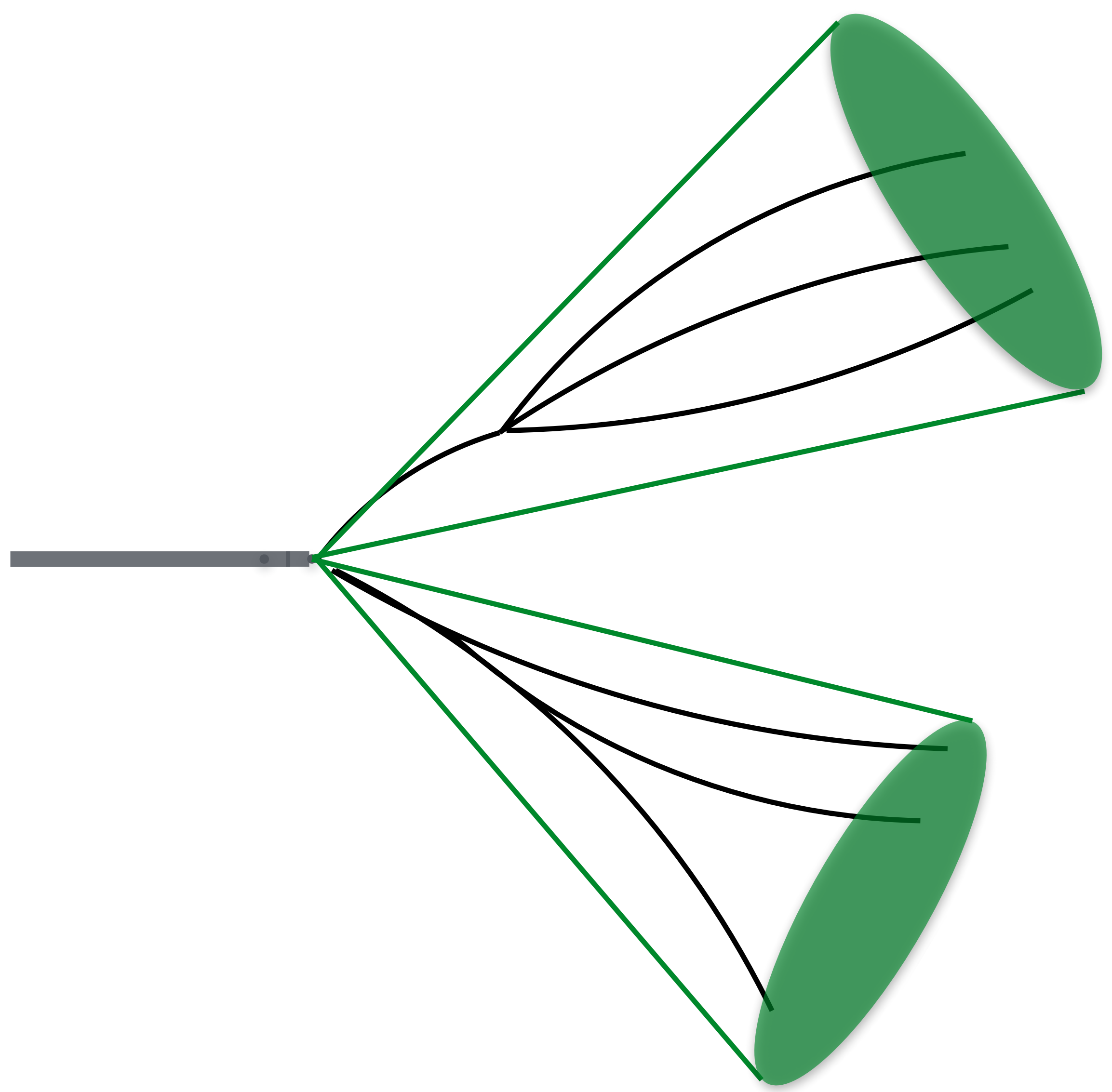
Higgs decays to heavy flavor quarks

$H \rightarrow b\bar{b}$



60% of Higgs bosons decay to b-quarks

$H \rightarrow c\bar{c}$

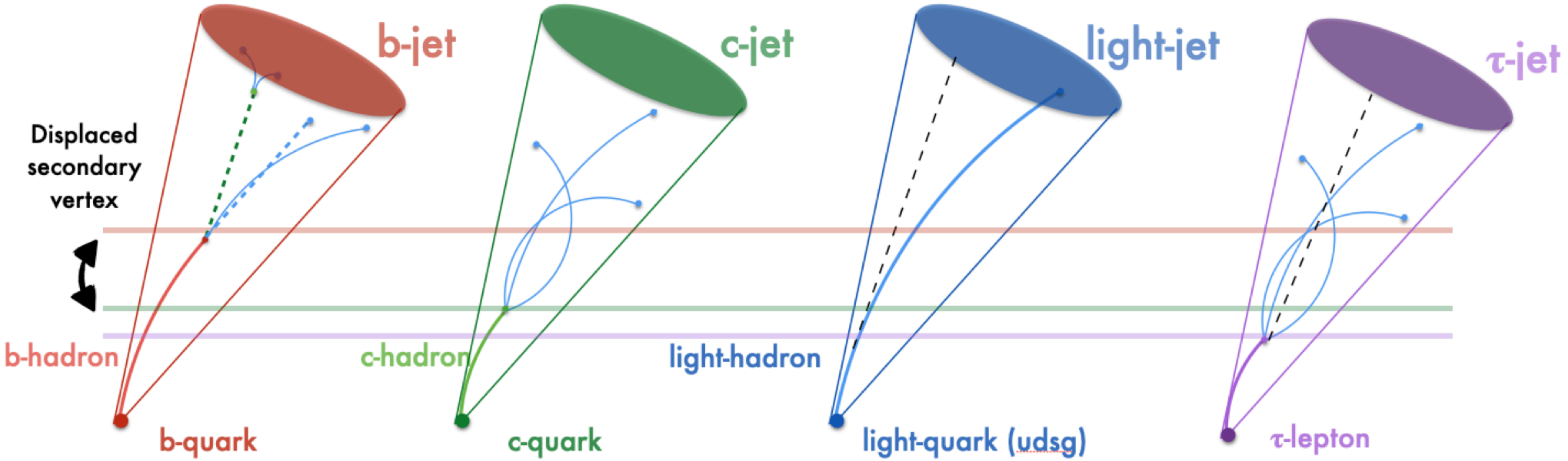


3% of Higgs bosons decay to c-quarks

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!

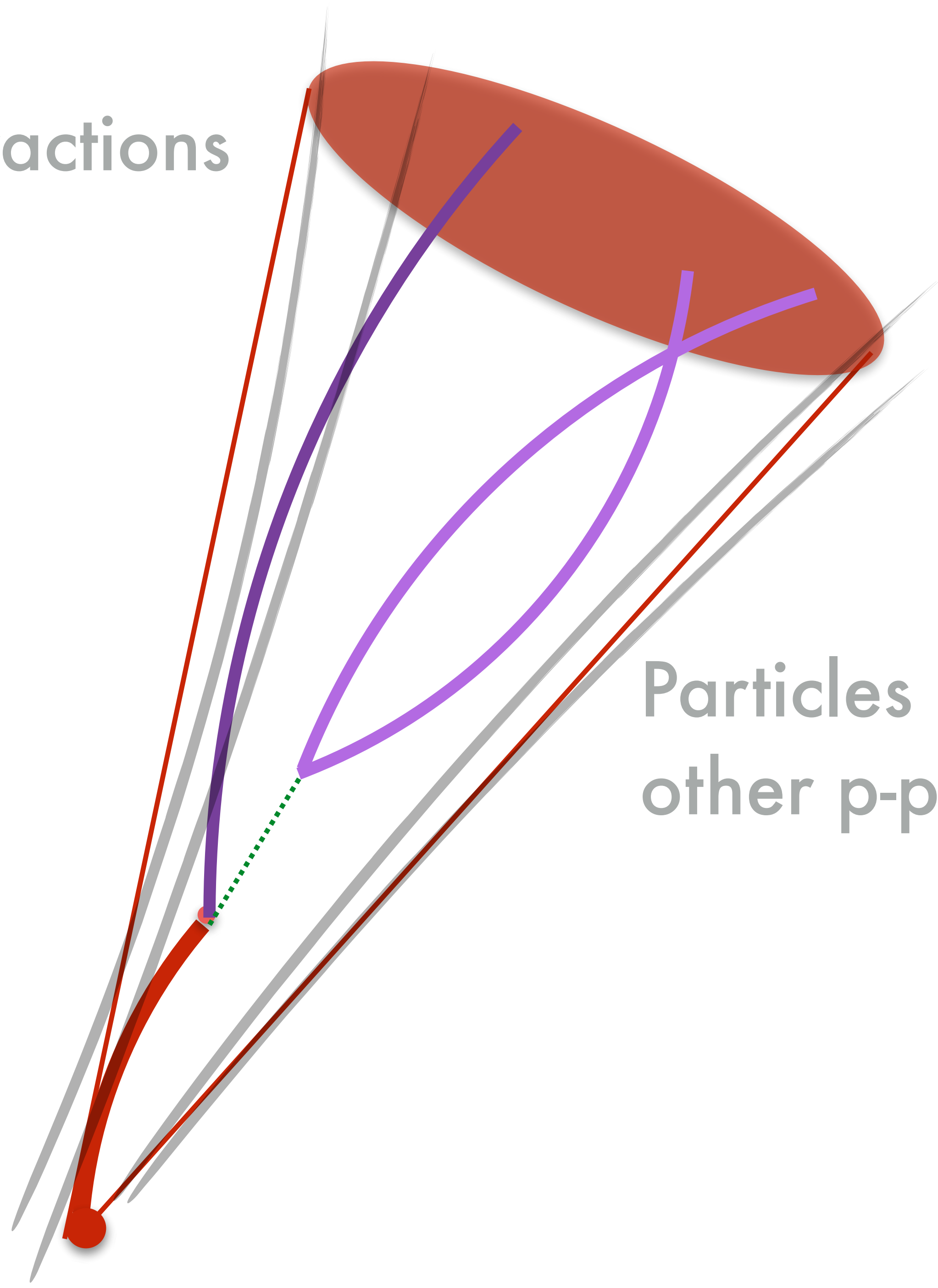
Flavor tagging concept



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

- Hadrons decay via W transition, top transitions are suppressed due to vey large mass
  - $b \to c$ and $c \to s$ 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

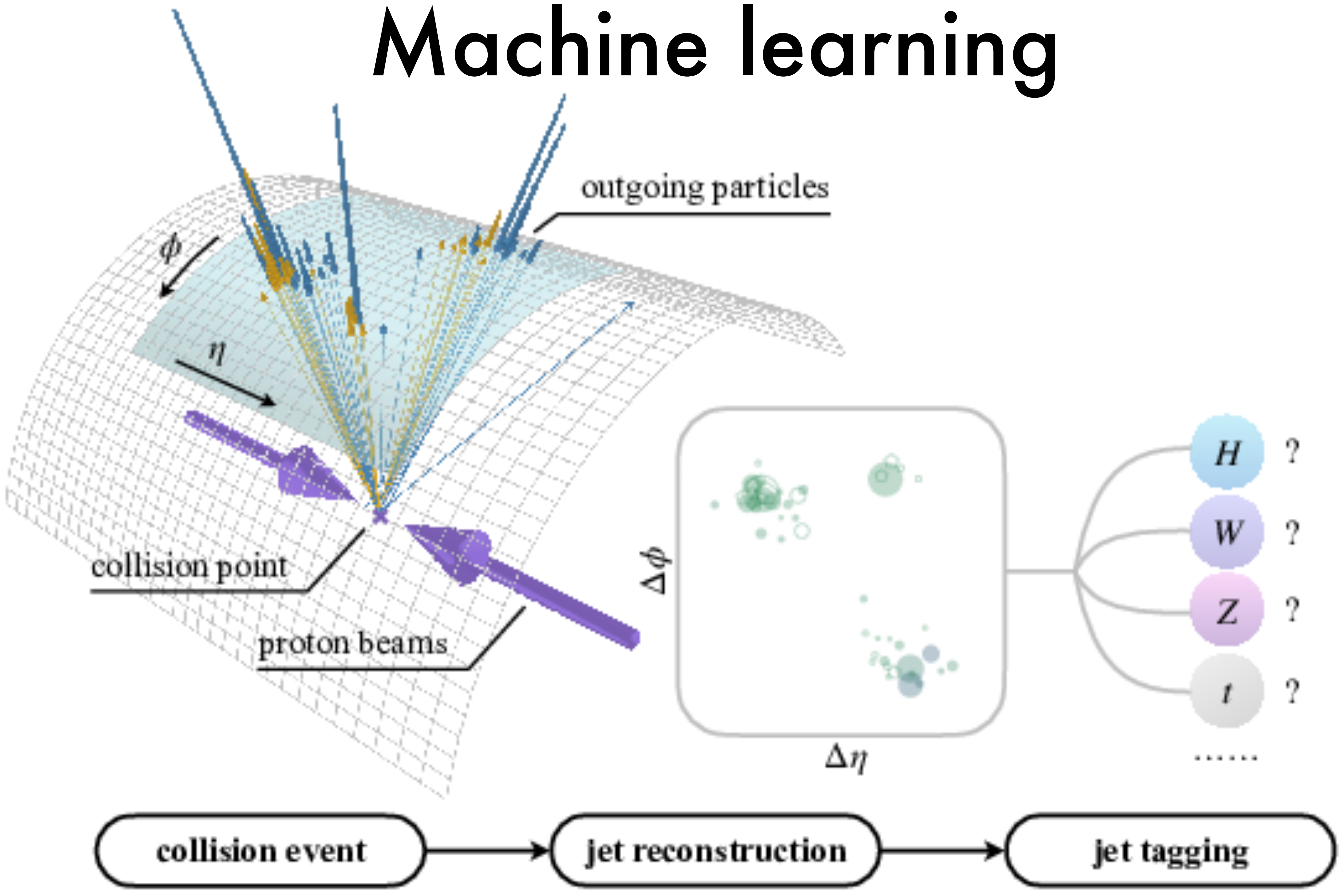
Paradigm shift for Run 3 and Run 2 re-analysis



Particles from
other p-p interactions

Particles from
other p-p interactions

Machine learning

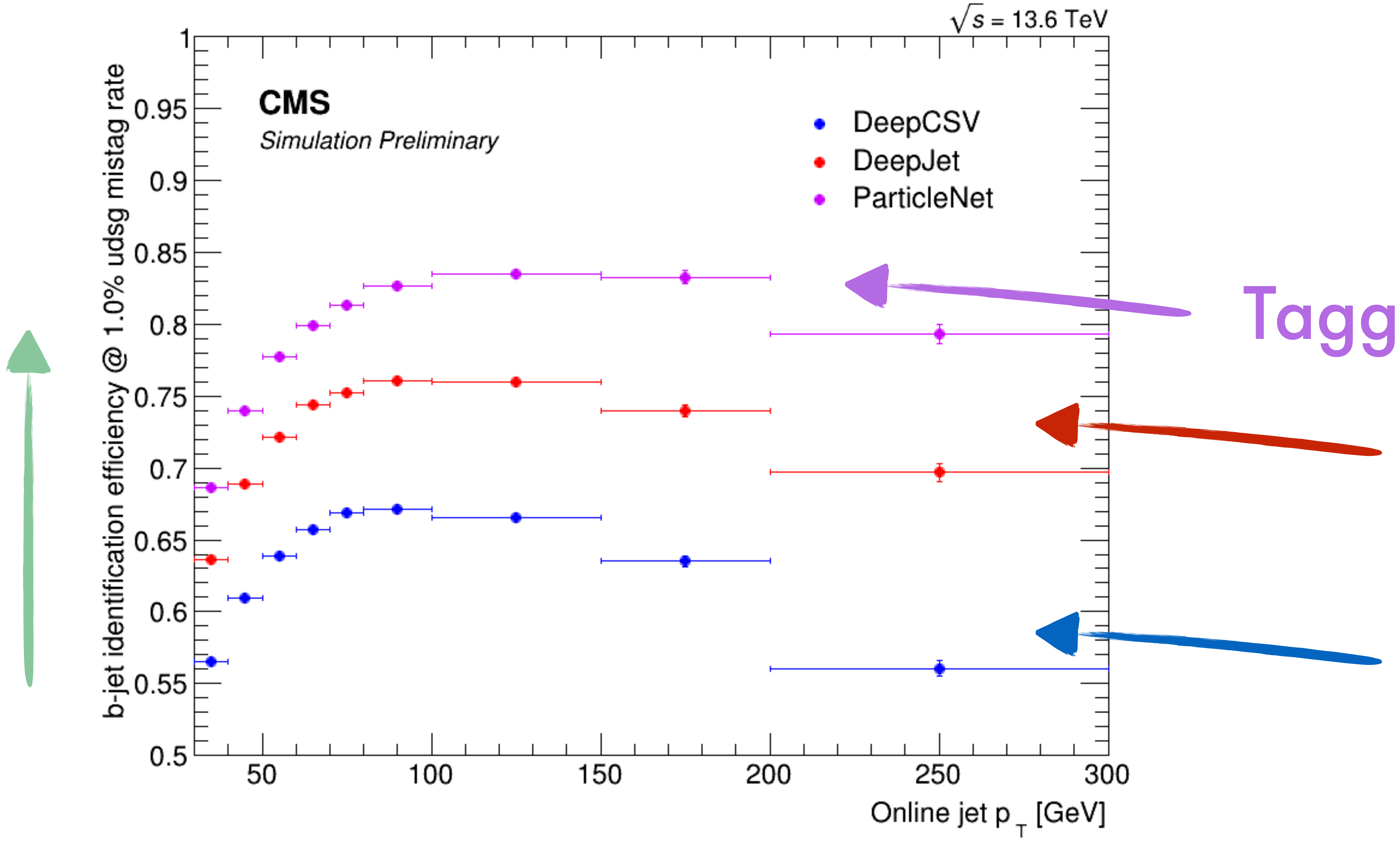


Advances in machine learning and computing (GPUs)

- 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

CMS DP-2023/021



Tagger in 2022

Tagger in 2018

Tagger in 2016

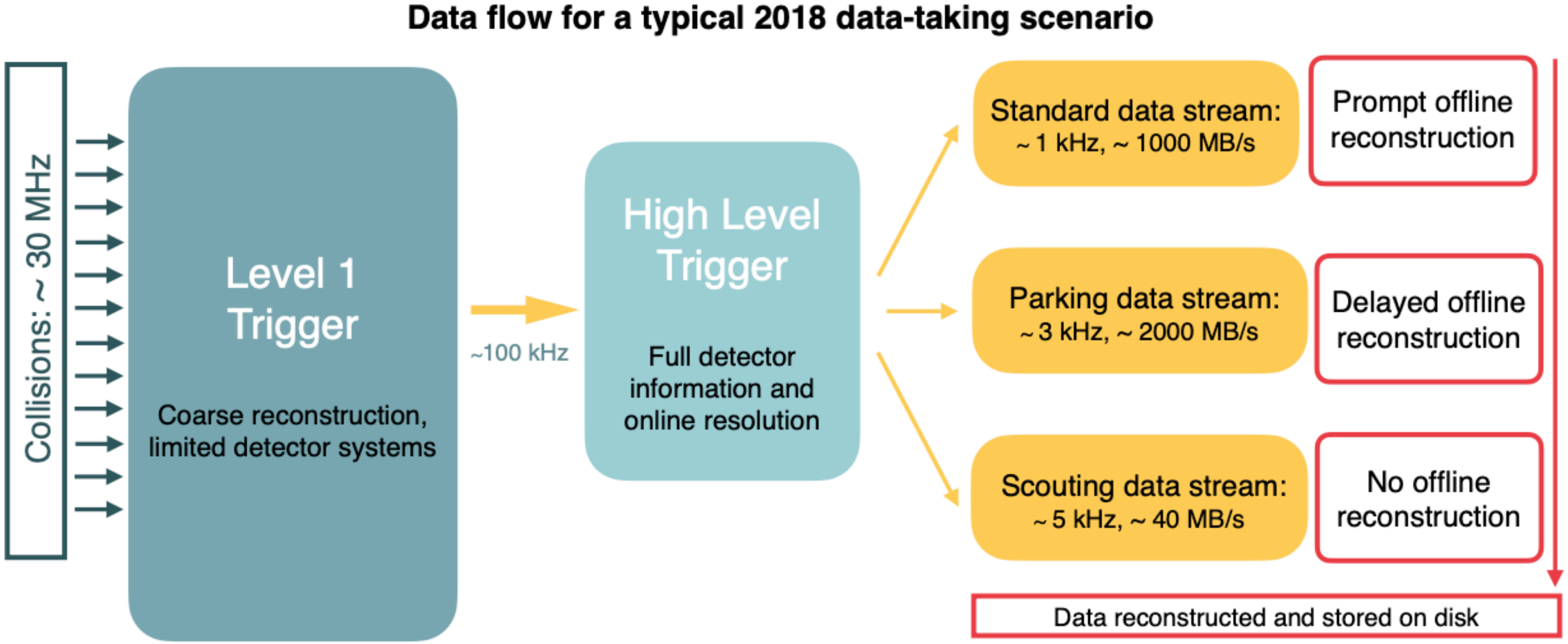
Performance of b-jet identification at fixed 1% mis-identification rate for other flavors

- 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

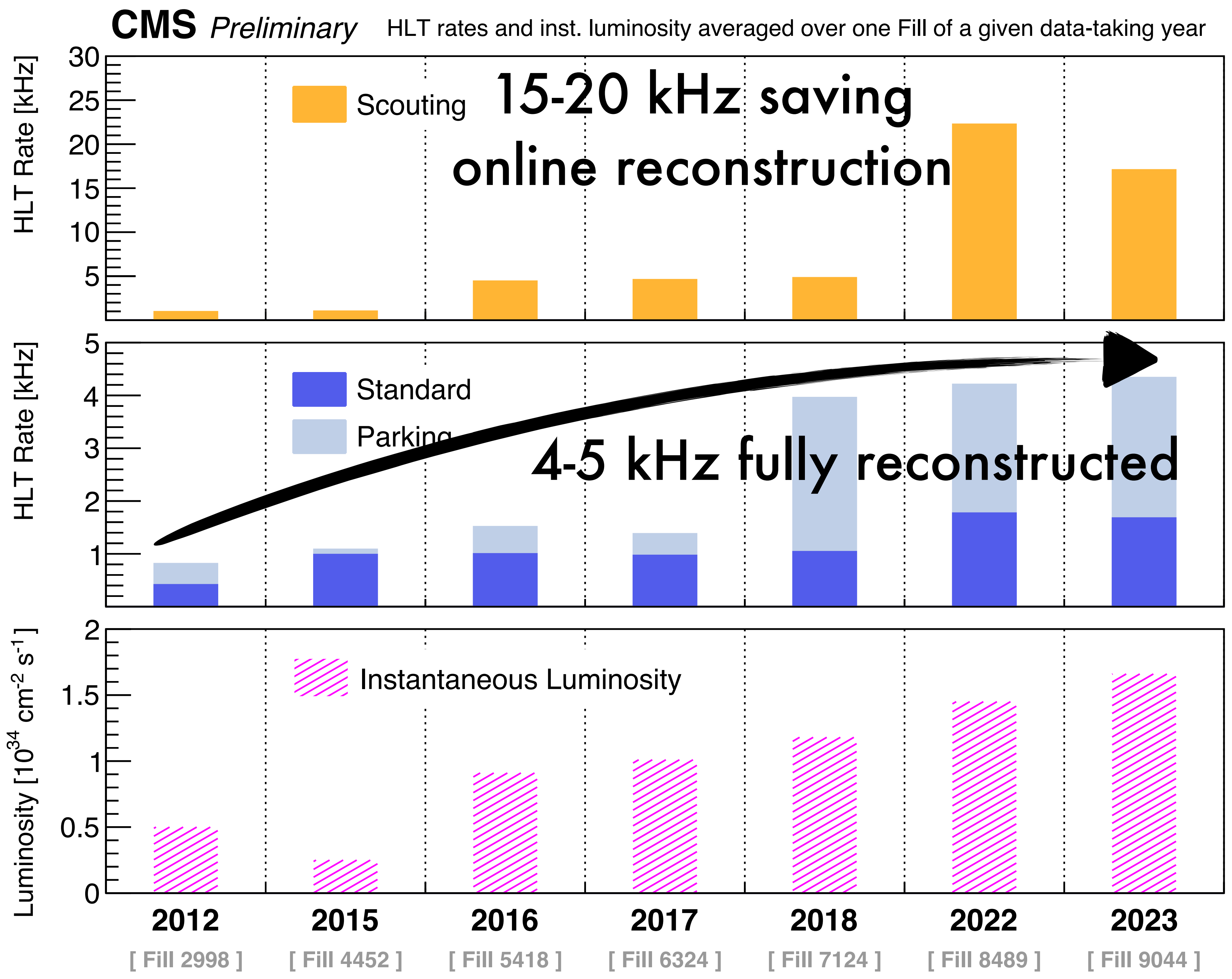
Data acquisition in 2018 and Run 3 (2022 - 2026):

- 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

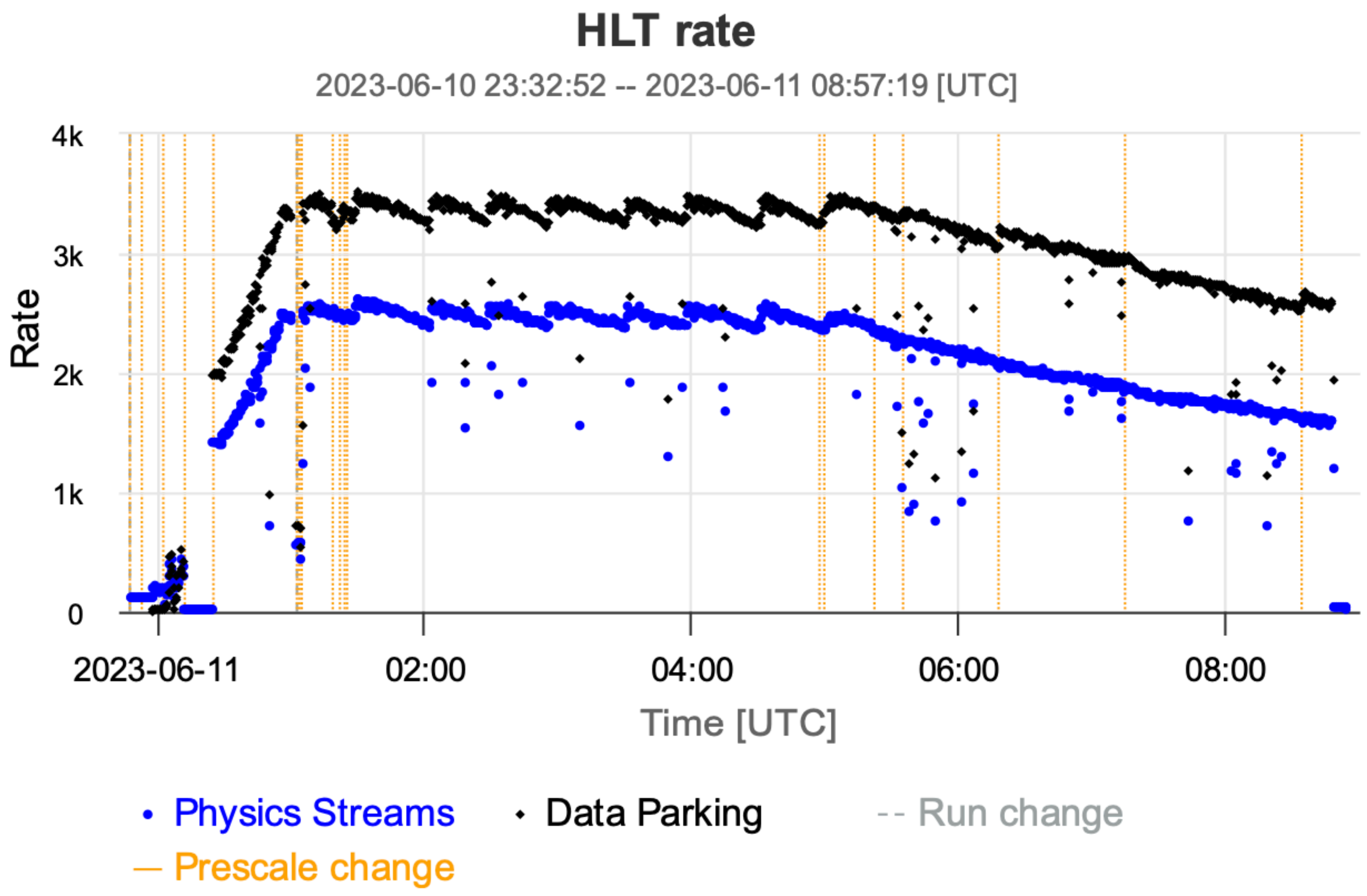
CMS-DP-2024/012

arXiv:2403.16134



15-20 kHz saving online reconstruction

4-5 kHz fully reconstructed



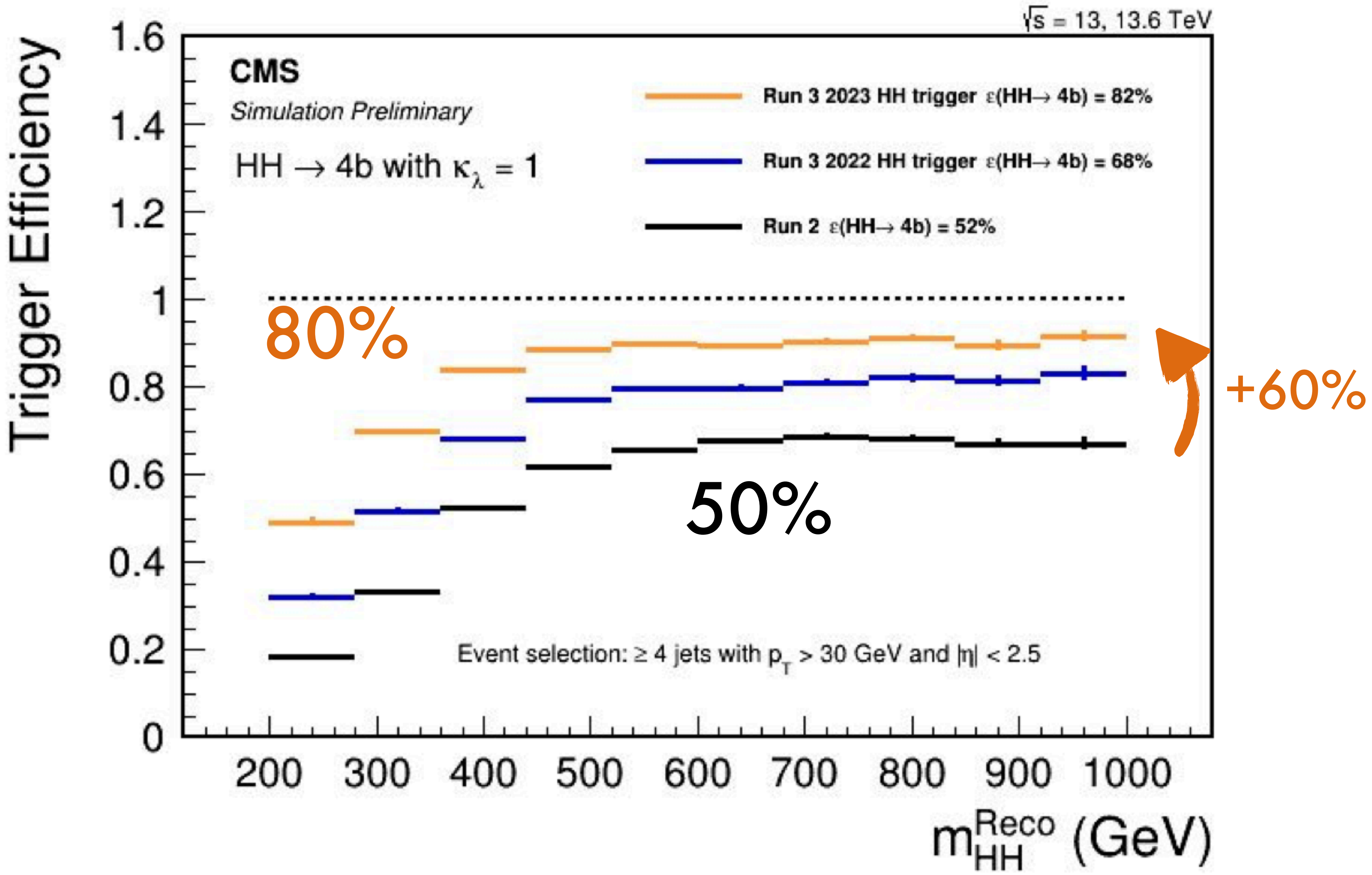
Extraordinary increase in computing capacities:

- 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!

