Measurements of the Higgs Boson Decay to a Bottom Quak-antiquark Pair with the ATLAS Experiment

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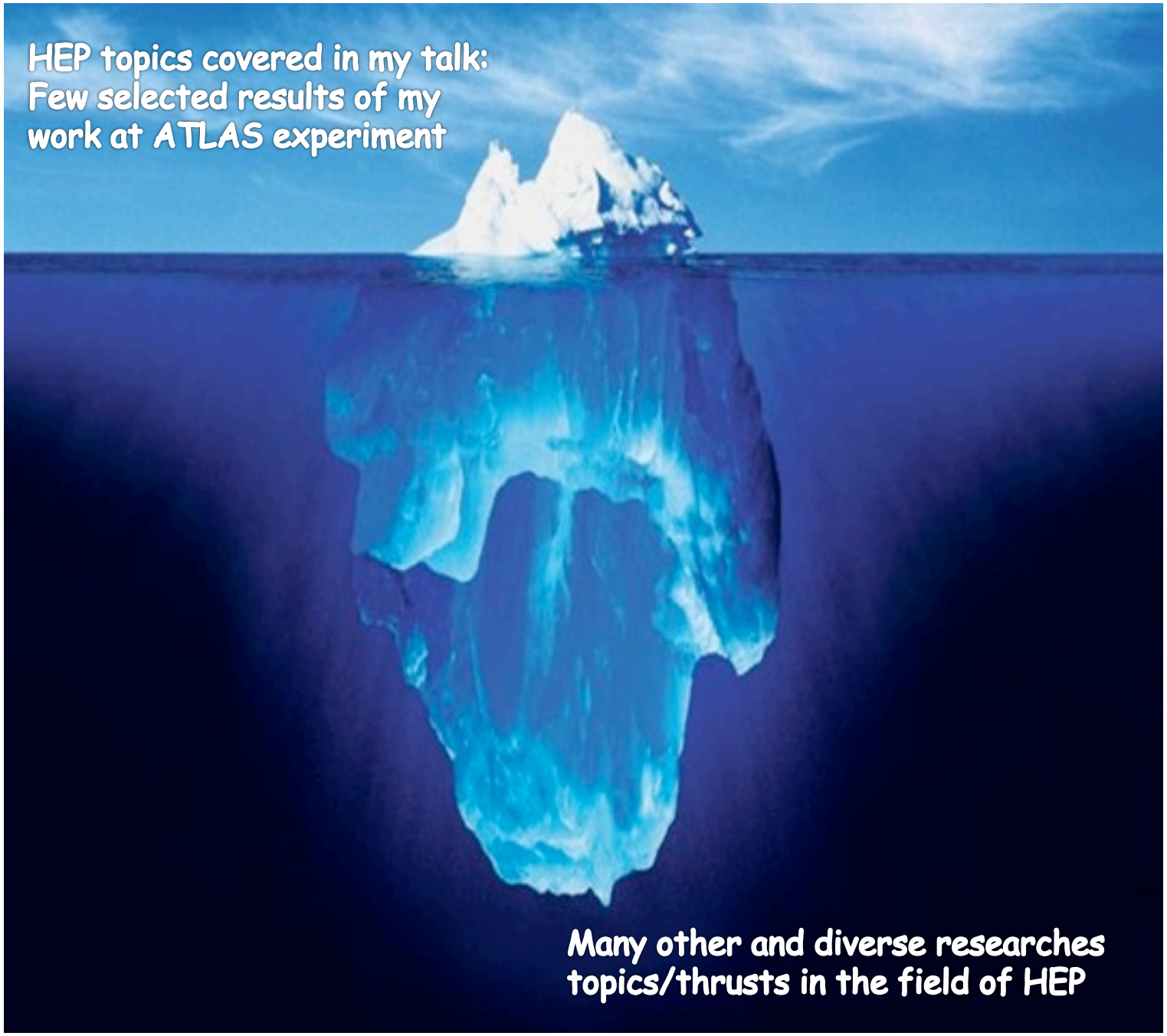
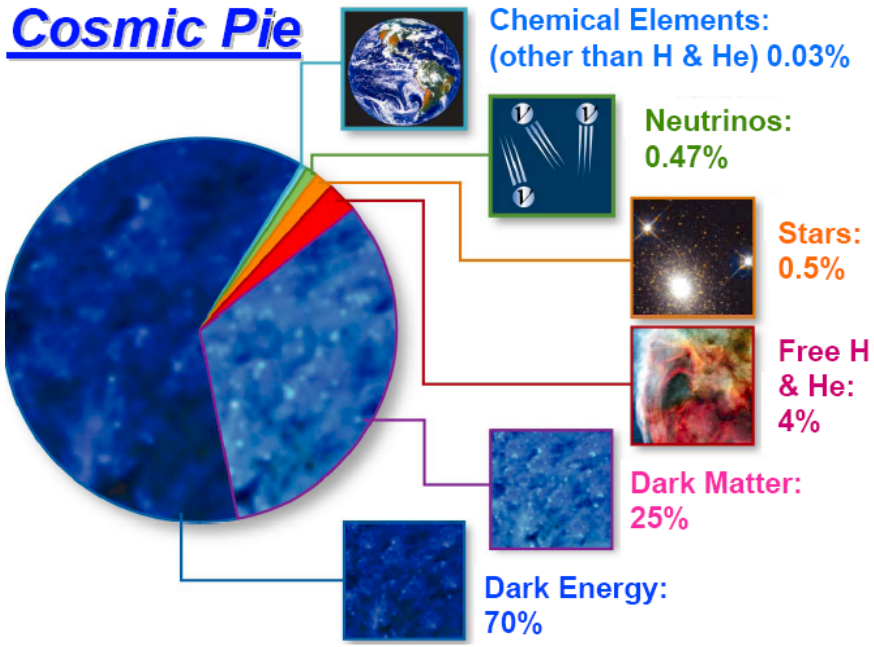

HEP topics covered in my talk:
Few selected results of my
work at ATLAS experiment
Many other and diverse researches
topics/thrusts in the field of HEP

Outline

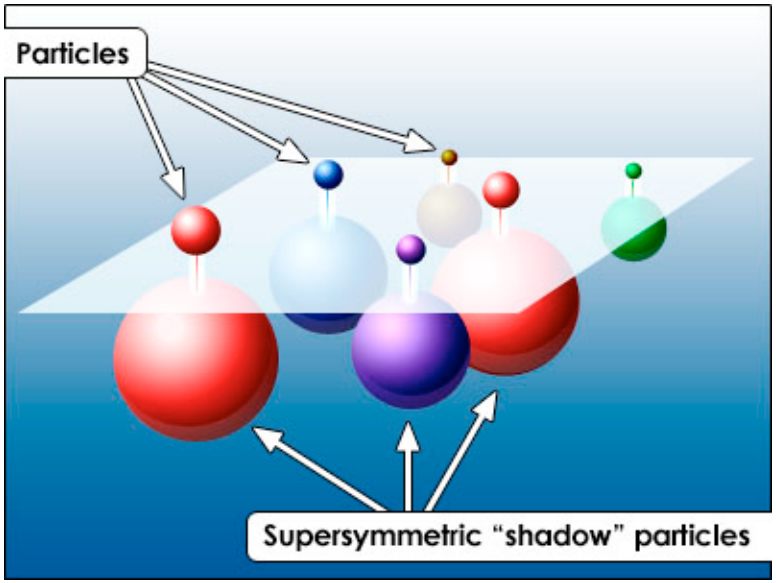
- Introduction and Motivation
- Evidence of Higgs decay to a bottom quark-antiquark pair
- Highly boosted hadronically decaying Higgs boson
- Conclusion

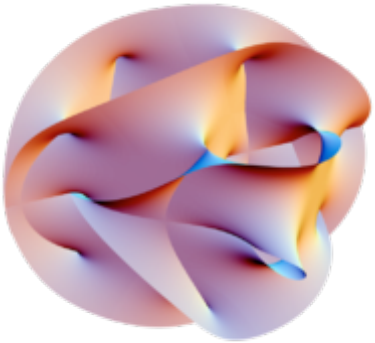
Open Questions in (Particle) Physics

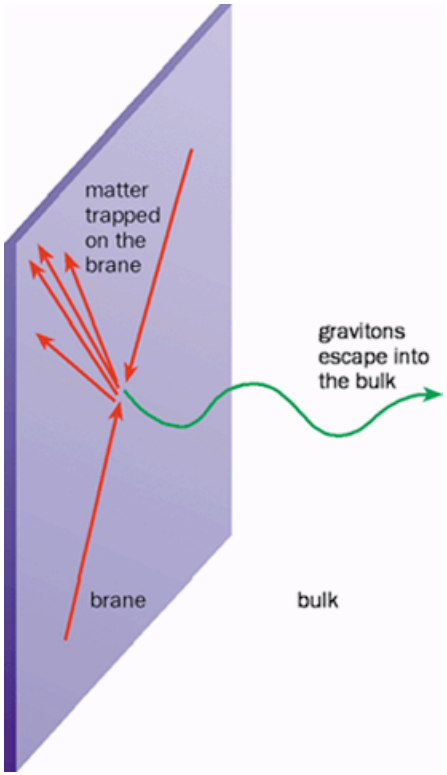


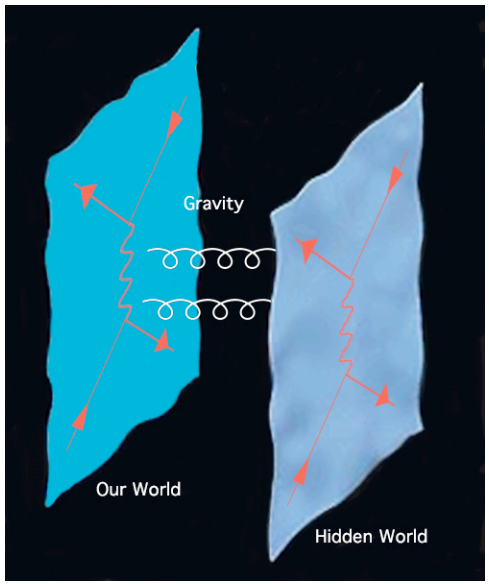
New Physics: Another revolution of physics (undiscovered principles of nature): New symmetries, new physical laws, new particles?

New Physics beyond the Standard Model



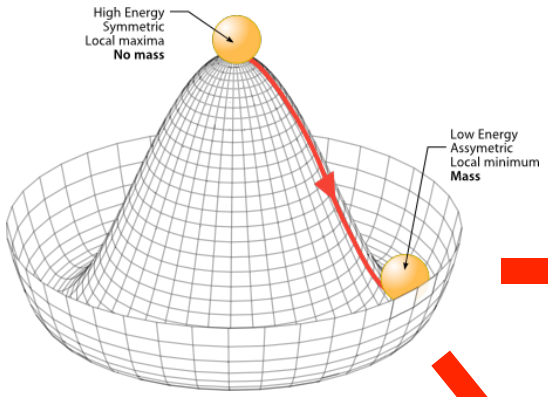






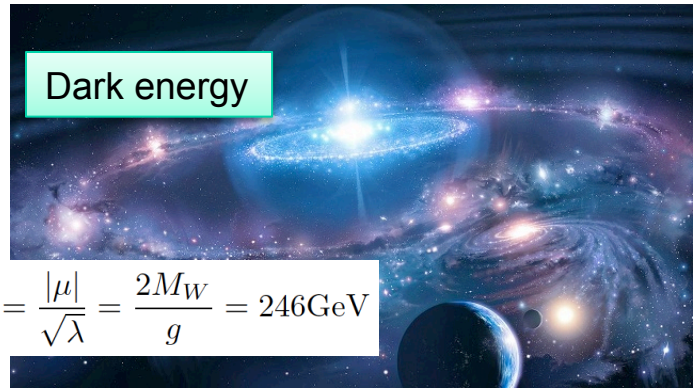
Many ideas: Supersymmetry (SUSY), Extra-dimensions,
Grant unify theory, String theory (26 dimension space), ……

Higgs Boson as a Probe for NP



$\Delta\mathcal{L} = -\lambda_{H\Phi} H^\dagger H \Phi^\dagger \Phi$

SM — HS(DM)

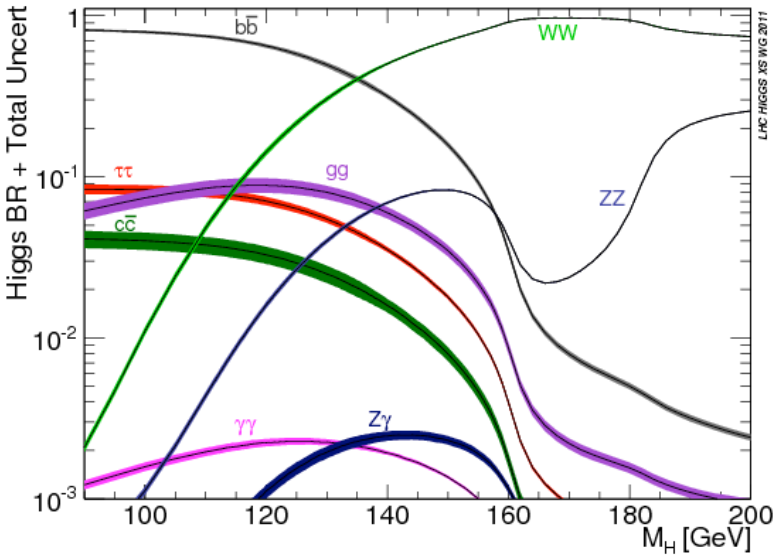


$$v = \frac{|\mu|}{\sqrt{\lambda}} = \frac{2M_W}{g} = 246\text{GeV}$$

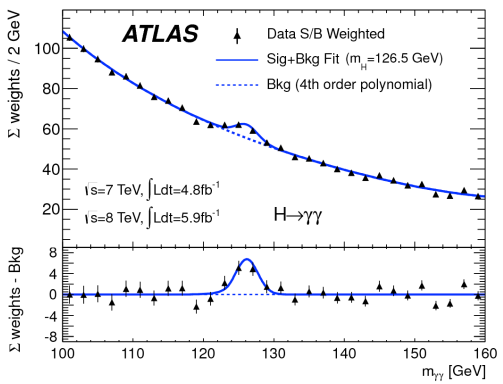
$$\mathcal{L}_Y^{quarks} = -\frac{v}{\sqrt{2}} \sum_{j,k} \left\{ \underbrace{\bar{d}_L^j Y_d^{jk} d_R^k + \bar{u}_L^j Y_u^{jk} u_R^k}_{\bar{d}_L^j \tilde{M}_{jk}^D d_R^k + \bar{u}_L^j \tilde{M}_{jk}^U u_R^k} + h.c. \right\}$$

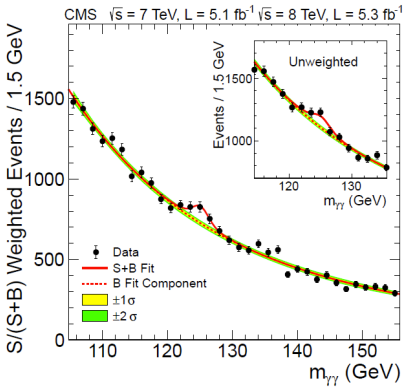
Precision measurement of Higgs properties is one of the best experimental probes to look for possible new physics hints

