Portraying Double Higgs at the Large Hadron Collider

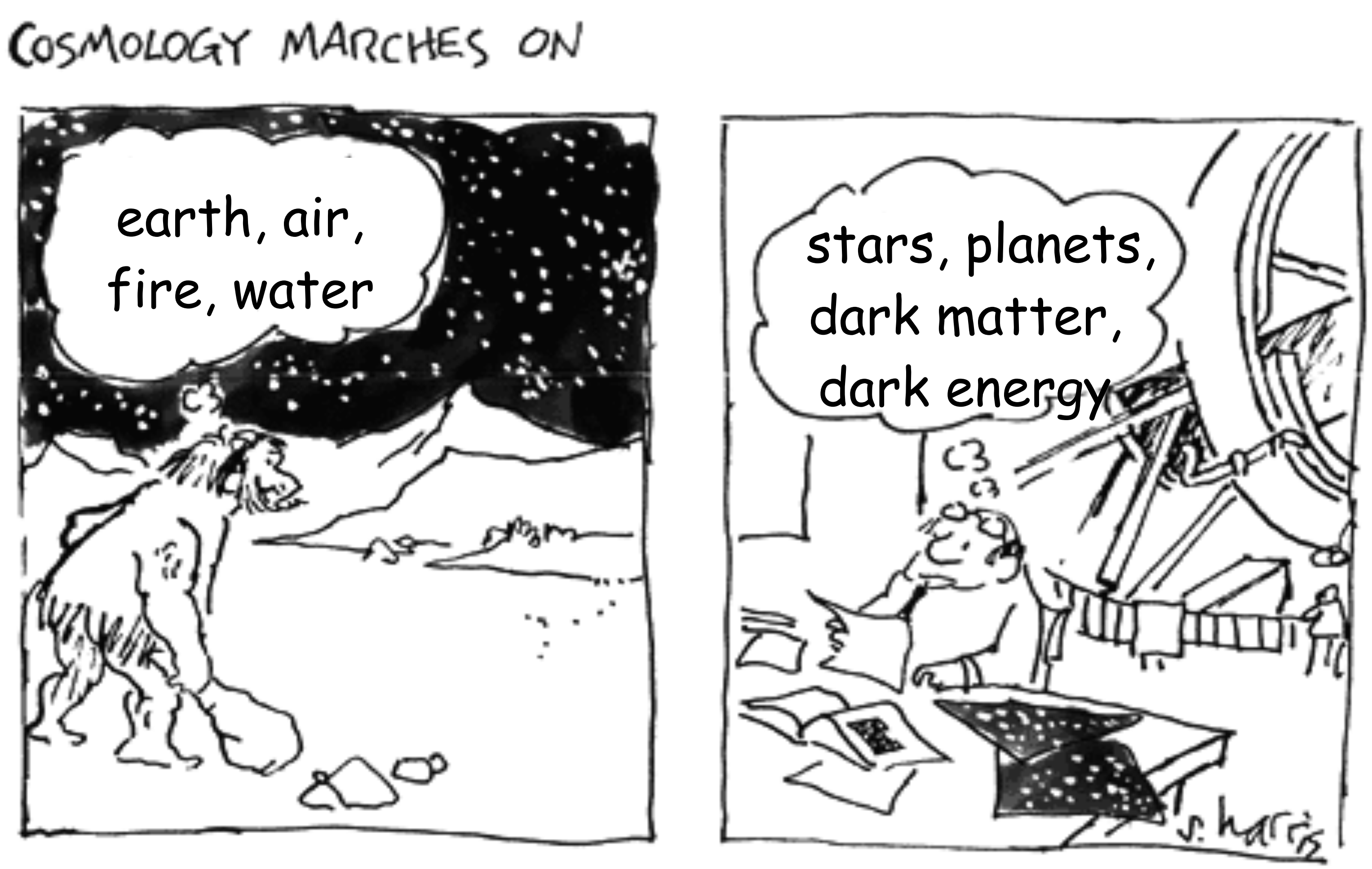
K.C. Kong

University of Kansas

Symposium on
Artificial Intelligence for Science, Industry and Society
October 21-25, 2019
Mexico City, UNAM

What is the universe made of?

- An age old question, but we live at a particularly interesting time:
  – We know how "big" the universe is.
  – We have no idea what most of it is made of.
- How does the universe work?



See overview talk by Michael Kagan

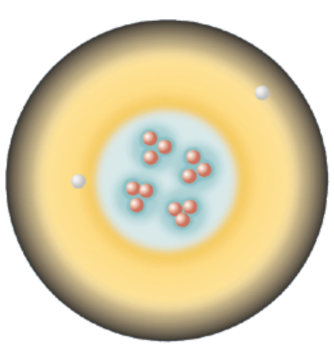
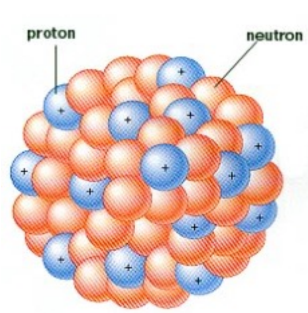
Physical Sciences

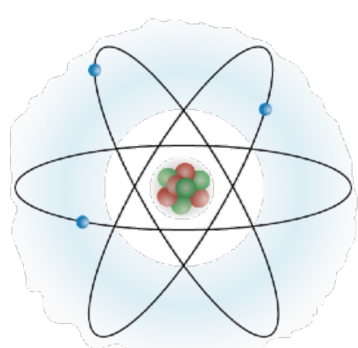
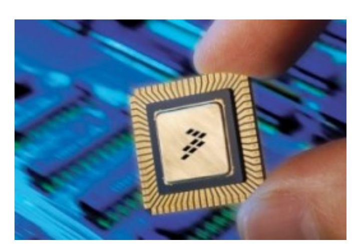
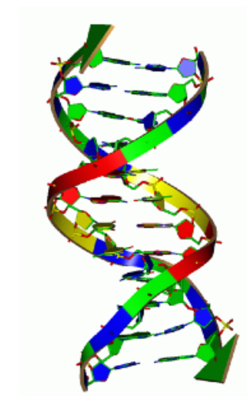
Mathematics | Physics and Astronomy | Chemistry | Earth System Science

Particle Physics | Atomic Physics | Biological Physics | Cosmology

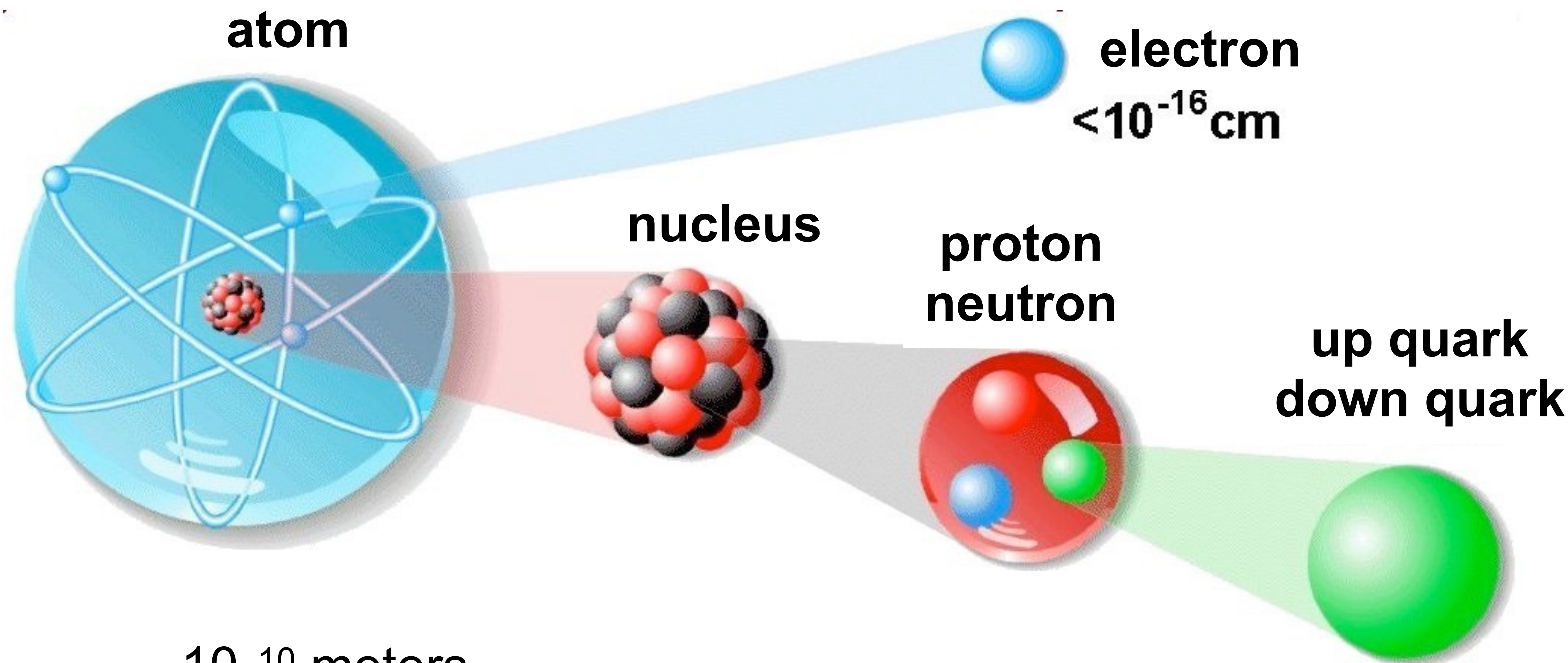
small ⟷ big

Nuclear Physics | Condensed Matter Physics | Astrophysics

SMALL: STATE OF THE ART



10^{-10} meters (thickness of human hair ~ 10^{-5} m)

10^{-14} meters

10^{-15} meters

$< 10^{-18}$ meters

Standard Model
(Periodic Table for Elementary Particles)

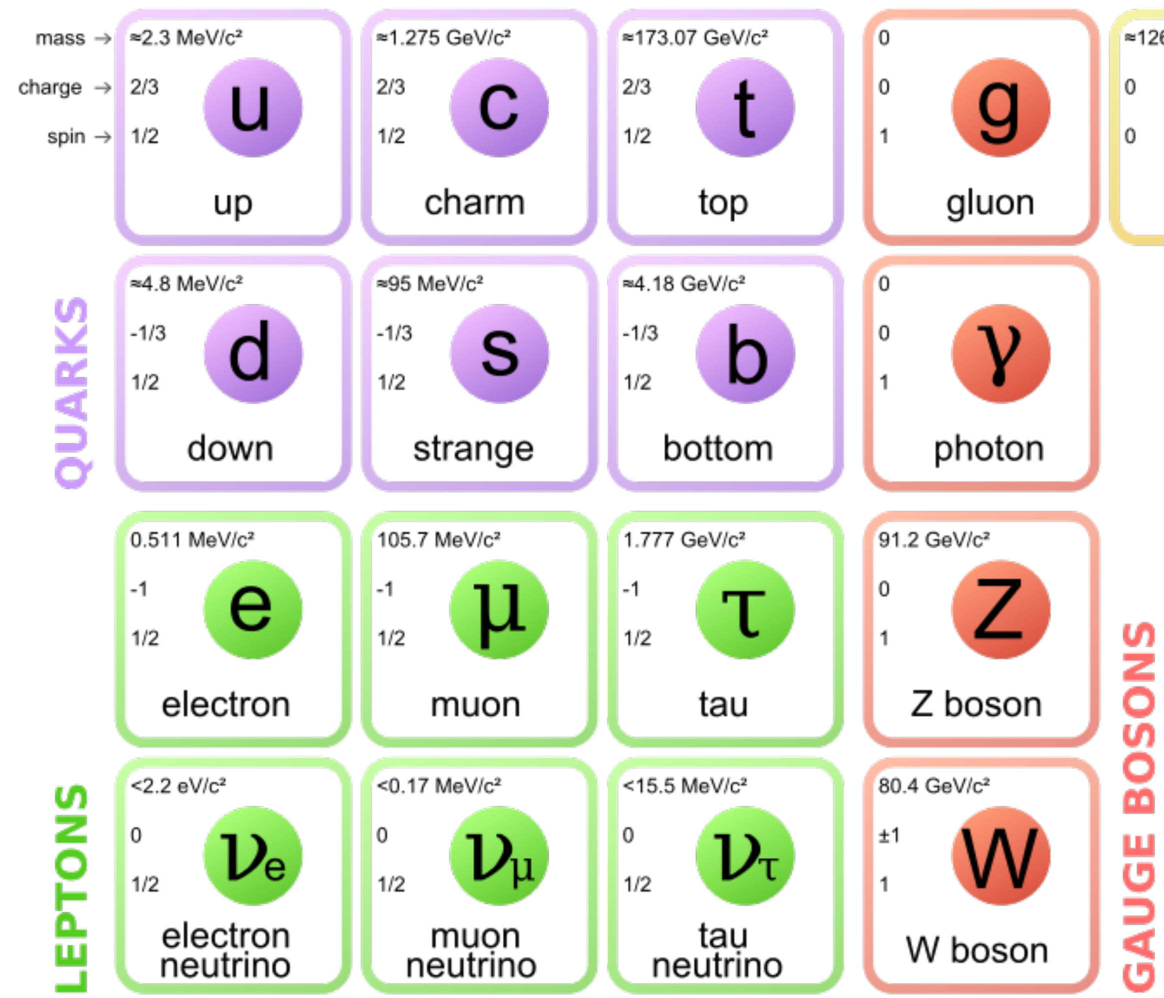
SLAC/BNL, 1974

CDF/D0, 1995

E288, 1977

Pluto, 1978
Jade/Pluto/Petra, 1979

1st evidence, SLAC, 1968



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DONUT, SLAC-LBL , 2000

- Fermions (named after Fermi)
  - Quarks and leptons
- Bosons (named after Bose)
  - Higgs and gauge bosons

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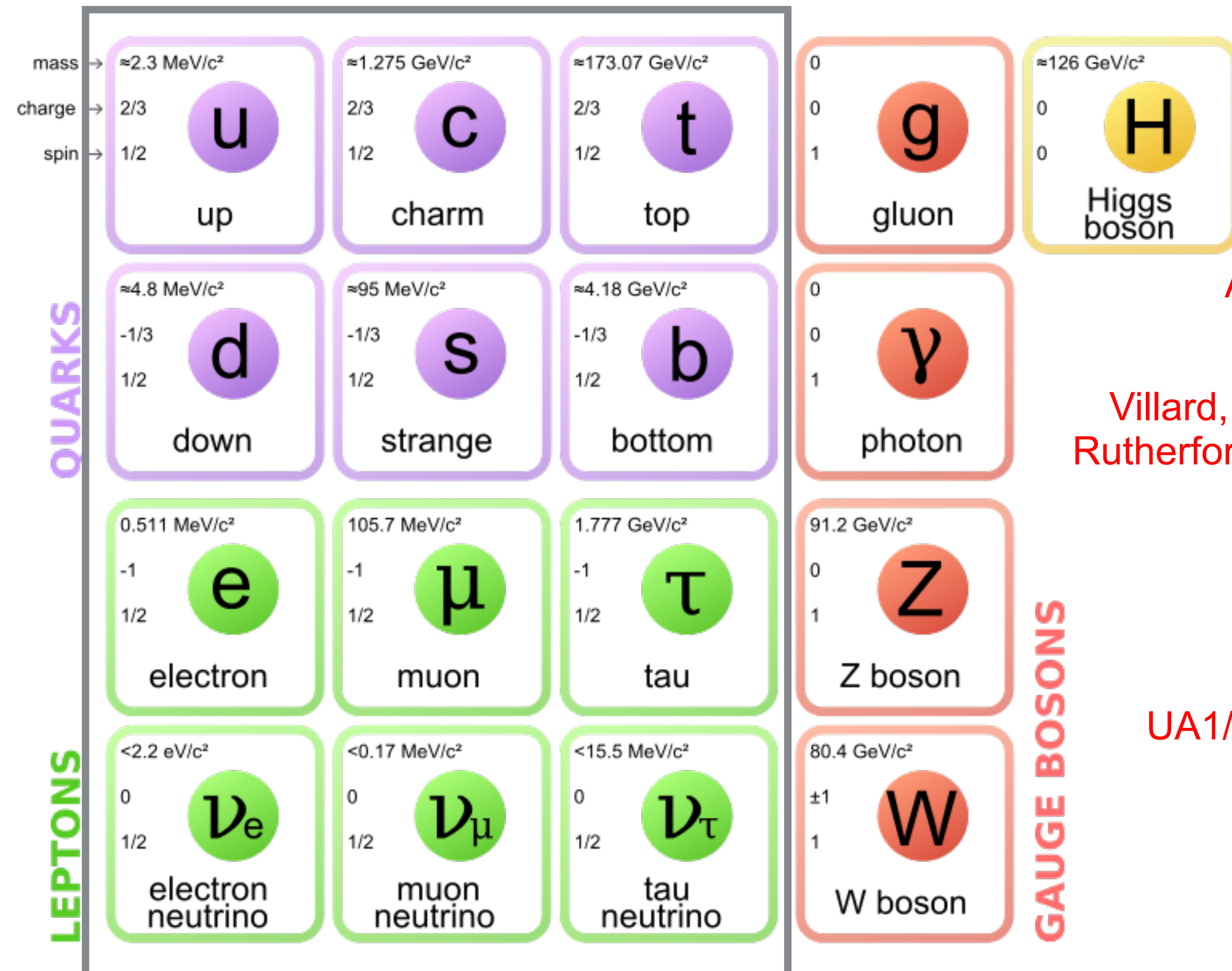