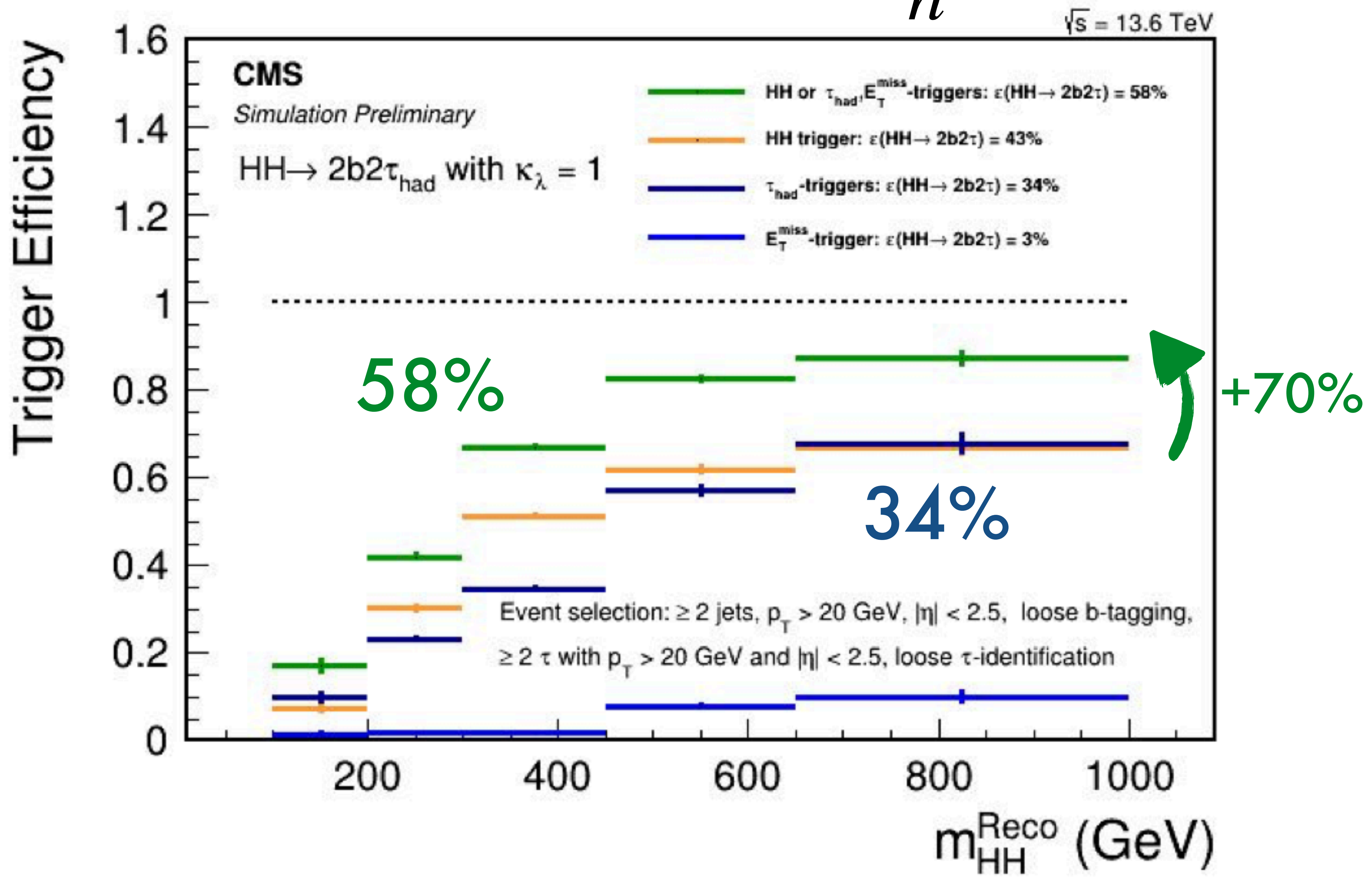
New triggers for multi-Higgs production

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

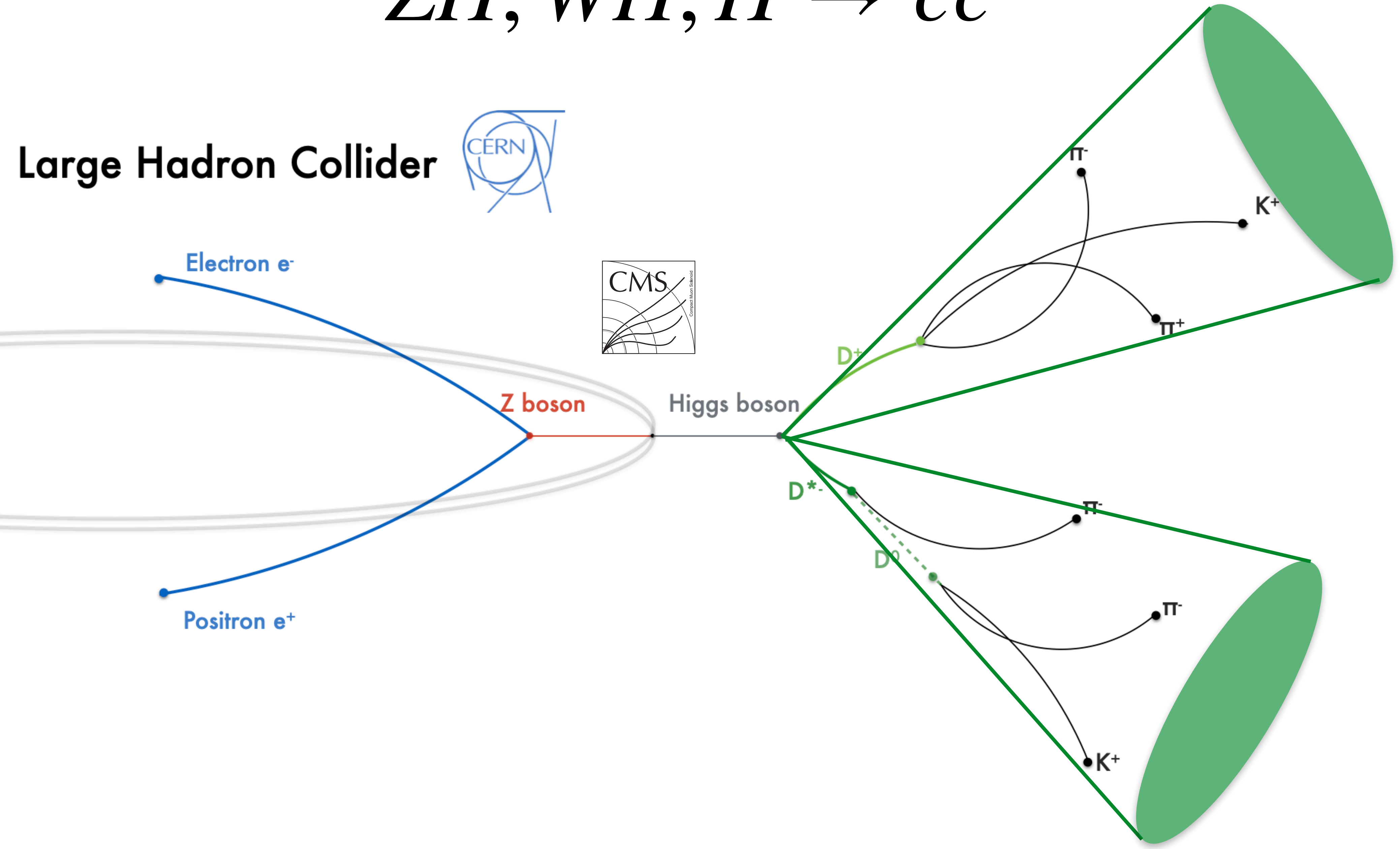
- Allows large increase in the number of multi-Higgs events recorded!
- In 2018: only recording 50% of $HH \rightarrow 4b$ and 34% of $HH \rightarrow 2b2\tau_h$ events
    - HH events are already hard to produce, we recorded only a small faction of them
- In Run 3: increased to **60% and 70% respectively**

With new flavor taggers and new triggers:
Improve existing analyses and
new analyses become possible!

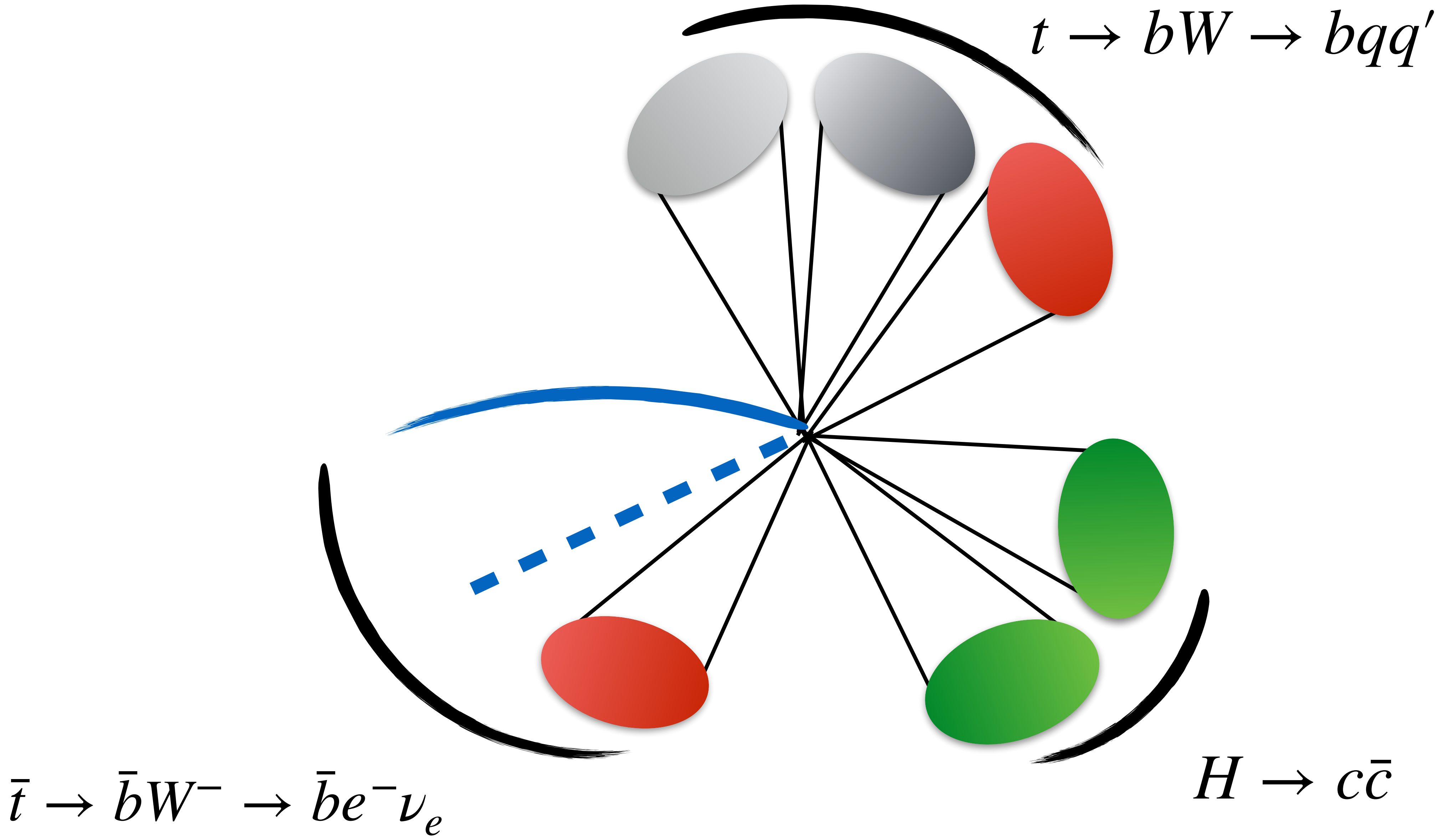
Run 2 ttHbb/cc

Towards the Higgs charm coupling

$ZH, WH, H \to c\bar{c}$



$t\bar{t}H, H \to c\bar{c}$



2000 events produced in Run 2

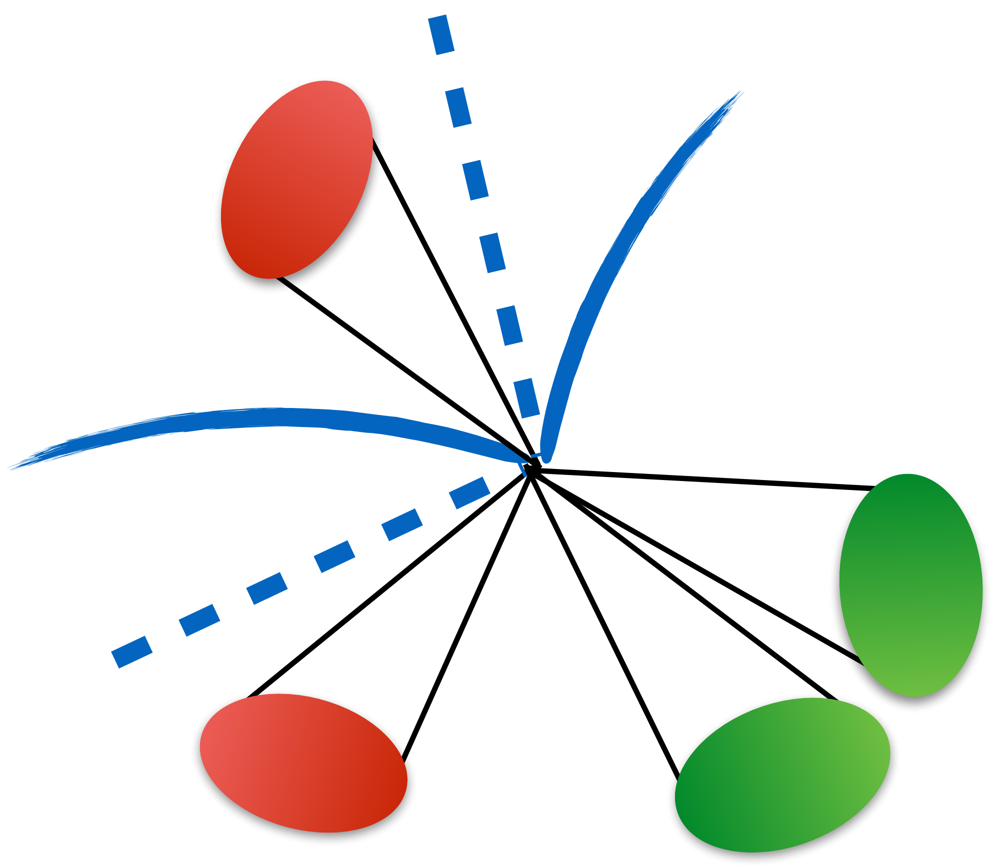
1600 events produced in Run 2

Until now, scientific consensus was the **ZH and WH** production: **golden channel for Higgs charm**

- Due to very large background from gluon productions
- Exploit leptons in the ZH and WH decays to try to measure Higgs to charm coupling
- VHcc results: < 8 x SM prediction with Run 2
- ttHcc: expected to be less sensitive, based on Hbb results and less performant c-tagging…

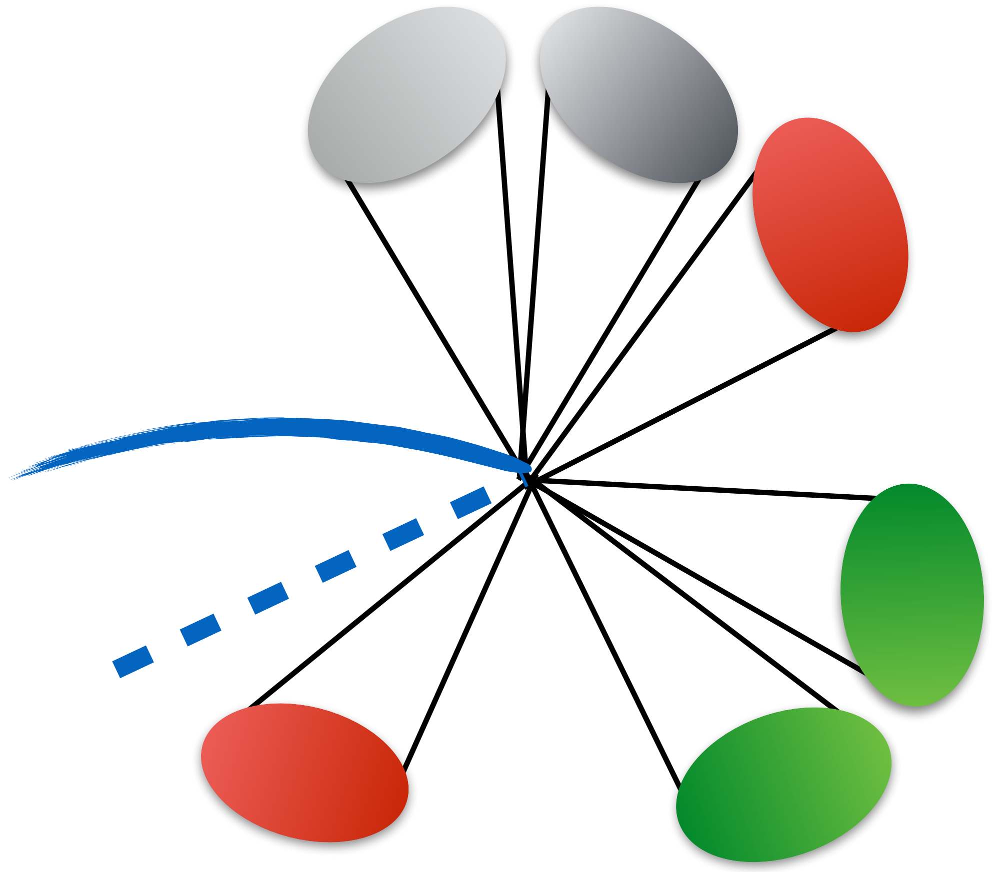
CMS ttHcc: decay channels

Di-leptonic



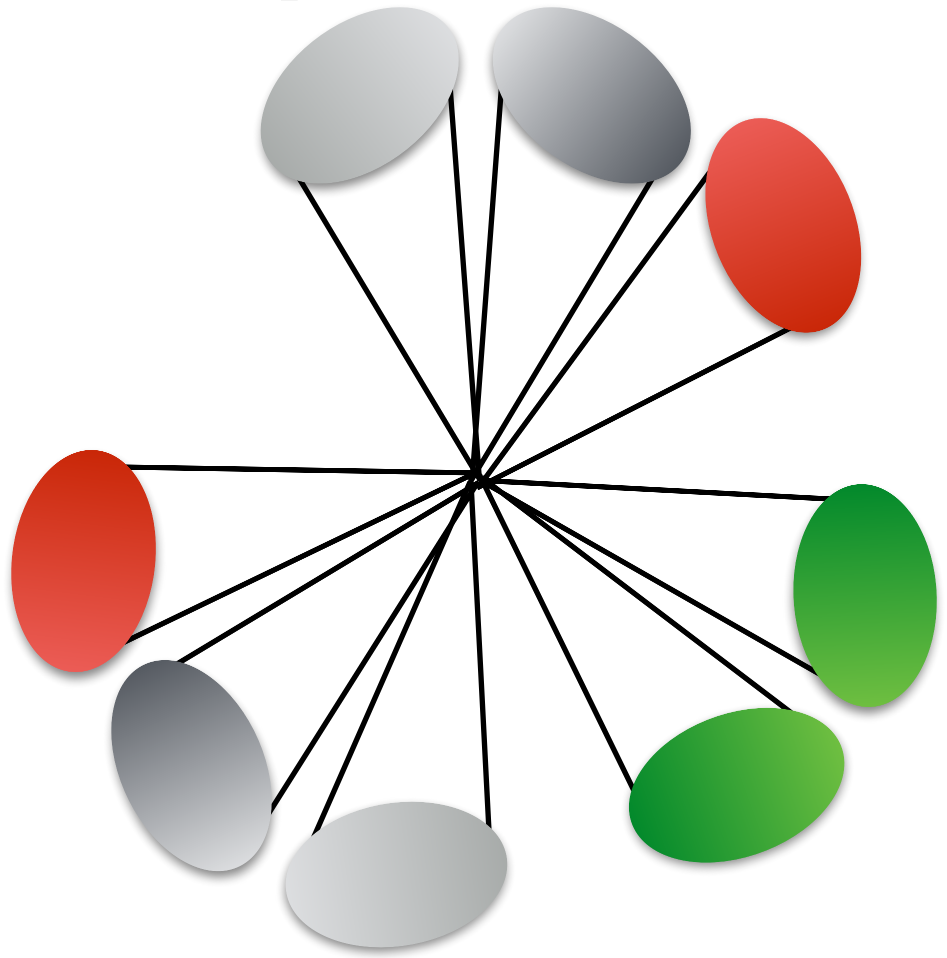
100 events

Single-leptonic



600 events

Fully-hadronic



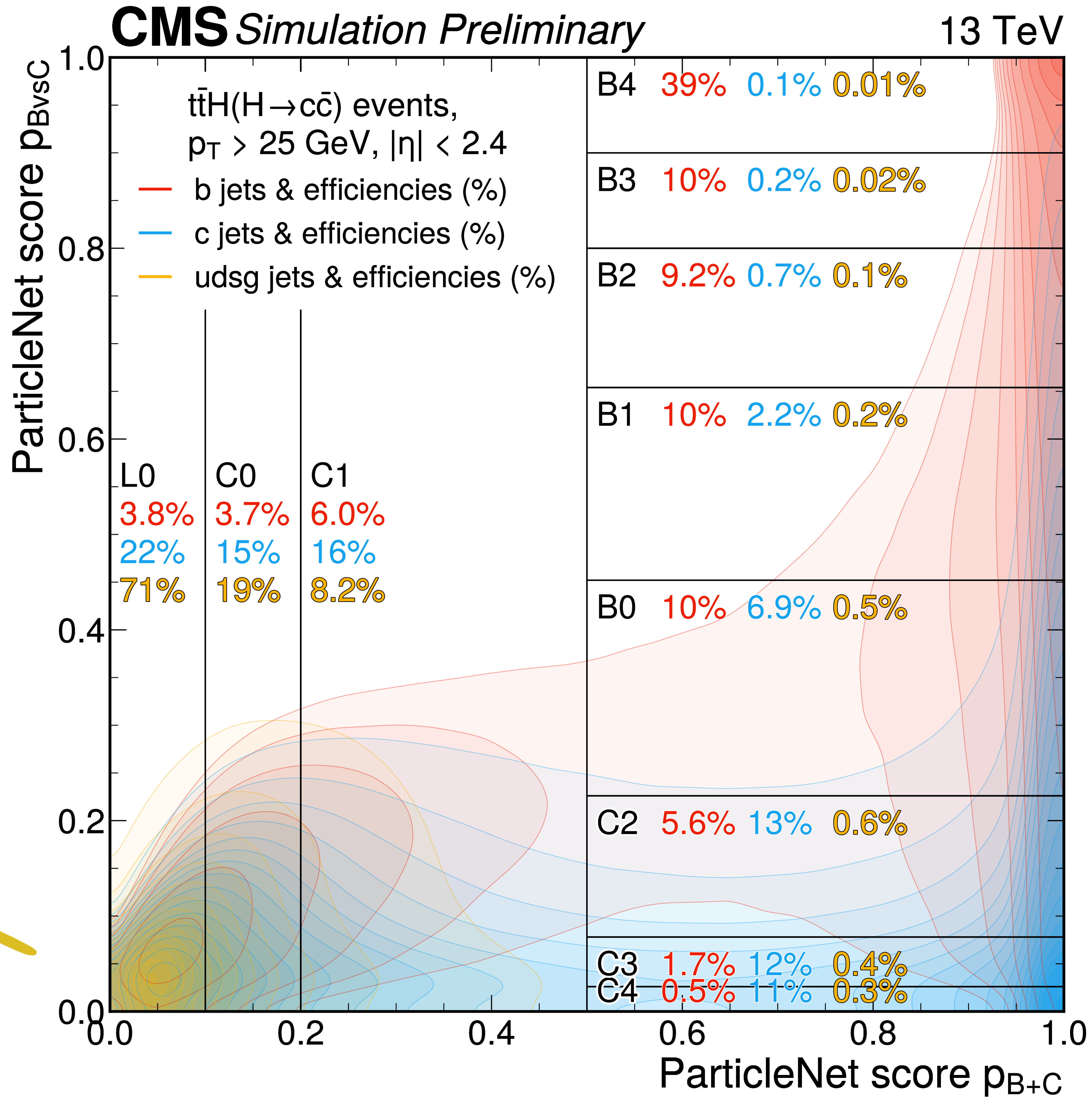
900 events

Three channels investigated: di-leptonic, single-leptonic, and fully-hadronic

- Di-leptonic: rare but very low background contamination, high trigger efficiency
- Single-leptonic: more events but larger background, high trigger efficiency
- Fully-hadronic: largest fraction, but very large backgrounds from multi jets, lower trigger
- All channels: **2 b-jet and 2 c-jets**, **heavily relying on flavor tagging!**

CMS ttHcc: decay channels

CMS-PAS-HIG-24-018



b-jets

Light-jets (udsg)

c-jets

Two dimensional plane of probabilities P(b+c) vs P(b vs c)

- Define 10 bins of purity separating b vs c vs light-jets
- Novel technology enables more ambitious strategies!

Machine learning strategy

CMS-PAS-HIG-24-018

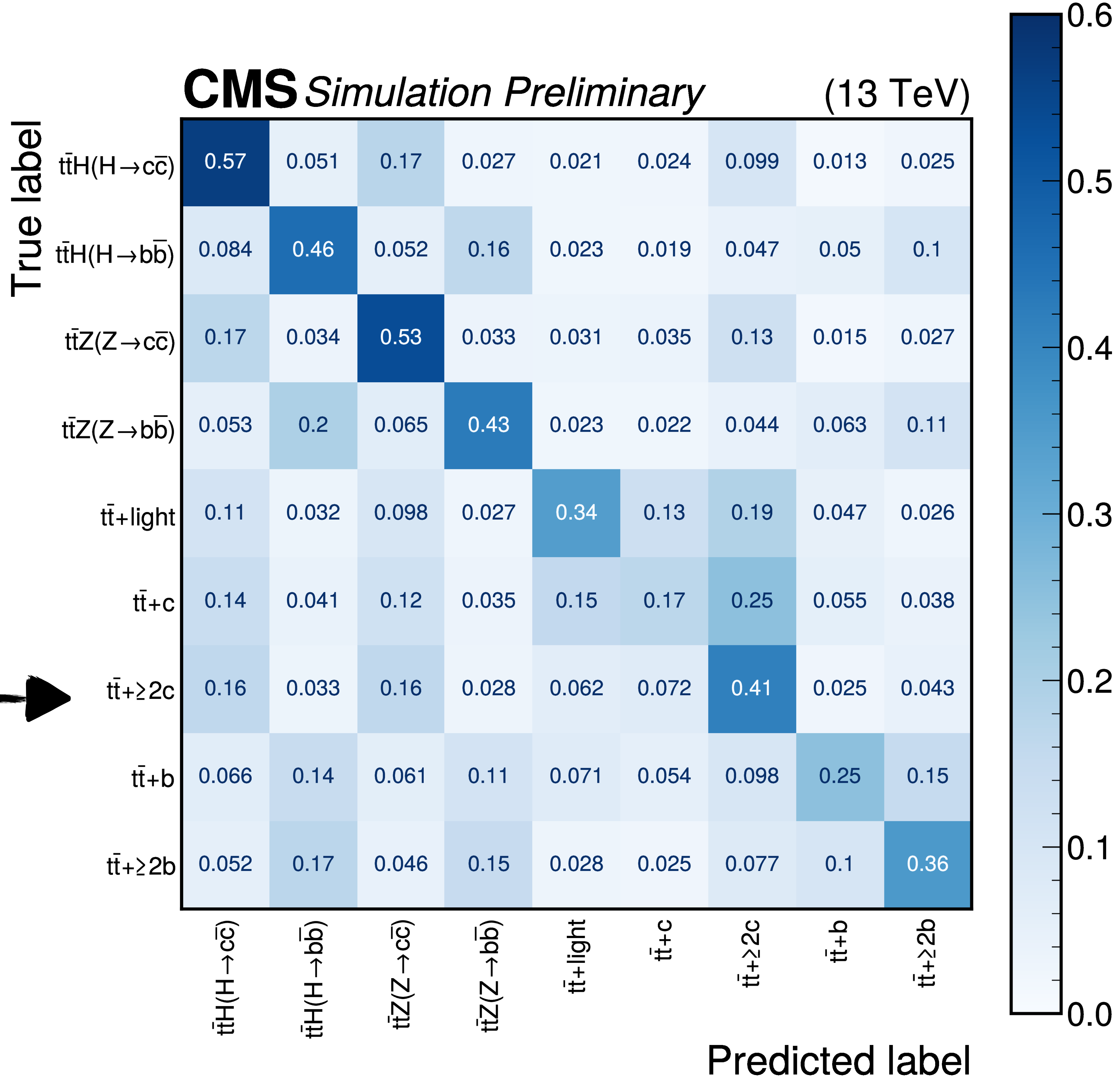
ttHcc

ttHbb

ttZcc

ttZbb

tt backgrounds



	$t\bar{t}H(H\to c\bar{c})$	$t\bar{t}H(H\to b\bar{b})$	$t\bar{t}Z(Z\to c\bar{c})$	$t\bar{t}Z(Z\to b\bar{b})$	$t\bar{t}$+light	$t\bar{t}$+c	$t\bar{t}+\geq 2c$	$t\bar{t}$+b	$t\bar{t}+\geq 2b$
$t\bar{t}H(H\to c\bar{c})$	0.57	0.051	0.17	0.027	0.021	0.024	0.099	0.013	0.025
$t\bar{t}H(H\to b\bar{b})$	0.084	0.46	0.052	0.16	0.023	0.019	0.047	0.05	0.1
$t\bar{t}Z(Z\to c\bar{c})$	0.17	0.034	0.53	0.033	0.031	0.035	0.13	0.015	0.027
$t\bar{t}Z(Z\to b\bar{b})$	0.053	0.2	0.065	0.43	0.023	0.022	0.044	0.063	0.11
$t\bar{t}$+light	0.11	0.032	0.098	0.027	0.34	0.13	0.19	0.047	0.026
$t\bar{t}$+c	0.14	0.041	0.12	0.035	0.15	0.17	0.25	0.055	0.038
$t\bar{t}+\geq 2c$	0.16	0.033	0.16	0.028	0.062	0.072	0.41	0.025	0.043
$t\bar{t}$+b	0.066	0.14	0.061	0.11	0.071	0.054	0.098	0.25	0.15
$t\bar{t}+\geq 2b$	0.052	0.17	0.046	0.15	0.028	0.025	0.077	0.1	0.36

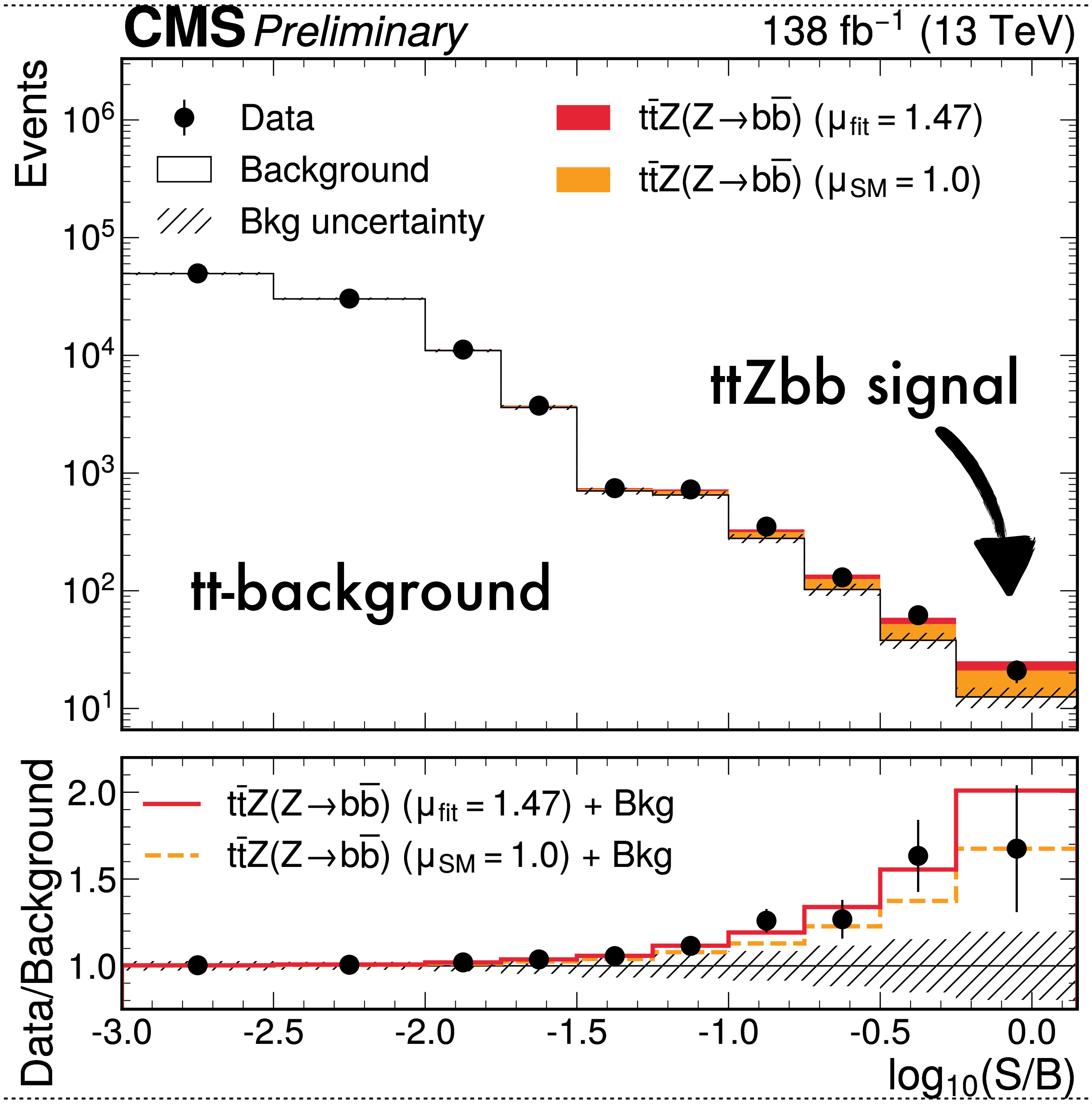
Flavor tagging strategy enables measurement of: ttHbb / ttHcc / ttZbb / ttZcc together

