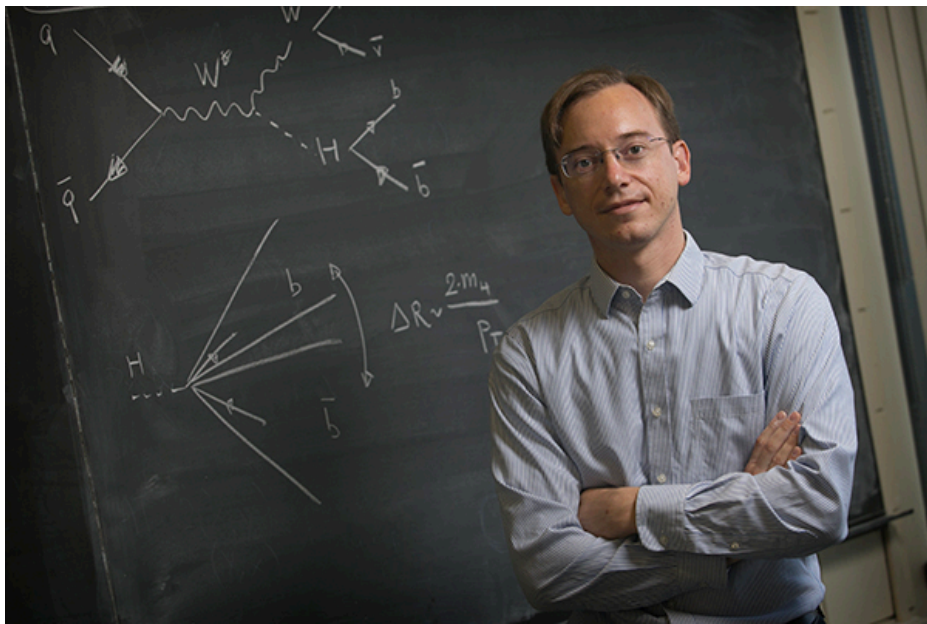


Physics of the Beauty (quark) and the Higgs (boson) at the LHC

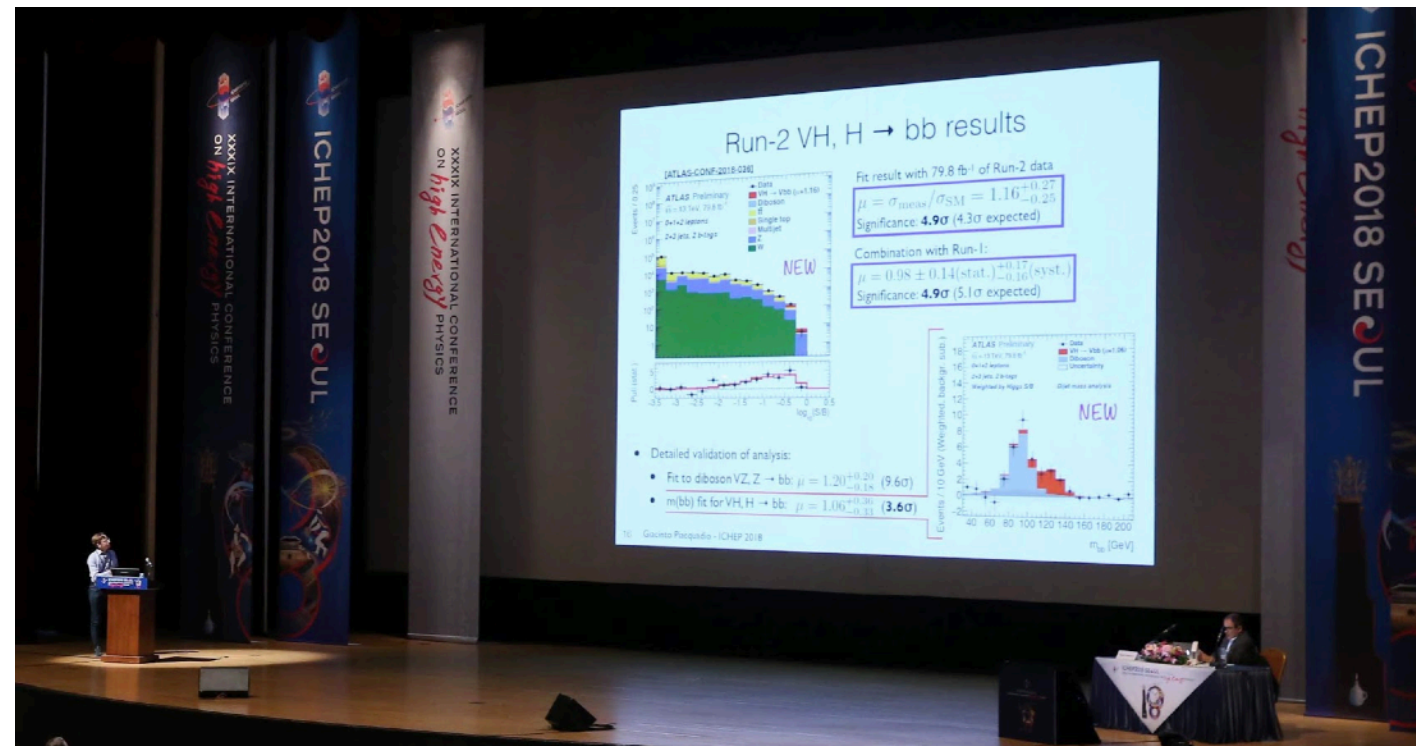
Prof. Giacinto Piacquadio
(Stony Brook University)

BNL Physics Department Summer Lecture
July 21st, 2025



Main interests: Higgs physics
Flavor Tagging, Tracking
Detectors, Future Colliders

Led the ATLAS Higgs group
(2018-2020)



Led the ATLAS Flavor Tagging
group in 2014-2016



My path:



San Francisco (2012-2016)



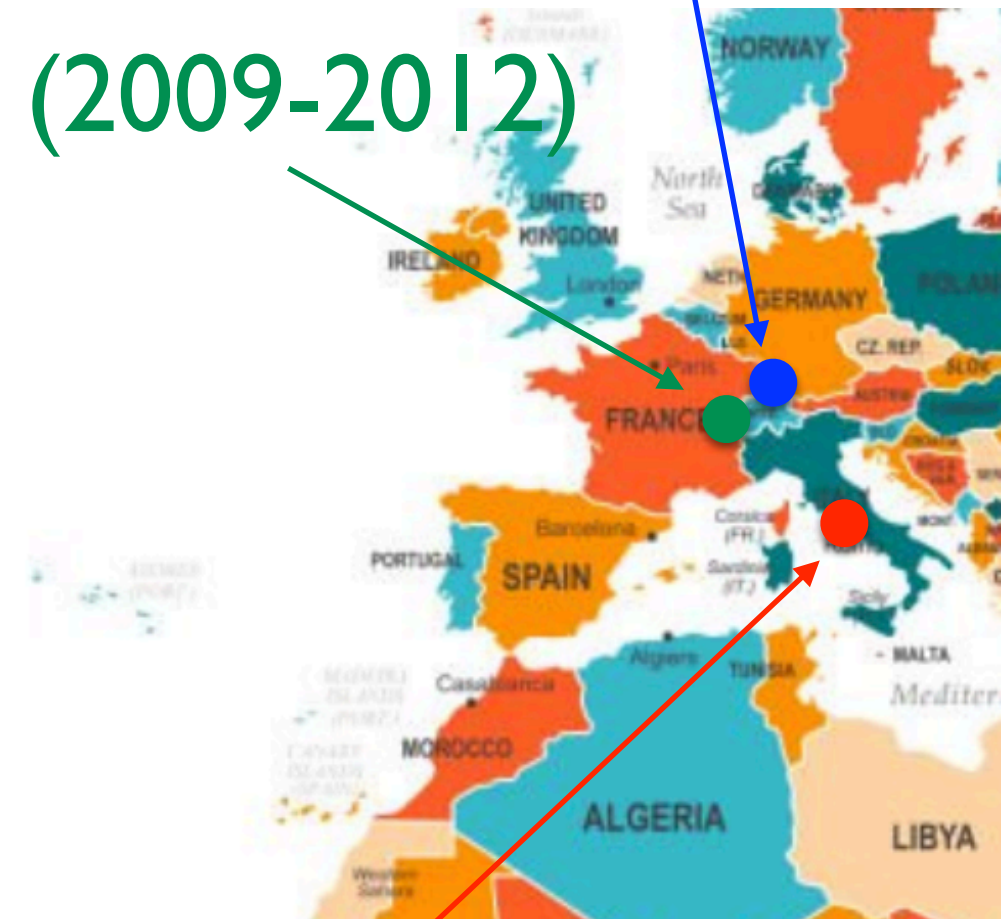
Stony Brook (2016-today)



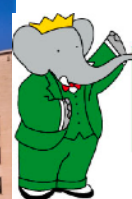
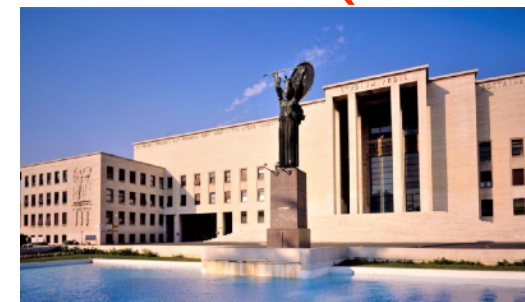
Freiburg (2005-2009)



CERN (2009-2012)



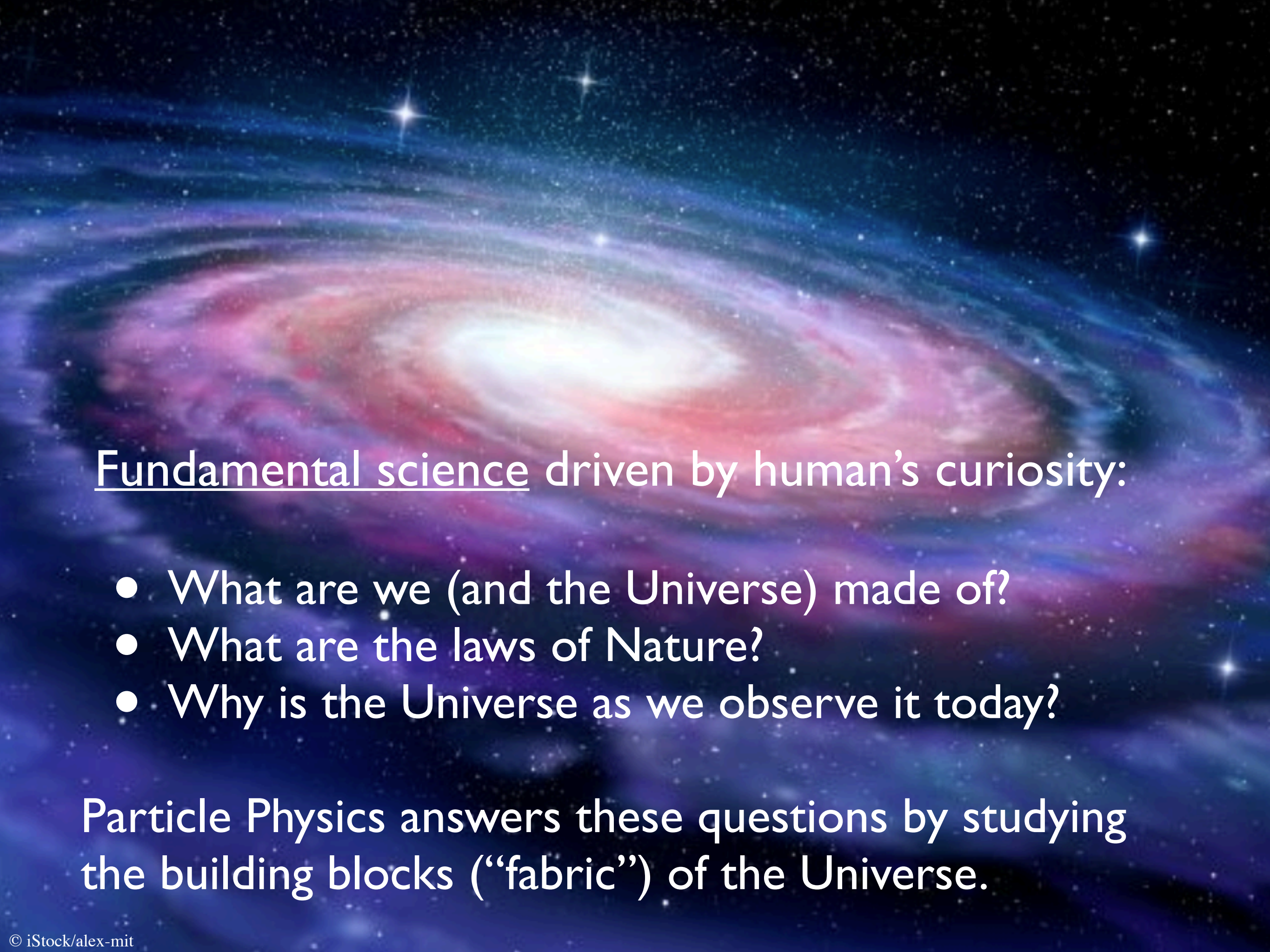
Rome (2004-2005)



BABAR

Fundamental science driven by human's curiosity:

- What are we (and the Universe) made of?
- What are the laws of Nature?
- Why is the Universe as we observe it today?



Fundamental science driven by human's curiosity:

- What are we (and the Universe) made of?
- What are the laws of Nature?
- Why is the Universe as we observe it today?

Particle Physics answers these questions by studying the building blocks (“fabric”) of the Universe.

This is the realm of Quantum physics!

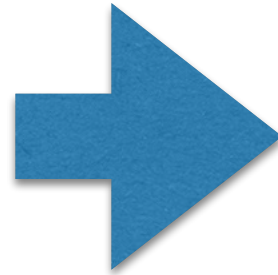
Heisenberg's uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

This is the realm of Quantum physics!

Heisenberg's uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$



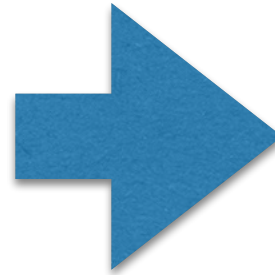
$$\Delta x \gtrsim \frac{\hbar}{p}$$

Small distances can only be resolved by high-momentum probes!

This is the realm of Quantum physics!

Heisenberg's uncertainty principle

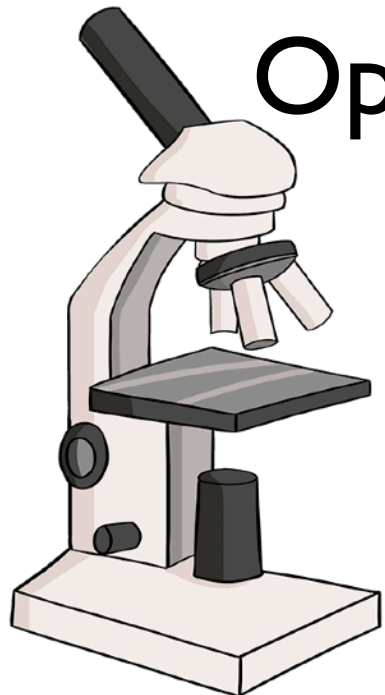
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$



$$\Delta x \gtrsim \frac{\hbar}{p}$$

Small distances can only be resolved by high-momentum probes!

Optical microscope



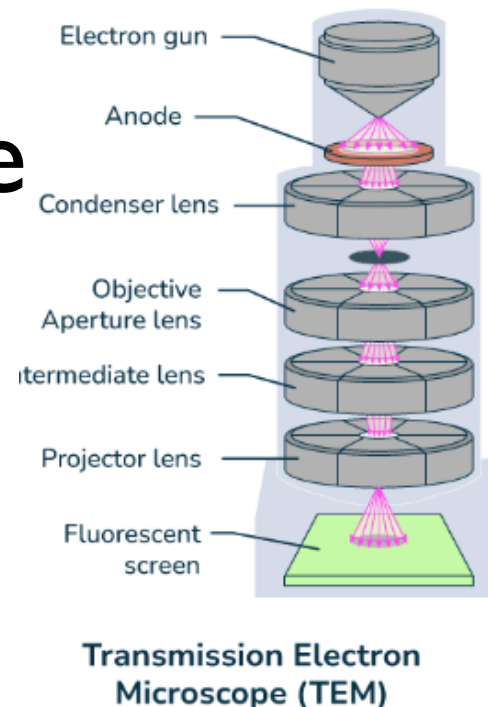
$$p_{\gamma} \sim 1 \text{ eV}$$

$$\Delta x \sim 100 \text{ \AA}$$

Electron microscope

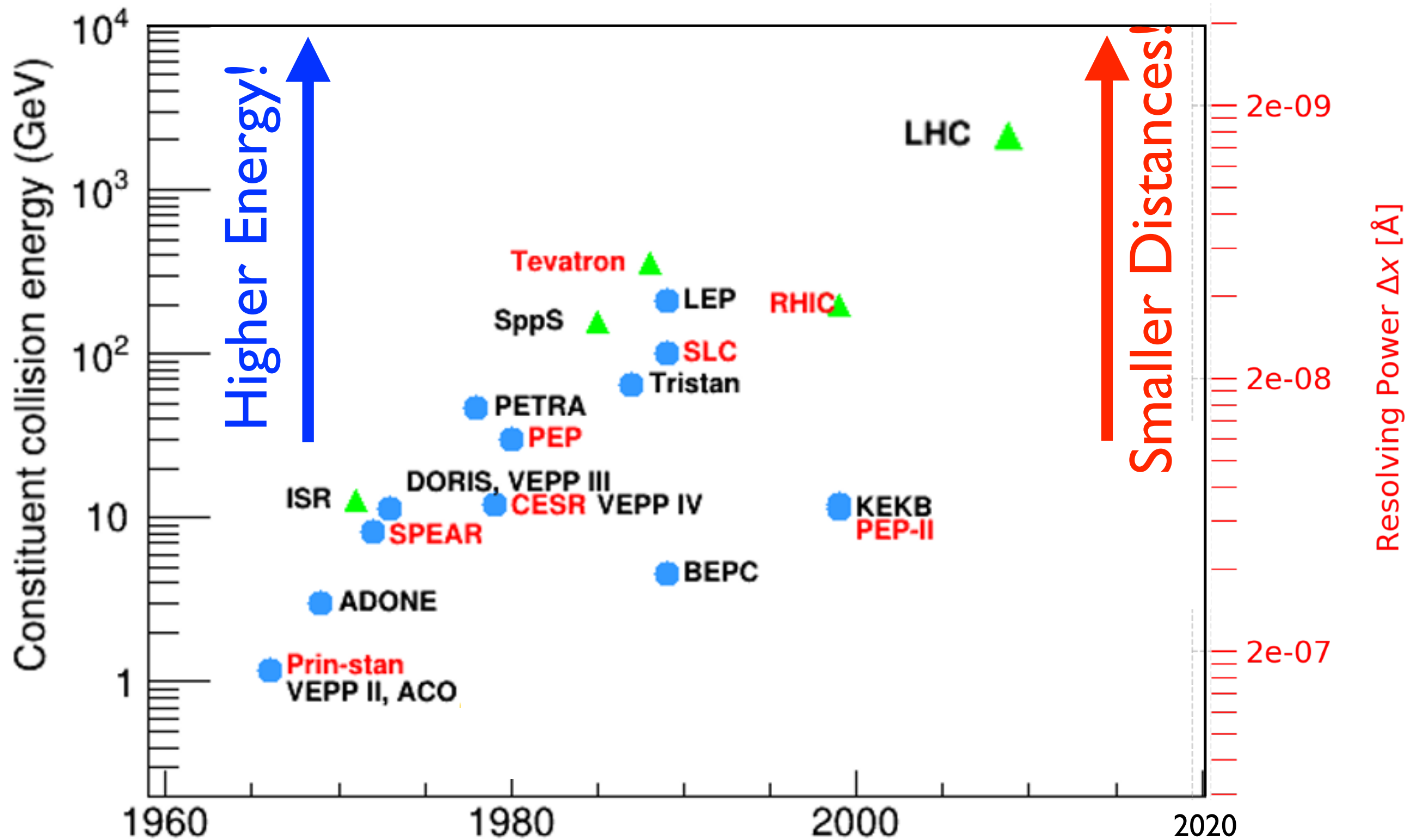
$$p_{e^{-}} \sim 1000000 \text{ eV}$$

$$\Delta x \sim 0.01 \text{ \AA}$$

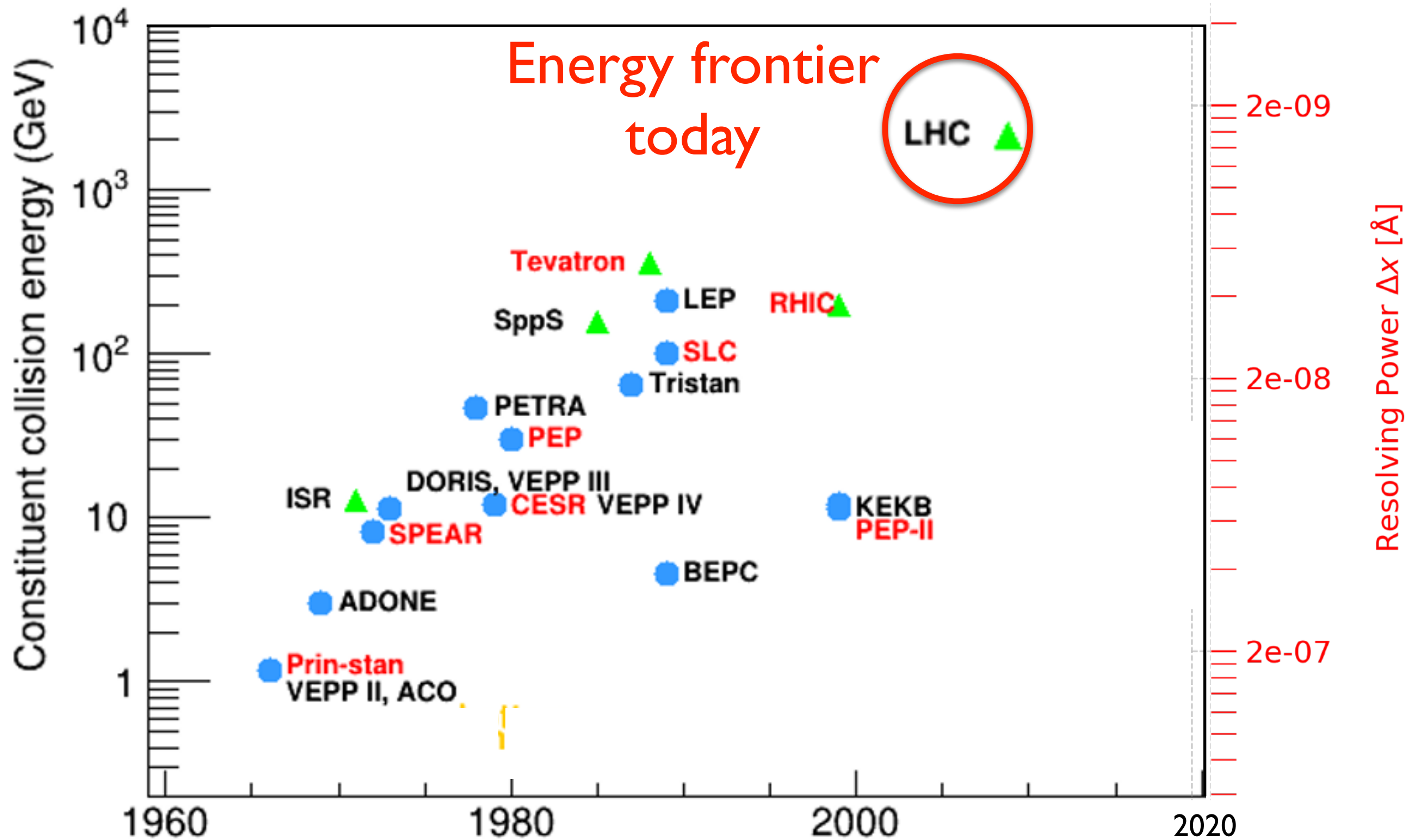


Transmission Electron Microscope (TEM)

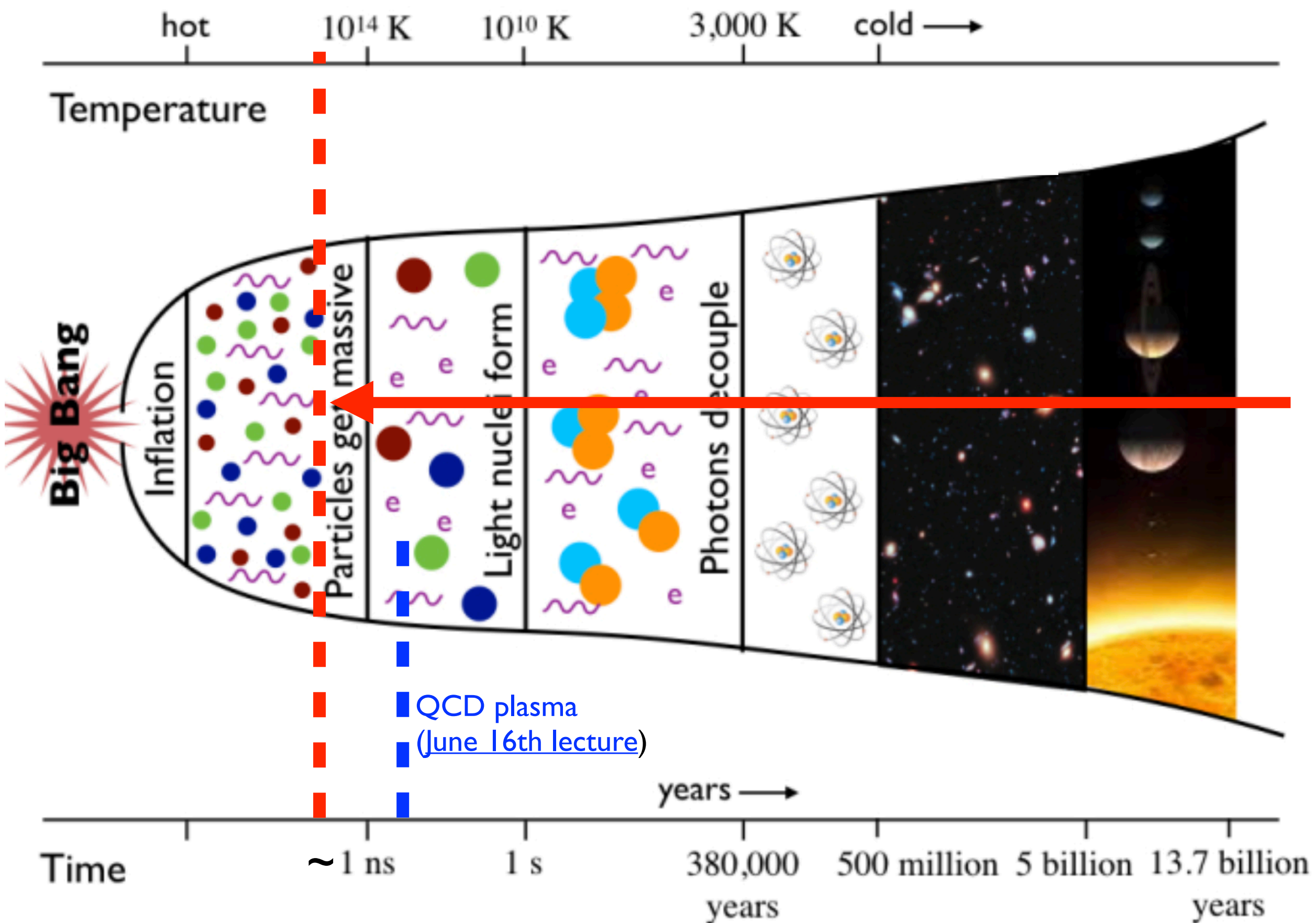
Particle Colliders as powerful microscopes:

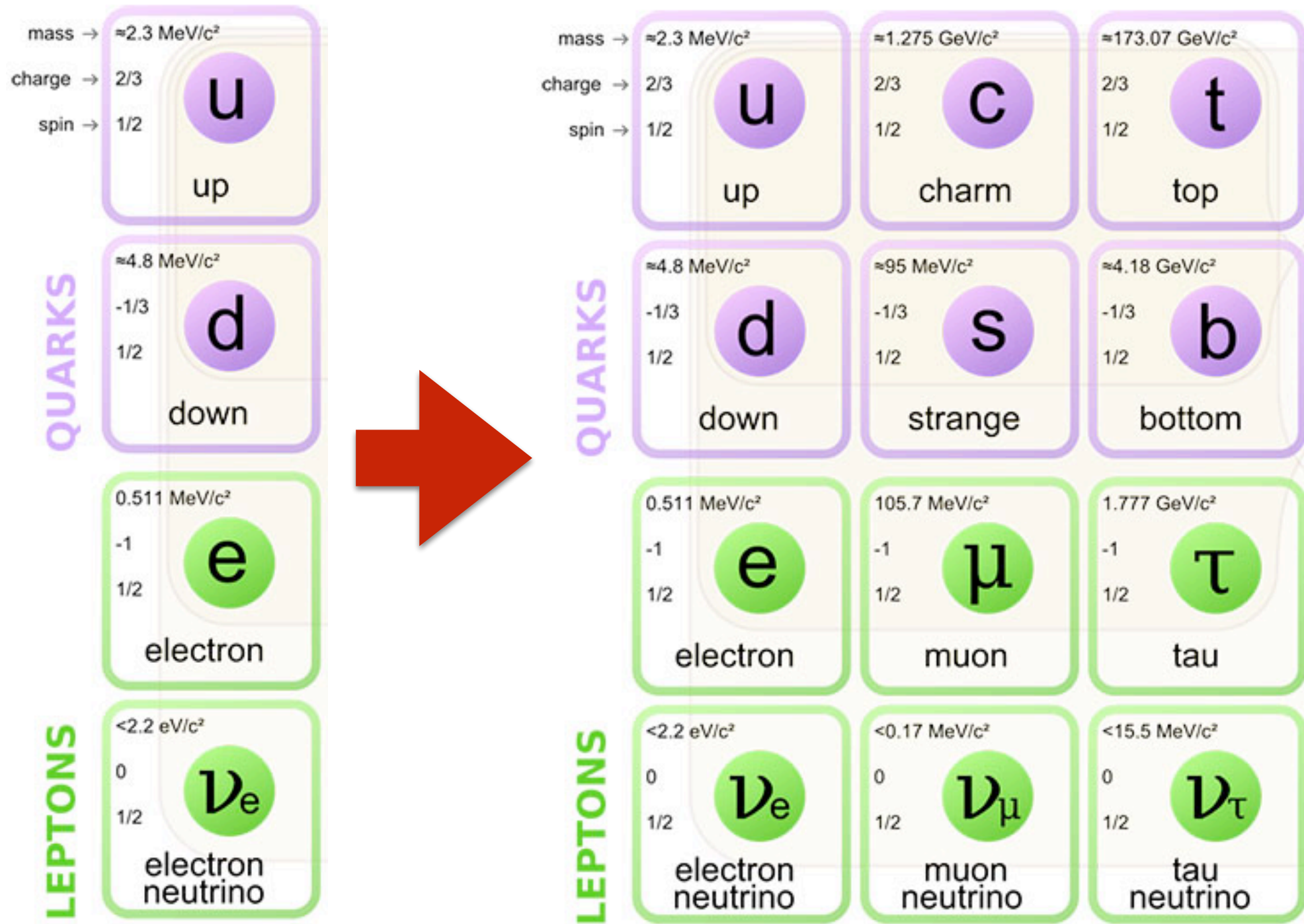


Particle Colliders as powerful microscopes:



Particle colliders as a “time machine”:





[wikipedia]

Matter around us

Matter in the early Universe

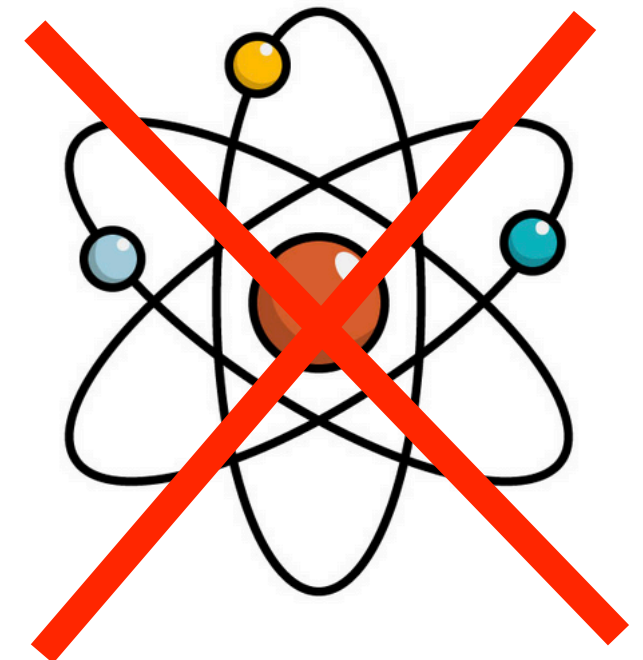
Standard Model of Particle Physics

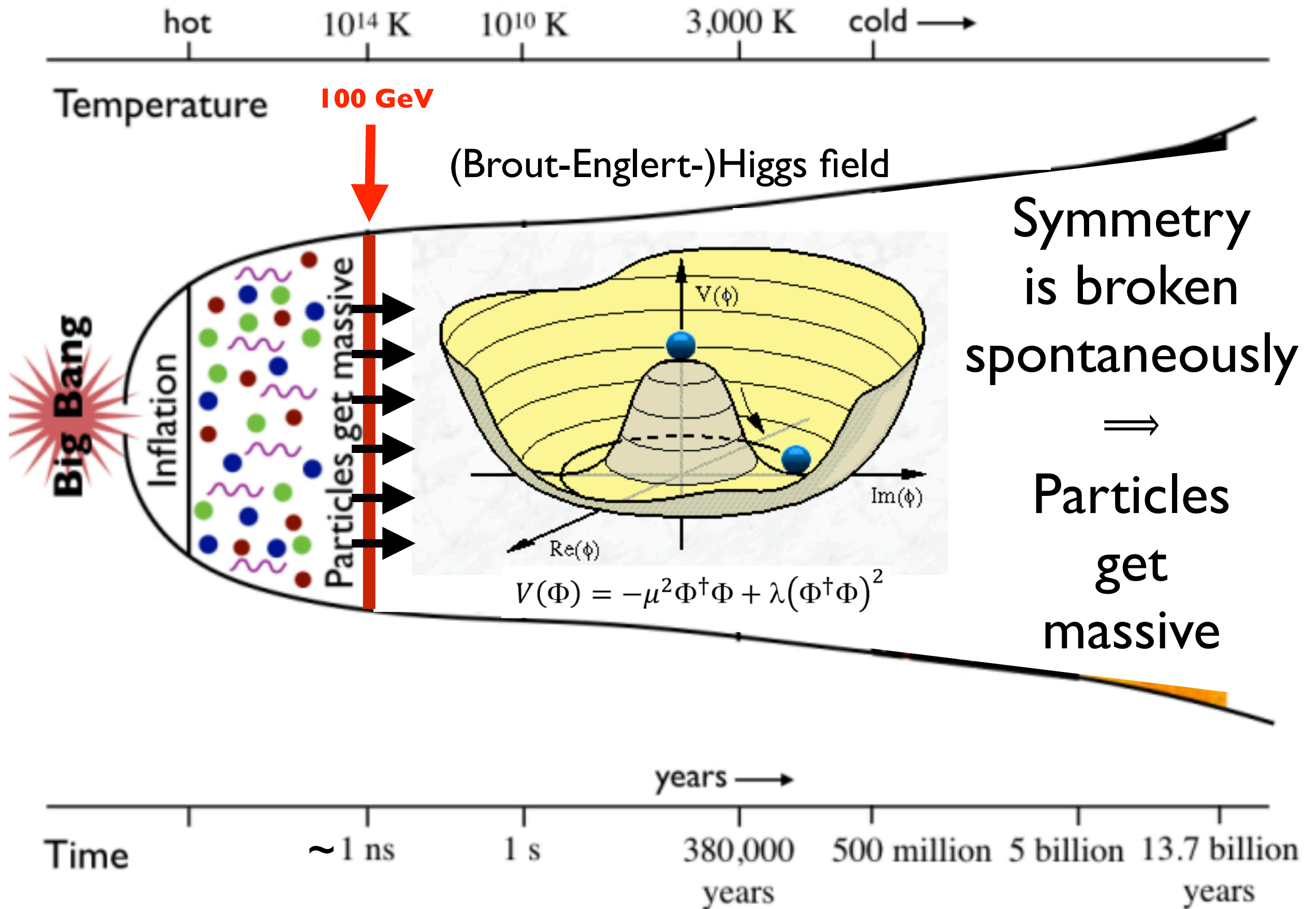
QUARKS	mass → charge → spin →	$\approx 2.3 \text{ MeV}/c^2$ $2/3$ $1/2$ u up	$\approx 1.275 \text{ GeV}/c^2$ $2/3$ $1/2$ c charm	$\approx 173.07 \text{ GeV}/c^2$ $2/3$ $1/2$ t top	0 0 1 g gluon
		$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$ d down	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$ b bottom	0 0 1 γ photon
		$0.511 \text{ MeV}/c^2$ -1 $1/2$ e electron	$105.7 \text{ MeV}/c^2$ -1 $1/2$ μ muon	$1.777 \text{ GeV}/c^2$ -1 $1/2$ τ tau	$91.2 \text{ GeV}/c^2$ 0 1 Z Z boson
		$< 2.2 \text{ eV}/c^2$ 0 $1/2$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $1/2$ ν_μ muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$ ν_τ tau neutrino	$80.4 \text{ GeV}/c^2$ ± 1 1 W W boson
					GAUGE BOSONS
LEPTONS					

Standard Model of Particle Physics

QUARKS	mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$  up	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$  charm	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$  top	mass → 0 charge → 0 spin → 1  gluon
	mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$  down	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$  strange	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$  bottom	mass → 0 charge → 0 spin → 1  photon
	mass → $0.511 \text{ MeV}/c^2$ charge → -1 spin → $1/2$  electron	mass → $105.7 \text{ MeV}/c^2$ charge → -1 spin → $1/2$  muon	mass → $1.777 \text{ GeV}/c^2$ charge → -1 spin → $1/2$  tau	mass → $91.2 \text{ GeV}/c^2$ charge → 0 spin → 1  Z boson
LEPTONS	mass → $< 2.2 \text{ eV}/c^2$ charge → 0 spin → $1/2$  electron neutrino	mass → $< 0.17 \text{ MeV}/c^2$ charge → 0 spin → $1/2$  muon neutrino	mass → $< 15.5 \text{ MeV}/c^2$ charge → 0 spin → $1/2$  tau neutrino	mass → $80.4 \text{ GeV}/c^2$ charge → ± 1 spin → 1  W boson
				GAUGE BOSONS

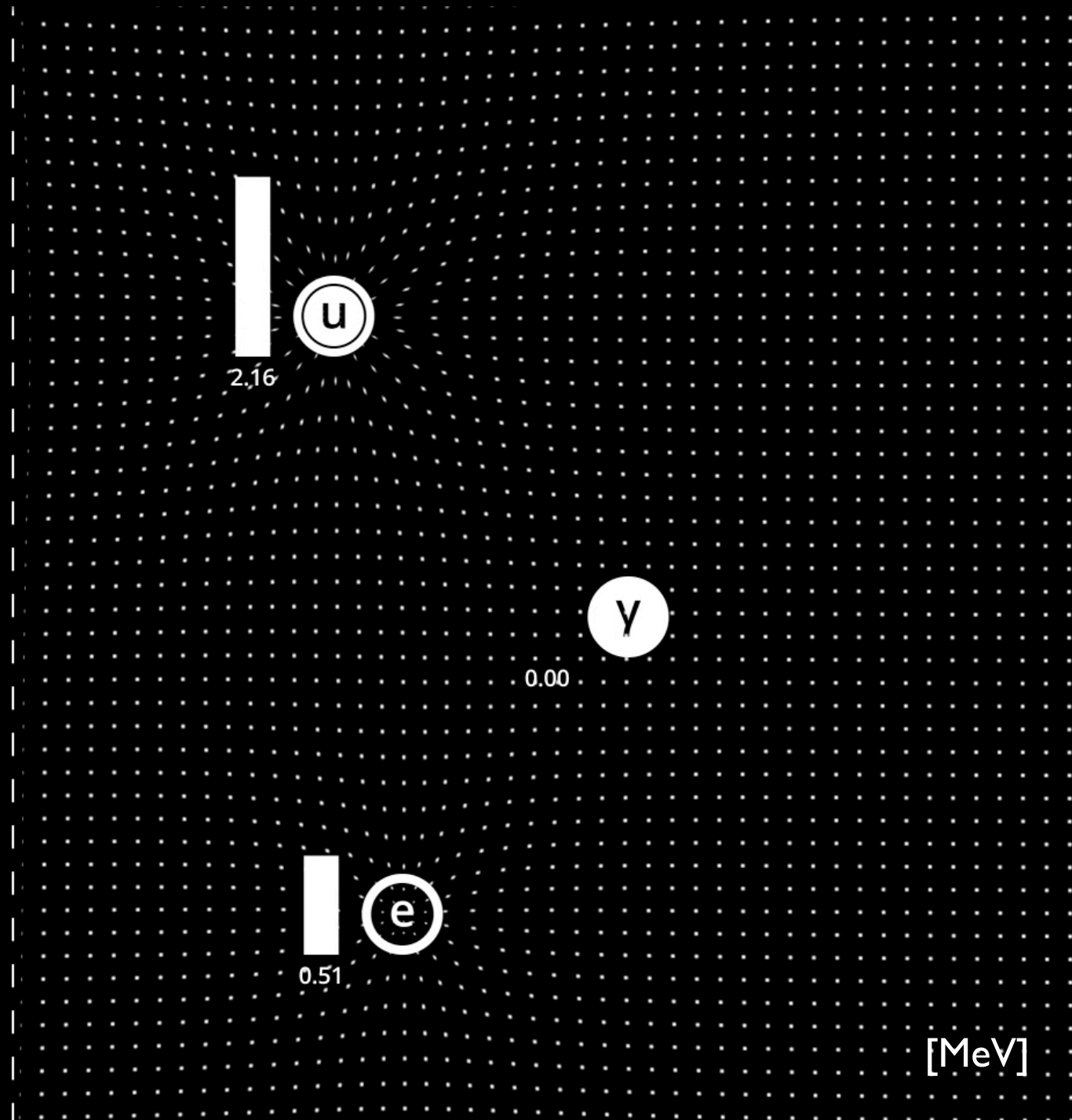
No mass





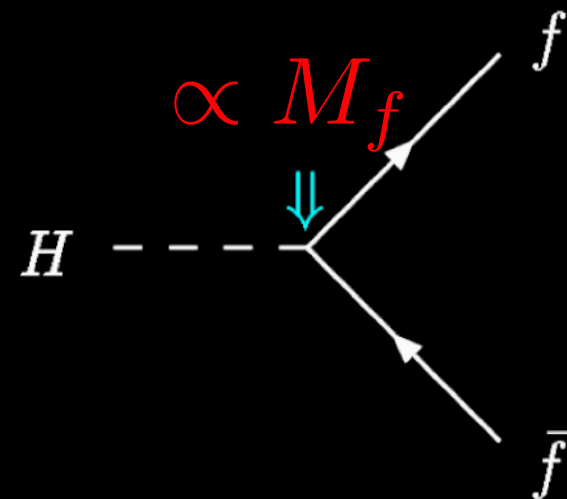
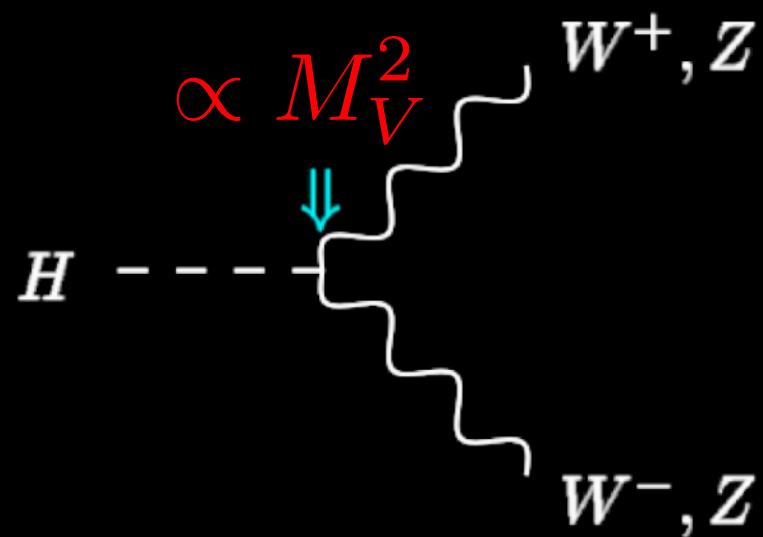
(Brout-Englert-)Higgs's Idea (1964)

Particles that **interact**
with this field **get mass**



(Brout-Englert-)Higgs's Idea (1964)

----- Higgs Boson (excitation of Higgs field)



Standard Model of Particle Physics

QUARKS	mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$  up	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$  charm	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$  top	mass → 0 charge → 0 spin → 1  gluon	mass → $\approx 126 \text{ GeV}/c^2$ charge → 0 spin → 0  Higgs boson
	mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$  down	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$  strange	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$  bottom	mass → 0 charge → 0 spin → 1  photon	
	mass → $0.511 \text{ MeV}/c^2$ charge → -1 spin → $1/2$  electron	mass → $105.7 \text{ MeV}/c^2$ charge → -1 spin → $1/2$  muon	mass → $1.777 \text{ GeV}/c^2$ charge → -1 spin → $1/2$  tau	mass → $91.2 \text{ GeV}/c^2$ charge → 0 spin → 1  Z boson	
LEPTONS	mass → $< 2.2 \text{ eV}/c^2$ charge → 0 spin → $1/2$  electron neutrino	mass → $< 0.17 \text{ MeV}/c^2$ charge → 0 spin → $1/2$  muon neutrino	mass → $< 15.5 \text{ MeV}/c^2$ charge → 0 spin → $1/2$  tau neutrino	mass → $80.4 \text{ GeV}/c^2$ charge → ± 1 spin → 1  W boson	GAUGE BOSONS

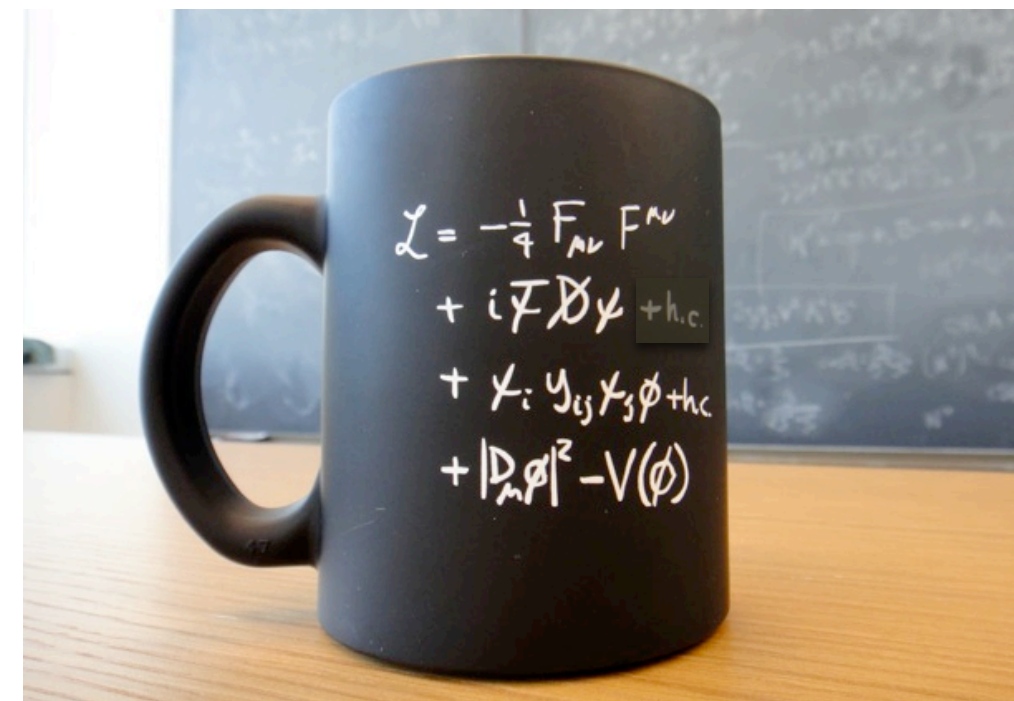
Discovered in 2012 at the
Large Hadron Collider (LHC),
 by *ATLAS and CMS Collaborations*



Standard Model of Particle Physics

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$1/2$	$1/2$	$1/2$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS

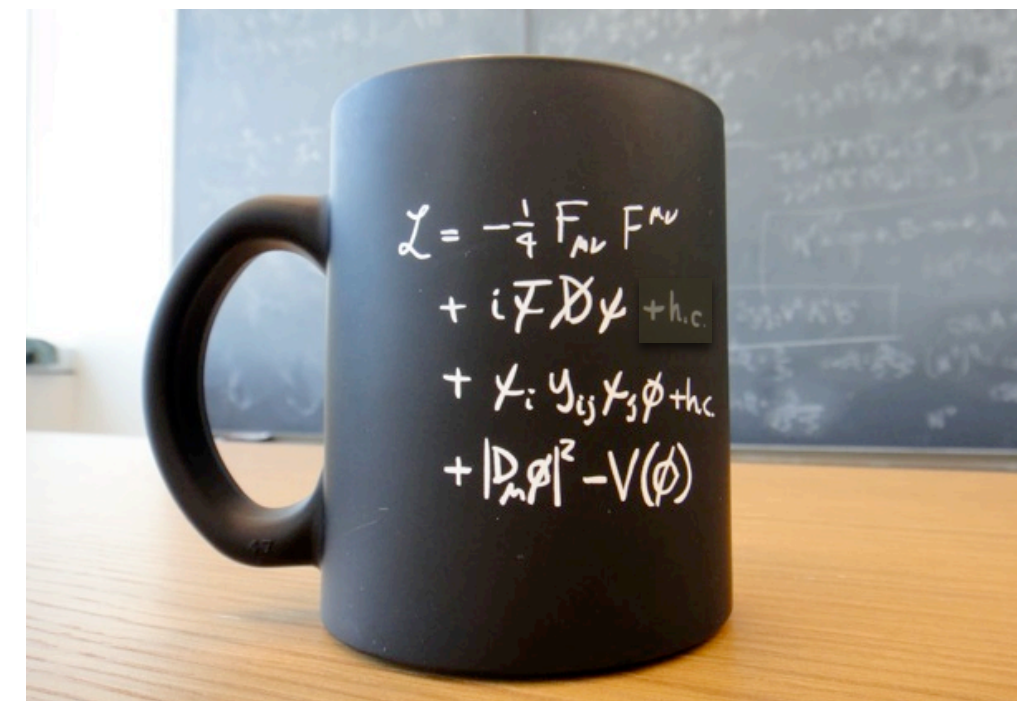
extremely successful
as discussed in
June 9th SM lecture
([link](#))



Standard Model of Particle Physics

QUARKS	mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$ u up	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ c charm	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ t top	mass → 0 charge → 0 spin → 1 g gluon	mass → $\approx 126 \text{ GeV}/c^2$ charge → 0 spin → 0 H Higgs boson
	mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ d down	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ s strange	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$ b bottom	mass → 0 charge → 0 spin → 1 γ photon	
	mass → $0.511 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ e electron	mass → $105.7 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ μ muon	mass → $1.777 \text{ GeV}/c^2$ charge → -1 spin → $1/2$ τ tau	mass → $91.2 \text{ GeV}/c^2$ charge → 0 spin → 1 Z Z boson	
LEPTONS	mass → $< 2.2 \text{ eV}/c^2$ charge → 0 spin → $1/2$ ν_e electron neutrino	mass → $< 0.17 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_μ muon neutrino	mass → $< 15.5 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_τ tau neutrino	mass → $80.4 \text{ GeV}/c^2$ charge → ± 1 spin → 1 W W boson	GAUGE BOSONS

Flavor physics
discussed in
June 23rd lecture
([link](#))



But many open questions...