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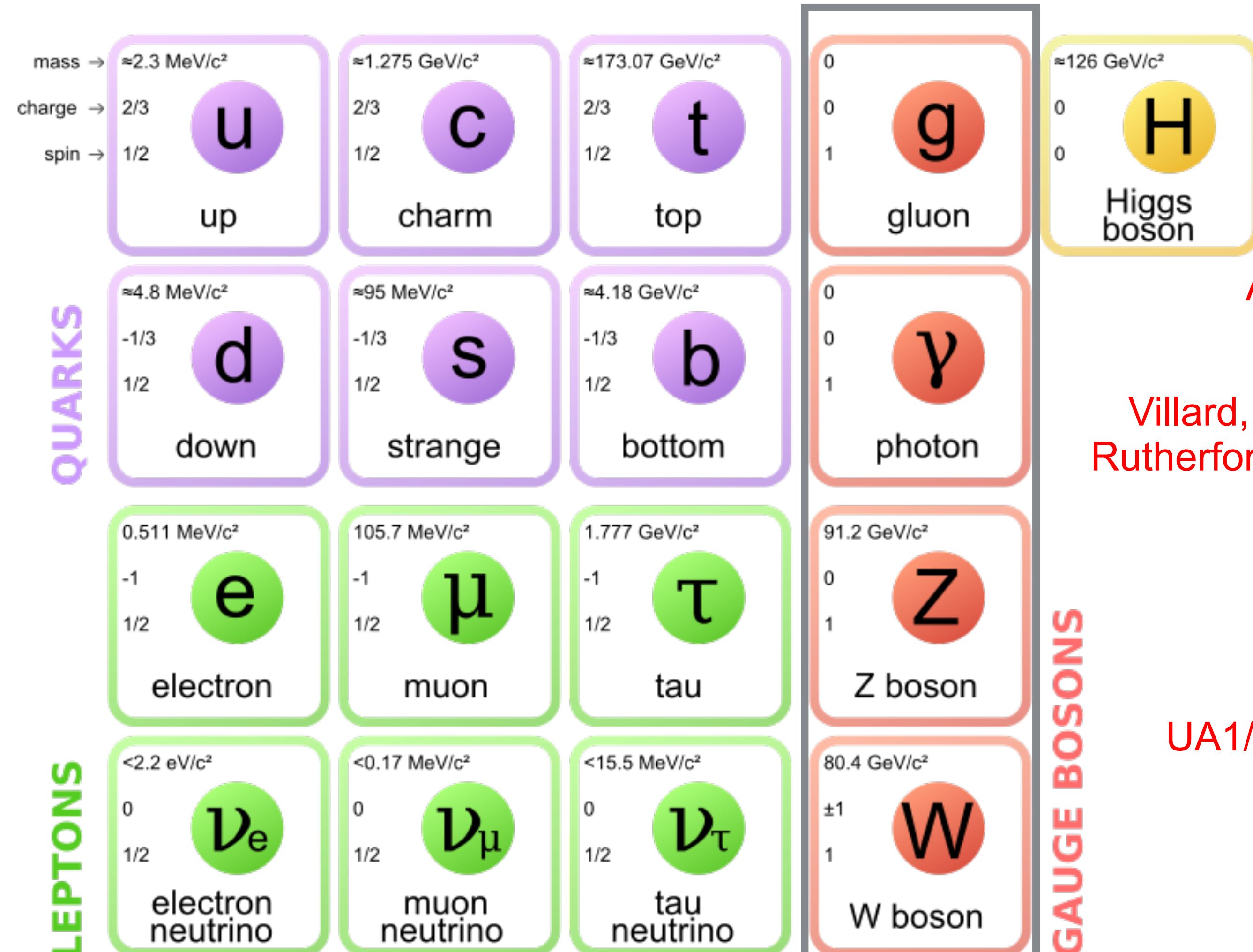

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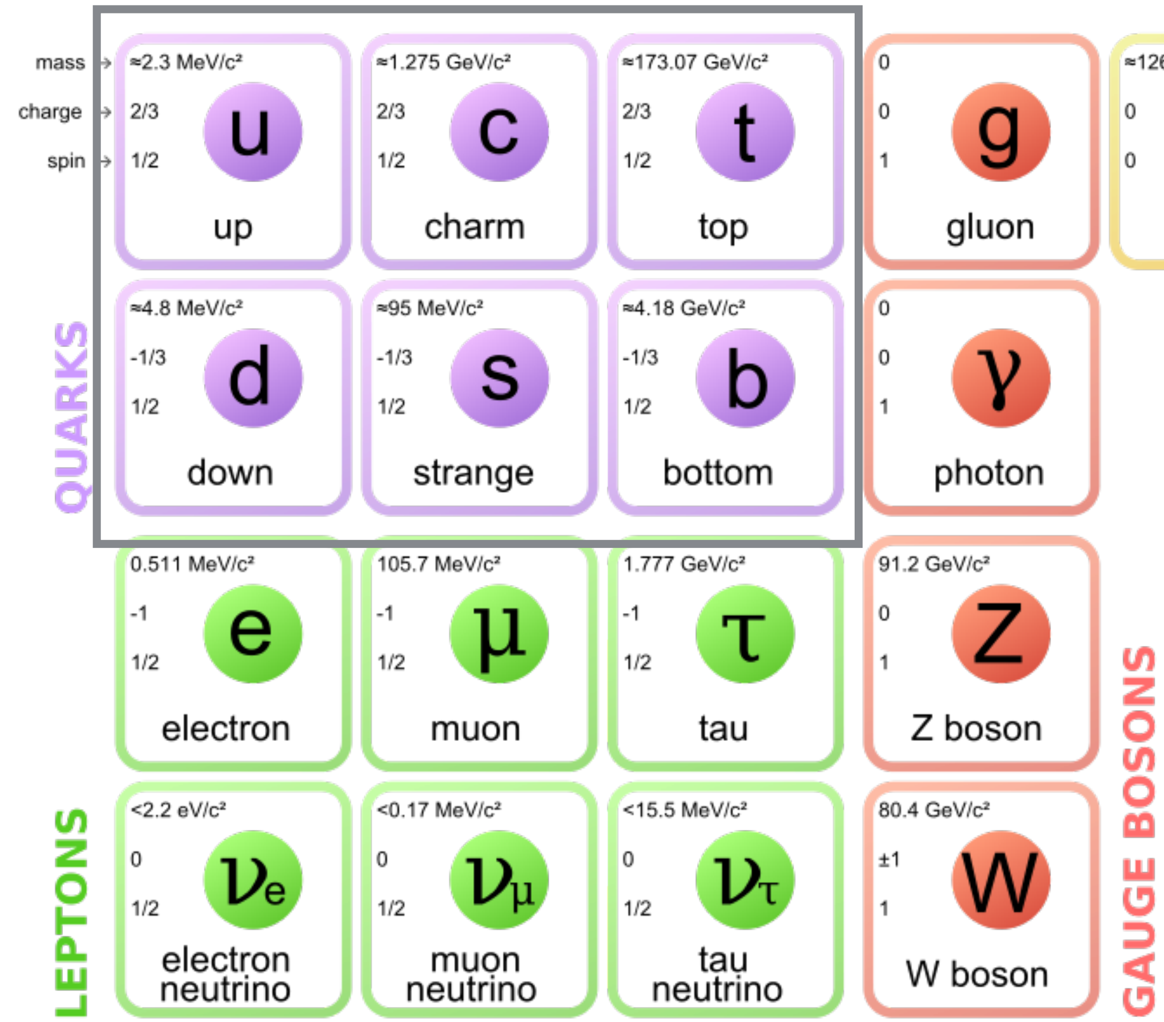

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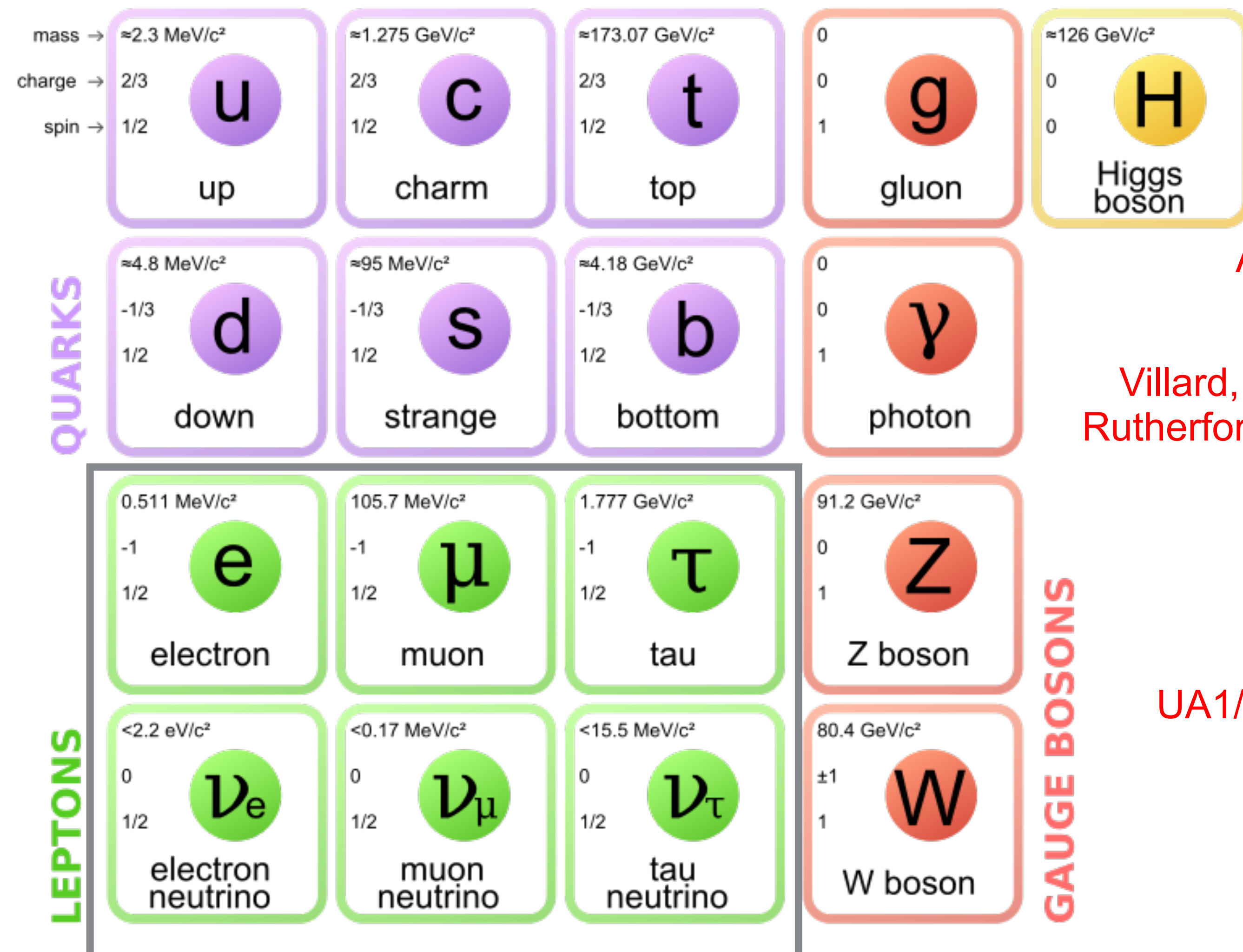

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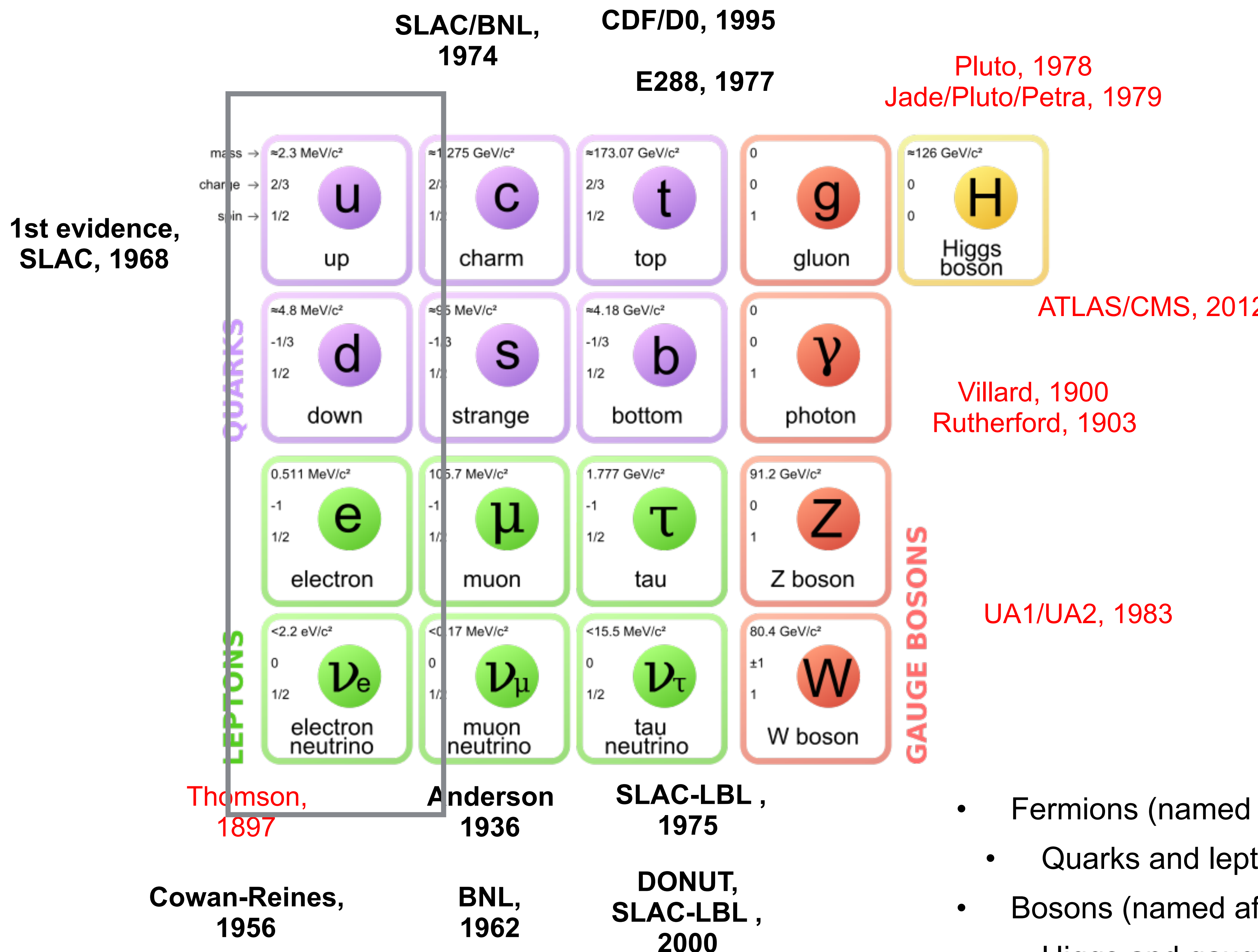

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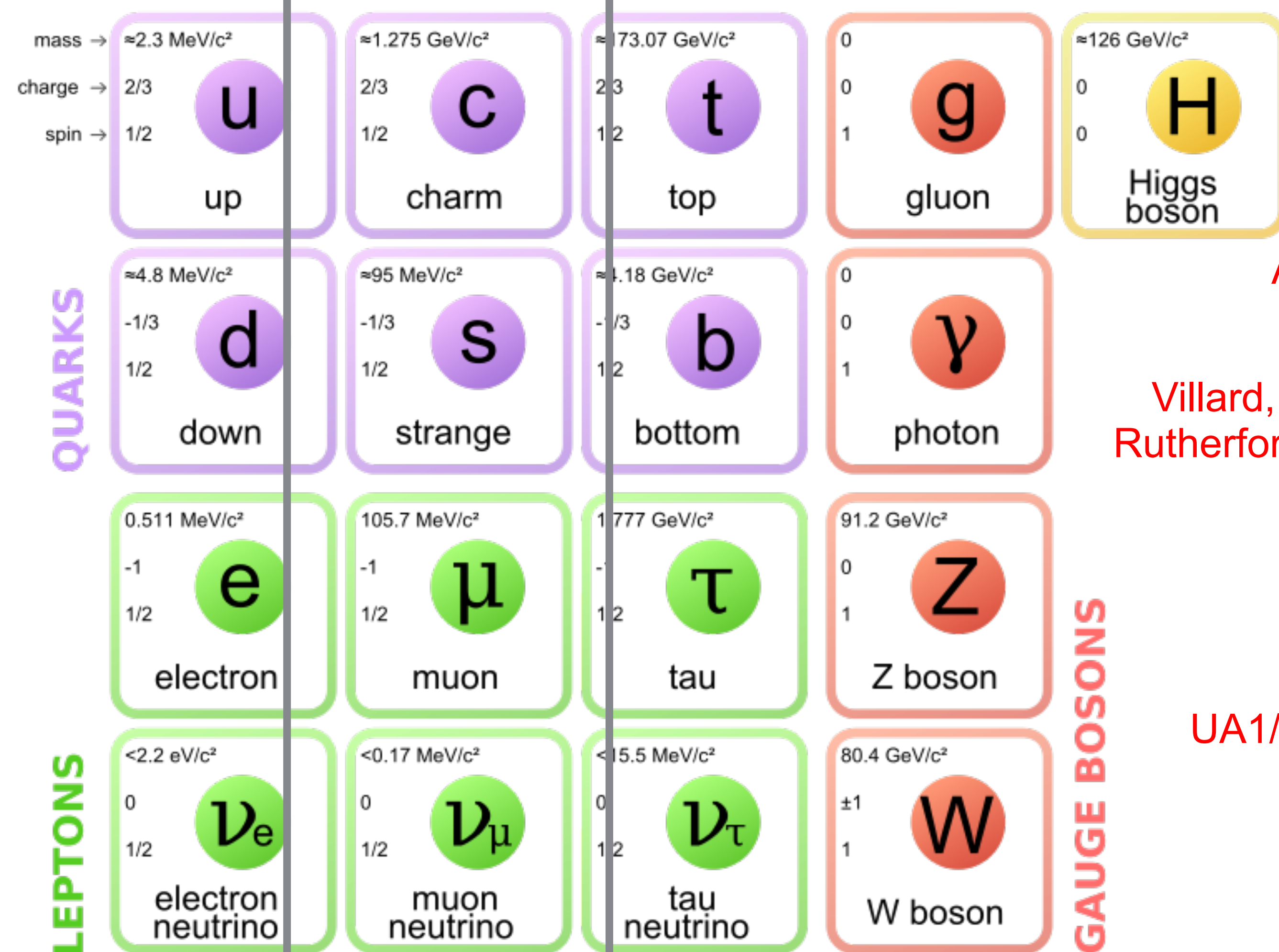

