

A scenic view of a coastal town, likely Cinque Terre, with colorful buildings (yellow, orange, white) built on a hillside overlooking a harbor. The water is blue, and there are several small boats docked in the foreground. The sky is clear and blue.

# **Reflections of the Higgs:** **Beauty, Charm, & Strangeness** **Across Eras**

**Seminario**  
**Genova 18/11/2025**

**Andrea Sciandra**

# Standard Model Shortcomings & the Higgs Boson

Almost every problem in Standard Model (SM) arises from Higgs boson...

$$\mathcal{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

Typeset: Gian Giudice

↑  
flavour

↑  
naturalness

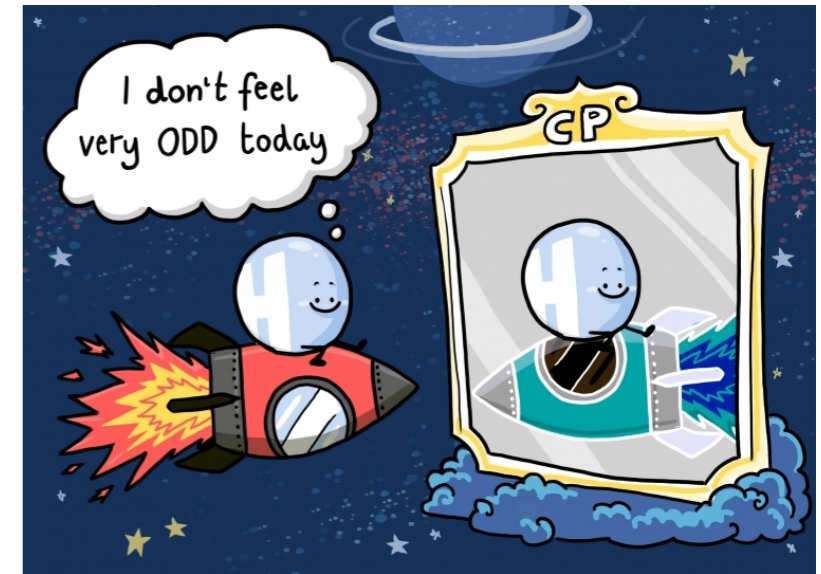
↑  
stability

↑  
cosmological constant

... simultaneously, simplest solution providing *EW symmetry breaking*

SM seems right as of today, but still *important issues* it cannot address, many related to the [physics of Higgs field](#):

- unification of interactions
- nature of dark matter
- connection to gravity
- nature of *EW symmetry breaking*
- origin of quark/lepton families
- masses and Yukawa couplings
- matter anti-matter asymmetry



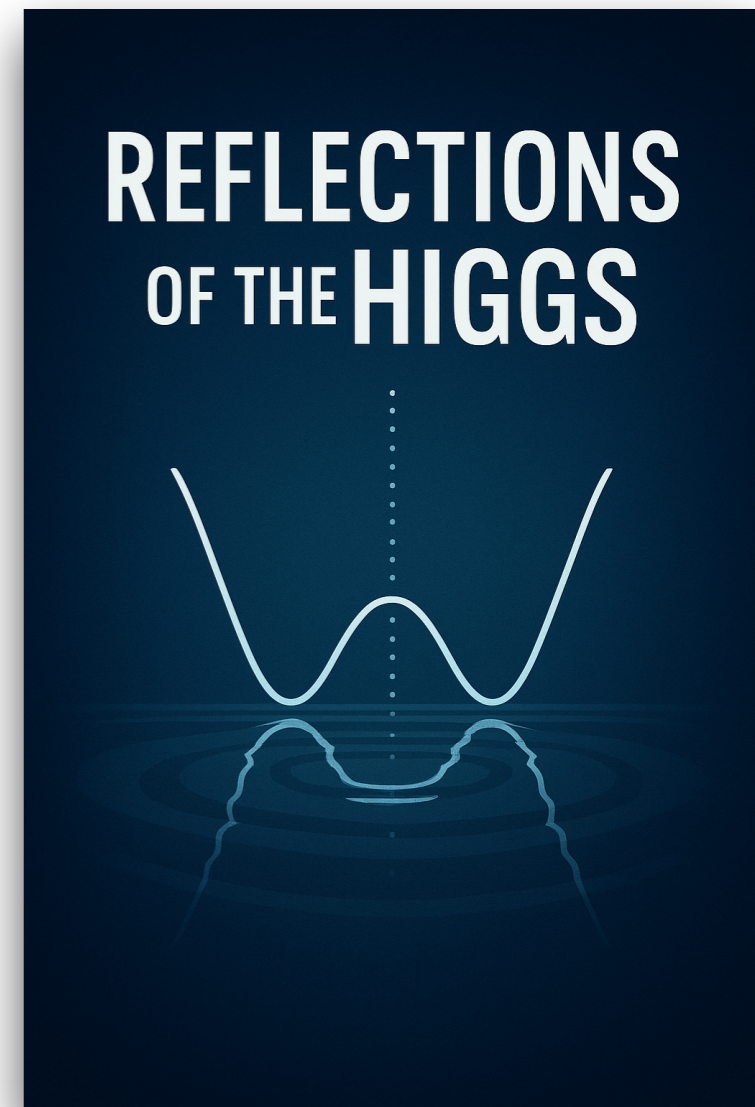
DESY/designdoppel

# The Higgs: a Mirror onto SM Shortcomings

Higgs “*reflection*” : the way Higgs physics may? might? should?! *reveal hidden aspects of the SM*

- The Higgs as the *unique scalar in the Standard Model*
  - Couples to everything with mass: *universal gateway*
  - Unstable to UV physics: *hierarchy problem*
  - Can mix with hidden sectors: *portal models*
  - Governs the vacuum structure: *self-coupling*
  - Controls *unitarity at high energies* (*VV scattering*)
- Other sectors can hint at new physics, *Higgs sector is the most theoretically motivated & experimentally sensitive window to whatever lies beyond Standard Model*
- The Higgs boson has the potential to be our **preferential mirror onto new physics**

$$\delta m_H^2 \sim \frac{\Lambda^2}{16\pi^2}$$



**Key question: “Is the Higgs exactly as the SM predicts?”**

*“If the Higgs wasn’t the SM one, how would its reflections look like?”*

# The Higgs: a Mirror onto SM Shortcomings

Higgs “*reflection*” : the way Higgs physics may? might? should?! *reveal hidden aspects of the SM*

- The Higgs as the *unique scalar in the Standard Model*
  - Couples to everything with mass: *universal gateway*

**Focus on three main topics:**

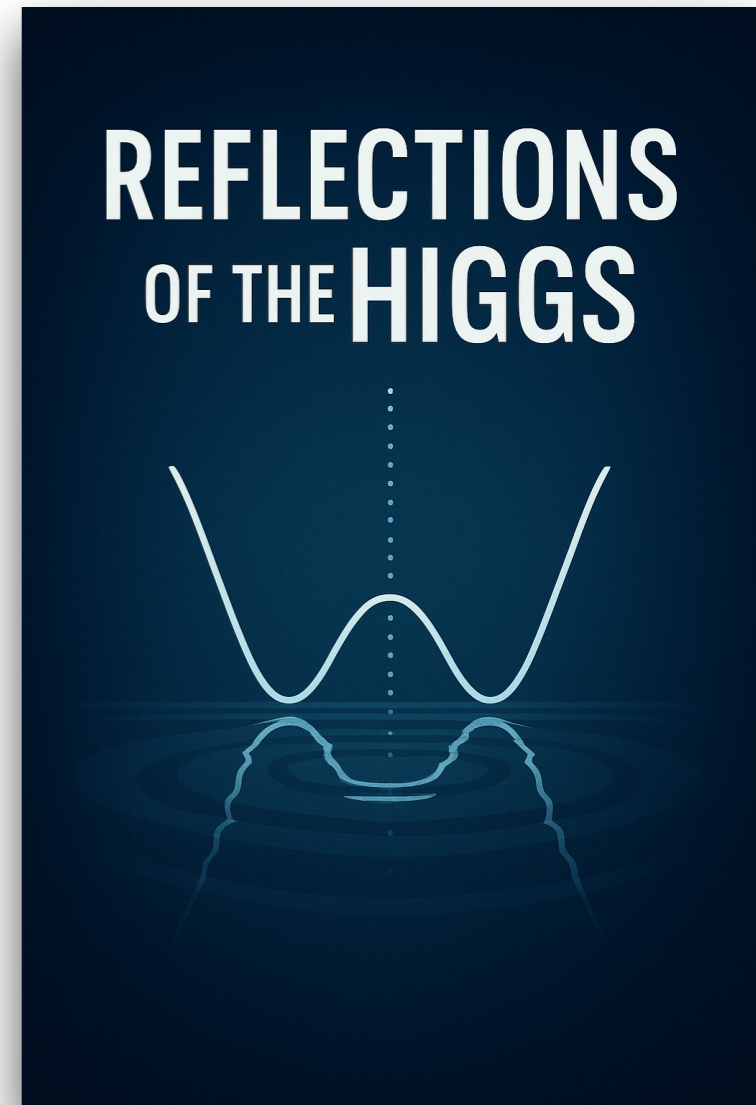
- **\* “Lighter” quark Yukawa couplings**
- **\* Higgs dynamics at high  $Q^2$**
- **\* Higgs potential**

*whatever lies beyond Standard Model*

- The Higgs boson has the potential to be our **preferential mirror onto new physics**

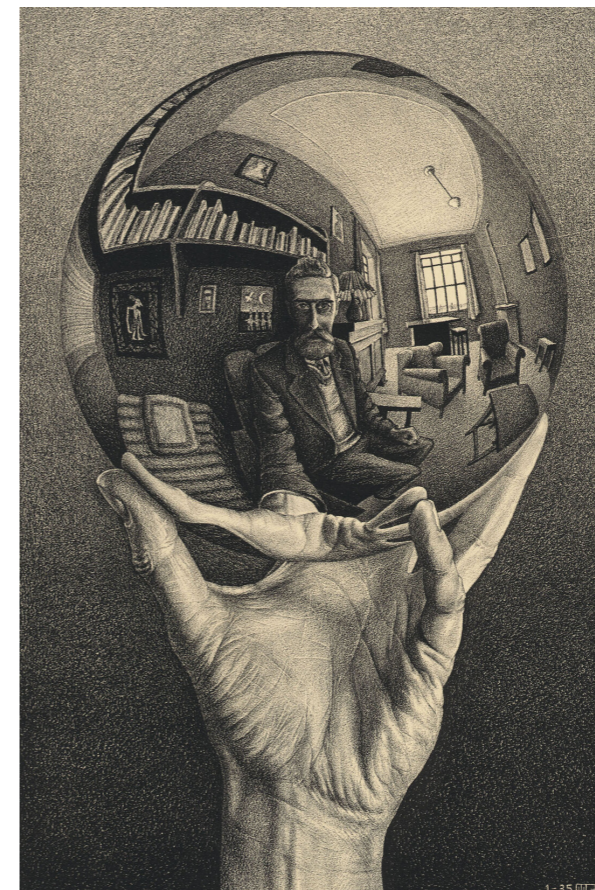
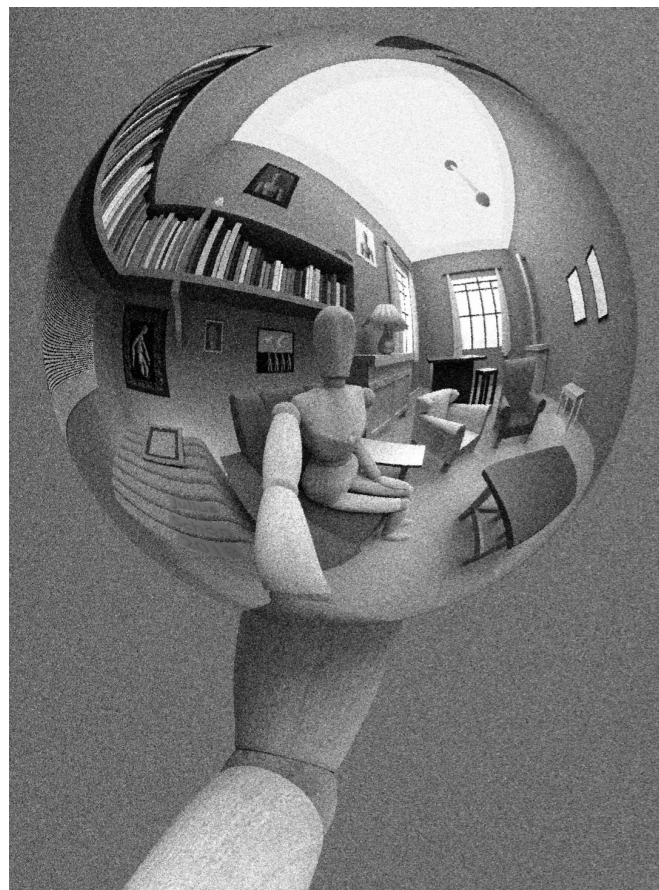
**Key question: “Is the Higgs exactly as the SM predicts?”**

*“If the Higgs wasn’t the SM one, how would its reflections look like?”*

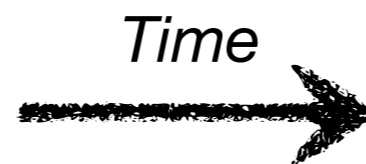


# The Mirror and... the Subject

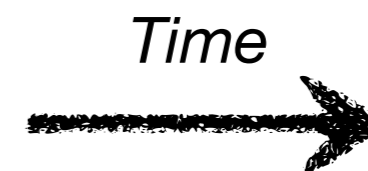
*Wise evolution of observables, machines & measurements across eras may ensure the successful program we are aiming for...*



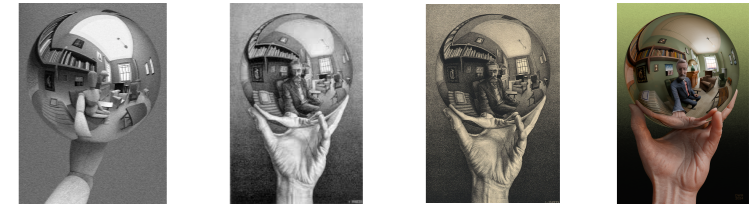
Better subjects...  
better *observables*



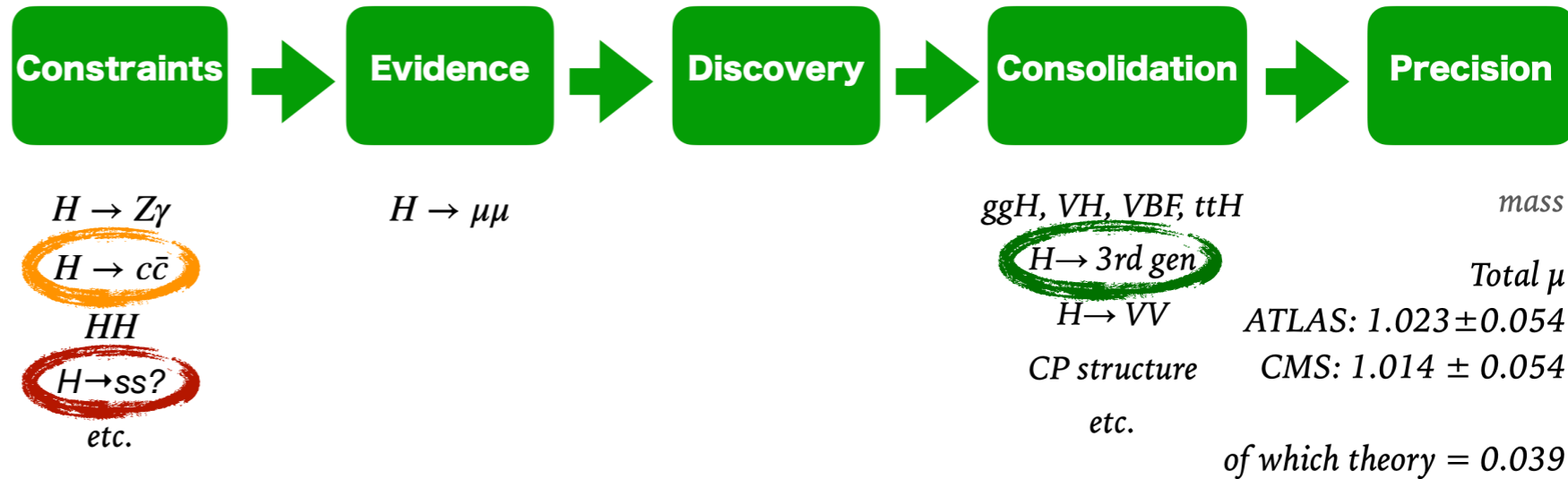
Better mirrors...  
better *machines/detectors*  
better *measurements*



# From discovery to precision



From discovery to precision: reflections of the Higgs boson across eras just started, 13 years after its discovery



- Higgs couplings vs. fermion masses:

$$m_i = g_i v$$

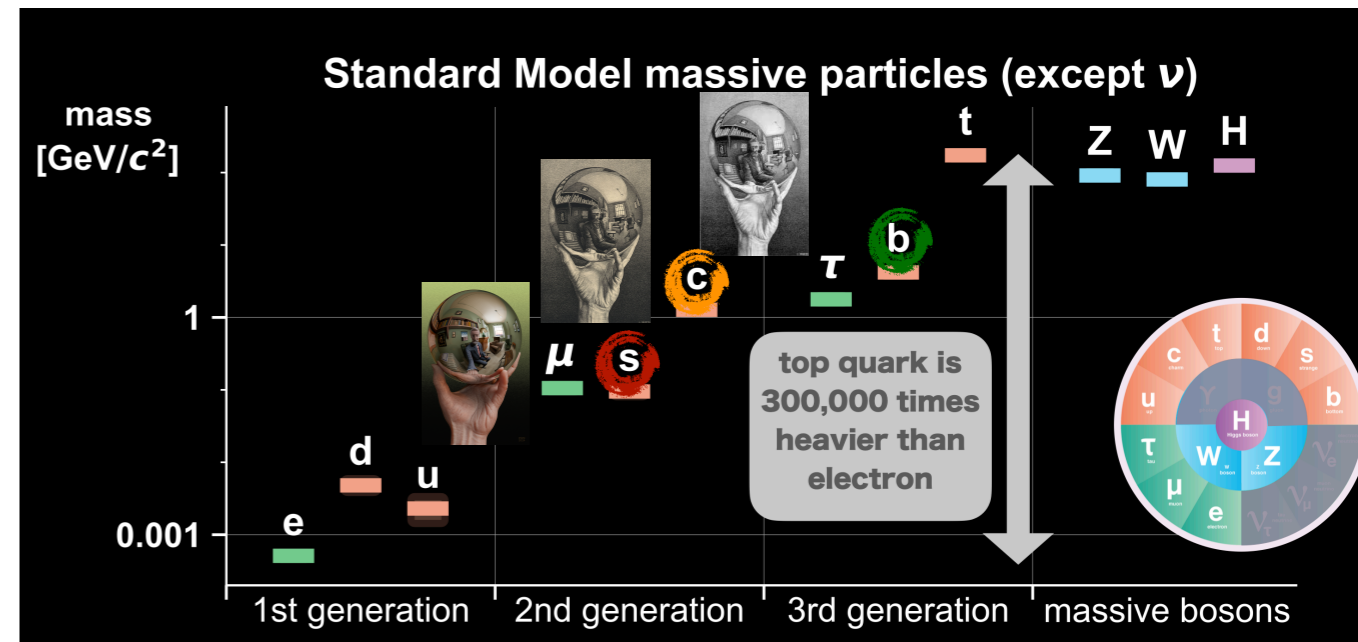
- After Newton and Einstein, establishing a new concept of “mass”!

- Proportionality: test of Yukawa mechanism
- Any deviation would directly indicate new dynamics - e.g. compositeness, extra dimensions, or mixing with new scalar states

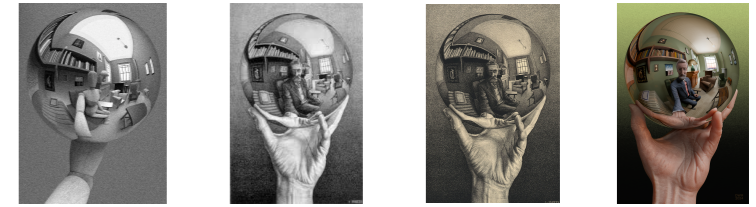
- beauty, charm, strangeness

→ probes of increasing subtlety

G. Salam



# Is it the **Standard Model Higgs?**



Does the Higgs couple to other particles as predicted?



Measure *deviation* in coupling from Standard Model

$$\delta = \frac{g_{\text{SM}} - g_{\text{NP}}}{g_{\text{SM}}}$$

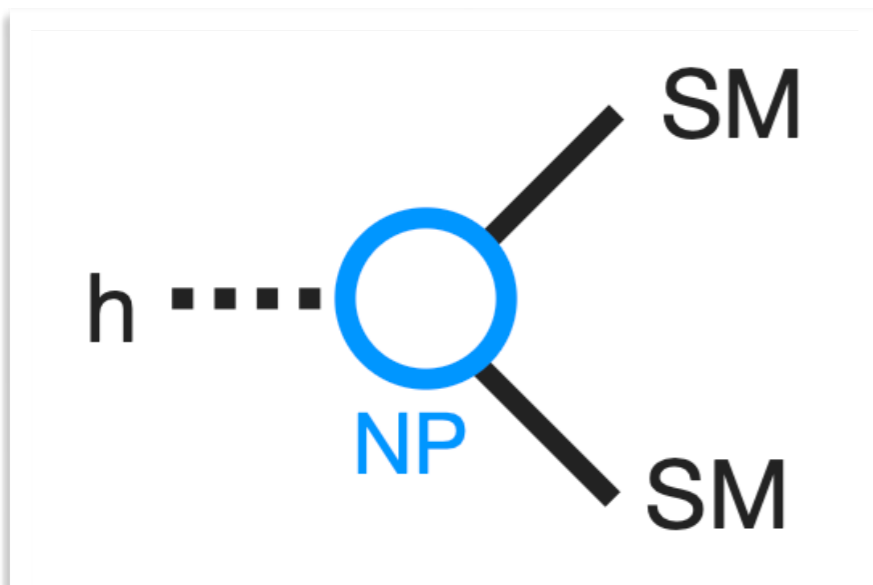
Coupling of *new physics* to SM  
Mass of new physics

$$g_{\text{NP}}$$

$$M_{\text{NP}}$$

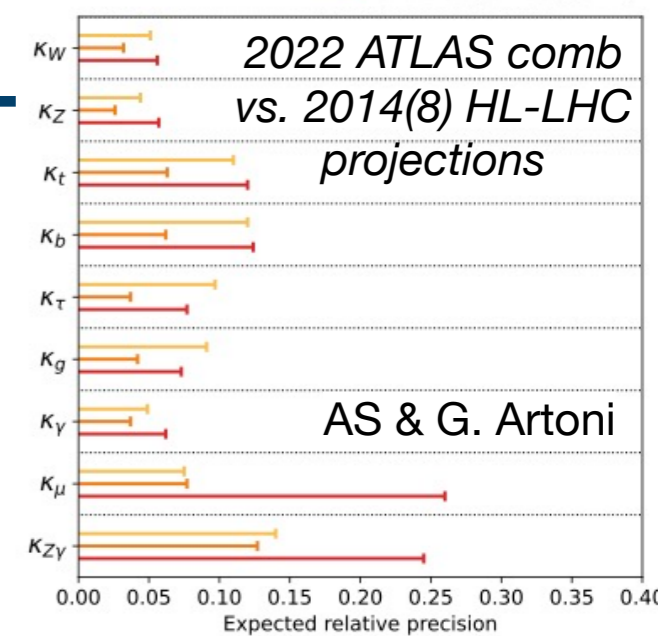
Map deviation to new physics coupling & scale

$$\delta \sim g_{\text{NP}}^2 \frac{(100 \text{ GeV})^2}{M_{\text{NP}}^2}$$

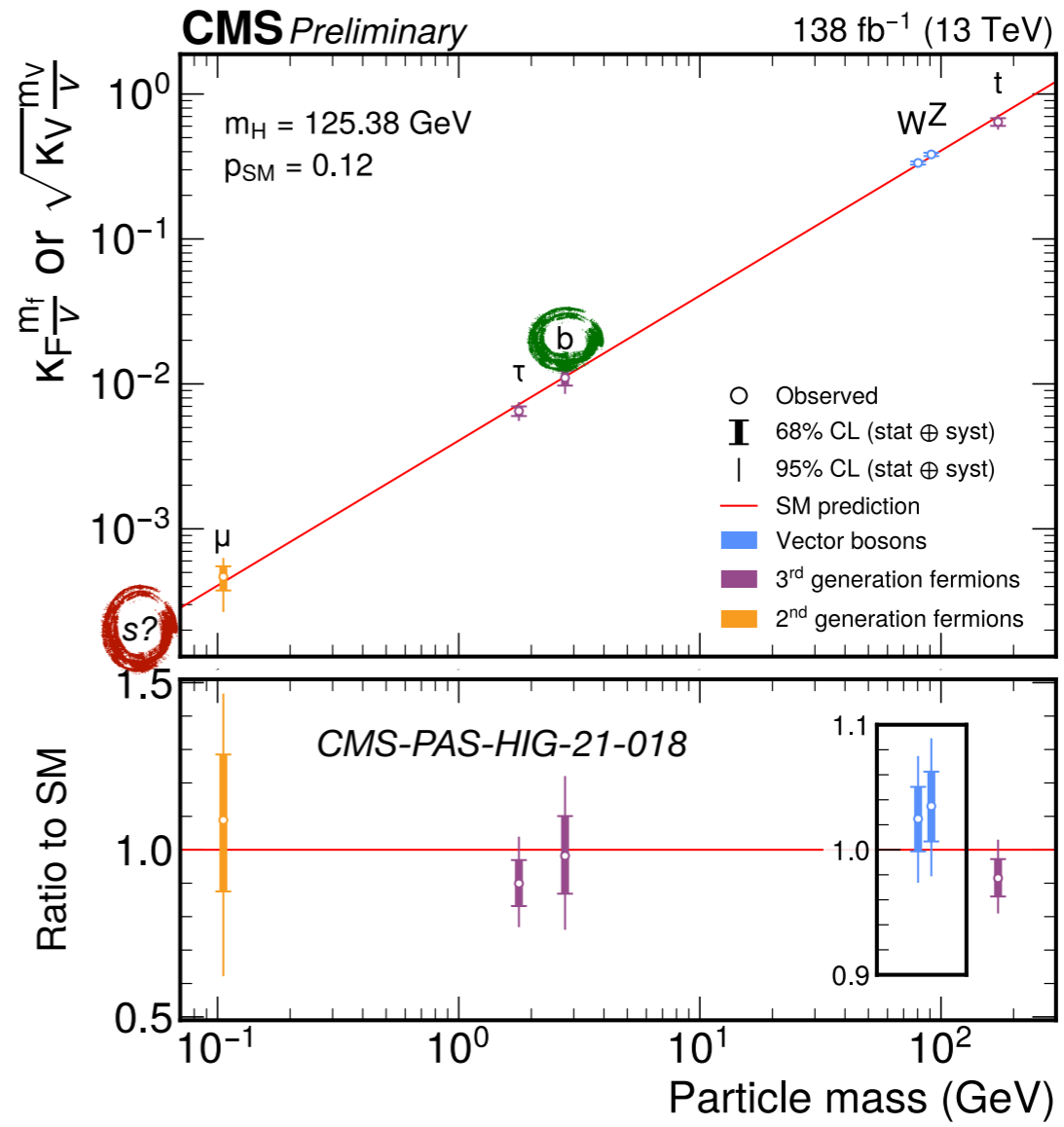
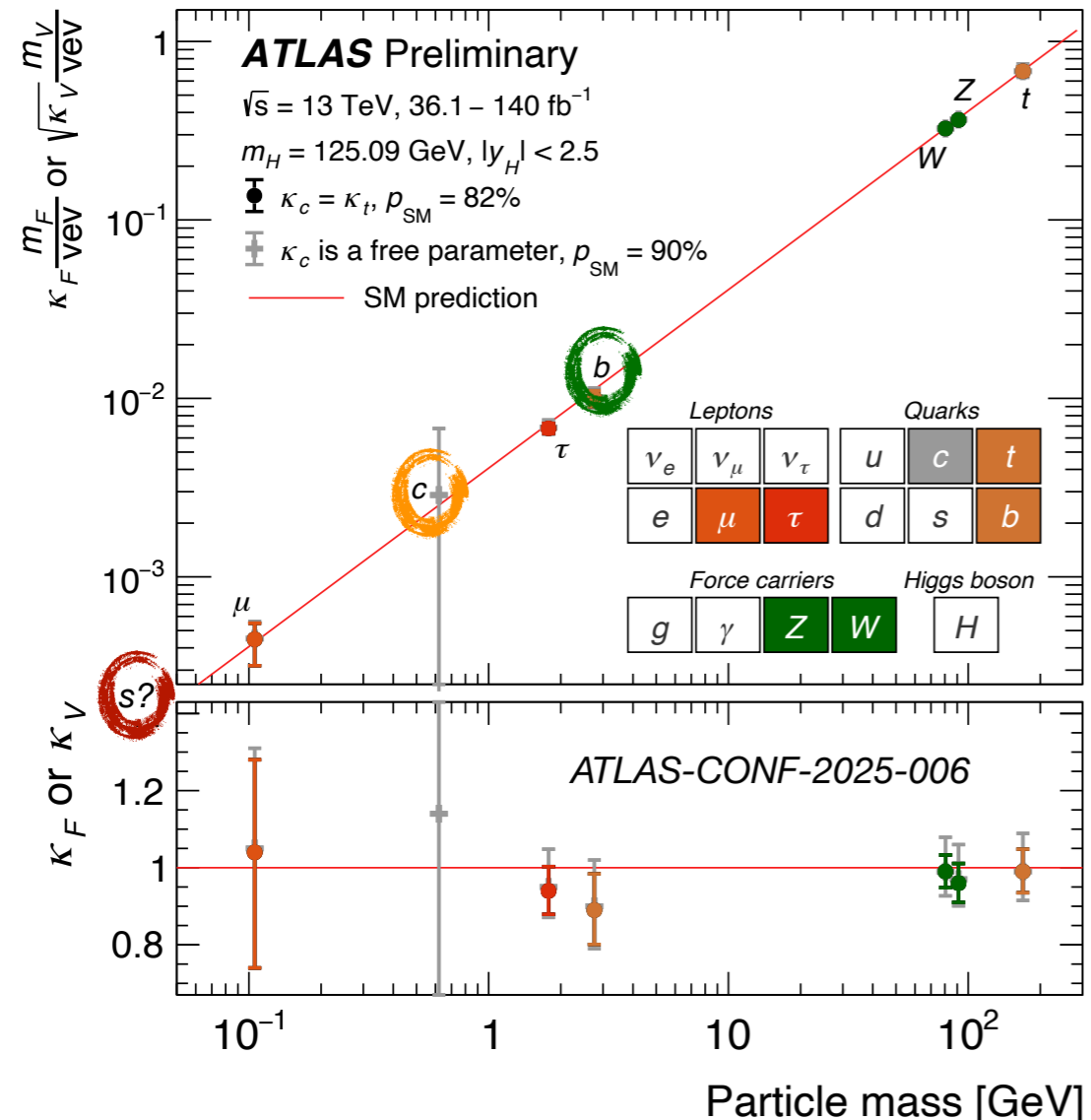


# Higgs & its Couplings to the “outer” World

ATL-PHYS-PUB-2014-016  
ATL-PHYS-PUB-2018-054  
Nature 607, 52-59 (2022)



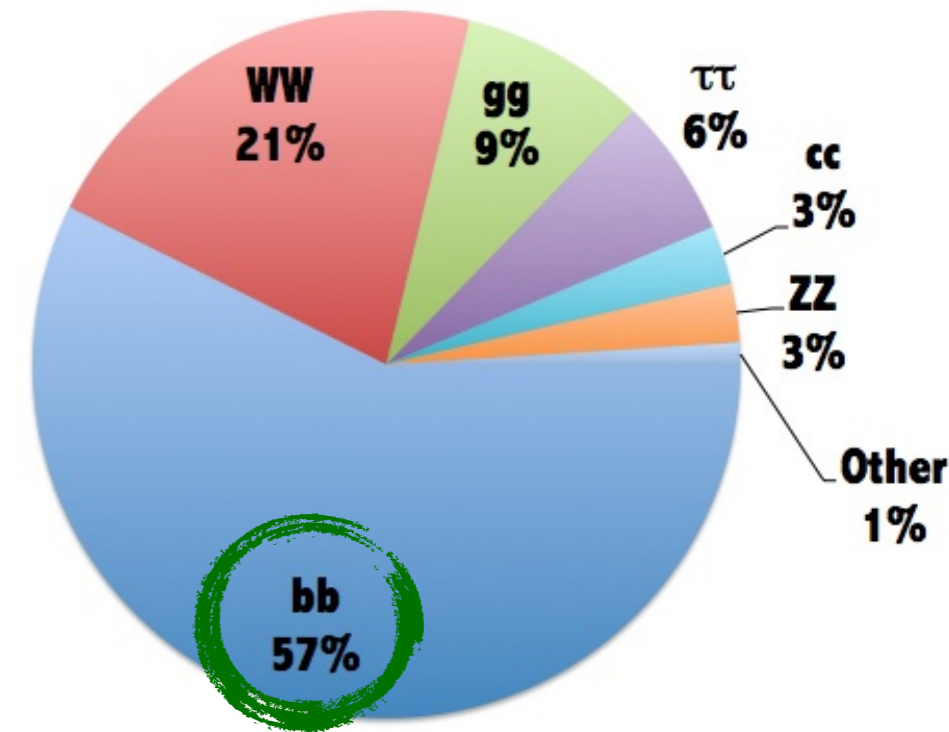
- Current precision ~2014 HL-LHC projections (20x Run-2 data)!
  - 2025 results updating Nature combination for 10<sup>th</sup> anniversary
- Impressive agreement with SM predictions
  - But, is our current accuracy “good enough”? Anywhere ~1%?!
  - How many couplings are yet to be explored?
- Huge *backgrounds* make *hadronic* final states challenging



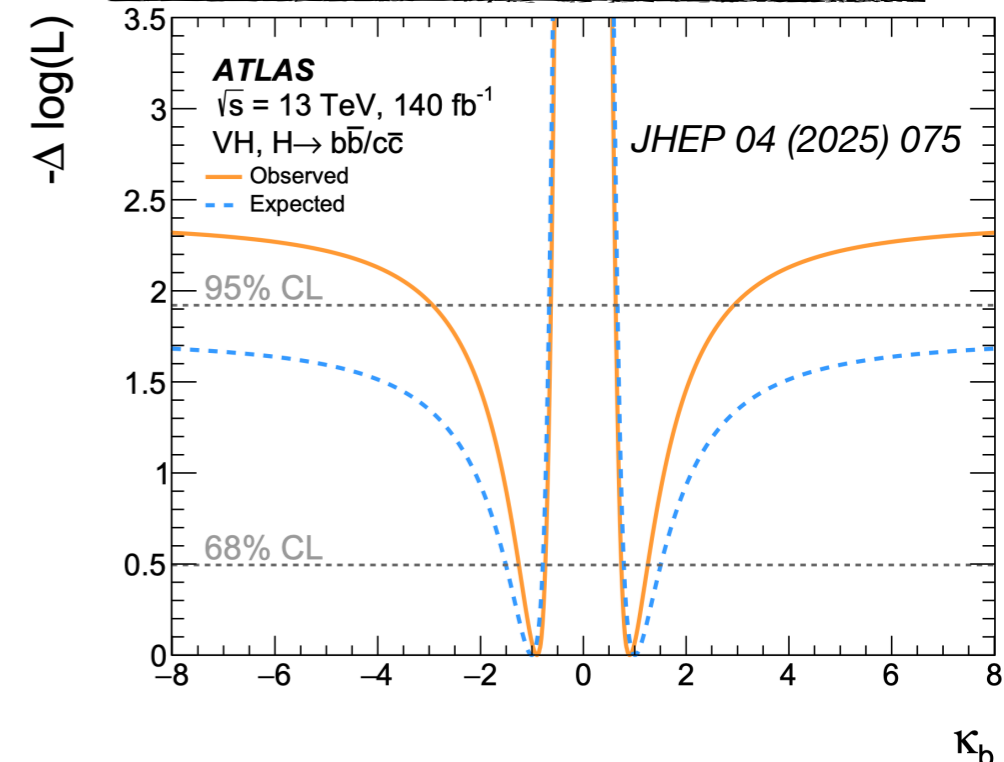
# “Beauty”: Third-Generation Couplings



- Milestone at the LHC:  $H \rightarrow bb$  discovery in 2018
  - 6 years after Higgs discovery, still a relatively young field!
  - Witnessing challenges of hadronic channels, in contrast to less-common Higgs-boson decay channels observed earlier
  - Huge improvements, entered *precision era*
- Historically driven by  $V(=W,Z)H$  production in “resolved” decay topology
  - Other production modes (e.g.  $ttH$ ) also contribute in a subleading way
- *Main uncertainties are challenging to reduce*
  - Signal and background, mainly  $W/Z$ +jets, modeling
  - Will be a main focus of full Run-3



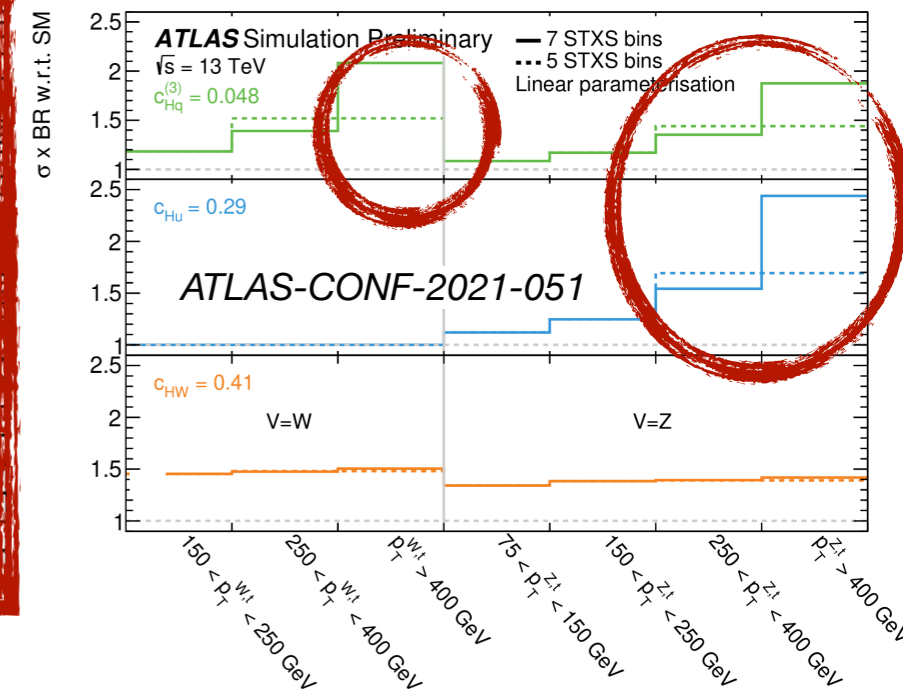
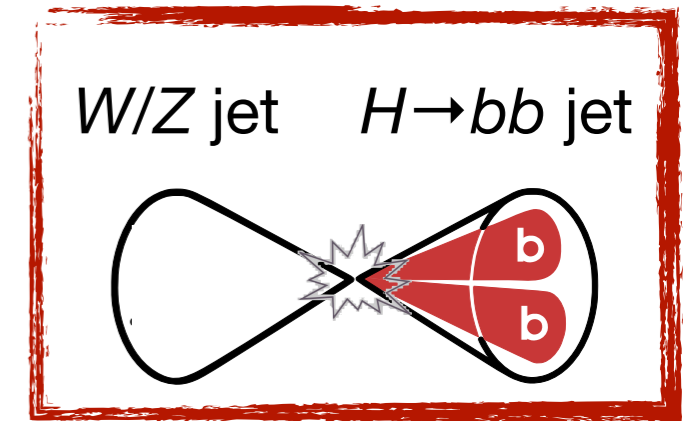
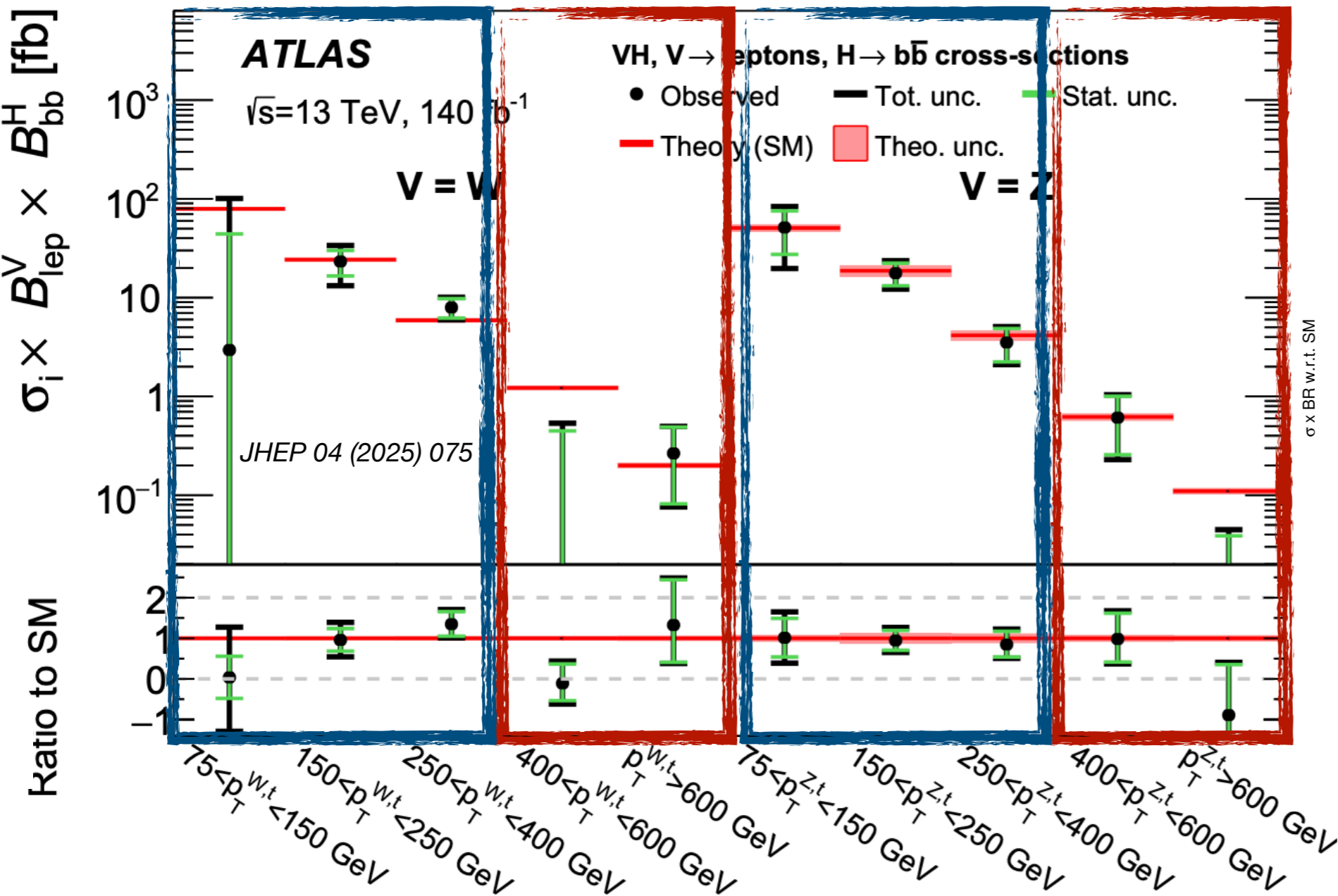
**$0.65 < |\kappa_b| < 1.37$  (95%CL)**



$$\mu_{VH}^{bb} = \frac{\kappa_b^2}{1 + B_{Hbb}^{\text{SM}} (\kappa_b^2 - 1) + B_{Hcc}^{\text{SM}} (\kappa_c^2 - 1)}$$

