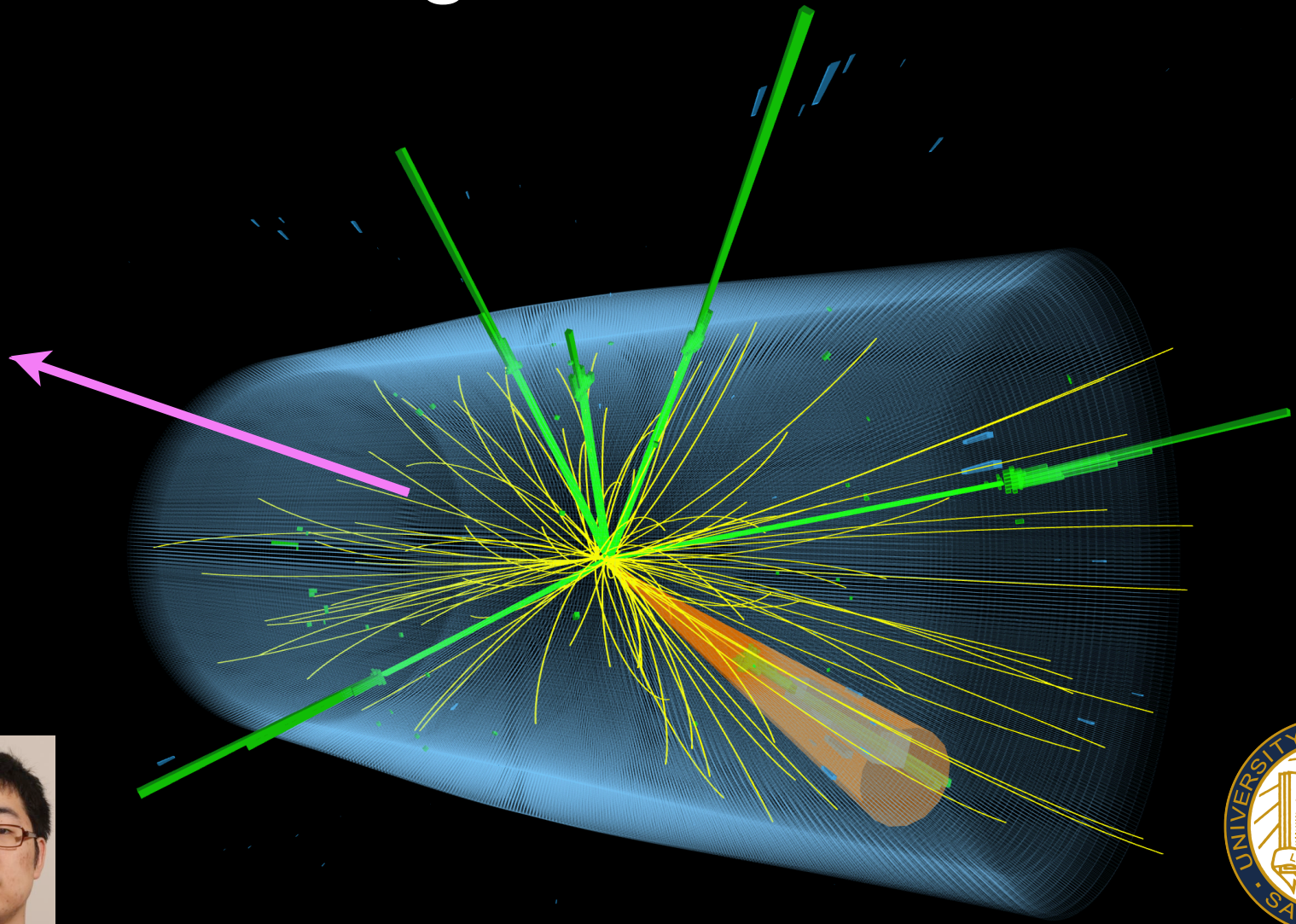
Multi-boson Physics at the Large Hadron Collider



Philip Chang

APCTP Seminar
August 5, 2020

Univ. of California San Diego

Outline

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- Why study multi-boson interactions (MBI)?
- How do we study MBI at LHC
- Some of the recent results from CMS Collaboration
- Future direction of MBI

Discovery of Higgs boson

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July 4, 2012

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Oct 8, 2013

The Nobel Prize in Physics 2013
François Englert, Peter W. Higgs

The Nobel Prize in Physics 2013

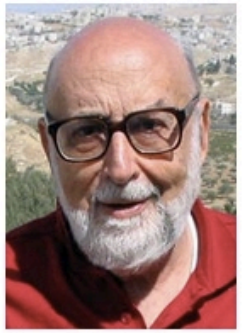

Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Discovery of advanced our understanding of origin of mass in a major way

Electroweak Sector of the Standard Model

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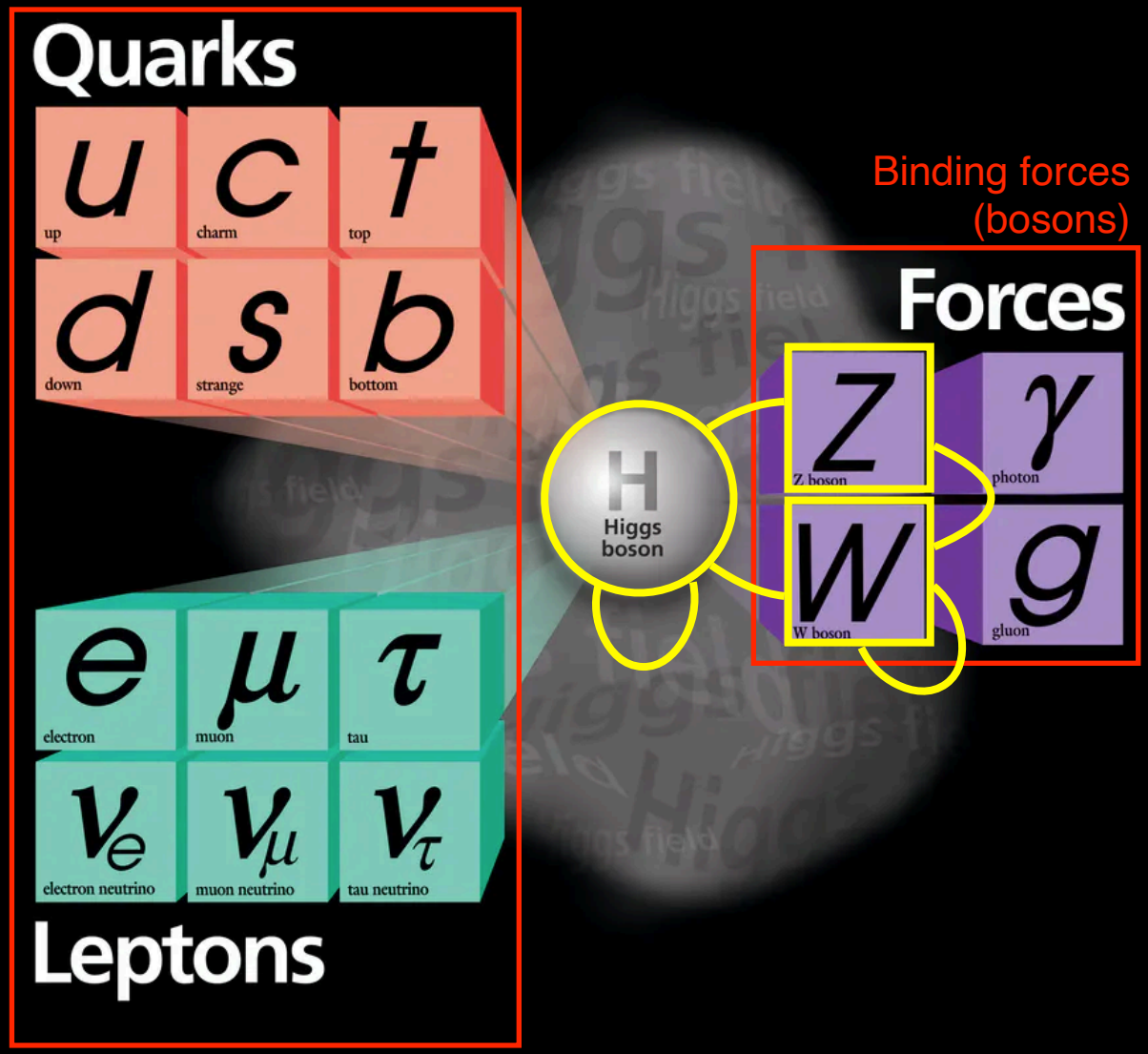
Building blocks of nature (fermions)



Binding forces (bosons)

At the heart of the electroweak sector we have the W, Z, and H bosons

Spin 1
- Mass of W is 80 GeV
- Mass of Z is 91 GeV

Spin 0
- Mass of H is 125 GeV

⇒ We must build upon this discovery to understand electroweak sector

We must understand the W, Z, H and their interactions

Electroweak Sector of the Standard Model

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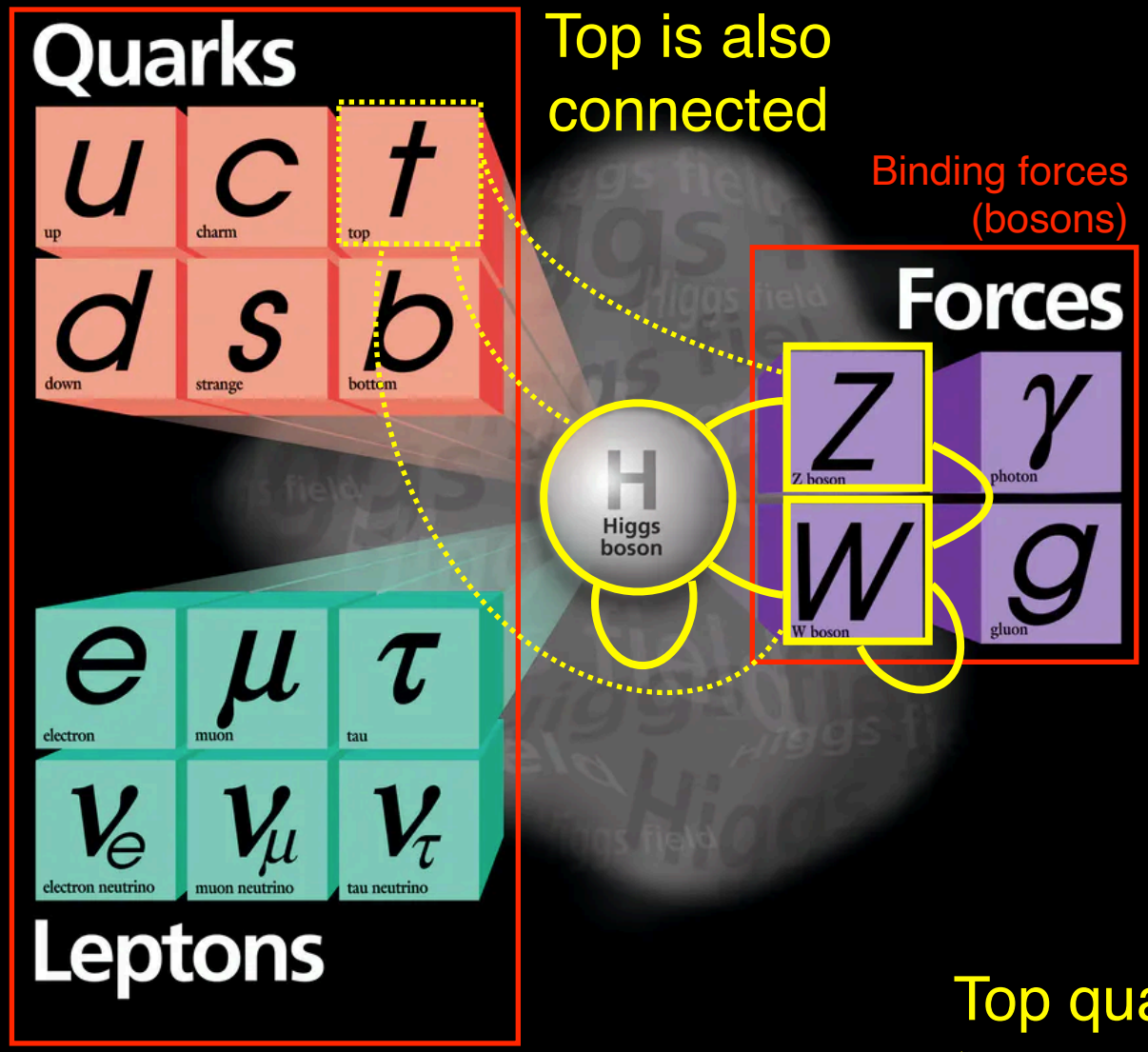

Top is also connected

Binding forces (bosons)

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Top quark

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Multi-*boson* interactions

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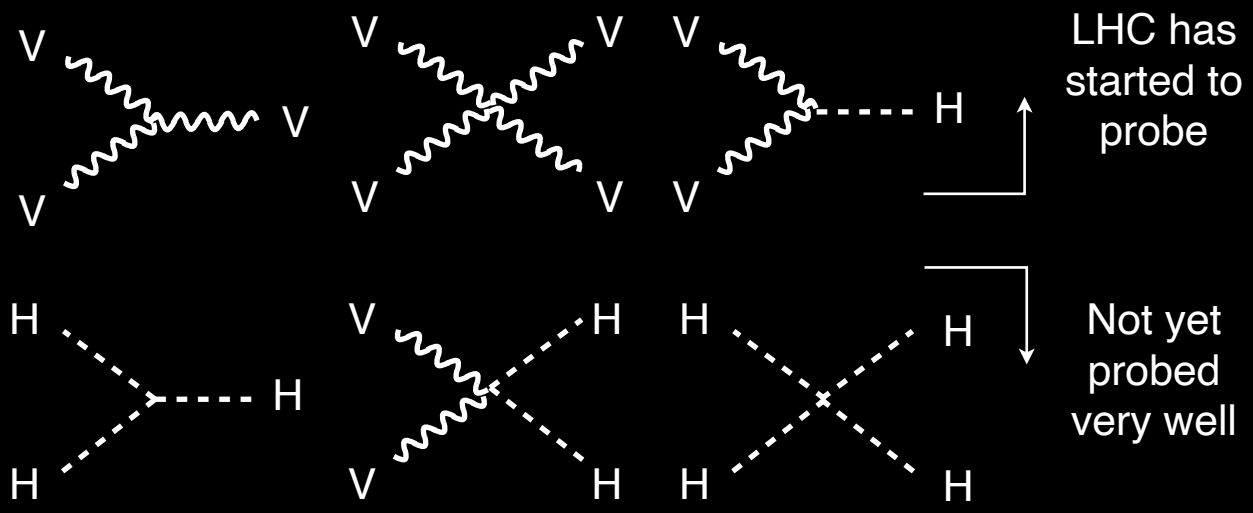
List of multi-boson interactions

V = W, Z



LHC has started to probe

Not yet probed very well

Some of them are probed well while some are not probed at all

Multi-~~boson~~ interactions

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massive-X (X = W, Z, H and top)

List of multi-boson interactions

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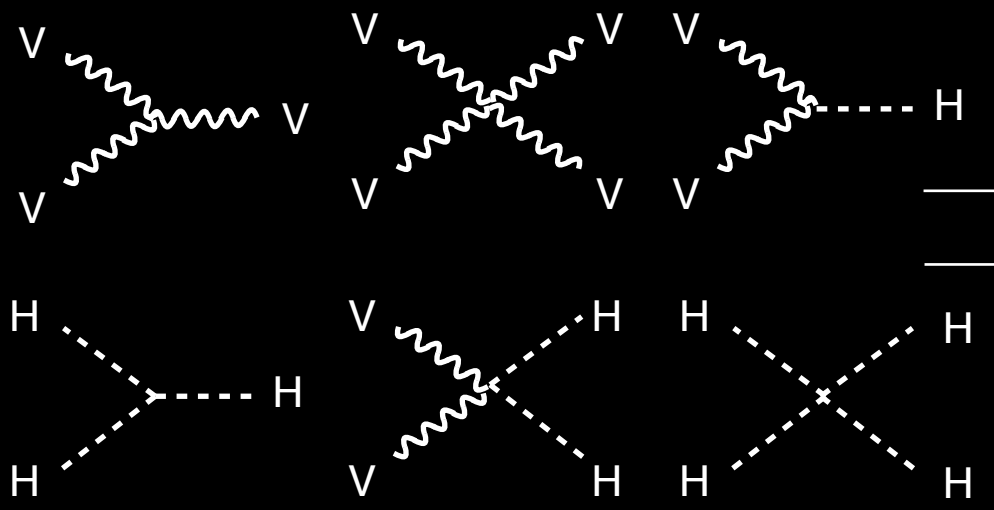

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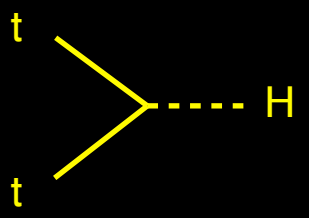

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Multi-boson interaction (MBI) at high E

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Lee, Quigg, Thacker (1977)

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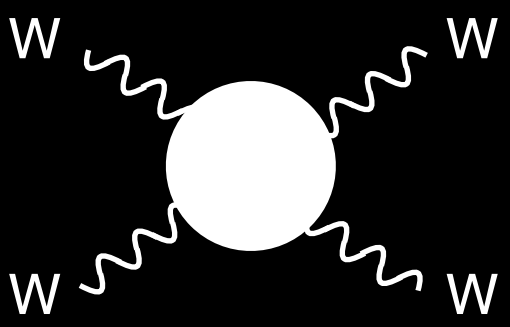
WW scattering



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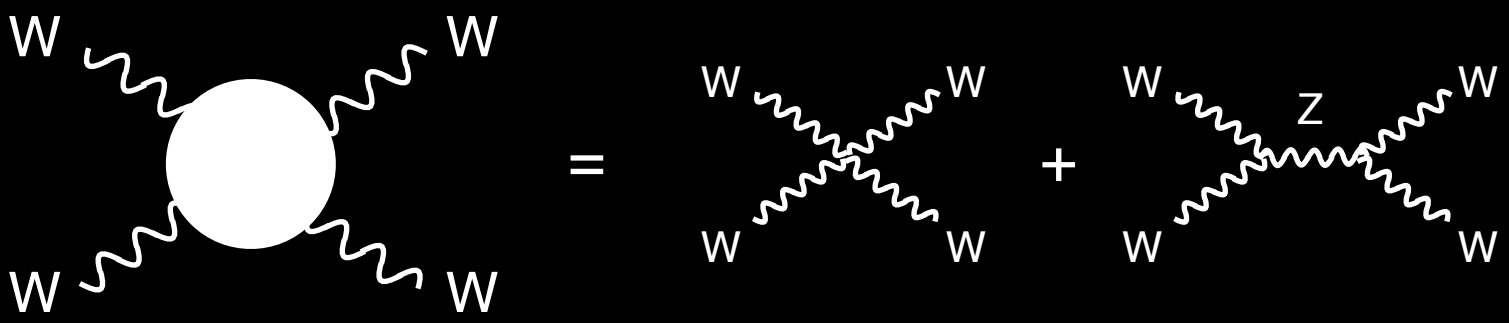
$P(WW \rightarrow WW) \sim E^2$
(i.e. ***at high E***, $P > 1$)



Bad high energy behavior

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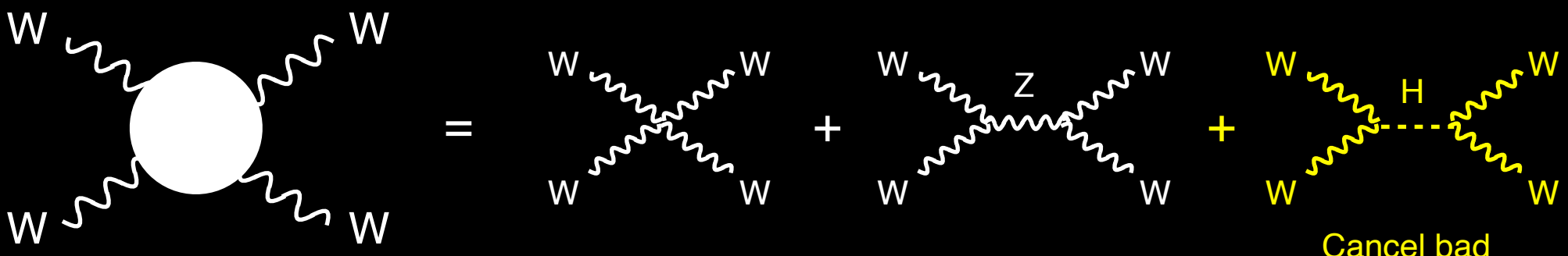

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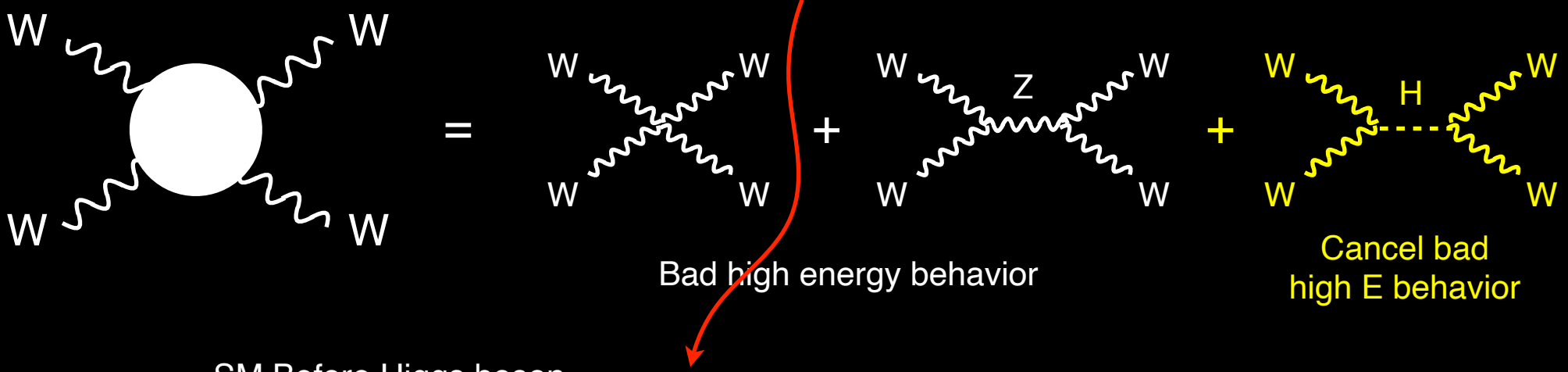
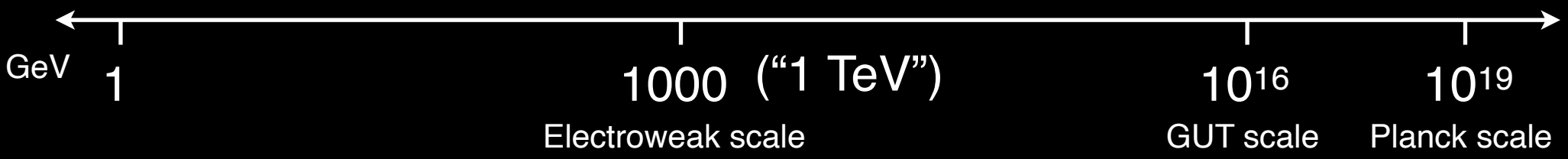


SM Before Higgs boson



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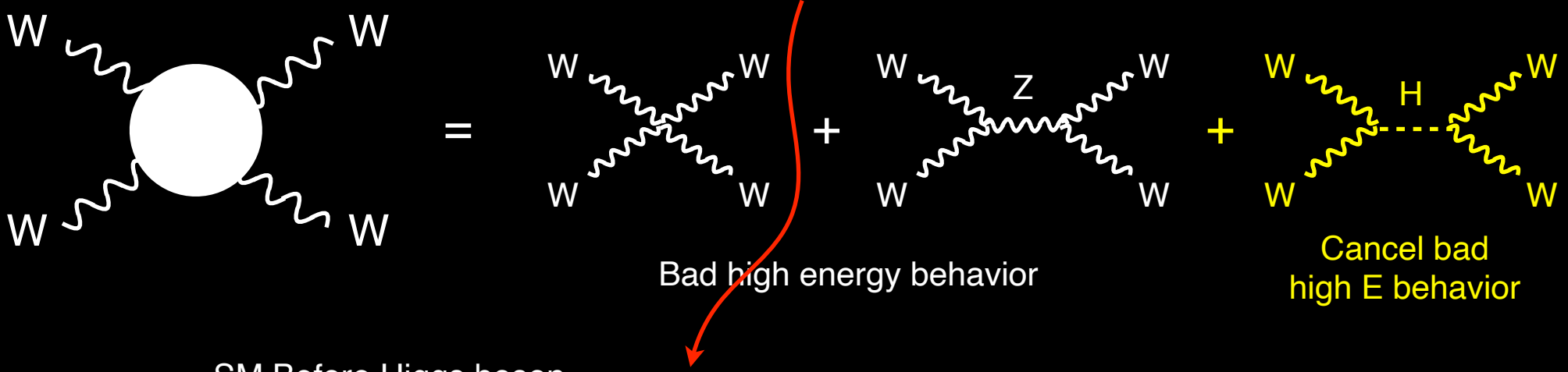

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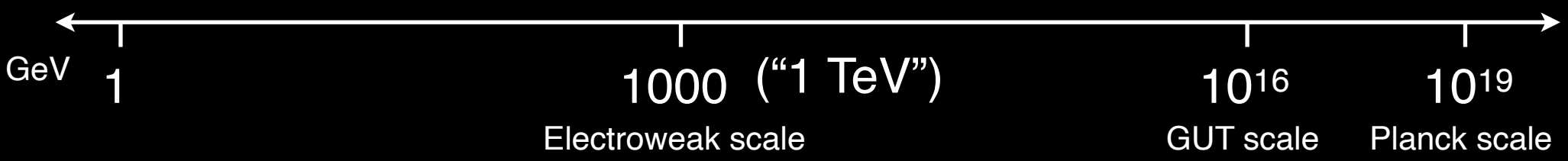

Previous experiments | LHC

Multi-boson interaction (MBI) at high E

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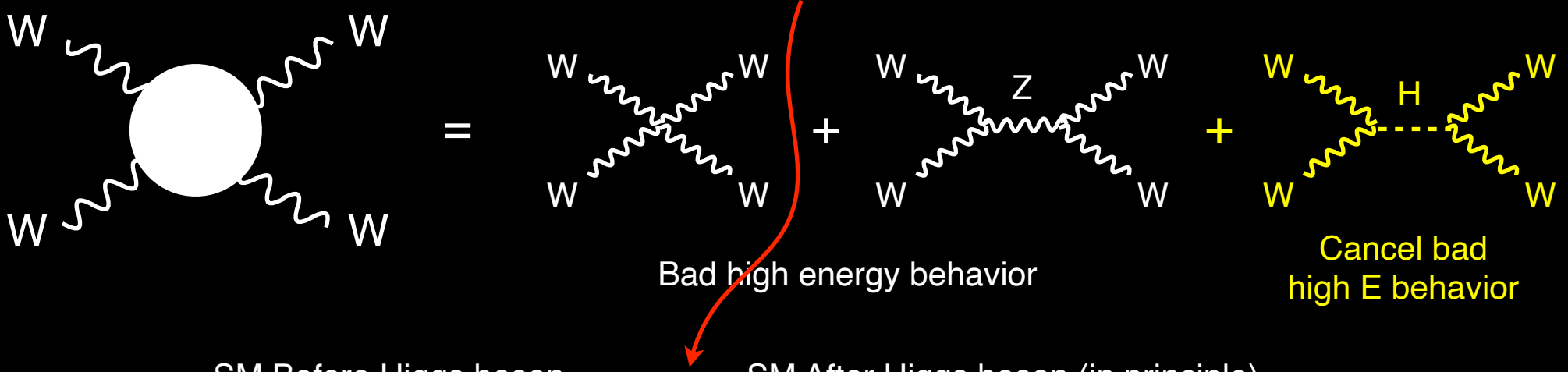
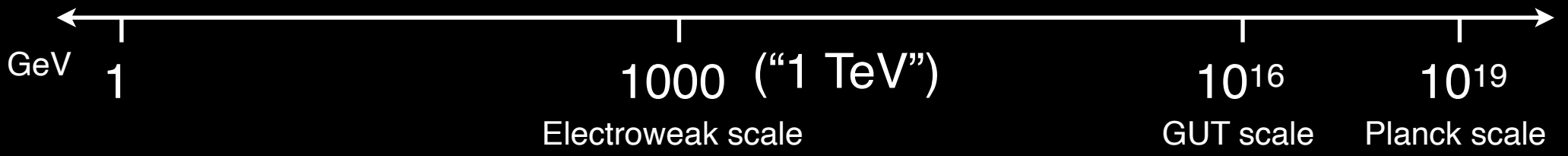


SM Before Higgs boson

SM After Higgs boson (in principle)



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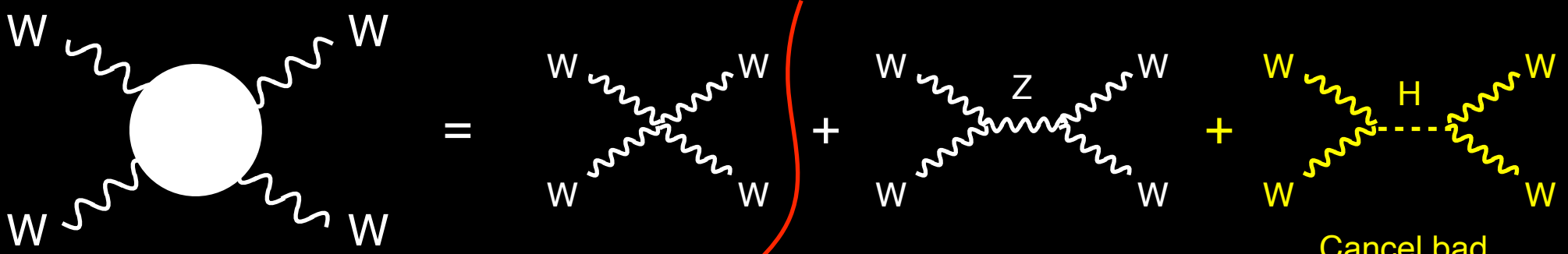

Bad high energy behavior

Cancel bad high E behavior

Previous experiments | LHC

Is this picture all true?

