

Boosted Higgs Boson: A Gateway to New Physics

IHEP Seminar

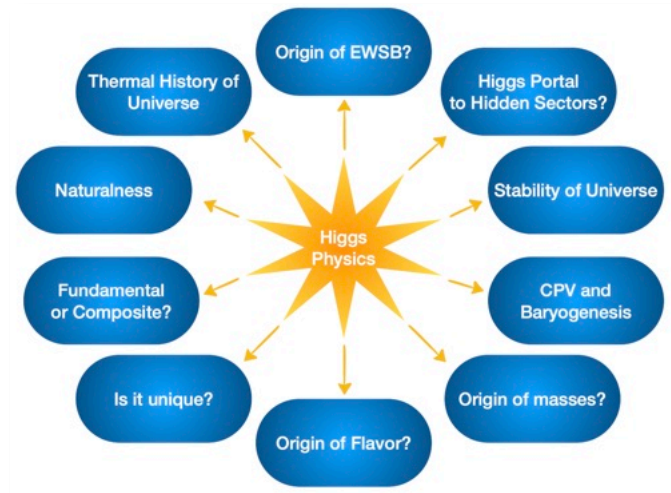
Zhi ZHENG

04/20/2025



Outline

Introduction



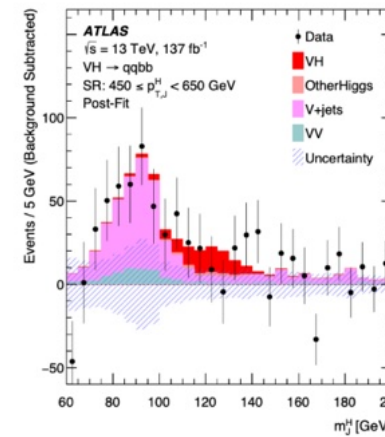
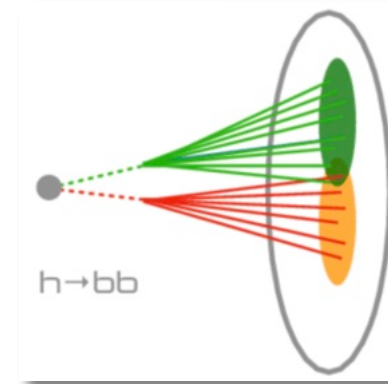
[Snowmass 2021](#)

The LHC and ATLAS Detector



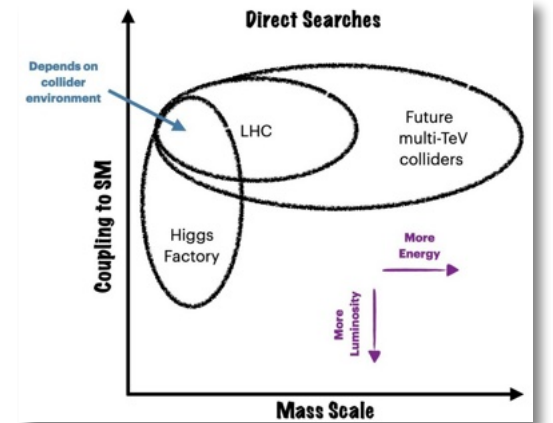
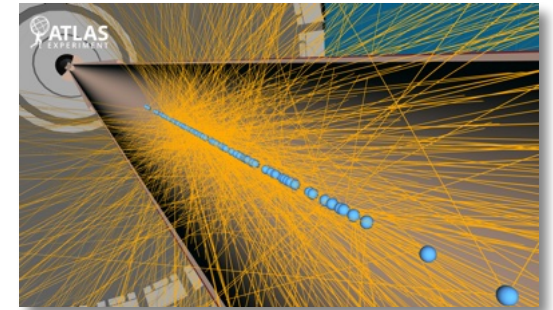
Credit to T. Anderson

Boosted Higgs Boson



[Phys. Rev. Lett. 132 \(2024\) 131802](#)

Future

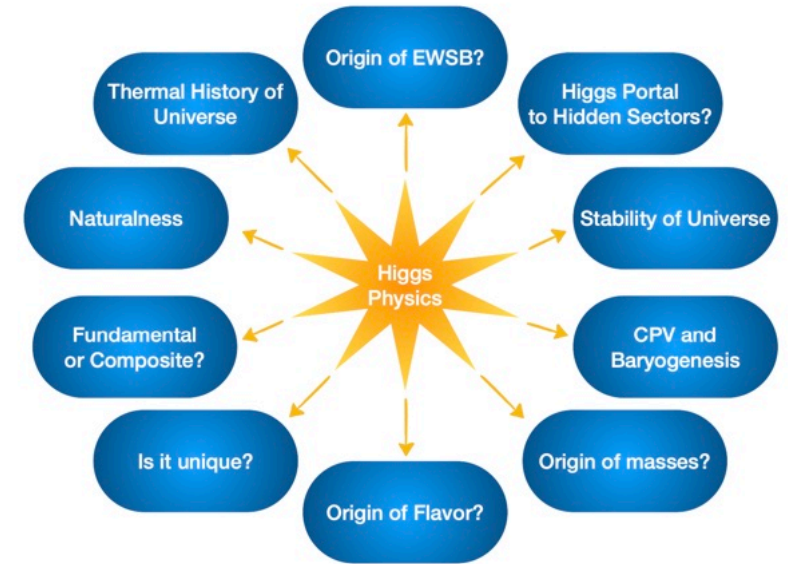
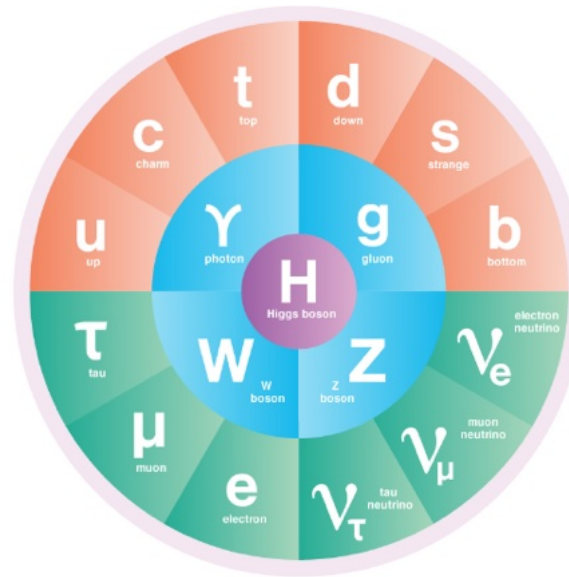
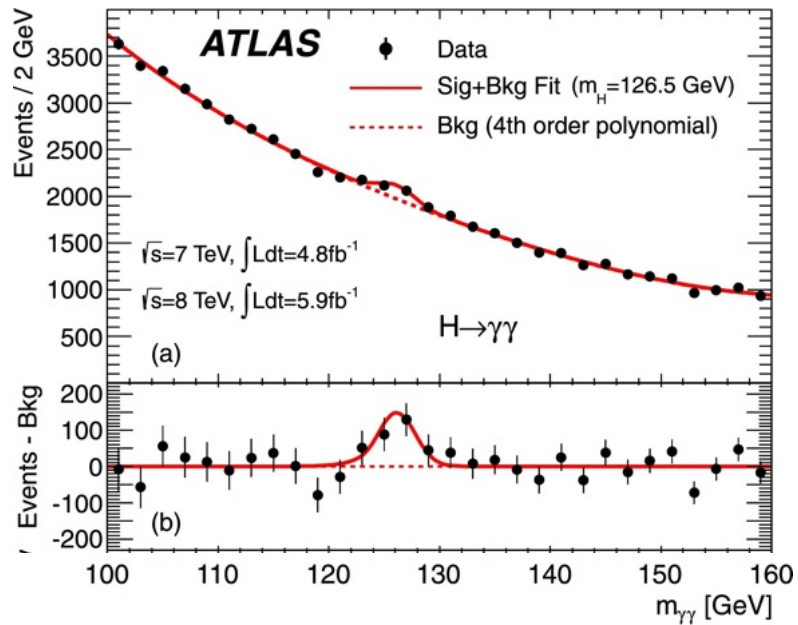


[Snowmass 2021](#)

Higgs as a probe for new physics

2012 July 4th: Discovery of “the/a” Higgs boson

[Phys.Lett. B716 \(2012\) 1-29](#)



Decoding New Physics (NP) from the Higgs Boson

ANY deviation from predictions implies a revolution in our understanding of the universe

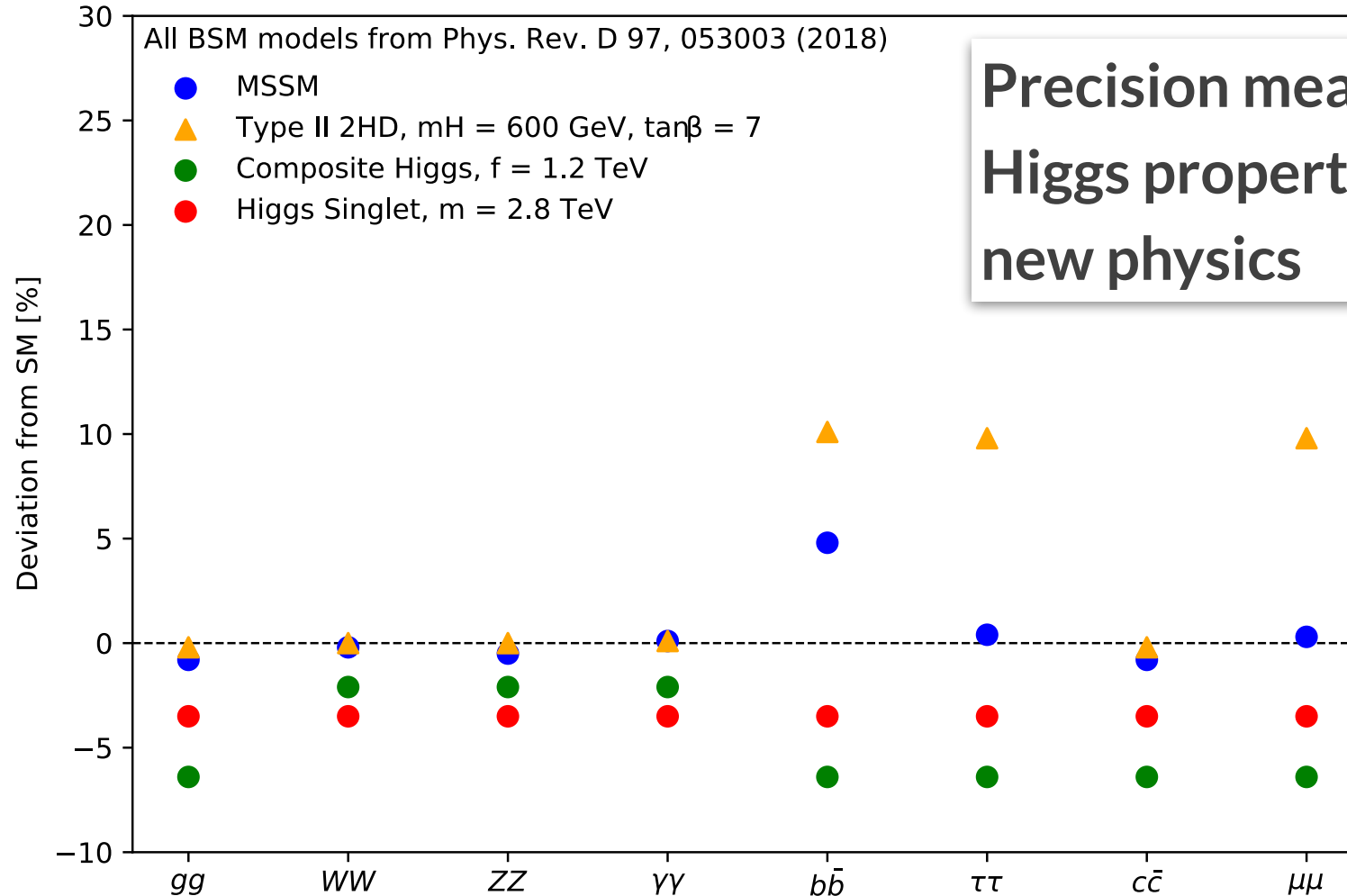
The Standard Model is an Intricate Structure

Patrick Meade



Decoding New Physics (NP) from the Higgs Boson

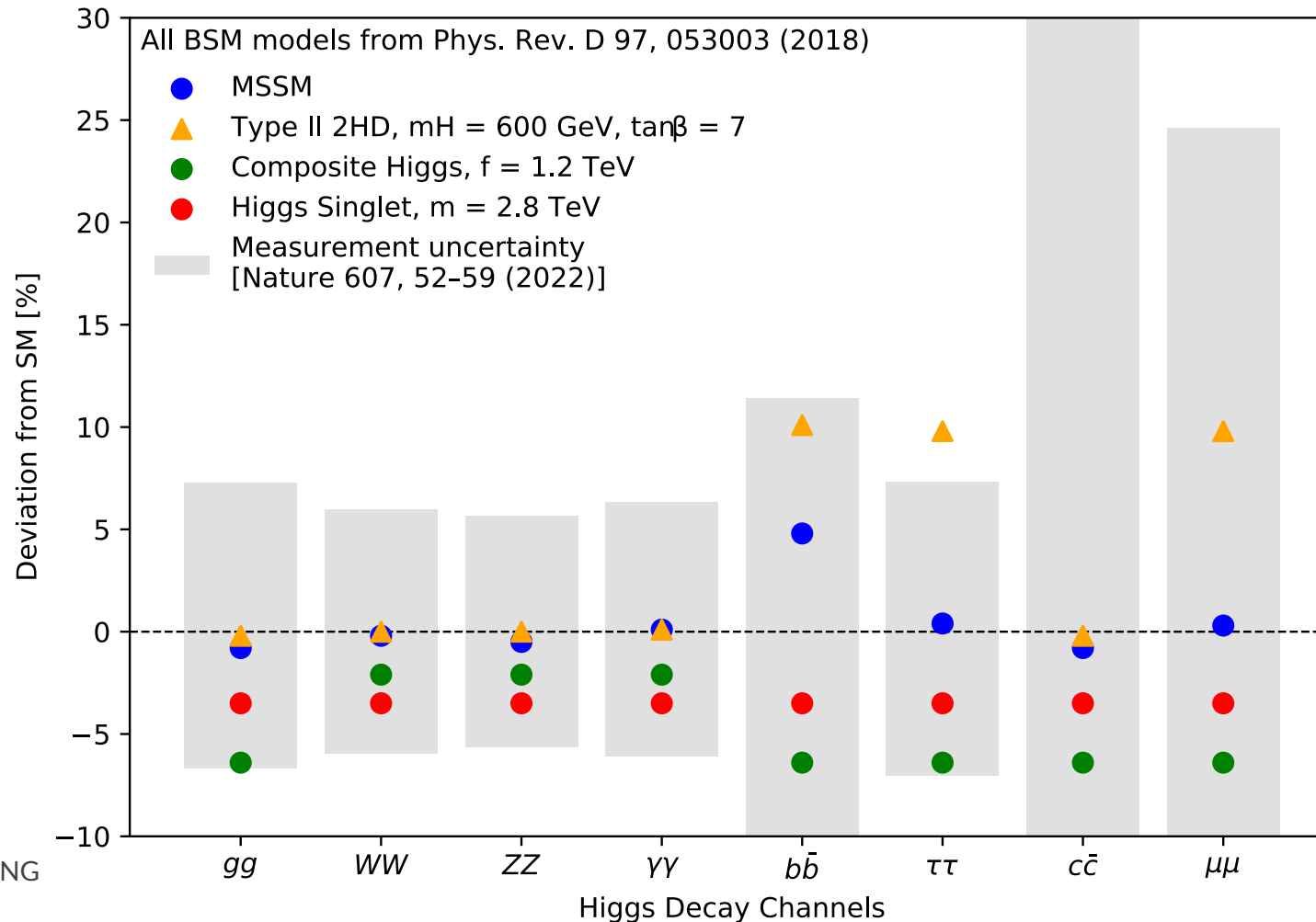
Beyond standard model physics (BSM) can modify Higgs properties



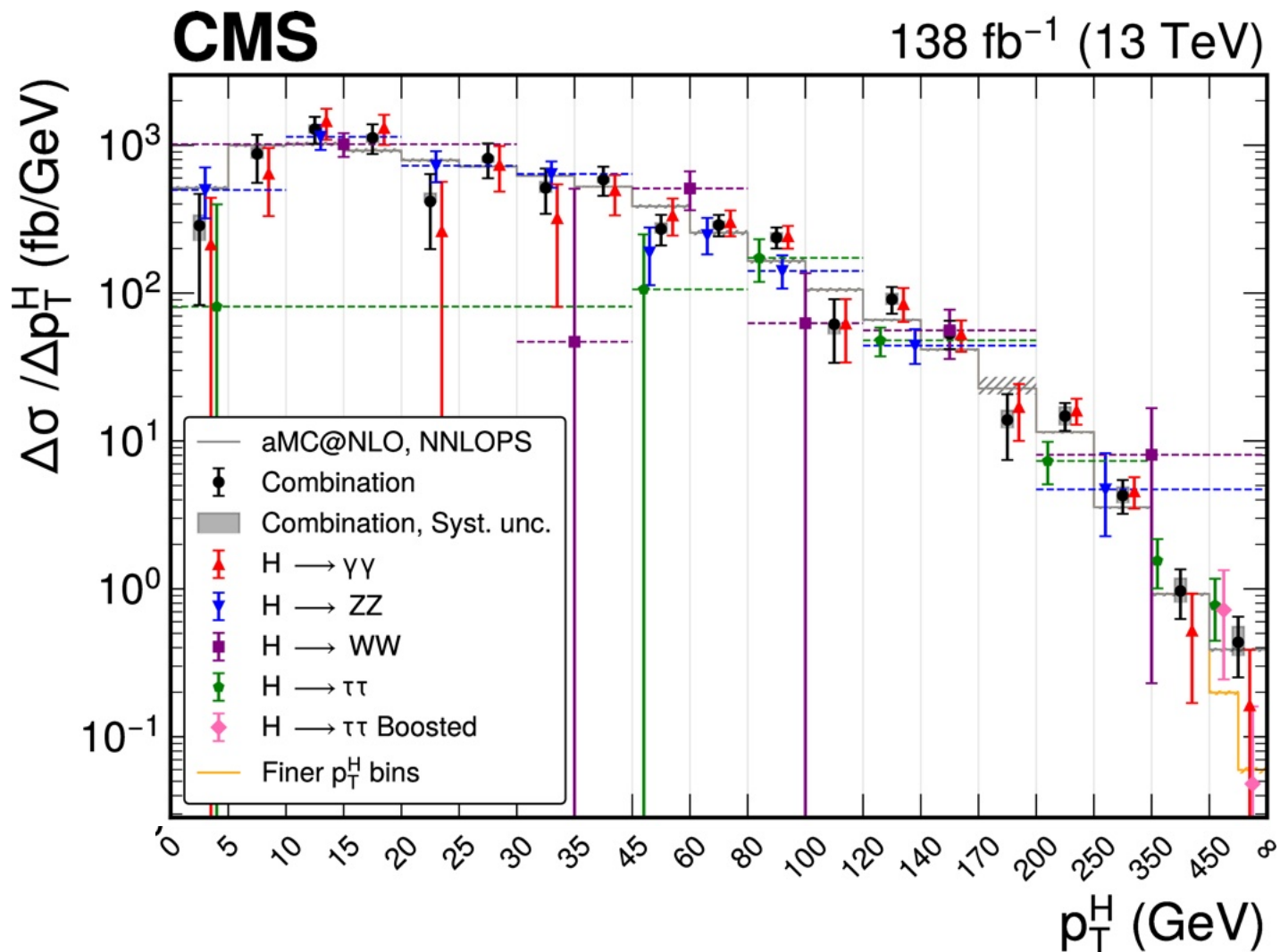
Precision measurements of Higgs properties may reveal new physics

Why inclusive Higgs measurements are not enough

Coupling measurement far from achieving the precision required to detect potential deviations from the SM



Differential Higgs measurements as next precision frontier

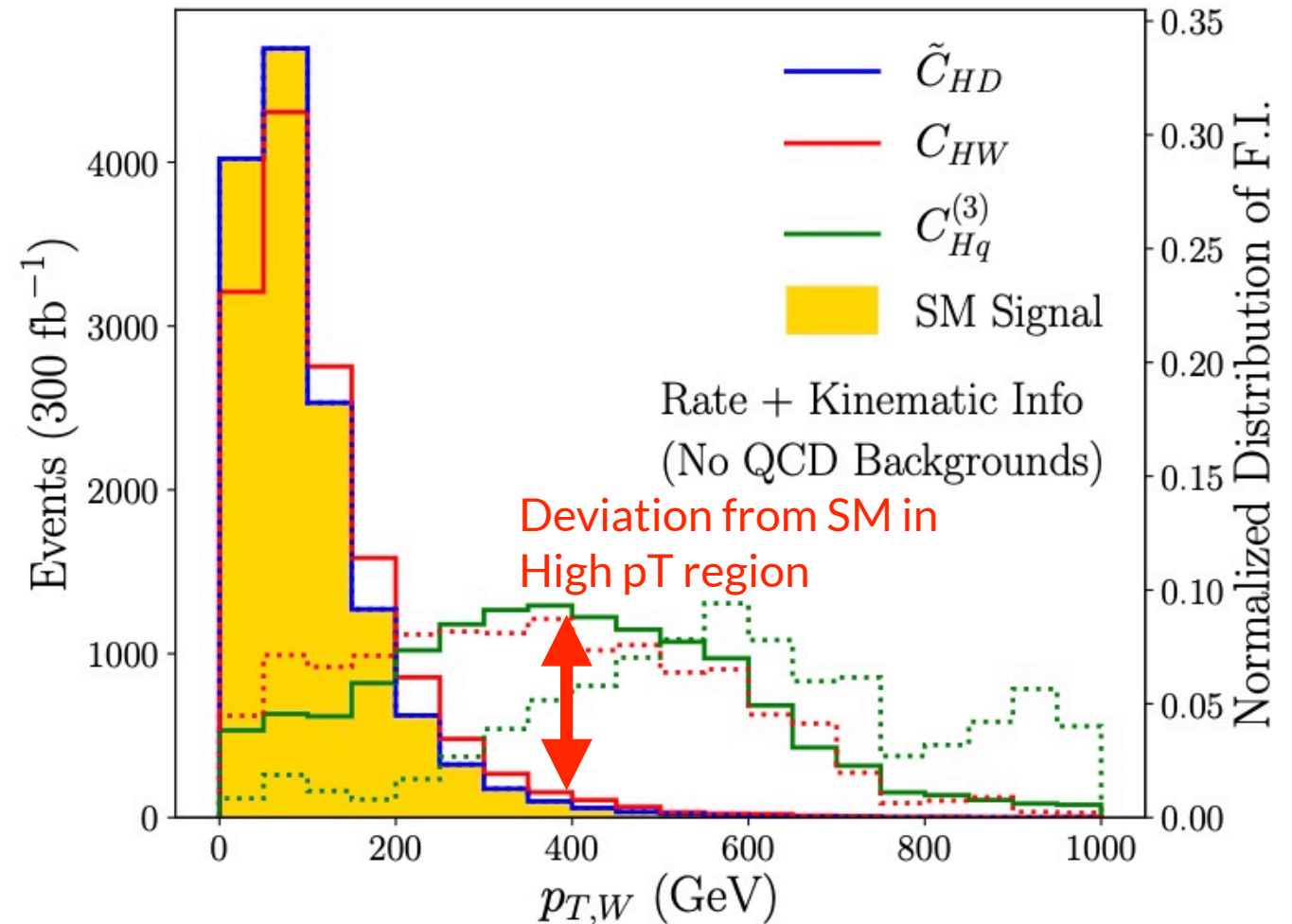
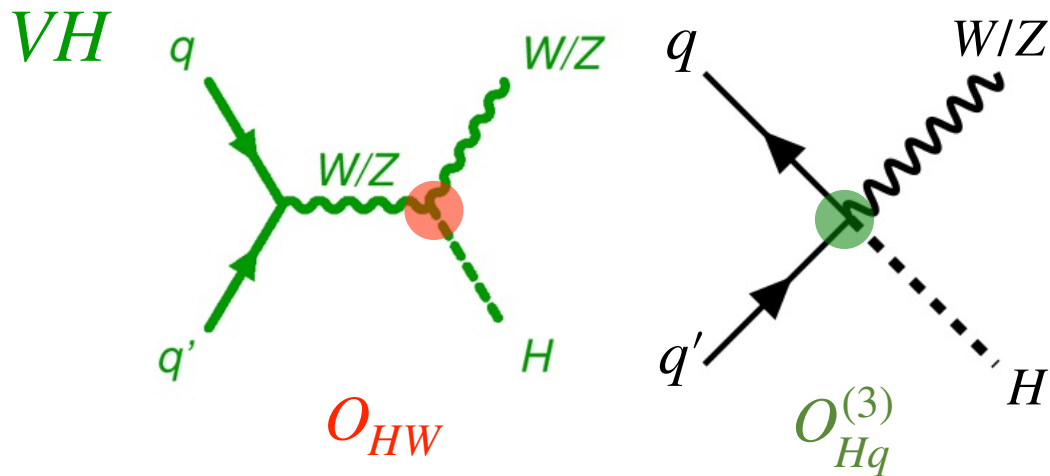


p_T spectrum is one of key tools to test SM and constrain new physics

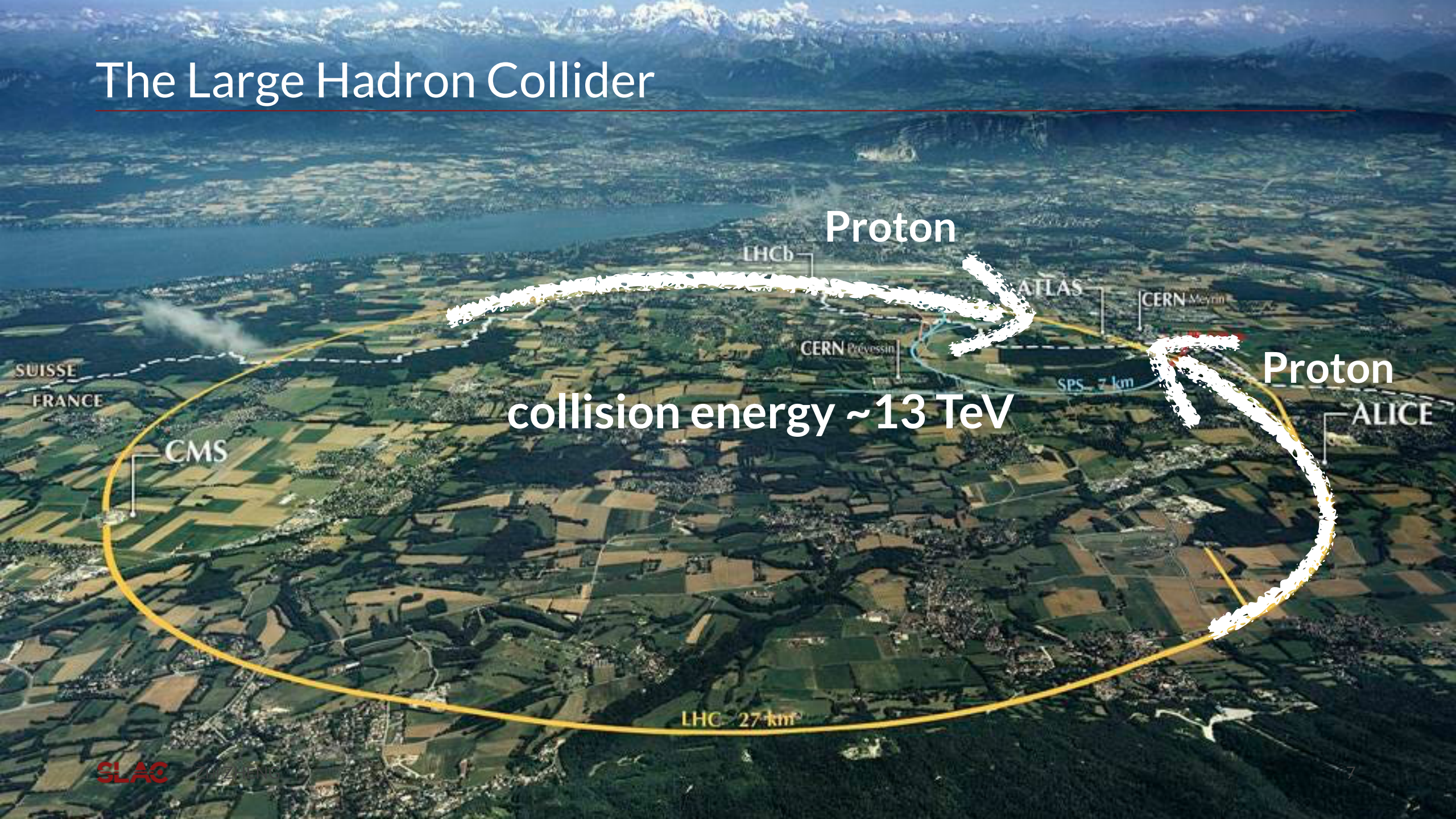
Decoding New Physics (NP) from the Higgs Boson