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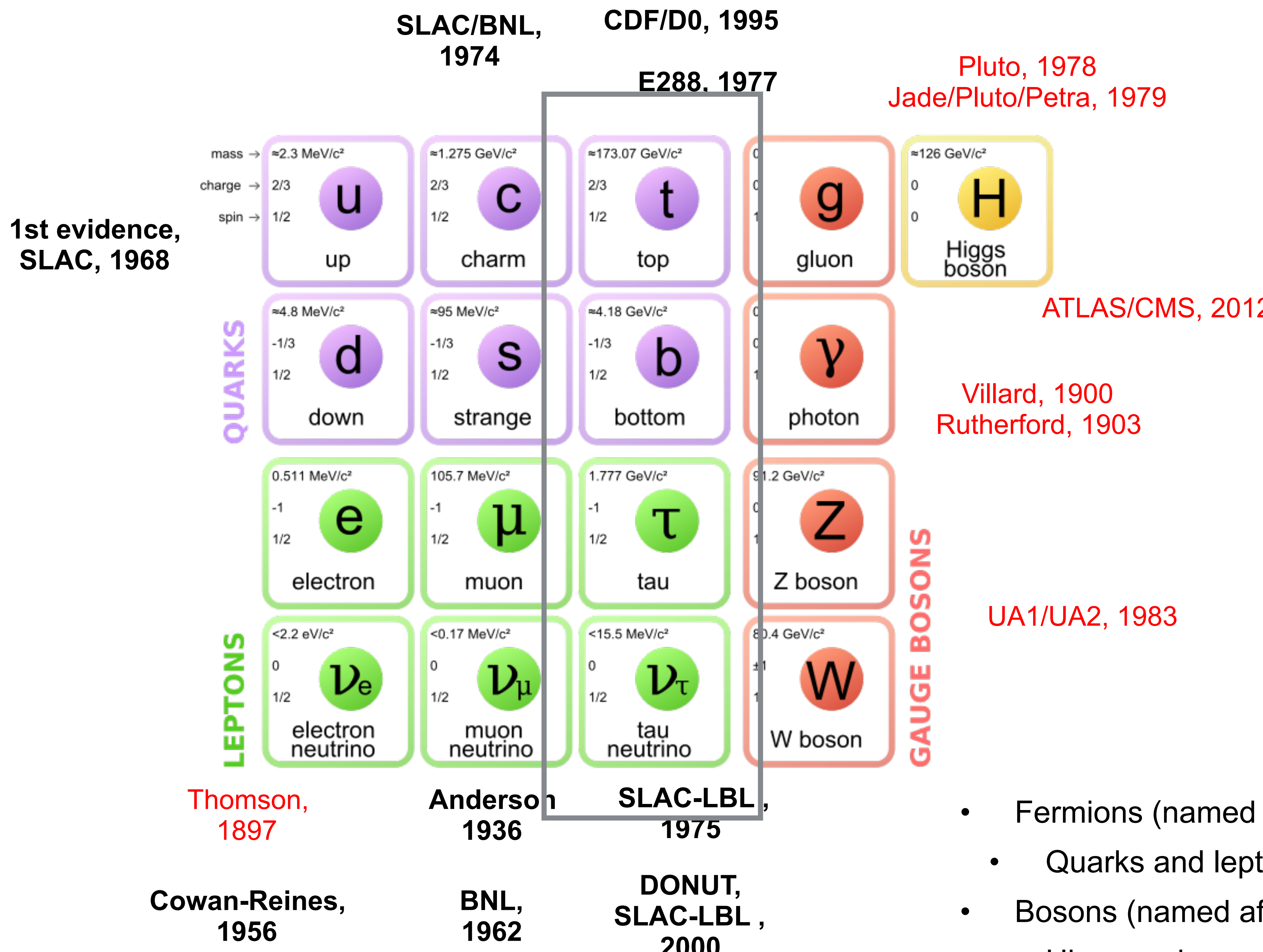

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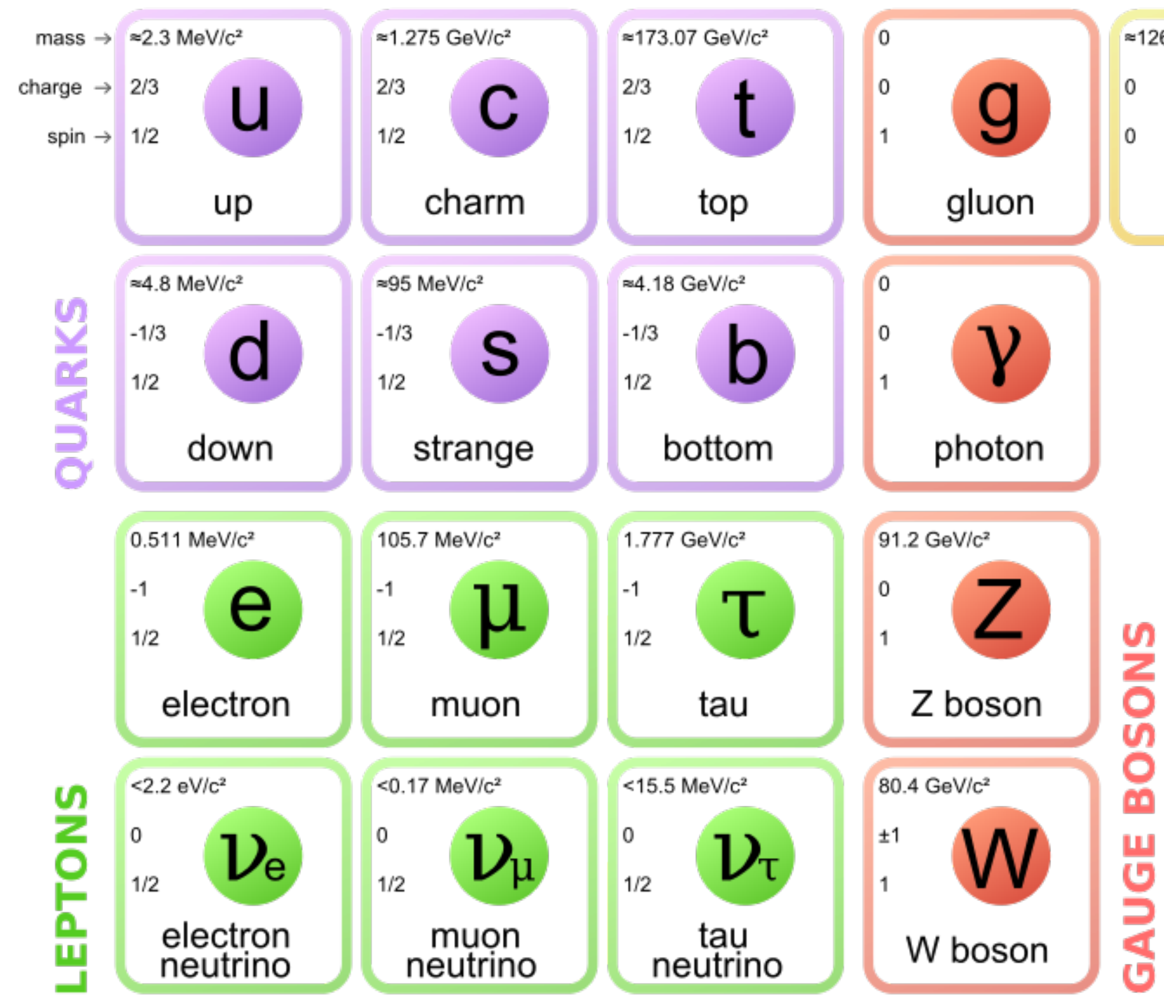

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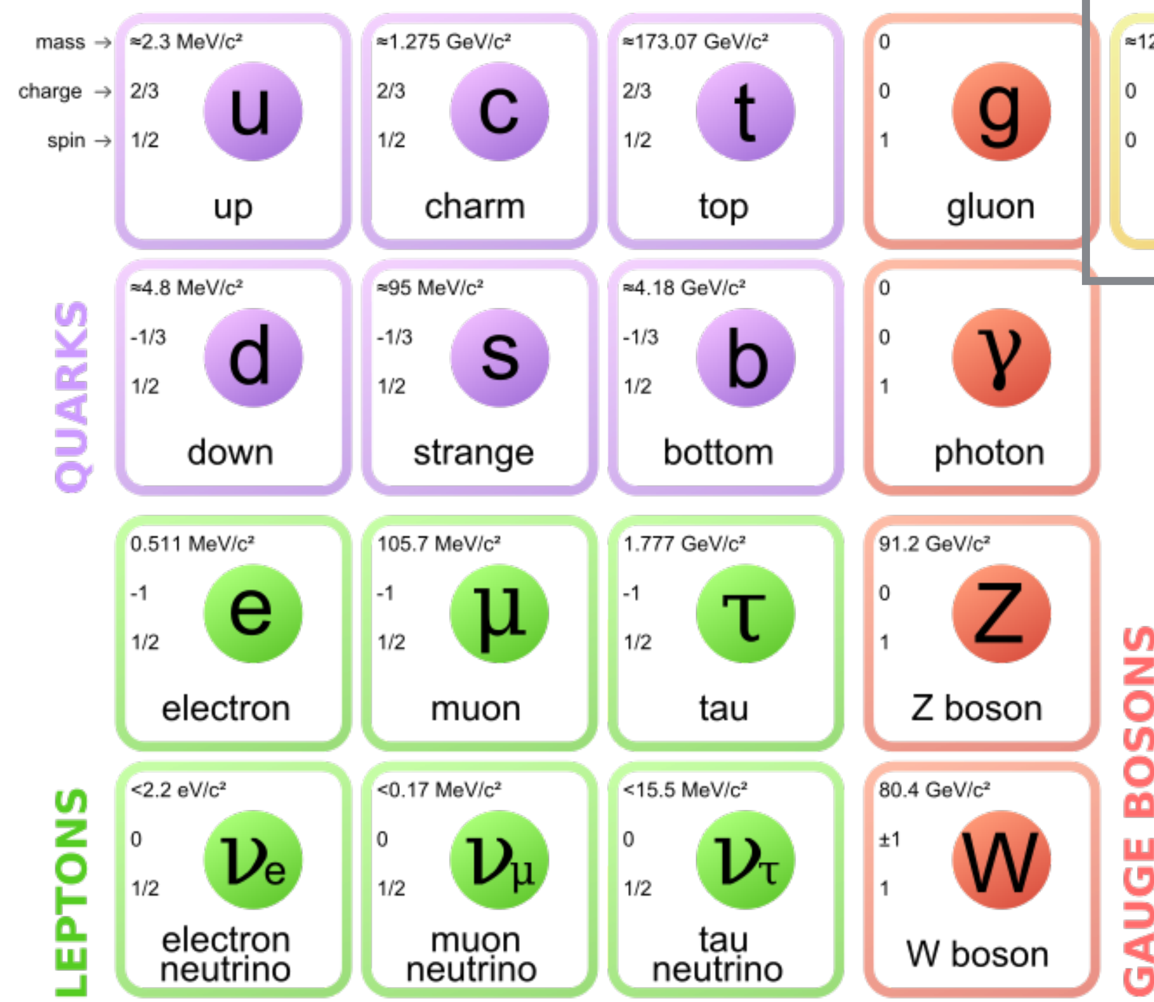

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$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

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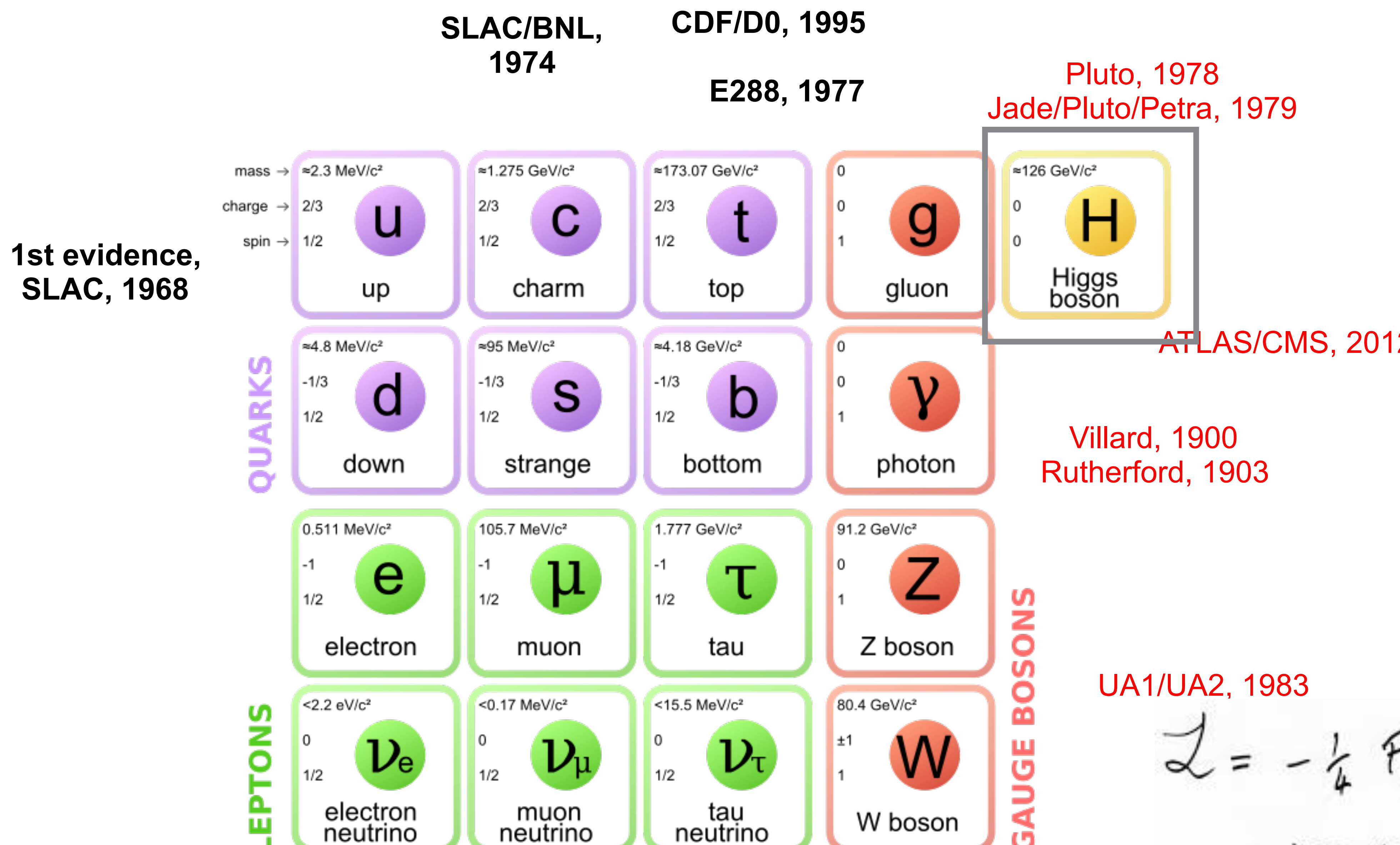

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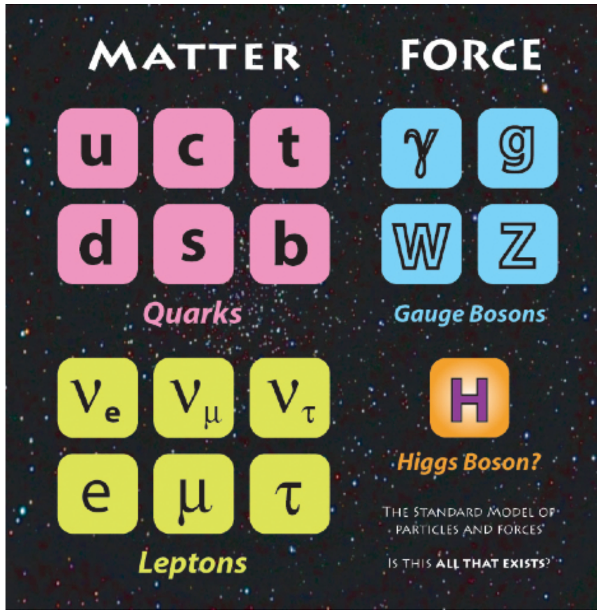
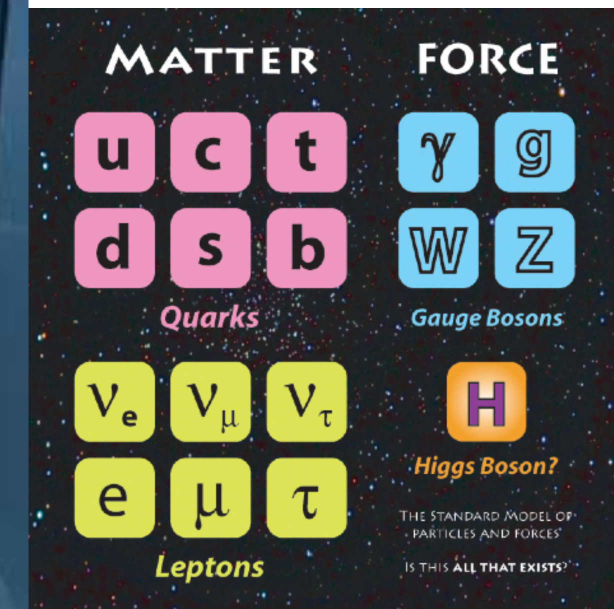
It is not just a table.
It contains profound mathematical formulation of our current understanding of the Universe.