Higgs Boson Properties and Status

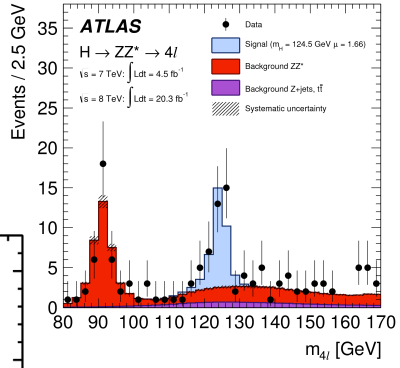


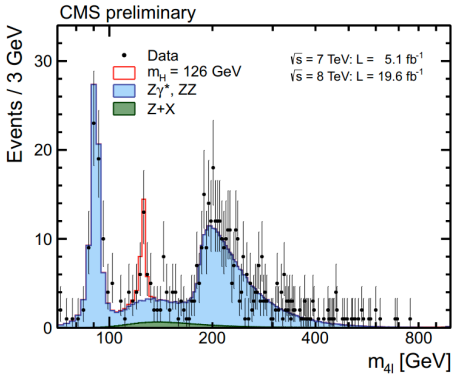
$H \to \gamma\gamma$



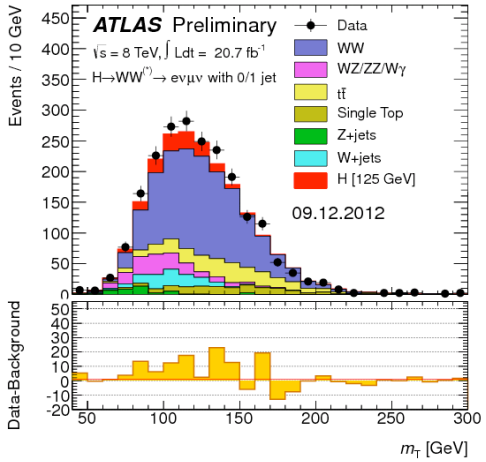


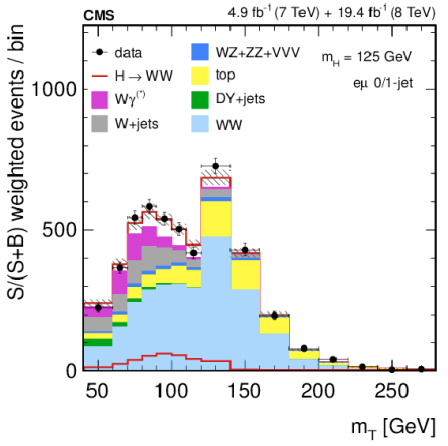
$H \to ZZ$





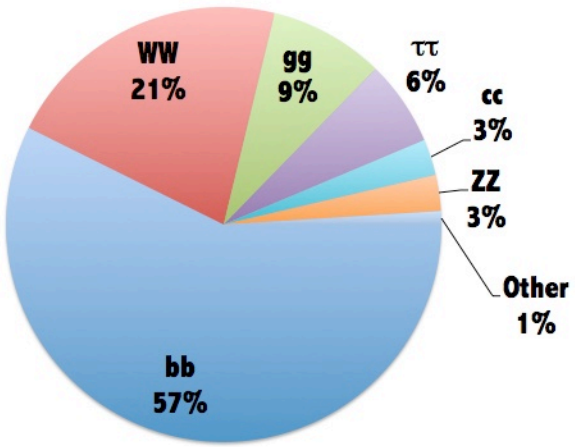
$H \to W^+W^-$

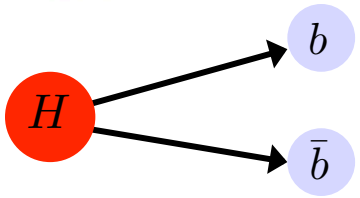




Higgs Boson Decay to bottom quarks

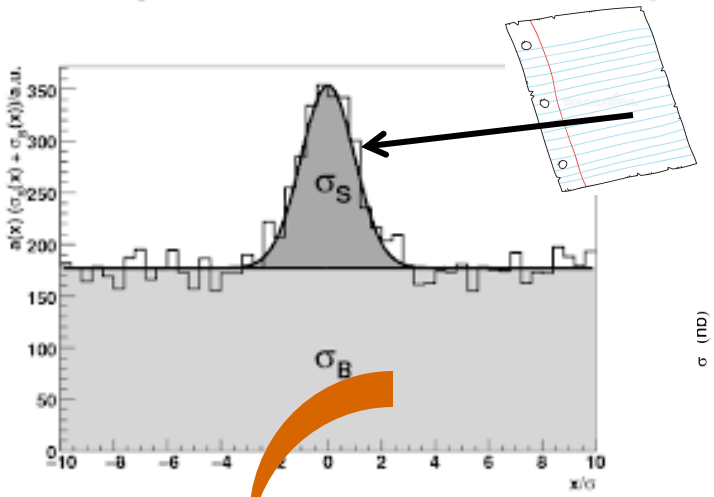
Higgs decays at m_H=125GeV

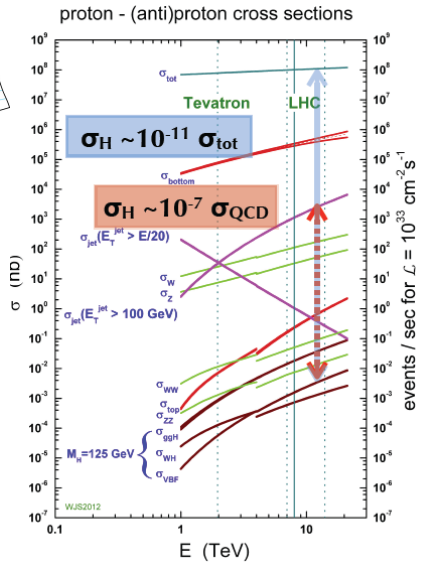




$$m_H = \sqrt{(p_b + p_{\bar{b}})^2}$$

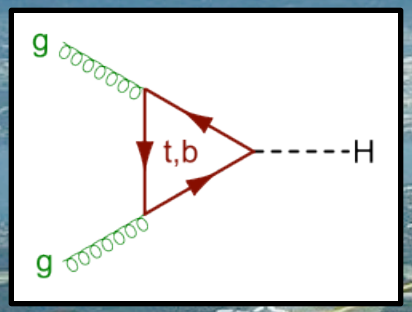
Need to reconstruct an individual quark
Need to identify the flavor of the quark
SM background is 10 orders of magnitude higher



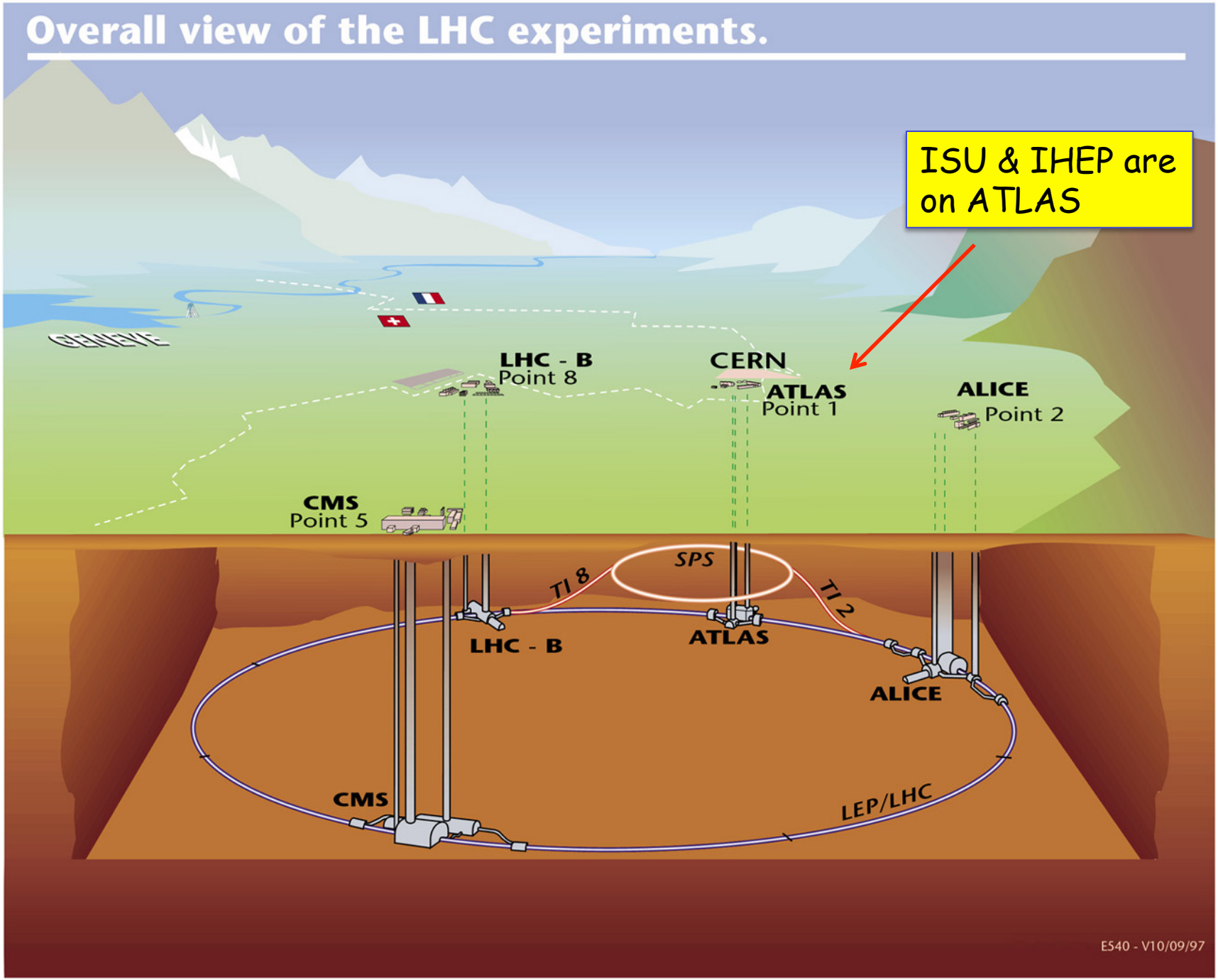


Large Hadron Collider (LHC) at CERN

40 millions Proton-proton collision at 13 TeV per second
1TeV=1000 GeV



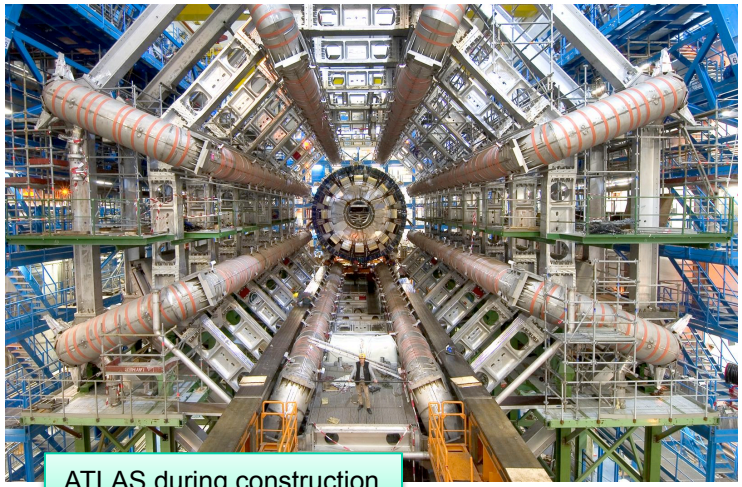
The 27 km long LHC tunnel


Overall view of the LHC experiments.
ISU & IHEP are on ATLAS
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