- Extensive using of machine learning, based on jets kinematics and flavor identification
- About **50% correct identification for signal**, about **10% mis-identification** for backgrounds

ttZbb and ttZcc validations

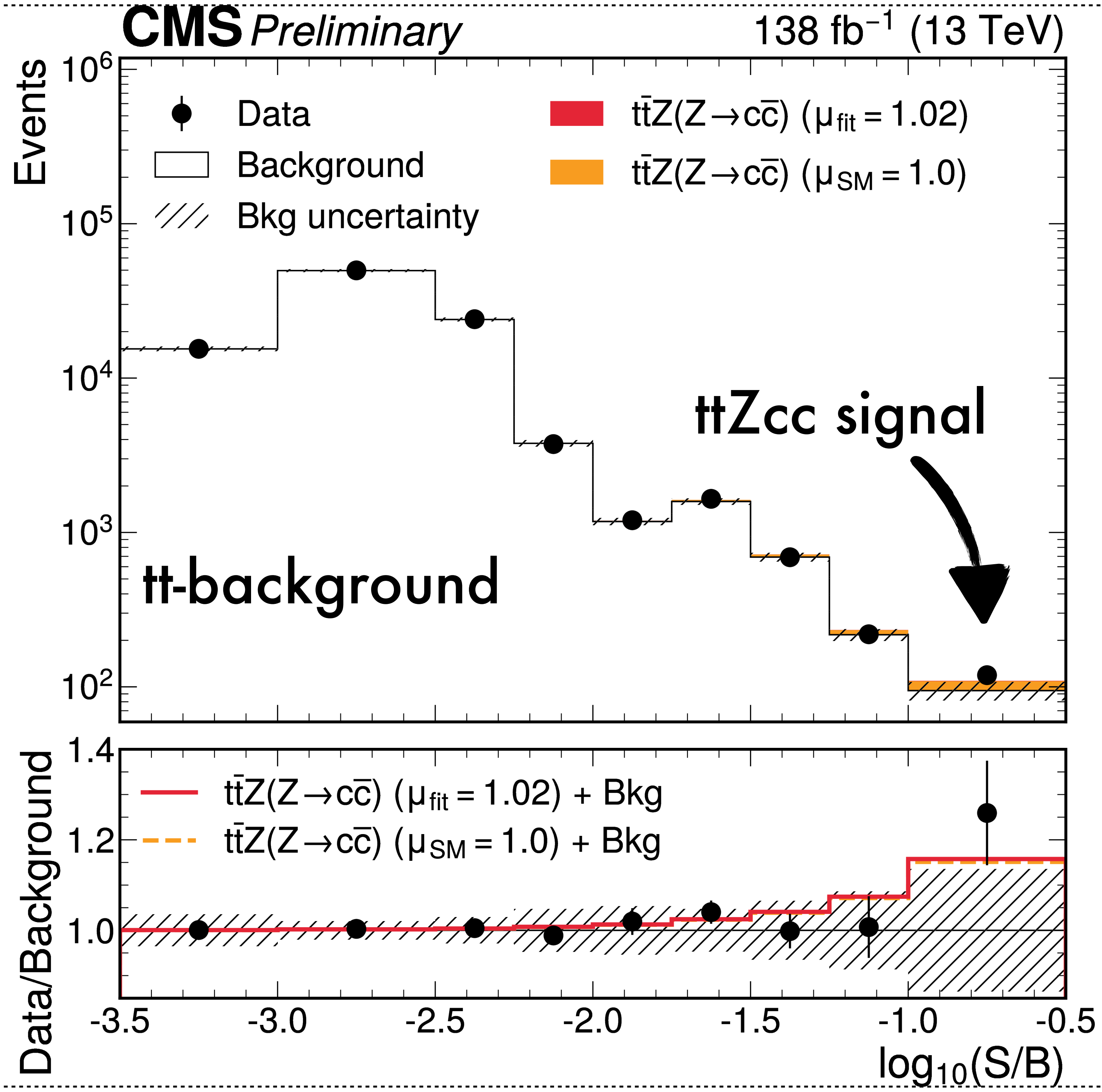
CMS-PAS-HIG-24-018

ttZbb



3.5σ

ttZcc



1.2σ

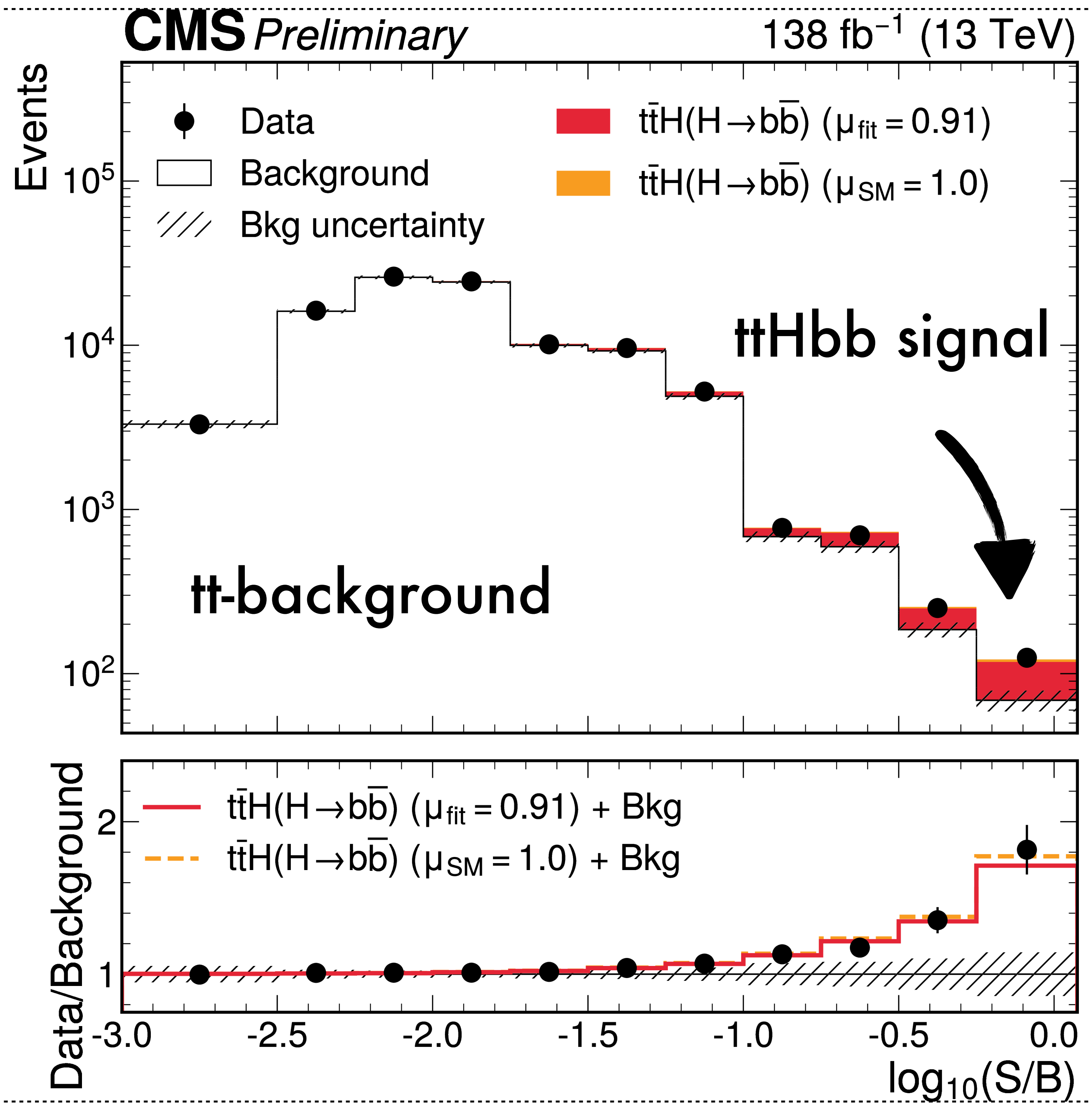
Validation: measure ttZbb and ttZcc: 3.5σ and 1.2σ (in agreement with SM prediction)

- ttZbb and ttZcc have the same decay rate
- **Difference in sensitivity arises from better b-tagging performance w.r.t c-tagging**

ttHbb and ttHcc measurements

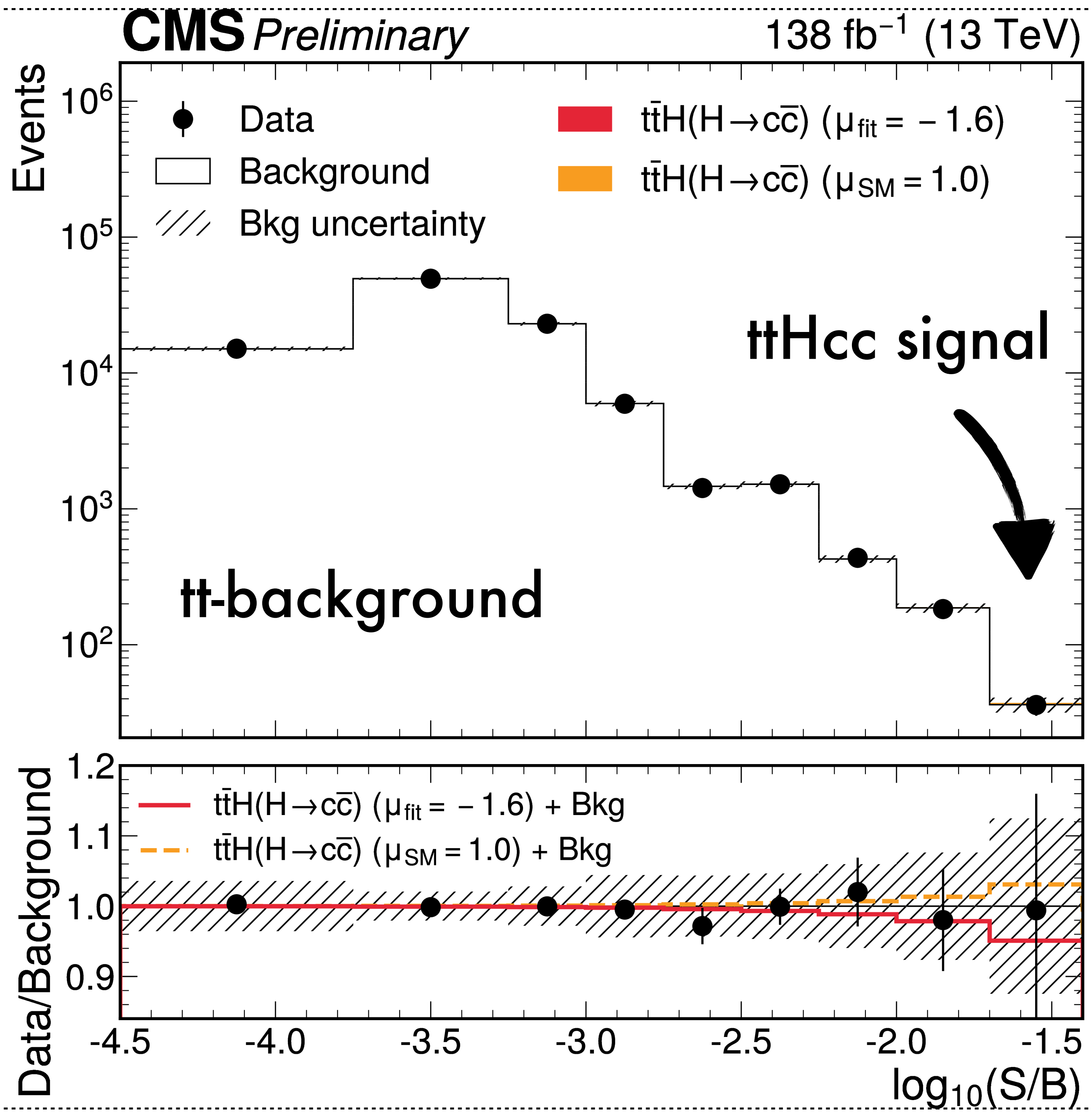
CMS-PAS-HIG-24-018

ttHbb



4.4σ

ttHcc



Upper limit: < 7.8x SM @ 95% CL

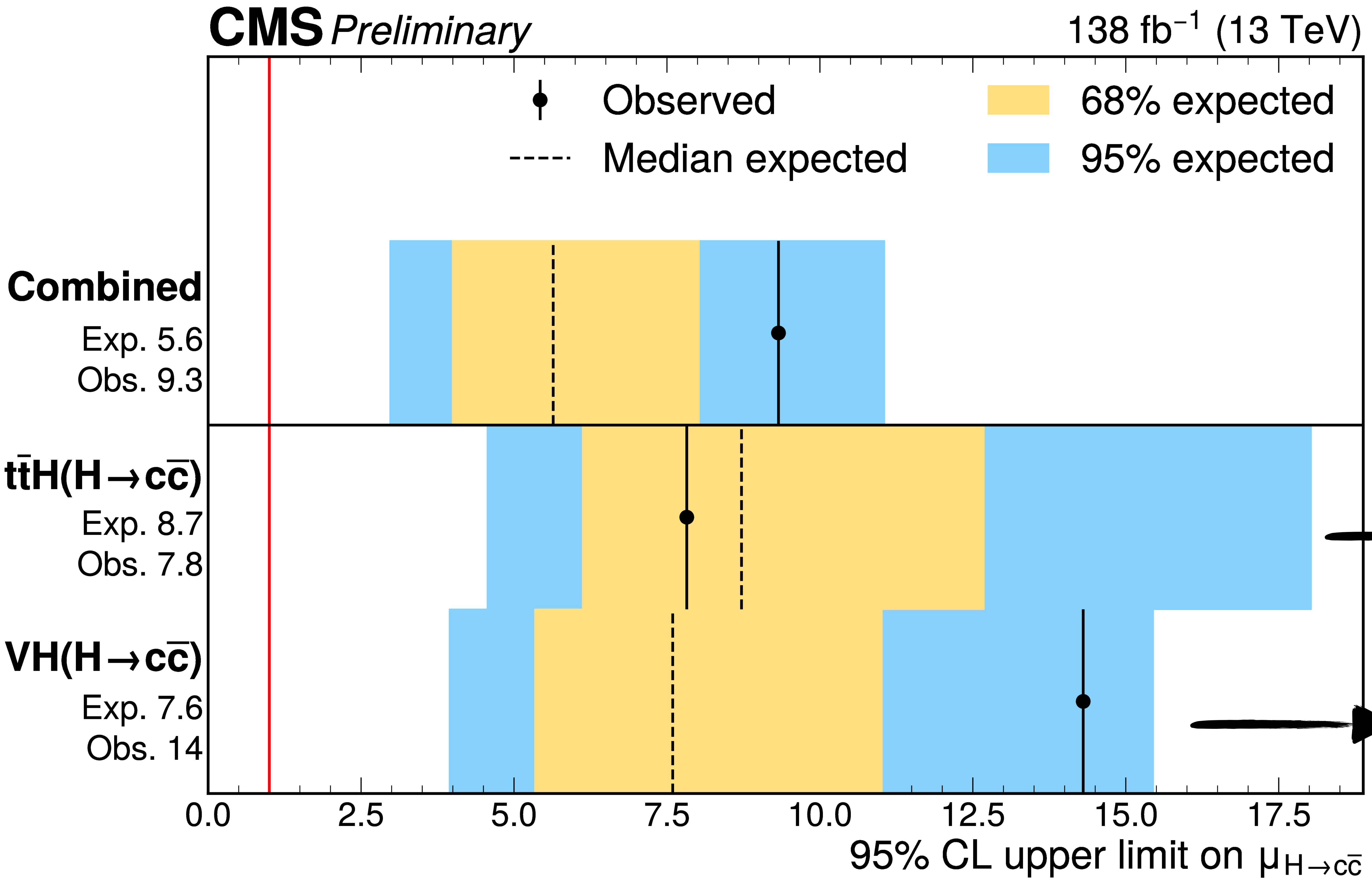
ttHbb: evidence for signal at 4.4σ in agreement with the SM prediction

ttHcc: upper limit with sensitivity of 7.8x SM prediction → first result of ttHcc at the LHC!

- Similar sensitivity between fully hadronic and semi-leptonic channel, lower sensitive for di-leptonic

Higgs-charm combination

CMS-PAS-HIG-24-018



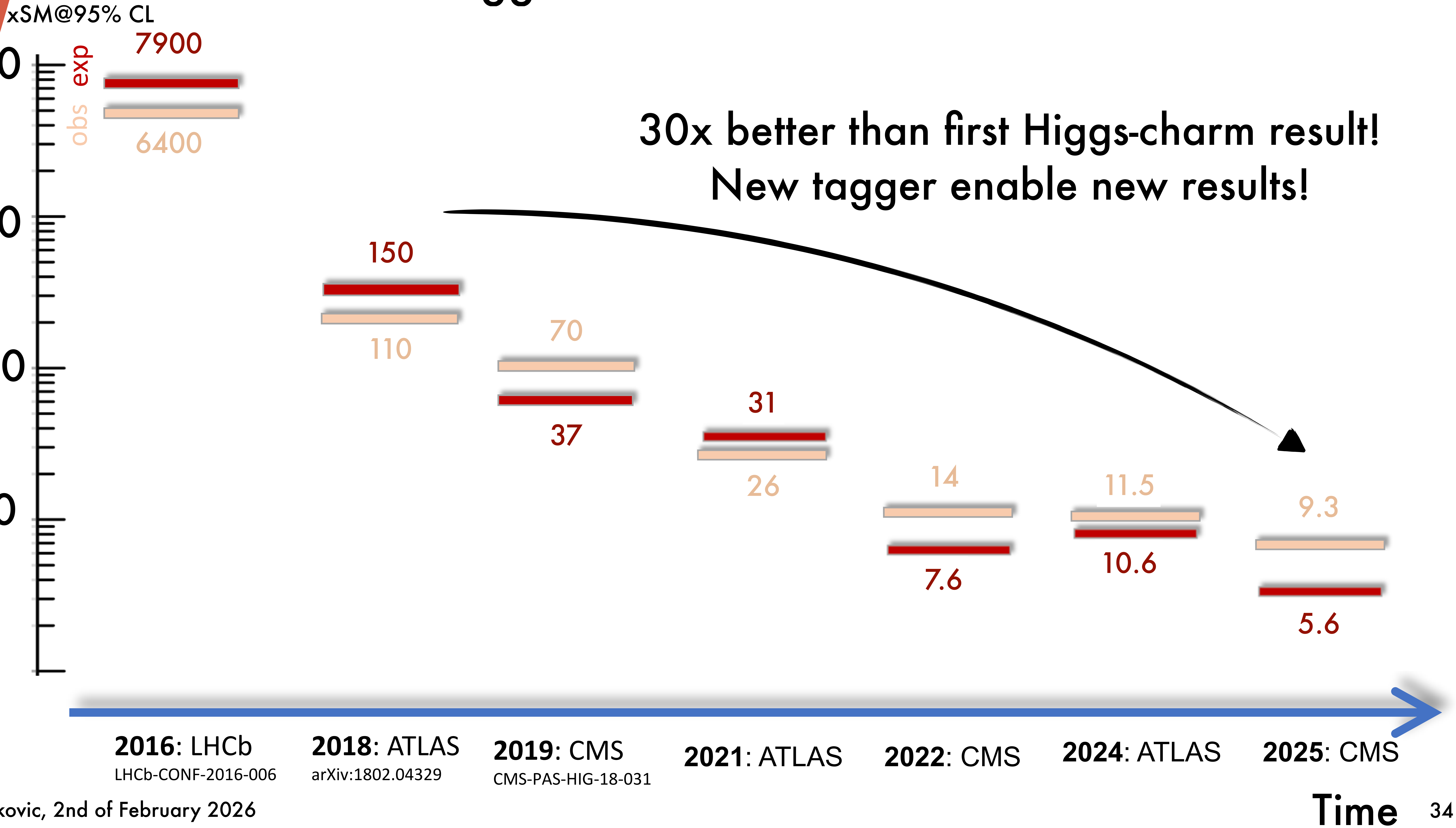
New channel!

Thought to be golden channel

Higgs-charm coupling: upper limit of 5.6 x SM prediction

- New channel ttHcc competitive with VHcc channel, thought to be golden channel!

Higgs charm evolution



30x better than first Higgs-charm result!
New tagger enable new results!

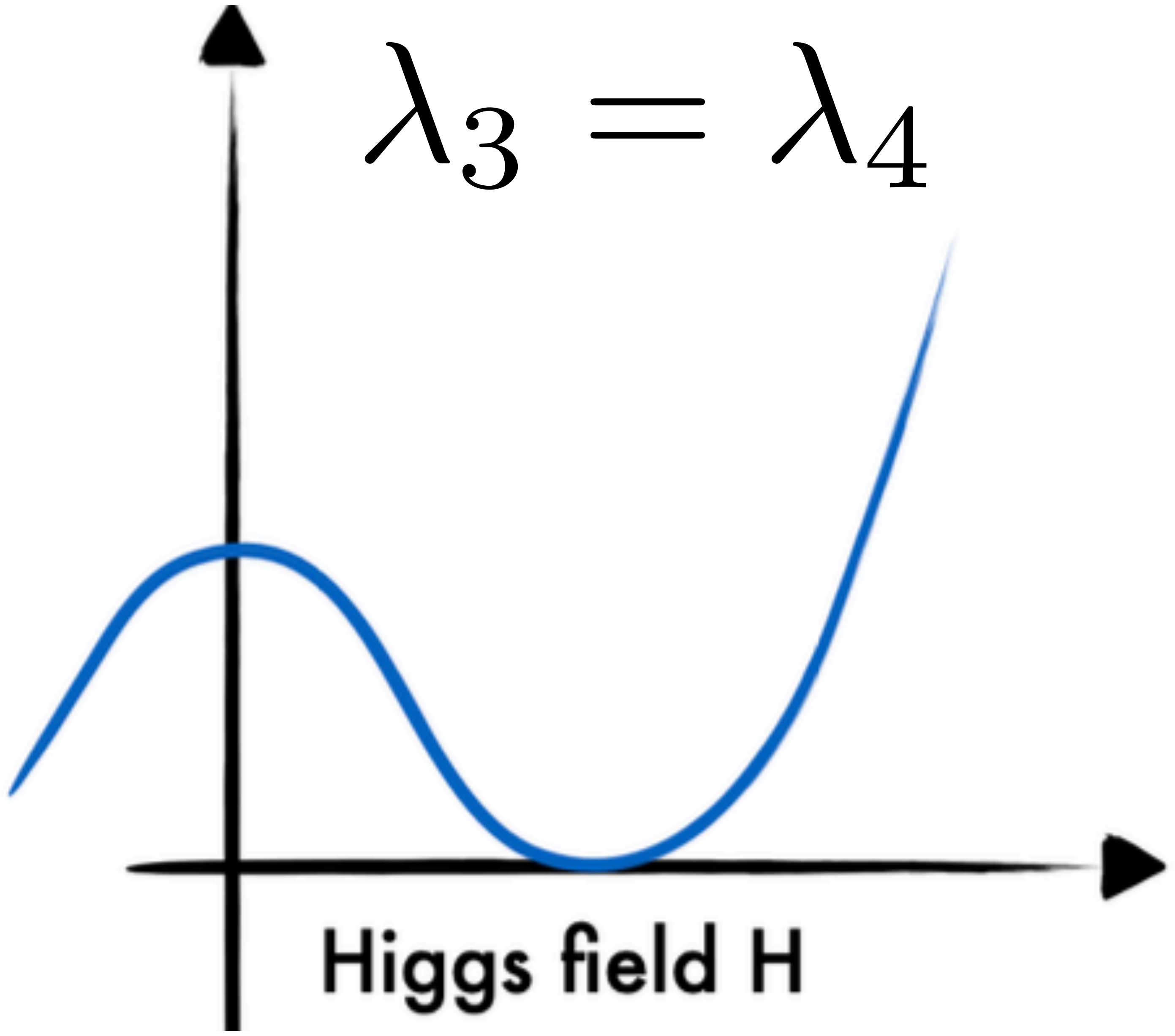
Run 2 and Run 3 HH4b

Measuring the Higgs potential: motivation

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

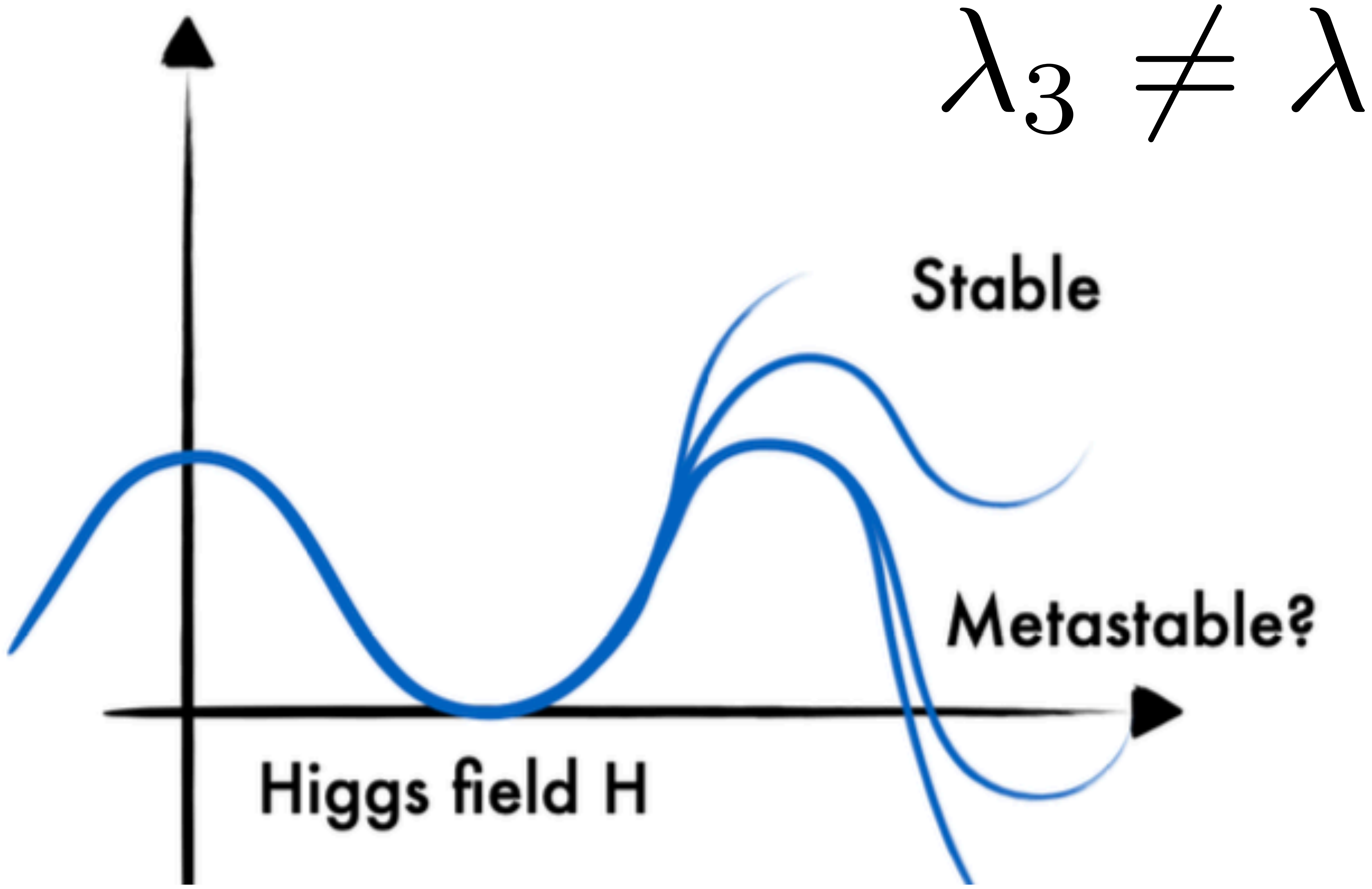
Standard Model

$$\lambda_3 = \lambda_4$$



New physics

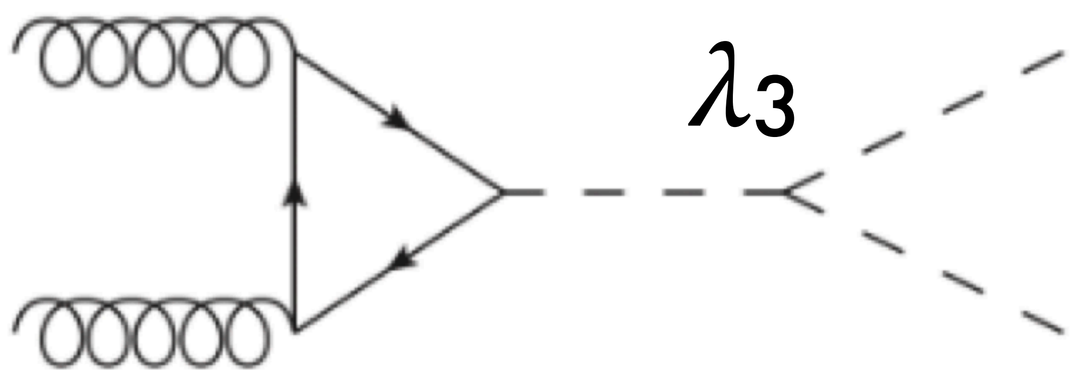
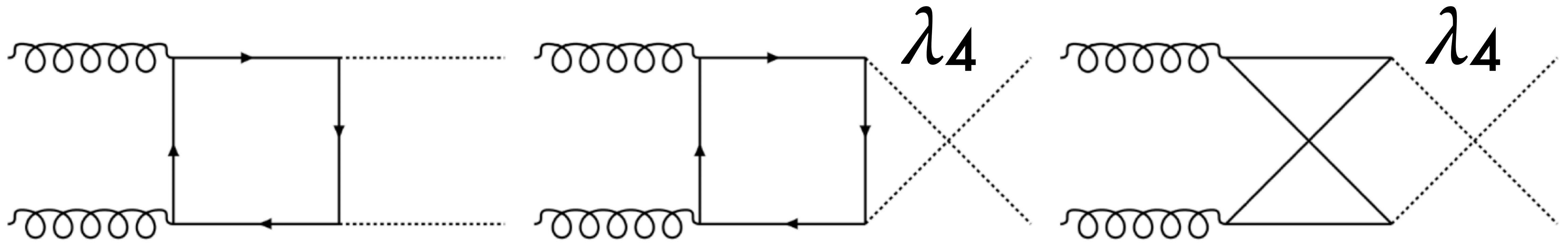
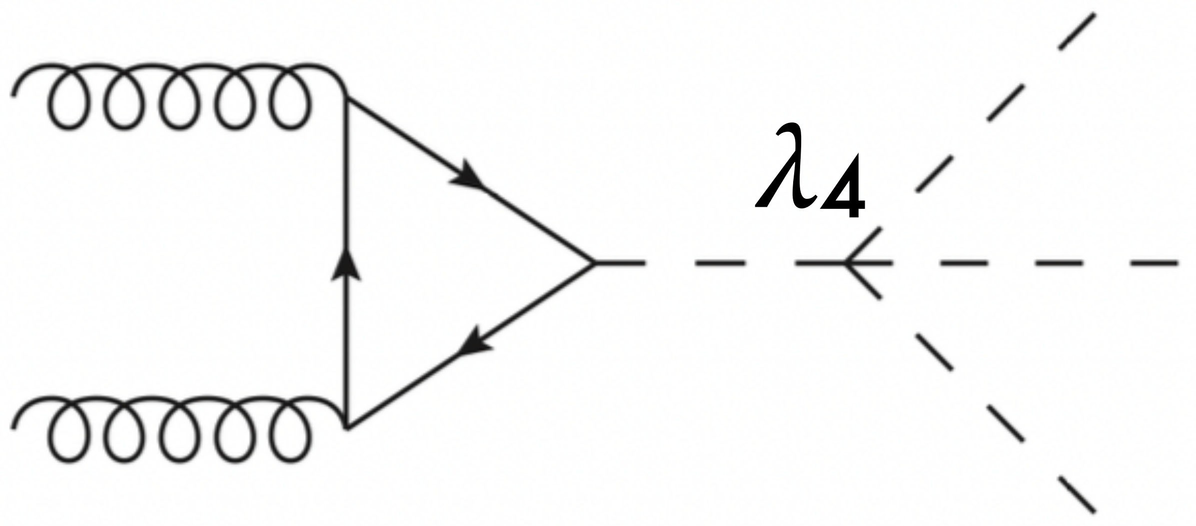
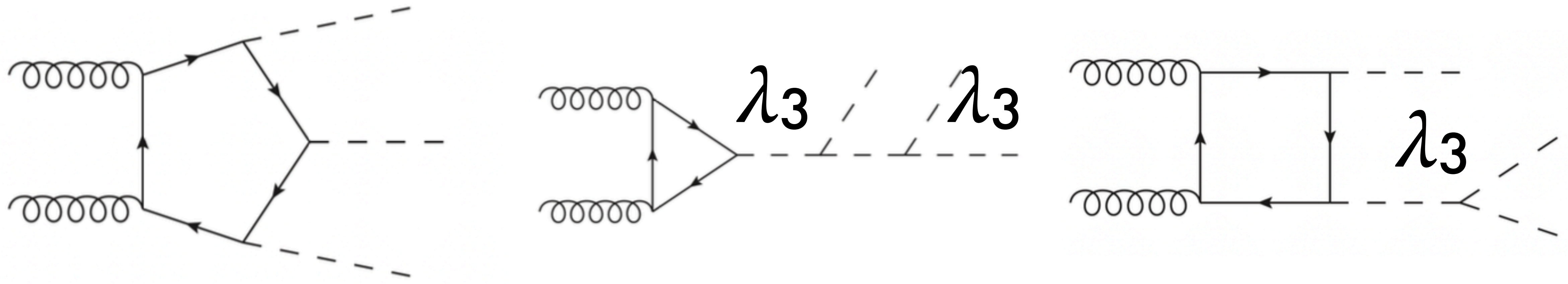
$$\lambda_3 \neq \lambda_4$$



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:

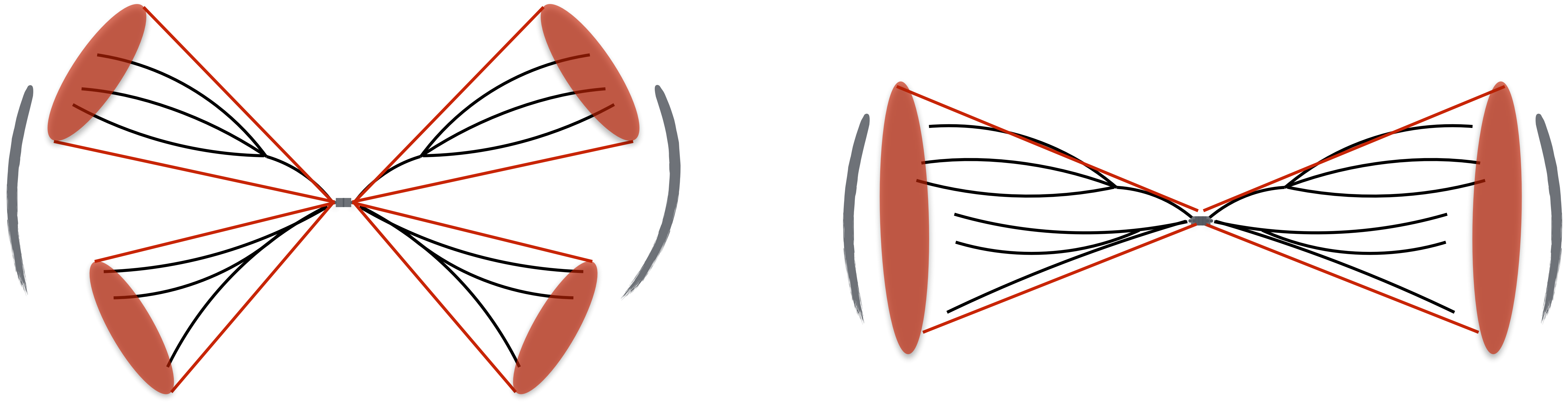
- Di-Higgs: nearly exclusively sensitive to λ_3 coupling (very small contribution from λ_4)
- Triple Higgs: sensitive to both λ_3 and λ_4 coupling

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

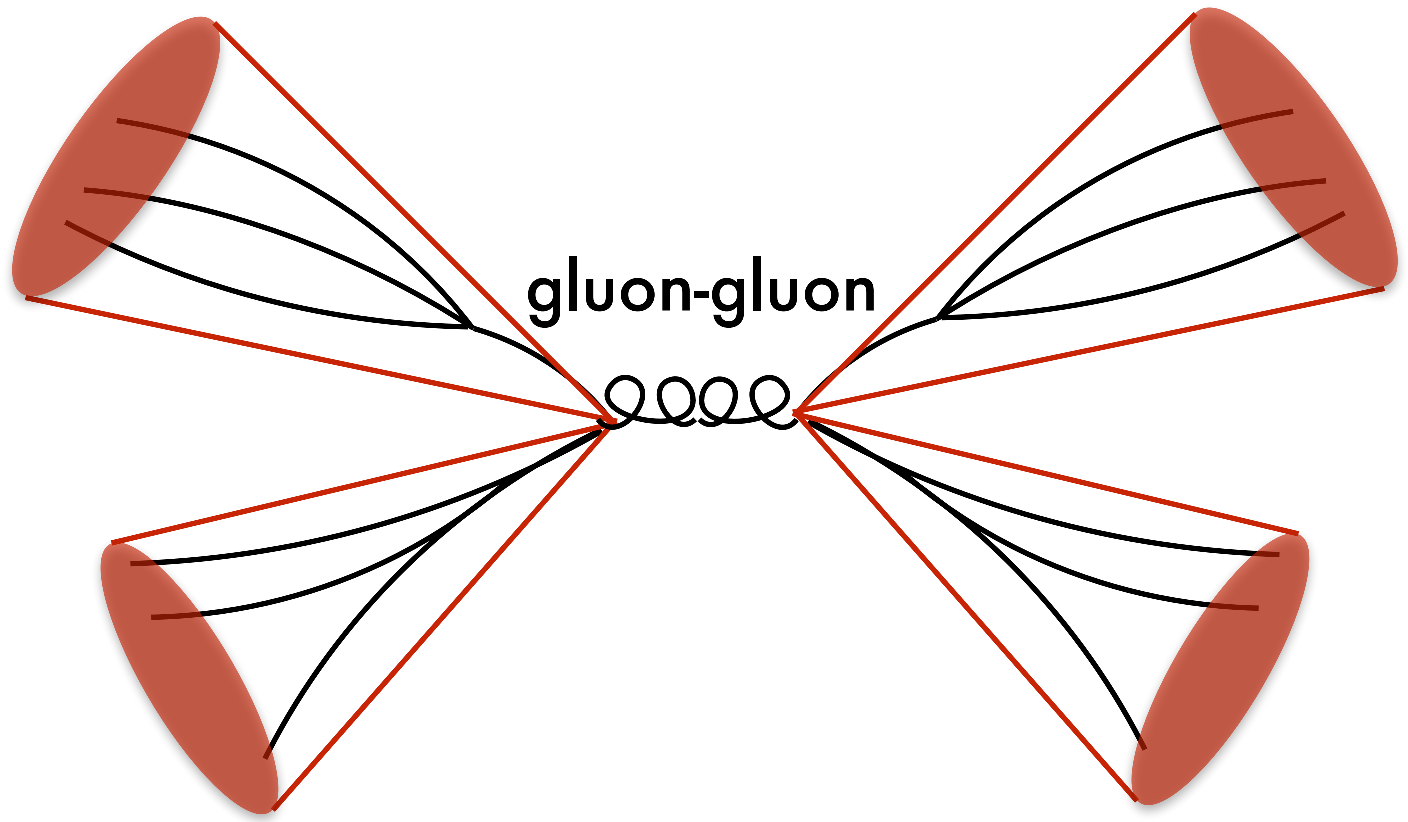
HH is at the centre of ATLAS and CMS physics program, HHH is novel and recently explored

Signal vs background: challenge

Higgs pairs production (HH)



Backgrounds



2000 events produced between 2016 and 2023

2 billion!

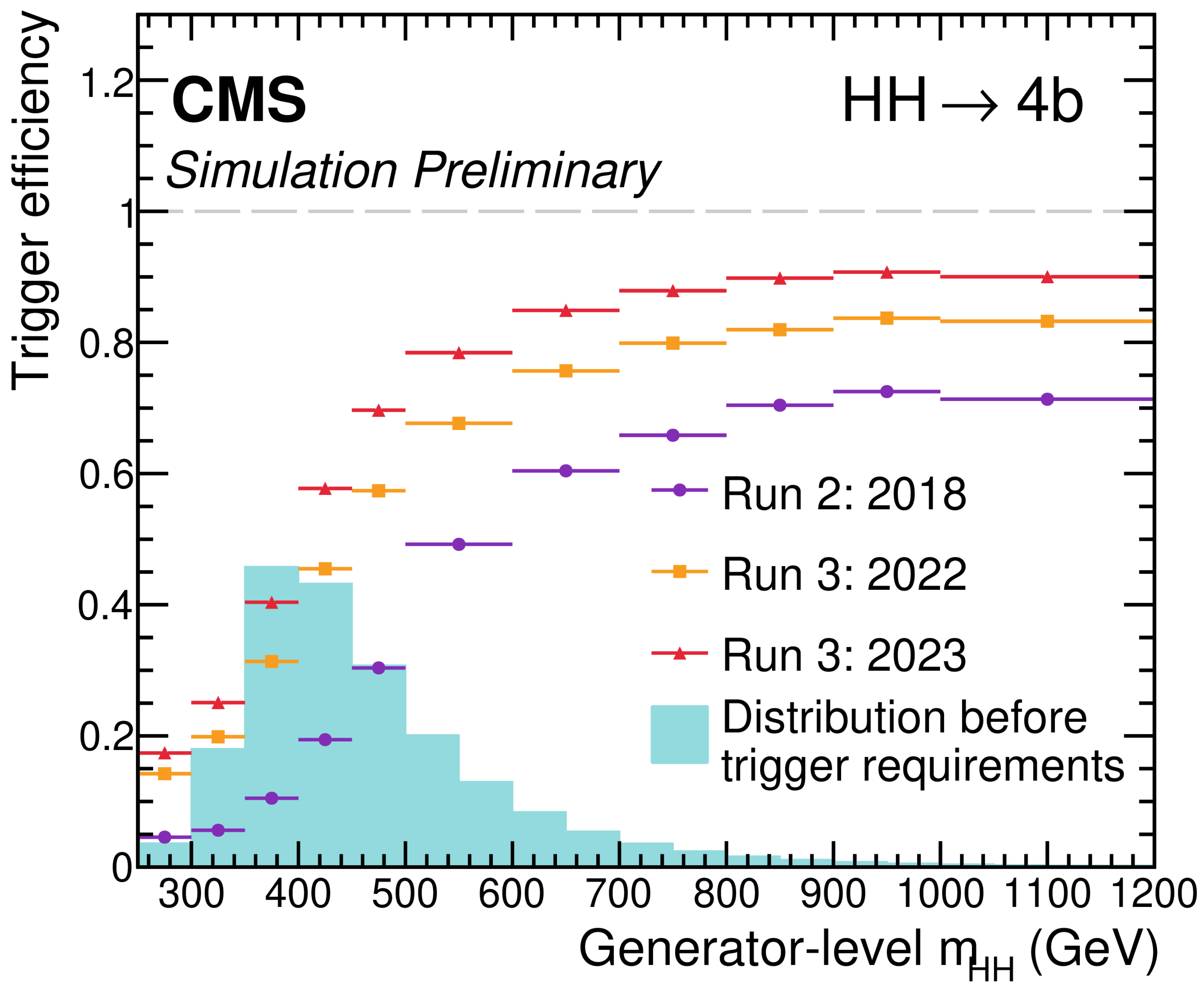
HH4b: extremely large background contamination with 4 b-jets in the final states

- Exploit HH topologies with 4 small-radius jets (resolved) and 2 large radius jets (boosted)
- Rely on pairing and correct assignment, exploiting the Higgs mass information!
- Use advanced machine learning to separate signal from background and model background
- 95% of background is from QCD multi-jets production, 5% from ttbar, other subdominant

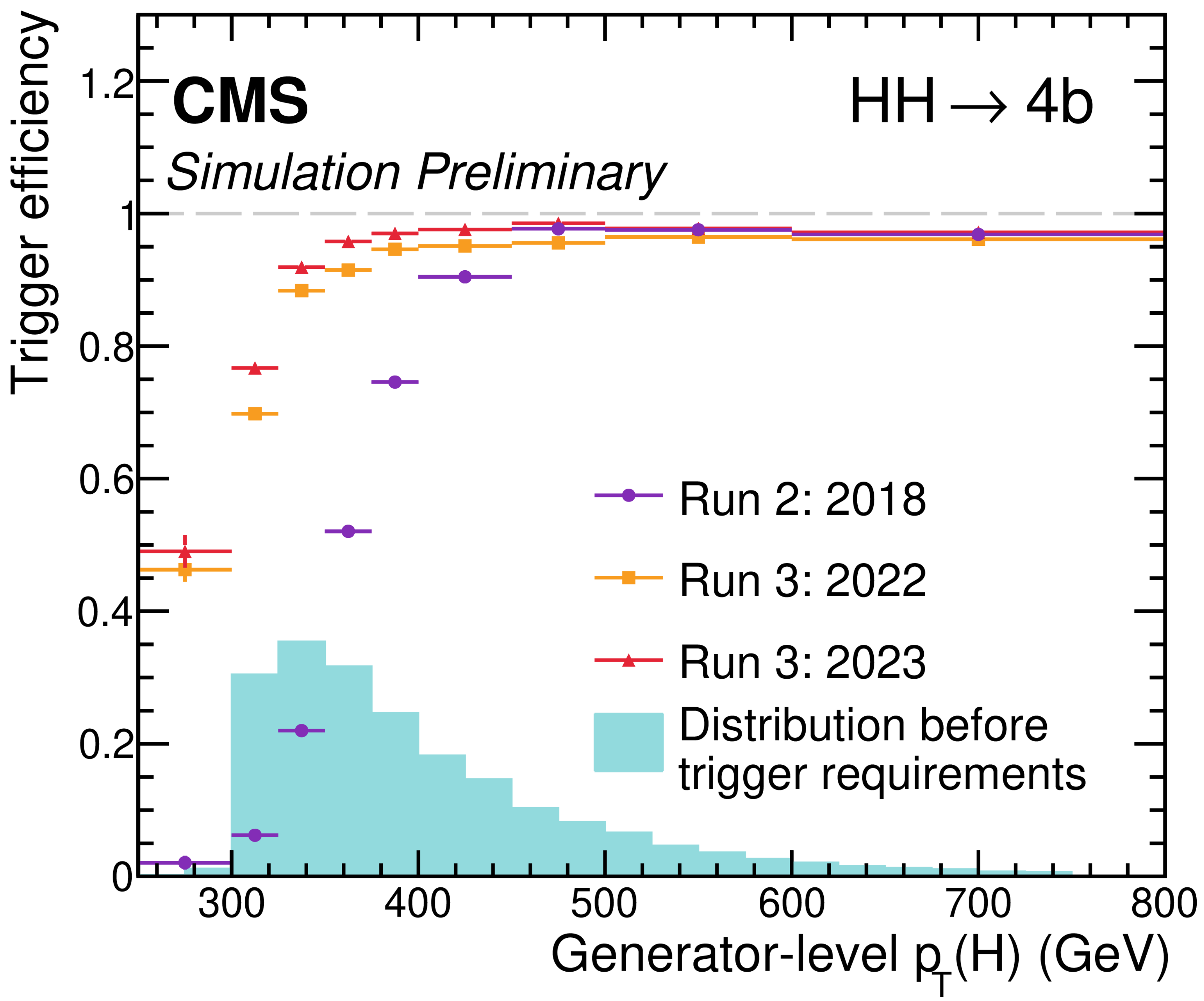
Trigger improvements

CMS-PAS-HIG-24-010

Resolved topologies



Boosted topologies

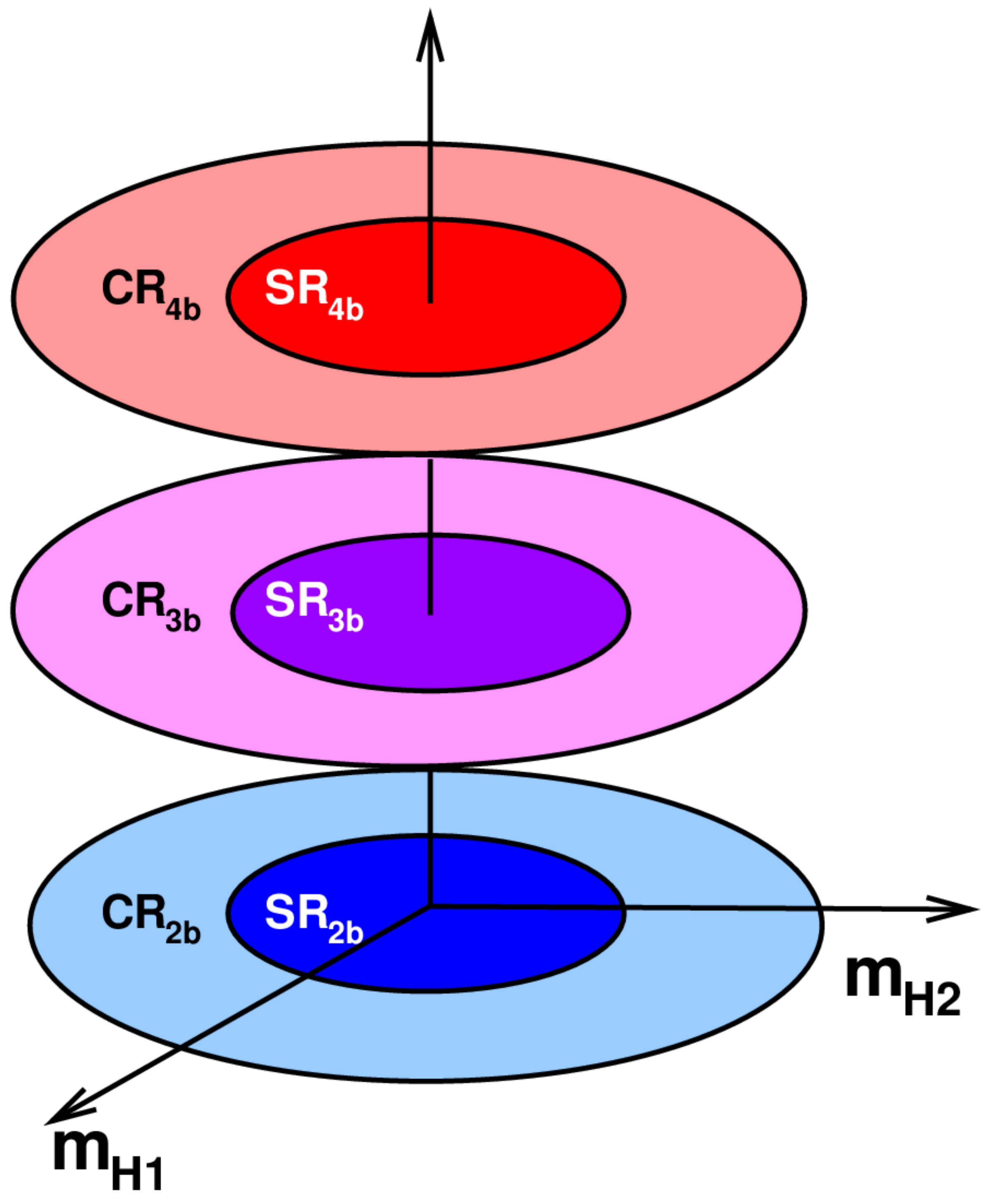


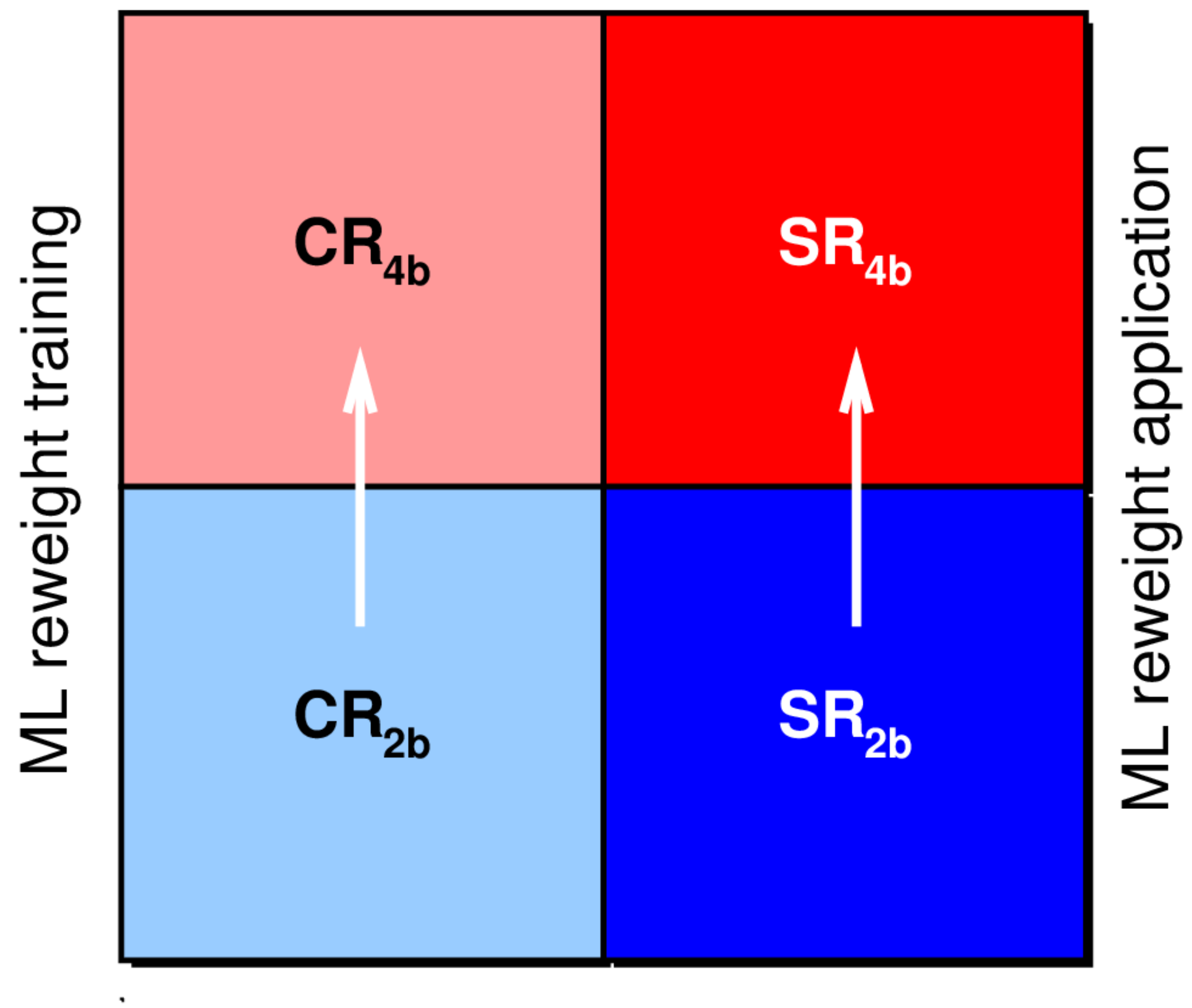
New flavor tagging incorporated in trigger for both small-radius and large radius jets

- Main limitations at trigger, large c-jets and light-jets background
- Better tagging enables higher efficiency for same rates
- More bandwidth allocated at the trigger level
  - When flavor anomalies from LHCb started disappearing, larger rate available for HH in CMS!
- Recording **50-70% more events at the trigger level,** allowing **large gains at analysis level**

Analysis strategy

CMS-PAS-HIG-24-010





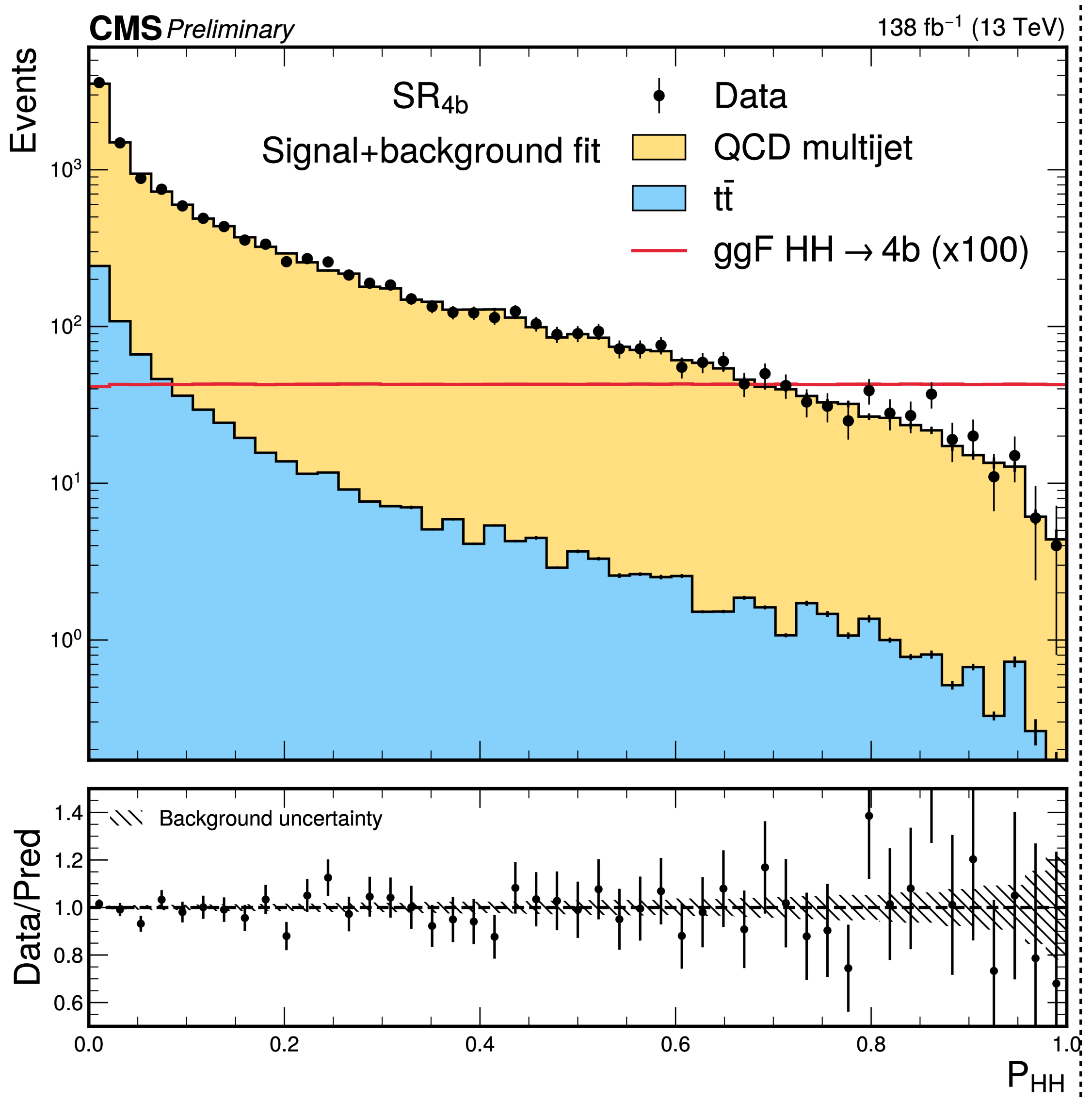
Exploit mass of two Higgs candidates to build signal and control regions:

- Large multi-jet background estimated in data-driven way
  - Control regions: machine learning to morph 2 b-tag data events to look like 4 b-tags
  - Apply in 2 b-tag signal region to estimate shape in 4 b-tag
  - 2 b-tag region available thanks to new triggers!
- Signal vs background: train second machine learning algorithm to separate signal vs data prediction
- Similar strategy used in both resolved and boosted topologies