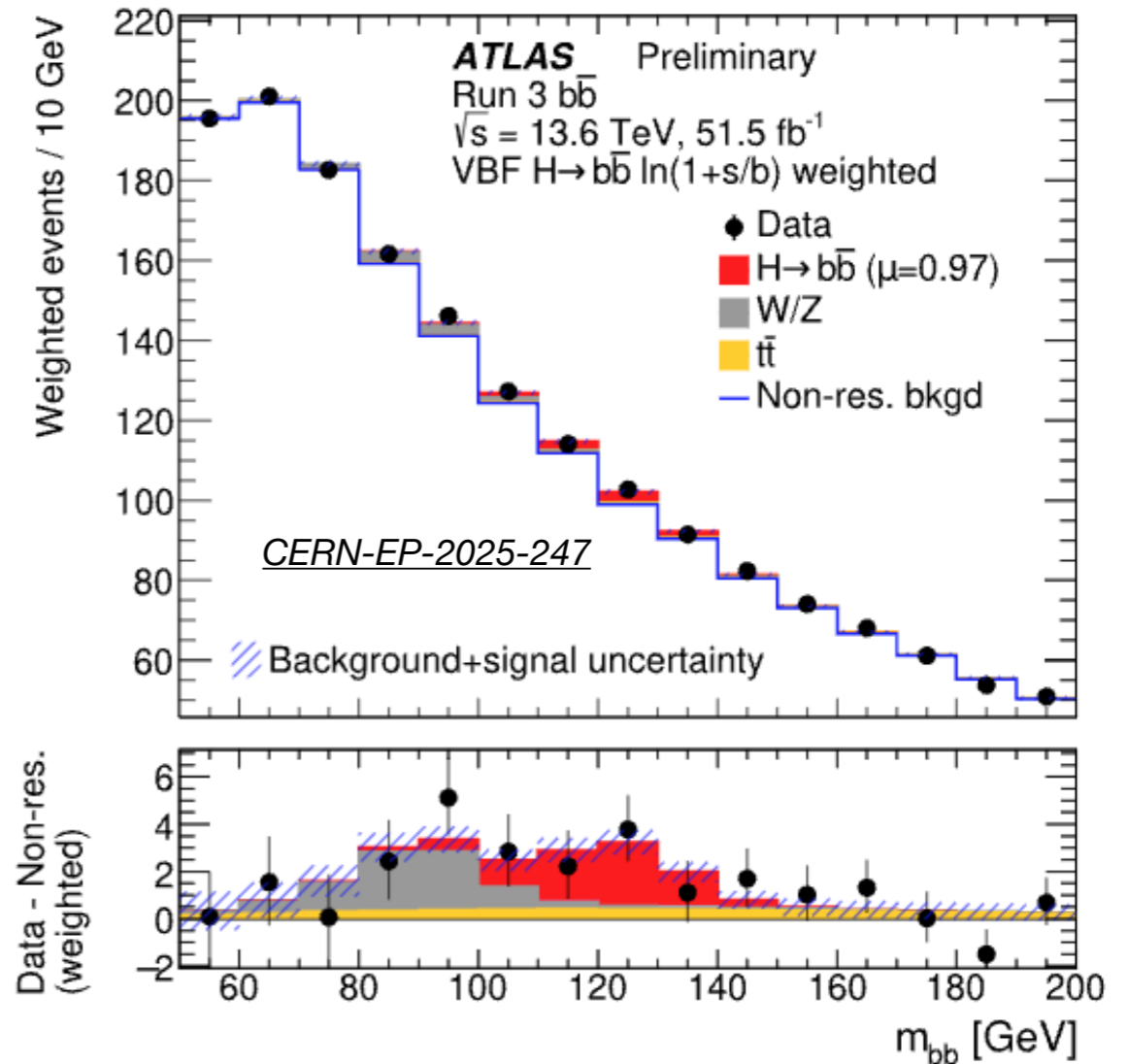
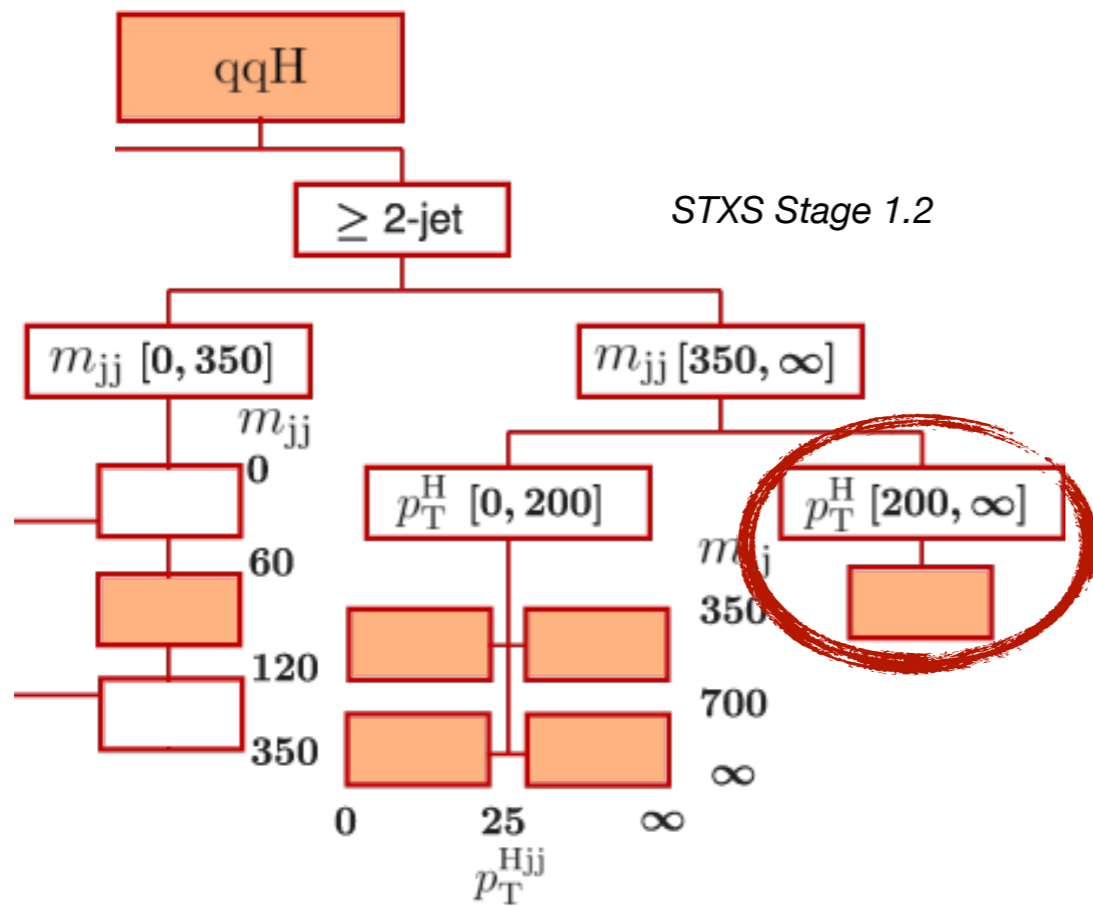
# “Beauty”: Third-Generation Couplings... & more!

- Combination of *resolved* & *merged* VH topologies allows for coverage of enormous phase space
  - Great constraints on Higgs kinematics up to  $p_T \sim 600$  GeV!
- Enhanced sensitivity to new physics from large  $M_{NP}$



# “Beauty”: Third-Generation Couplings... & more!

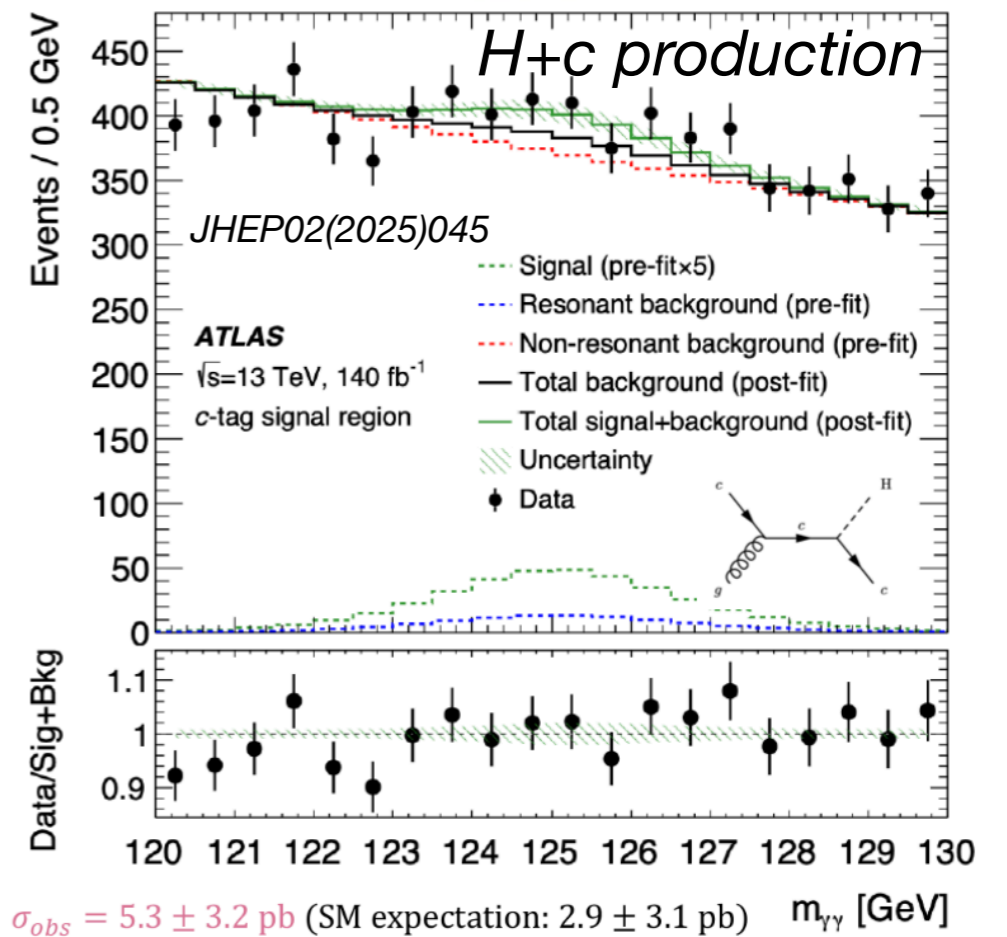
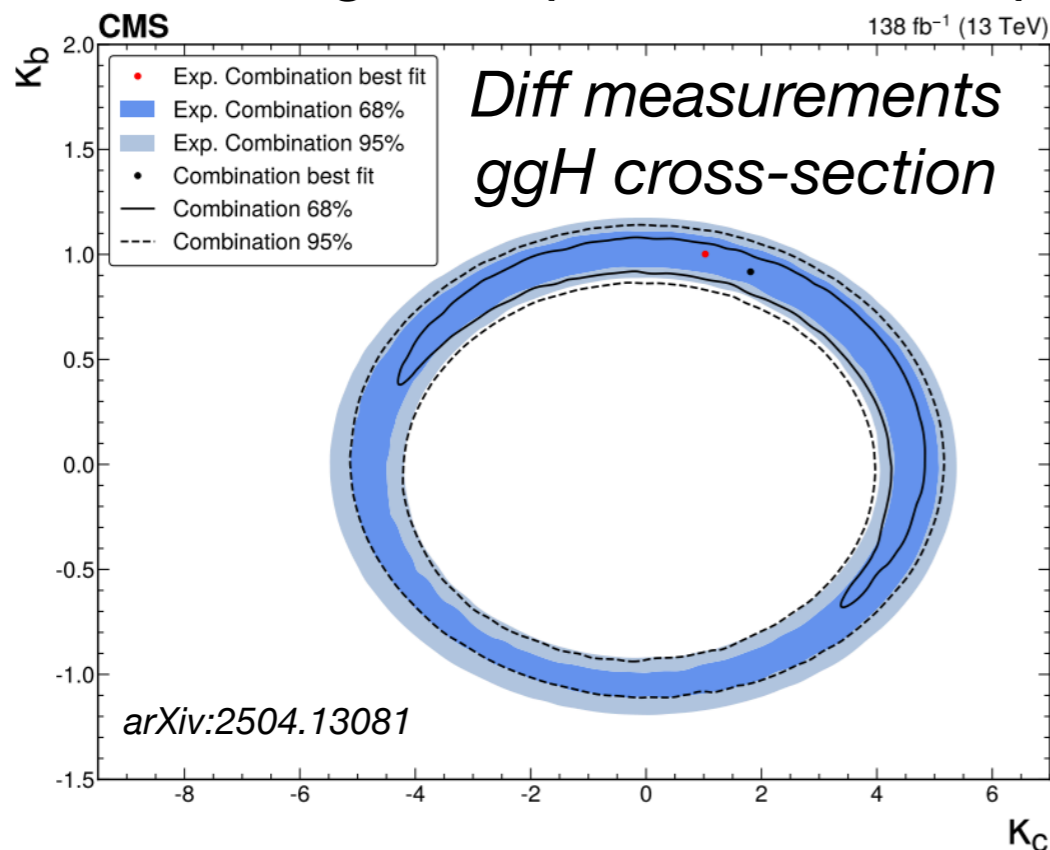
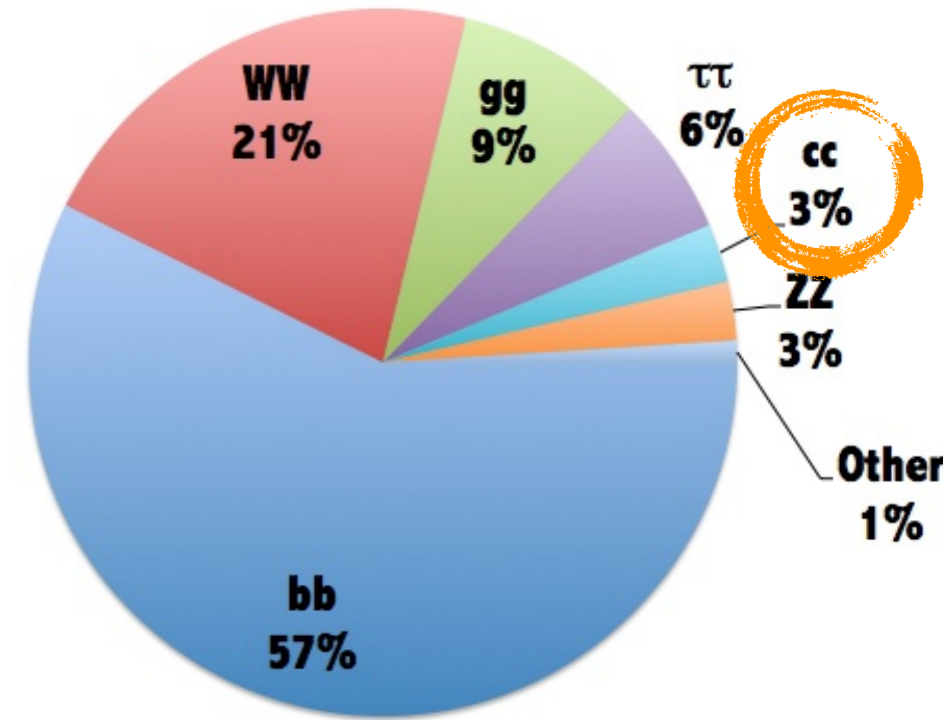
- Recently, first evidence of VBF  $H \rightarrow bb$  production by ATLAS
  - Channel dominated by Higgs  $p_T > \sim 200$  GeV
  - **Great prospects for high momentum in VBF too!**



Being  $H \rightarrow bb$  the most frequent decay, it probes high  $Q^2$  production (more later)

# “Charm”: Second-Generation Frontier

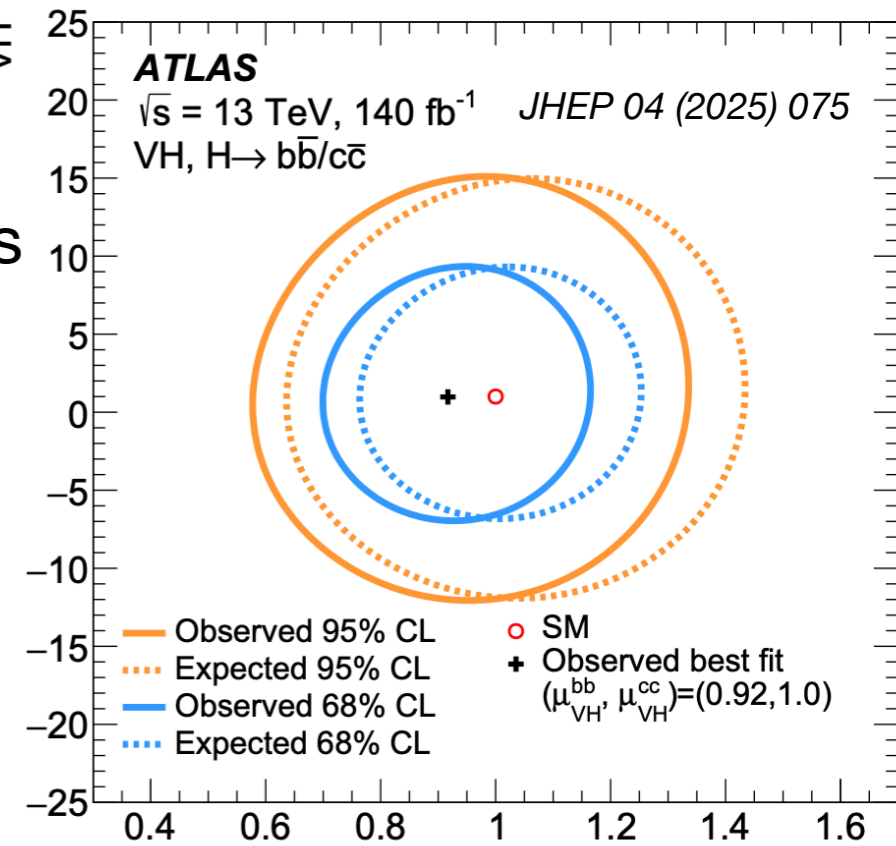
- Hunt for **charm Yukawa coupling**
  - Different approaches keep changing landscape
  - Direct & indirect probes, dominated by direct search for  $H \rightarrow cc$  decay
- Trying to squeeze out sensitivity: now probed in *all main production modes!*
- **Far from discovery**, very challenging channel
  - $\sim 3.5x$  lighter than bottom,  $\sim 20x$  smaller BR, more difficult to identify
  - Once thought “impossible” attempt at the LHC...



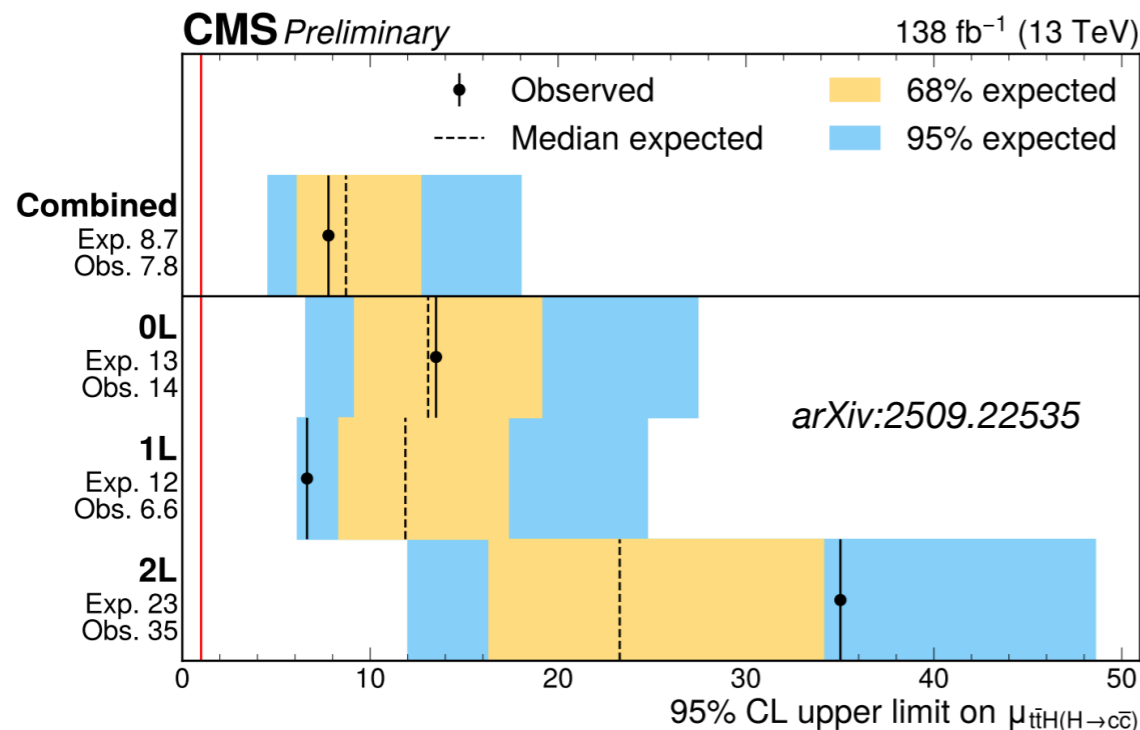
# “Charm”: Second-Generation Frontier

$\mu_{VH}^{cc}$

- Direct: not only statistics, need to **identify charm jets!**
  - Constant improvement in performance, new techniques (e.g. finer & finer b/c-tagging...)
- Historically, business started in  $VH$  production mode
- **Impressive new result by CMS probing  $t\bar{t}H$** 
  - Huge boost from dedicated discriminant to reduce background
- Fresh off the press:  **$VBF H \rightarrow cc$** !  $\sim 1$   $VH \rightarrow cc$  channel
  - Promising, statistically dominated



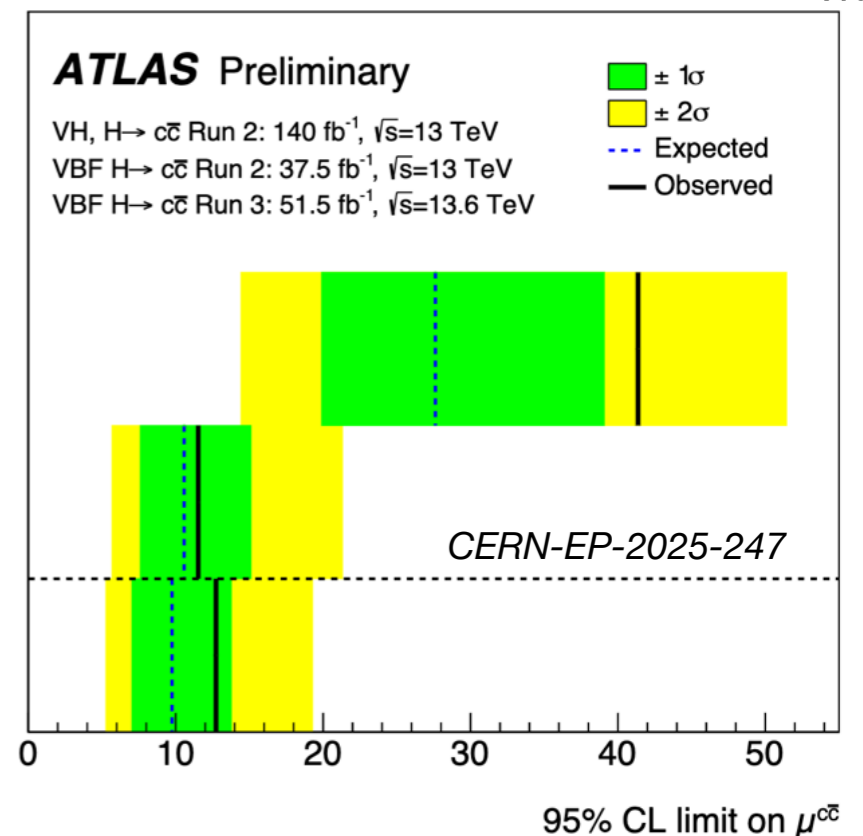
$\mu_{VH}^{bb}$



**VBF  $H \rightarrow c\bar{c}$**   
 Exp. =  $27.6 \times \text{SM}$   
 Obs. =  $41.4 \times \text{SM}$

**VH,  $H \rightarrow c\bar{c}$**   
 Exp. =  $10.6 \times \text{SM}$   
 Obs. =  $11.5 \times \text{SM}$

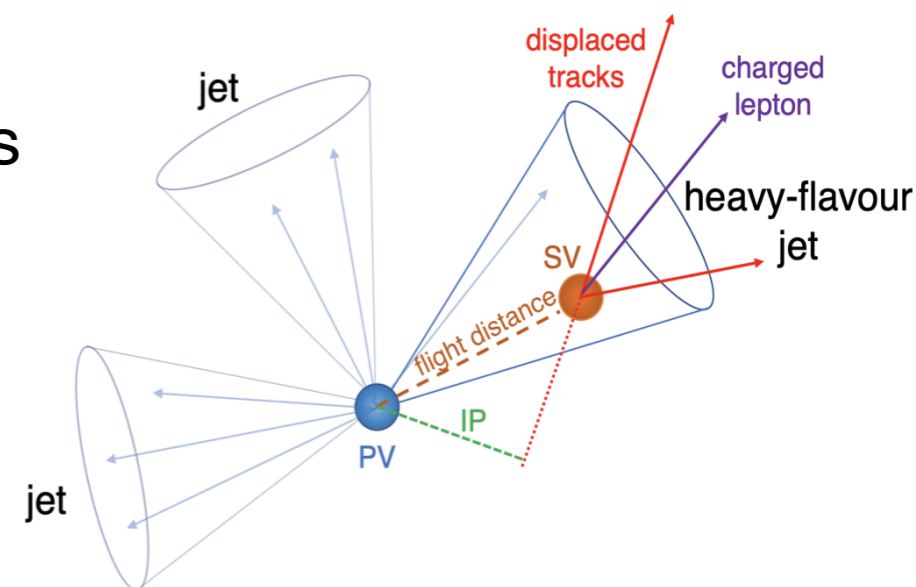
**Combined**  
 Exp. =  $9.8 \times \text{SM}$   
 Obs. =  $12.7 \times \text{SM}$



# “Charm”: Tools for 2<sup>nd</sup> Gen Frontier

- **Charm tagging based on:**

- Decay length  $\sim 150\text{-}300\ \mu\text{m}$ , displaced vertices/tracks
- Relatively large invariant mass
- Specific track multiplicity:  $\sim 3$  charged particles on average
- Non-isolated charged leptons from semileptonic decays: BR $\sim 10\%$

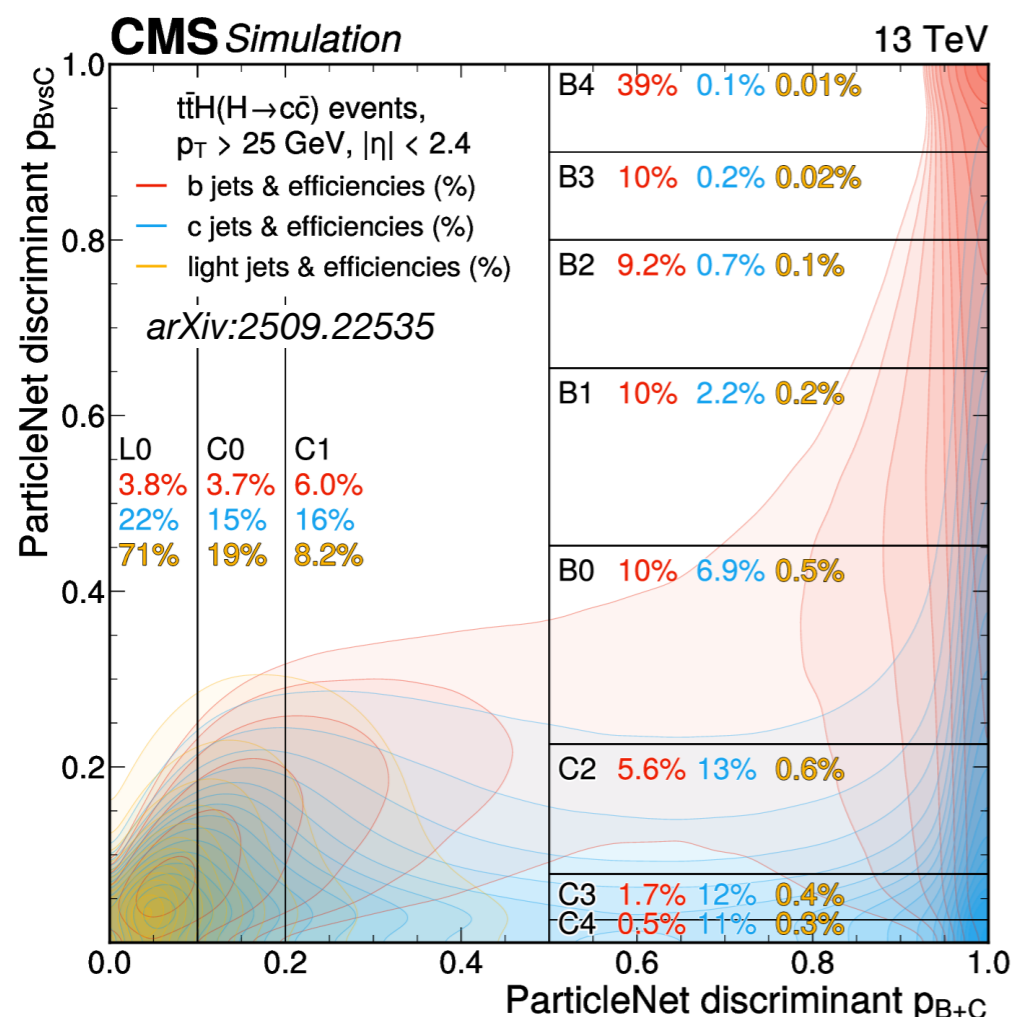


- **Challenges of charm tagging**

- Modelling uncertainties in fragmentation & semileptonic BR
- Intermediate E profiles, between b & light
- Many b-jets contain c hadrons from  $b \rightarrow c$

- **2D tagging**

- No clean, abundant data samples of prompt charm jets to calibrate on
- Systematic uncertainties larger than those for b-jets by x2-5

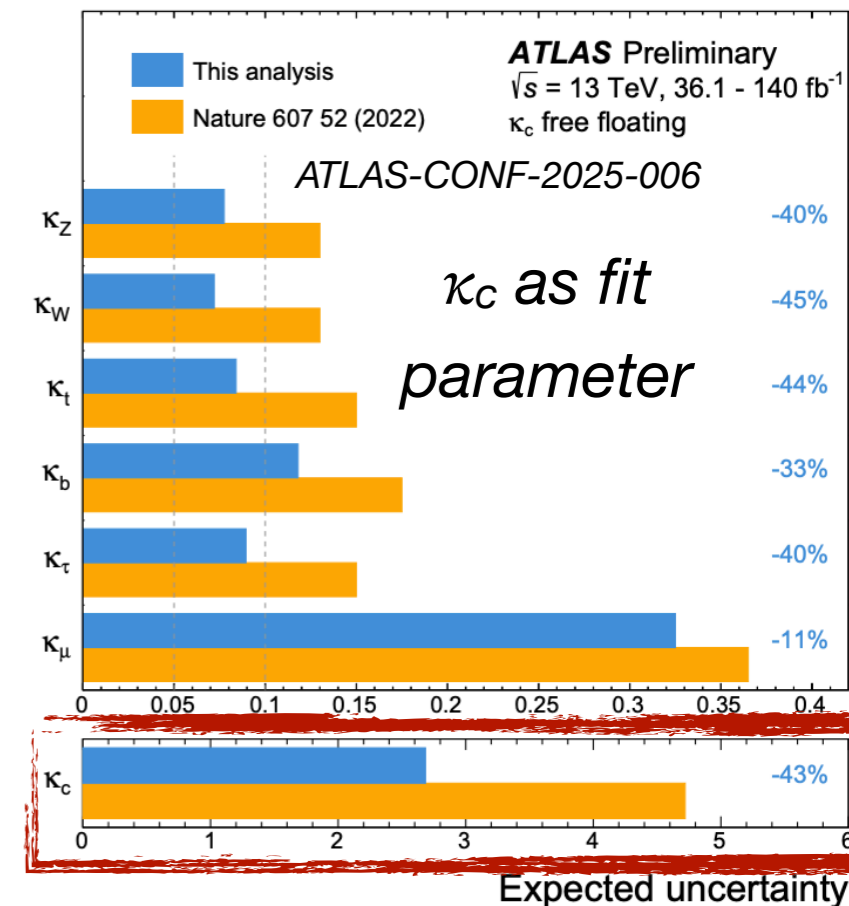
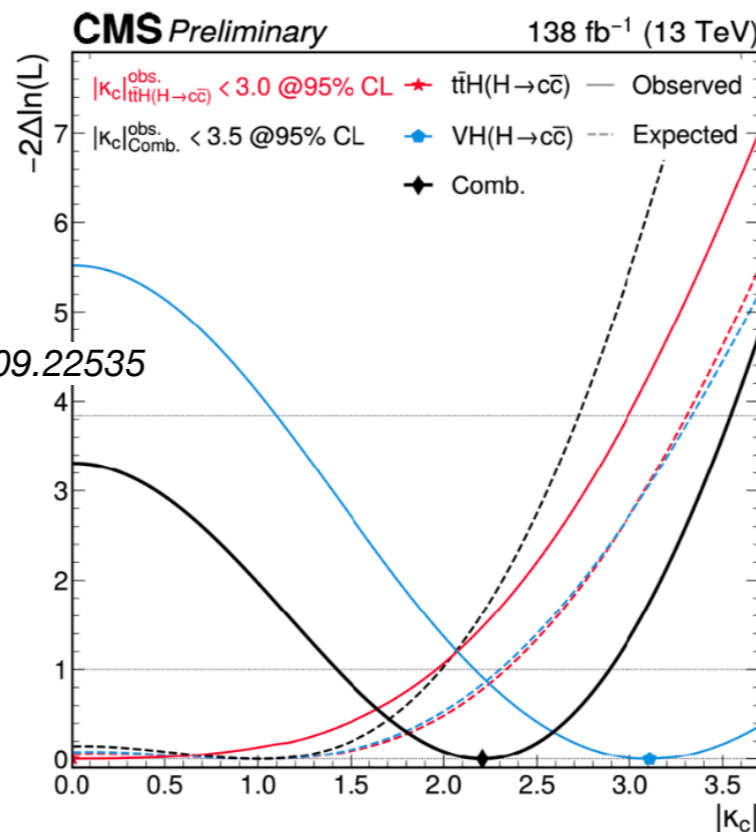
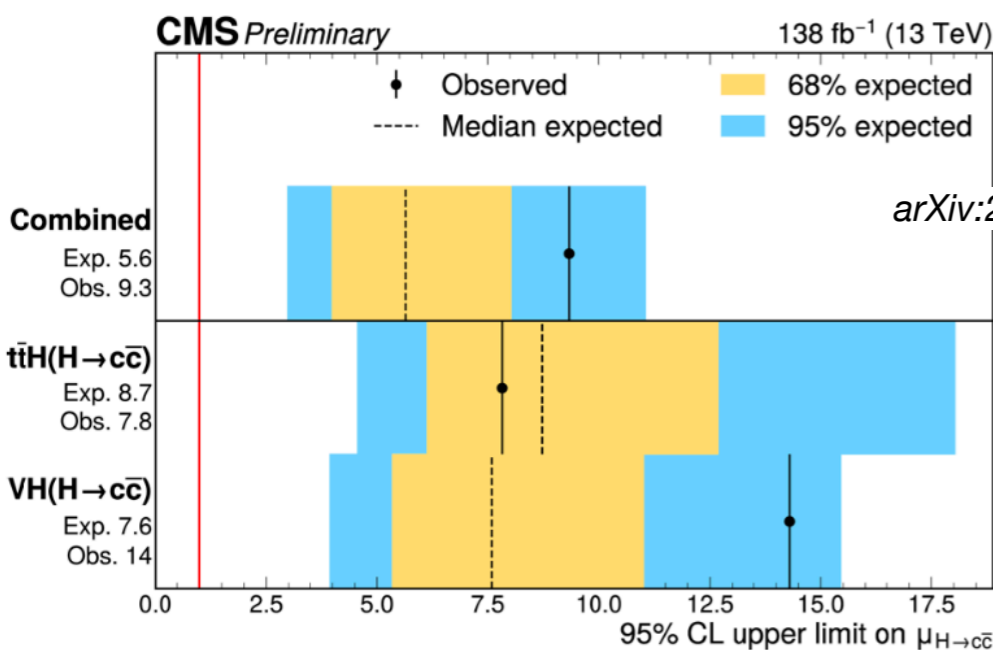


# “Charm”: Second-Generation Frontier



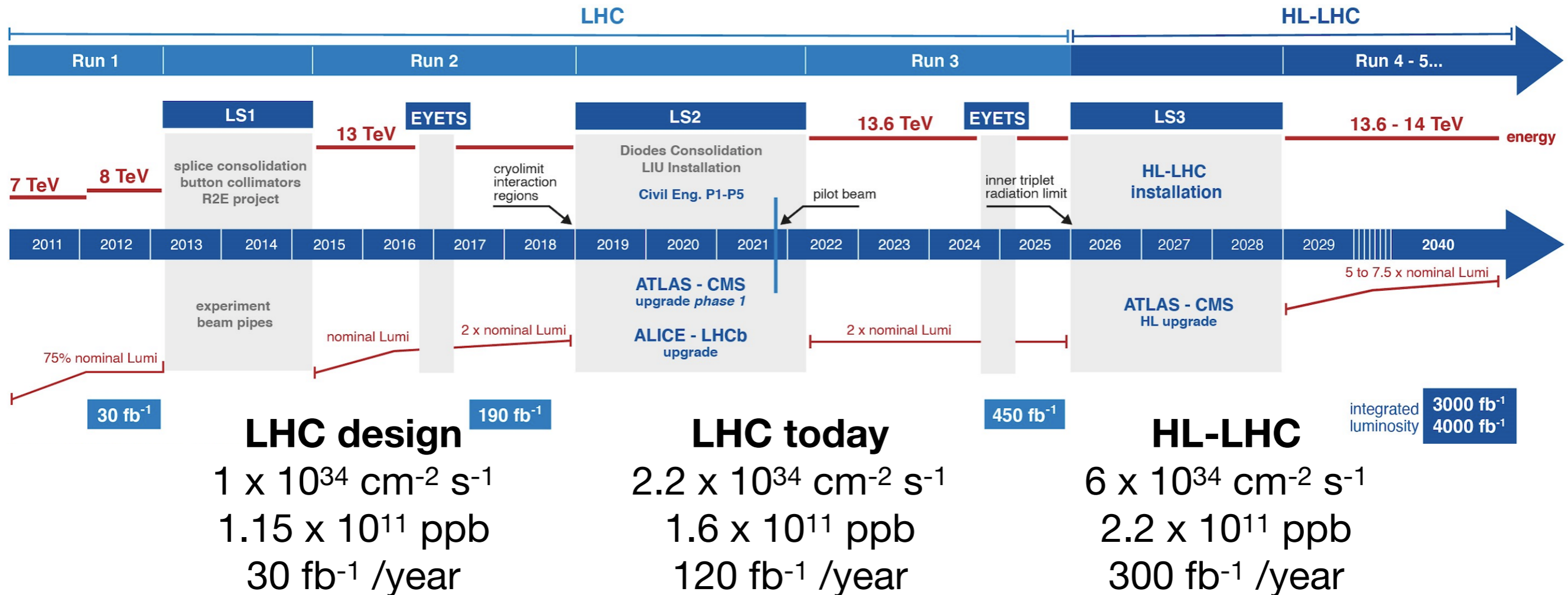
- Best limit on  $H \rightarrow cc$  to date by CMS, combining  $VH$  &  $t\bar{t}H$
- Impact of  $\kappa_c$  on simultaneous determination of Higgs couplings
  - Re-analysis of ATLAS Run-2 data allowed for *reduction of 43%* on exp.  $\kappa_c$  uncertainty
  - **Reached enough sensitivity to solve loose constraint on Higgs width when  $H \rightarrow cc$  ( $\kappa_c$ ) is included (free)**
  - New channels, explored in Run-3, will team up to further constrain  $\kappa_c$
- Future ahead of us: *Can the HL-LHC measure  $\kappa_c$ ?*

**$|\kappa_c| < 3.5$  (2.7 exp.) @95%CL**



# The Path Forward: The HL-LHC Era

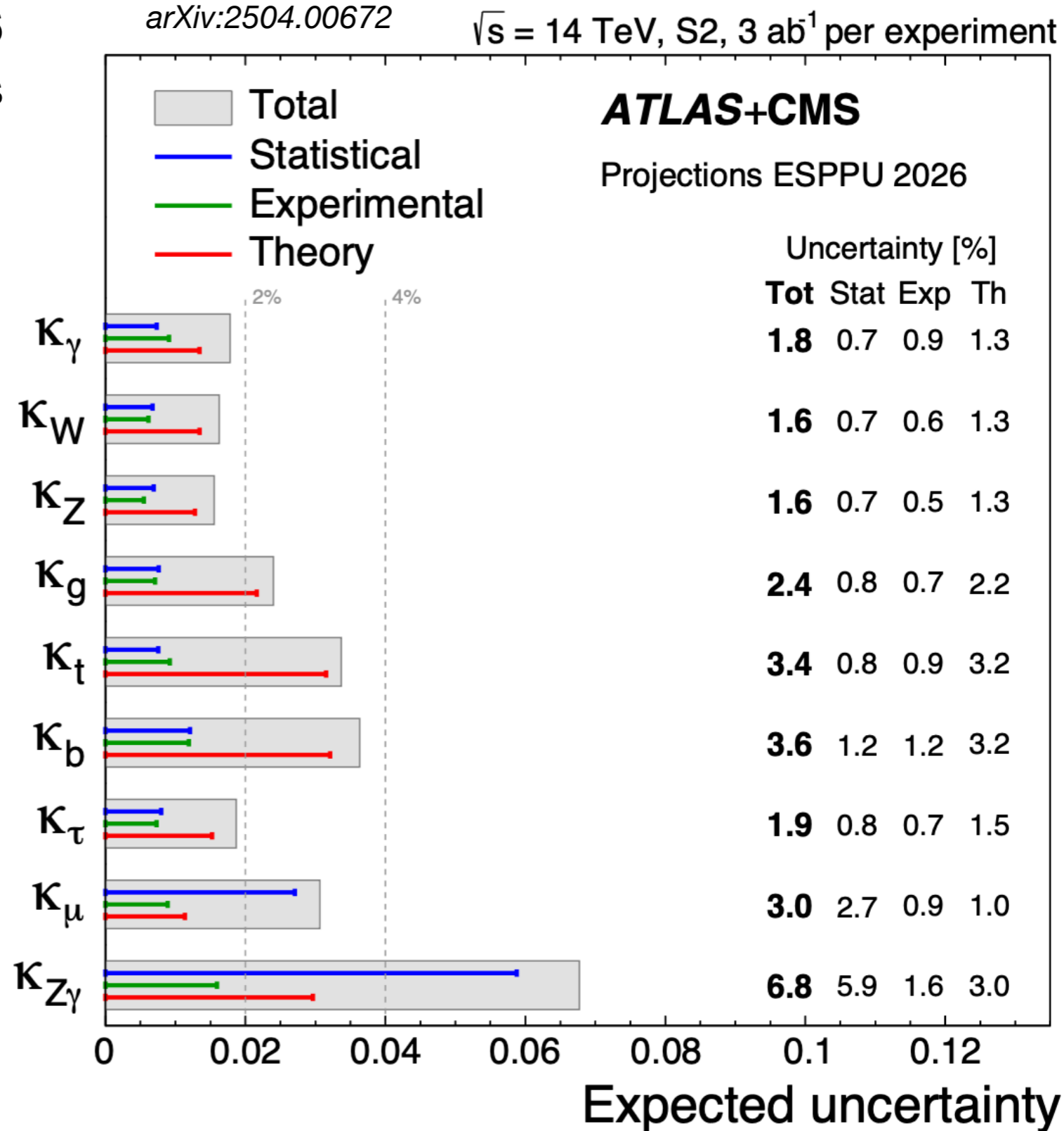
- HL-LHC kicks off in Run-3, currently expected June 2030
  - Expect up to  $3 \text{ ab}^{-1}$  @14 TeV, i.e. *180M Higgs bosons!*
- Among main “Higgs” goals:
  - *Percent-level accuracy* on modifiers for dominant couplings
  - Measurements of *rare Higgs boson couplings* to fermions and vector bosons
  - Precise measurements of *differential cross-sections*