Multi-boson interaction (MBI) at high E

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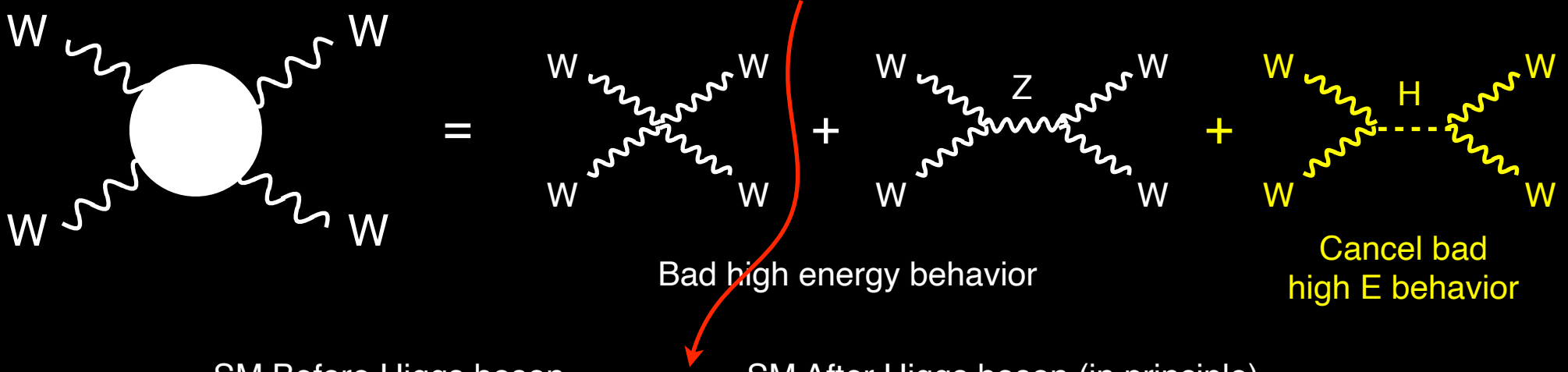

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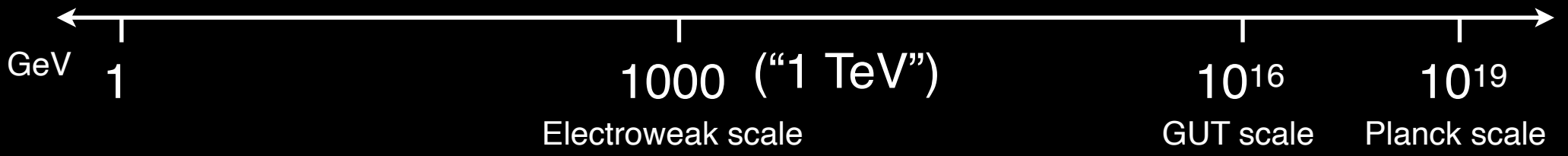

Previous experiments | LHC

Is this picture all true?

Crucial test of electroweak theory

Higgs potential

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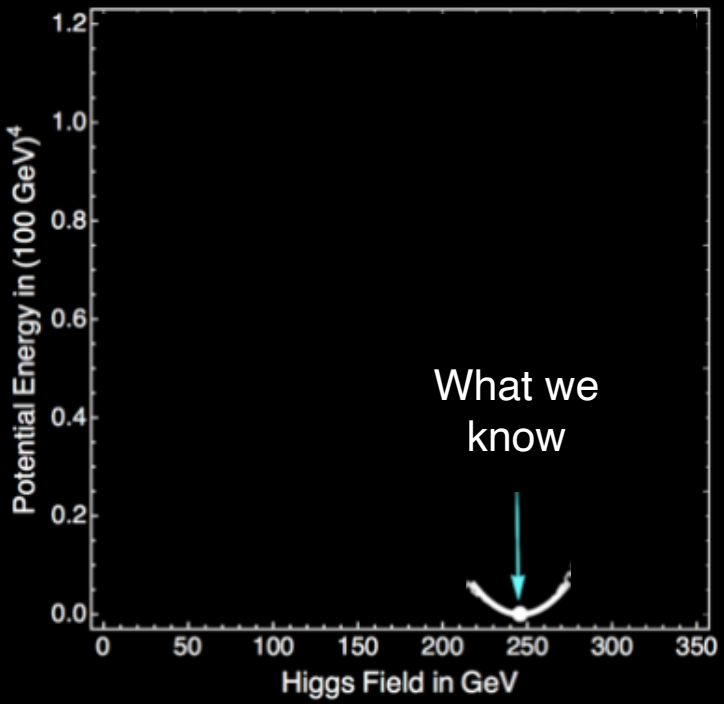
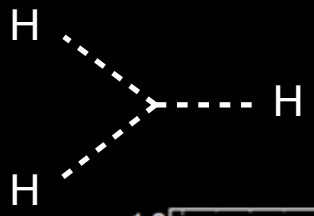


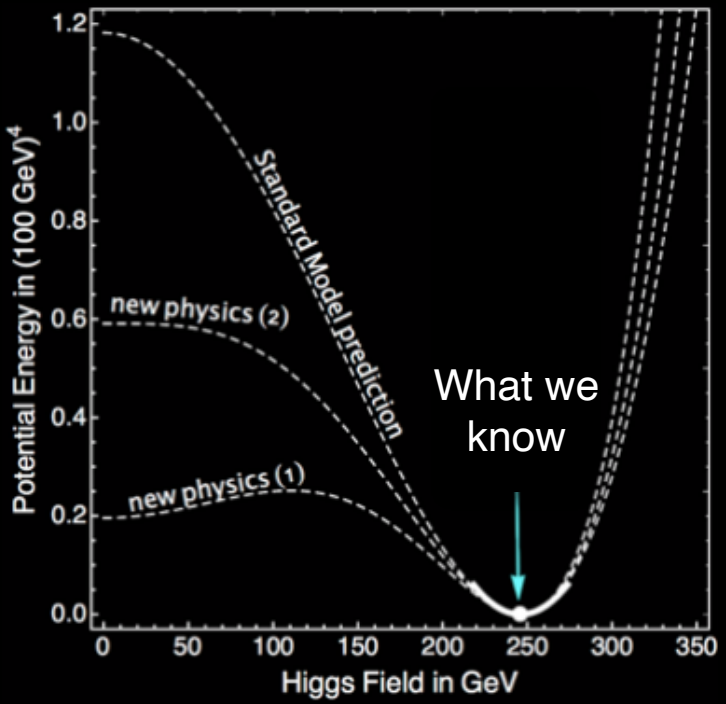
How is electroweak symmetry broken?

https://indico.cern.ch/event/687651/contributions/3403318/attachments/1851013/3038718/LHCP2019_TheoryVision_Craig.pdf

Higgs potential

Chang
UCSD





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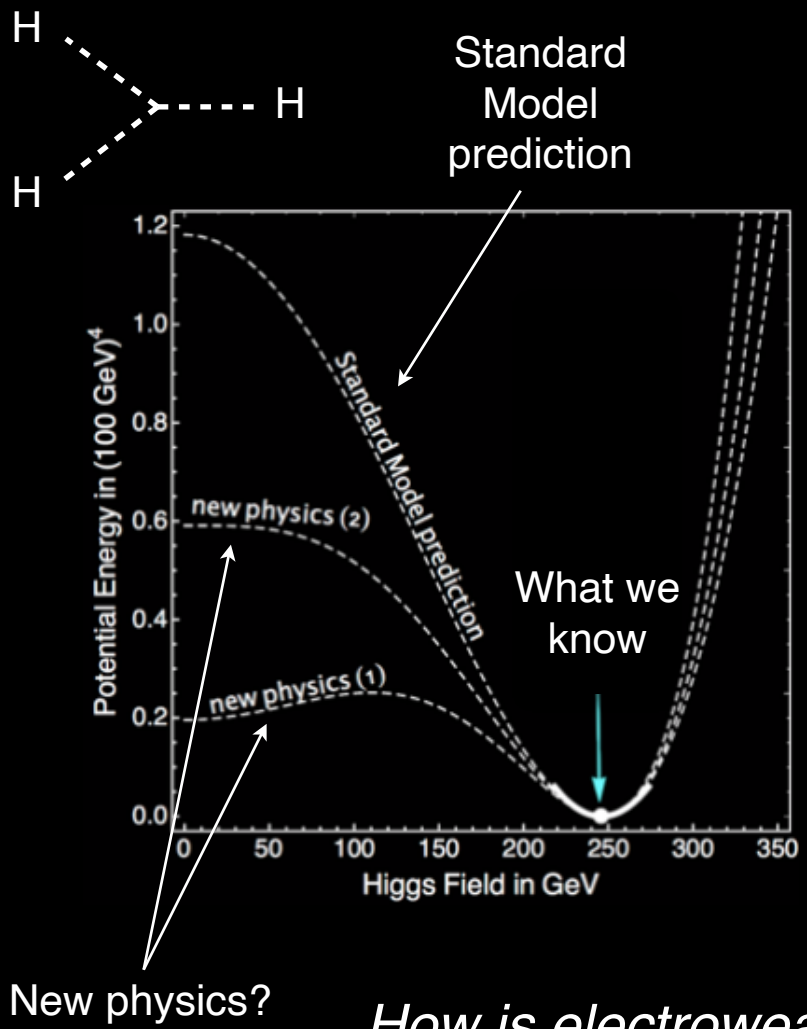

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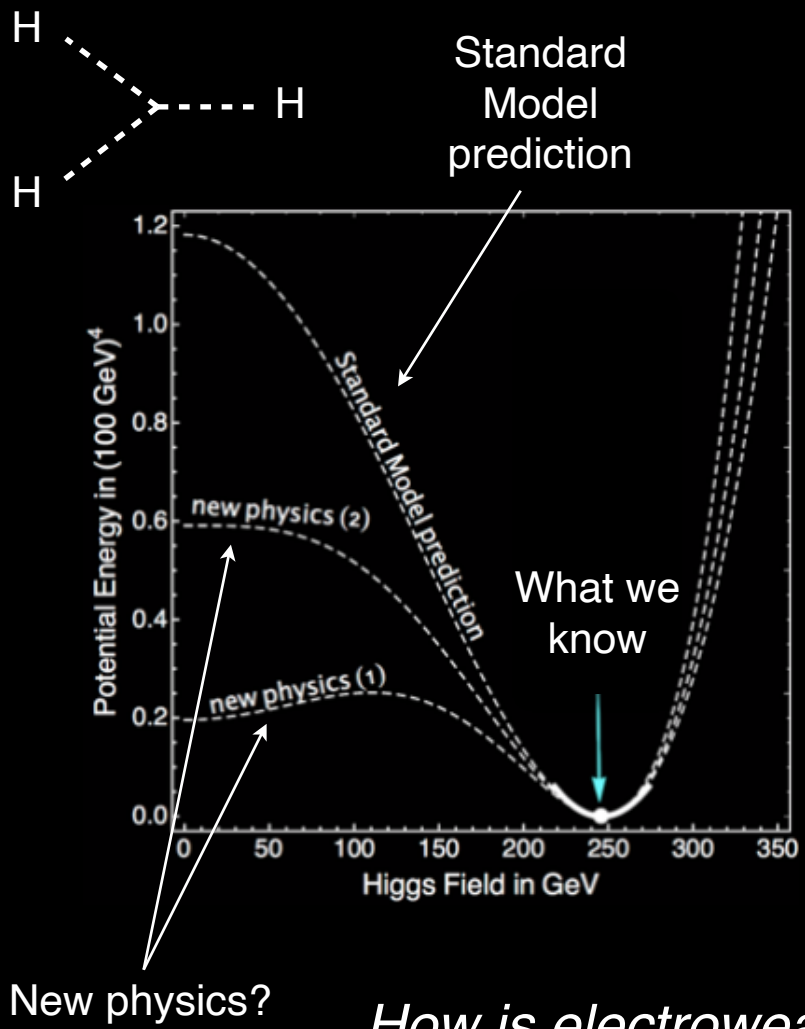
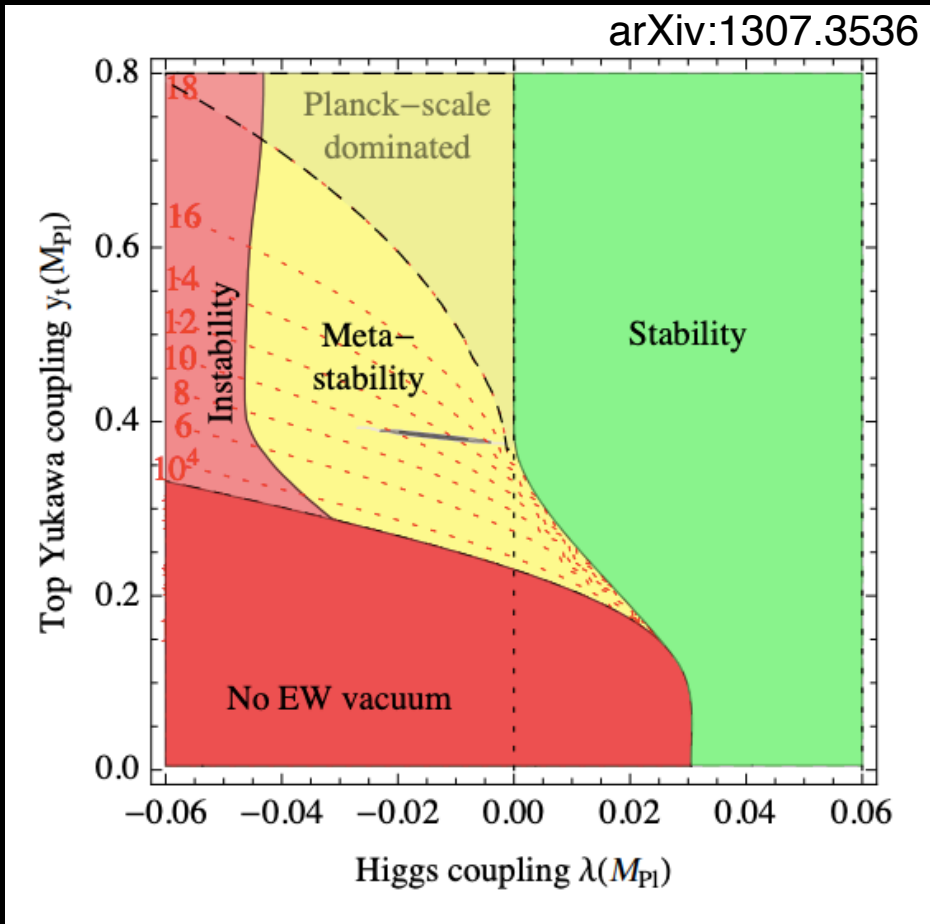


How is electroweak symmetry broken?

What is the fate of the universe?



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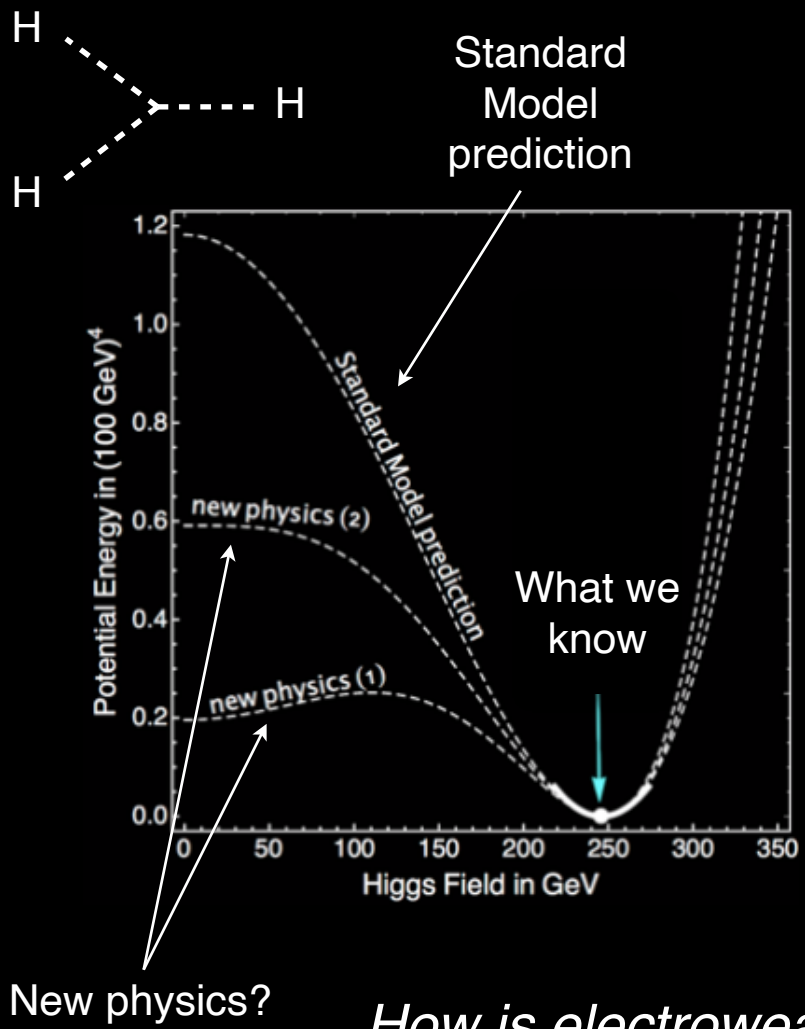

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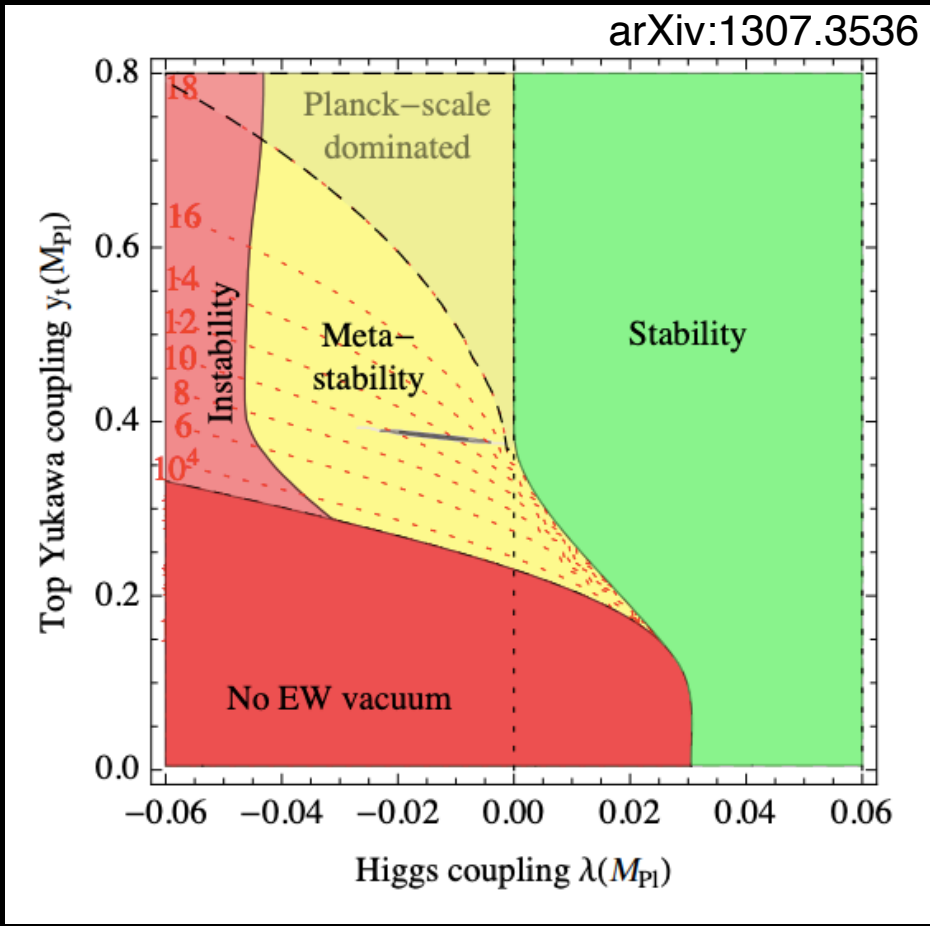

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Understanding Higgs potential have deep implications to cosmology

How do we probe TeV scale MBI?

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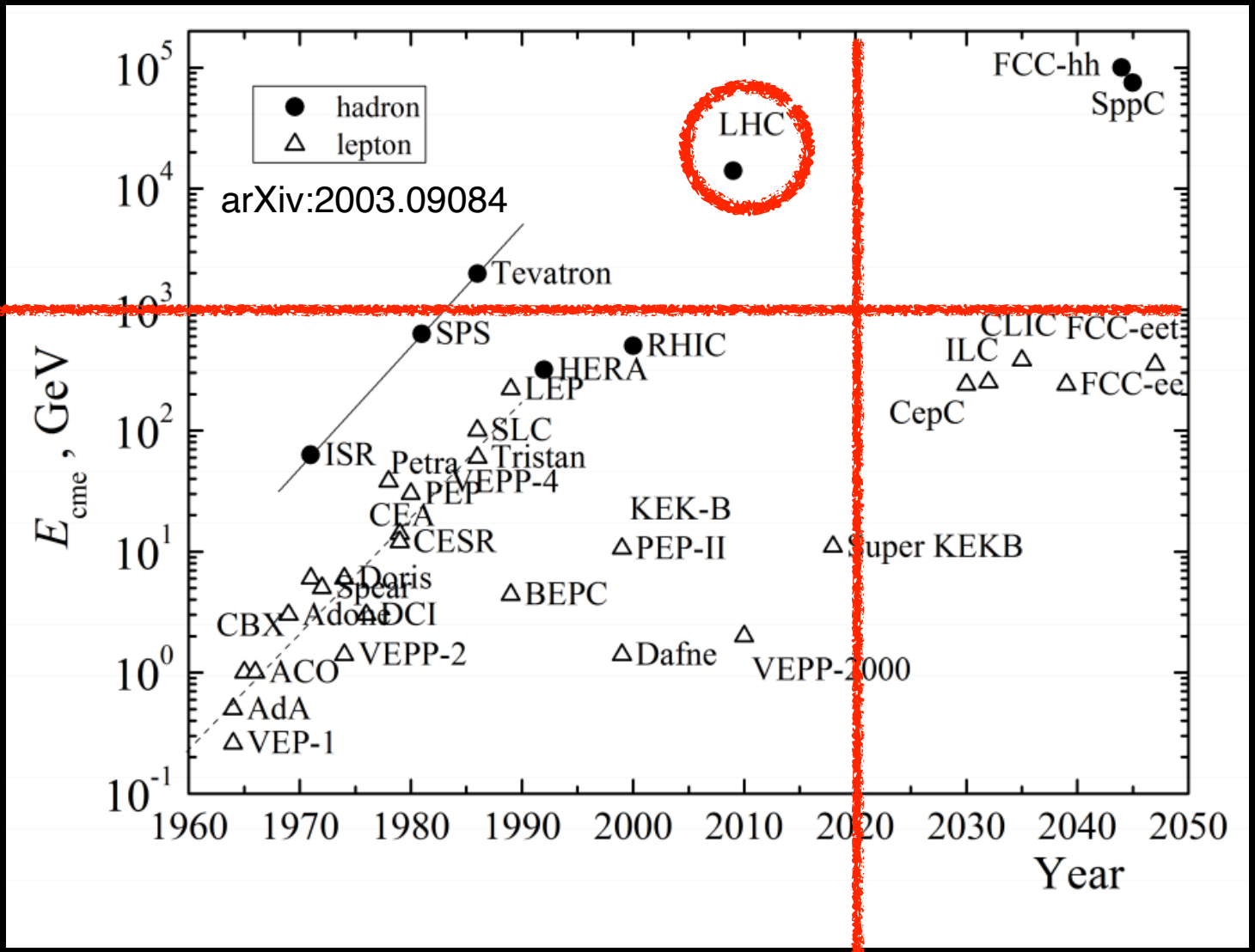
TeV



Today

(Currently, only) Hadron colliders can probe TeV scale MBI

How does hadron collisions probe MBI?