The Power of Boosted Higgs

JHEP 1911 (2019) 034



The Large Hadron Collider



Proton

Proton

collision energy ~13 TeV

LHCb

ATLAS

CERN Meyrin

CERN Provençin

SPS 7 km

ALICE

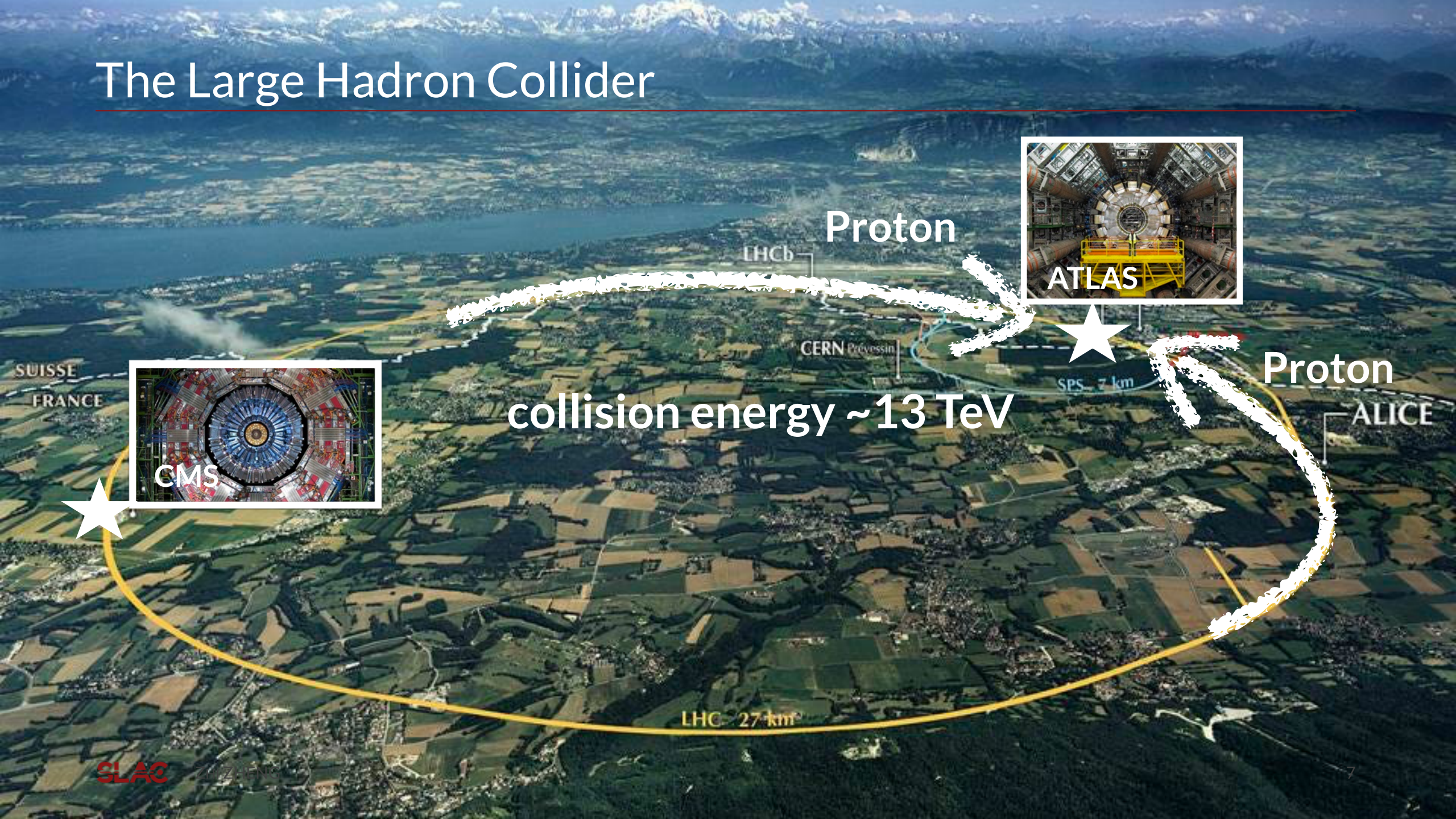
CMS

LHC 27 km

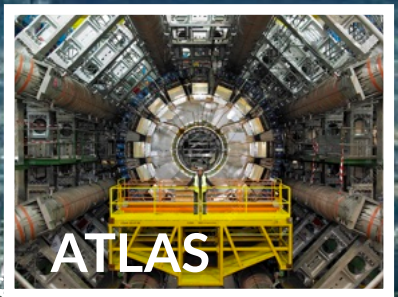
SUISSE
FRANCE

SLAC

The Large Hadron Collider



Proton



ATLAS



Proton

ALICE

collision energy ~13 TeV

LHC 27 km

SPS 7 km

CERN Provisin

LHCb

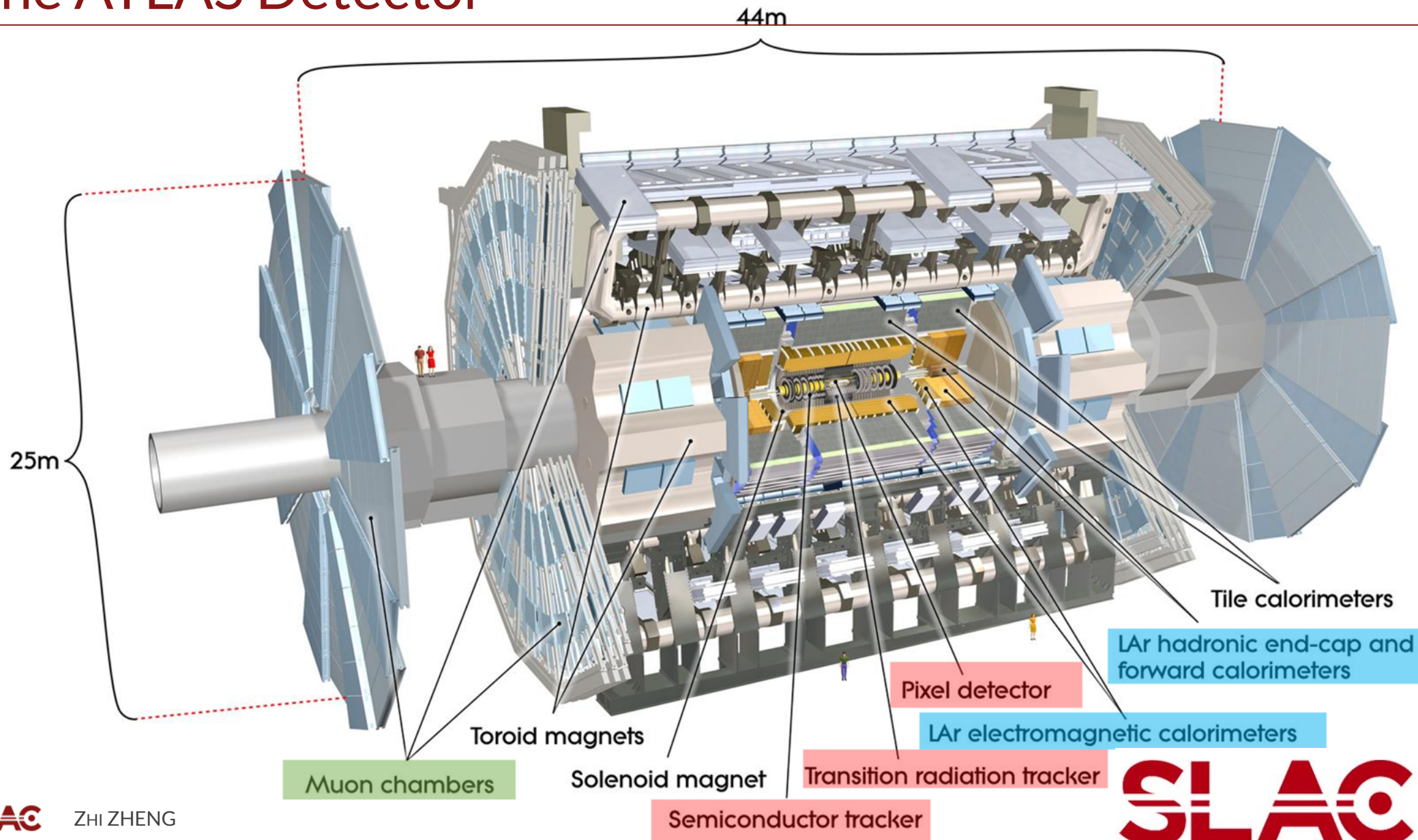


CMS

SUISSE
FRANCE

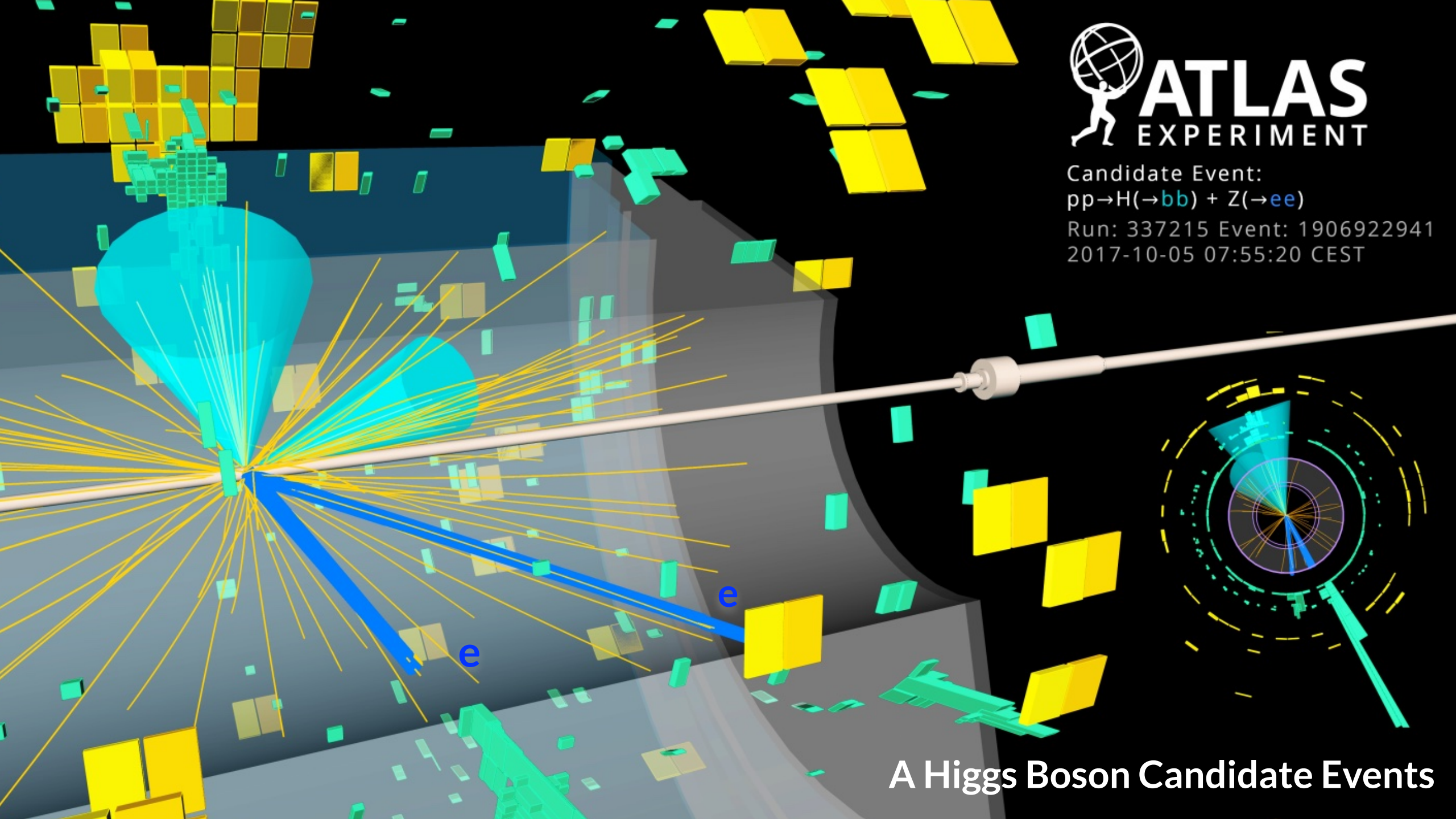
SLAC

The ATLAS Detector



Candidate Event:
 $pp \rightarrow H(\rightarrow bb) + Z(\rightarrow ee)$

Run: 337215 Event: 1906922941
2017-10-05 07:55:20 CEST

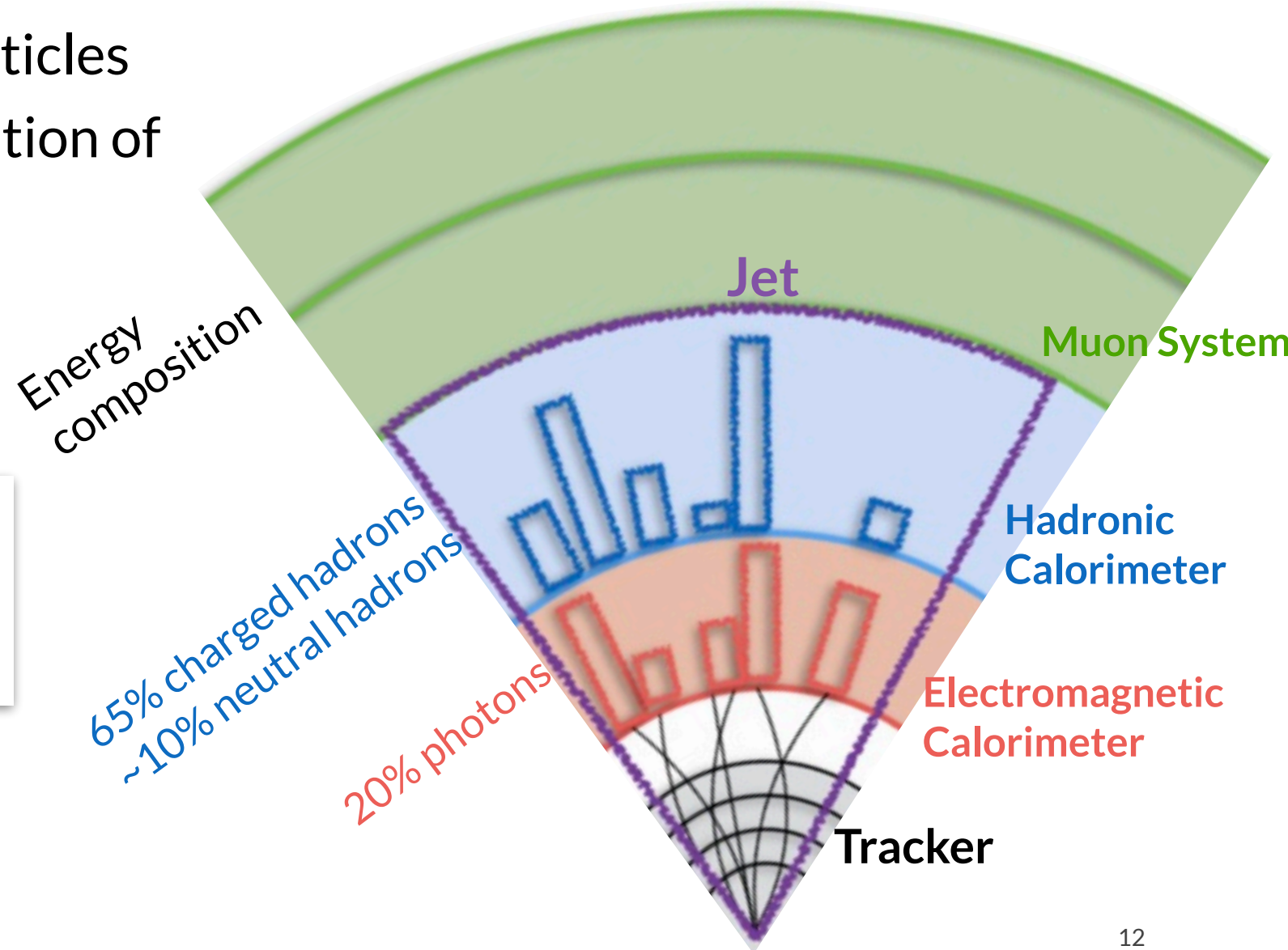


A Higgs Boson Candidate Events

Jet

Jet is seen as a spray of particles produced by the hadronization of quarks and gluons

*Determining which elementary particle initiated a jet is a critical task

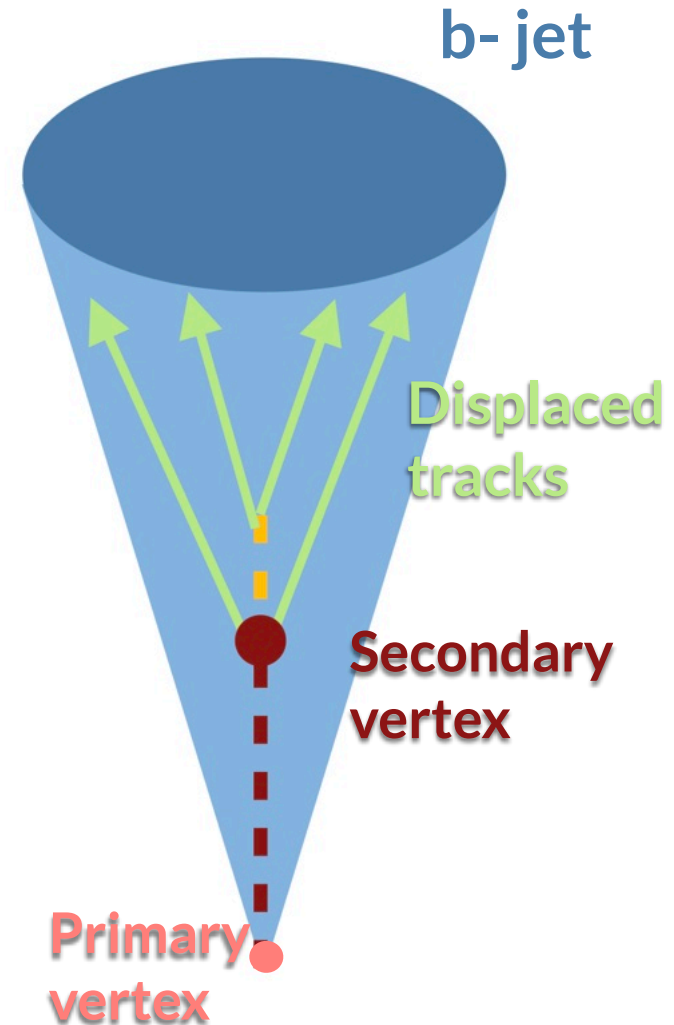


Jet

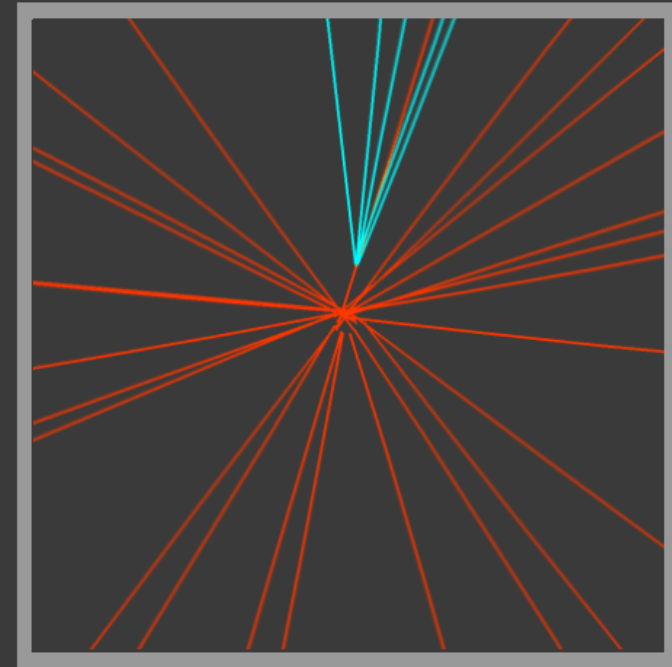
Jet is seen as a spray of particles produced by the hadronization of quarks and gluons

Bottom (b)-jets : jets originate from b-quark

- “Long” lifetime: $\tau \sim 1.5$ ps
- Many displaced tracks



Decay length = 3.7 mm
Decay length significance = 22
Lifetime = 3.1 ps
Vertex mass = 2.5 GeV
Number of tracks = 5



A b-jet candidate event in 2009

Decay length = 3.7 mm
Decay length significance = 22
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Number of tracks = 5

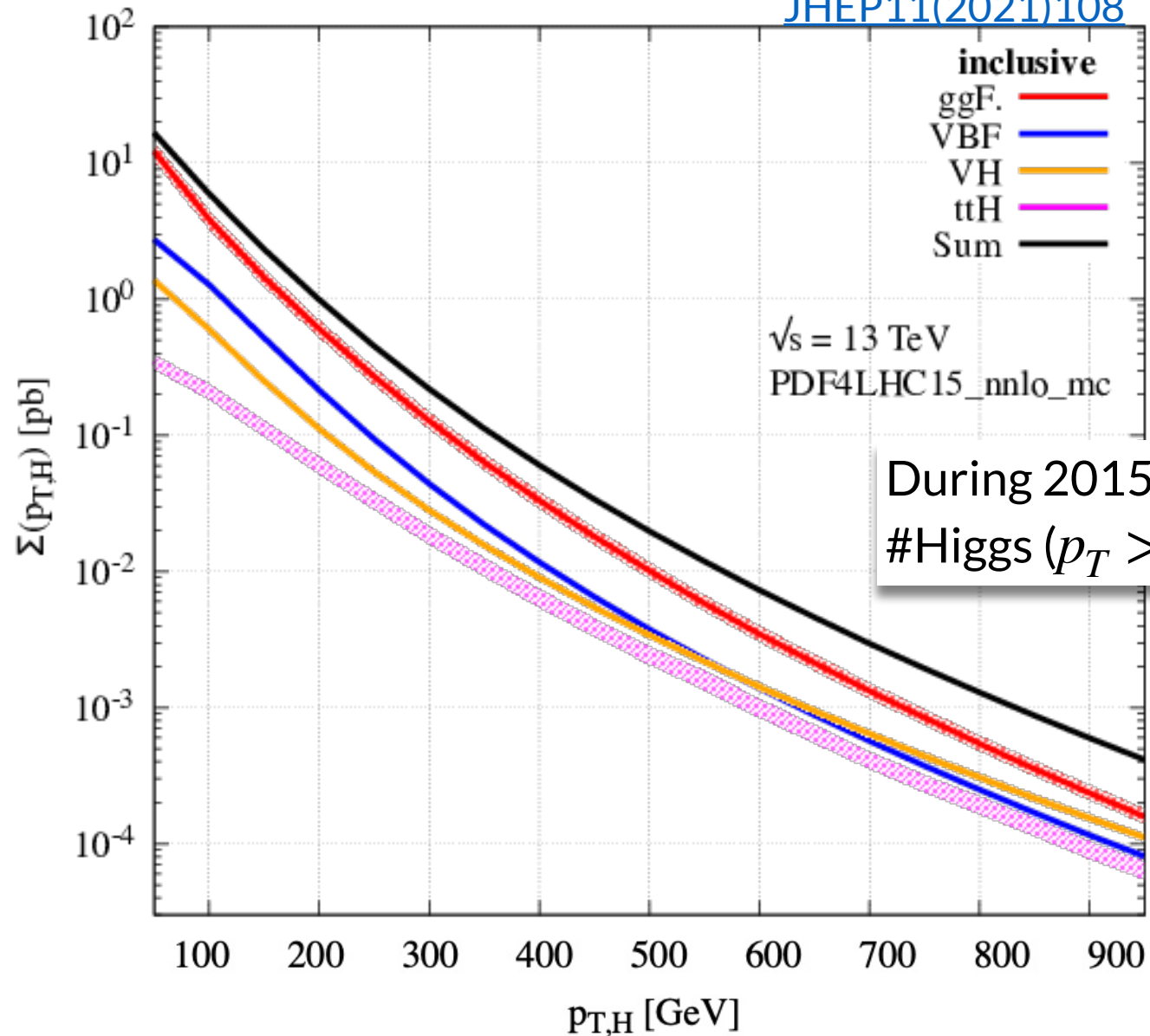


Precise Particle Tracking Detector is Crucial

A b-jet candidate event in 2009

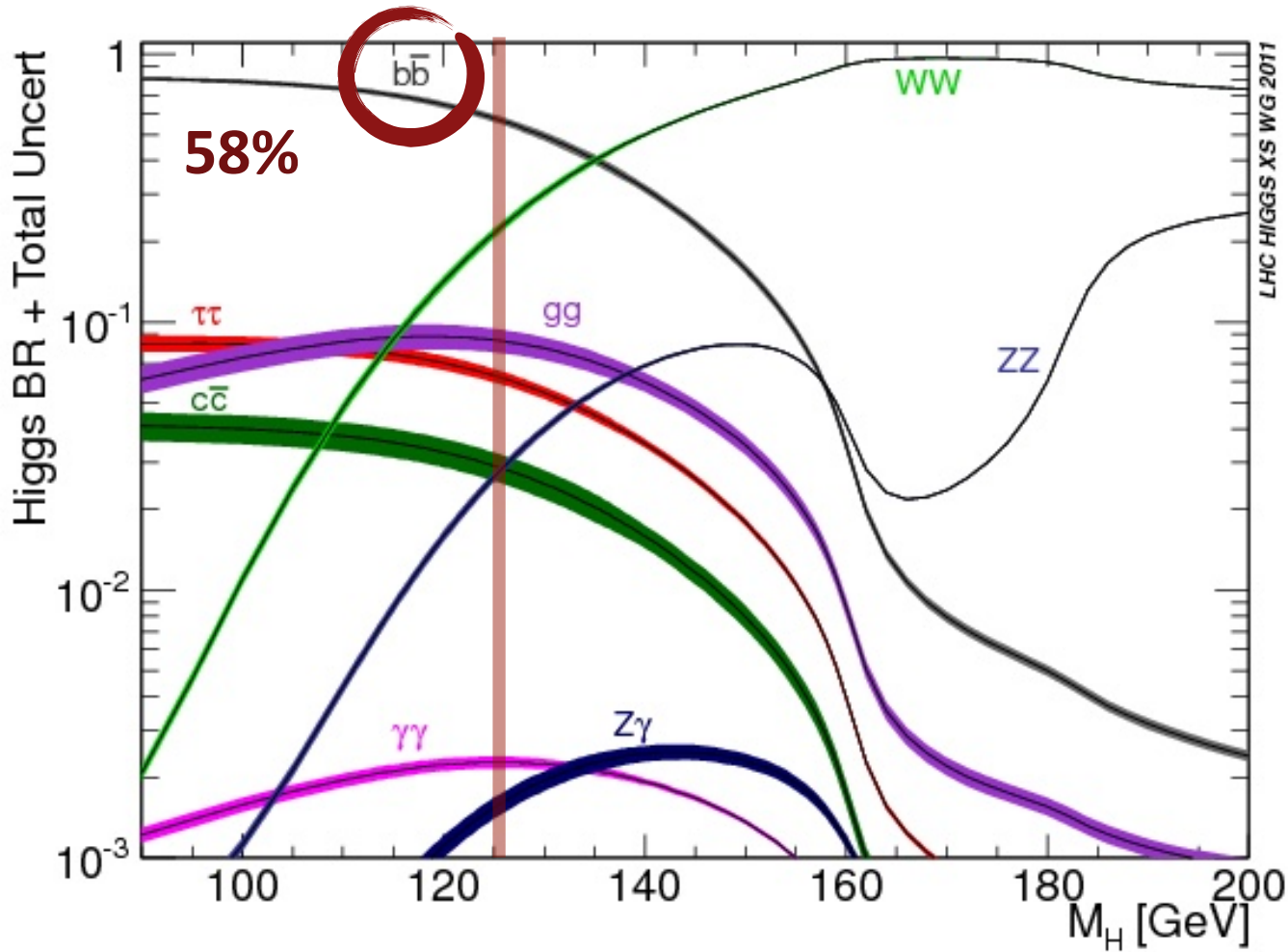
Why boosted Higgs becomes accessible now

JHEP11(2021)108



During 2015-2018:
#Higgs ($p_T > 400$ GeV) ~ 3700

Higgs at LHC: $H \rightarrow b\bar{b}$



The largest branching fraction of Higgs decay

- $b\bar{b}$ has statistics to access Higgs in the high p_T region

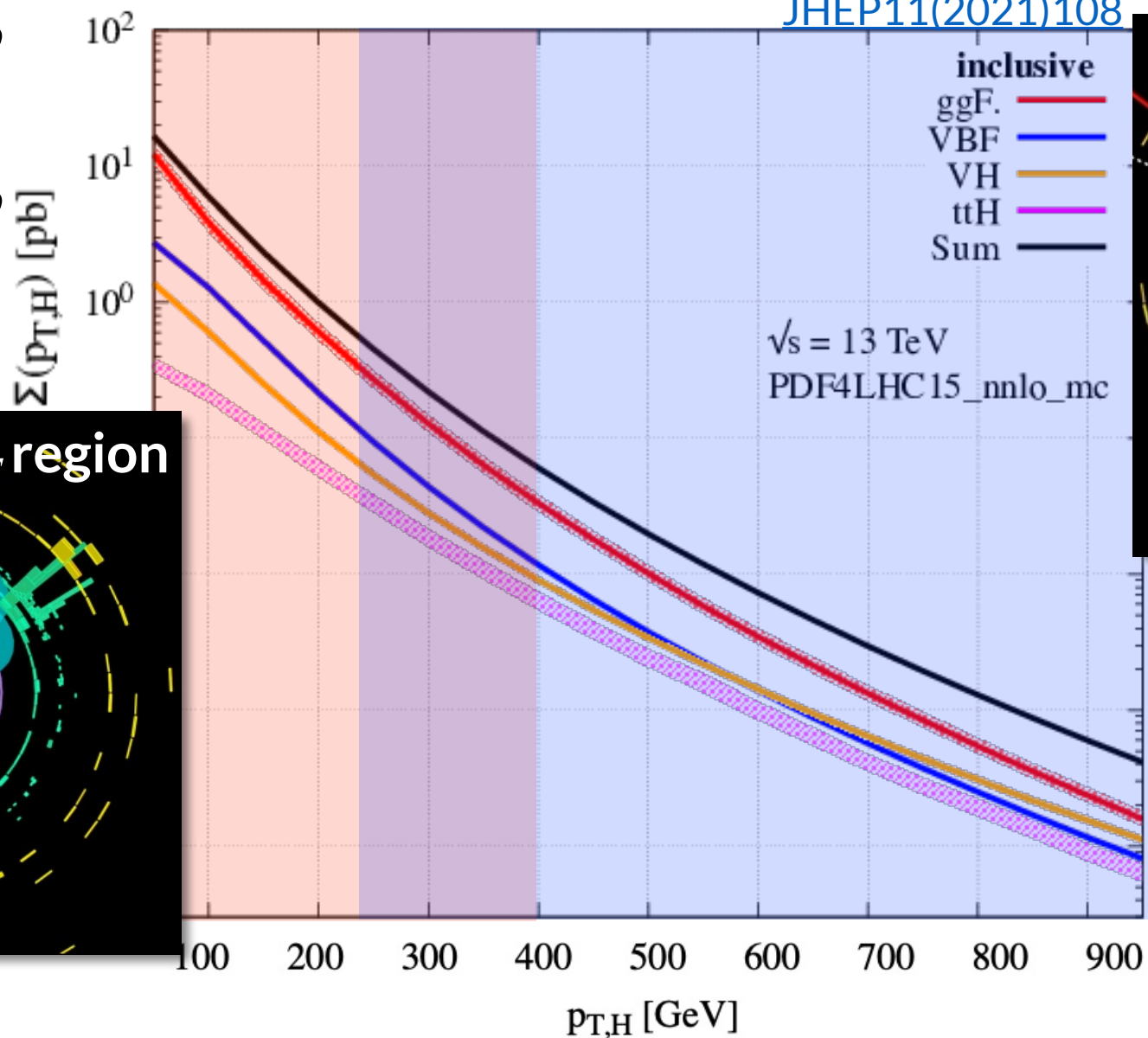
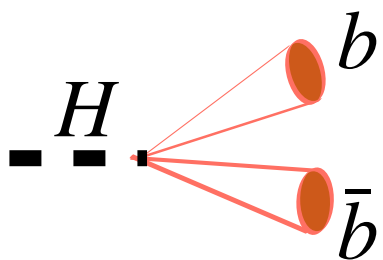
HOWEVER Very Difficult