But many open questions...
will focus here on 2!

(1)

For comparison:



proton mass

Leptons

~ 0

ν_e

electron

~ 0

ν_μ

muon

~ 0

ν_τ

tau

Quarks

.

up



charm

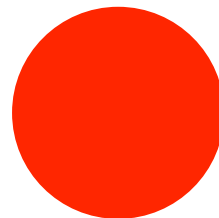
top

.

down

.

strange

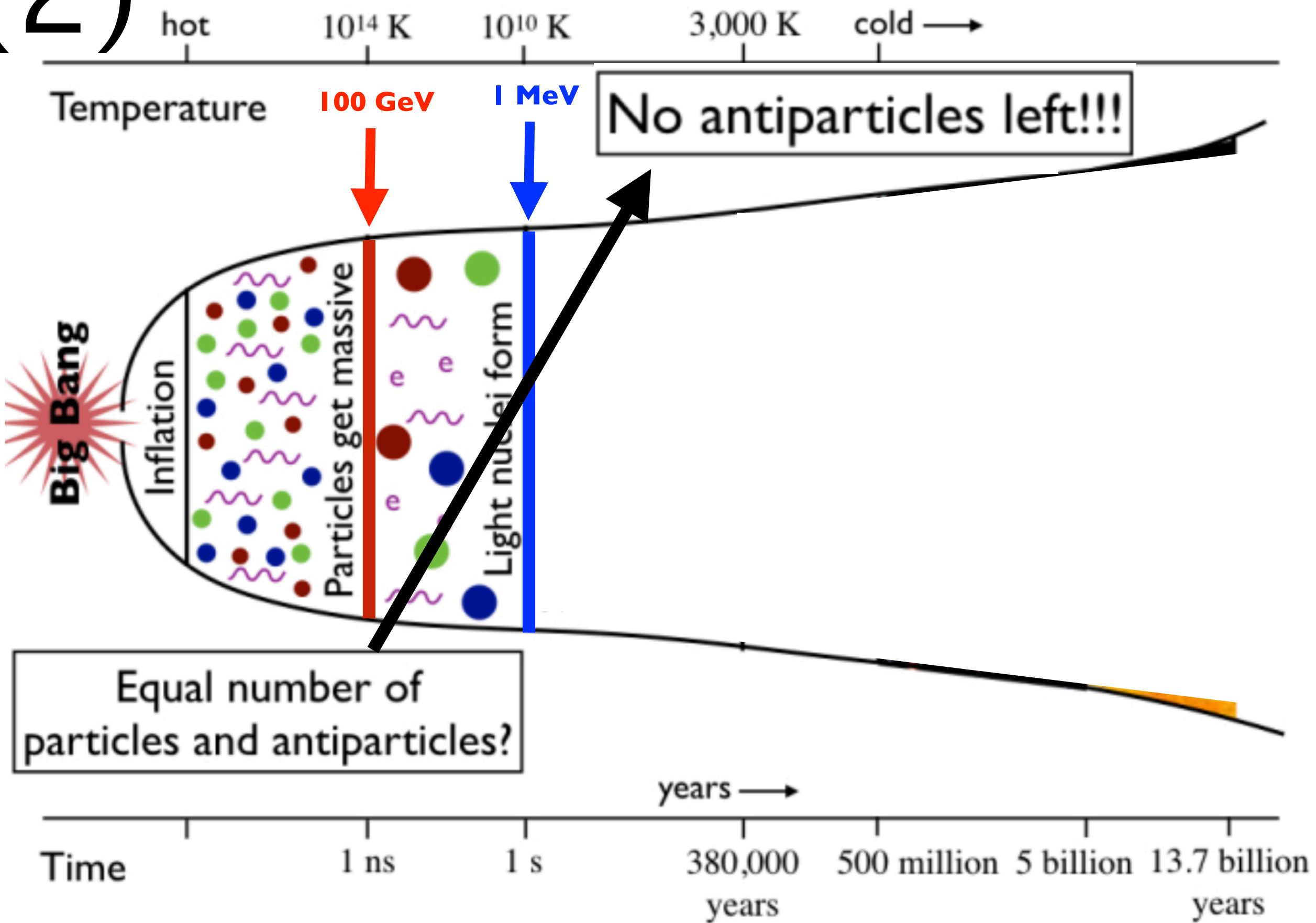


bottom

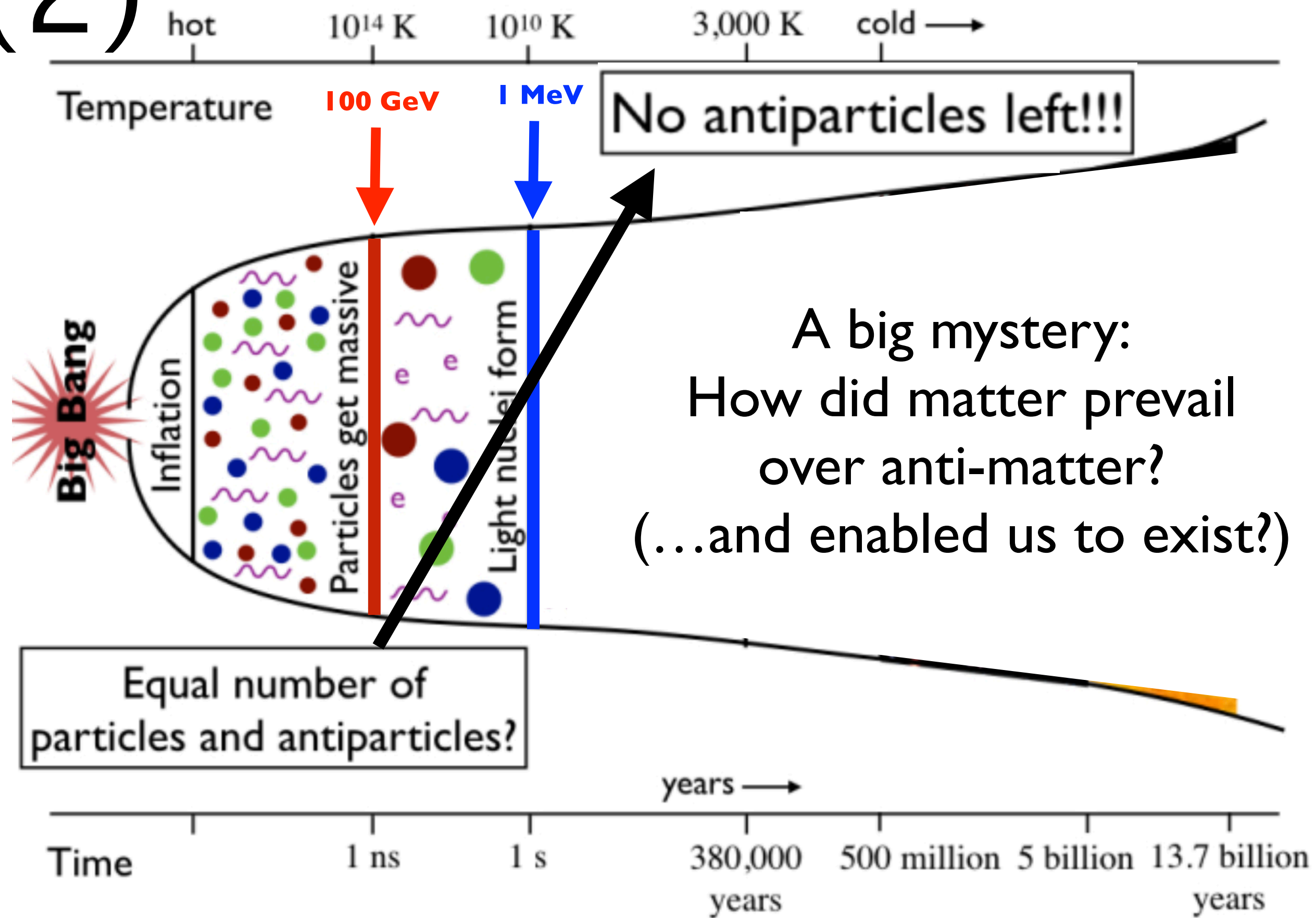
Why is the mass so large?

Is the Higgs field responsible for the mass of all fermions?
Why are fermion masses so vastly different?

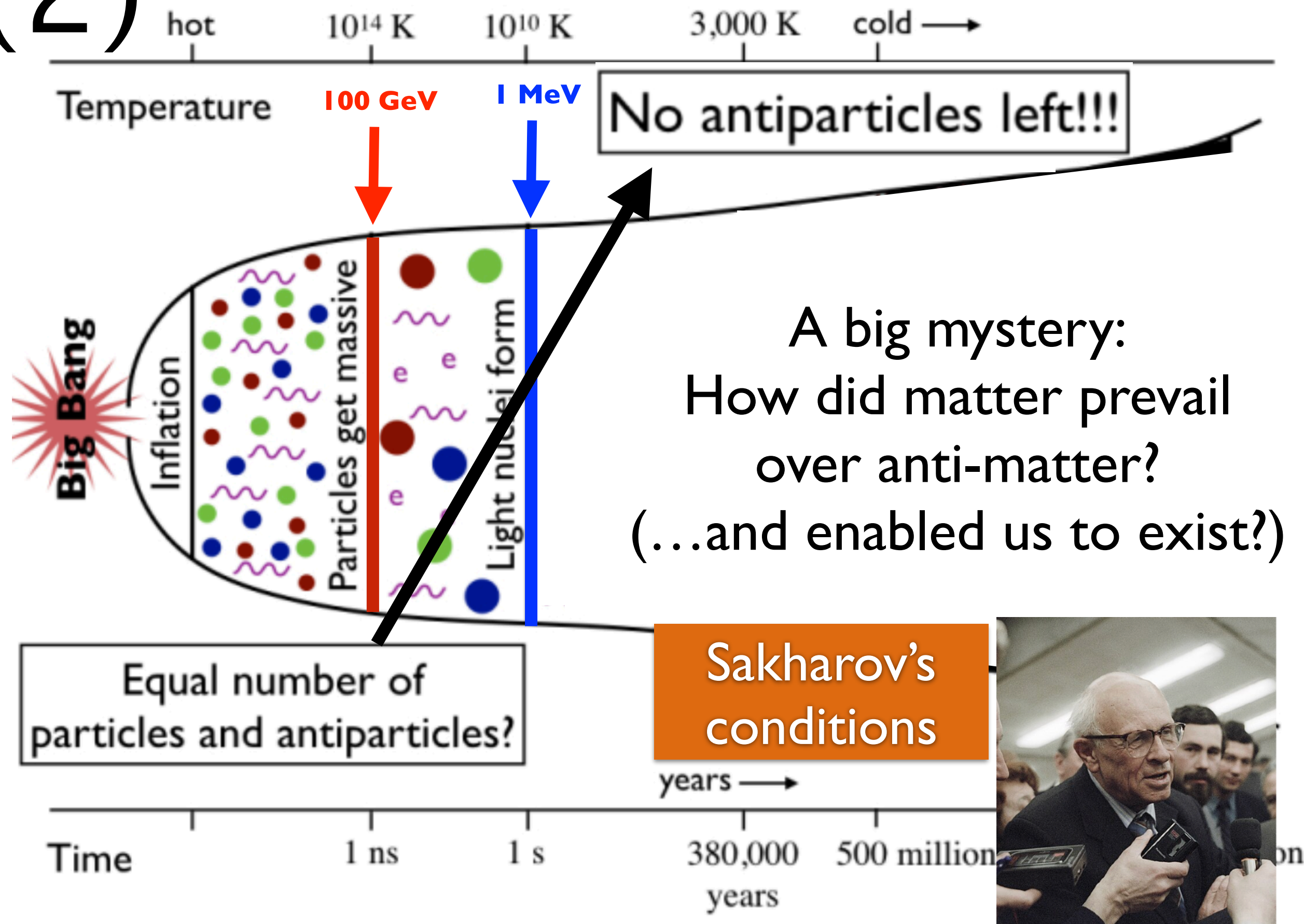
(2)



(2)

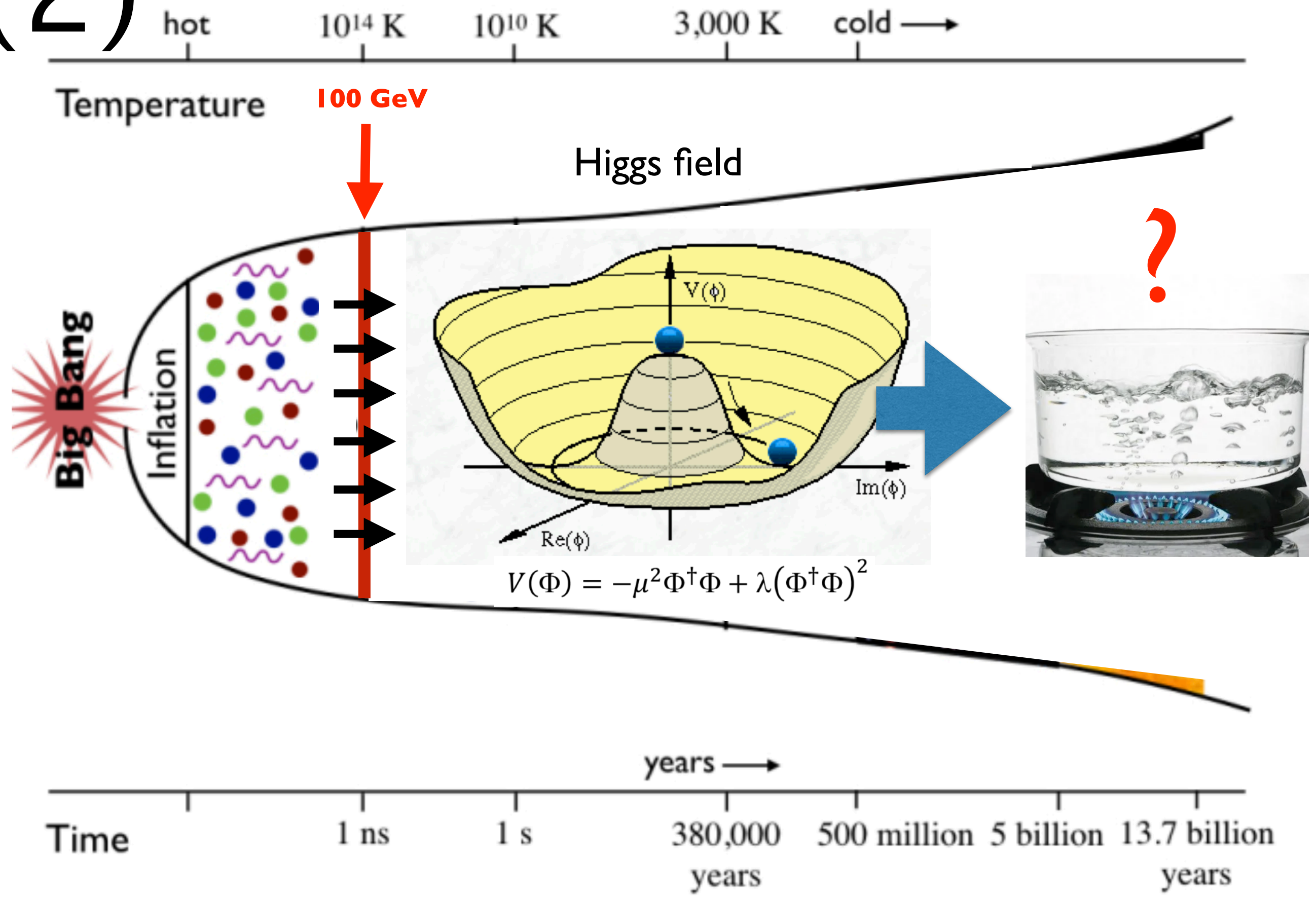


(2)

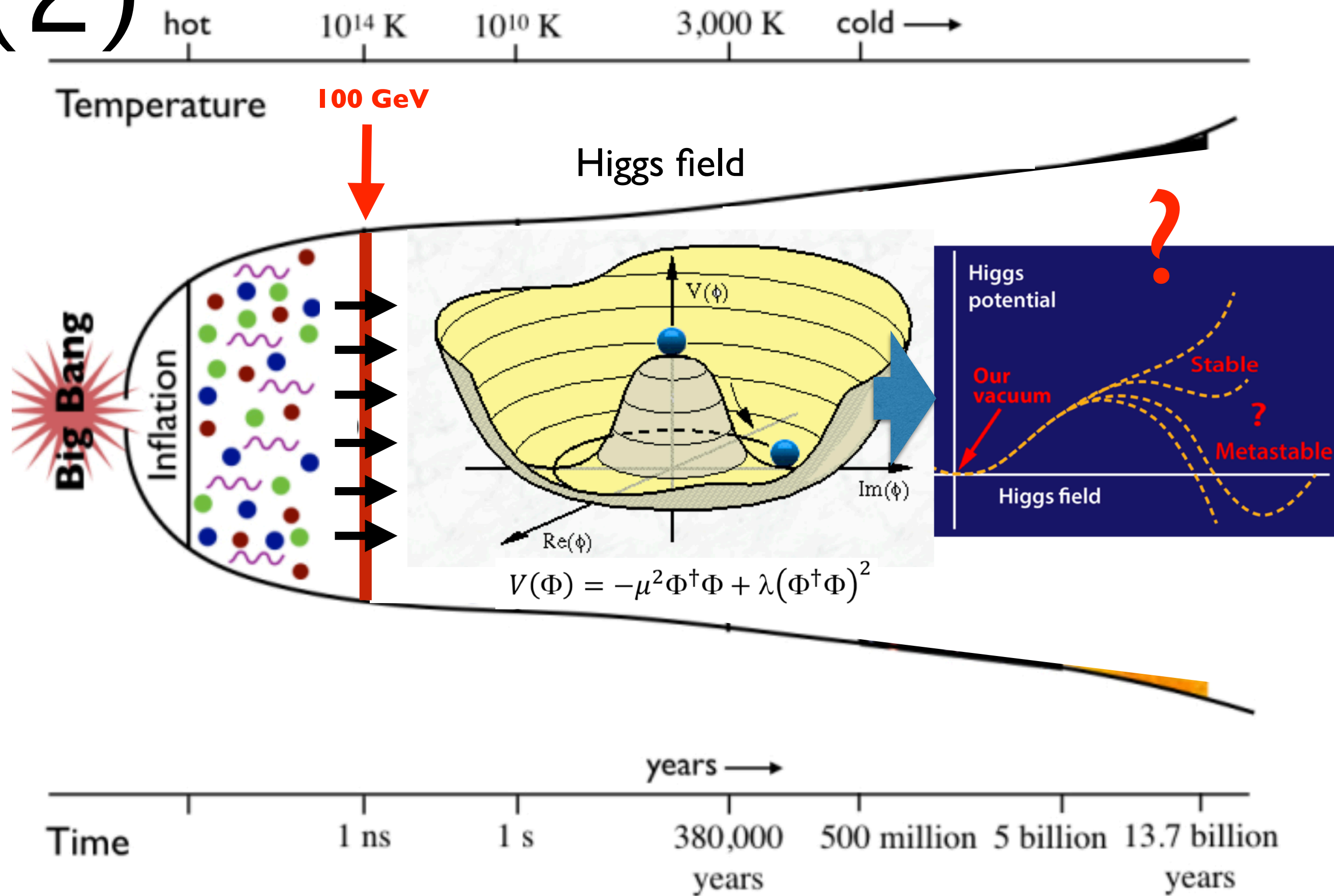


A big mystery:
How did matter prevail
over anti-matter?
(...and enabled us to exist?)

(2)



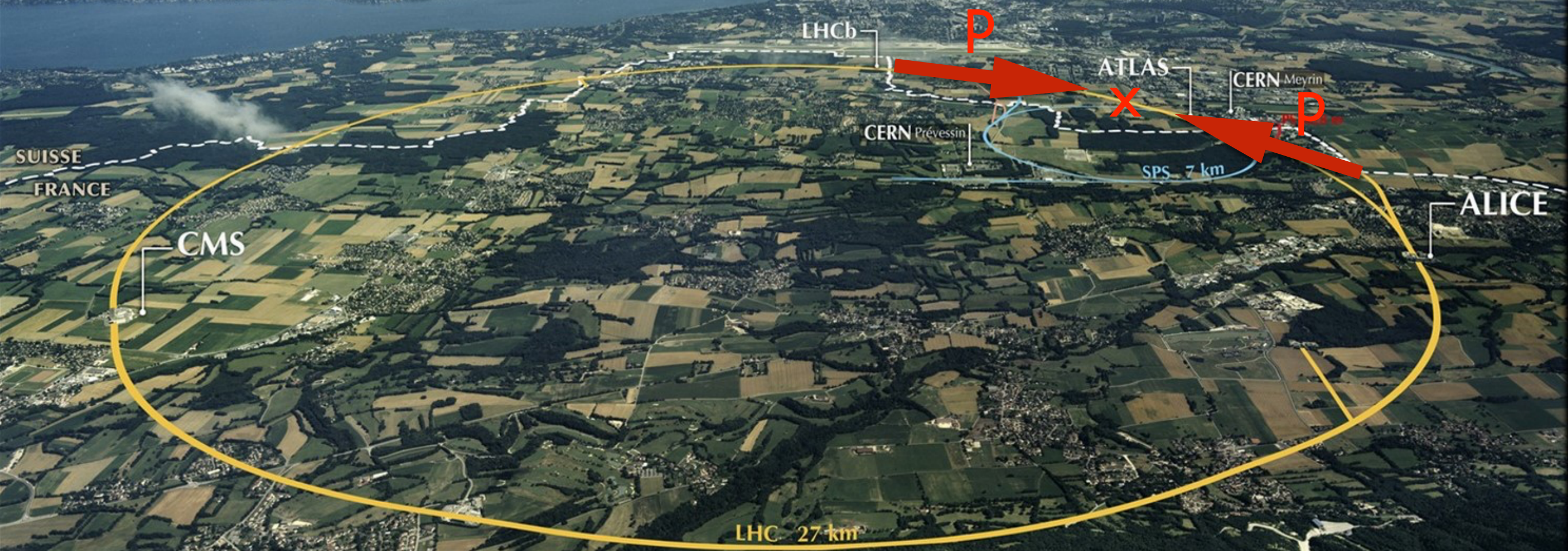
(2)



The Higgs Boson as a tool

How do we produce the Higgs Boson?

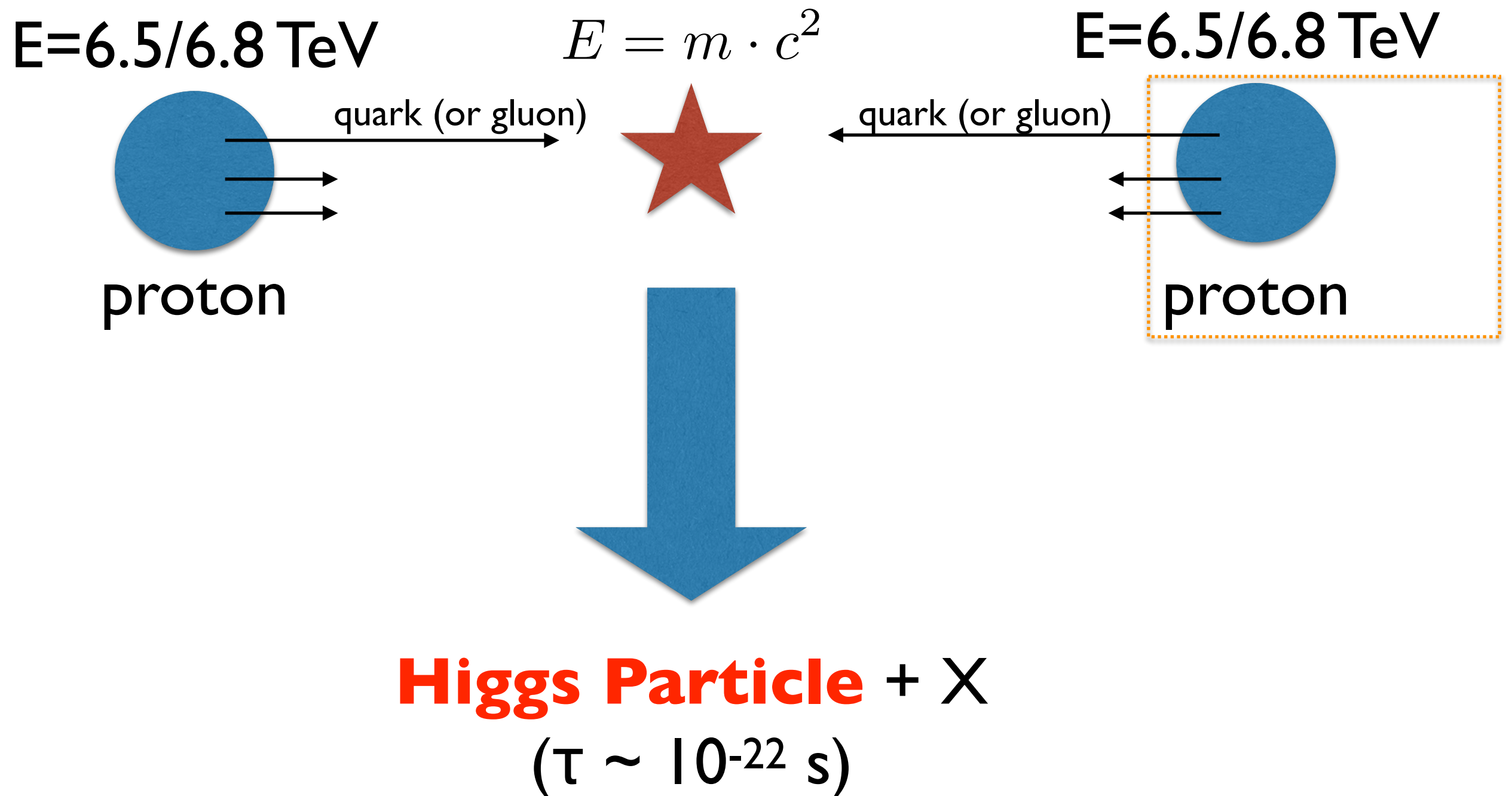
We use the most powerful accelerator and particle collider on Earth:
the **LHC** (Large Hadron Collider)



- 27 km ring, ~100 m underground
- Collision energy in Run-3: **13.6 TeV** (~15,000x times proton mass)
- Protons collide 40 million times per second

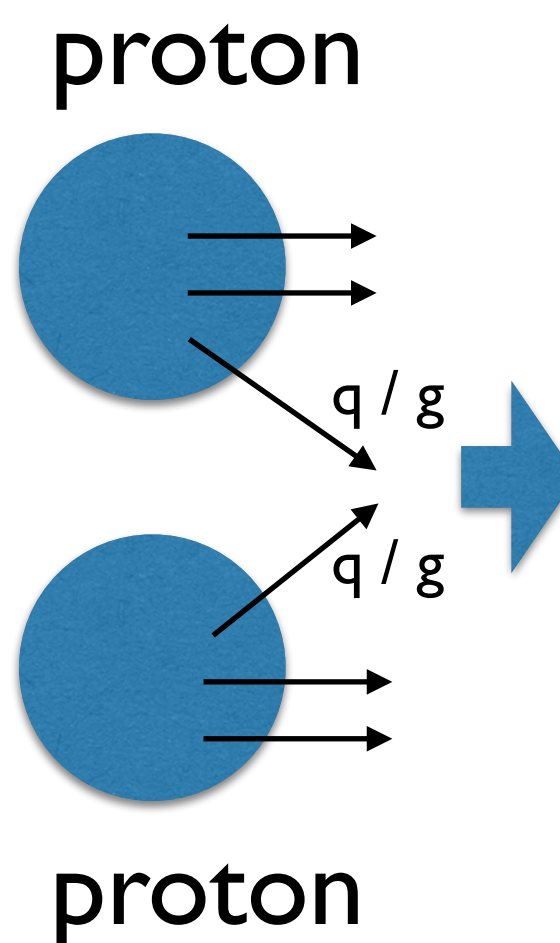
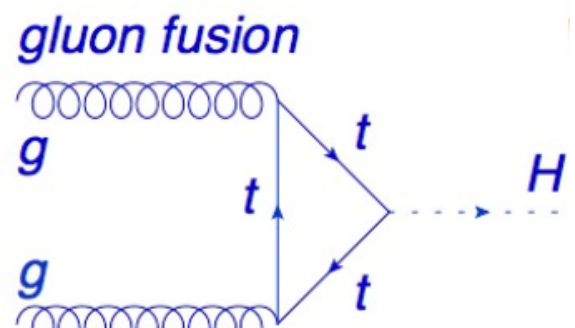
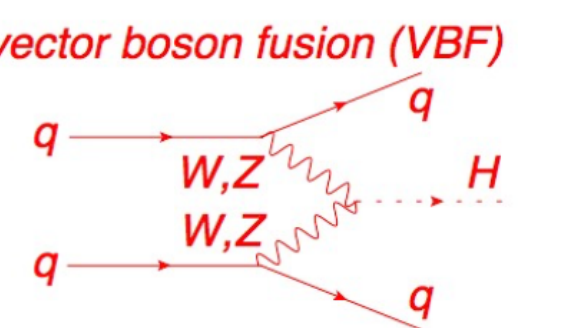
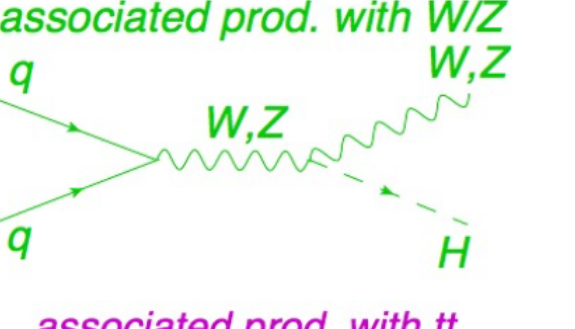
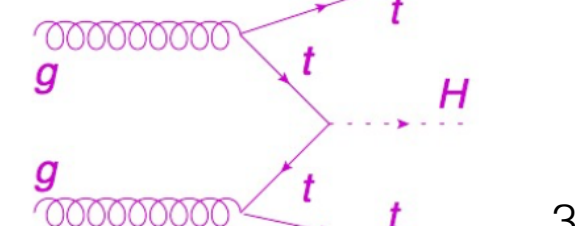
How do we produce the Higgs Boson?

- Out of less than one every billion interactions, a Higgs Boson is produced.



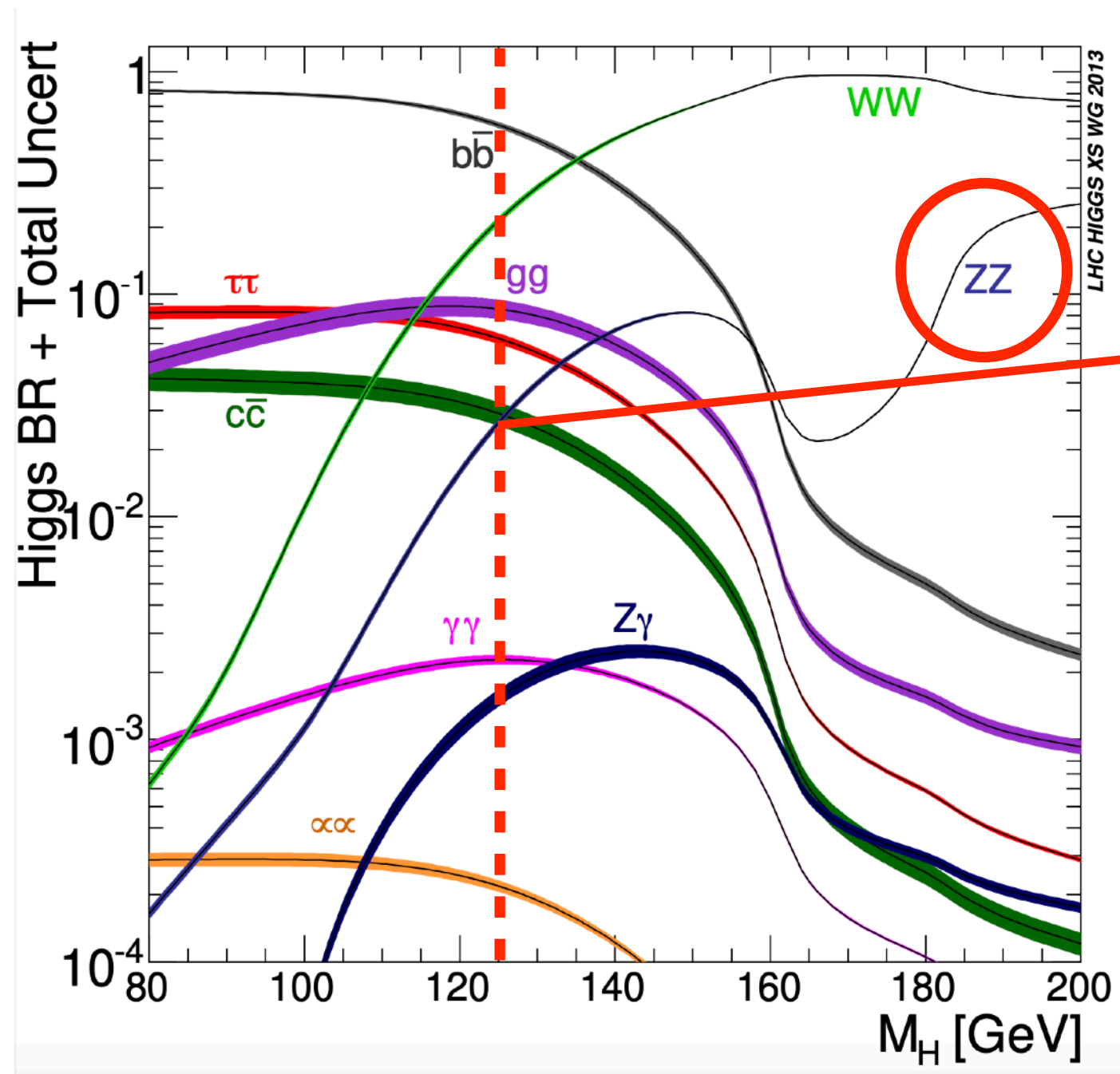
What is the ★?

At the **LHC** there are many ways to **produce** a Higgs boson, they only depend on **m_H** .

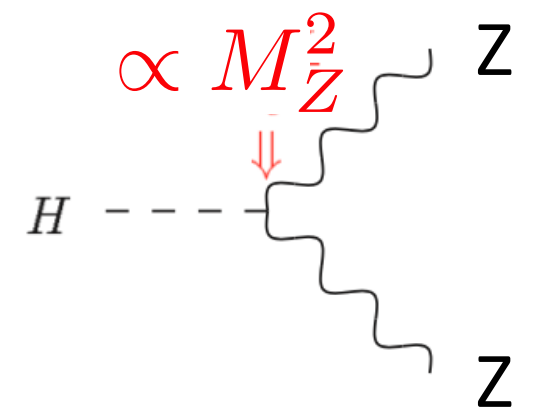
	Production modes	Probability (13 TeV)	Additional signatures
 proton proton	 <i>gluon fusion</i>	48.5pb	None
	 <i>vector boson fusion (VBF)</i>	3.8pb	2 jets
	 <i>associated prod. with W/Z</i>	2.25pb	W,Z
	 <i>associated prod. with tt</i>	0.5pb	top+anti-top

Higgs Particle + X

($\tau \sim 10^{-22}$ s)



Vector
bosons



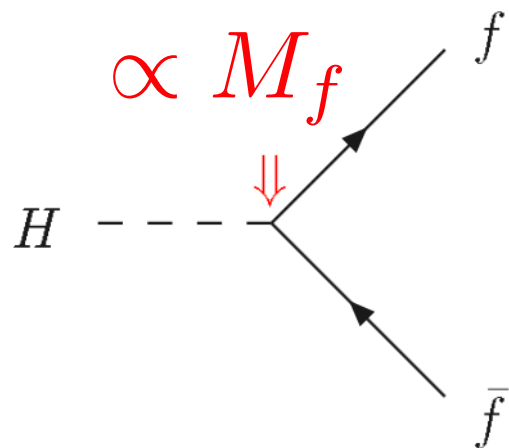
(“golden
channel”)

Higgs Particle + X

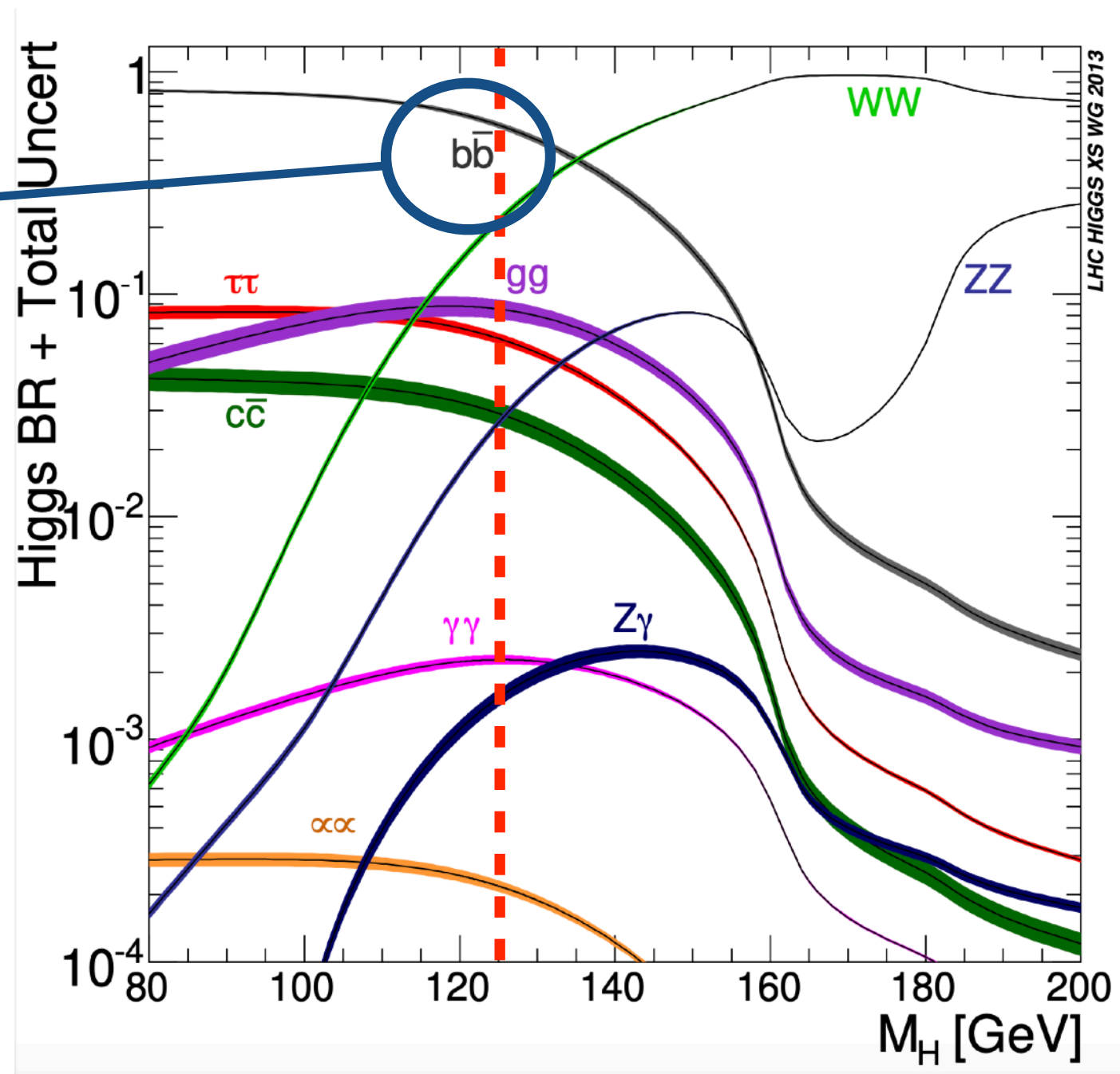
($\tau \sim 10^{-22}$ s)



Fermions



(challenging!)