*Detector upgrades for same (or better) performance at 200 PU as in Run-3 with 60 PU*

# The HL-LHC Era - Steps Forward for the Higgs

- Combined LHC input to ESPPU2026
- Scenarios considered for projections of physics deliverables from actual analyses
  - Scaling *luminosity*
  - *Efficiency* of object reconstruction, identification & resolution assumed as Run-2 → detector upgrades compensate harsher conditions
  - *Cross-section* rescaled to 14 TeV
- **HL-LHC will shrink Higgs coupling uncertainties by roughly x2-3 compared to Run-2**
- Expect **observation of  $H \rightarrow \mu\mu/Z\gamma$**
- *Percent-level* loop-induced couplings sensitivity to BSM effects
- **Theory uncertainties become dominant!**



# The HL-LHC Era - Bottom & Charm

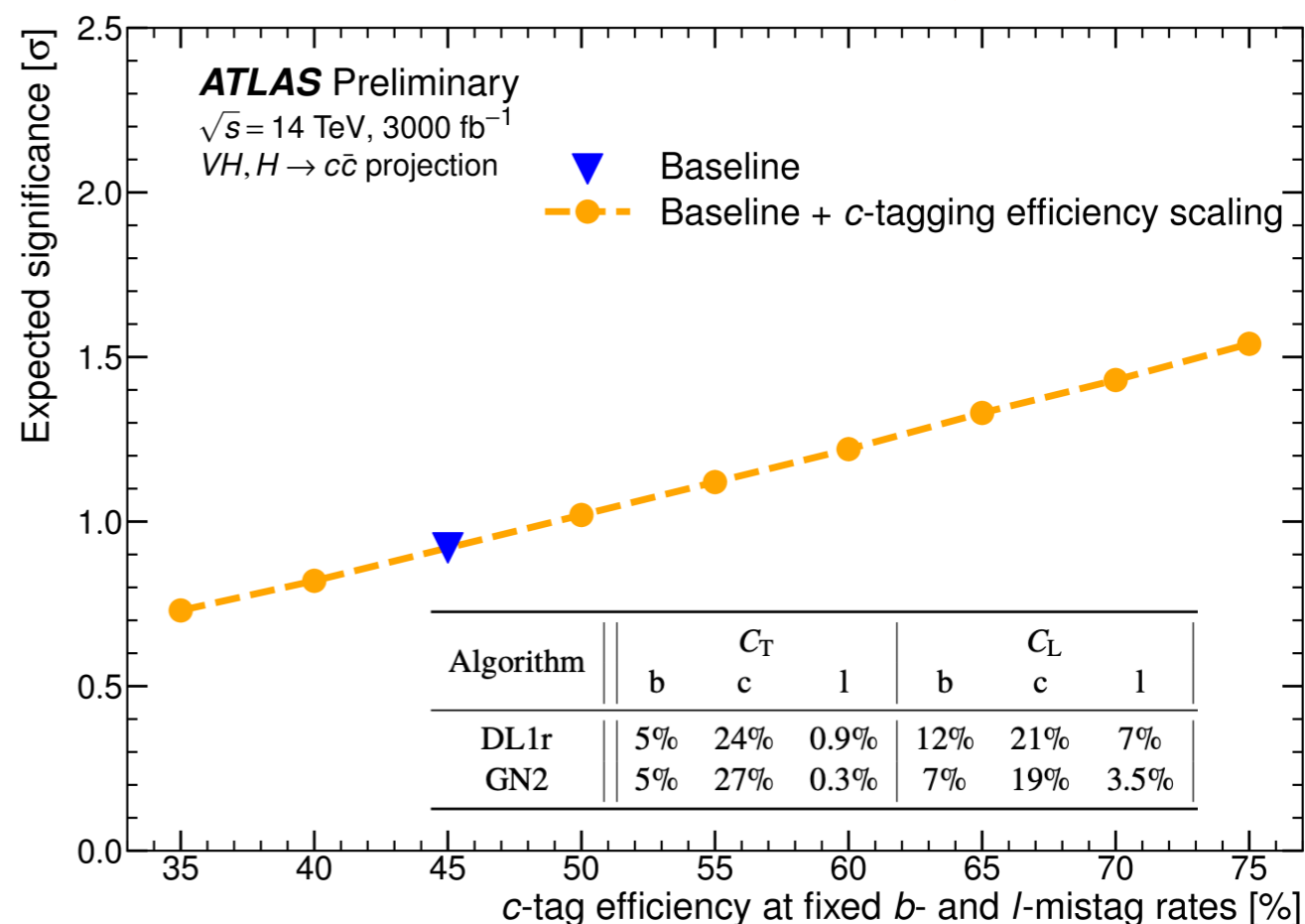
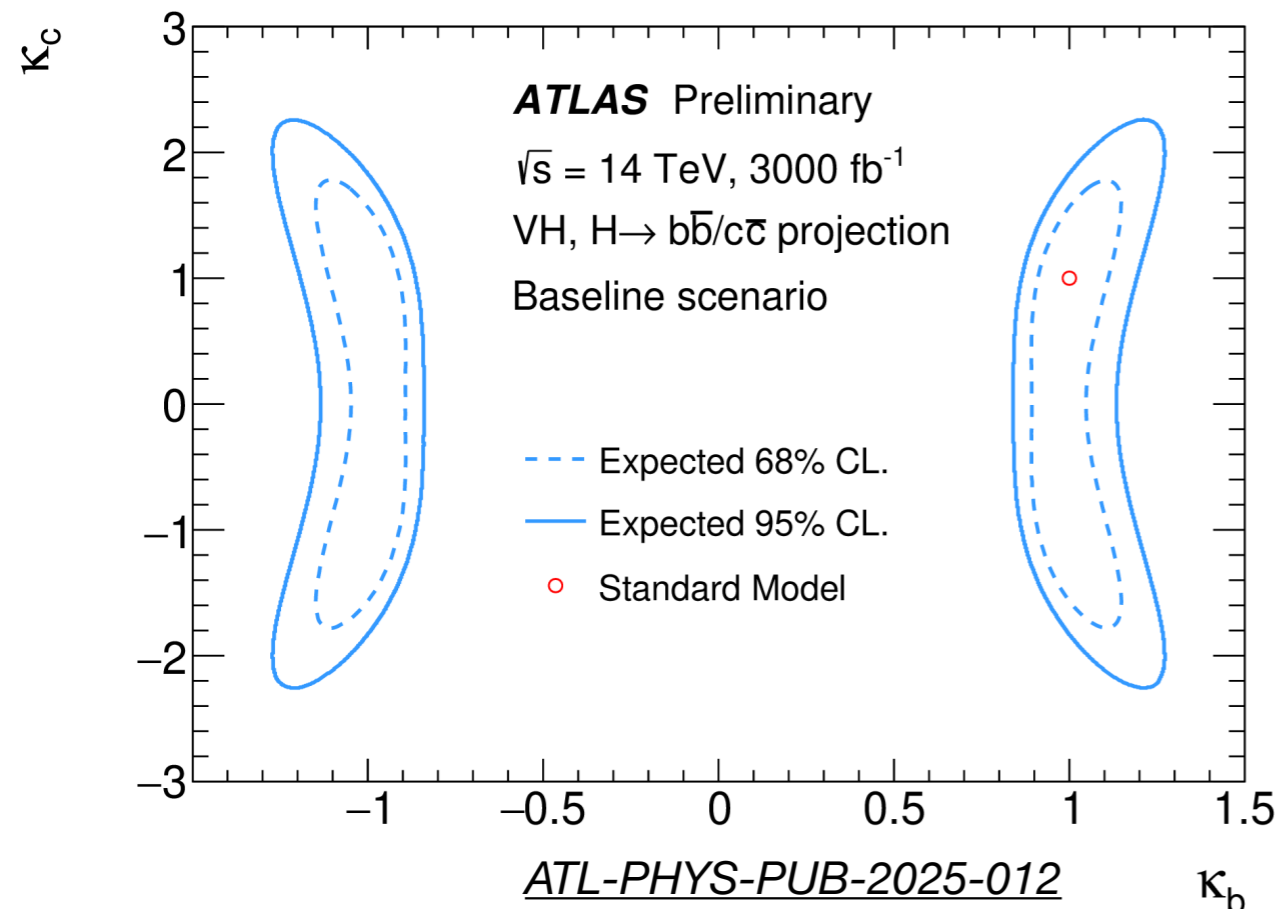


- Most recent  $VH(bb/cc)$  HL-LHC projections (by ATLAS) for ESPPU2026
- **Coupling to bottom improved to  $\sim 5\%$  level**
- **Decay to charm known  $\sim 1\sigma$**
- Dependence on performance of **taggers**:  
*we will do better than that!*

**$\kappa_b$  with fixed  $\kappa_c=1$**   
 **$0.89 < |\kappa_b| < 1.15$  (95%CL)**

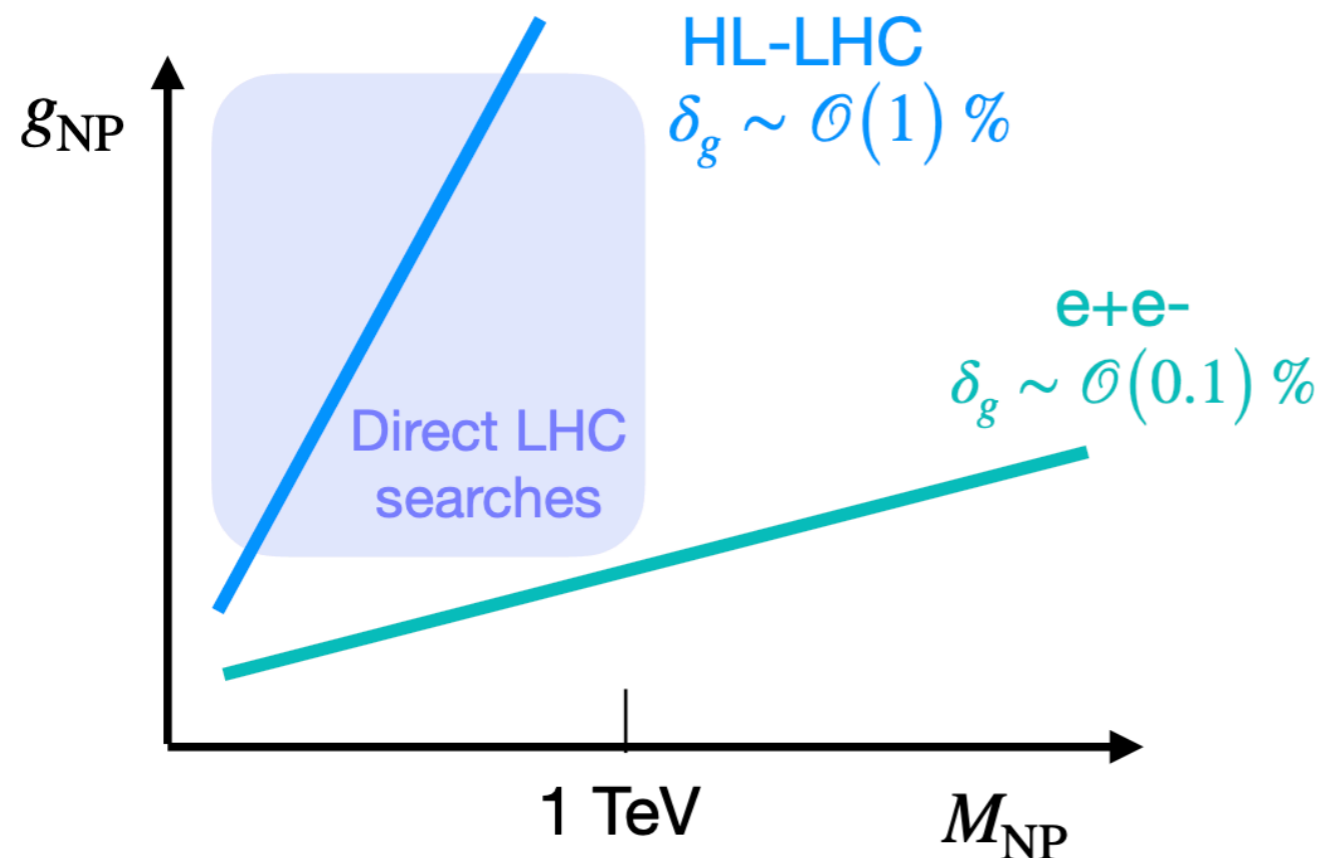
**$\kappa_c$  with fixed  $\kappa_b=1$**   
 **$|\kappa_c| < 1.84$  (95%CL)**

**Excluded to be smaller than  
ratio of b-to-c quark masses**  
 **$|\kappa_c|/|\kappa_b| < 2.58$  ( $5\sigma$ )**



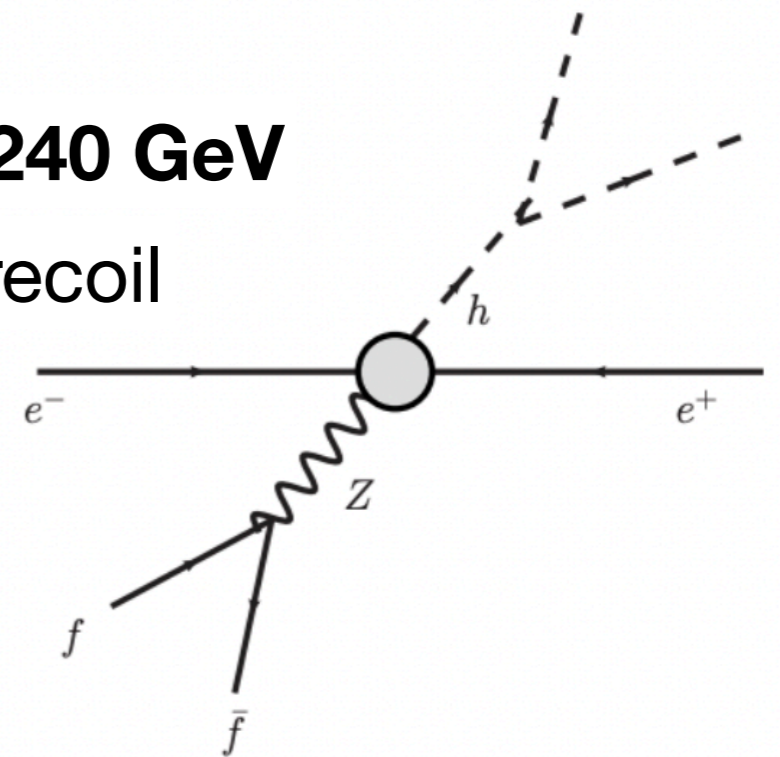
# From HL-LHC to $e^+e^-$ Collider

- To meaningfully exceed HL-LHC, need to measure Higgs couplings to  $O(0.1)\%$ 
  - Effectively: produce **millions of Higgs bosons in a clean  $e^+e^-$  environment** “shovel ready”
- Apart from couplings, many “Higgs” opportunities...
  - Model independent total width,  $H \rightarrow$  invisible, **rare decays**



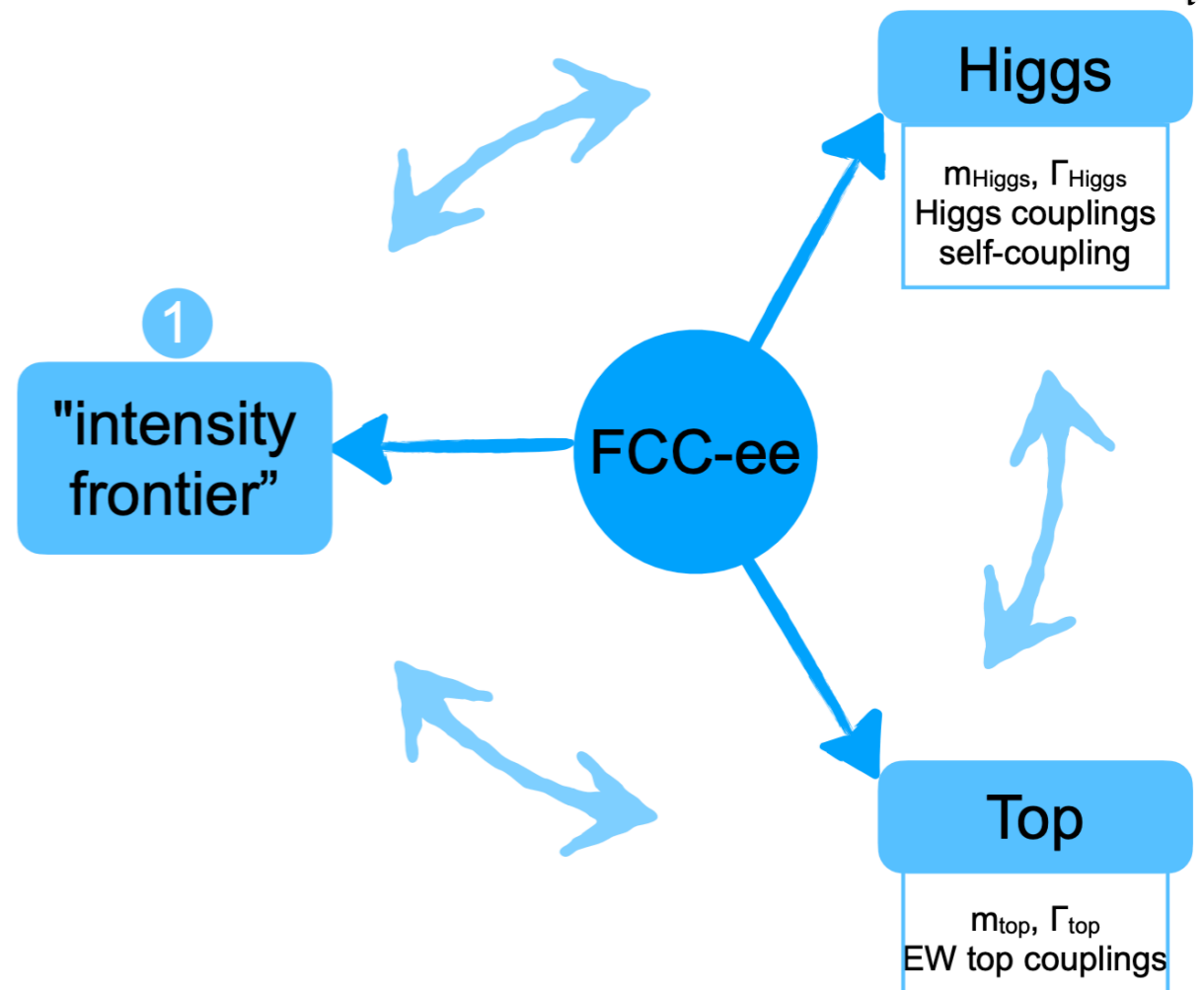
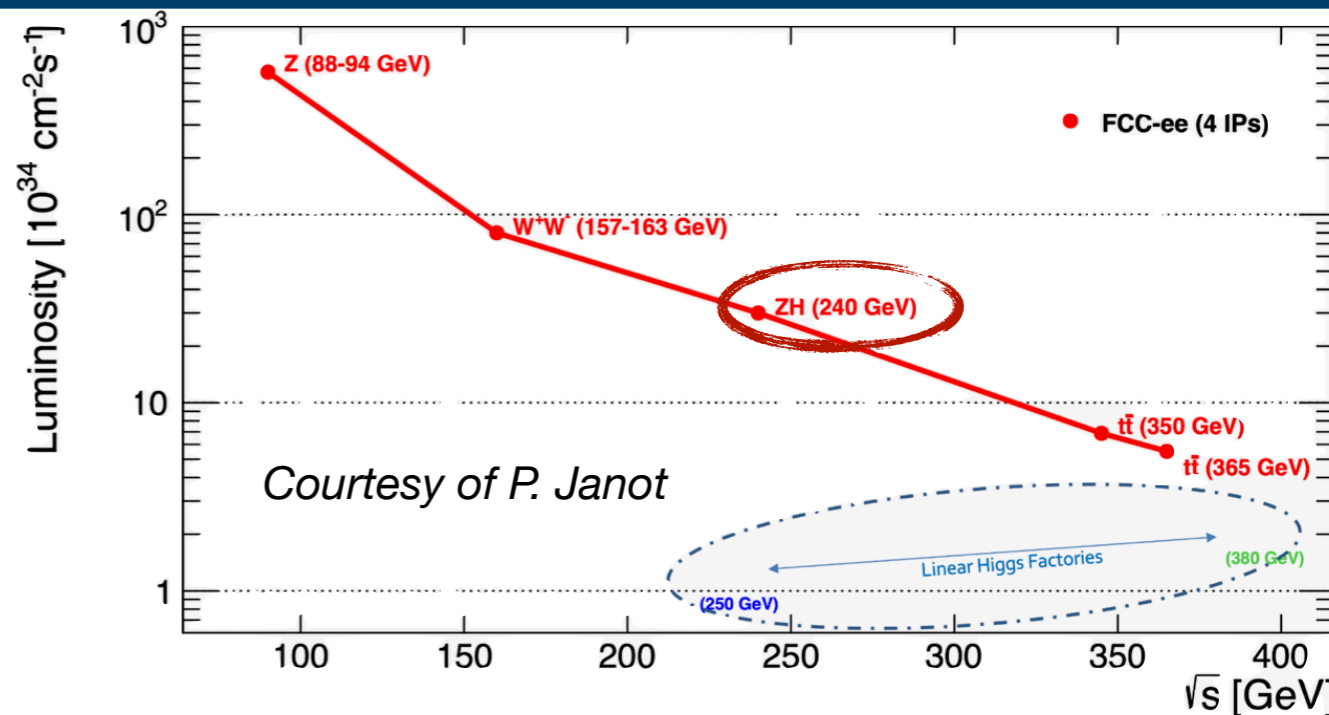
**Unique at 240 GeV**

Higgs recoil



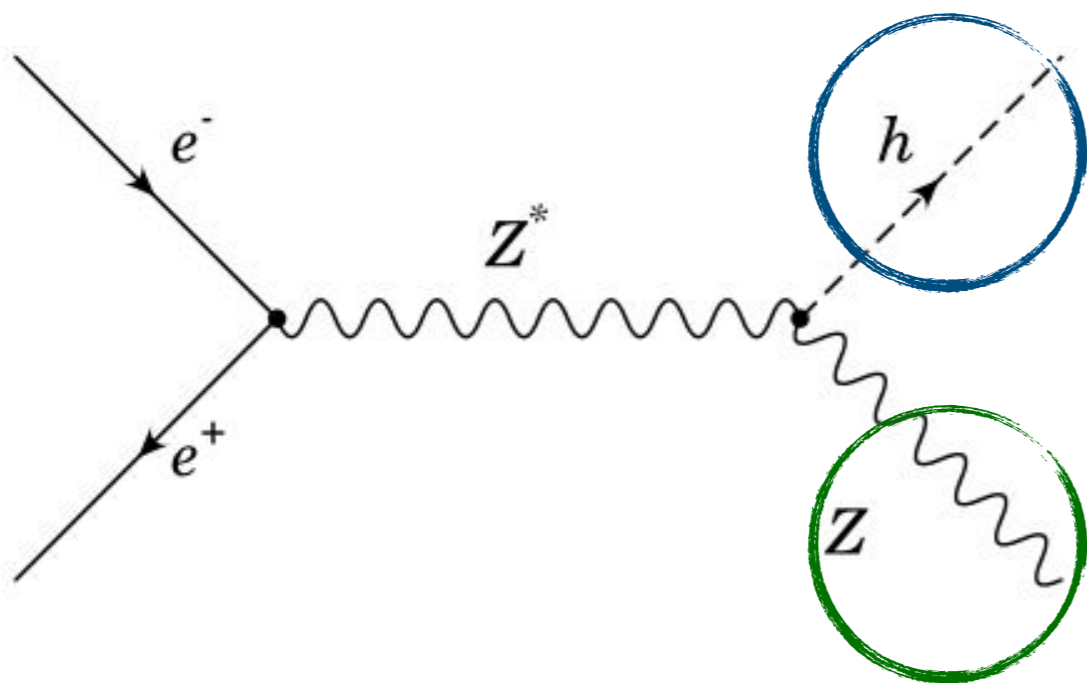
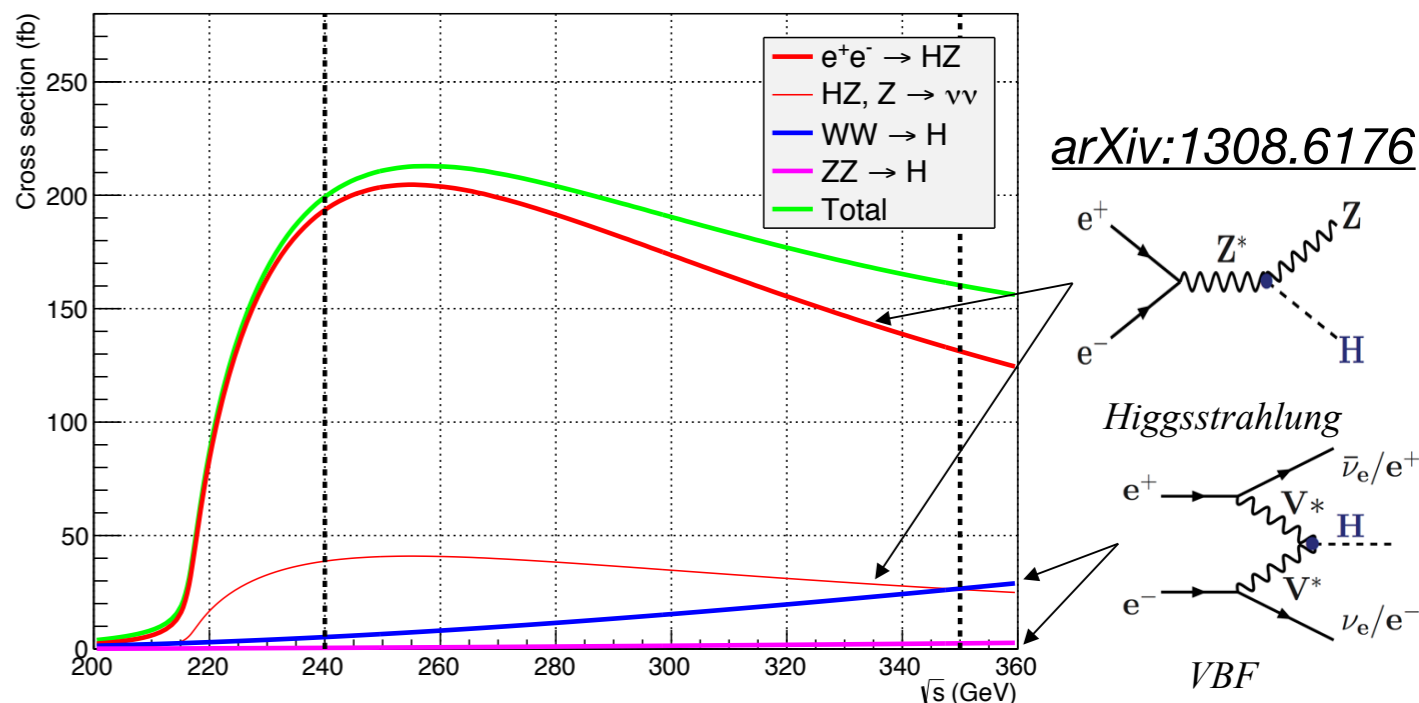
# The FCC-ee case

- FCC-ee : 91 km circular collider with 4 interaction points for 15 yrs, start around 2045
- Amazing potential for precision Higgs. Goals:
  - **O(10) improvements in Higgs couplings**
  - Currently **challenging/“impossible” decay modes** like  $cc/gg$  &  $ss$
  - Absolute  **$g_z$  coupling**
  - *Higgs self-coupling* from  $ZH$  cross sections at 240 & 365 GeV
  - Unique opportunity to test *electron Yukawa*
- *QCD & EWK physics, quark-flavor physics, searches for FCNC, top-quark properties* (with  $\sqrt{s} = 345 - 365$  GeV), etc...
- Exquisite luminosity for ultimate precision:
  - 200k Z bosons / second (LEP/minute)
  - 20k W bosons / hour
  - **4k Higgs bosons / day**
  - 6k tops / day



# Higgs Production @FCC-ee

- At 240 GeV Higgs boson is produced in association with a Z boson
  - **Tag Z and measure Higgs couplings!**
- Used the analysis to study & optimise the tracker design and performance (more later)



- Higgs boson reconstruction:
  - Particular focus on hadronic decays, e.g.  $H \rightarrow bb/cc/gg/ss(?) \dots$

- Z-boson reconstruction:
  - Explore several decay modes
  - Usage of “recoil mass”

# Z( $\rightarrow ll, \nu\nu, jj$ )H - Expected Precision @240 GeV



Analysis	H $\rightarrow b\bar{b}$	H $\rightarrow c\bar{c}$	H $\rightarrow gg$	H $\rightarrow s\bar{s}$	H $\rightarrow ZZ$	H $\rightarrow WW$	H $\rightarrow \tau\tau$
Z $\rightarrow l^+l^-$	0.68	4.02	2.18	234	13.7	1.78	4.1
Z $\rightarrow q\bar{q}$	0.32	3.52	3.07	409	52.1	8.74	110
Z $\rightarrow \nu\bar{\nu}$	0.33	2.27	0.94	137	19.8	1.89	22
comb	0.21	1.66	0.80	105	10.1	1.16	4.0

*Relative uncertainty (in %) at 68% CL on signal strengths in the various Higgs decay channels*

- CAVEAT: exploiting parametric simulation
- Signal & most background processes: free normalisations correlated across categories determined by the fit
- Meet physics goals:
  - **Improve precision by  $O(10)$  wrt HL-LHC**
  - Extend to couplings that are (probably) impossible at HL-LHC (strange above all)
    - **Opportunity to fully establish Higgs couplings!**



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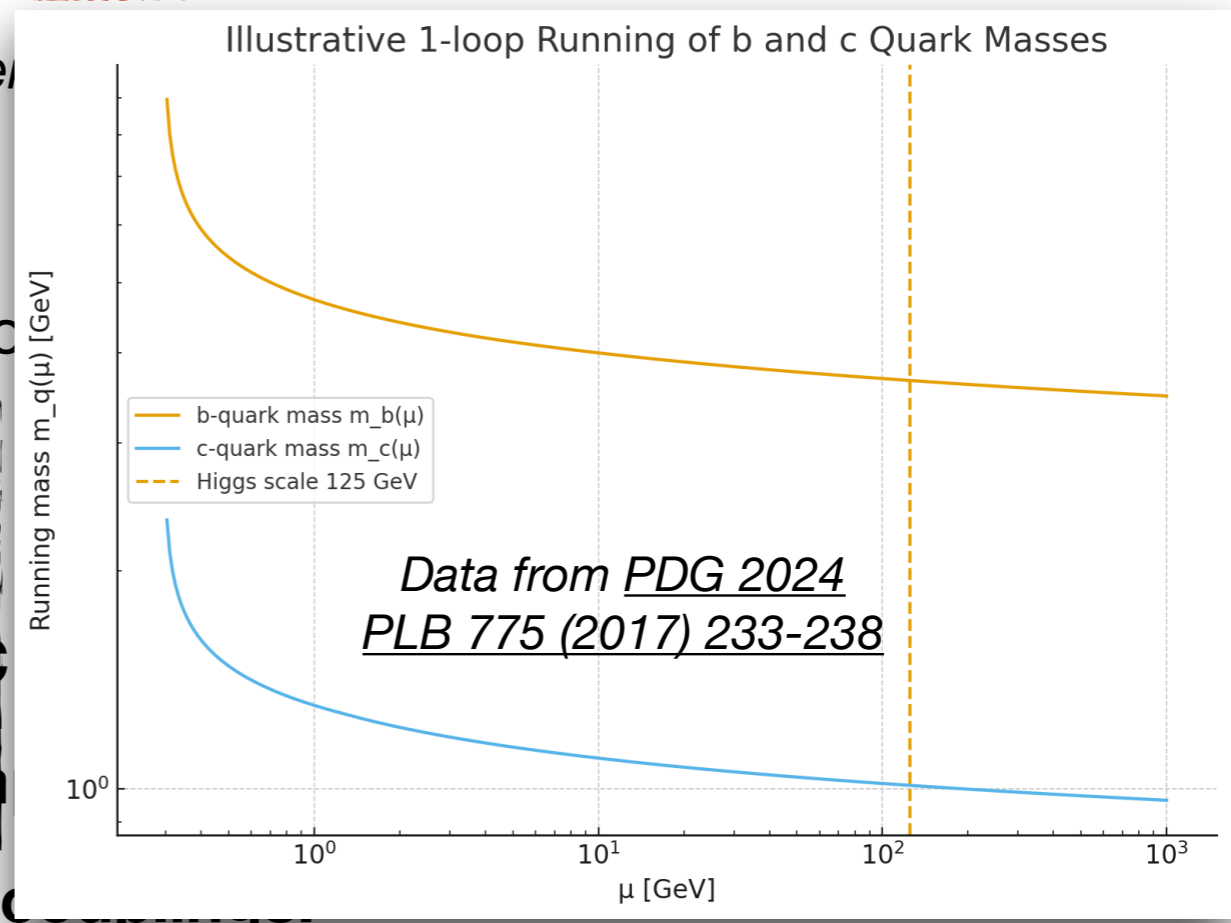
Relative uncertainty (in %) at 68% CL on signal strength

- CAVEAT: exploiting parametric simulation
- Signal & most background processes: free no



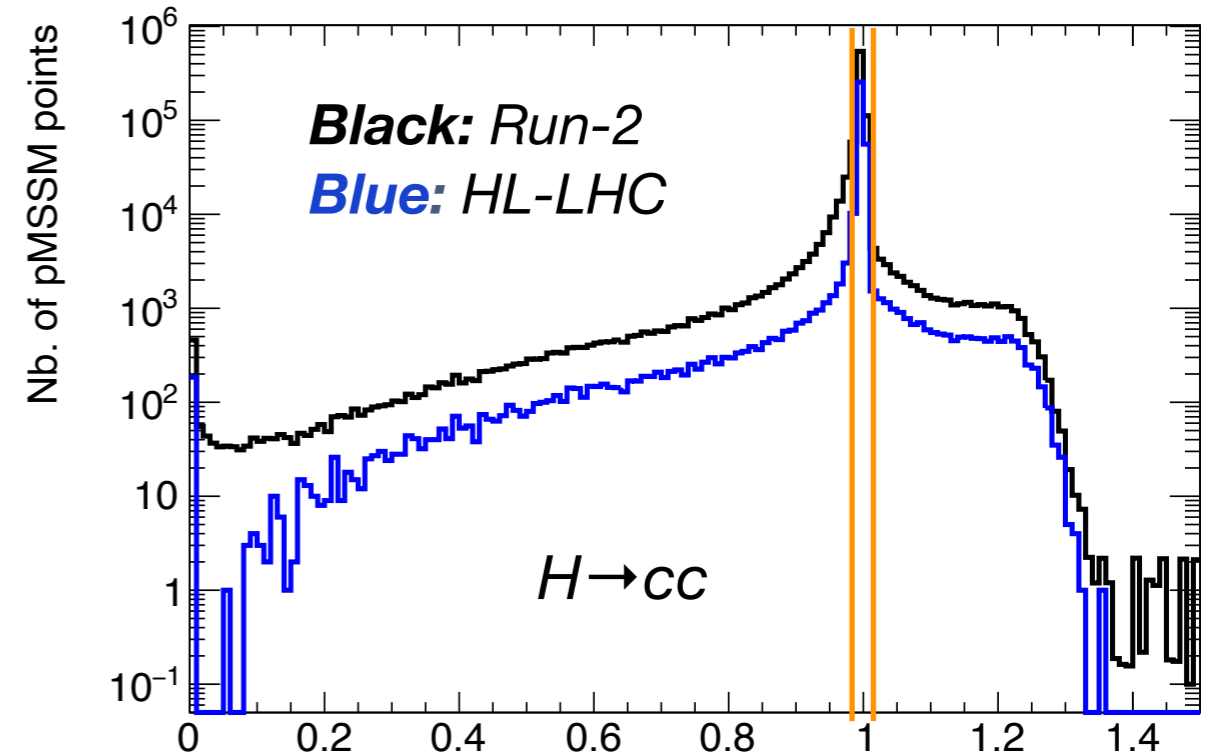
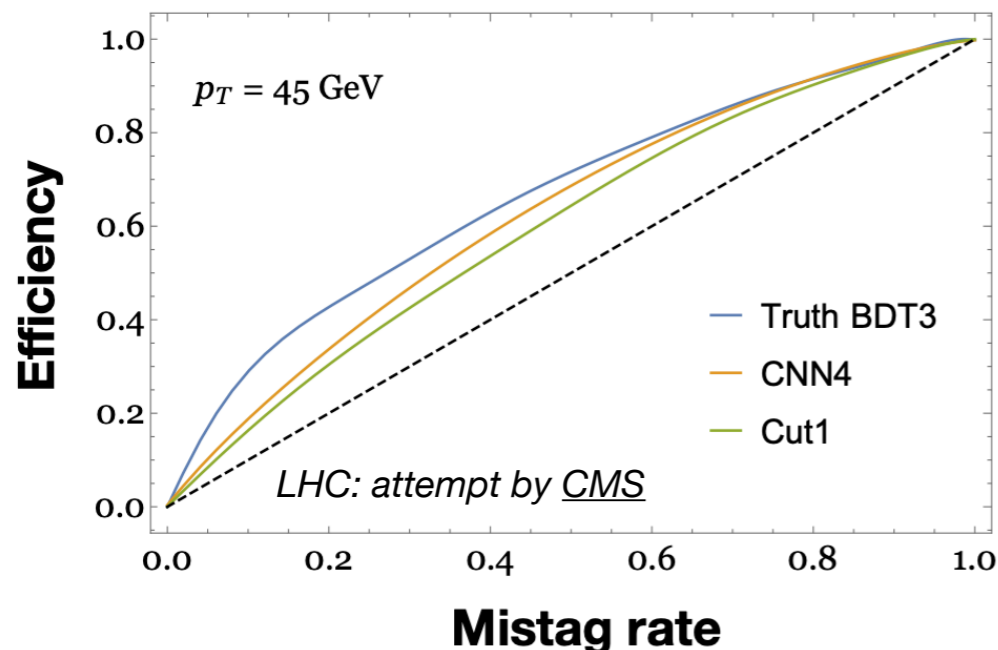
*Sensitivity to few-percent effects from running of b/c-quark mass across electroweak scales (e.g.  $m_b$  down to  $\sim 33\% m_b \rightarrow m_H$ )*

- Opportunity to fully establish Higgs couplings

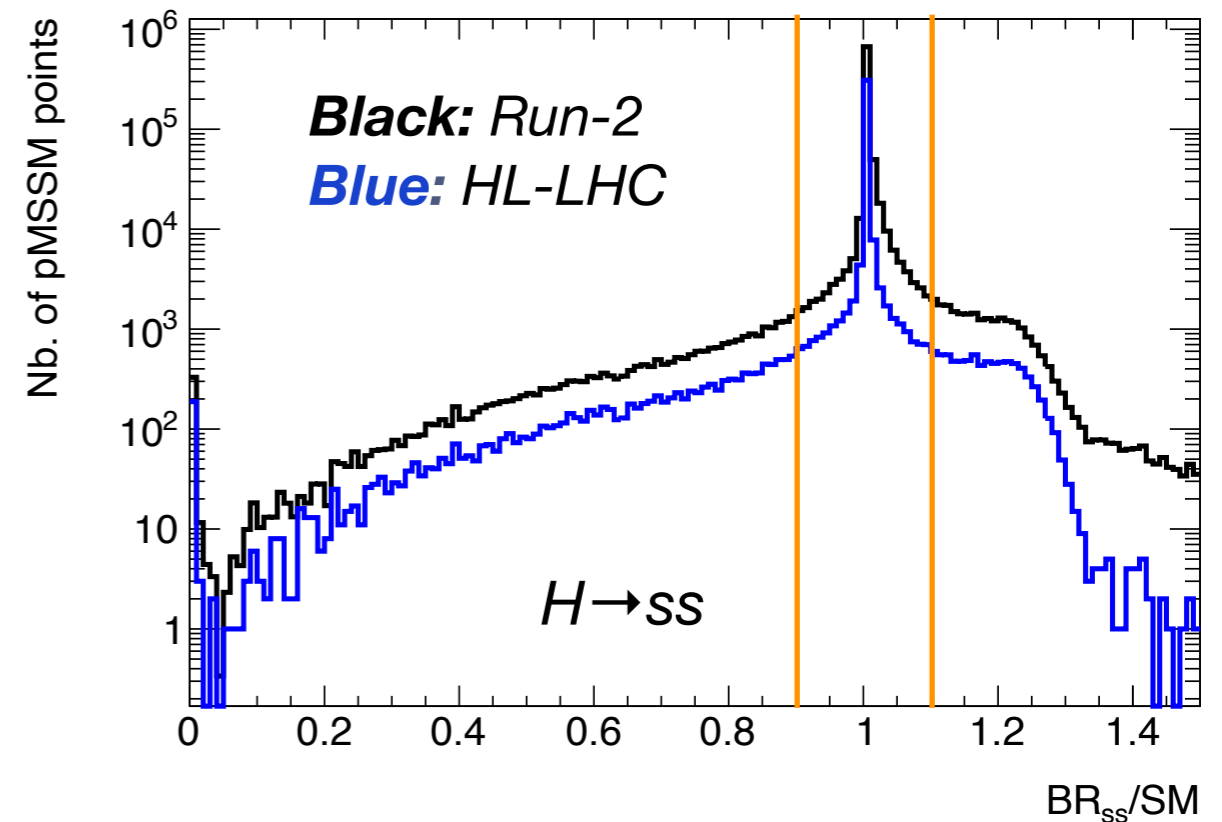


# “Strangeness” - ULTRA Rare Decays

- May new physics subtly hide into targeted couplings?
  - E.g. range of  $H \rightarrow cc/ss$  BR values allowed within 68%CL by current constraints on “pMSSM” parameters
- Attempts to tag strange jets at LHC
  - $H \rightarrow ss$  hopeless: relatively small mass/coupling/Higgs decay BR ( $\sim 14x$  lighter than charm)
- We might do this at FCC-ee
  - Evidence for  $H \rightarrow ss$ , provided sufficient statistics/optimal search?