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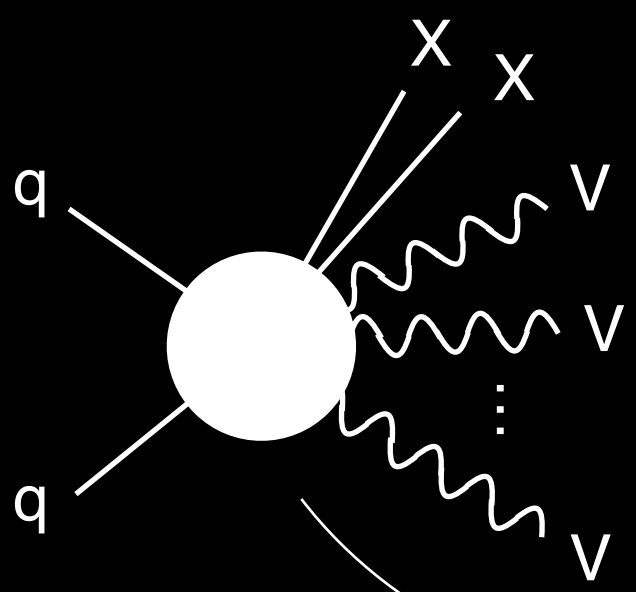
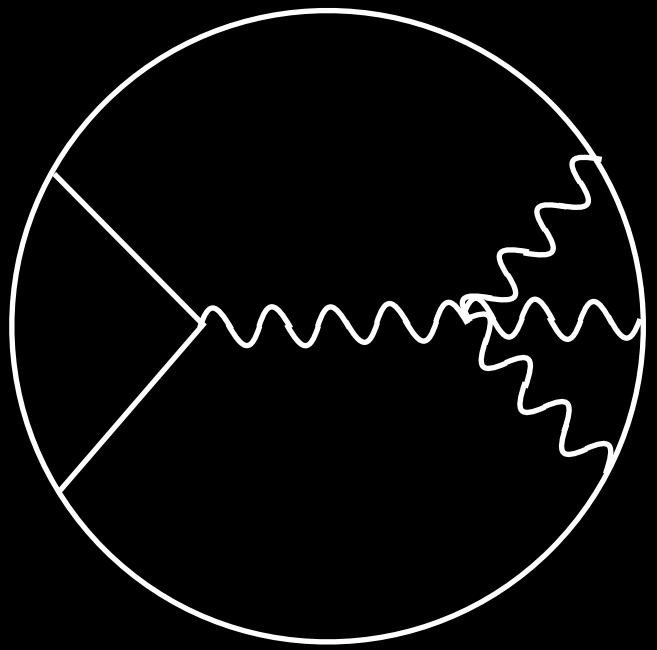
Consider multi-object production process
(i.e. 2 → 2, 3, 4, … scattering processes)

$pp \rightarrow nV + mX$



Can probe quartic gauge coupling



For example

Measure multi-boson production rates to study multi-boson interactions

How does hadron collisions probe MBI?

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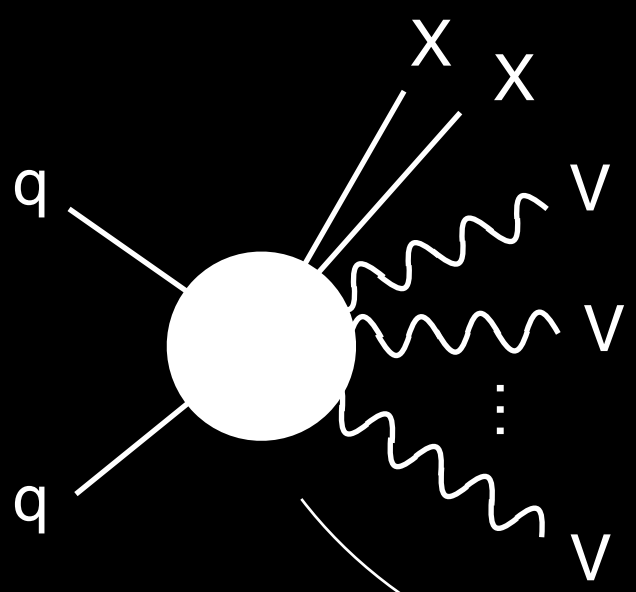
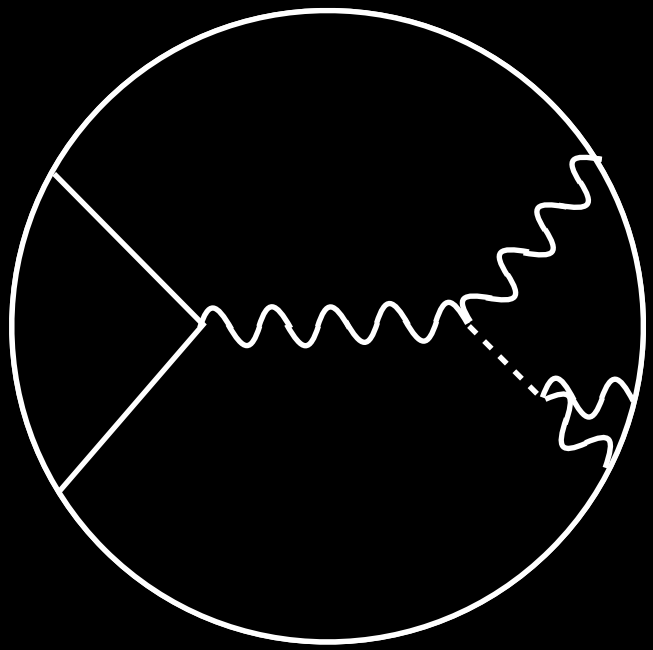


Can also probe
Higgs-gauge
coupling



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Boson collider!

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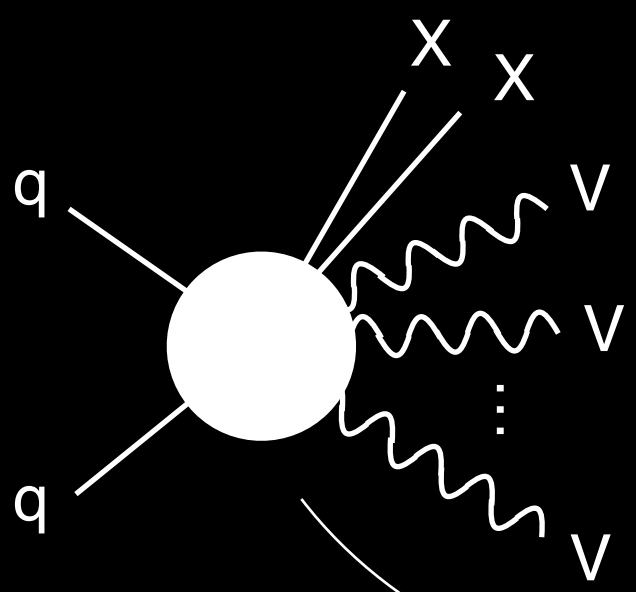

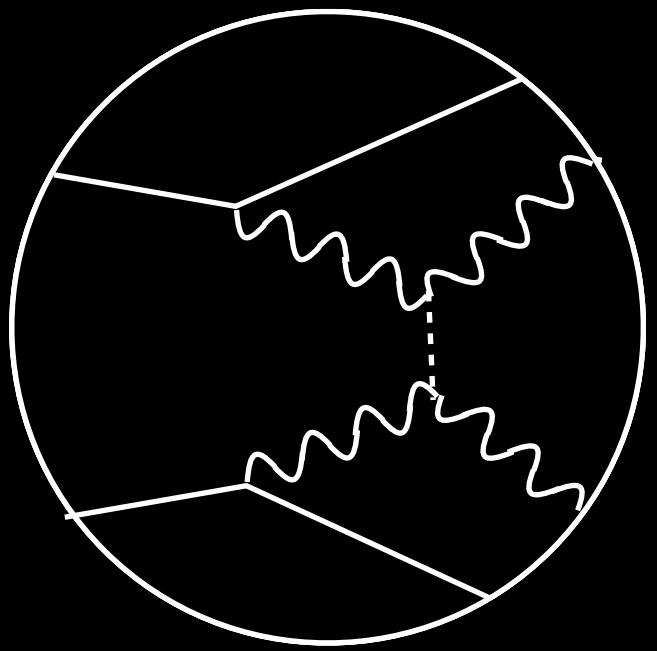

For example

Measure multi-boson production rates to study multi-boson interactions

Multi-boson processes are rare

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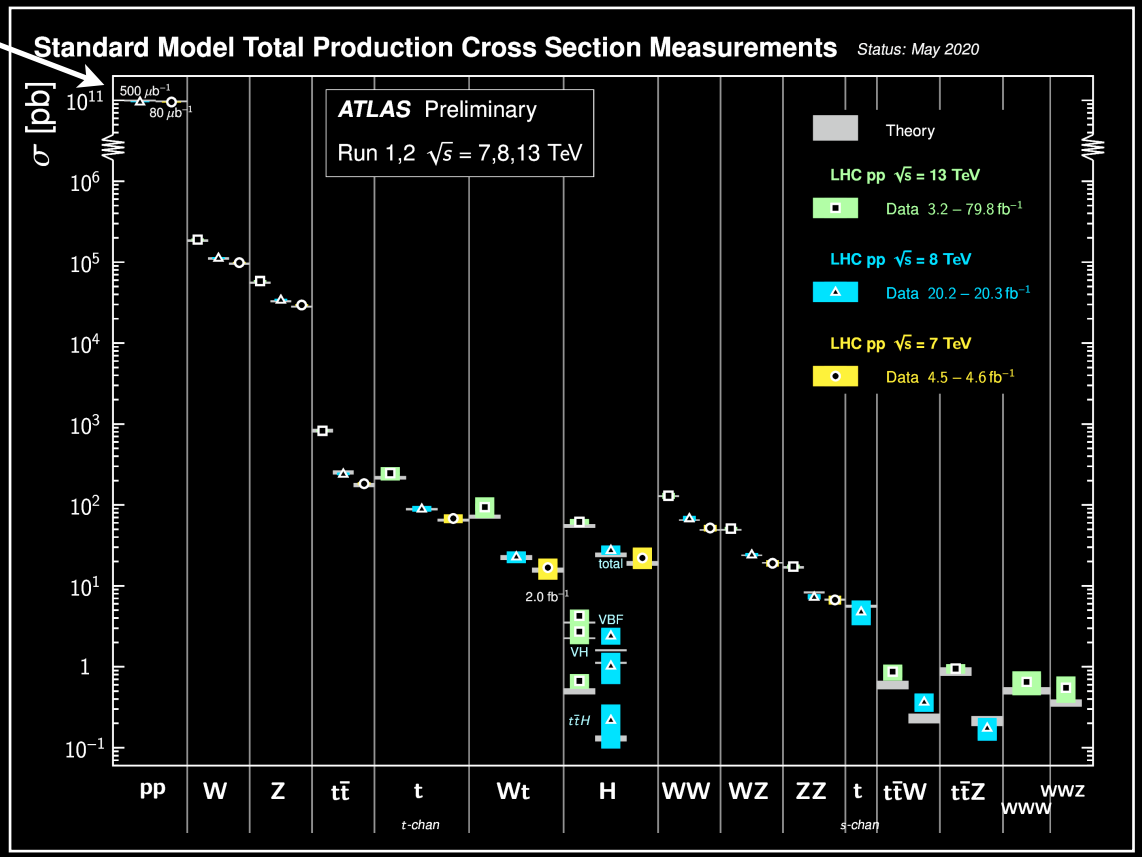
If total cross section is “1”



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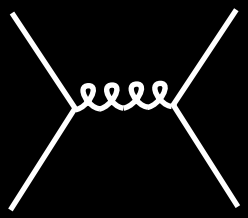
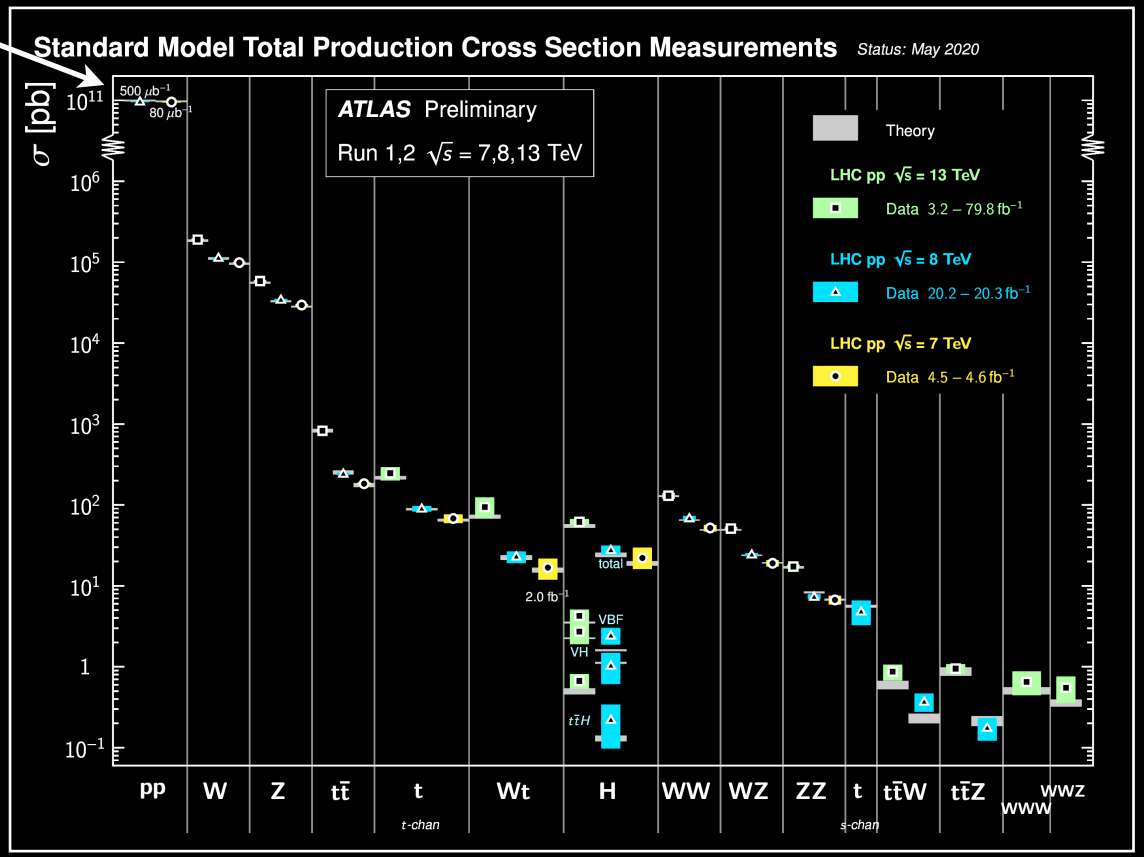
Majority are QCD events





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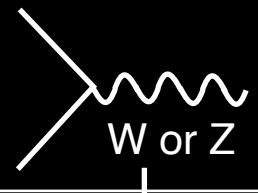
Single boson production $\sim \frac{1}{\text{O(1-10 Million)}}$



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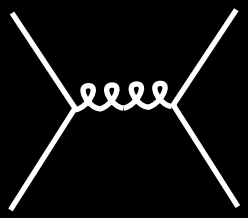

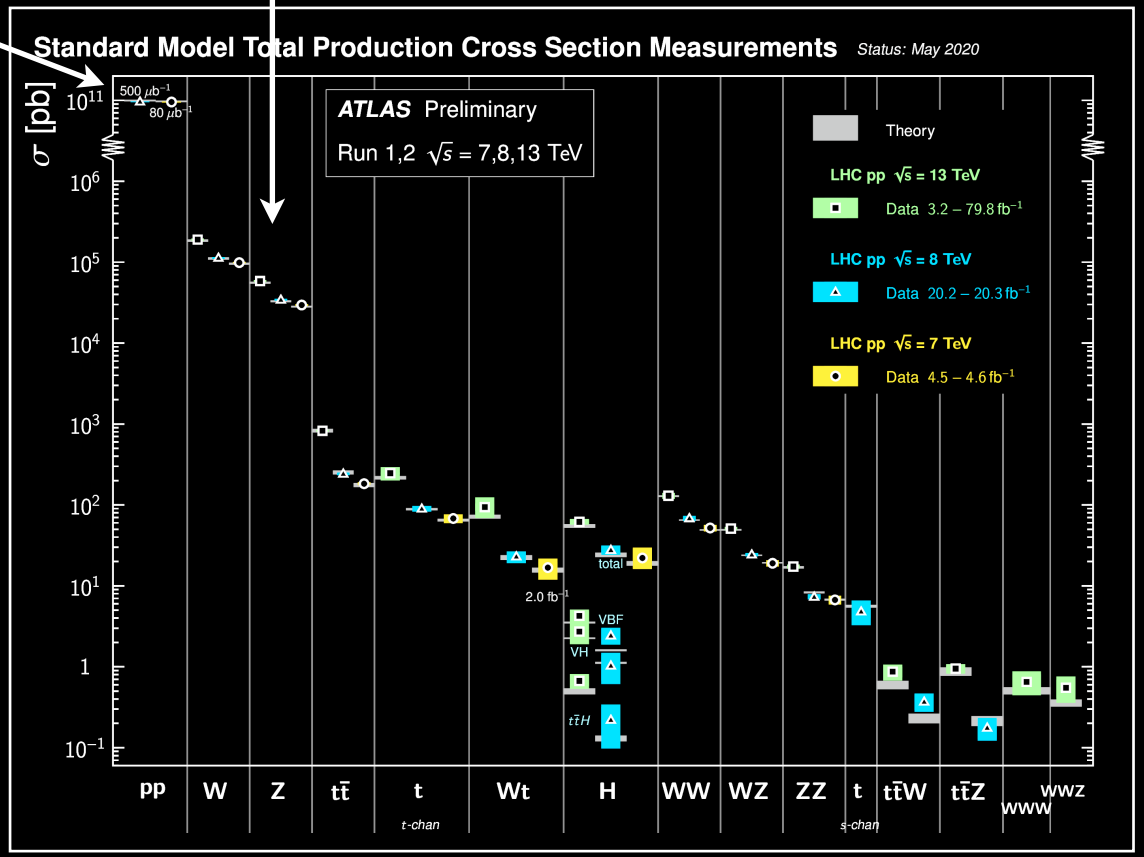

Multi-boson processes are rare

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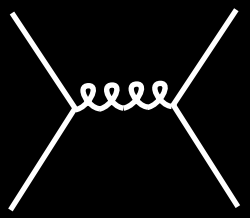
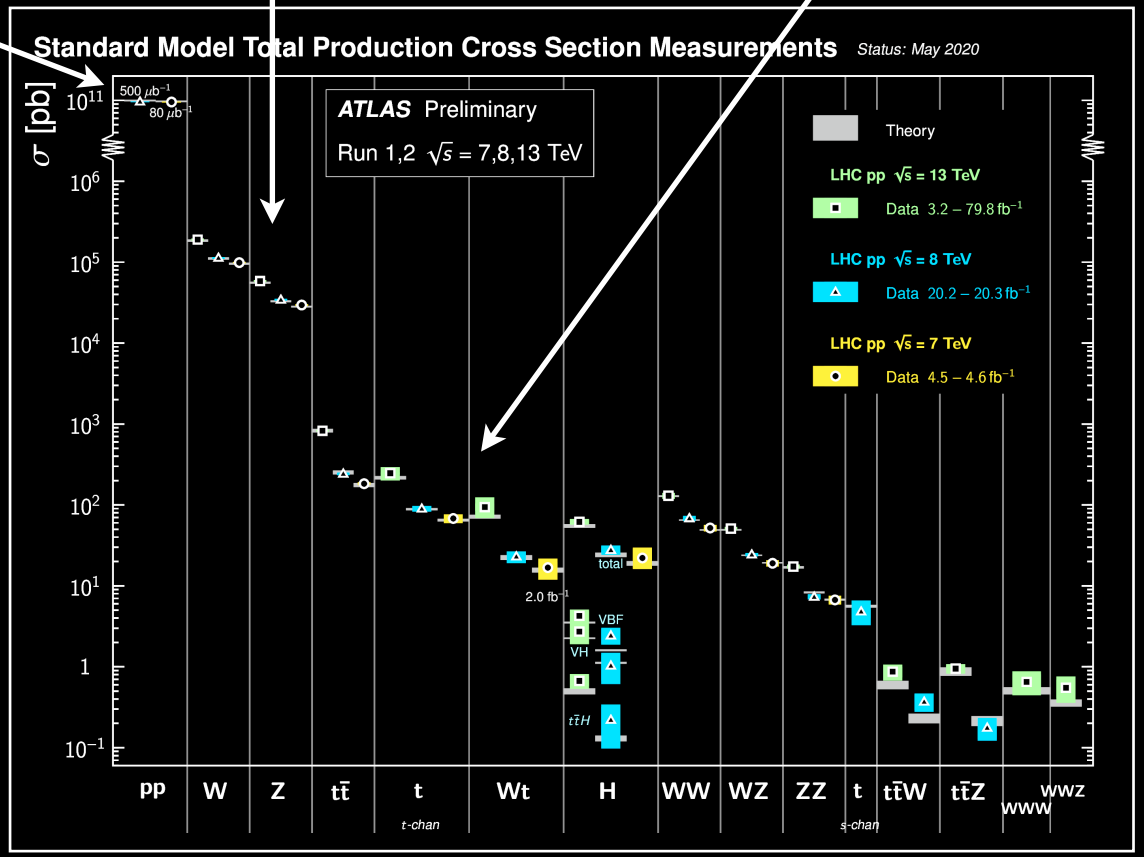
Single boson production ~ $\frac{1}{\text{O(1-10 Million)}}$

Top quark events ~ $\frac{1}{\text{O(100 Million)}}$

If total cross section is “1”

Majority are QCD events





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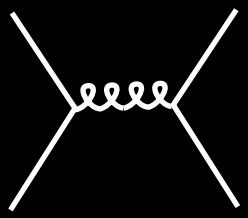

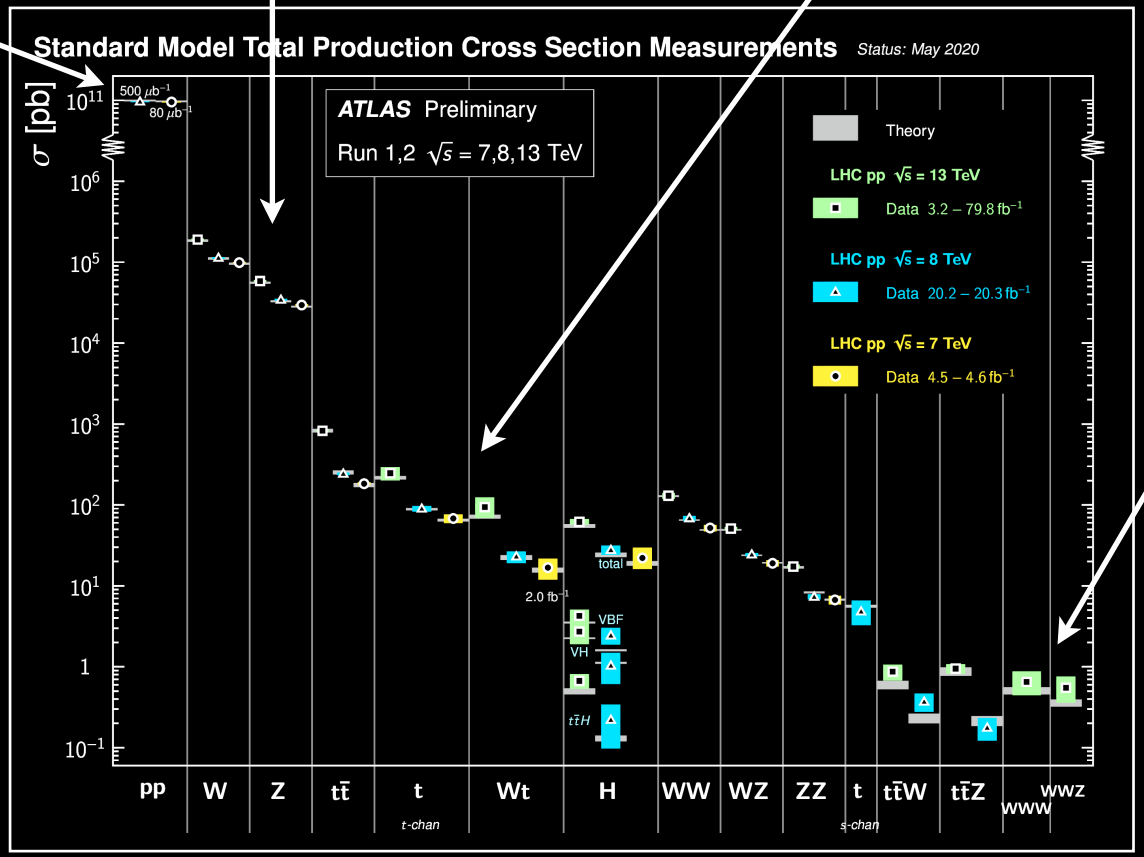

Multi-boson processes ~ $\frac{1}{\text{O(Trillion)}}$

or rarer

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UCSD

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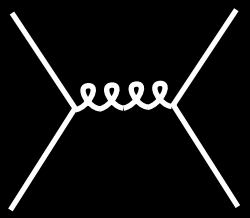
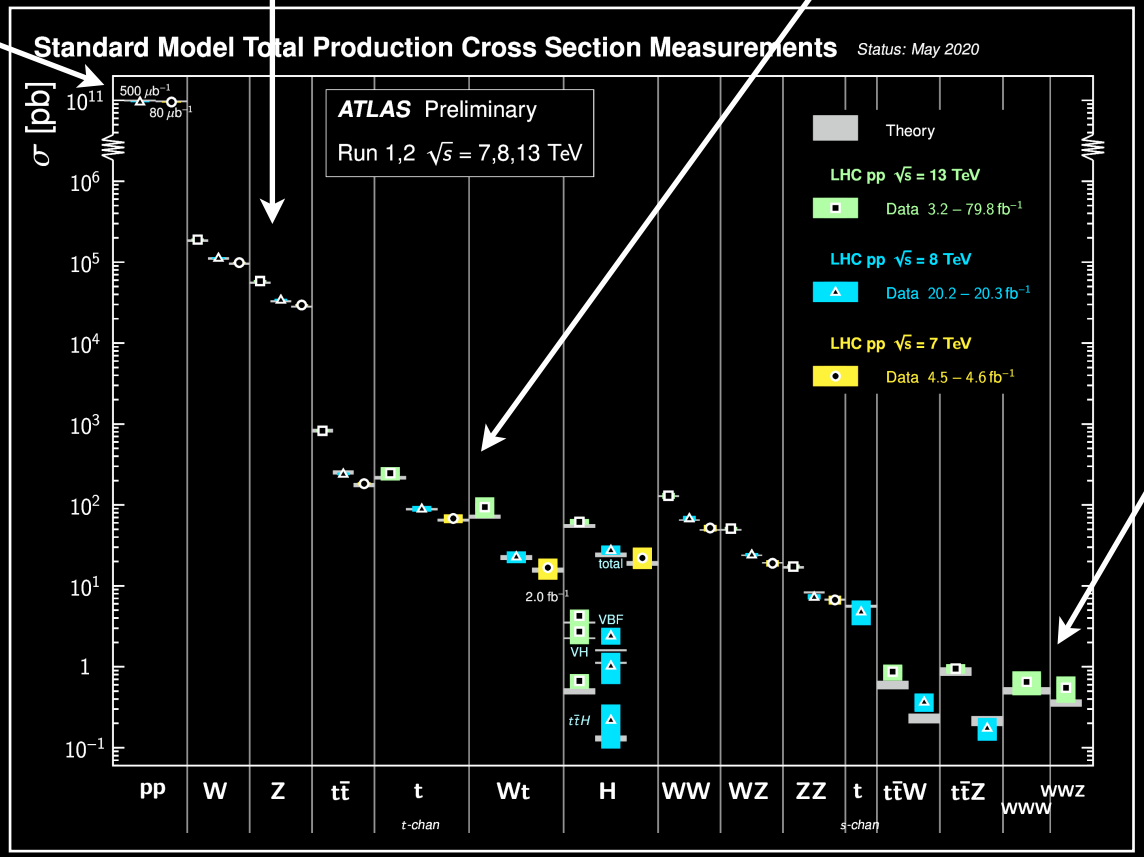
If total cross section is “1”