ATLAS
EXPERIMENT

Run Number: 336852, Event Number: 883966

Date: 2017-09-29 09:19:23 CEST

65 vertices

μ

Higgs Particle

μ

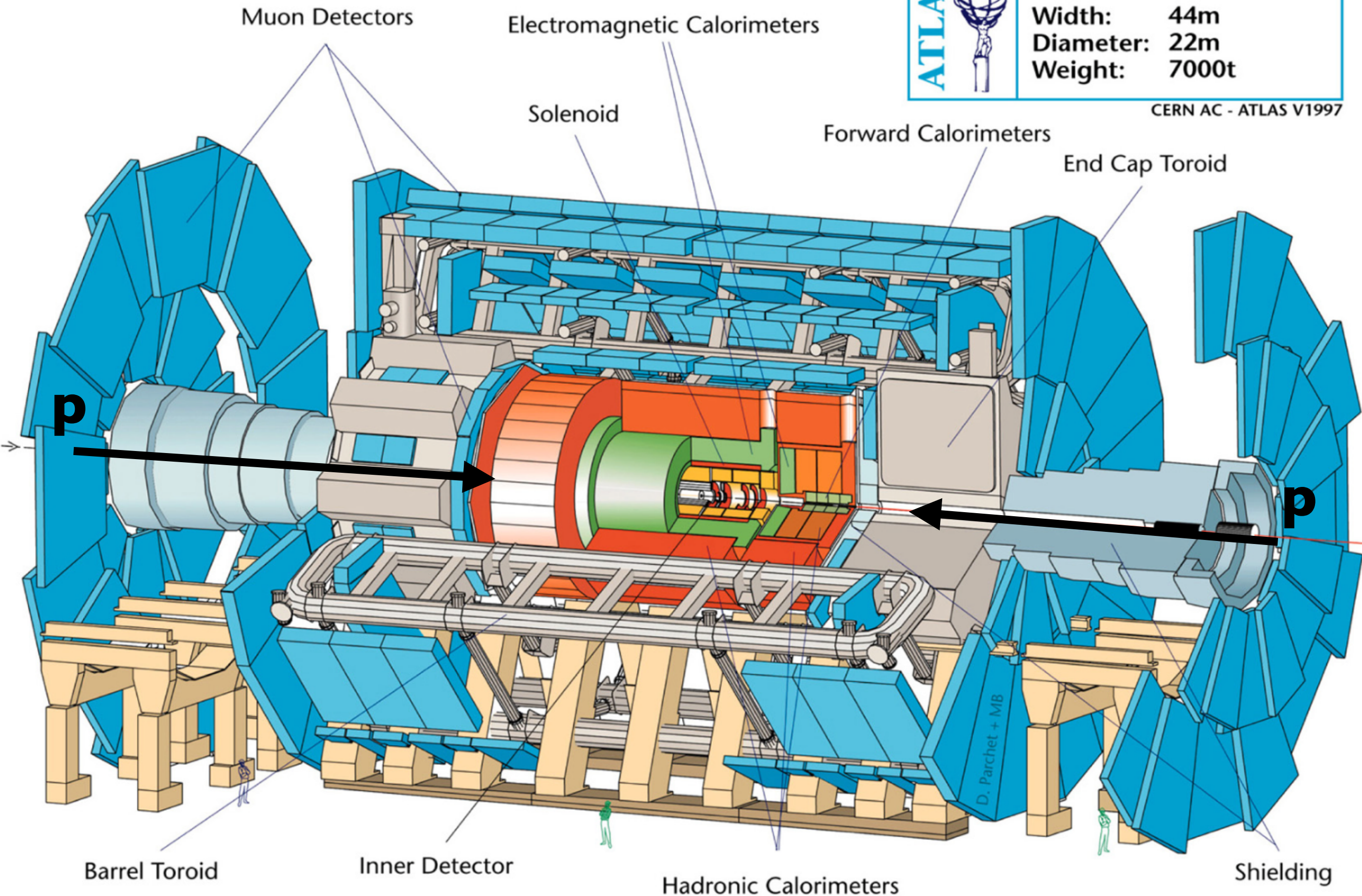
- ATLAS and CMS are “giant cameras” recording collision fragments
- Fast electronics & a large computer farm to select events online, and store only one every $\sim 15,000$ collisions (40 MHz $\rightarrow$ 3000 Hz, ~ 30 PBytes per year)

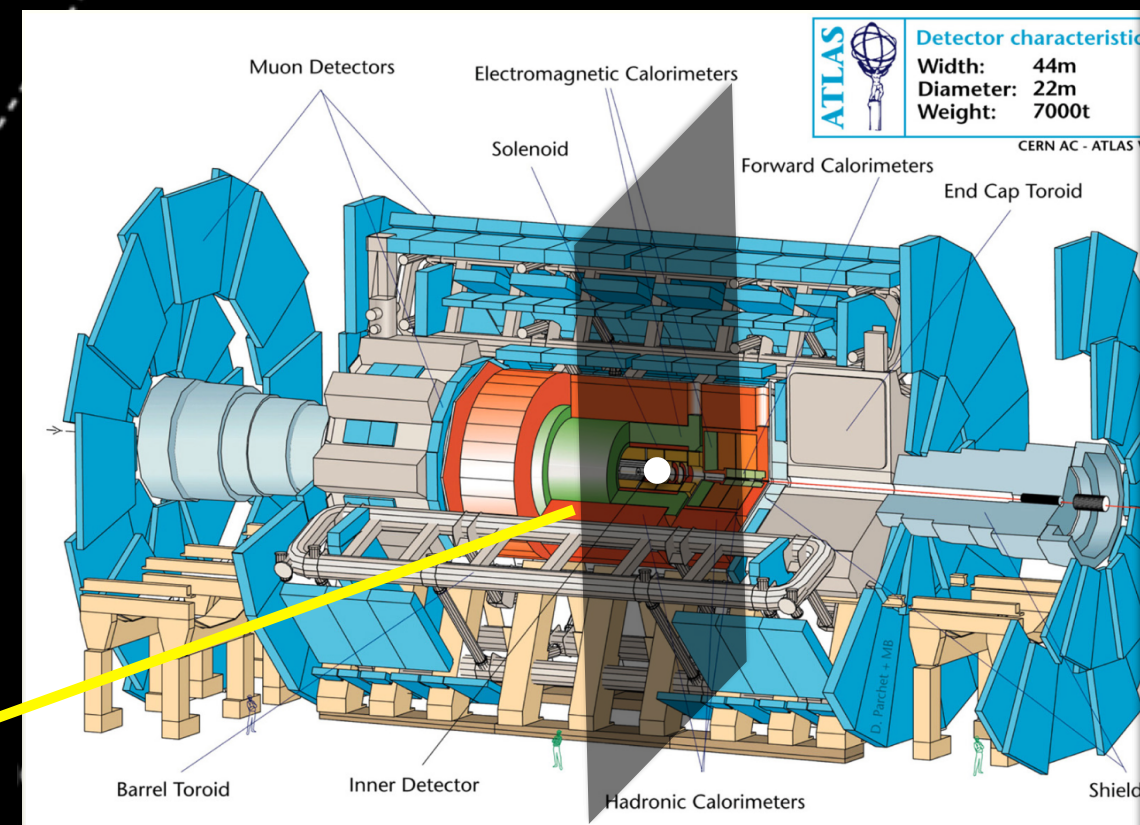
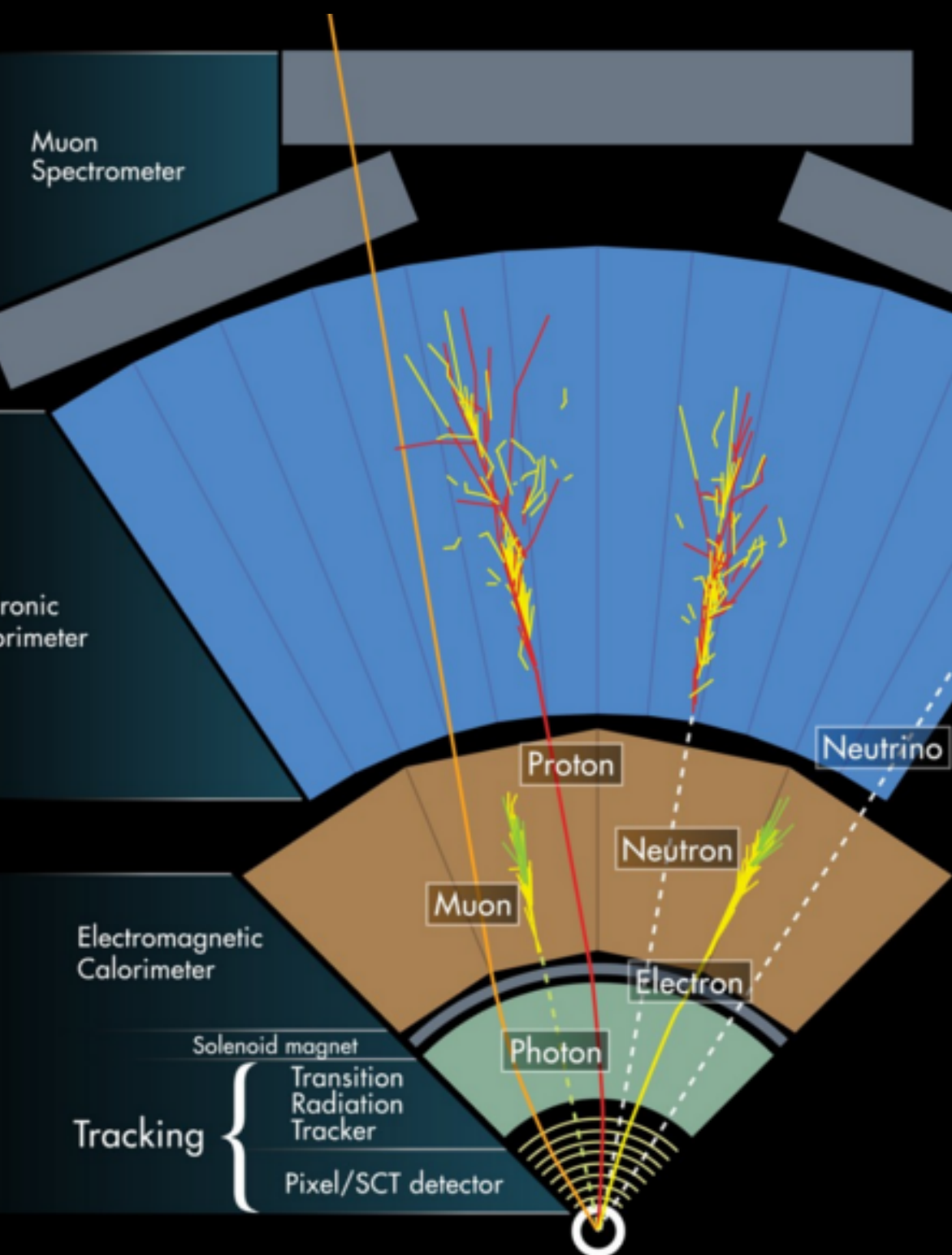



Detector characteristics

Width: 44m
Diameter: 22m
Weight: 7000t

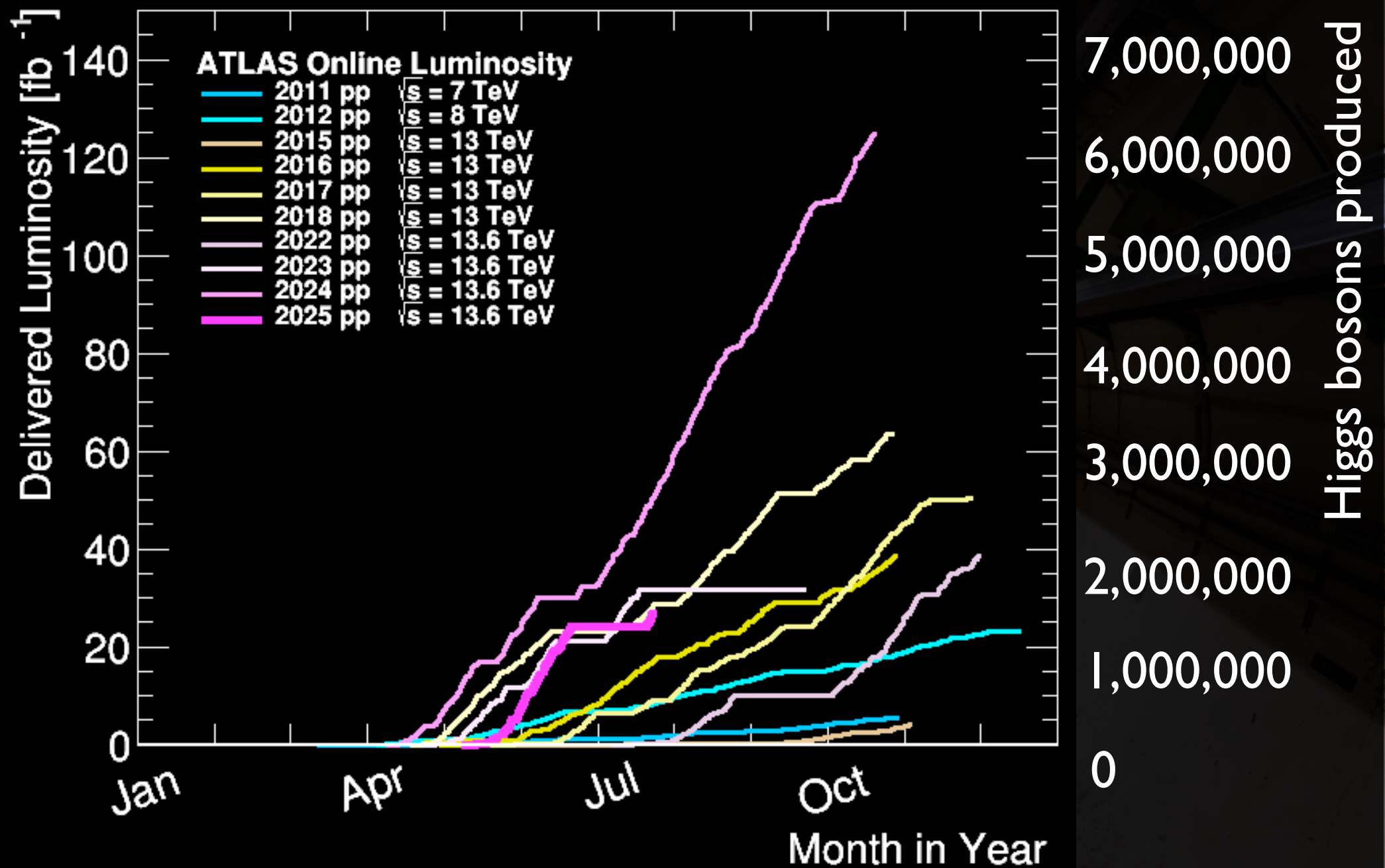
CERN AC - ATLAS V1997





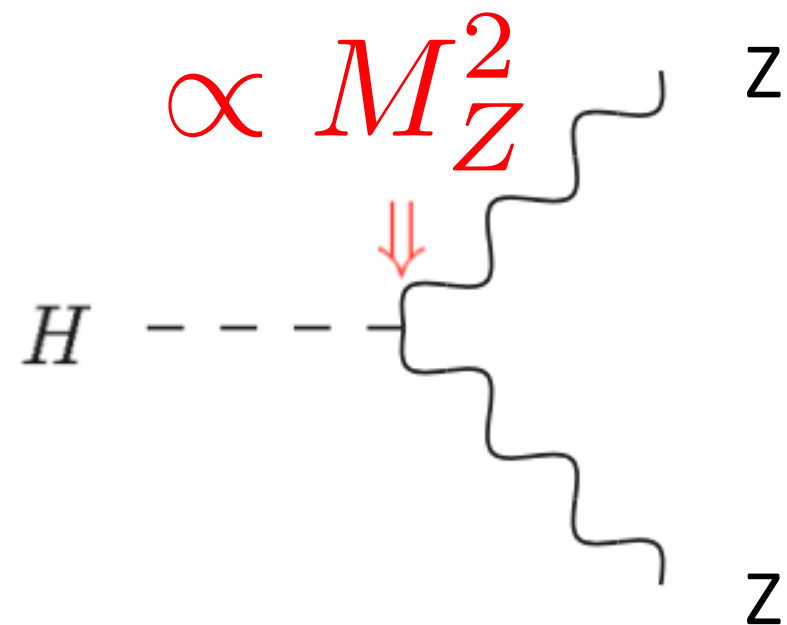
- Reconstruct momenta of neutral and charged particles
- Identify their type, exploiting all sub-detectors

How many Higgs bosons did the LHC deliver?



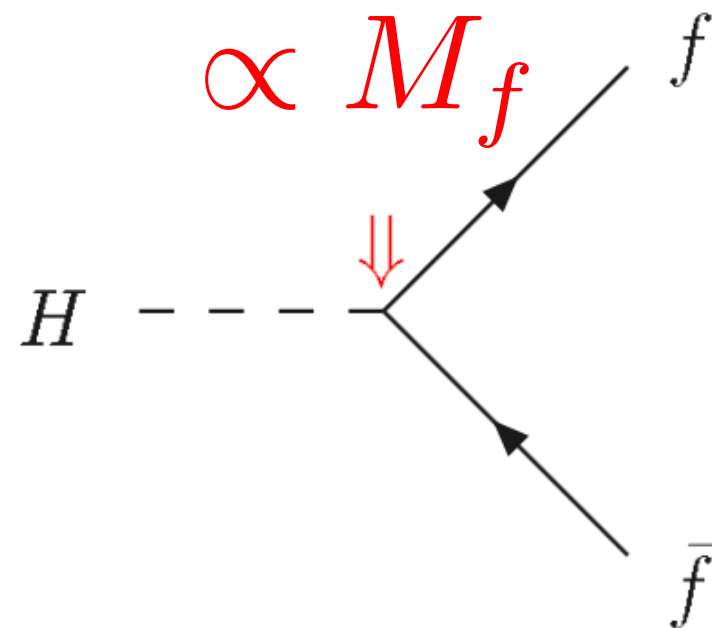
> 15,000,000 Higgs bosons out of > 20,000,000,000,000,000 collisions

Vector bosons



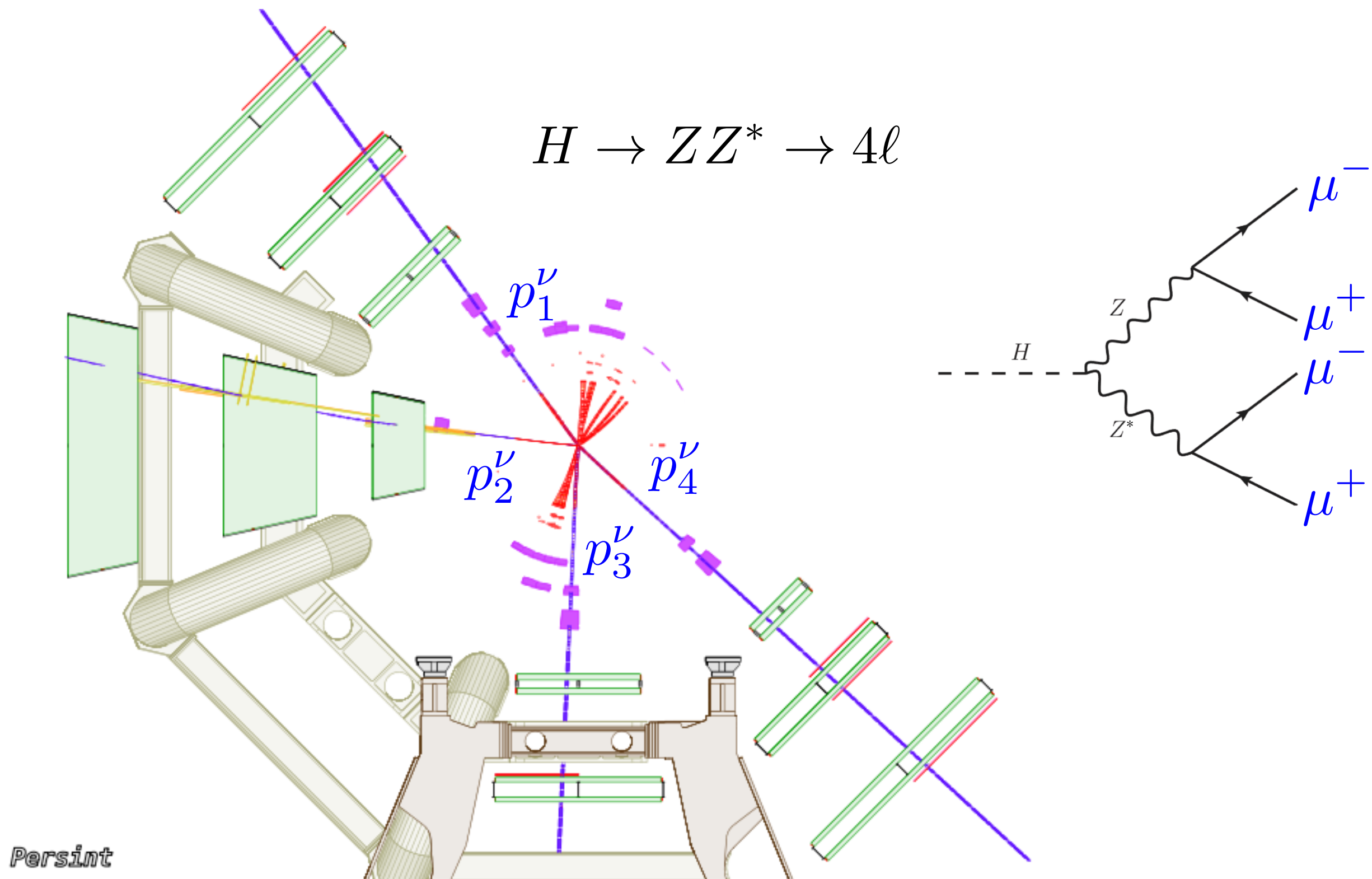
$$H \rightarrow ZZ^*$$

Fermions



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

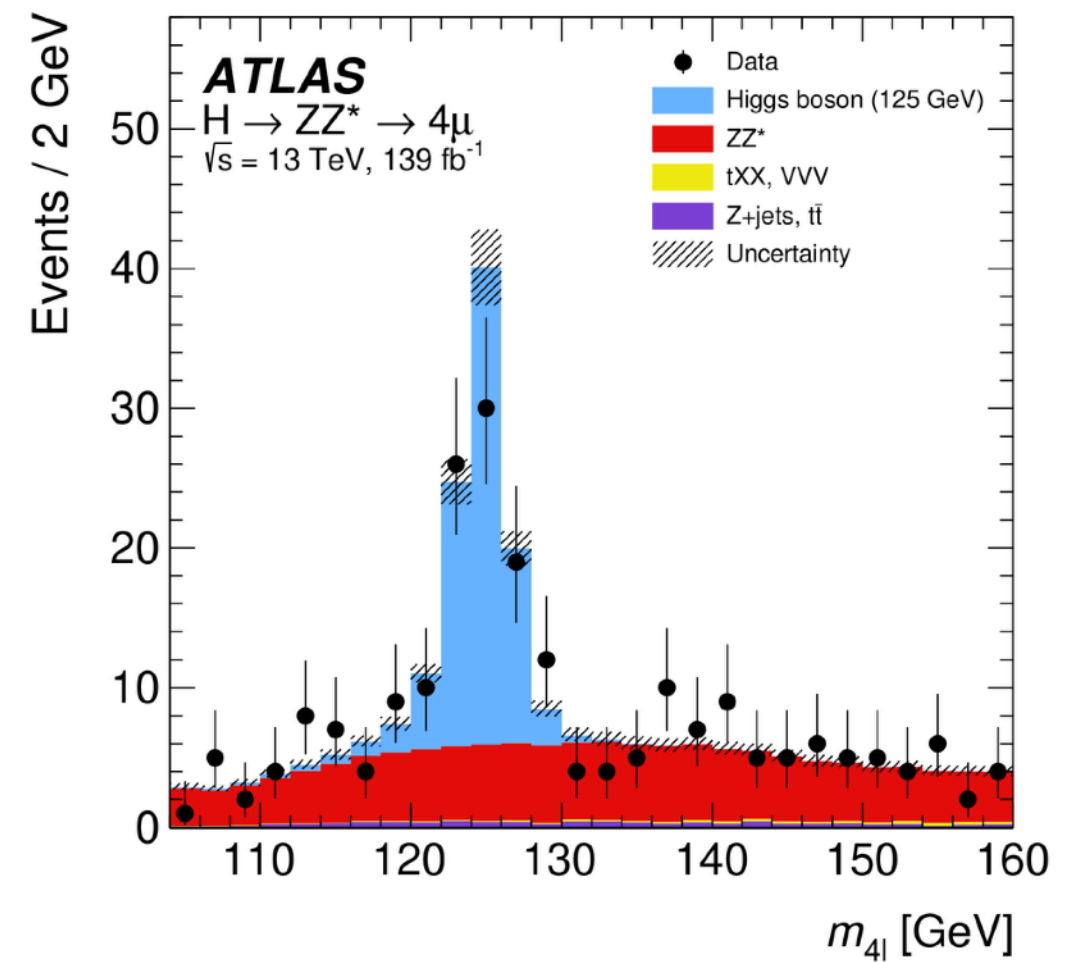
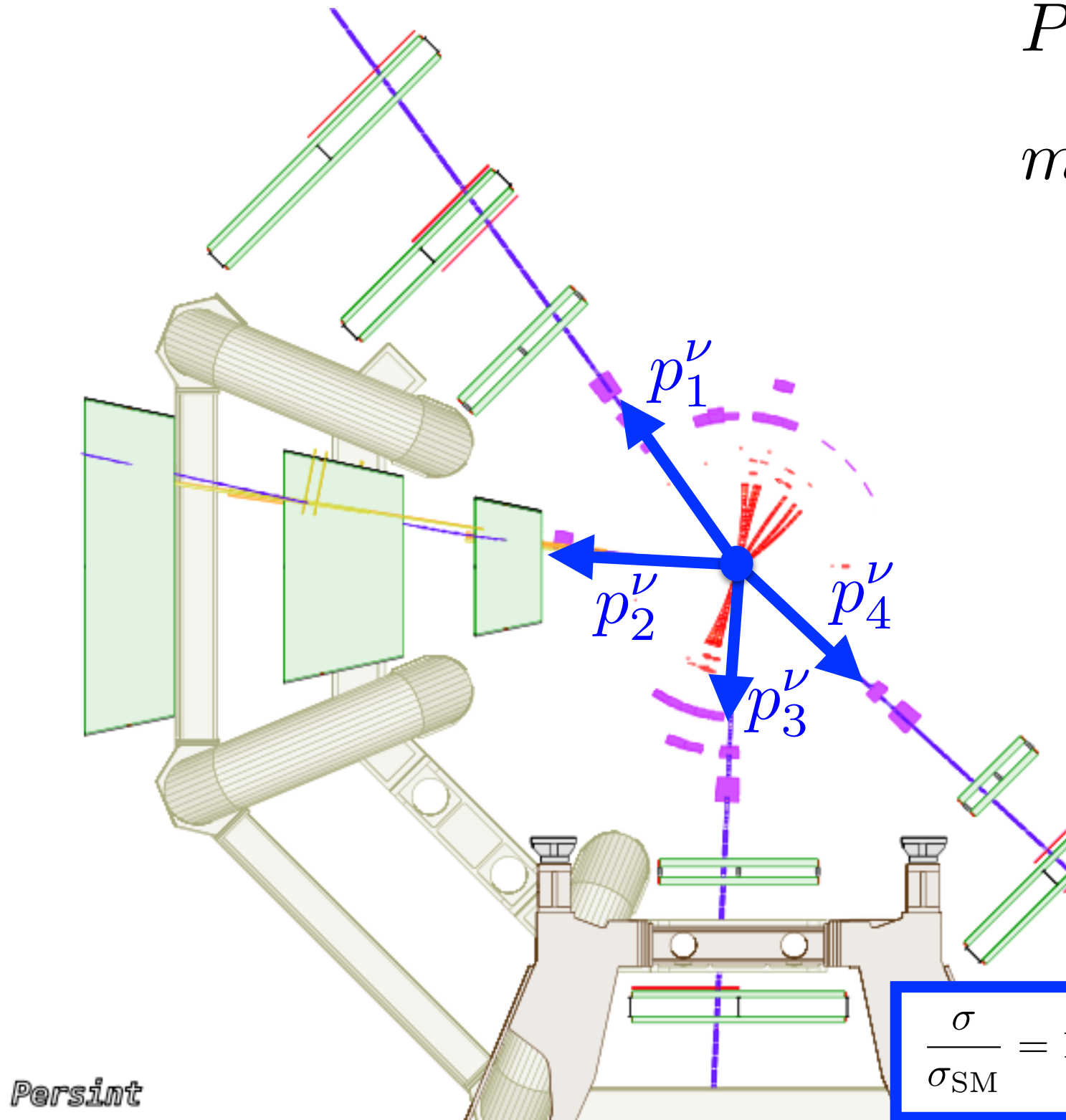
$$H \rightarrow ZZ^* \rightarrow 4\ell$$



Persint

$$P^\nu = p_1^\nu + p_2^\nu + p_3^\nu + p_4^\nu$$

$$m_{4l} = \sqrt{P^\nu P_\nu}$$



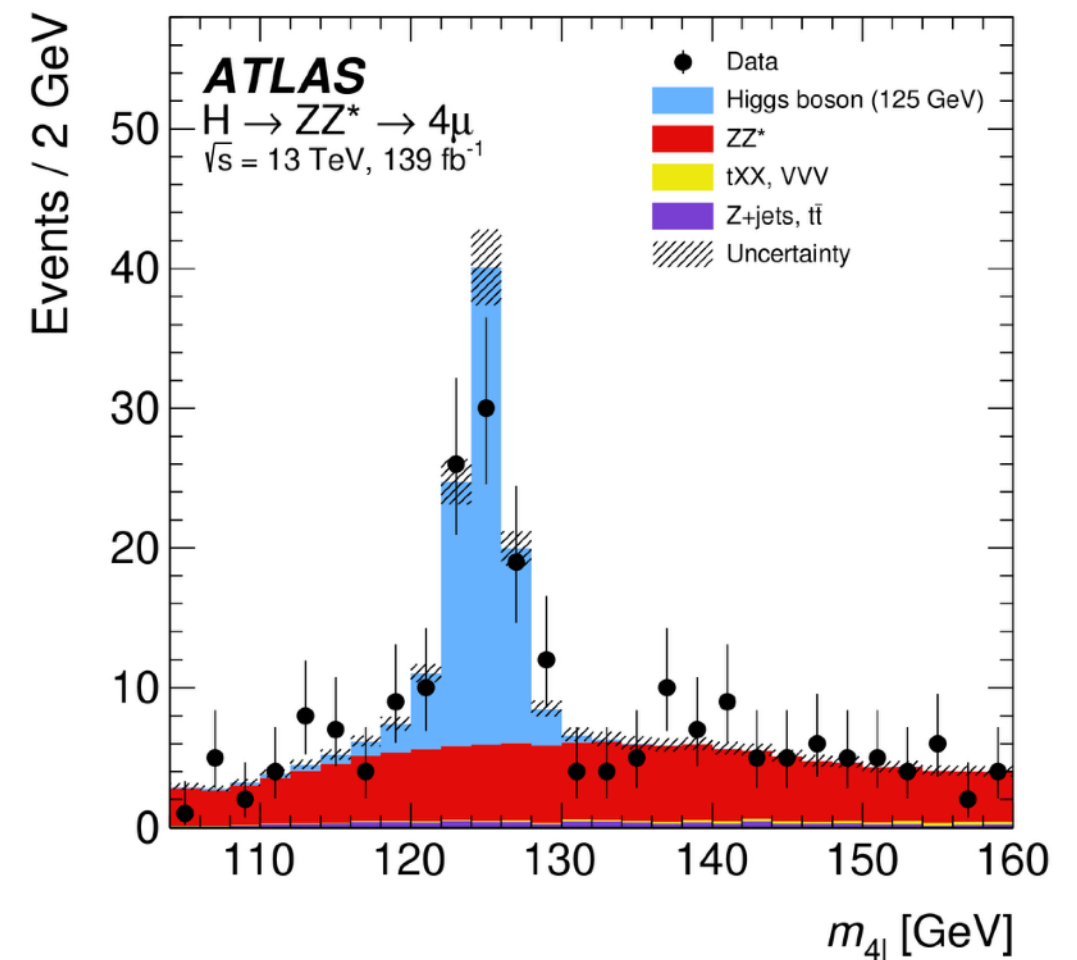
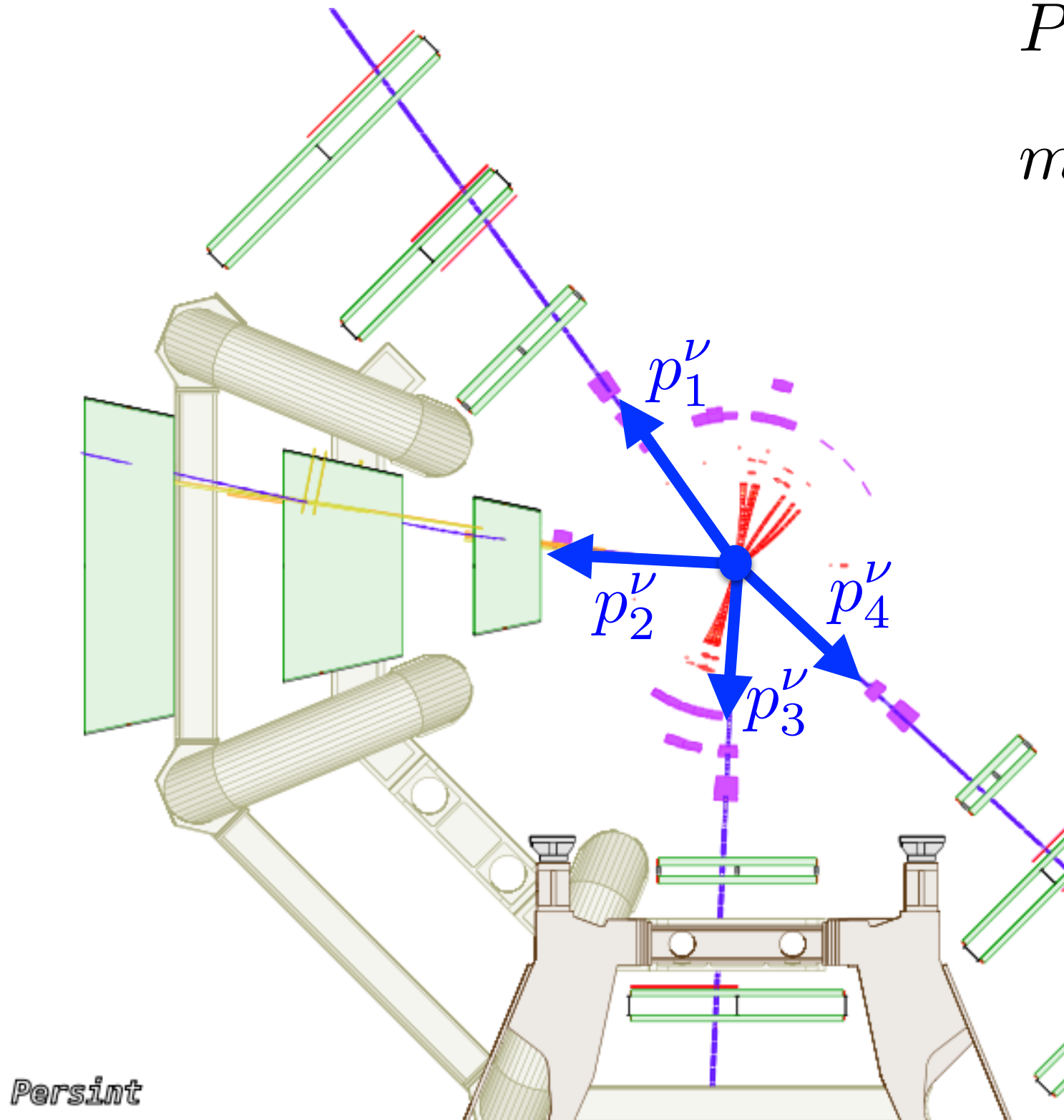
$$\frac{\sigma}{\sigma_{\text{SM}}} = 1.01 \pm 0.08(\text{stat.}) \pm 0.04(\text{exp.}) \pm 0.05(\text{th.})$$

Persint

[Eur. Phys. J. C (2020) 80:957]

$$P^\nu = p_1^\nu + p_2^\nu + p_3^\nu + p_4^\nu$$

$$m_{4l} = \sqrt{P^\nu P_\nu}$$

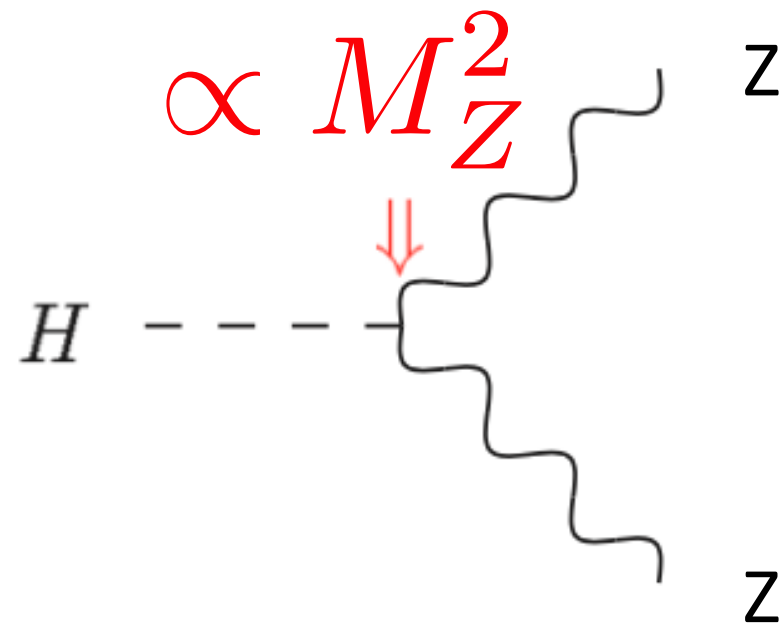


[Phys. Rev. Lett. 131 (2023) 251802]

$$m_H = (125.11 \pm 0.11) \text{ GeV}$$

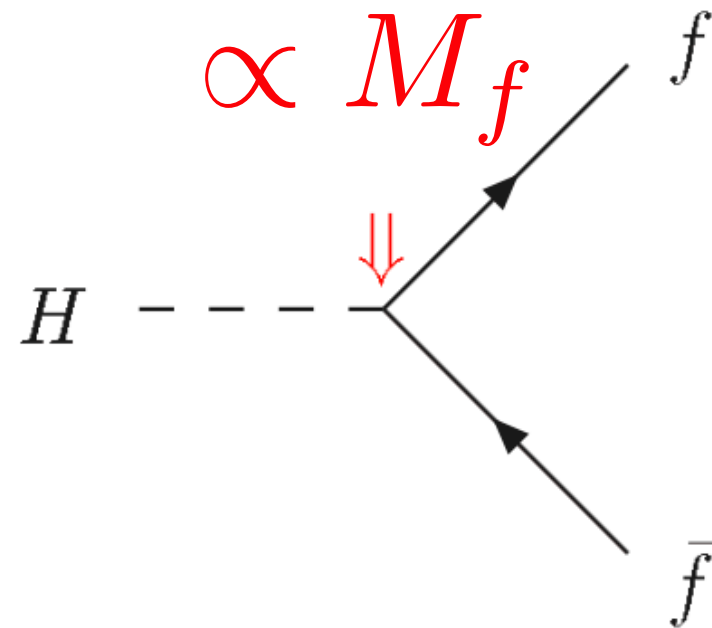
< 1 % precision!

Vector bosons



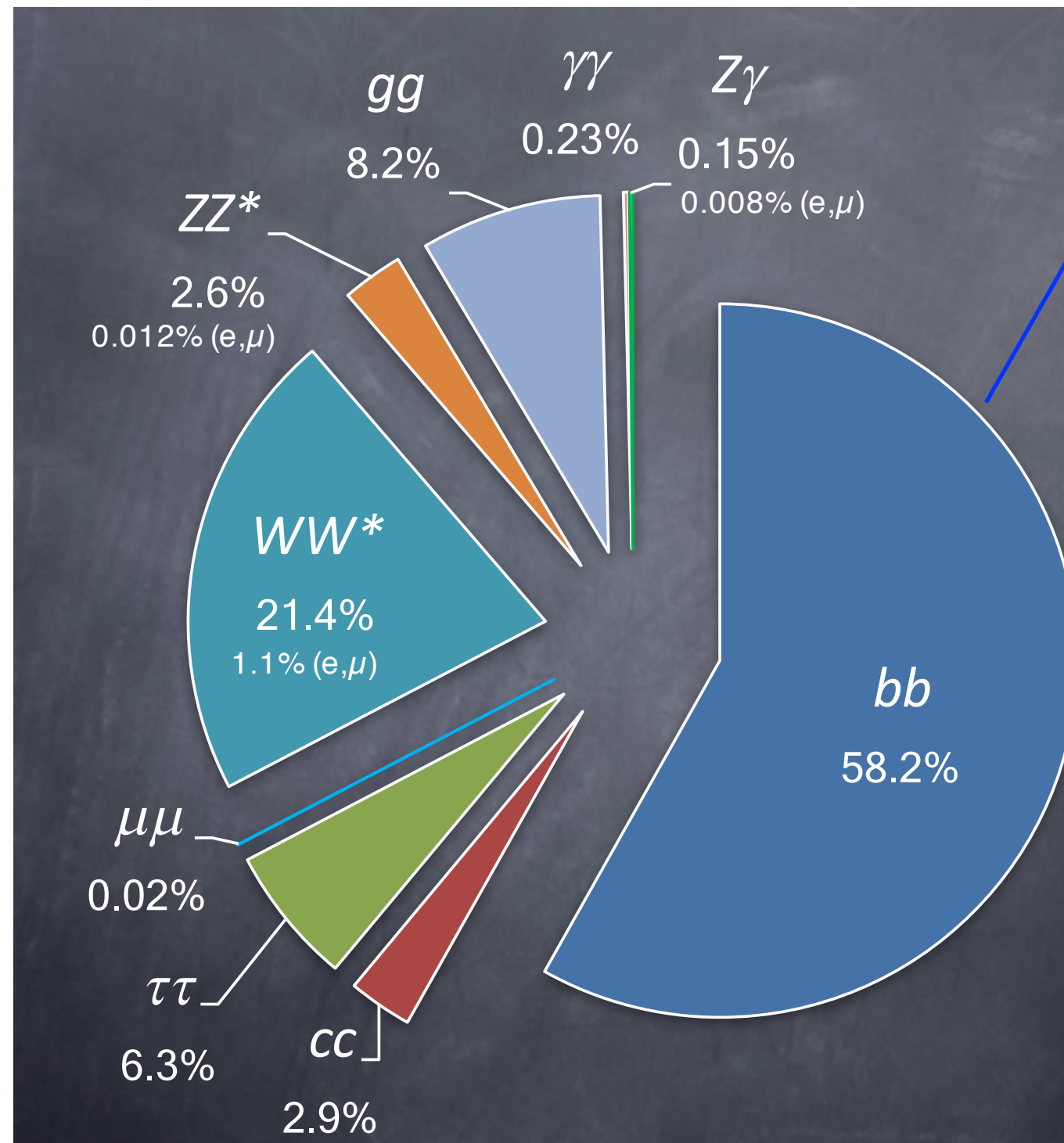
$$H \rightarrow ZZ^*$$

Fermions



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

(beauty quarks!)