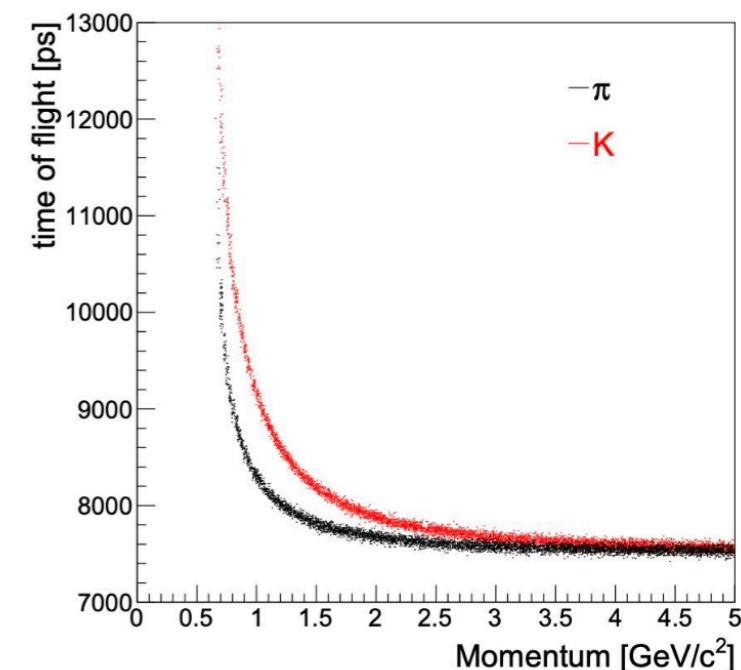
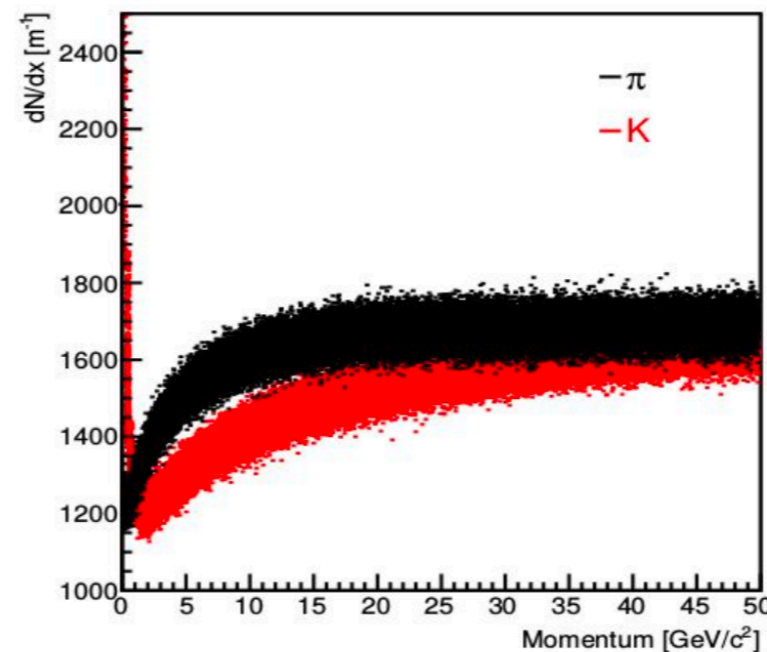
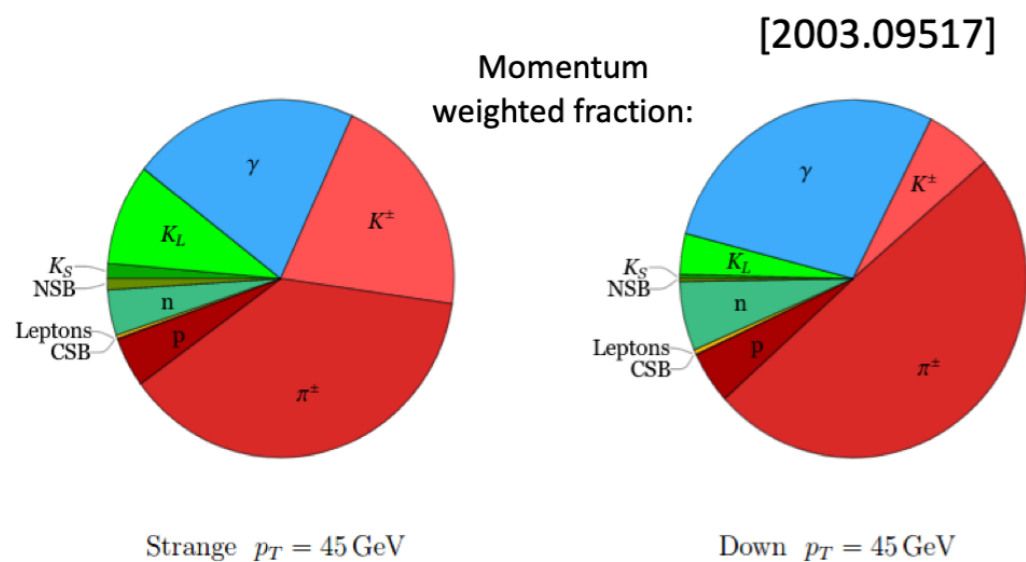


Developments of work in [PRD 106, 055002](#)



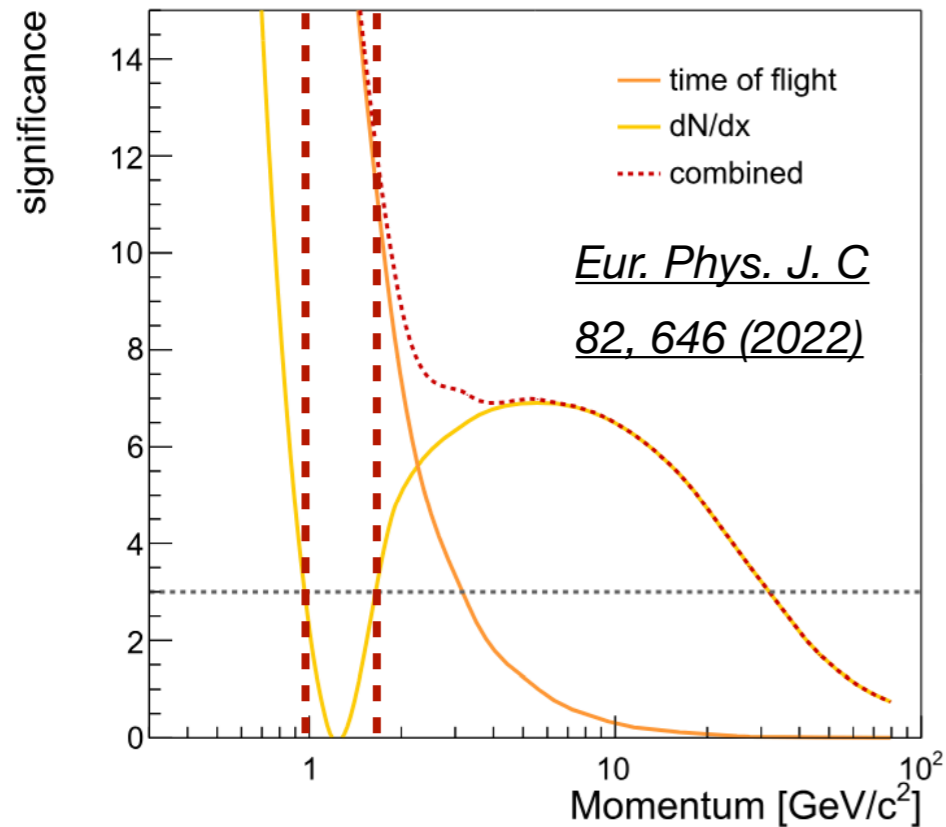
# Strange Tagging & PID @FCC-ee

- **Strange** tagging, exploiting large **Kaon** content
  - Charged requiring K/ $\pi$  separation, neutral  $K_S \rightarrow \pi\pi$ ,  $K_L$
  - Benefitting from good Particle IDentification (**PID**): timing detectors, Cherenkov detectors, charged energy loss (silicon/gas)
- Count **number of primary ionisation clusters** along track path
- **Time-of-Flight** results in good K/ $\pi$  separation at low momenta
- Dedicated modules developed in Delphes



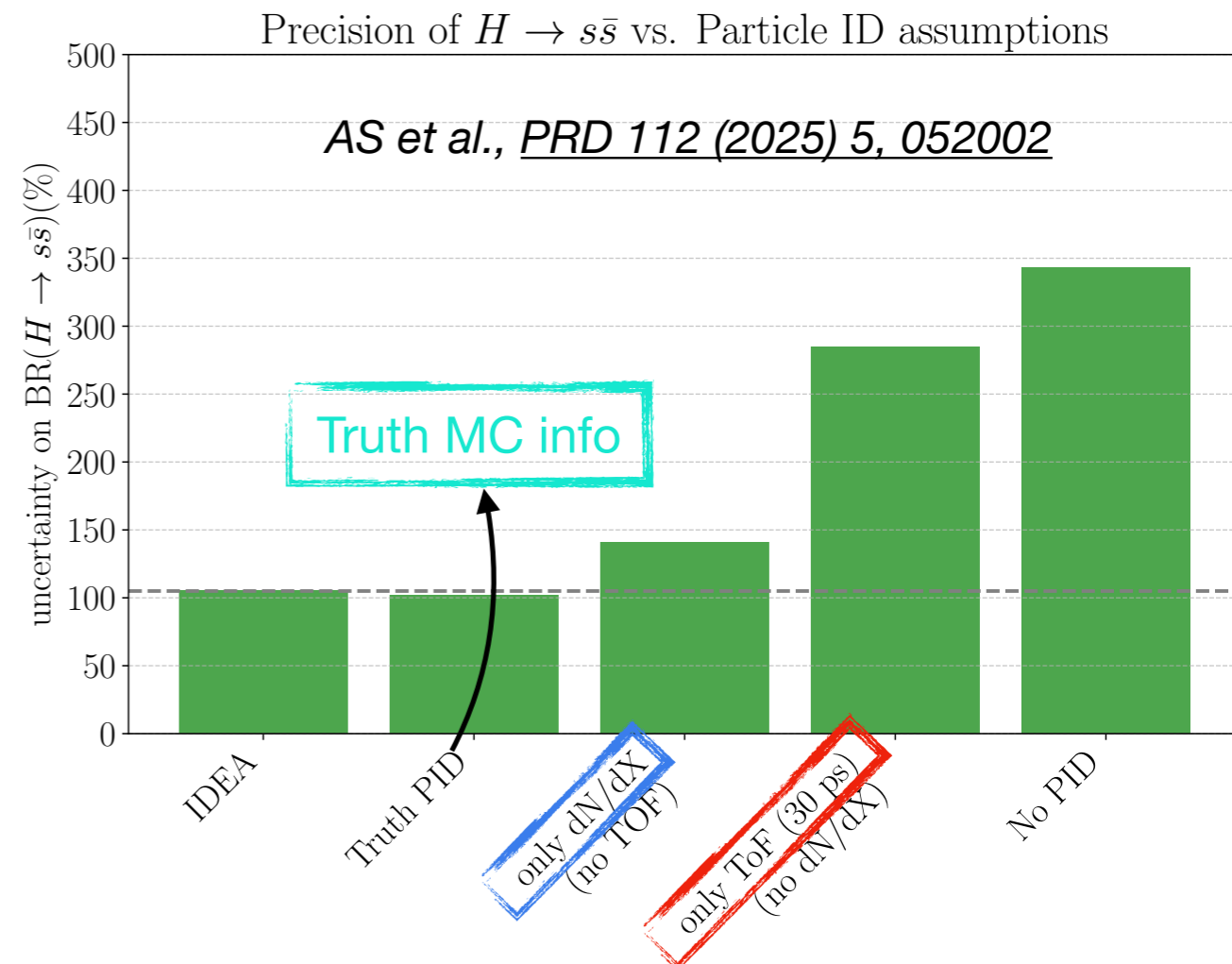
# Higgs Couplings & Detector Requirements @FCC-ee

- Our measurement goals determine our machines... and our detectors!
- Among Higgs couplings, **strange is most stringent** in terms of detector requirements



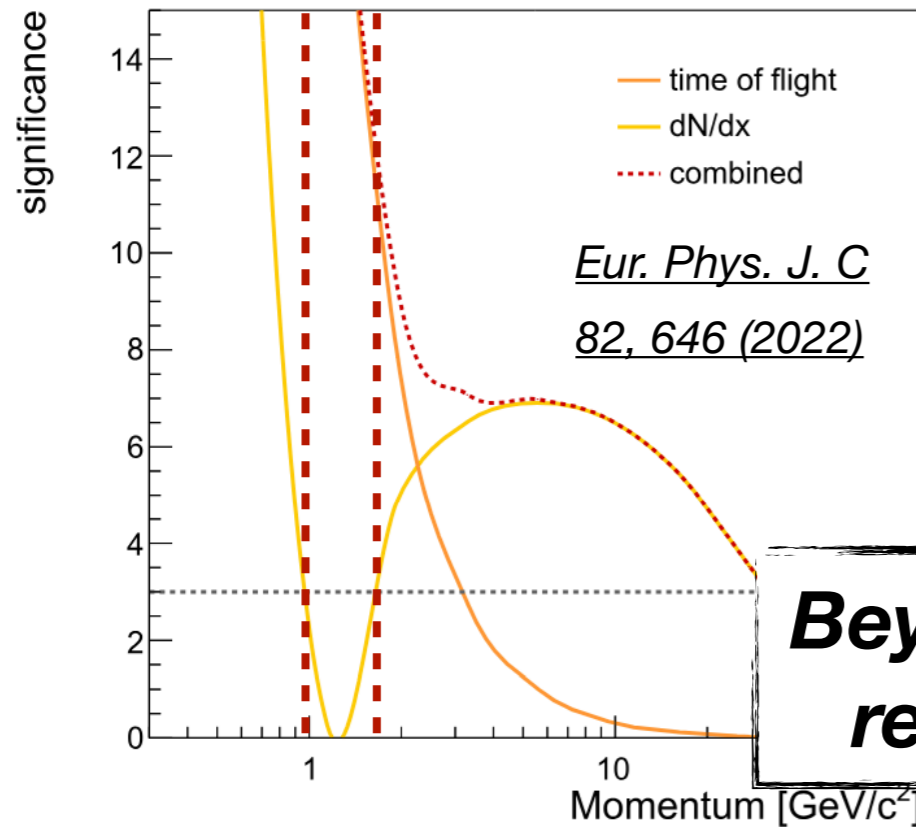
- PID: crucial ingredient for strange-quark jet identification ( $H \rightarrow ss$ )
- Need:
  - **Cluster counting** ( $dN/dx$ ) measurement at high momentum - Cherenkov detectors (RICH)
  - Time of Flight ( $ToF$ ) measurement at low momentum ( $\sim 1$  GeV)

- From full propagation through the  $ZH$  analyses:
  - IDEA detector concept PID performance close to “perfect” PID
  - Impact of  $dN/dx \gg ToF$ 
    - Observe factor  $\sim 3$  degradation in  $H \rightarrow ss$  when **lacking  $dN/dx$  information**
  - **PID really crucial for  $H \rightarrow ss$  determination**



# Higgs Couplings & Detector Requirements @FCC-ee

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  - **Cluster counting** ( $dN/dx$ ) measurement at high momentum - Cherenkov detectors (RICH)
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**Beyond couplings, the Higgs reflects its own dynamics**

→  $s\bar{s}$  vs. Particle ID assumptions

*PRD 112 (2025) 5, 052002*

- From full propagation through the  $ZH$  analyses:
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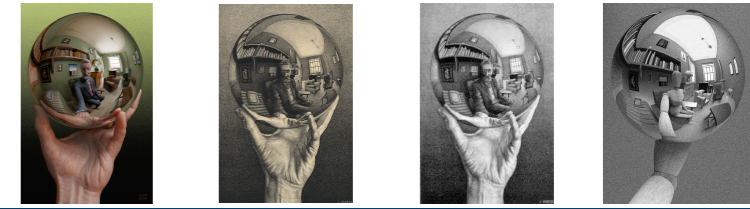


# From precision **BACK** to discovery

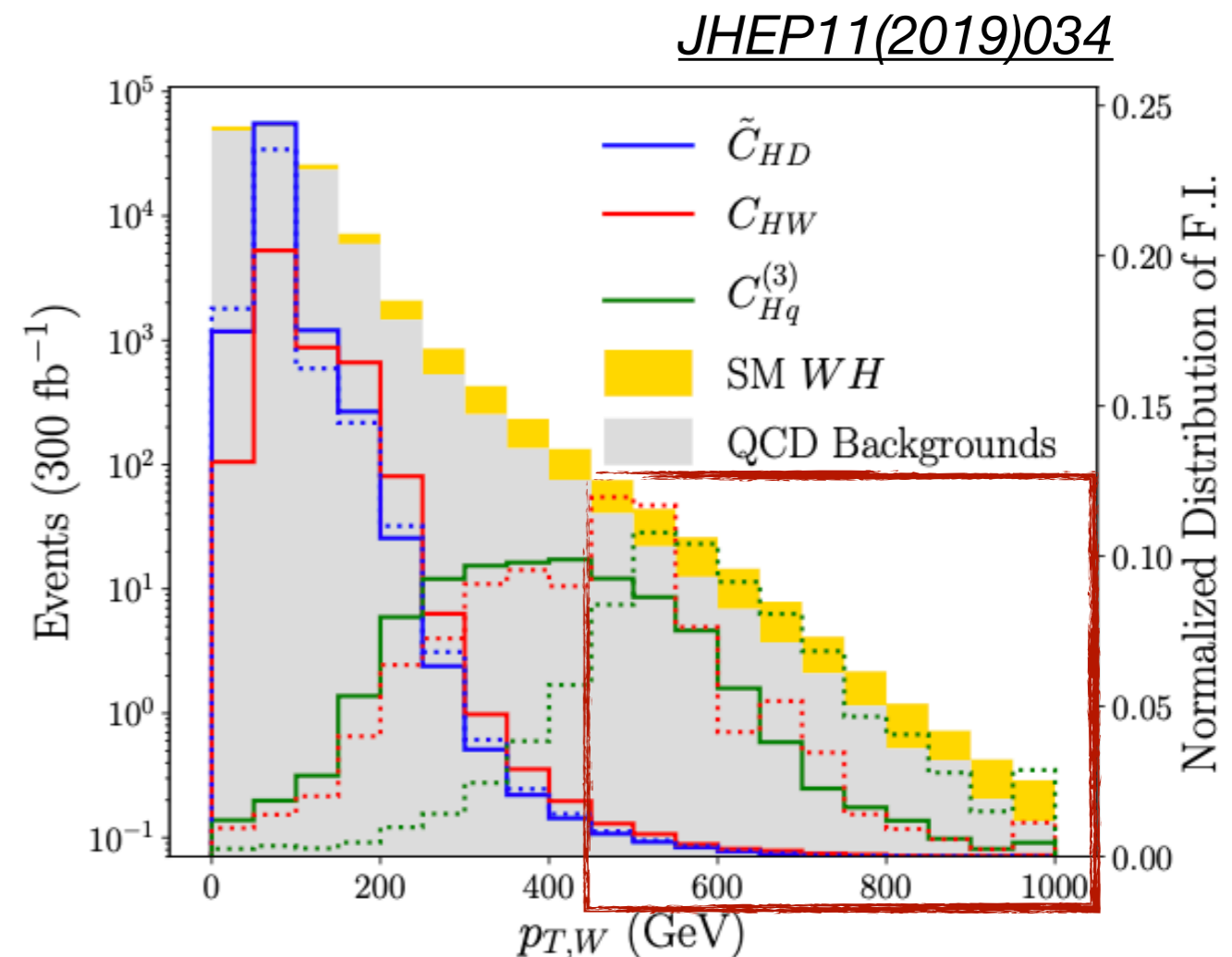
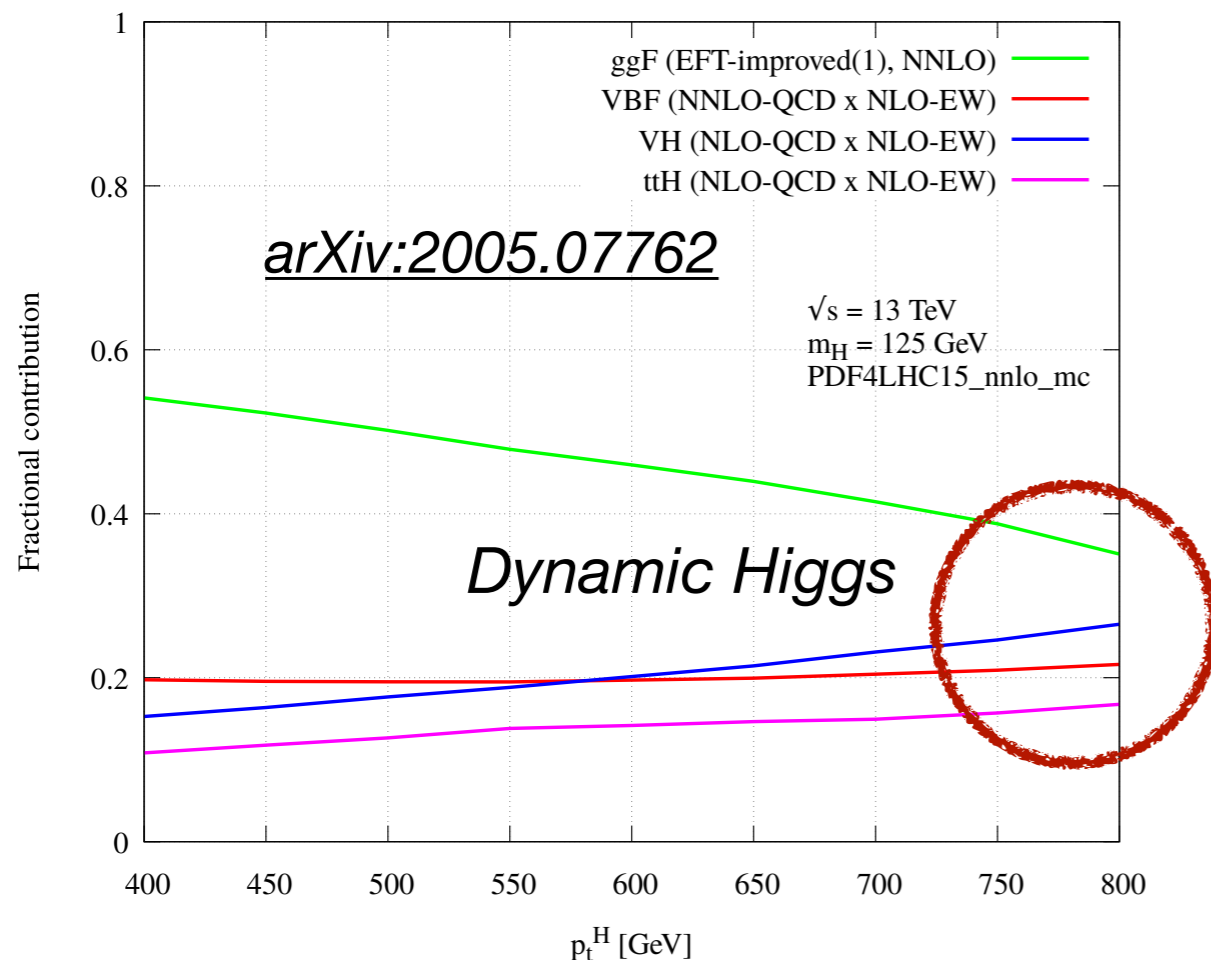
## Intermezzo



# From precision BACK to discovery

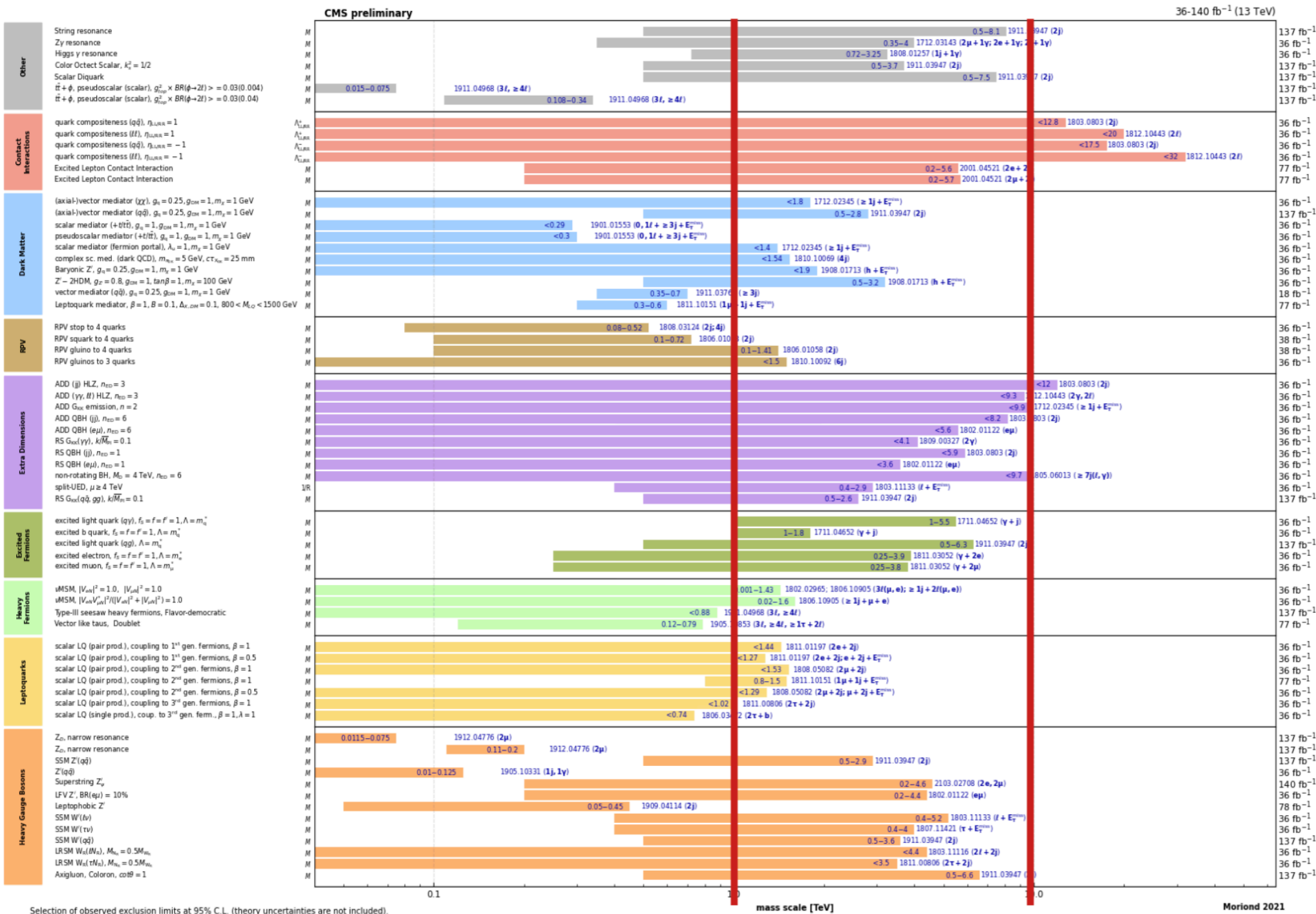


- And, yet, once we get precise enough... we enter *discovery mode* again
- Rare decays, new prod modes, subtle corners of phase-space once inaccessible!
  - Among them: **Higgs production at extremely high momentum**, shifting interest from static to **dynamic** properties of the Higgs boson
  - All production modes contribute similarly towards  $p_T^H \sim 1$  TeV
- **Enhanced by powers of  $E/\Lambda$**
- **Loop-level modifications**



# High-energy: What do Experiments tell us?

Overview of CMS EXO results



What do experiments tell us?

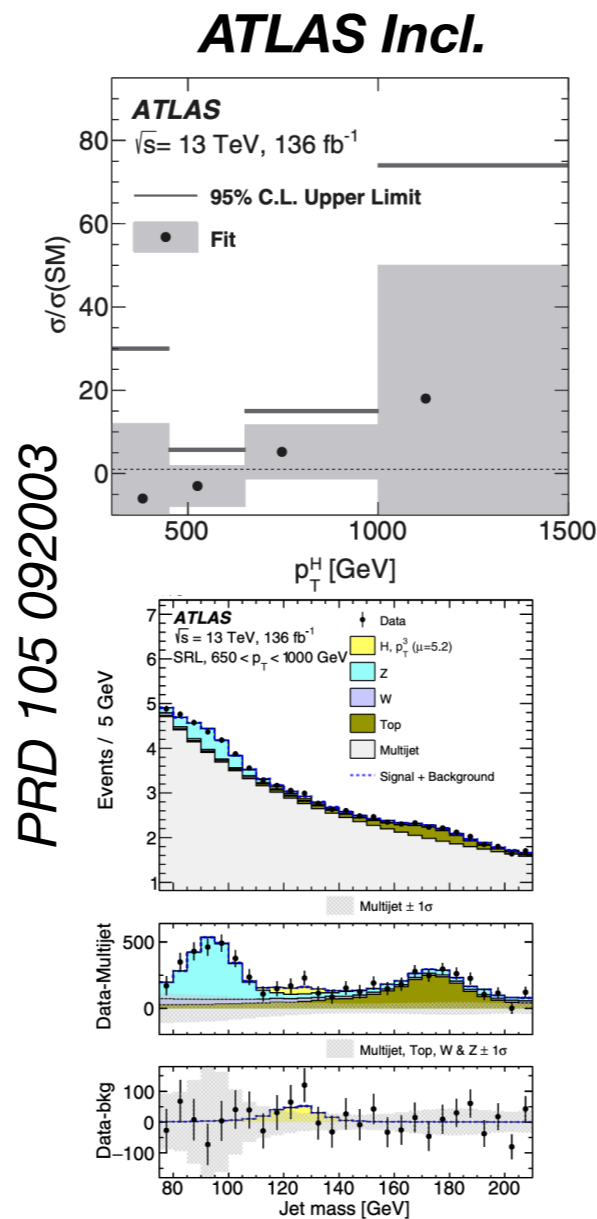
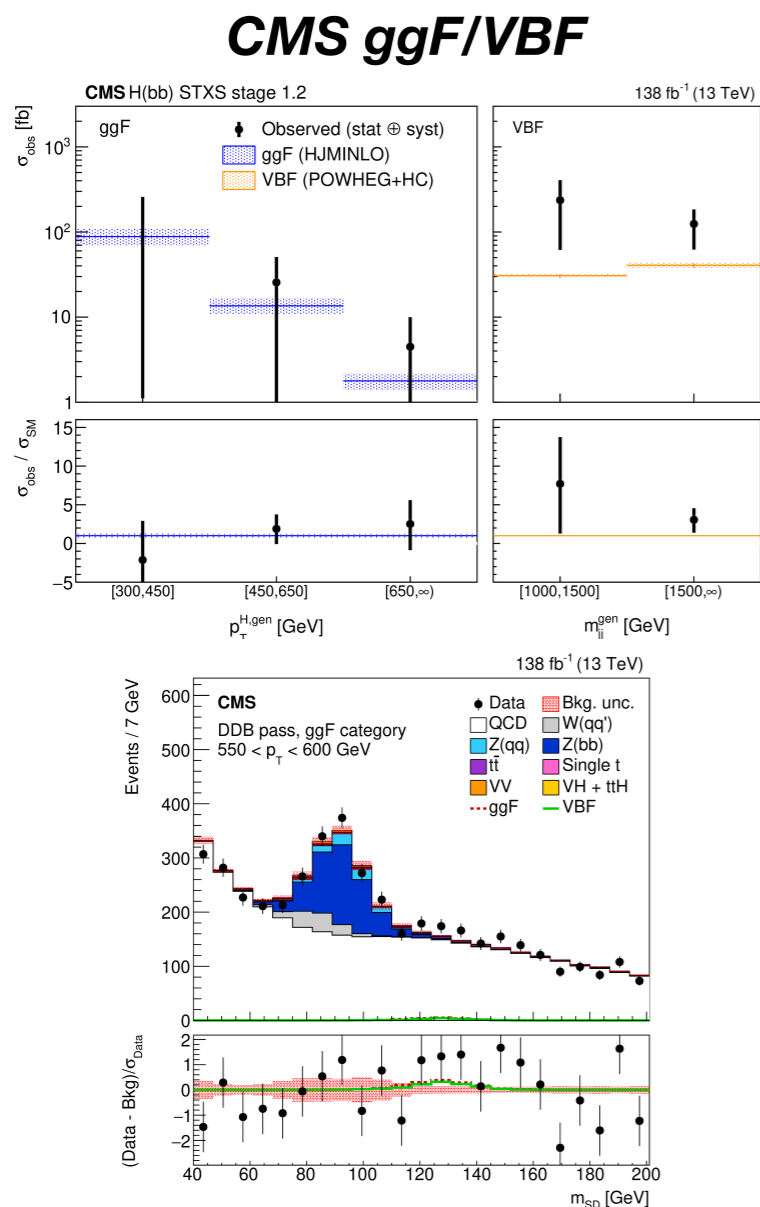
New physics seems to be relatively heavy!

...aka what we will not be able to “directly” probe at e<sup>+</sup>e<sup>-</sup> colliders

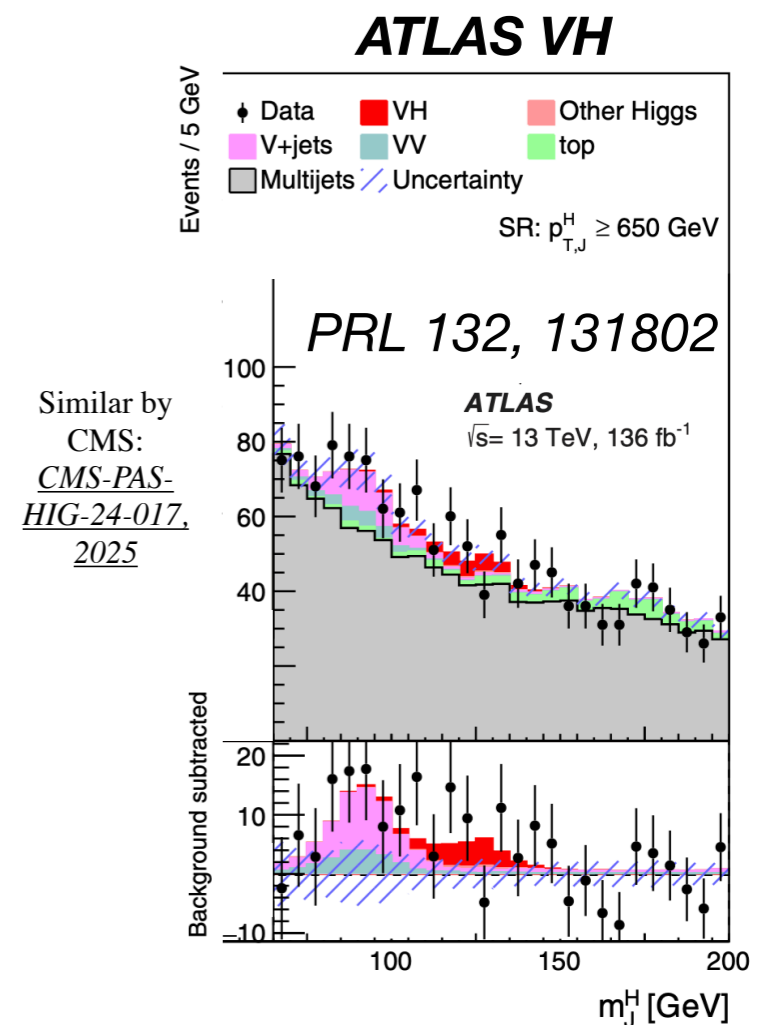
# High-energy dynamics of the Higgs

- Exploring **Higgs high-energy dynamics** in all main production modes
- **Fully hadronic final states** to enhance acceptance
  - Cope with large challenging backgrounds
- Deep understanding of  $H \rightarrow bb$  taggers & jet mass/ $p_T$  calibration required

JHEP 12 (2024) 035



PRD 105 092003



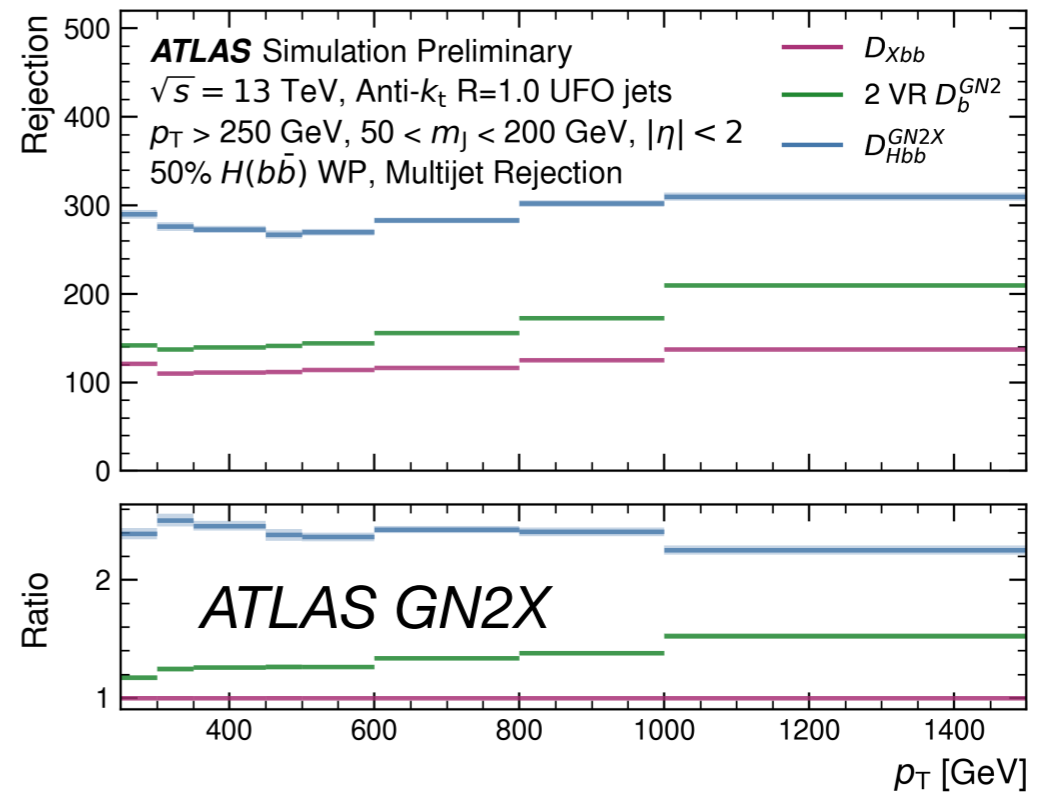
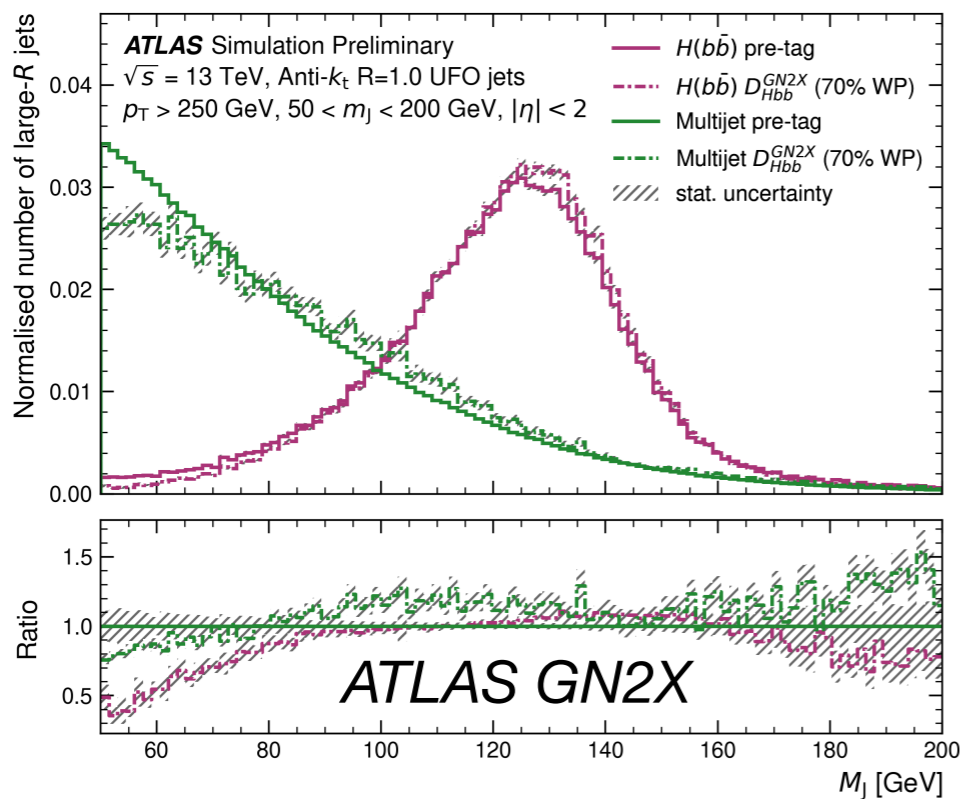
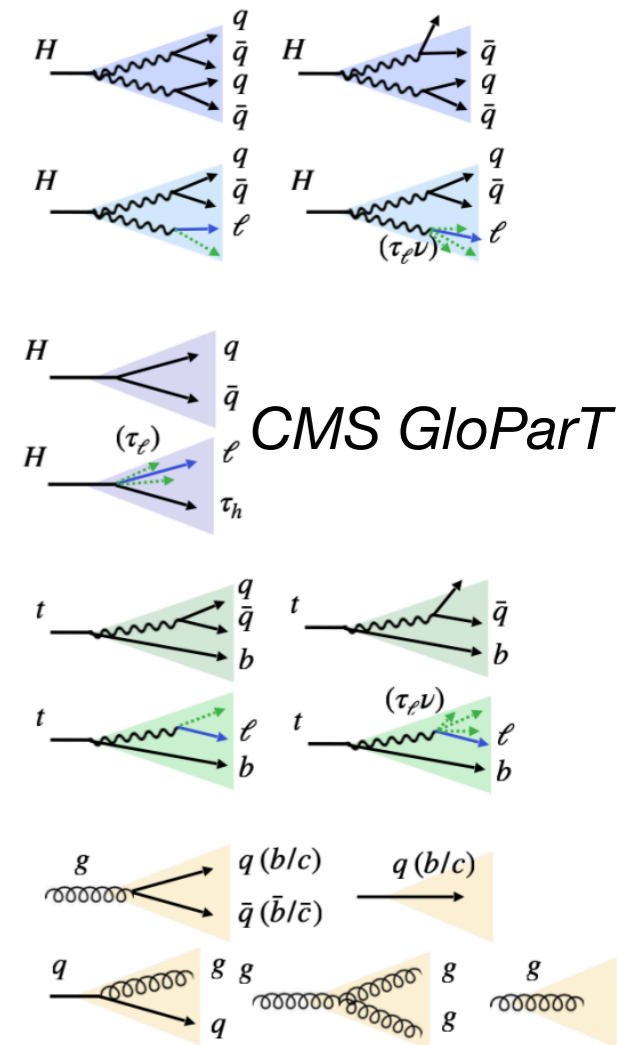
Similar by  
 CMS:  
CMS-PAS-  
HIG-24-017,  
2025