- large contamination of multijets (QCD)

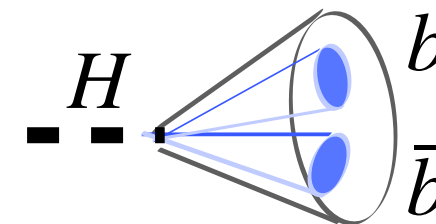
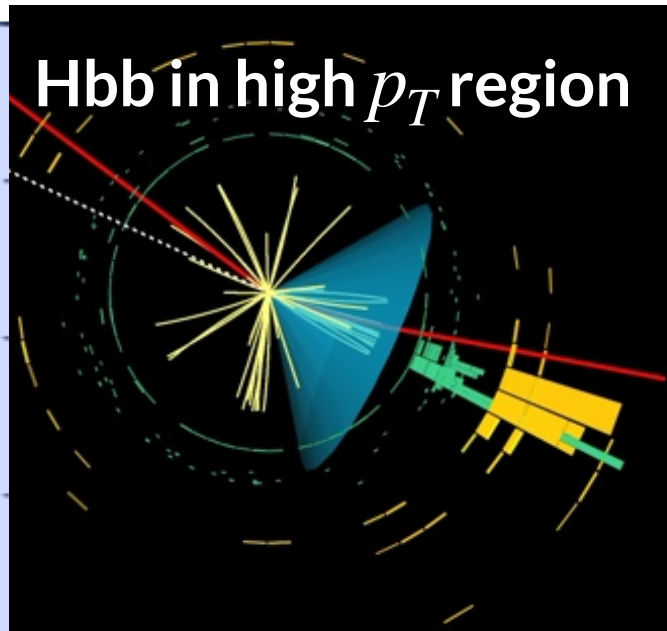
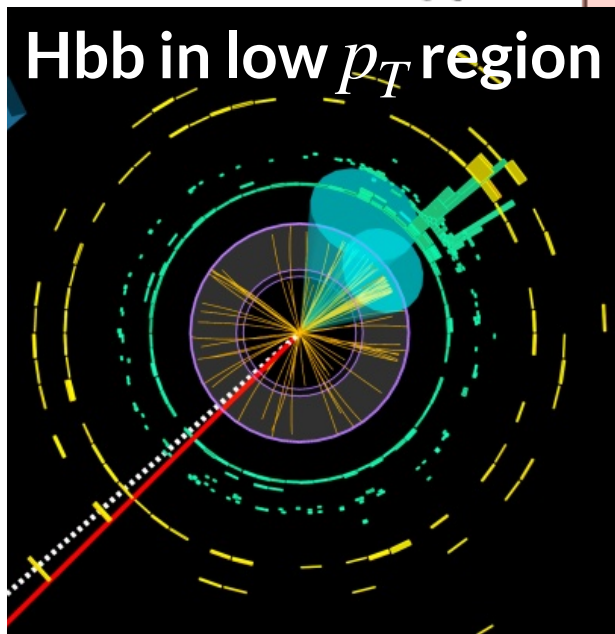
3700 Higgs vs **8 M** QCD

From resolved to boosted Higgs

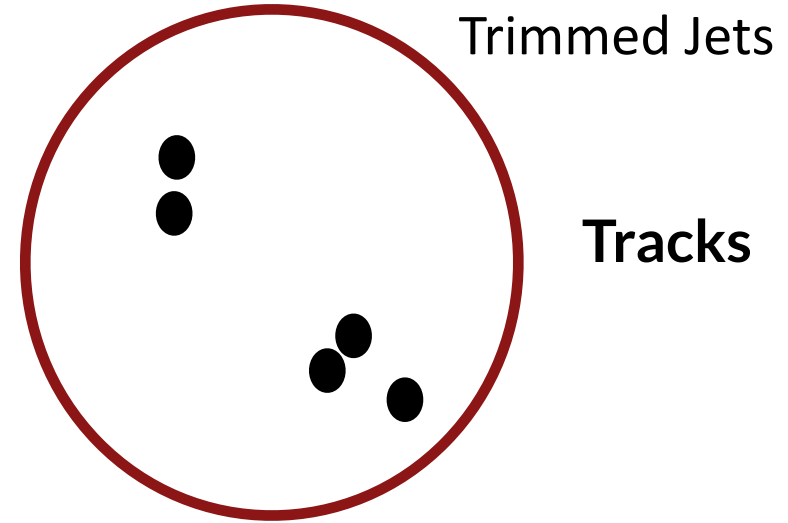
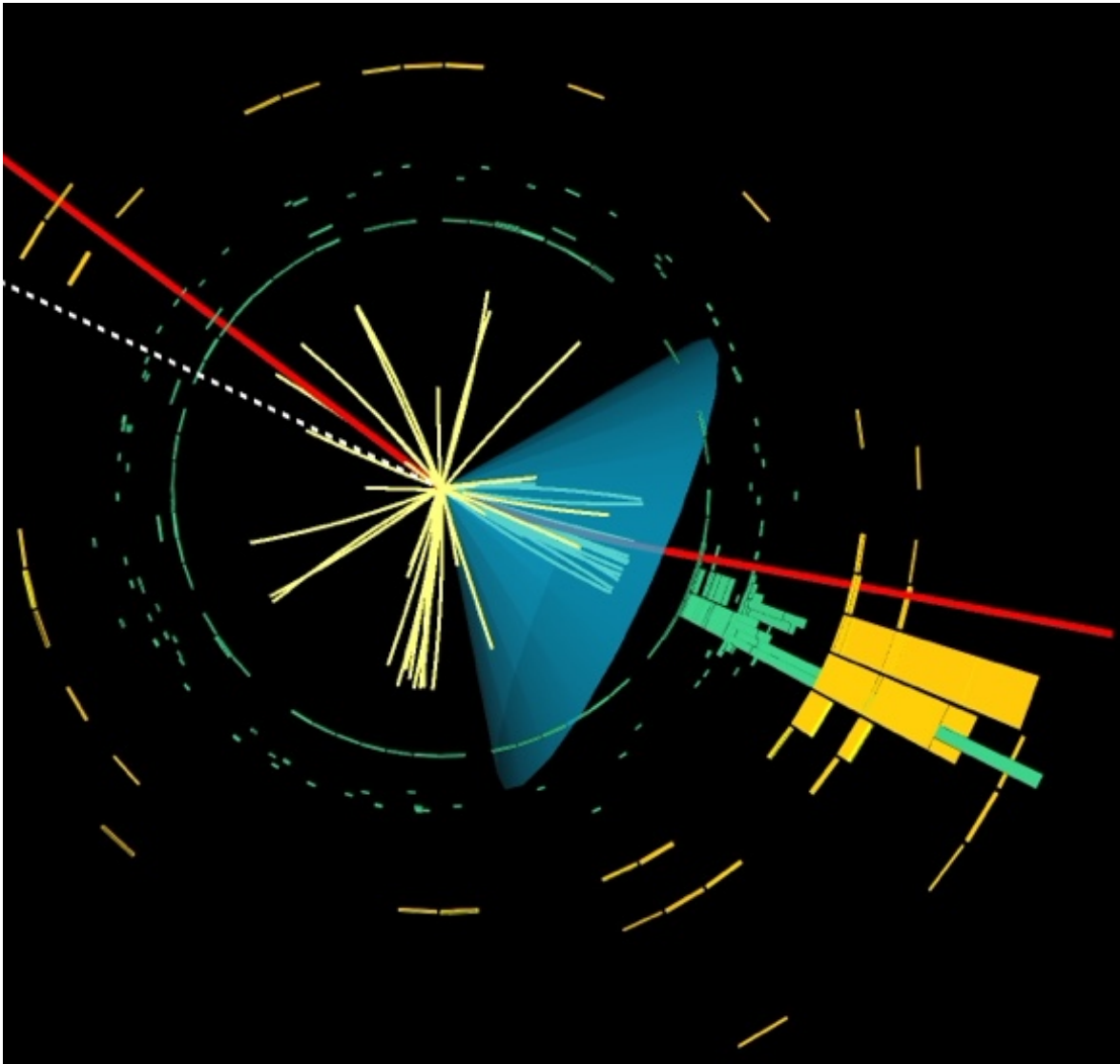
JHEP11(2021)108



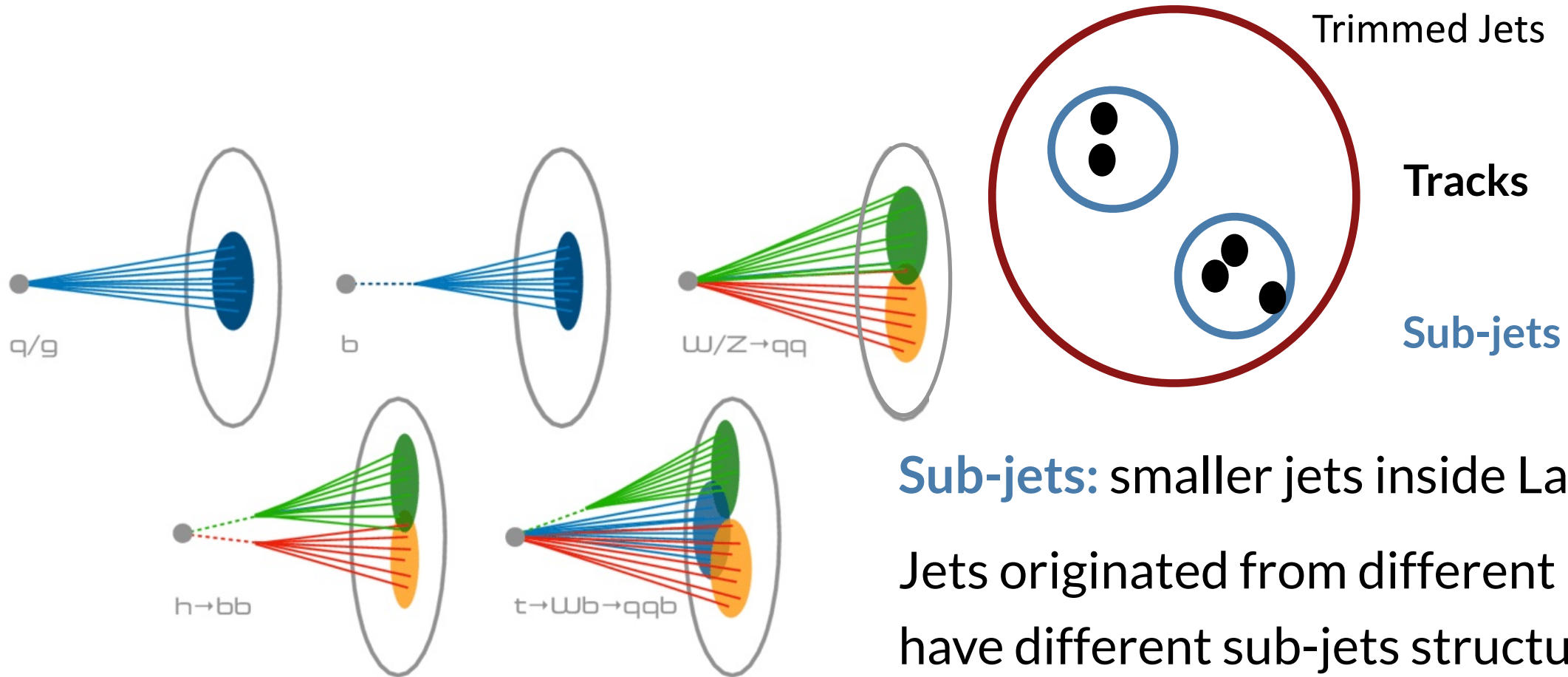
Hbb in low p_T region



Look Inside Jets

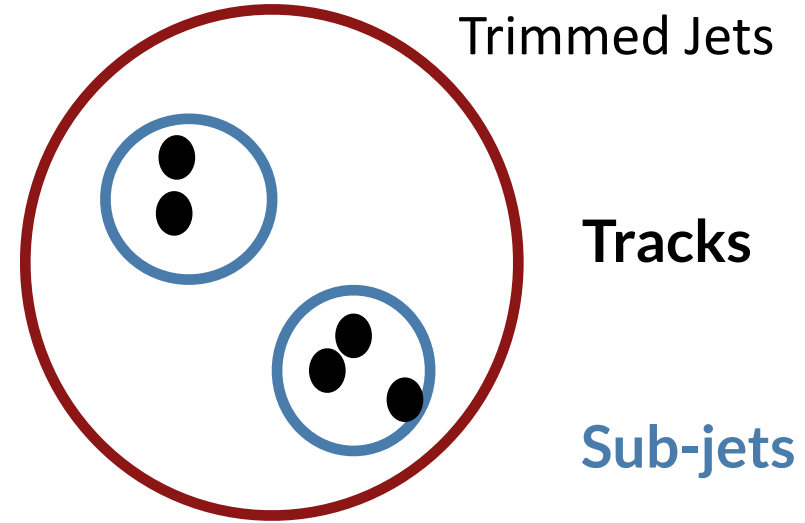
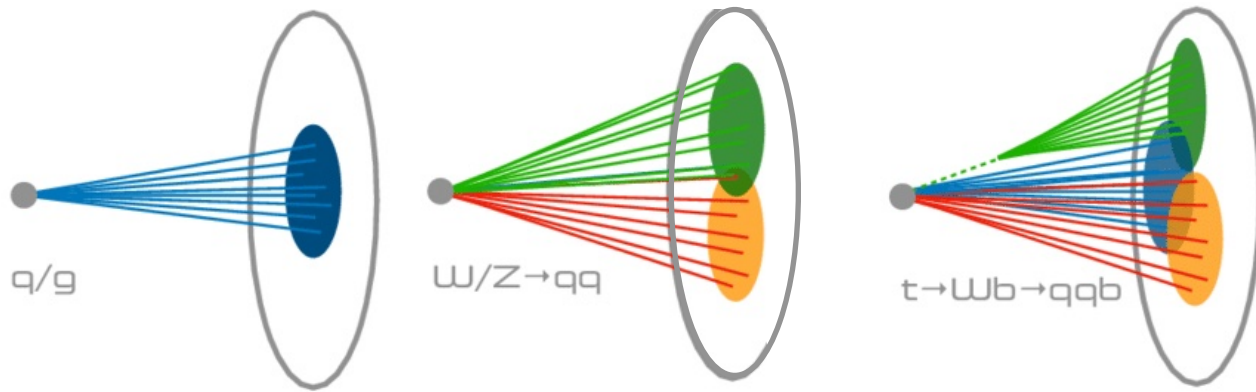


Look Inside Jets

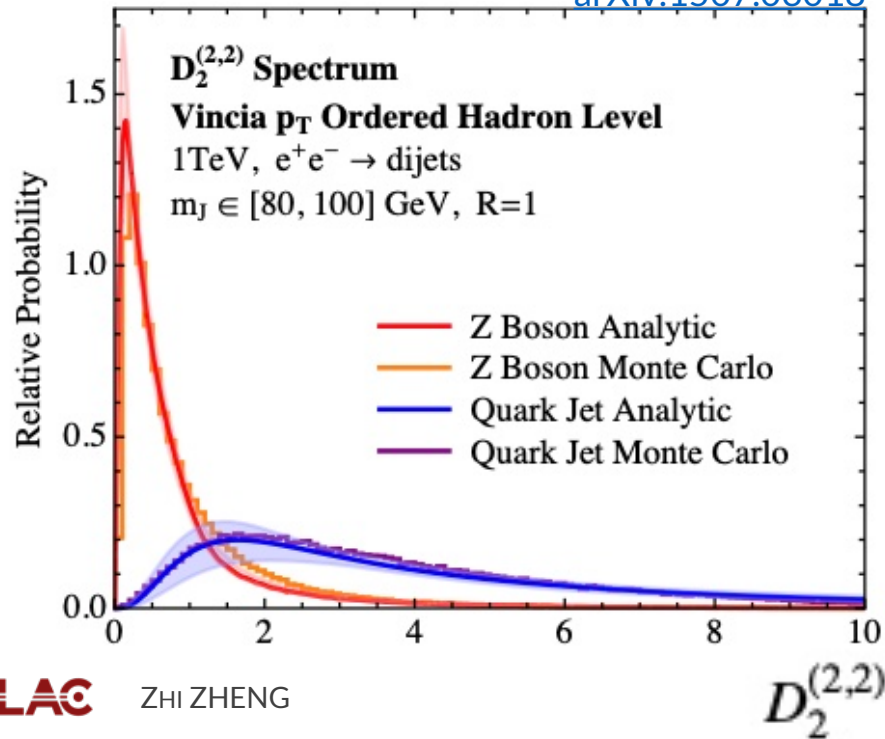


Sub-jets: smaller jets inside Large-R jets
Jets originated from different particles
have different sub-jets structure

Look Inside Jets



[arXiv:1507.03018](https://arxiv.org/abs/1507.03018)

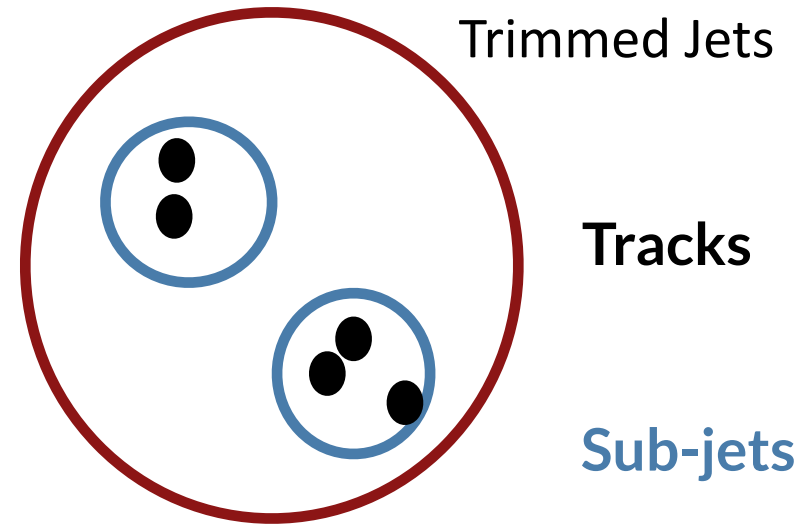
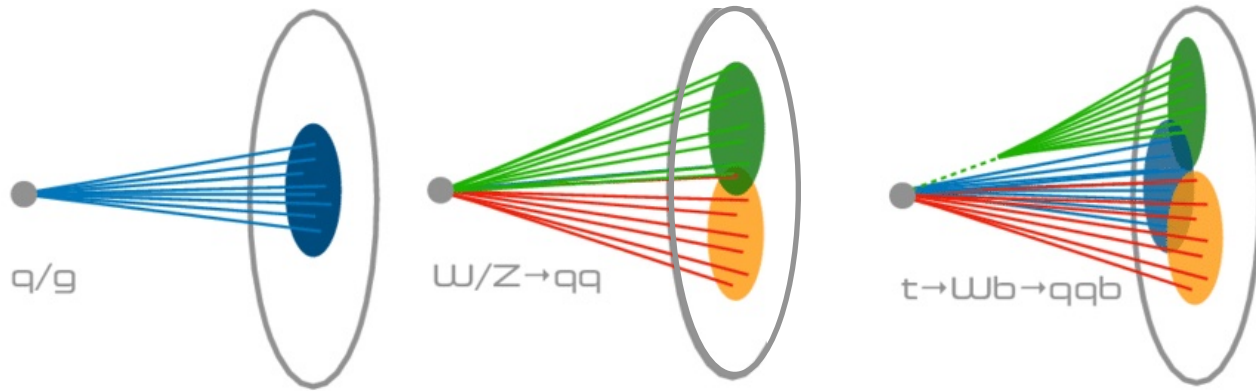


Sub-jets: smaller jets inside Large-R jets

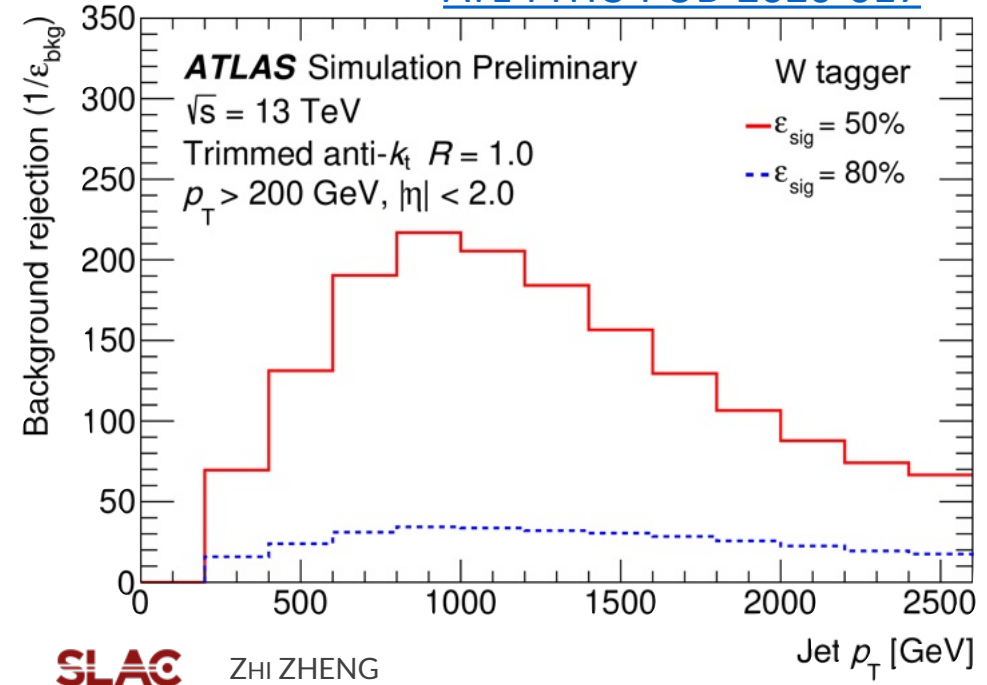
Explore the energy correlation inside jet

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3} = \frac{\text{Diagram 1}}{(\text{Diagram 2})^3}$$

Look Inside Jets



[ATL-PHYS-PUB-2020-017](#)



Sub-jets: smaller jets inside Large-R jets

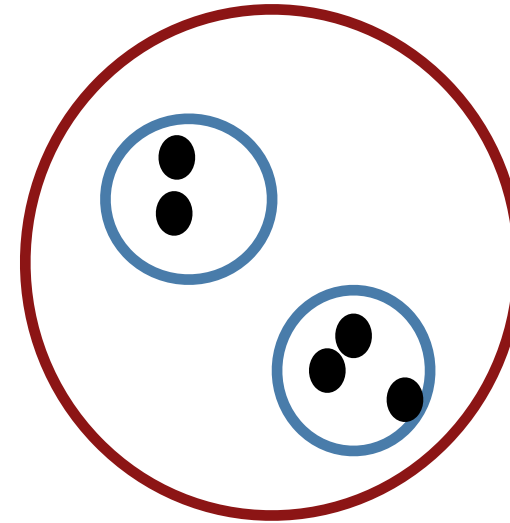
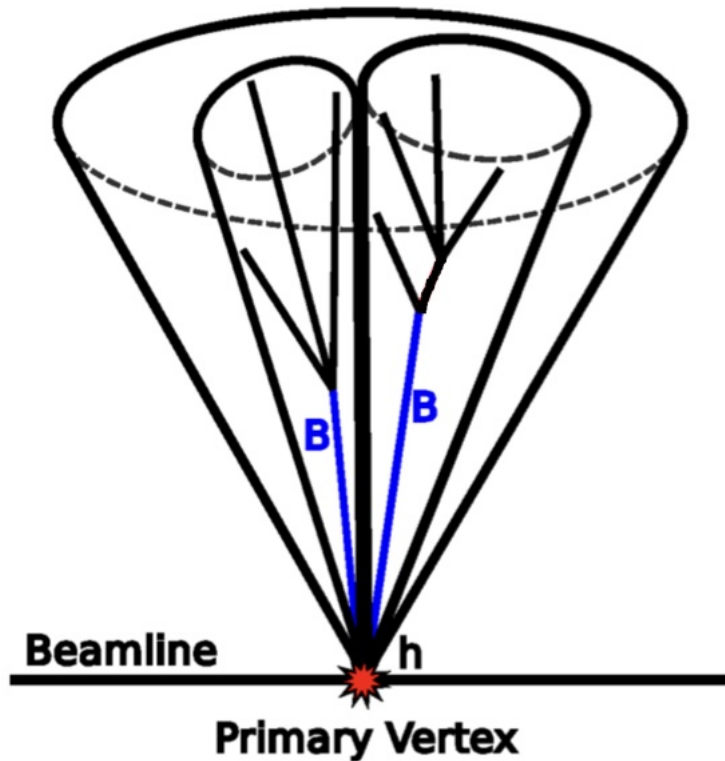
Explore the energy correlation inside jet

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3} = \frac{\text{Diagram 1}}{(\text{Diagram 2})^3}$$

Look Inside Jets: $H \rightarrow bb$ Tagger

Identify Higgs: [ATL-PHYS-PUB-2017-010](#)