Majority are QCD events





Multi-boson processes ~ $\frac{1}{\text{O(Trillion)}}$ or rarer

Need to have large number of *pp* collisions to study MBI

Large Hadron Collider at CERN

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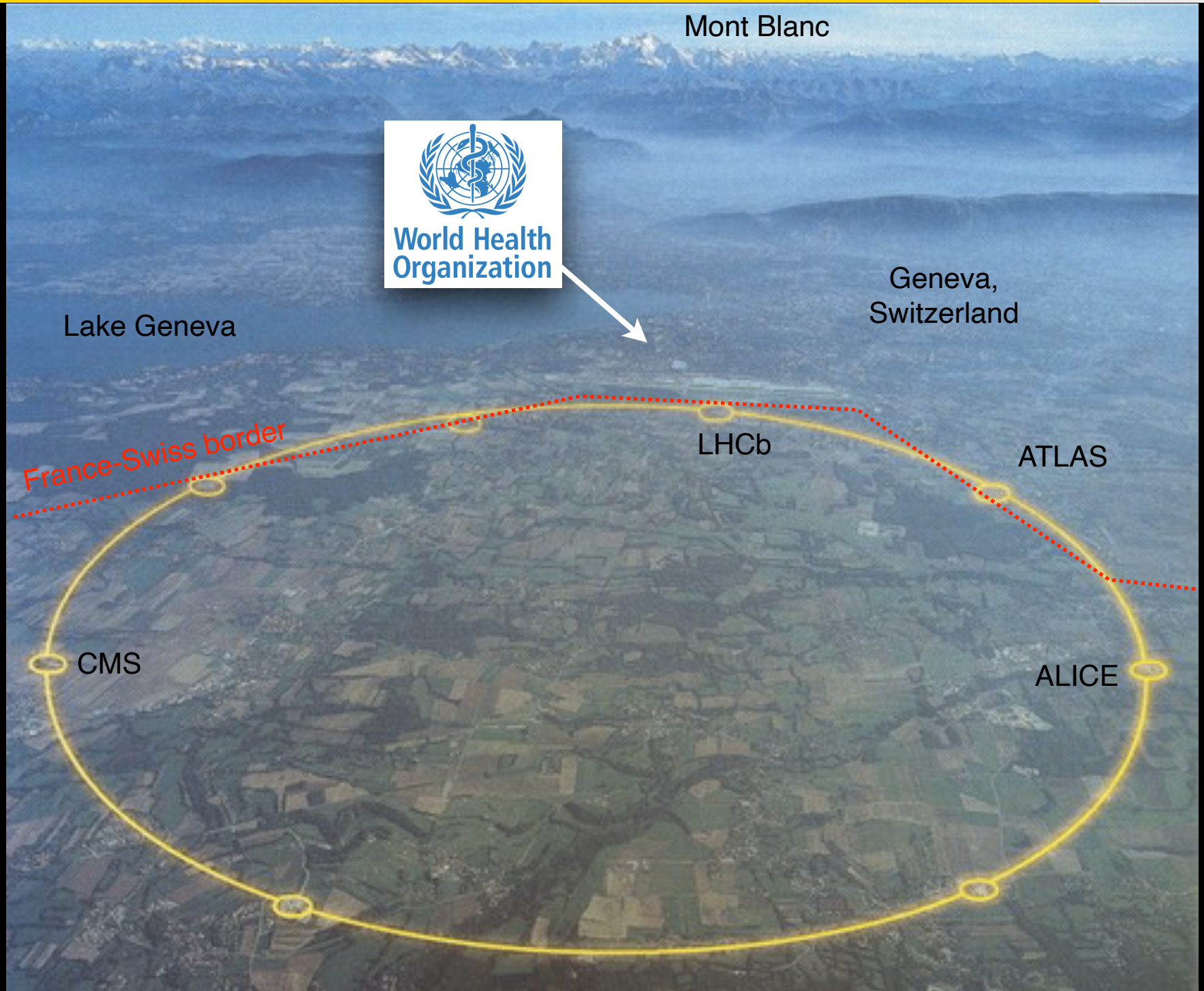
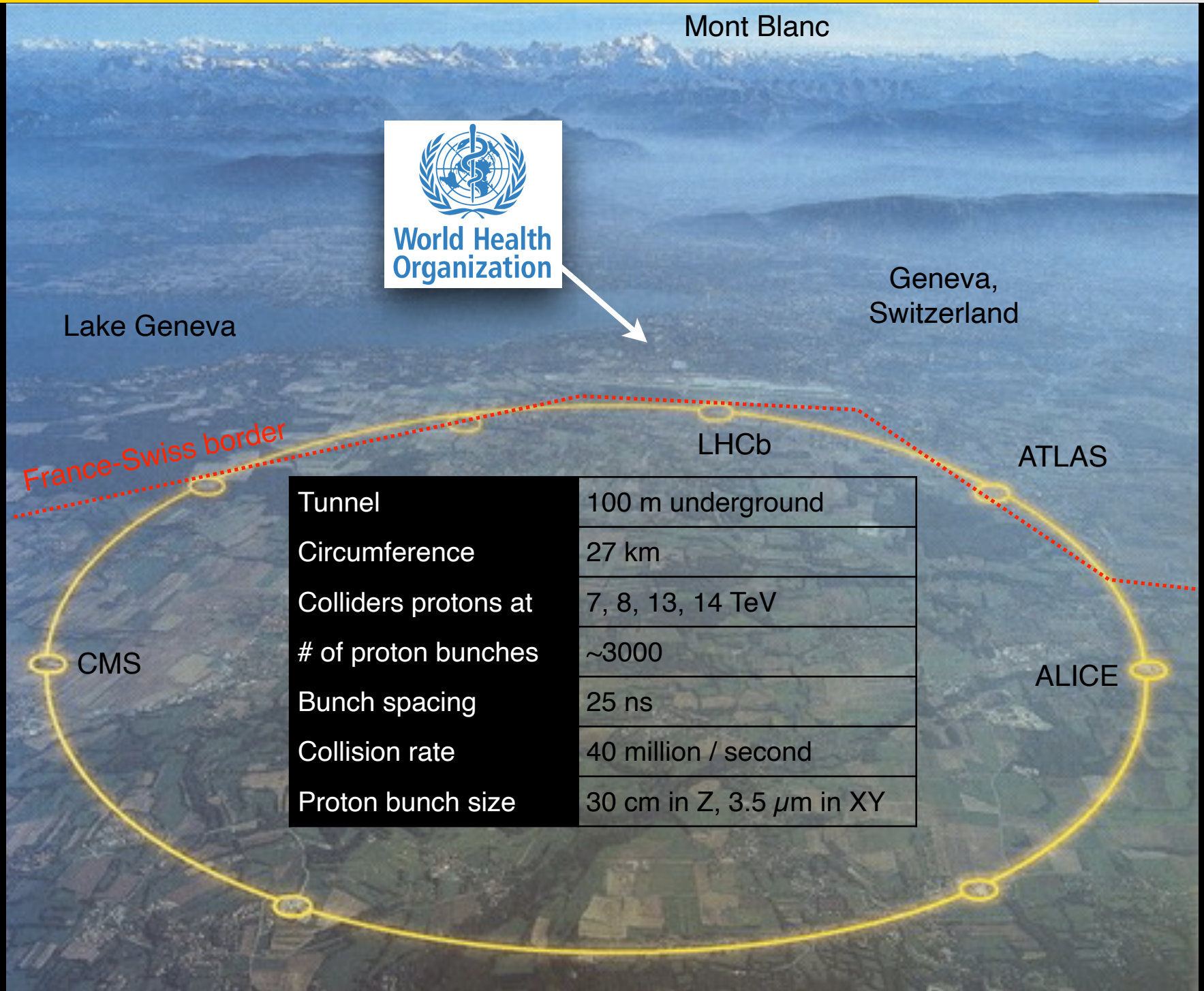
UCSD



Large Hadron Collider at CERN

Chang
UCSD



Tunnel	100 m underground
Circumference	27 km
Colliders protons at	7, 8, 13, 14 TeV
# of proton bunches	~3000
Bunch spacing	25 ns
Collision rate	40 million / second
Proton bunch size	30 cm in Z, 3.5 μm in XY

Large Hadron Collider at CERN

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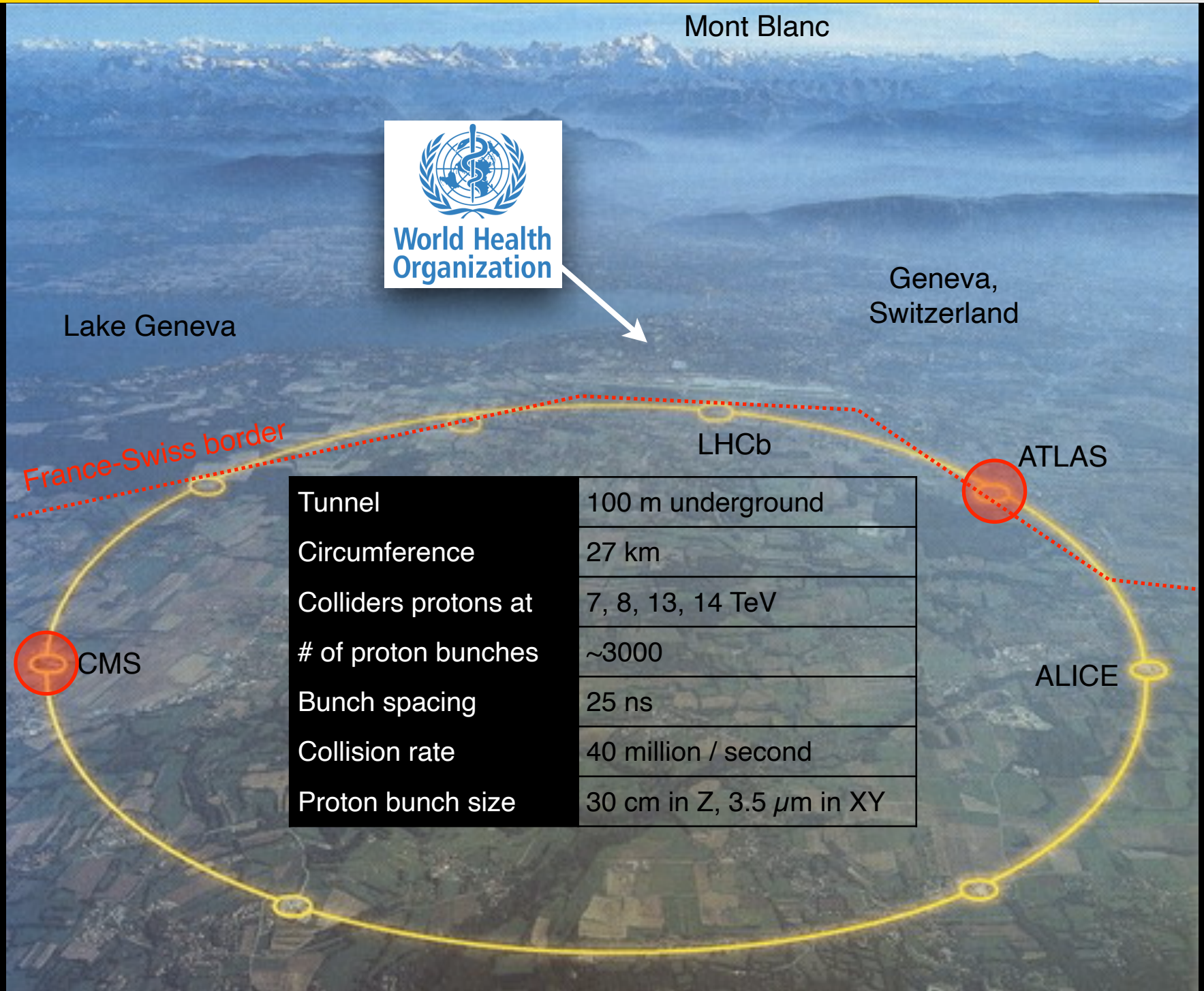

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Experiments

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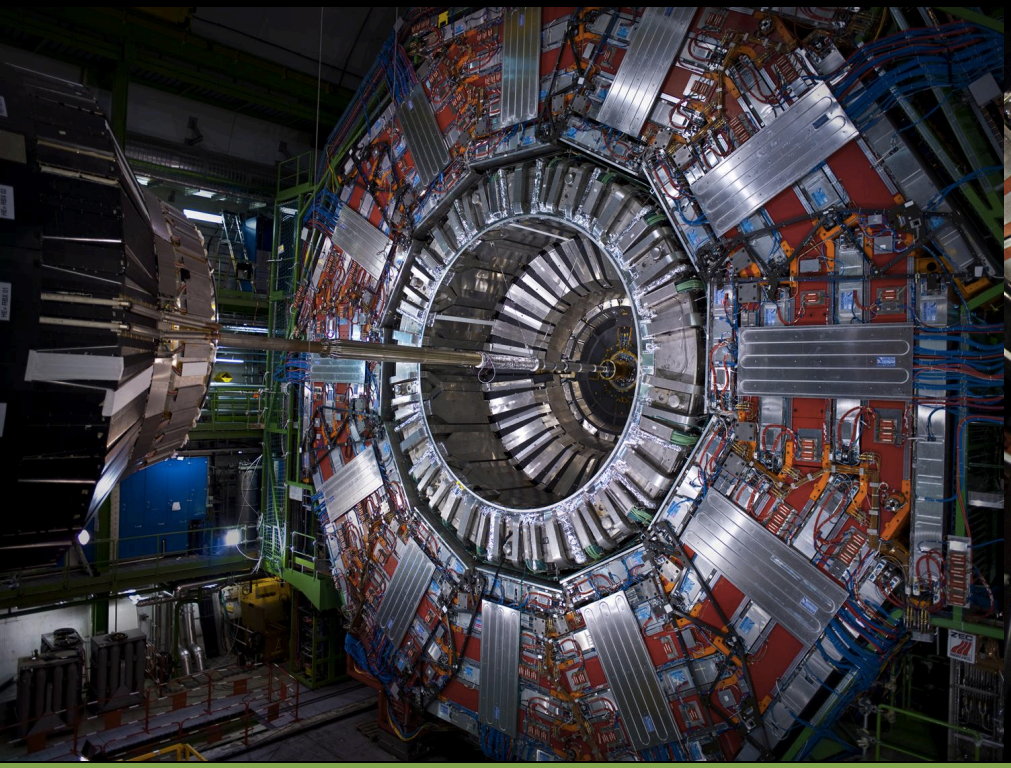
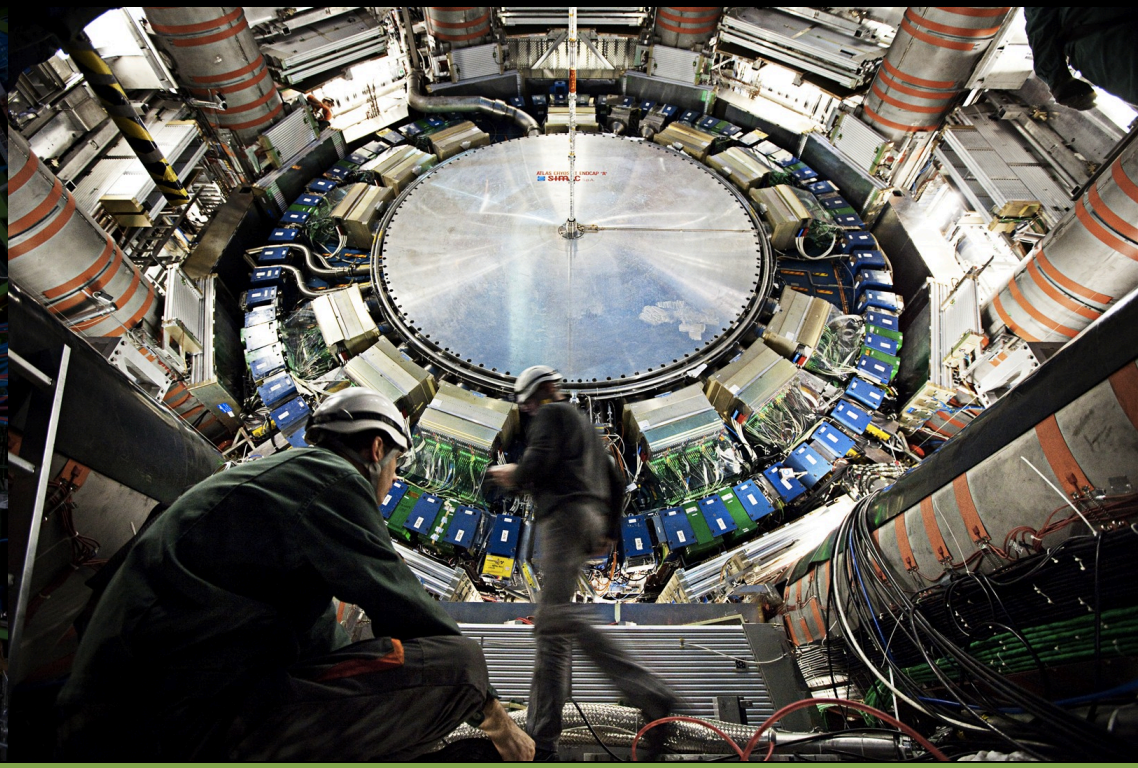
CMS experiment

ATLAS experiment





MBIs are mostly studied by two LHC experiments: ATLAS and CMS

Disclaimer

To first order two experiments have similar results

I am currently a member of CMS Collaboration
(Was also a member in ATLAS Collaboration in the past)

I may inadvertently show (highlight) CMS' results over ATLAS' simply because I am more familiar with CMS results.

Proton beam collision at the LHC

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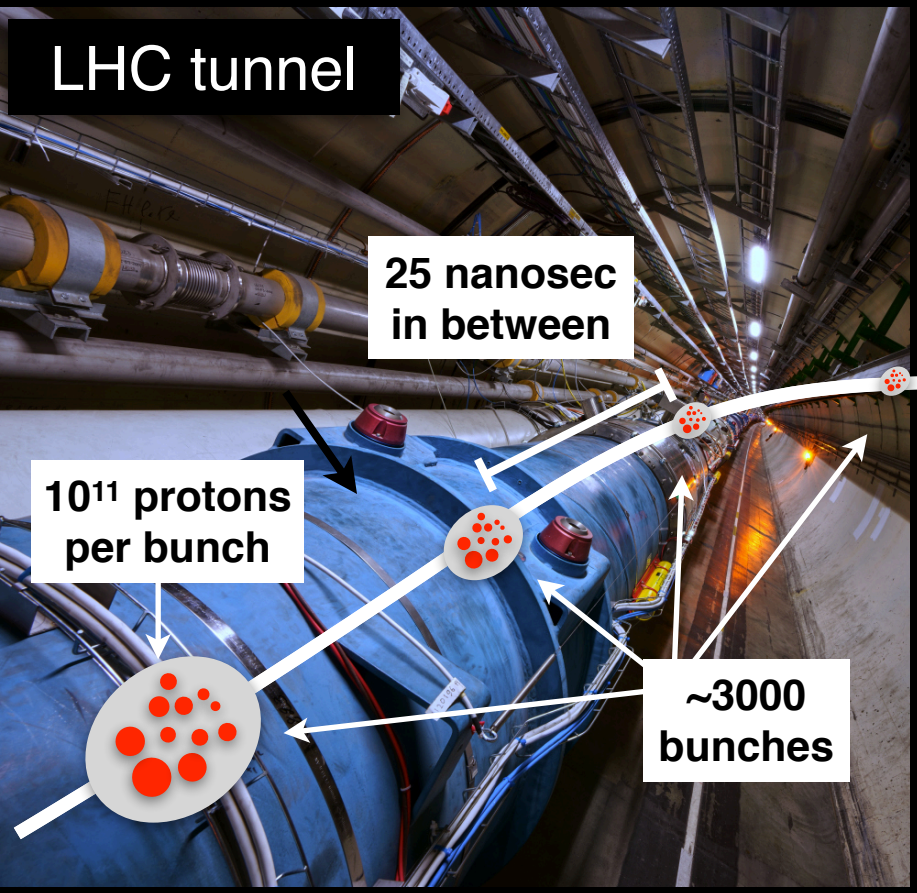

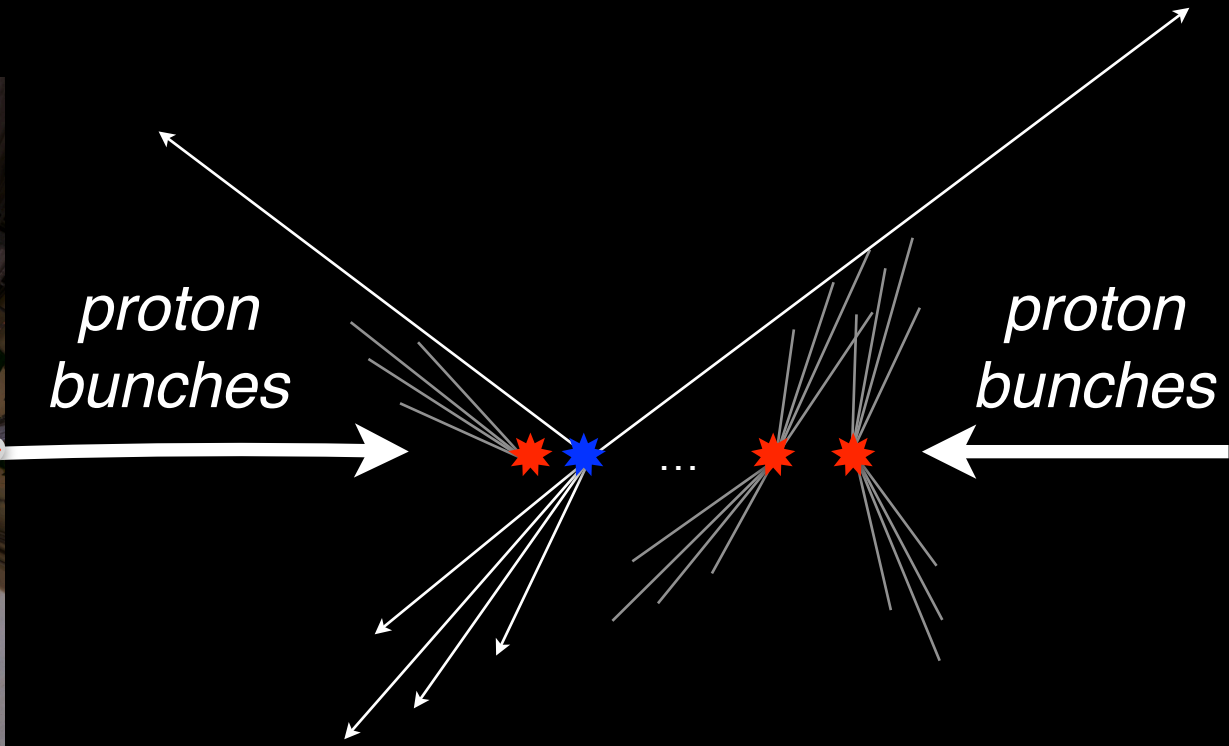

LHC provides highest energy *pp* collisions ever recorded

Proton beam collision at the LHC

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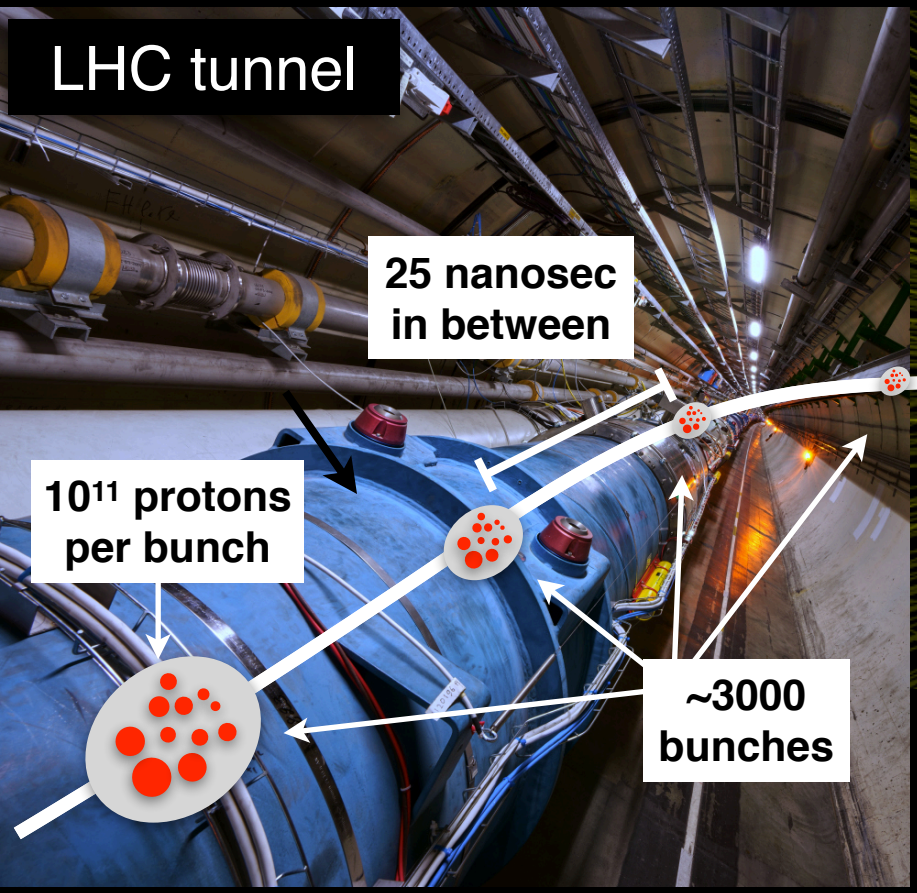
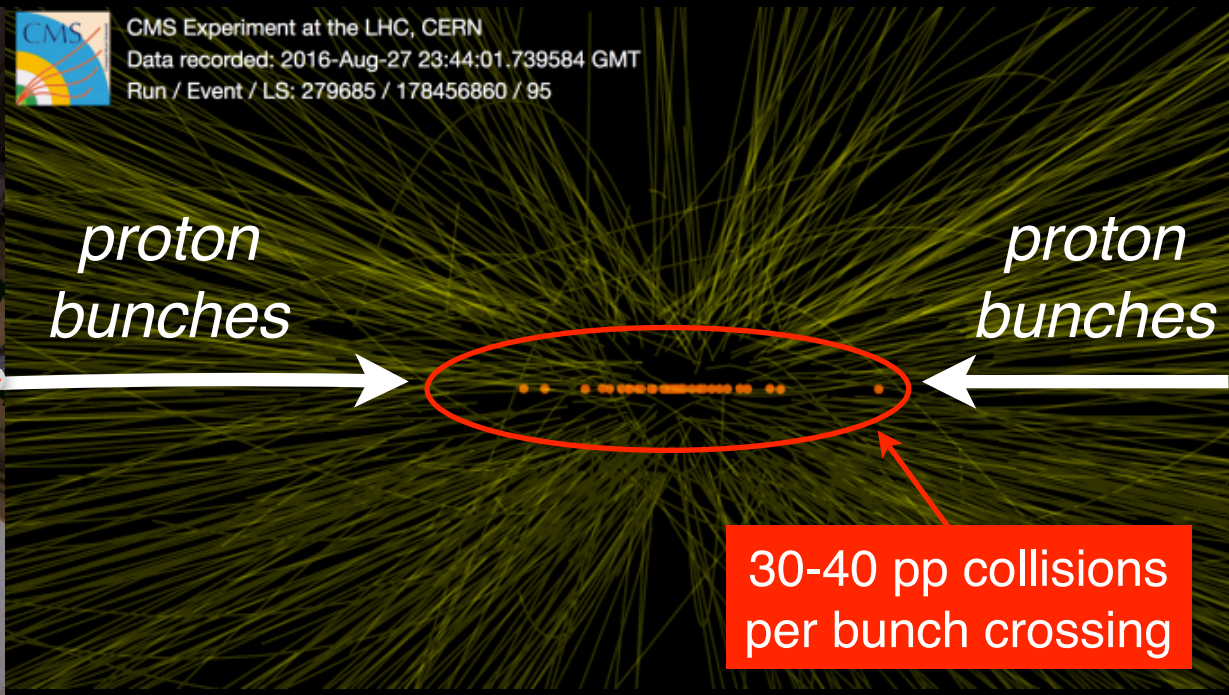
UCSD