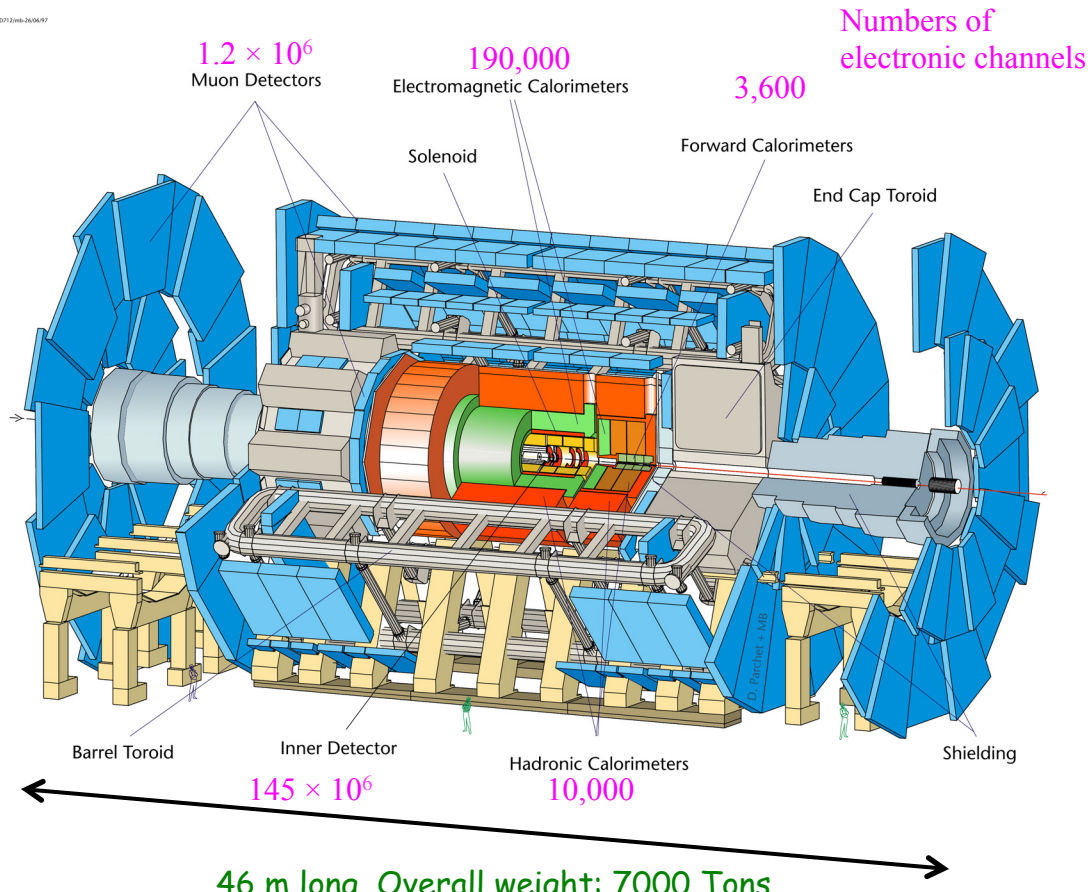
The ATLAS Detector

Designed & Built with cutting edge/innovative technologies by HEP physicists

ATLAS superimposed on the 5 story building

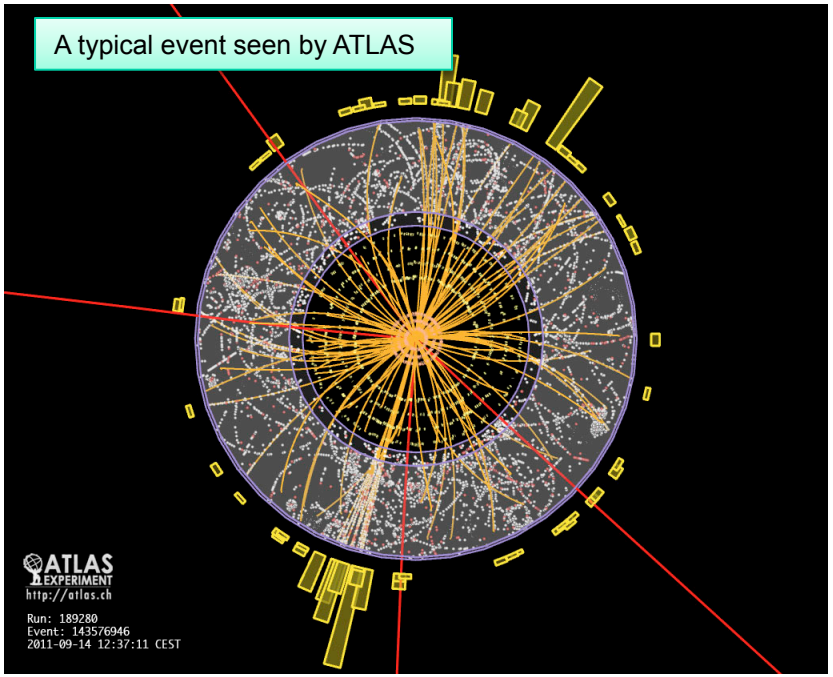


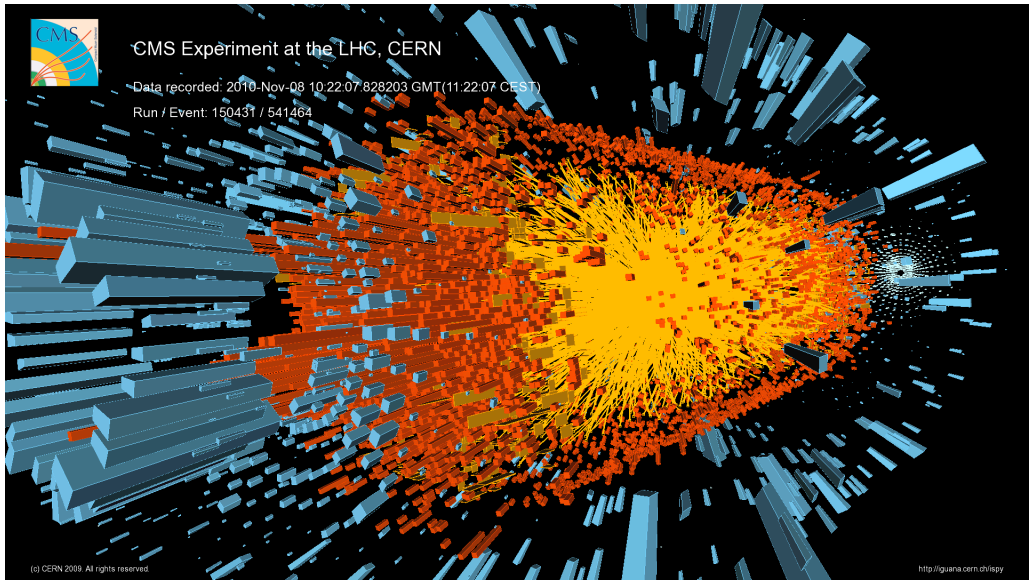
ATLAS during construction



~3000 scientists from 174 Institutions and 38 Countries

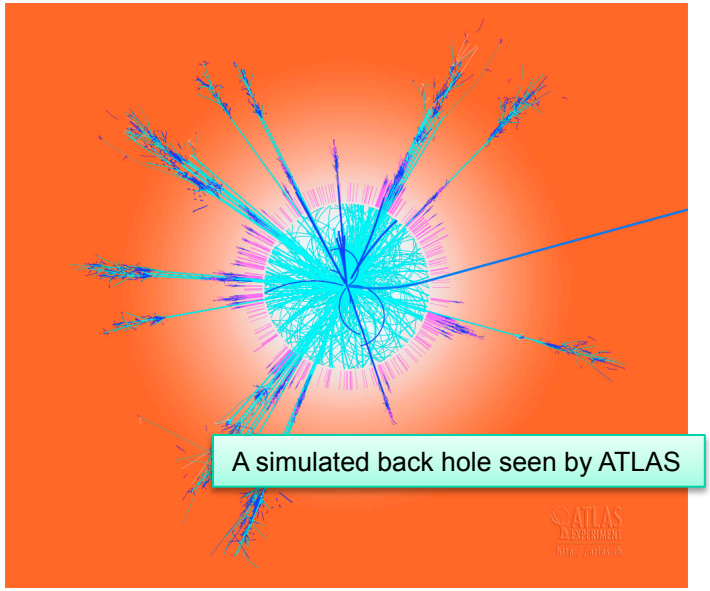
Challenges in HEP research





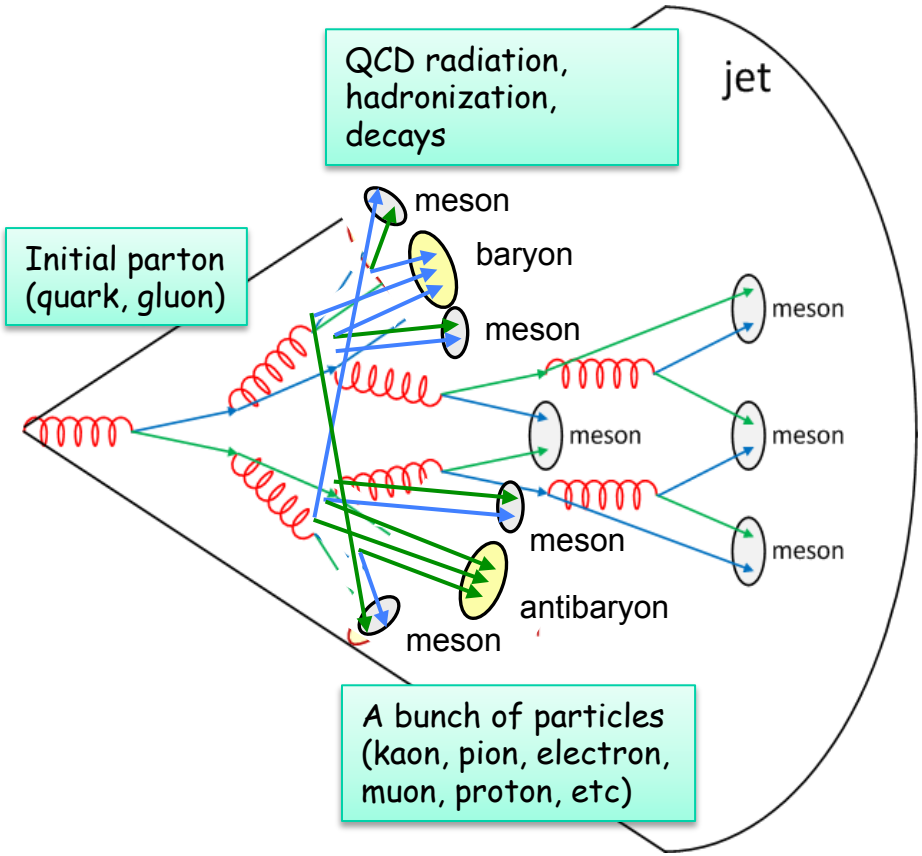
10^{11} (10,000 millions) protons/bunch per 25 ns
~70 inelastic collision per event
64 TB/second data produced
~4 hours MC simulation per event

Complicated event topologies
Small signal/background ~ 10^{-6} – 10^{-9}
Sophisticated data analysis approaches
Data analysis: Looking for a needle in a haystack



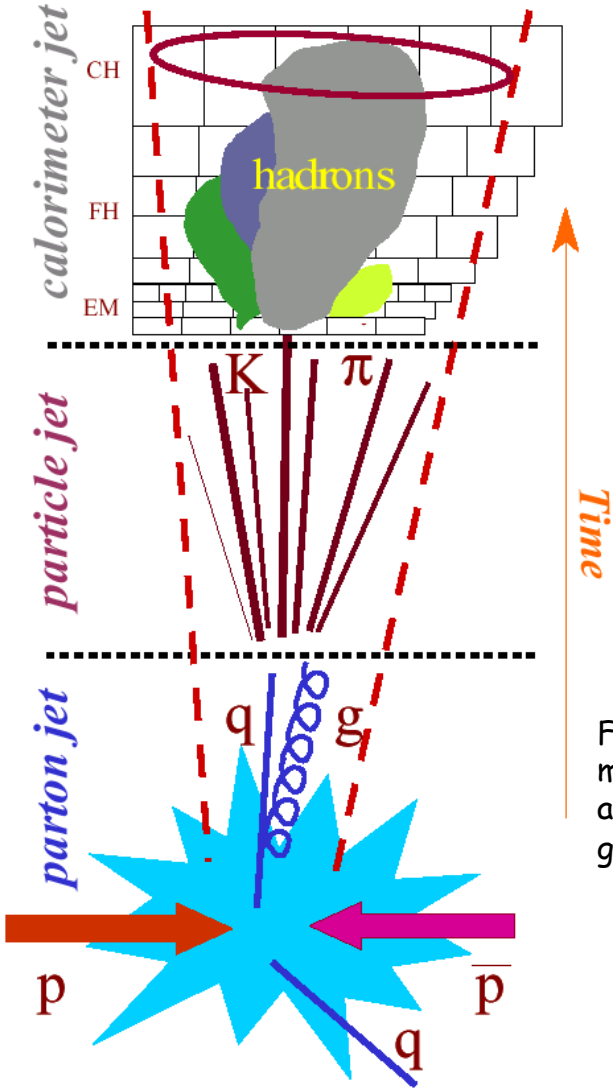
Jet: Reconstruction of quark and gluon

The theorist's view



Jet: representative of initial parton
One jet = one quark or gluon

The experimentalist's view

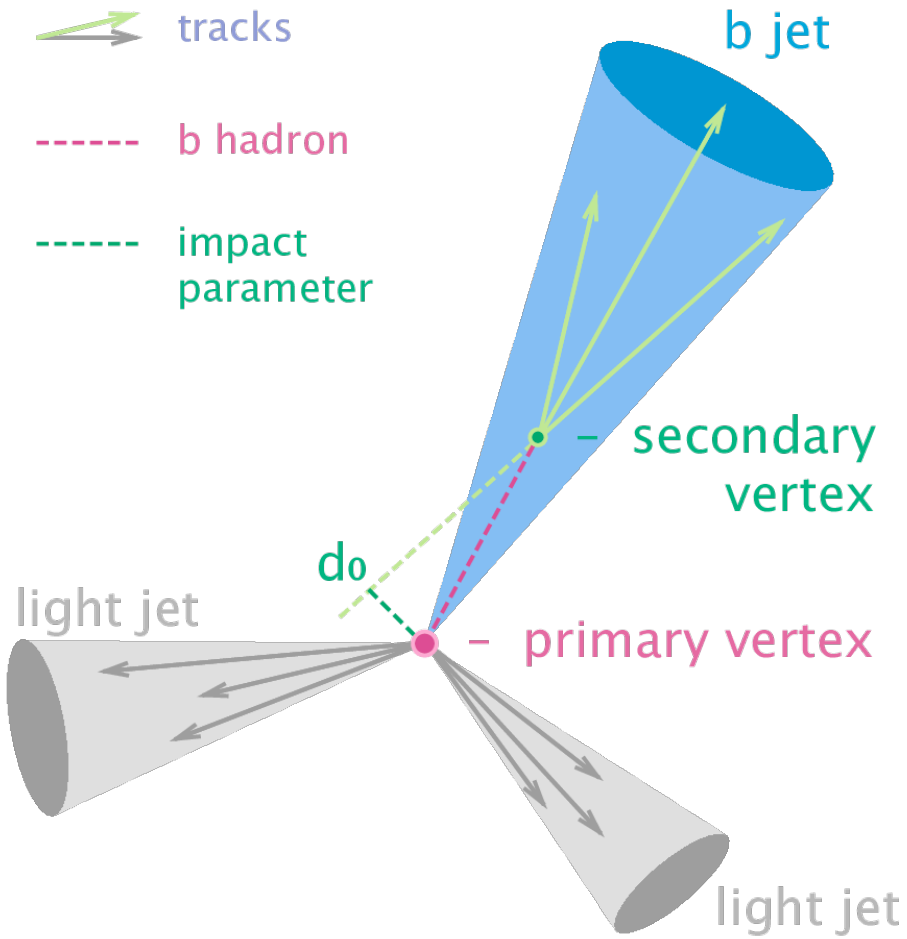


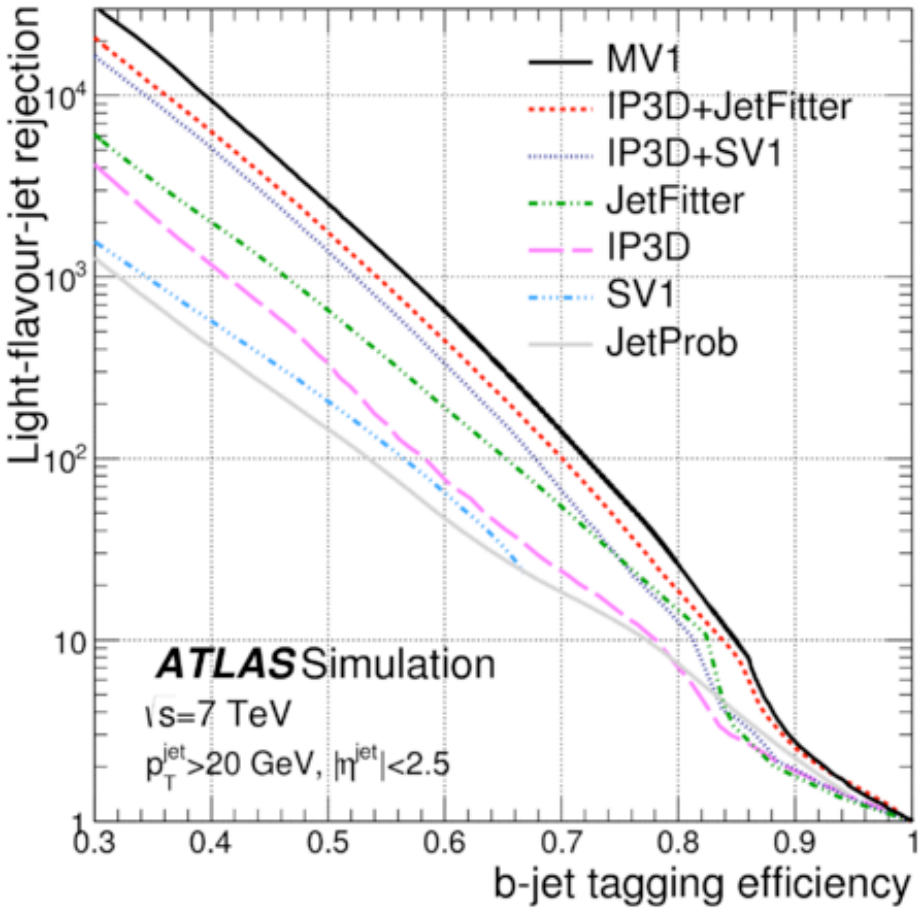
Energy deposition in clusters inside Calorimeter