- Tag individual subjets

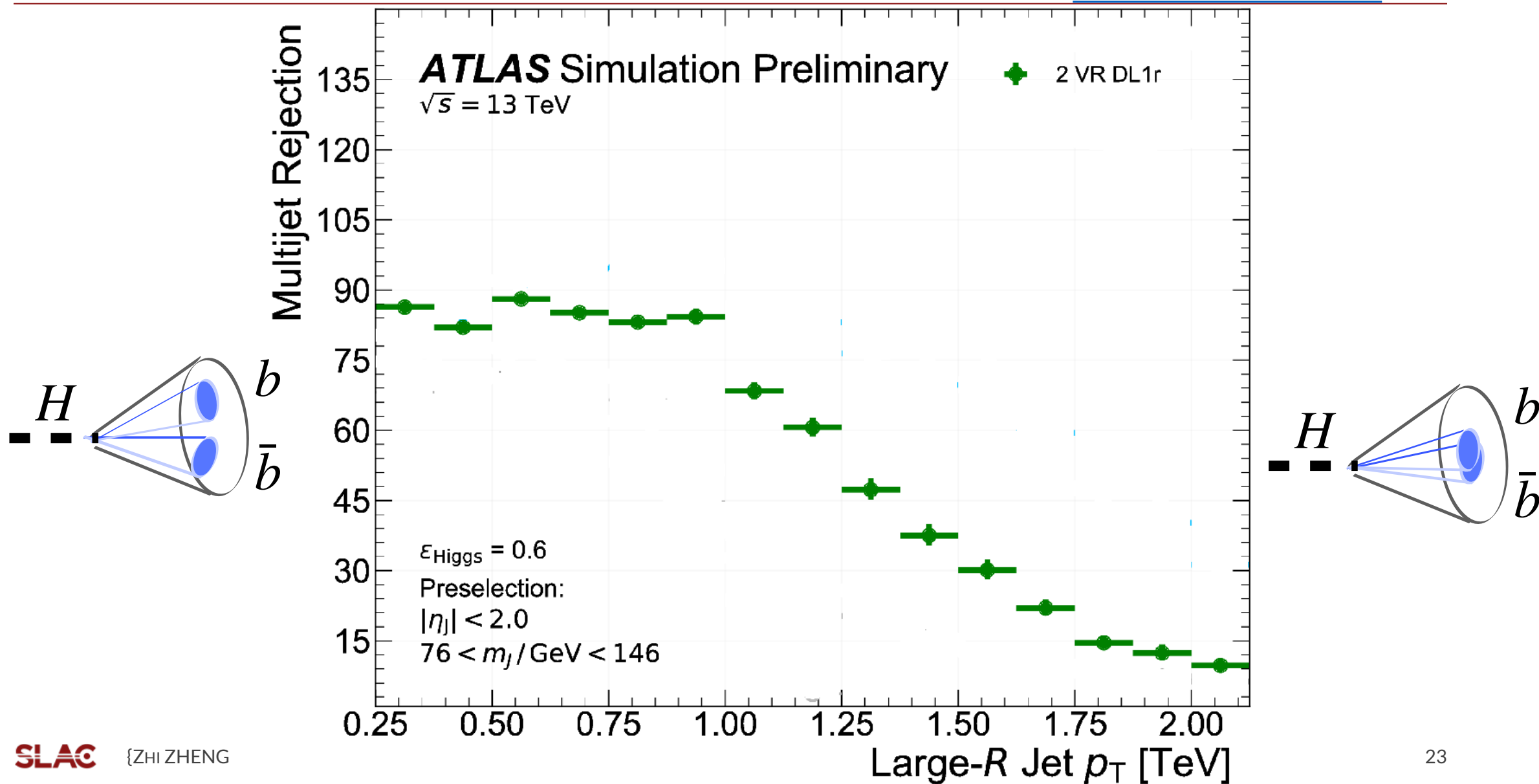


Tracks

Sub-jets

Look Inside Jets: $H \rightarrow b\bar{b}$ Tagger

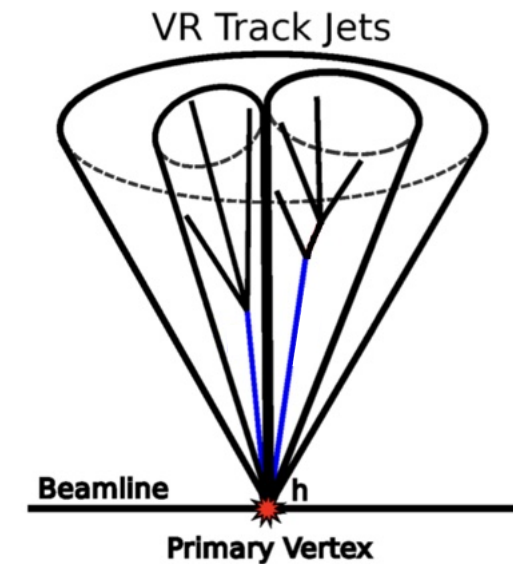
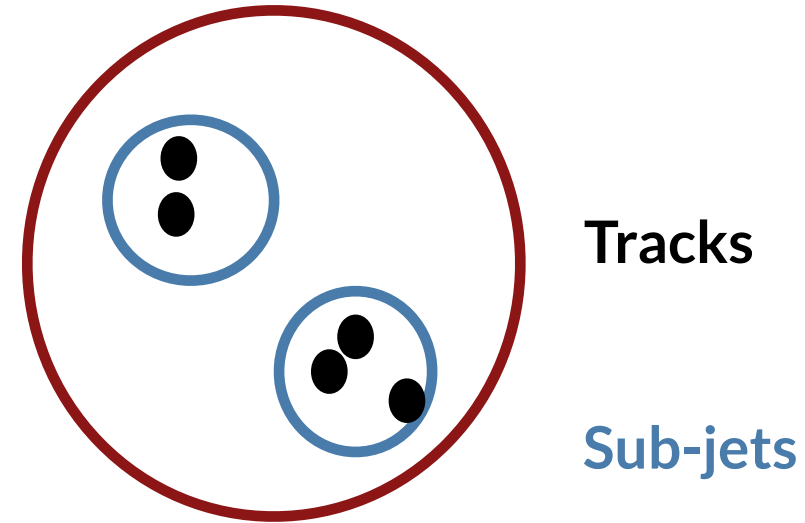
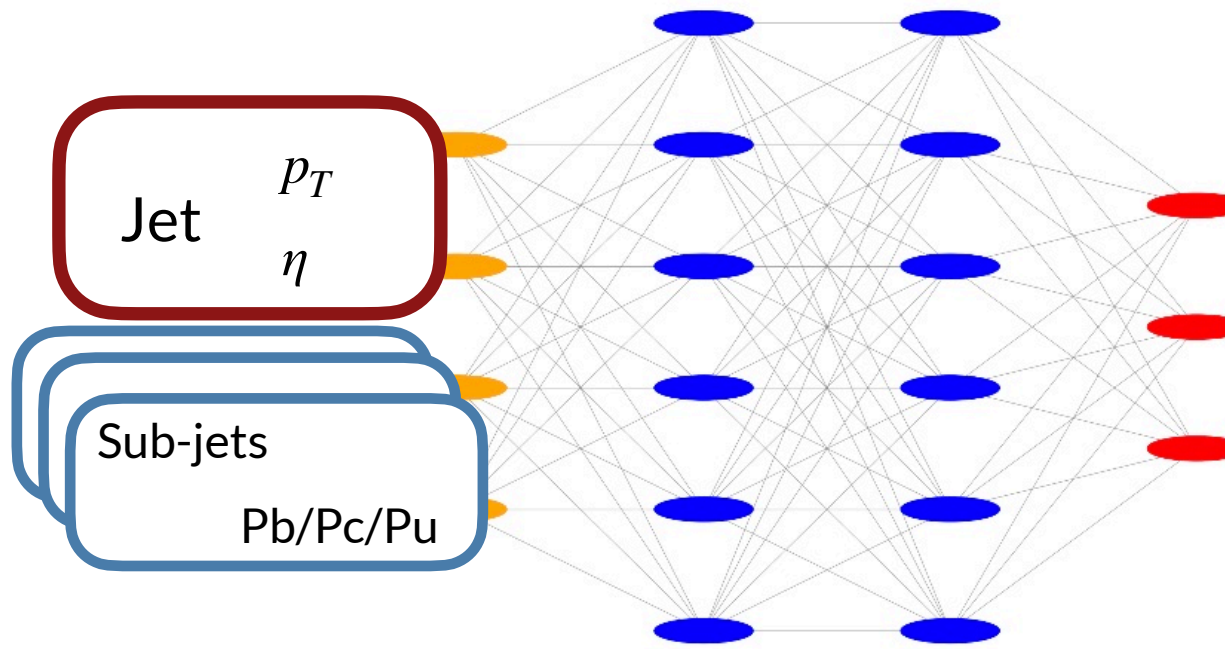
ATL-PHYS-PUB-2020-019



Look Inside Jets: $H \rightarrow bb$ Tagger

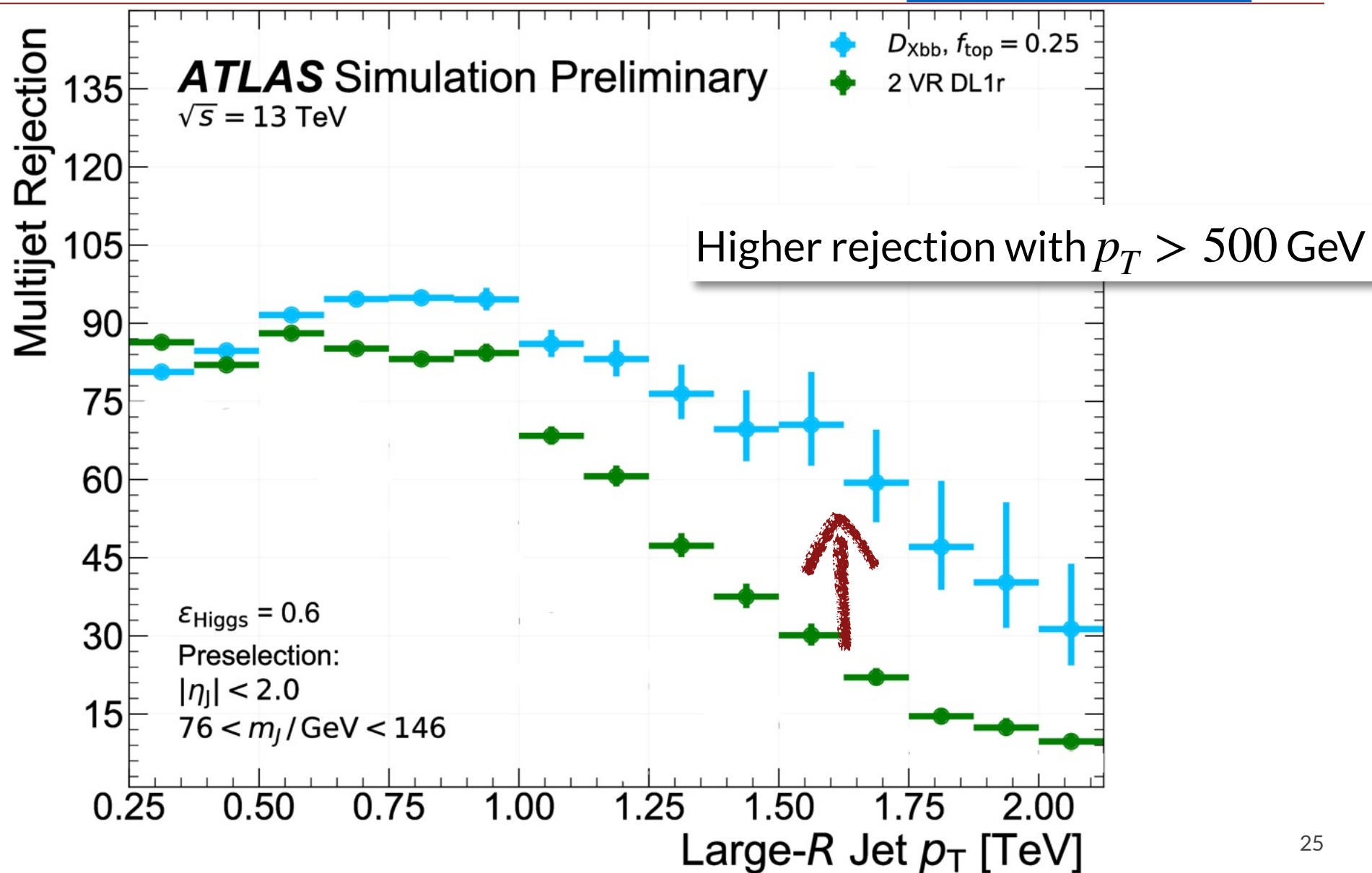
Identify Higgs: [ATL-PHYS-PUB-2020-019](#)

- Neural Network using b-tagging associated to variable radius track-jets and jet information



Look Inside Jets: $H \rightarrow bb$ Tagger

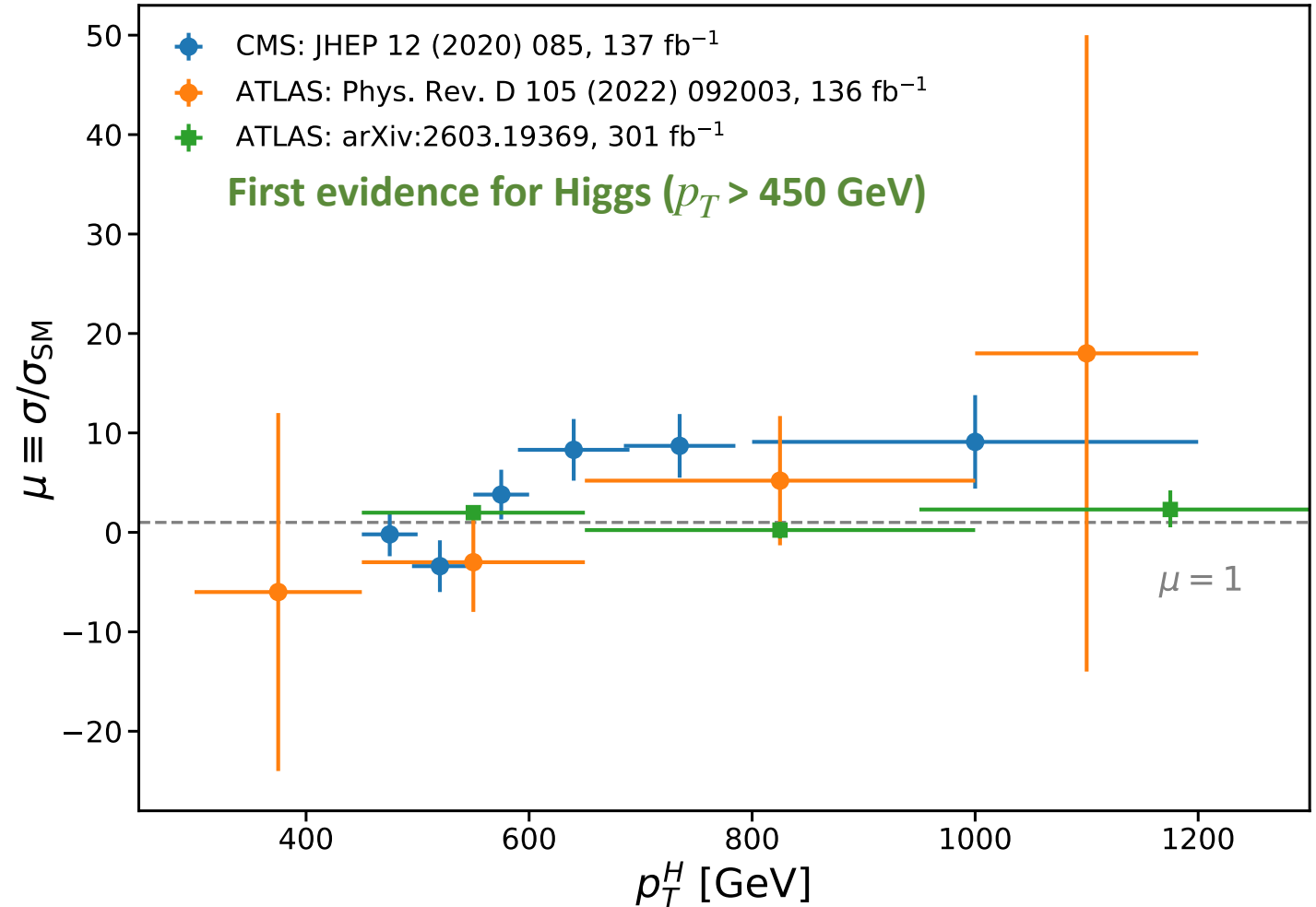
ATL-PHYS-PUB-2020-019



Higgs in the Boost Region

Advancement of **novel jets substructure and ML** enabled searches for $H \rightarrow bb$ in hadronic final states despite the large irreducible QCD background:

- p_T^H differential measurement of Higgs boson in $b\bar{b}$ decay channel in both ATLAS and CMS



Higgs in the Boost Region: Different Production

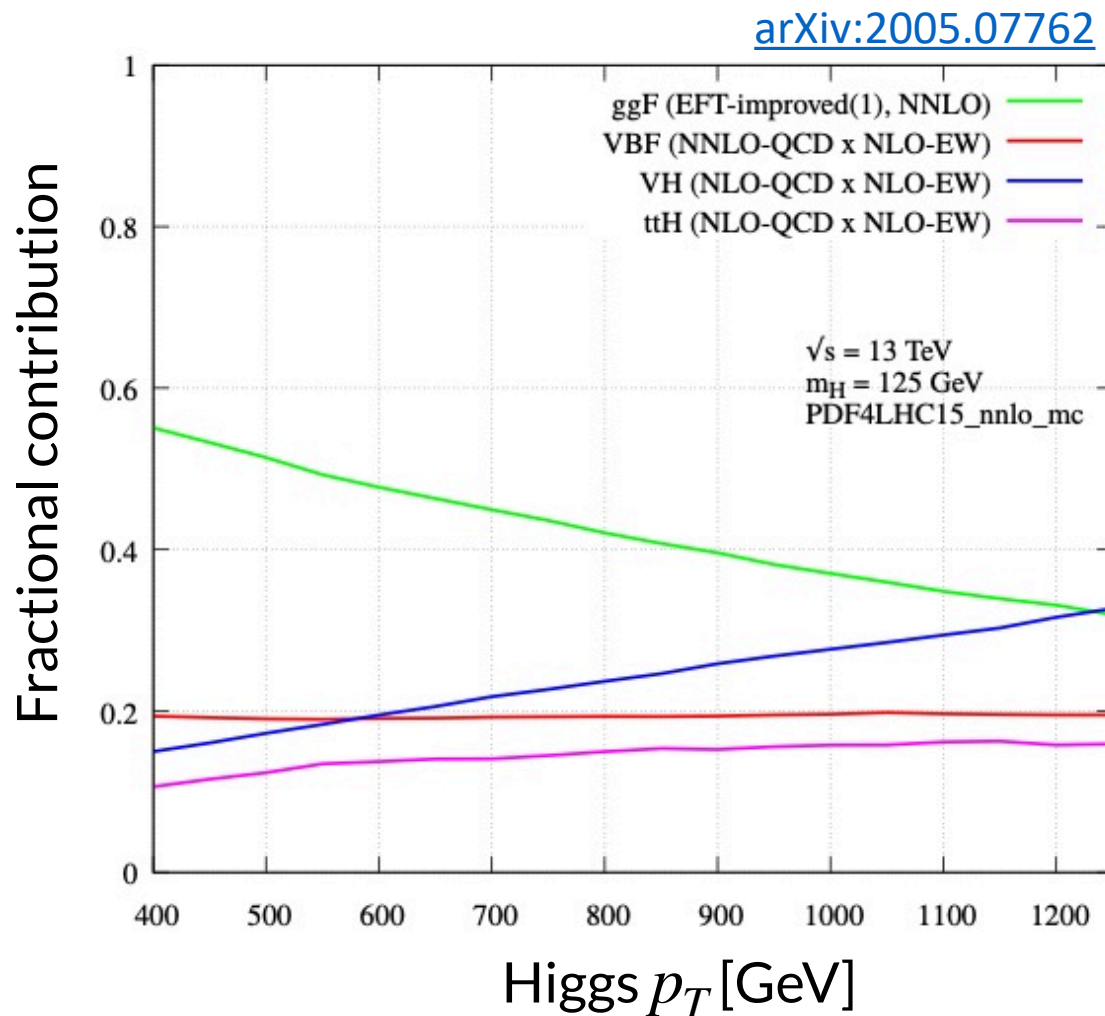
All production modes

contribute similarly toward p_T^H

~ 1 TeV

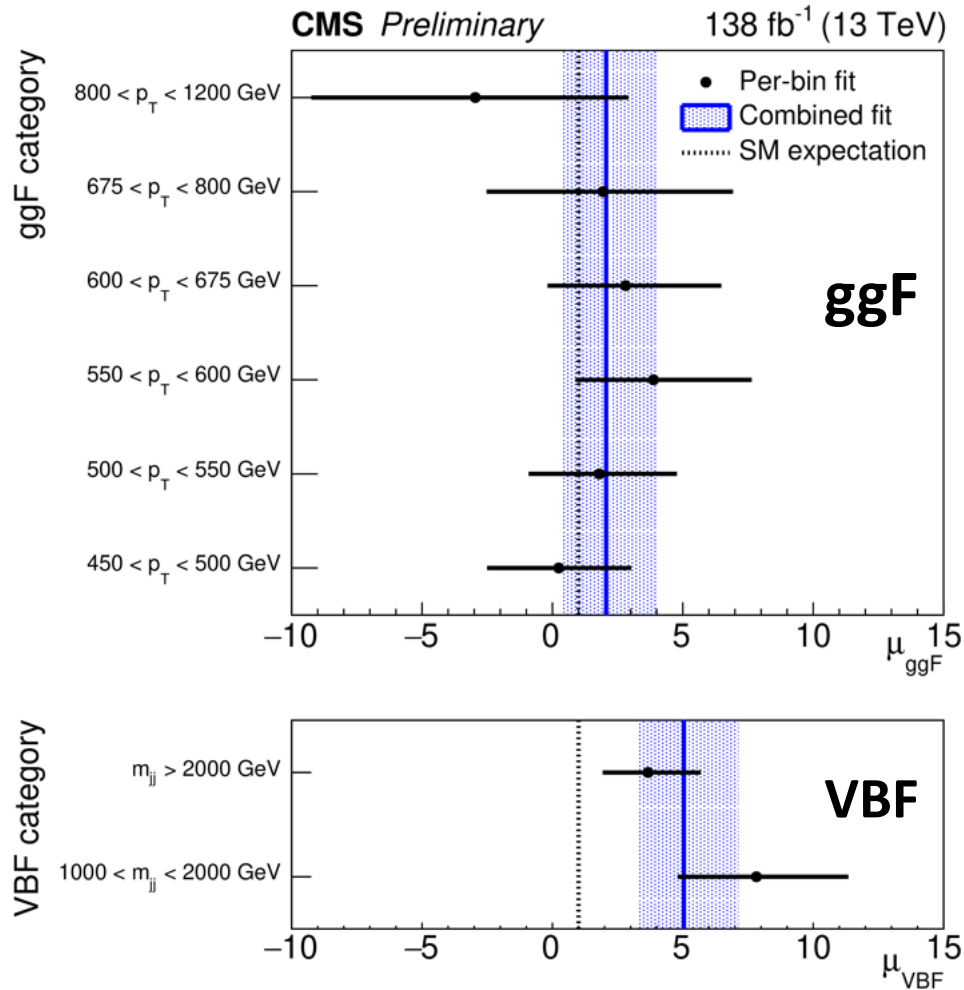
- At 1TeV VH will be the leading production mode

Understanding each production mechanism in high p_T regime for the Higgs boson is important



Higgs in the Boost Region: Different Production

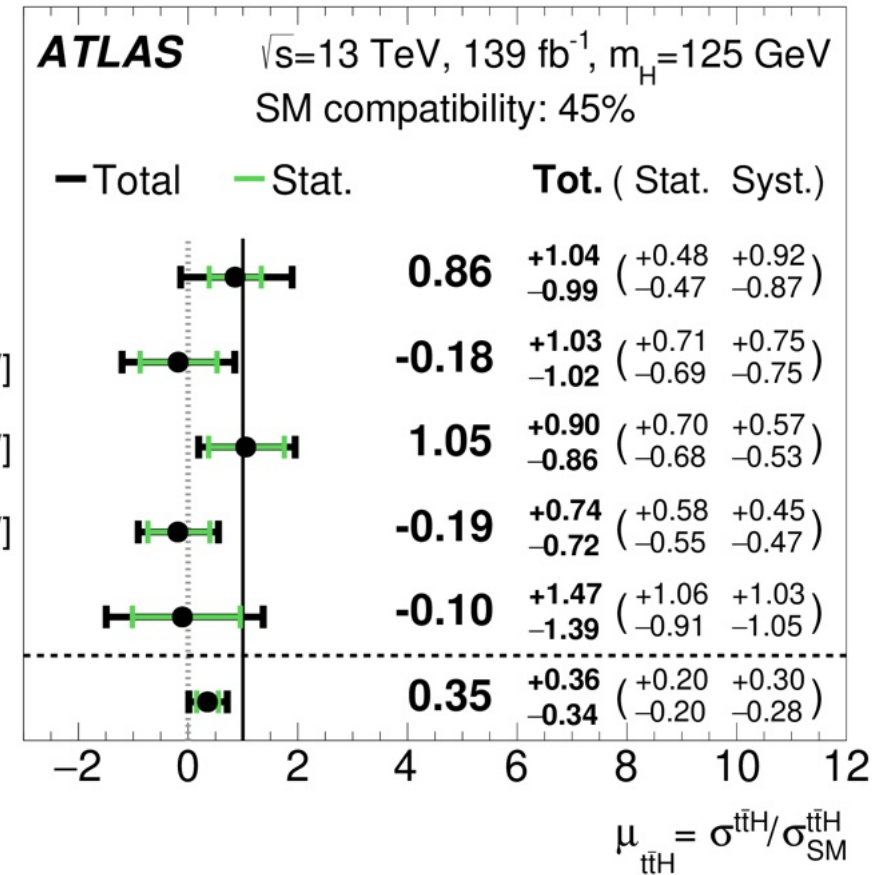
[JHEP 12 \(2024\) 035](#)



ttH

$\mu_{\text{ttH}}, \hat{p}_T^H \in [0, 120) \text{ [GeV]}$
 $\mu_{\text{ttH}}, \hat{p}_T^H \in [120, 200) \text{ [GeV]}$
 $\mu_{\text{ttH}}, \hat{p}_T^H \in [200, 300) \text{ [GeV]}$
 $\mu_{\text{ttH}}, \hat{p}_T^H \in [300, 450) \text{ [GeV]}$
 $\mu_{\text{ttH}}, \hat{p}_T^H \in [450, \infty) \text{ [GeV]}$
 Inclusive

[JHEP 06 \(2022\) 97](#)

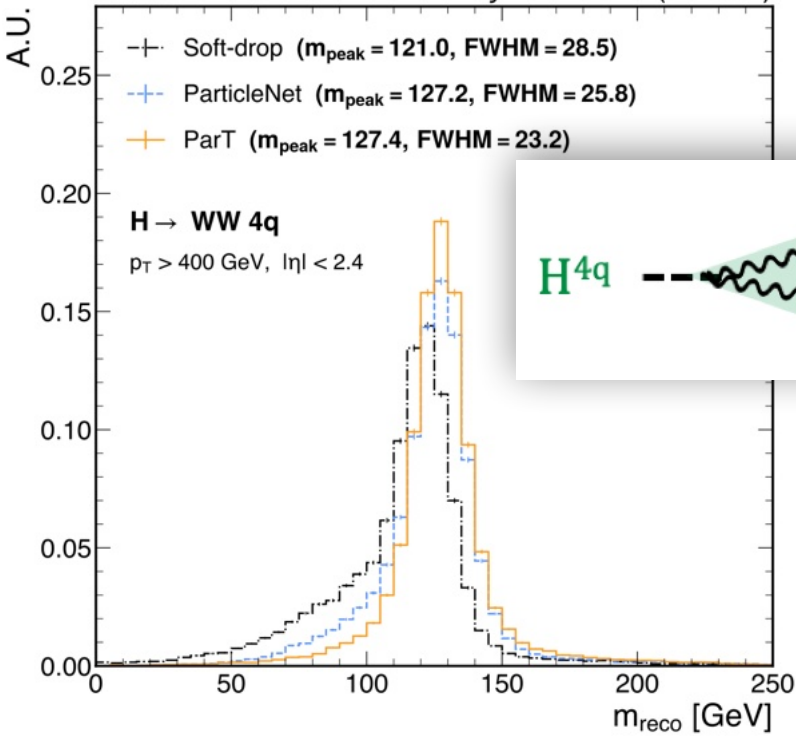


Higgs in the Boost Region: Decay mode expansion

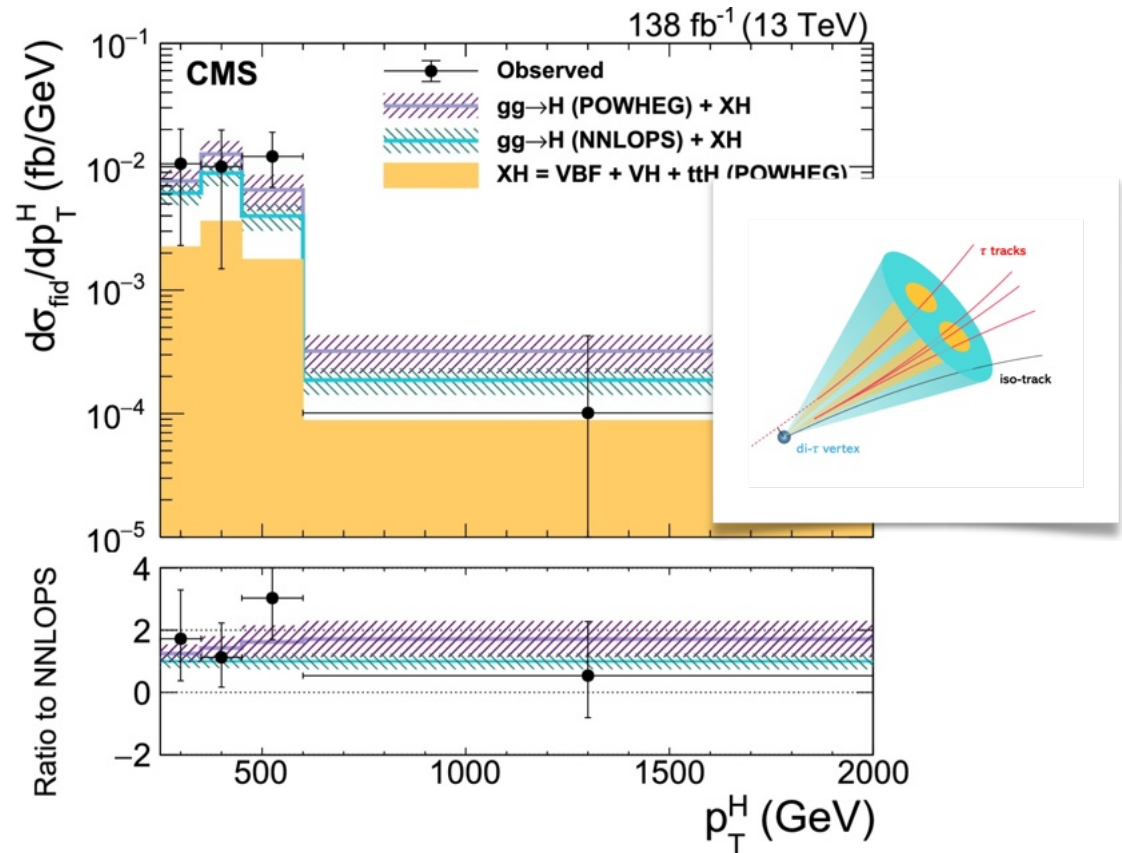
$H \rightarrow WW$

[arXiv:2603.22233](https://arxiv.org/abs/2603.22233)