Data / background model comparison

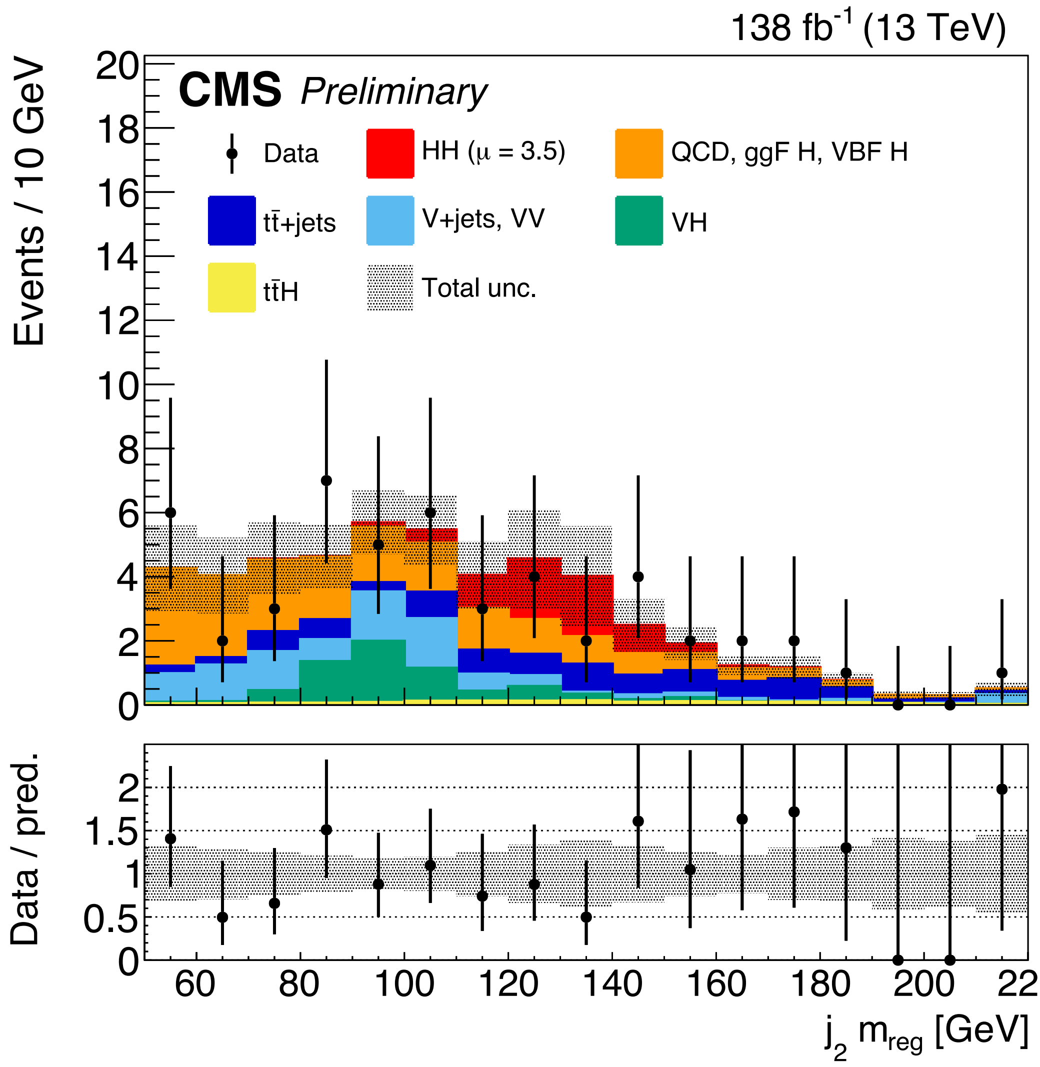
CMS-PAS-HIG-24-010

Run 2 resolved



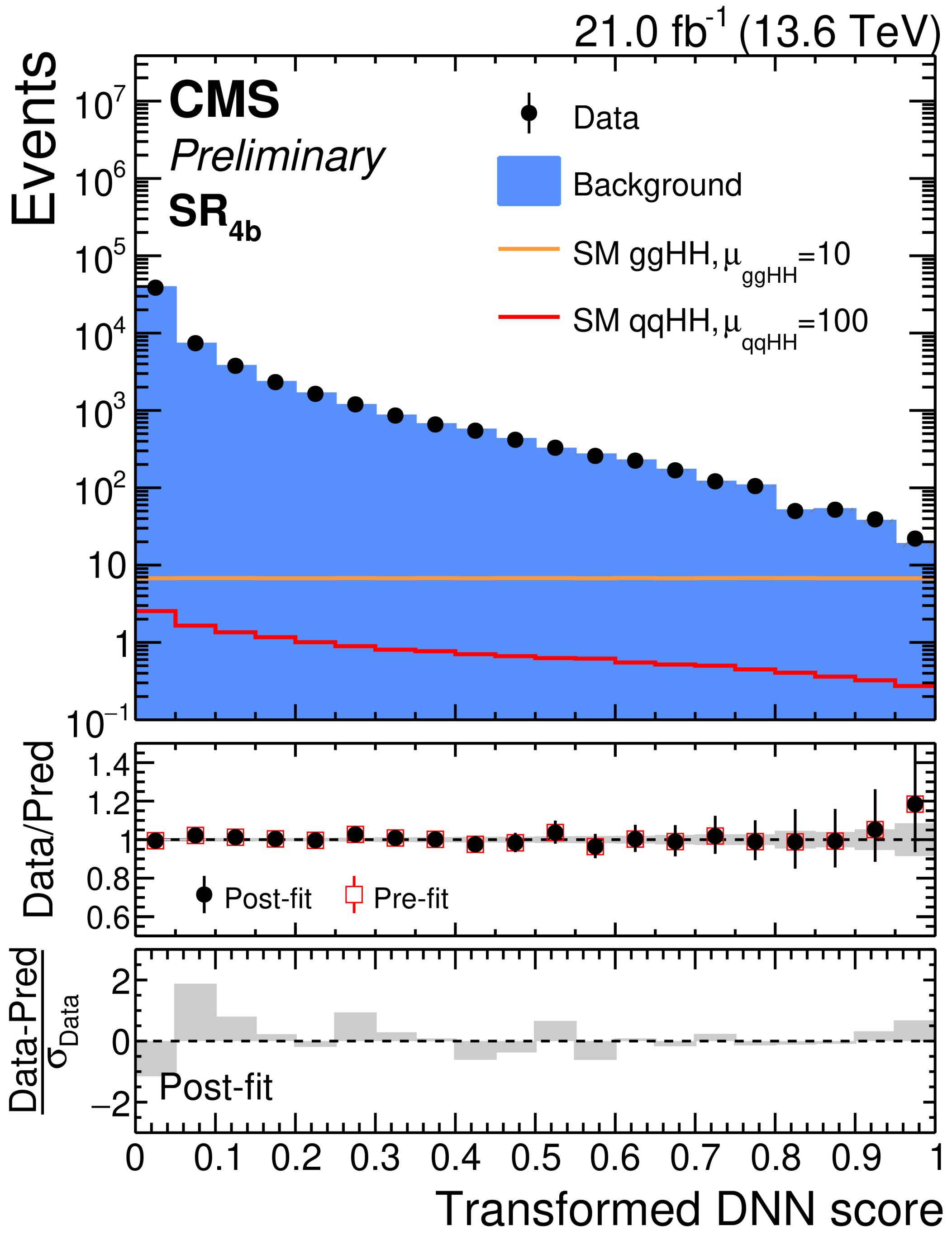
Upper limit < 5.9 x SM

Run 2 boosted



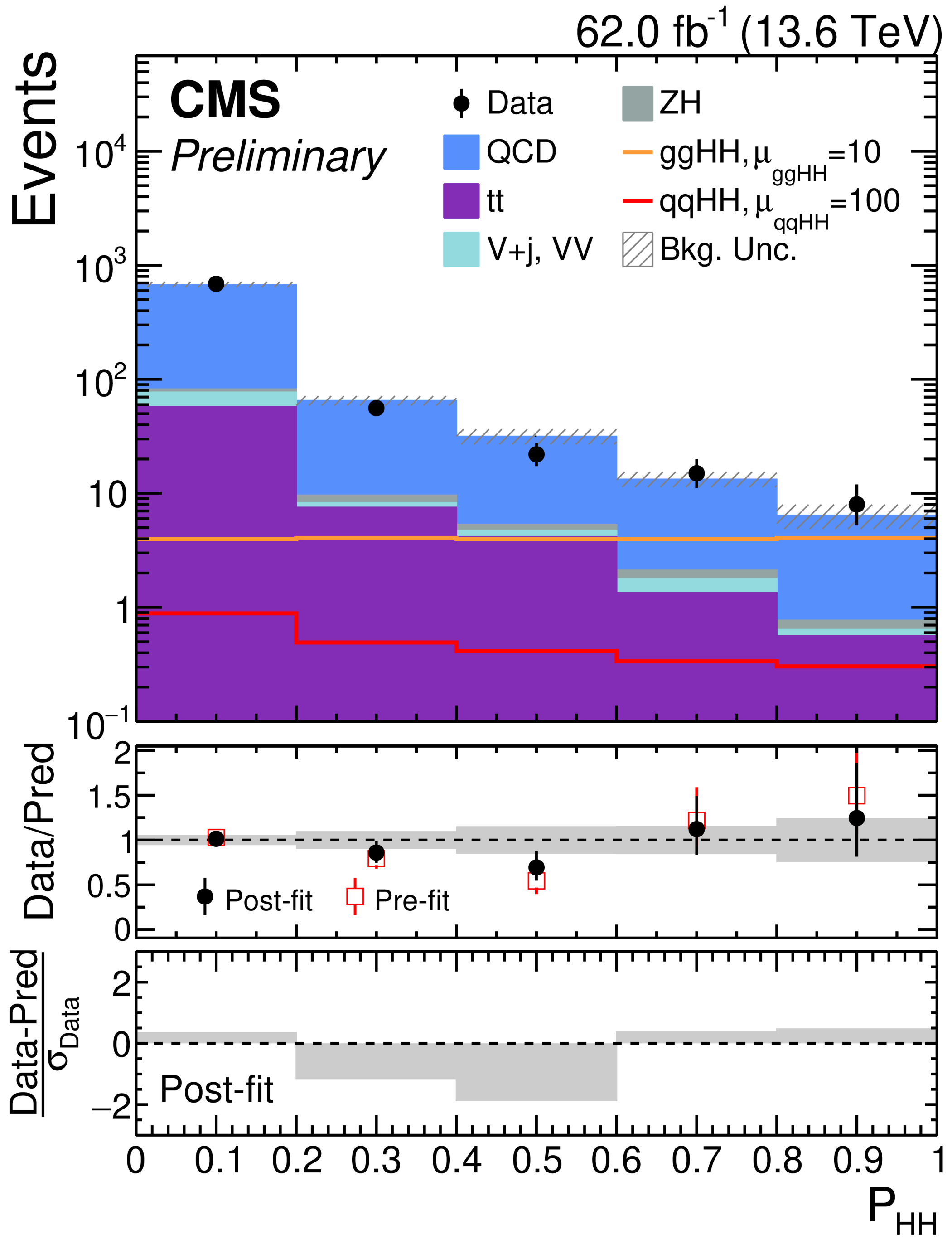
Upper limit < 5.5 x SM

Run 3 resolved



Upper limit < 5.5 x SM

Run 3 boosted



Upper limit < 8.1 x SM

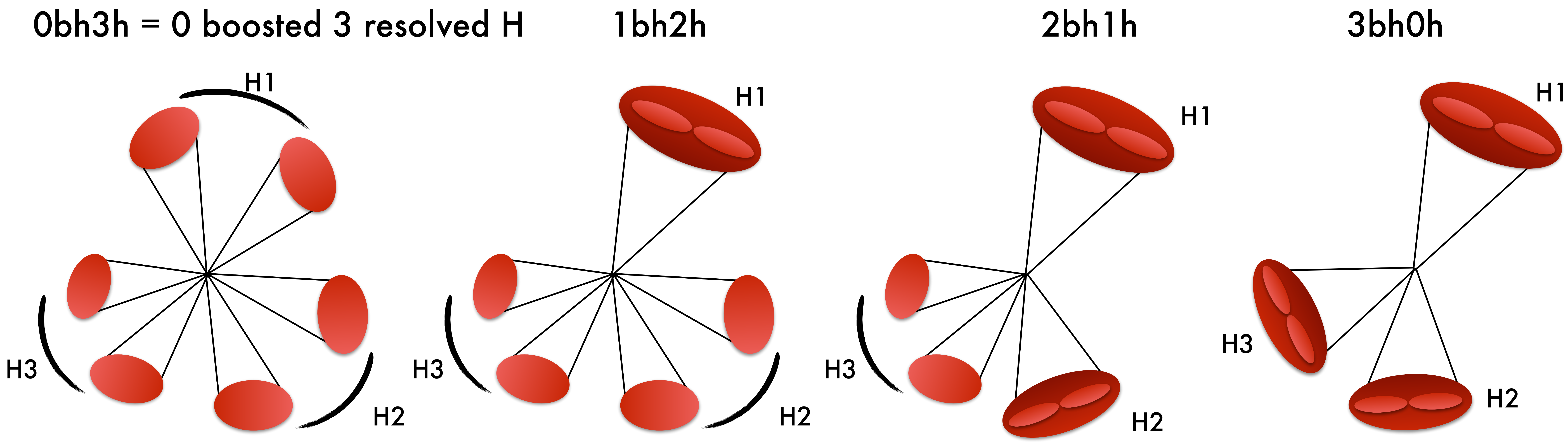
Run 3 (61 fb-1) strategy is **as sensitive as Run 2 (140 fb-1) with half the dataset!**

- Large improvement enabled by new flavor tagging and trigger strategy
- Naive combination of Run 2 and Run 3: **about 2.8 x SM**, one of the most sensitive channels at the LHC!
- Enables to **accelerate** the **HH and Higgs self-coupling discovery**!

Run 2 HHH6b

Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012



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**

Reconstructible Higgs in **AK8**	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%

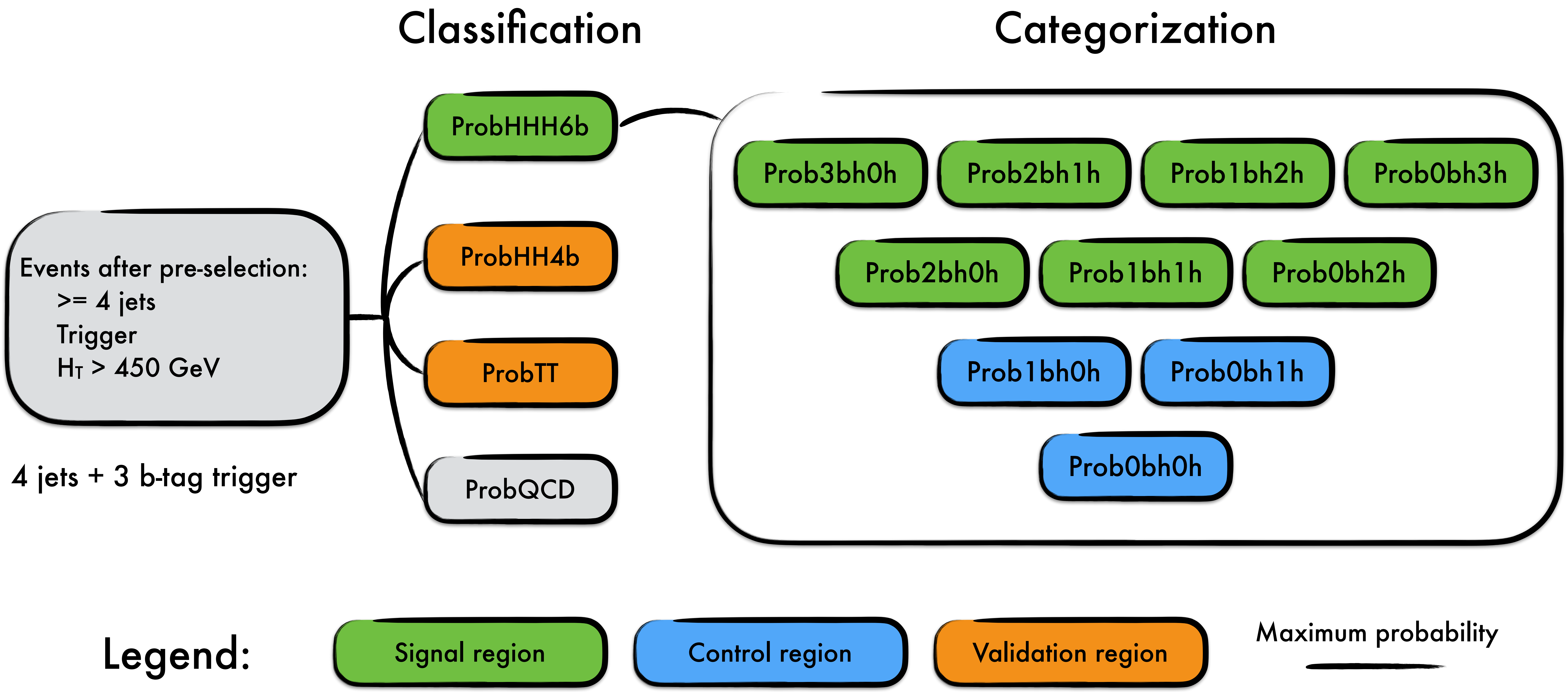
3Higgs **27%**

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

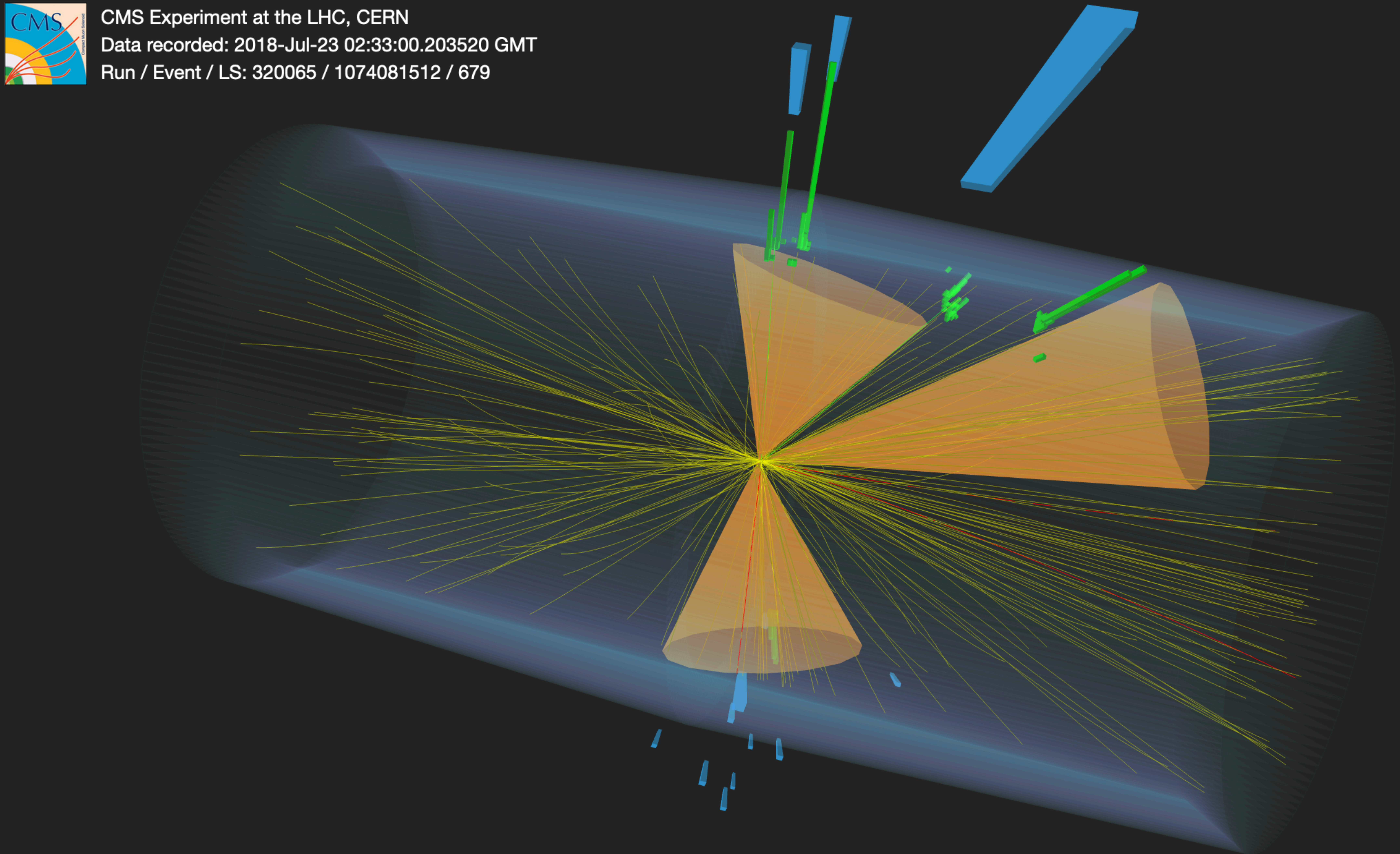
Prob0bh0h

Legend: 🟩 Signal region 🟦 Control region 🟧 Validation region — Maximum probability

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

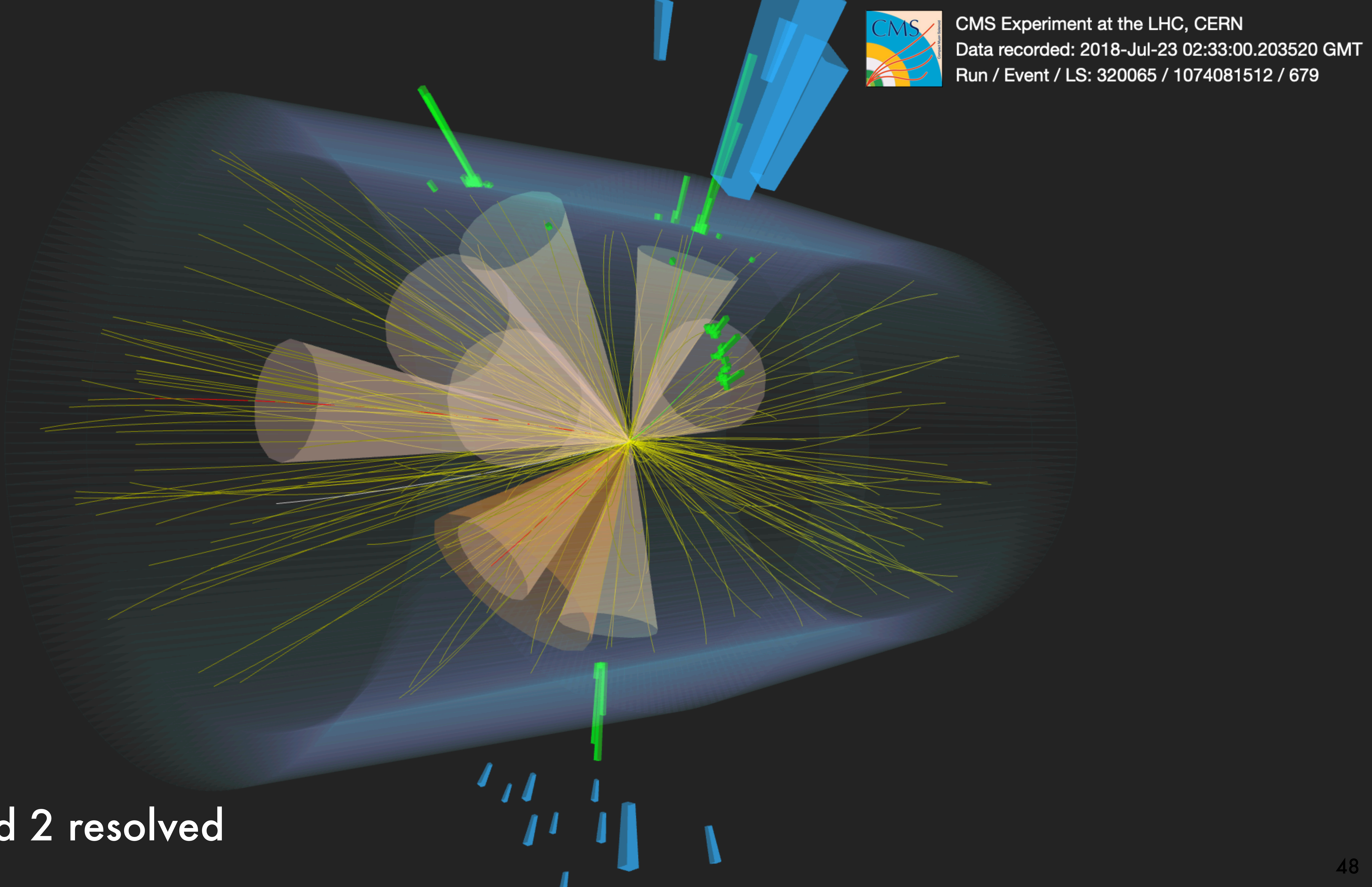
Train two machine learning networks (attention network) used

- 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



3 boosted 0 resolved

2 boosted 1 resolved



1 boosted 2 resolved

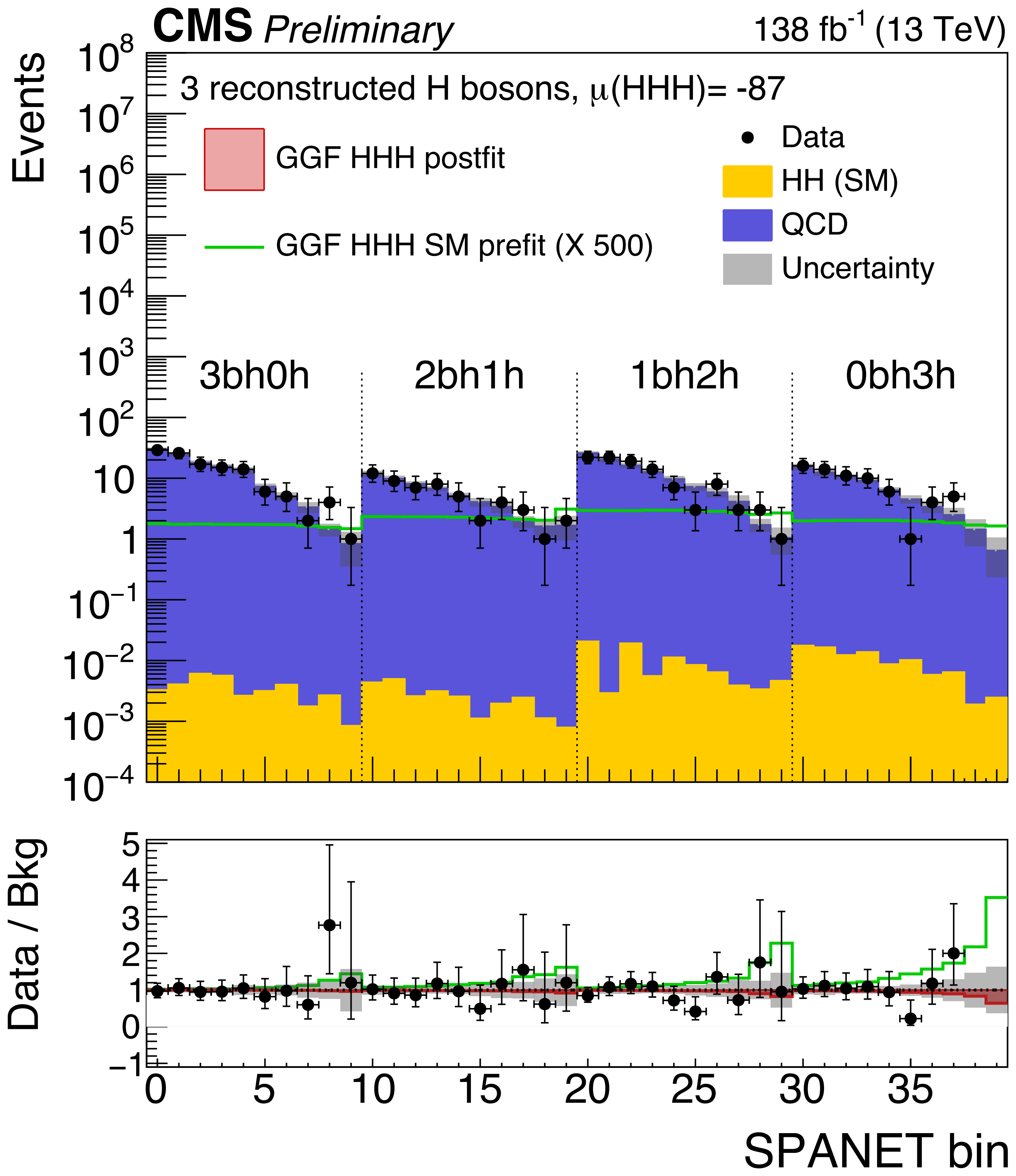
0 boosted 3 resolved

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

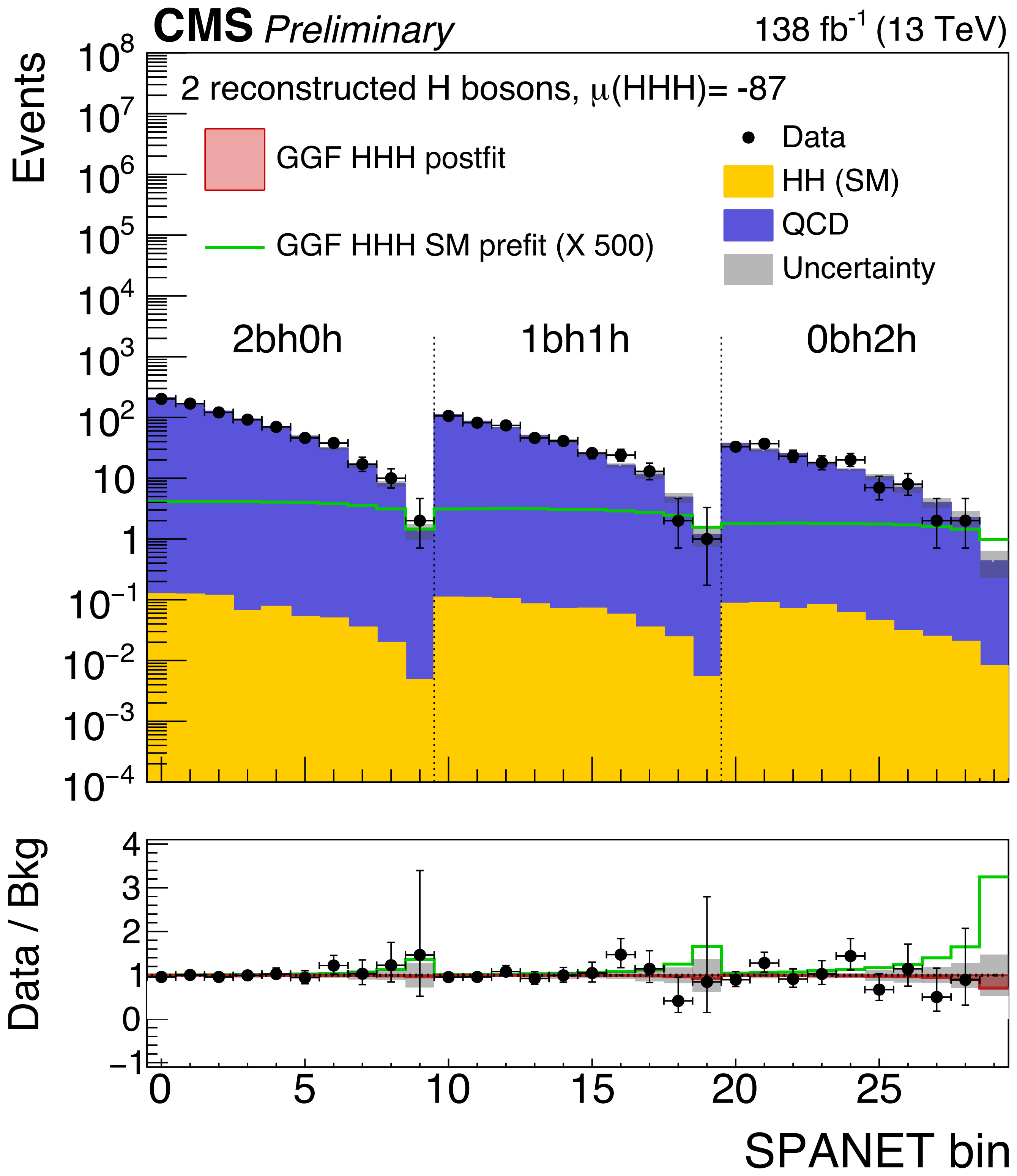
Non-resonant $HHH \to 6b$

CMS-PAS-HIG-24-012

3 reconstructed Higgs bosons



2 reconstructed Higgs bosons



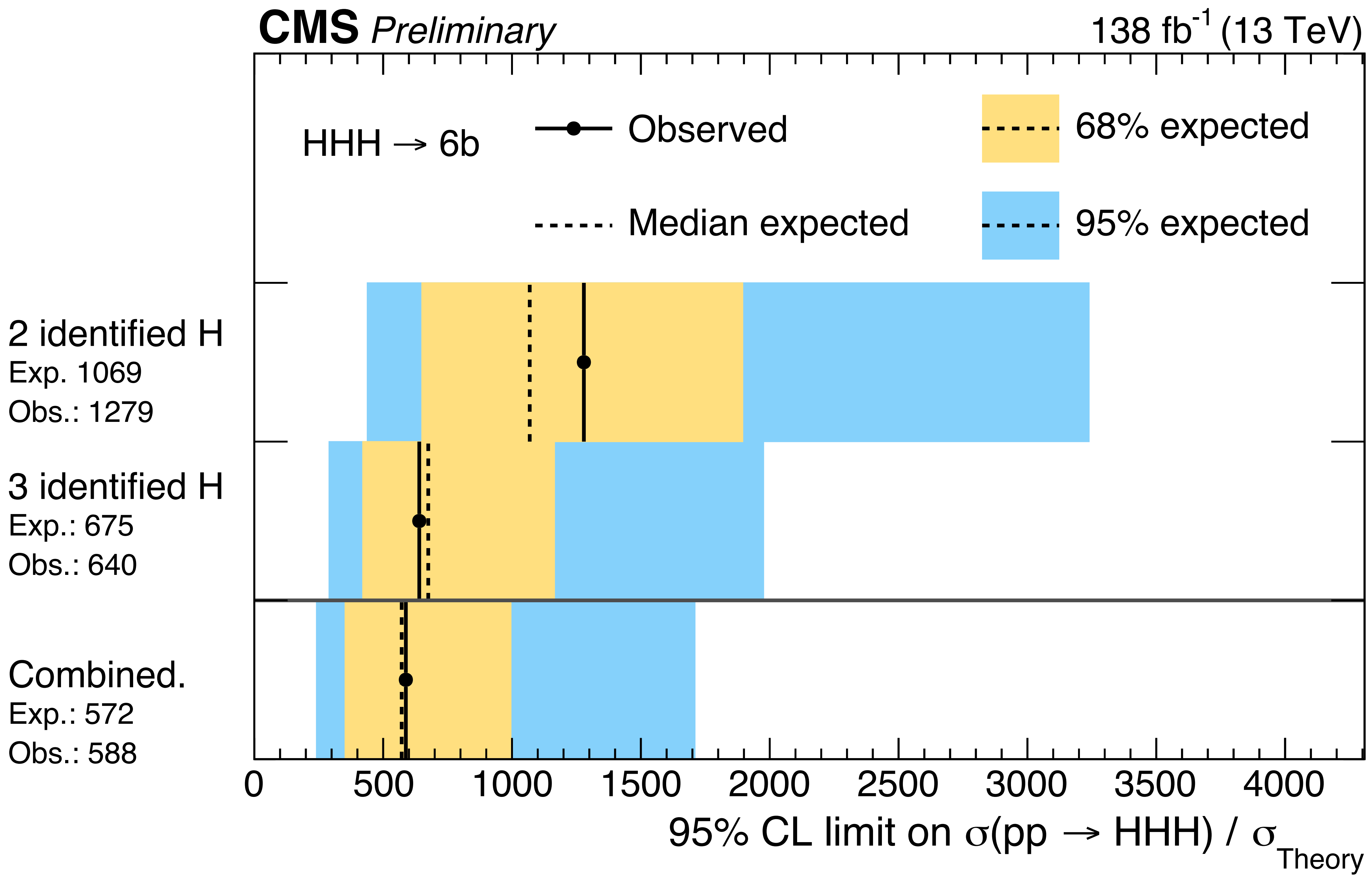
Background modeling: data driven approach due to overwhelming QCD

- 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

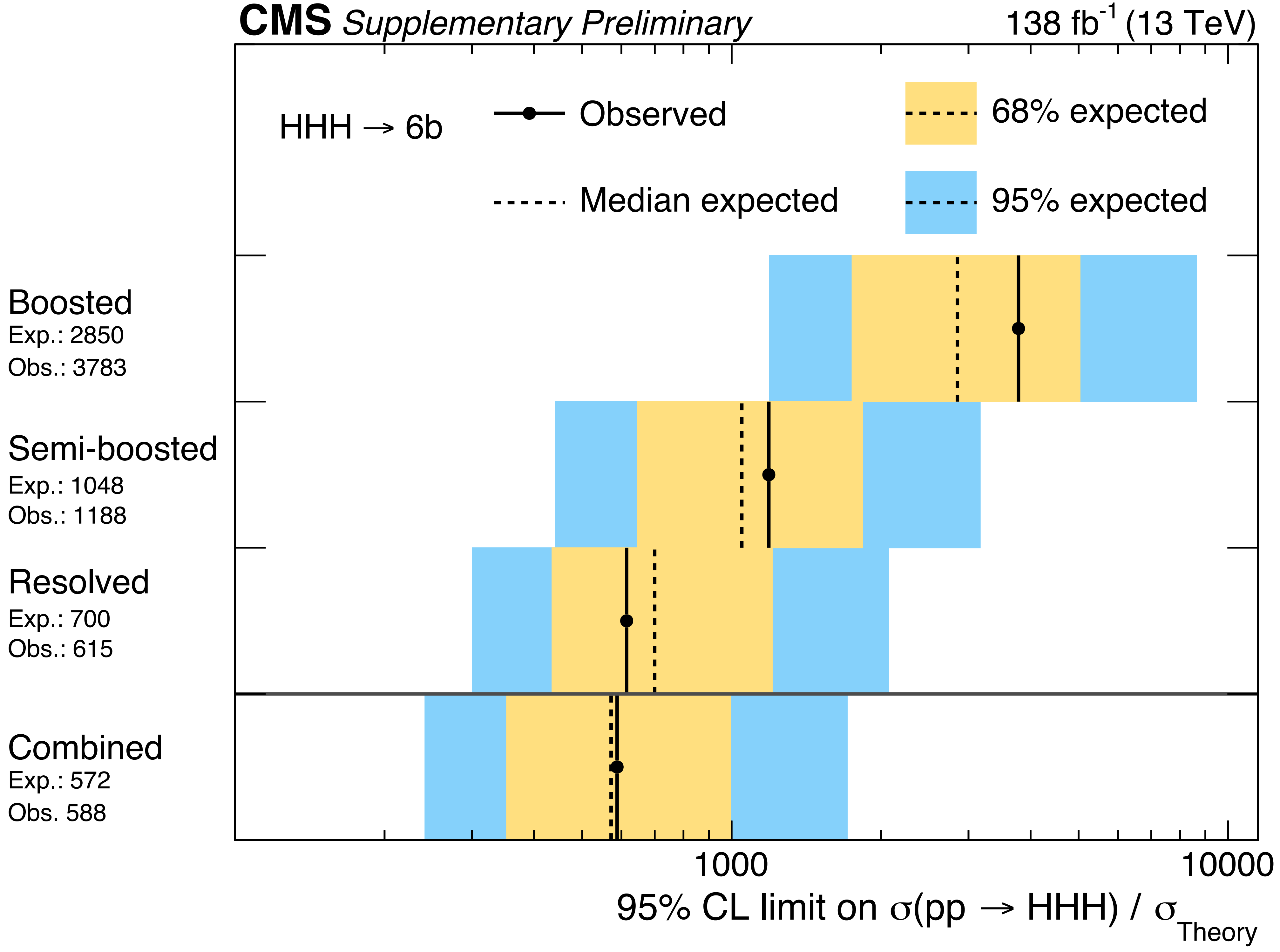
Non-resonant $HHH \rightarrow 6b$

CMS-PAS-HIG-24-012

Categories breakdown



Topology breakdown



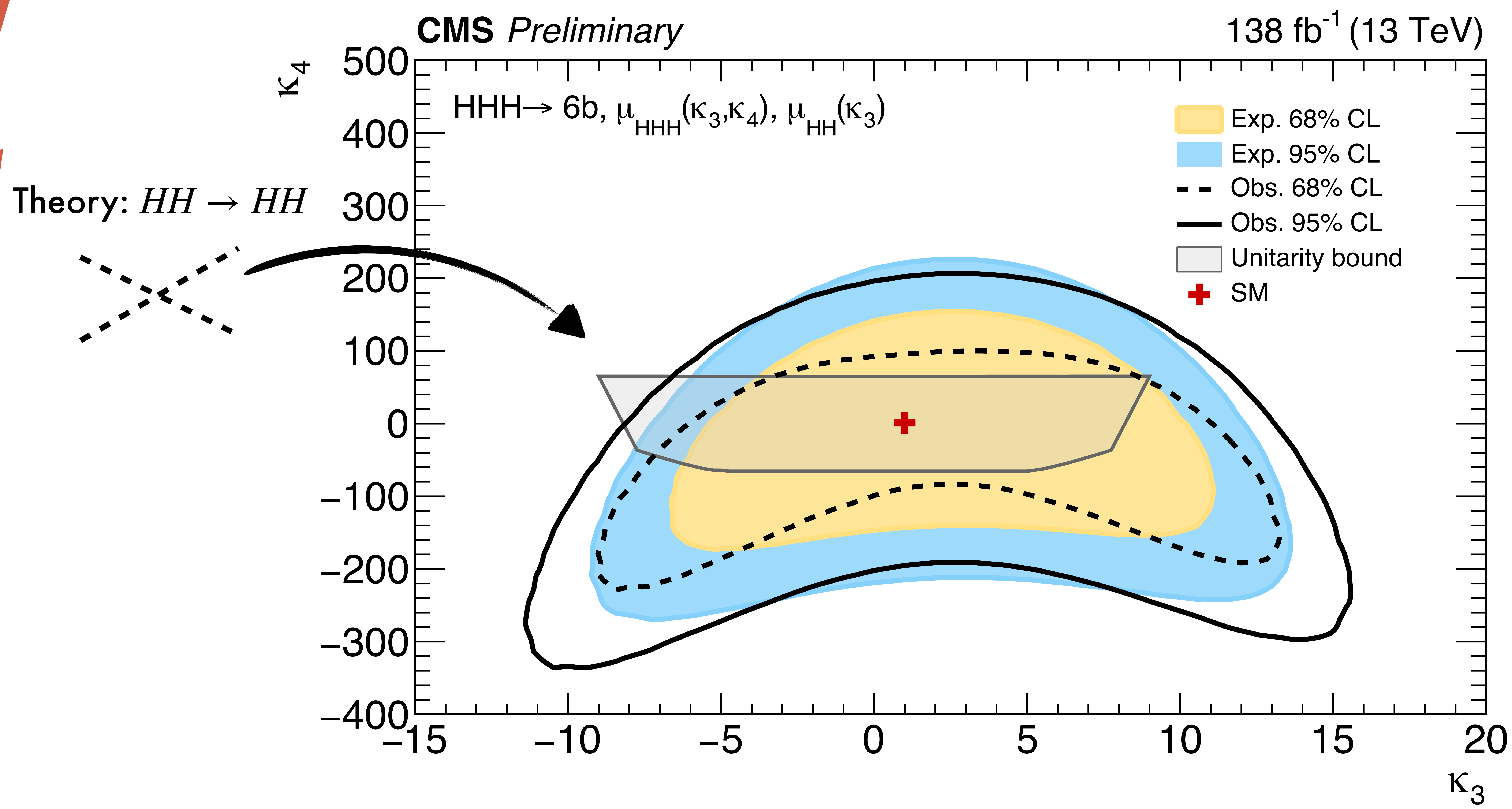
Result: observed (expected) limit of $\mu < 588\ (572)$ x the SM at 95% CL

- 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!