Treat each cluster as a particle

Form a jet with 4 momentum → same as parton (quark, gluon)

Identify Jets from b Quarks: b-Tagging

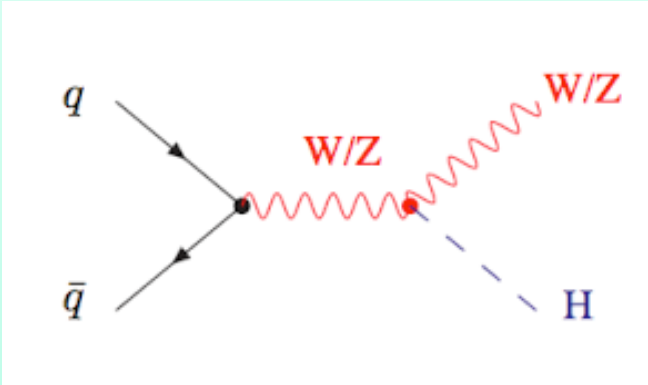




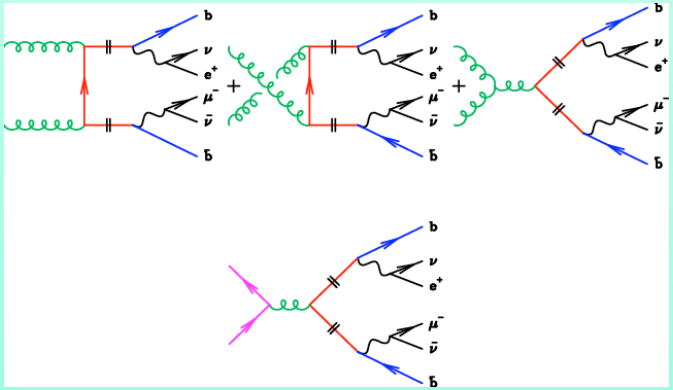
Applying for b-tagging reduce the background of $H \to b\bar{b}$ by a factor of ~10000

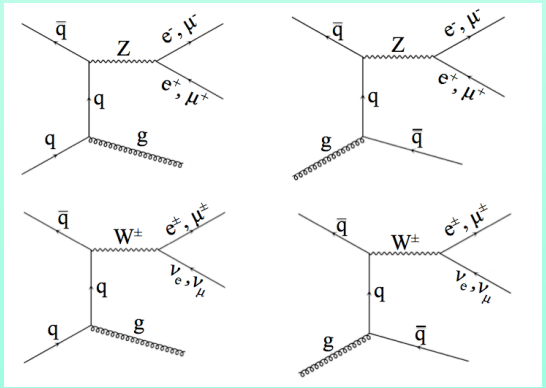
Search for Production of $VH(H \to b\bar{b})$

- Background still ~ 10^6 times higher than H->bb
  - ✓ Dominate by b quarks productions
- Require associate production with a vector boson (V=W/Z)
  - ✓ W/Z decay leptonically
  - ✓ Further reduce background by ~1000



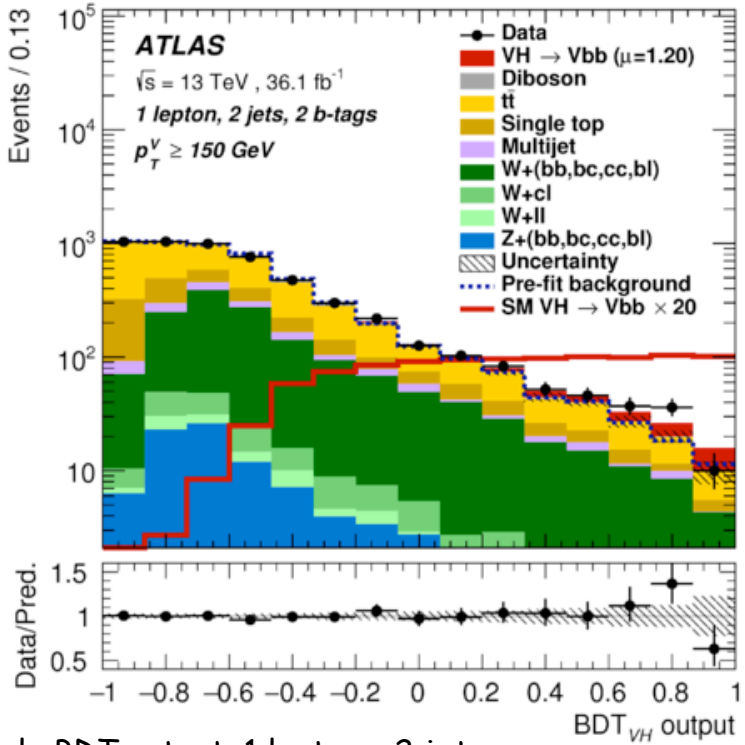
- Dominated background are W/Z+bb and top productions





Multivariate Analysis of $VH(H \to b\bar{b})$

- M_{bb} is single most discriminating variables
  - ✓ Construct BDT (Boost Decision Tree) of several variables to boost sensitivities
  - ✓ M_{bb}, $\Delta R(bb)$ and $p_T(V)$ most important variables
- Separate training for each signal topology

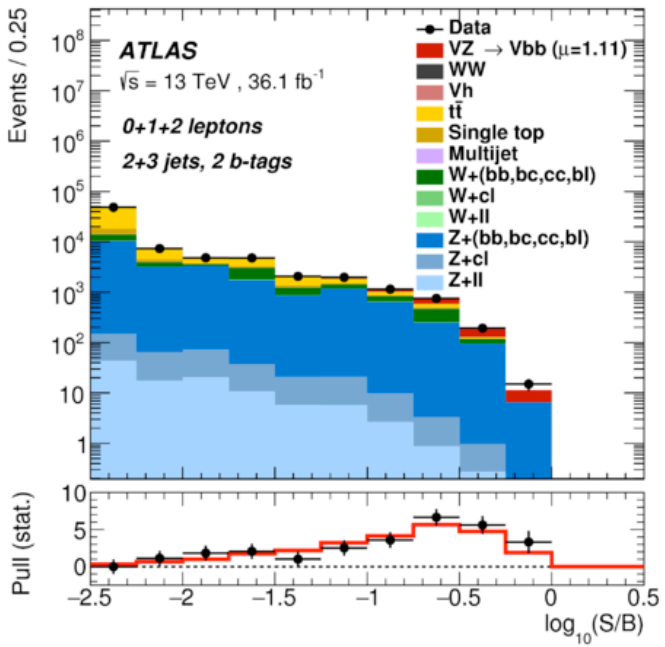


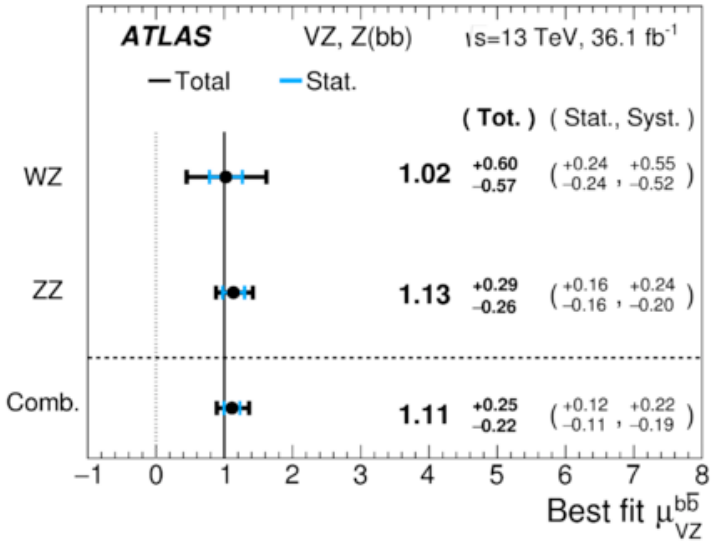
Example BDT output, 1 lepton + 2 jets

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b}_1, \vec{b}_2)$	×	×	×
$\lvert\Delta\eta(\vec{b}_1, \vec{b}_2)\rvert$	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
m_{eff}	×		
$\min\lvert\Delta\phi(\vec{\ell}, \vec{b})\rvert$		×	
m_T^W		×	
$m_{\ell\ell}$			×
m_{top}		×	
$\lvert\Delta Y(\vec{V}, \vec{bb})\rvert$		×	
	Only in 3-jet events		
$p_T^{\text{jet}_3}$	×	×	×
m_{bbj}	×	×	×

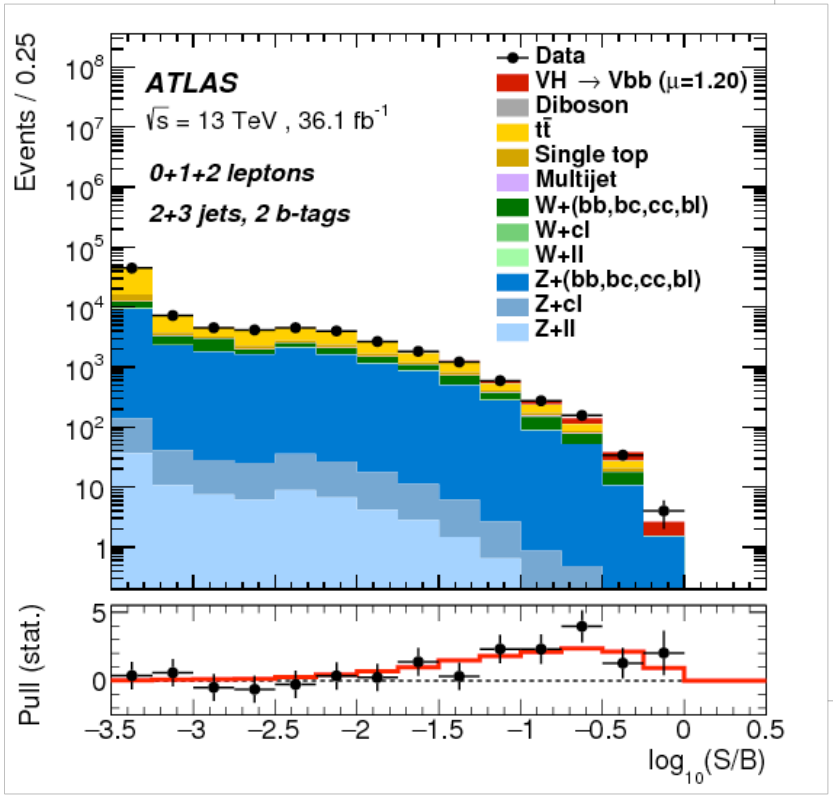
Validate Analysis using $VZ(Z \to b\bar{b})$

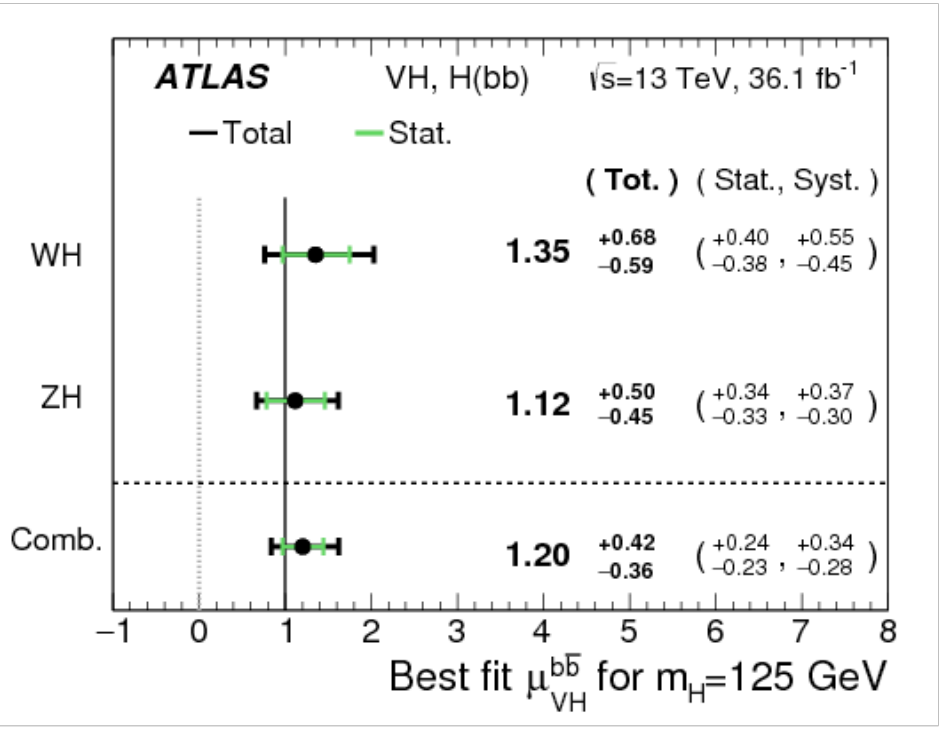
- Analysis heavily relies on correct Monte Carlo simulation
- Validate the analysis approach by measuring SM VZ (Z->bb) production
  - ✓ Almost identical event topology as VH (H->bb) except for different m_{bb}
  - ✓ VH production well understood from other measurements
    - Full leptonically final states
  - ✓ Apply identical analysis approach as VH
- Good consistent with the theory prediction
  - ✓ 99% compatibility between different channels
  - ✓ 5.8 (5.3) σ observed (expected) significance
  - ✓ First Observation of VZ(Z->bb) at ATLAS