Current Particle Physics Model is INCOMPLETE



- Where are anti-particles in our universe?
- Where is Gravity in the table?
- Why there are three generations?
- Why are there three forces (besides gravity)?
- Why isn't only one kind of force (Grand Unified Theory)?
- Why do we need Higgs particle?
- Why some particles are heavy and some are light?
- Dark matter / Dark Energy
- How natural is this theory?
  - Naturalness; coincidence; fine tuning; multi-verse

del is



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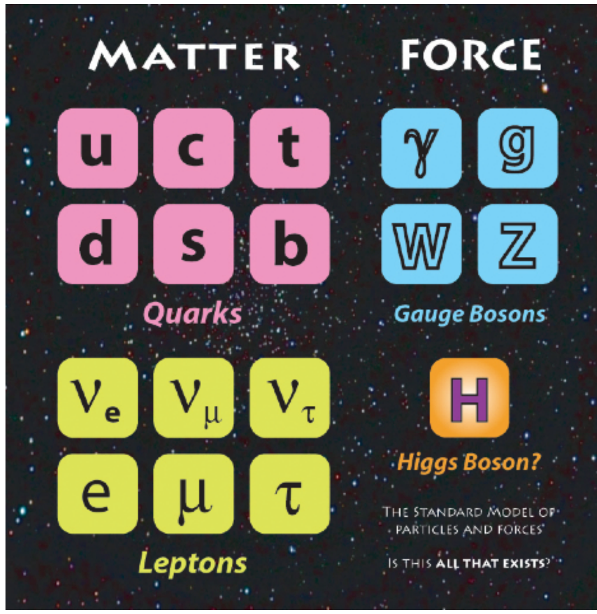

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Higgs mass = bare mass - counter terms

Now we perform various experiments and among many other exciting experiments…..

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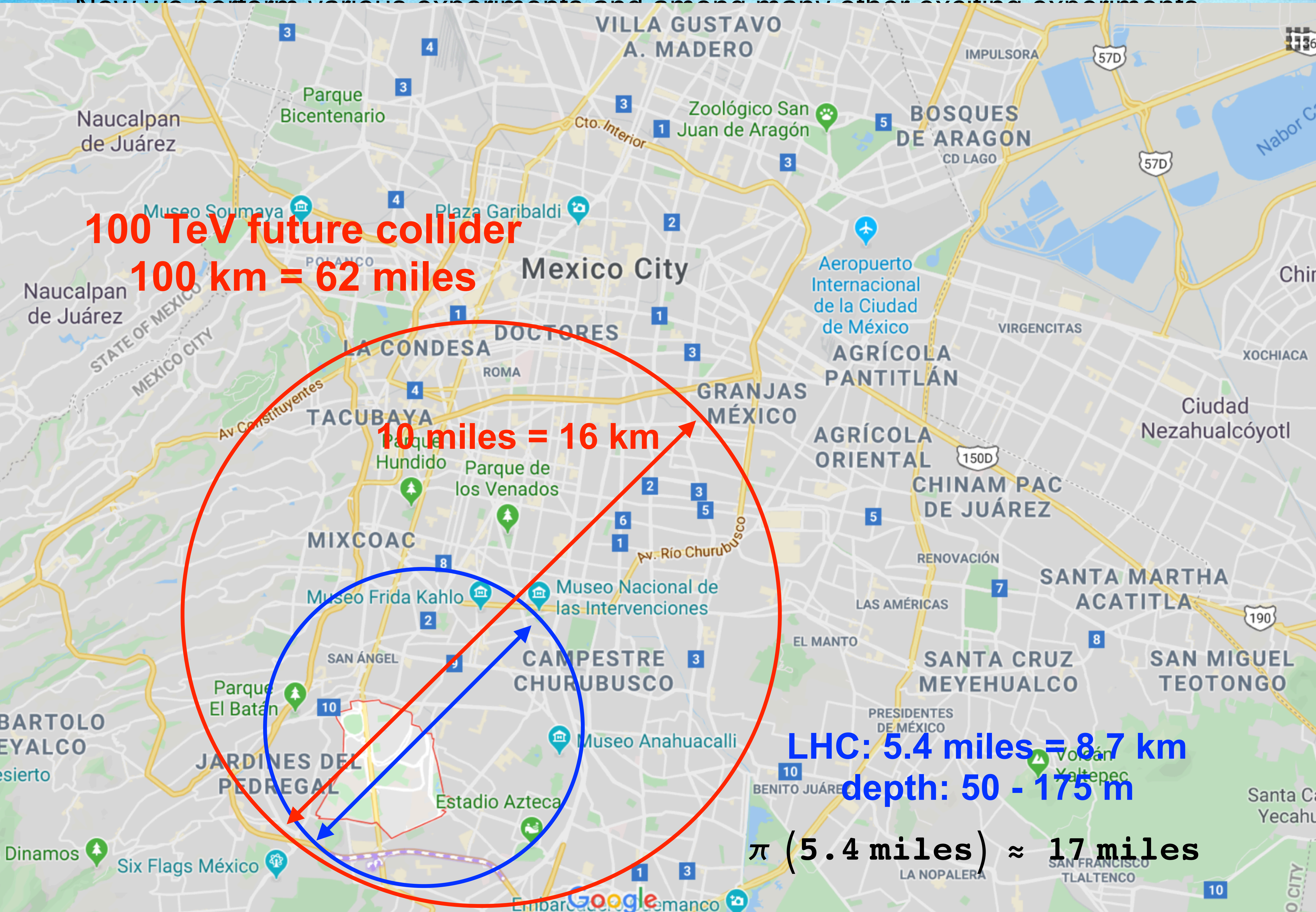
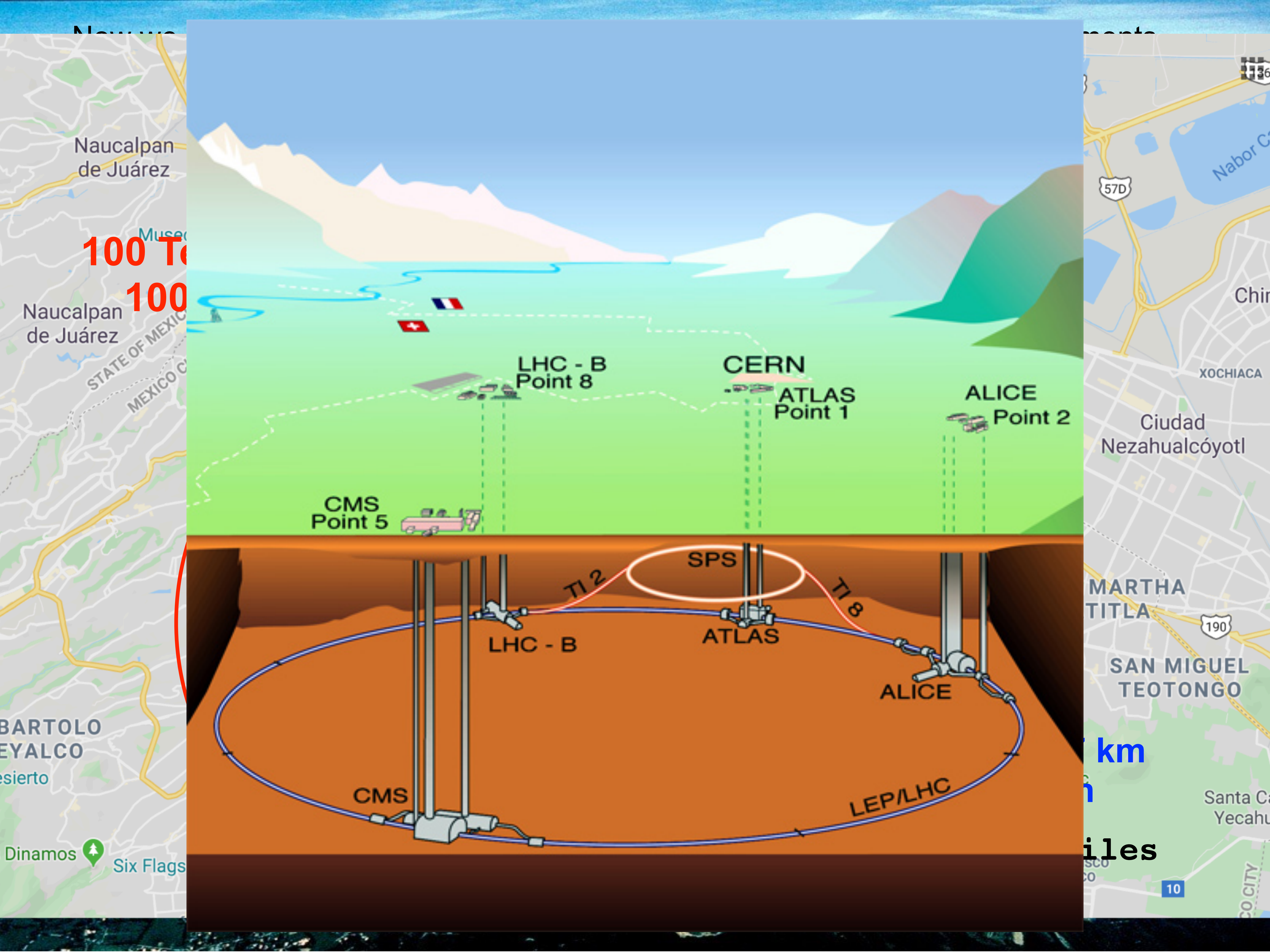
LARGE HADRON COLLIDER

- Located at CERN, near Geneva
- Hadron: protons and nuclei
- Large: 17 miles of vacuum and superconducting magnets
- Accelerates protons to 99.999999% the speed of light, 10,000 round trips per second
- Proton beams squeezed down to 64 microns
- 100 million proton-proton collisions per second
- More than 5000 Ph.D. physicists from > 100 countries
- ~$10 billion project
- Conceived 1984, approved 1994
- Beams in Sept 2008, run I begun 2009, run II 2015@13TeV



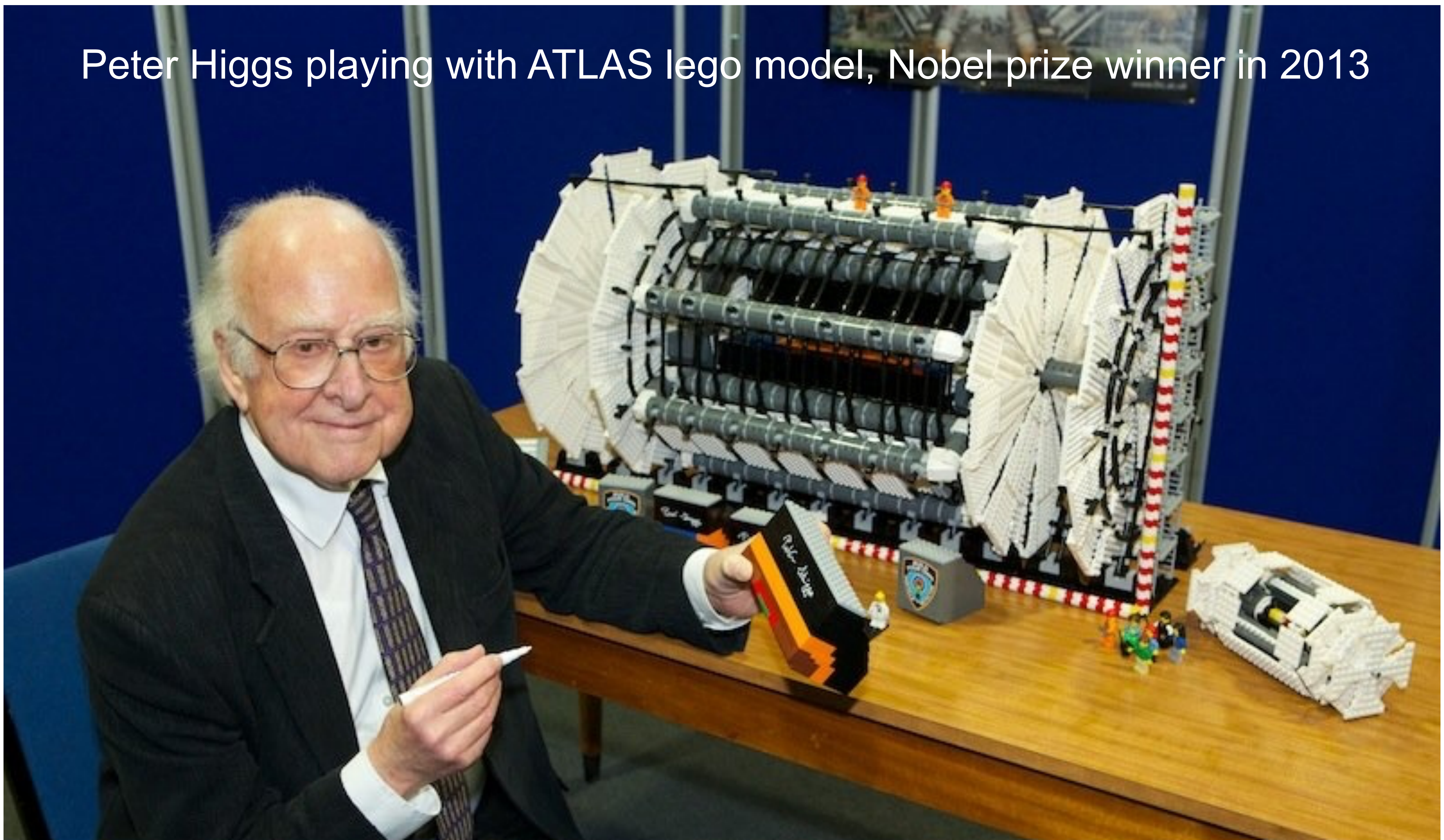
100 TeV future collider
100 km = 62 miles
10 miles = 16 km
LHC: 5.4 miles = 8.7 km
depth: 50 - 175 m
π (5.4 miles) ≈ 17 miles
Mexico City
VILLA GUSTAVO A. MADERO
Naucalpan de Juárez
Parque Bicentenario
Cto. Interior
Zoológico San Juan de Aragón
BOSQUES DE ARAGON
CD LAGO
IMPULSORA
57D
Museo Soumaya
Plaza Garibaldi
POLANCO
Aeropuerto Internacional de la Ciudad de México
STATE OF MEXICO
MEXICO CITY
LA CONDESA
DOCTORES
ROMA
VIRGENCITAS
XOCHIACA
AGRÍCOLA PANTITLÁN
GRANJAS MÉXICO
Av Constituyentes
TACUBAYA
Parque Hundido
Parque de los Venados
AGRÍCOLA ORIENTAL
150D
CHINAM PAC DE JUÁREZ
Ciudad Nezahualcóyotl
MIXCOAC
Av. Río Churubusco
RENOVACIÓN
Museo Frida Kahlo
Museo Nacional de las Intervenciones
LAS AMÉRICAS
SANTA MARTHA ACATITLA
190
EL MANTO
SAN ÁNGEL
CAMPESTRE CHURUBUSCO
SANTA CRUZ MEYEHUALCO
SAN MIGUEL TEOTONGO
Parque El Batán
PRESIDENTES DE MÉXICO
Museo Anahuacalli
JARDINES DEL PEDREGAL
BENITO JUÁREZ
Estadio Azteca
Dinamos
Six Flags México
LA NOPALERA
SAN FRANCISCO TLALTENCO
Google



LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 2
TI 8
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
Naucalpan de Juárez
Naucalpan de Juárez
Ciudad Nezahualcóyotl
XOCHIACA
MARTHA
SAN MIGUEL TEOTONGO
Dinamos
57D
190
10

Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

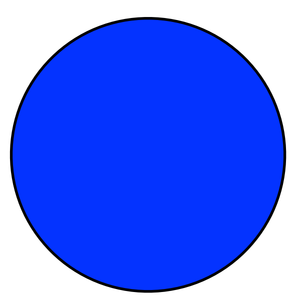
- about 9500 Lego pieces
- roughly 50:1 in scale (close to scale with the LEGO man)
- material cost of about 2000 Euros
- about 1 m x 0.5 m x 0.5 m in size