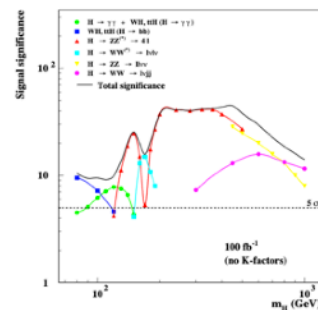
$$H \rightarrow b\bar{b}$$

(decays to
**2 beauty
quarks**)

1999



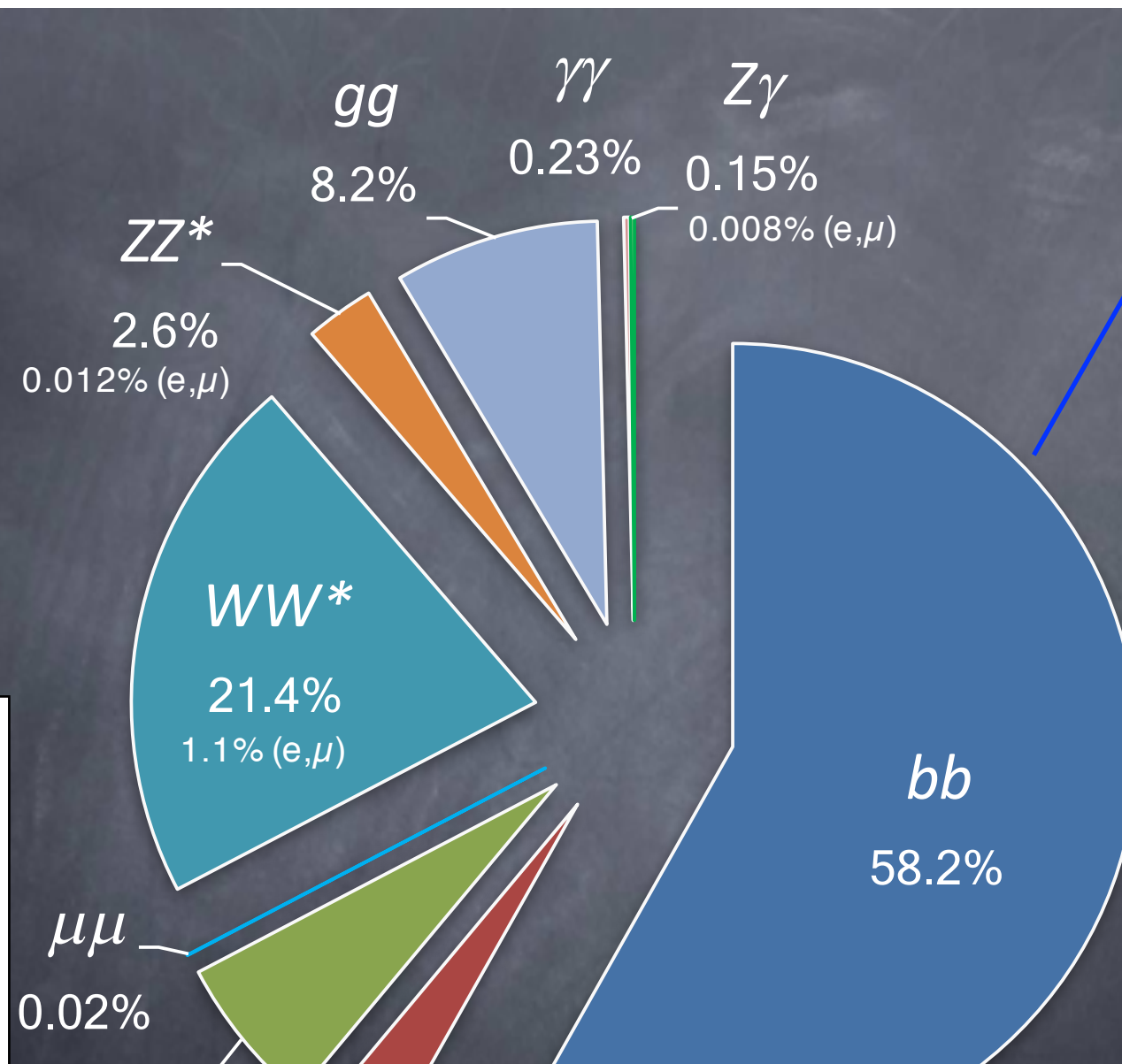
ATLAS DETECTOR AND PHYSICS PERFORMANCE



Technical Design Report

Issue: 1
Revision: 0
Reference: ATLAS TDR 15, CERN/LHCC 99-15
Created: 25 May 1999
Last modified: 25 May 1999
Prepared By: ATLAS Collaboration

Volume II



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

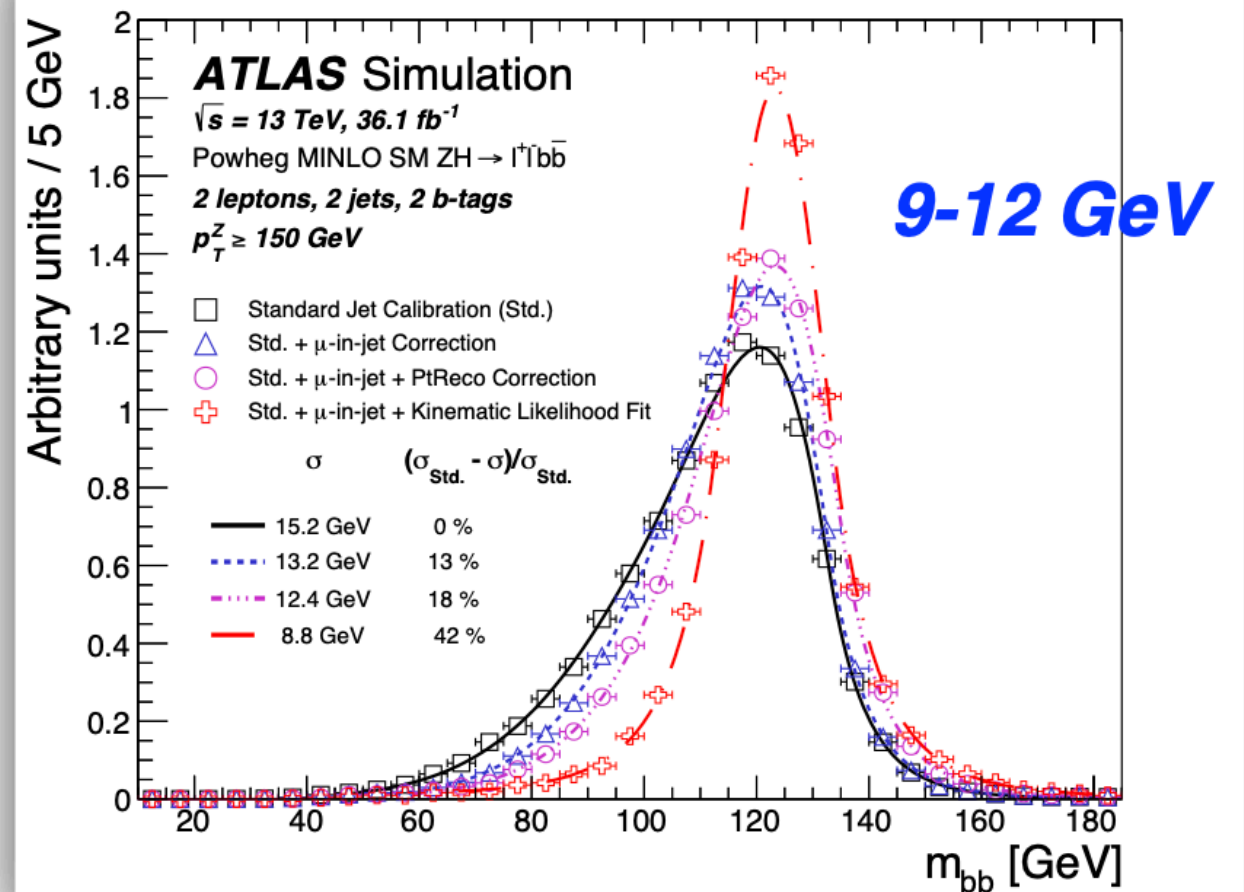
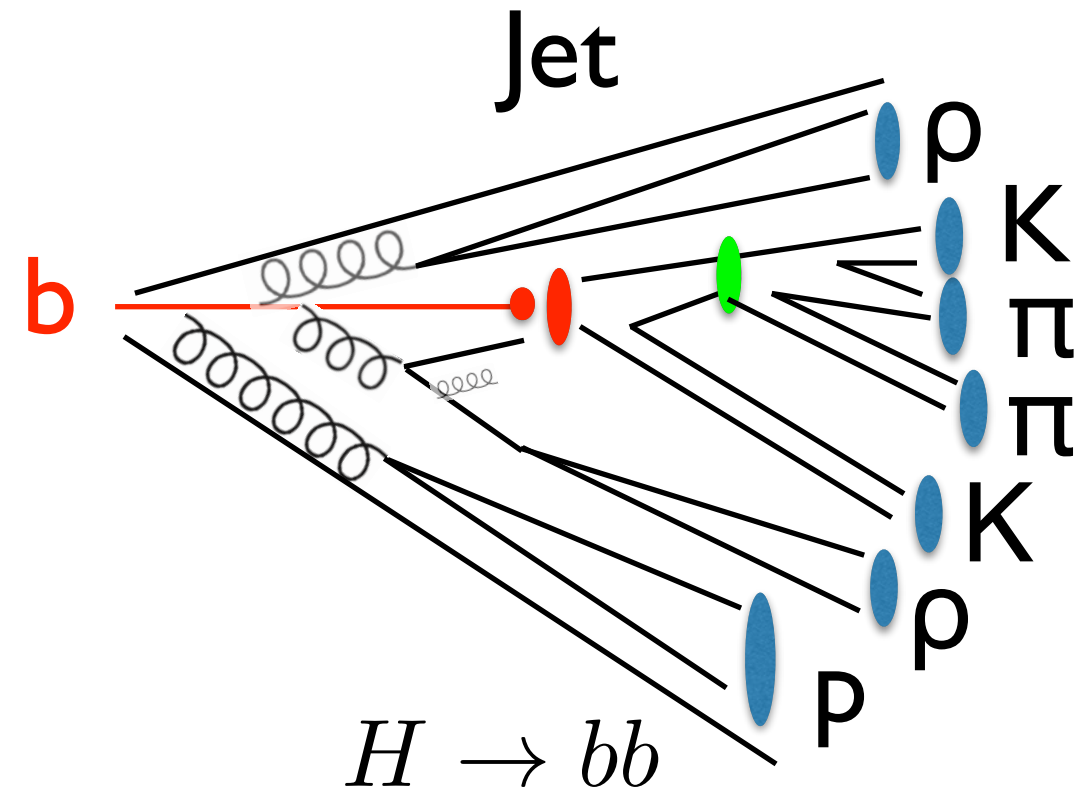
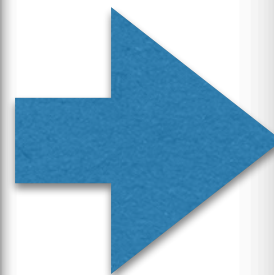
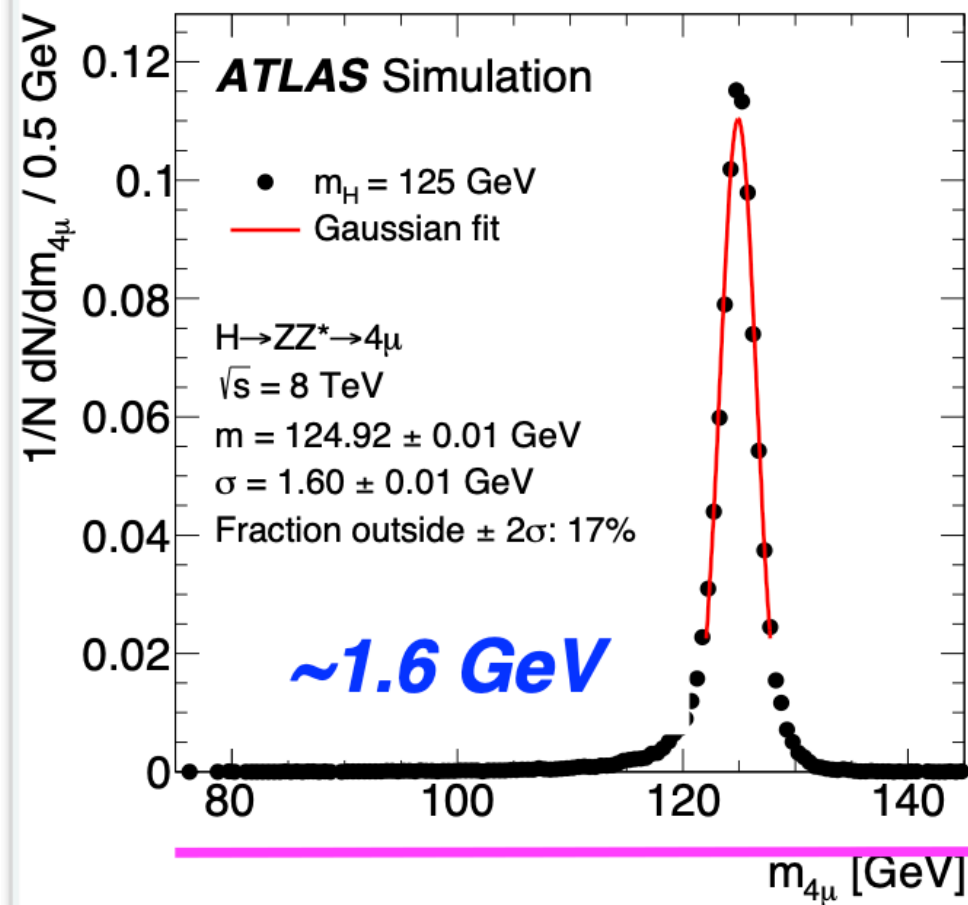
(decays to
**2 beauty
quarks**)

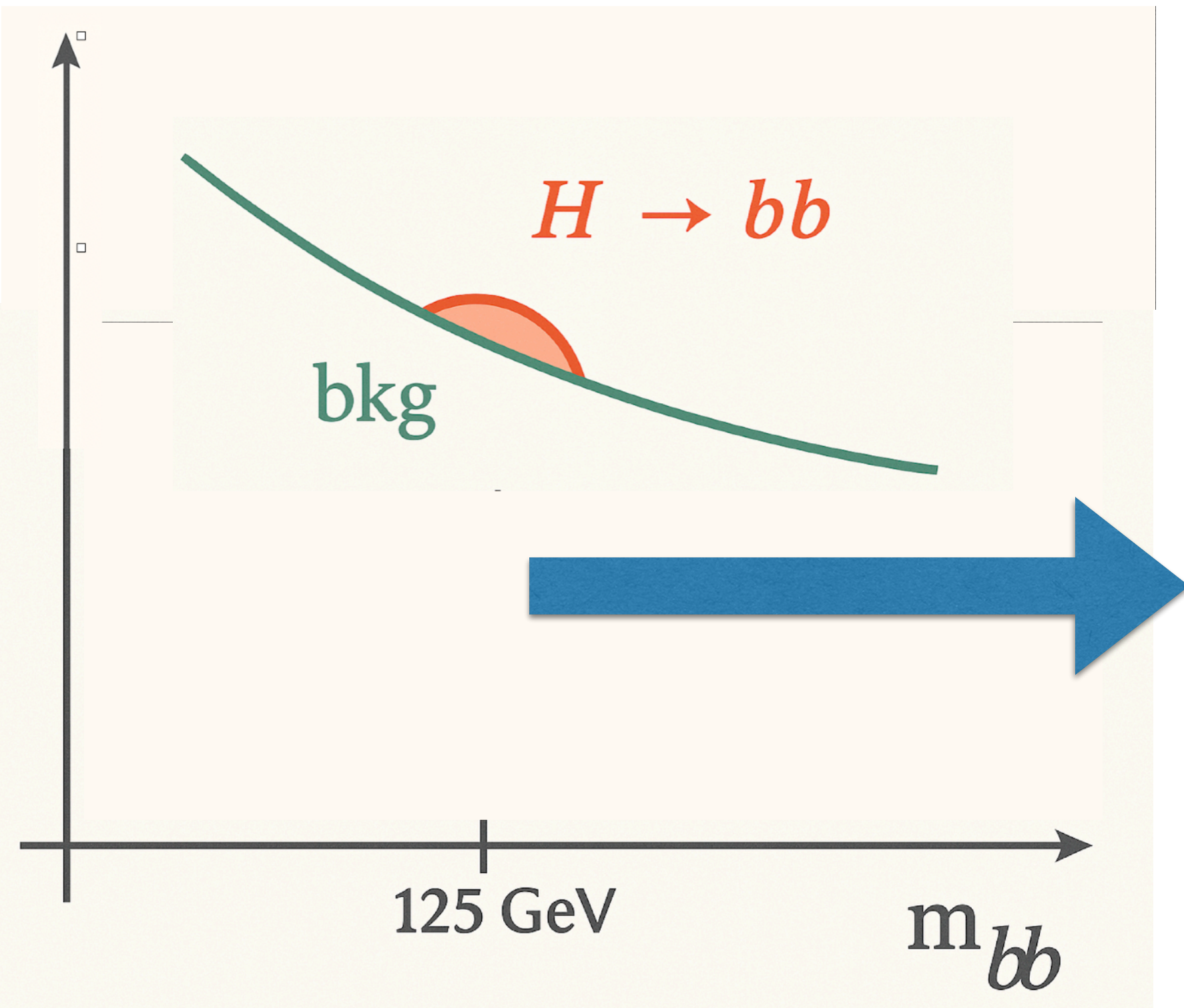
“In conclusion, the extraction of a signal from $(W)H \rightarrow b\bar{b}$ decays ... will be very difficult at the LHC, even under the most optimistic assumptions”

Muon

μ —————

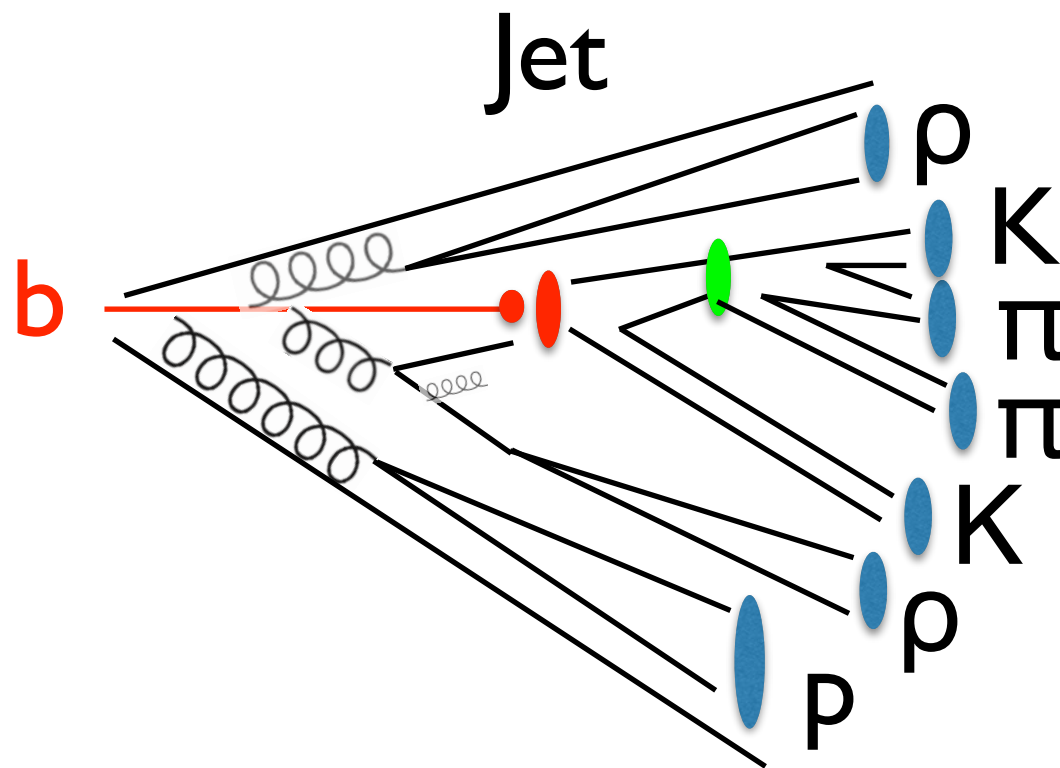
$$H \rightarrow ZZ^* \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$





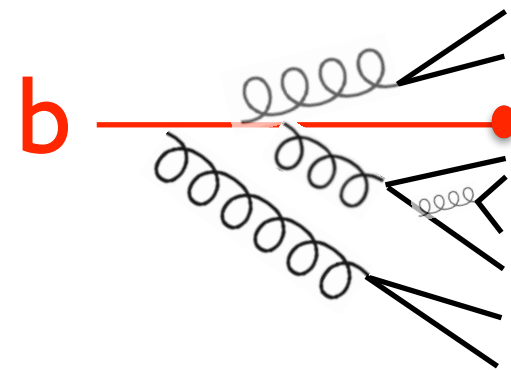
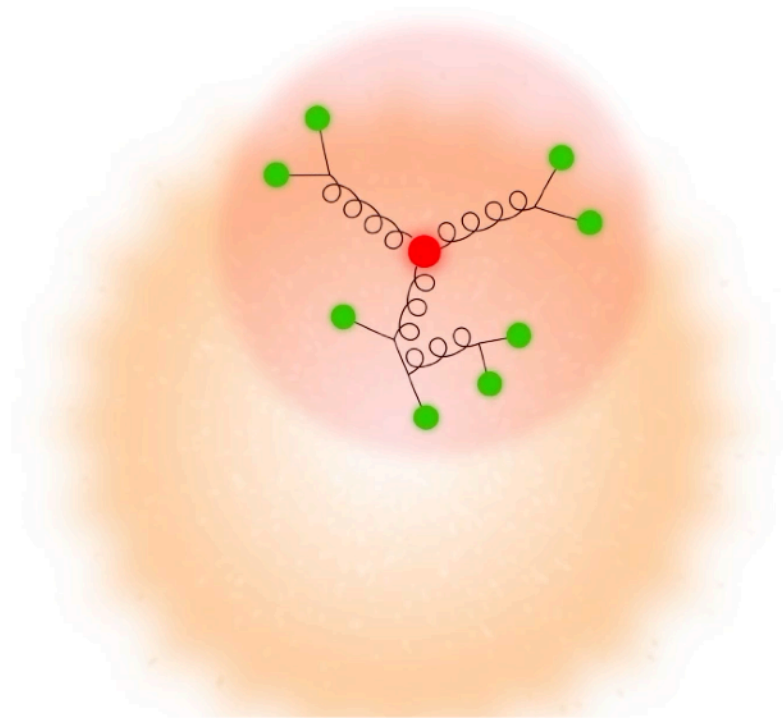
Need to reject
jets without
beauty-quarks

How do we “see” the beauty quarks?



B-quarks at high energy

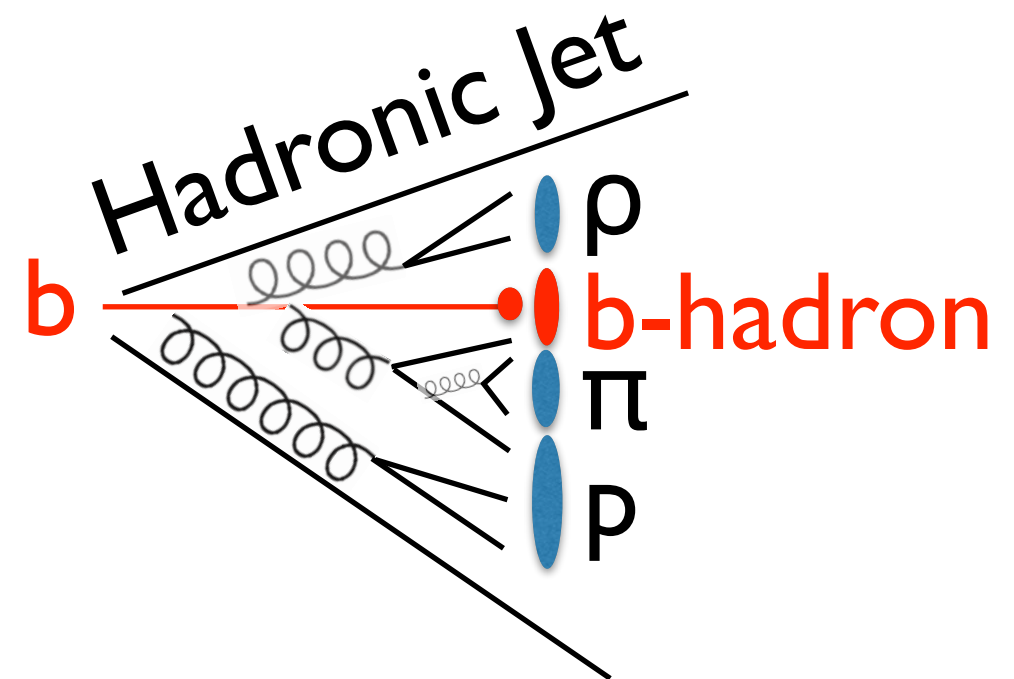
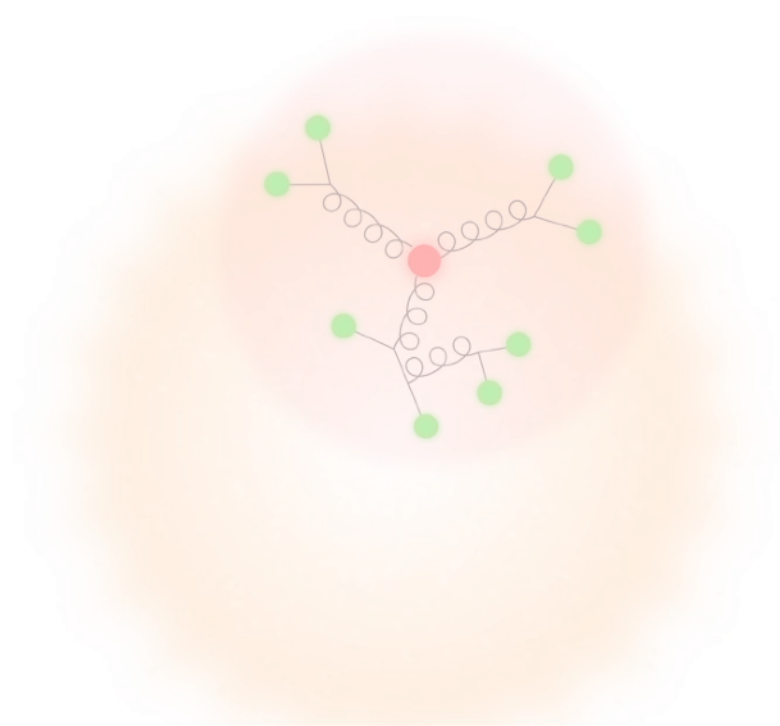
$$p\,p \rightarrow \dots \rightarrow \text{b-quark} + \dots$$



A b-quark produced in a high energy collision “radiates” gluons and quarks.

B-quarks at high energy

$$p\ p \rightarrow \dots \rightarrow \text{b-quark} + \dots$$

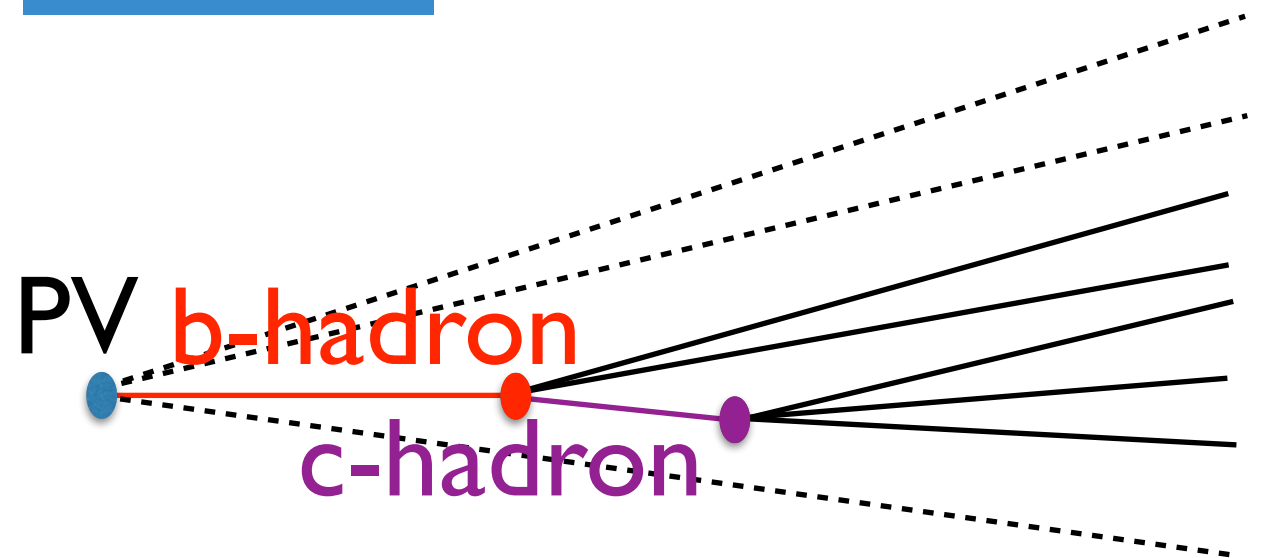
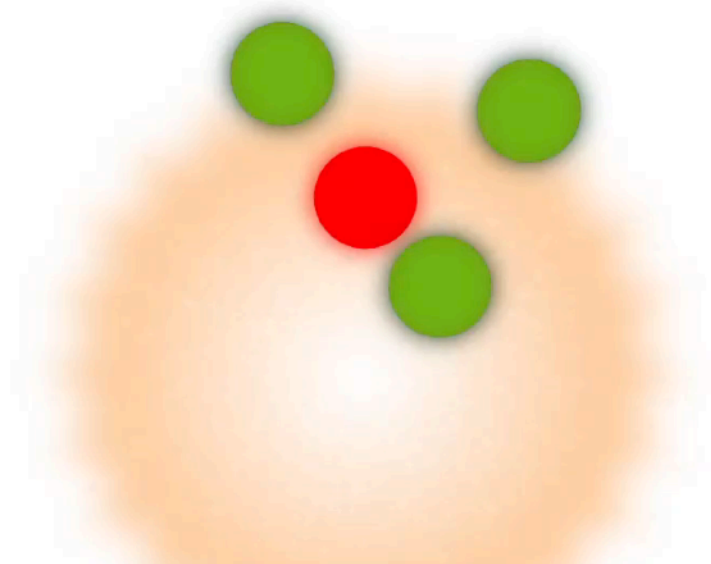


Quarks hadronize into mesons and baryons (“jet” of particles).
First key property: most of the jet energy (~80%) goes into the b-hadron. **Second key property:** mass of b-hadron (5 GeV)

A long lifetime

$$L = \beta\gamma c\tau = \frac{p}{m} c\tau$$

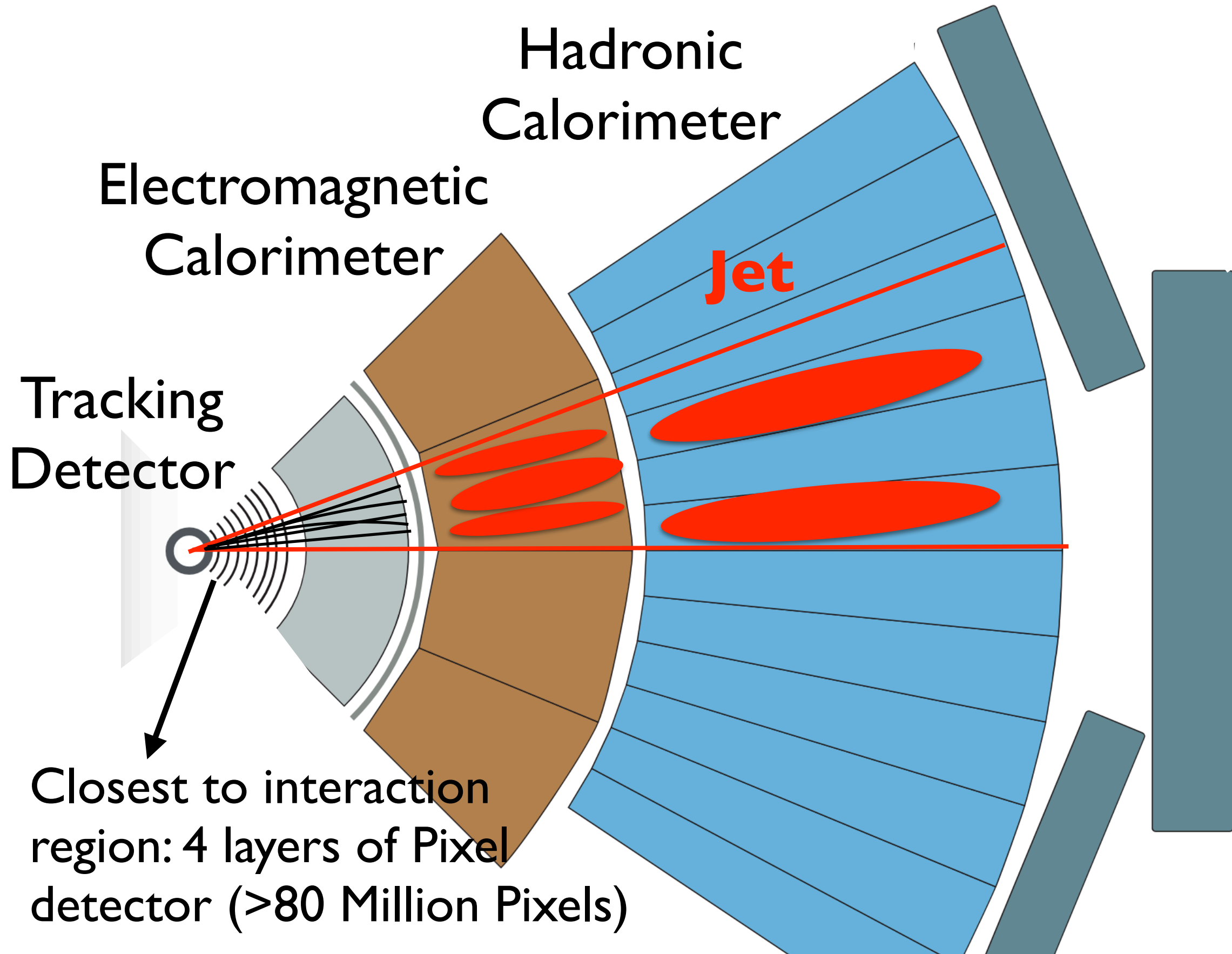
p [GeV]	Decay length
60 GeV	~4.3mm
200 GeV	~14mm
2 TeV	~14cm



Third key property: the b-hadron has significant lifetime ($1.5 \cdot 10^{-12}$ s), compared to other particles (e.g. Higgs boson lives for 10^{-22} s).

Fourth key property: high decay multiplicity (av: 5 charged particles)

Reconstructing the jet:

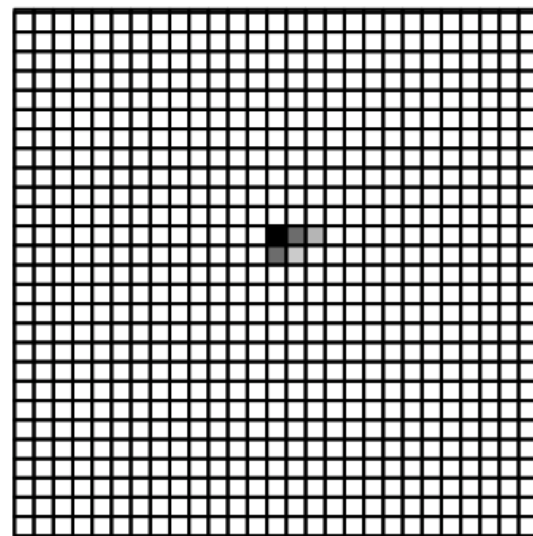


Start from clusters...

proton
beam



Pixel Detector



Large
Charge

No
Charge

Typical "image" from one particle
crossing a pixel detector

Pixel detector layers

proton
beam

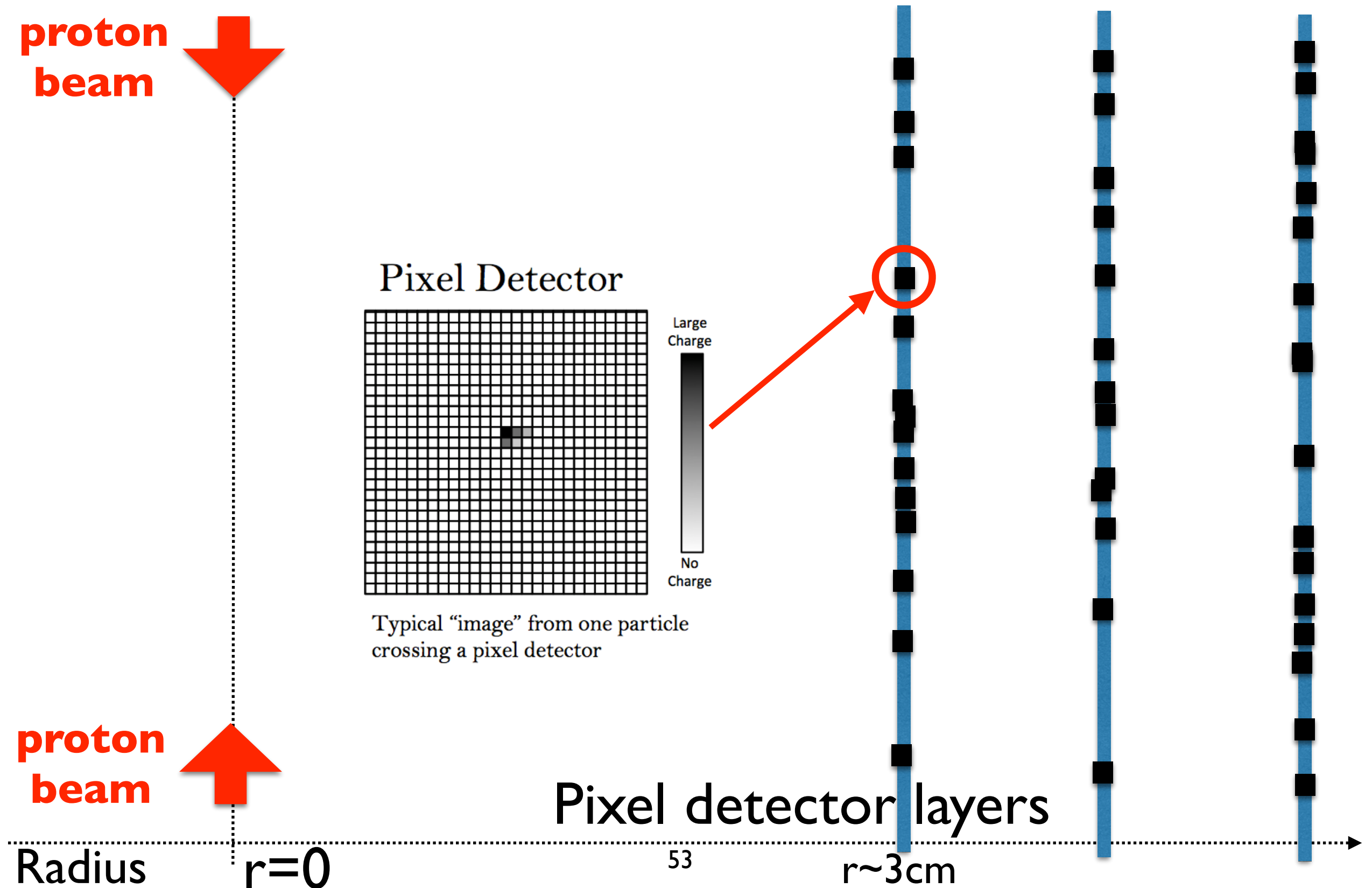


Radius

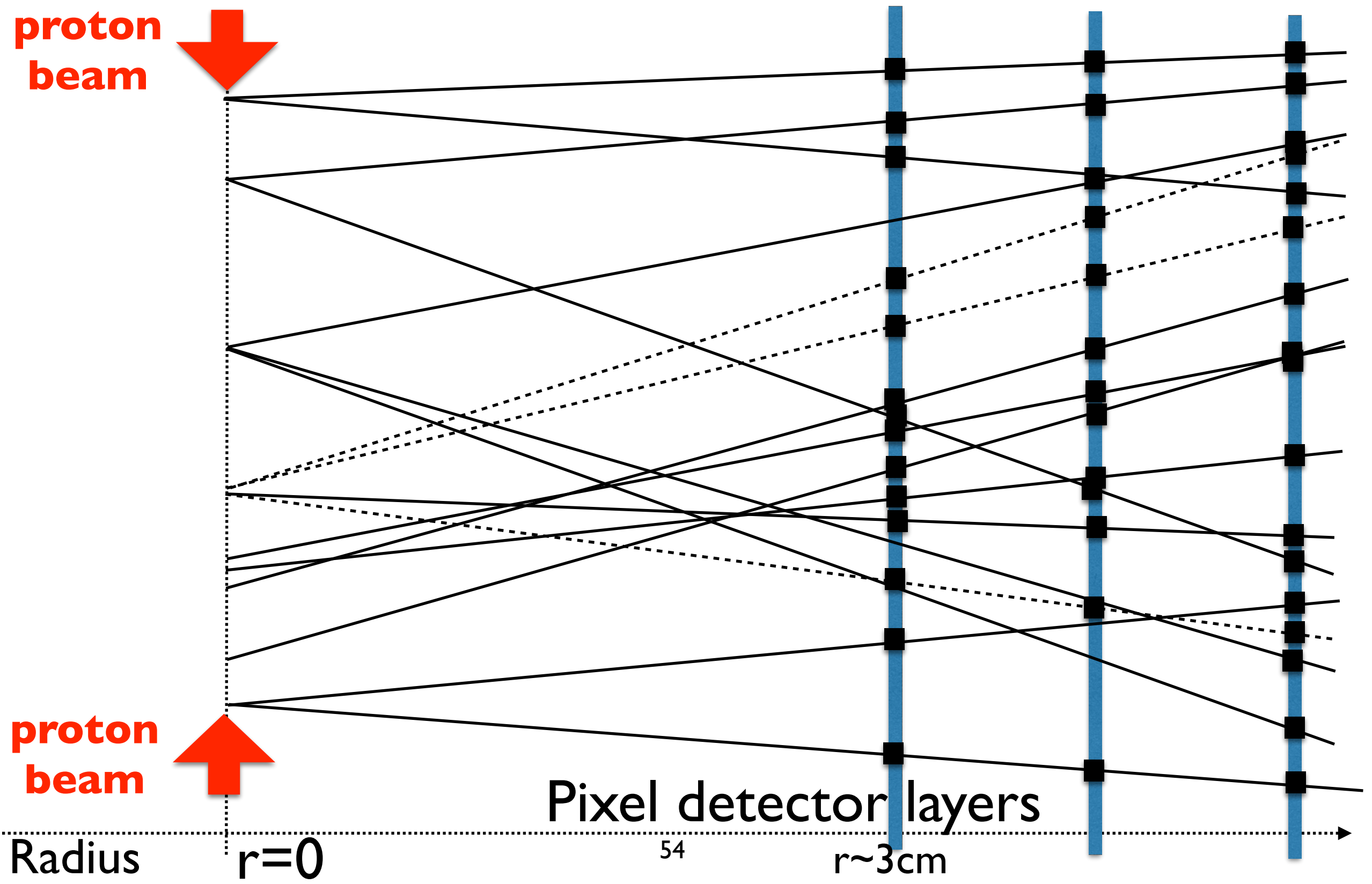
$r=0$

53

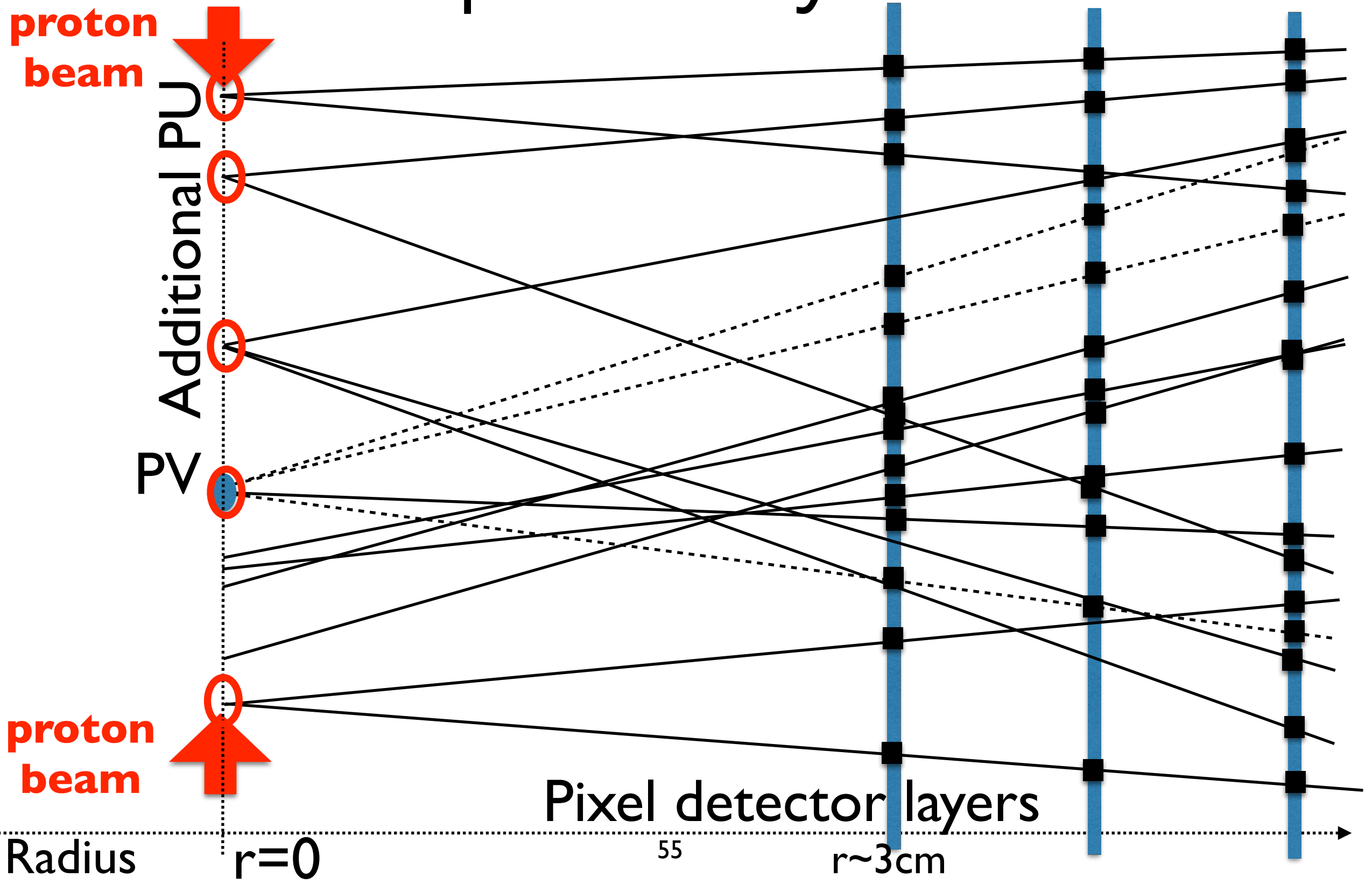
$r \sim 3\text{cm}$



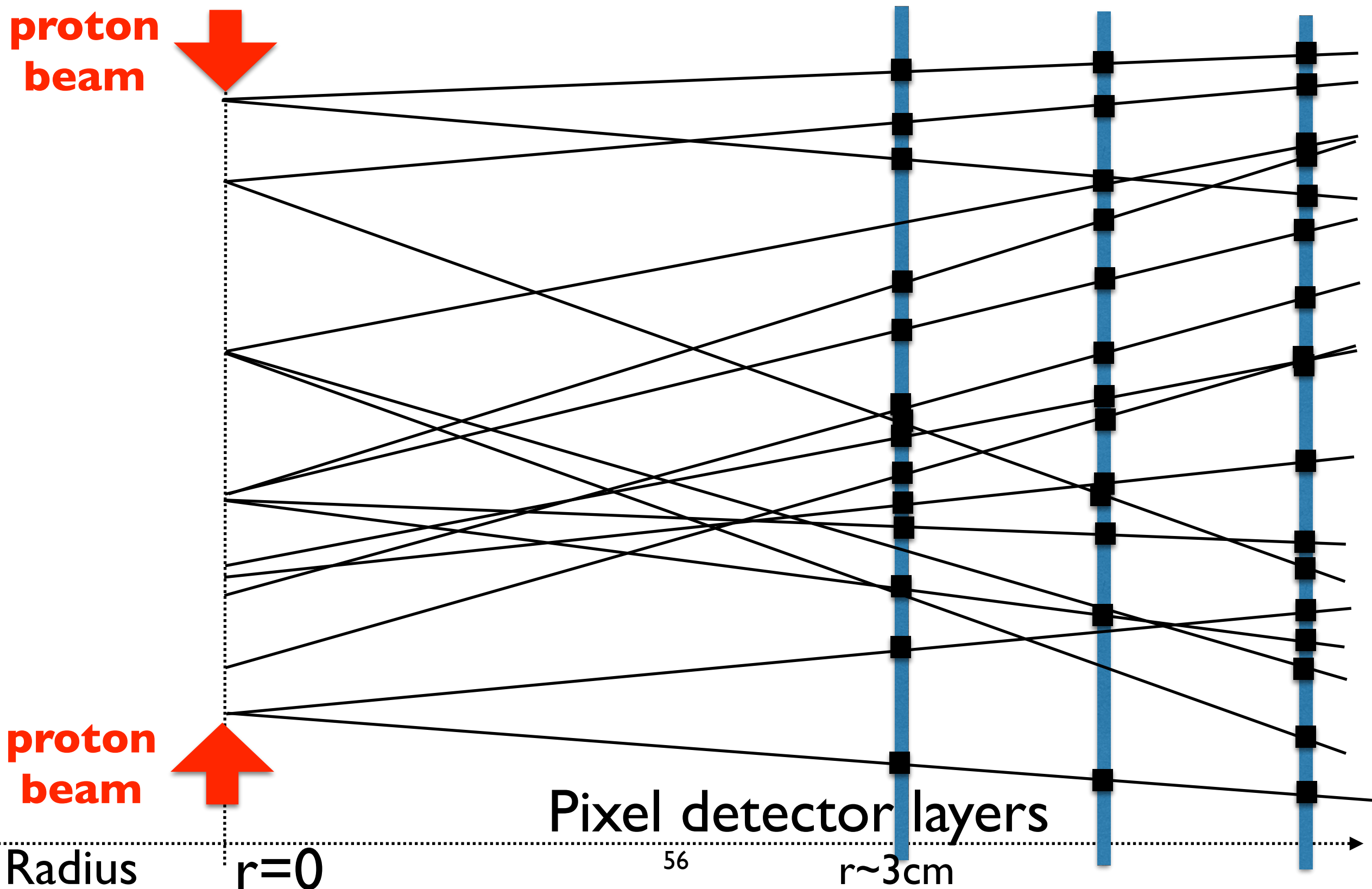
Then reconstruct tracks...