Results of $VH(H \to b\bar{b})$ Measurements



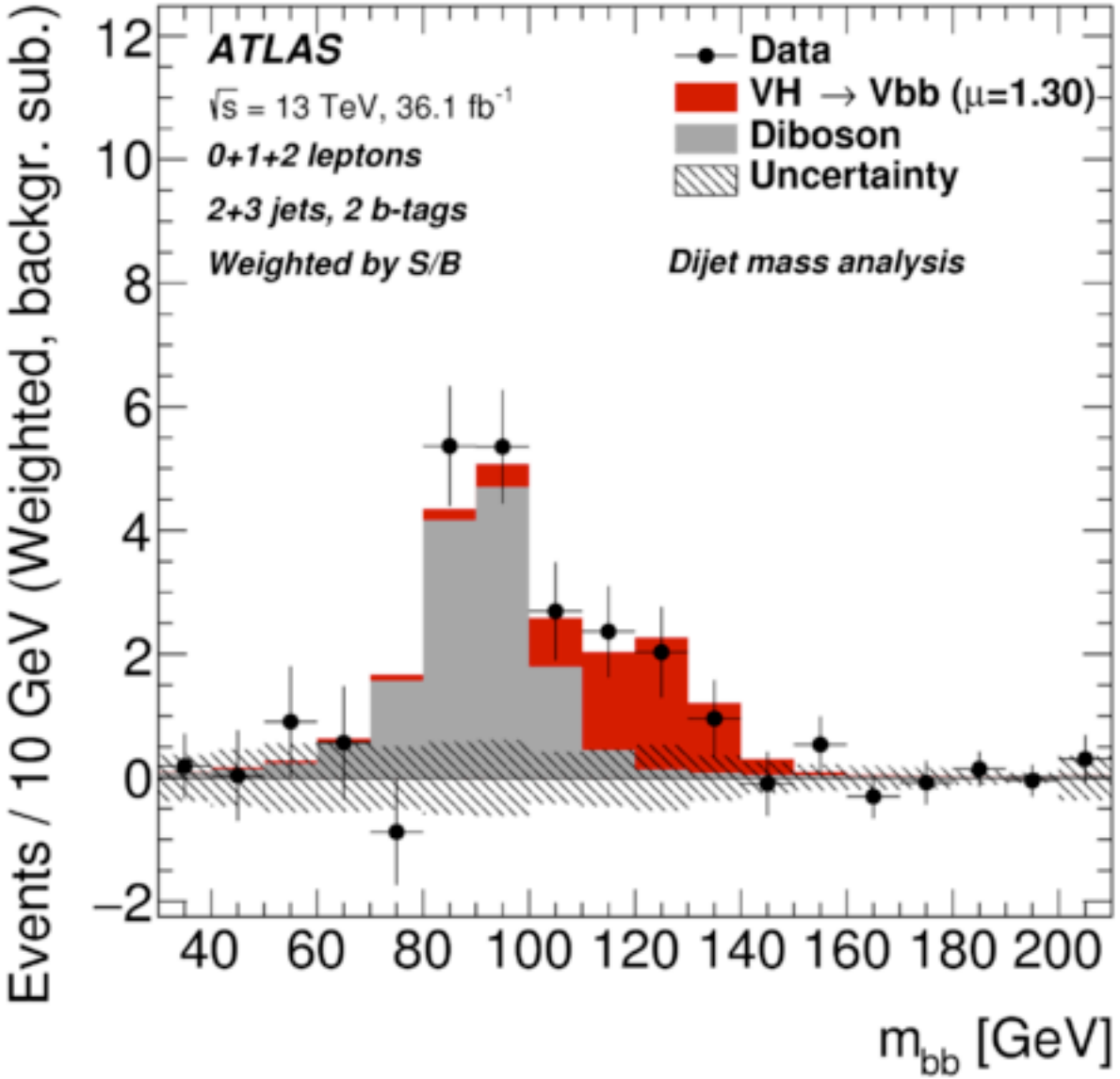


- 3.5 (3.0) σ observed (expected) sigbificance
- **Evidence of VH(H->bb)**
- Systematically limited

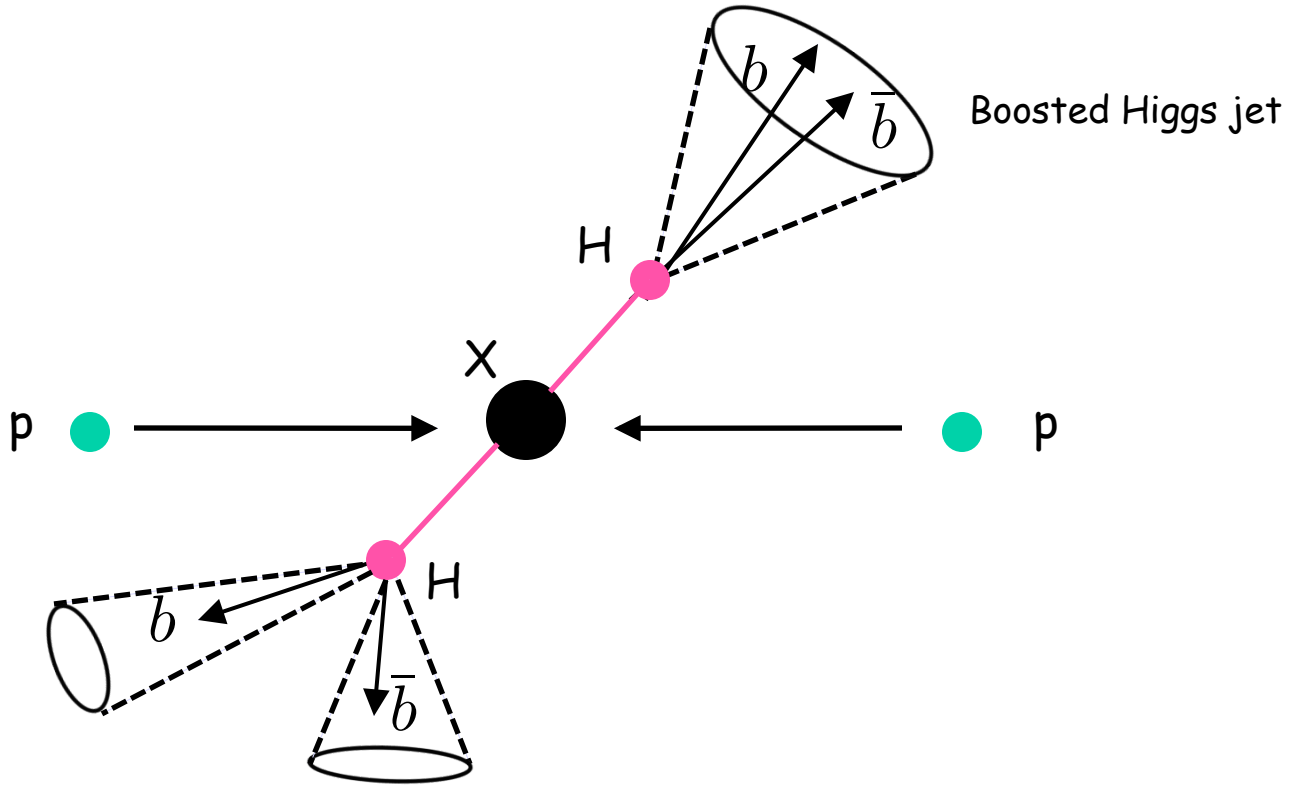
Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	4.2%	30%	1.7	0.5
1-lepton	3.5%	1.1%	1.8	2.3
2-lepton	3.1%	0.019%	1.9	3.6
Combined	0.12%	0.019%	3.0	3.5

Results of $VH(H \to b\bar{b})$ Measurements

- Validate BDT analysis with an independent analysis based on m_{bb}
- Less experimental sensitivity (2.8σ)
- Observe 3.5σ signal strength



Boosted Hadronically decaying Higgs Boson

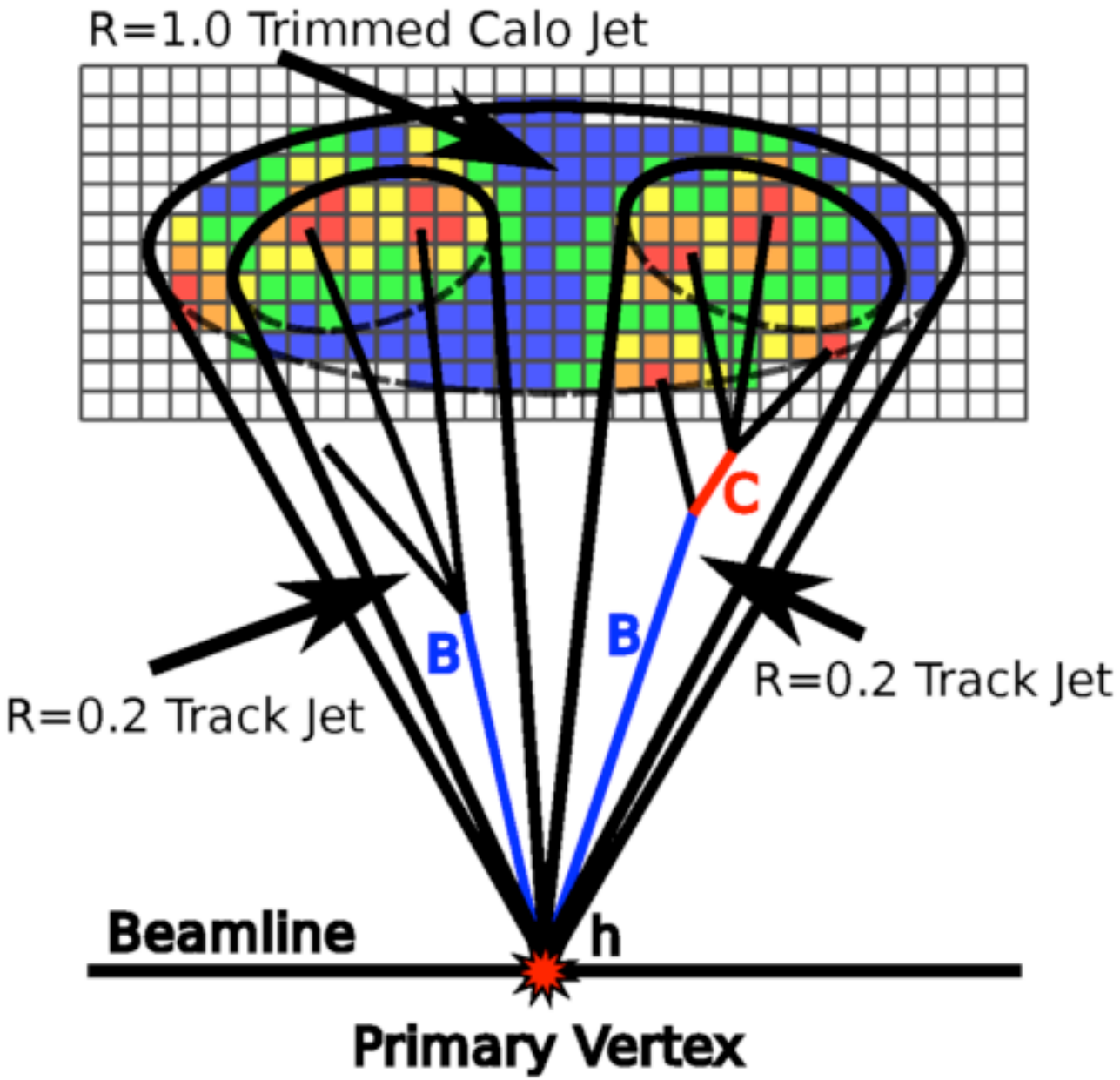


- Many NP models predict heavy resonance decaying to final states with Higgs

$$X \to HH, HV(V = W/Z), H\gamma$$

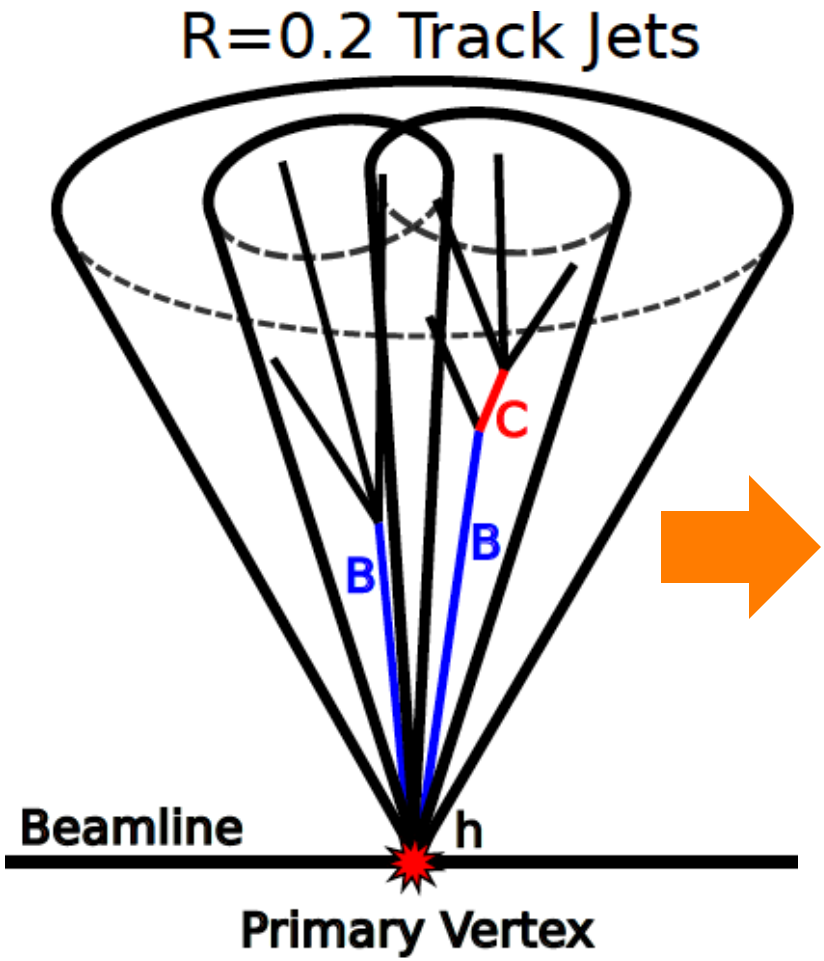
  - ✓ Hadronically decaying product are highly colimated
  - ✓ Both quarks reconstructed inside a single jet with large cone size
    - ✓ Similar problems for boosted hadronically decaying W/Z/top