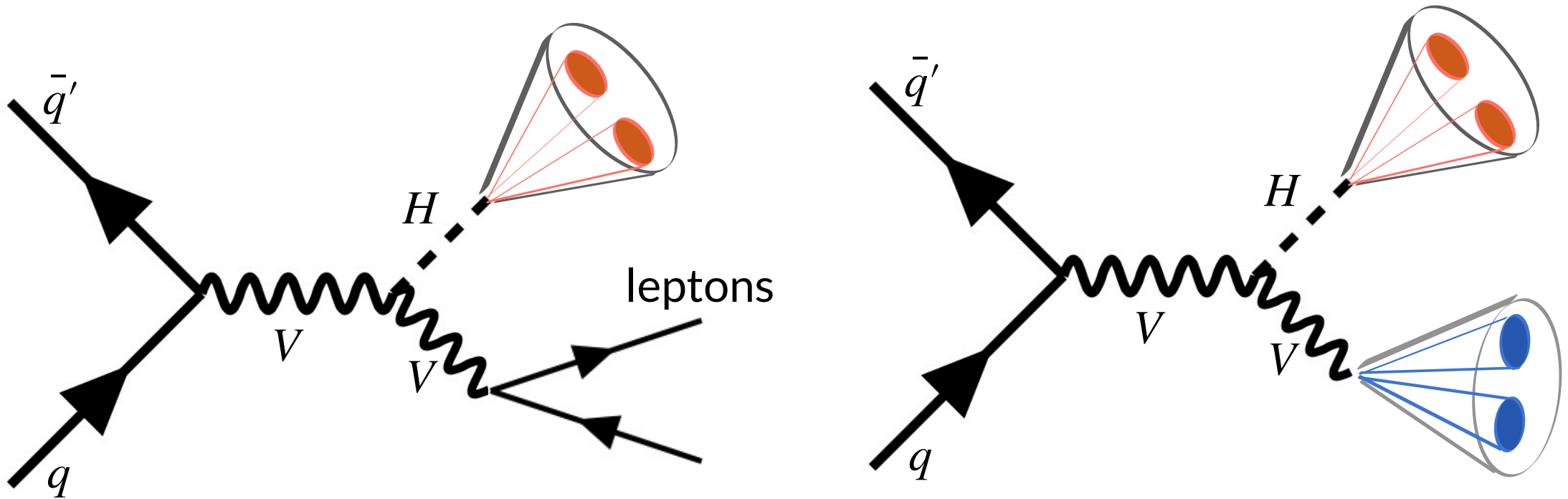
CMS Simulation Preliminary (13 TeV)



$H \rightarrow \tau\tau$



Higgs in the Boost Region: VH

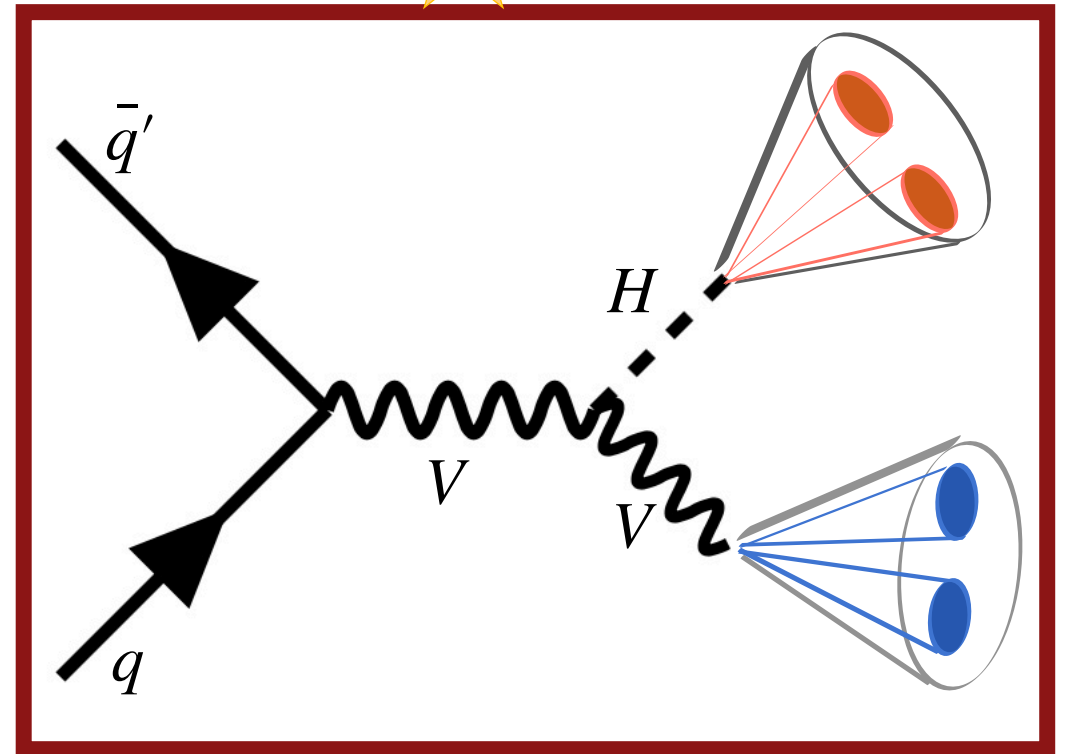
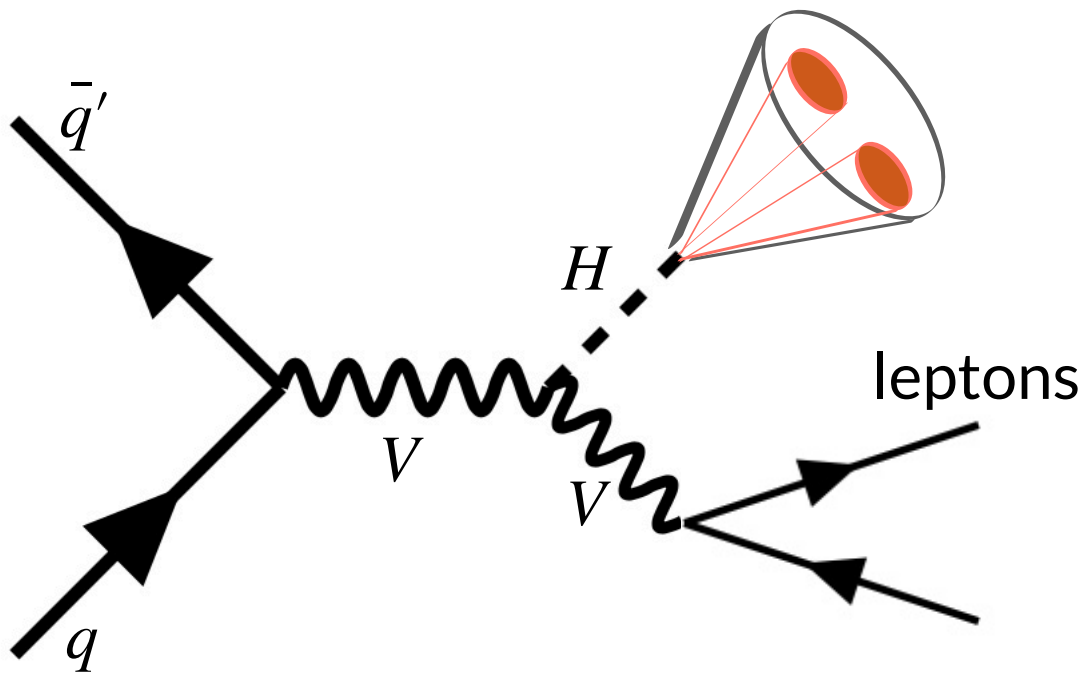


Higgs in the Boost Region: VH

[Phys. Rev. Lett. 132 \(2024\) 131802](#)

Signal events increase by a factor of two in all hadronic channel compared with $V(\rightarrow \text{lepton})H$

$V(\rightarrow qq)H$ ★ First Measurement



V(\rightarrow qq)H: Event Selection

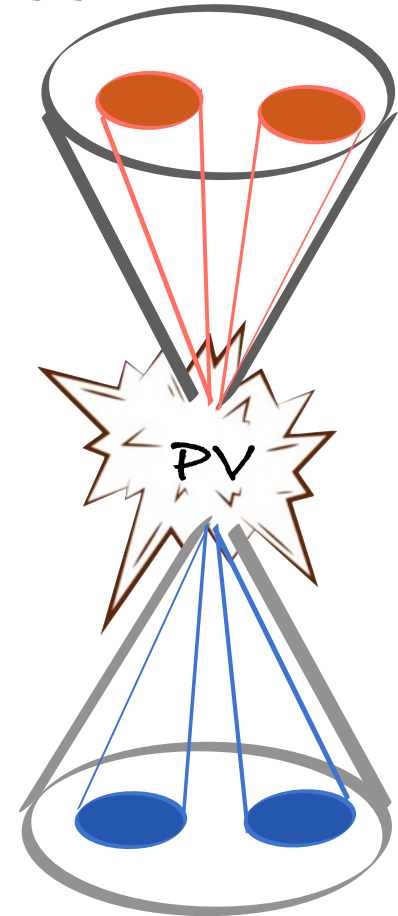
Single large-R ($R=1.0$ anti- k_t) jet trigger with mass and p_T threshold

At least **two large-R jets** $p_T > 200$ GeV & $|\eta| < 2$

- p_T - leading jet: $p_T > 450$, $M_J > 60$ GeV
- Second p_T - leading jet: $M_J > 40$ GeV

Events with isolated charge leptons are rejected

Higgs candidate



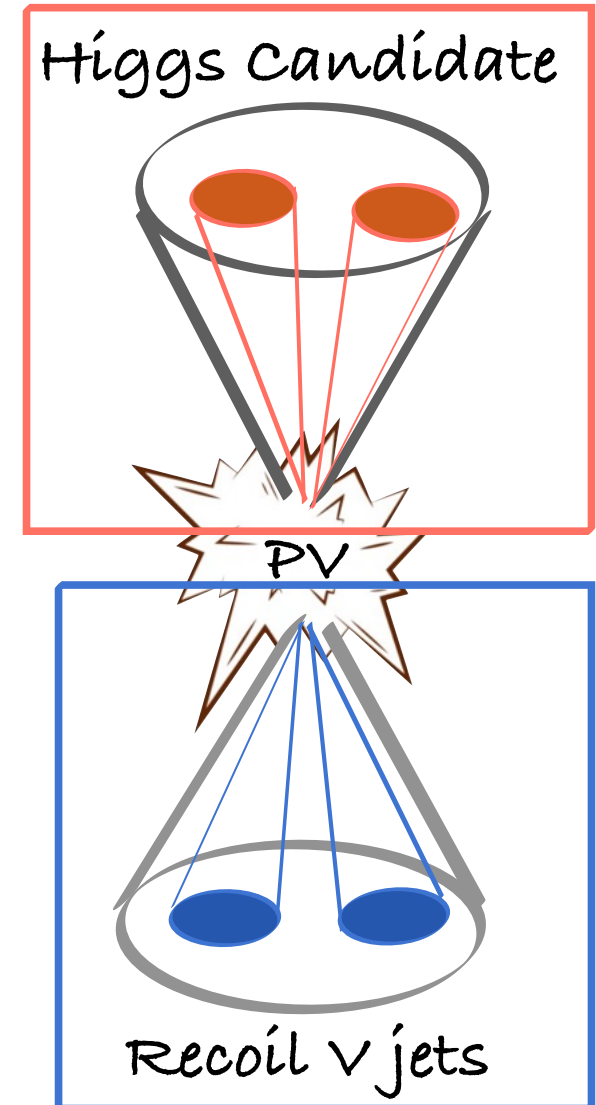
Recoil ν jets

$V(\rightarrow qq)H$: Higgs Candidate

At least one of the two p_T -leading jets must pass $H \rightarrow b\bar{b}$ tagger requirements

- The jet passing $H \rightarrow b\bar{b}$ tagger requirements is the Higgs candidate
- If both, the jet with larger mass is the Higgs candidate

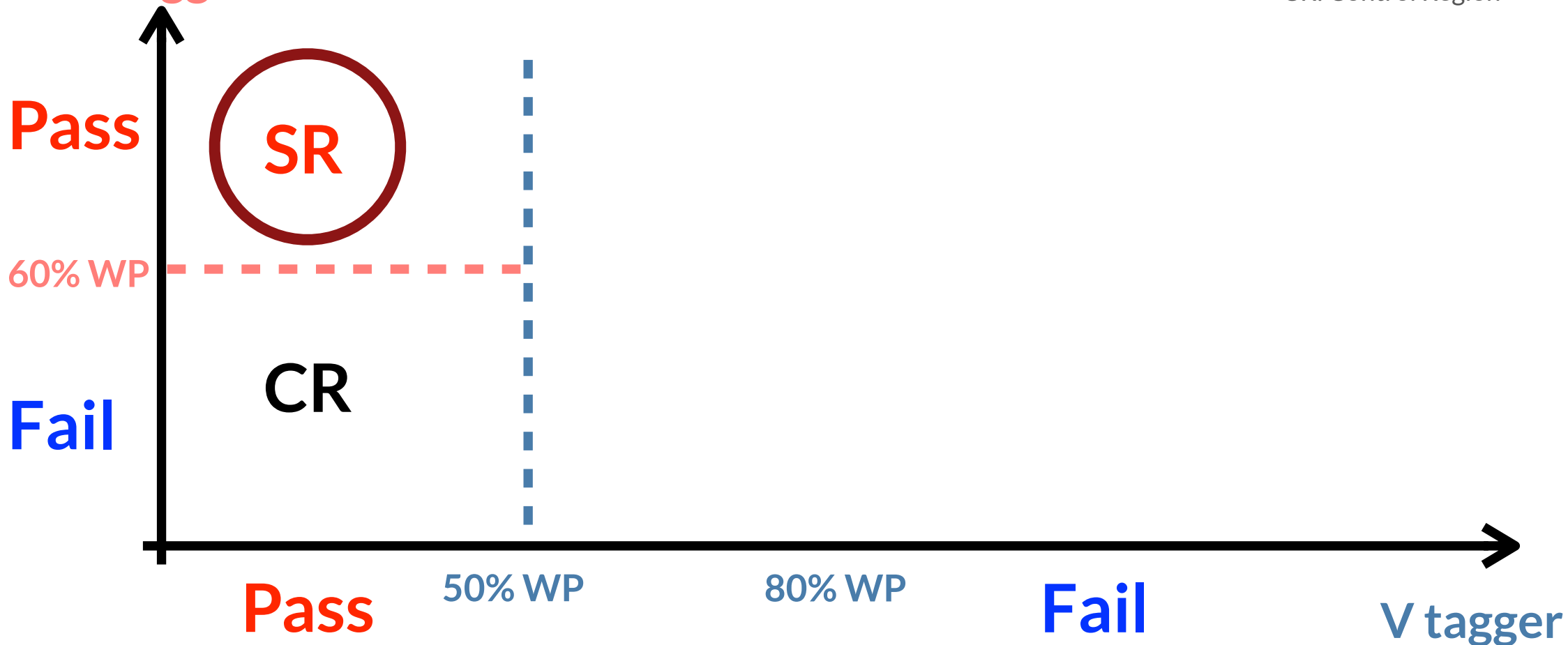
The recoil jet must pass V tagger



Event Selection

$H \rightarrow b\bar{b}$ tagger

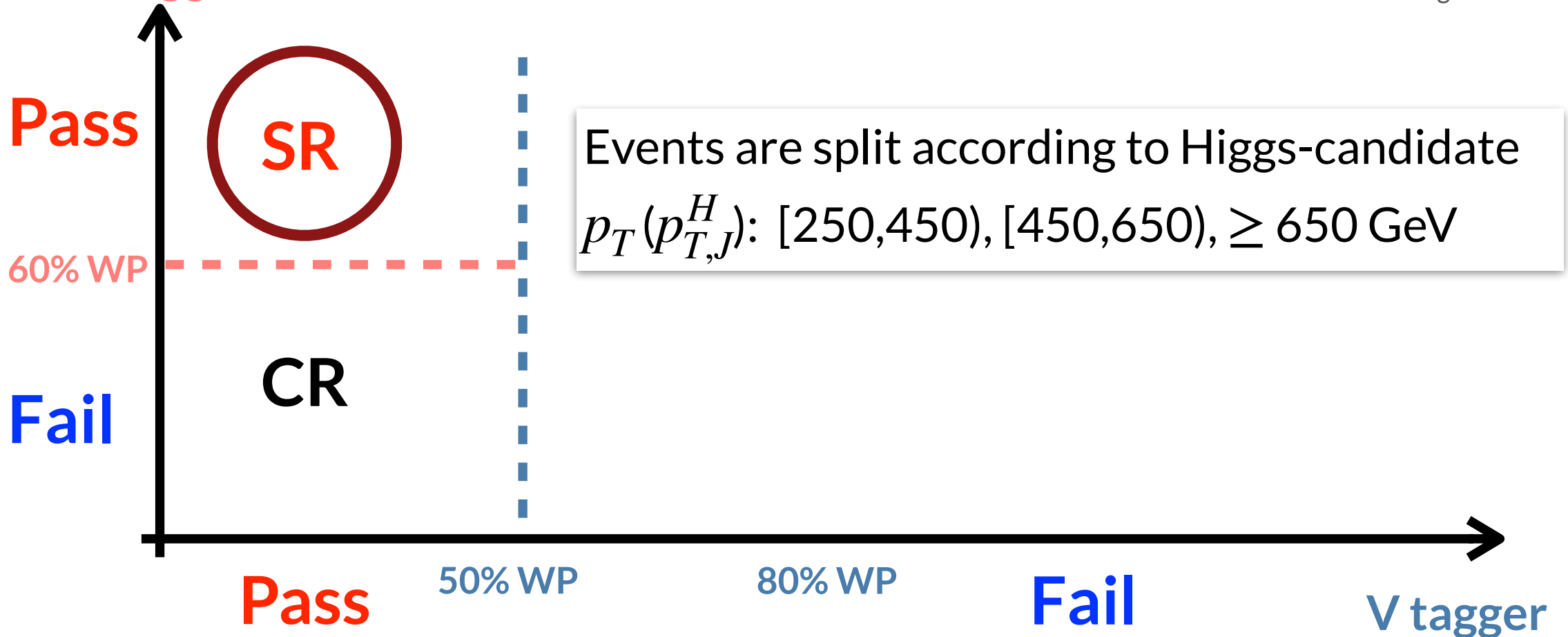
*SR: Signal Region
*CR: Control Region



Event Selection

$H \rightarrow b\bar{b}$ tagger

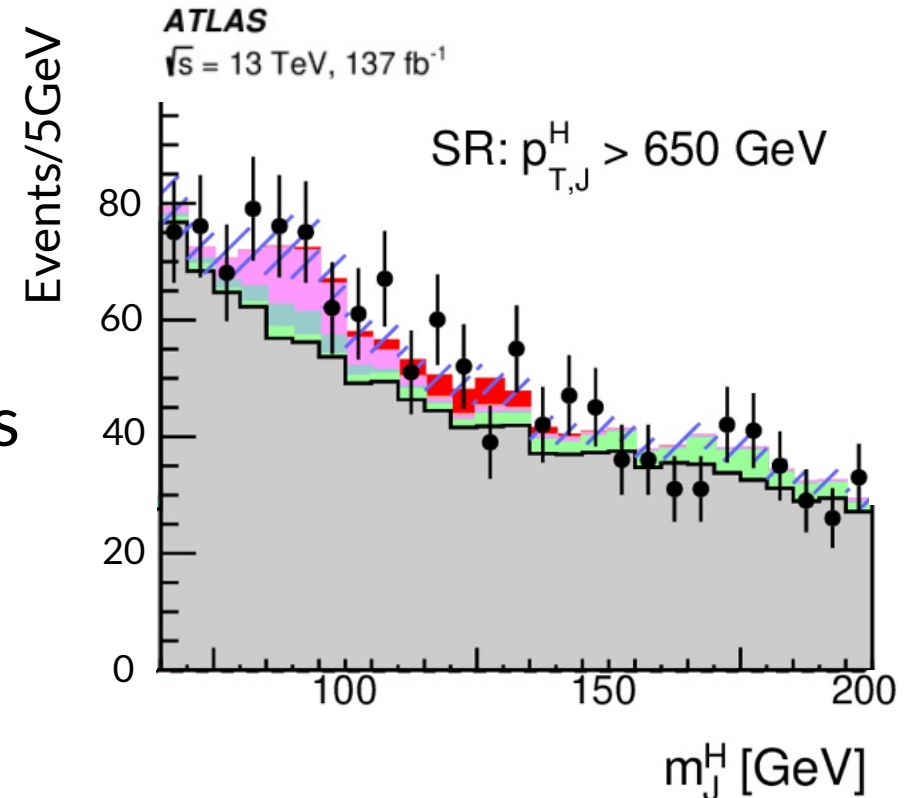
*SR: Signal Region
*CR: Control Region



Signal Region: Signal & Background Composition

Background dominated by multijets production (**90%**)

- $t\bar{t}$ (5%), VV(0.7%)
 - V+jets (3.6%): used as validation of multijets background method
- The key is to have full control of multijets background estimation
- Two **data-driven** estimations in place



Analysis Strategy

$H \rightarrow b\bar{b}$ tagger

Pass

SR

VR

60% WP

Validate multi-jet background estimation method

Fail

CR

Derive multi-jets background

Pass

50% WP

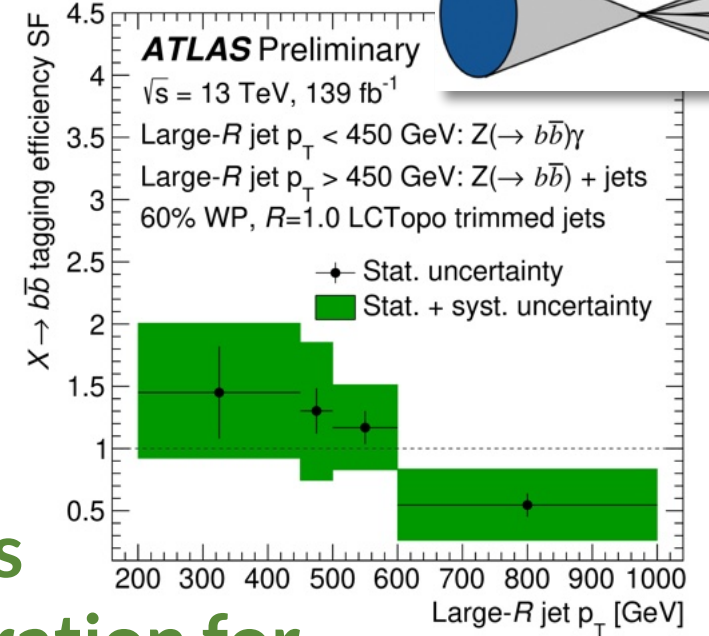
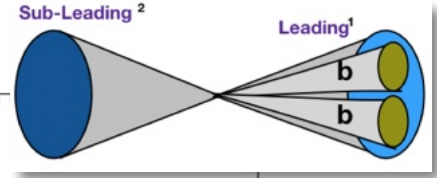
80% WP

Fail

V tagger

- *SR: Signal Region
- *CR: Control Region
- *VR: Validation Region

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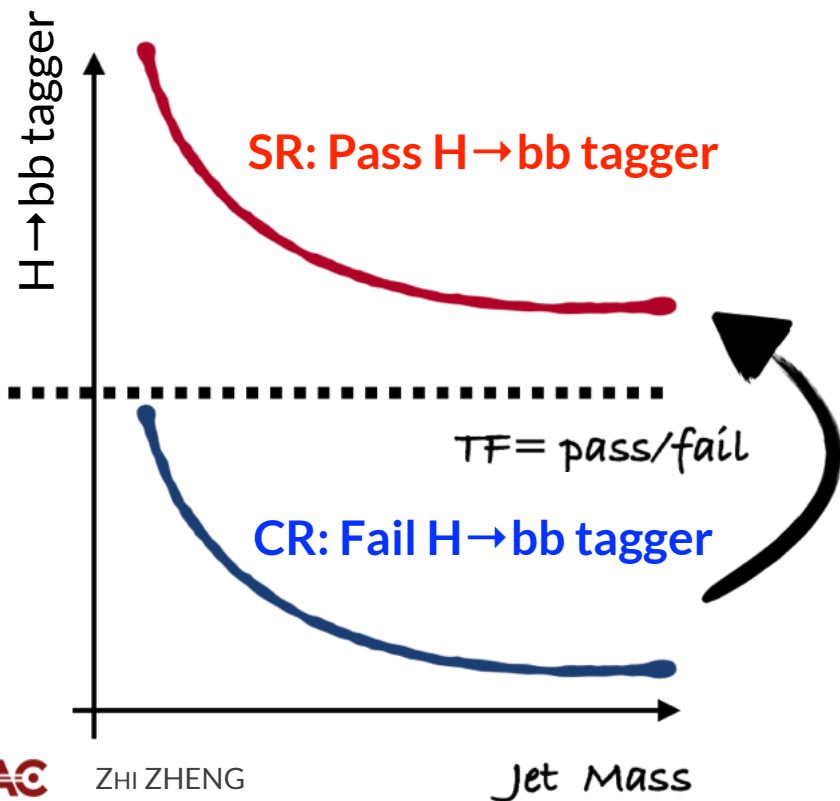


Z+jets
 Calibration for
 $H \rightarrow b\bar{b}$ tagger

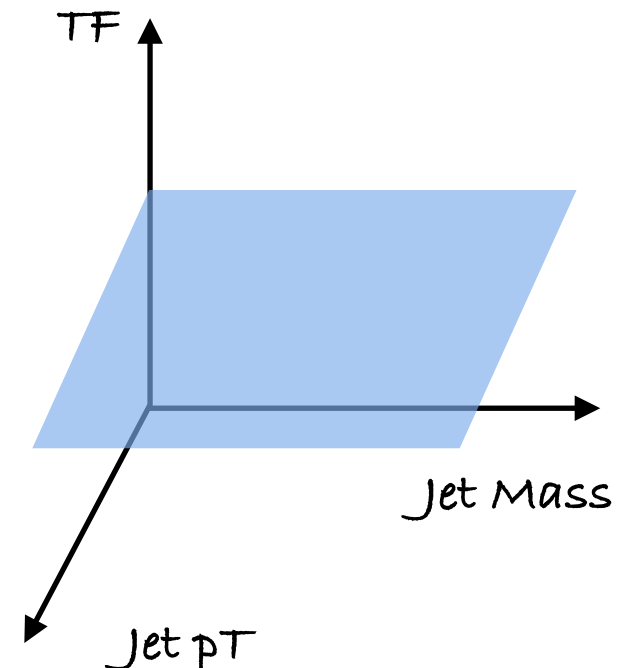
Multijets Background Estimation

Aim to predict the multijet mass distribution in the pass $H \rightarrow bb$ tagger region using events in fail $H \rightarrow bb$ tagger region:

$$\text{Signal Region (SR)} = \text{Control Region (CR)} \times \text{Transfer Factor (TF)}$$