Peter Higgs playing with ATLAS lego model, Nobel prize winner in 2013

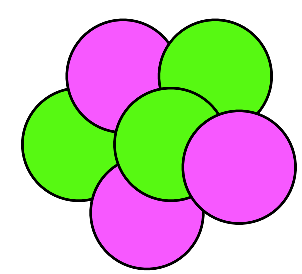
1:48 scale

MICROSCOPES

Higher energies → shorter wavelengths



low resolution



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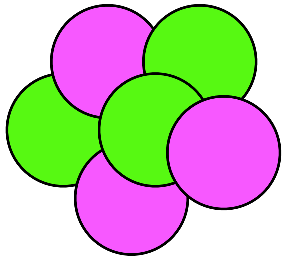

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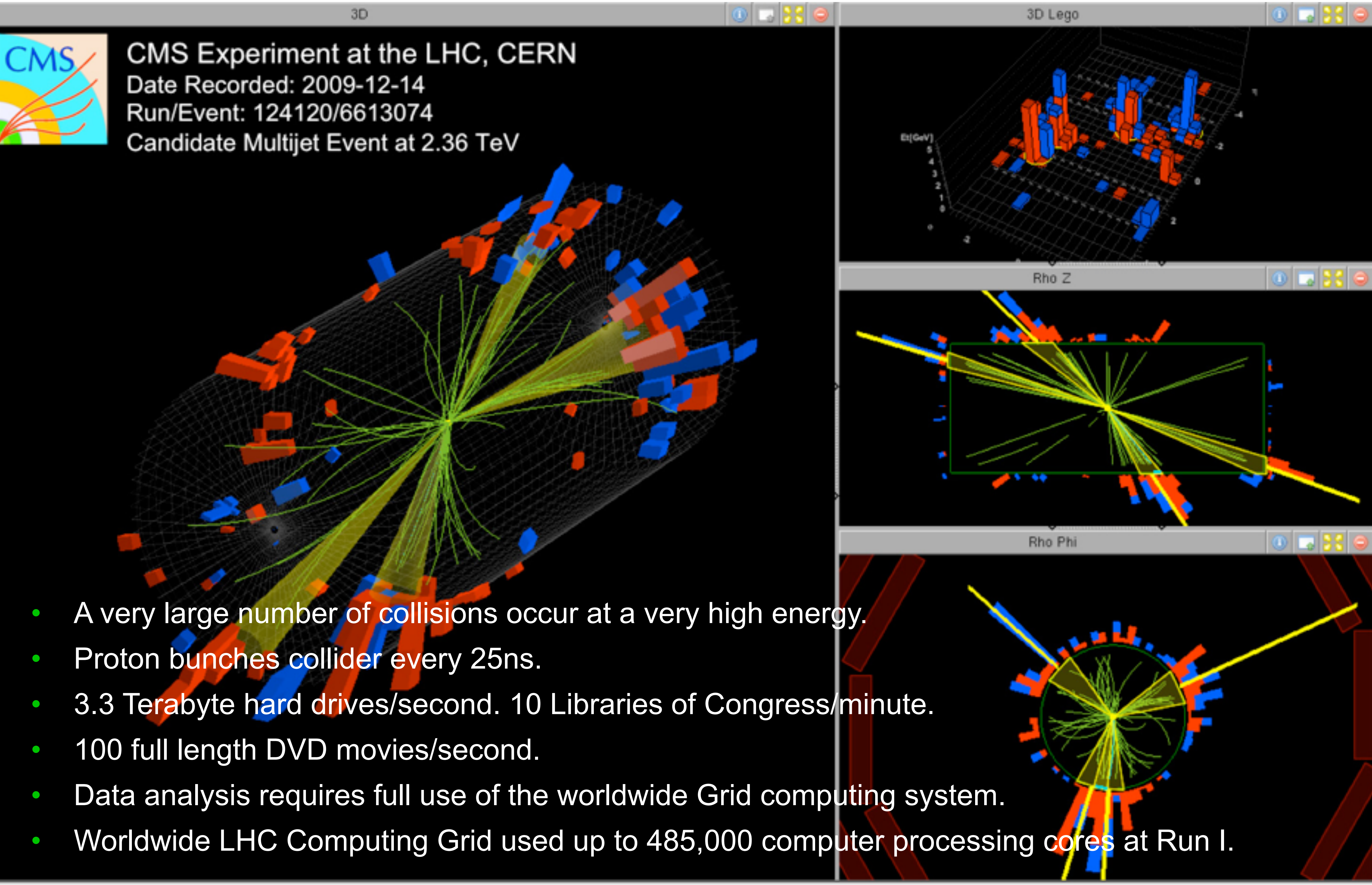


- A very large number of collisions occur at a very high energy.
- Proton bunches collider every 25ns.
- 3.3 Terabyte hard drives/second. 10 Libraries of Congress/minute.
- 100 full length DVD movies/second.
- Data analysis requires full use of the worldwide Grid computing system.
- Worldwide LHC Computing Grid used up to 485,000 computer processing cores at Run I.

WHAT THE LHC IS LOOKING FOR

- More Higgs bosons
- New quark-, electron-, or neutrino-like particles
- Quark and electron substructure
- New forces
- Black holes
- Extra dimensions
- Dark matter

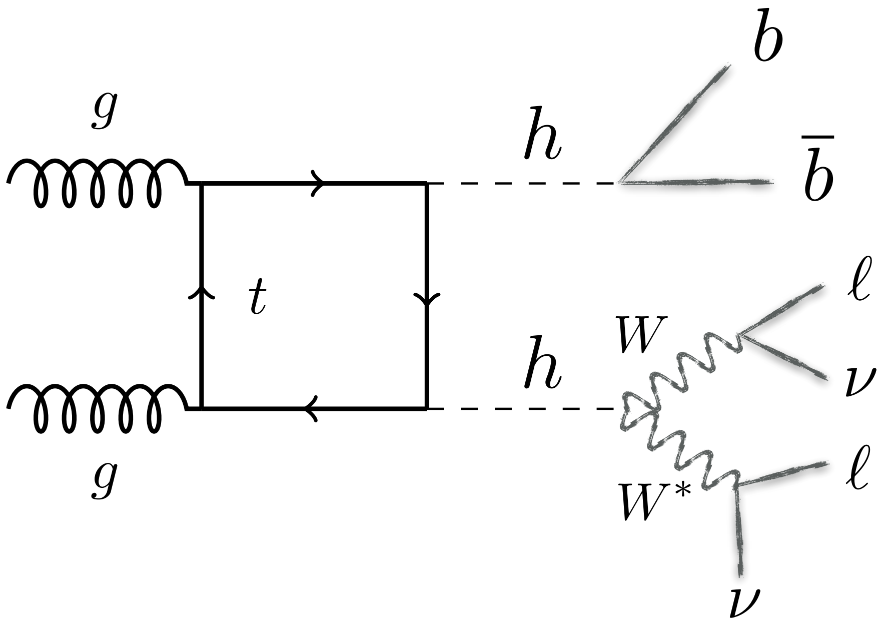
  ….

- Ideas not yet thought of

H. Murayama

One of the best motivation: Higgs potential

Why double Higgs (*hh*) ?



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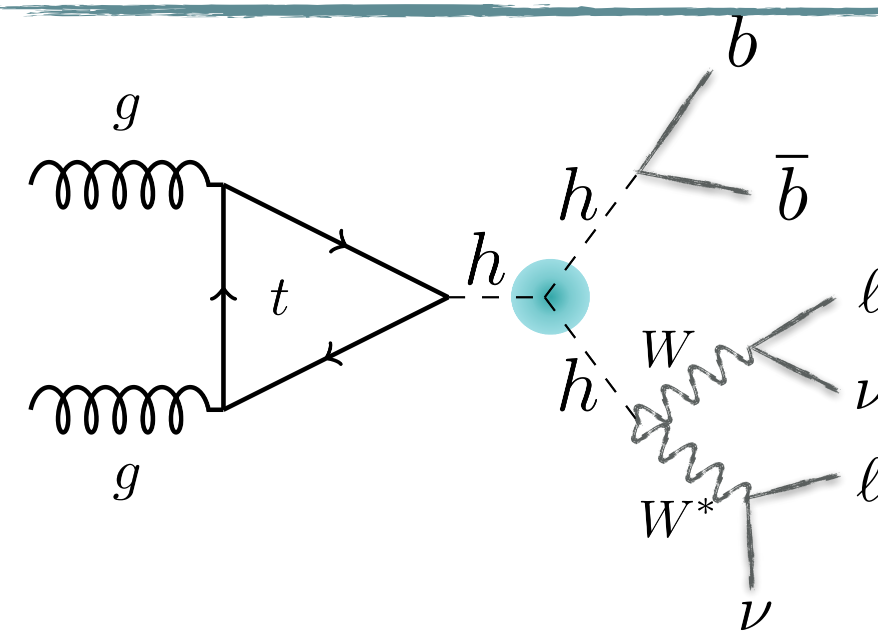
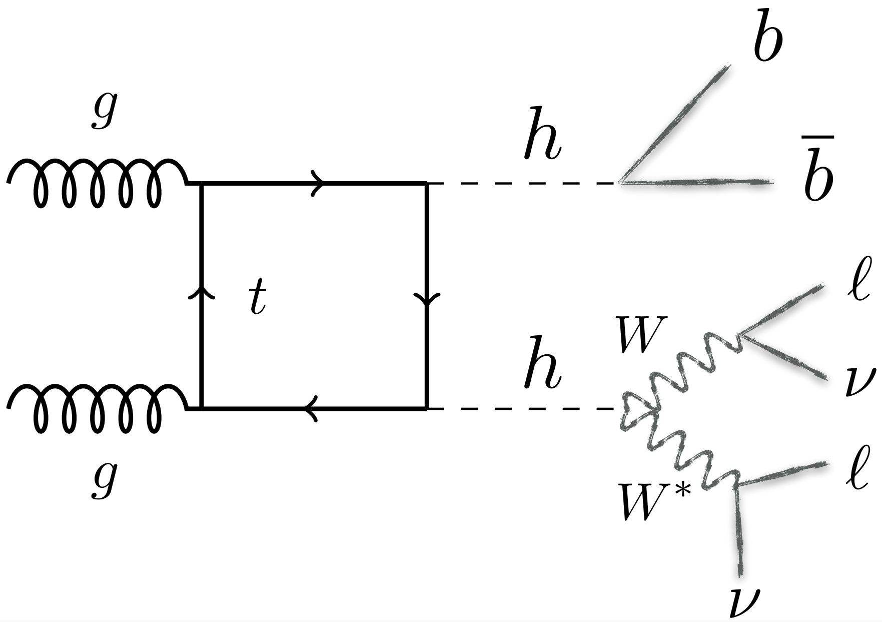


$$V_h = \frac{m_h^2}{2} h^2 + c_3 \frac{m_h^2}{2v} h^3 + c_4 \frac{m_h^2}{8v^2} h^4$$

$$\sim c_3 y_t^2 \frac{\alpha_S}{4\pi} \frac{m_h^2}{\hat{s}} \left(log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$$

- We will focus on the triple Higgs self-coupling (c_3), with all other couplings set to their SM values. c3 is accessible at the HL-LHC but c4 needs 100 TeV collider.
- The knowledge of c_3 is crucial to reconstruct the Higgs potential for better understanding EWSB. Many BSM scenarios allow large deviations for c_3.
- The c_3 is sensitive at lower-energy bins where the backgrounds are large.
- That's why probing c_3 is notoriously difficult.

Why double Higgs (*hh*) ?



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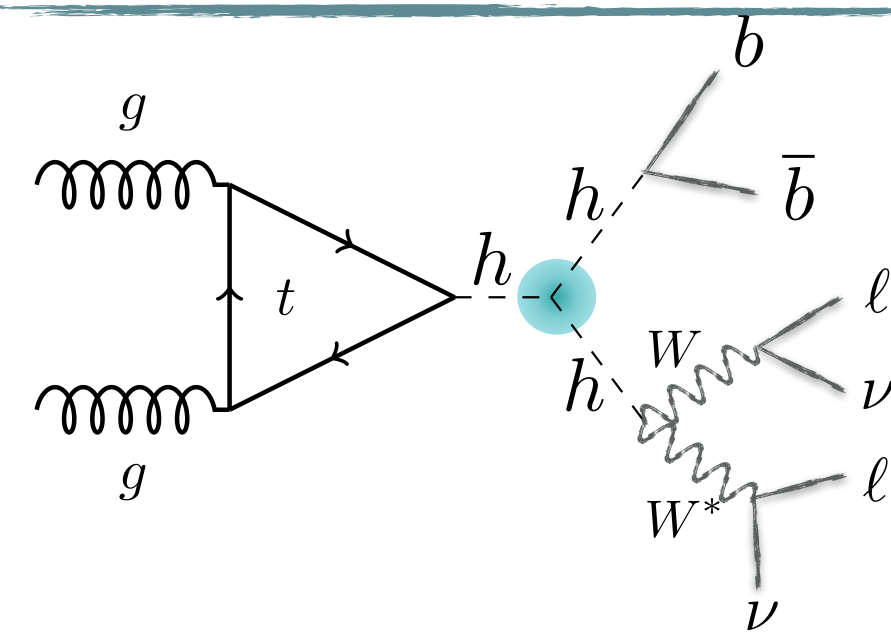

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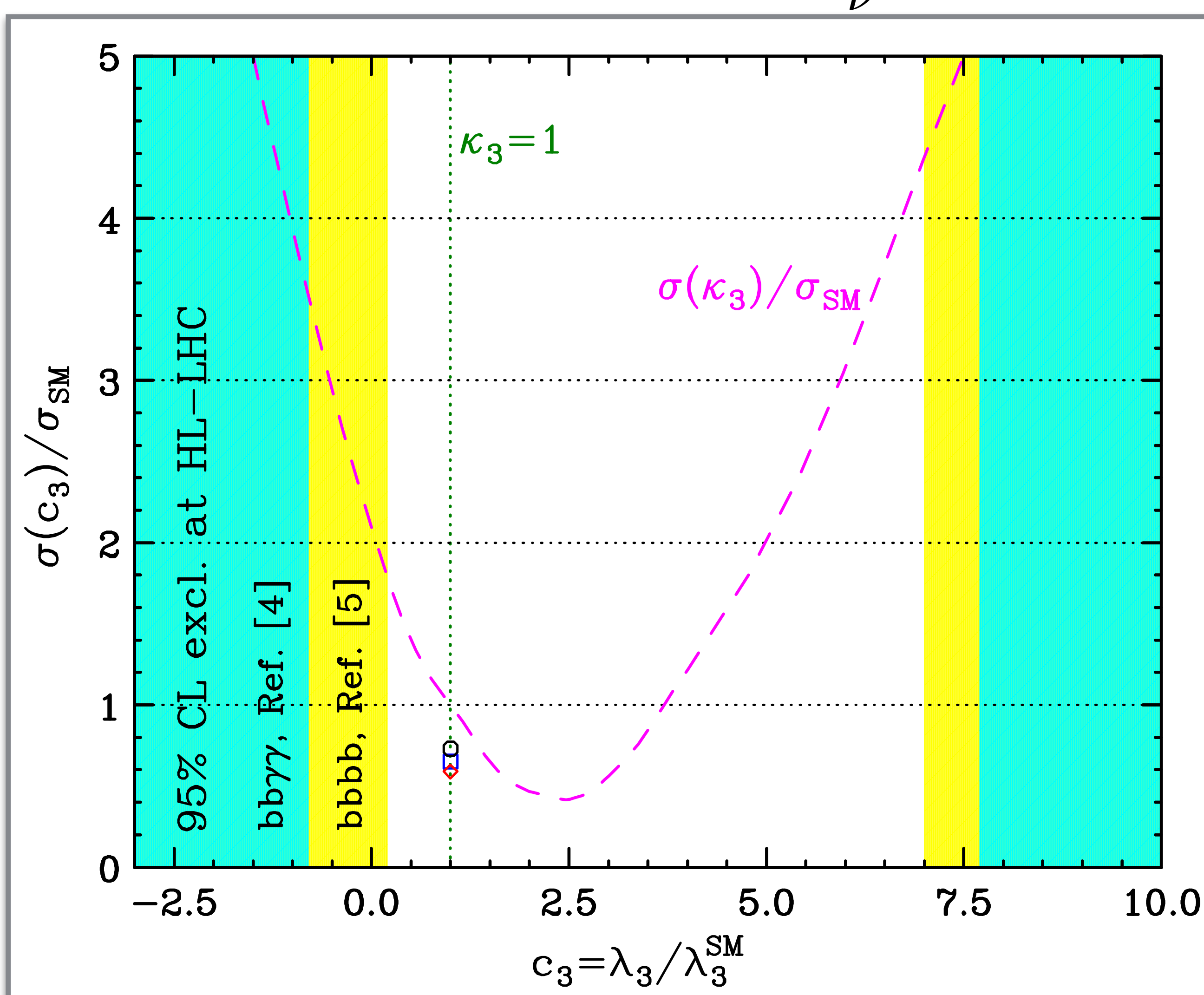


g (c_3), with all other couplings set to their SM
needs 100 TeV collider.

he Higgs potential for better understanding EWSB.
or c_3.

the backgrounds are large.