(35 pp collisions) × (40 MHz) =
~1.5 billions *pp* collisions per second

Large dataset of

LHC provides highest energy *pp* collisions ever recorded

Data collected by LHC experiments

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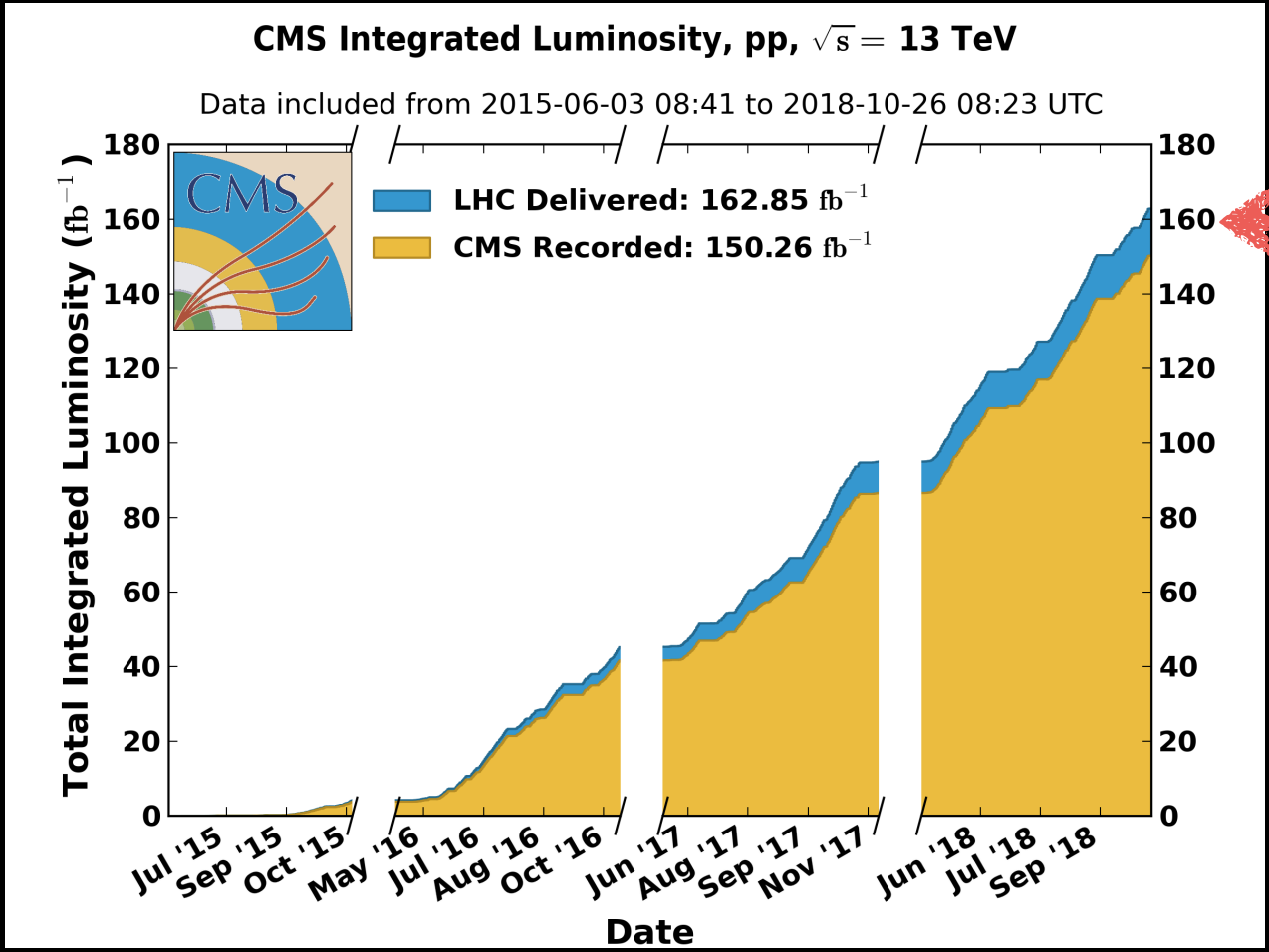
Total amount of pp collision data delivered by LHC, and recorded by CMS experiment (ATLAS is similar)



~15 quadrillion pp collisions

From 2015 to 2018, ATLAS and CMS experiments each recorded around 15 quadrillion *pp* collision events

⇒ O(1k - 10k) Multi-boson processes

LHC's large data enables us to study rare multi-boson processes

Recap

Higgs discovery was a big triumph

Building on discovery, we must verify multi-boson interactions

Studying multi-boson production probes multi-boson interactions

Multi-boson productions are *rare*

It requires large and energetic pp collisions data

⇒ *We need the LHC to probe multi-boson interactions*

Title

But how do we select the interesting O(1000) events out of 10^{16} pp collision events?

$\Rightarrow$ Select events with specific features present in multi-boson but not in other background events

Decay of W, Z bosons

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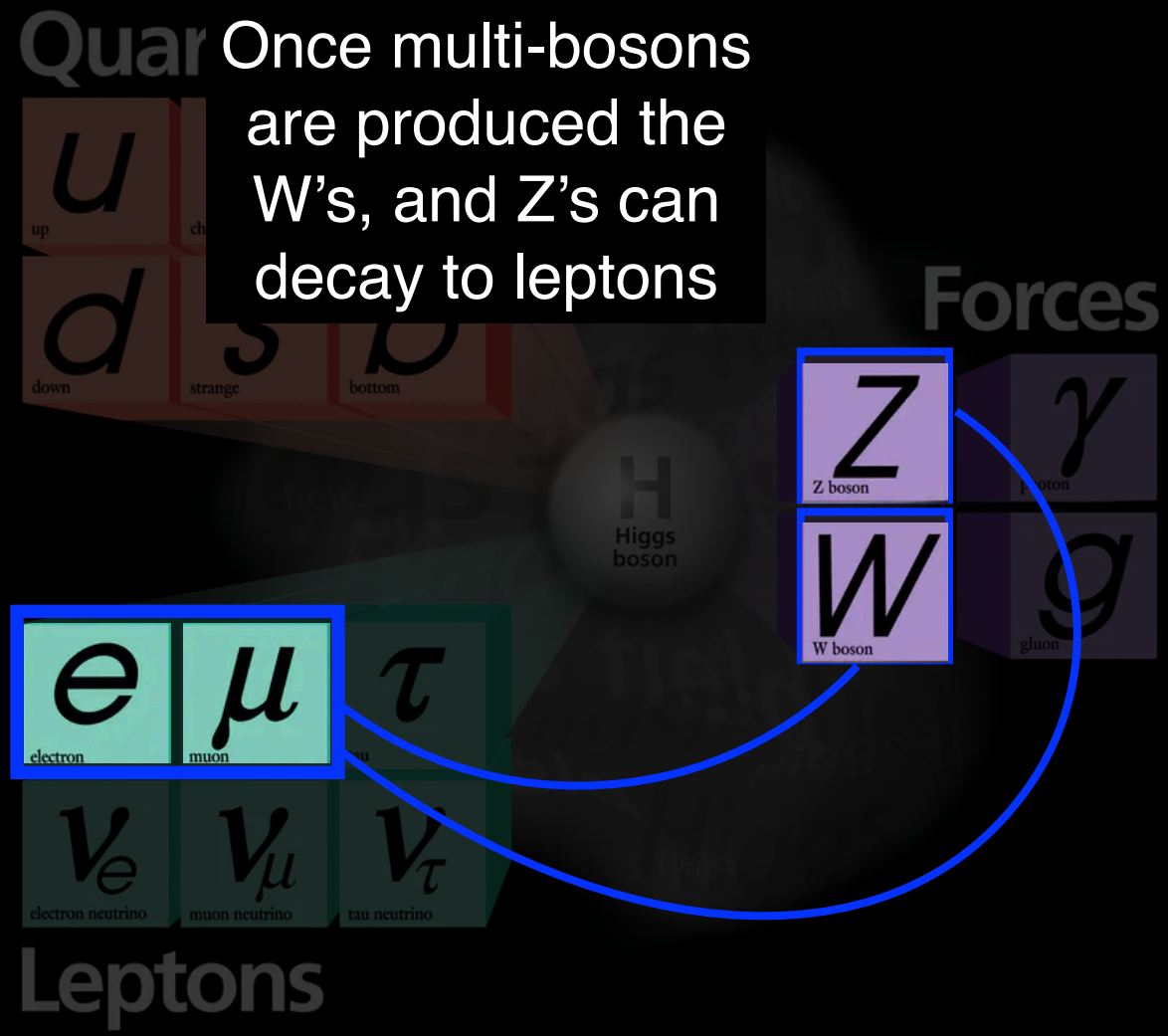
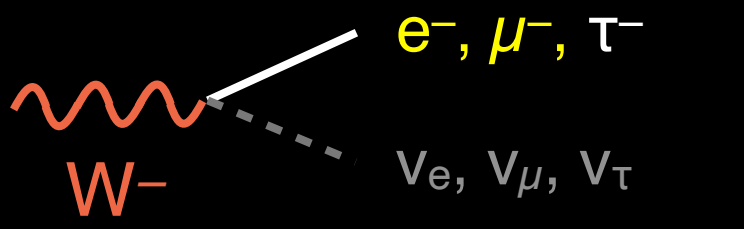
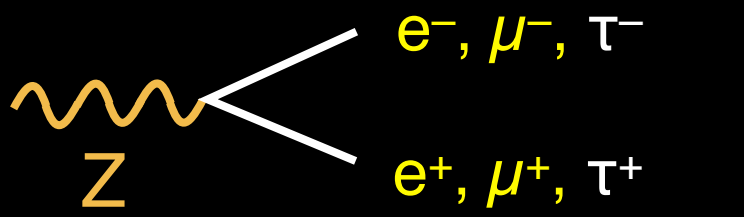
UCSD

Once multi-bosons are produced the W's, and Z's can decay to leptons





~10% each flavor



~3% each flavor

W's and Z's produced can be identified via electrons and muons

Decay of W, Z bosons

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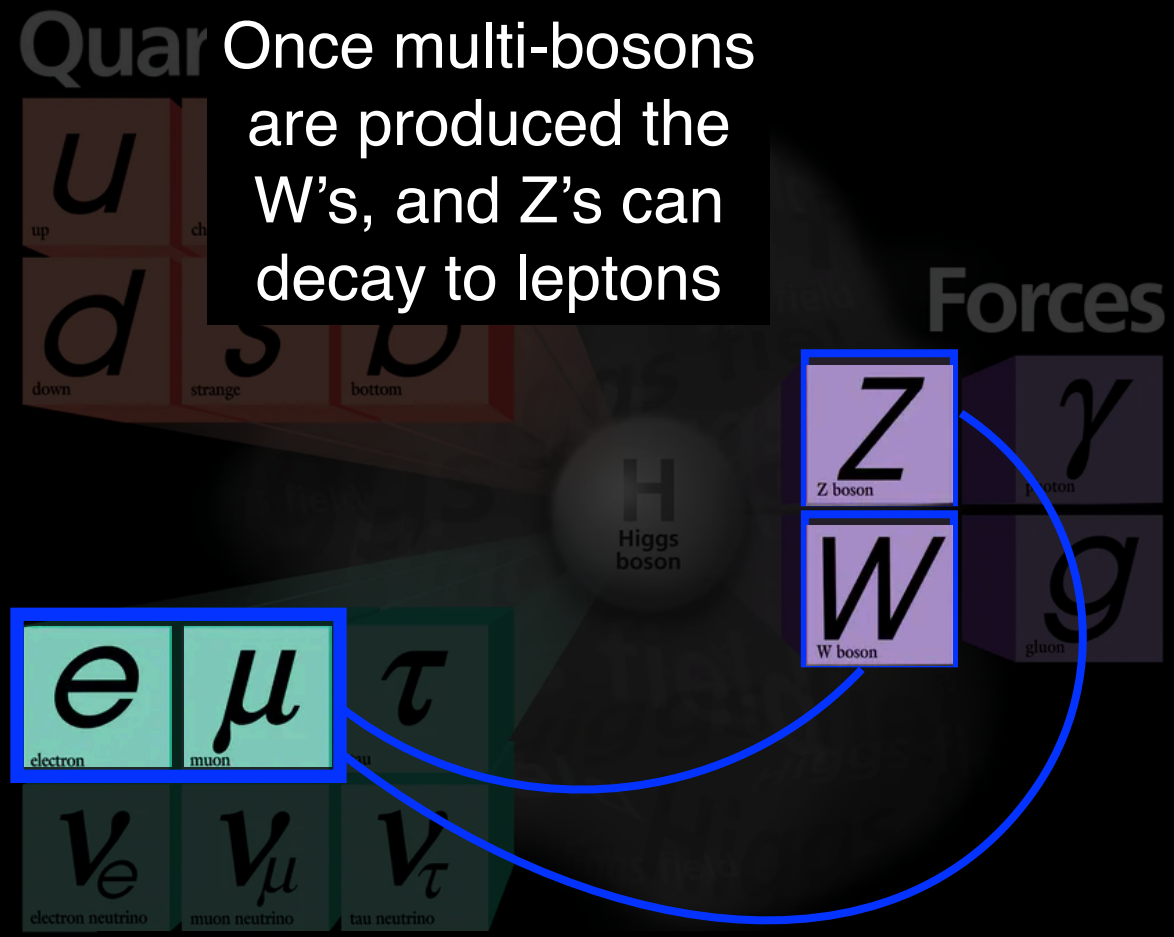
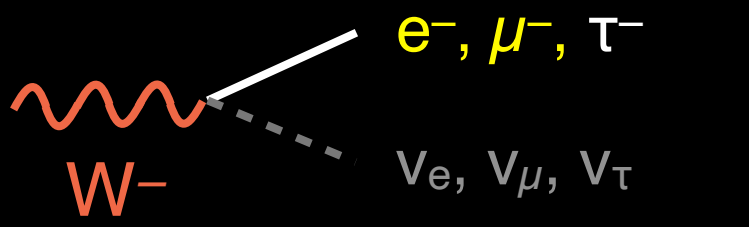
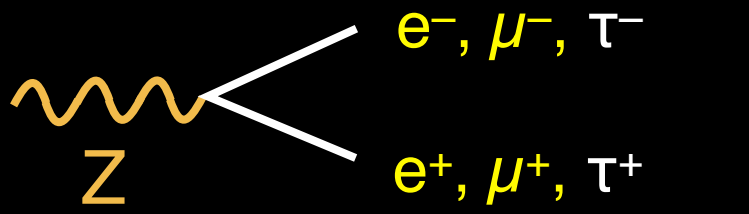
UCSD

Once multi-bosons are produced the W's, and Z's can decay to leptons





~10% each flavor



~3% each flavor

If all W's from pp → WWW decays to e or μ's ⇒ O(100s) events

If all Z's from pp → ZZZ decays to e or μ's ⇒ ~2 events

W's and Z's produced can be identified via electrons and muons

Overview of lepton physics at the LHC

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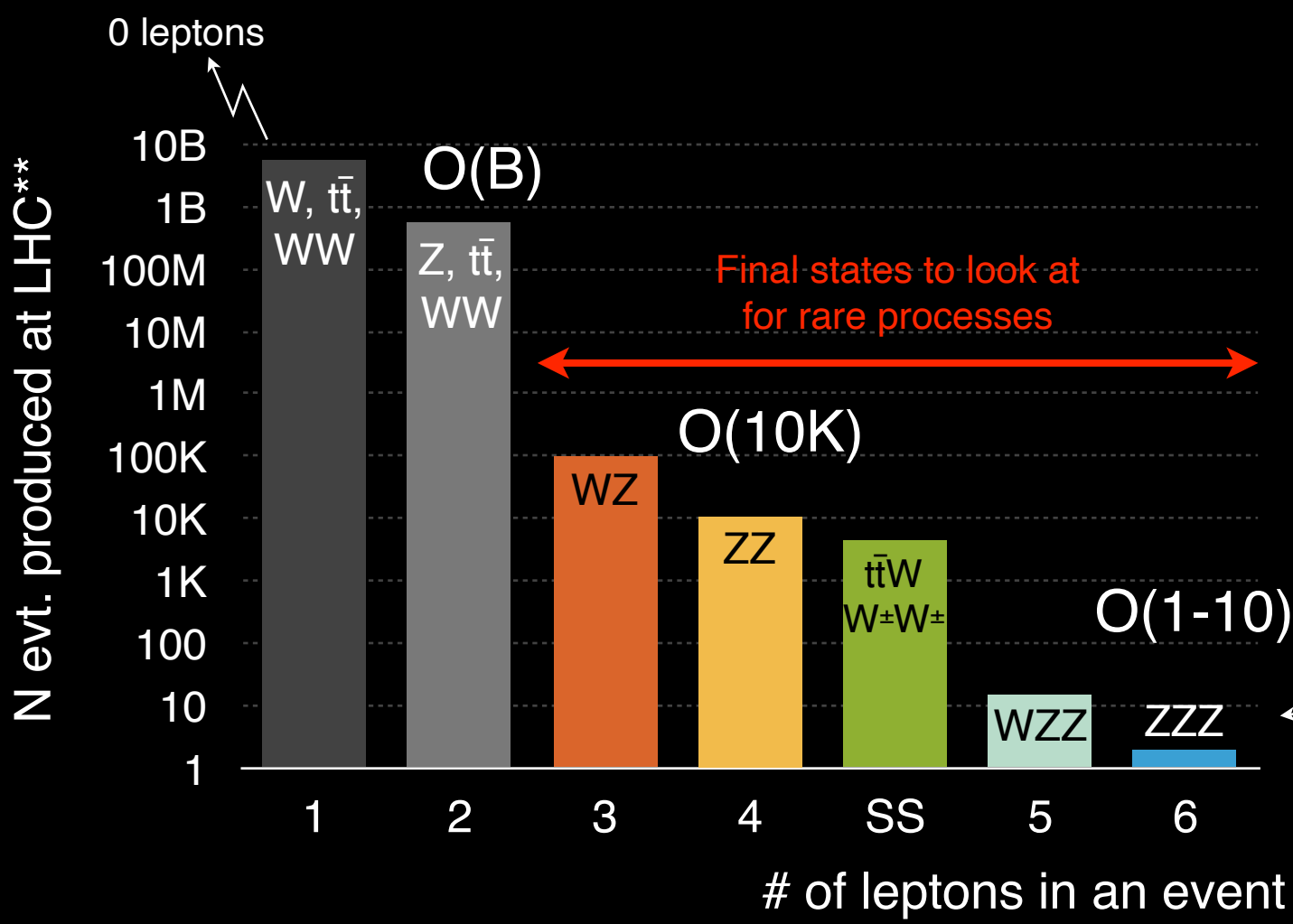
UCSD

**N events estimated from W, Z, tt̄, WW, WZ, ZZ, tt̄W, WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring τ → e, μ



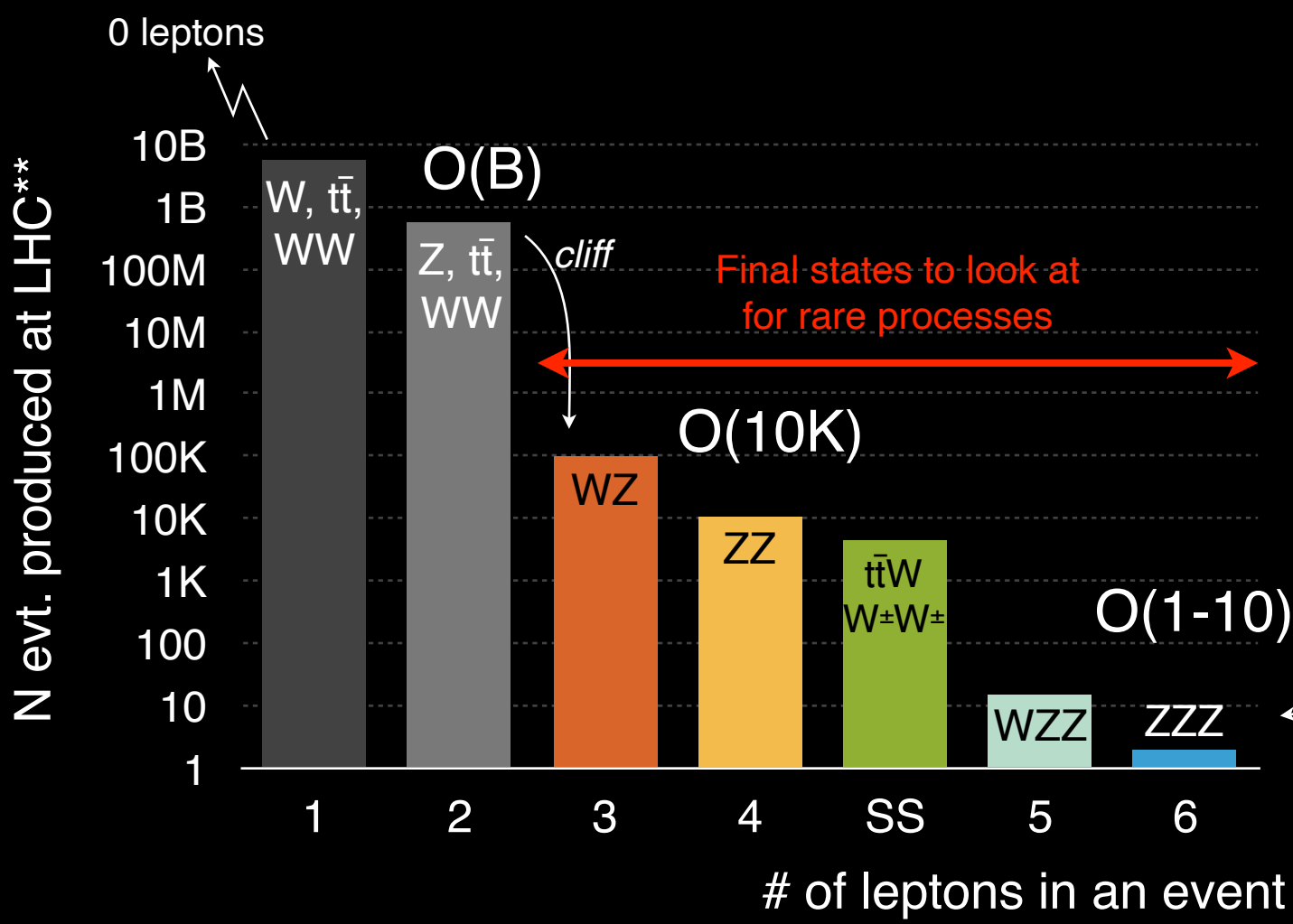
If one only looks at 5 or 6 lepton events, there will be very small backgrounds

Target large # of lepton events for multi-boson productions (∵ lower bkg.)

Overview of lepton physics at the LHC

Chang
UCSD

**N events estimated from W, Z, tt̄, WW, WZ, ZZ, tt̄W, WZZ, ZZZ cross section with theoretical branching fractions without detector effects and ignoring τ → e, μ



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Overview of lepton physics at the LHC

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UCSD

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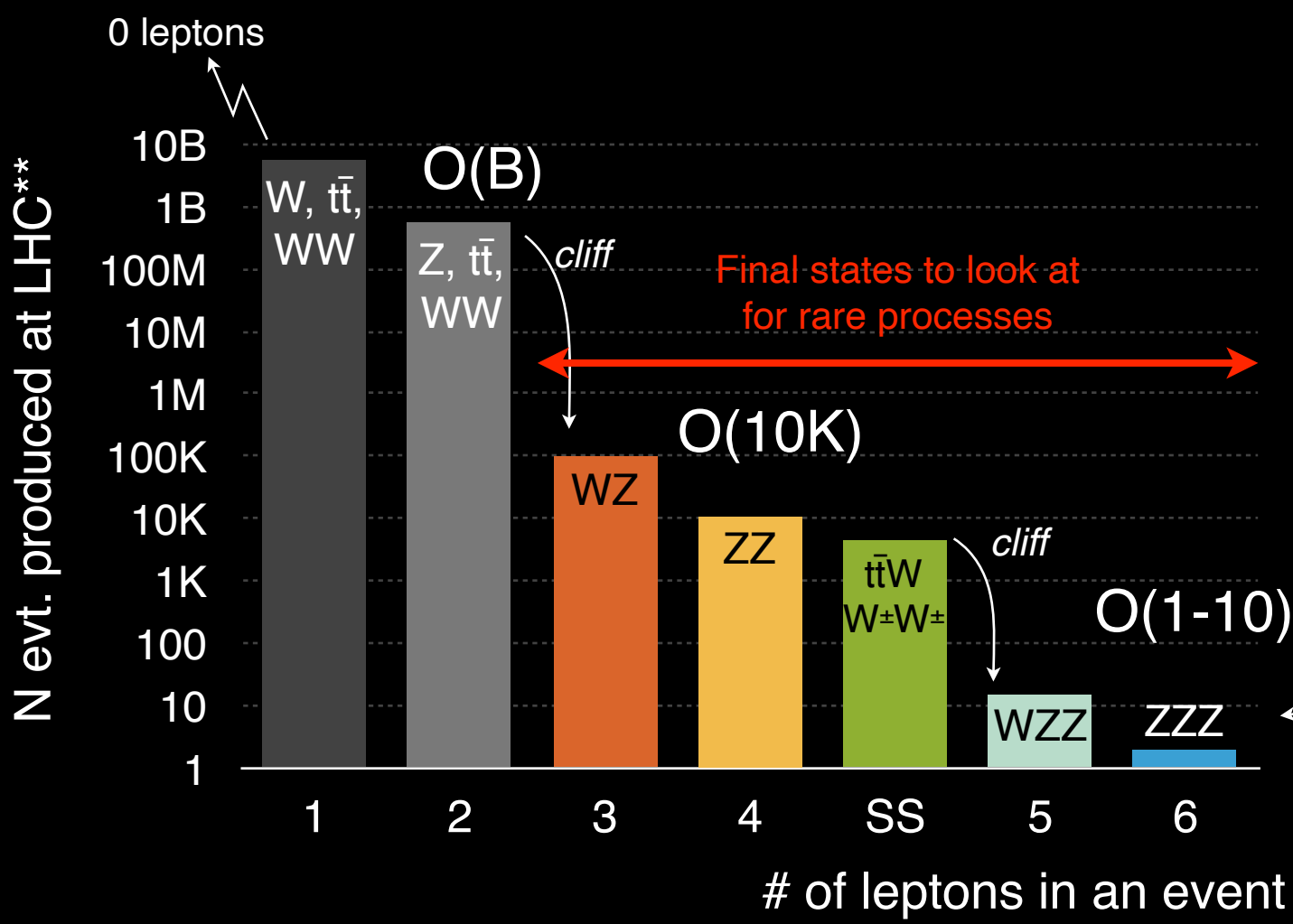

Target large # of lepton events for multi-boson productions (∵ lower bkg.)