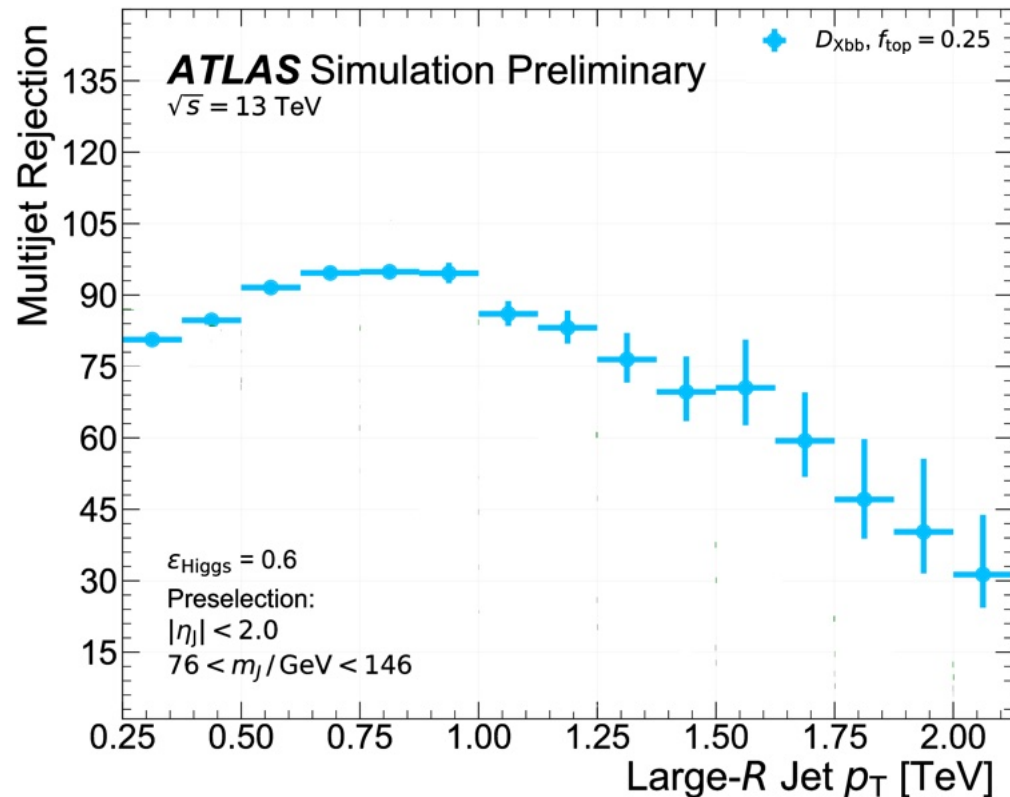


TF as a function of Jet mass m and p_T



Multijets Background Estimation

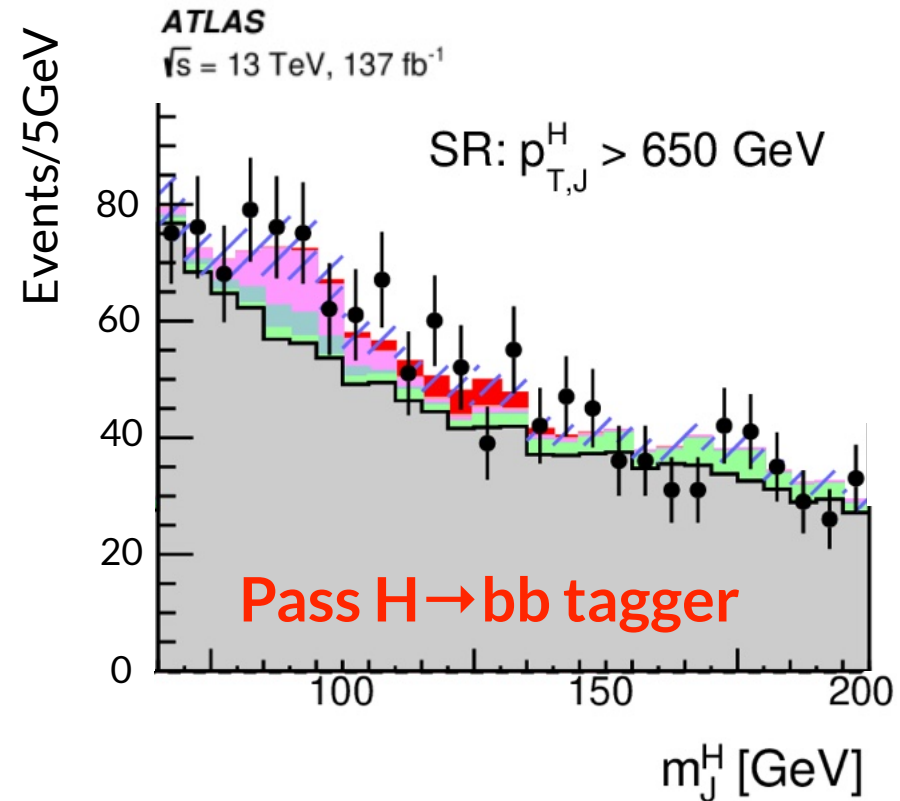
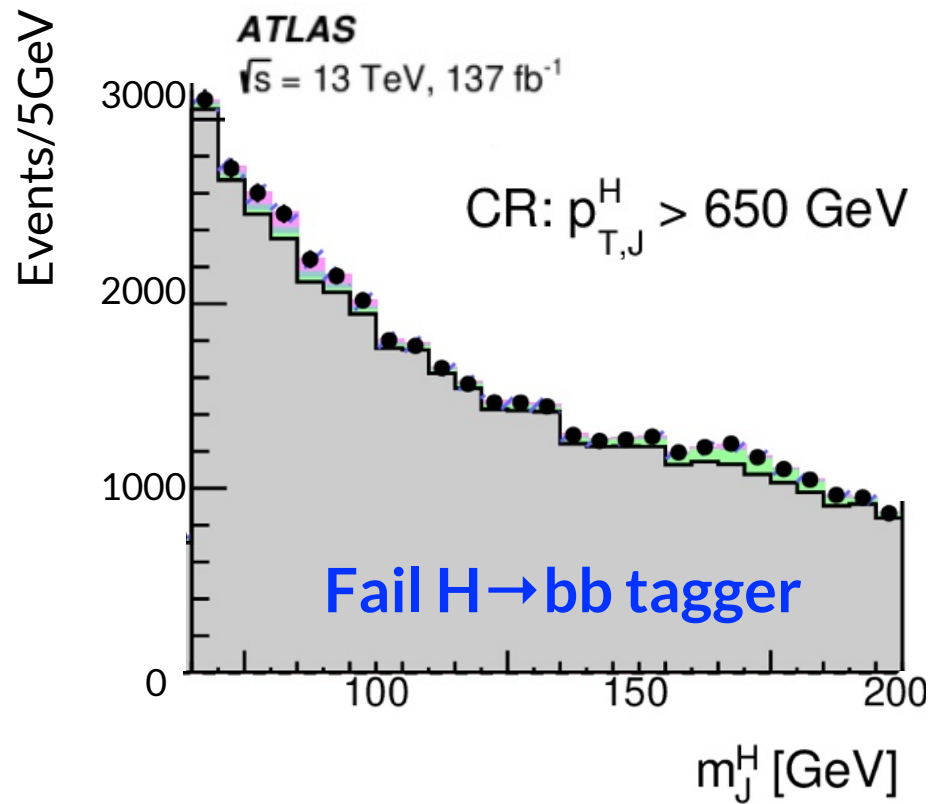
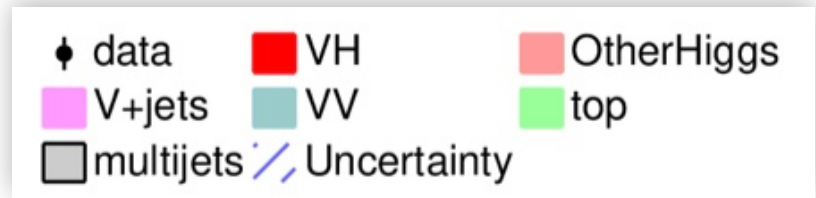
Aim to predict the multijet mass distribution in the pass $H \rightarrow bb$ tagger region using events in fail $H \rightarrow bb$ tagger region:



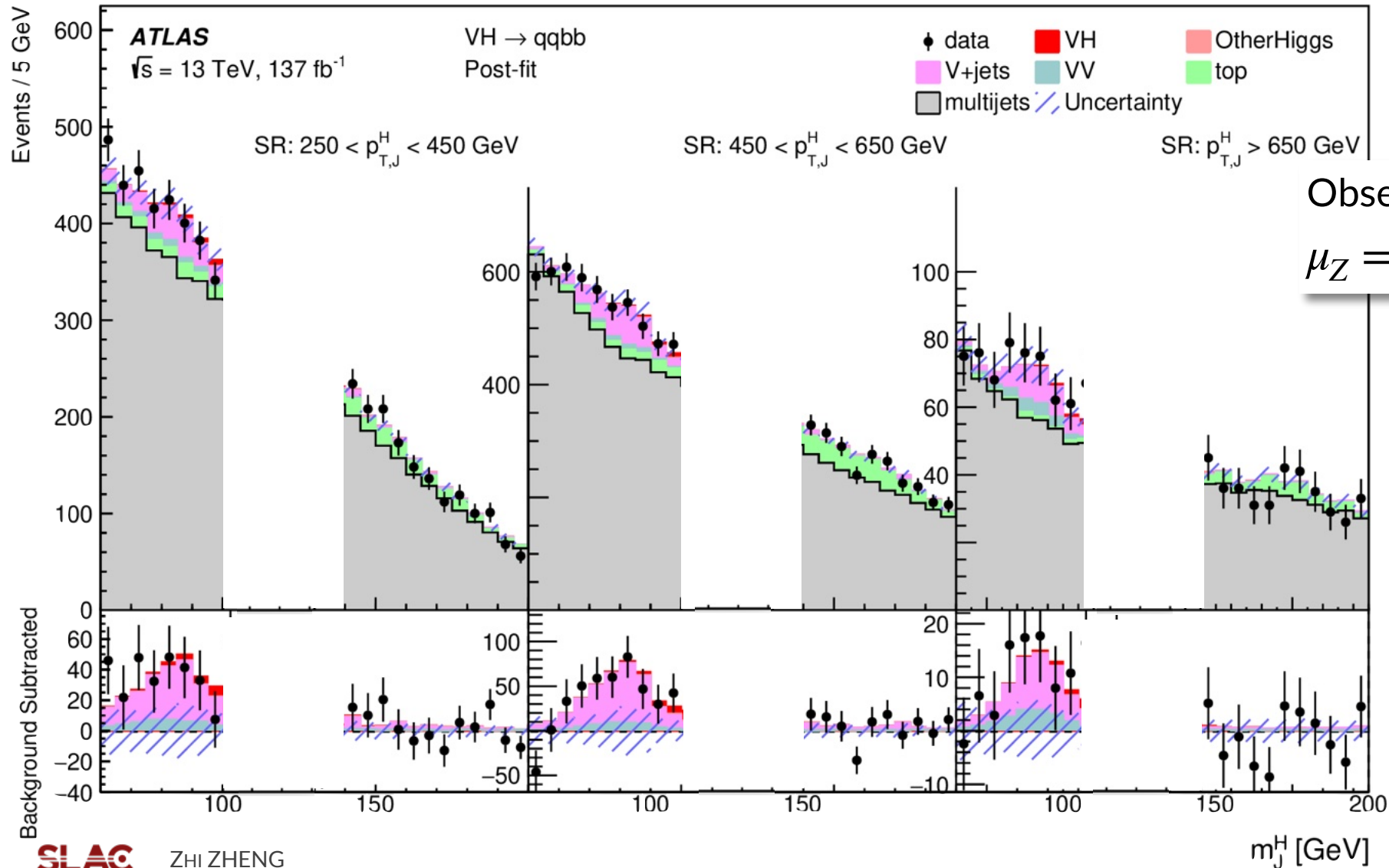
$H \rightarrow bb$ tagger has some correlation with jet p_T and mass and thus TF shows

- TF as a function of $\rho = \log(m^2/p_T^2)$ and p_T
- Polynomial order determined via Fisher F-test
 - 1 st in both p_T and ρ

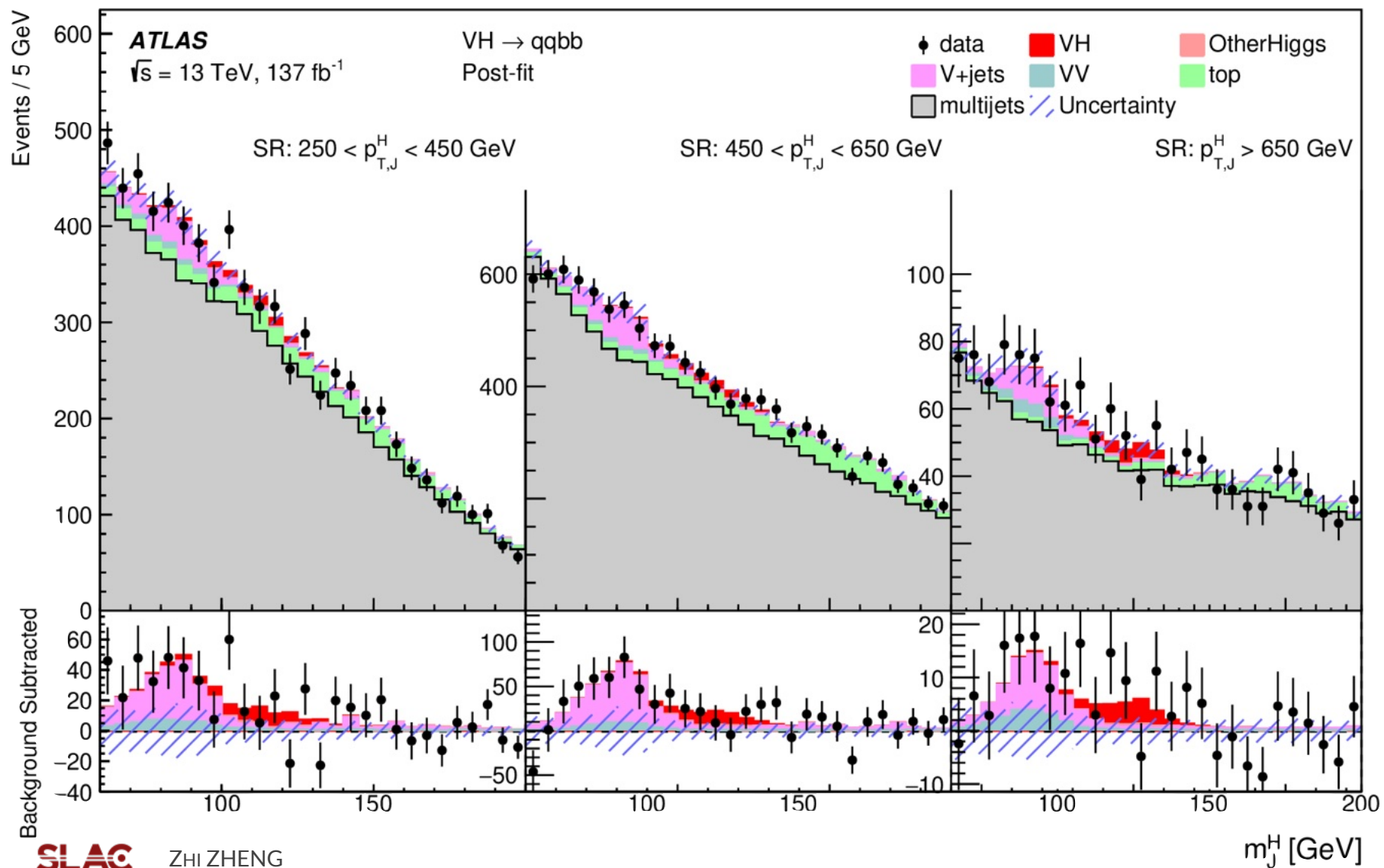
Multijets Background Estimation: CR & SR



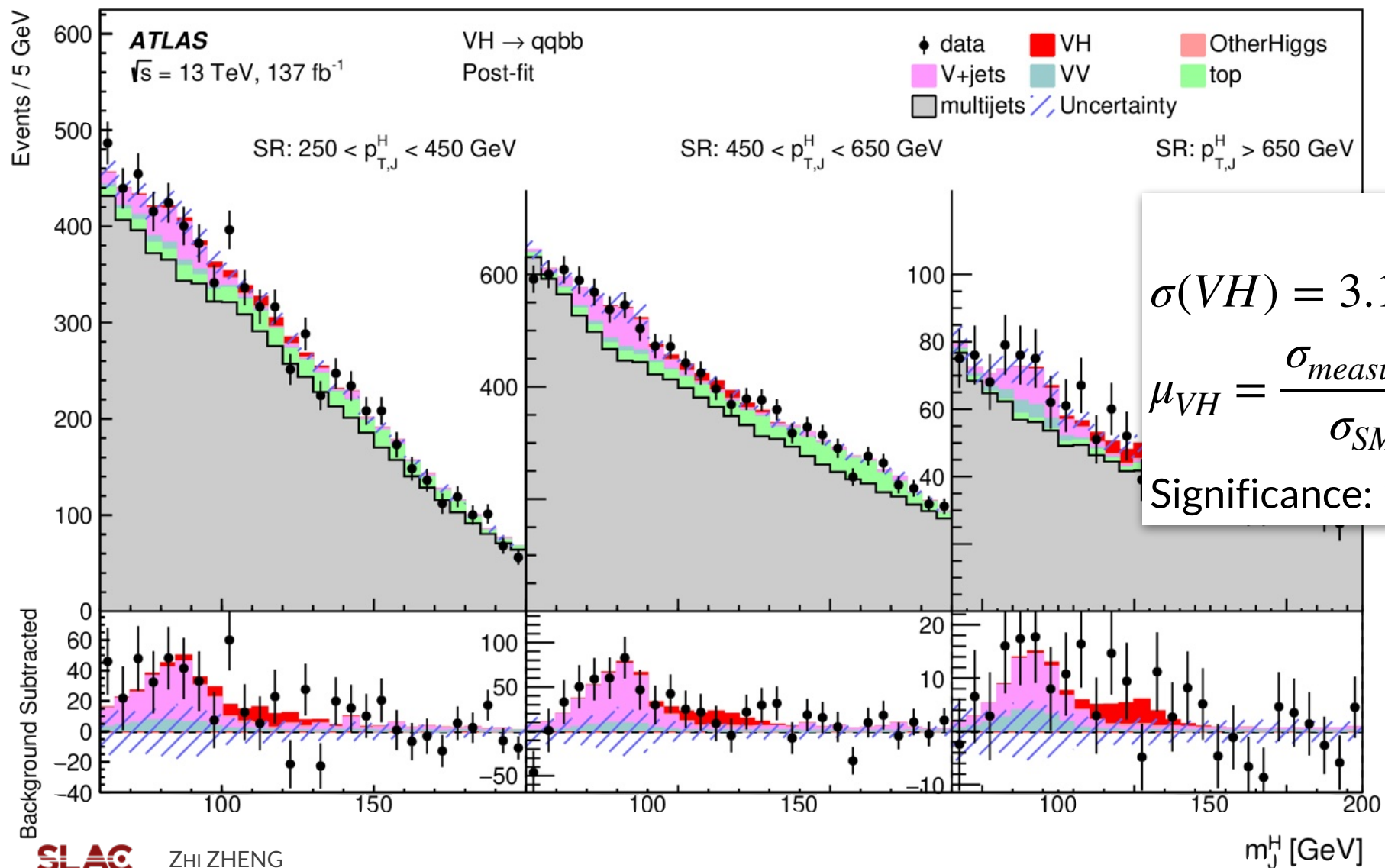
Multijets Background Estimation: Z+Jets Validation



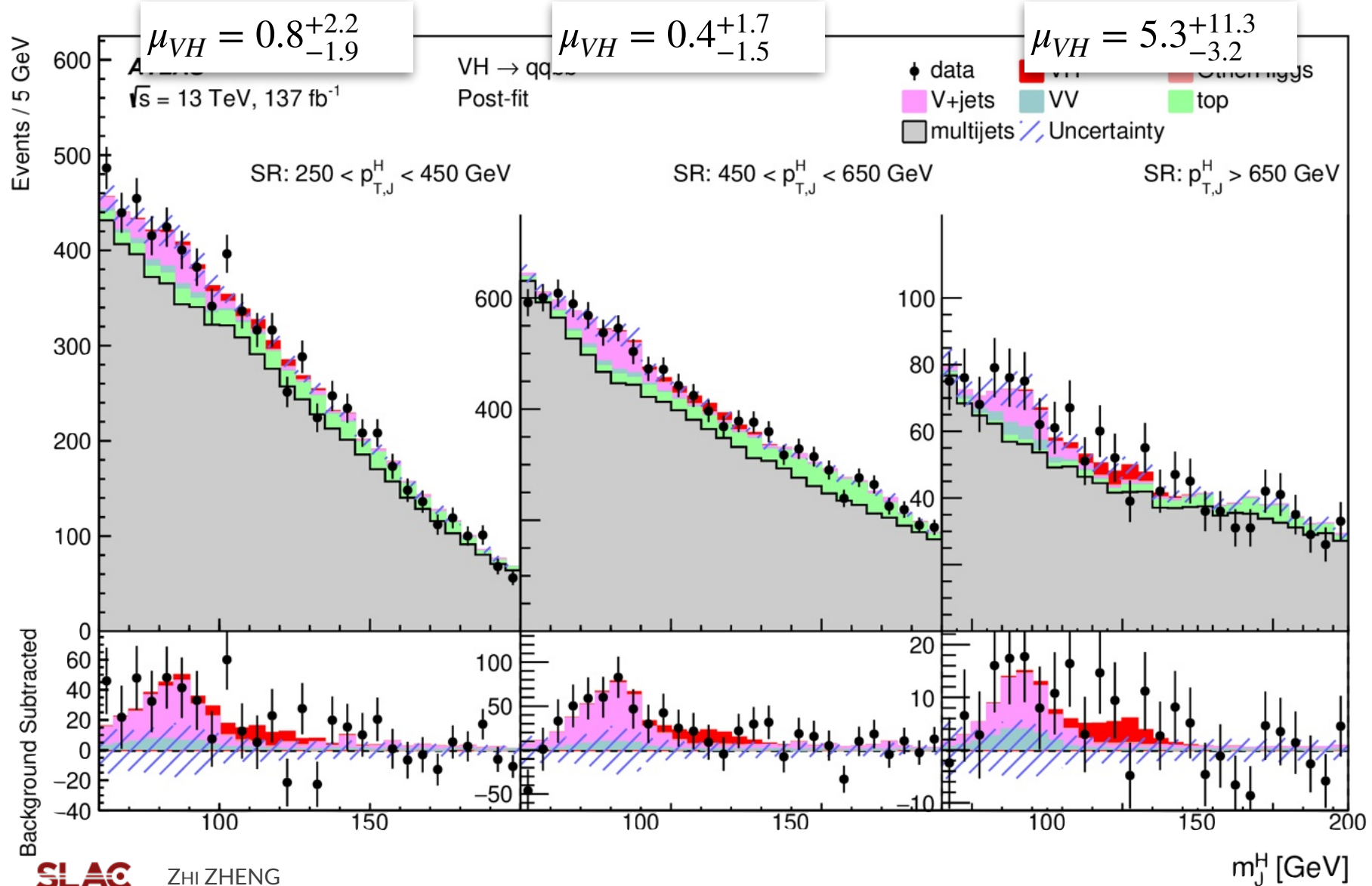
First Measurement of VH in Full Hadronic Channel



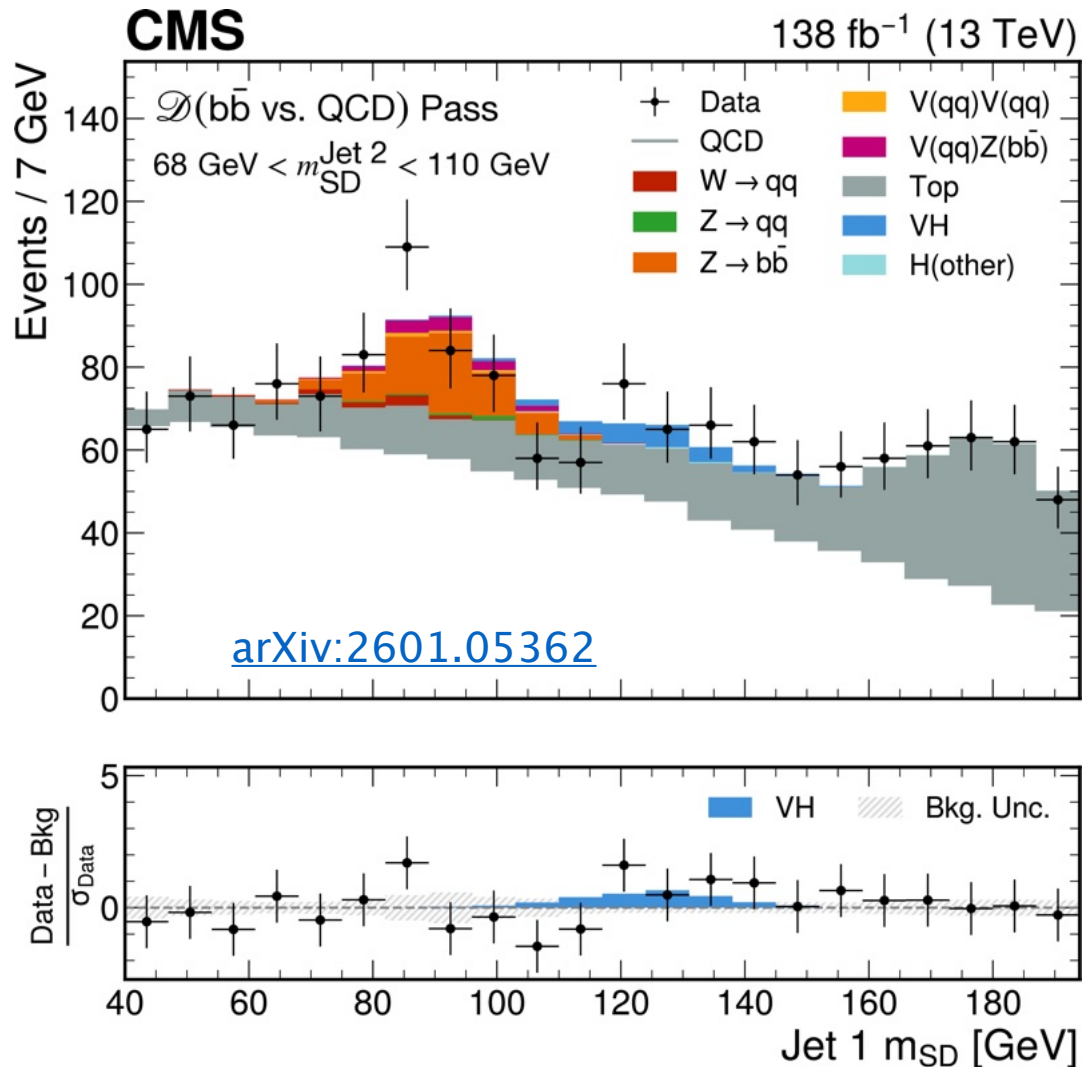
First Measurement of VH in Full Hadronic Channel



First Measurement of VH in Full Hadronic Channel



First Measurement of VH in Full Hadronic Channel



CMS

$$\mu_{VH} = \frac{\sigma_{\text{measured}}(VH)}{\sigma_{SM}(VH)} = 0.72^{+0.75}_{-0.71}$$

Significance: 1 σ

ATLAS

$$\sigma(VH) = 3.1 \pm 1.3(\text{stat})^{+1.8}_{-1.4}(\text{syst}) \text{ pb}$$

$$\mu_{VH} = \frac{\sigma_{\text{measured}}(VH)}{\sigma_{SM}(VH)} = 1.39^{+1.02}_{-0.88}$$

Significance: 1.7 σ

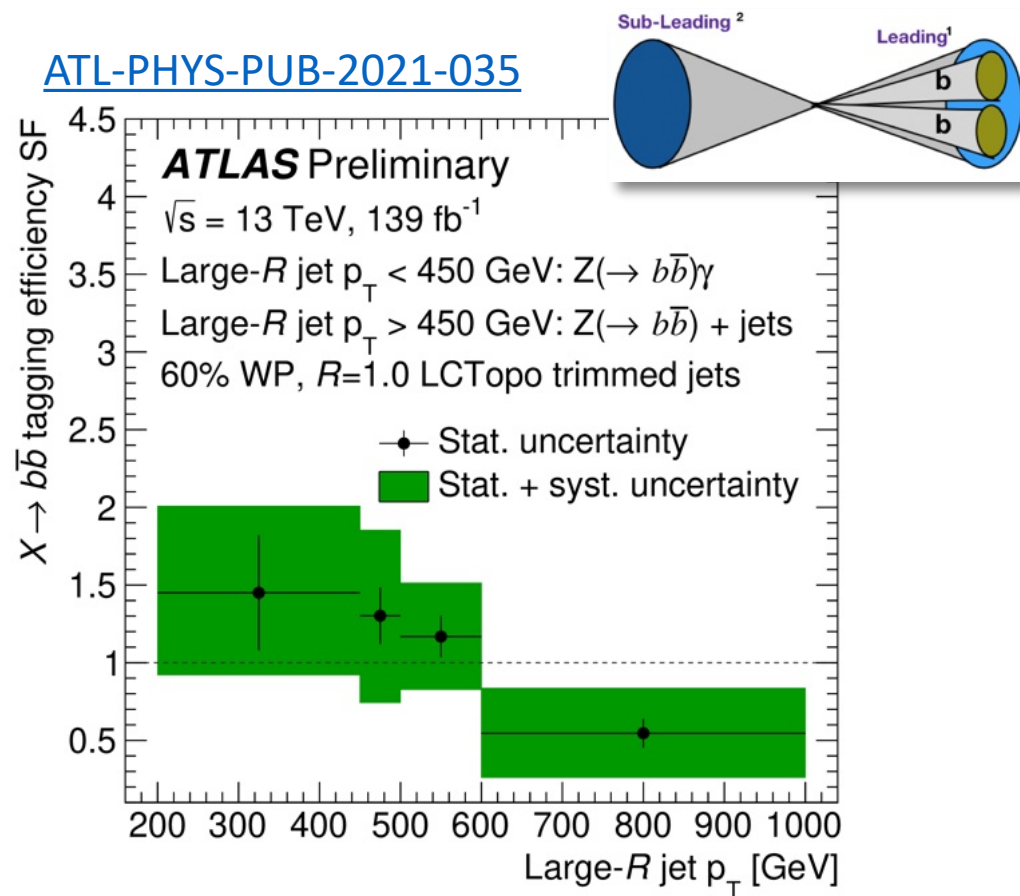
What is next:

Uncertainty source	$\delta\mu$
Signal modeling	+0.10 -0.02
MC statistical uncertainty	+0.13 -0.13
Instrumental (pileup, luminosity)	+0.012 -0.004
Large- R jet	+0.13 -0.14
Top-quark modeling	+0.14 -0.15
Other theory modeling	+0.05 -0.03
$H \rightarrow b\bar{b}$ tagging	+0.52 -0.23
Multijet estimate (TF uncertainty)	+0.52 -0.41
Multijet modeling (TF vs. BDT)	+0.14 -0.18
Total systematic uncertainty	+0.80 -0.61
Signal statistical uncertainty	+0.60 -0.60
Z +jets normalization	+0.42 -0.20
Total statistical uncertainty	+0.63 -0.63
Total uncertainty	+1.02 -0.88

What is next: $H \rightarrow bb$ tagger calibration

Uncertainty source	$\delta\mu$
Signal modeling	+0.10 -0.02
MC statistical uncertainty	+0.13 -0.13
Instrumental (pileup, luminosity)	+0.012 -0.004
Large- R jet	+0.13 -0.14
Top-quark modeling	+0.14 -0.15
Other theory modeling	+0.05 -0.03
$H \rightarrow b\bar{b}$ tagging	+0.52 -0.23
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Z +jets normalization	+0.42 -0.20
Total statistical uncertainty	+0.63 -0.63
Total uncertainty	+1.02 -0.88

[ATL-PHYS-PUB-2021-035](#)



Limited by statistics

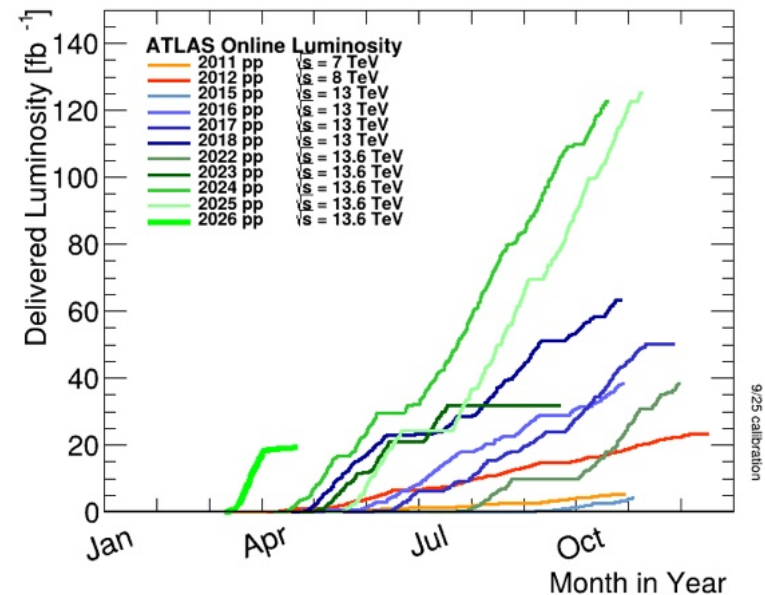
What is next:

Uncertainty source	$\delta\mu$
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Total uncertainty	+1.02 -0.88

Shape of multijets data-driven estimate :

- Statistical nature \rightarrow will decrease if we have more data

$\sim 2\times$ Data (18M Higgs) collected by the end of 2026



What is next:

Uncertainty source	$\delta\mu$
Signal modeling	+0.10 -0.02
MC statistical uncertainty	+0.13 -0.13
Instrumental (pileup, luminosity)	+0.012 -0.004
Large- R jet	+0.13 -0.14
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Shape of multijets data-driven estimate :

- Statistical nature
- Depend on the TF correlation to jet mass and p_T

$$N_{\text{pass}}^{\text{QCD}}(p_{T_i}, m_j) = \sum_{k,l} \alpha_{kl} \rho_{ij}^{kl} p_{T_i} \times N_{\text{fail}}^{\text{QCD}}(p_T, m)$$

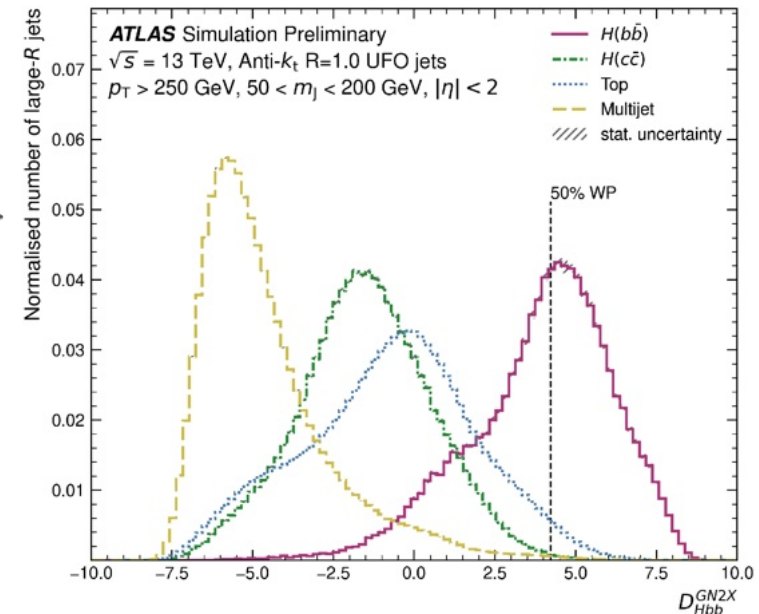
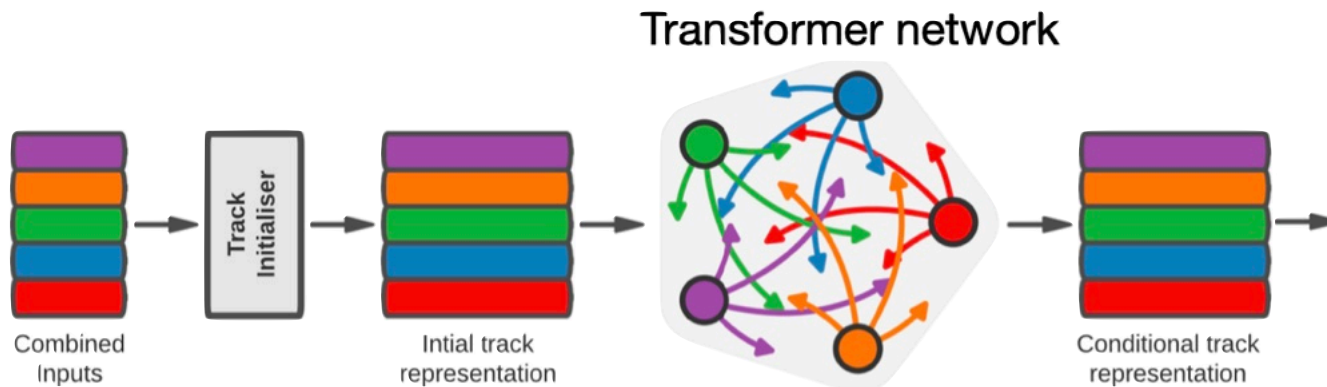
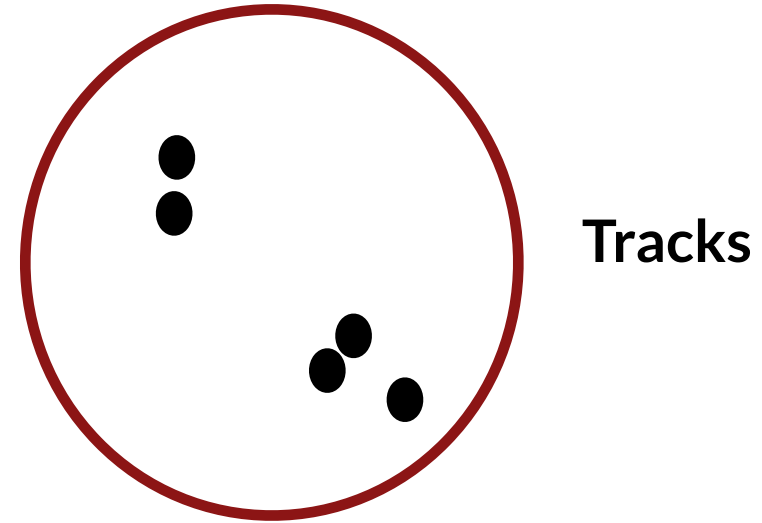
Lower order of α_{kl} means less uncertainty from TF method

Need a $H \rightarrow b\bar{b}$ tagger depends less on jet mass and p_T

What is next: Better $H \rightarrow bb$ Tagger

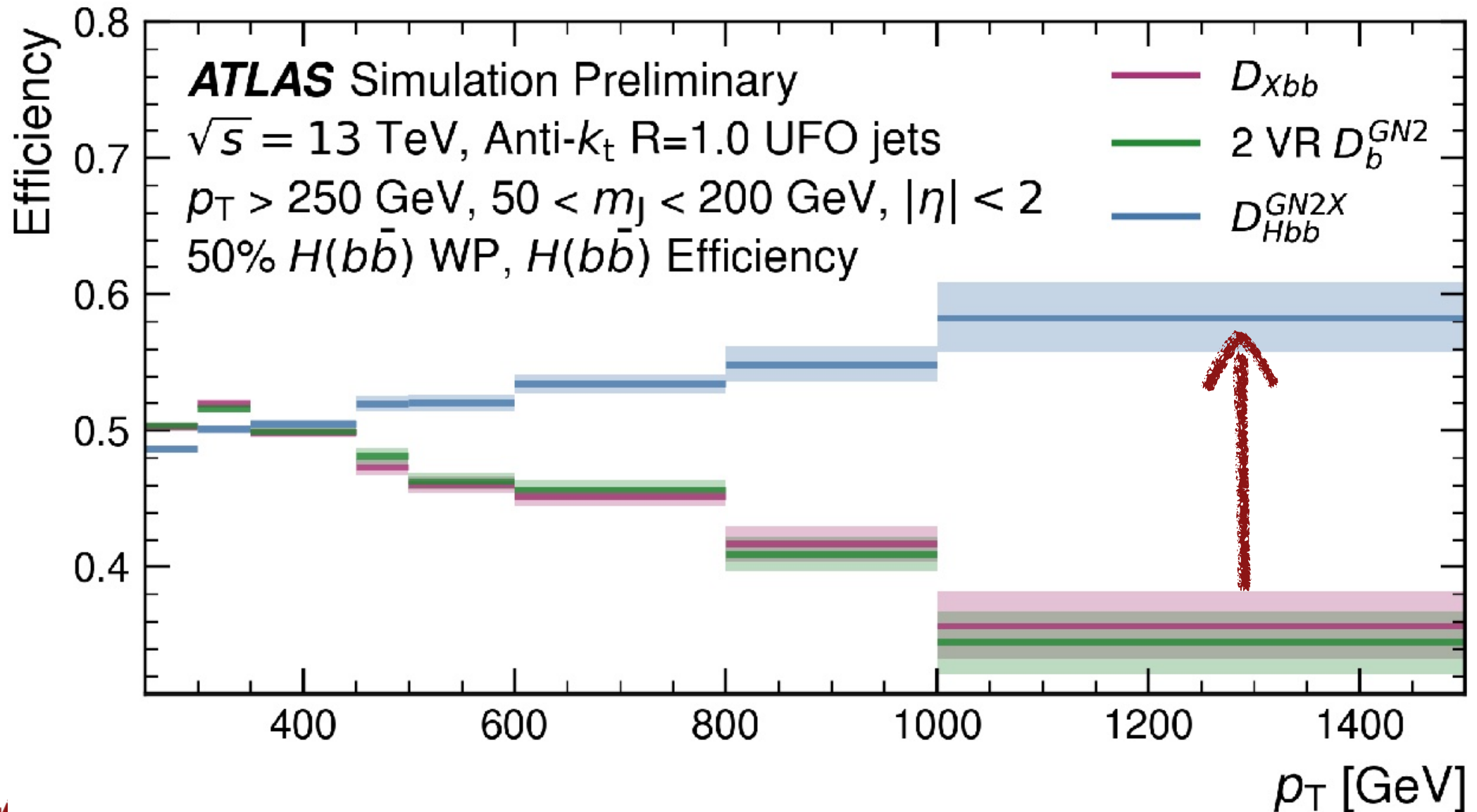
Identify Higgs: [ATL-PHYS-PUB-2023-021](#)

Transformer network using jet features and track features



What is next: Better $H \rightarrow b\bar{b}$ Tagger

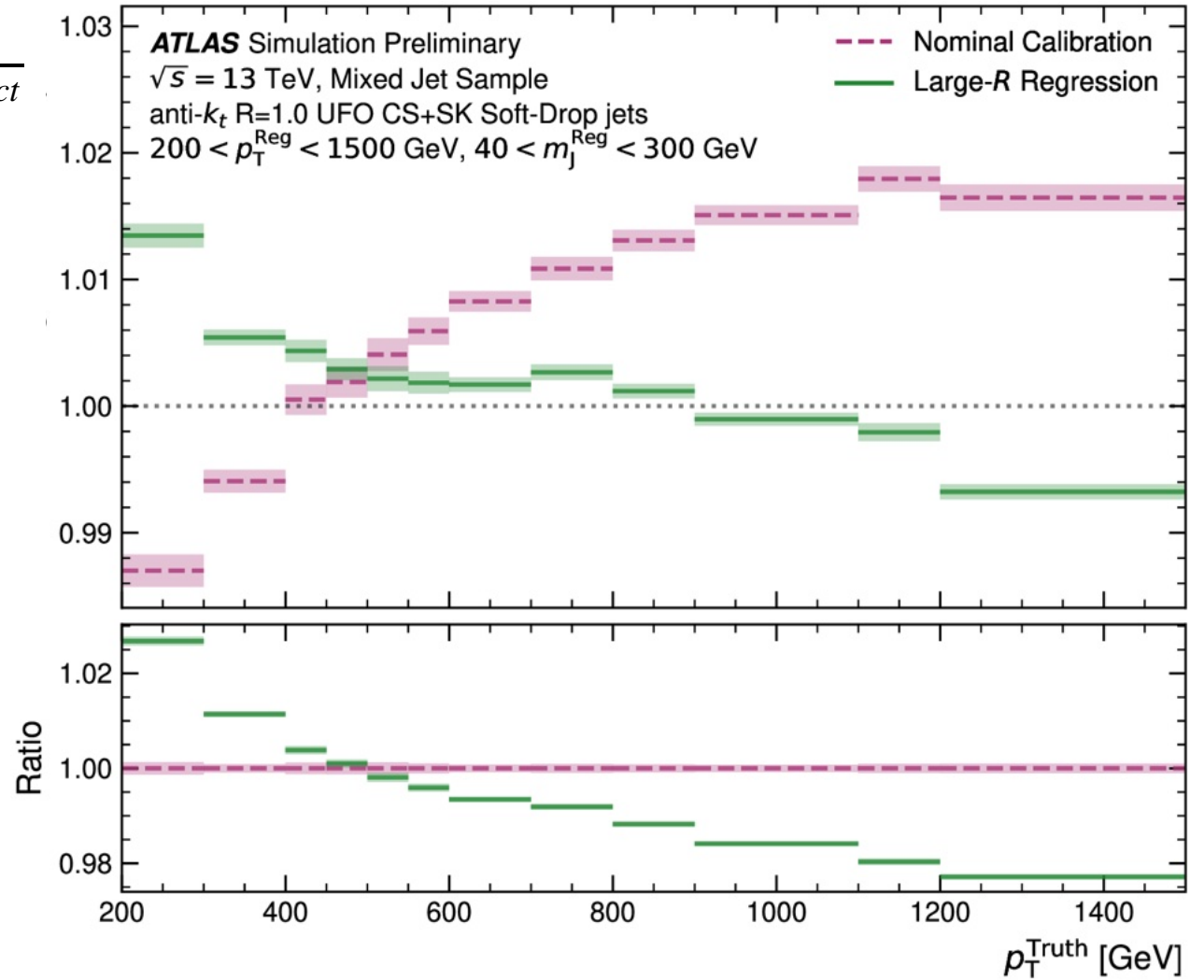
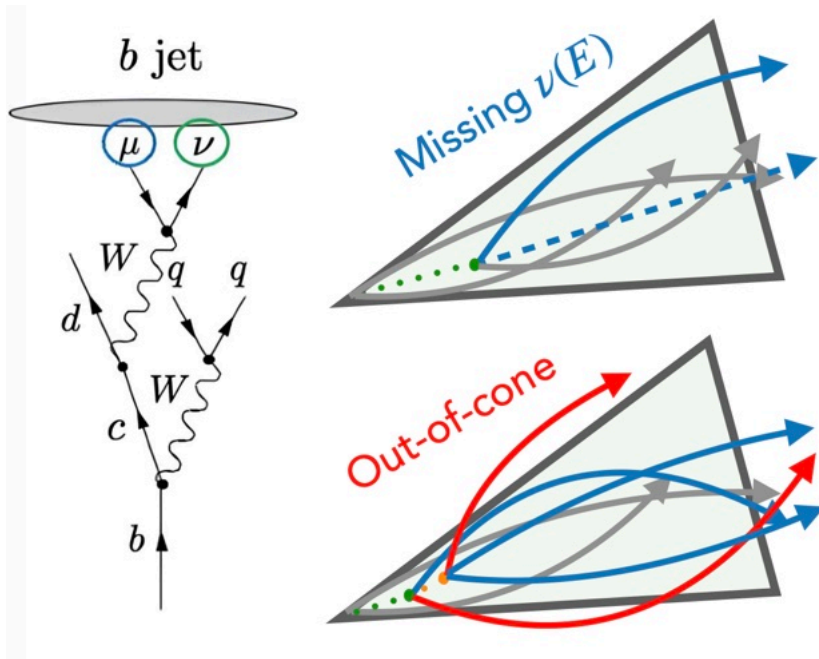
ATL-PHYS-PUB-2023-021



What is next: Better Resolution

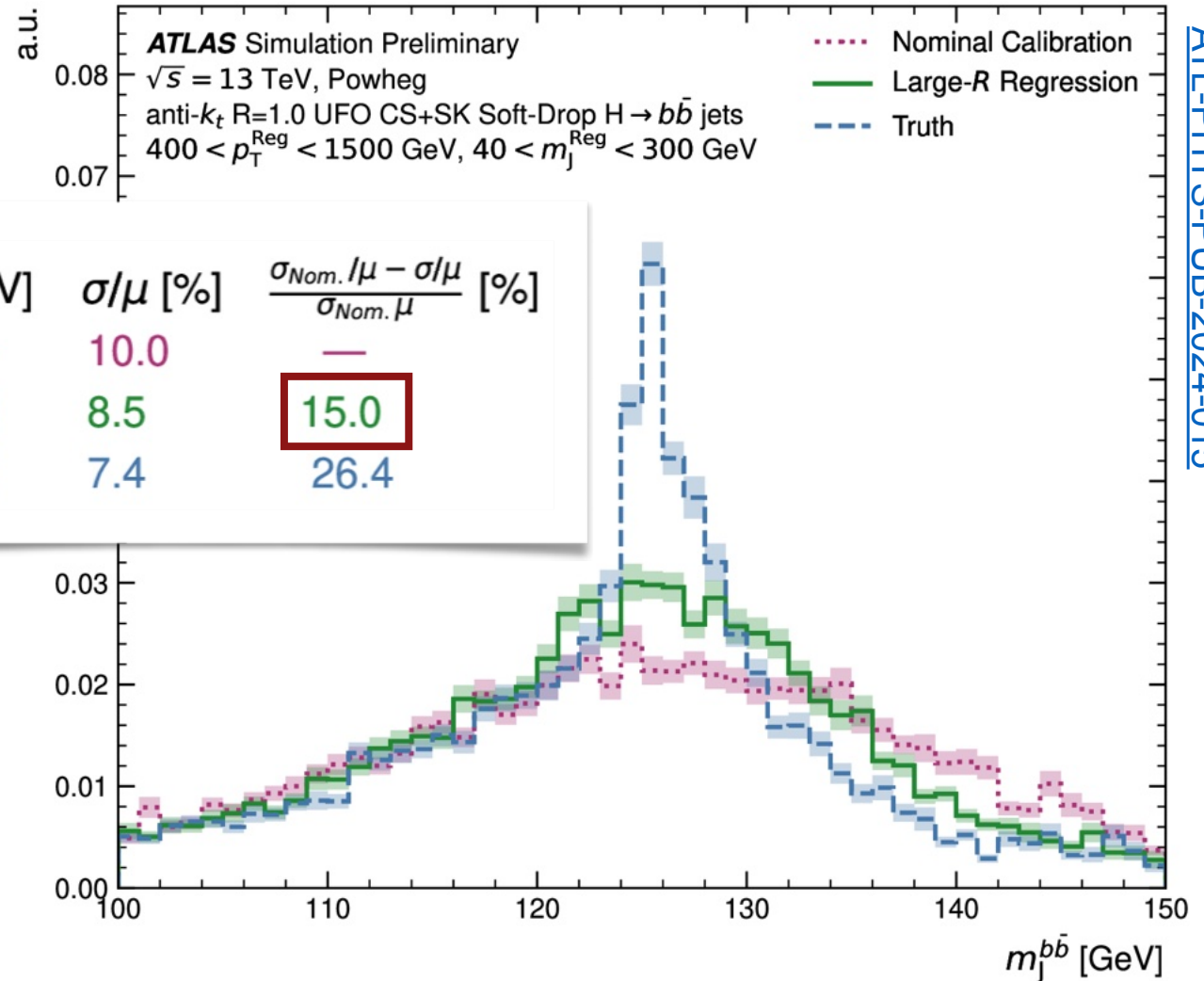
How to improve b-jets resolution?

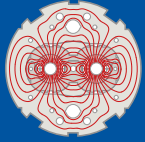
$$\frac{m_J^{truth}}{m_J^{reconstruct}}$$



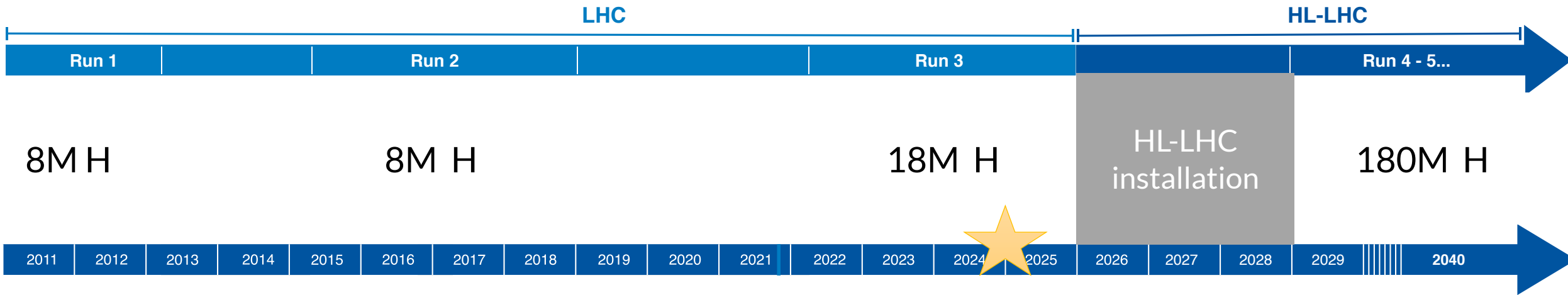
What is next: Better Resolution

Transformer based calibration drastically improves resolution



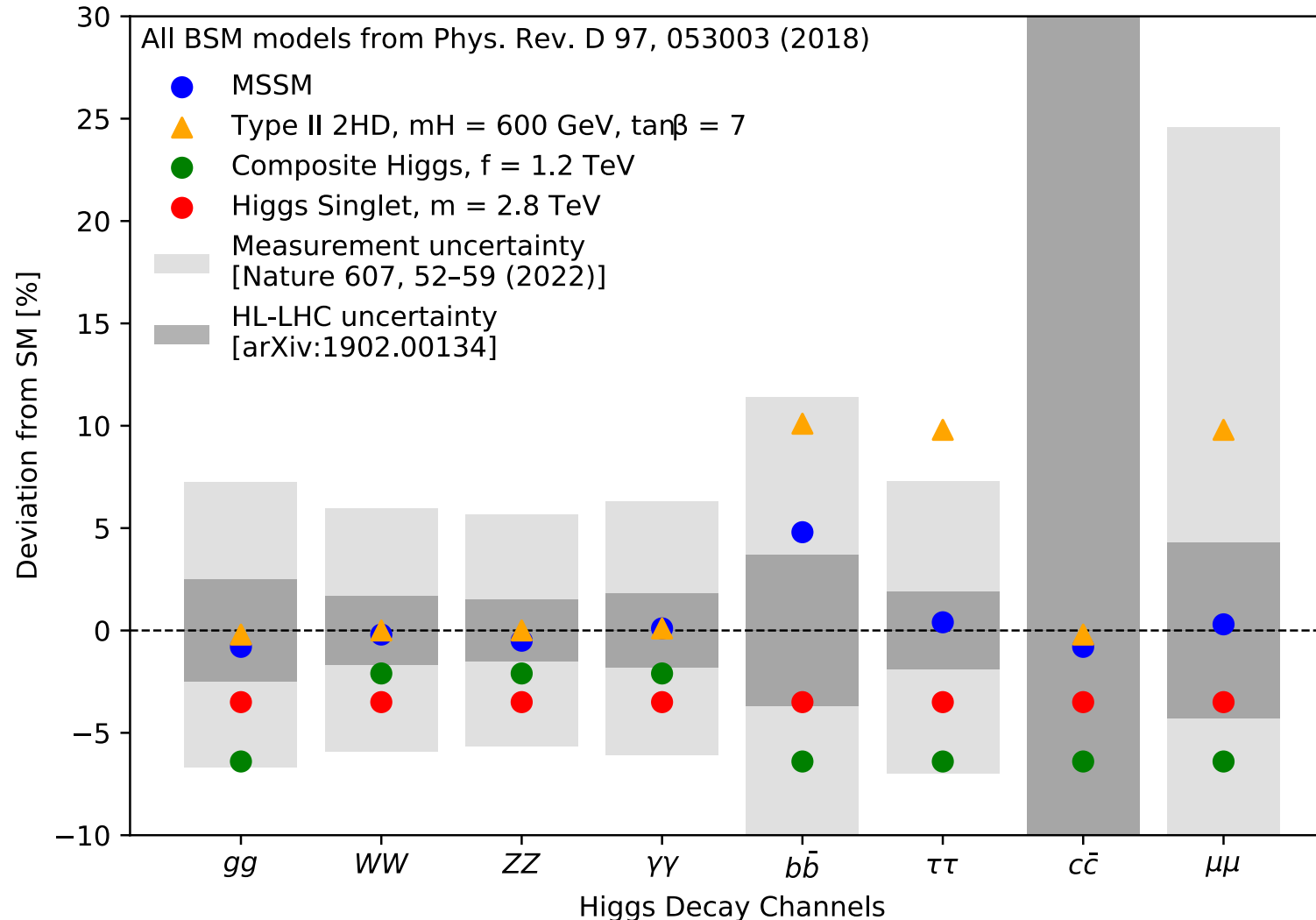


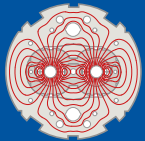
LHC / HL-LHC Plan



LHC → HL-LHC: Coupling

With 20× more data, Higgs couplings reach precision ~ 5%





LHC / HL-LHC Plan



LHC

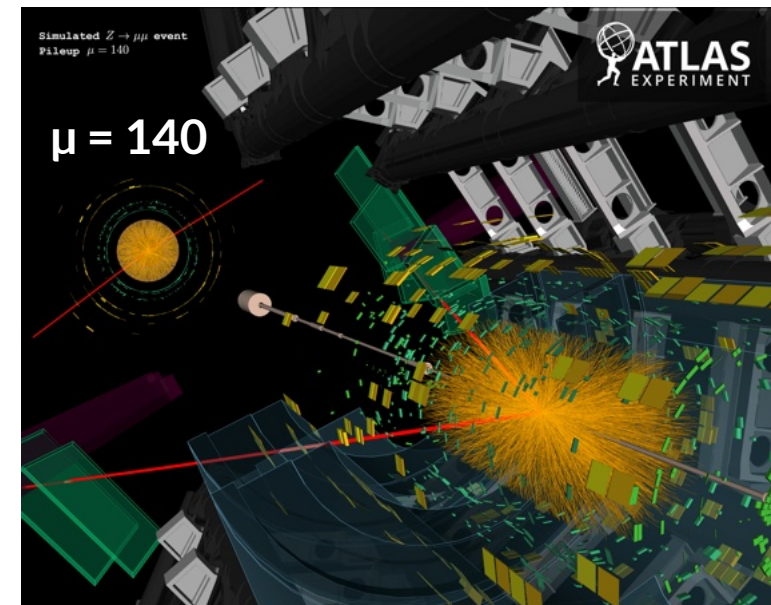
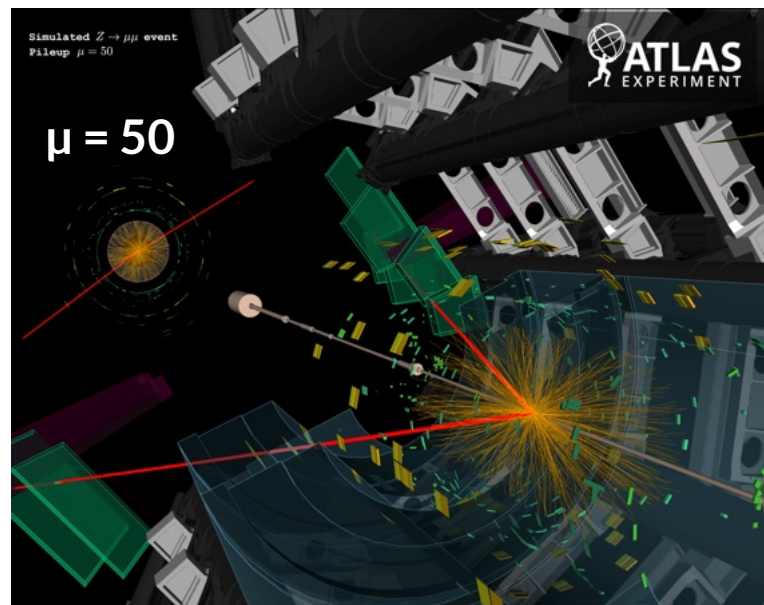
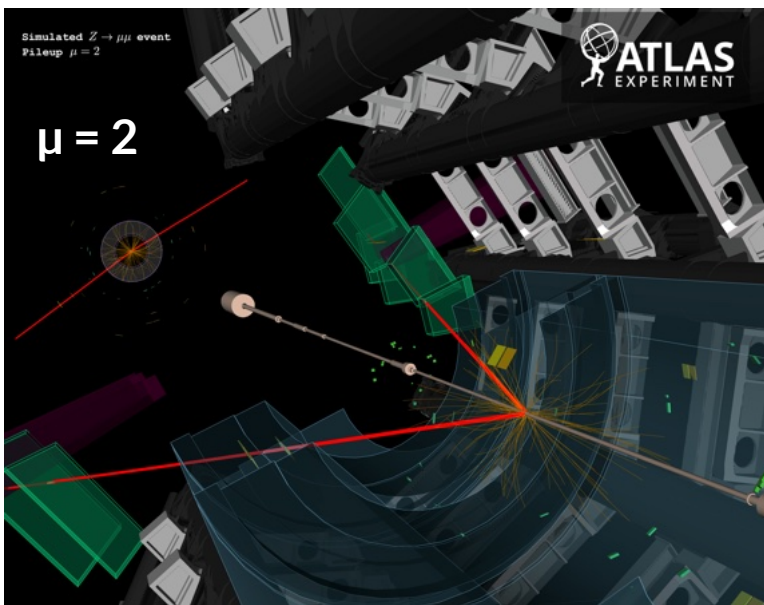
HL-LHC

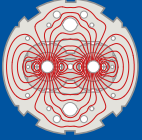
Run 1

Run 2

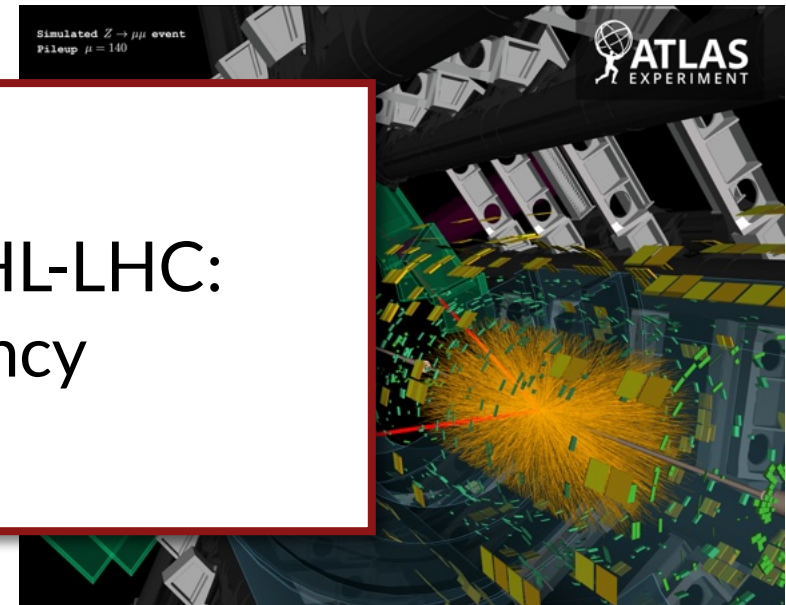
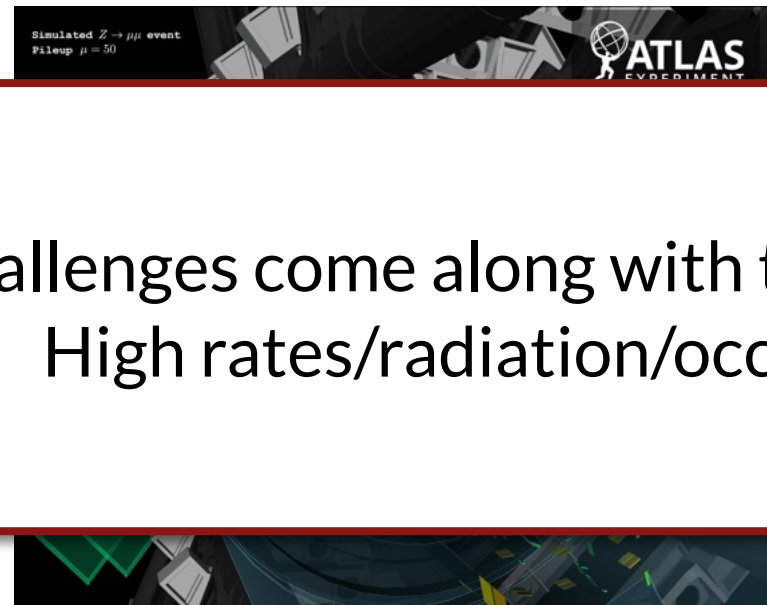
Run 3

Run 4 - 5...