Decays

1 fb = 10^{-39} cm^2

$$\sigma(hh)^{NNLO}_{SM} \simeq 40.7 \text{ fb} \quad (\text{ 14 TeV })$$

higher branching ratios

cleaner final state

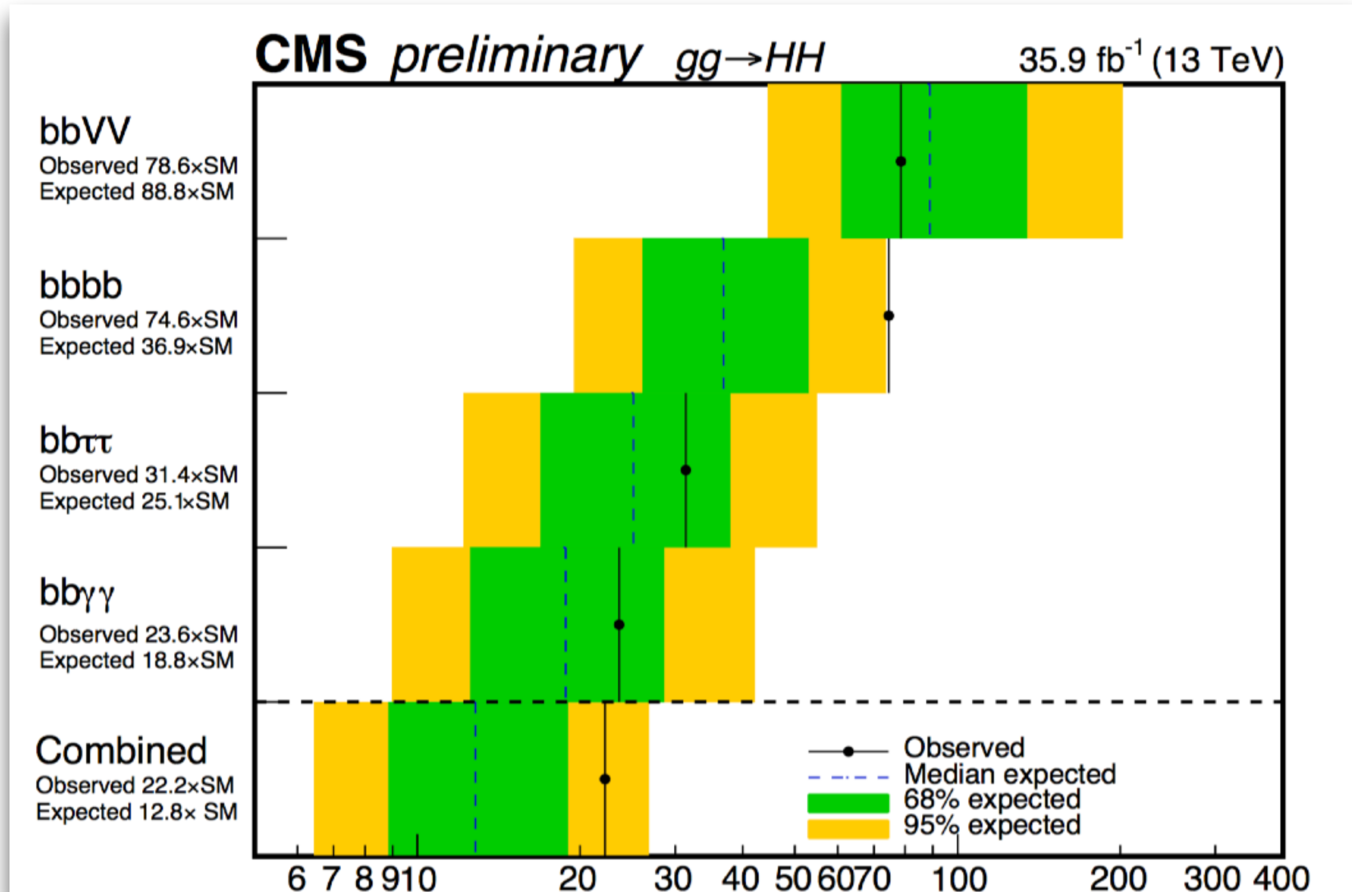
	bb	WW^*	$\tau\tau$	ZZ^*	$\gamma\gamma$
bb	33%				
WW^*	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ^*	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.1%	0.028%	0.012%	0.0005%

1902.00134	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

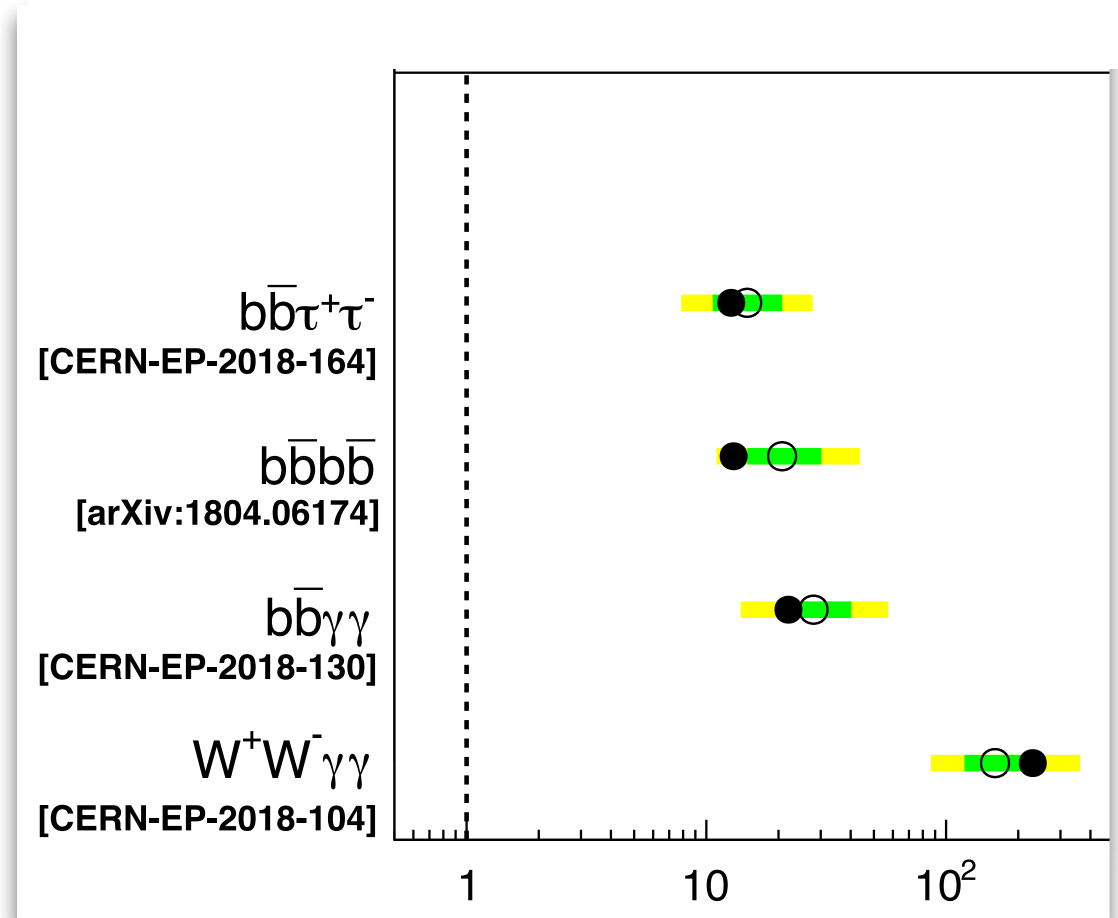
4σ expected for ATLAS+CMS!

- These measurements are challenged by a low σ (hh) and small branching ratios (BR).
- No single channel is expected to reach 5 sigma at HL-LHC.
- The combination of different channels is crucial. bbWW has good potential for further improvement.

$$\sigma_{hh}^{observed}/\sigma_{hh}^{SM} = 22$$



$$\sigma_{hh}^{observed}/\sigma_{hh}^{SM} = 13$$



$$95\%\ CL\ on\ \sigma_{hh}/\sigma_{hh}^{SM}$$

1902.00134

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	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

4σ expected for ATLAS+CMS!

- These measurements are challenged by a low σ (hh) and small branching ratios (BR).
- No single channel is expected to reach 5 sigma at HL-LHC.
- The combination of different channels is crucial. bbWW has good potential for further improvement.

Cross sections @14 TeV LHC

$\sigma_{hh} = 40.7$ fb (NNLO) (only two studies in the dilepton channel)

$\sigma_{hh} \cdot 2 \cdot \mathrm{BR}(h \to b\bar{b}) \cdot \mathrm{BR}(h \to WW^* \to \ell^+ \ell^- \nu \bar{\nu}) = 0.648\,\mathrm{fb}$

ℓ denotes an electron or a muon, including leptons from tau decays.

- tt: 953.6 pb (NNLO)
- tth: 611.3 fb (NLO)
- ttV (V=W, Z): 1.71 pb (NLO)
- DY: $\mathrm{k}_{QCD \otimes QED}^{NNLO,DY} \approx 1$
- Irreducible jjllnunu: k_NLO = 2
- tWj: 0.51 pb (after cuts, including all relevant branching fractions)

$\sigma_{bknd} \sim 10^5 \sigma_{hh}$

	Signal	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}V$	$\ell\ell bj$	$\tau\tau bb$	$tw + j$	$jj\ell\ell\nu\nu$	σ	S/B
Baseline cuts: $\not{p}_T > 20$ GeV, $p_{T,\ell} > 20$ GeV, $\Delta R_{\ell\ell} < 1.0$, $p_{T,b} > 30$ GeV, $\Delta R_{bb} < 1.3$, $m_{\ell\ell} < 65$ GeV, $95 < m_{bb} < 140$ GeV	0.01046	1.8855	0.0269	0.0179	0.0697	0.0250	0.2209	0.0113	0.38	0.0046

cross section in fb

tt: 84% tW: 9.8% DY+jets: 3.1% tth: 1.2% tautau + bb: 1.1% ttV: 0.8%

*hh → bbWW**: *dilepton channel*

HL-LHC, 14 TeV, L=3 ab $^{-1}$

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi JHEP 2017

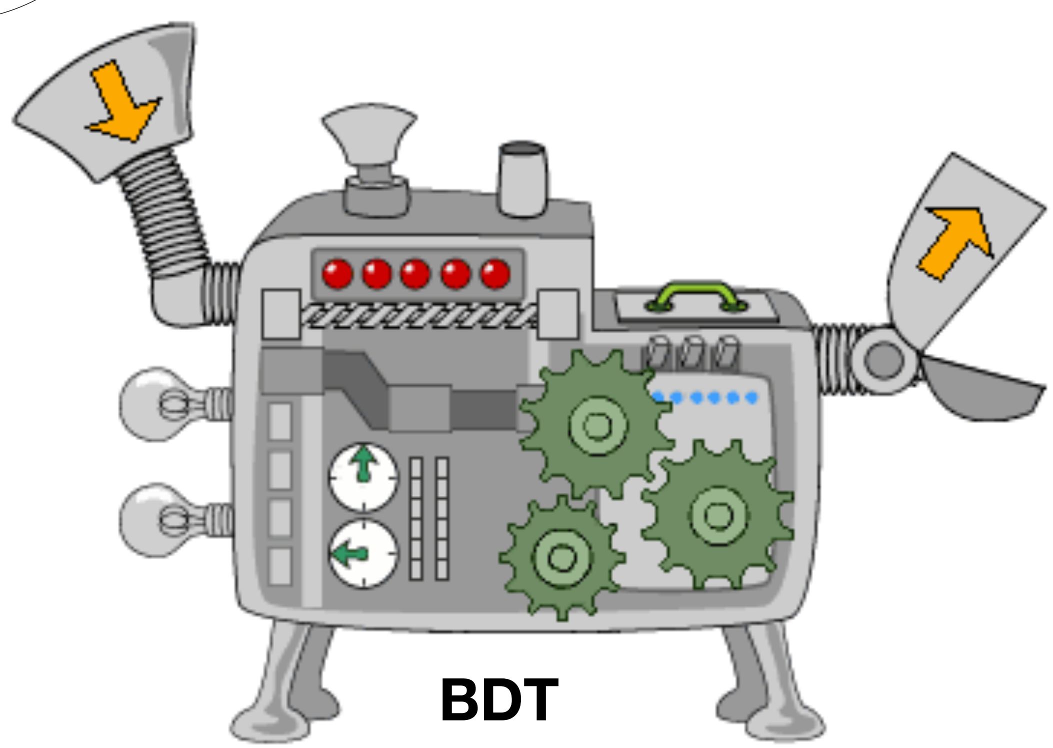
$\not\!\!E_T$

$p_{T,\ell_{1/2}}$ $\Delta\phi_{bb\,\ell\ell}$

$\Delta R_{\ell\ell}$ ΔR_{bb}

m_{bb} $m_{\ell\ell}$

$p_{T,bb}$ $p_{T,\ell\ell}$



$hh \to bbWW^*$: *dilepton channel*

HL-LHC, 14 TeV, L=3 ab $^{-1}$

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi JHEP 2017

$\not{E}_T$

$p_{T,\ell_{1/2}}$ $\Delta\phi_{bb\,\ell\ell}$

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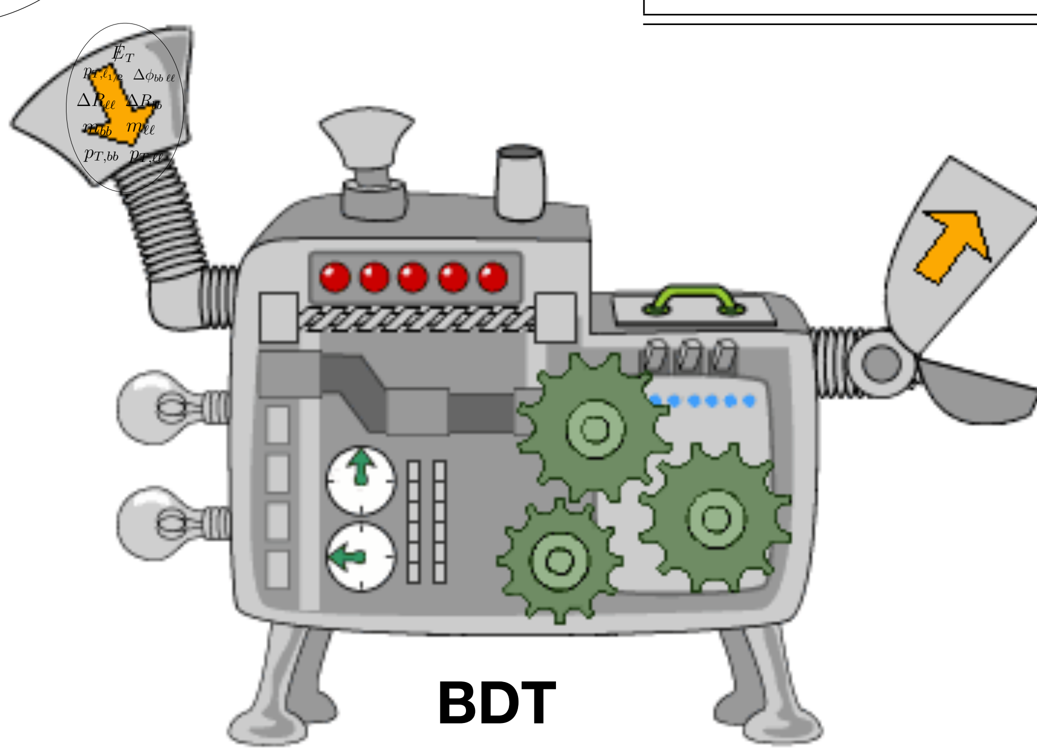
Sl. No.	Process	Order	Events
Background	$t\bar{t}$ lep	NNLO [128]	2080.52
	$t\bar{t}h$	NLO [111]	131.66
	$t\bar{t}Z$	NLO [130]	106.31
	$t\bar{t}W$	NLO [129]	35.97
	$hb\bar{b}$	NNLO (5FS) + NLO (4FS) [111]	~ 0
	$\ell\ell b\bar{b}$	LO	842.72
	Total		3197.18
Signal ($hh \to b\bar{b}WW \to b\bar{b}\ell\ell + \not{E}_T$)		NNLO [70]	35.20
Significance ($S/\sqrt{B}$)			0.62



$hh \to bbWW^*$: *dilepton channel*

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Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi JHEP 2017