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

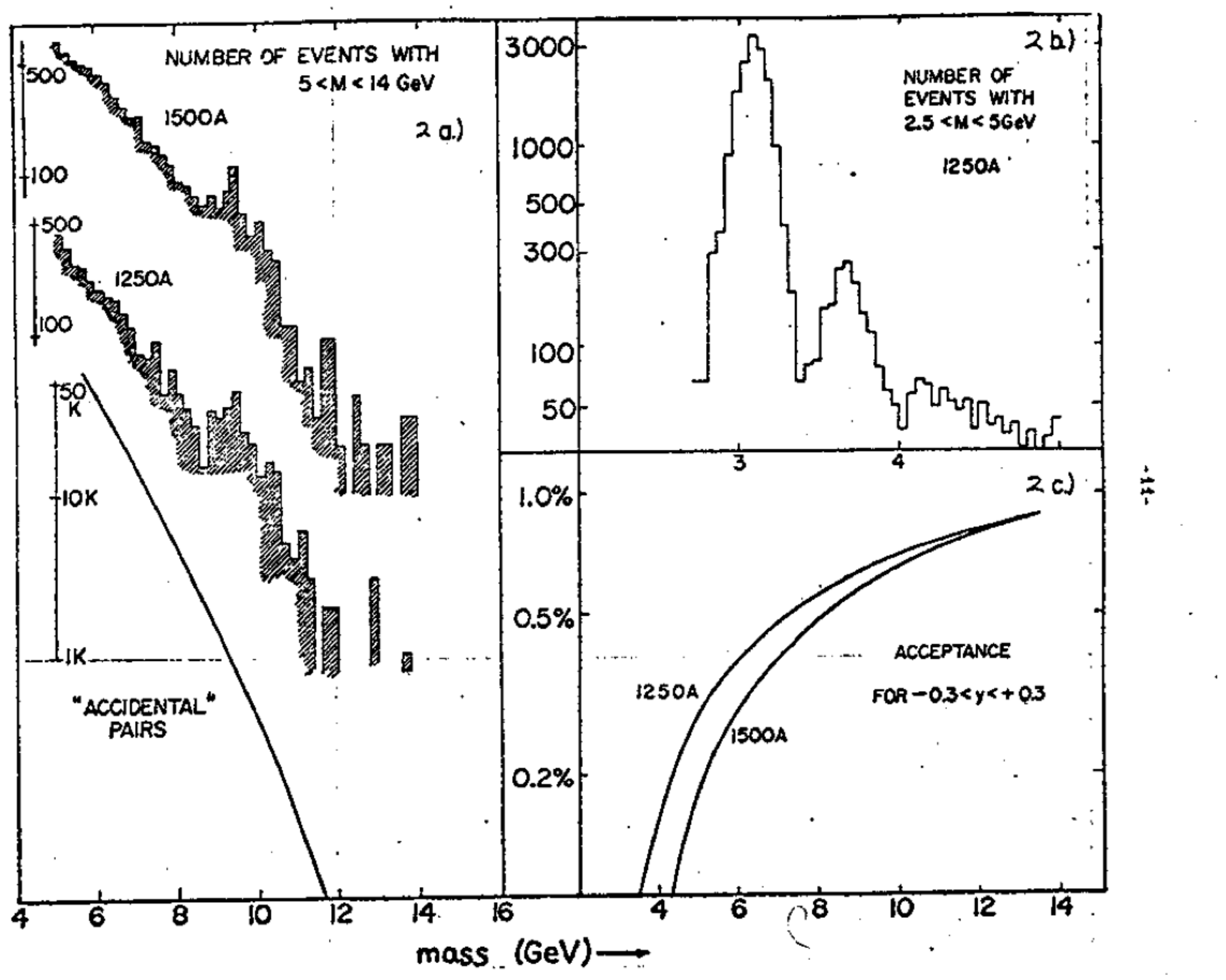
- Deviations constrained to $-7 < \kappa_3 < 12$ and $-190 < \kappa_4 < 190$

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

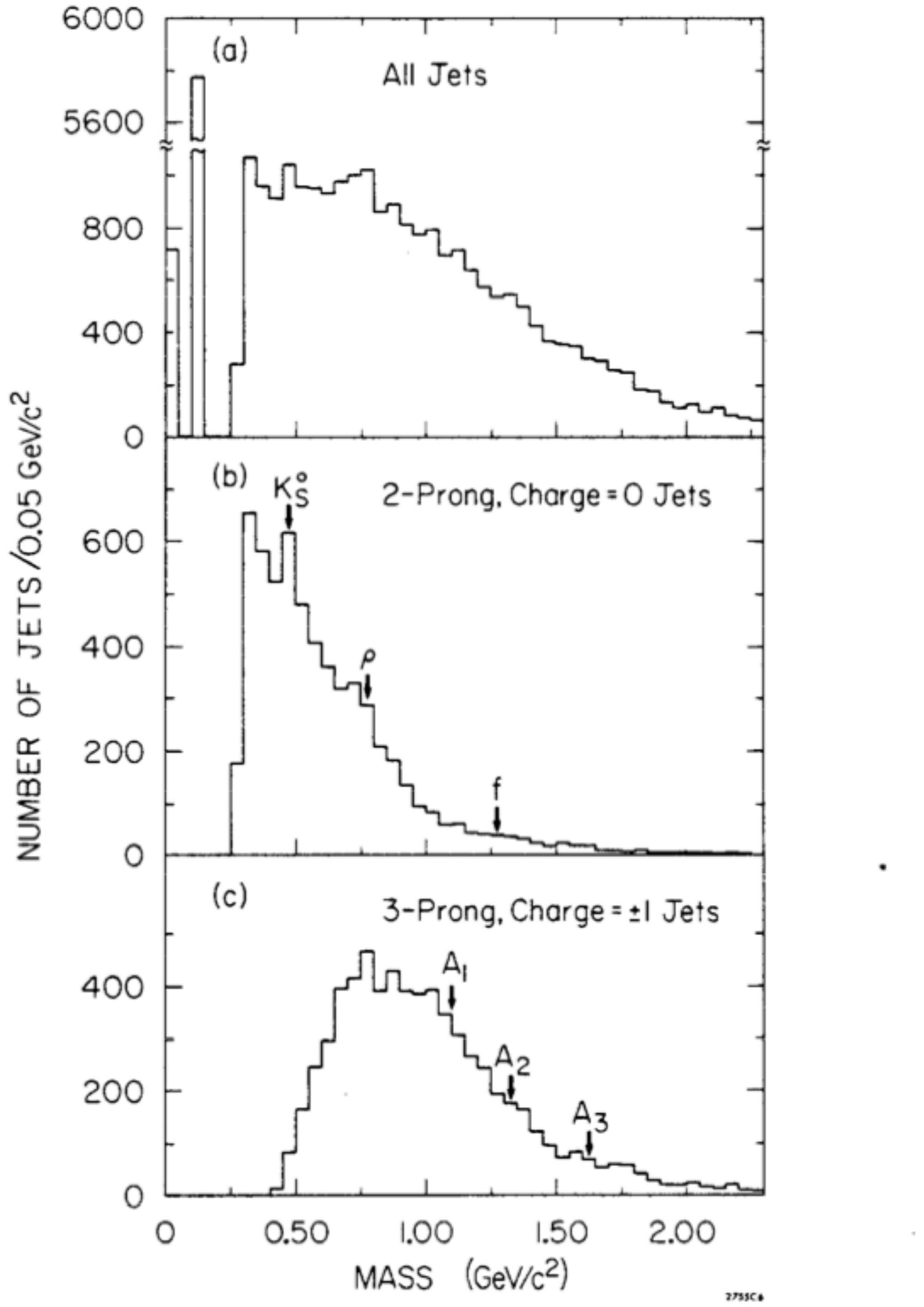
Where do we go from here: jet-charge tagger

Jet charge tagging

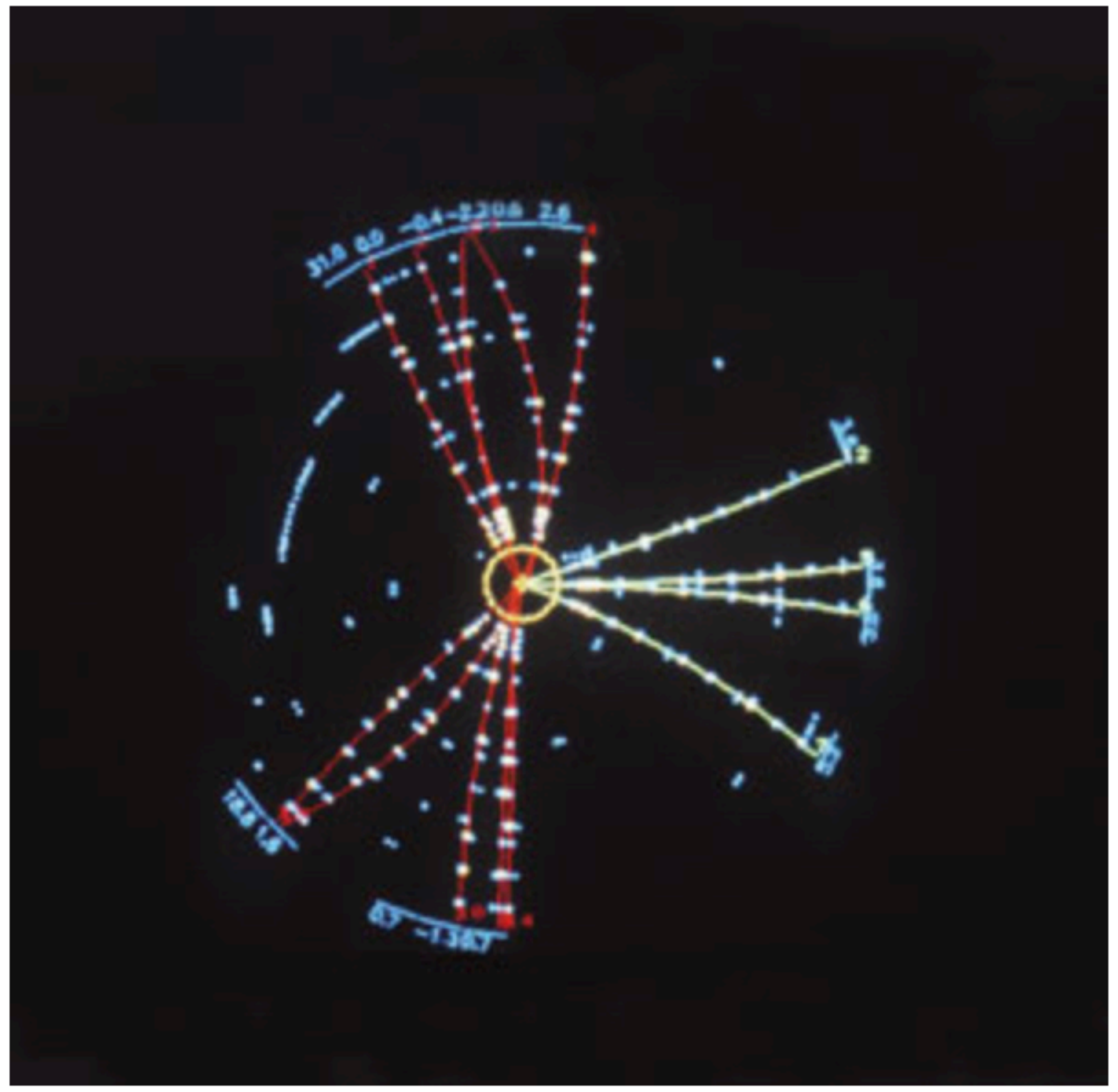
[1977 b-quark discovery at Fermilab]



[1975 jet discovery at SLAC]



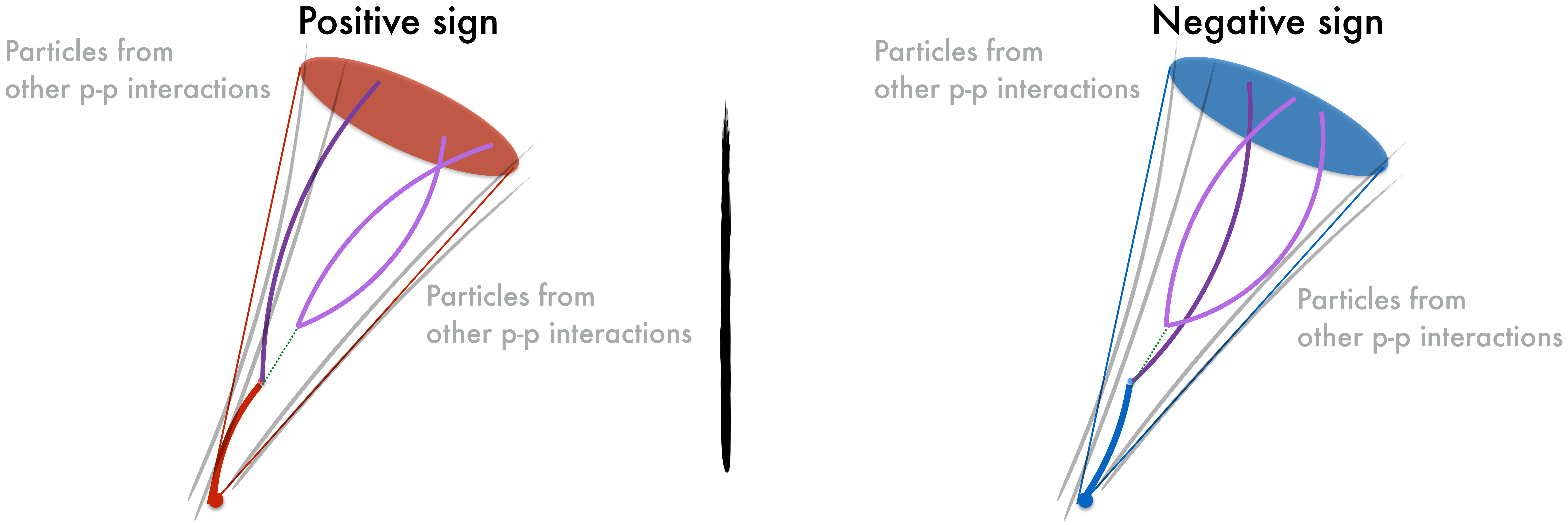
[1979 gluon discovery at DESY]



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?



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

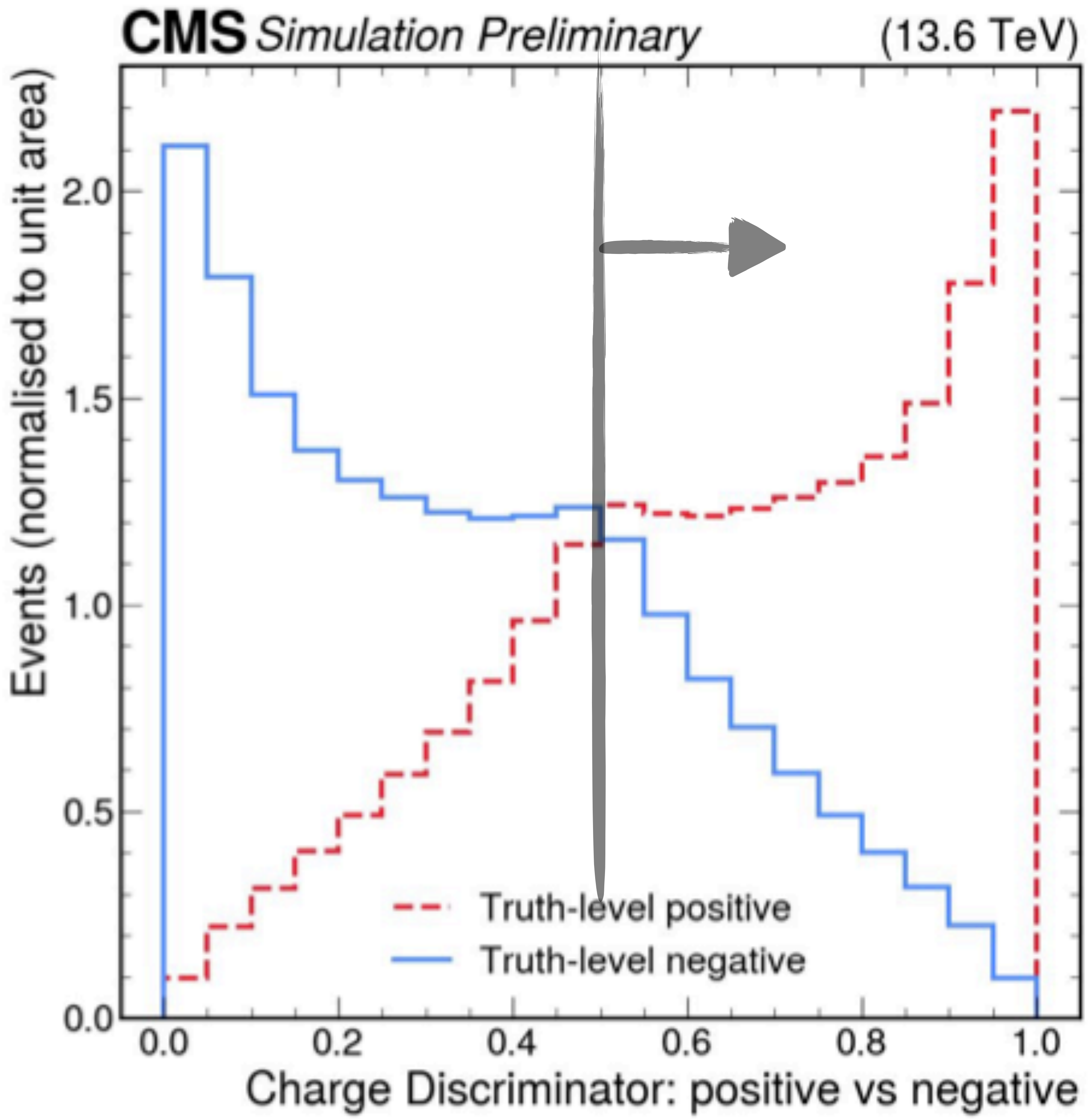
- Large variety of hadron decays: $B^- \to D^0\pi^-$ is one of the largest decay mode and only 0.5% of all B^-
- Contamination from additional particles produced in secondary proton-proton interactions
- Algorithmic limitations resulting in performance of 50-60% on CMS data, restricted to high rate process!

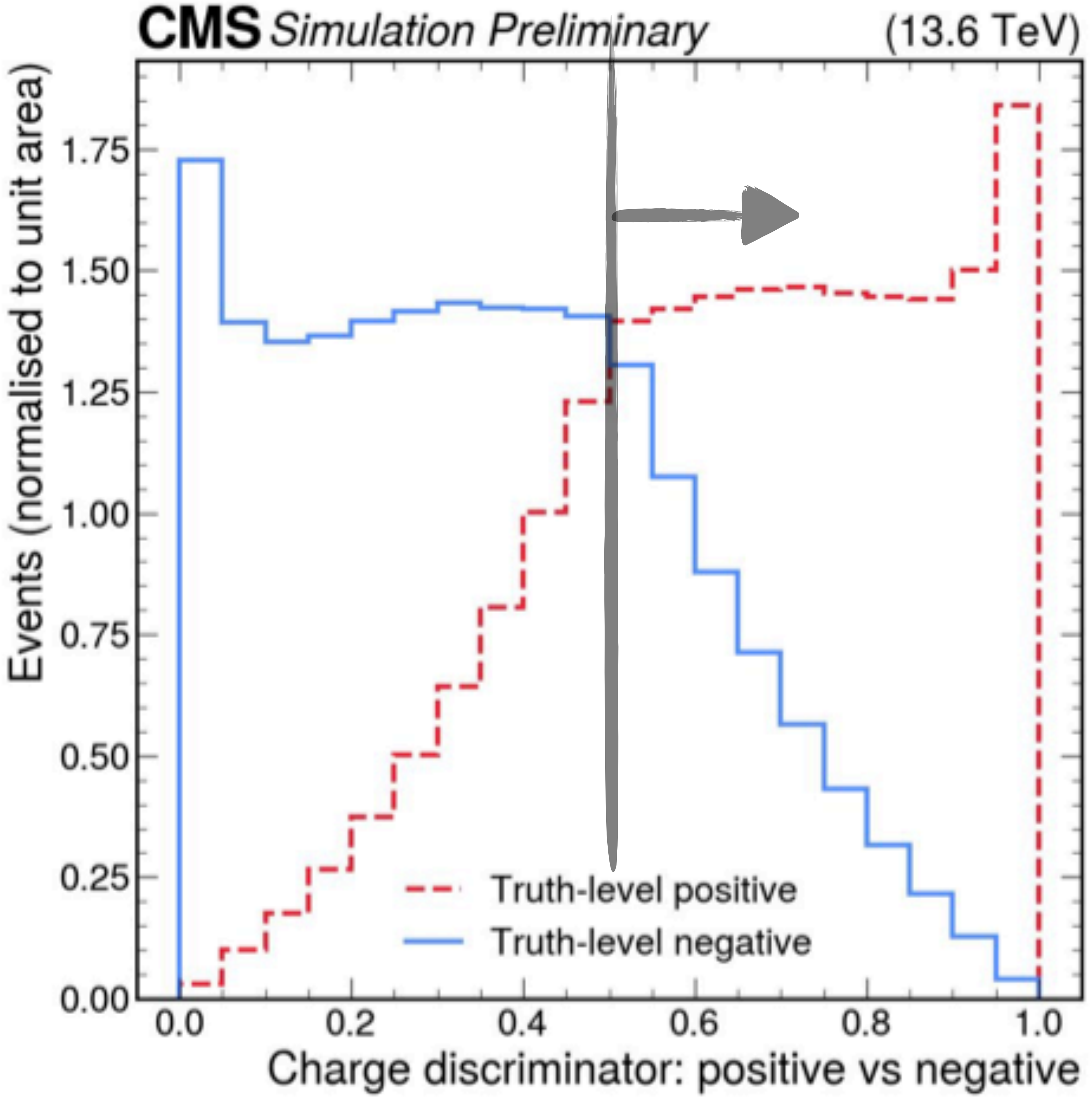
Timely: algorithms applied to b- and c-jet tagging improved performance by x10 to 100!

- 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

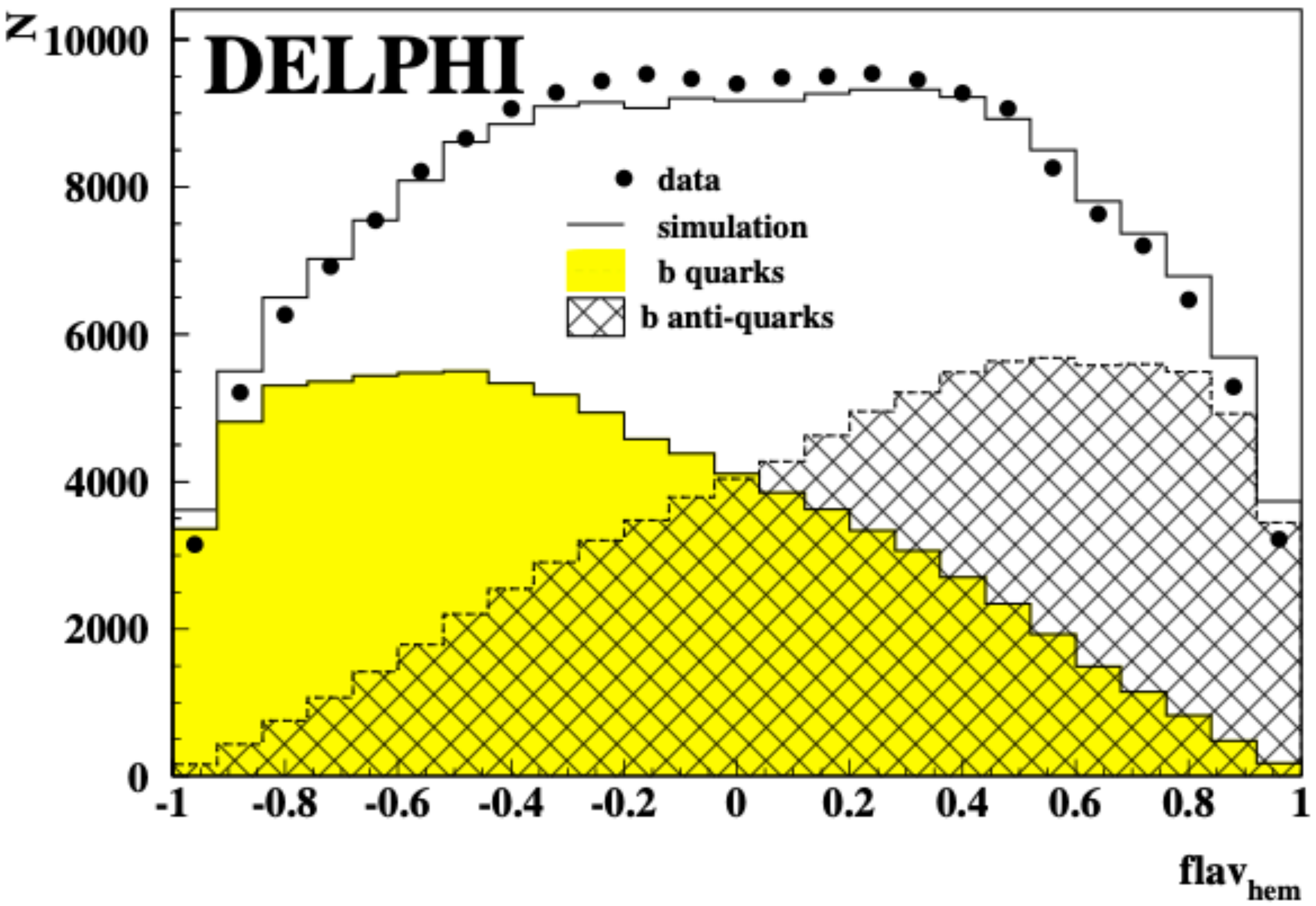
Demonstrates feasibility:

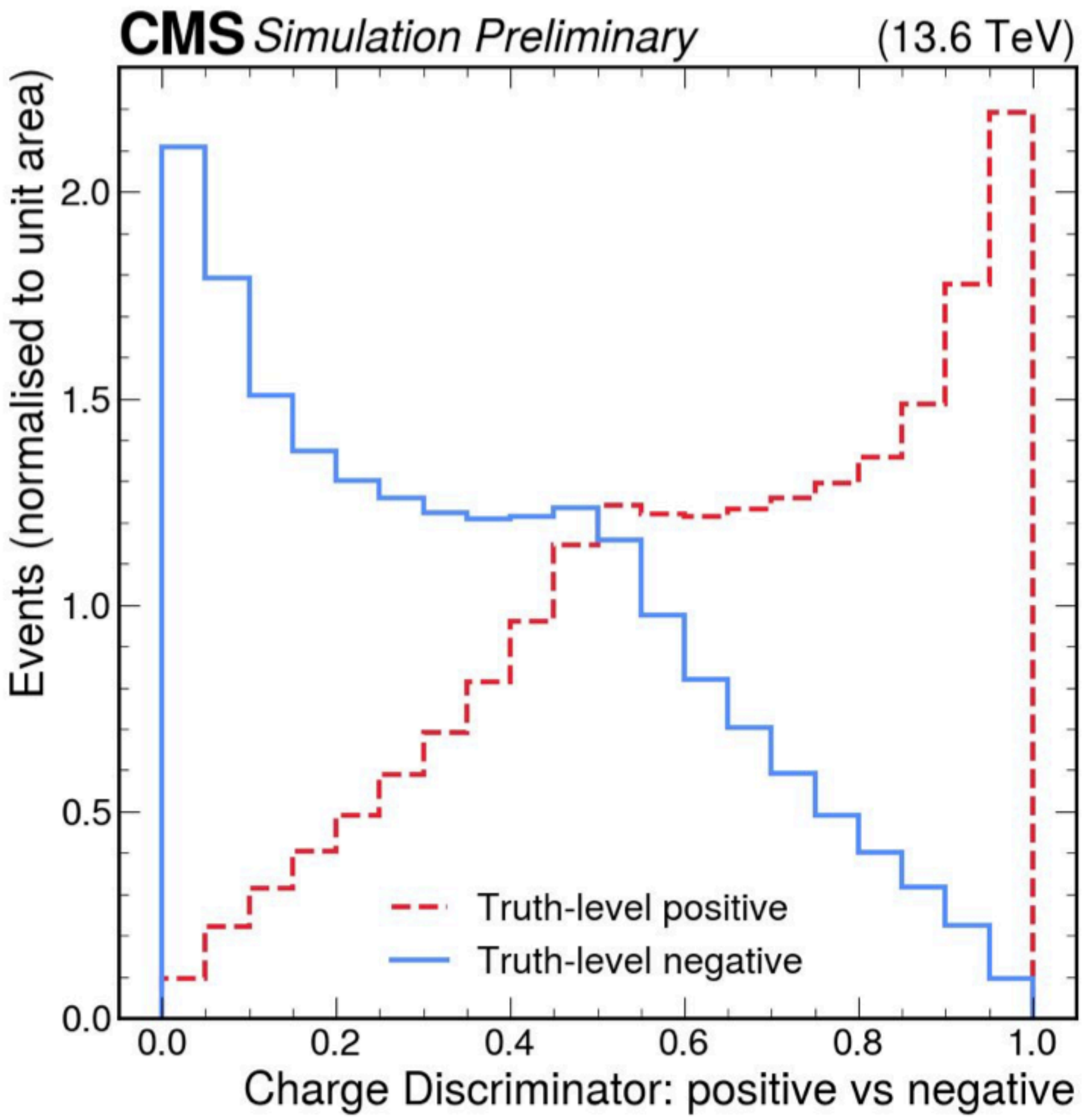
- Improvements in machine learning and physics driven inputs will maximize performance of algorithms!
- If flavor tagging can predict history, this is the **first** and **worst** jet-charge tagger performance in CMS!