... and primary vertices



Is this a b-quark jets?



proton
beam



PV

proton
beam



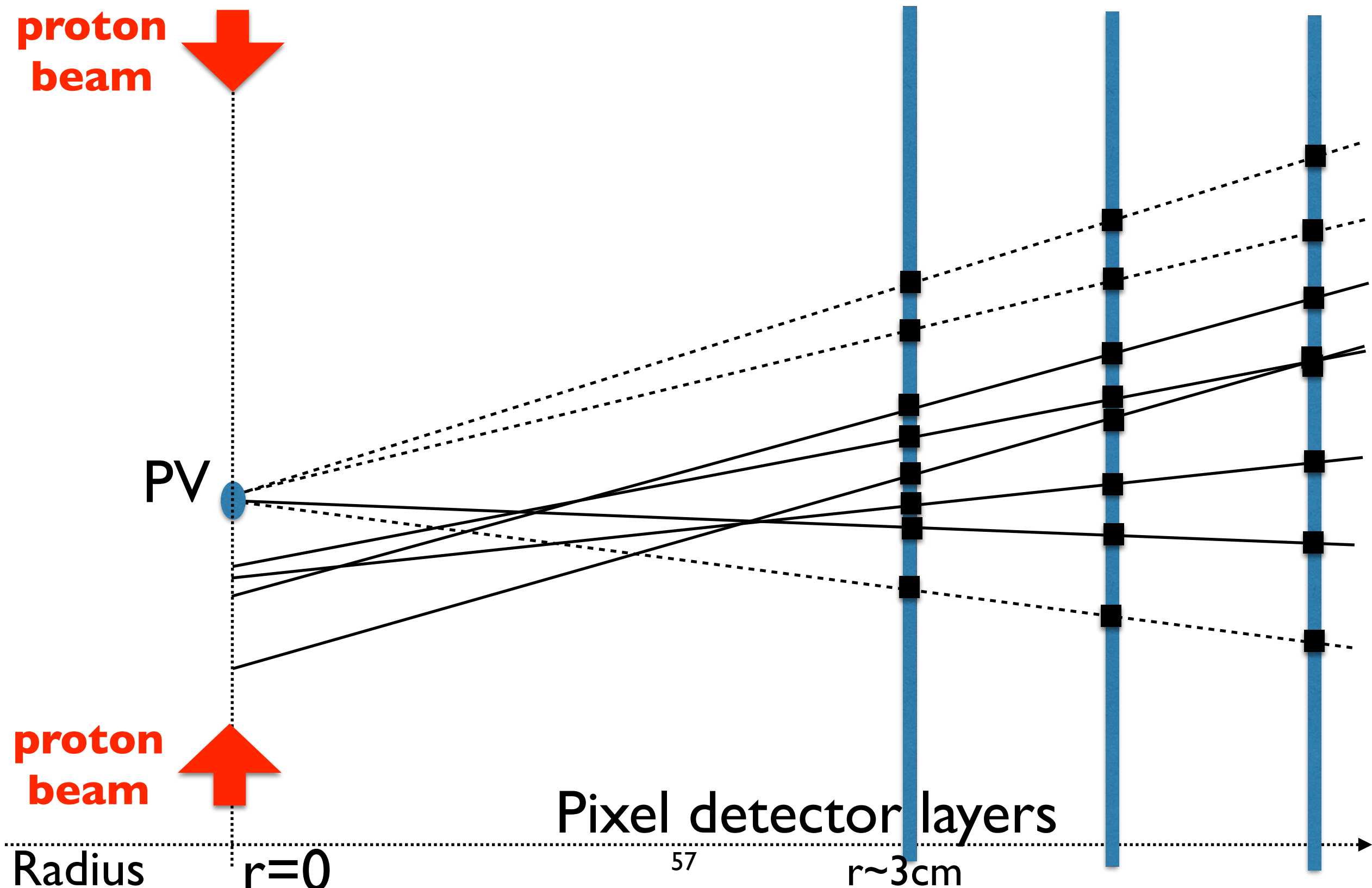
Radius

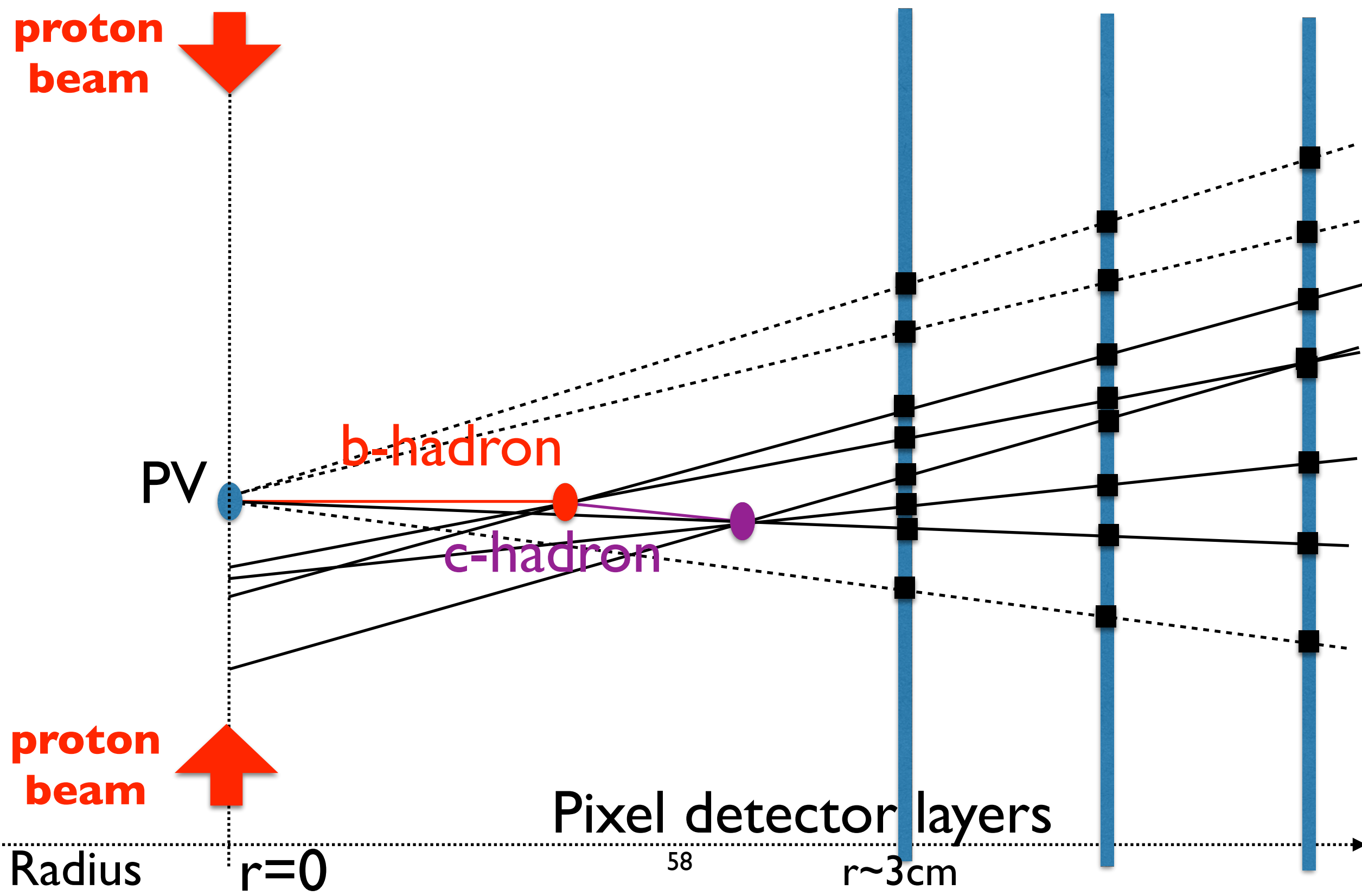
$r=0$

57

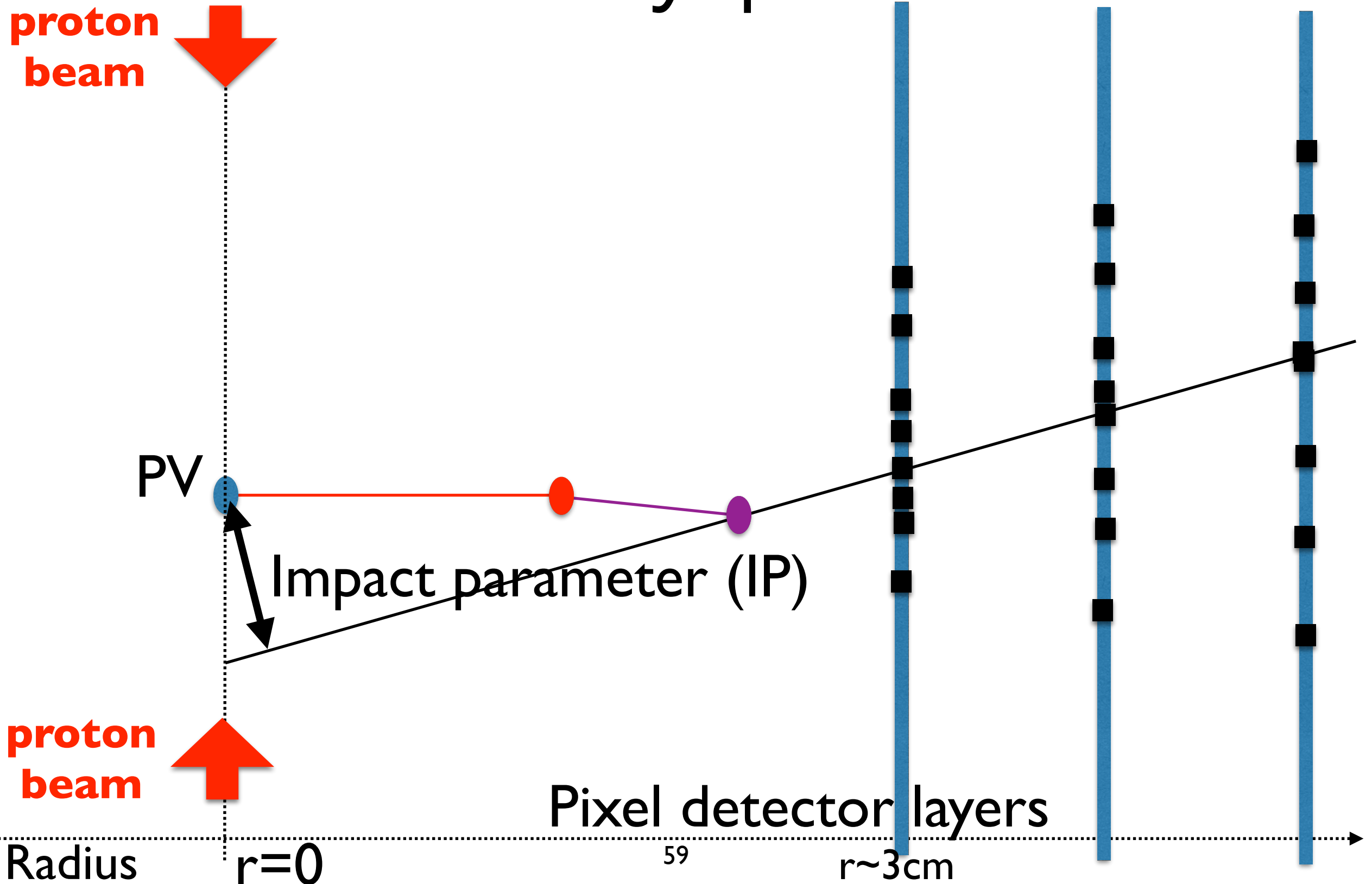
$r \sim 3\text{cm}$

Pixel detector layers





Another key parameter

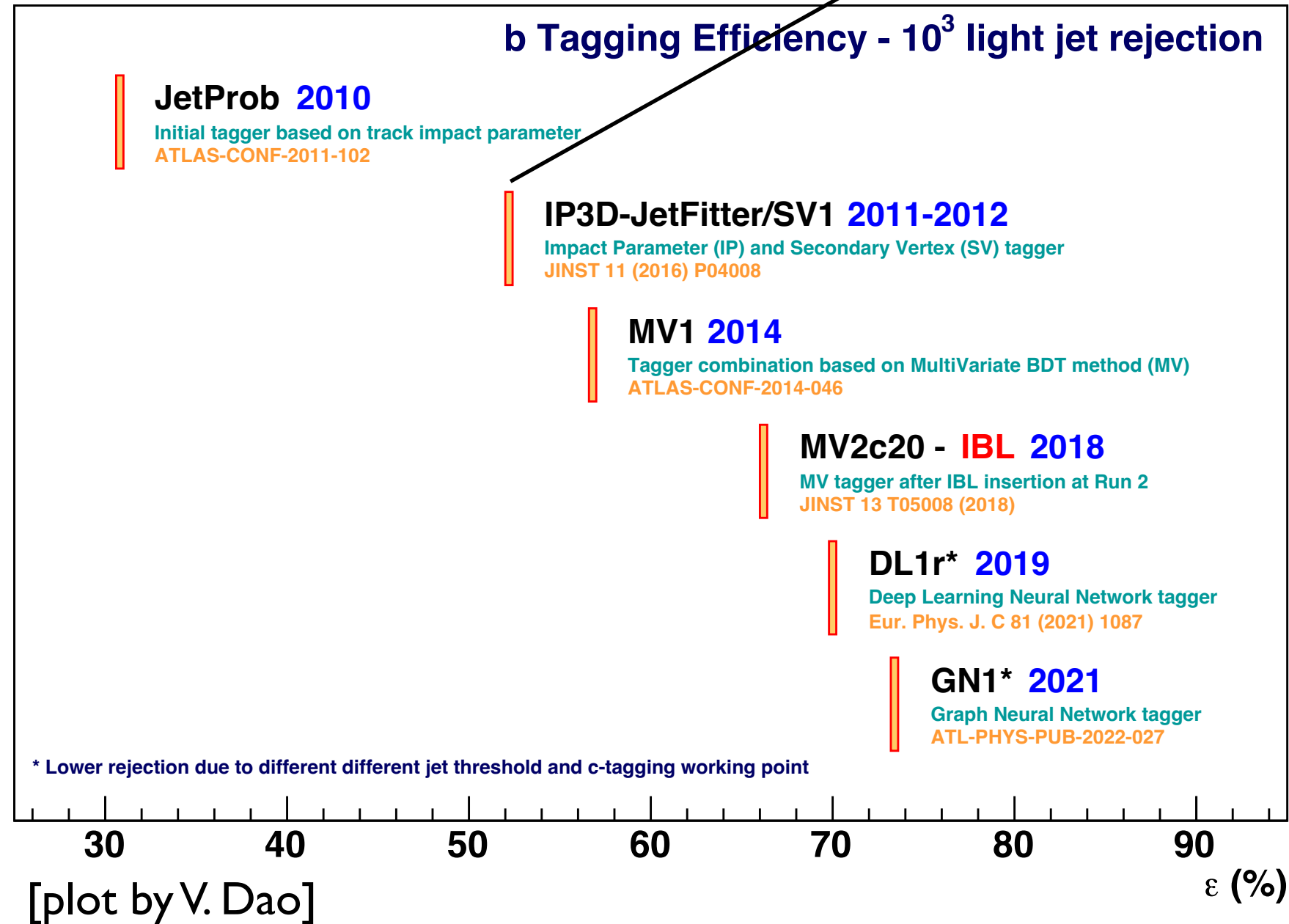


Progress in b-jet identification highlighted by

Fabiola Gianotti at

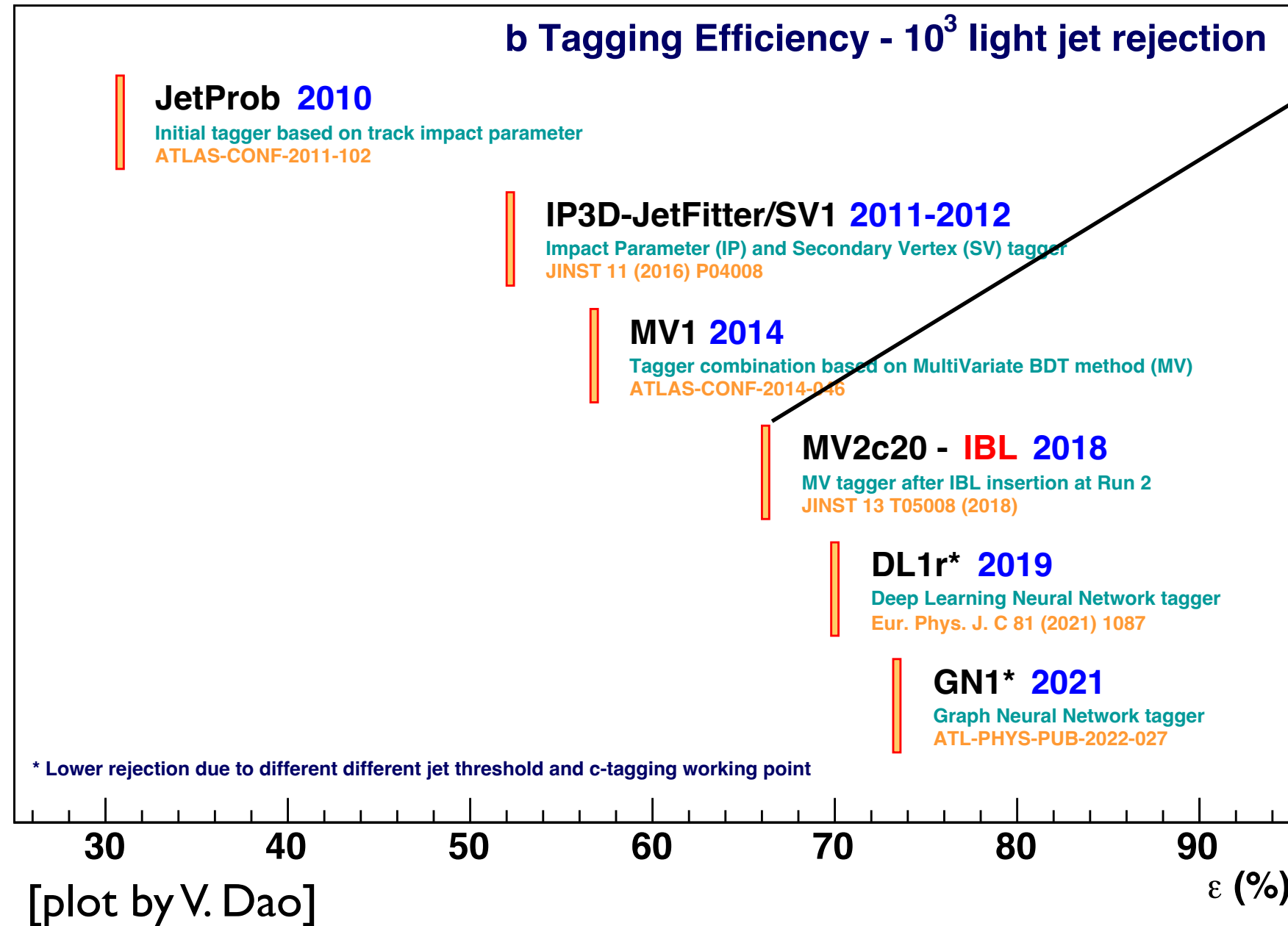


State-of-the-art
vertex reconstruction algorithms

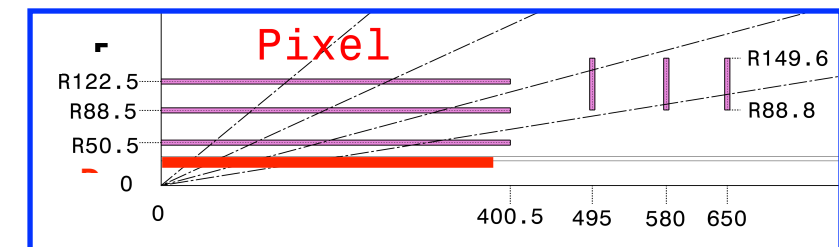


Progress in b-jet identification highlighted by

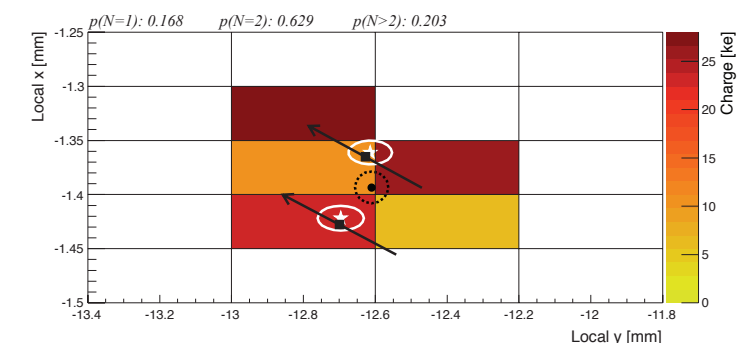
Fabiola Gianotti at



new innermost Pixel layer “inserted” before Run-2



+new algorithm to split merged clusters



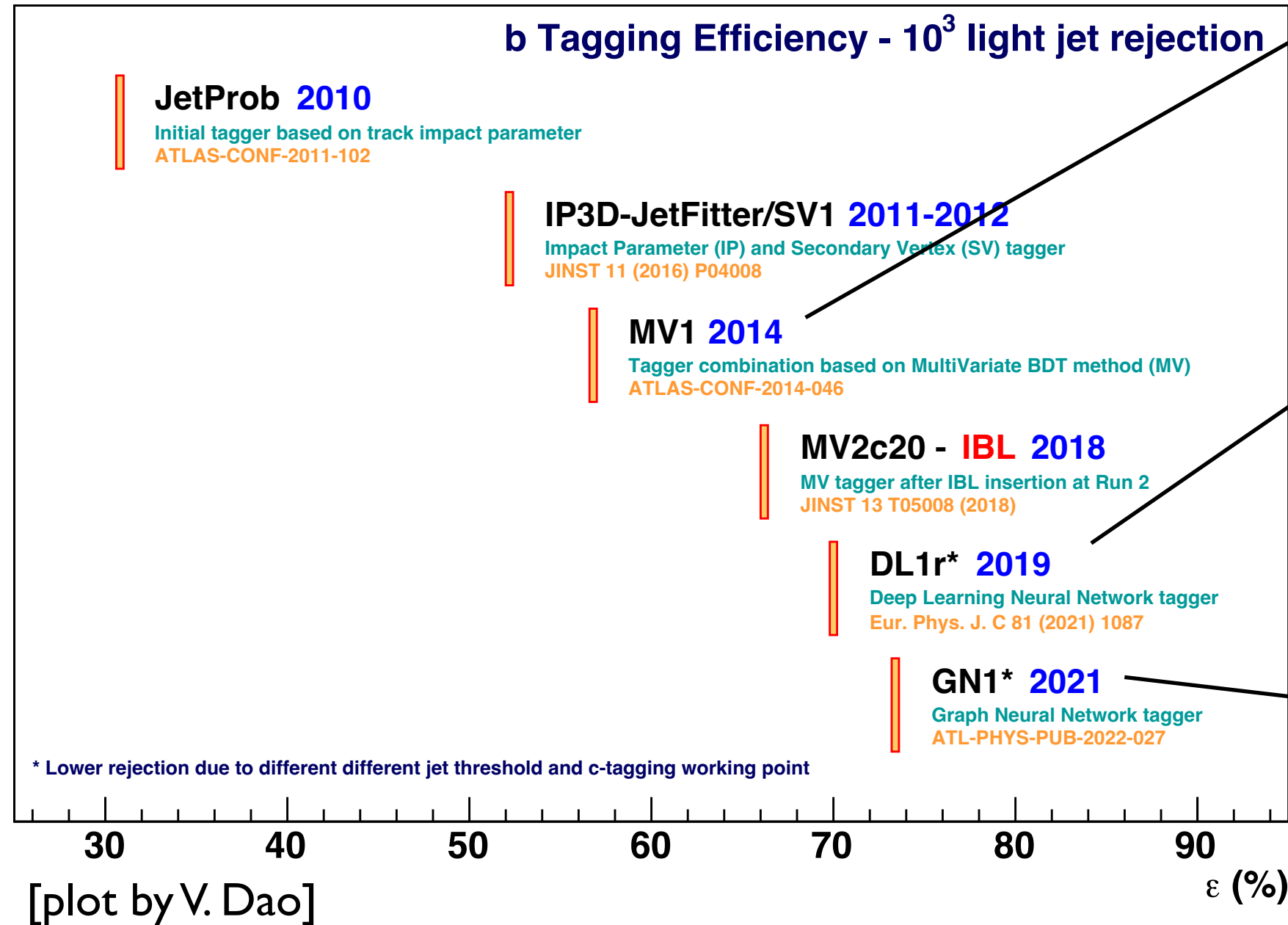
[GP et al, JINST 9 (2014) P09009;
Eur. Phys. J. C 77 (2017) 673]

Progress in b-jet identification highlighted by

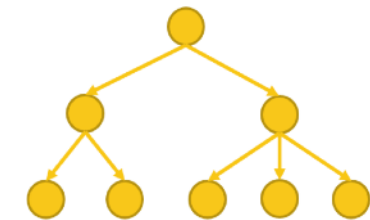
Fabiola Gianotti at



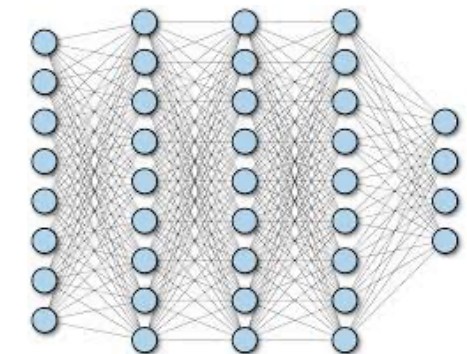
The advent of machine learning...



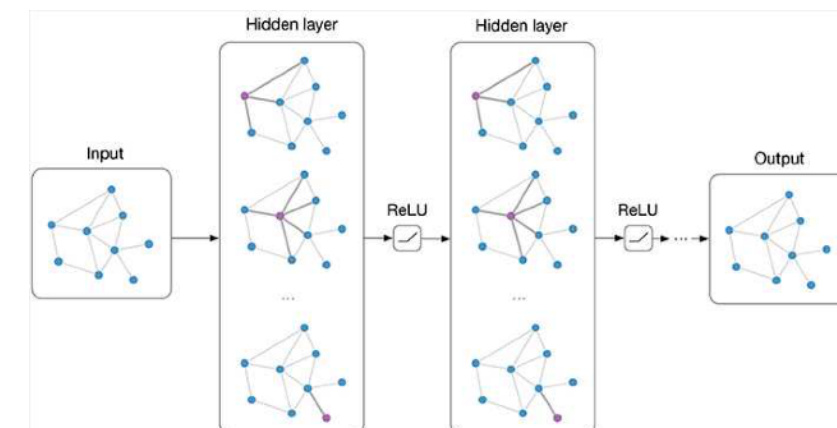
Boosted Decision Trees



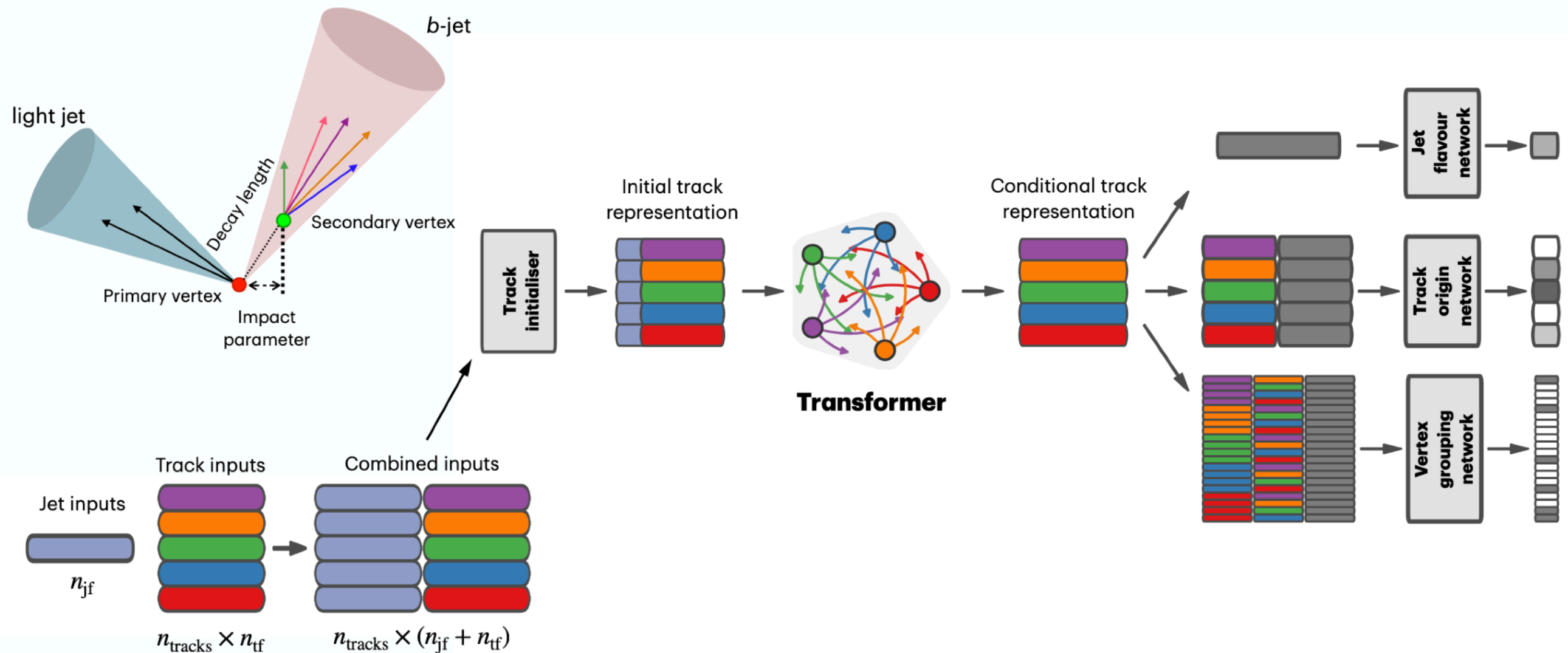
Fully-connected Deep Neural Network



Graph Neural Network

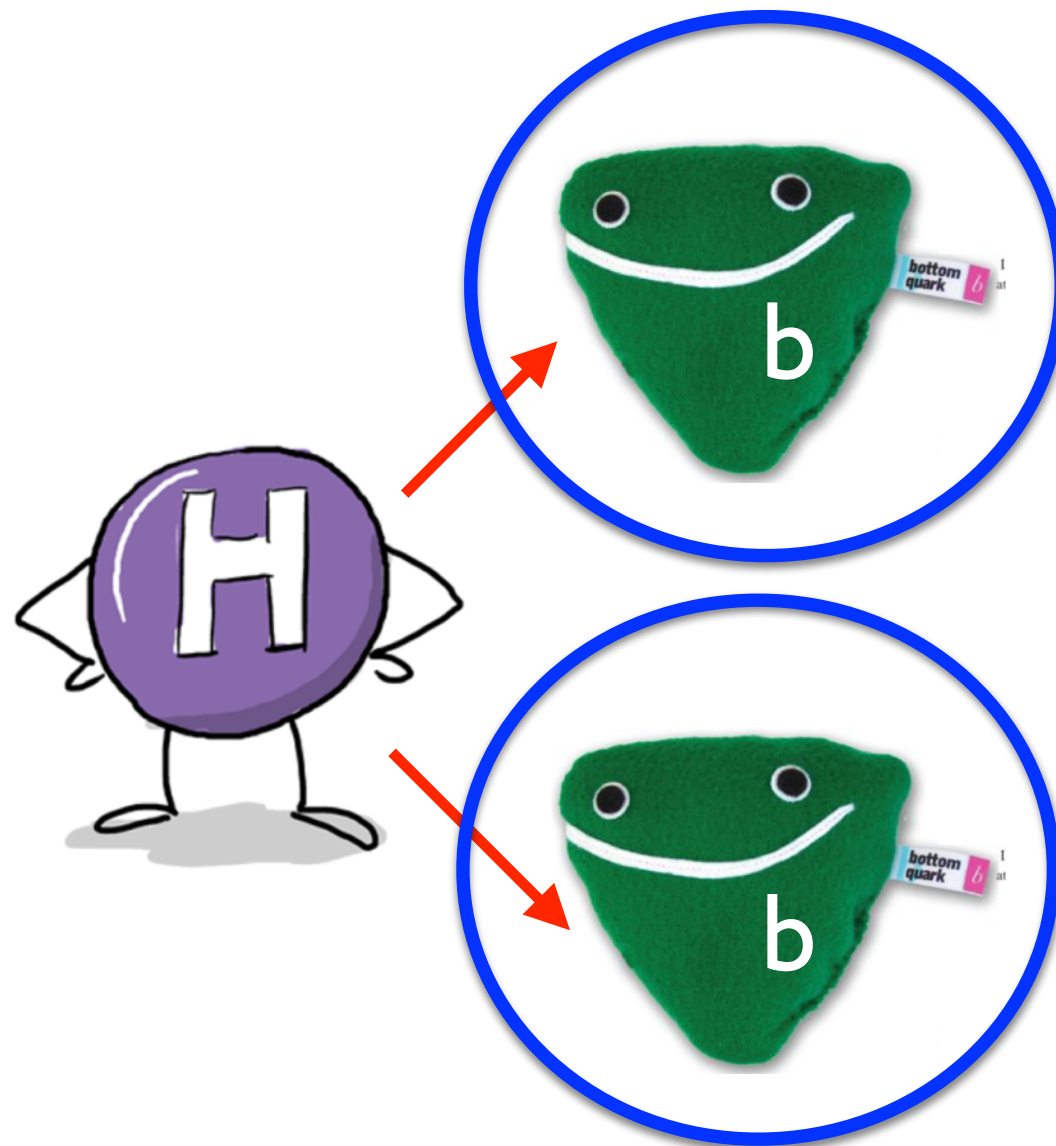


State-Of-The-Art Tagger w/ Transformer architecture



[<https://arxiv.org/pdf/2505.19689>, submitted to Nature Communications]

Now that we can “tag” b-quark jets, how do we see $H \rightarrow bb$?





ATLAS
EXPERIMENT

tagged b-jet

tagged b-jet

$Z \rightarrow \nu\nu$

Run: 284213
Event: 19270203
2015-10-31 04:17

tagged b-jet

$$P_\mu = p_1^\mu + p_2^\mu$$
$$m_{bb} = \sqrt{P^\mu P_\mu}$$

tagged b-jet

p_1^μ
 p_1^μ
 p_2^μ

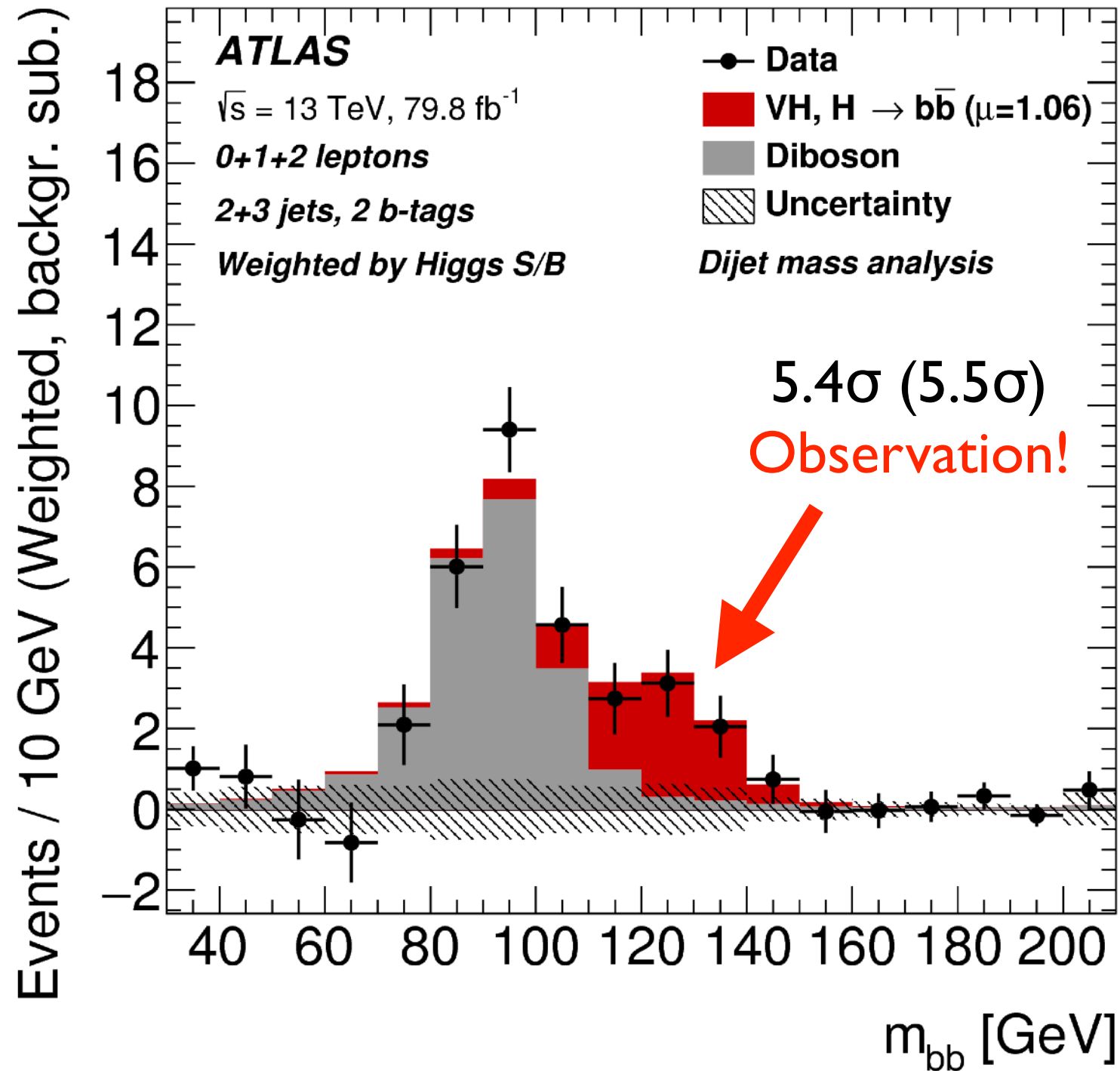
$Z \rightarrow \nu\nu$

Run: 284213
Event: 19270203
2015-10-31 04:17

Observation! (2018)

Run-2 80 fb⁻¹

2018



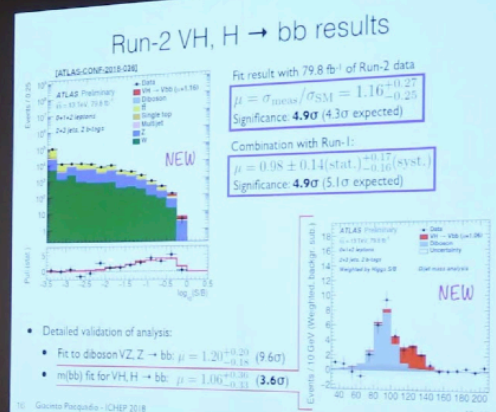
Observation! (2018)

ATLAS announces observation of Higgs to bb decays
(ICHEP 2018 in South Korea)

SCIENTIFIC
AMERICAN®

Physicists Observe the Higgs
Boson's Elusive Decay

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERN COURIER
VOLUME 58 NUMBER 7 SEPTEMBER 2018



me!

LHC EXPERIMENTS

ATLAS observes Higgs-boson decay to b quarks



impossibility of allowing weak vector bosons (the W and Z) to acquire mass. The discovery

The Brout-Englert-Higgs mechanism solves the apparent theoretical

to account for almost 60% of all possible decays, had remained elusive up to now. Observing this decay mode and measuring its rate is mandatory to confirm (or not) the mass generation for fermions via Yukawa interactions, as predicted in the SM.

pairs produced via the strong interaction. To overcome this challenge, it was necessary to consider production processes that are less copious, but exhibit features not present in strong interactions. The most effective of these is the associated production of the Higgs boson with a W or Z boson. The

symmetry
dimensions of particle physics

topics

LHC scientists detect most favored Higgs decay

NATIONAL GEOGRAPHIC

Elusive Elementary Particle Finally Caught Decaying—Get the Facts

Not seeing the Higgs boson break down like this would have been very bad for our understanding of how the universe works.

Search ▾ US edition ▾
The Guardian

Two quarks for Muster Higgs

Since the big discovery of 2012, the Large Hadron Collider at CERN has been accumulating data and making steady progress. Two recent results establish the origins of the mass of the two heaviest quarks

physicsworld

PARTICLES AND INTERACTIONS | R

Higgs boson seen de

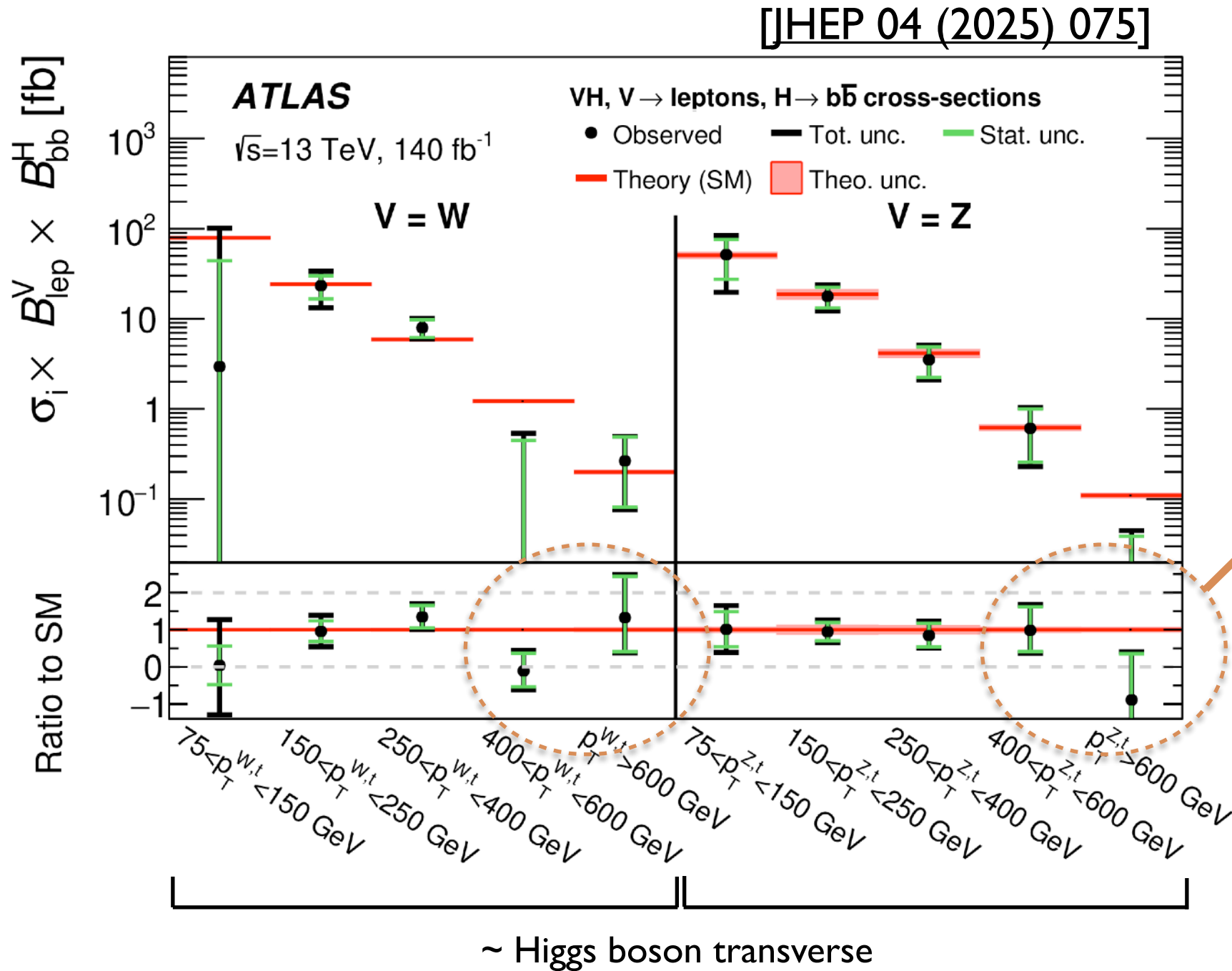
Science

An elusive Higgs boson decay has finally been spotted

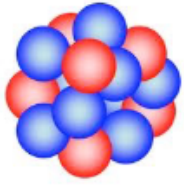
c|net

Why decaying Higgs bosons and the quarks they create matter

Measurement of decay distributions (2024)



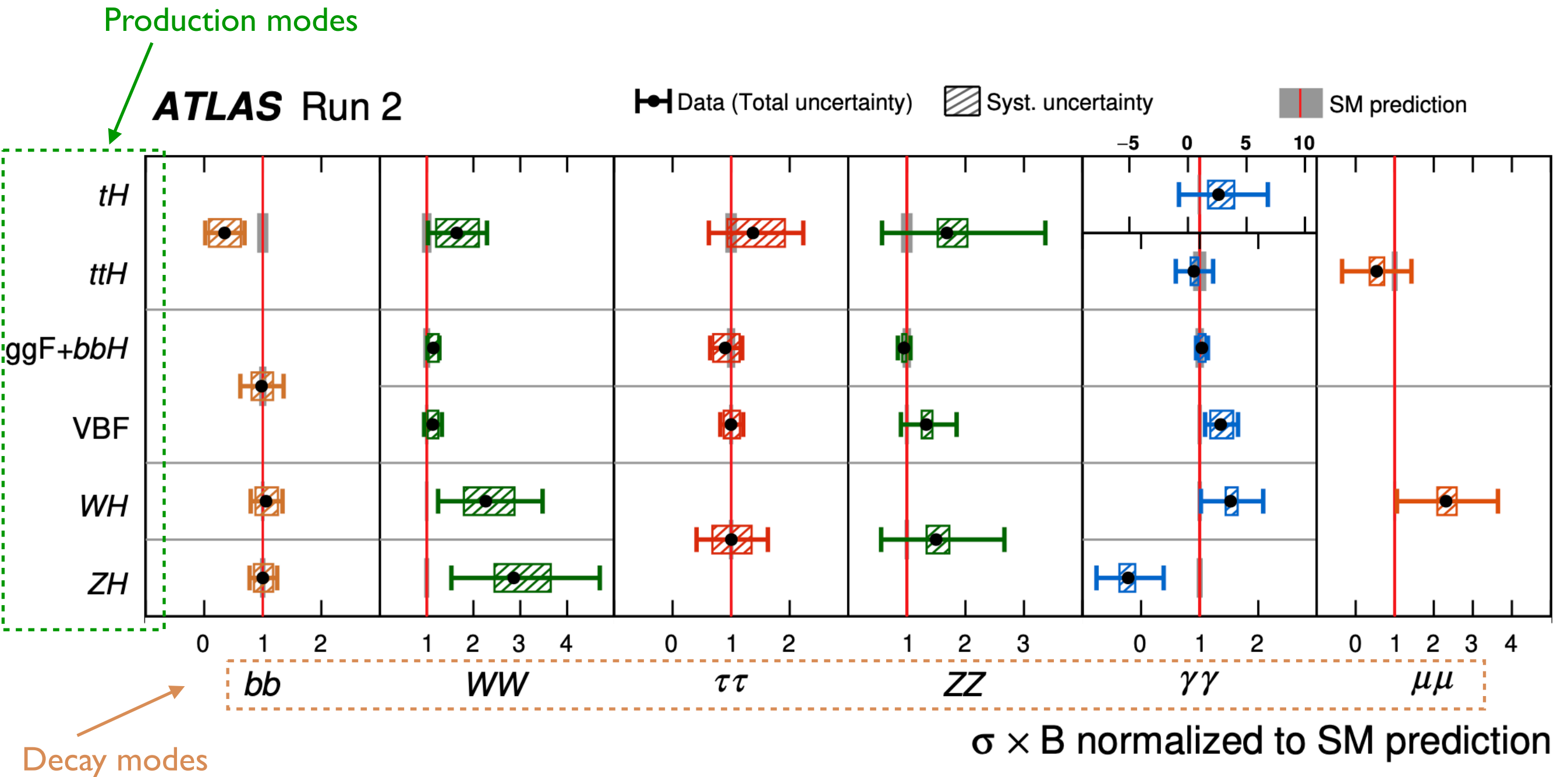
Is the Higgs boson
fundamental or
composite?