Kinematic region	Observed $\mu$	Observed $\sigma$ [fb]	Expected $\sigma$ [fb]
$250 \leq p_T^{\text{H}} < 450 \text{ GeV},  y_{\text{H}}  < 2$	$0.8^{+2.2}_{-1.9}$	$47^{+125}_{-109}$	(<363) 57.0
$450 \leq p_T^{\text{H}} < 650 \text{ GeV},  y_{\text{H}}  < 2$	$0.4^{+1.7}_{-1.5}$	$2_{-9}^{+10}$	(<24) 5.9
$p_T^{\text{H}} \geq 650 \text{ GeV},  y_{\text{H}}  < 2$	$5.3^{+11.3}_{-3.2}$	$6_{-4}^{+13}$	(<43) 1.2

# Tagging Boosted Higgs

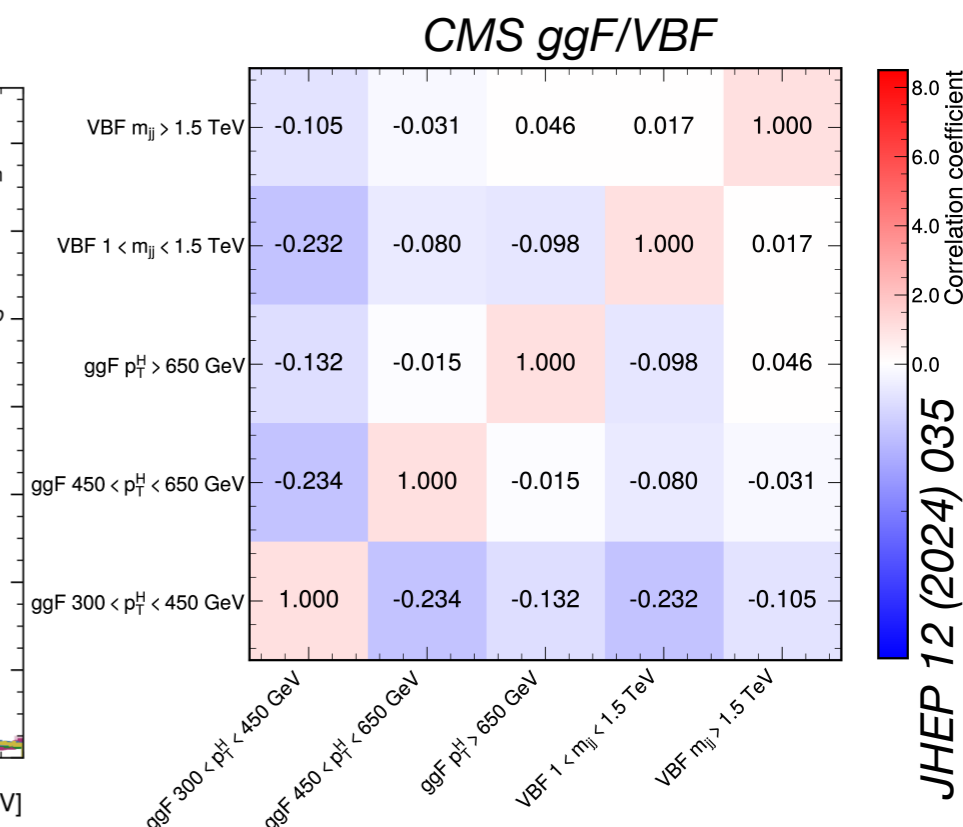
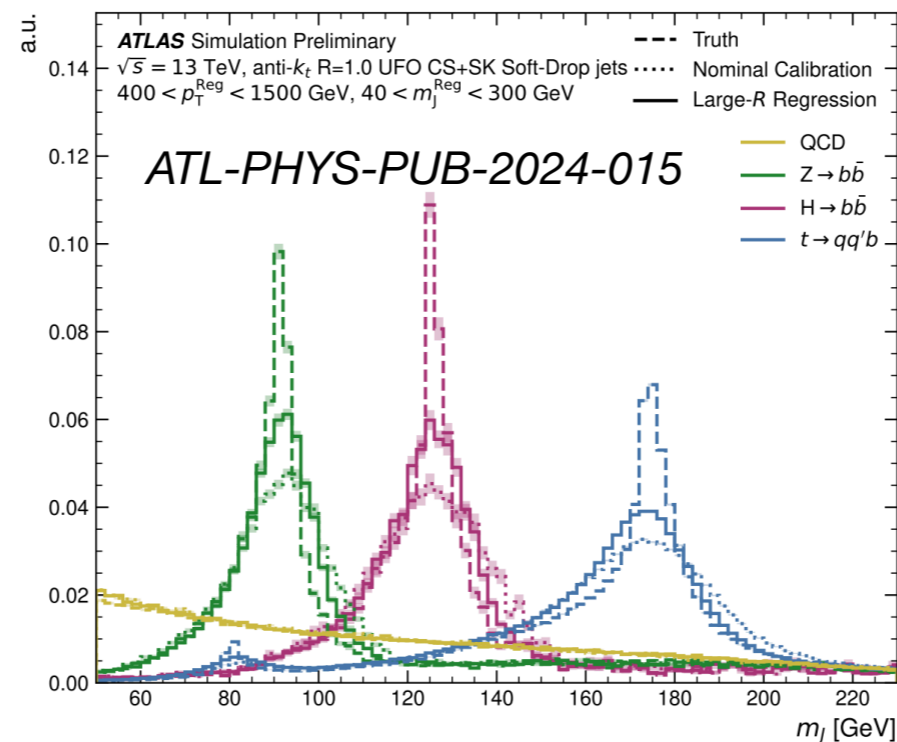
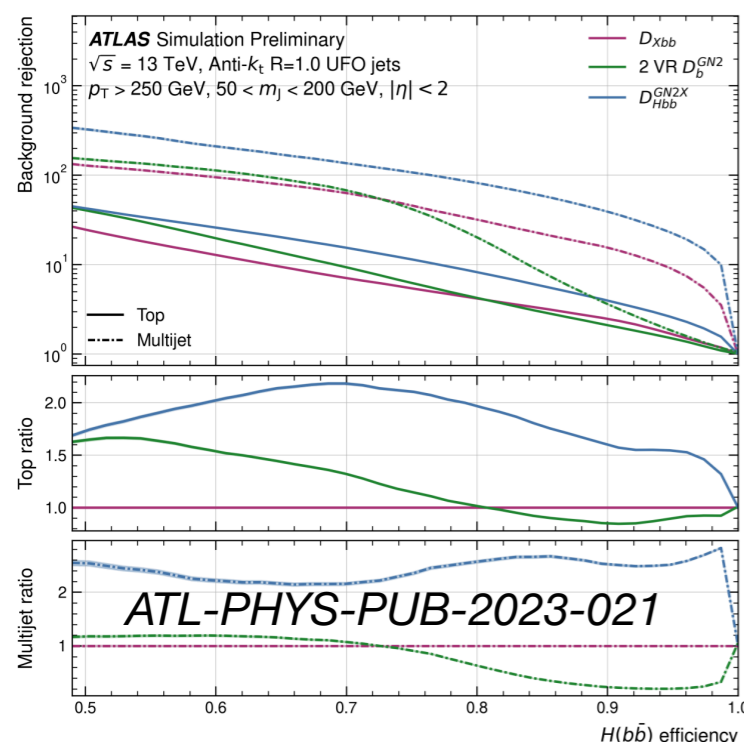
- Inputs: **O(100)** tracks associated with large jet containing all decay products (+secondary vertices in CMS)
- Transformer network architecture with **multiple scores for multiple final states**
- Mass decorrelation*: training with flat mass spectrum to prevent alg from learning mass

Process	Final state/ prongness	heavy flavour	# of classes
H→VV (full-hadronic)	qqqq	0c/1c/2c	3
	qqq		3
H→WW (semi-leptonic)	evqq	0c/1c	2
	μvqq		2
	τ <sub>e</sub> vqq		2
	τ <sub>μ</sub> vqq		2
	τ <sub>h</sub> vqq		2
H→qq		bb	1
		cc	1
		ss	1
		qq (q=u/d)	1
H→ττ	τ <sub>e</sub> τ <sub>h</sub>		1
	τ <sub>μ</sub> τ <sub>h</sub>		1
	τ <sub>h</sub> τ <sub>h</sub>		1
t→bW (hadronic)	bqq	1b + 0c/1c	2
	bq		2
t→bW (leptonic)	bev	1b	1
	bμv		1
	bτ <sub>e</sub> v		1
	bτ <sub>μ</sub> v		1
	bτ <sub>h</sub> v		1
QCD		b	1
		bb	1
		c	1
		cc	1
		others (light)	1



# Perspectives for Improvements on Run-3 Data

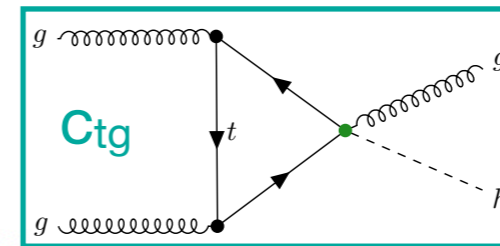
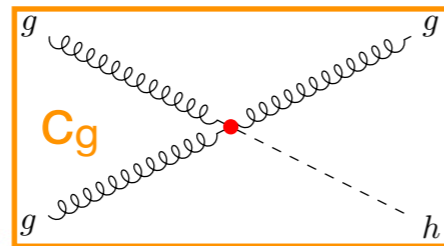
- Improvements on:
  - $H \rightarrow bb$  tagging**, ATLAS:  $\sim x3$  background rejection for same signal efficiency!
  - Jet mass/ $p_T$  resolution**
    - Mass resolution determines significance  $\sim$ linearly
    - $p_T$  resolution determines magnitude of off-diagonal elements
    - Measurable in-situ and/or in dedicated control samples
    - $\sim 30\%$  relative improvements from dedicated regression techniques
  - Data-driven estimate** of main non-resonant backgrounds
    - Improvable by better constraining bkg shape, thanks to better  $H \rightarrow bb$  taggers
- All in all, with a factor  $\sim 3.5x$  more data by June 2026, we may expect to get  $\sim$ an order of magnitude better towards & beyond 1 TeV!**



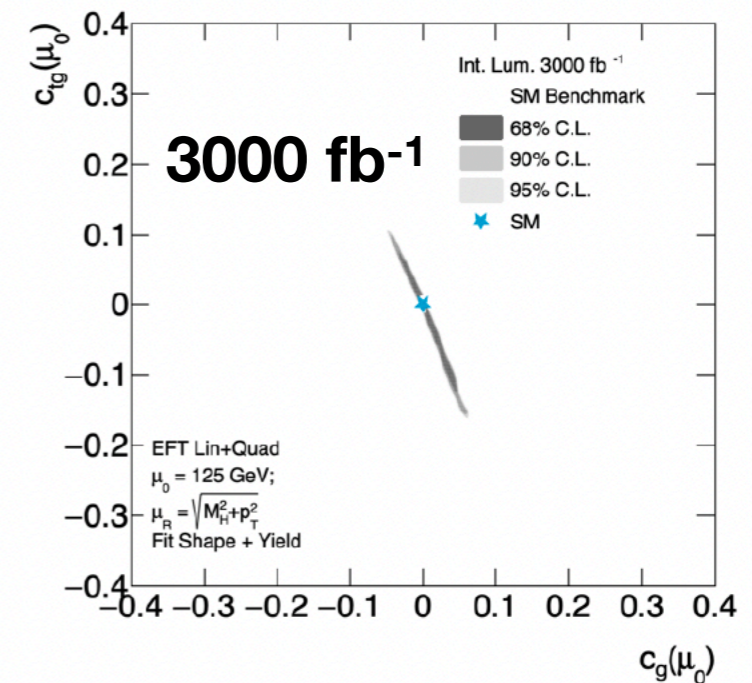
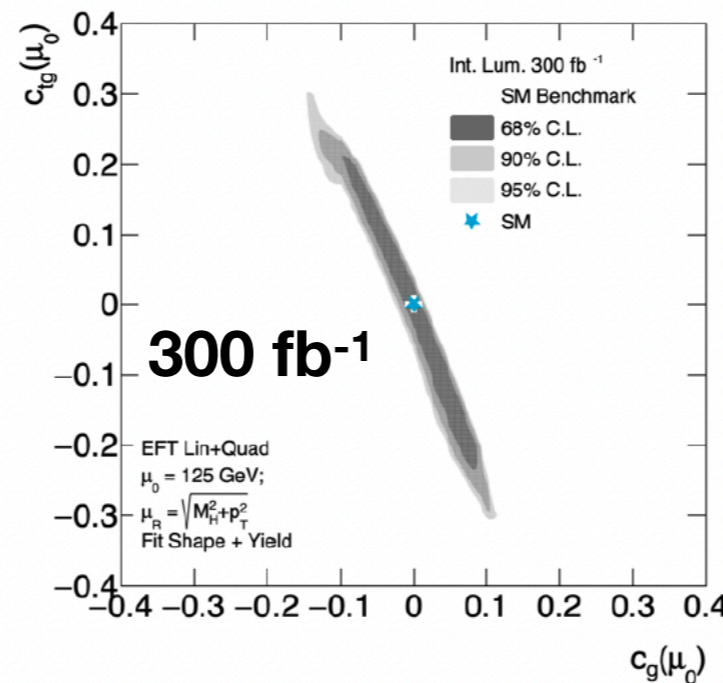
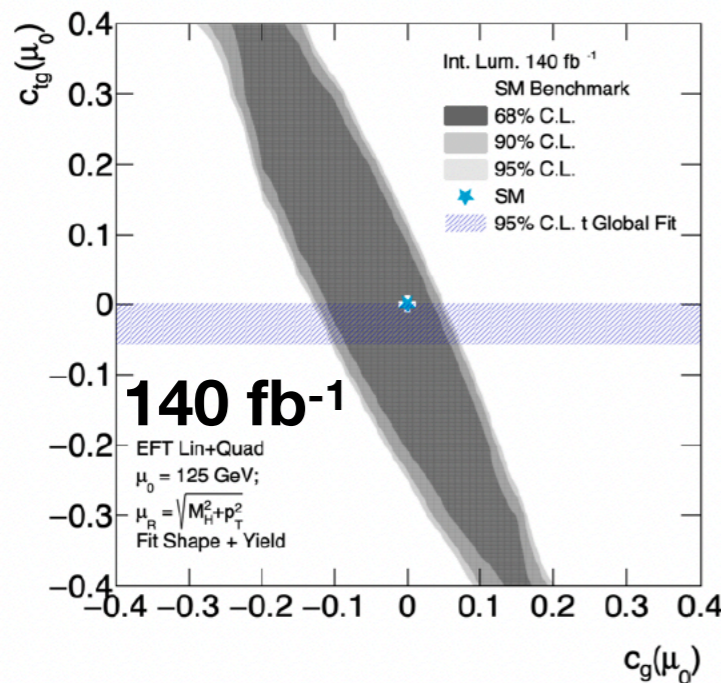
# Projections for High-energy dynamics



- Improvements in knowledge of **Higgs dynamics** at high  $p_T$
- Impressive **constraints** on effects from **BSM** physics
- As an example, projections on **gluon-Higgs point-like** & **chromomagnetic** EFT operators
  - *Improving constraints by orders of magnitude!*



Projections of main EFT parameters ( $c_g, c_{tg}$ ) constraints from ATLAS boosted  $ggH(bb)$



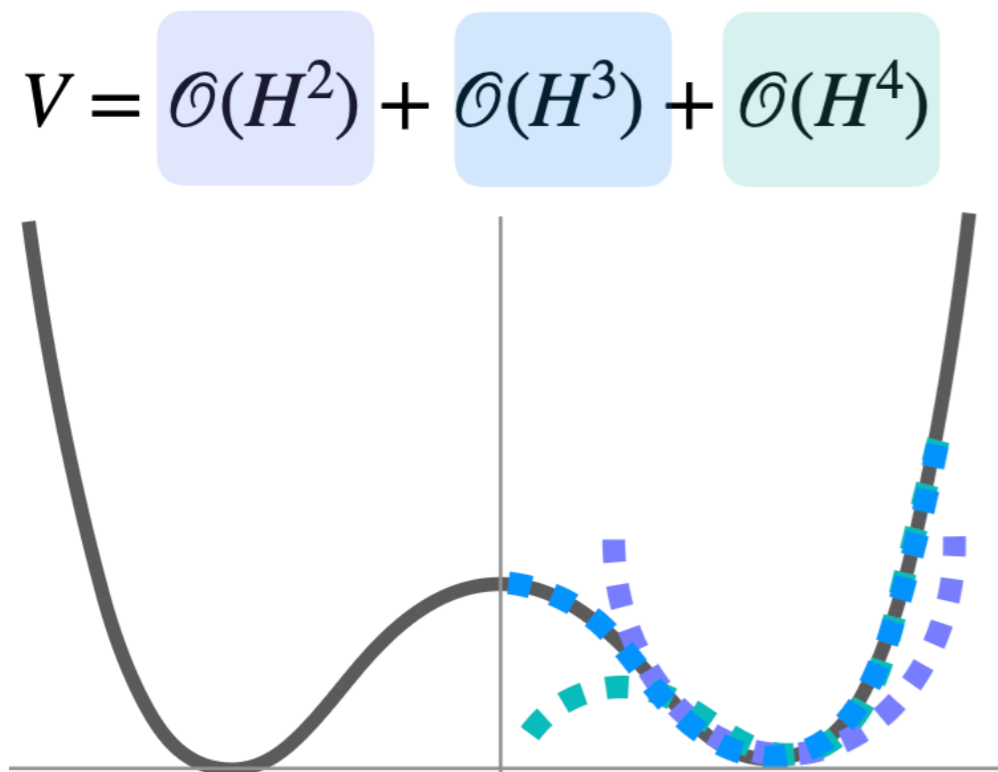
**Our knowledge of Higgs dynamics may remain unbeaten for a while after HL-LHC**

# Briefly... Self-Reflections

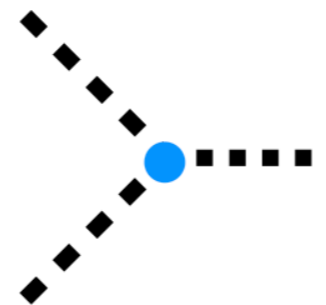


# Briefly... Self-reflection: Higgs Potential

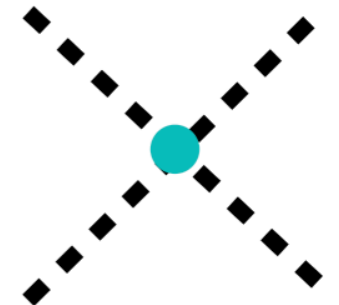
- What is the **shape of Higgs potential**?
- We've only measured the *minimum* of this potential, gives us harmonic oscillator term  
 $m_H^2 = 2\mu^2 = 2\lambda v^2$
- Taylor series expand around the minimum



Higgs trilinear-coupling



Higgs quartic coupling



$$\frac{|V_{\min}^{(\text{Higgs})}|}{\rho_{\Lambda}^{\text{obs}}} \sim 10^{55}$$

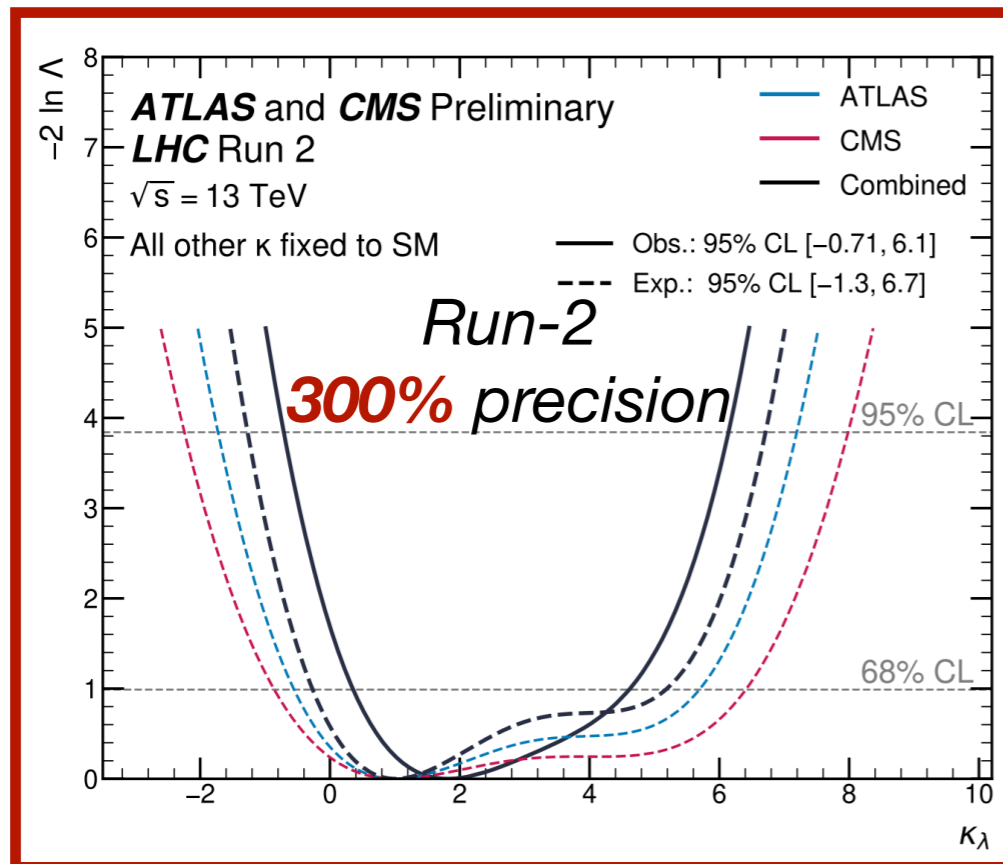
***The Higgs field beautifully breaks symmetry - and catastrophically breaks our understanding of the vacuum***

# Briefly... Self-reflection: Higgs **Self-Coupling**

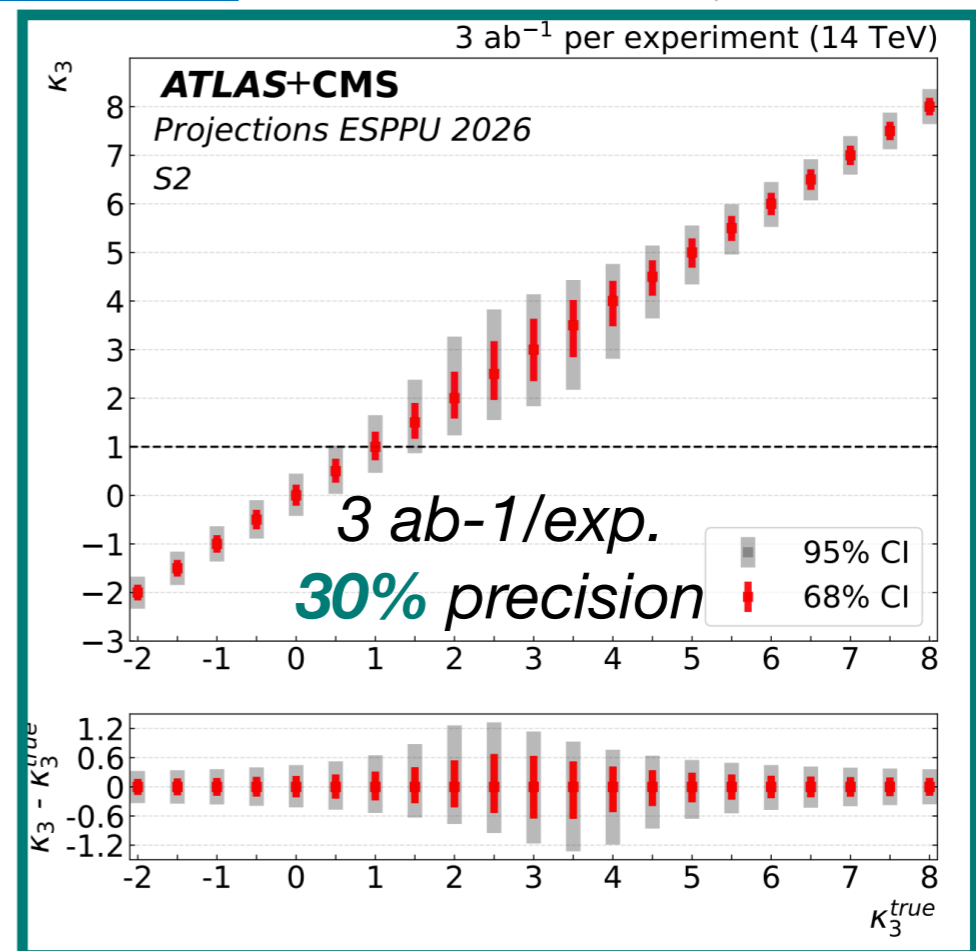
- *How precise* has to be our knowledge of Higgs potential?
- **New physics may modify it significantly!**
  - Compositeness, new scalar singlets, heavy loops, etc...
- **Current** status & **HL-LHC** projections

Physics scenario	Shift in $\kappa\lambda$	Required precision
Composite	10-30%	<10%
Singlet scalar	50-100%	<20%
EFT dim-6	36-4% ( $\Lambda$ : 1-2 TeV)	<b>5-10%</b> for $\Lambda=2-3$ TeV
Heavy weakly-coupled scalars	10%	<b>5-20%</b>

CMS PAS HIG-25-014  
ATLAS-CONF-2025-012

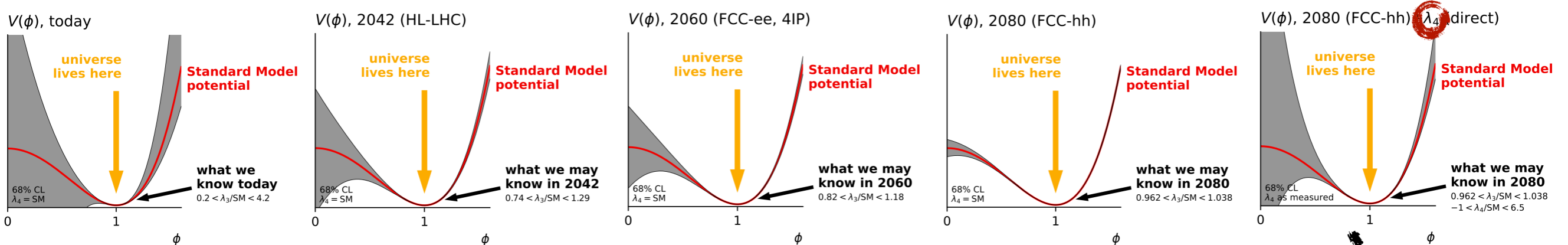


ATL-PHYS-PUB-2025-018  
CMS-HIG-25-002

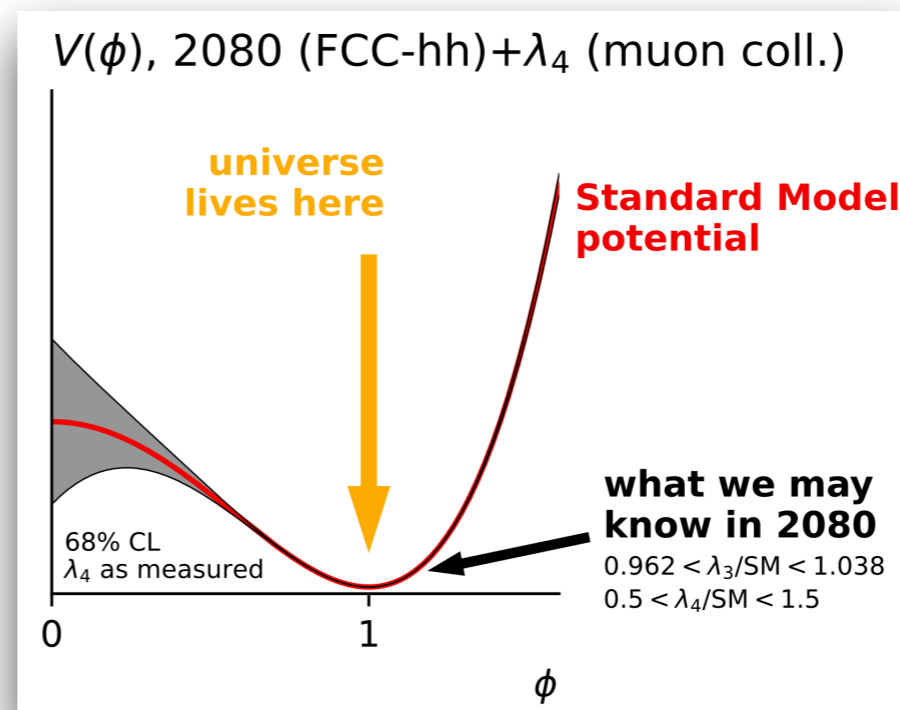


# Mapping Higgs Potential: Self-Couplings Across Colliders

- To test whether the Higgs field truly gives mass - or hides new dynamics - we **must measure  $\lambda_3$  at 10% level,  $\lambda_4$  at 50% level**
- HL-LHC will tell us if the Higgs potential is *roughly* SM-like
- *FCC-hh* (had version of FCC-ee) will finally let us *measure* its shape
- *$\mu$  colliders*: clean environment of  $e^+e^-$  machine with E reach of hadron collider

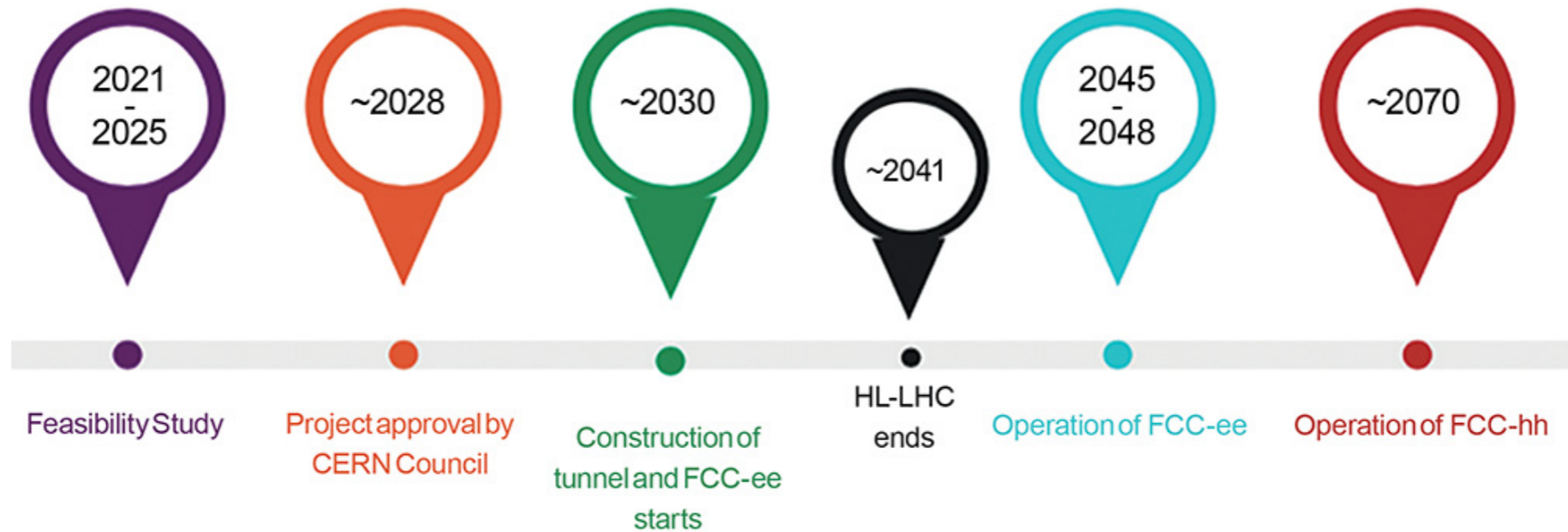
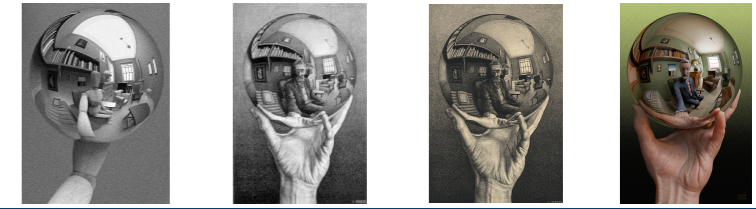


- Quadrilinear coupling ( $\lambda_4$ )
  - Essentially *unmeasurable* at HL-LHC (HHH  $\sigma \sim 0.01$  fb)
  - @100 TeV (FCC-hh+ $\mu$  coll.) HHH  $\sigma \sim 0.1$  fb: 1000 events
    - $O(50\%)$  if  $\lambda_3$  constrained



G. Salam

# Summary of the Future

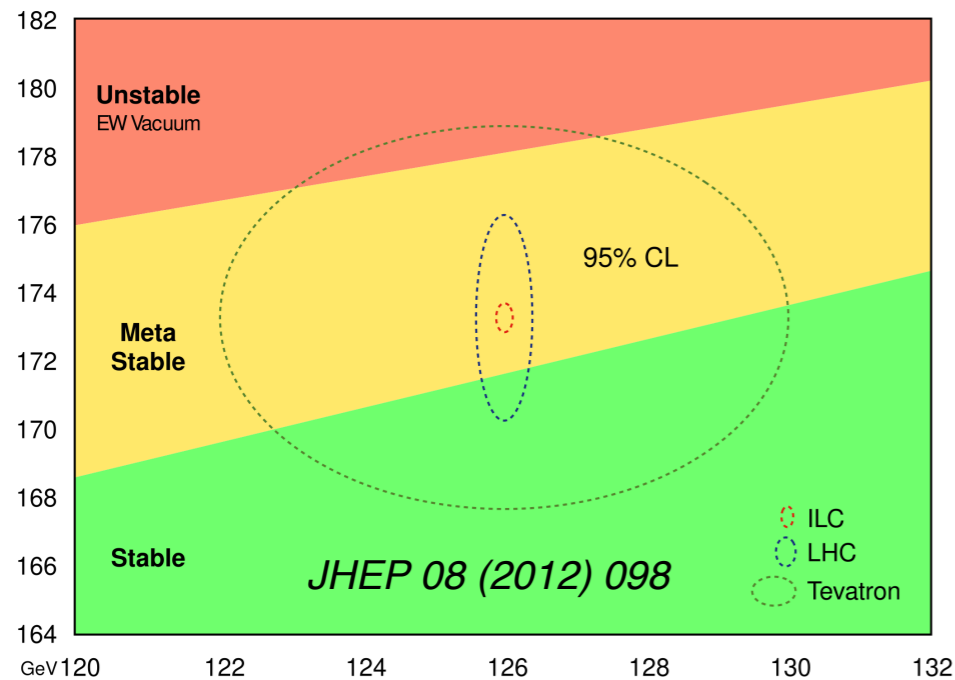


Observable	Current	HL-LHC	FCC-ee	FCC-hh (+ $\mu$ coll.)
$K_b$	15-20%	10%	0.5-1%	-
$K_C(s)$	150%(-)	<90%(-)	2(30-100)%	-
High- $p_T$ dynamics	limited	1-10%	-	TBD
$\lambda_3$	300%	20-30%	indirect	3-5%
$\lambda_4$	-	-	-	300(50)%

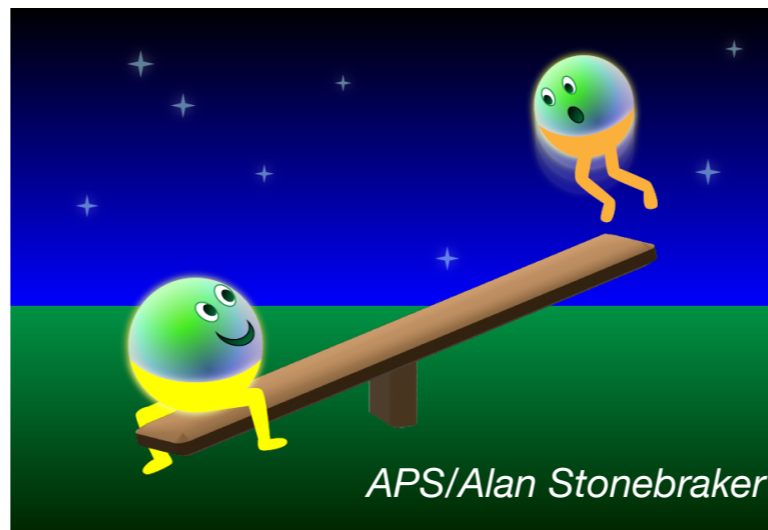
# Many Open Questions

- A LOT more on the way than what we've seen today! A LOT remains mysterious!
- Plenty of opportunities: **our exploration of the Higgs boson has just started!**

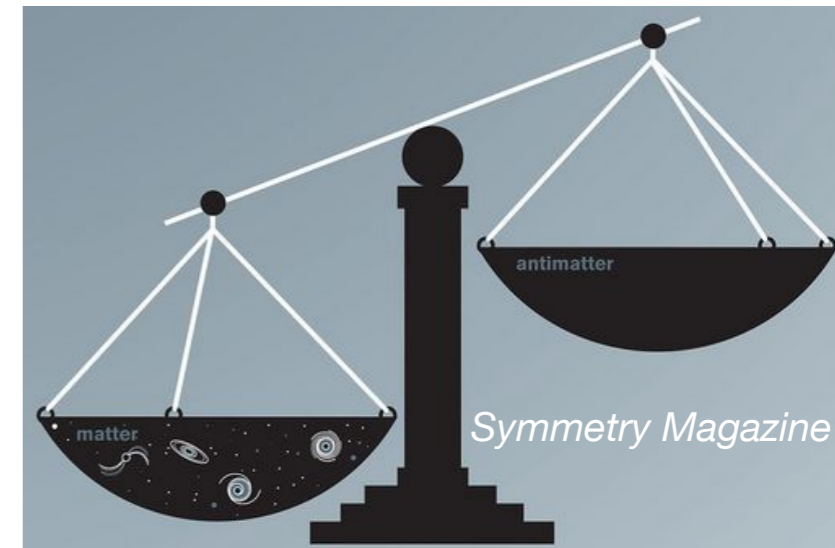
*Vacuum stability & high-scale Higgs potential*



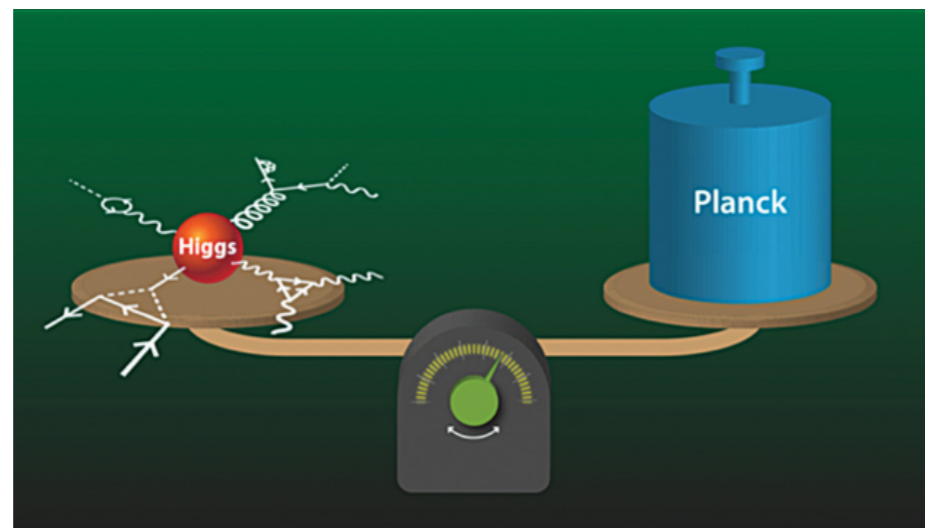
*Neutrino masses and mixings*



*Matter–antimatter asymmetry*



*The hierarchy problem/  
naturalness*



*Origin of flavor*

*Strong CP problem*

*No quantum gravity in the SM*

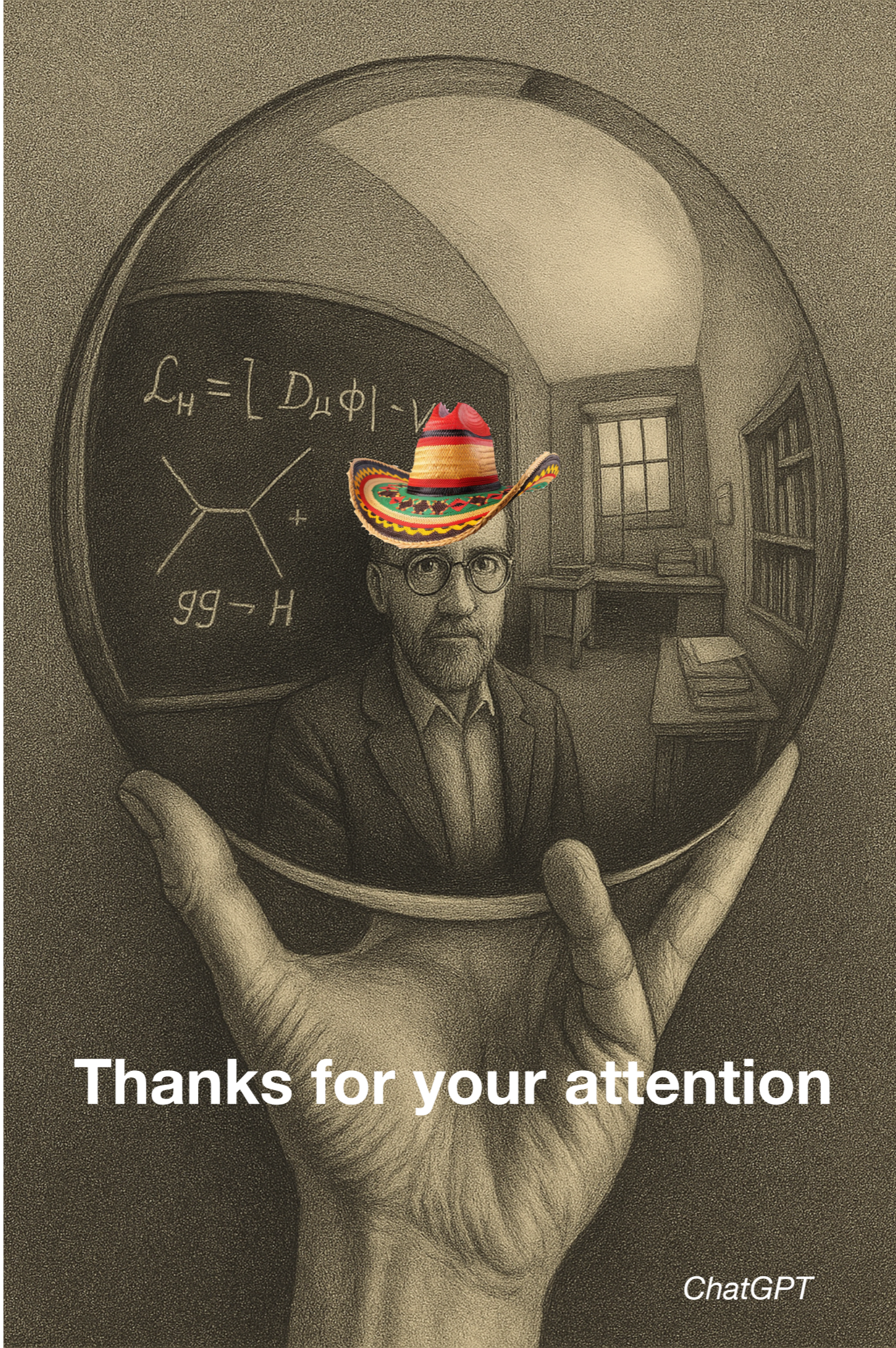
# Conclusion

Recap of Higgs *reflections*:

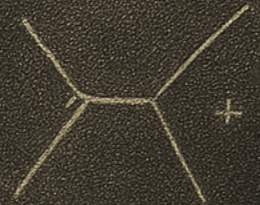
- **Beauty** → established
- **Charm** → emerging
- **Strangeness** → still hidden
- **Self-reflection** → on the horizon
- **Dynamics** → still so much to explore, at hadronic colliders...  
unique opportunity!