Typical search strategy

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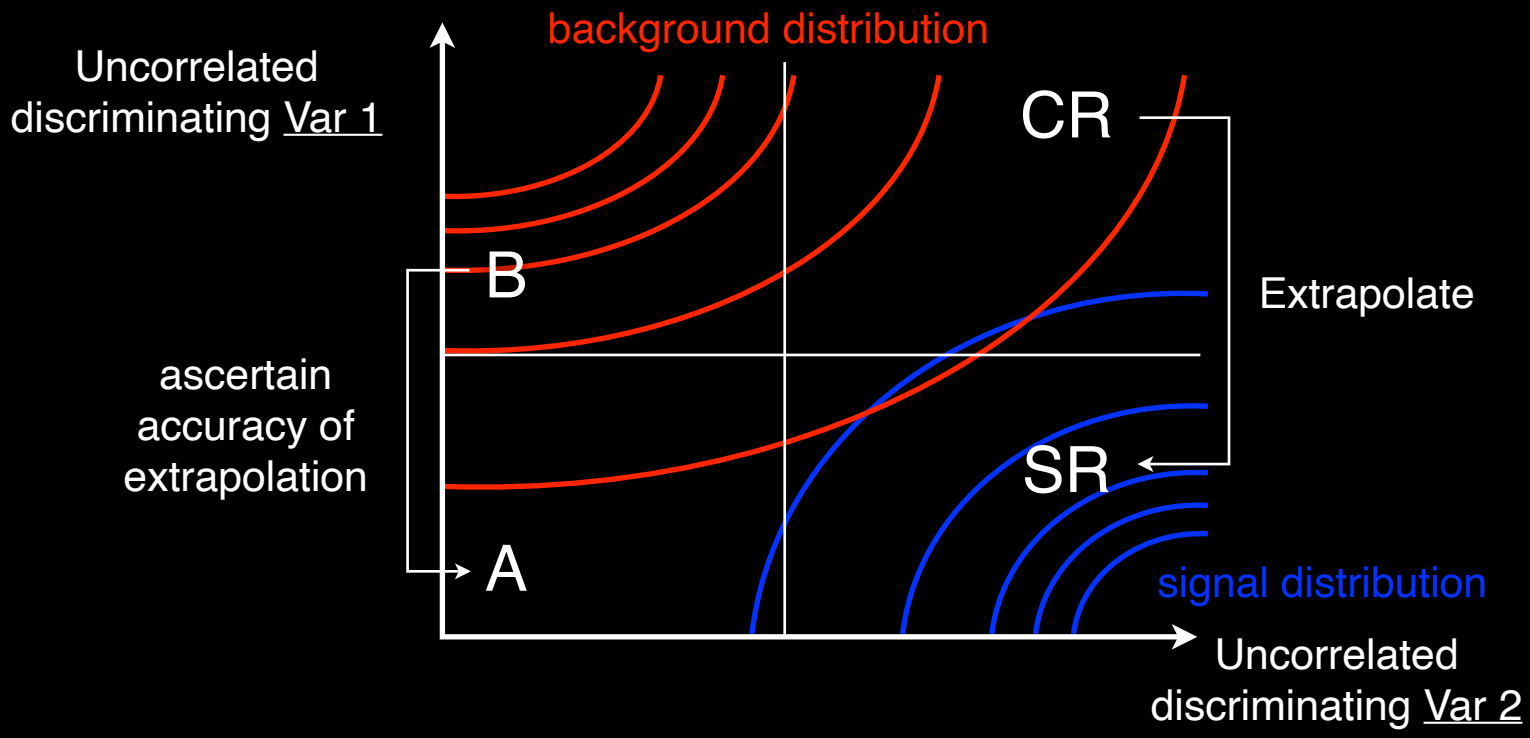
1. Define low background signal regions (SRs)
2. Estimate background yields by extrapolating from bkg. enriched control region (CR)
3. Ascertain accuracy of the extrapolation from a different sample



Make smart choices (brains) then execute to deliver (brawns)

Worldwide LHC Computing Grid (Brawns)

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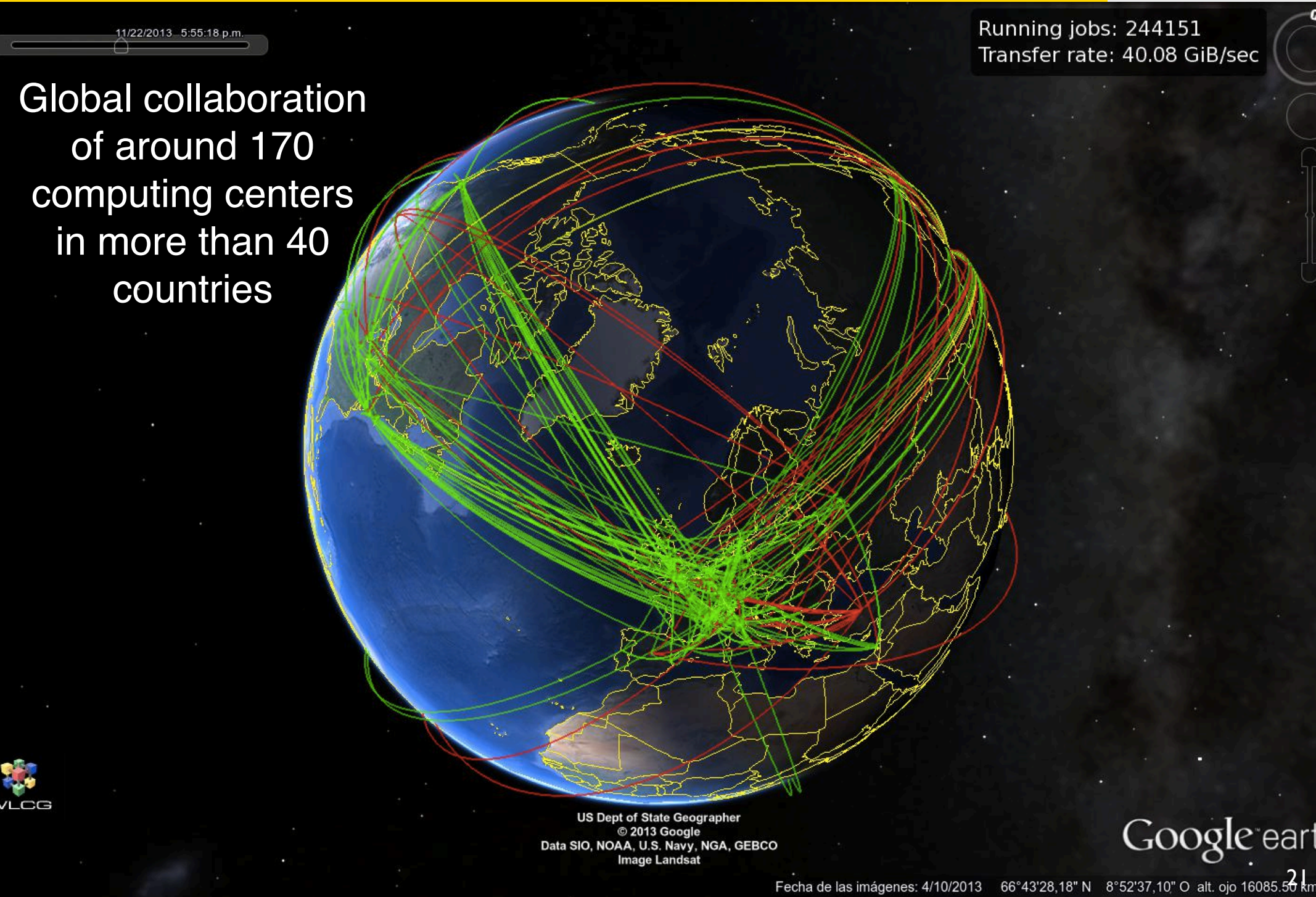

Details on the operation

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Detectors have ~70M channels

× few bytes per channel

× 40 MHz event rate

× 1/1000 zero-suppression

⇒ O(10) TB / s

× “one” year (4 × 10^6 secs)

⇒ O(100) Exabyte / year

× 1/100,000 event filtering

⇒ ~5 PB / year

After some processing e.g. CMS provides ~10 PB of data and simulation for analysis

This is reprocessed twice a year

Then this is further reduced by x10 and is processed monthly

Then we further reduce it x5 and can be done in a ~week

And then we further reduce it ~few TB that can be processed daily

Recent results in multi-boson physics

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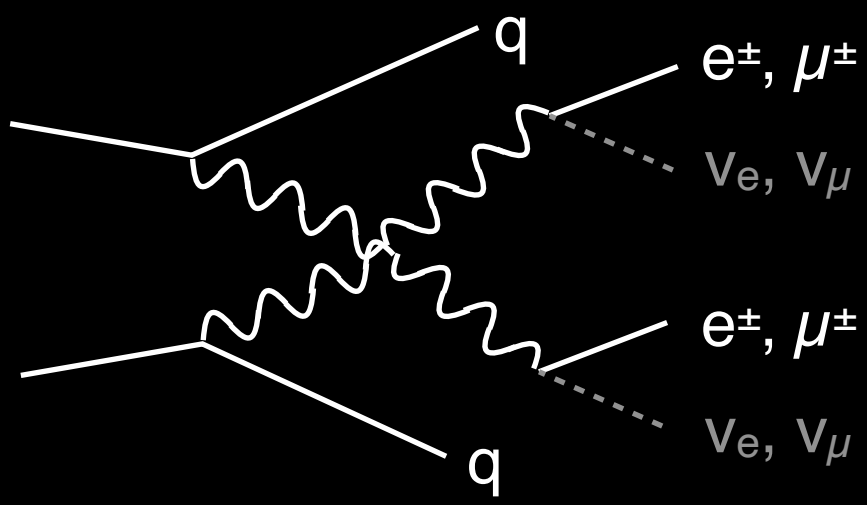
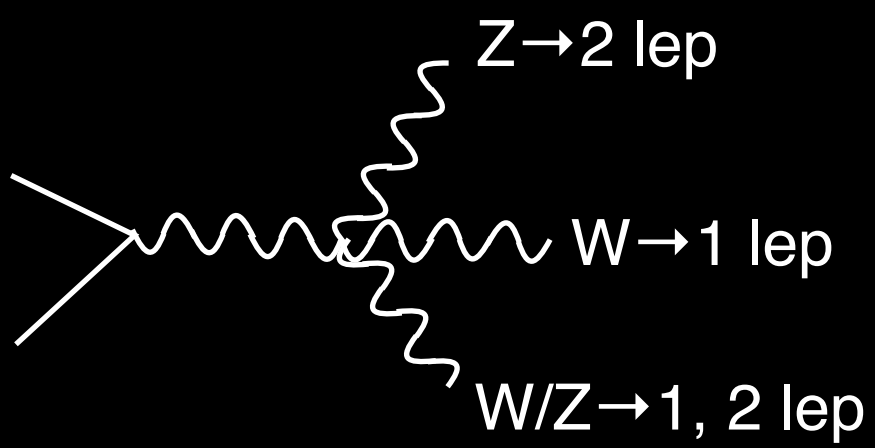
- Several important results have come out recently from both ATLAS and CMS
- I will highlight a few (from CMS)
- (Disclaimer: Rest of the talk from here on will focus mostly on CMS)

WW scattering



Same-sign dilepton + 2 quarks

Tri-boson process



4 or 5 leptons

⇒ electrons, muons, and jets reconstructions are crucial

CMS experiment measures leptons well

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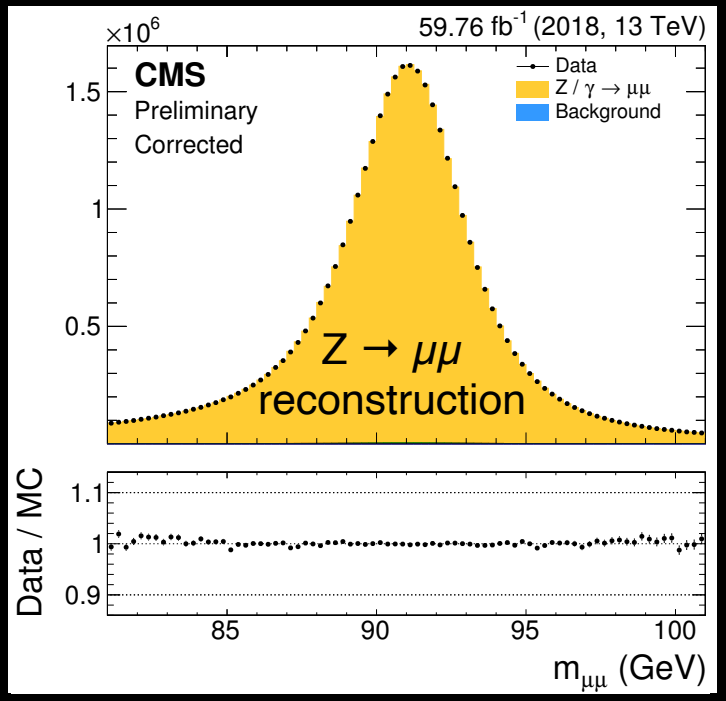
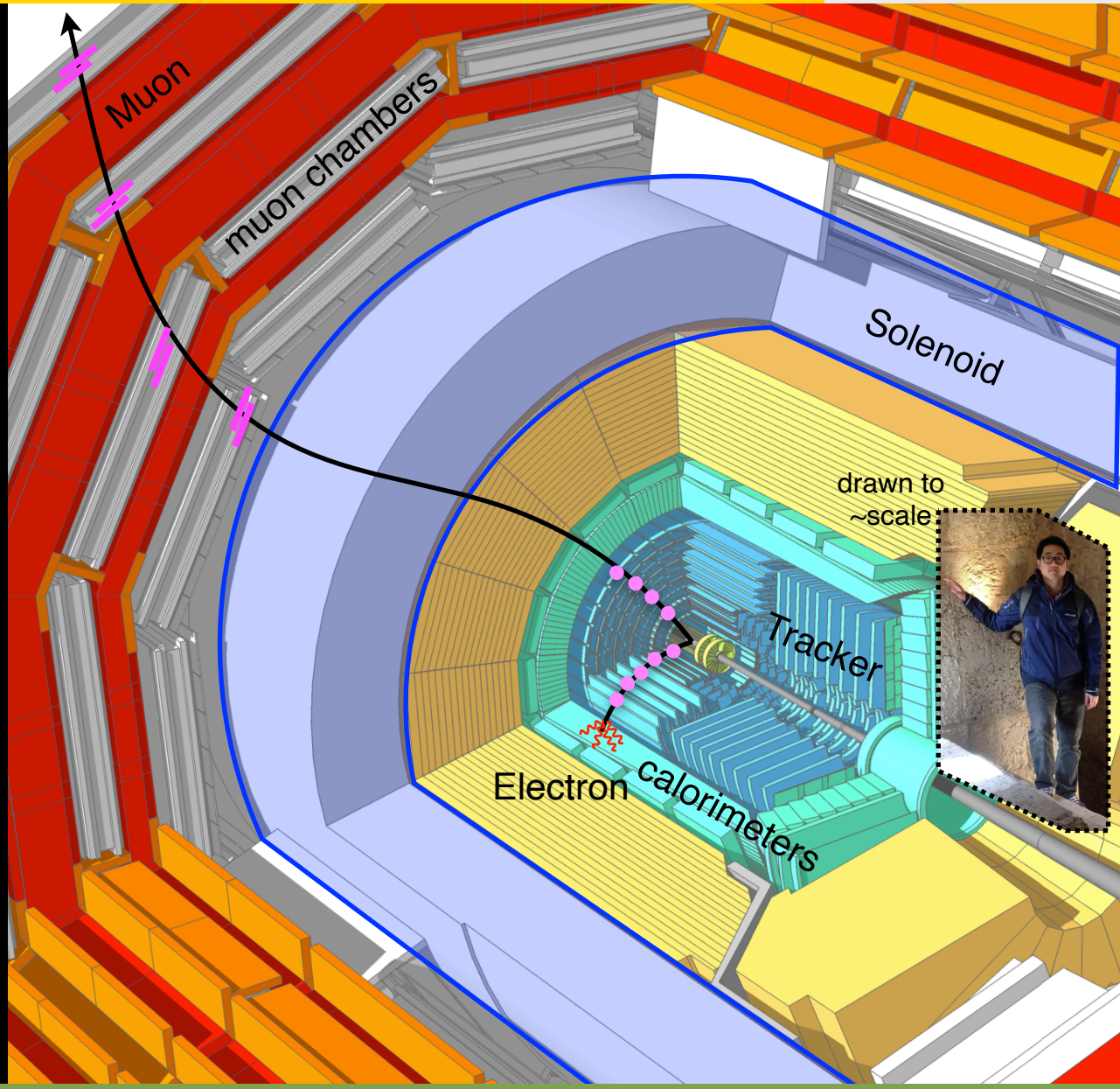
e/μ among the best measured particles at CMS by combining tracker, calorimeter, and chambers measurements

(1-2% resolution for well measured ones)





Excellent lepton reconstruction and simulation

Jet formation and identification

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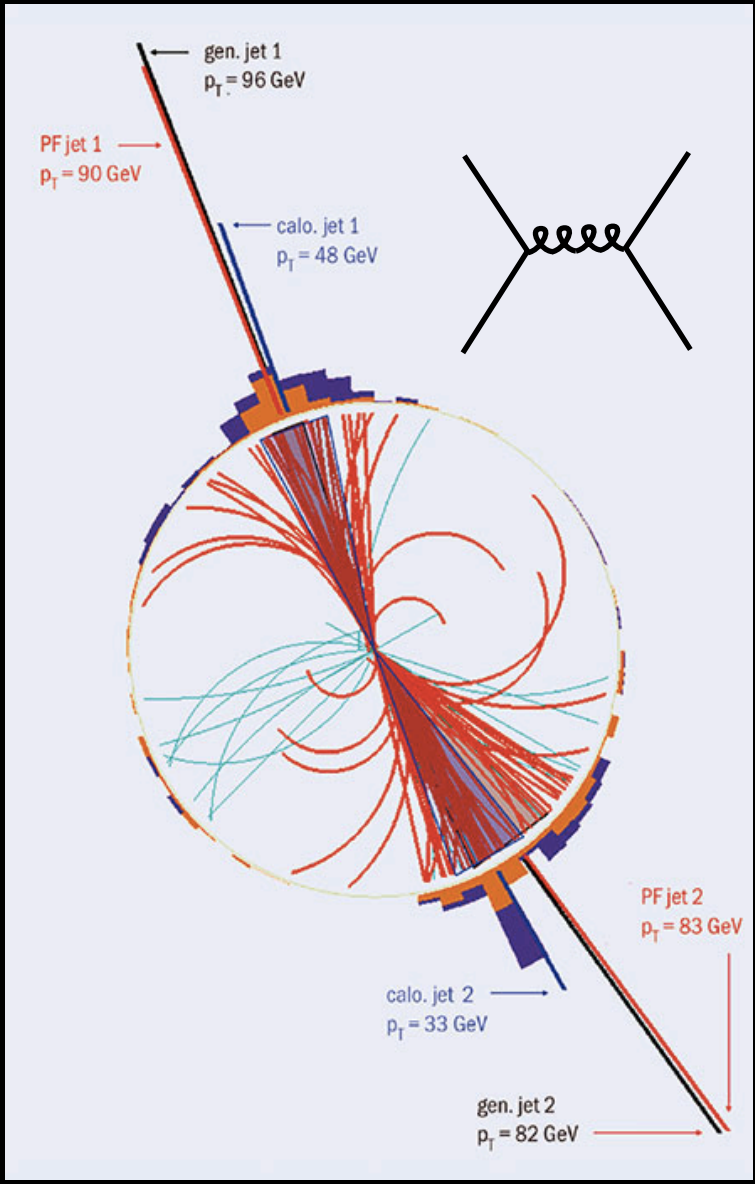
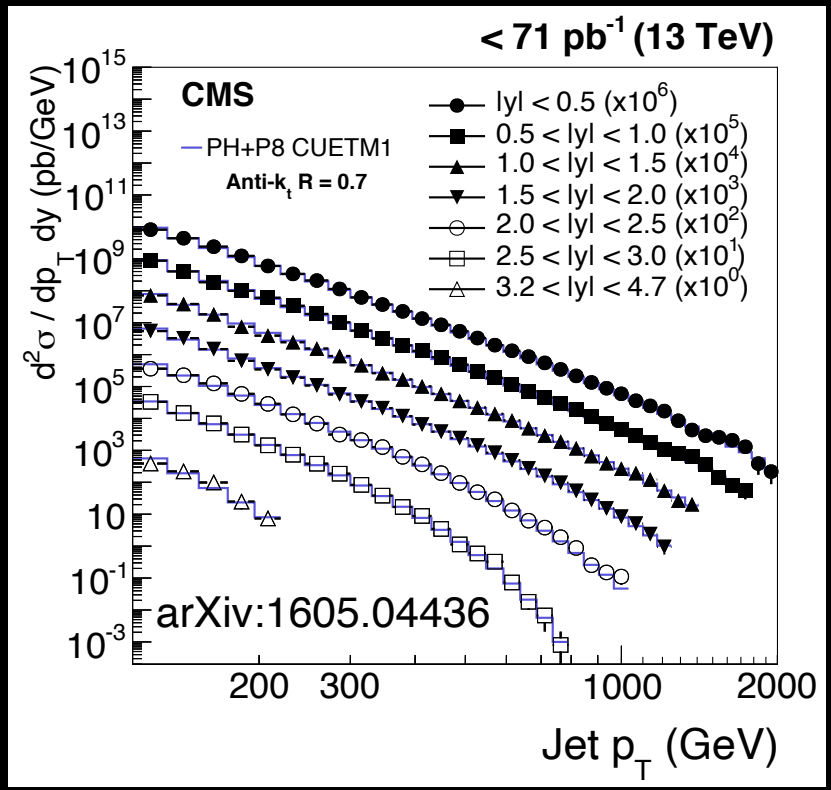


Quarks and gluons produced from pp collisions manifest as a "jet" of particles



Excellent jet reconstruction and simulation

Jets from vector boson scattering

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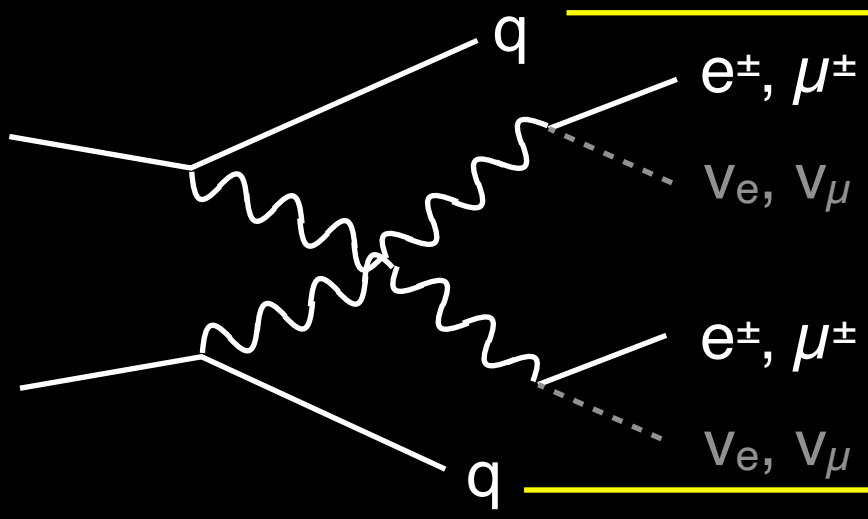
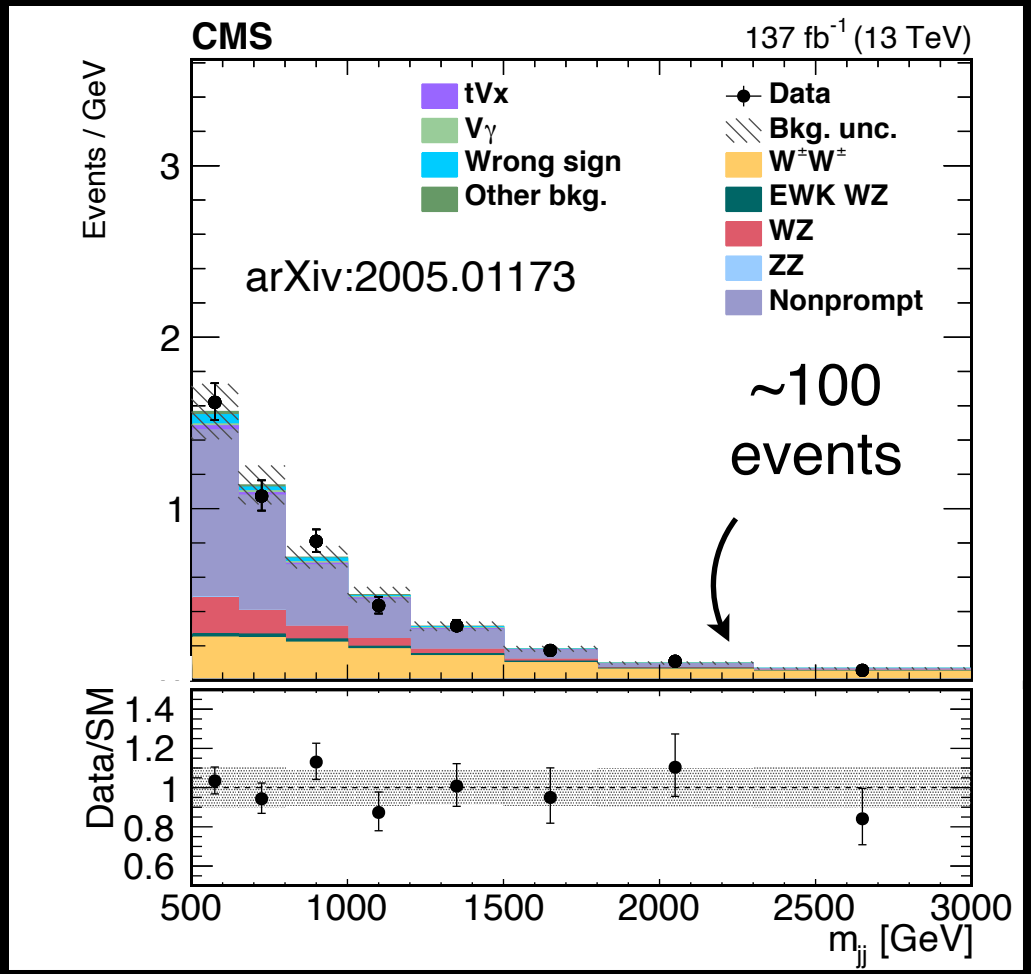
WW scattering