 $r_H \sim \frac{\hbar}{p_T^H}$?

No enhancement
at high momentum
seen so far.

Is the Higgs field responsible for the mass
of all vector bosons and fermions?

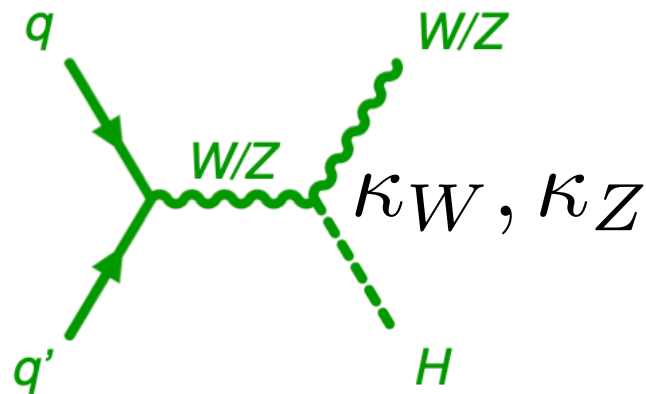
Rate measurements in 25 channels are combined



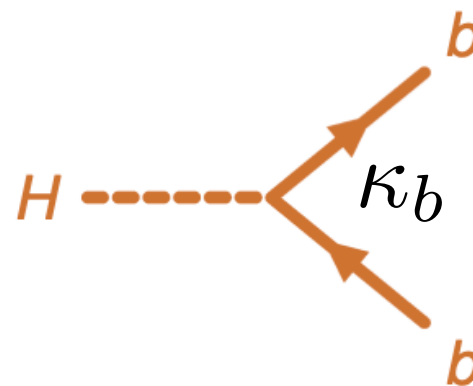
and used to determine coupling strengths

Example of production x decay

Production



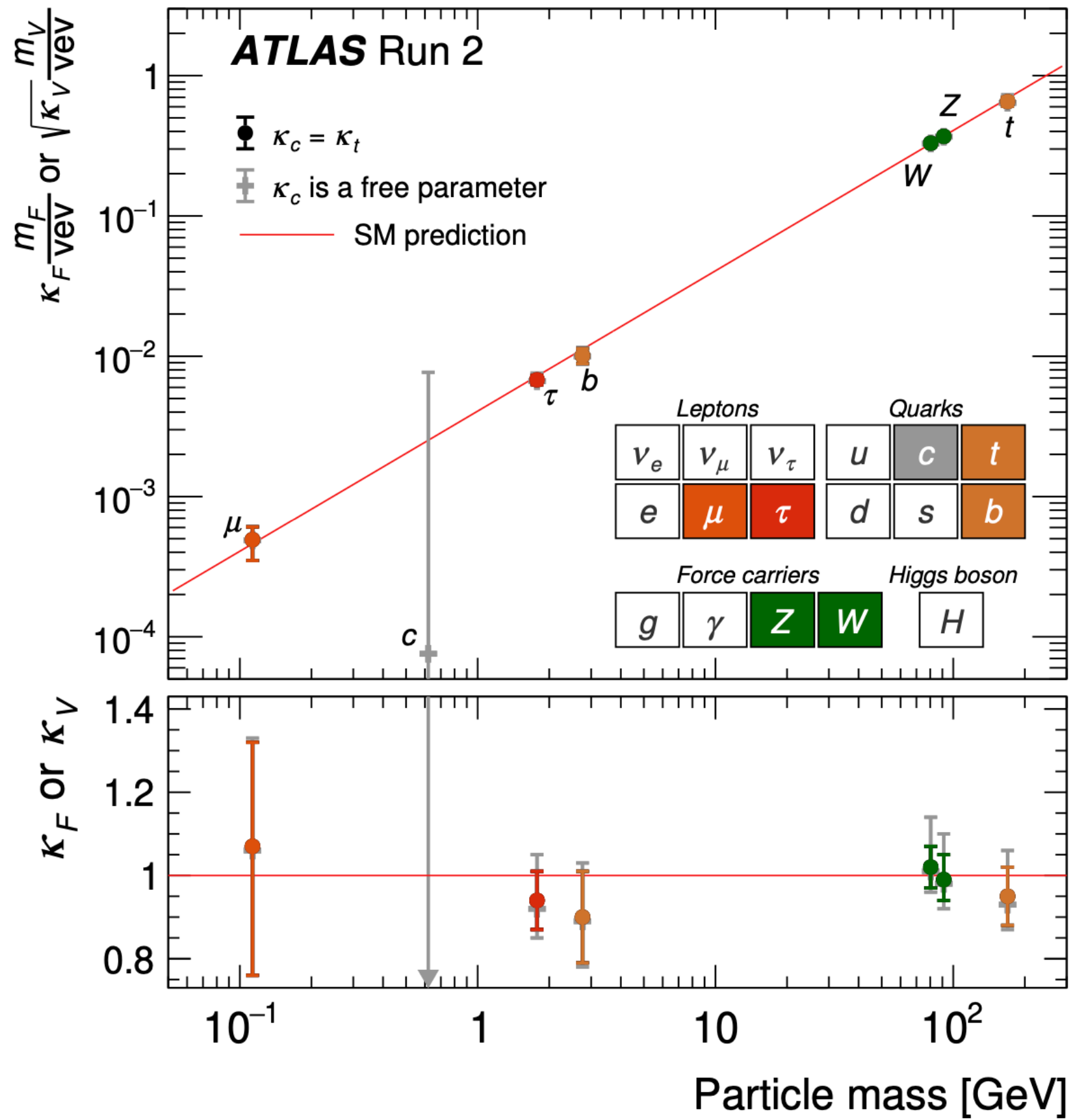
Decay



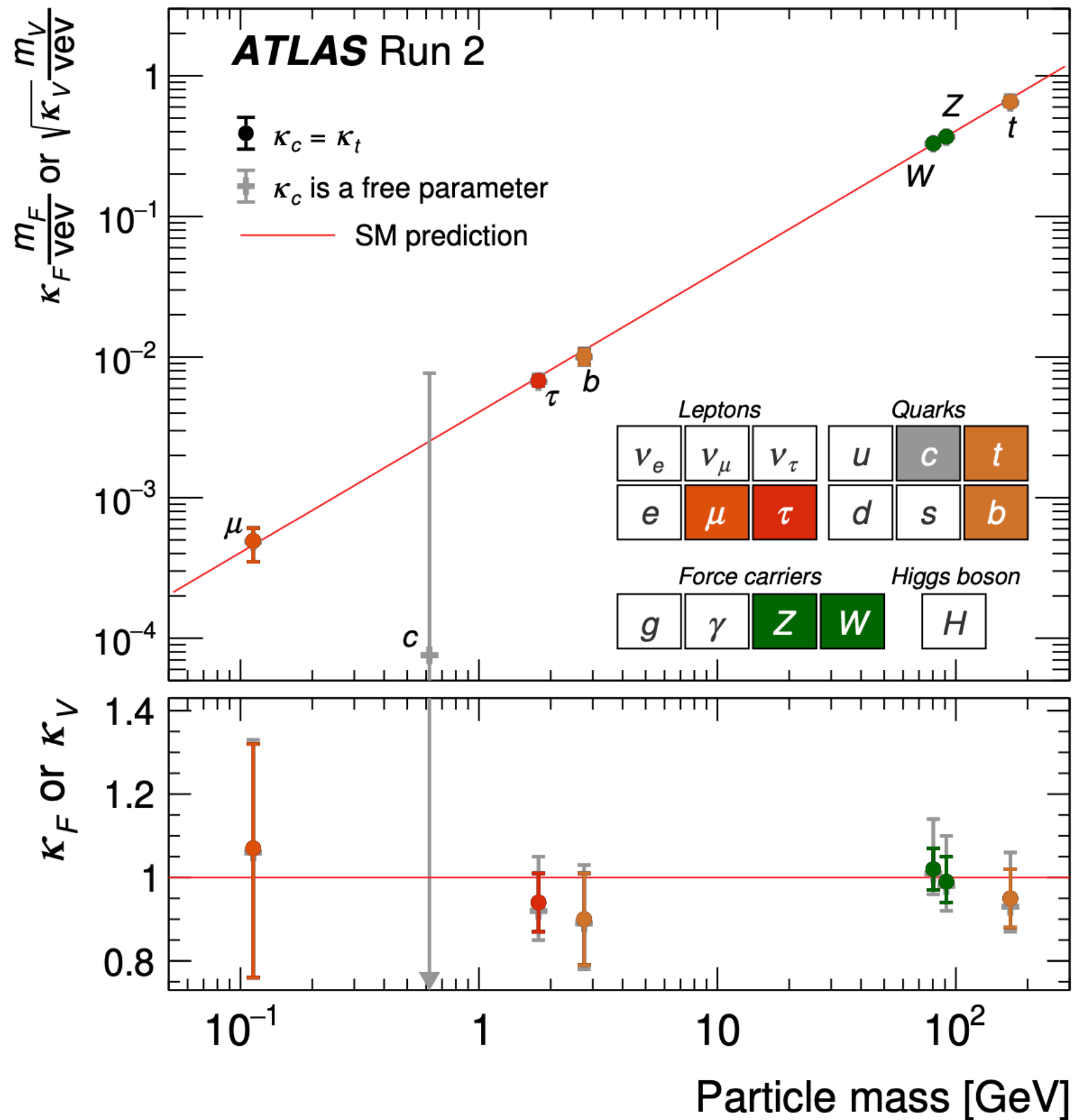
- In general, any Higgs boson measurement is sensitive to the product of the coupling in **production** and **decay**:

$$\sigma(i \rightarrow H \rightarrow f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

- Best measurement from combining all possible **production modes**, with all possible **decay modes**
- **Performed in Higgs combination of all measurements**



κ = coupling
rescaling
factor



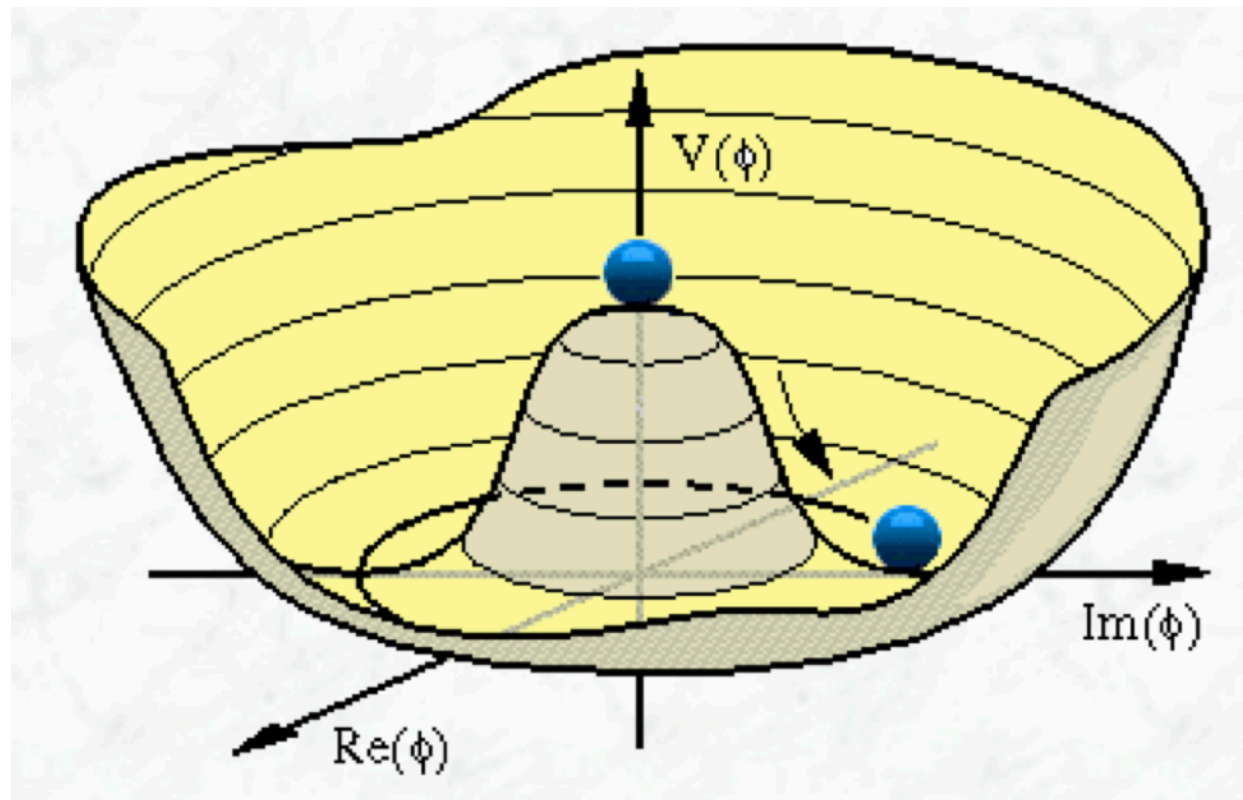
Couplings scale with particle mass⁽²⁾ within 5-10%

Confirms Higgs mechanism gives mass to vector bosons and 3rd generation fermions

First hint of couplings to 2nd generation

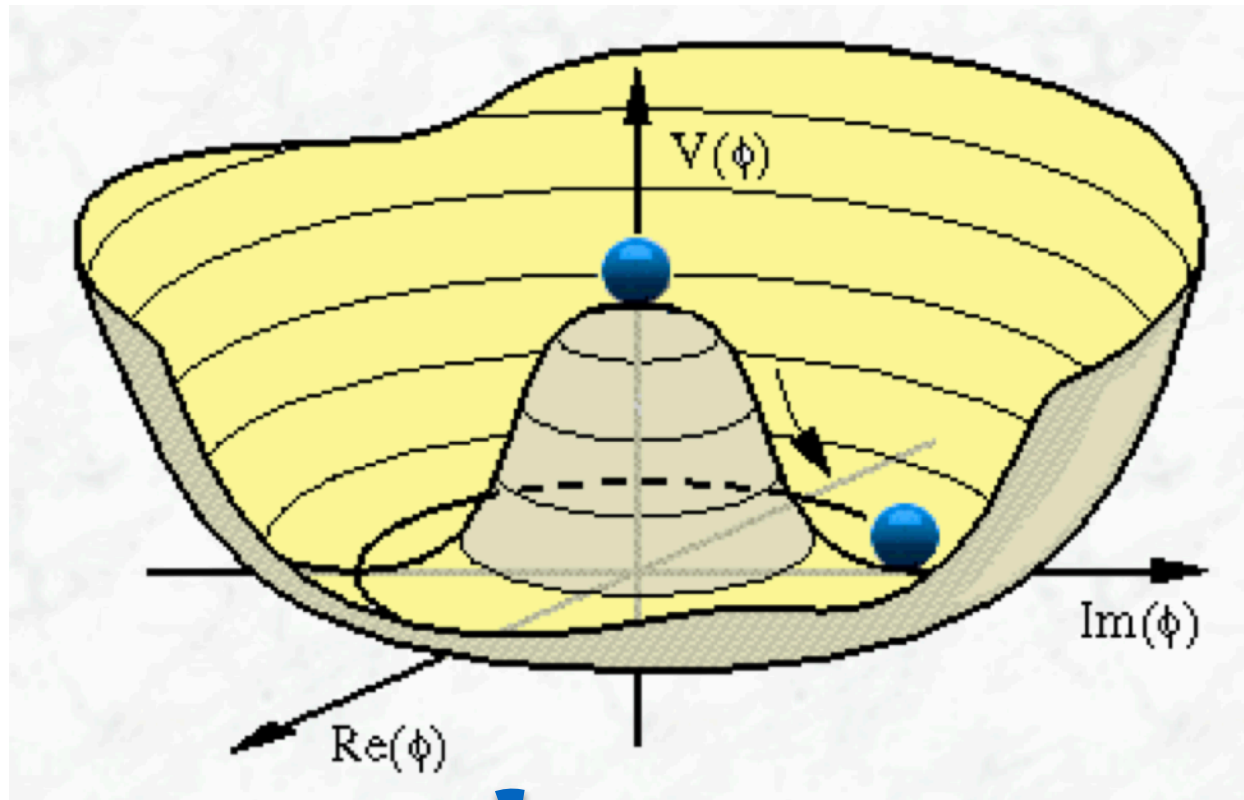
What is the shape
of the Higgs potential?

Higgs field potential



$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

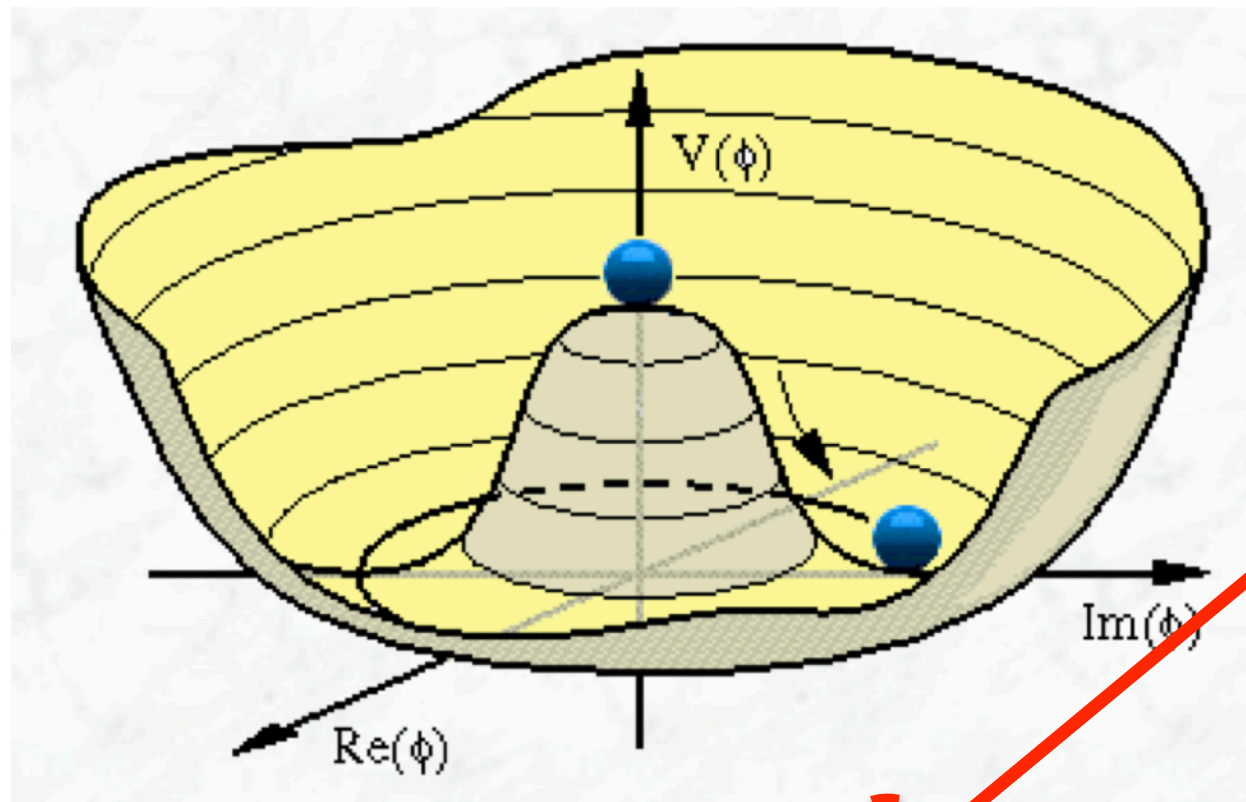
Higgs field potential



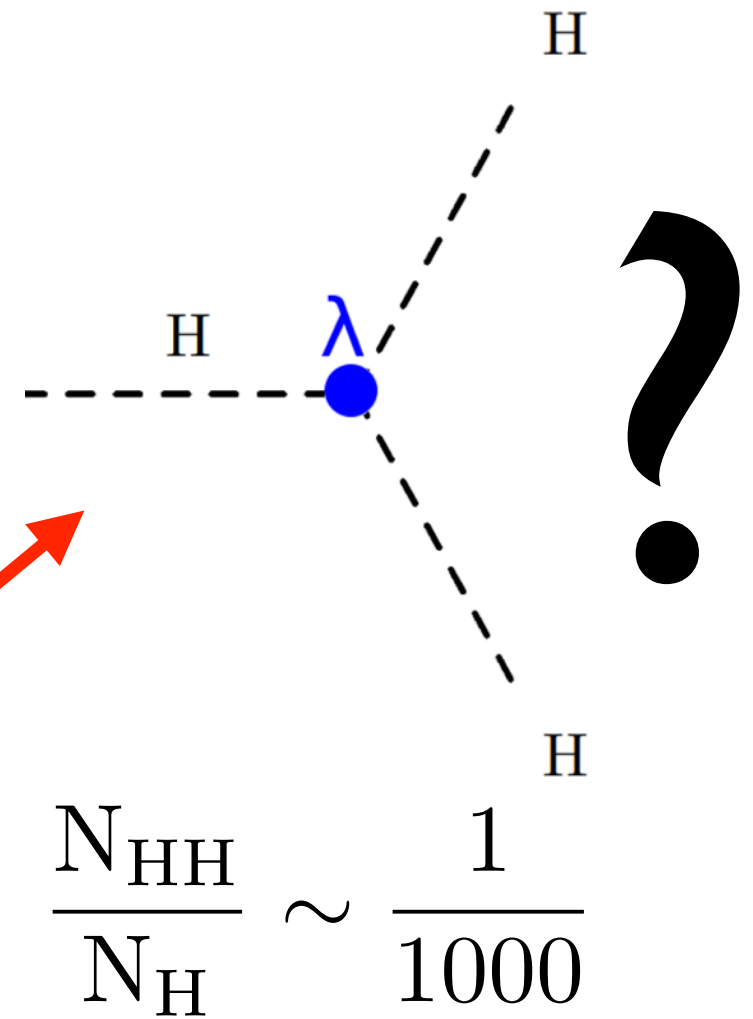
$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$m_H^2 = -2\mu^2$

Higgs field potential



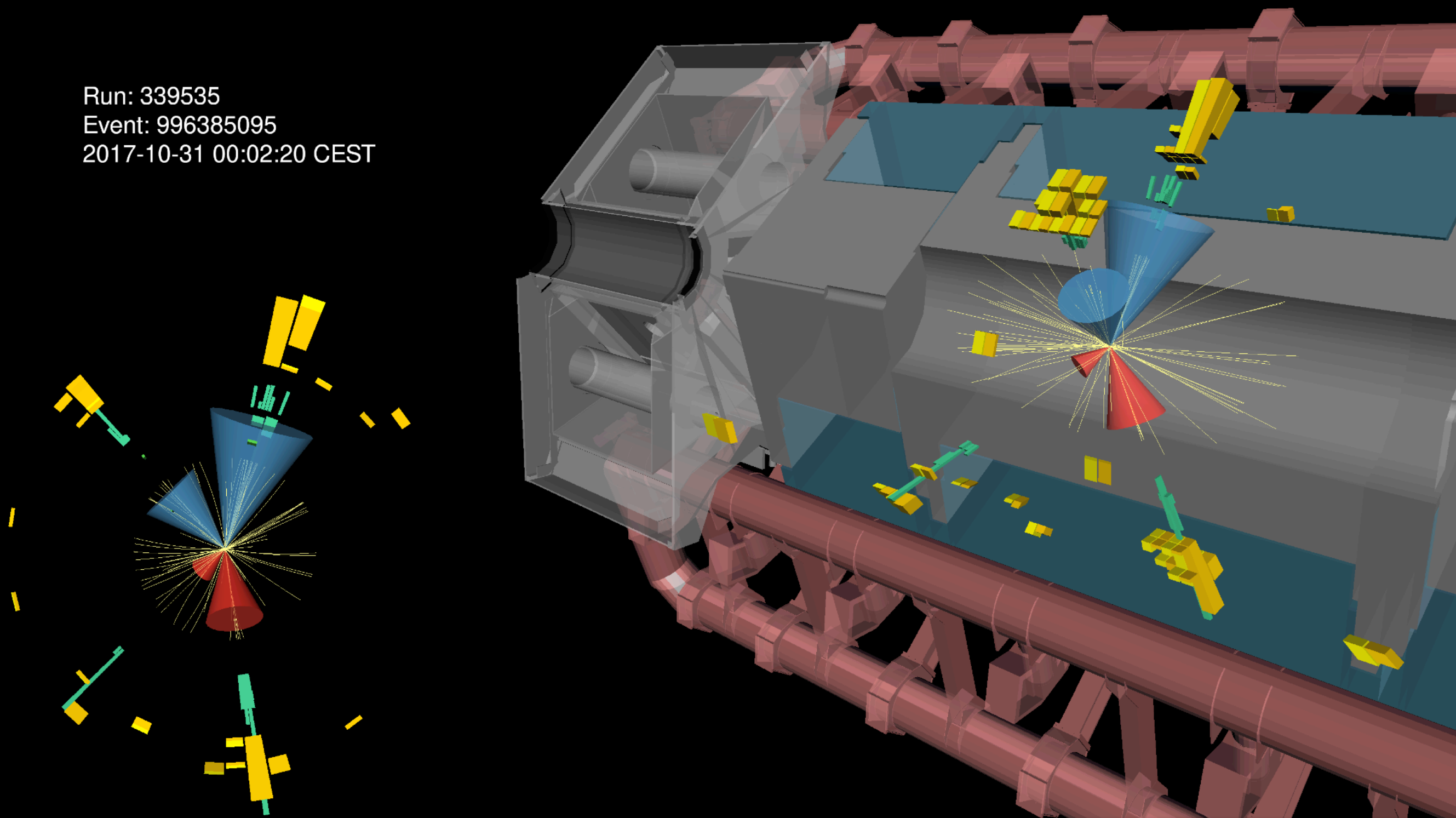
$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$



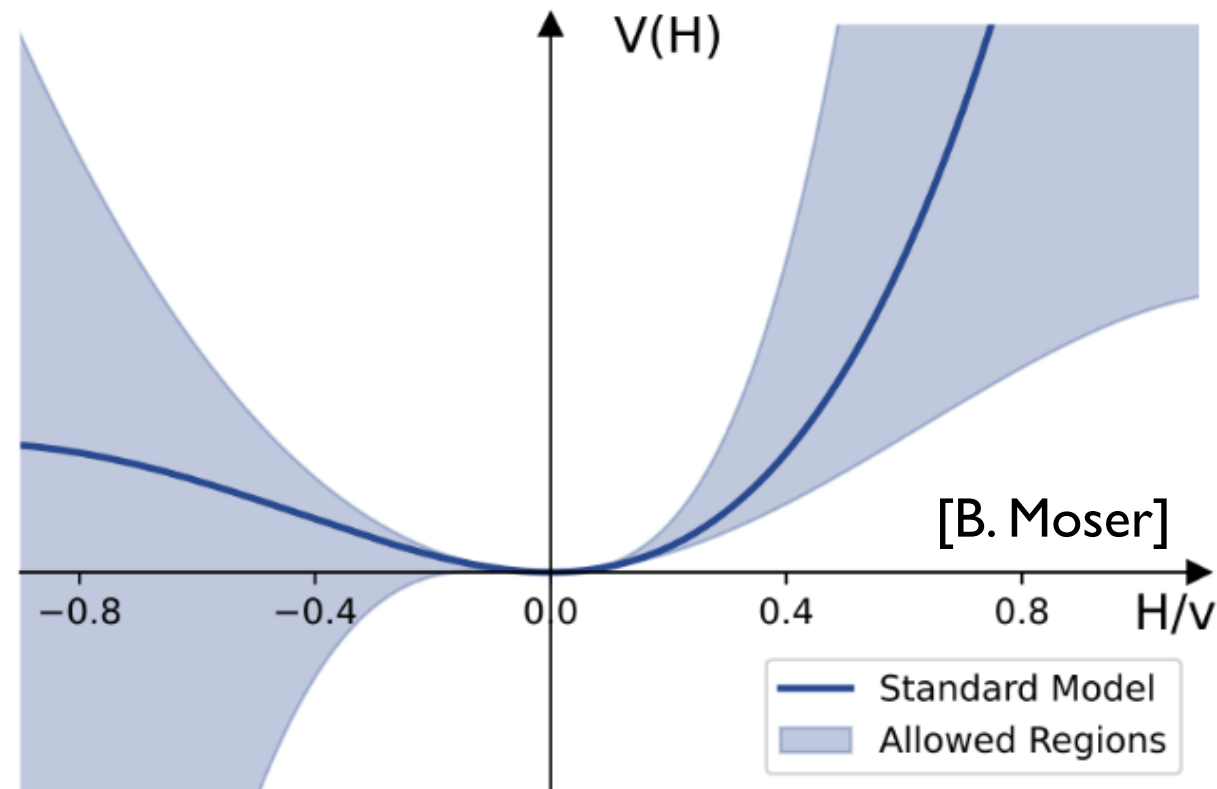
$$\frac{N_{HH}}{N_H} \sim \frac{1}{1000}$$

$$HH \rightarrow bb\tau\tau$$

Run: 339535
Event: 996385095
2017-10-31 00:02:20 CEST

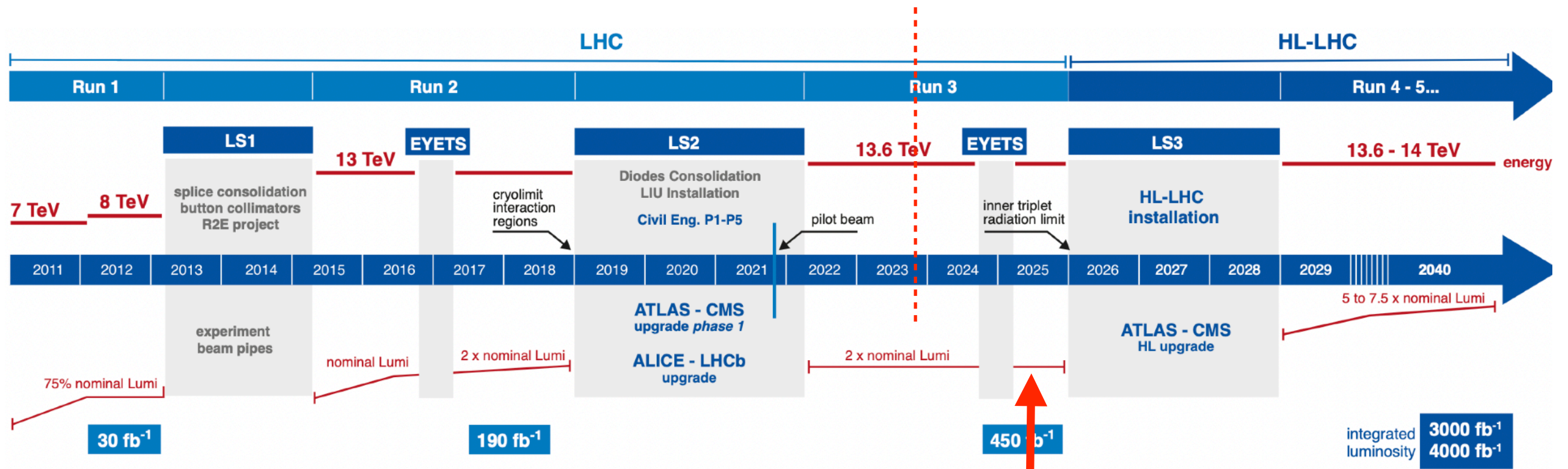


Constraints on Higgs boson self-coupling:



$$\kappa_\lambda = \frac{\lambda}{\lambda_{\text{SM}}} \in [0.2, 5.9] \quad @95\% \text{ CL} \quad [-500\%, +590\%]$$

Prospects for High-Luminosity LHC



Today

(only ~10% of final expected LHC data)

~16 years
from now

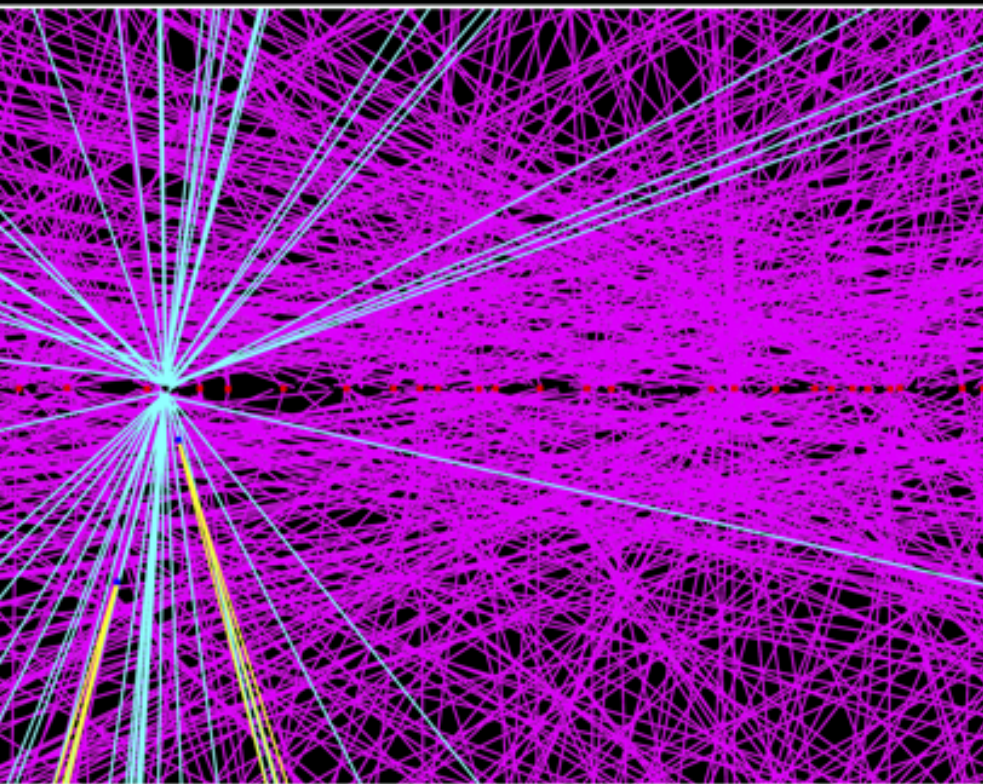
- Run-3 ongoing: ~2x more data by end-of-2026
- Then HL-LHC: ~7x more data by ~2040



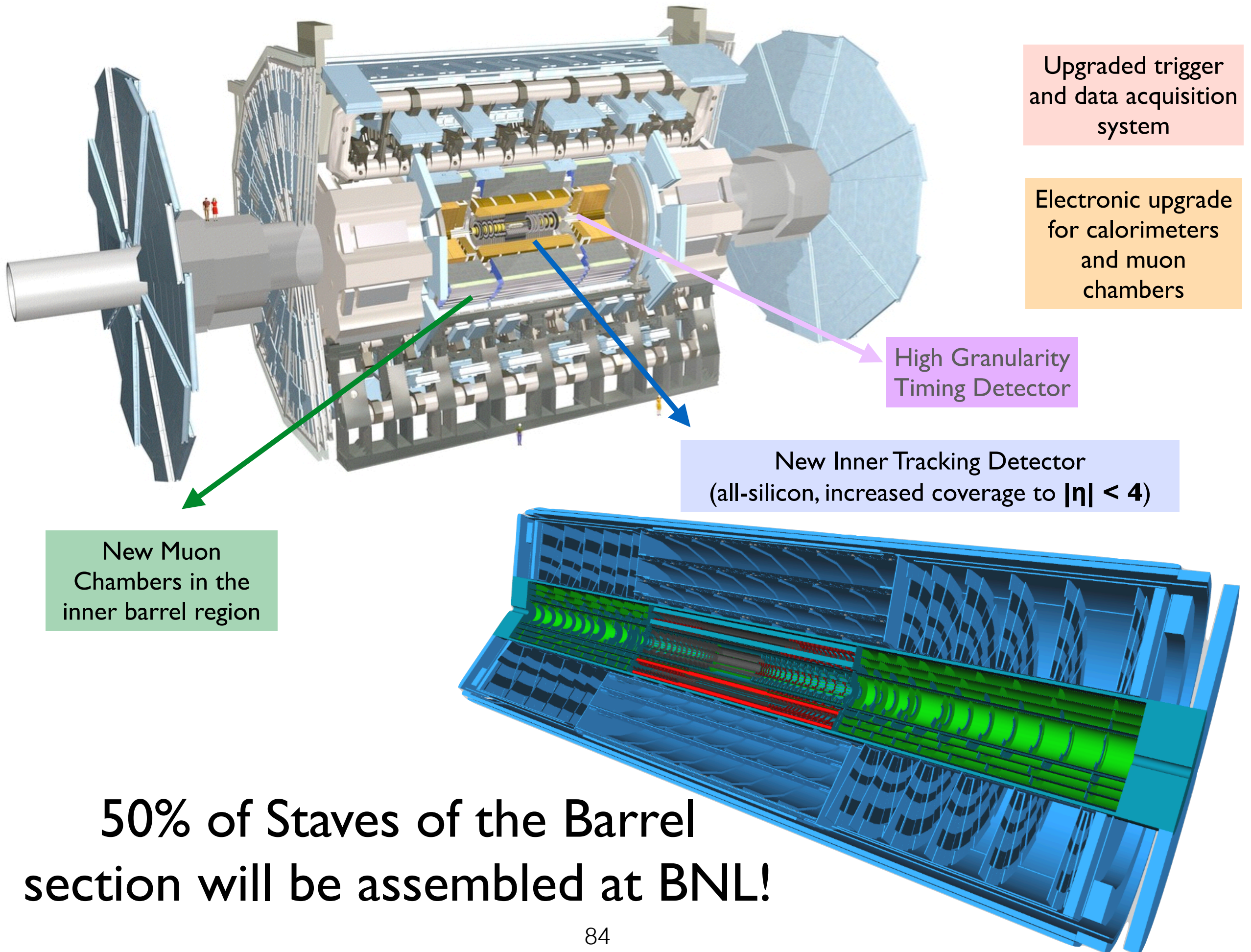
ATLAS

EXPERIMENT

HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$

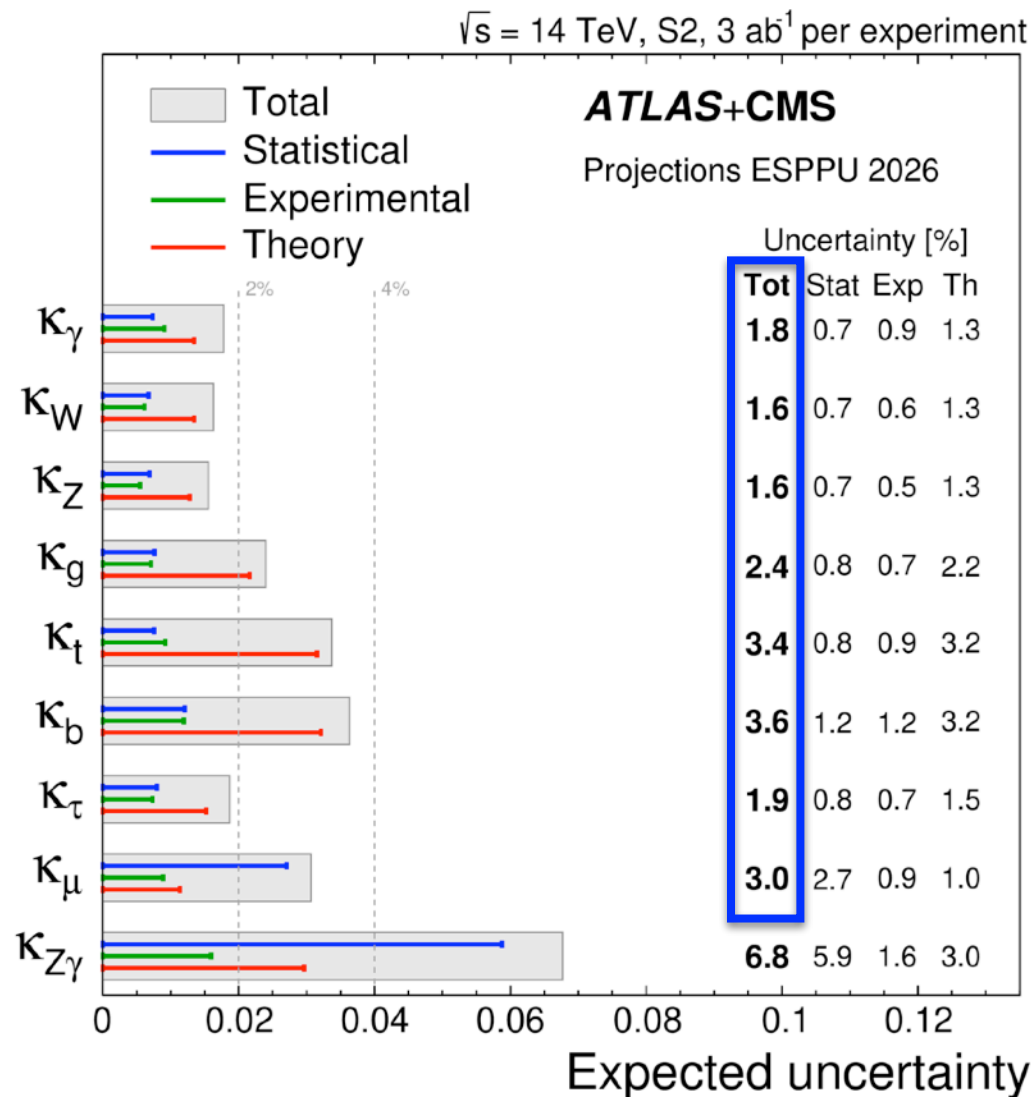


Up to 200 pile-up interactions!