*Each era sharpens the mirror in which we see the Higgs -  
and perhaps, new physics*



$$\mathcal{L}_H = [D_\mu \phi] - v$$



$$gg \rightarrow H$$

Thanks for your attention

---

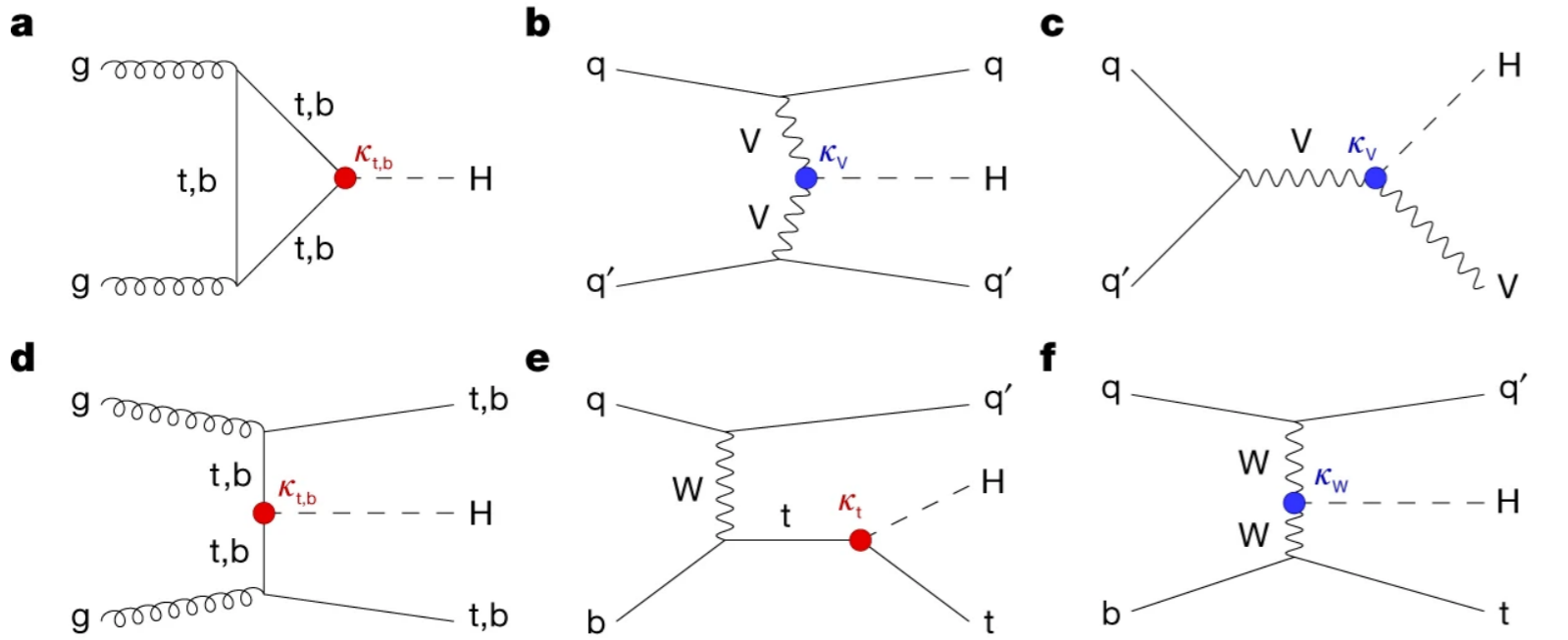
# BACKUP

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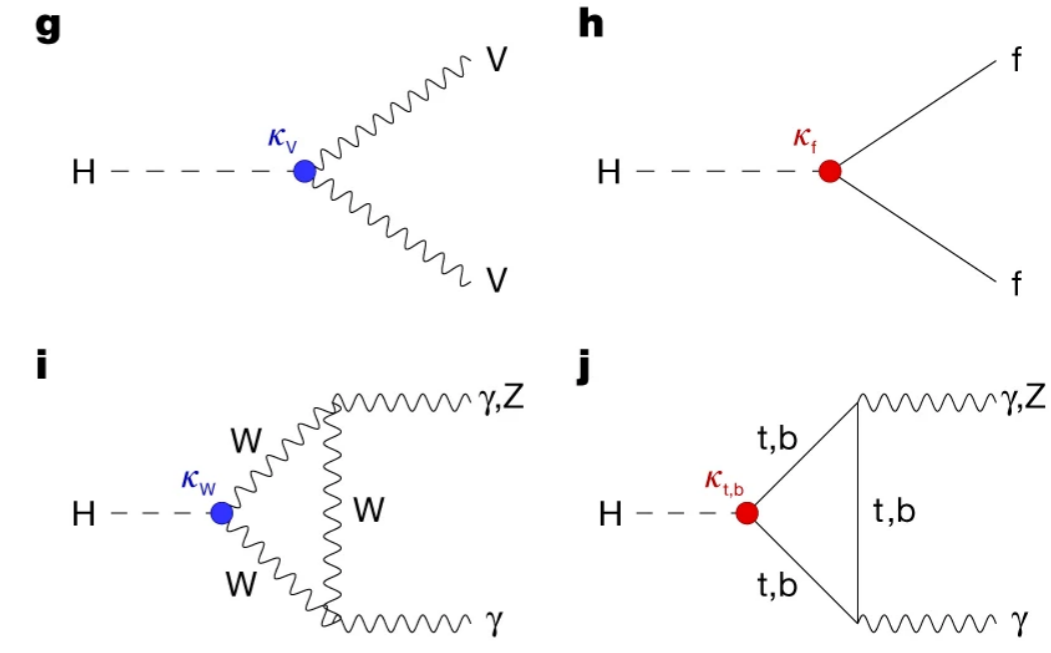
# LHC - Couplings

# LHC - Couplings accessibility

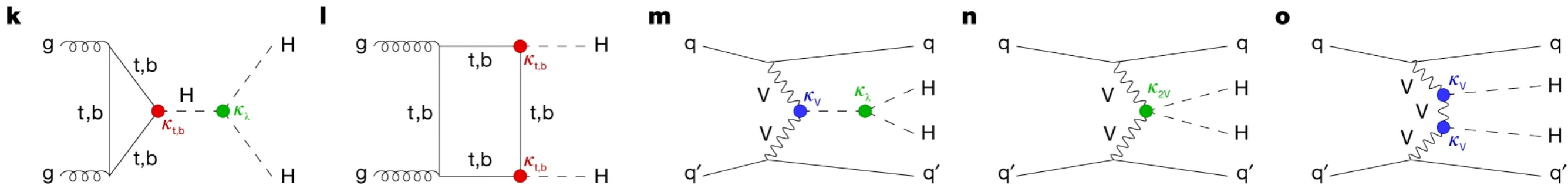
Higgs boson production modes



Higgs boson decay channels

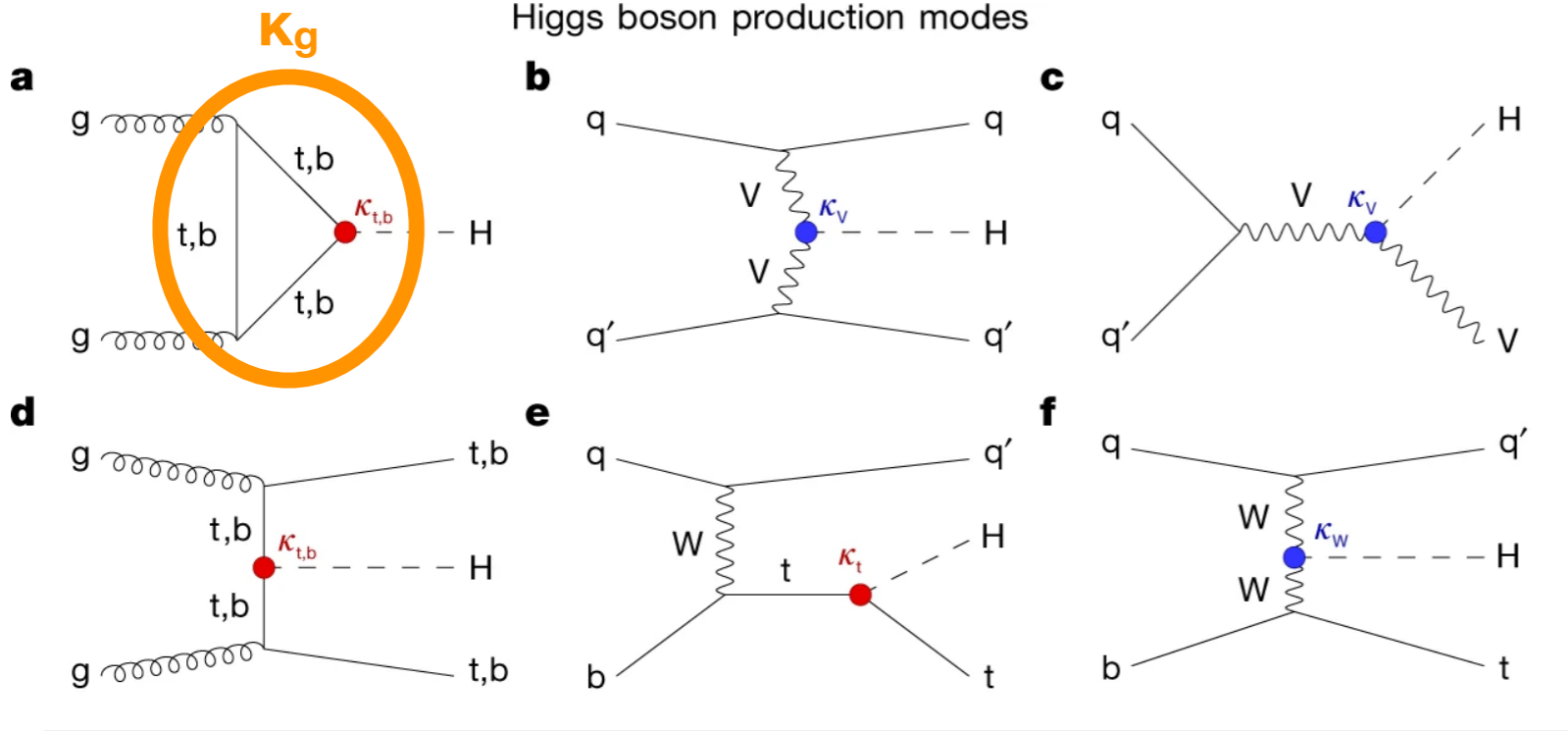


Higgs boson pair production

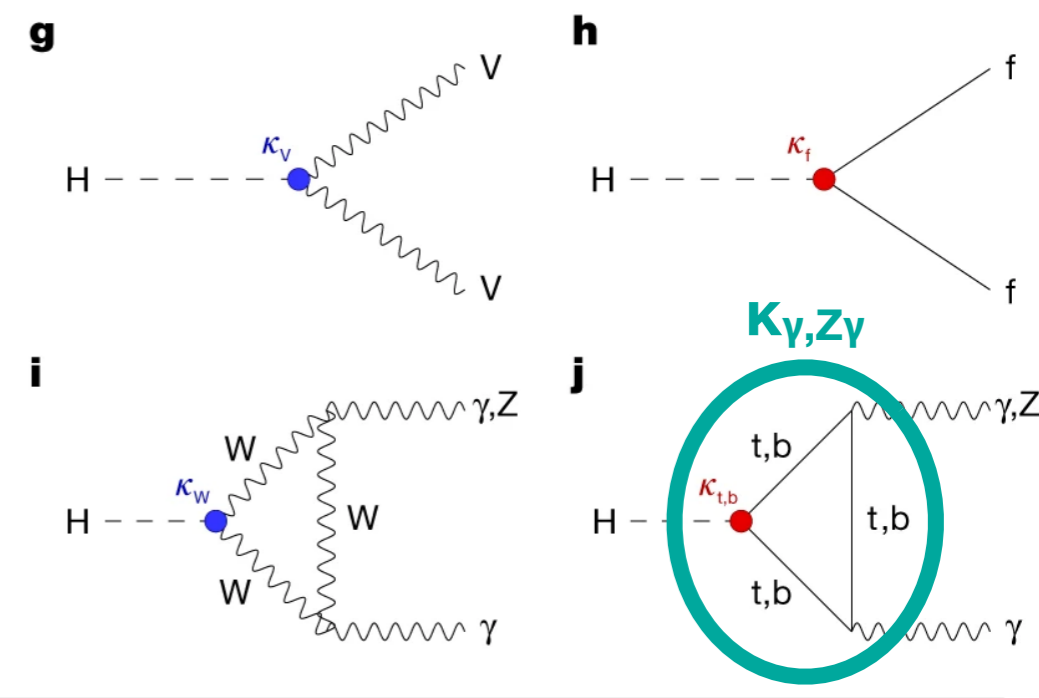


# LHC - Couplings accessibility

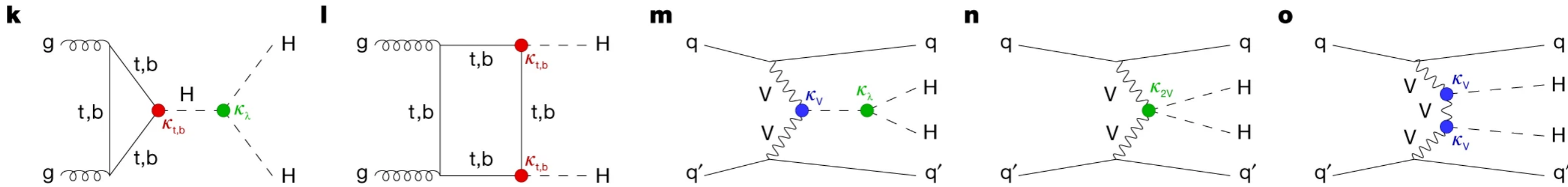
Higgs boson production modes



Higgs boson decay channels



Higgs boson pair production

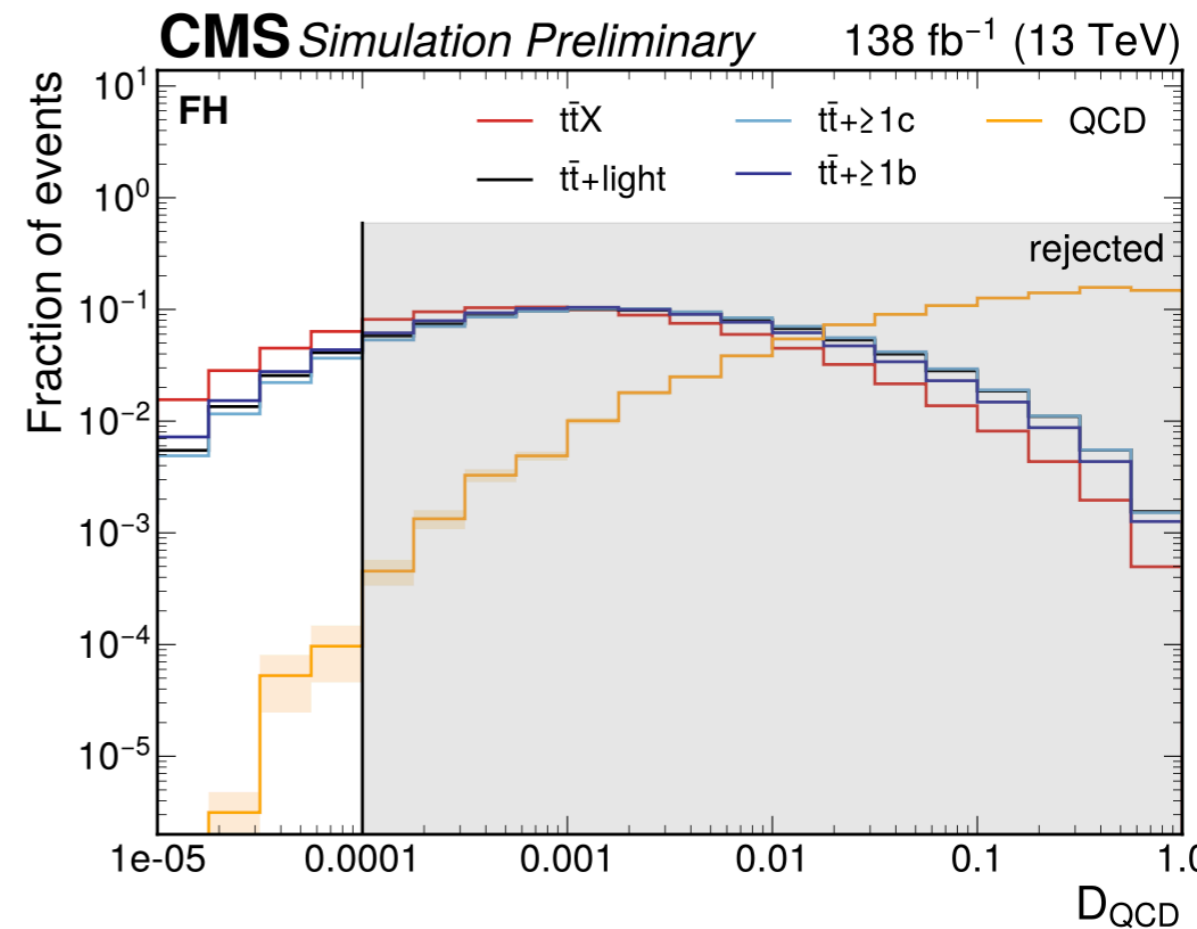
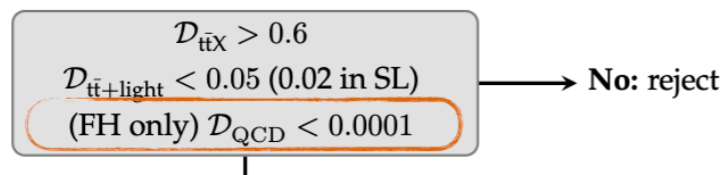


Loop-induced processes! Use effective parameterization or (for example):

$$\kappa_g(\kappa_t, \kappa_b, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

# CMS ttHcc background rejection

- Use scores ( $D_X$ ) to select & categorise events

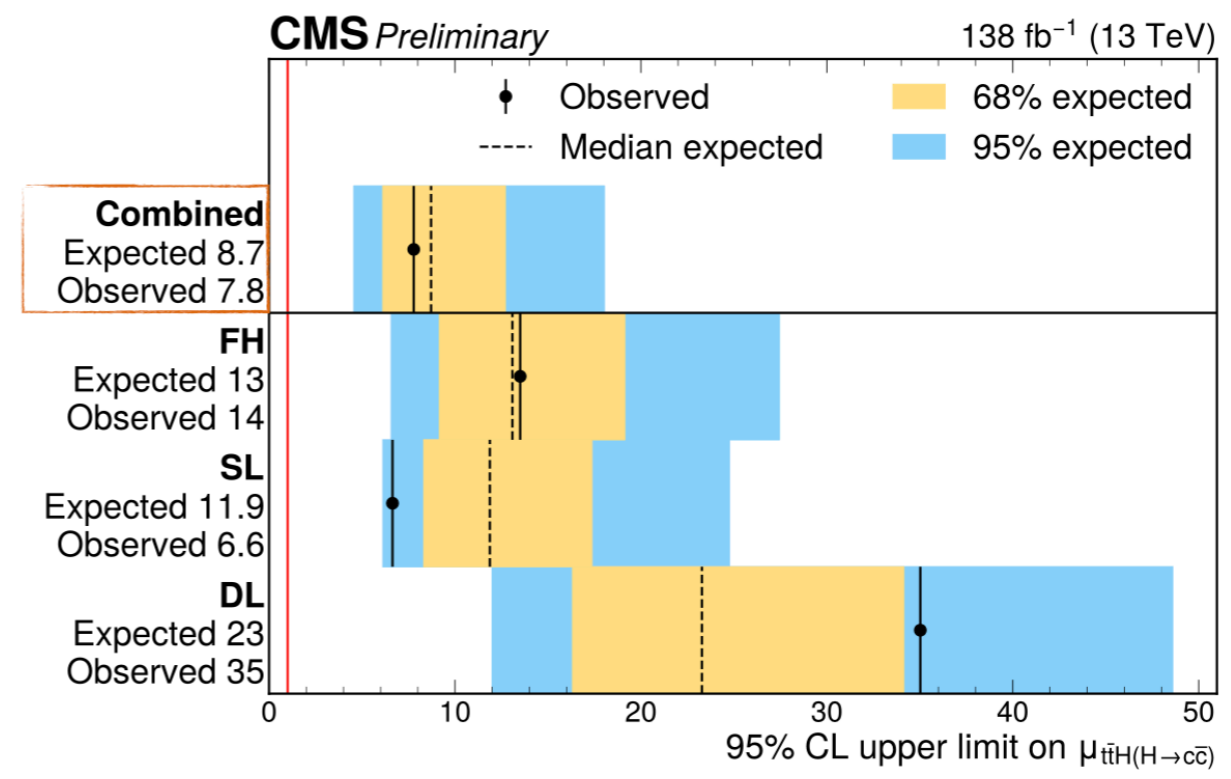
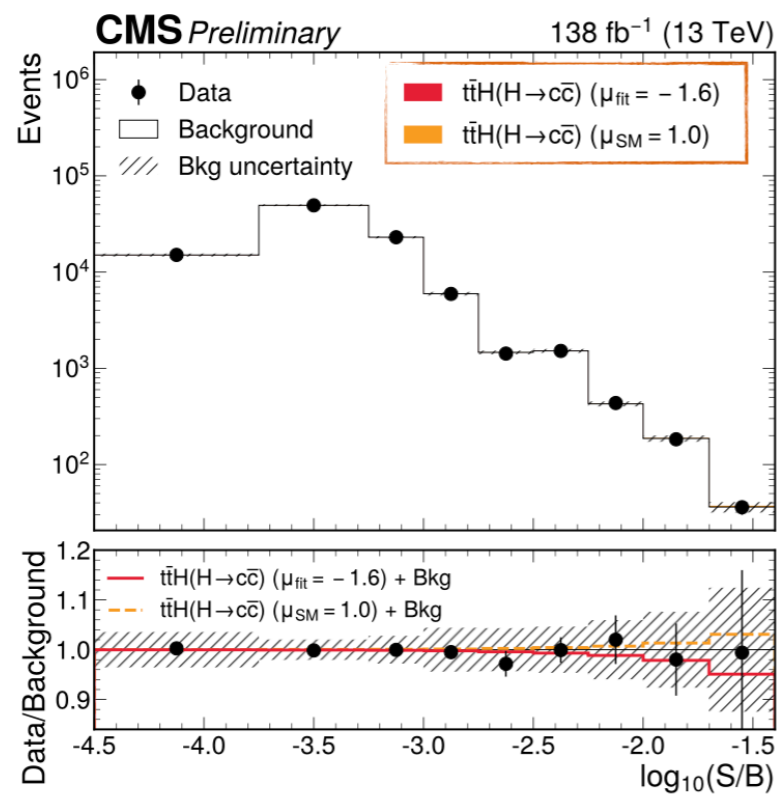
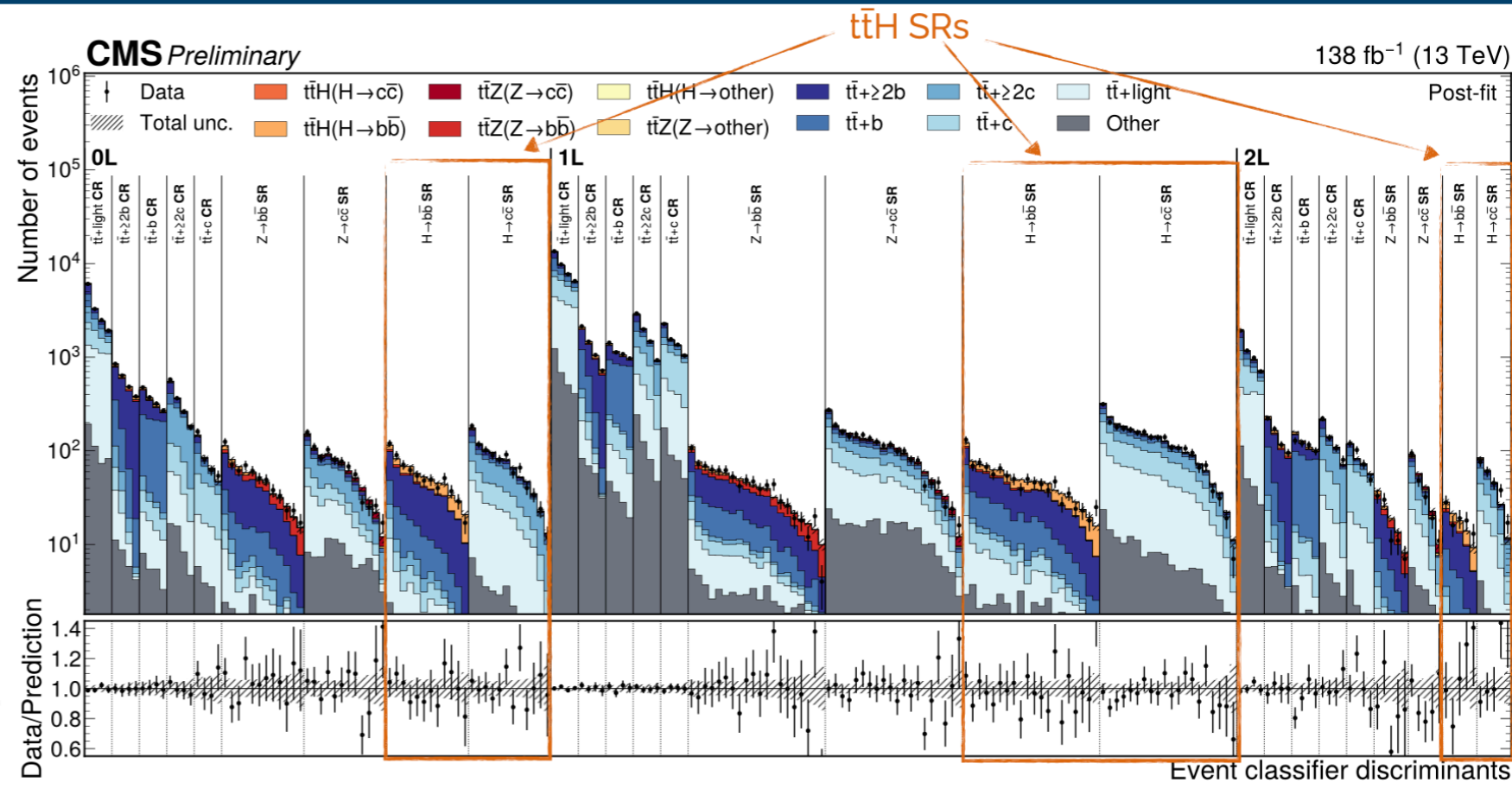
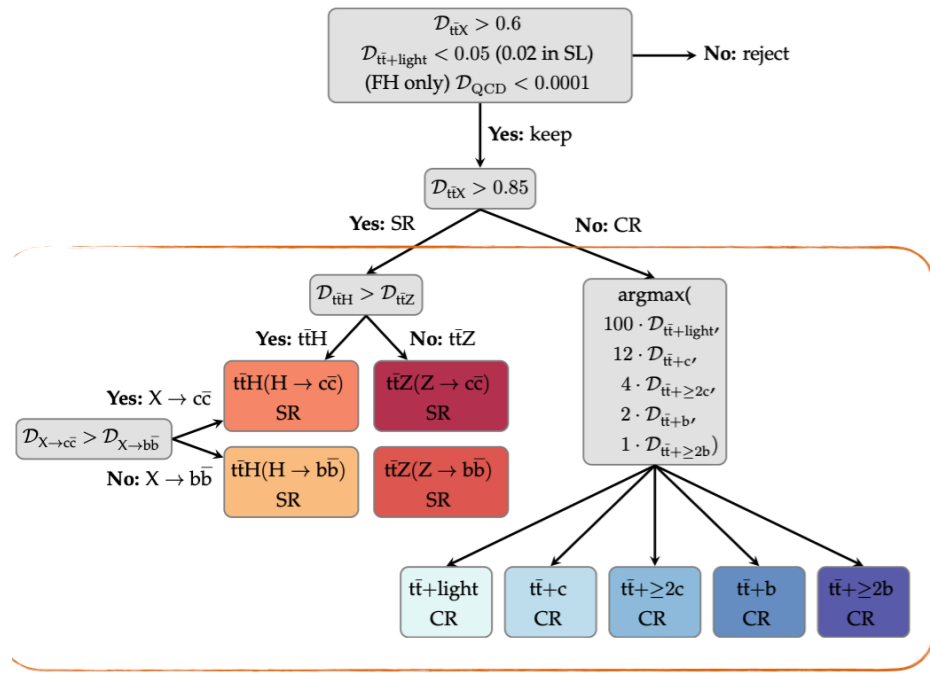


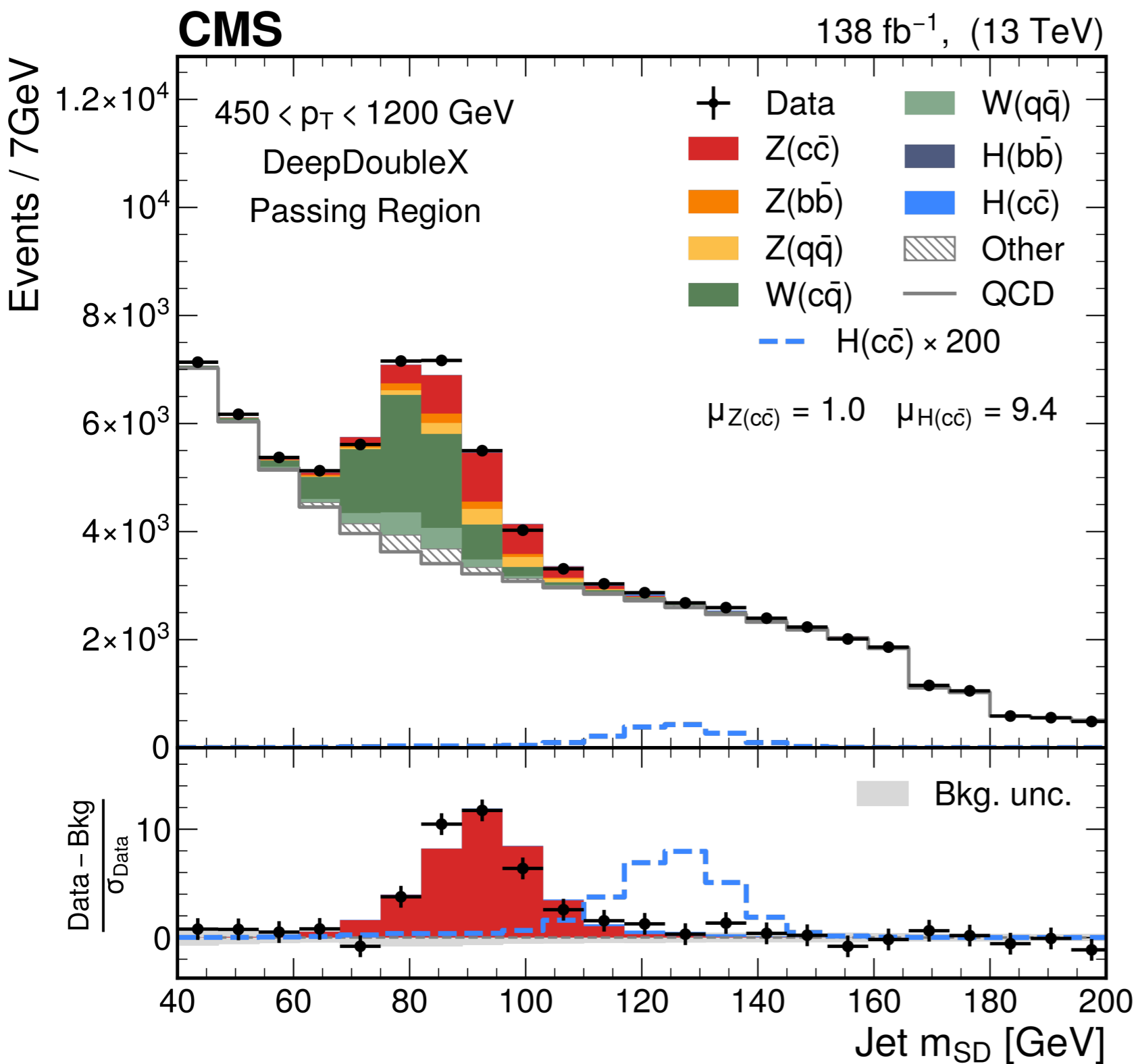
- 1) Remove QCD and  $t\bar{t}+light$  contributions via selections on background scores

QCD suppression in FH channel:

- Event classifier very good at separating QCD ↔  $t\bar{t}$
- Only use events with QCD score  $< 10^{-4}$ 
  - QCD contribution becomes negligible (< 1%)**
  - At the cost of signal efficiency (~ 15%)

# CMS ttHcc background categorisation





**Zcc**

$$1.00^{+0.17}_{-0.14} \text{ (syst)} \pm 0.08 \text{ (theo)} \pm 0.06 \text{ (stat)}$$

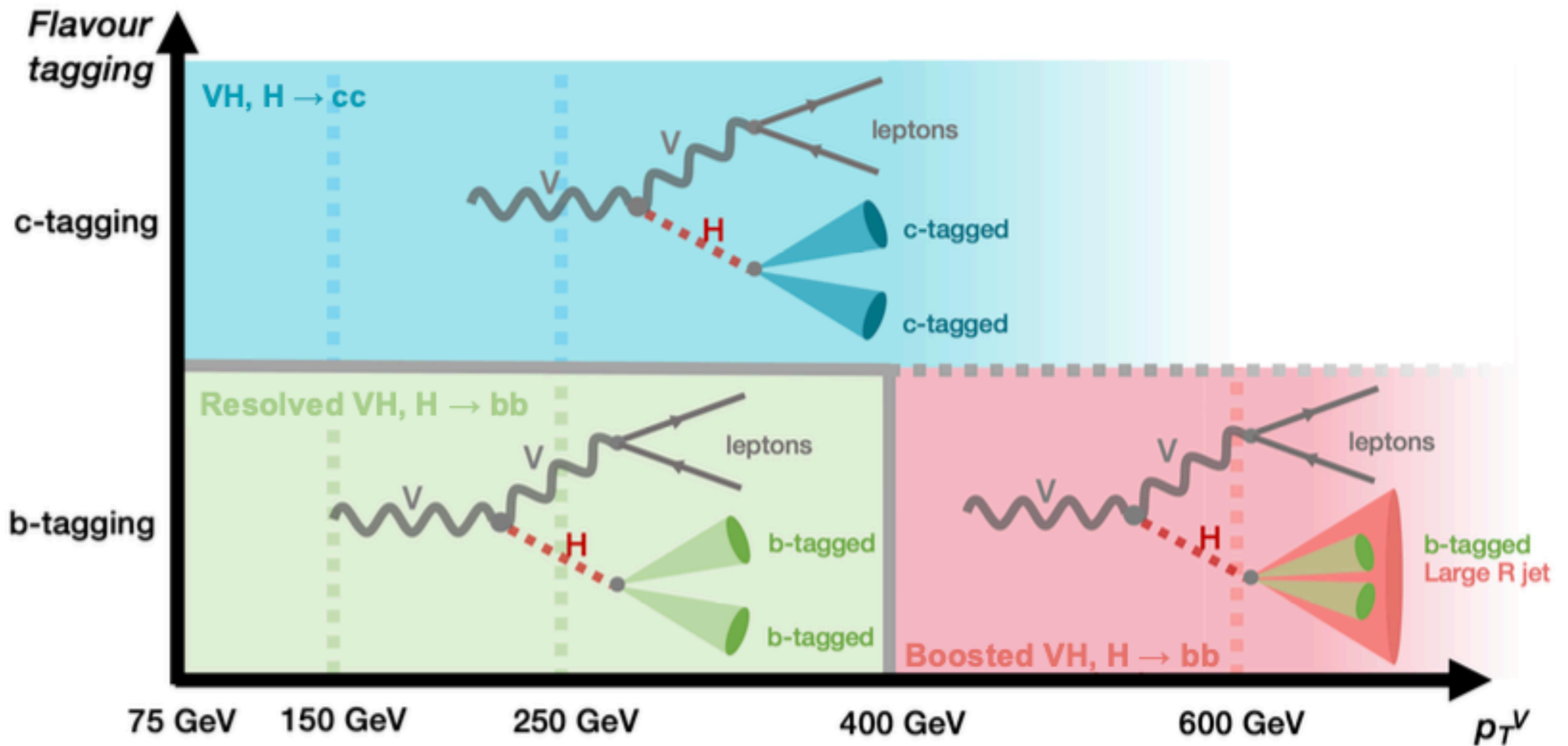
**Hcc**

$$< 47(39) \times \sigma_{SM}$$

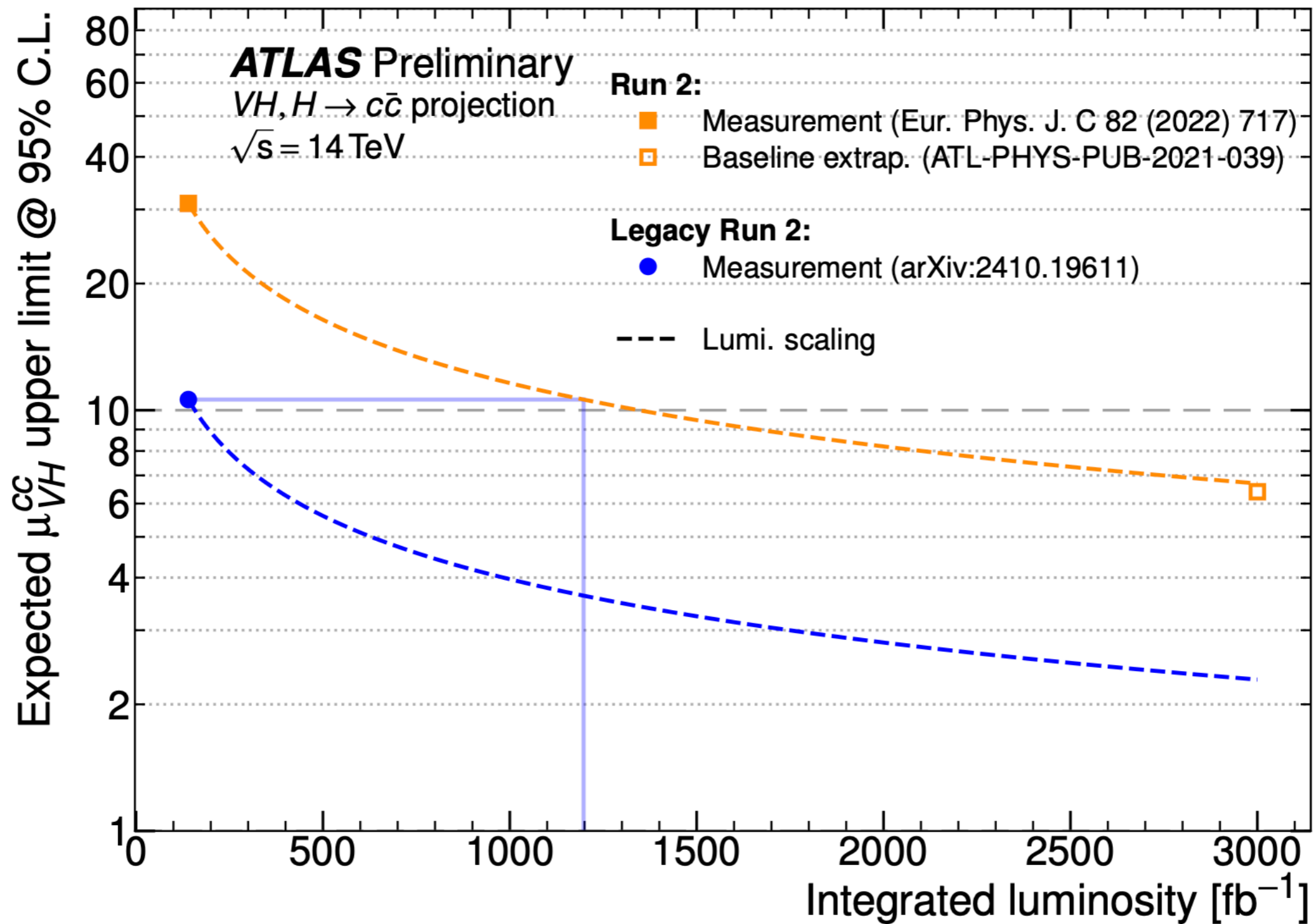
---

# HL-LHC b/c

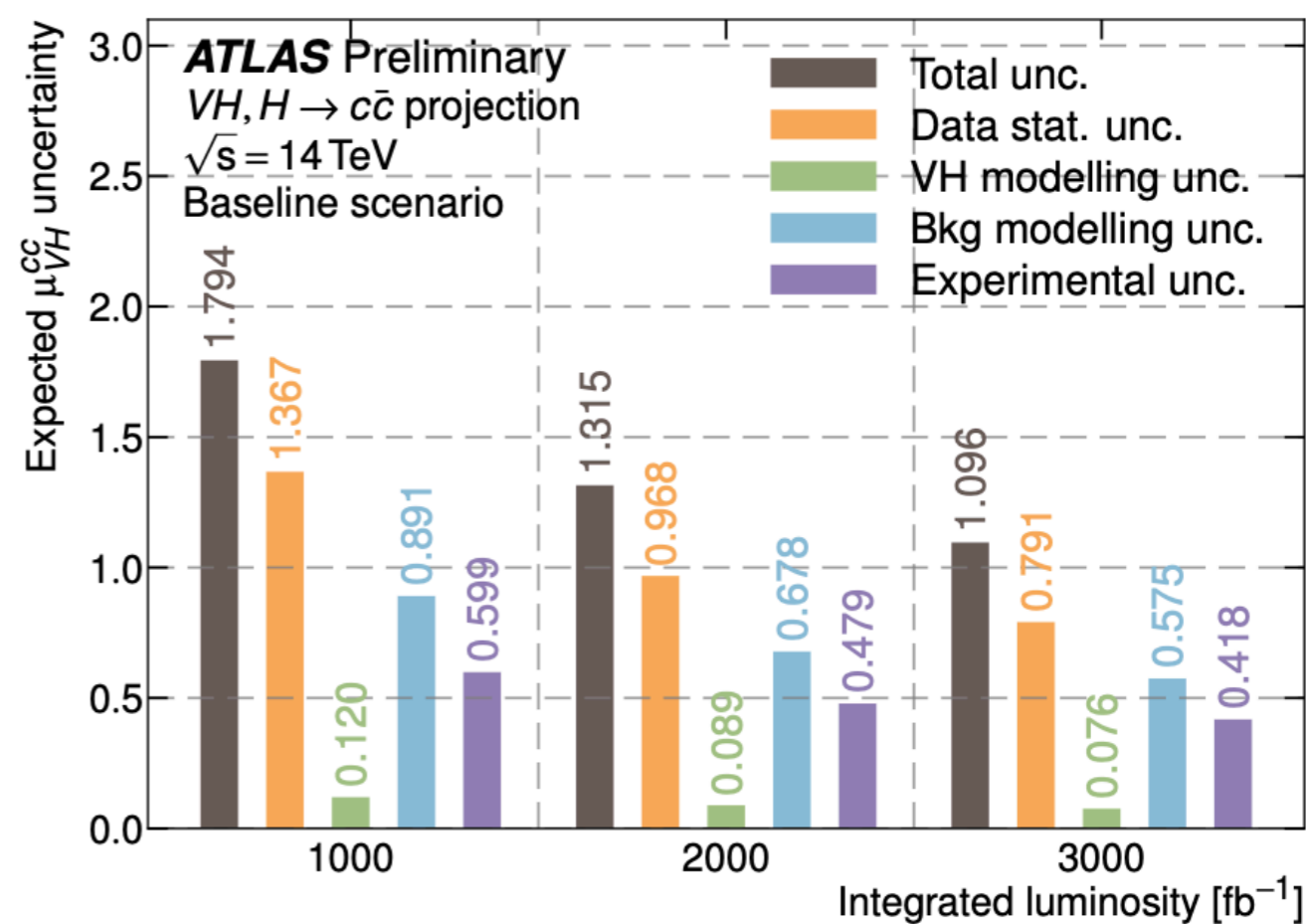
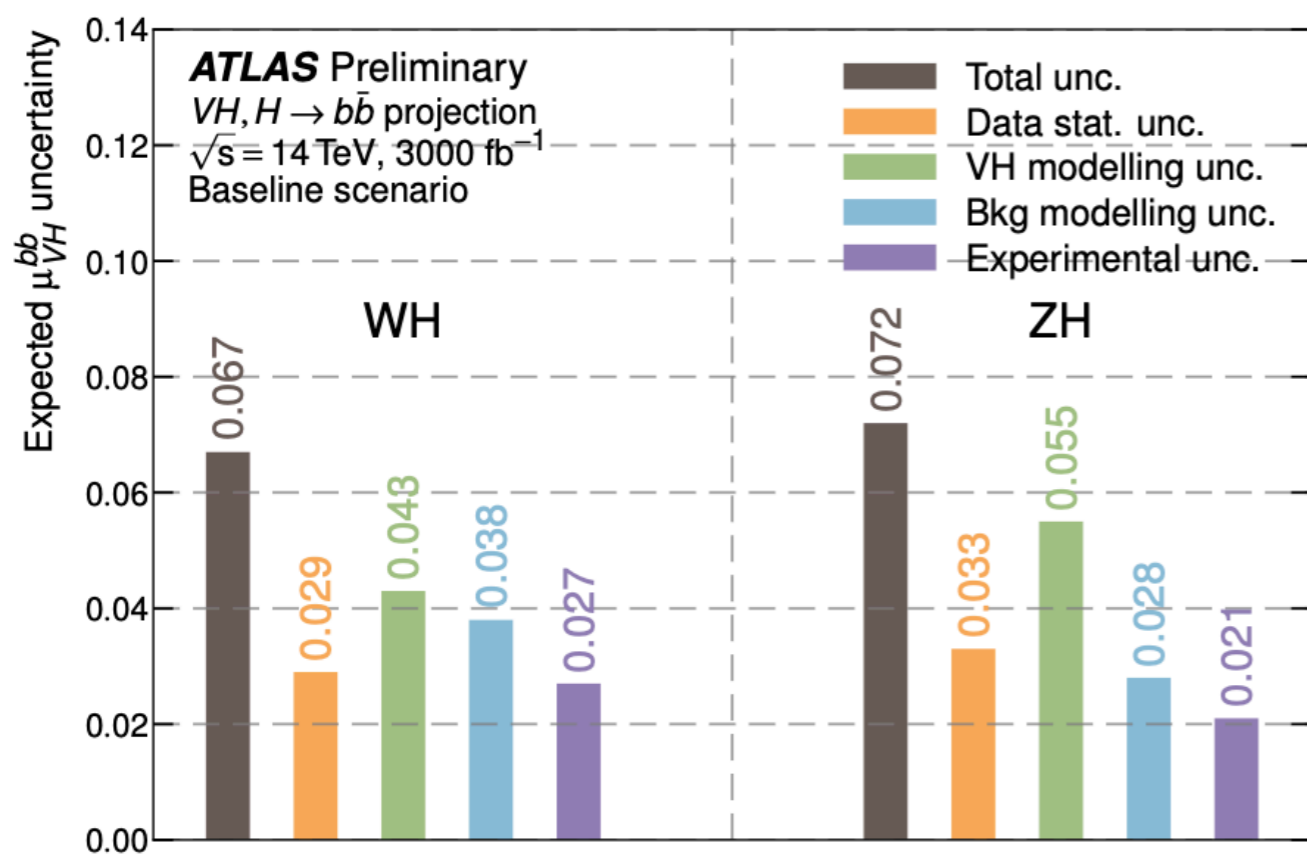
# HL LHC: VHbbcc more plots