Same-sign dilepton + 2 quarks



Two jets from VBS process tend to have relatively high invariant mass

Jets from vector boson scattering

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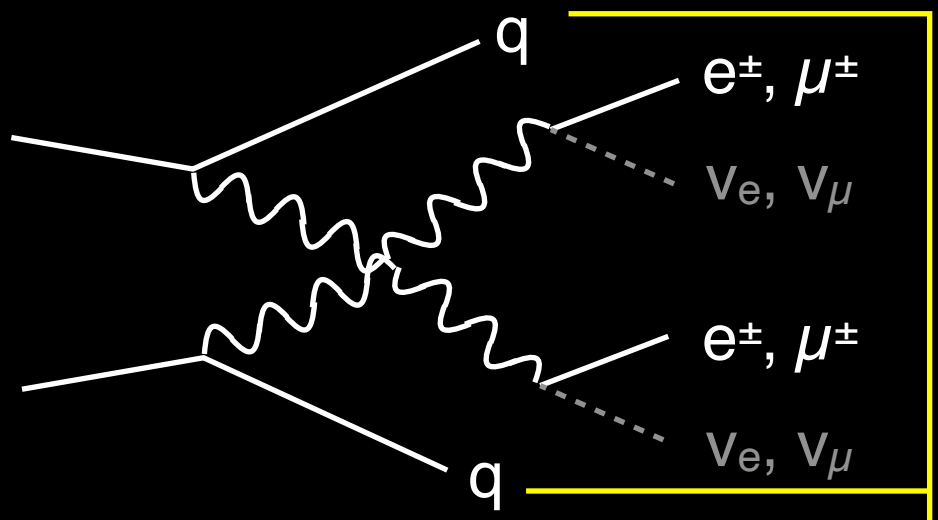
WW scattering



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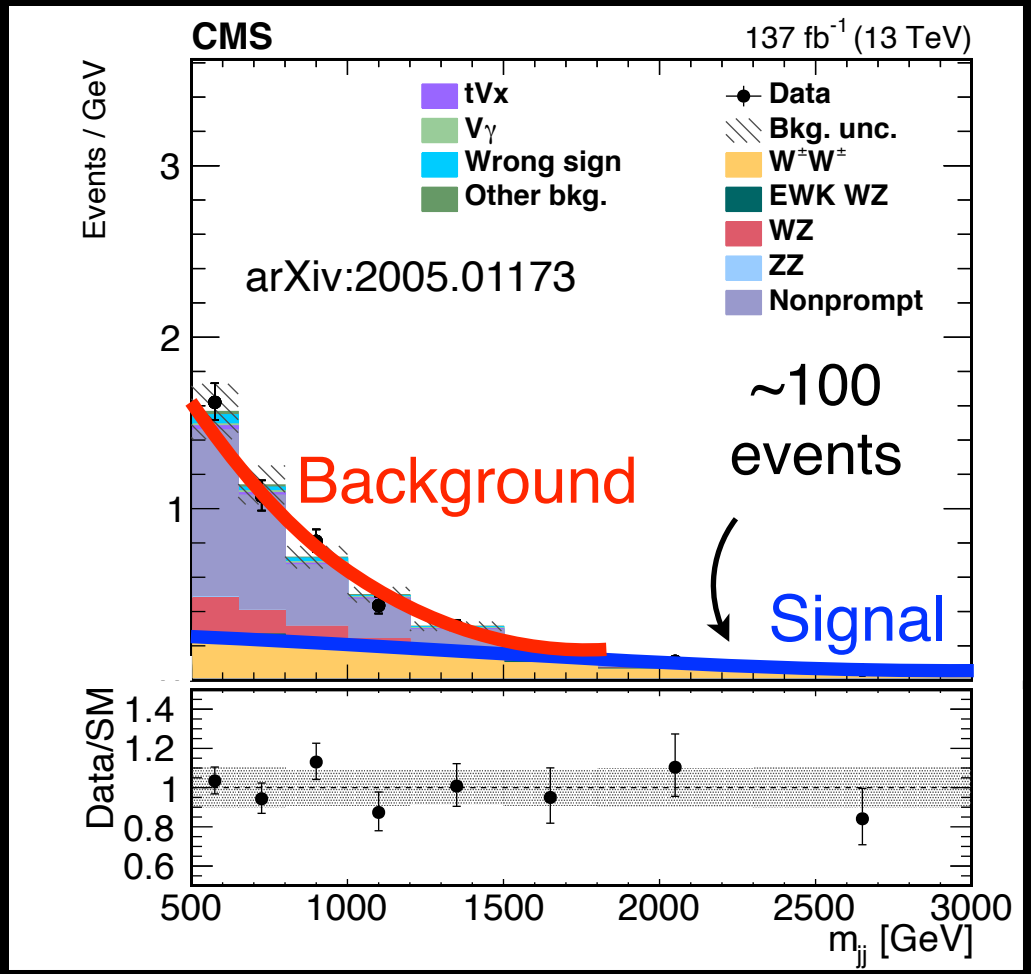

Two jets from VBS process tend to have relatively high invariant mass

Features of Z → ll decay

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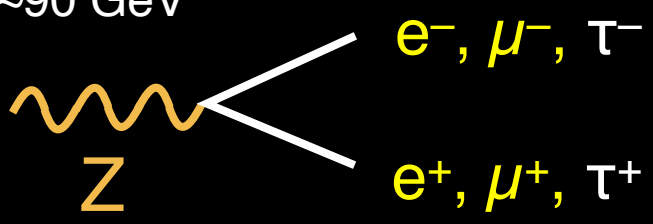
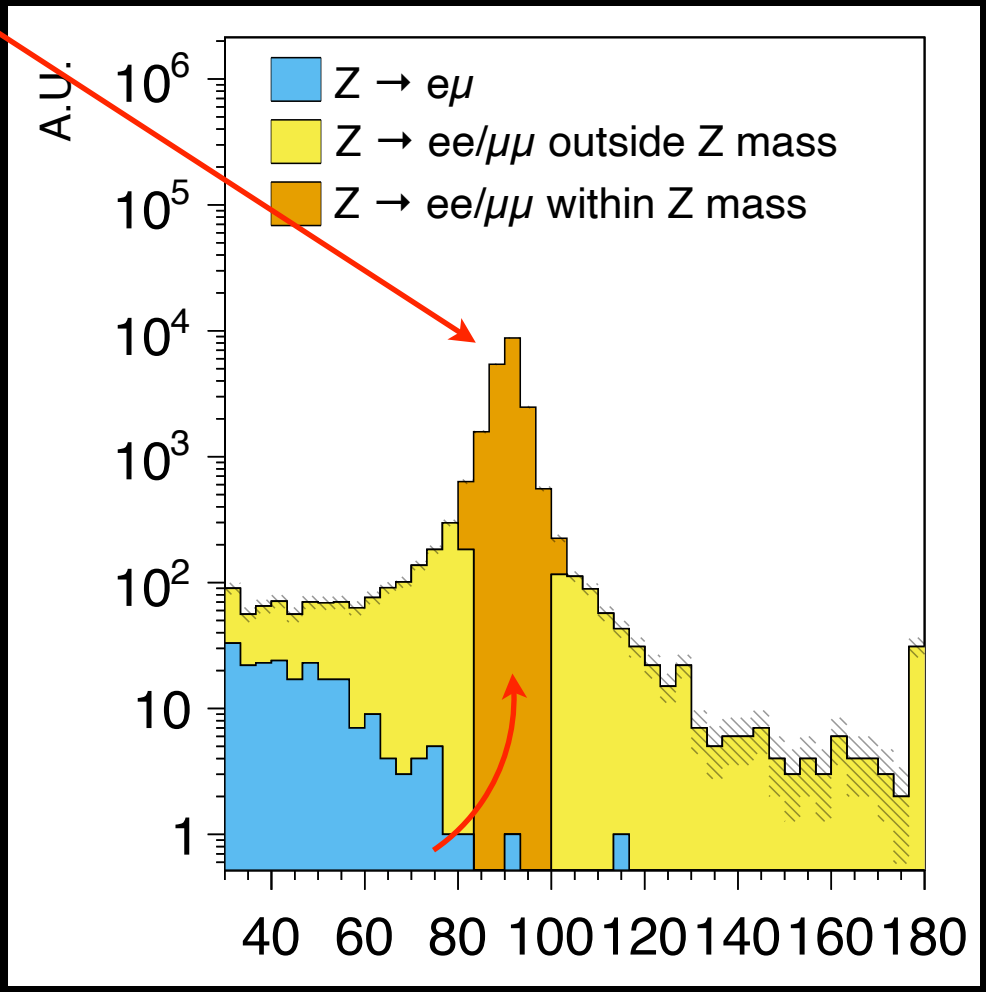
mass of Z
~90 GeV



~3% each flavor

Plot of dilepton mass from Z→ll decay



**Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV P_T cuts

Z decays predominantly to ee/*μμ* on-shell

Features of Z → ll decay

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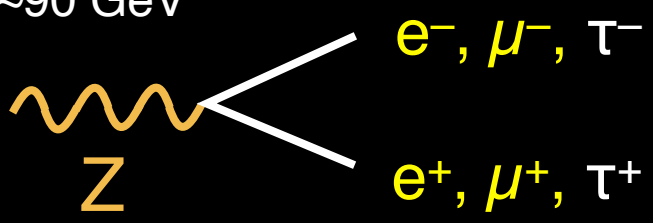
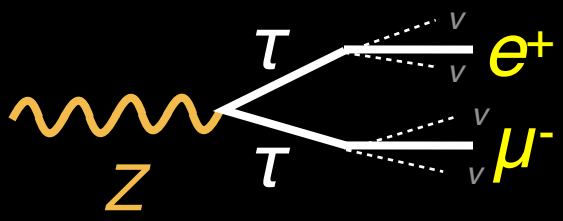
mass of Z
~90 GeV

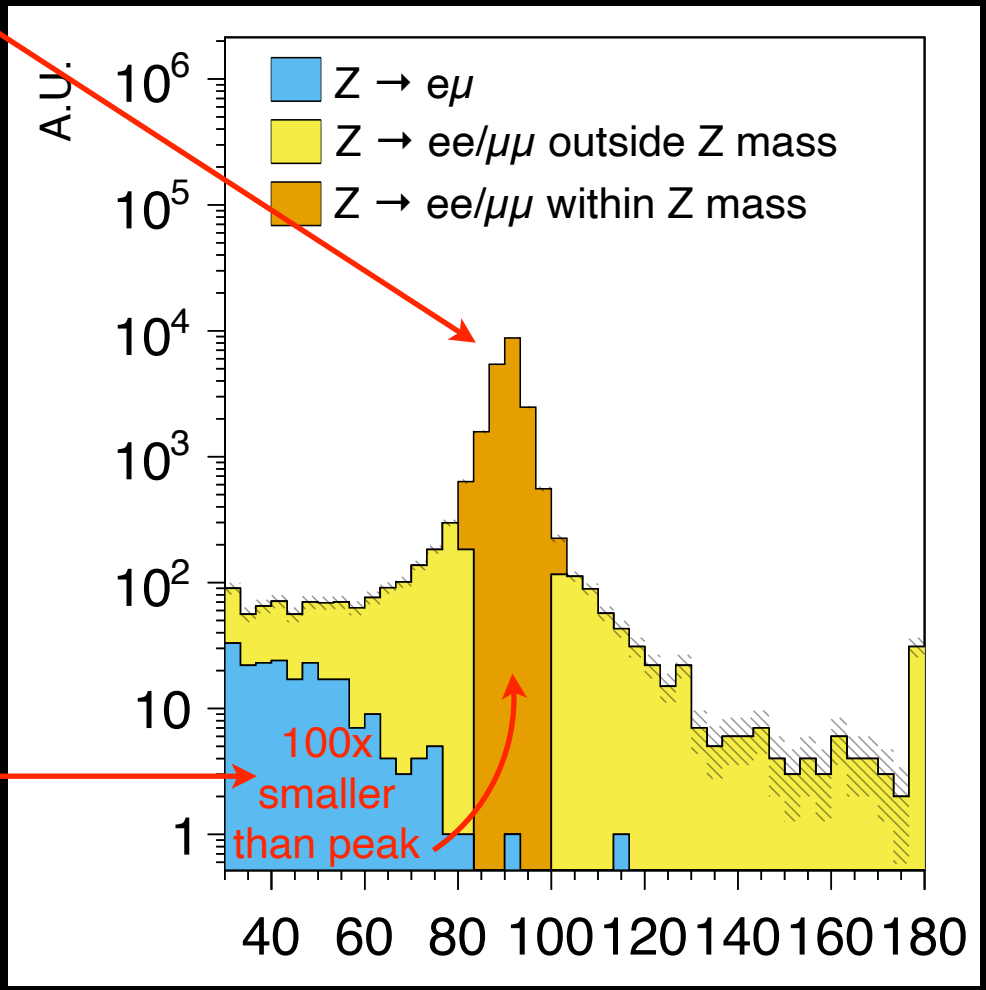


~3% each flavor



If one selects $e\mu$ final state, Z is reduced by 2 orders of magnitude
(e, μ from τ are soft)

Plot of dilepton mass from Z→ll decay



**Simulated w/ MadGraph/Pythia/Delphes with 25/10 GeV P_T cuts

Z decays predominantly to ee/μμ on-shell

Exploiting Z decay features

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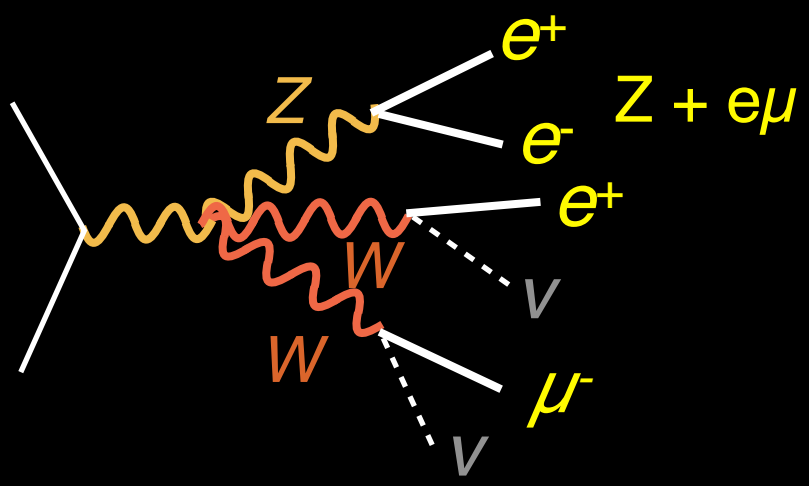
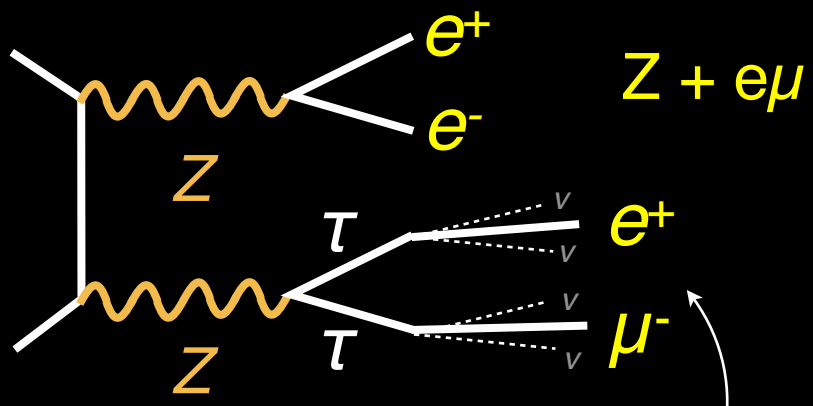
	Signal	Background
4 lepton		

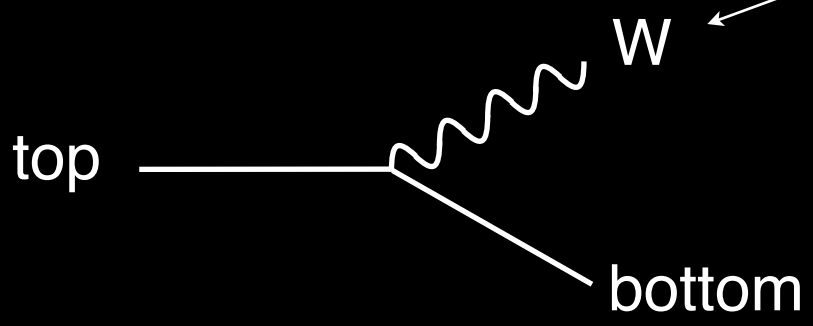
Highly suppressed
due to flavor choice

Flavor choice can reduce background while not affecting signal

Top quark decay features

Top quark is produced more abundantly than multi-bosons (see slide 9 for typical rates)

Produces W bosons that are not of our interest



When produced top quark decays ~100% of the time to b quark and a W boson

bottom quark has a long-lifetime (flight distance ~ 100s of μm)

⇒ Tag bottom quark and reject events with bottom quarks

Machine learning in LHC

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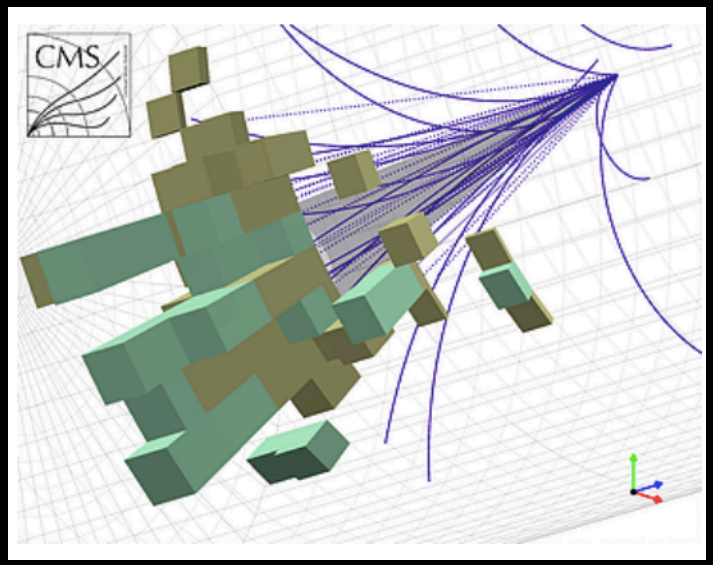
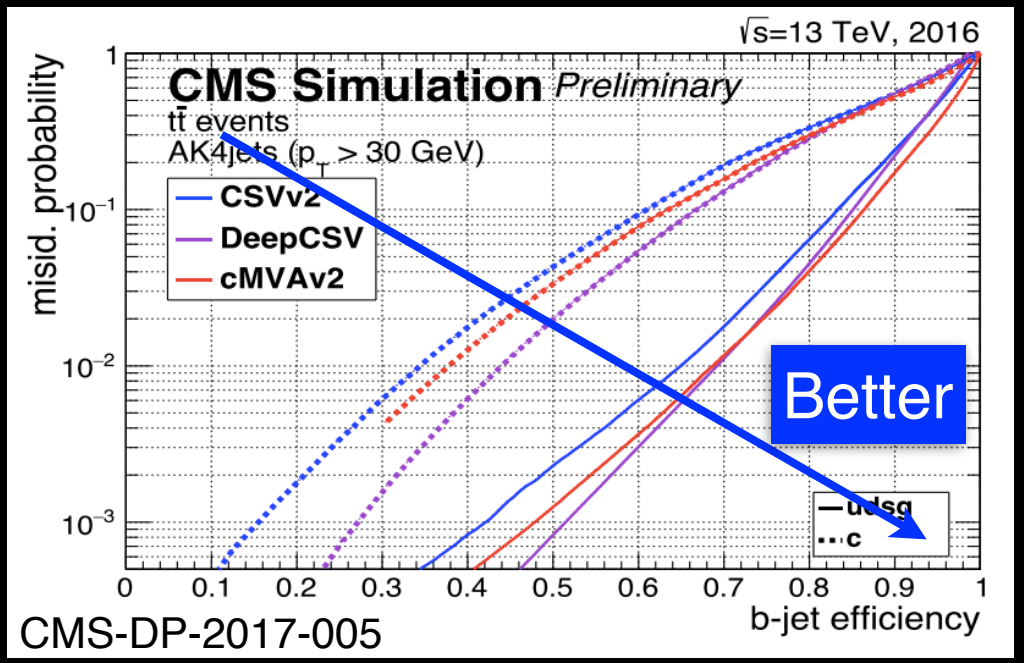
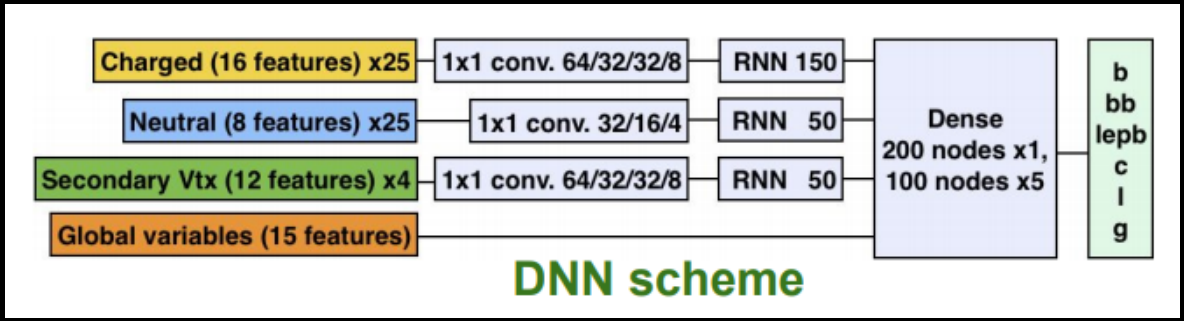
Was this from bottom quark?





Train deep neural network



b-tagging via machine learning is one of many successful application of ML that is continually growing in particle physics

b quark jets tagging

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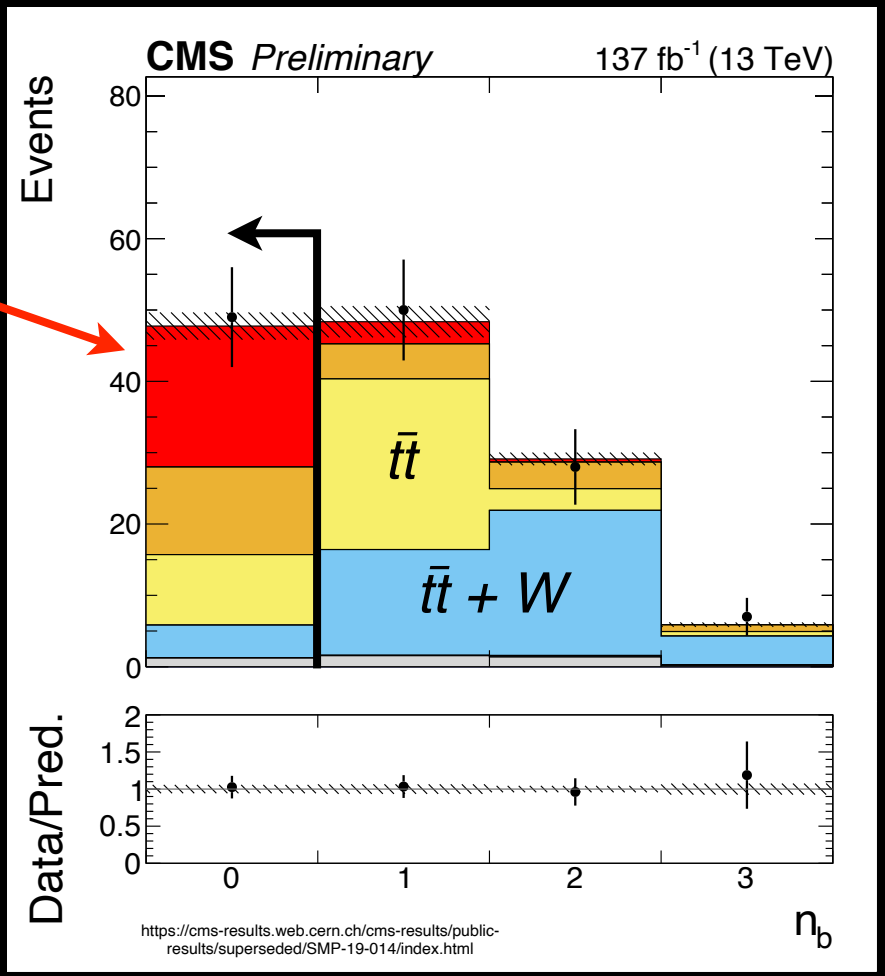
Tri-boson



Number of b-tagged jets in the event

Reject events with bottom quark to reduced backgrounds from top quark

Applying ML to event classifier

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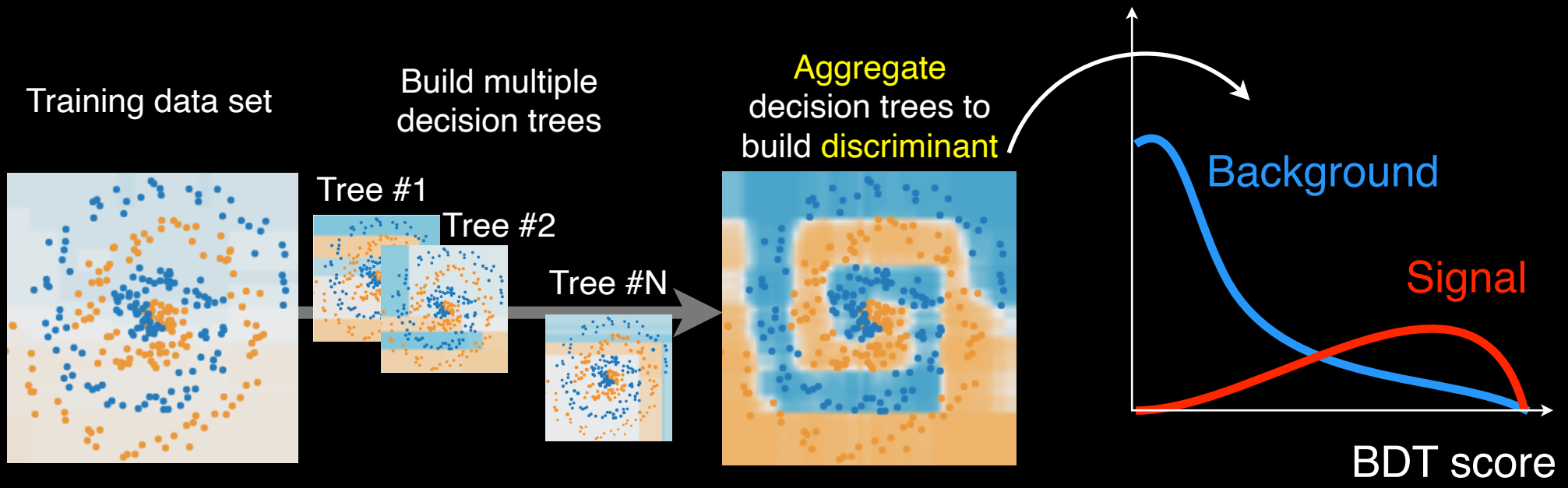
Boosted decision tree is widely used in many analyses at the LHC



https://arogozhnikov.github.io/2016/07/05/gradient_boosting_playground.html

Train dedicated boosted decision trees to maximize sensitivity

WWZ signal vs. ZZ or ttZ backgrounds

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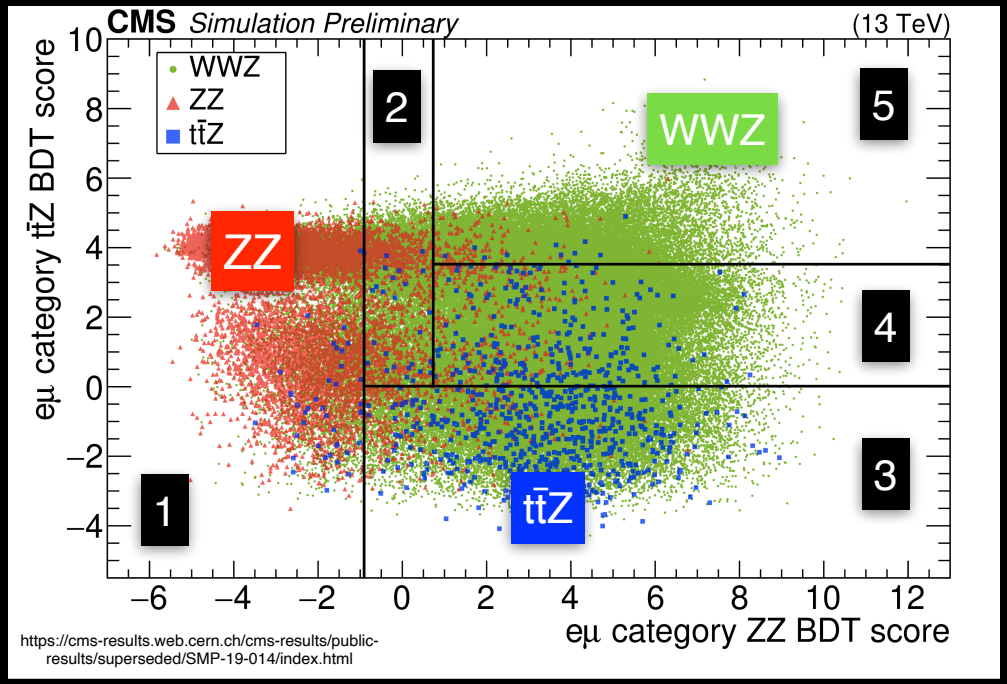
2D plane in BDT scores