Identify 2 b in a single jet: double b-tagging

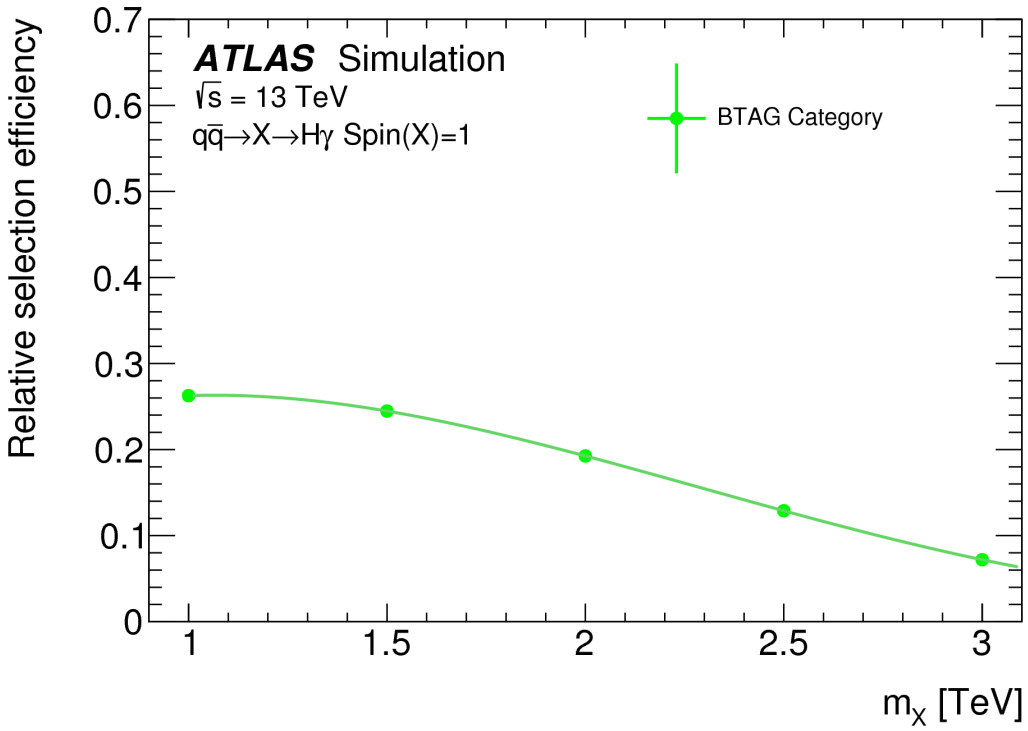


Problems for highly boosted Higgs Boson

Track jets overlapping for Higgs with very high momentum

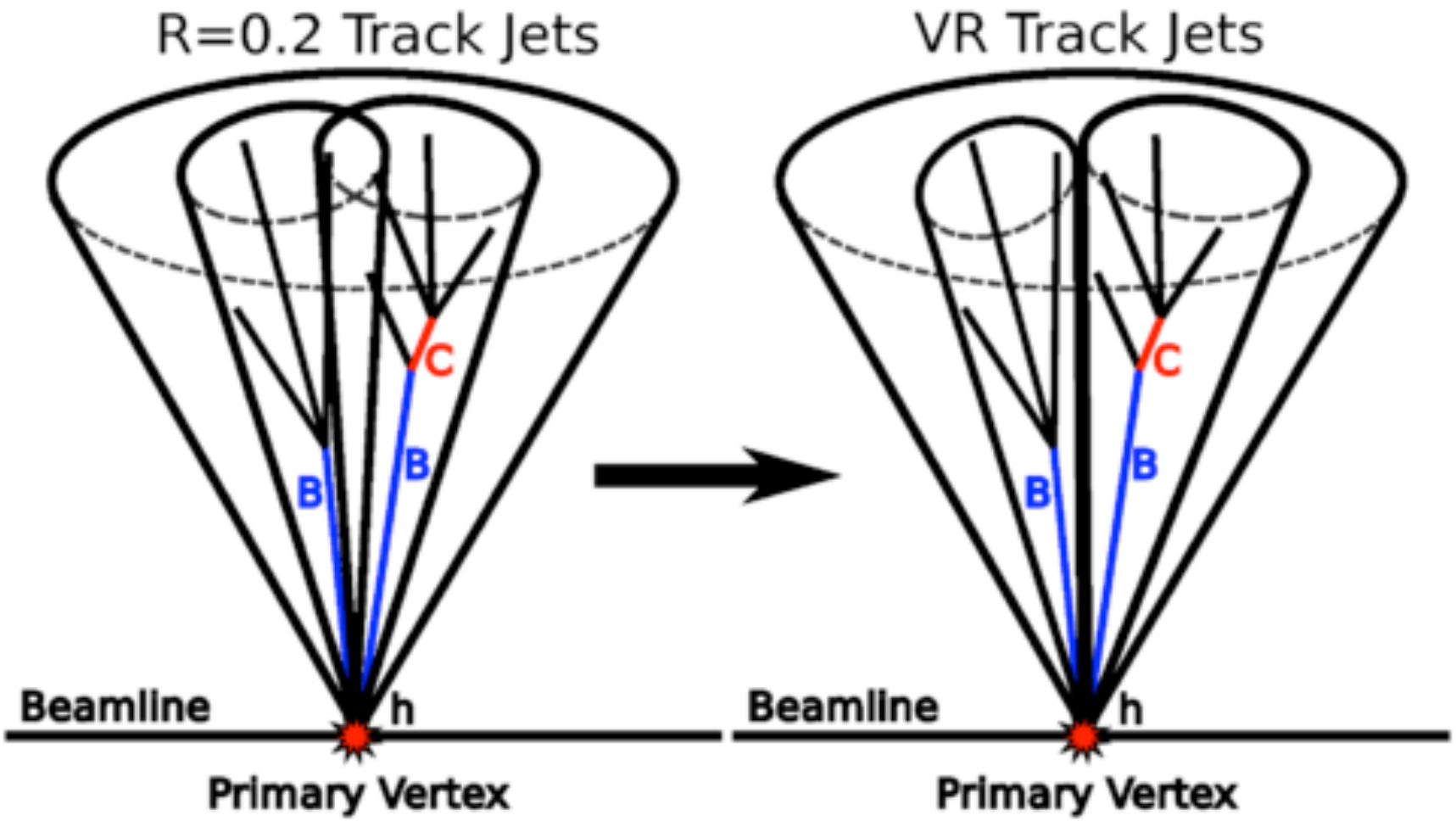


Significant efficiency loss for resonance with higher mass



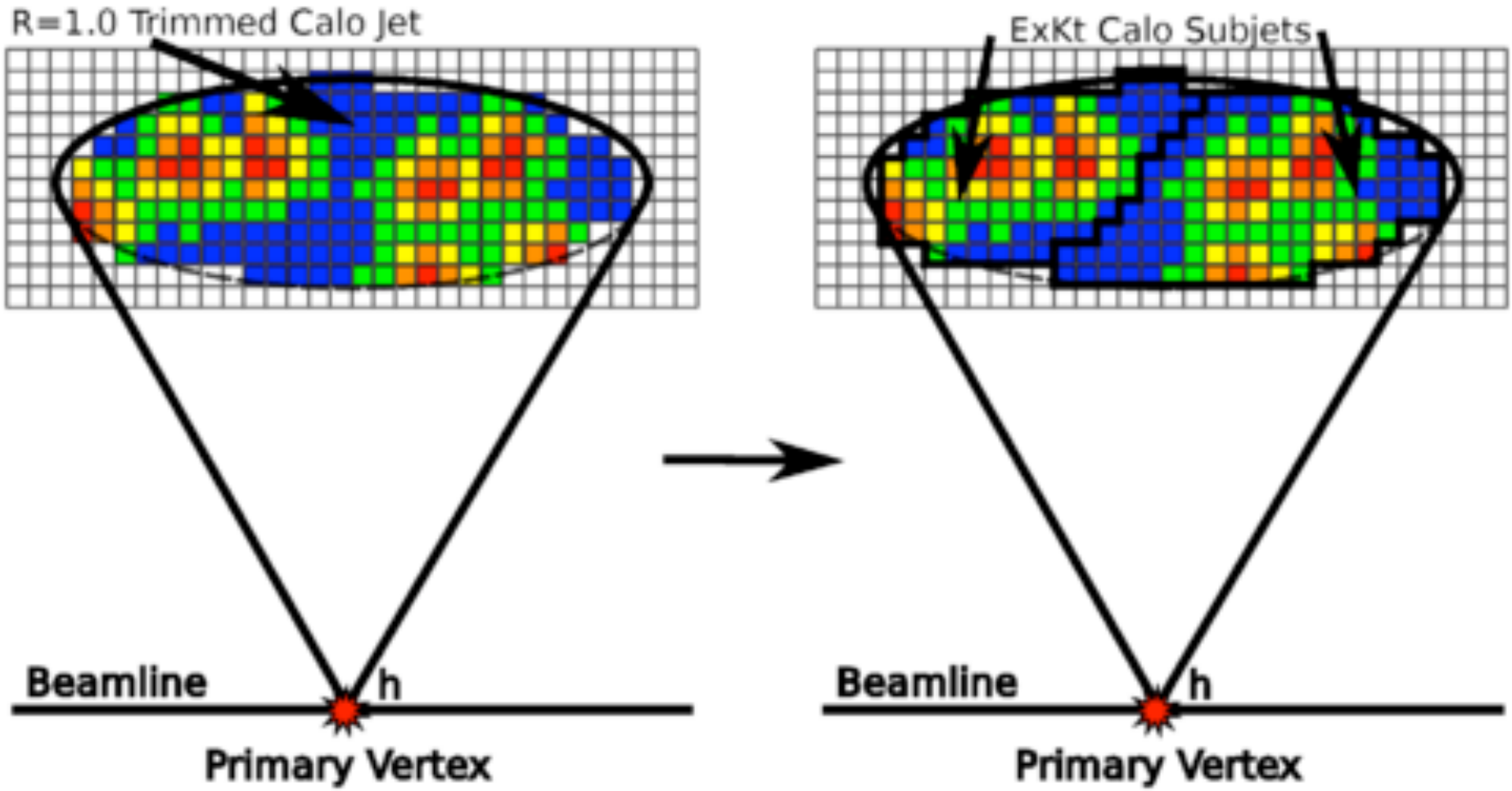
Variable Radius (VR) Track Jets

Cluster anti-k_T track jets using $R_{\text{eff}} = \max(R_{\min}, \min(R_{\max}, \rho/\rho_T))$



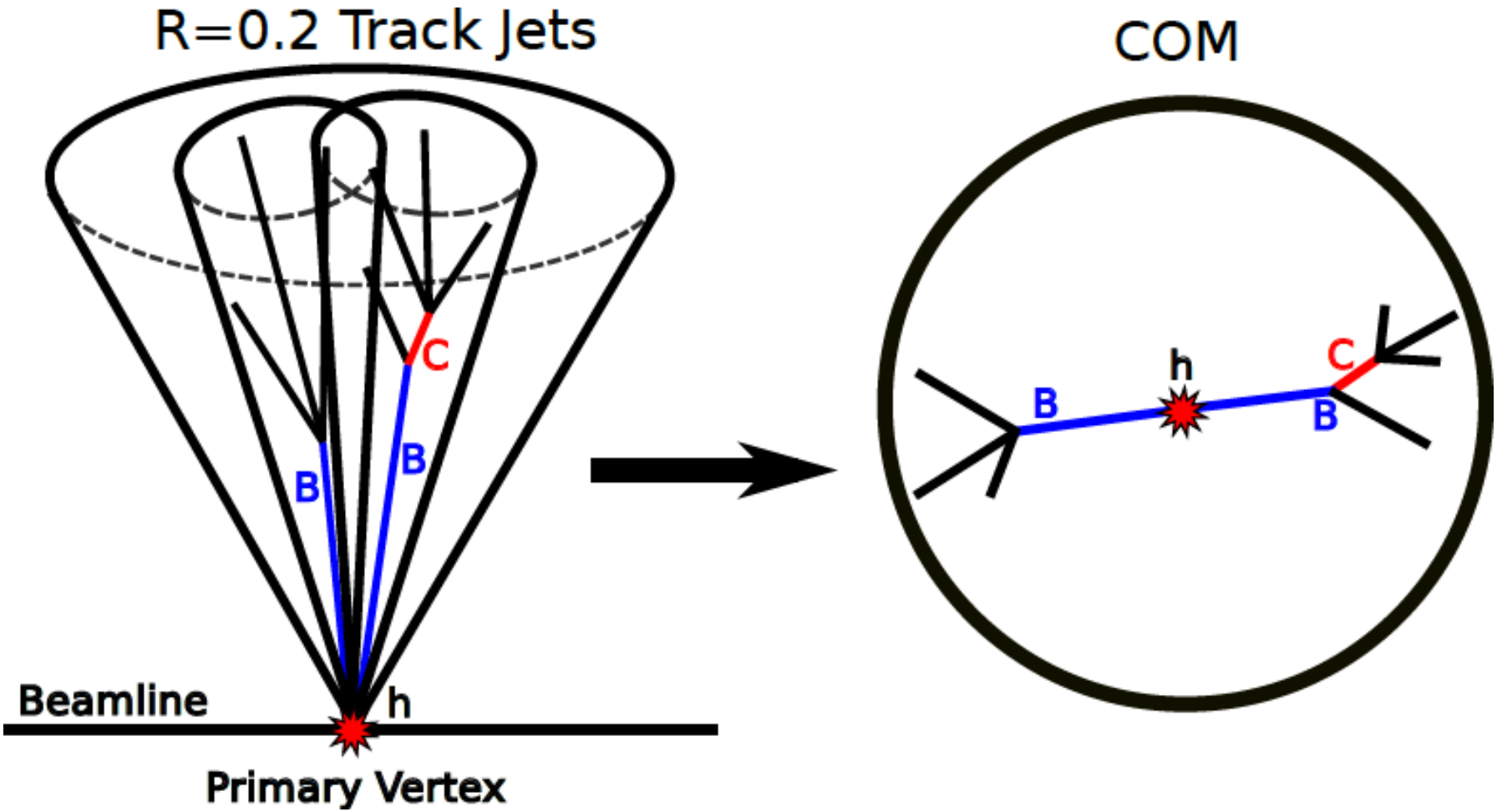
Exclusive k_T Subjets

- Using Higgs jet constituents to cluster k_T jet
- Undo the last clustering step to form exactly 2 subjets