LHC / HL-LHC Plan

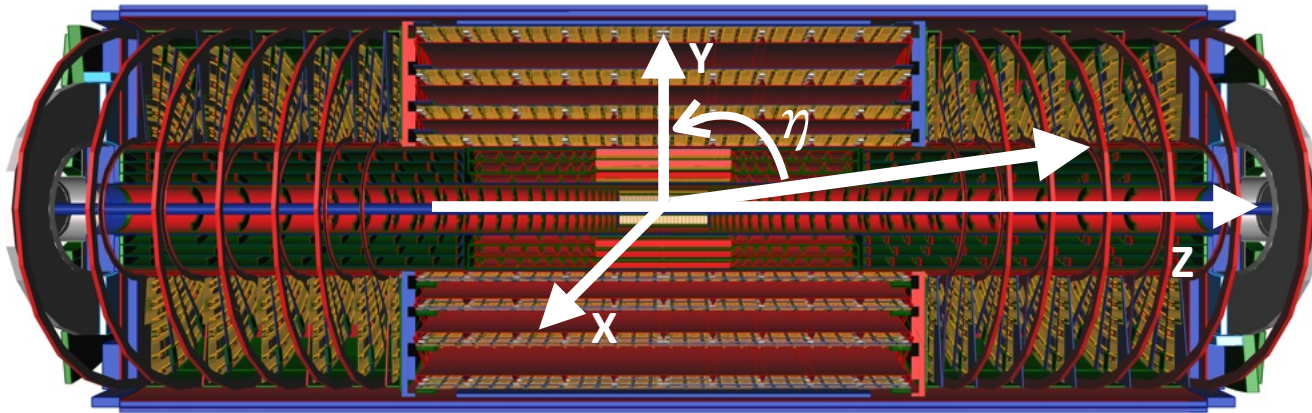


Challenges come along with the HL-LHC:
High rates/radiation/occupancy

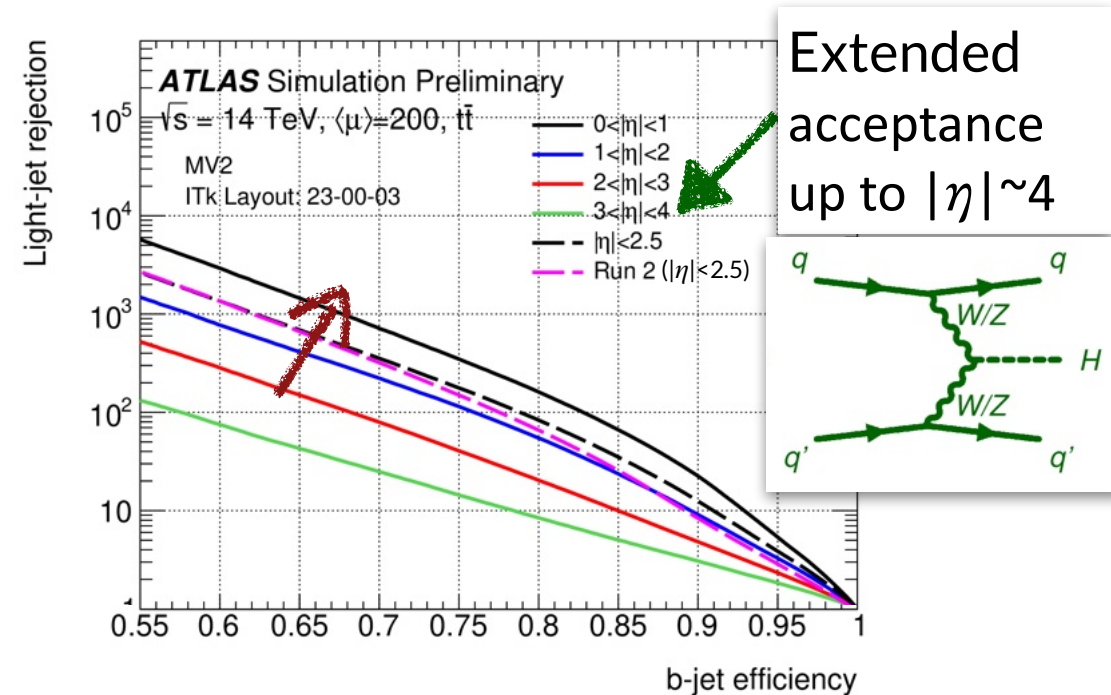
The Upgrade of the Pixel Detector for the HL-LHC

A new, whole-silicon, tracker (ITk) • to maintain physics performance in the harsher HL-LHC environment

Maintain/improve tracking, vertexing, b/c-tagging performance with ITk



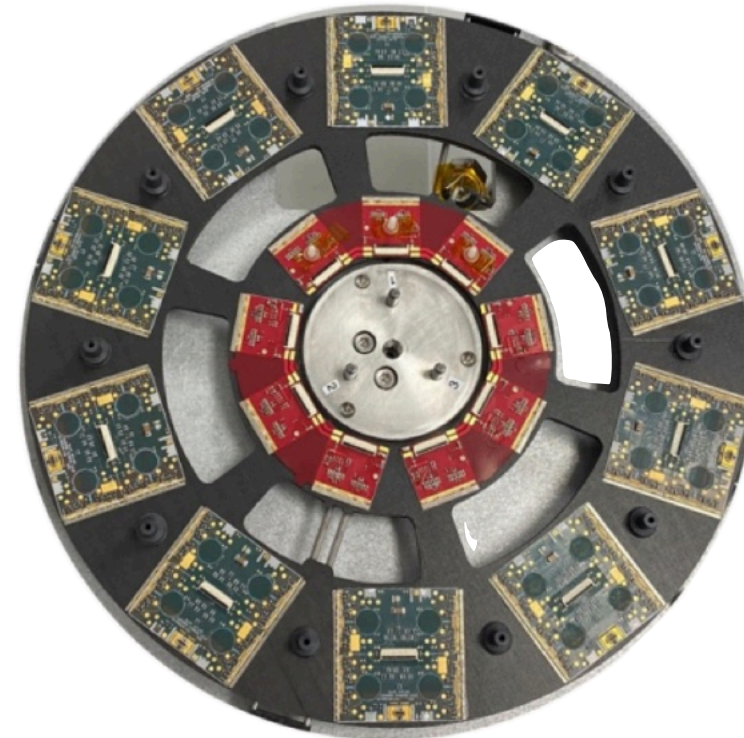
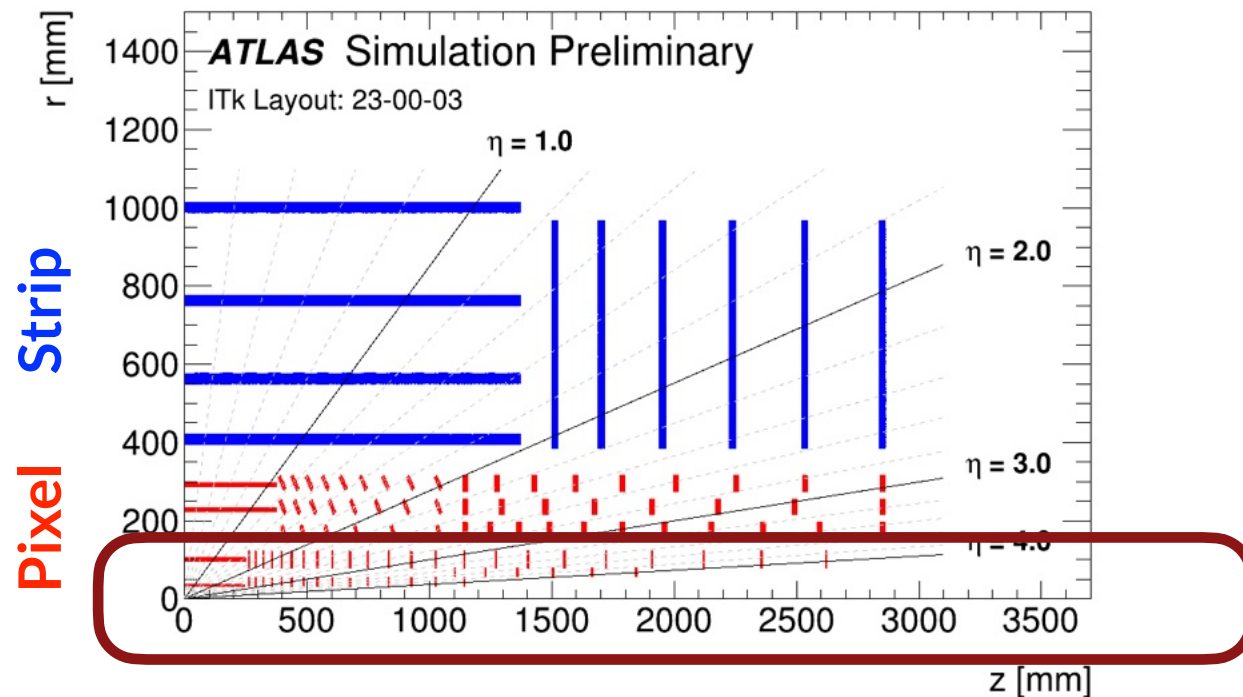
[ATL-PHYS-PUB-2021-024](#)



The Upgrade of the Pixel Detector for the HL-LHC

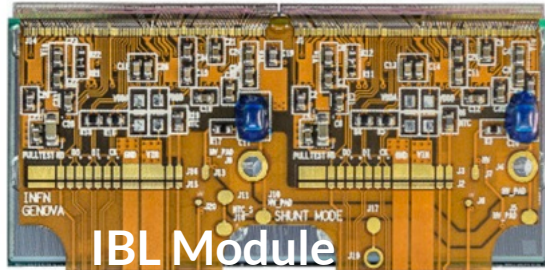
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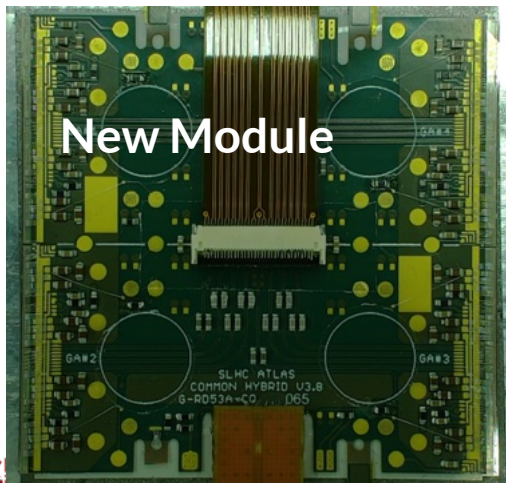
The Upgrade of the Pixel Detector for the HL-LHC

A new, whole-silicon, tracker (ITk) • to maintain physics performance in the harsher HL-LHC environment



Pixel Size

50×250

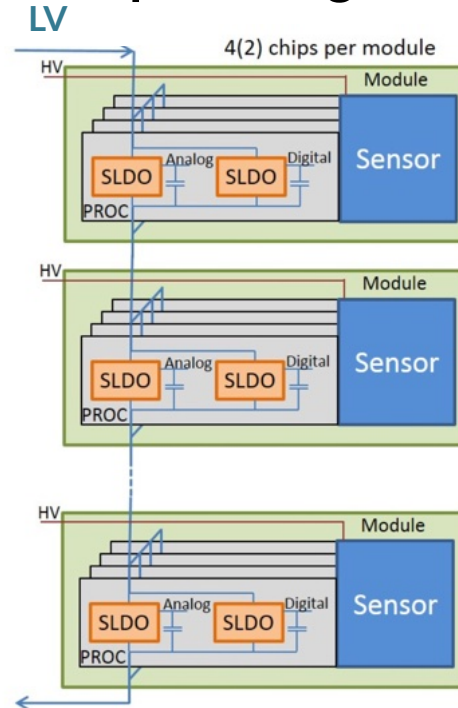


50×50

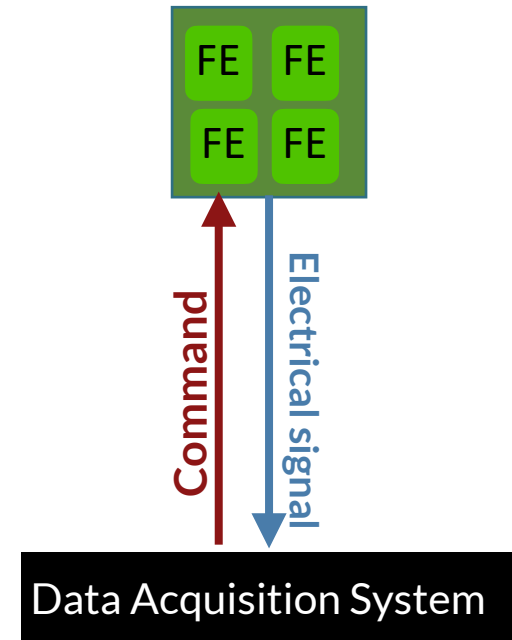
Or

100×25

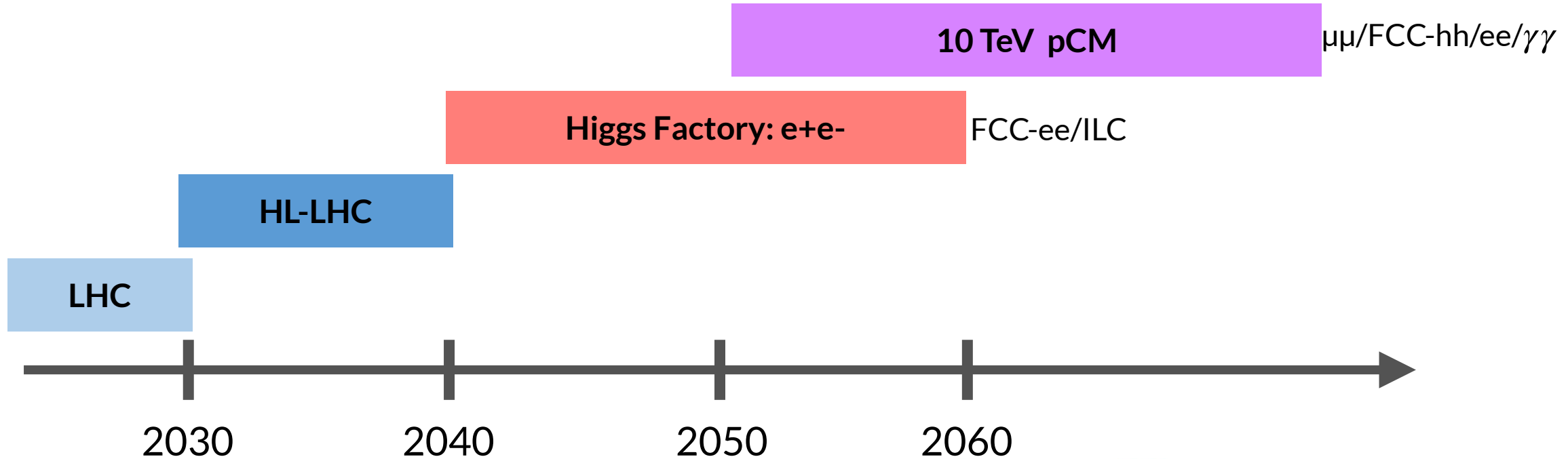
New powering scheme



New Data transmission needs



Beyond HL-LHC



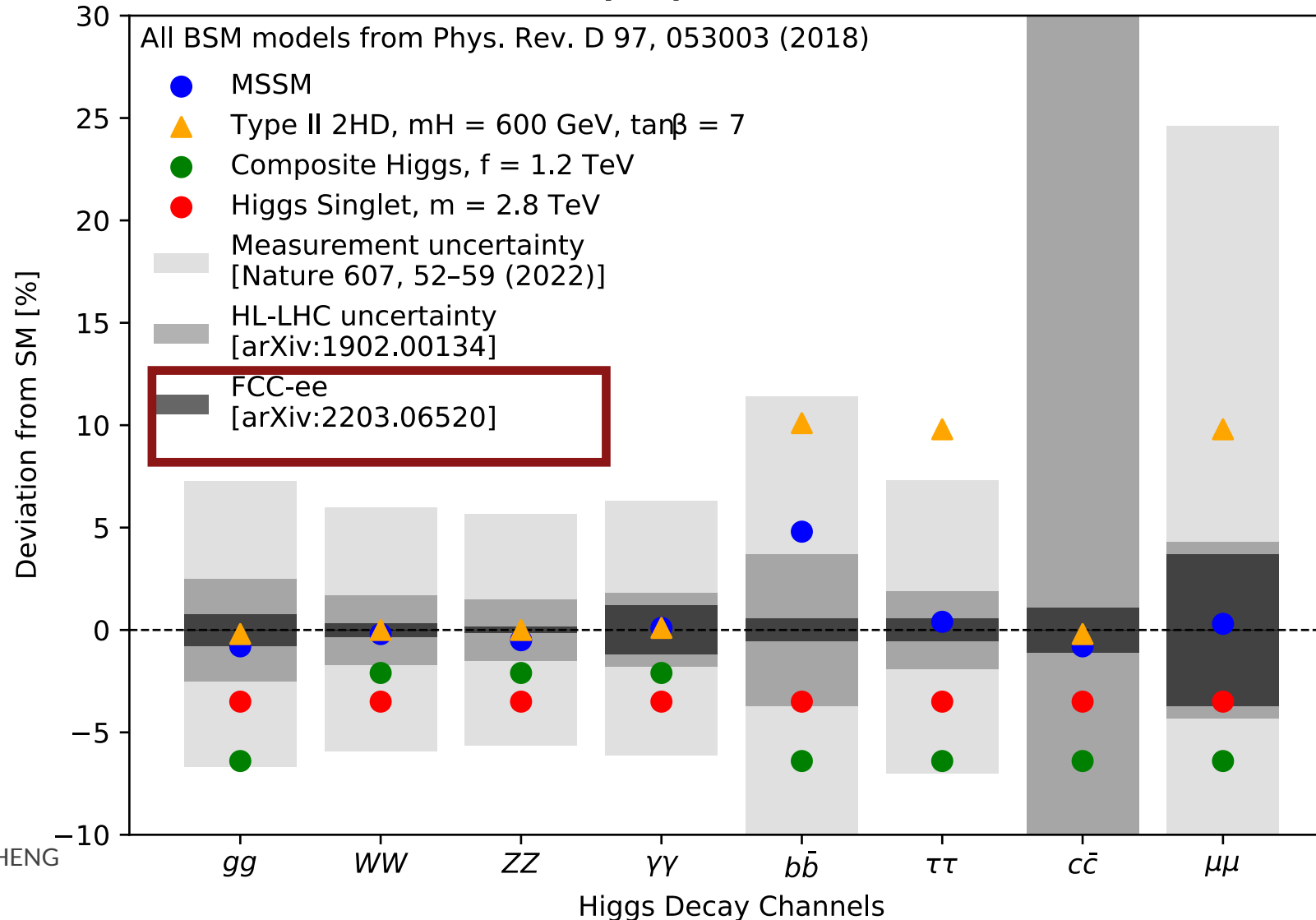
A Higgs factory is the next step toward fully revealing the secrets of the Higgs boson within the quantum realm. We advocate substantial US participation in the design and construction of accelerators and detectors for an offshore facility, and we advocate investment of effort to support development of the Future Circular Collider-electron (e^-) positron (e^+) (FCC-ee) and the International Linear Collider (ILC), along with a parallel and increasingly intensive program of R&D pursuing revolutionary accelerator and detector technologies. These are crucial for a leadership role in the design and construction of the Higgs factory and for our aspiration to lead and potentially host a next high-energy collider facility beyond the Higgs factory.



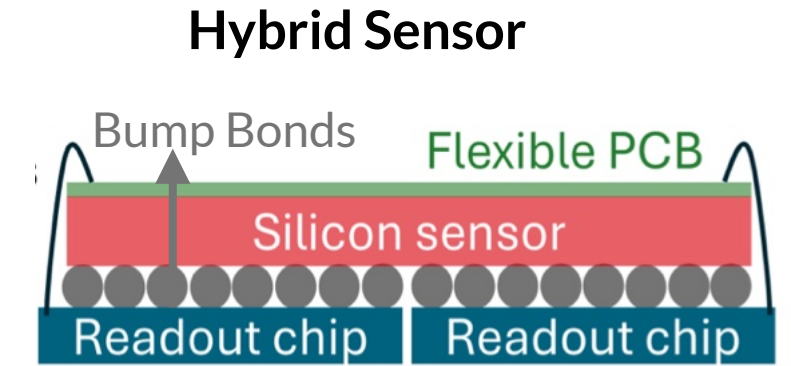
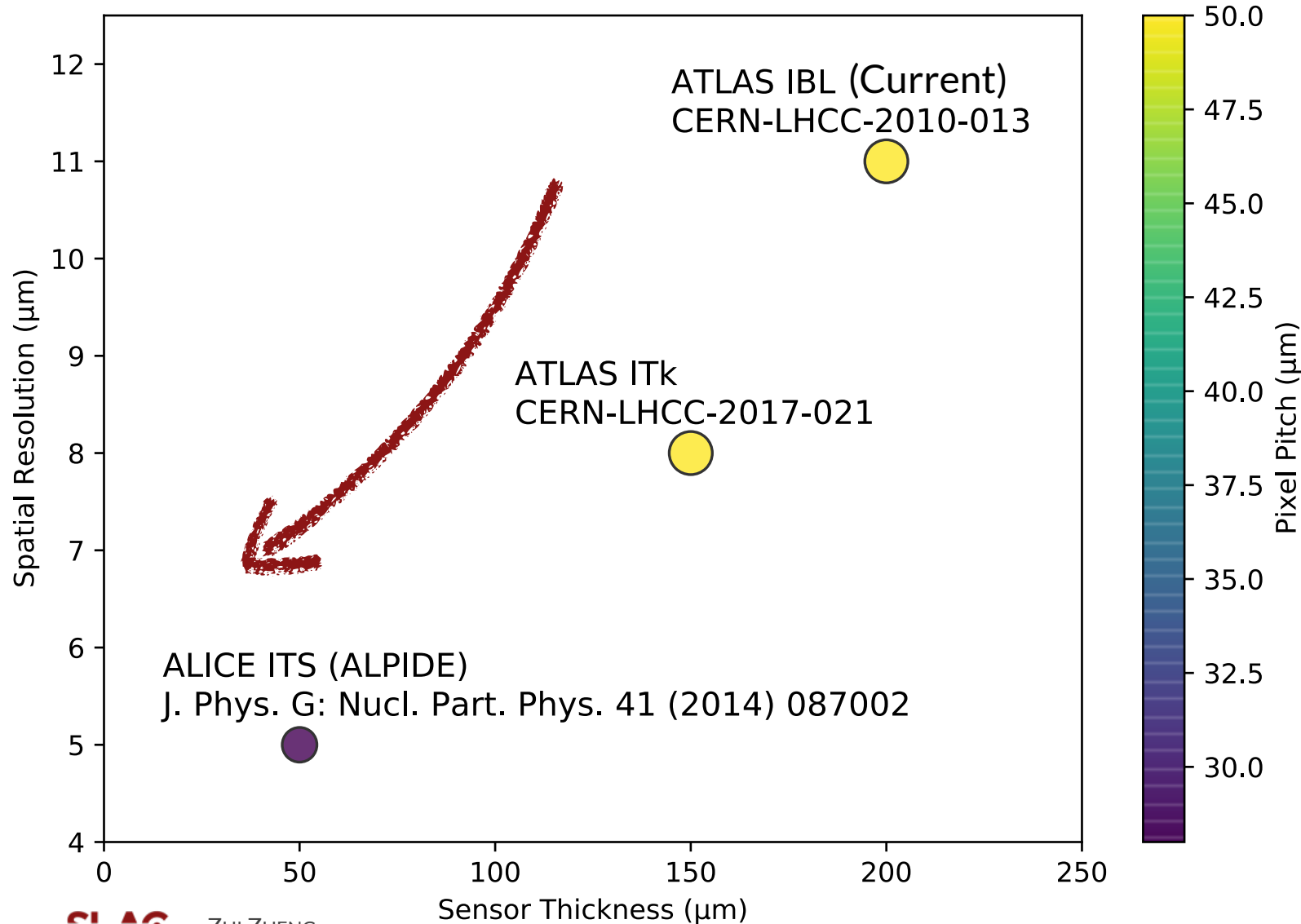
[P5 \(Particle Physics Project Prioritization Panel\)](#)

Beyond HL-LHC

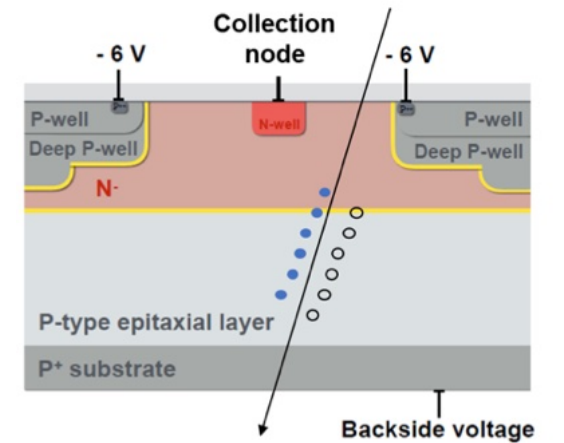
Building a detector to fulfill the physics needs is crucial



How to Make a Better Tracker: Pixel



Monolithic Active Pixel Sensor (ITS)



Summary

Precision measurements of Higgs properties may reveal new physics

- **Boosted Higgs** is a promising tool to unveil the BSM
- Advancements in **jet techniques** and **machine learning** are opening new opportunities in boosted Higgs studies

The coming decades promise exciting developments in Higgs physics

- The HL-LHC will deliver 20× more data, making **detector upgrades** essential for survival in this challenging environment
- Long term planning for **future experimental programs** is already underway

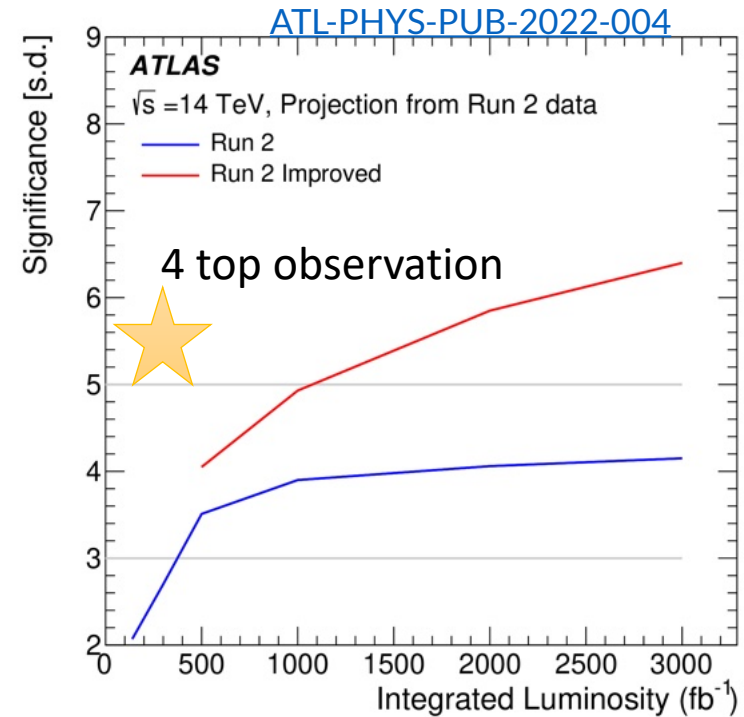
Summary

Precision measurements of Higgs properties may reveal new physics

- Boost
- Adv
- oppo
- The co
- The
- esse
- Long
- unde

Go Beyond Expectations

New Tools, New Strategies
can totally change what
we can learn



new

THANK YOU FOR LISTENING

[Phys. Rev. Lett. 132 \(2024\) 131802](https://arxiv.org/abs/2401.13180)