More WWZ like

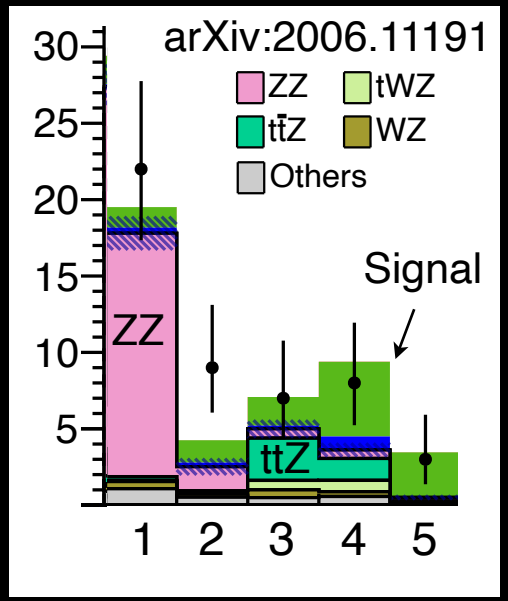
More ttZ like



More ZZ like

More WWZ like

5 bins are created from 2D planes



O(10) signal events

Use multi-classifier machine learning technique to maximize sensitivity

Very rare 5 lepton events

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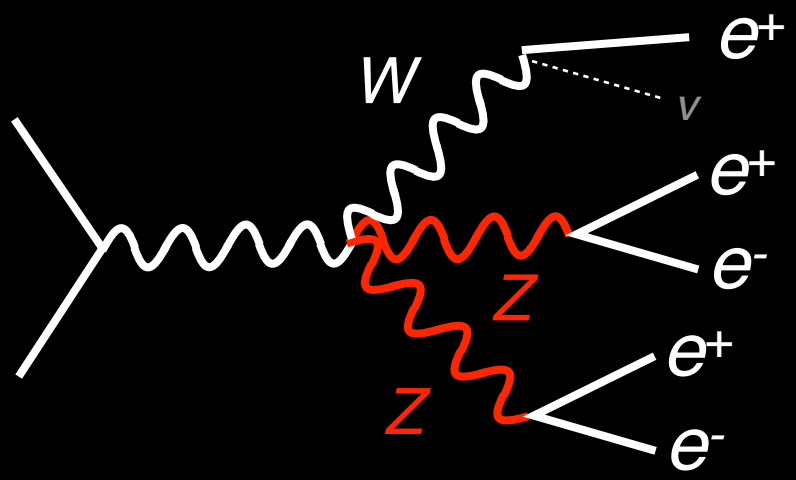

- Once you make signal selection there aren't much background left
- Expected total of 2 events with 3:1 signal to background ratio
- And we've observed 3 events
- Only now becoming accessible to study!

5 lepton events are clean and are becoming accessible for the first time

5 lepton event display

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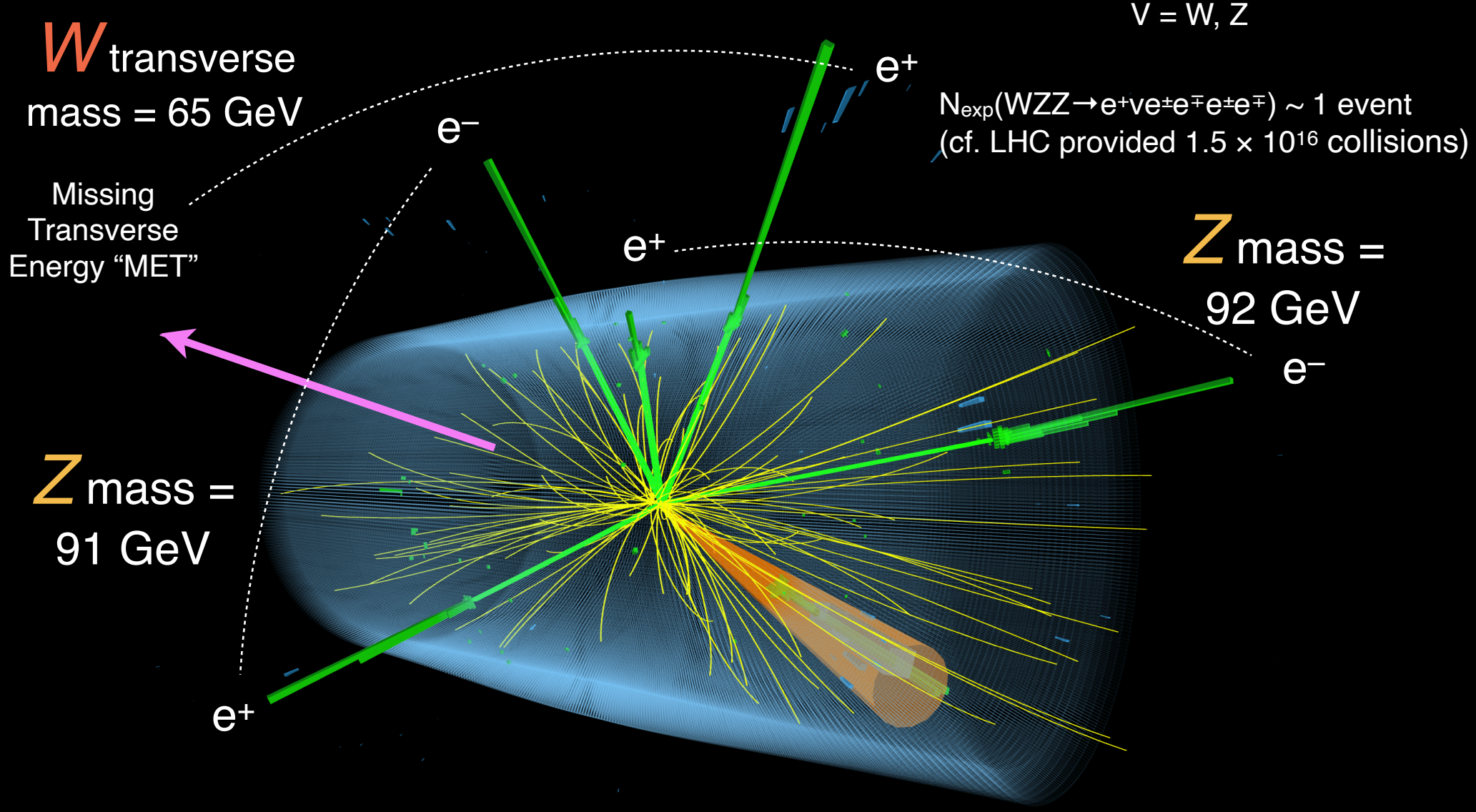
CMS experiment at the LHC, CERN
Data recorded: 2016-Oct-09 21:24:05.010240 GMT
Run 282735, Event No. 989682042 LS 491



V = W, Z

$N_{exp}(WZZ \rightarrow e^{+}\nu e^{\pm}e^{\mp}e^{\pm}e^{\mp}) \sim 1$ event
(cf. LHC provided 1.5×10^{16} collisions)

WW scattering results

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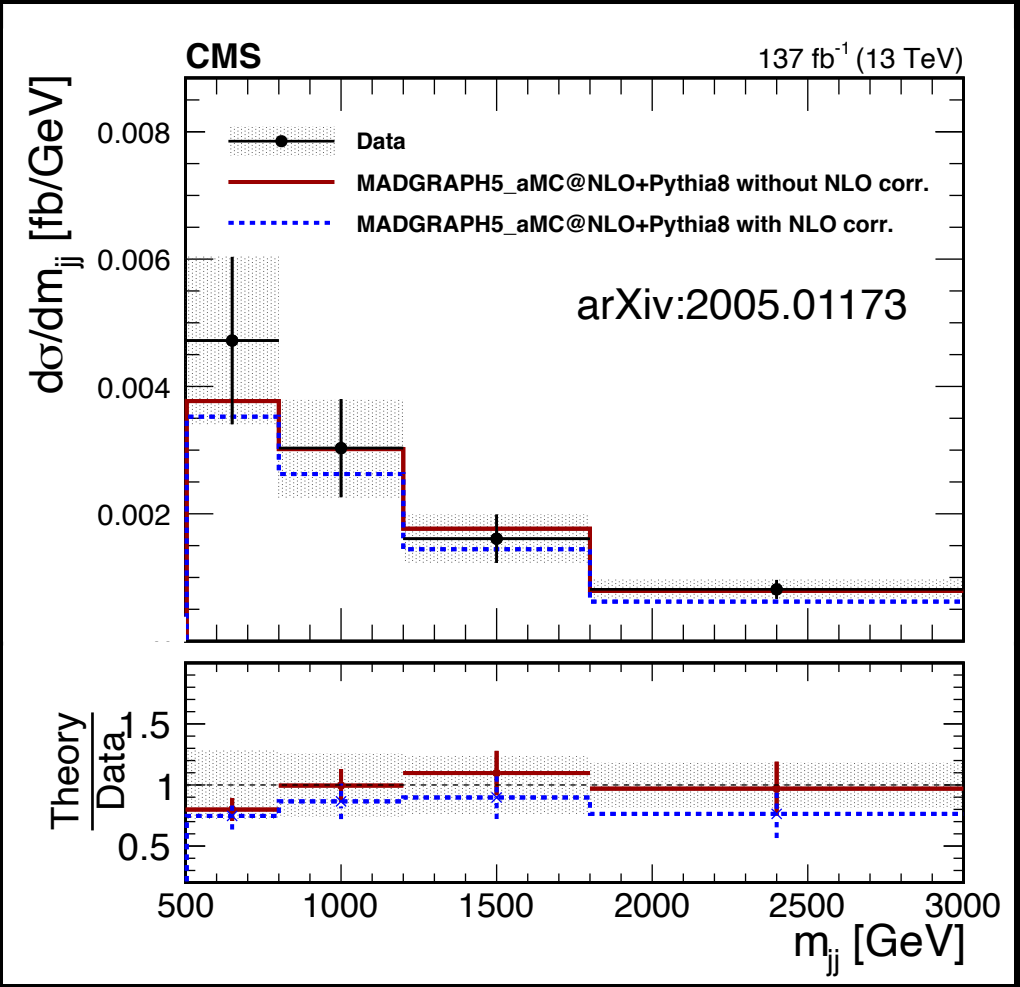

- O(100) events observed
- Measure the production rates as a function of important variables
- The measured cross section is compatible with the SM

WW scattering cross section has been measured and found to be consistent with SM

Results

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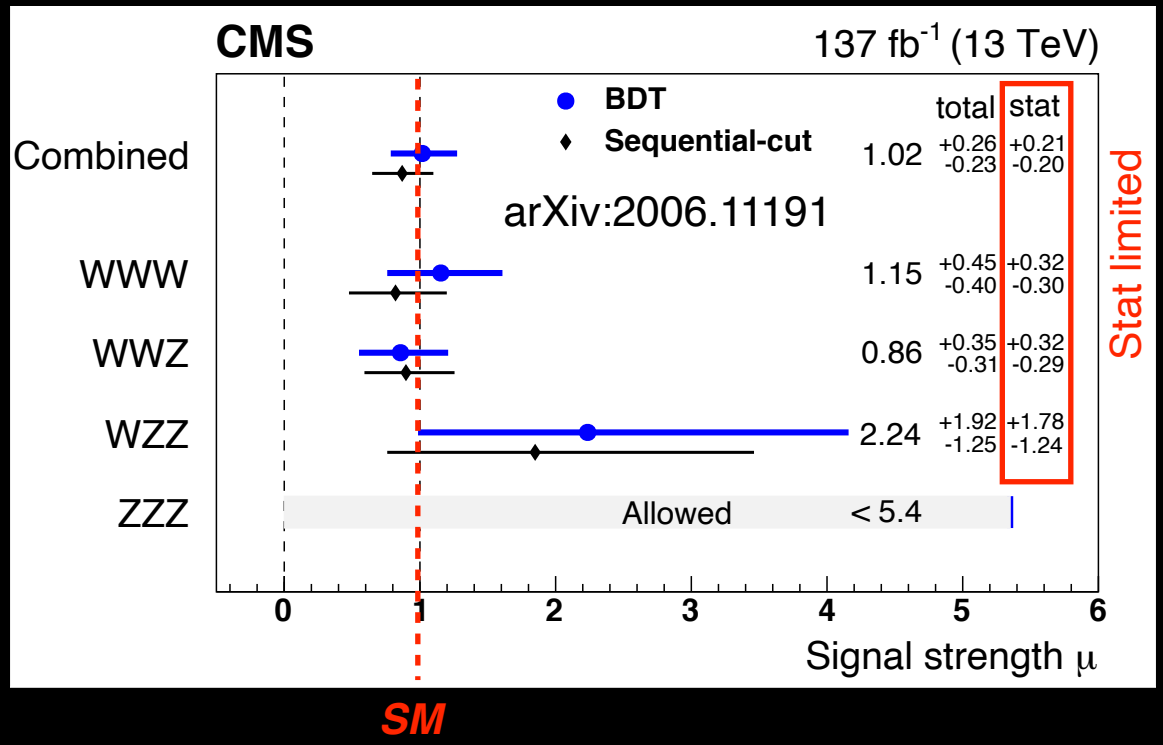
O(10) events only
⇒ measure total cross section

VVV mode	Significance [σ]
WWW	**3.3** (3.1)
WWZ	**3.4** (4.1)
WZZ	1.7 (0.7)
ZZZ	0 (0.9)
Combined	**5.7** (5.9)



Signal strength μ = Measured cross section / Theoretical cross section

- We have observed production of three massive gauge boson for the first time!
- We also found evidences separately for the WWW and WWZ production.
- The cross sections are compatible with the standard model expectation.

First observation of VVV and evidences for WWW and WWZ productions

HL-LHC

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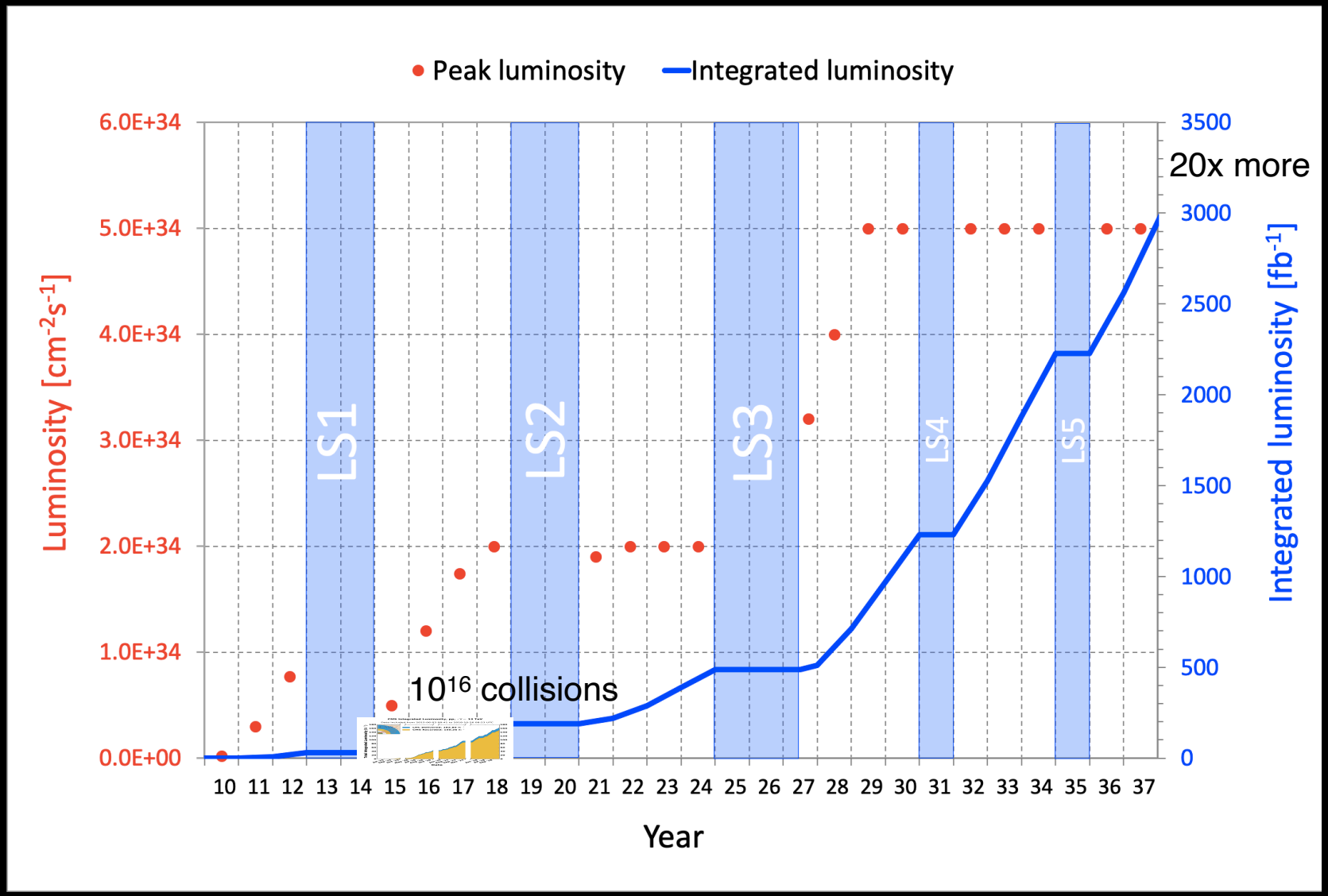

We've only seen ~5% of the total data LHC will provide in its lifetime

Future of multi-boson interaction

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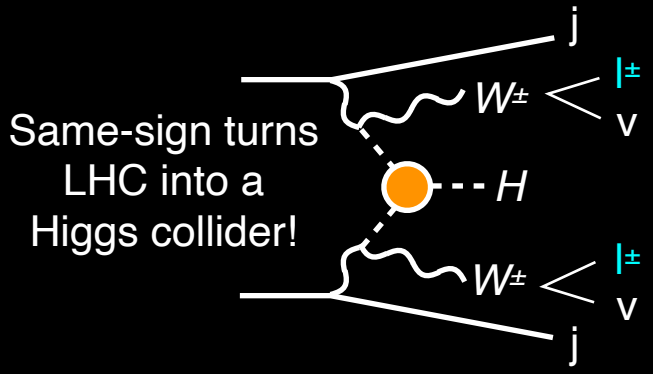
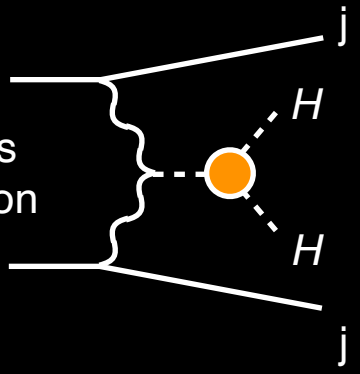
$pp \rightarrow W^{\pm}W^{\pm}H\,jj$



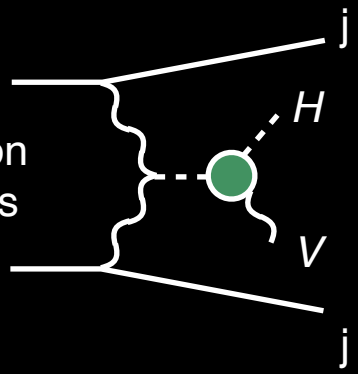
Same-sign turns LHC into a Higgs collider!

$pp \rightarrow HH\,jj$



Di-higgs production

$pp \rightarrow VH\,jj$



VH production with VBS jets

arXiv:1812.09299 Henning, Lombardo, Riembau, Riva
arXiv:2006.09374 Stolarski, Wu

There are many more rare events that we should search for and study

Future colliders

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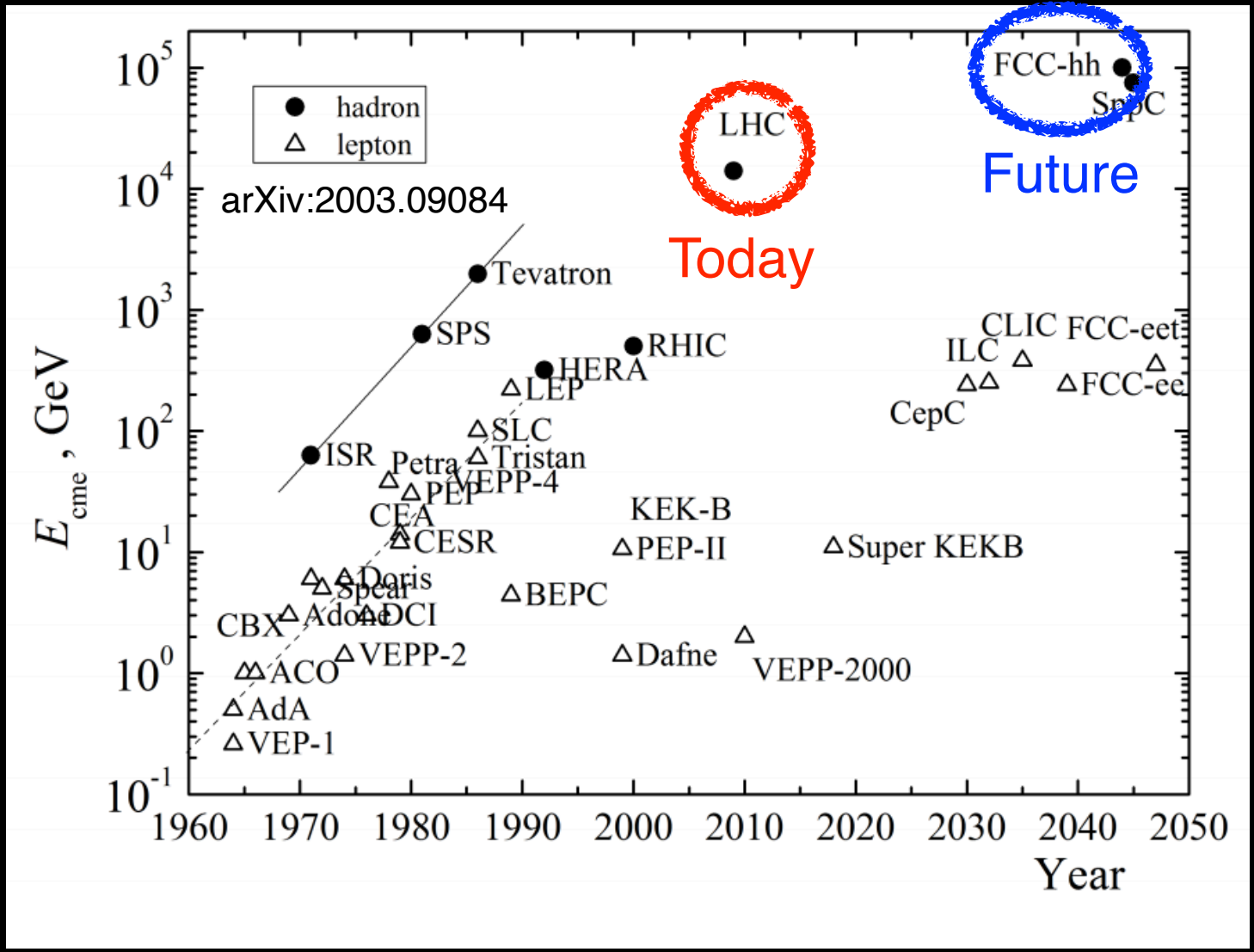

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least **100 TeV** …"

— 2020 Update of the European Strategy for Particle Physics

Ultimately FCC-hh with 100 TeV collider will map out the Higgs potential

Summary

- Building on the discovery of the Higgs boson we must study the multi-boson interactions and its compatibility with the Standard Model
- LHC has now collected large enough data to allow for the first time study some of the rare multi-boson processes
- Recently we have made an observation of triboson and established evidence for for several important multi-boson processes
- In the future with 20x more data many more interesting processes will also be studied as well

Electroweak sector

$$\mathcal{L}_\phi = D_\mu \phi^\dagger D_\mu \phi + \mu^2(\phi\phi^\dagger) - \frac{\lambda}{4}(\phi\phi^\dagger)^2 - \frac{1}{4}W^{i\mu\nu}W^i_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$

$$\phi(x) = \begin{pmatrix} 0 \\ \frac{v+H(x)}{2} \end{pmatrix}$$

$$D_\mu = \partial_\mu + i\frac{g}{2}\sigma_j W^j_\mu + 2ig'Y B_\mu$$

$$\begin{aligned}\mathcal{L}_\phi = & \frac{1}{2}(\partial_\mu H \partial^\mu H) - \mu^2 H^2 \\ & -\frac{1}{4}(\partial_\mu W_{i\nu} - \partial_\nu W_{i\mu})(\partial^\mu W_i^\nu - \partial^\nu W_i^\mu) \\ & +\frac{1}{8}g^2v^2(W_{1\mu}W^{1\mu} + W_{2\mu}W^{2\mu}) \\ & +\frac{1}{8}v^2(gW_{3\mu} - g'B_\mu)(gW_3^\mu - g'B^\mu) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\end{aligned}$$

Title