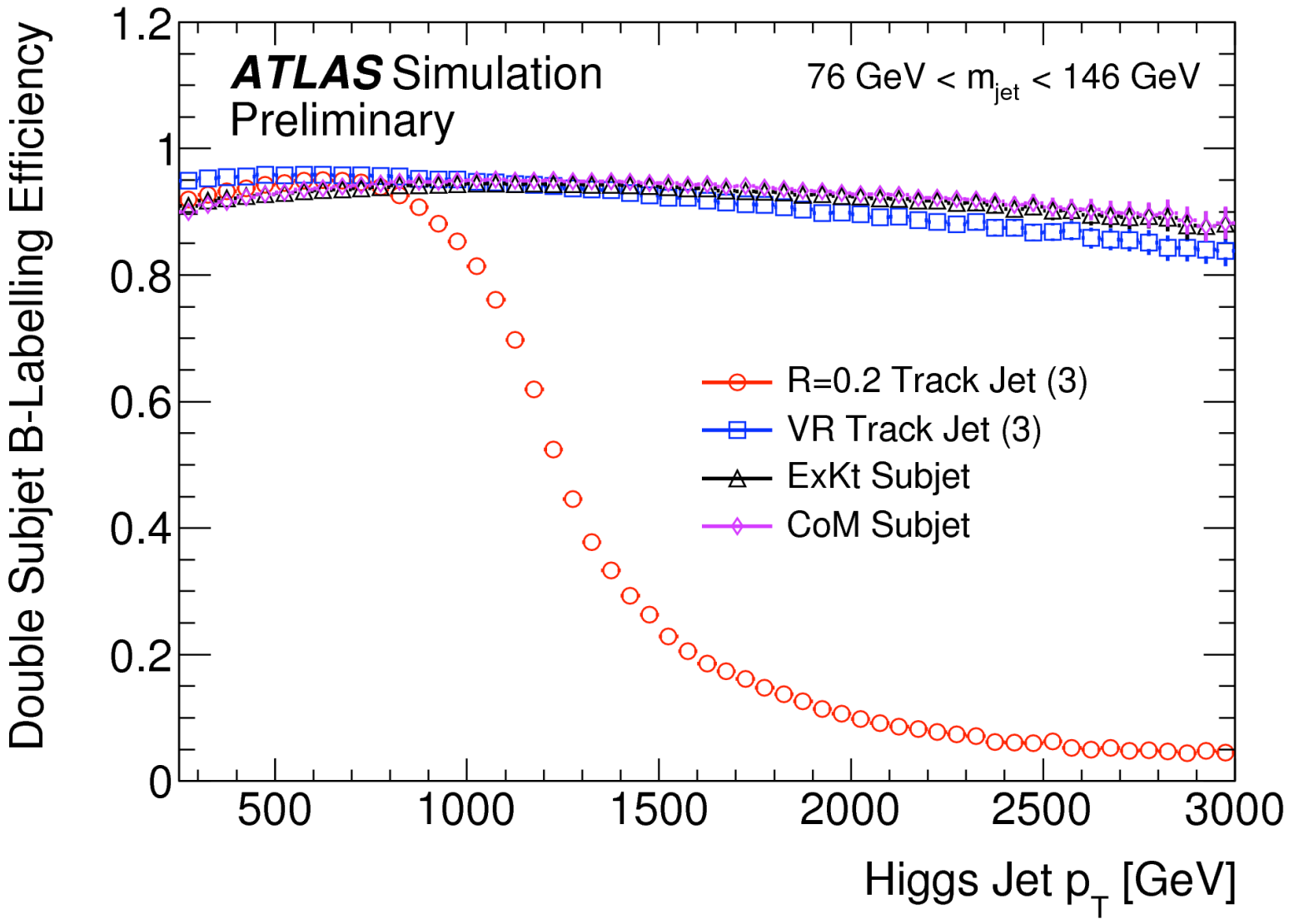


Center of Mass Subjets

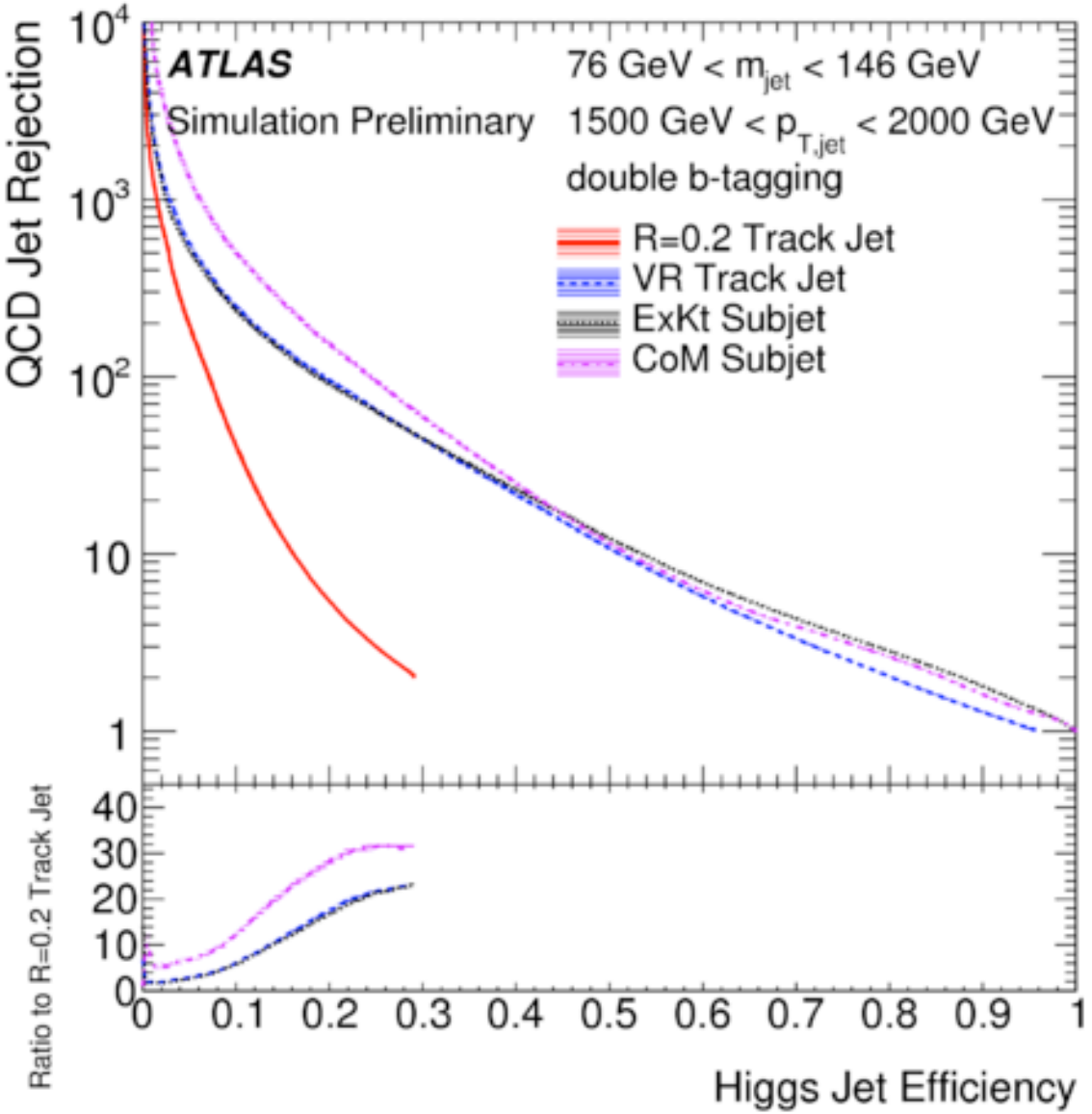
- Boost to the Higgs jet center of mass frame (COM)
- Use Higgs jet constitutes to cluster 2 EECambridge subjets
- Use angular seperation in COM for track-to-subjet association
- Boost back to the lab frame to apply for b-tagging



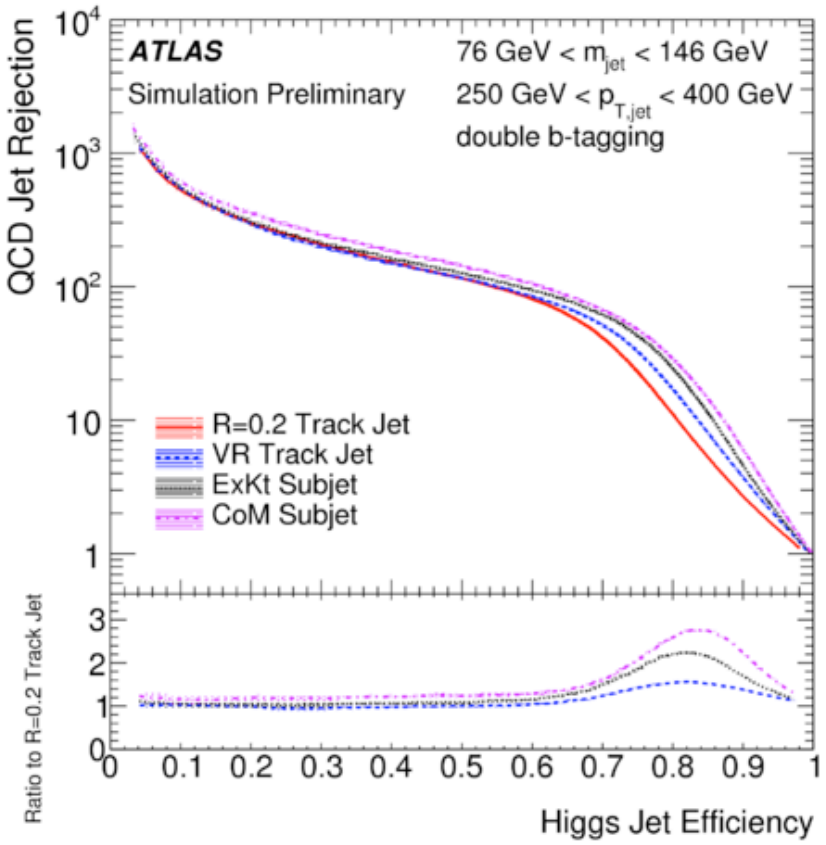
Reconstruction Efficiencies

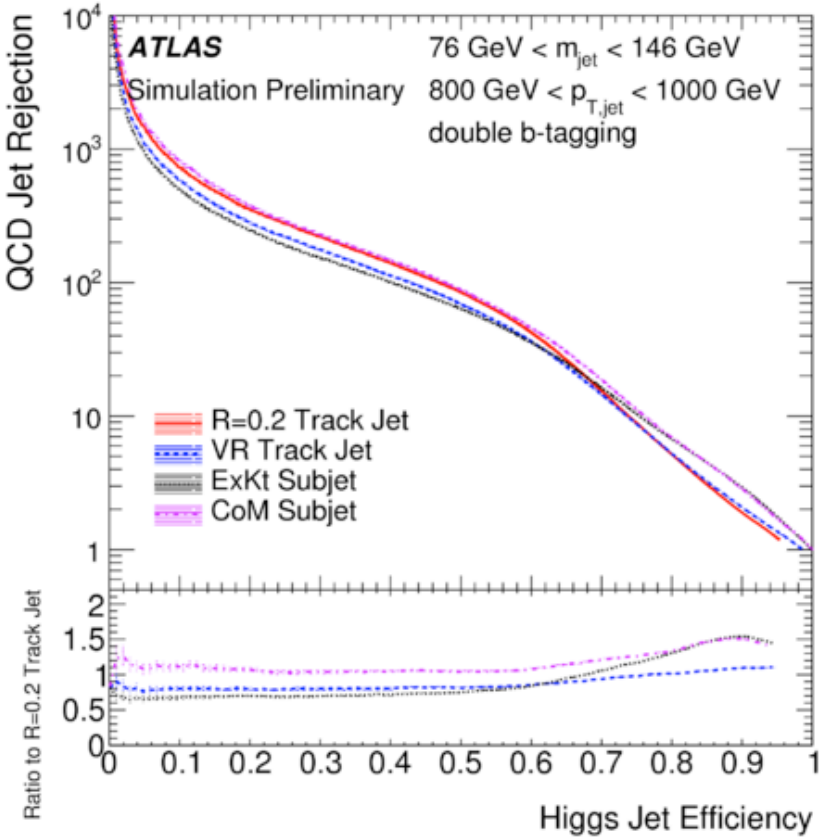


Double b-tagging vs. QCD Jet Rejection

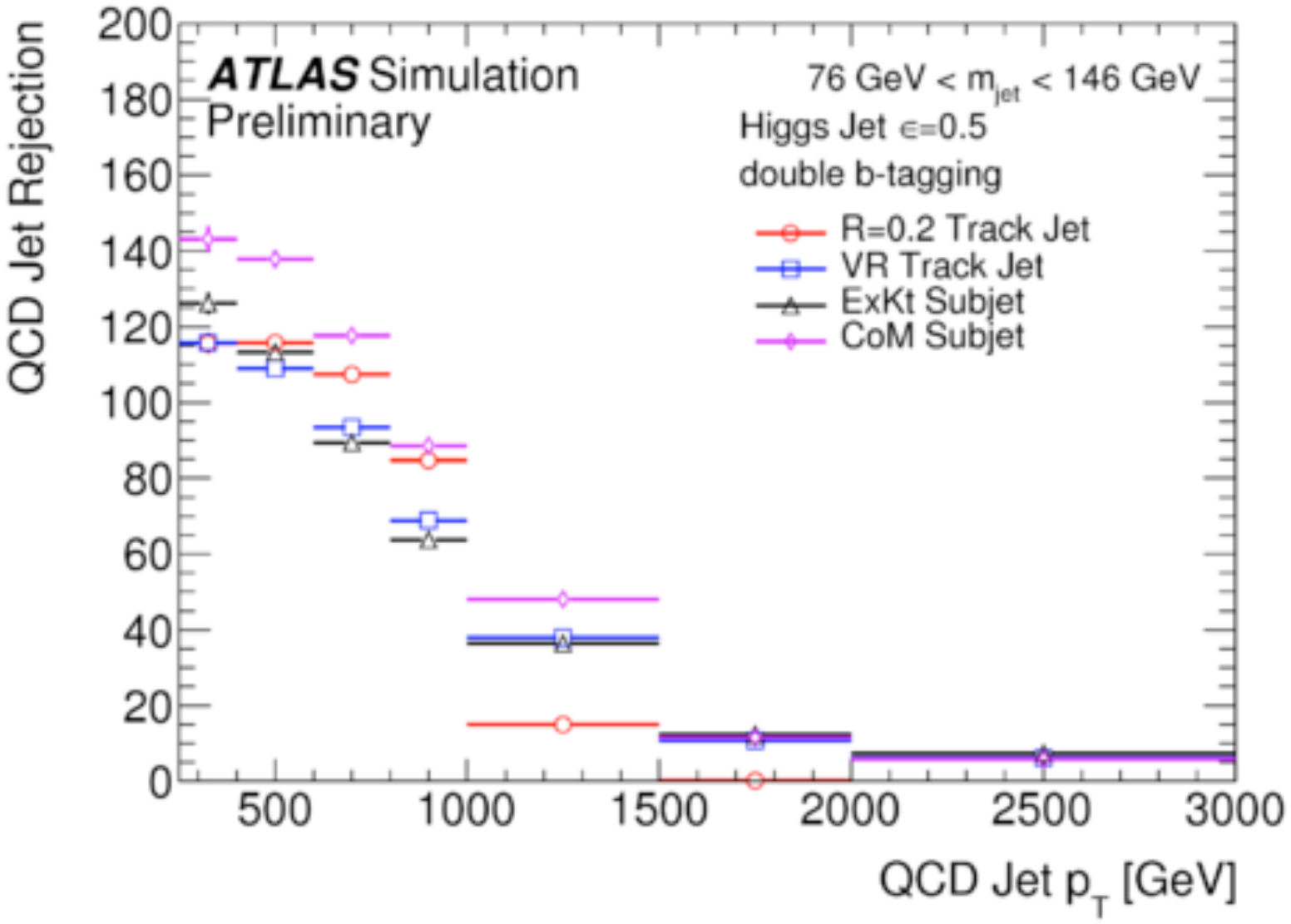


Double b-tagging vs. QCD Jet Rejection





Double b-tagging vs. QCD Jet Rejection



Summary and Conclusion

- Higgs boson serves as an important probe for NP
- Evidence of Higgs to bottom quark-antiquark at ATLAS
- New algorithms to identify highly boosted hadronically decaying Higgs boson
- Many works are still ongoing
  - ✓ Observation of H->bb with more data
  - ✓ Calibration of advanced Higgs double b-tagging
  - ✓ Expect results soon