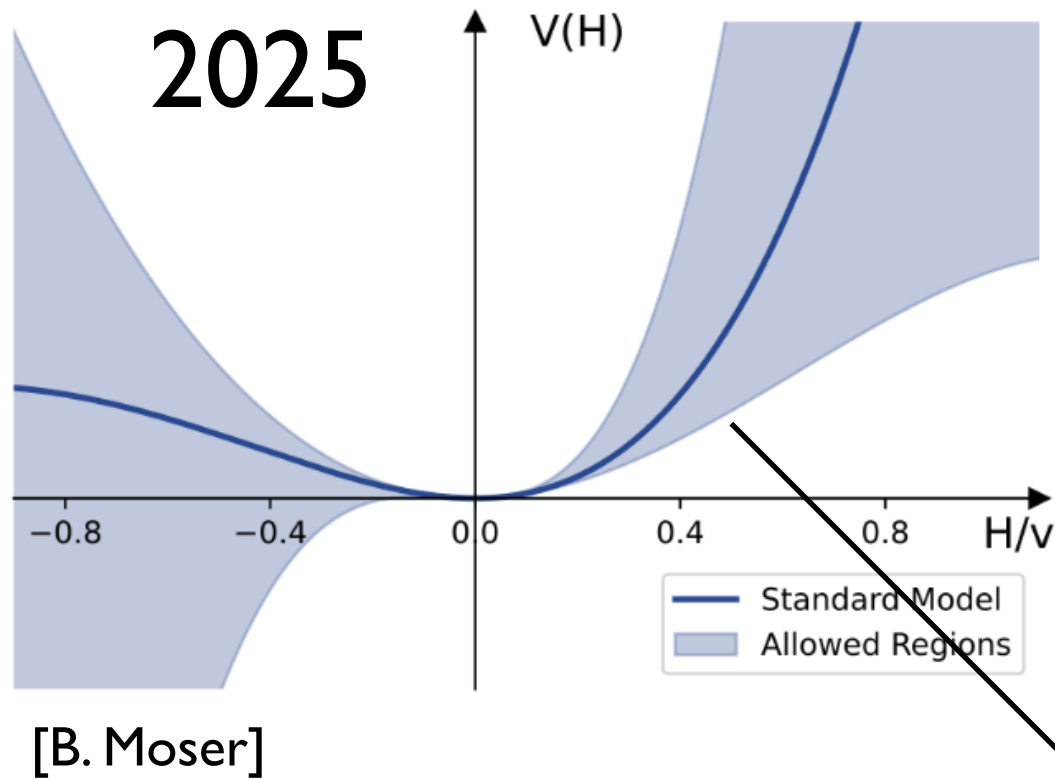


ATLAS+CMS expect to:

- reach a precision of 1.5% to 4% on most Higgs boson couplings
- observe $H \rightarrow \mu\mu$ (but not $H \rightarrow cc$)

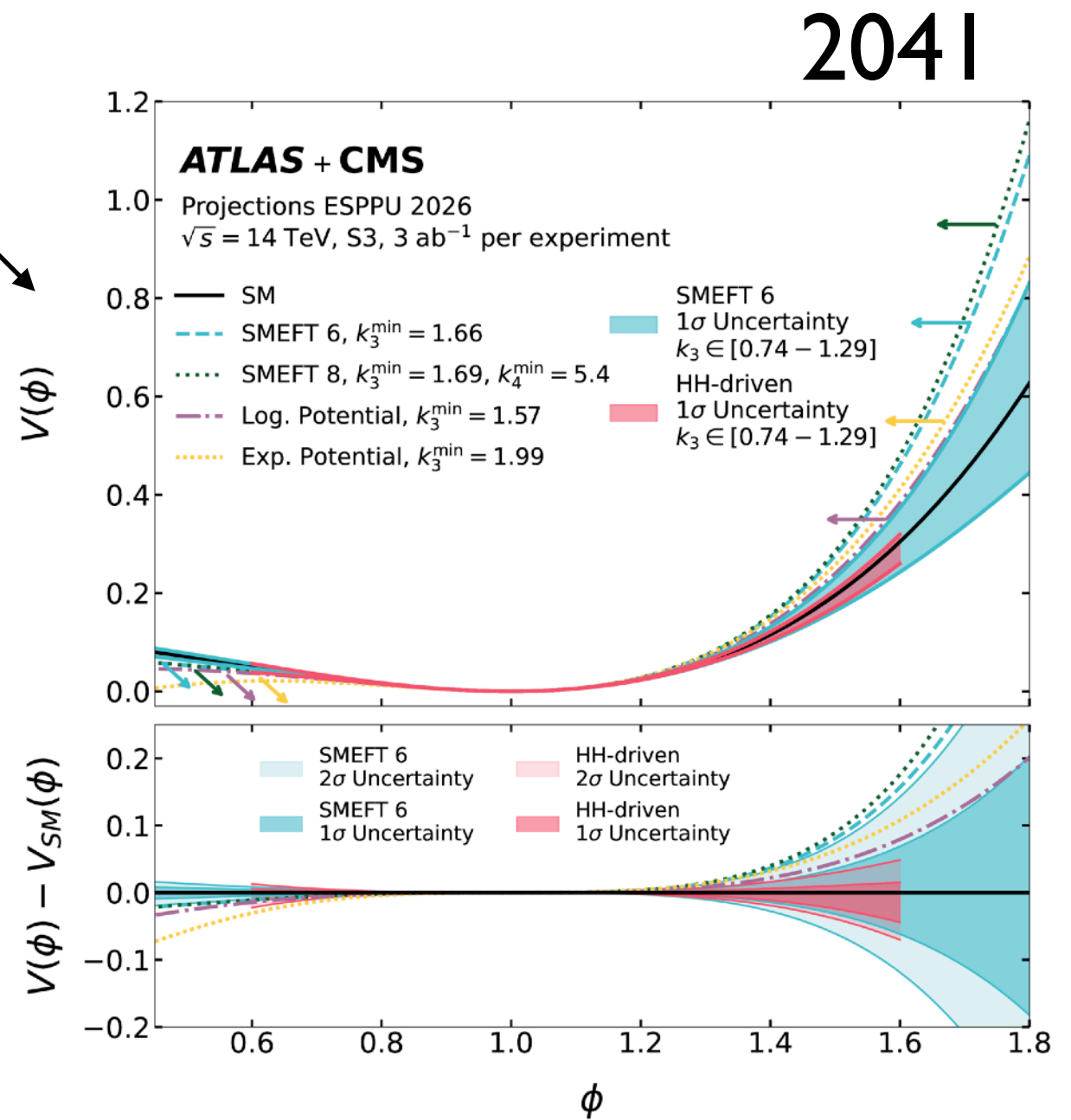


κ = coupling
rescaling
factor



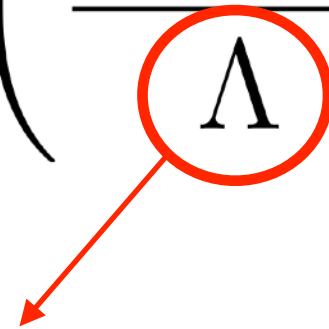
ATLAS+CMS expect to:

- measure the Higgs boson-self coupling with better than 30% precision



Is this precise “enough”?

Deviation expected on
Higgs boson couplings

$$\sim 5\% \times \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2$$


Energy scale of
(yet unknown) New Physics

With 1% precision, can reach New Physics scales of
a few TeV.

Towards the next-generation collider

Pivotal Moment for Particle Physics

- Routinely, the Particle Physics Community develops a strategy for the future
 - US Particle Physics Priorization process (P5) ended in 2023
 - European Strategy Process for Particle Physics currently ongoing, recommendations expected **by end of 2025**
- **Most favored option:**
 - **Europe:** Electron-positron collider (**FCC-ee**: *intensity frontier*) possibly followed by proton-proton collider (**FCC-hh**: *energy frontier*)
 - **US:** participate in FCC and prepare for a Muon Collider on US soil
- Alternative in **China:** CEPC, similar in scope to FCC

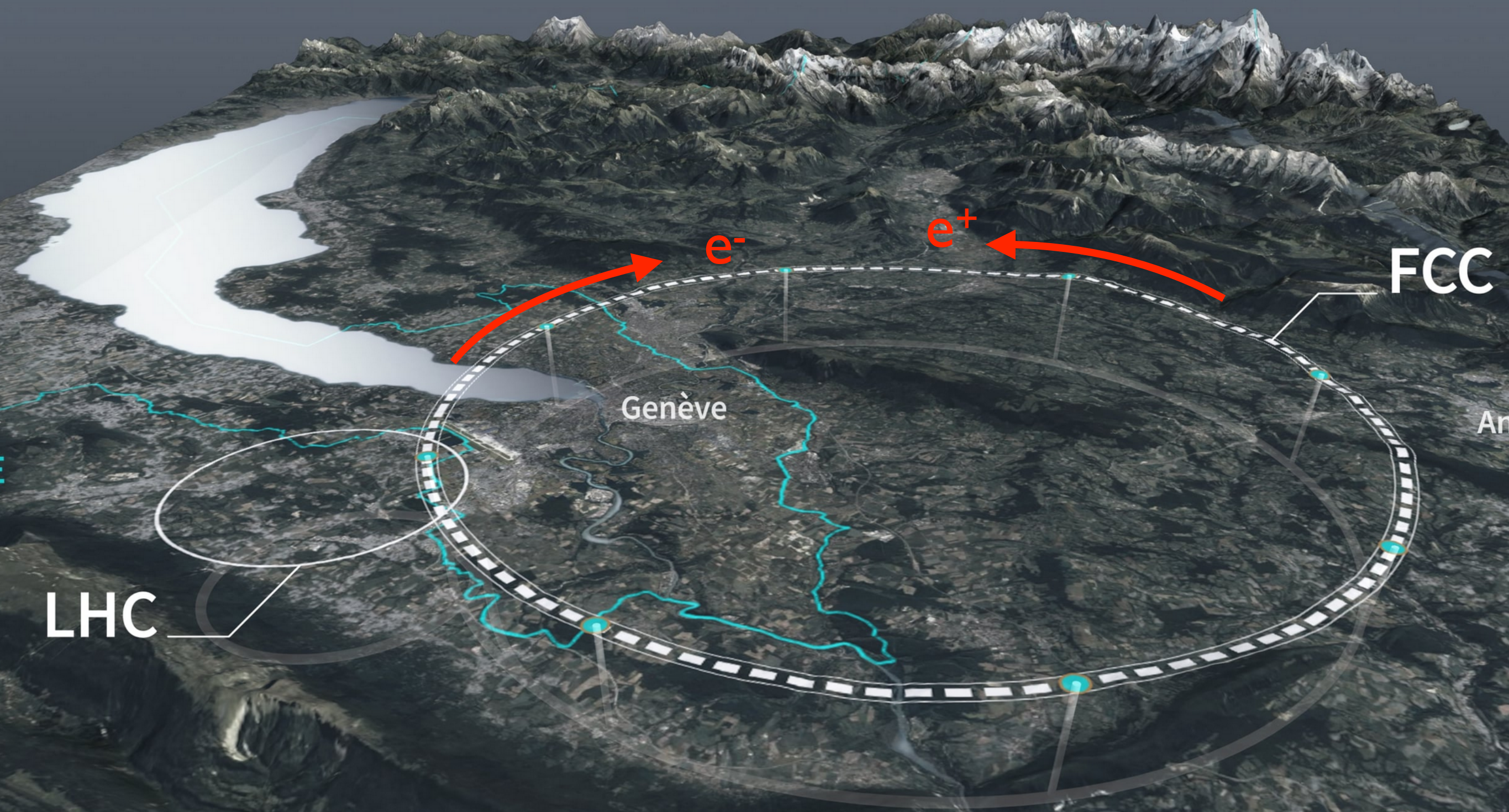


FCC

Genève

LHC

$L \sim 91 \text{ km}$



LHC

Genève

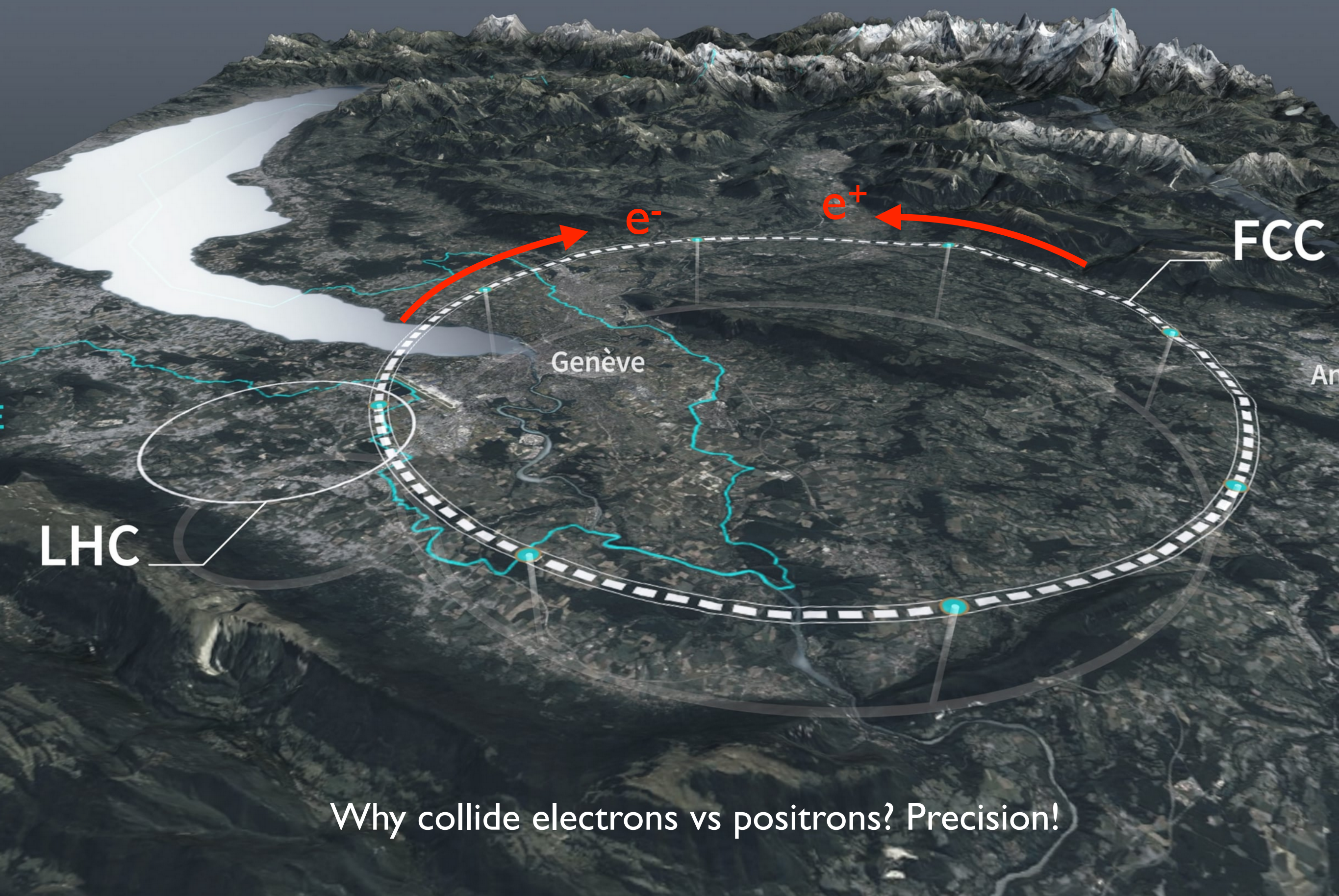
FCC

e^-

e^+

Why a ~91 km ring?

$$\frac{\Delta E_{\text{syn}}}{\text{revolution}} \propto \frac{E_{\text{beam}}^4}{R}$$



LHC

Genève

e^-

e^+

FCC

An

Why collide electrons vs positrons? Precision!

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	—	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$ \kappa_s $ (%)	—	$^{+29}_{-67}$
Γ_H (%)	—	0.78
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}

*model-dependent
assumption on Higgs width

FCC-ee would
enable to decrease
uncertainties up to
a factor of 10!

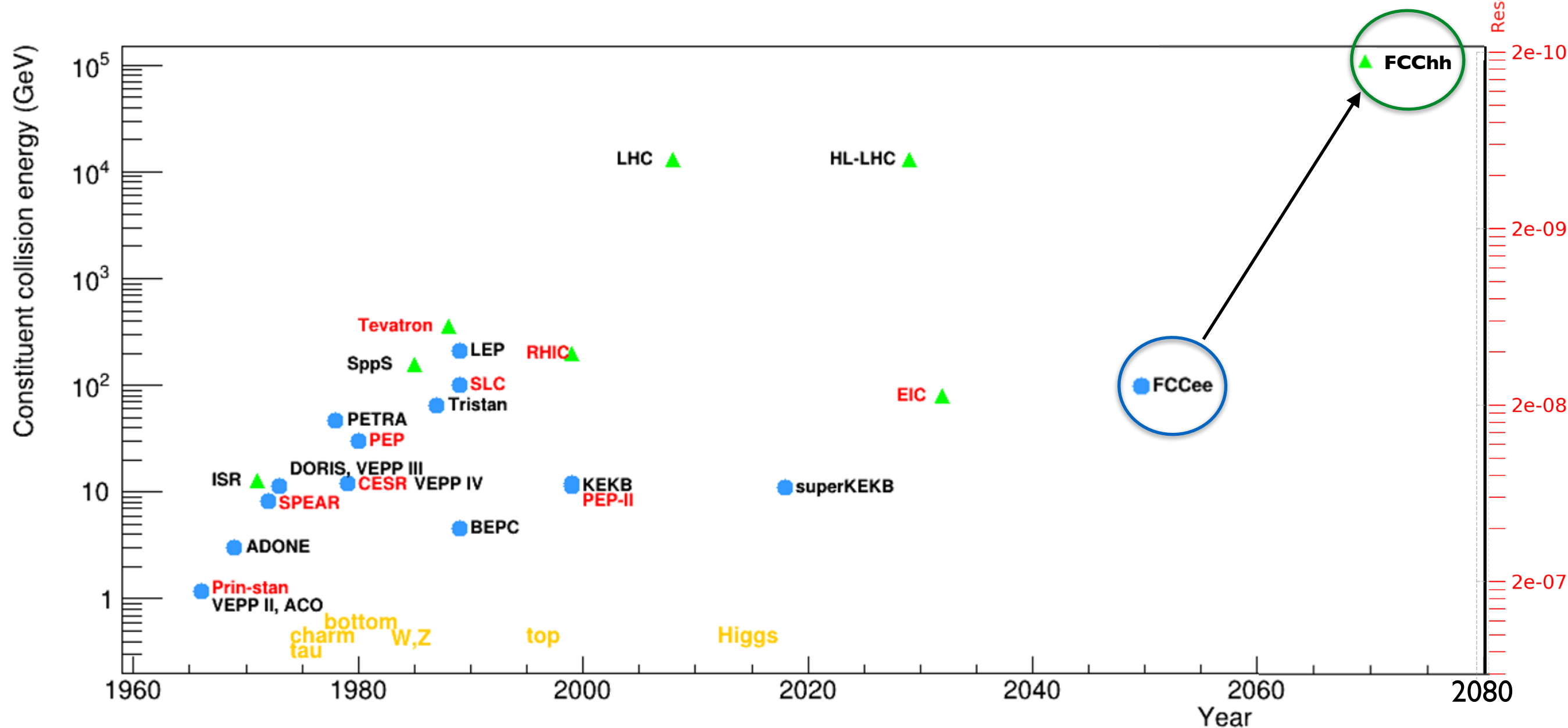
(equivalent to
a New Physics
energy reach
of 3-10 TeV)

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	—	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$ \kappa_s $ (%)	—	+29 −67
Γ_H (%)	—	0.78
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}

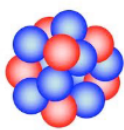
*model-dependent
assumption on Higgs width

Measure
couplings to 2nd
generation quarks

From precision to energy frontier

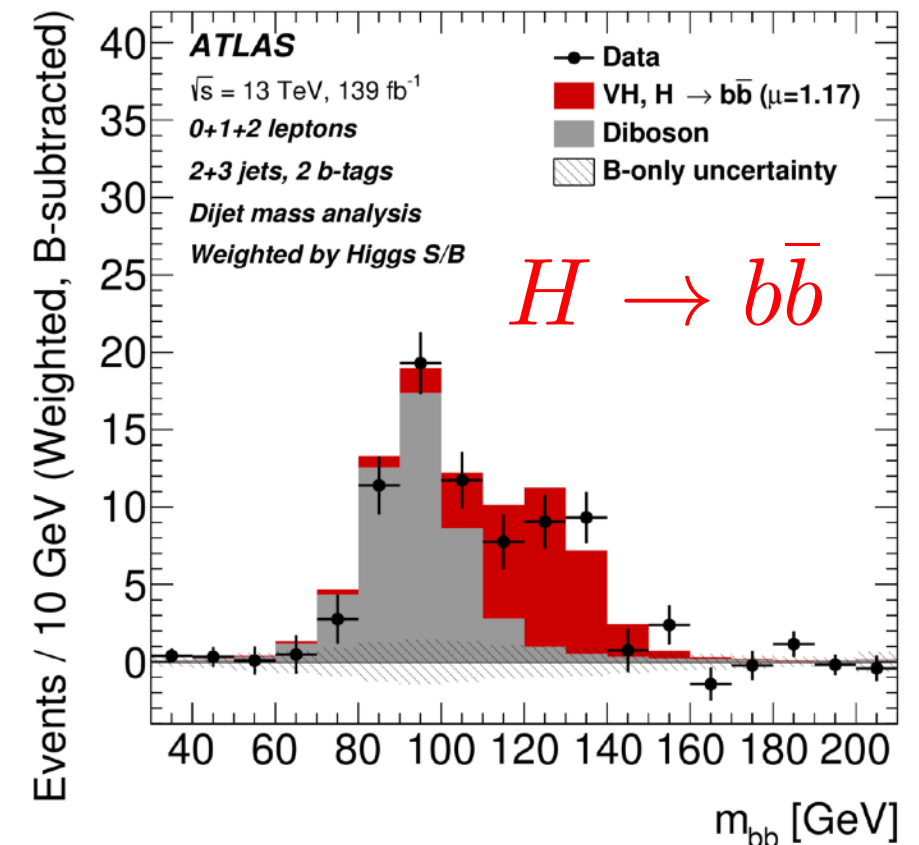


91-km tunnel can be reused for a 100~TeV proton proton collider (to start in ~2070), for direct searches of New Physics at the 10~TeV energy scale.

Higgs boson  $r_H = 1/m_*$?

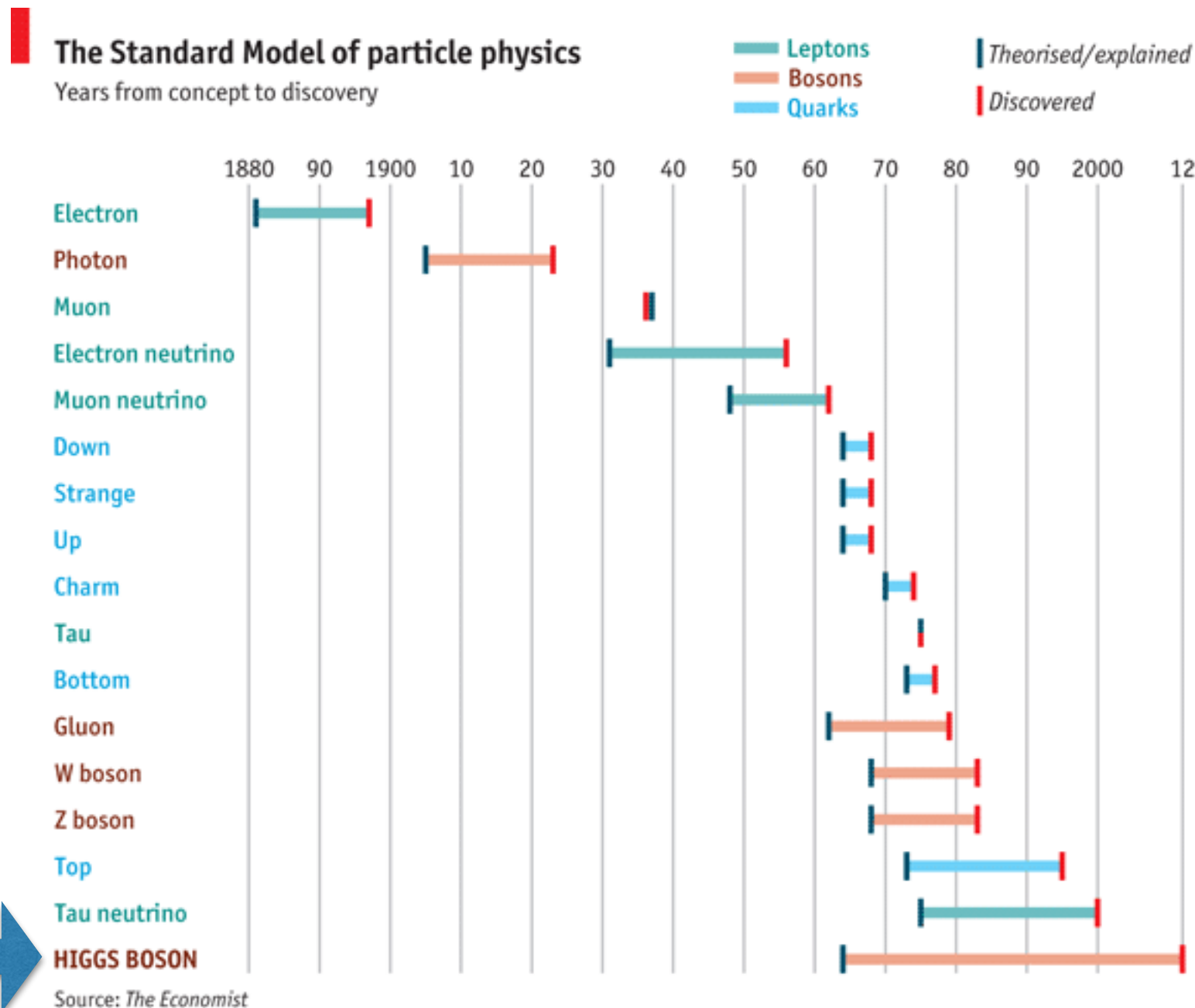
Summary

- Higgs boson opened new era of exploration in particle physics, and into the early history of the Universe.
- Is the Higgs mechanism responsible for all **fermion** and boson masses?
- Can the Higgs potential help explain the matter-antimatter asymmetry of our Universe?
- There must be New Physics (NP) that holds the answers!
 - Is the NP scale **~1-2 TeV**? Then the **HL-LHC** may find it!
 - Is it **~5-10 TeV**? Then the **Future Circular Collider** could reveal it!
- Next few years crucial for upgrading the detector for HL-LHC (2030-2040) and establishing the next big project in Particle Physics (>2045)

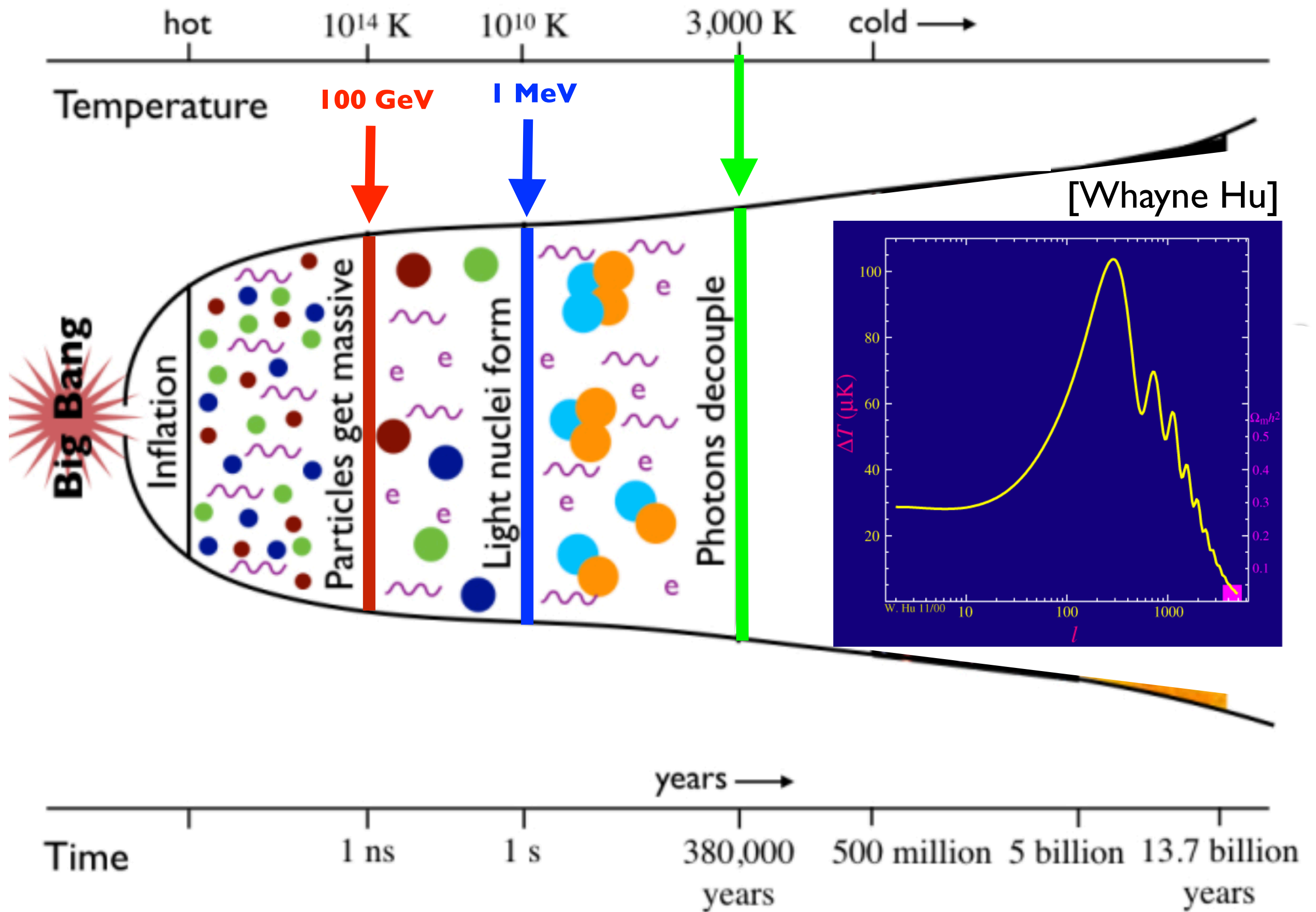


Backup

A successful paradigm

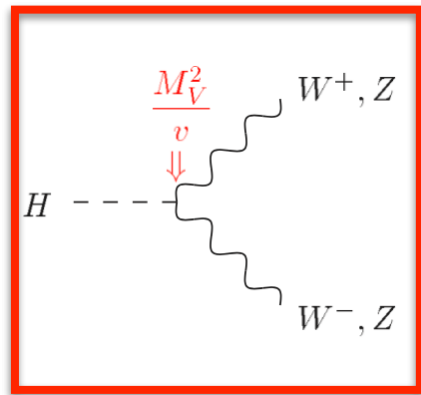


- More than 100 years to complete the current Standard Model of Particle Physics (SM)
- Very healthy interaction of theory predictions and experimental evidence...
- The Higgs boson took >50 years from prediction (60s) to discovery (2012)!



[Whayne Hu]

Higgs Boson interactions



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi$$

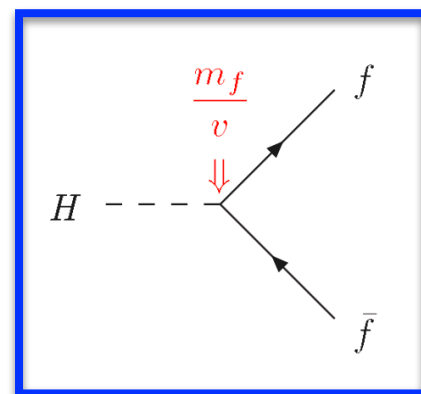
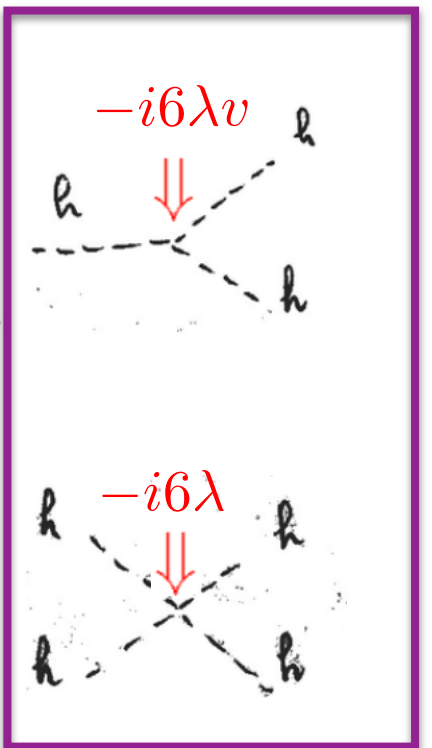
$$+ |D_\mu \phi|^2 + V(\phi)$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + \text{h.c.}$$

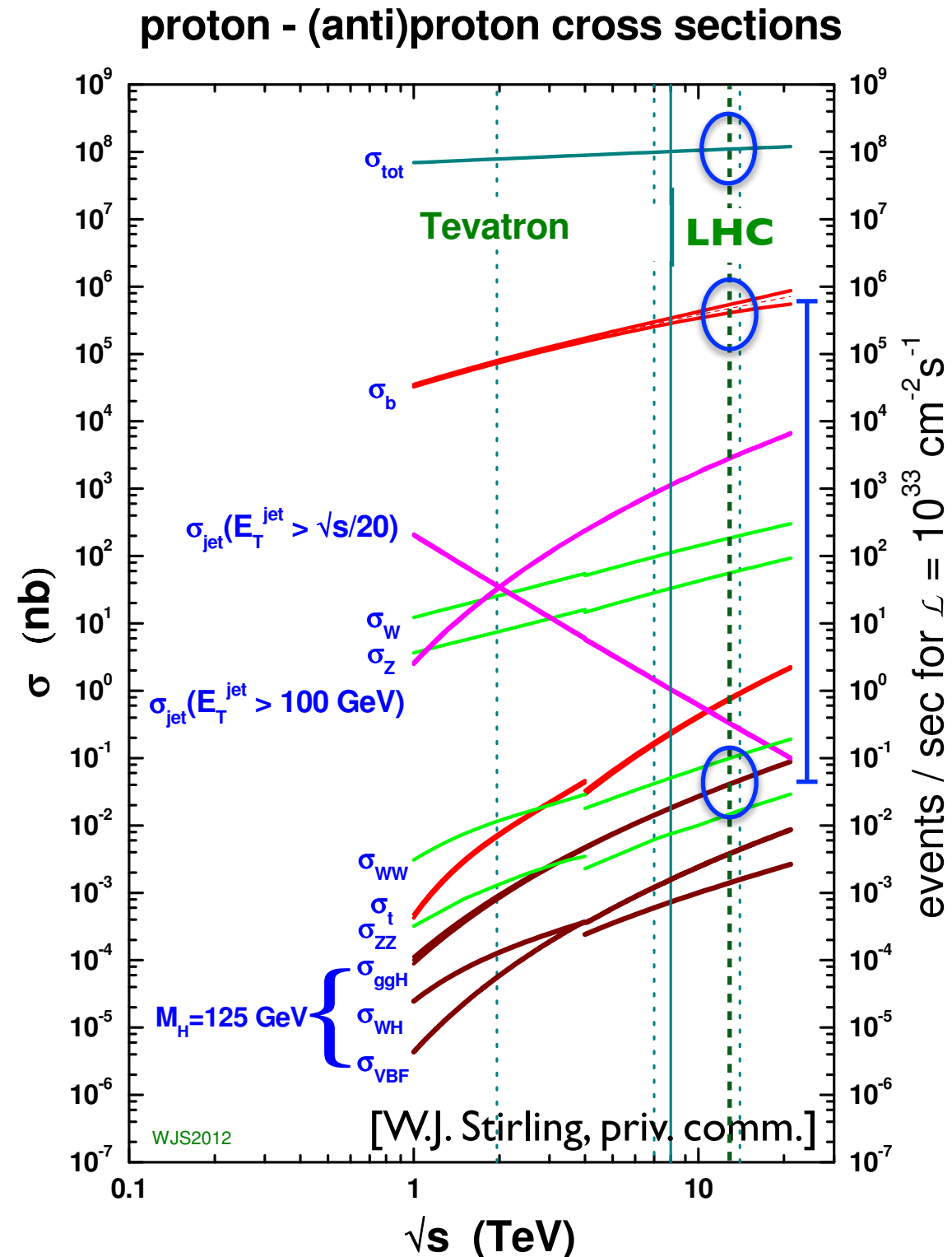
$$\mu^2(\phi^* \phi)$$

Higgs Boson mass

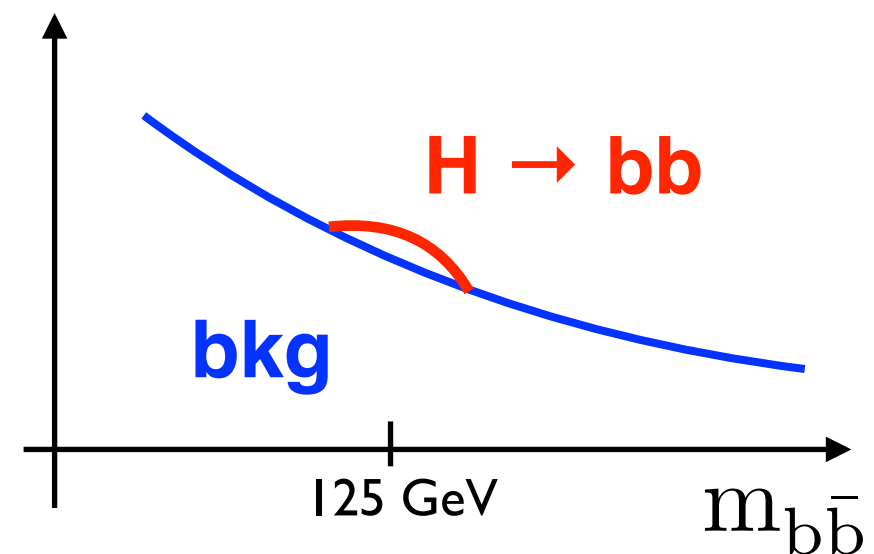
$$\lambda(\phi^* \phi)^2$$



Why is Higgs $\rightarrow$ bb so difficult?



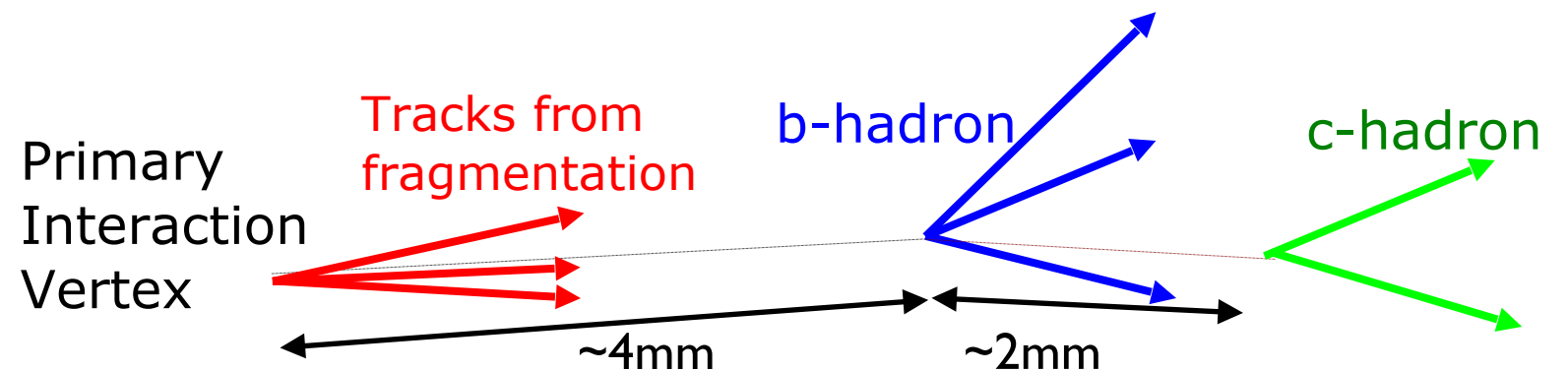
- pp collisions produce a copious amount of quarks (observed as jets), inducing a **large continuum background**



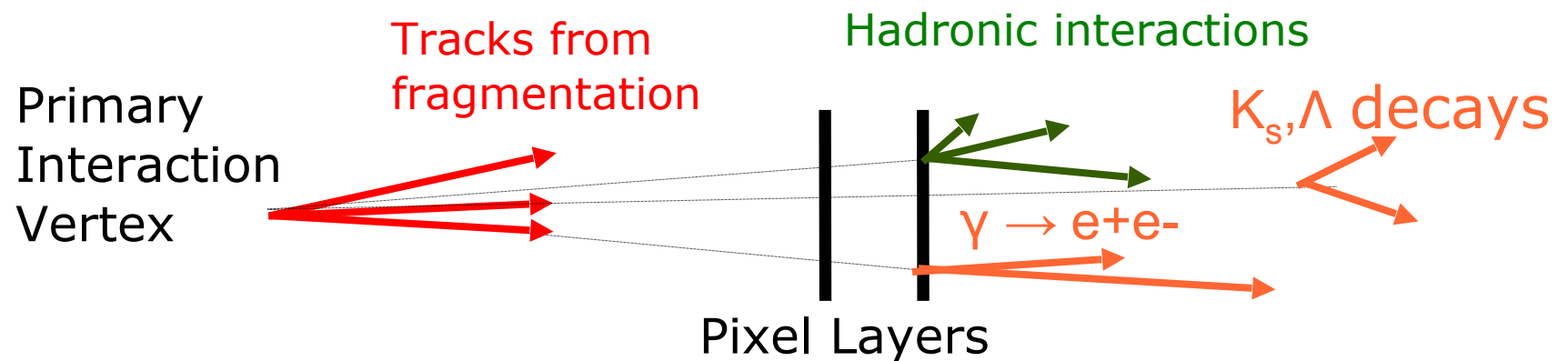
- The **Higgs to beauty quarks** signal is hard to extract from the **background**!
- Changing this picture required significant advances in detector technology, b-quark identification, analysis techniques and theory!