# HL LHC: VHbbcc more plots



# HL LHC: VHbbcc more plots



---

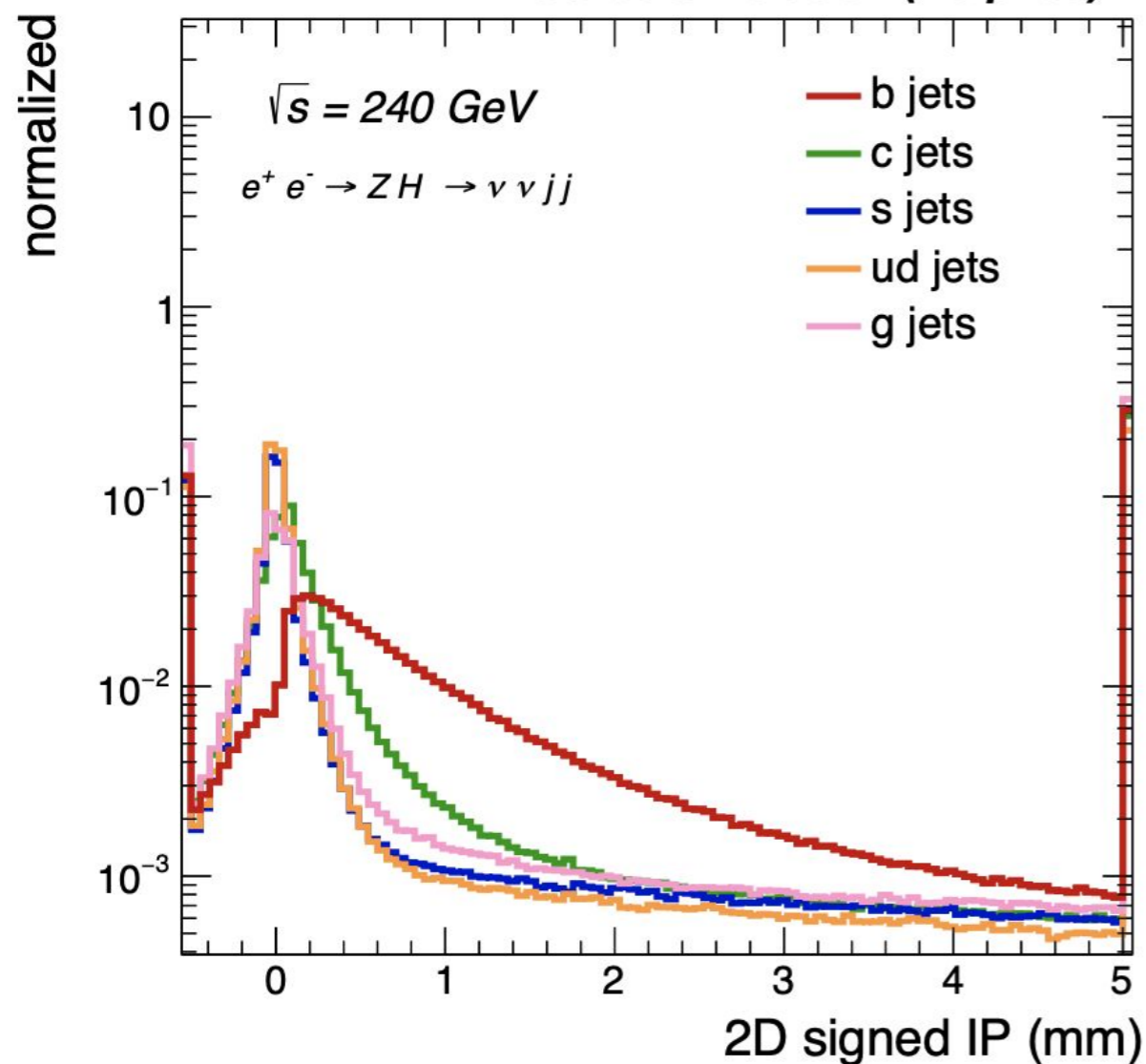
# FCC-ee

# FCC-ee Tagger - Input Variables

- Comparison of input distributions for different jet flavours

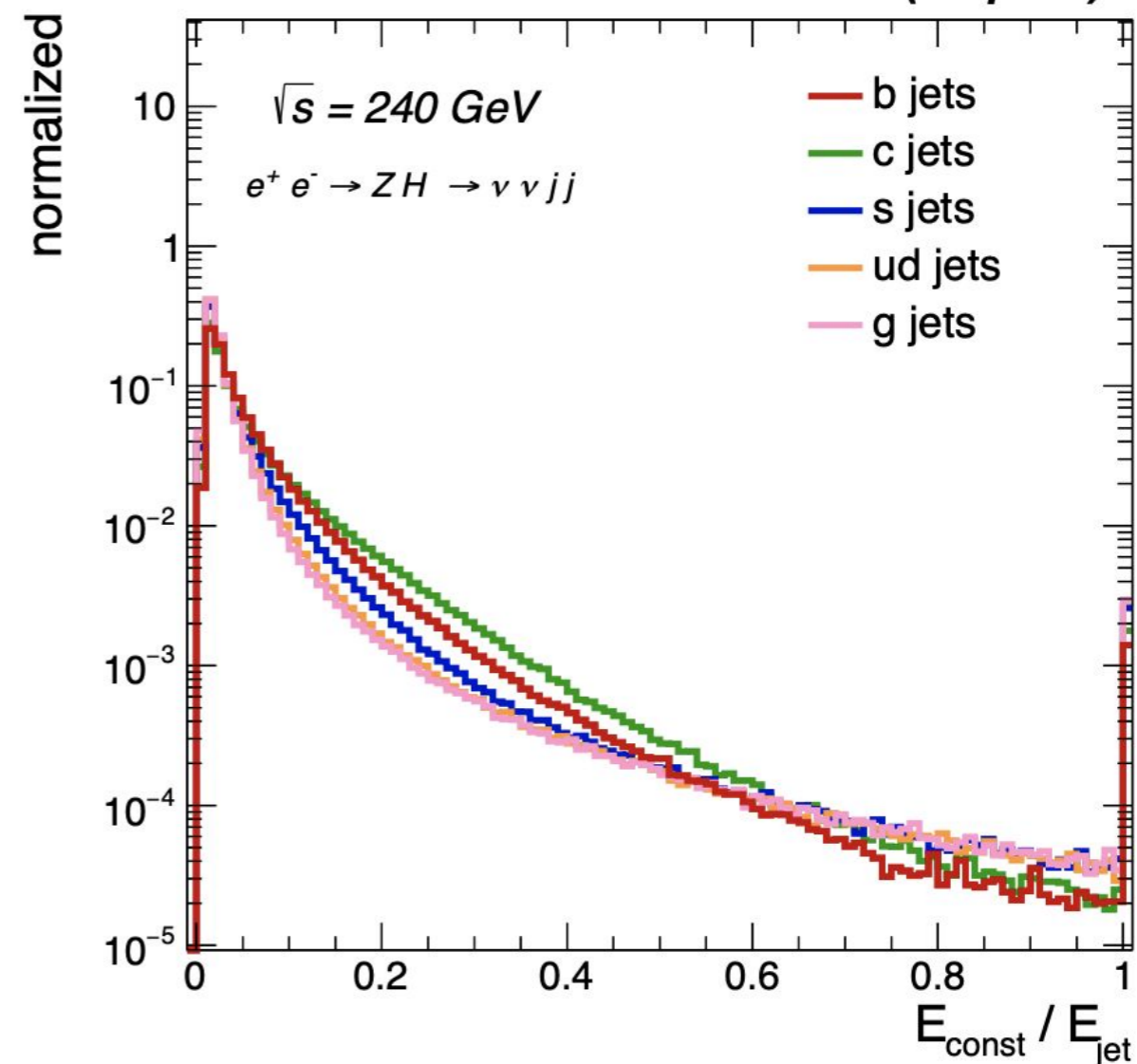
## Impact parameter (d0)

FCC-ee simulation (Delphes)



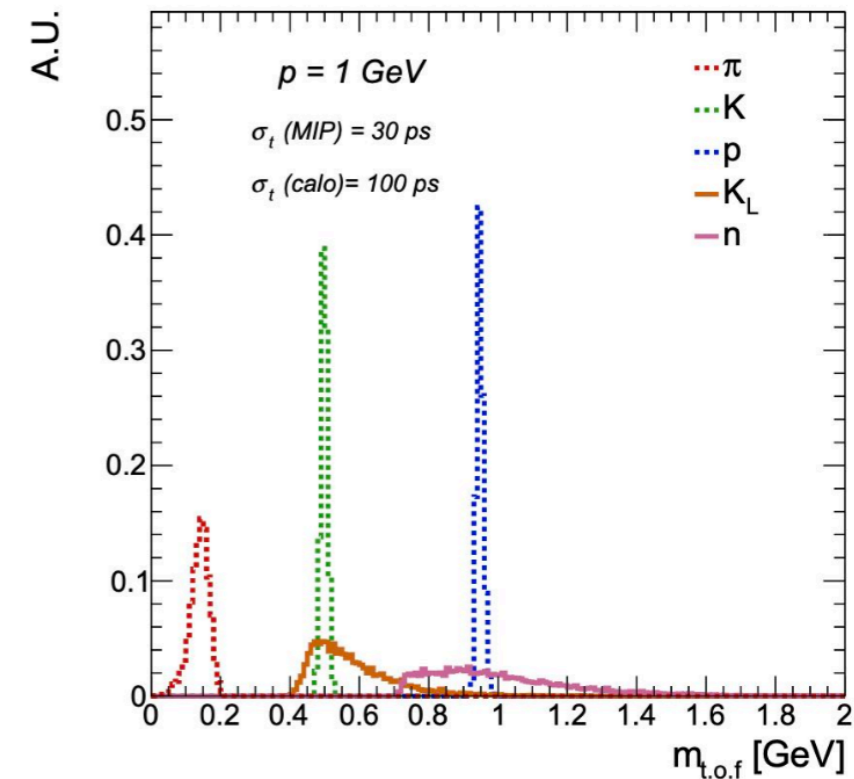
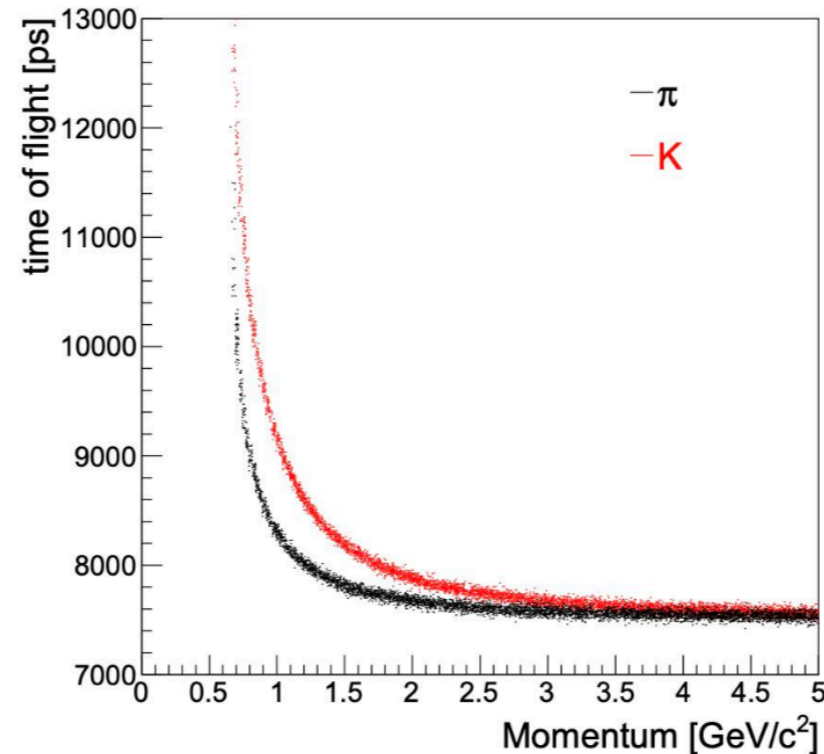
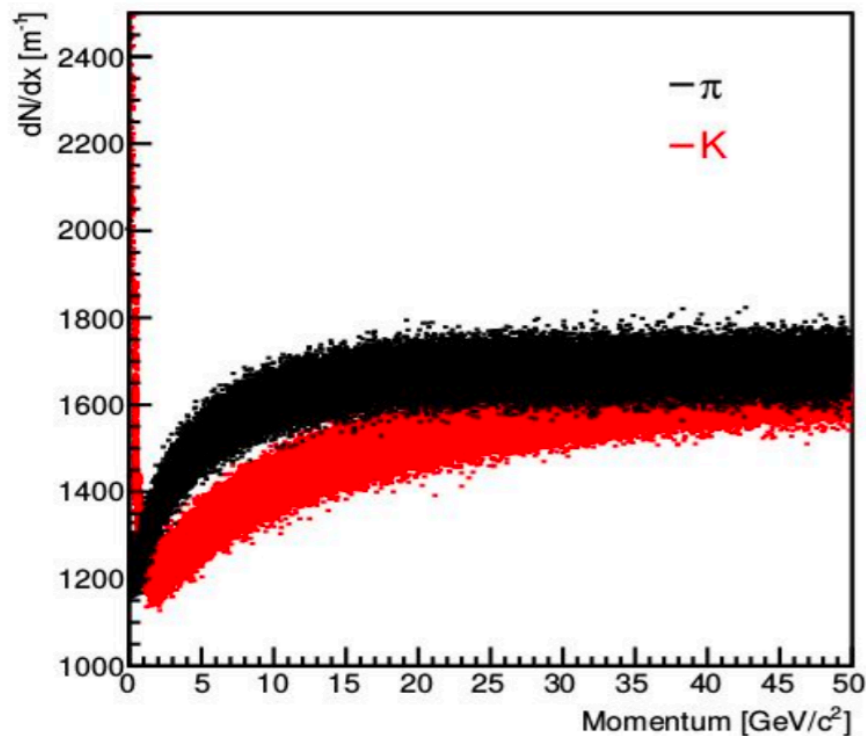
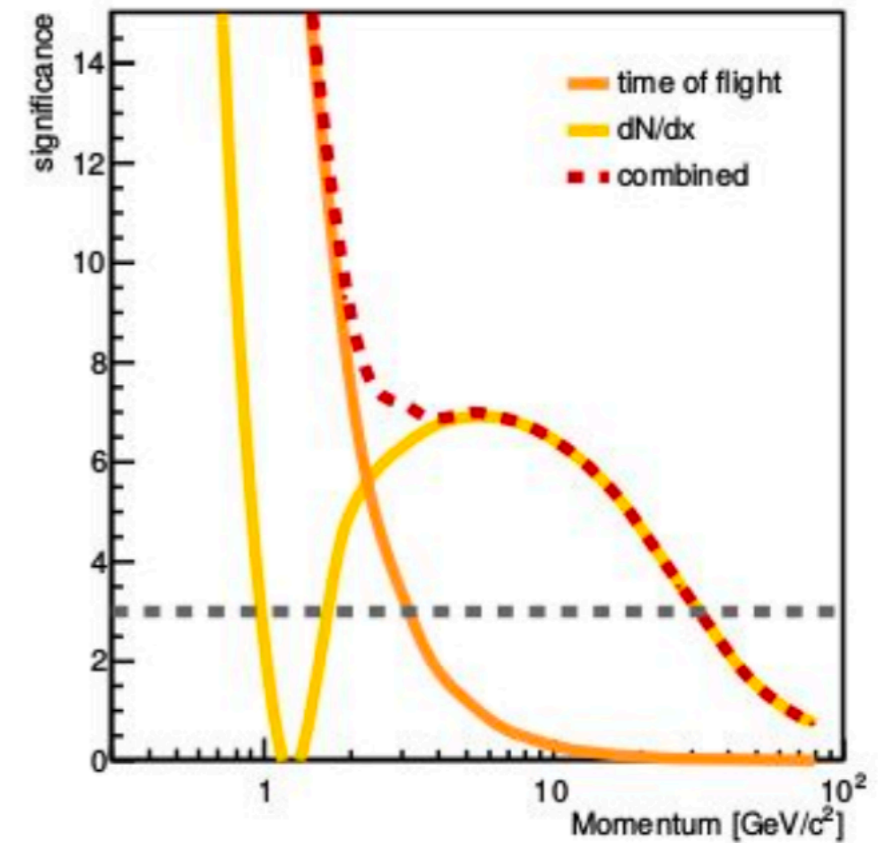
## Constituent relative energy

FCC-ee simulation (Delphes)



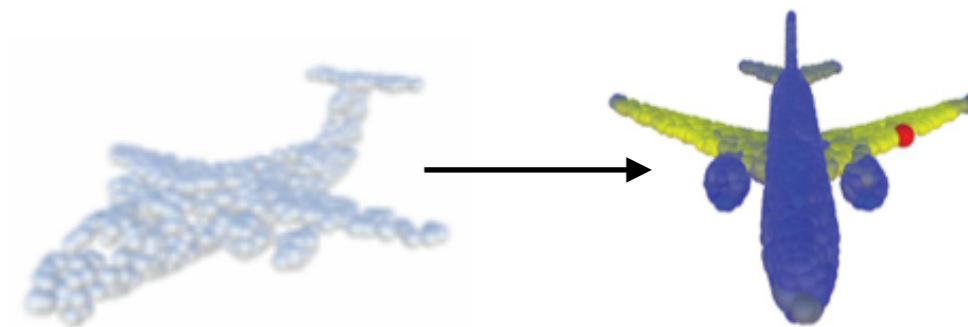
# Particle ID: Cluster Counting & Time-of-Flight

- Count number of primary ionisation clusters along track path
- Time-of-Flight results in good K/ $\pi$  separation at low momenta
- Dedicated modules added in Delphes



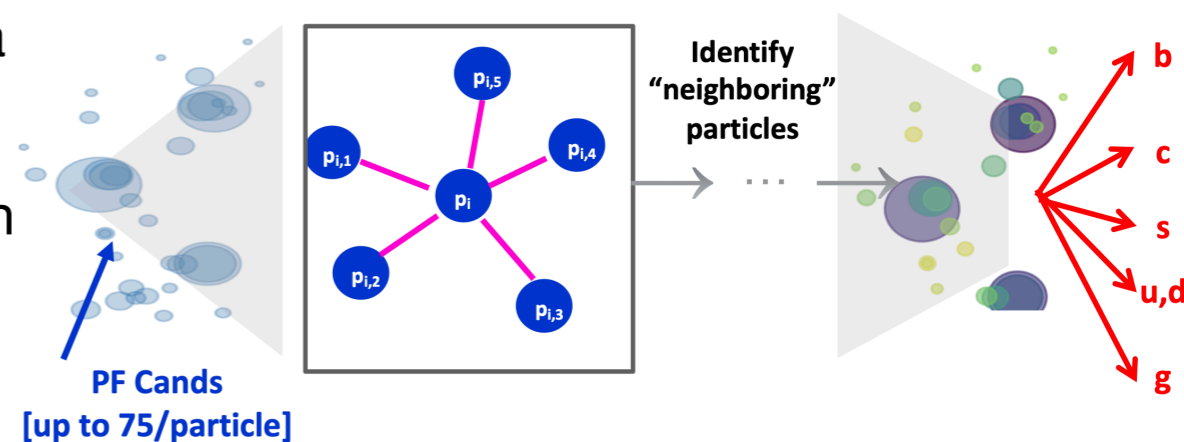
# The ParticleNet Tagger

- Graph-based tagger, where each jet is treated as a “cone” of reconstructed particles traversing the detector
- Particle-flow (PF) principle: particle candidates are mutually exclusive and have lots of info associated with
  - E/p, position
  - Impact parameters, particle type
  - Timing
- Experiments at the LHC moving(ed...) towards particle-based jet tagging, exploiting the whole information directly related to PF candidates
  - Full info, reco potential & detector granularity
- kT jet-reconstruction algorithms to reco jets: unordered sets of particles with correlations & relationships. Graph-Neural-Network architecture for ParticleNet:
  - Identify properties of “particle cloud”, represented as a **graph**
  - Each particle: **node** of the graph; connections between particles: the **edges**
  - Learn local structures → move to more global ones



From this article

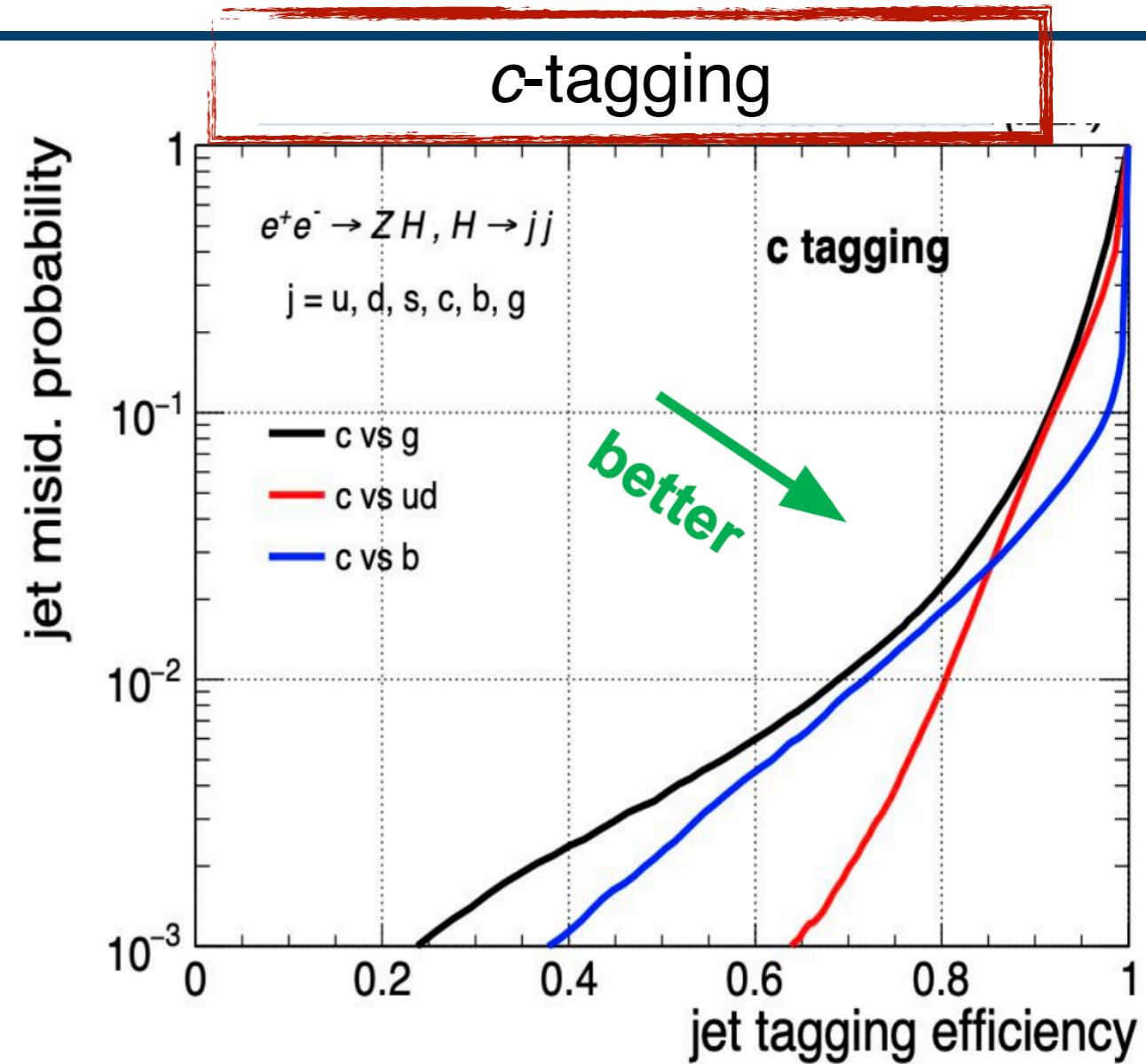
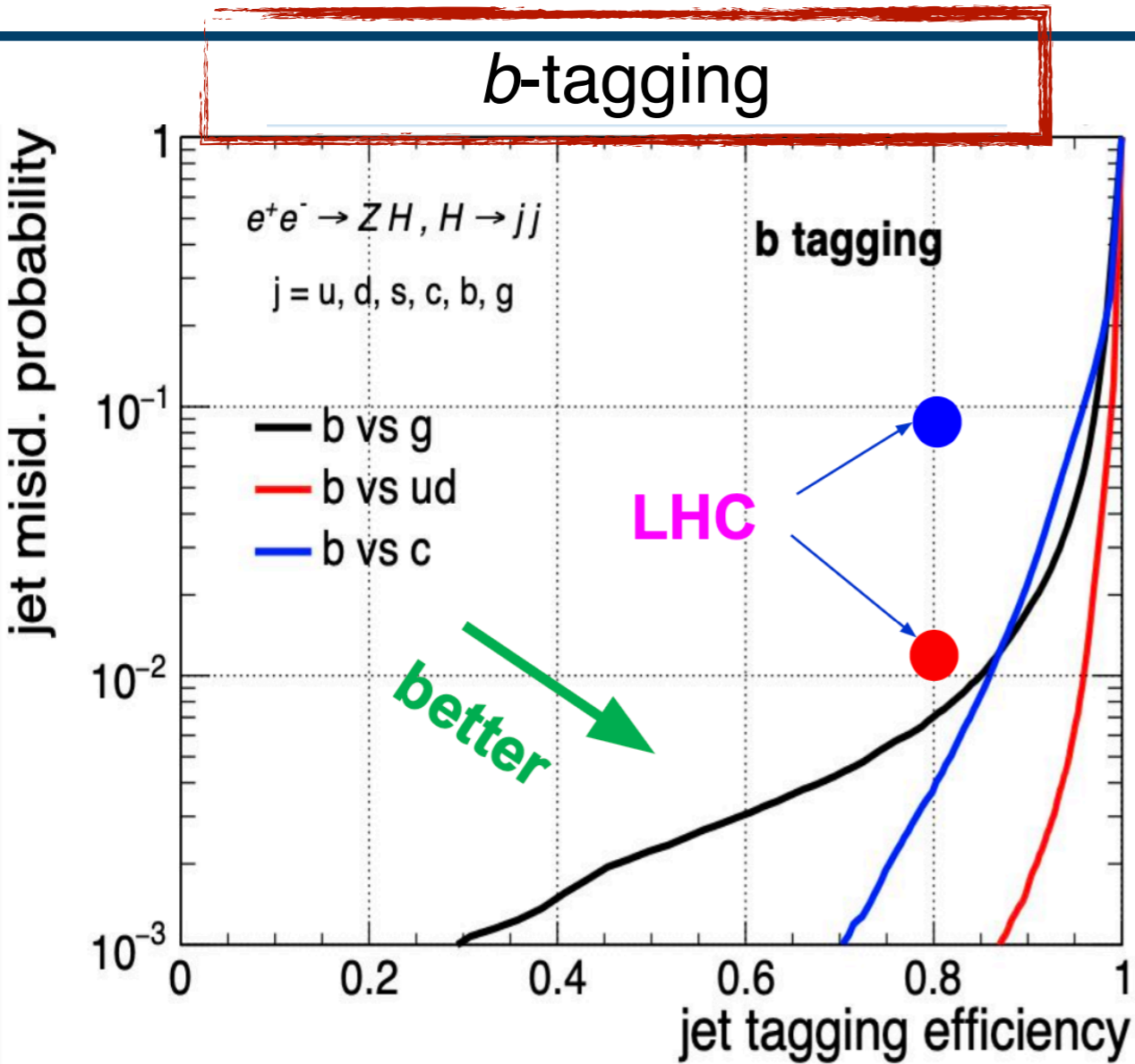
[O(50) properties/particle]  
x [~50-100 particles/jet]  
~O(1000) inputs/jet



# Full List of Input Variables

Variable	Description
Kinematics	
$E_{\text{const}}/E_{\text{jet}}$	energy of the jet constituent divided by the jet energy
$\theta_{\text{rel}}$	polar angle of the constituent with respect to the jet momentum
$\phi_{\text{rel}}$	azimuthal angle of the constituent with respect to the jet momentum
Displacement	
$d_{xy}$	transverse impact parameter of the track
$d_z$	longitudinal impact parameter of the track
$\text{SIP}_{2\text{D}}$	signed 2D impact parameter of the track
$\text{SIP}_{2\text{D}}/\sigma_{2\text{D}}$	signed 2D impact parameter significance of the track
$\text{SIP}_{3\text{D}}$	signed 3D impact parameter of the track
$\text{SIP}_{3\text{D}}/\sigma_{3\text{D}}$	signed 3D impact parameter significance of the track
$d_{3\text{D}}$	jet track distance at their point of closest approach
$d_{3\text{D}}/\sigma_{d_{3\text{D}}}$	jet track distance significance at their point of closest approach
$C_{ij}$	covariance matrix of the track parameters
Identification	
$q$	electric charge of the particle
$m_{\text{t.o.f.}}$	mass calculated from time-of-flight
$dN/dx$	number of primary ionisation clusters along track
<code>isMuon</code>	if the particle is identified as a muon
<code>isElectron</code>	if the particle is identified as an electron
<code>isPhoton</code>	if the particle is identified as a photon
<code>isChargedHadron</code>	if the particle is identified as a charged hadron
<code>isNeutralHadron</code>	if the particle is identified as a neutral hadron

# b/c-tagging Performance



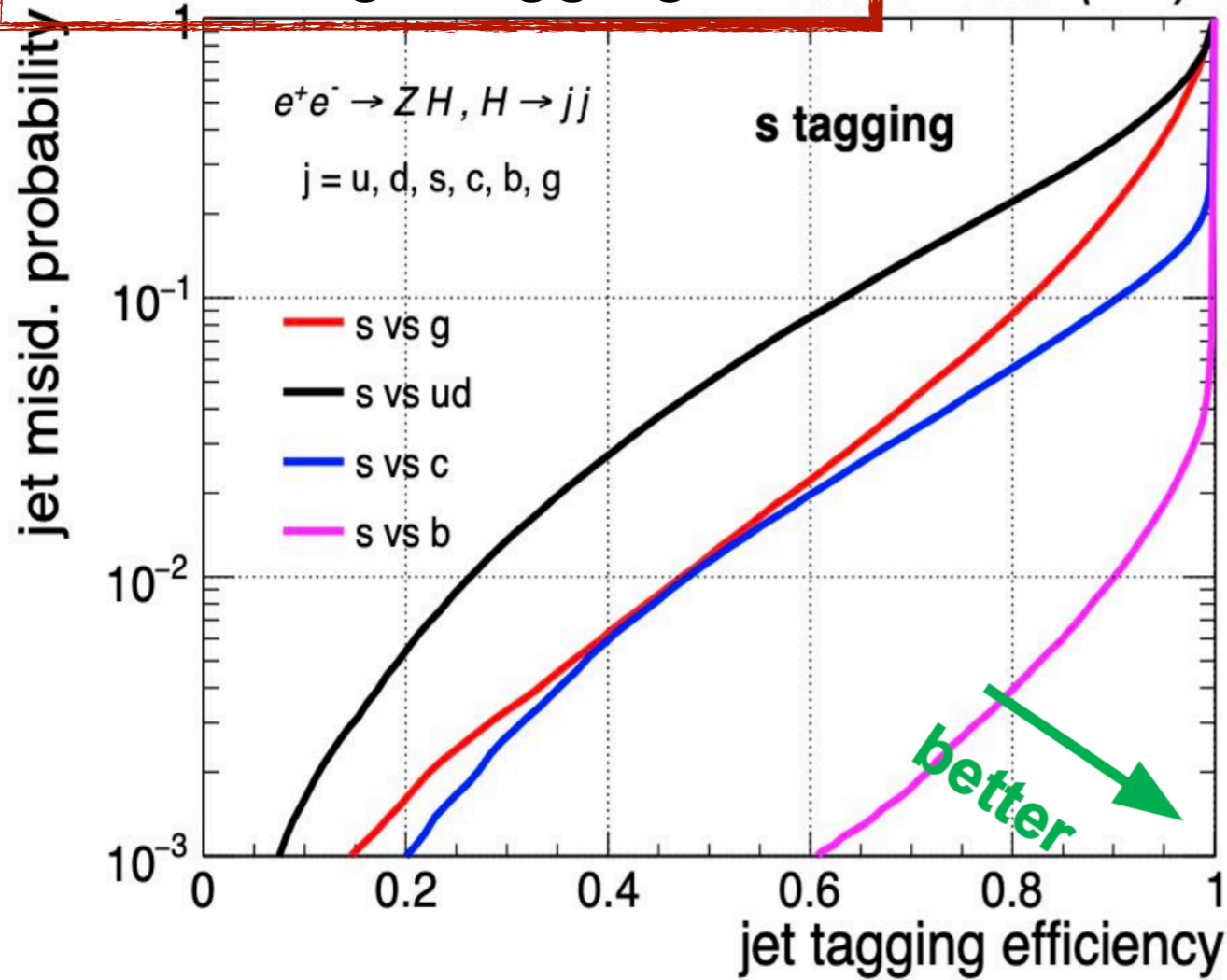
WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.1%	2%
Medium	80%	0.7%	<0.1%	0.3%

WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

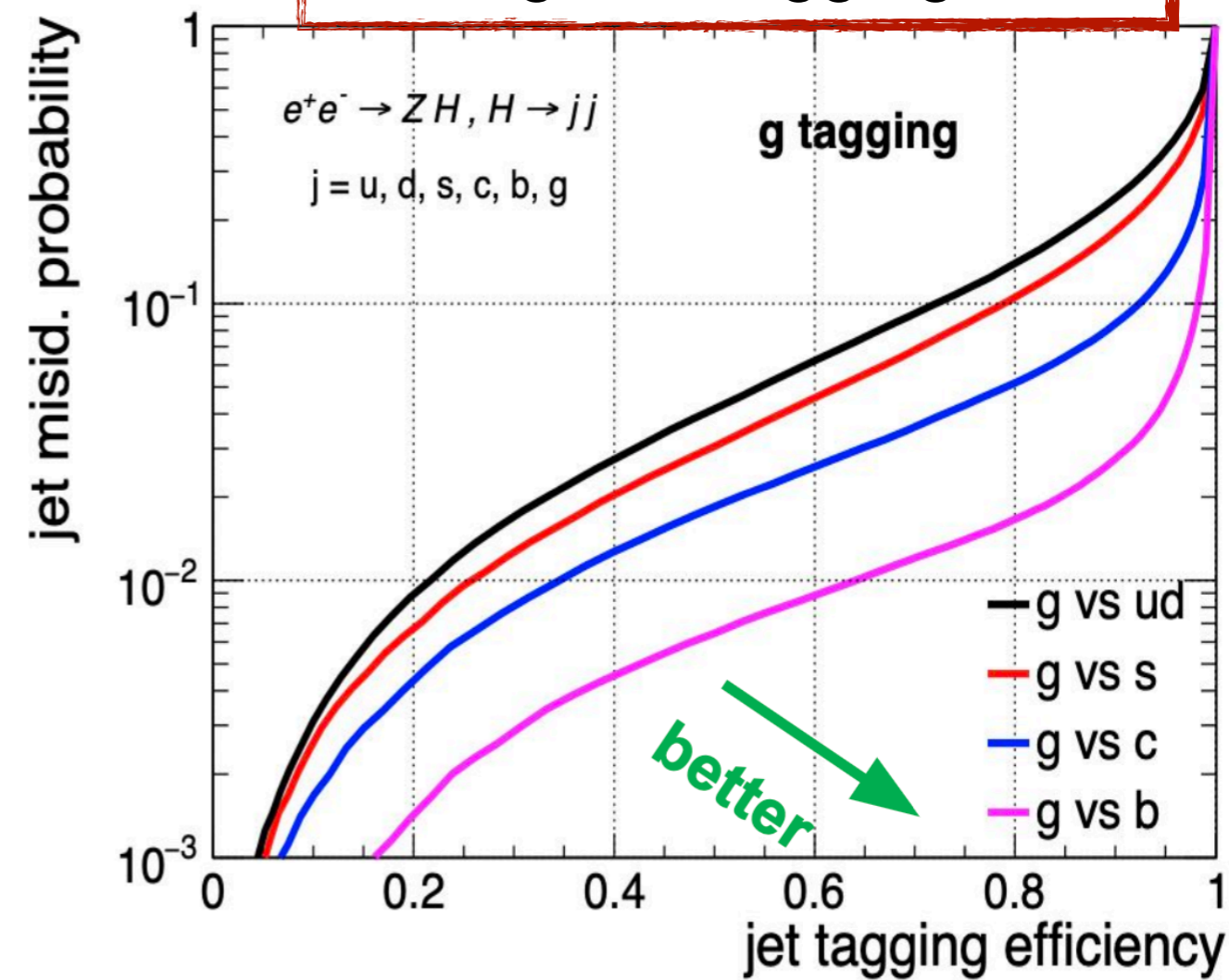
# s/g-tagging Performance

## strange-tagging

FCC-ee Simulation (IDEA)