DELPHI charge tagger

DP-2025-071

DELPHI

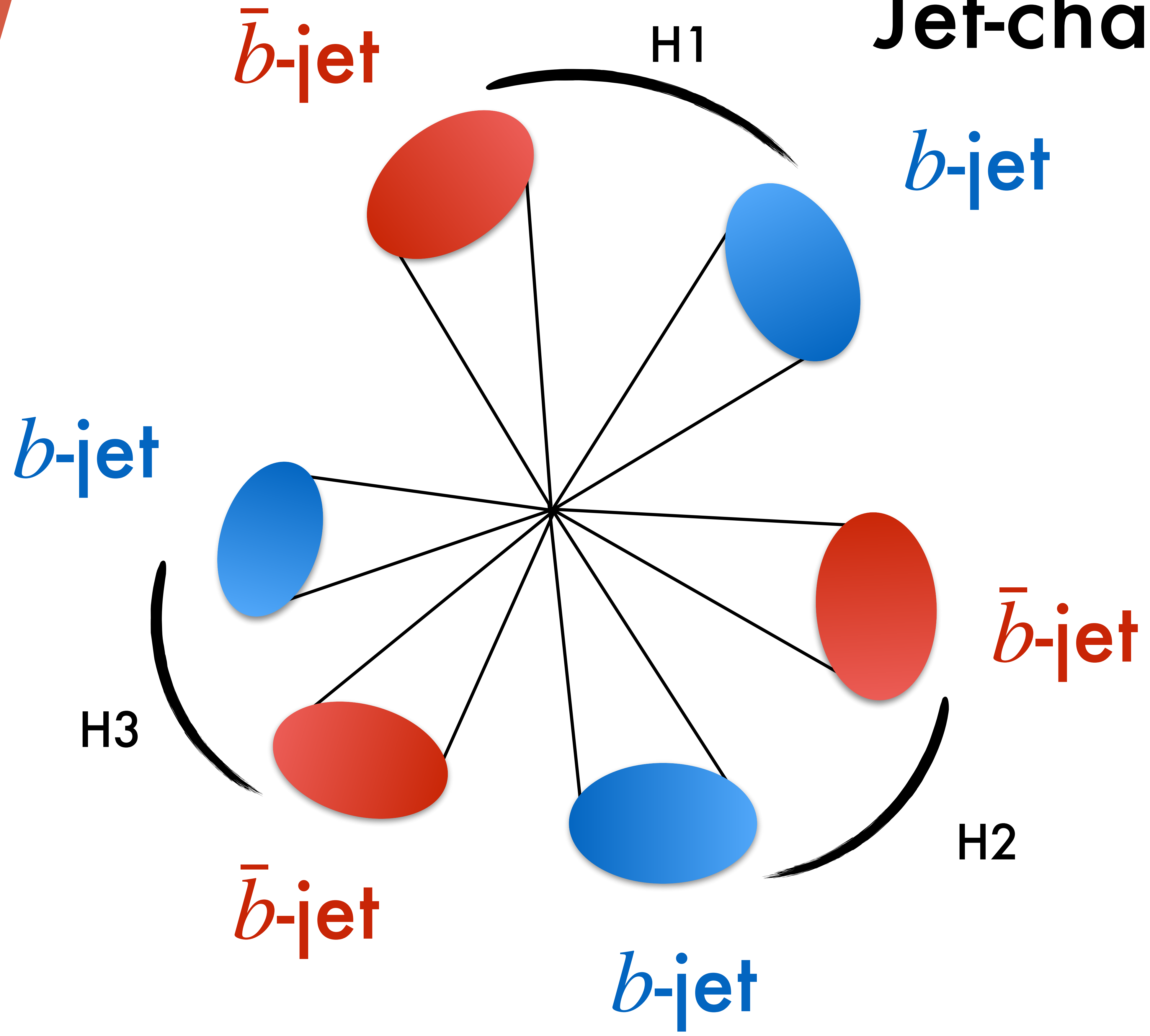




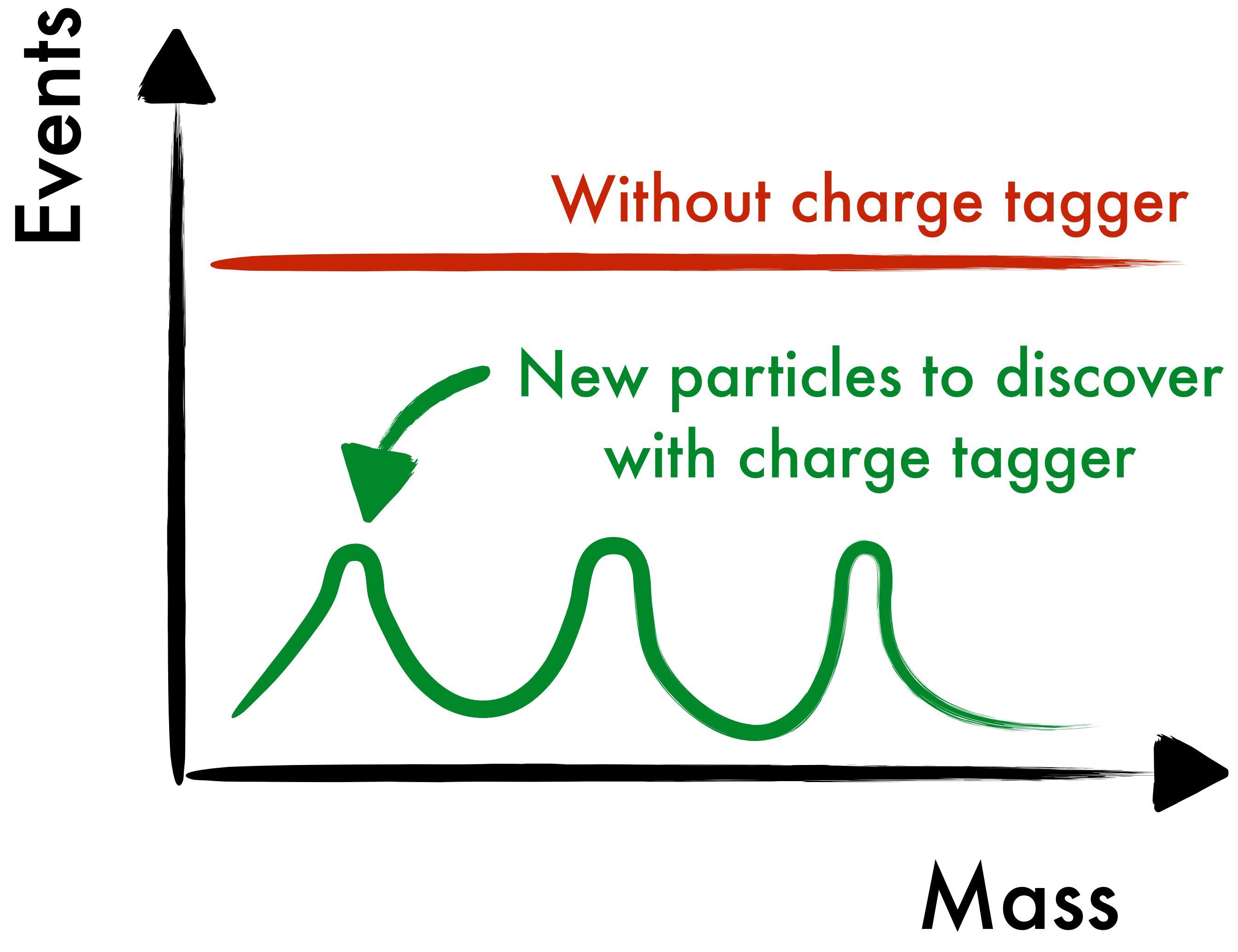
DELPHI: best jet-charge tagger of LEP using DNN on 1994 data

- 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

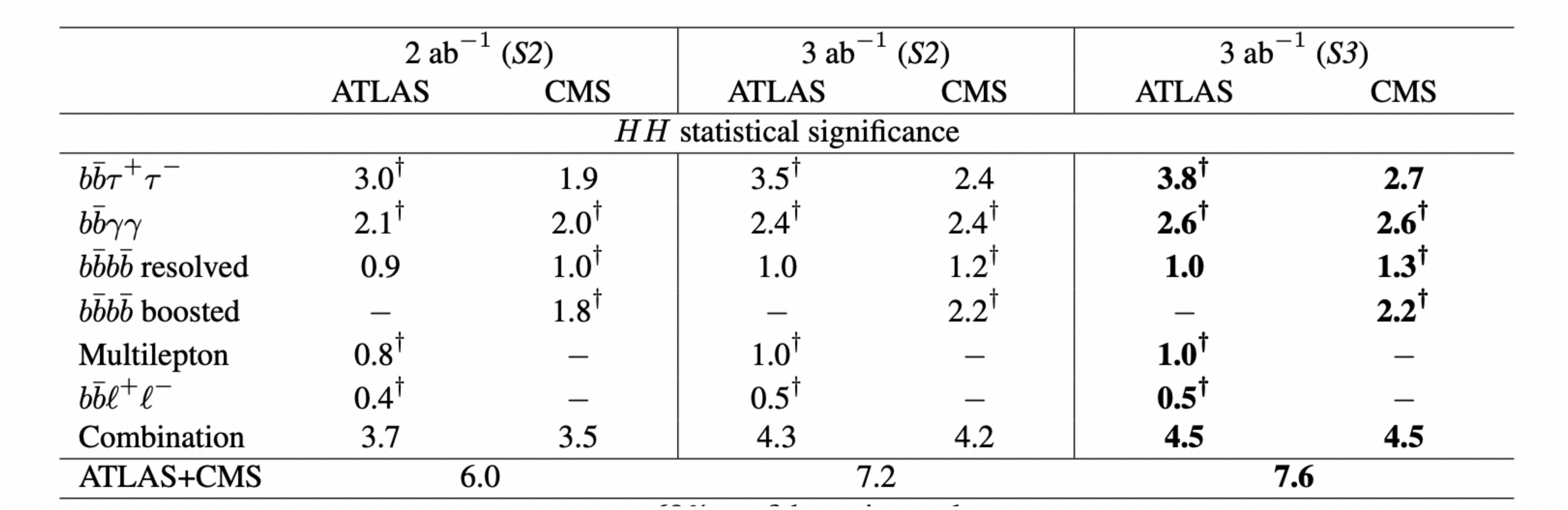
- HHH is extremely challenging, need extraordinary tools to measure it at the LHC

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

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

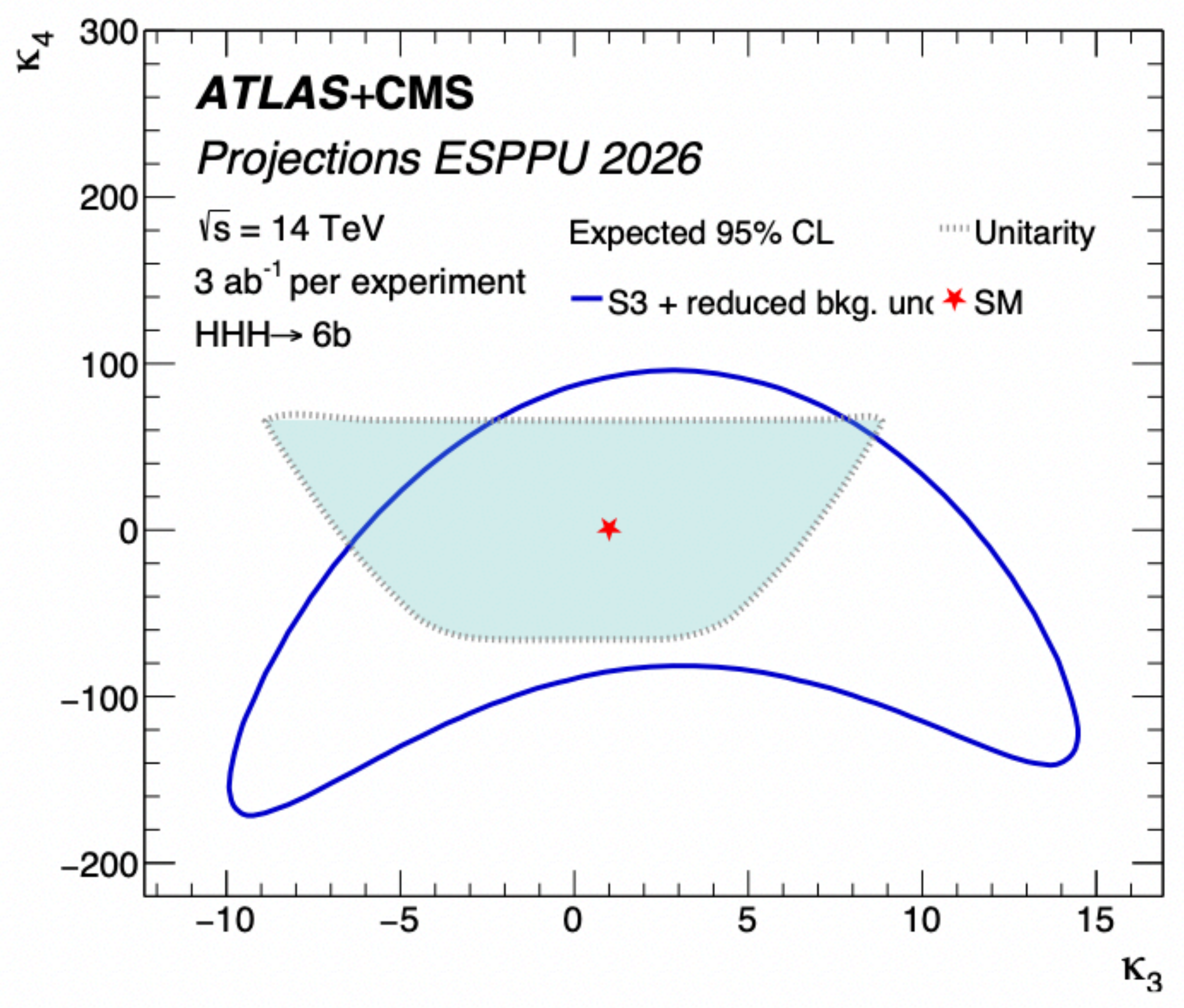
Summary

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**

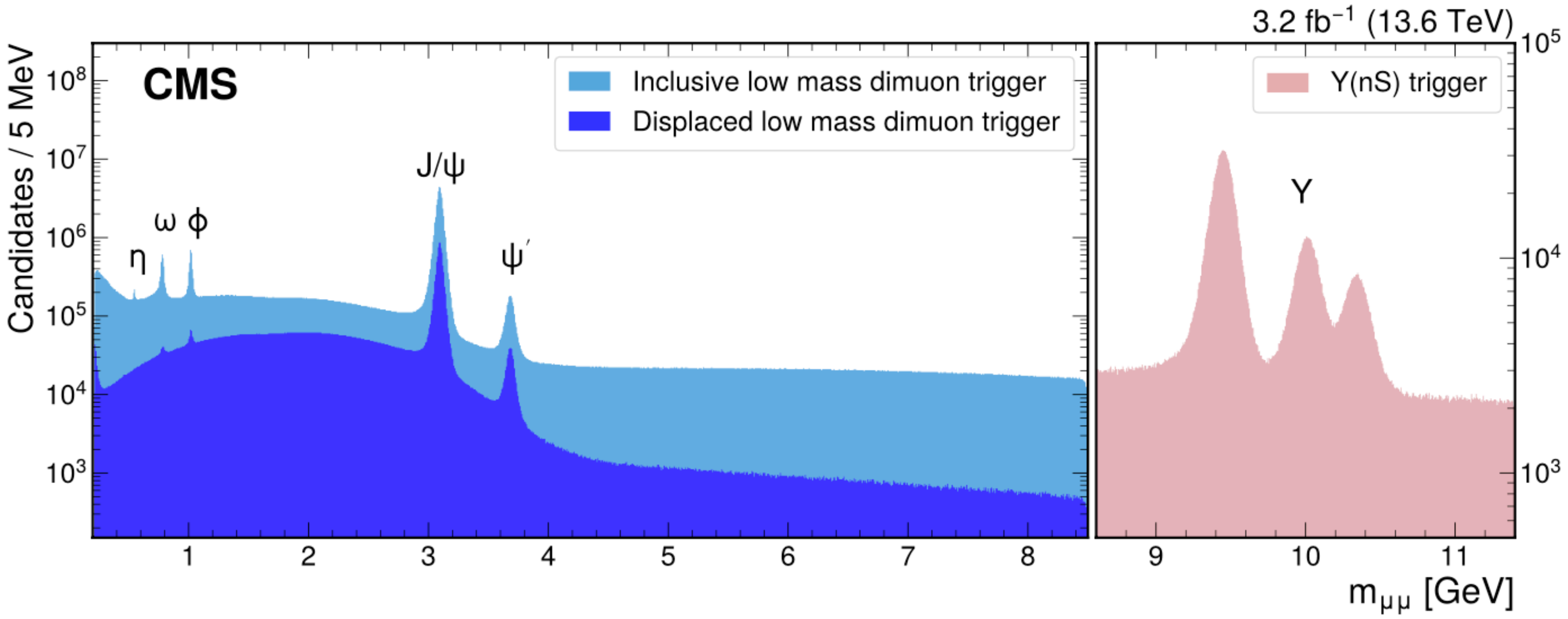
- **HH, HHH** and **ttHcc** processes can **only be pursued at the LHC, next 10-20 years will be crucial**
- **Great time** to be a 2σ **physicist**! Stay tuned for more results **in the decade of heavy flavor**!

Back-up

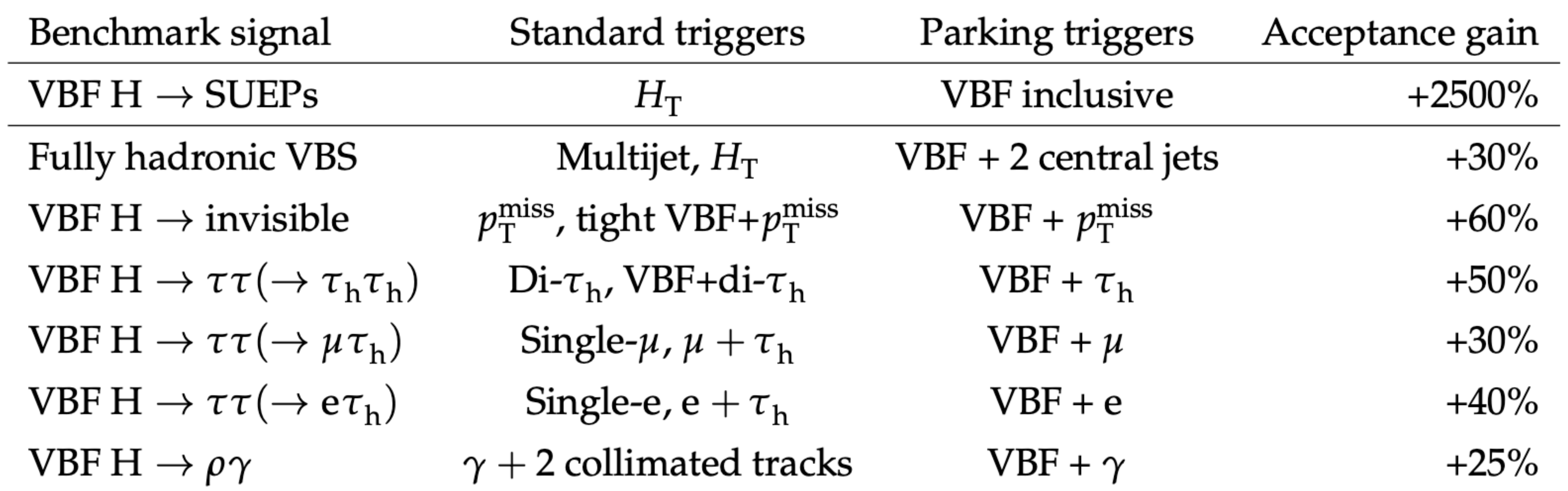
Parking rates allocation

CMS DP-2023/043
arXiv:2403.16134

B-physics: low mass dimuon triggers **1.6 kHz**

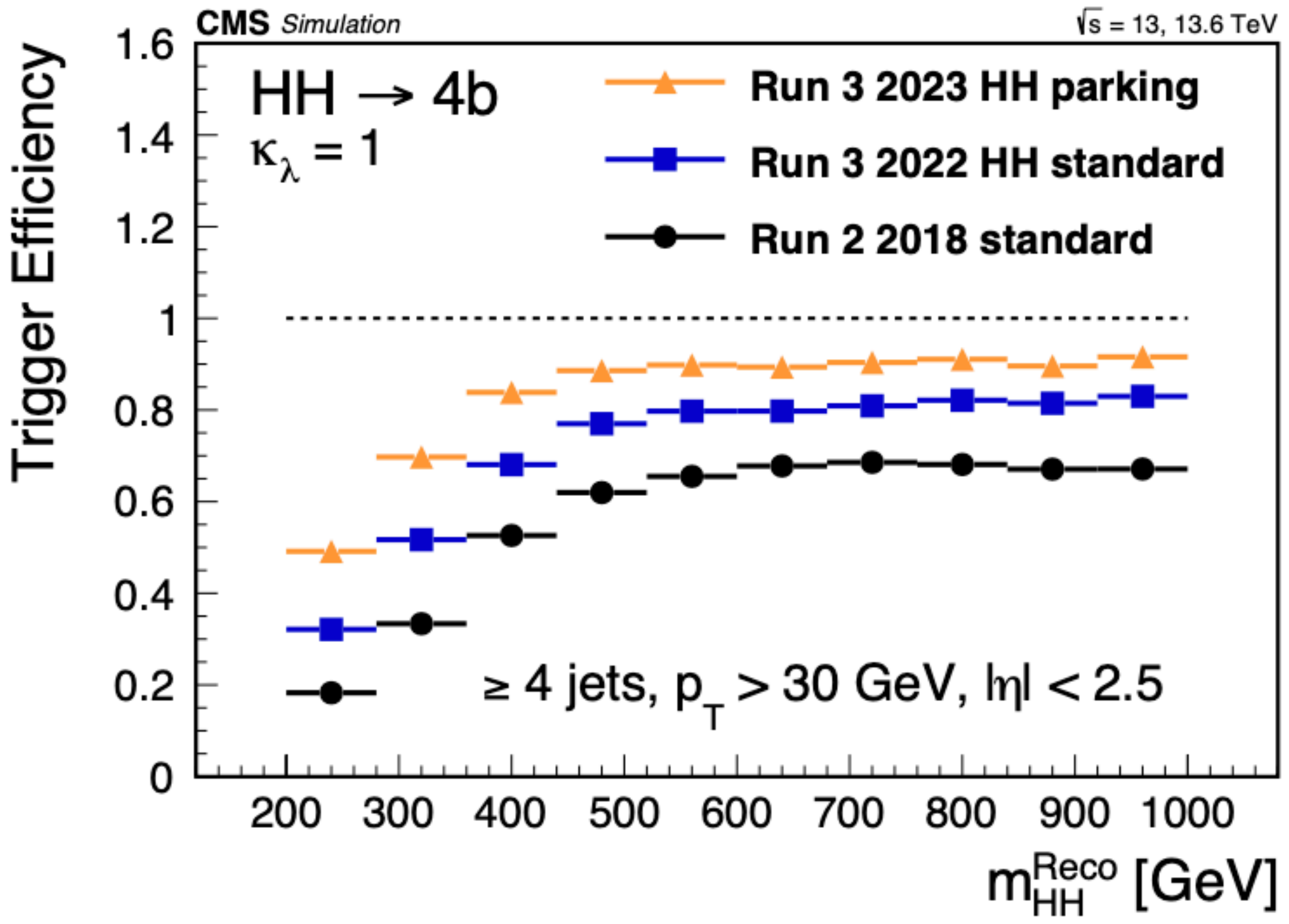


VBF triggers: inclusive and object specific **1.2 kHz**

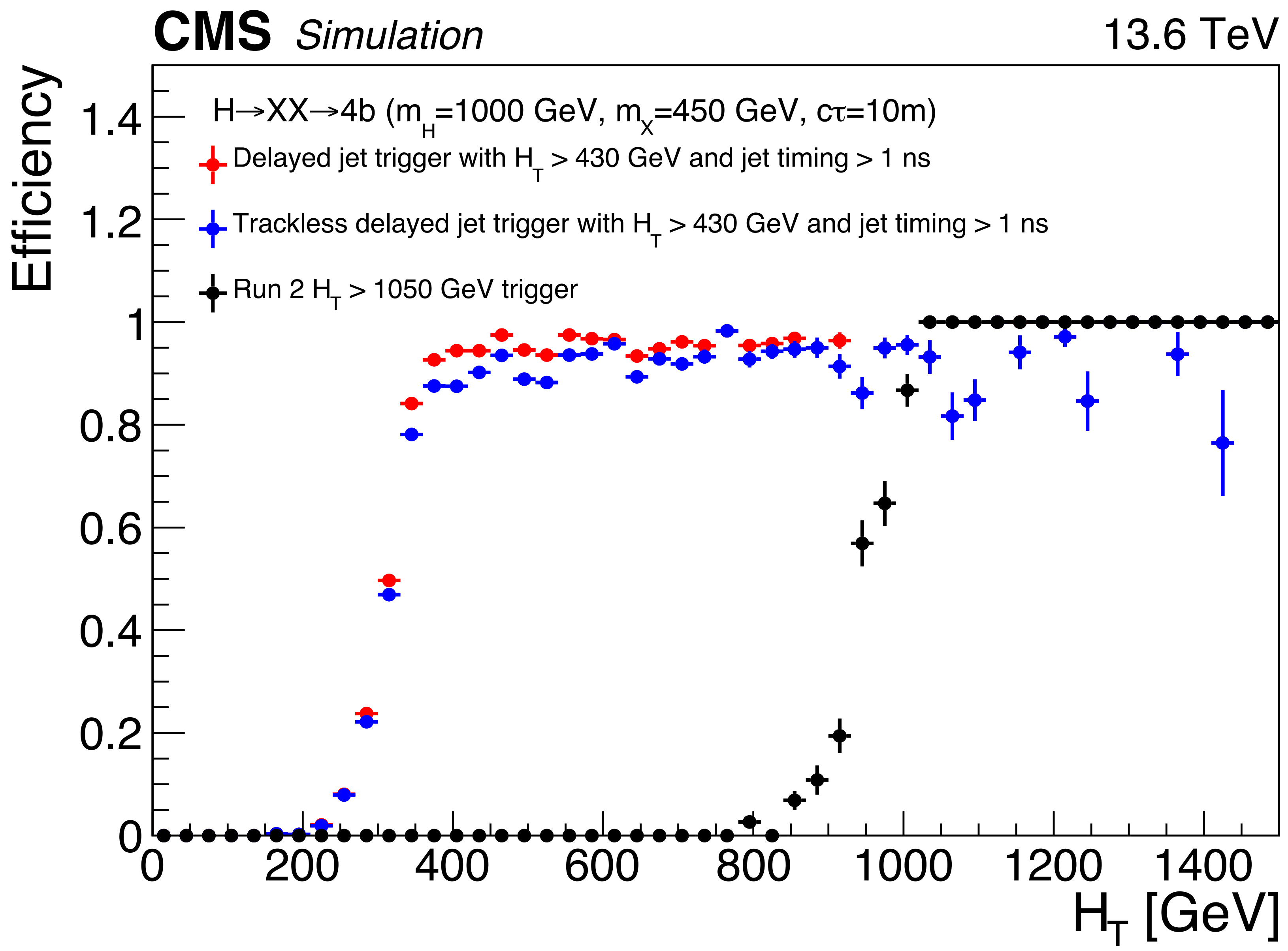


Benchmark signal	Standard triggers	Parking triggers	Acceptance gain
VBF H $\to$ SUEPs	H_{T}	VBF inclusive	+2500%
Fully hadronic VBS	Multijet, H_{T}	VBF + 2 central jets	+30%
VBF H $\to$ invisible	$p_{\mathrm{T}}^{\mathrm{miss}}$, tight VBF+$p_{\mathrm{T}}^{\mathrm{miss}}$	VBF + $p_{\mathrm{T}}^{\mathrm{miss}}$	+60%
VBF H $\to \tau\tau(\to \tau_{\mathrm{h}}\tau_{\mathrm{h}})$	Di-τ_{h}, VBF+di-τ_{h}	VBF + τ_{h}	+50%
VBF H $\to \tau\tau(\to \mu\tau_{\mathrm{h}})$	Single-μ, $\mu + \tau_{\mathrm{h}}$	VBF + μ	+30%
VBF H $\to \tau\tau(\to \mathrm{e}\tau_{\mathrm{h}})$	Single-e, e + τ_{h}	VBF + e	+40%
VBF H $\to \rho\gamma$	γ + 2 collimated tracks	VBF + γ	+25%