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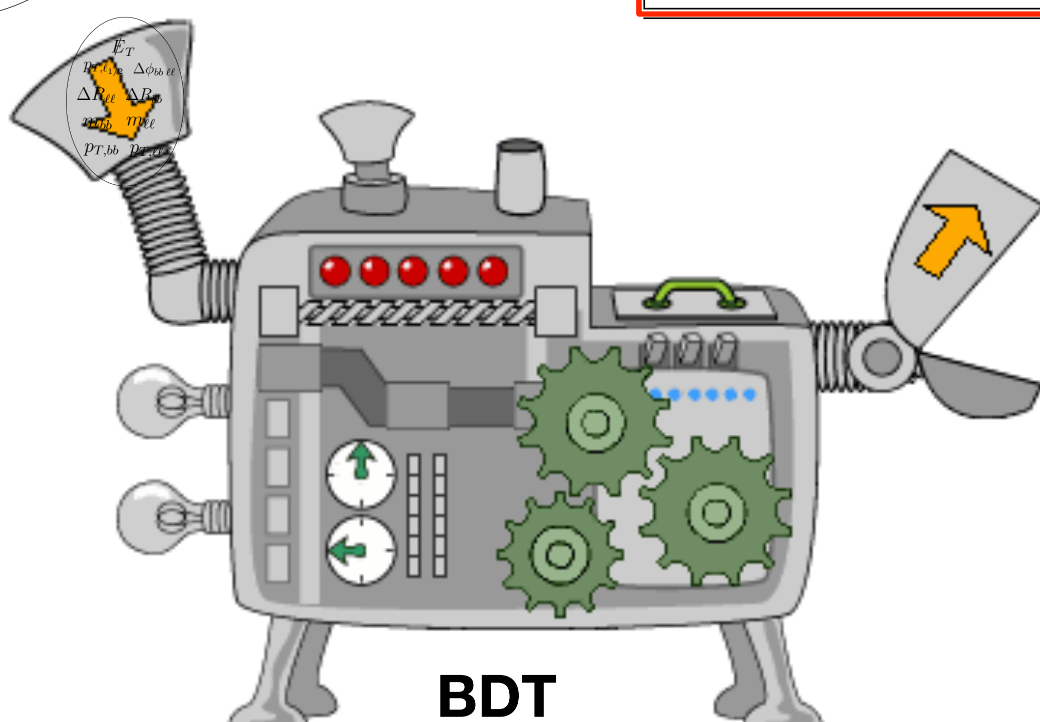

$hh \to bbWW^*$: dilepton channel

HL-LHC, 14 TeV, L=3 ab $^{-1}$

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi JHEP 2017

$\not{E}_T$

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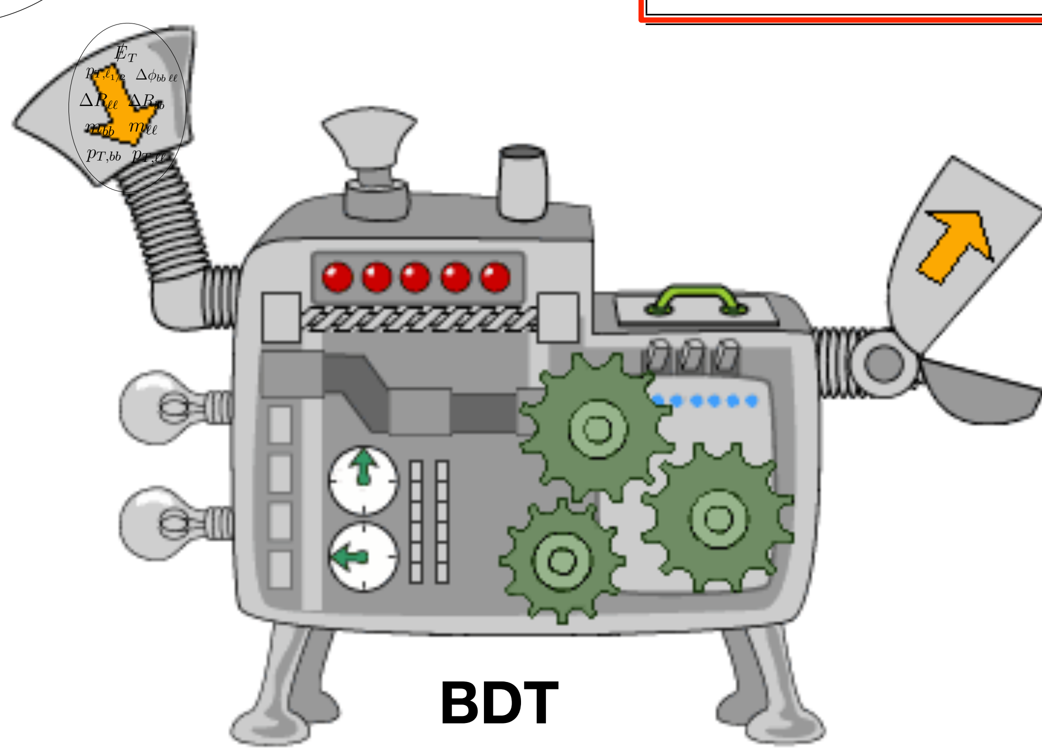
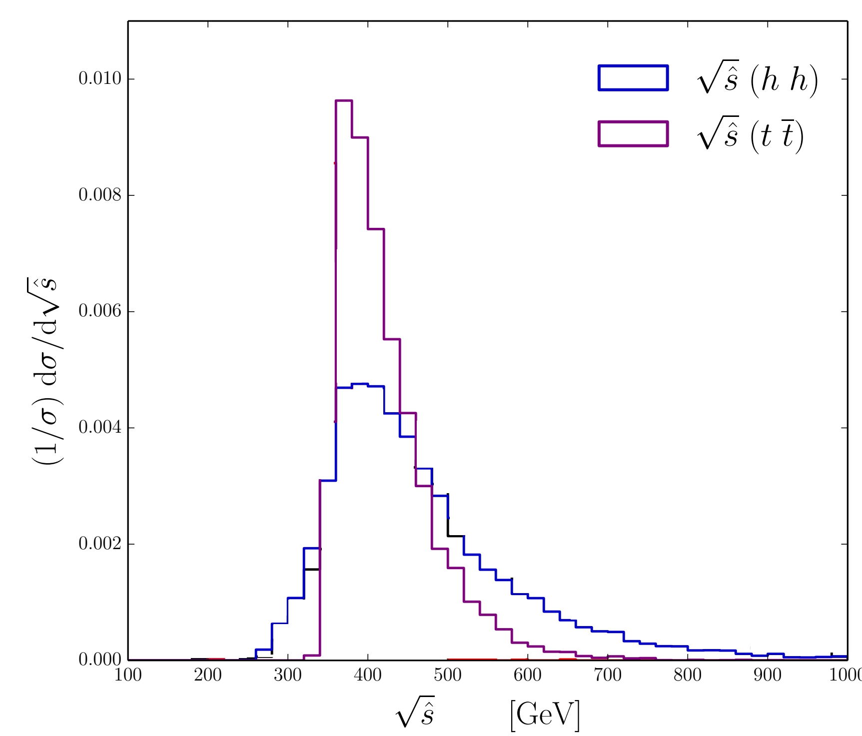
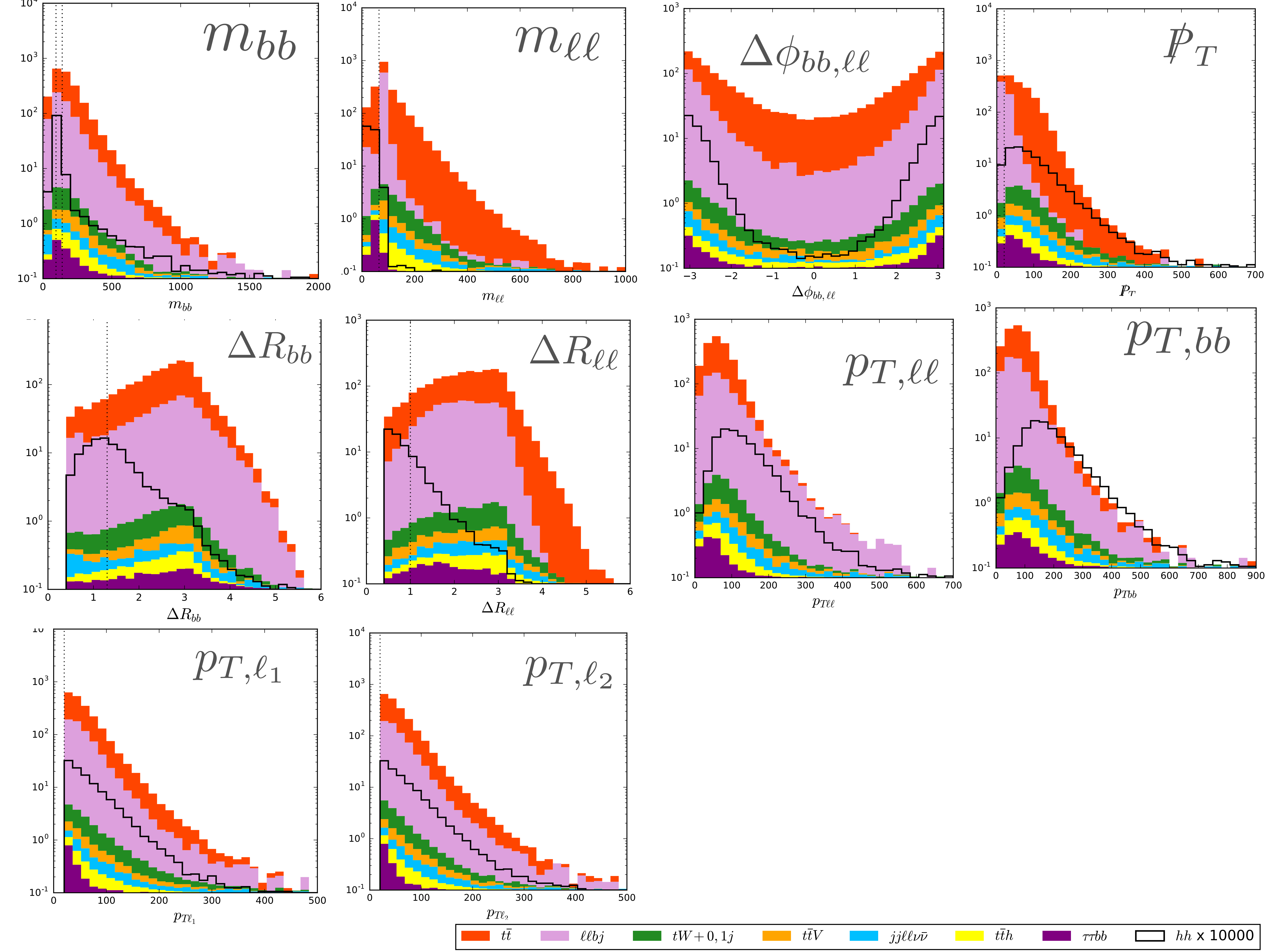
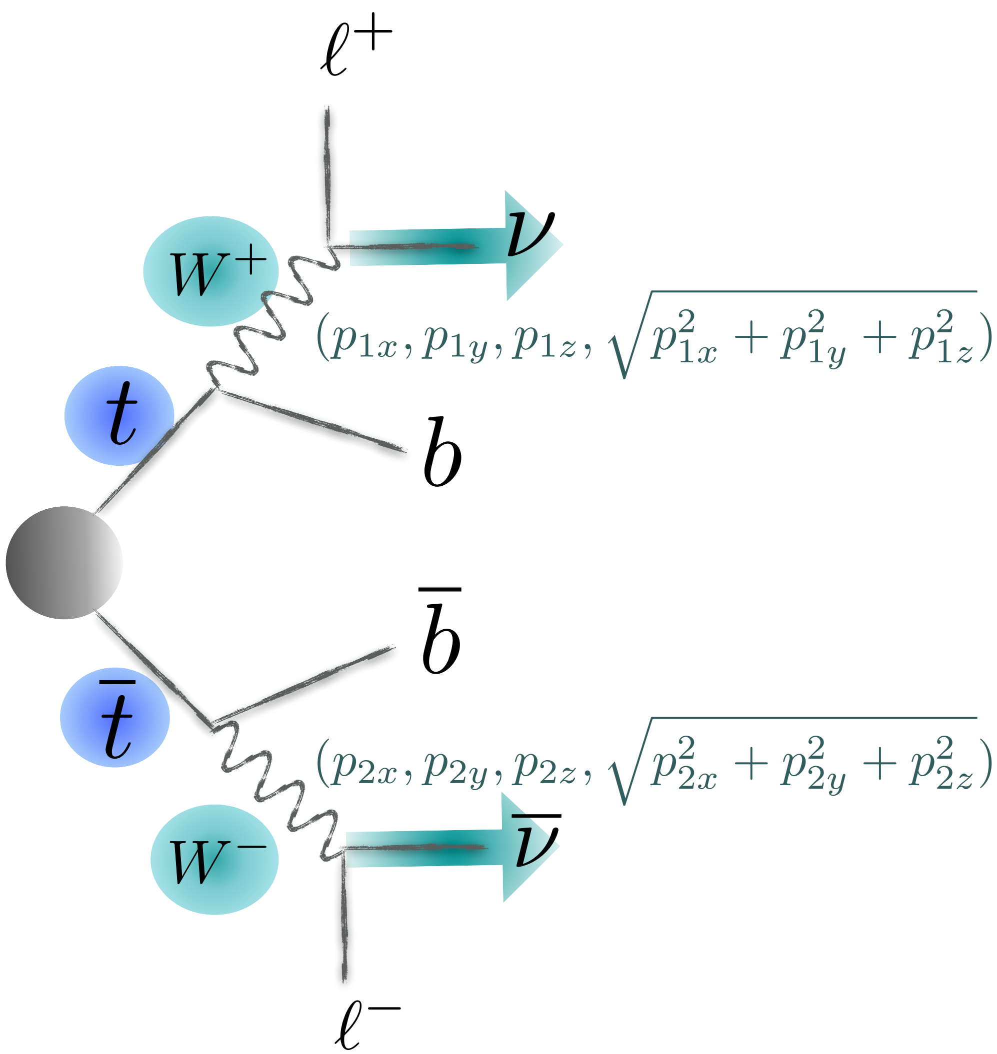






m_{bb}
$m_{\ell\ell}$
$\Delta\phi_{bb,\ell\ell}$
$\not{p}_T$
ΔR_{bb}
$\Delta R_{\ell\ell}$
$p_{T,\ell\ell}$
$p_{T,bb}$
p_{T,ℓ_1}
p_{T,ℓ_2}
$p_{T\ell\ell}$
p_{Tbb}
$p_{T\ell_1}$
$p_{T\ell_2}$
$t\bar{t}$
$\ell\ell bj$
$tW+0,1j$
$t\bar{t}V$
$jj\ell\ell\nu\bar{\nu}$
$t\bar{t}h$
$\tau\tau bb$
hh x 10000

Topness (T)



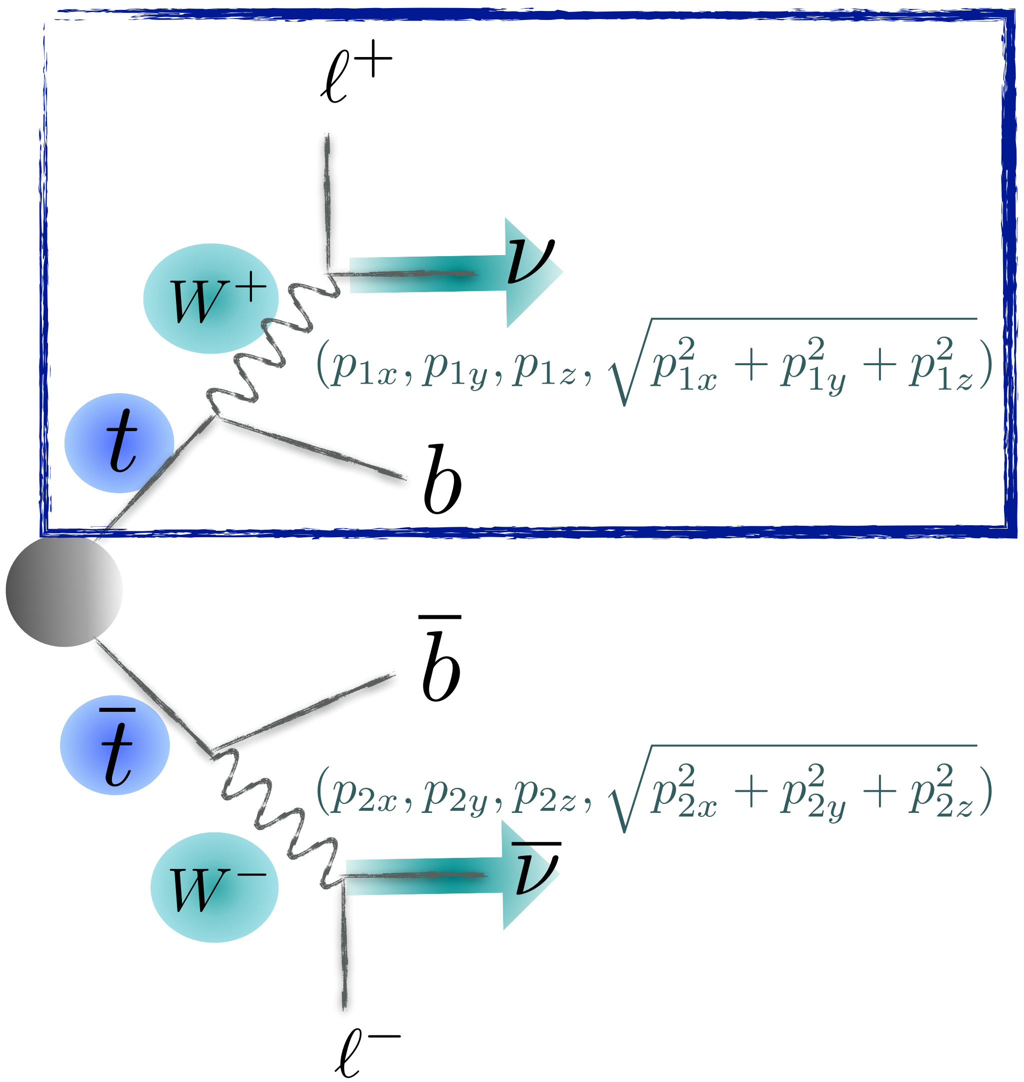
$$\chi_{ij}^2 \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m_{b_i \ell^+ \nu}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^+ \nu}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{b_j \ell^- \bar{\nu}}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^- \bar{\nu}}^2 - m_W^2\right)^2}{\sigma_W^4} \right]$$

$$T \equiv min\left(\chi_{12}^2 \, , \, \chi_{21}^2\right)$$

two possible ways of paring b and ℓ

- Topness provides a degree of consistency to dileptonic $t\bar{t}$ production.
- It scans over 6 unknowns of neutrino momenta with four on-shell masses and missing E_T constraints.
- And find a minimum of the likelihood function.