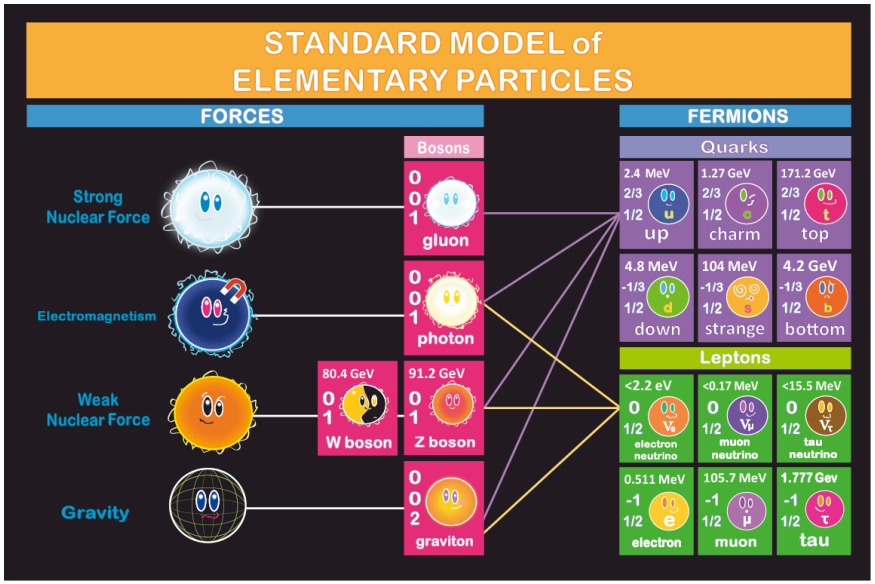
ATLAS: arXiv:1708.03299
C.Chen: arXiv:1507.06913
ATLAS: ATL-PHYS-PUB-2017-010
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2017-010/

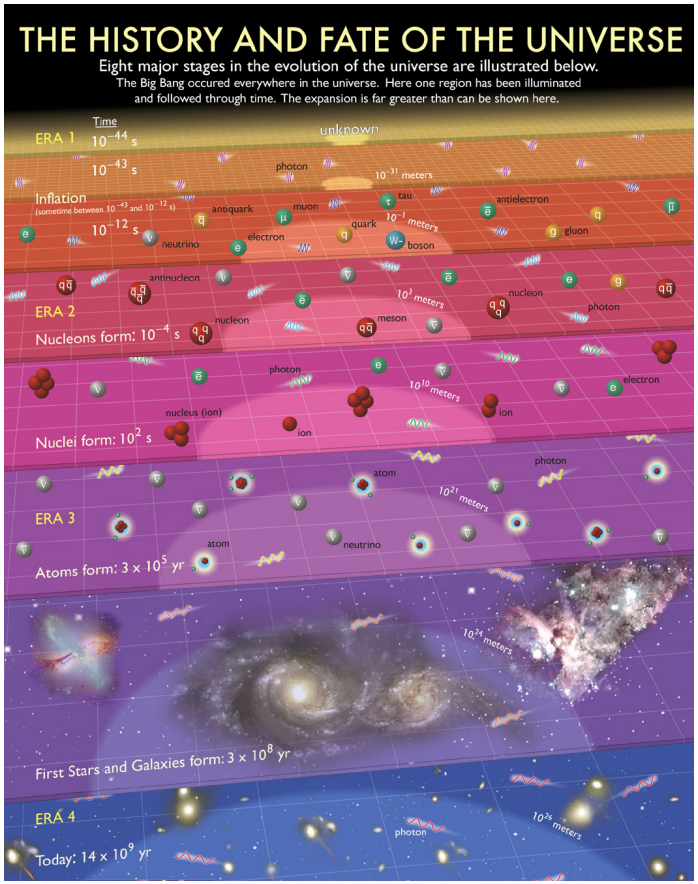
Thanks a lot for your time and attentions !

Backup Slides

What is High Energy Physics

Study matter and physics processes (elementary particles and their interaction) at the smallest scale and highest energy available in the laboratory (accelerator)



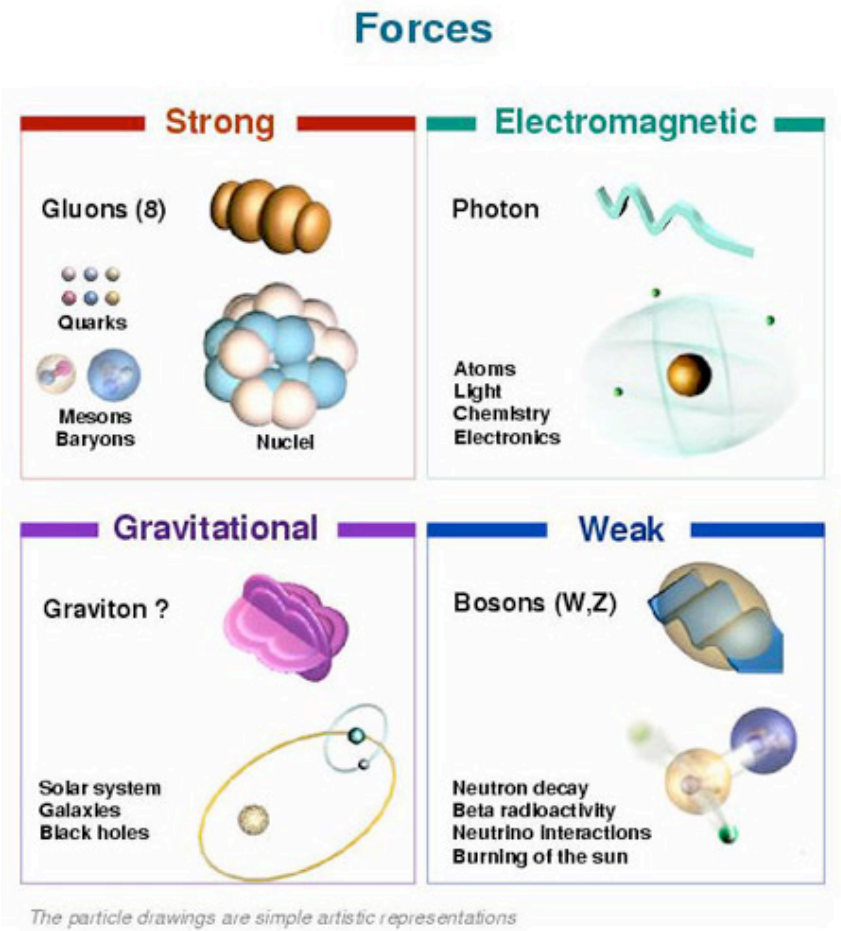


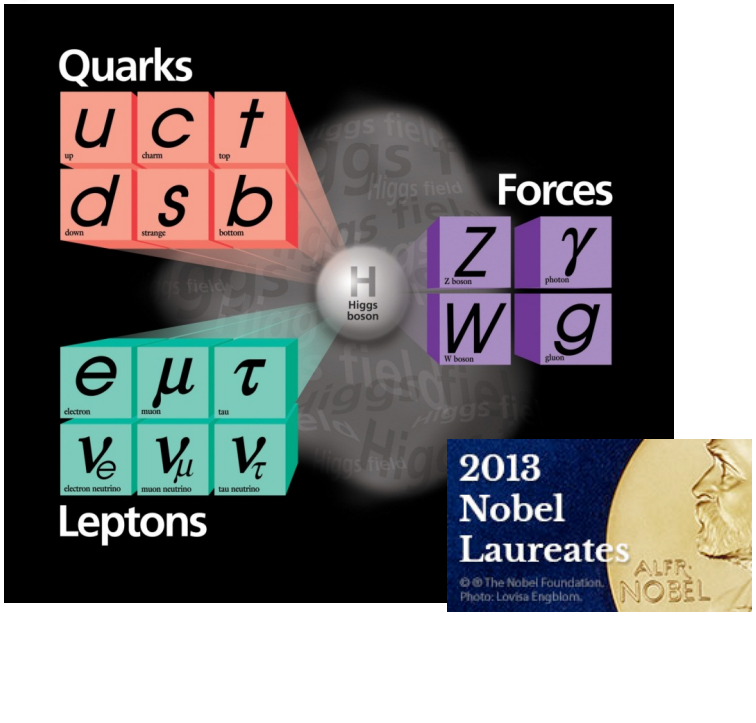
Standard model (SM): most fundamental and self consistent physics theory to explain phenomena observed in nature

Standard Model + Gravity = Basic Building blocks of our Knowledge in Physics
(≠ understanding the complexity of the nature ! Too difficult for HEP physicists !
Leave them for our friends in CMP, Astronomy, Chemistry, biology ……)

Particle Physicist View of the Universe

Many types of force (interaction) seen in our daily lives/universe
All known forces of nature can be traced to the 4 fundamental interactions
(Established by experimental observations)





Higgs boson: allow derive three fundamental interaction (Electromagnetic force, strong interaction and weak interaction) from the first principle (Gauge invariance) in physics with some basic assumptions (number of particles and their quantum numbers etc.)

Lessons/Opportunity in Particle Physics

- Do we understand the fundamental principles of nature?
- Same question asked more than 100 years ago:

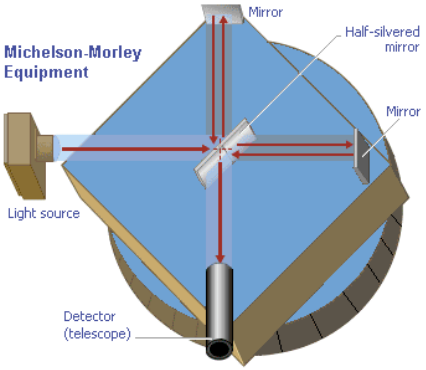
Lt. Cmdr. Albert A Michelson

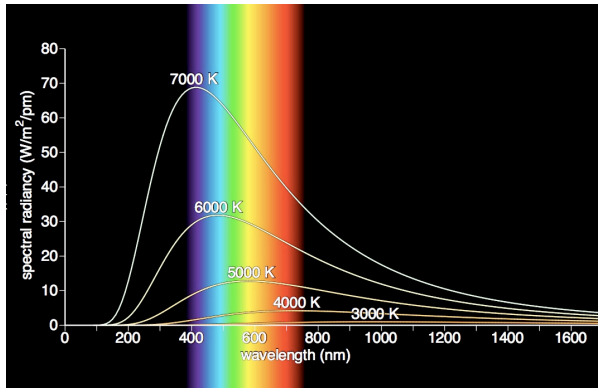
"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote."

1894, seven years after his experiment disproving existence of aether

- Two puzzles: Speed of light (SR), Black body radiation (QM)

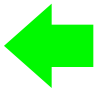
Michelson-Morley experiment





Higgs Decay

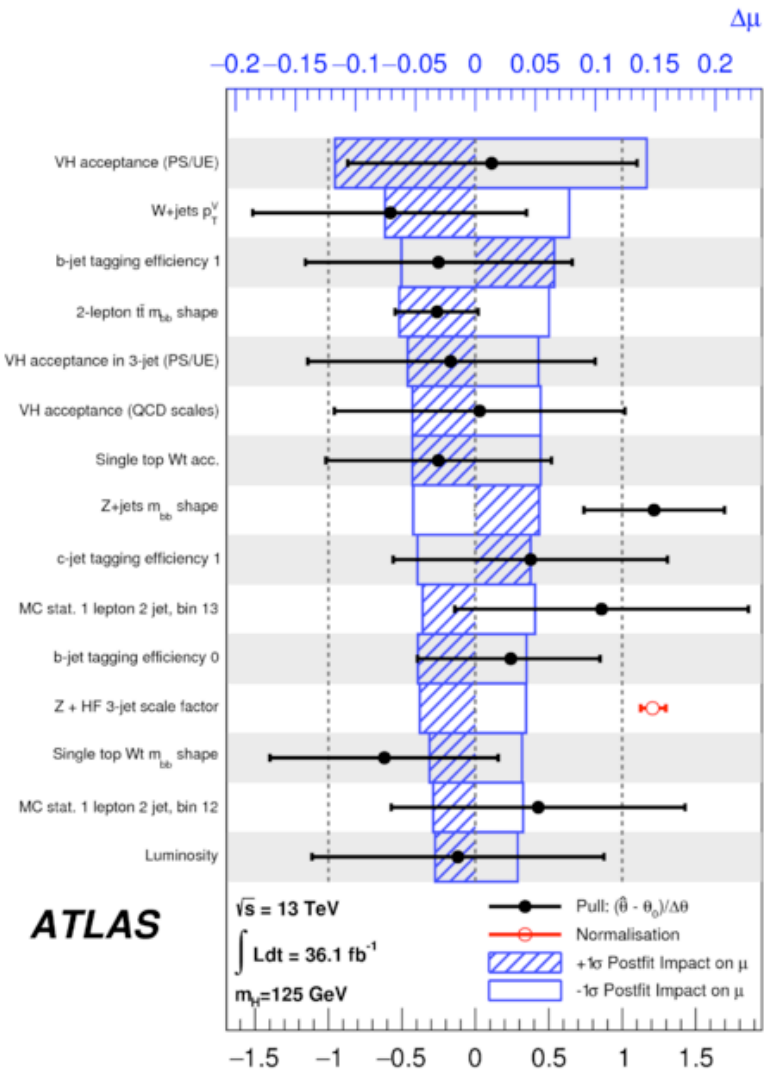
Decay Mode	Branching Fraction	*Useful* Branching fraction	Background Level
Bottom quarks	60%	30%	Tens of thousands:1
WW*	15%	~2%	Few:1
ZZ*	4%	0.014%	Comparable
gluons	10%	10%	Millions:1
taus	8%	6%	A long story
Charm quarks	6%	3%	Tens of thousands:1
Two photons	0.2%	0.2%	Few:1



For a ~125 GeV Higgs

The quantity of signal is but one element in designing an analysis. The level of background is at least as important. While I will only barely touch on it, so is trigger ability: you cannot analyze an event that you didn't record.

Systematic Uncertainties of $VH(H \to b\bar{b})$

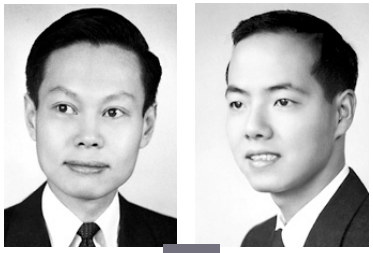


From experiment to great ideas in theory

Continuous electron spectrum in the β-decay of the nucleon:
Proposal of **neutrino** (Wolfgang Pauli 1930, Enrico Fermi 1934)

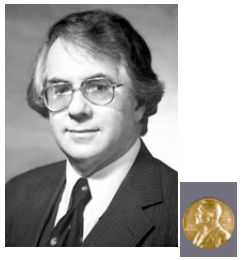

Pauli

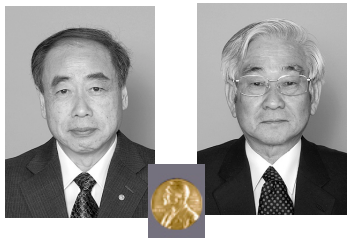

Fermi


Yang Lee

Lack of exp. test of parity conservation in Weak processes:
Proposal of testing **party violation**
(Chen-Ning Yang & Tsung-Dao Lee 1956)

Very small decay rate: $K^0 / \overline{K}^0 \rightarrow \mu^+ \mu^-$
Proposal of GIM mechanism → prediction of **charm quark**
(Sheldon Glashow, John Iliopoulos & Luciano Maiani 1970)


Glashow


Kobayashi Maskawa

Observation of CP vialition in neutral Kaon dacay in 1964:
Proposal of CKM mechanism and predict of **top quark**
(Makoto Kobayashi & Toshihide Maskawa 1973)

Double b-tagging vs. Top Bg Rejection