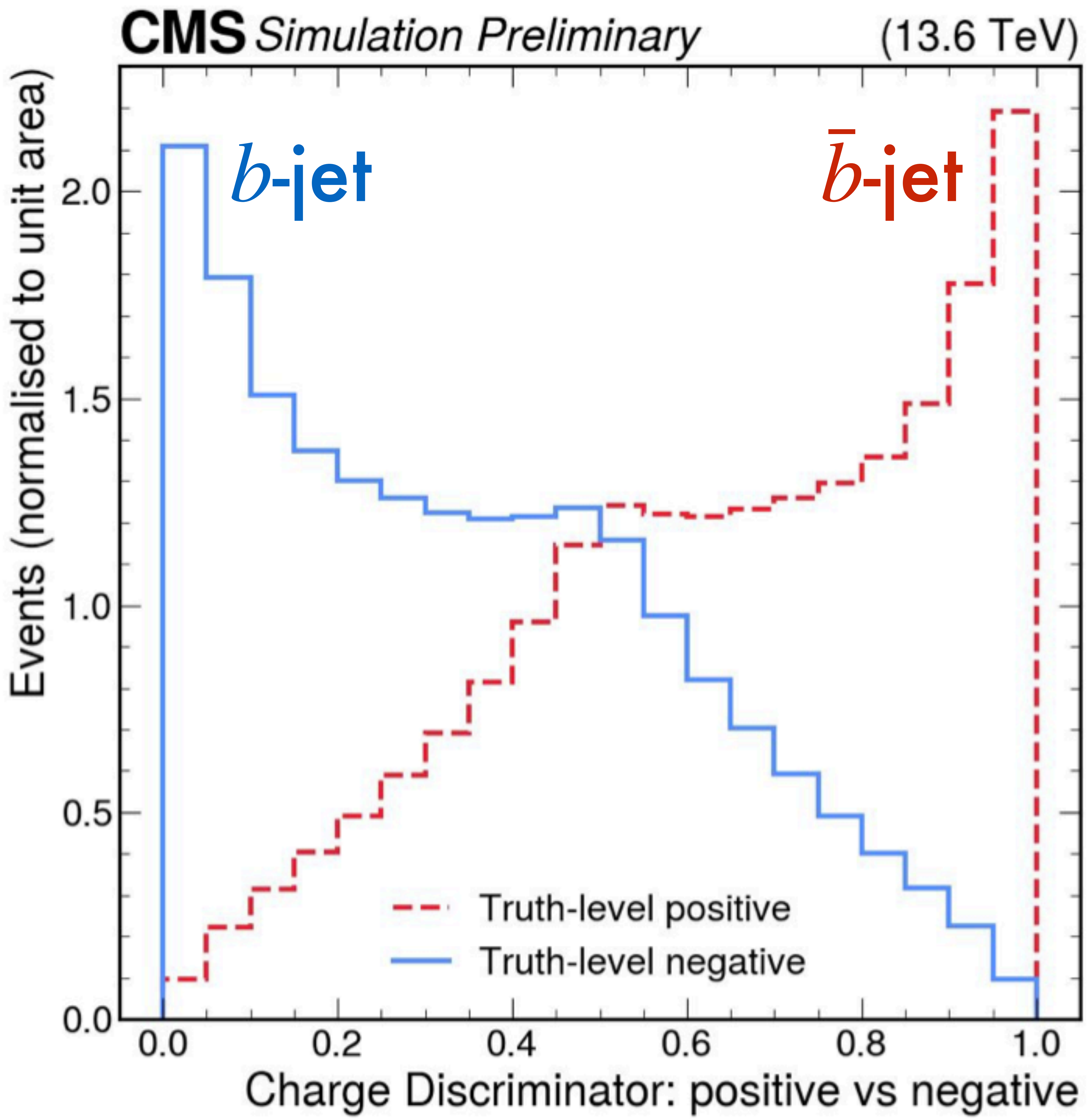
HH and HHH parking **0.3 kHz**

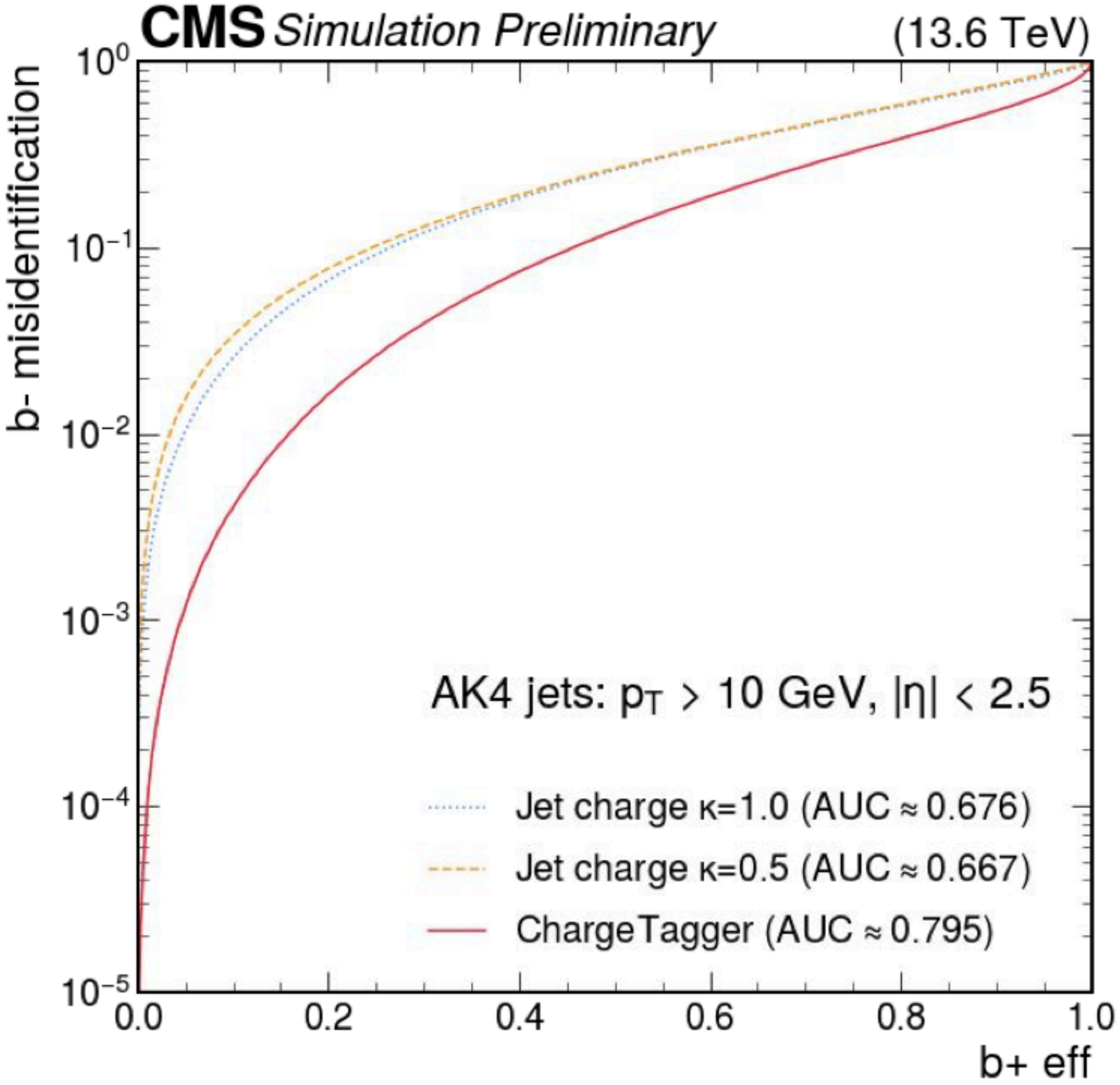


Long lived particles: **0.2 kHz**

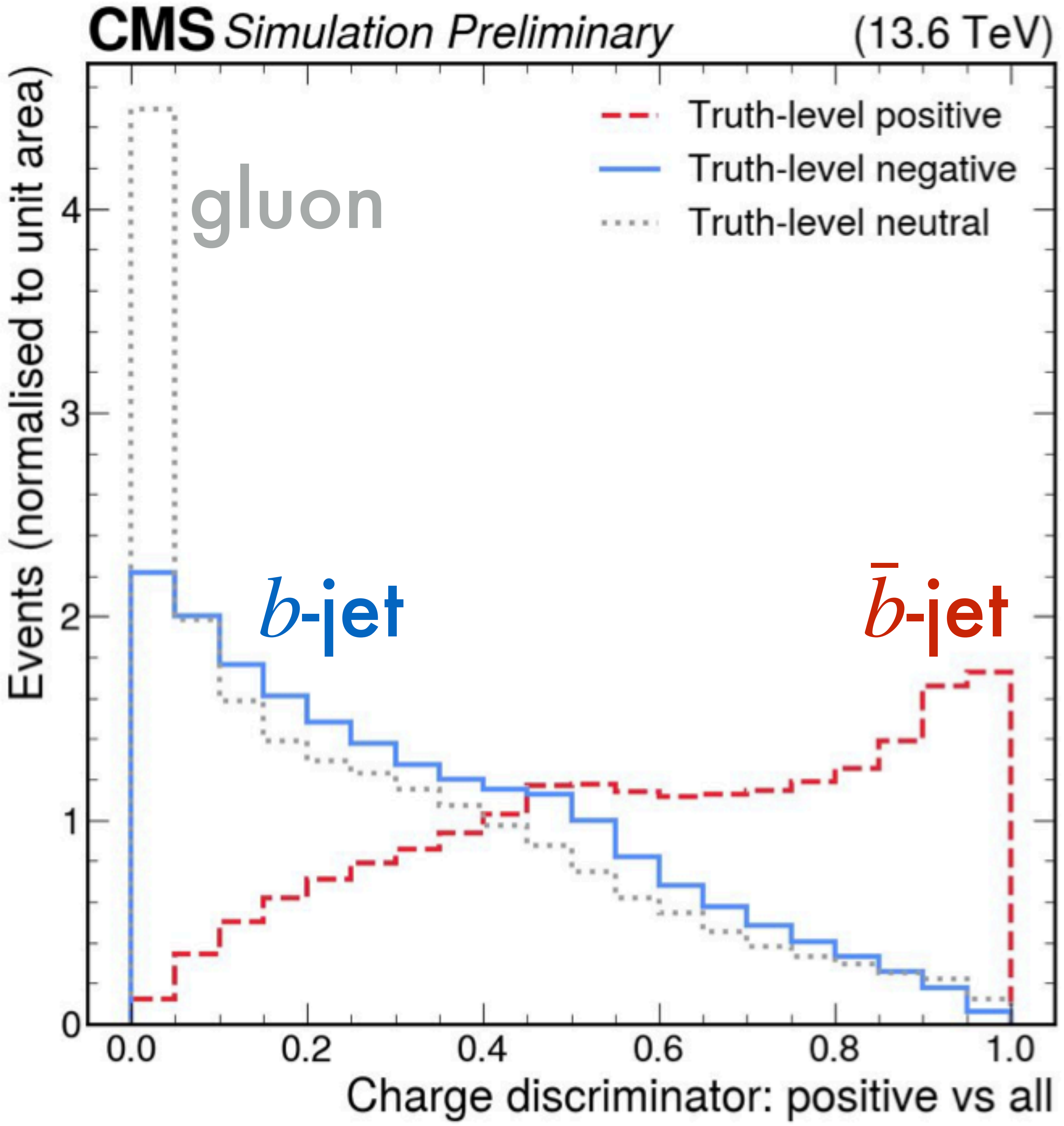


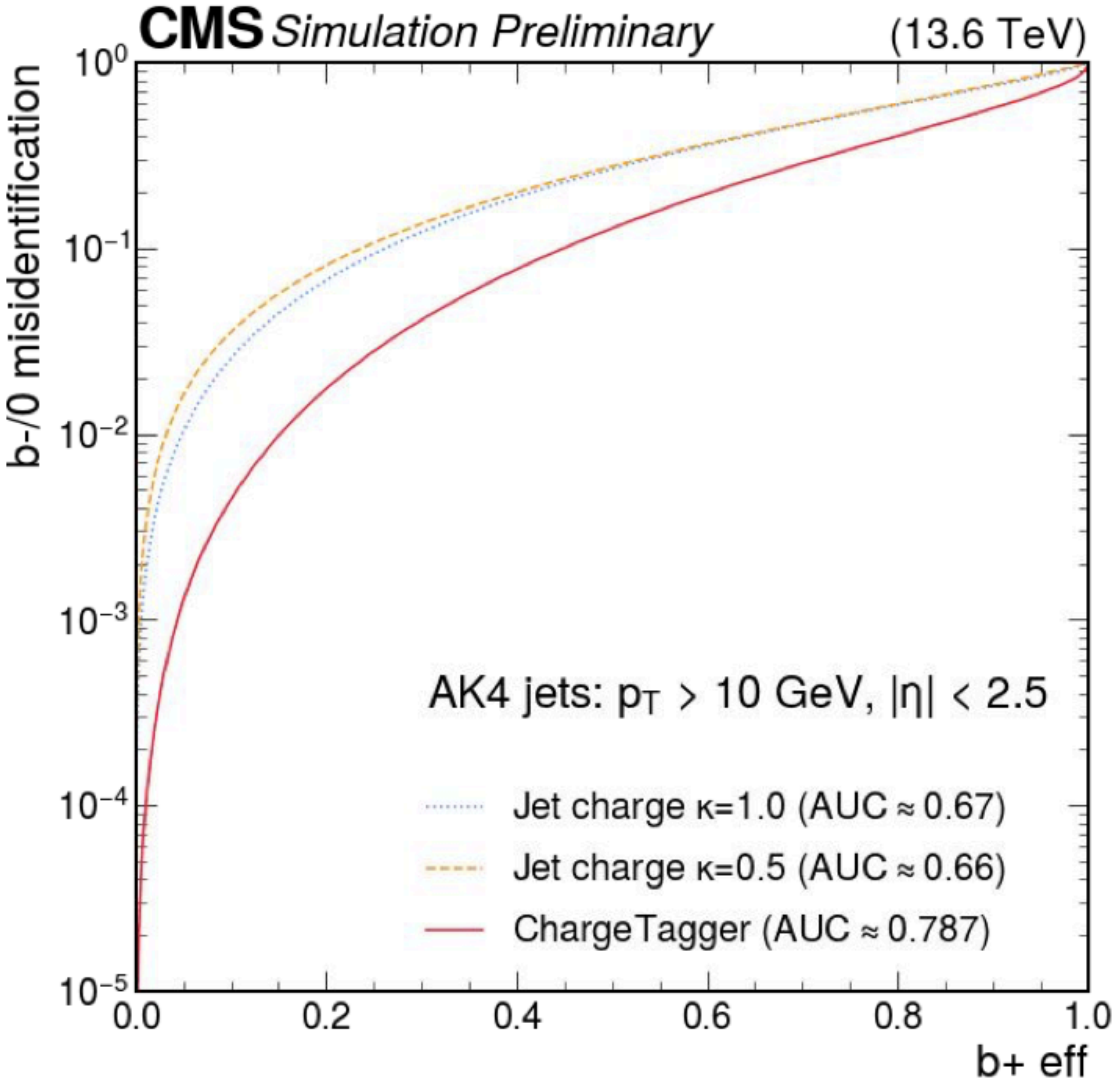
Charge-tagger





Charge-tagger





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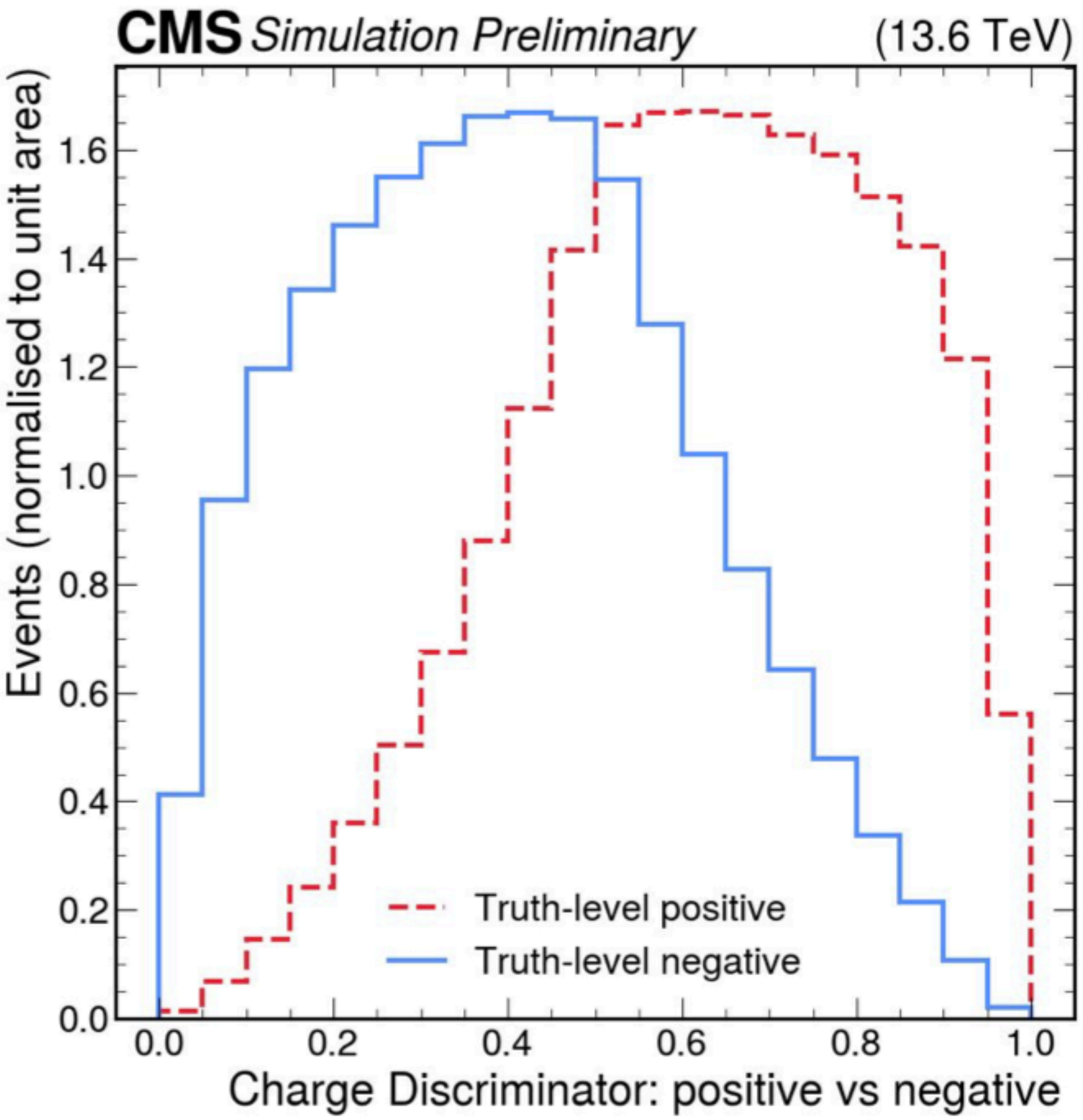

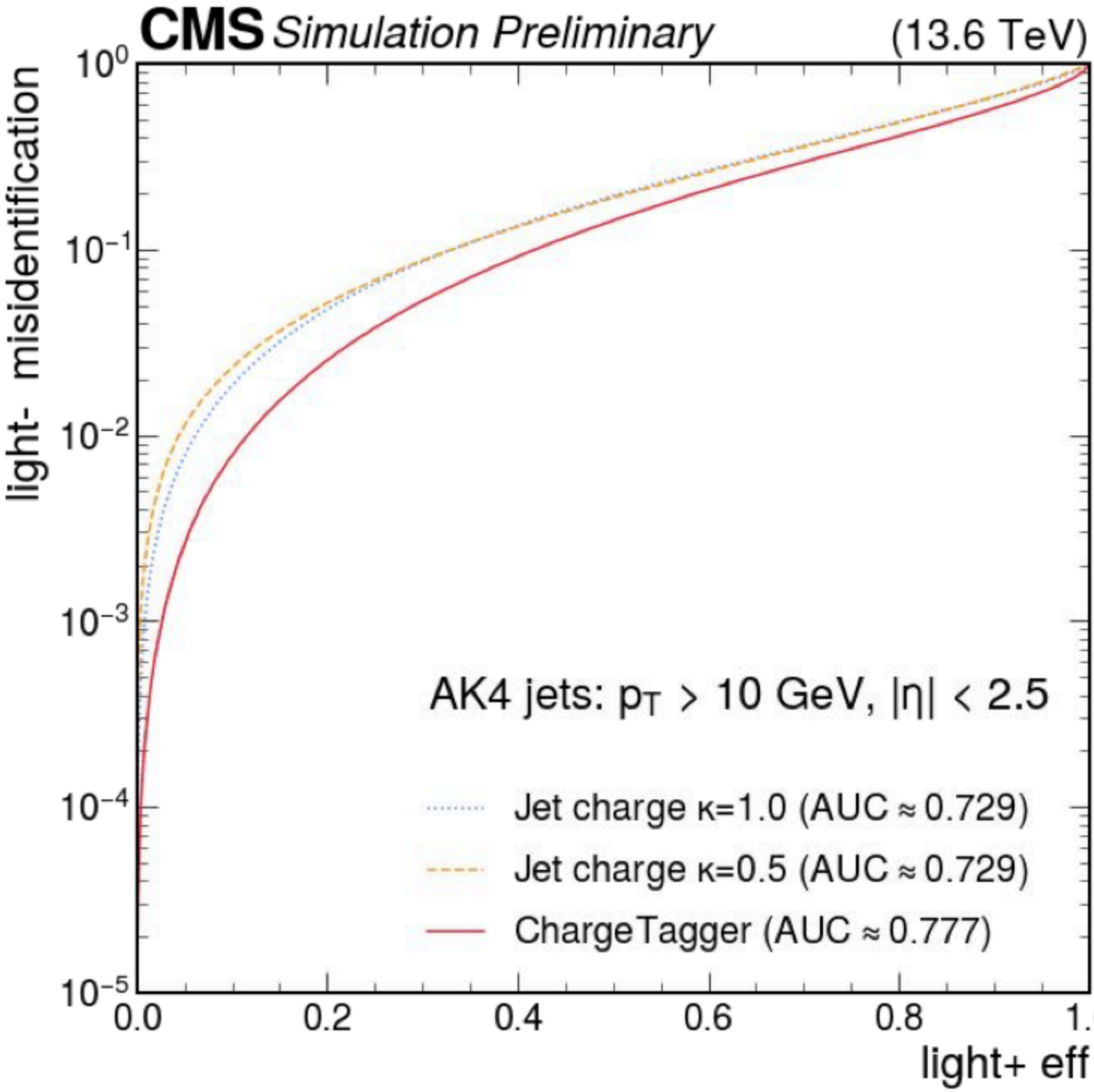

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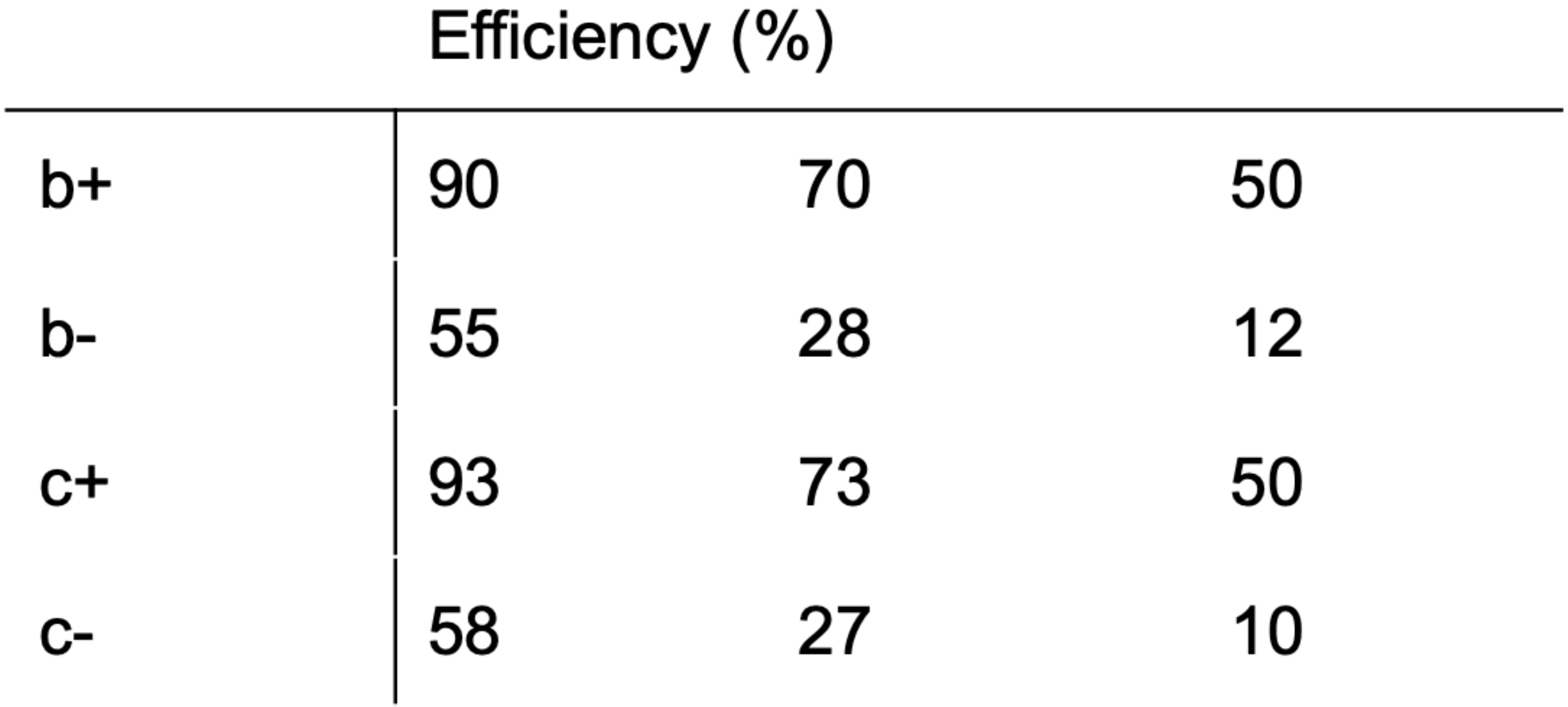
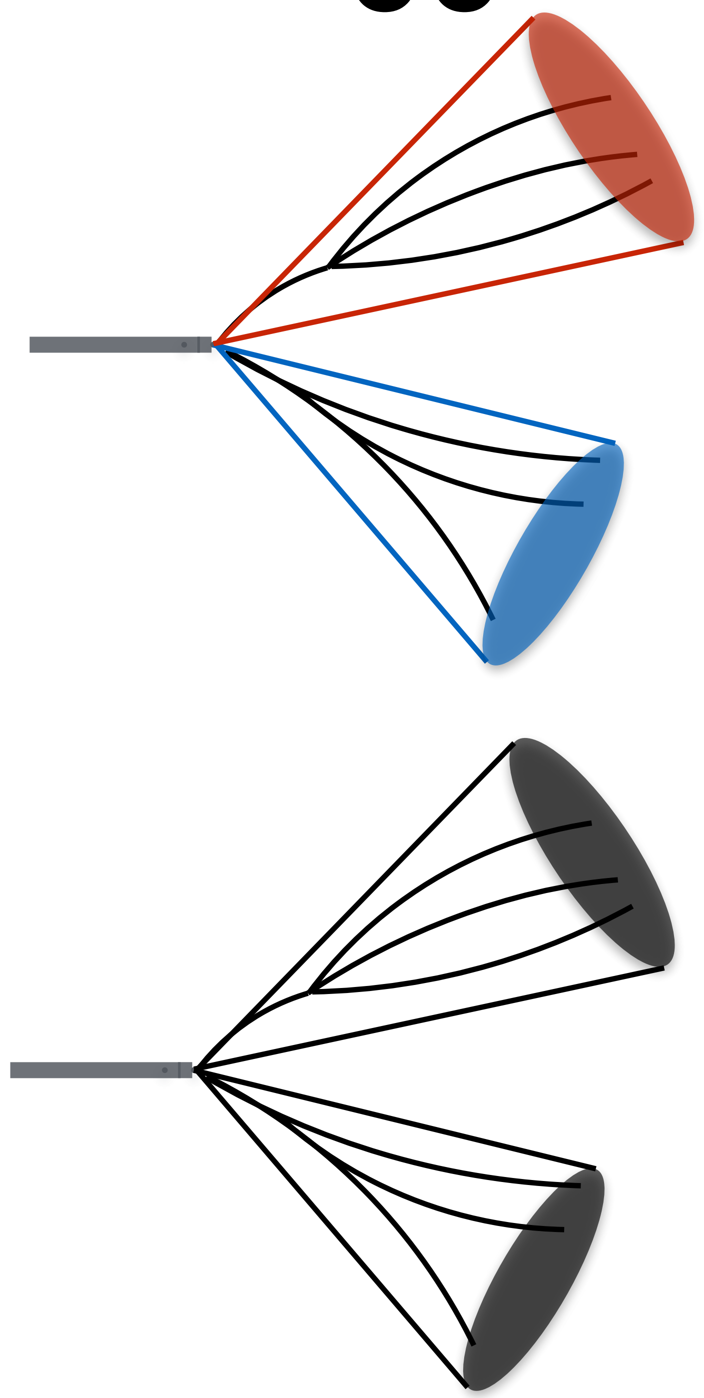


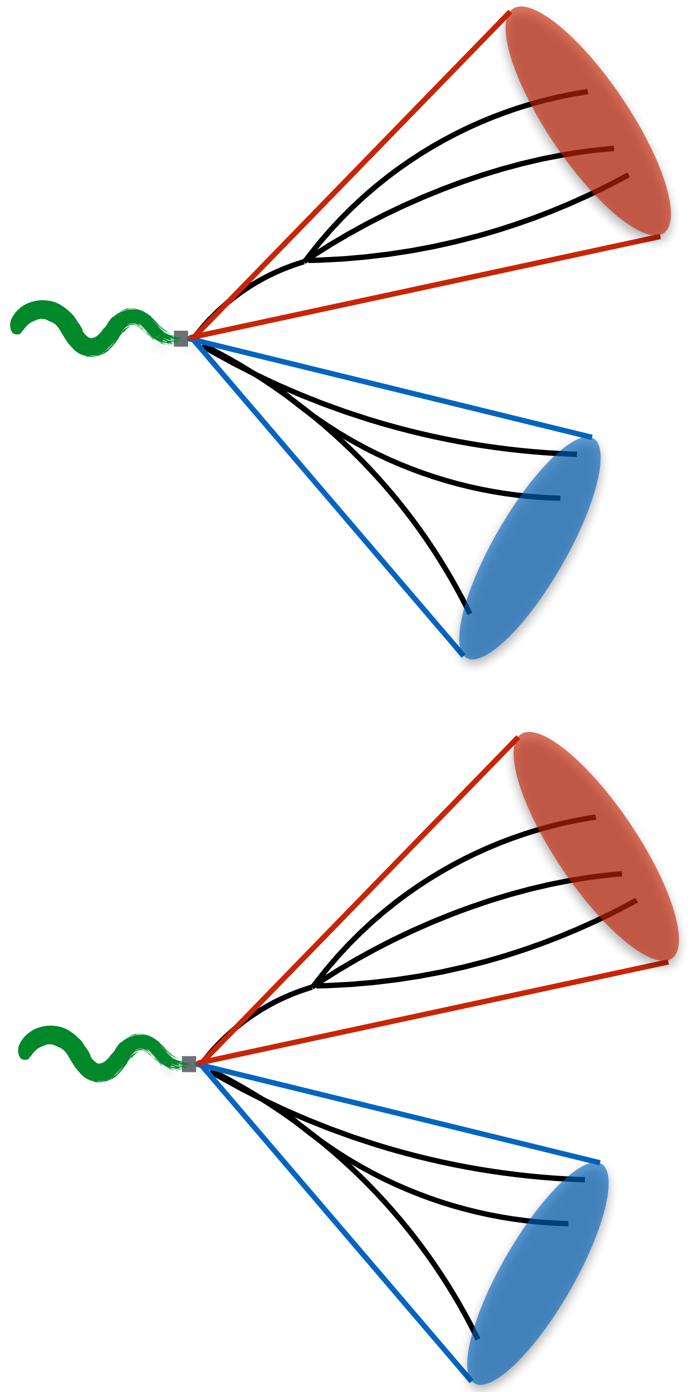
	Efficiency (%)		
b+	90	70	50
b-	55	28	12
c+	93	73	50
c-	58	27	10

Potential impact on CMS physics program

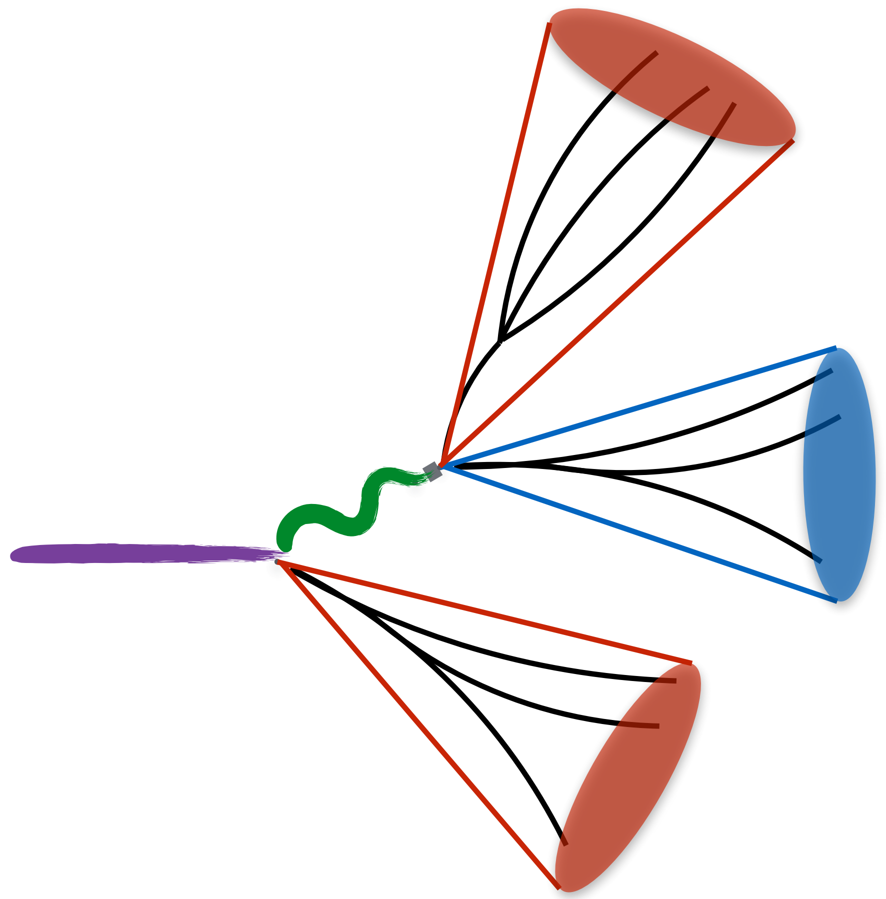
Higgs



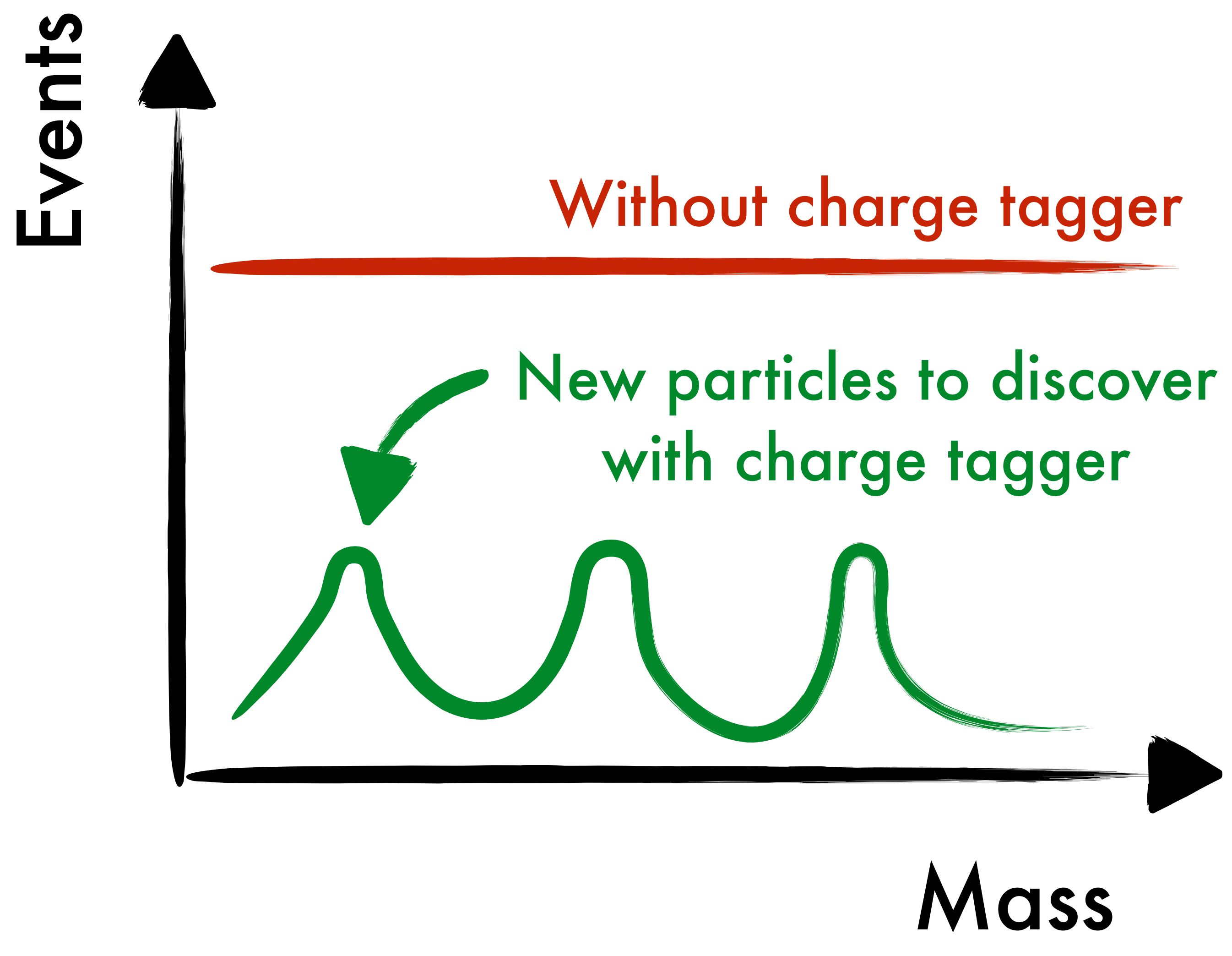
W,Z



Top



New physics?



Conservation of electric charge is a fundamental property of matter!

- Jet-charge tagger: add completely new and orthogonal dimension to probe LHC data
- Large and profound impact on ATLAS and CMS, from precision measurements to new physics!

Identification of b- and c-hadrons used in **50% of CMS publications** → similar **impact** expected for **jet-charge tagger**!

Uncertainties ttH

Uncertainty source	$\Delta\mu$ ($\Delta\mu/\Delta\mu_{\text{tot}}$)			
	$\mu_{t\bar{t}H(H\to c\bar{c})}$		$\mu_{t\bar{t}H(H\to b\bar{b})}$	
Statistical	3.3	(74%)	0.14	(57%)
$t\bar{t}$+jets normalizations	1.4	(32%)	0.06	(26%)
$t\bar{t}Z$ normalizations	0.4	(8.4%)	0.06	(30%)
Theory	2.1	(47%)	0.18	(75%)
Signal	0.7	(15%)	0.11	(47%)
$t\bar{t}+\geq1b$	0.7	(15%)	0.14	(60%)
$t\bar{t}+\geq1c$	1.4	(32%)	0.01	(5.8%)
$t\bar{t}$+light	1.3	(29%)	0.01	(5.2%)
Minor backgrounds	0.2	(4.6%)	0.01	(4.6%)
Experimental	2.0	(47%)	0.07	(31%)
Jet flavor tagging	1.7	(39%)	0.07	(28%)
Size of the simulated samples	1.1	(24%)	0.05	(21%)
Jet energy scale and resolution	0.8	(18%)	0.02	(8.6%)
Lepton identification	0.3	(6.0%)	0.02	(6.3%)
Integrated luminosity	0.1	(2.0%)	0.02	(6.2%)

“First comes the observation, then comes the measurement”

I. Rabi to L. Lederman, quoted in Lederman’s Nobel lecture in 1988

I organize a book club together with Joel Butler at Fermilab

- Main topic: what can history teach us about building a collider!
  - Tunnel Visions
  - Fermilab
  - Nobel Dreams
  - Covers: Main Ring / UA1 / UA2 / Tevatron / CDF / DZero
  - Would be happy to talk about it / show some slides
  - Would be even more happy to hear stories about these days!
  - Available to meet today to discuss!