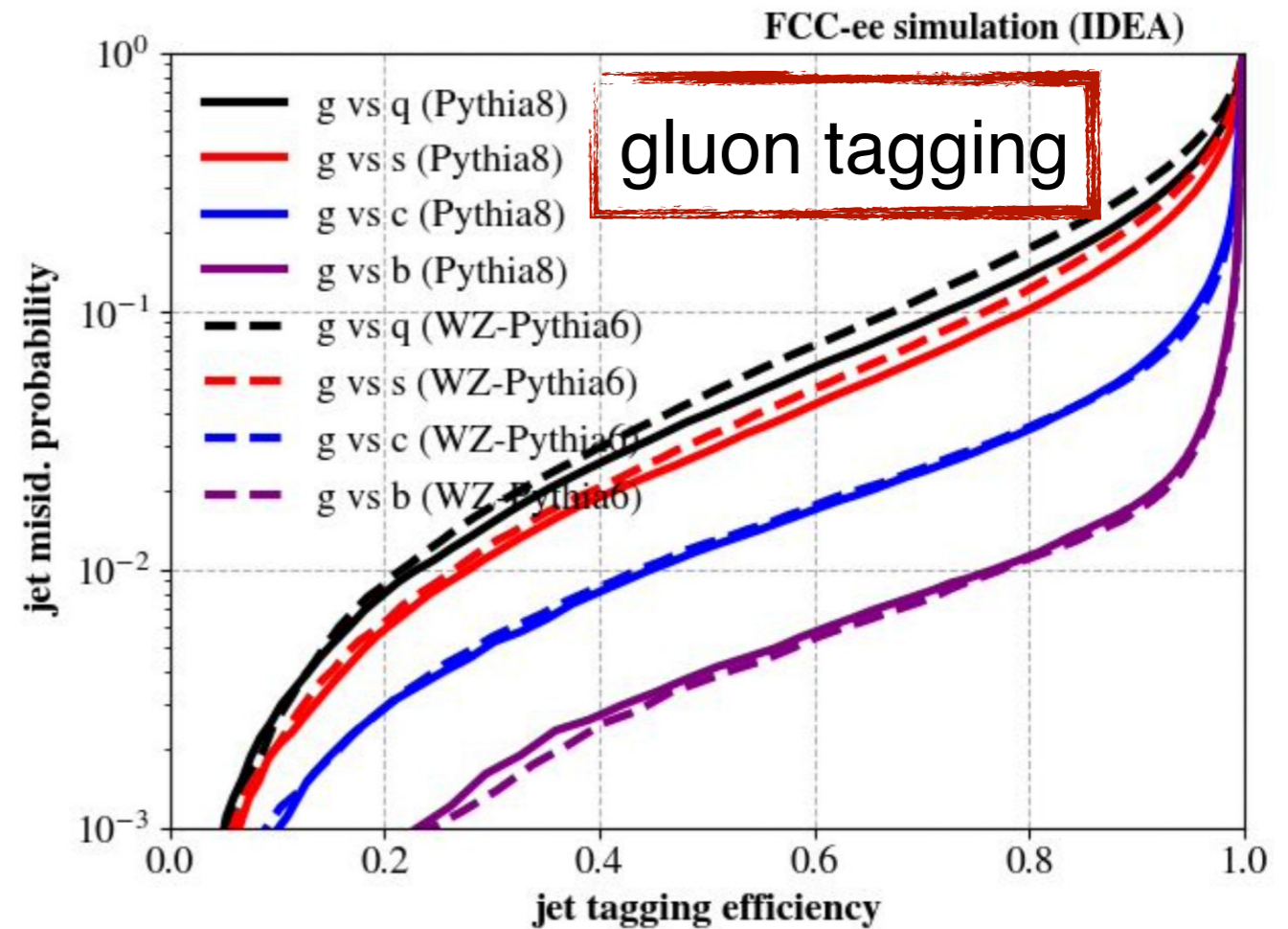
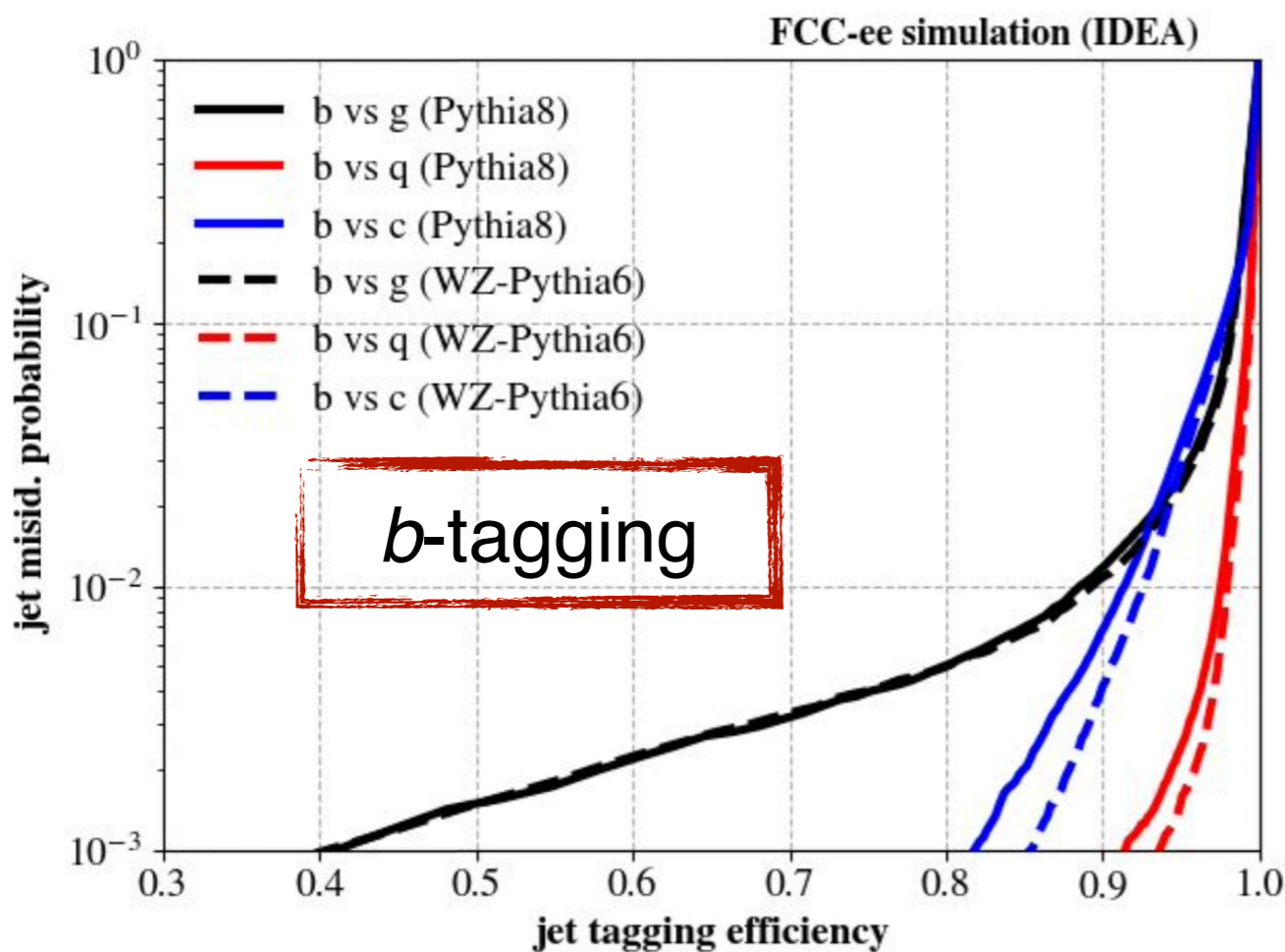
## gluon-tagging



WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

WP	Eff (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	25%	7%	2.5%
Medium	80%	15%	5%	2%

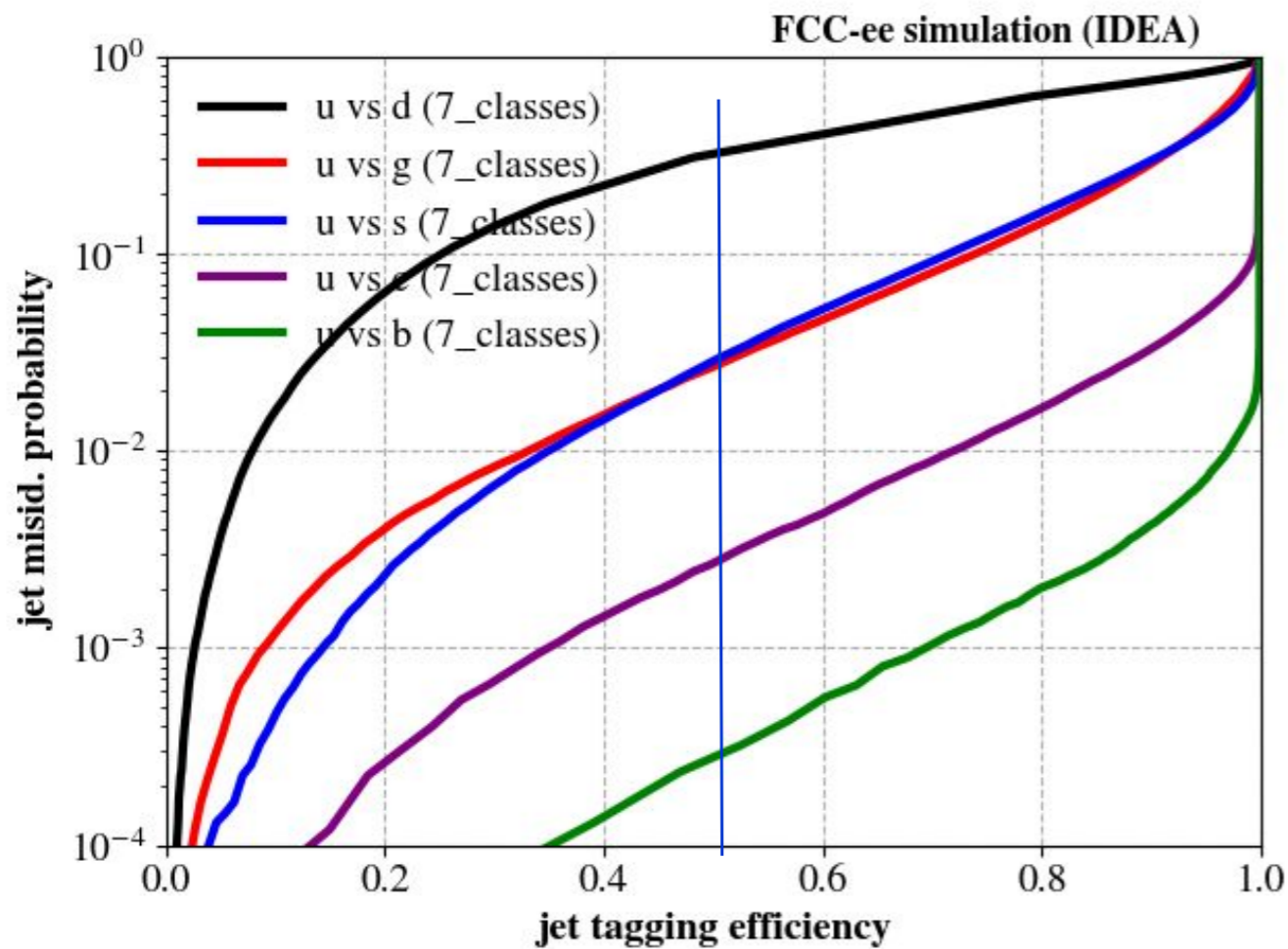
- ParticleNet-ee trained using Pythia 8 samples
  - Tested on Pythia 8 samples (solid lines)
  - Tested on WZ+Pythia 6 samples (dashed lines)



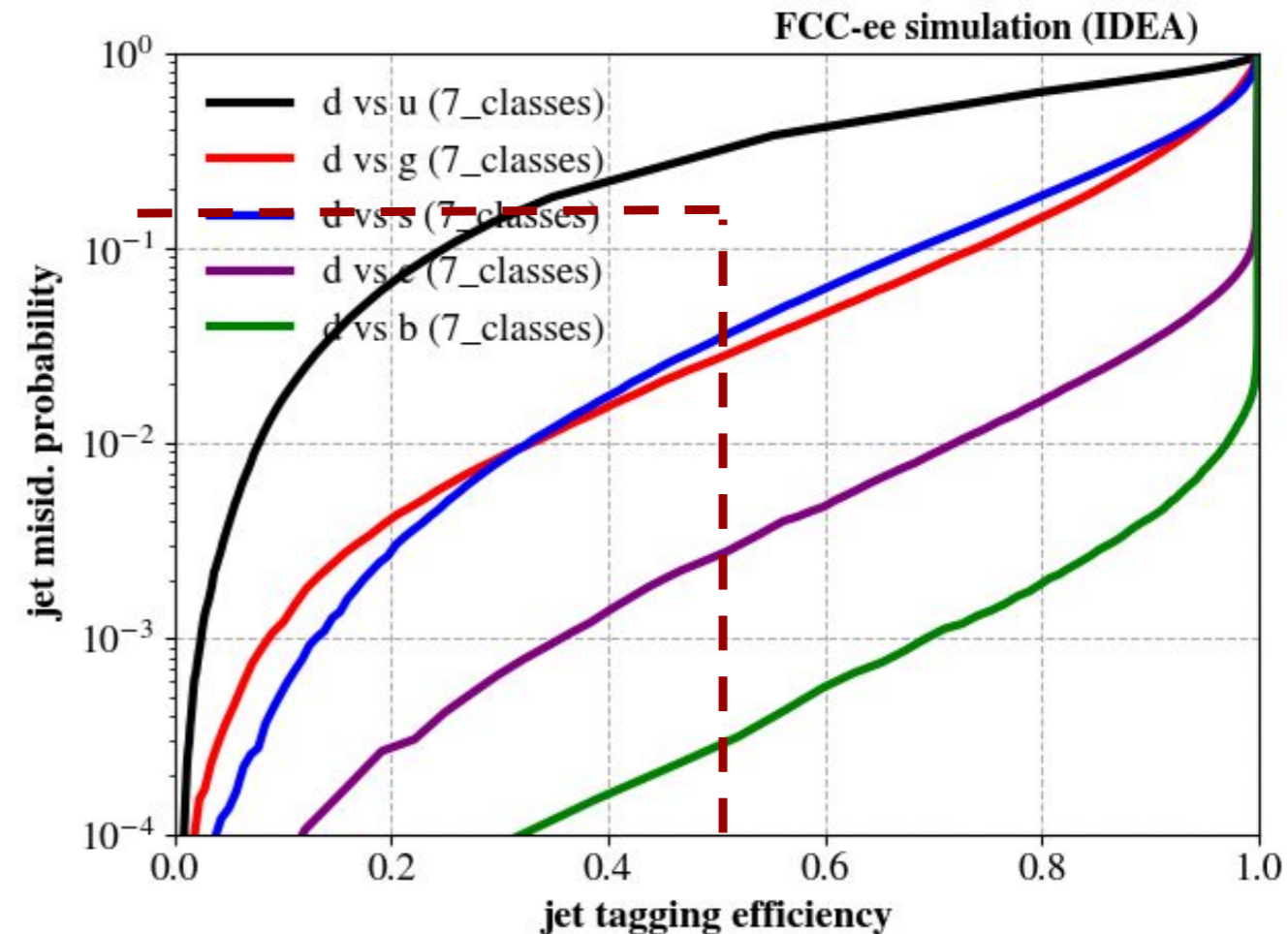
- Modest dependence on choice of generator
- More parton showers being explored (Sherpa, Herwig, etc...)

# The Future: Up & Down Tagging!

Up-tagging



Down tagging



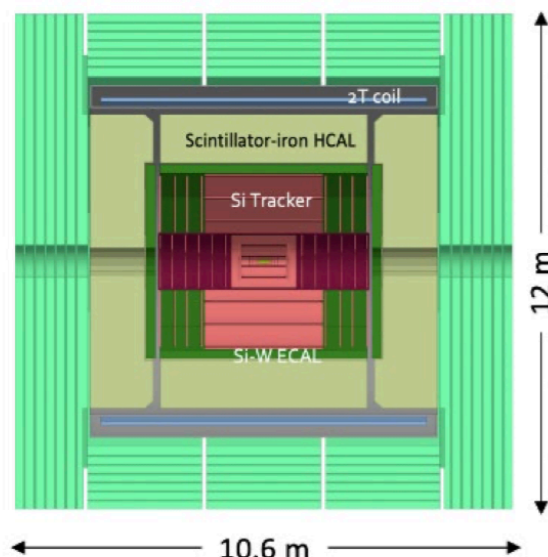
- Up vs. Down discrimination seems ~possible thanks to jet charge
- 50% signal efficiency for 30% bkg efficiency (better than random coin toss)

# Current Detector Concepts

## Current Detector Concepts

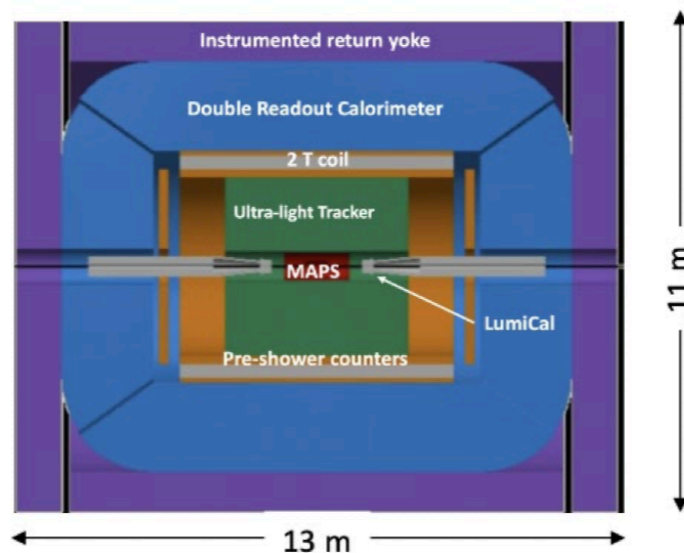
From Marc-André's talk

CLD



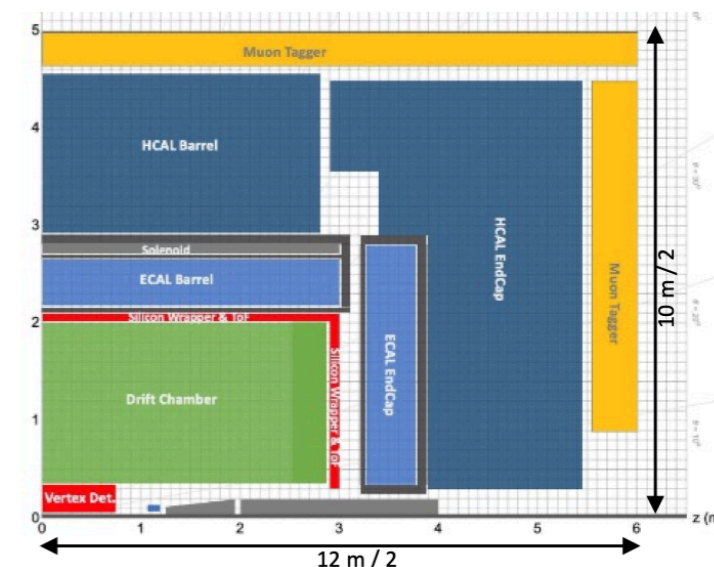
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - $\sigma_p/p, \sigma_E/E$
  - PID ( $\mathcal{O}(10\text{ ps})$  timing and/or RICH)?
  - ...

IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, ...

ALLEGRO

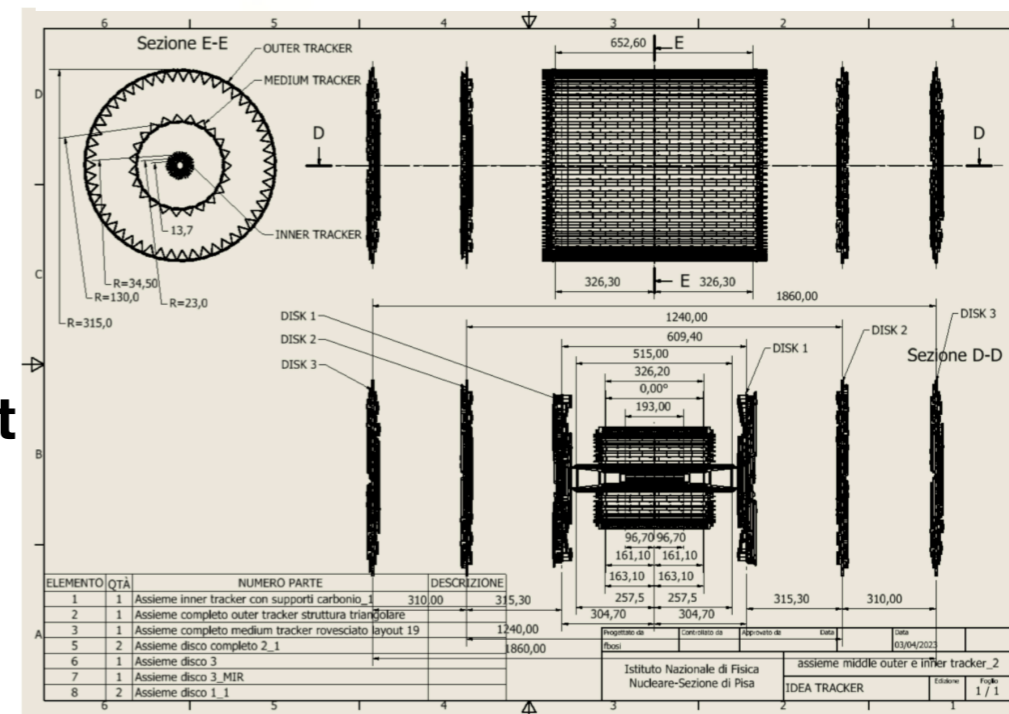


- The "new kid on the block"
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, ...
  - Software & performance studies

FCC-ee CDR: <https://link.springer.com/article/10.1140/epjst/e2019-900045-4>

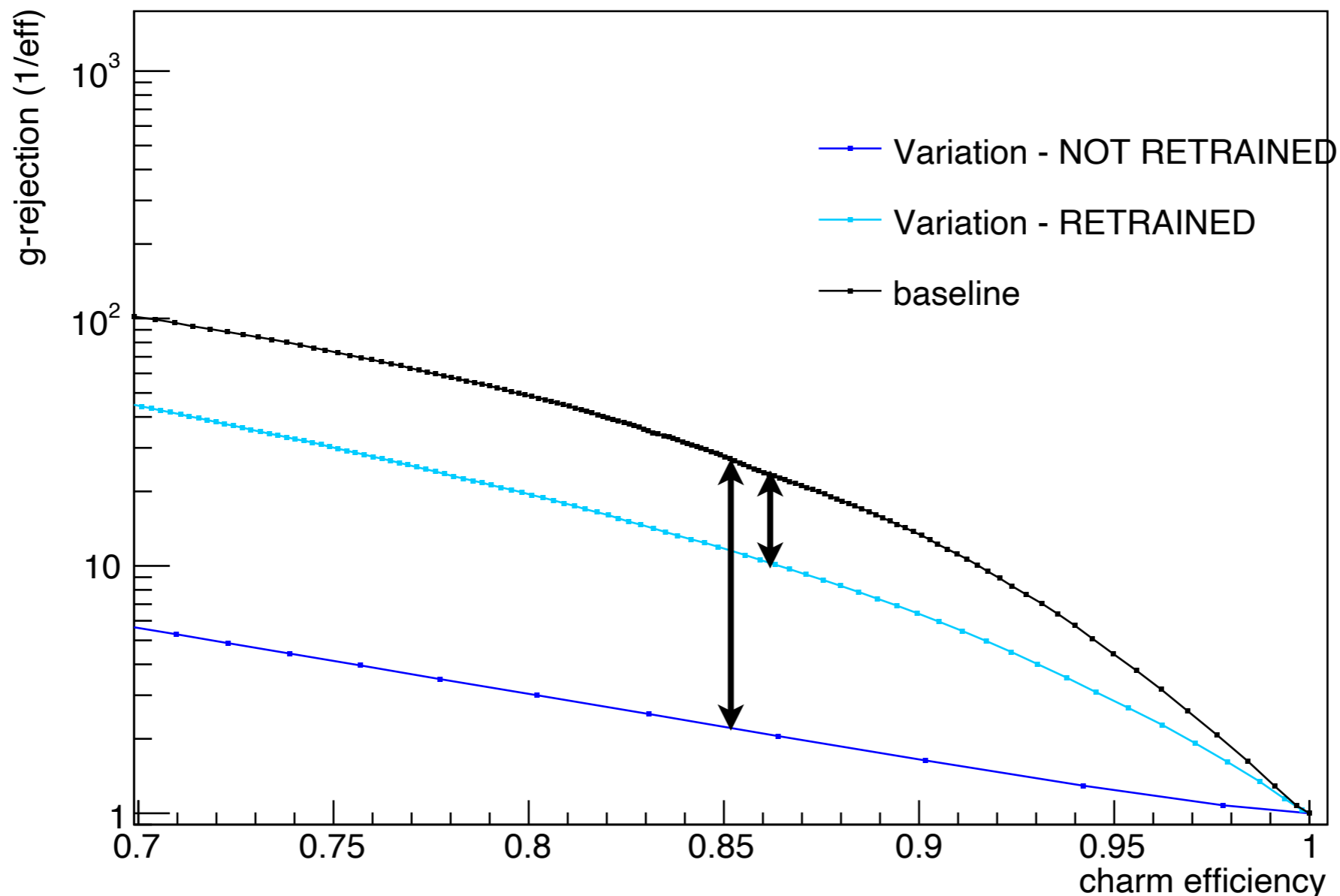
# The (IDEA) Tracker as an Opportunity

- Different possible detector scenarios, *tracker* particularly relevant to flavour-tagging
  - **PID capabilities:** timing, energy loss (gas/silicon)
  - **Amount (e.g. n. of layers) & quality of material**
  - **Hit resolution**
- Baseline IDEA detector as a well-established reference for detector-performance studies
  - Opportunity to access impact of detector configurations/properties on physics performance
  - A lot already studied in the past [[Eur. Phys. J. C 82, 646 \(2022\)](#)]
  - **More & refined studies conducted for Final State Report** [[Phys.Rev.D 112 \(2025\) 5, 052002](#)]
- Current IDEA pixel/tracking system:
  - beam pipe at 1cm, 3 *innermost* VTXD barrel layers: 1.2cm, 2cm, 3.15cm
  - PID:  $dN/dx + 30ps$  ToF system



IDEA tracker layout from F. Palla's [talk](#)

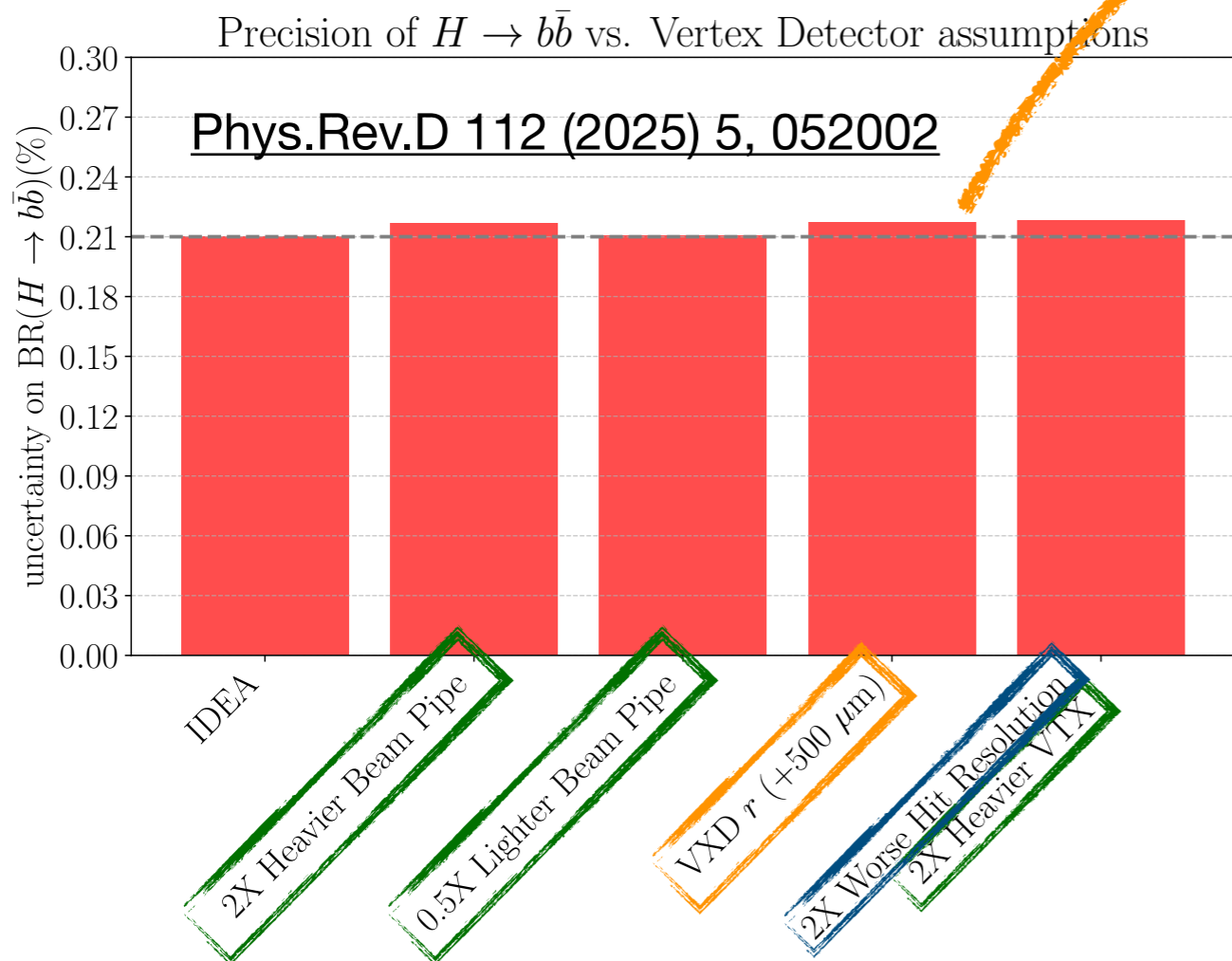
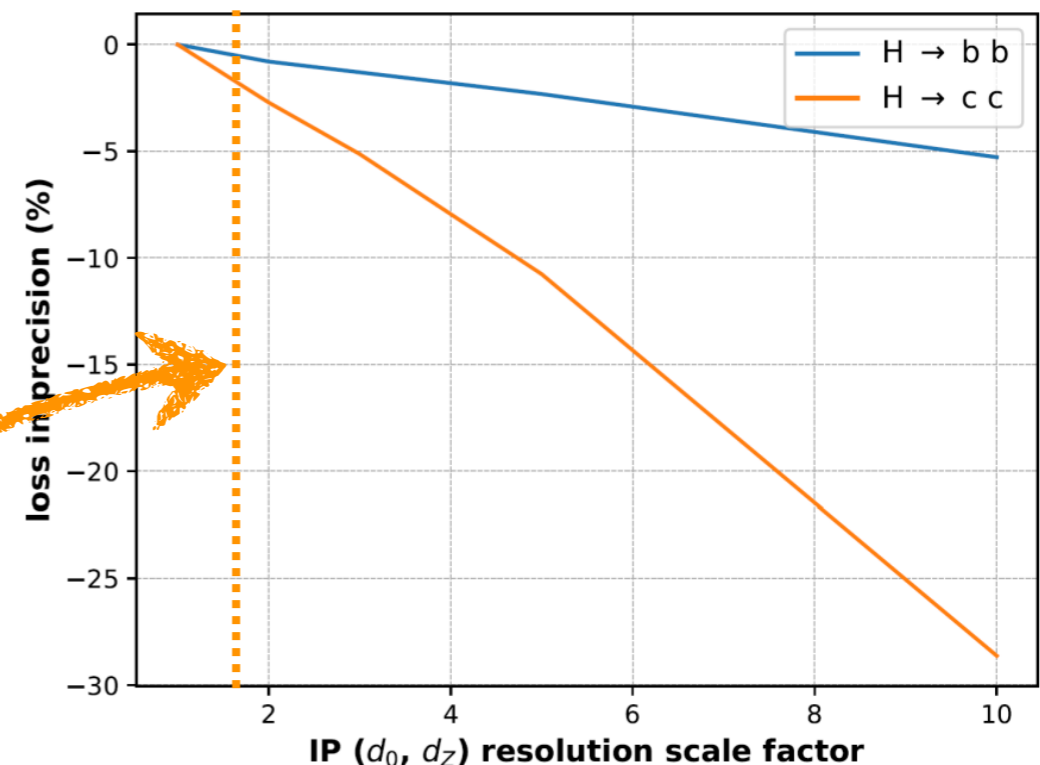
# Why is Retraining Necessary?



- Obviously, given a detector configuration, ParticleNet would be trained against it
- Re-training allows recovering of (a significant) part of drop in performance
  - **Need re-training for fair & meaningful performance assessment of each point in the detector-configuration space**

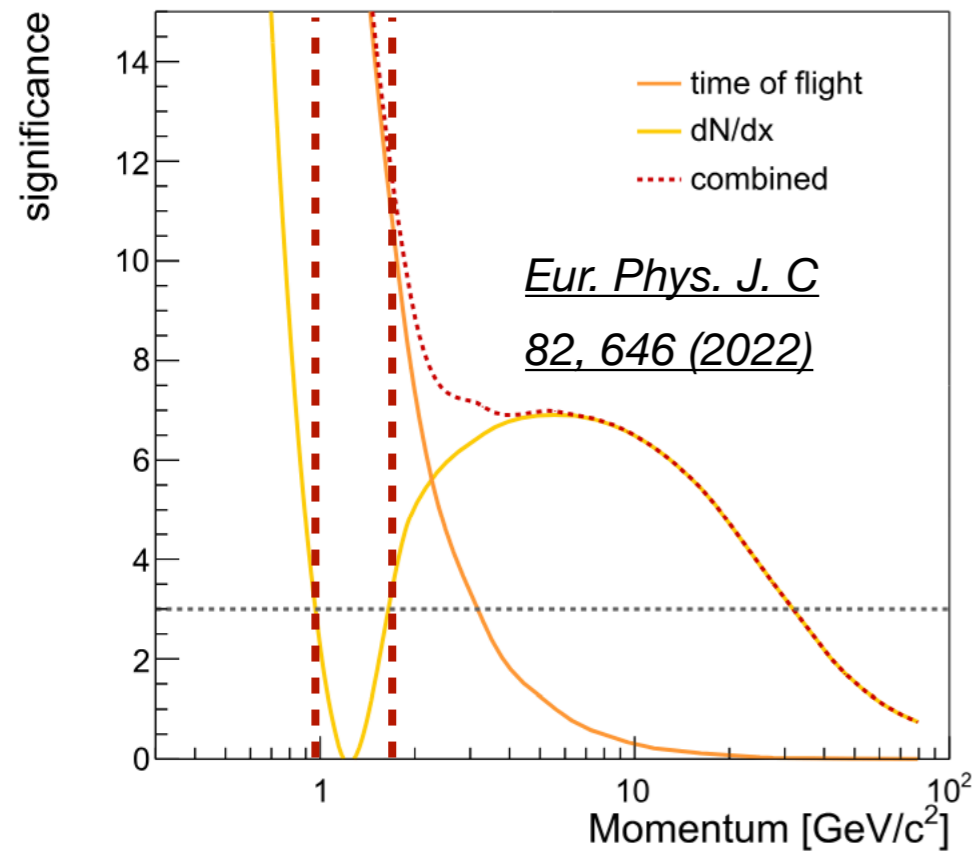
# Impact Parameter Resolution & Vertexing

- The IP resolution is the major driver of charm and bottom jet identification
  - B (D) mesons travel a finite decay length of 500 (150)  $\mu\text{m}$
- Worse impact on  $H \rightarrow cc$  vs  $H \rightarrow bb$  due to smaller displacement and smaller S/B



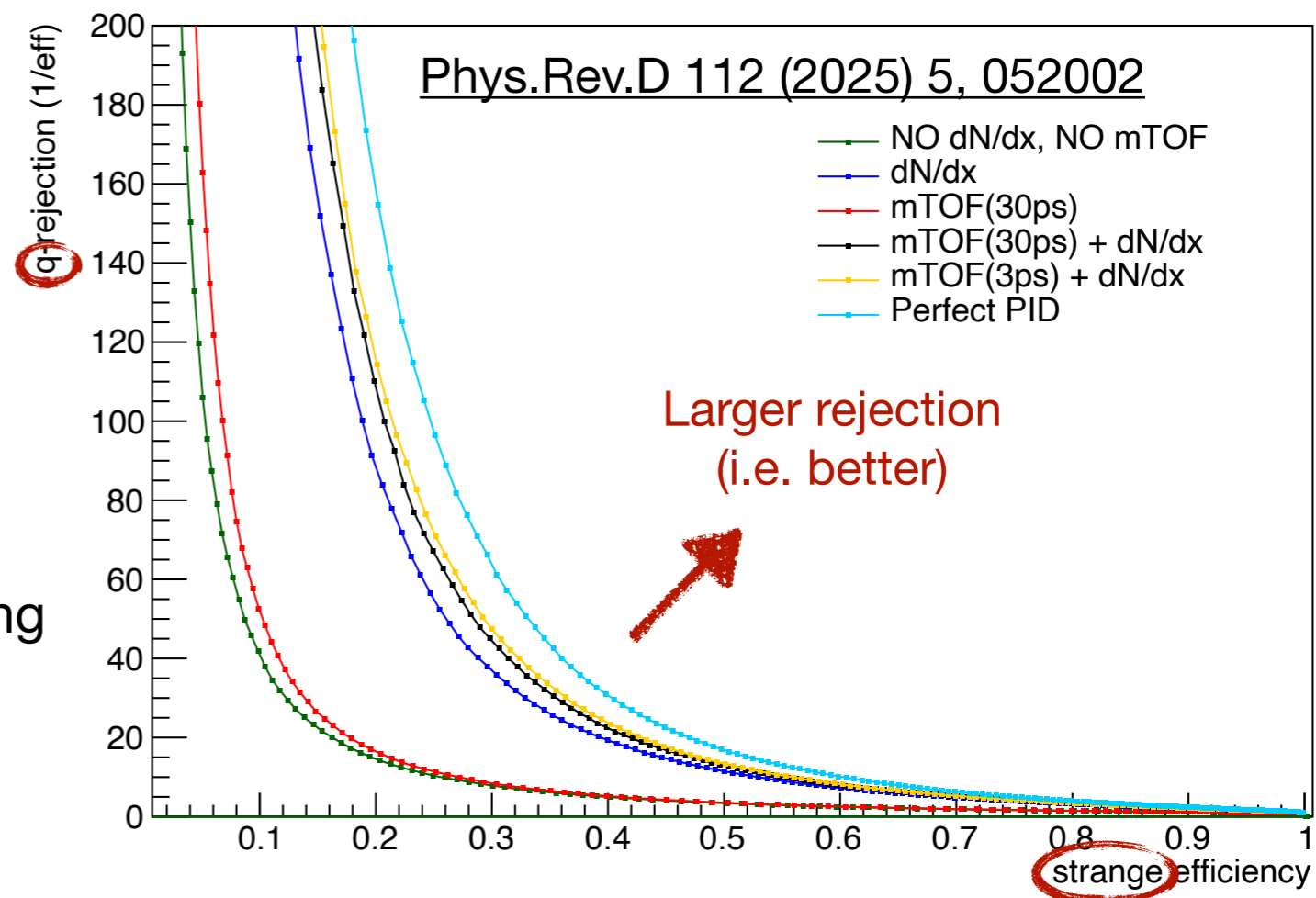
- Precise IP determination driven by:
  - Single point resolution**
  - Radial distance of first tracking layer** (high  $p$ )
  - Material budget** (low  $p$ ) - eventually limited by beam-pipe material
- Studied these effects through full propagation:
  - Simulated each detector response through Delphes
  - Re-trained jet-flavour tagger
  - Evaluated Higgs couplings performance
- Small effects observed in  $H \rightarrow bb$  (and  $H \rightarrow cc$ )

# Charged Hadron Particle Identification



- Particle Identification (PID) is a crucial ingredient for strange-quark jet identification ( $H \rightarrow ss$ )
- Need:
  - Cluster counting ( $dN/dx$ ) measurement at high momentum - Cherenkov detectors (RICH)
  - Time of Flight (ToF) measurement at low momentum ( $\sim 1 \text{ GeV}$ )

- Tagger retraining shows that:
  - IDEA detector concept PID performance close to “perfect” (i.e. truth) PID
  - Impact of  $dN/dx \gg \text{ToF}$  on strange tagging



# H → bb/cc/ss/gg Analysis Strategy in a Nutshell

- Signal signature:  $H \rightarrow jj$ ,  $j=b,c,s,g,\tau$
- Main background processes:  $WW/ZZ/Z$ ,  $qqH$ ,  $H \rightarrow WW$ ,  $H \rightarrow ZZ$
- Key ingredients:
  - Leptons, missing E & jets
  - Jet reconstruction: N=2 Durham kT exclusive algorithm
  - ParticleNet jet tagger with 4 categories:  $b,c,s,g$
- Analysis:
  - Event pre-selection: lepton veto,  $\cos(\vartheta)$
  - Categorisation based on tagger scores
  - Fit with floating 10% background normalisation uncertainty (to be constrained) & 4 signal strengths (i.e.  $H \rightarrow bb, cc, ss, gg$ )

$\sqrt{s}$	240 GeV		365 GeV	
channel	ZH	WW → H	ZH	WW → H
ZH → any	±0.31		±0.52	
$\gamma H \rightarrow$ any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	±5.6 (*)
H → $\mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 (*)	±2.1 (*)
H → ZZ*	±2.5		±8.3 (*)	±4.6 (*)
H → $\gamma\gamma$	±3.6		±13	±15
H → Z $\gamma$	±11.8		±22	±23
H → $\nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

Phys.Rev.D 112 (2025) 5, 052002

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# Potential

# Hierarchy of HH Channels @HL-LHC

	2 ab <sup>-1</sup> (S2)		3 ab <sup>-1</sup> (S2)		3 ab <sup>-1</sup> (S3)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
<i>HH</i> statistical significance						
<i>b<math>\bar{b}</math><math>\tau^+\tau^-</math></i>	3.0 <sup>†</sup>	1.9	3.5 <sup>†</sup>	2.4	<b>3.8<sup>†</sup></b>	<b>2.7</b>
<i>b<math>\bar{b}</math><math>\gamma\gamma</math></i>	2.1 <sup>†</sup>	2.0 <sup>†</sup>	2.4 <sup>†</sup>	2.4 <sup>†</sup>	<b>2.6<sup>†</sup></b>	<b>2.6<sup>†</sup></b>
<i>b<math>\bar{b}b\bar{b}</math> resolved</i>	0.9	1.0 <sup>†</sup>	1.0	1.2 <sup>†</sup>	<b>1.0</b>	<b>1.3<sup>†</sup></b>
<i>b<math>\bar{b}b\bar{b}</math> boosted</i>	–	1.8 <sup>†</sup>	–	2.2 <sup>†</sup>	–	<b>2.2<sup>†</sup></b>
Multilepton	0.8 <sup>†</sup>	–	1.0 <sup>†</sup>	–	<b>1.0<sup>†</sup></b>	–
<i>b<math>\bar{b}l^+l^-</math></i>	0.4 <sup>†</sup>	–	0.5 <sup>†</sup>	–	<b>0.5<sup>†</sup></b>	–
Combination	3.7	3.5	4.3	4.2	<b>4.5</b>	<b>4.5</b>
ATLAS+CMS	6.0		7.2		7.6	
$\kappa_3$ 68% confidence interval						
<i>b<math>\bar{b}\tau^+\tau^-</math></i>	[0.3, 1.8] <sup>†</sup>	[0.1, 3.0]	[0.4, 1.7] <sup>†</sup>	[0.2, 2.2]	<b>[0.5, 1.6]<sup>†</sup></b>	<b>[0.3, 2.0]</b>
<i>b<math>\bar{b}\gamma\gamma</math></i>	[0.3, 2.0] <sup>†</sup>	[0.2, 2.3] <sup>†</sup>	[0.4, 1.8] <sup>†</sup>	[0.3, 2.0] <sup>†</sup>	<b>[0.5, 1.7]<sup>†</sup></b>	<b>[0.4, 1.9]<sup>†</sup></b>
<i>b<math>\bar{b}b\bar{b}</math> resolved</i>	[-0.7, 6.3]	[-0.6, 7.6] <sup>†</sup>	[-0.5, 6.1]	[-0.3, 7.3] <sup>†</sup>	<b>[-0.5, 6.1]</b>	<b>[-0.3, 7.2]<sup>†</sup></b>
<i>b<math>\bar{b}b\bar{b}</math> boosted</i>	–	[-0.6, 8.5] <sup>†</sup>	–	[-0.4, 8.2] <sup>†</sup>	–	<b>[-0.4, 8.2]<sup>†</sup></b>
Multilepton	[-0.2, 4.9] <sup>†</sup>	–	[-0.1, 4.7] <sup>†</sup>	–	<b>[-0.1, 4.7]<sup>†</sup></b>	–
<i>b<math>\bar{b}l^+l^-</math></i>	[-2.4, 9.3] <sup>†</sup>	–	[-2.2, 9.2] <sup>†</sup>	–	<b>[-2.1, 9.1]<sup>†</sup></b>	–
Combination	[0.6, 1.5]	[0.4, 1.7]	[0.6, 1.5]	[0.5, 1.6]	<b>[0.6, 1.4]</b>	<b>[0.6, 1.5]</b>
ATLAS+CMS uncertainty	–32% / +37%		–27% / +31%		<b>–26% / +29%</b>	

<sup>†</sup> used in the ATLAS+CMS combination