Separate b-jets from other jets

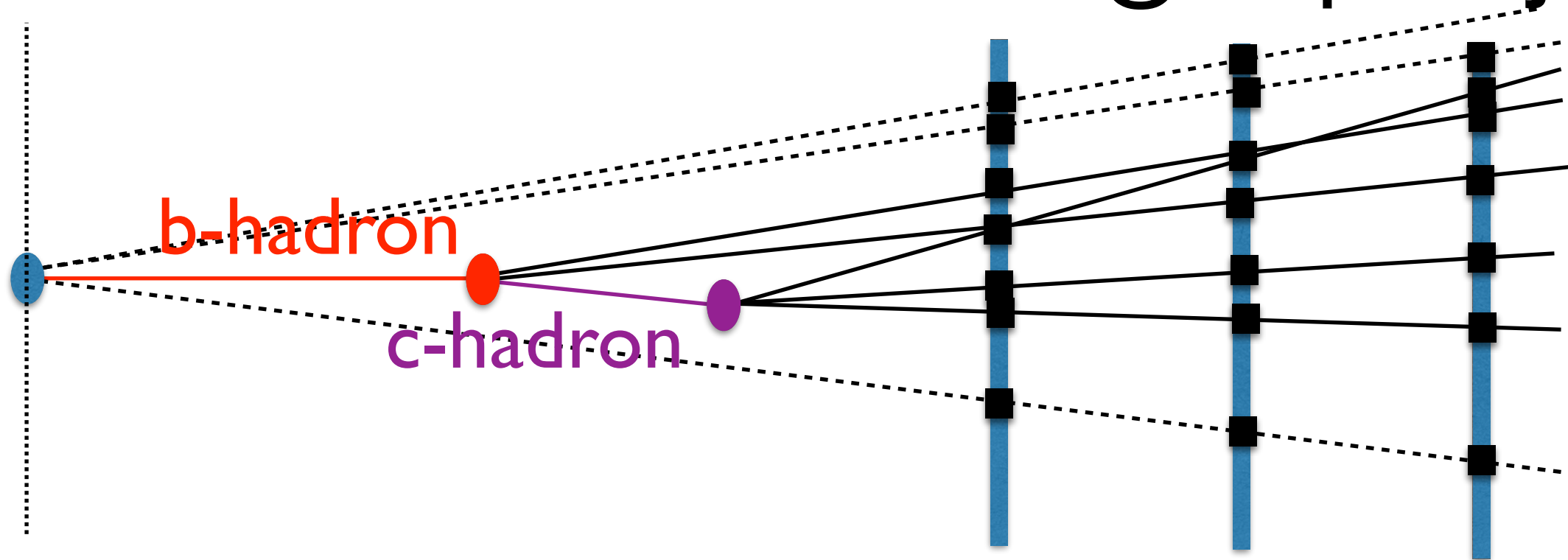
B-quark jets



Light-flavour jets (u,d,s-quark, gluon)

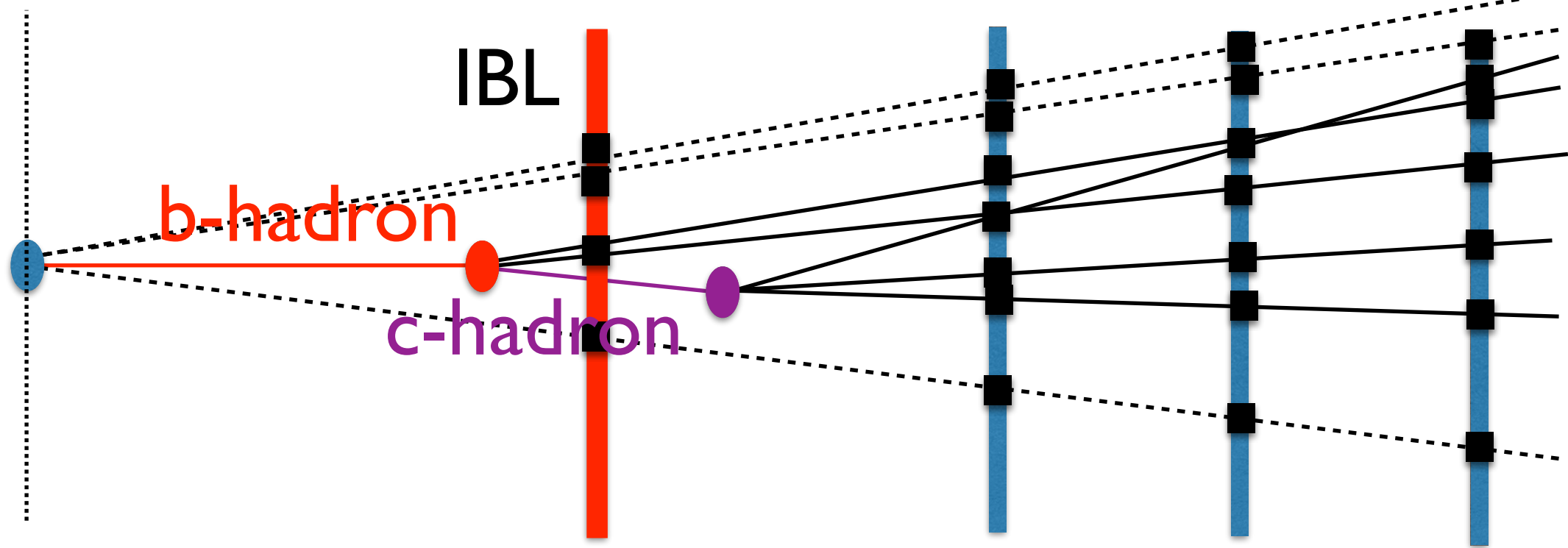


The “issue” with high p_T jets

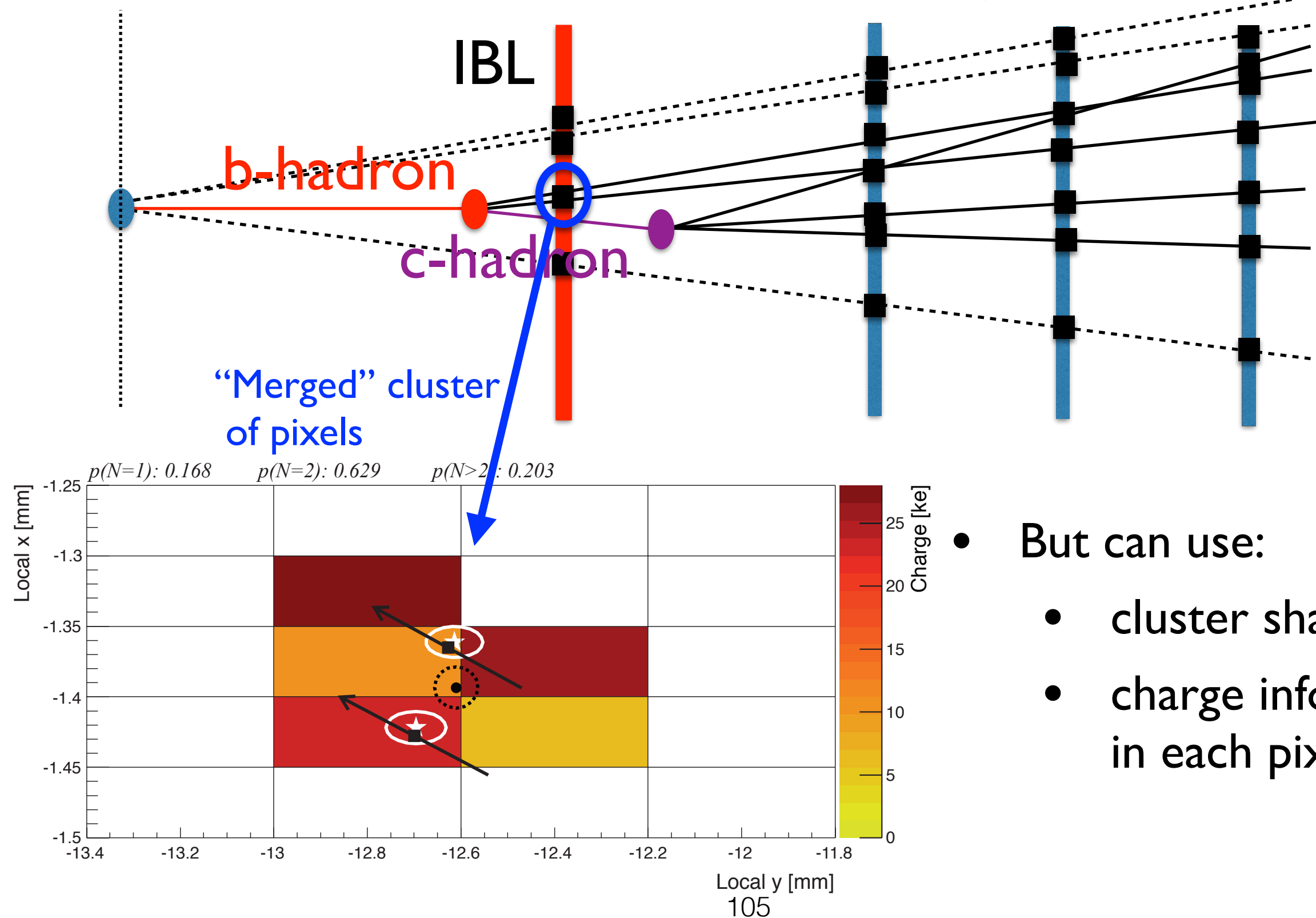


(p_T = transverse momentum)

The “issue” with high $p_{T,jets}$



The “issue” with high pT jets



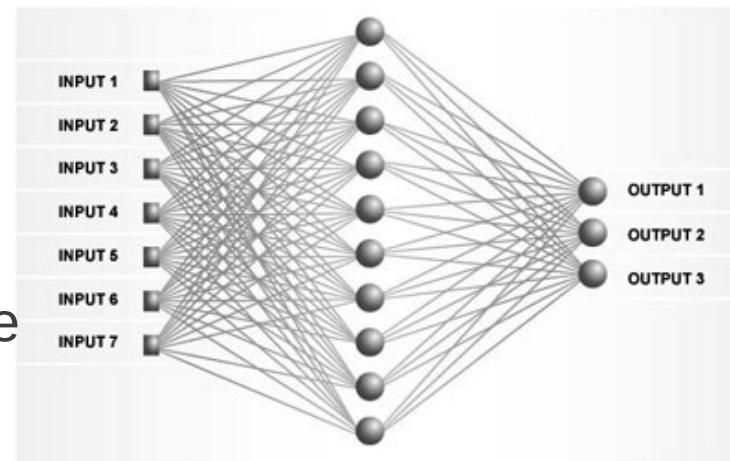
- But can use:
 - cluster shape
 - charge information in each pixel

The “issue” with high p_T jets

INPUT nodes

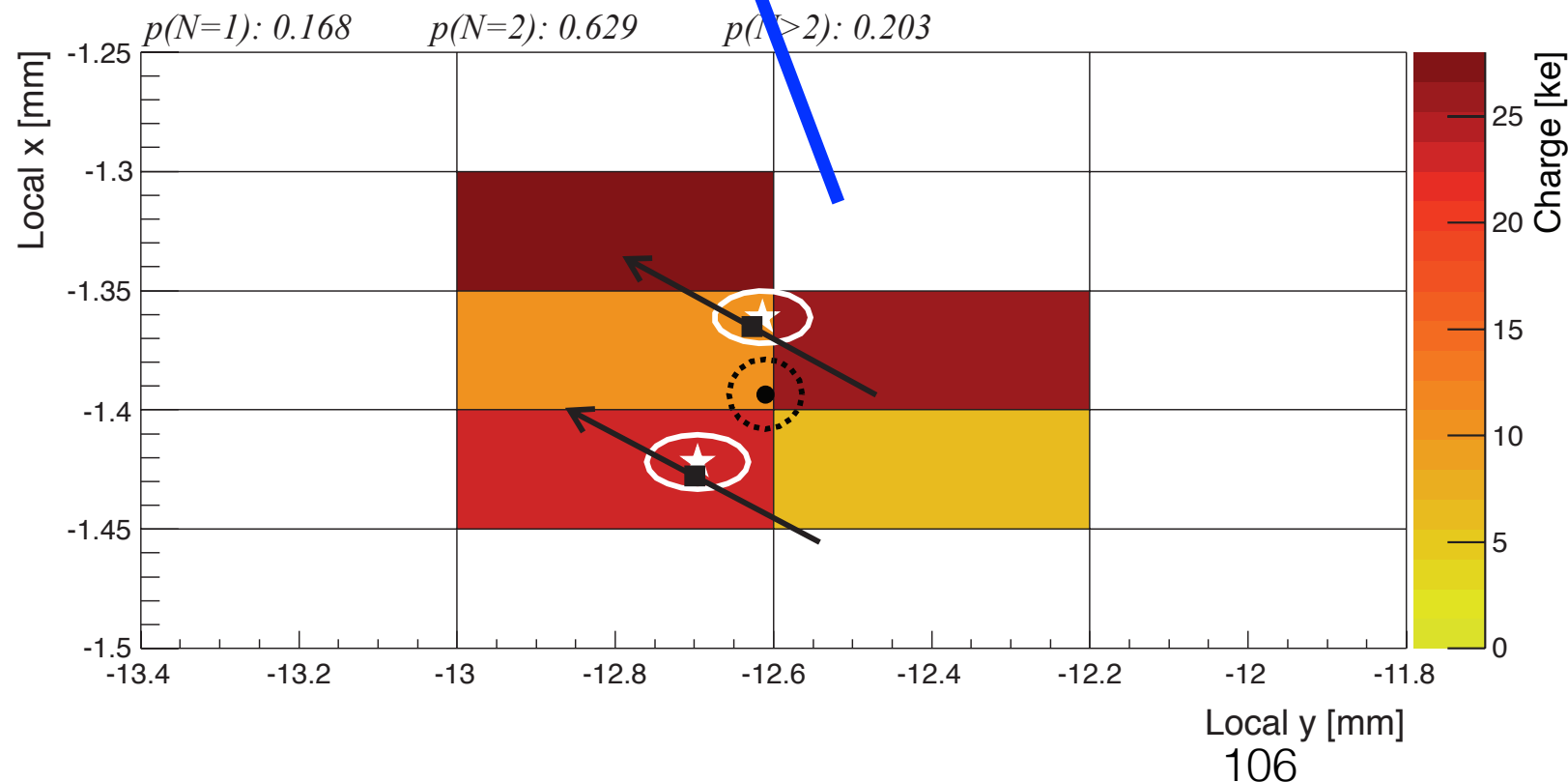
- 7x7 pixel matrix with calibrated charges
- vector of z pitches
- track incidence angle
- layer number

Neural Network



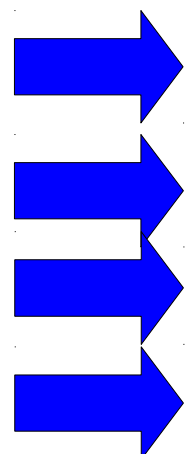
OUTPUT nodes

- How many subclusters?
- What is their position?
- What is their associated distribution? → (error)



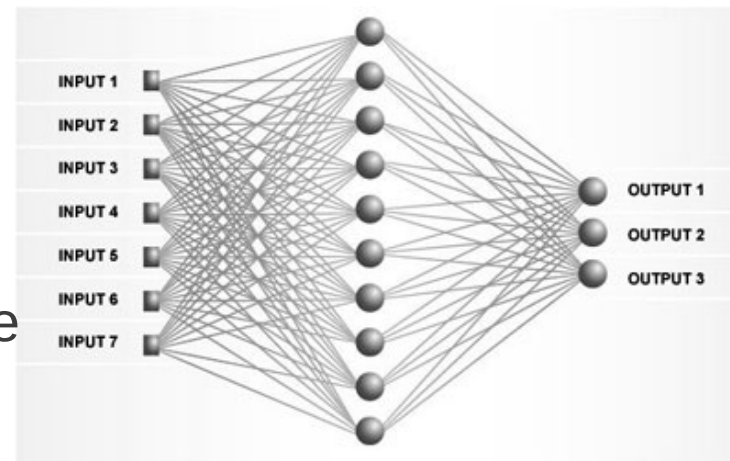
The “issue” with high pT jets

INPUT nodes

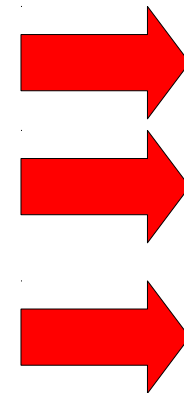


7x7 pixel matrix with calibrated charges
vector of z pitches
track incidence angle
layer number

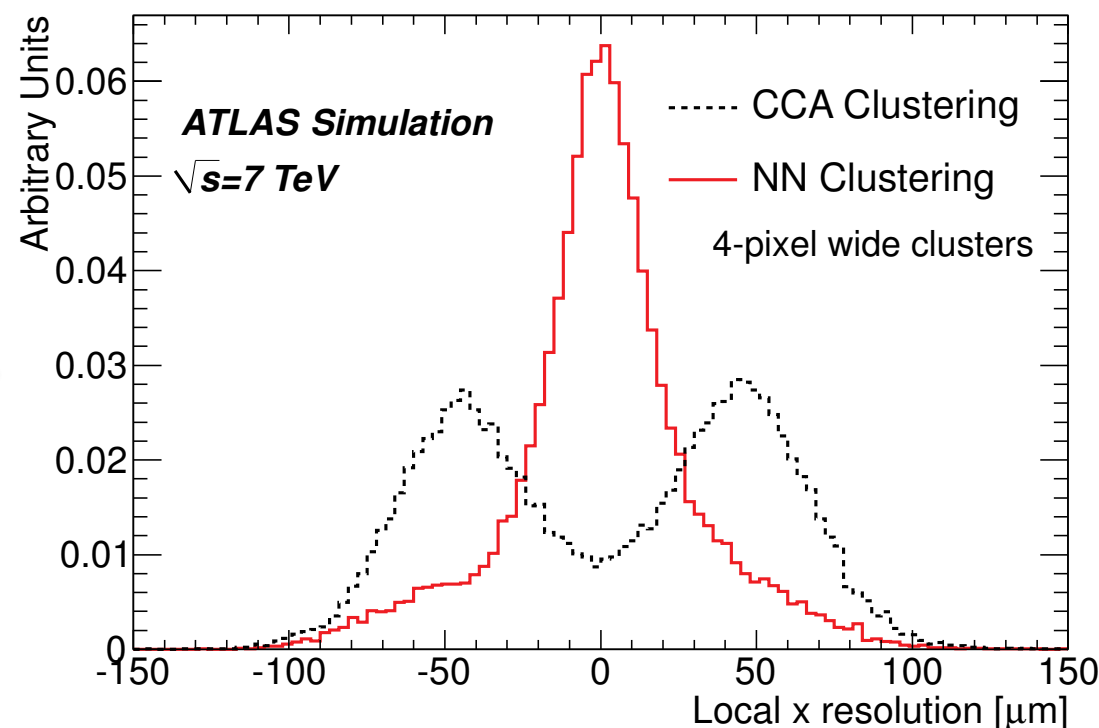
Neural Network



OUTPUT nodes



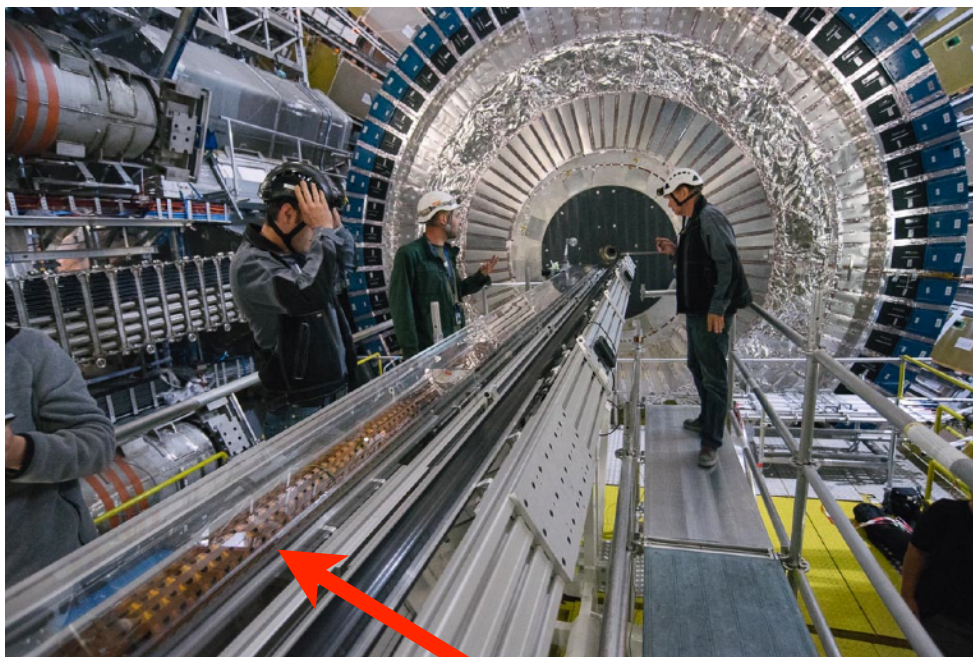
How many subclusters?
What is their position?
What is their associated distribution? → (error)



- Significantly improved the tracking performance for high pT b-jets ahead of Run-2!

Silicon pixel detector

- Ability to identify beauty-quark jets driven by first layers of Pixel detector



new innermost
layer “inserted”
before Run-2

[IBL TDR, CERN-LHCC-2010-013]

PIXEL detector (since Run-1)

Layers: 3 barrel, 3 end-caps + IBL

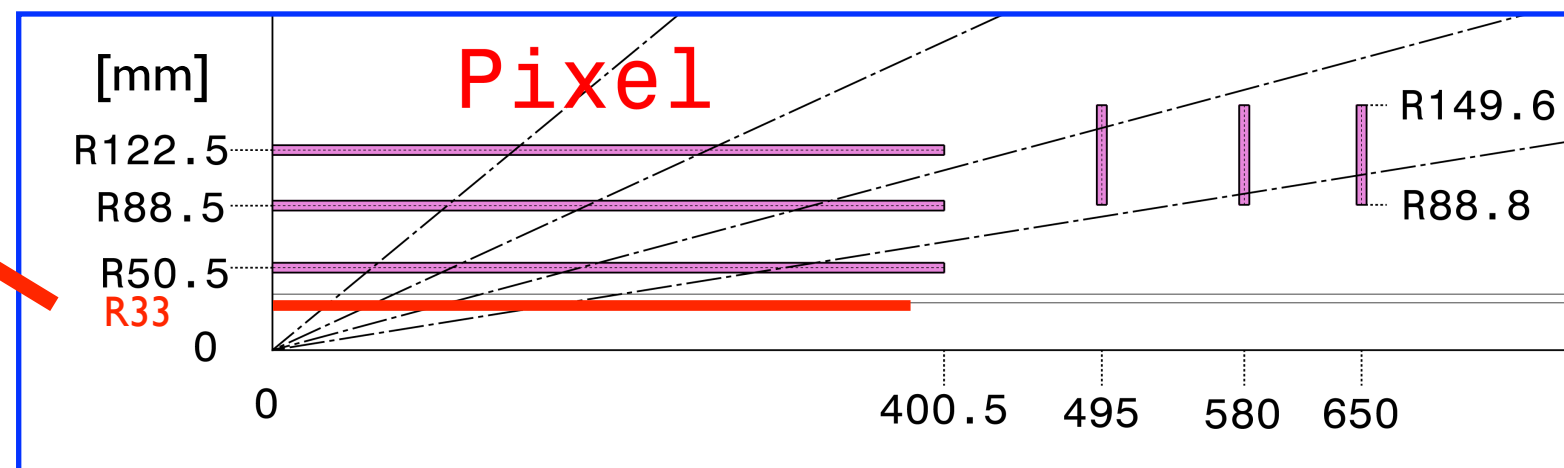
Pixel size: $50\ \mu\text{m} \times 400\ \mu\text{m}$

~80M channels

+Insertable B-Layer (IBL)

Pixel size: $50\ \mu\text{m} \times 250\ \mu\text{m}$

~6M channels



kappa-3 scenario		CEPC	FCC-ee ₂₄₀	FCC-ee ₃₆₅	FCC-ee/eh/hh
	κ_W [%]	0.88	0.88	0.41	0.19
	κ_Z [%]	0.18	0.20	0.17	0.16
	κ_g [%]	1.	1.2	0.9	0.5
	κ_γ [%]	1.3	1.3	1.3	0.31
*	$\kappa_{Z\gamma}$ [%]	6.3	10.*	10.*	0.7
	κ_c [%]	2.	1.5	1.3	0.96
*	κ_t [%]	3.1	3.1	3.1	0.96
	κ_b [%]	0.92	1.	0.64	0.48
*	κ_μ [%]	3.9	4.	3.9	0.43
	κ_τ [%]	0.91	0.94	0.66	0.46
BR _{inv} (<%, 95% CL)		0.27	0.22	0.19	0.024
BR _{unt} (<%, 95% CL)		1.1	1.2	1.	1.

FCC-hh will provide the ultimate precision on Higgs boson couplings, including rare decays

Start of FCC-ee physics run

Start accelerator commissioning

Start detector commissioning

End of HL-LHC

Start detector installation

Start accelerator installation

Industrialisation and component production
Technical design & prototyping completed

Detector component production
Four detector TDRs completed

Start of ground-breaking and CE at IPs

Detector CDRs (>4) submitted to FC³

End of HL-LHC upgrade: more ATS personnel available
FCC Approval: Start of prototyping work

End of HL-LHC upgrade: more detector experts available
FC³ formation, call for CDRs, collaboration forming

FCC Feasibility Study Report

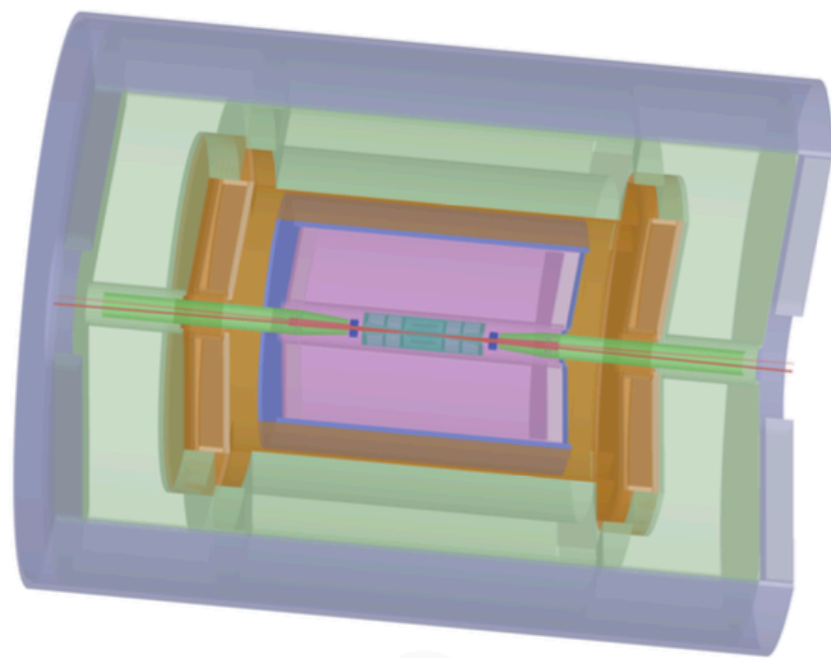
European Strategy Update: FCC Recommendation

Detector EoI submission by the community

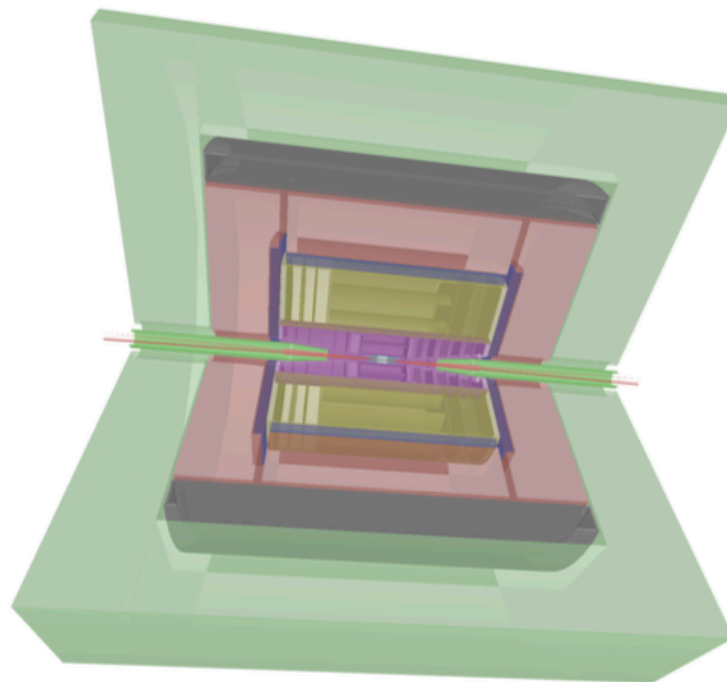
FCC-ee Accelerator

Key dates

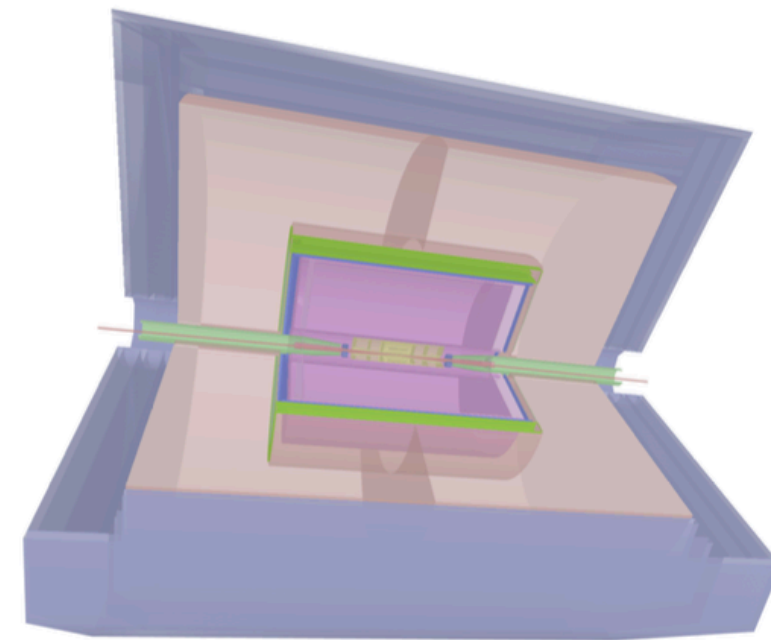
FCC-ee Detectors



ALLEGRO



CLD



IDEA

Three initial detector concepts used for simulation studies.

Active participation from US physicists (HFCC); Subdetector R&D groups forming.

Expression of Interest for a
lightweight vertex detector for FCC-ee

Involved Laboratories:

Italy: INFN - Genova, Frascati, Milano, Padova, Perugia, Pisa, Torino, Trieste-Udine

Switzerland: ETH Zurich, Paul Scherrer Institute, University of Zurich

United States of America: Brown University, BNL, FNAL, LBNL, MIT, SLAC, Stony Brook University

Contact persons:

Fabrizio Palla^{*1}, Attilio Andreazza², Nicola Bacchetta^{3,9}, Manuel Rolo⁴, Florencia Canelli⁵, Armin Ilg⁵, Anna Macchiolo⁵, Malte Backhaus⁶, Rainer Wallny⁶, Lea Caminada⁷, Grzegorz W. Deptuch⁸, Loukas Gouskos⁹, Artur Apresyan¹⁰, Carl Haber¹¹, Christoph Paus¹², Caterina Vernieri¹³, Valerio Dao¹⁴, and Giacinto Piacquadio¹⁴

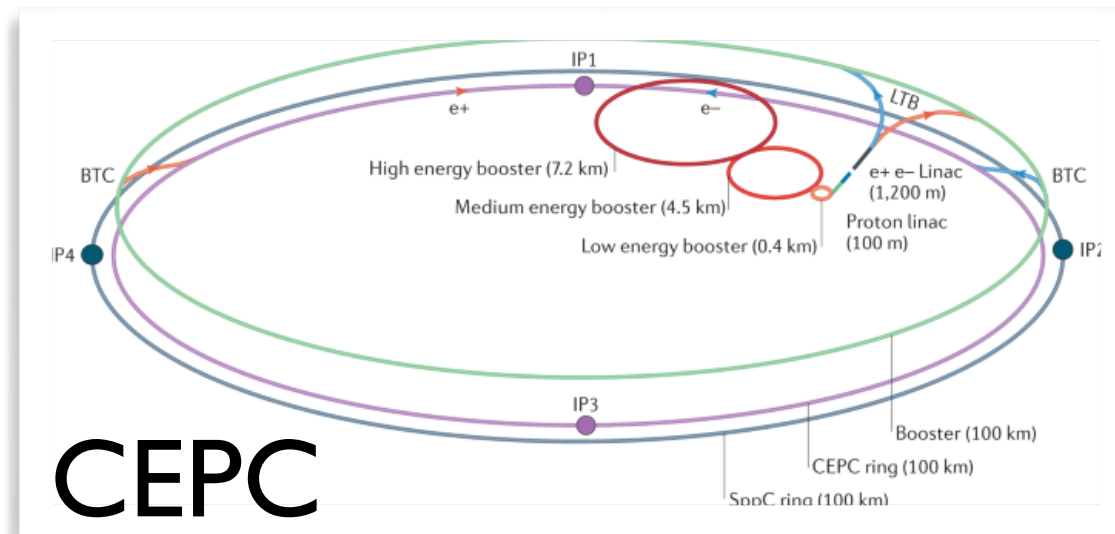
FCC-ee Workshop: Tracking Detectors and Software

7–9 May 2025

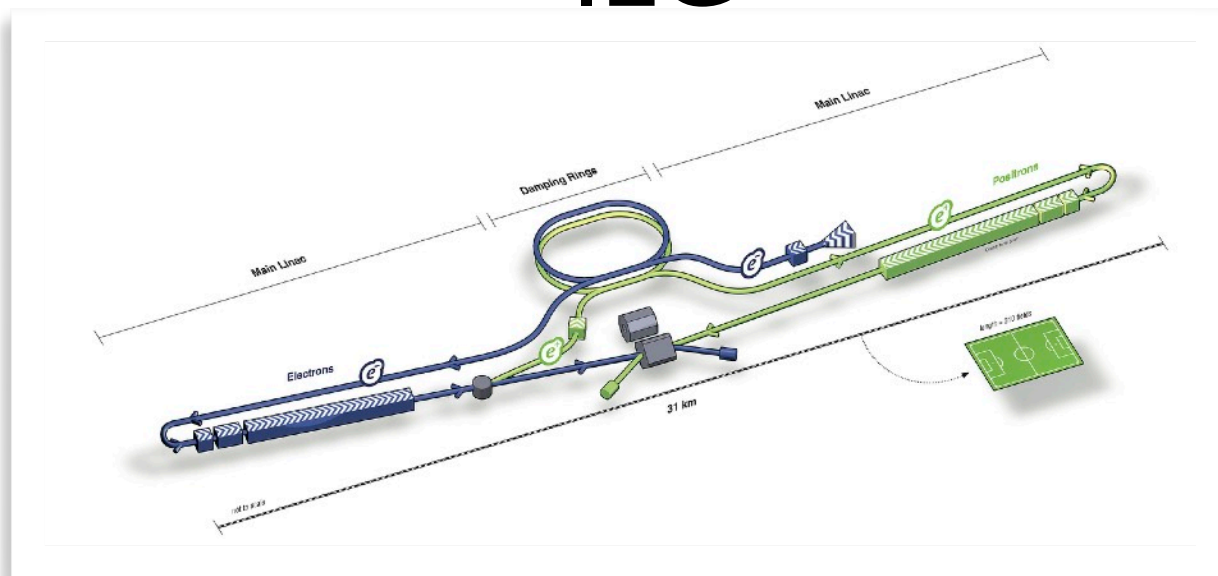
Brookhaven National Laboratory

US/Eastern timezone

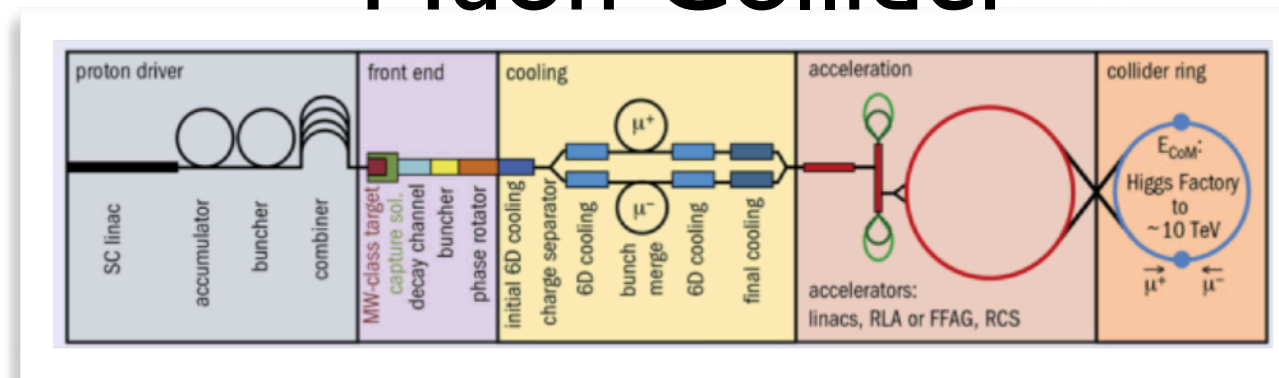
Other options?



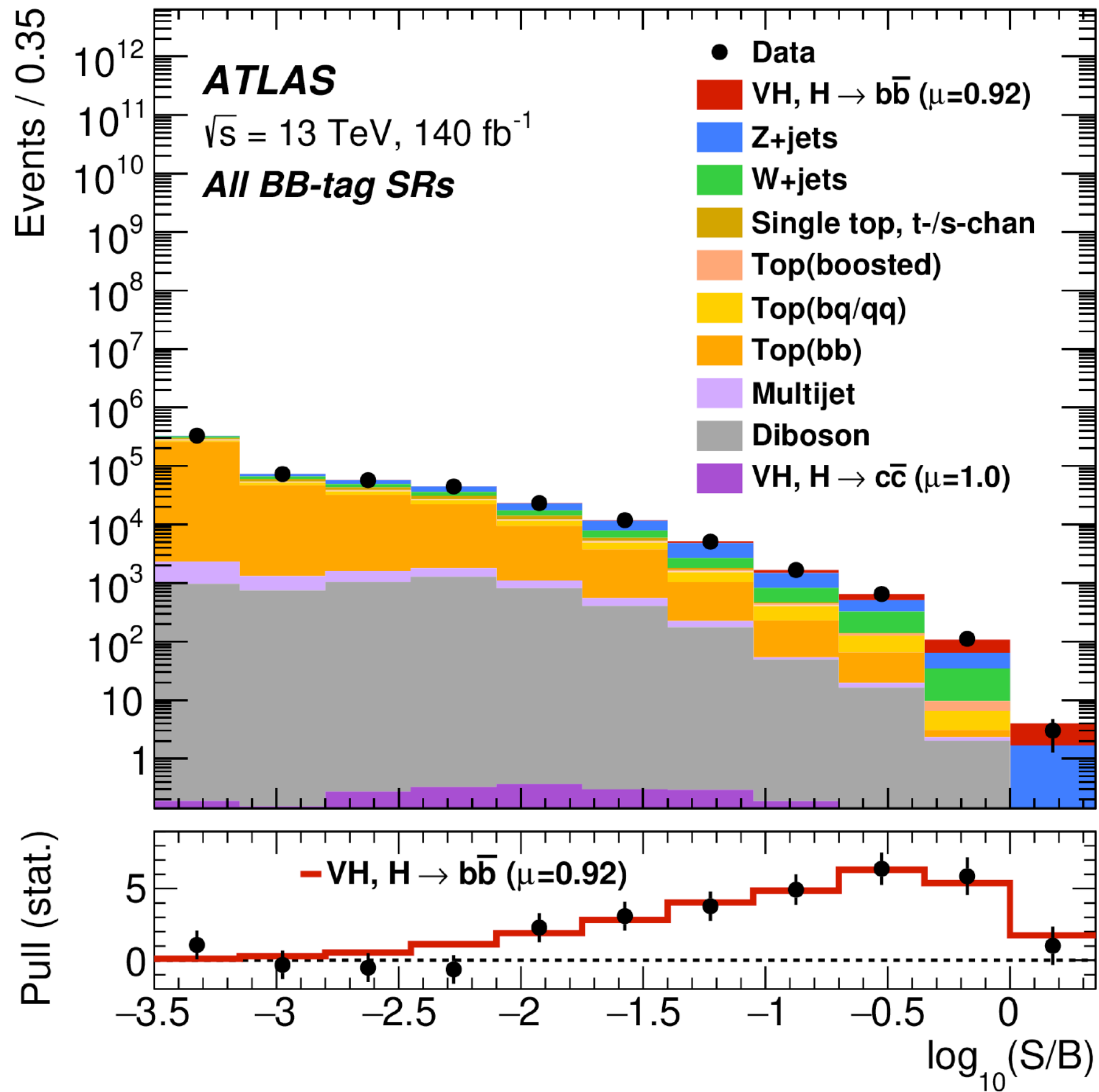
ILC

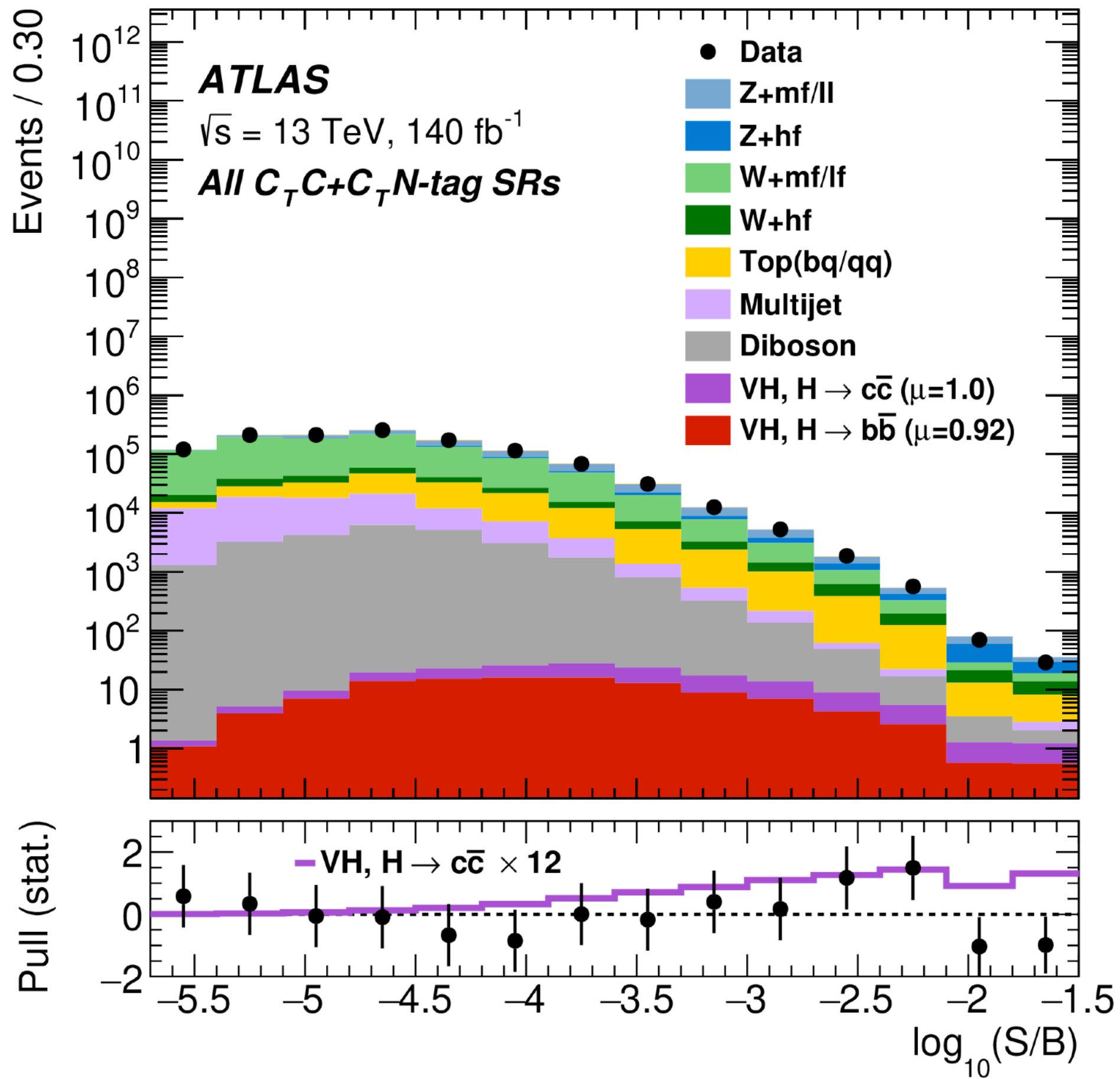


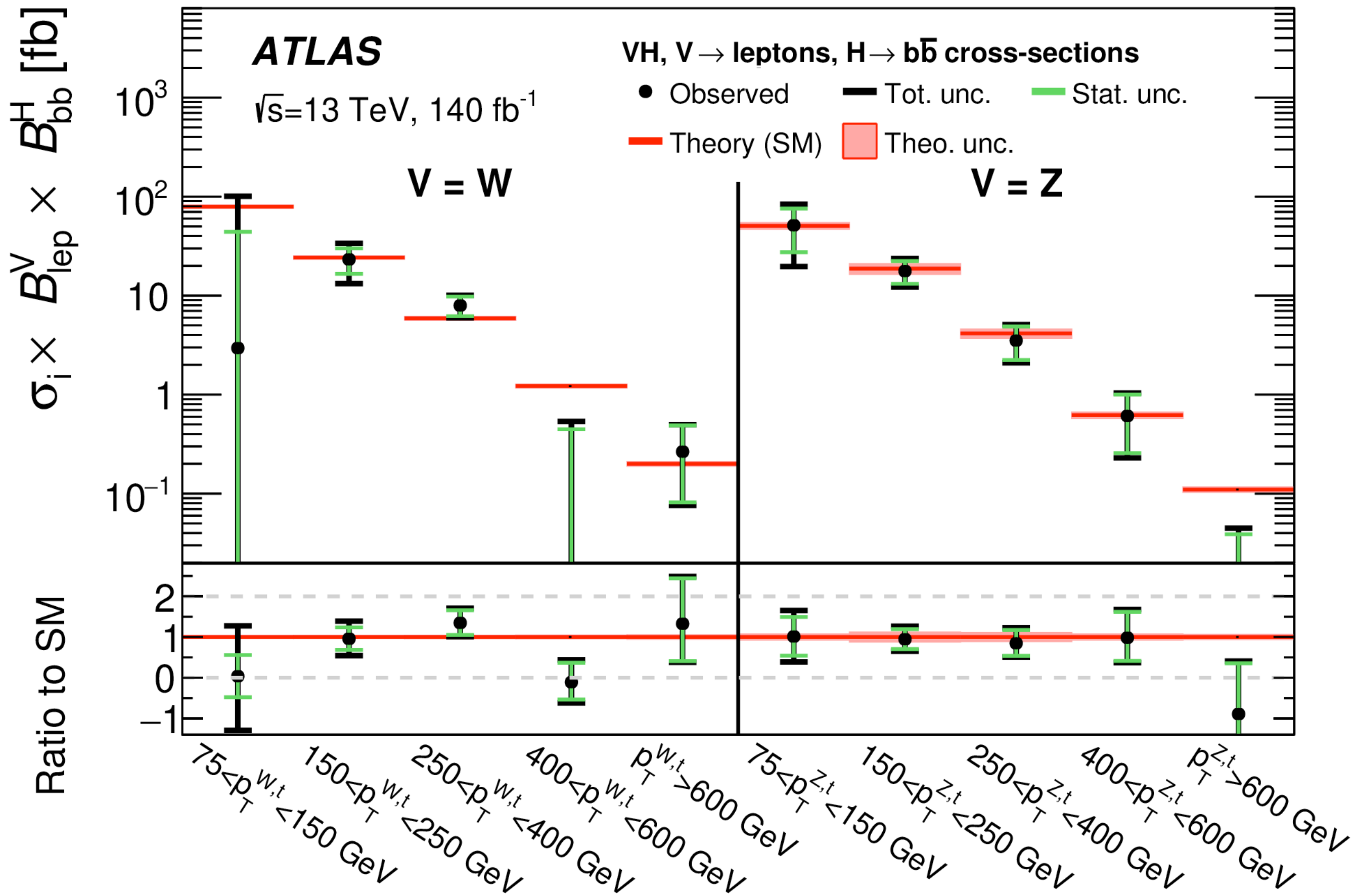
Muon Collider

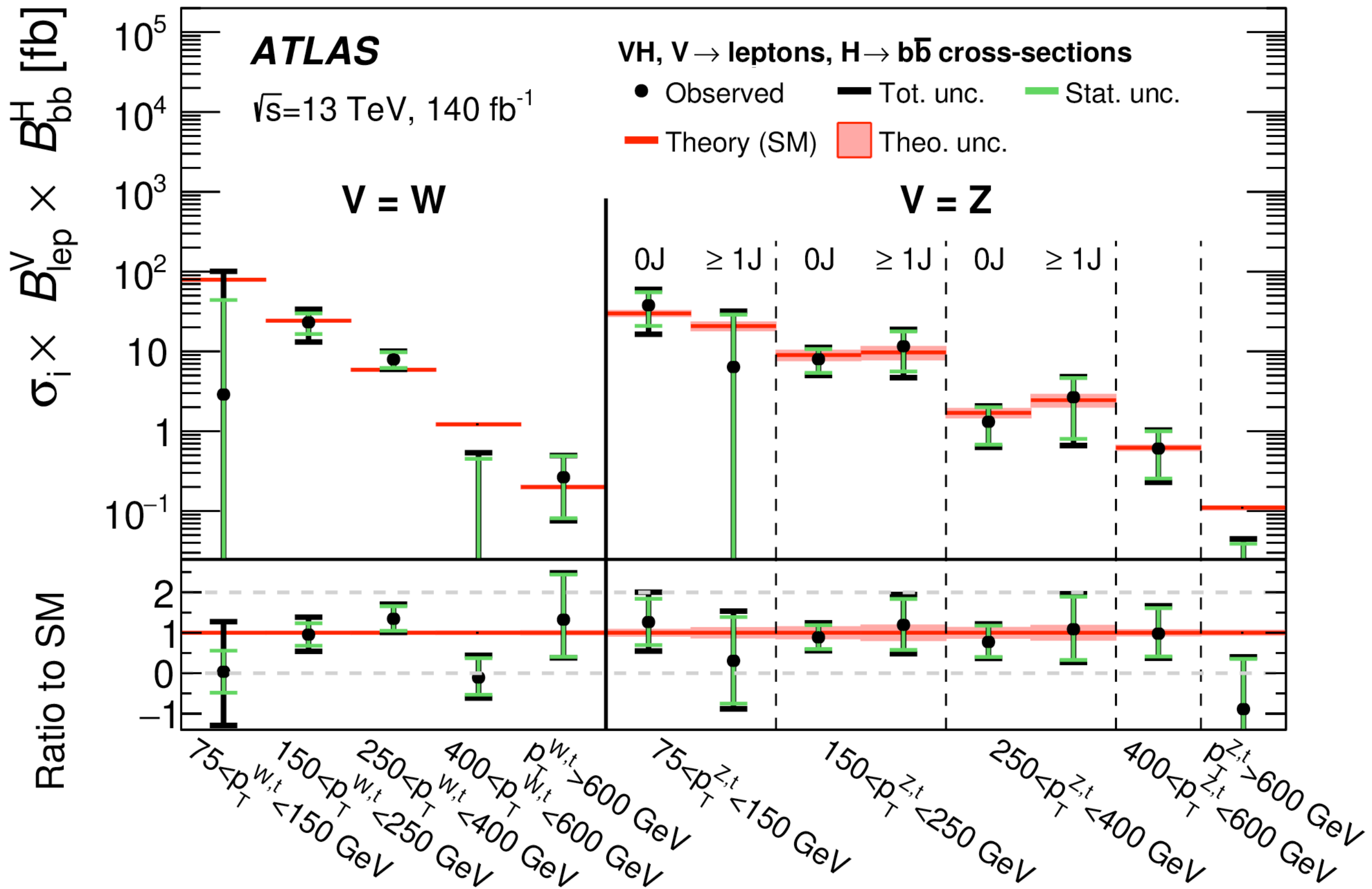


Common aim: Higgs couplings with sub-% precision, self-coupling with <5% precision









ATLAS

$\sqrt{s}=13\text{ TeV}, 140\text{ fb}^{-1}$

$VH, H \rightarrow b\bar{b}/c\bar{c}$

— Observed

- - - Expected

Expected $\pm 1\sigma$

Expected $\pm 2\sigma$

0 lepton

Exp.= $17 \times \text{SM}$

Obs.= $14 \times \text{SM}$

1 lepton

Exp.= $17 \times \text{SM}$

Obs.= $21 \times \text{SM}$

2 lepton

Exp.= $18 \times \text{SM}$

Obs.= $22 \times \text{SM}$

Combination

Exp.= $11 \times \text{SM}$

Obs.= $12 \times \text{SM}$