Topness (T)



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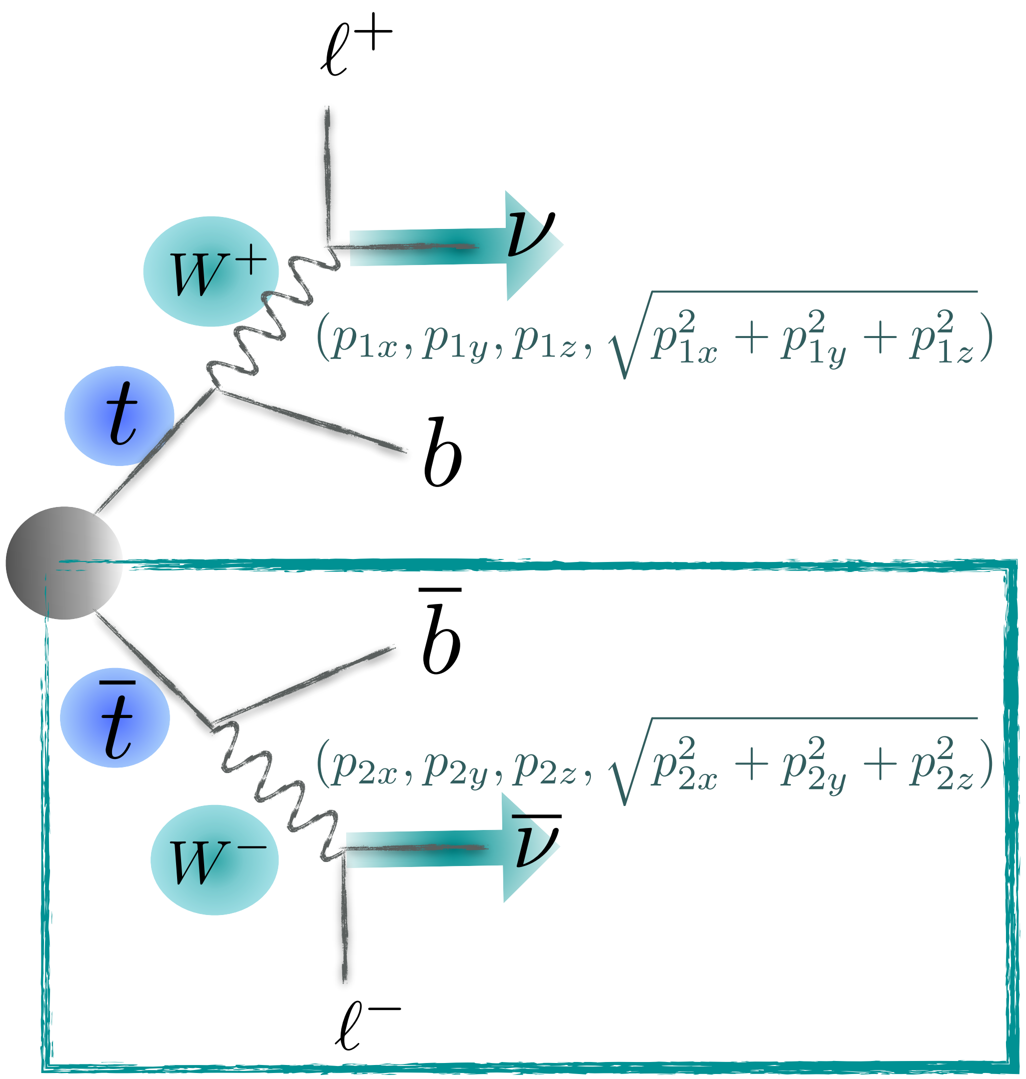

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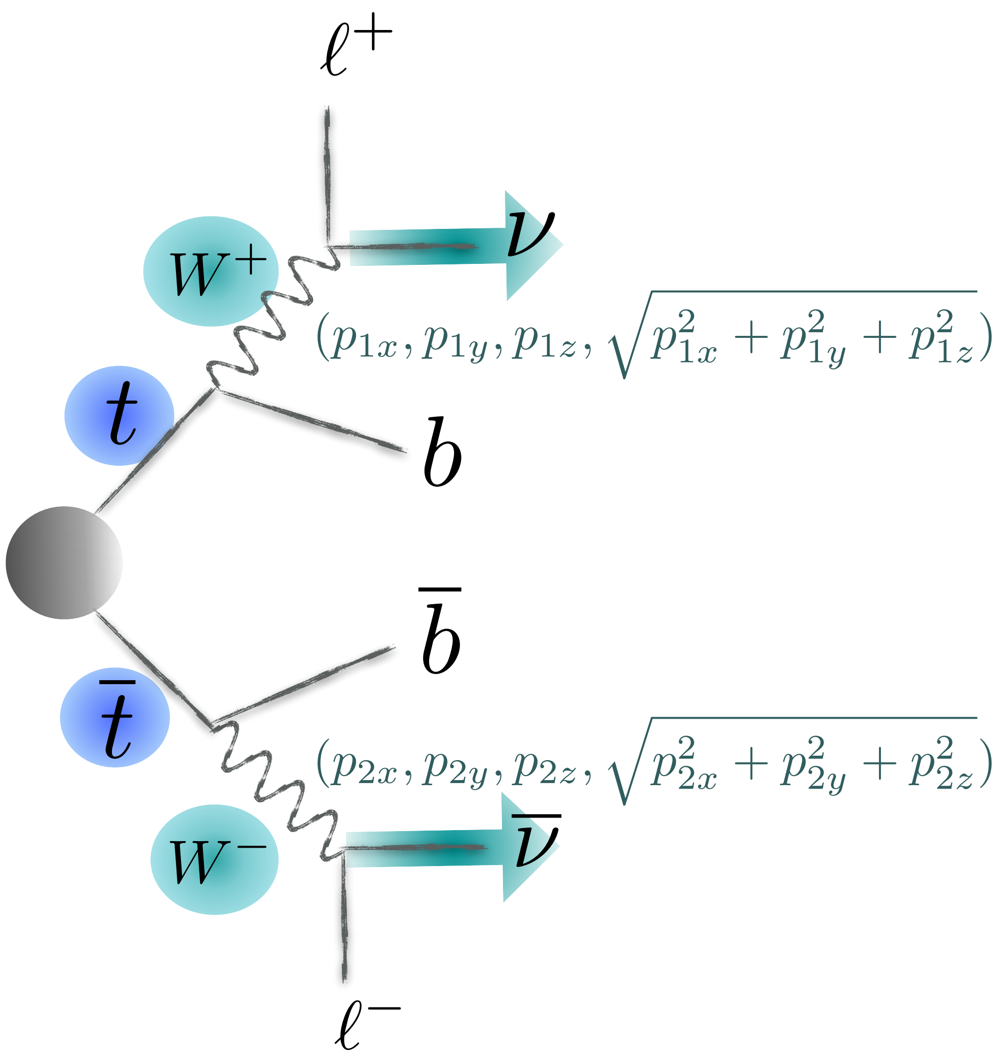

$$\chi^2_{ij} \equiv \min_{\vec{\not p}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i \ell^+ \nu} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^+ \nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{b_j \ell^- \bar{\nu}} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} \right]$$

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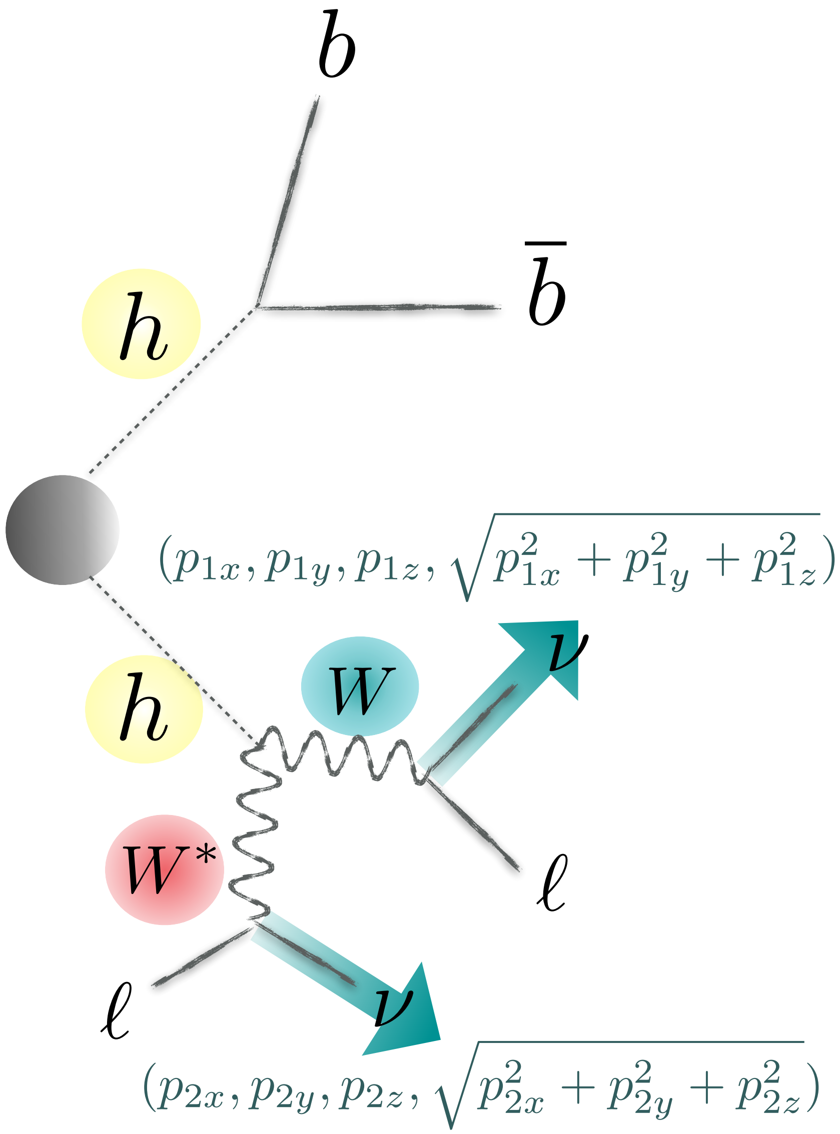
Higgsness (H)



$$H \equiv \min_{\not{\vec{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{\ell^+\ell^-\nu\bar{\nu}} - m_h^2\right)^2}{\sigma^4_{h_\ell}} + \frac{\left(m^2_{\nu\bar{\nu}} - m^2_{\nu\bar{\nu},peak}\right)^2}{\sigma^4_\nu} + min\left(\frac{\left(m^2_{\ell^+\nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{\ell^-\bar{\nu}} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}}, \frac{\left(m^2_{\ell^-\bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{\ell^+\nu} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}} \right) \right],$$

$\sim m_h - m_W$
off-shell

- Higgsness provides a degree of consistency to dileptonic $h \to WW^*$ system.
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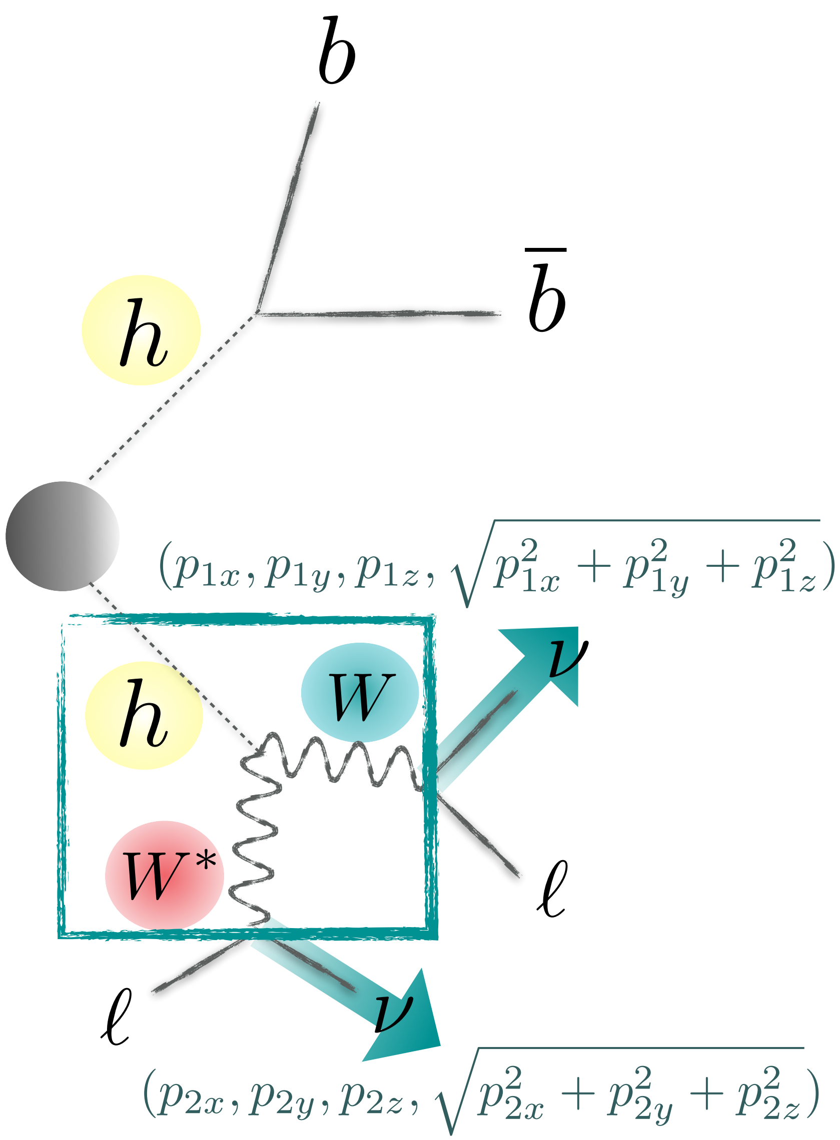
- Its distribution is wide, but there is a peak, which can constrain hh system further.

Higgsness (H)



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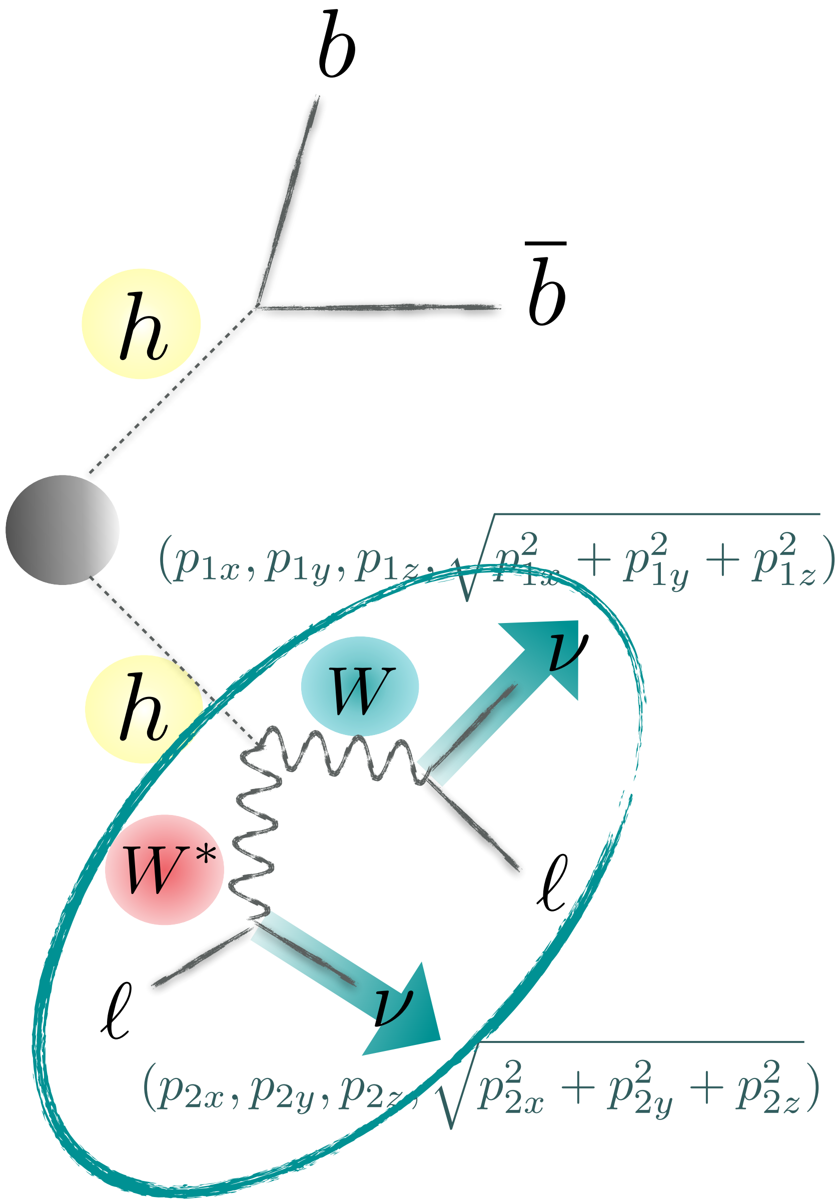

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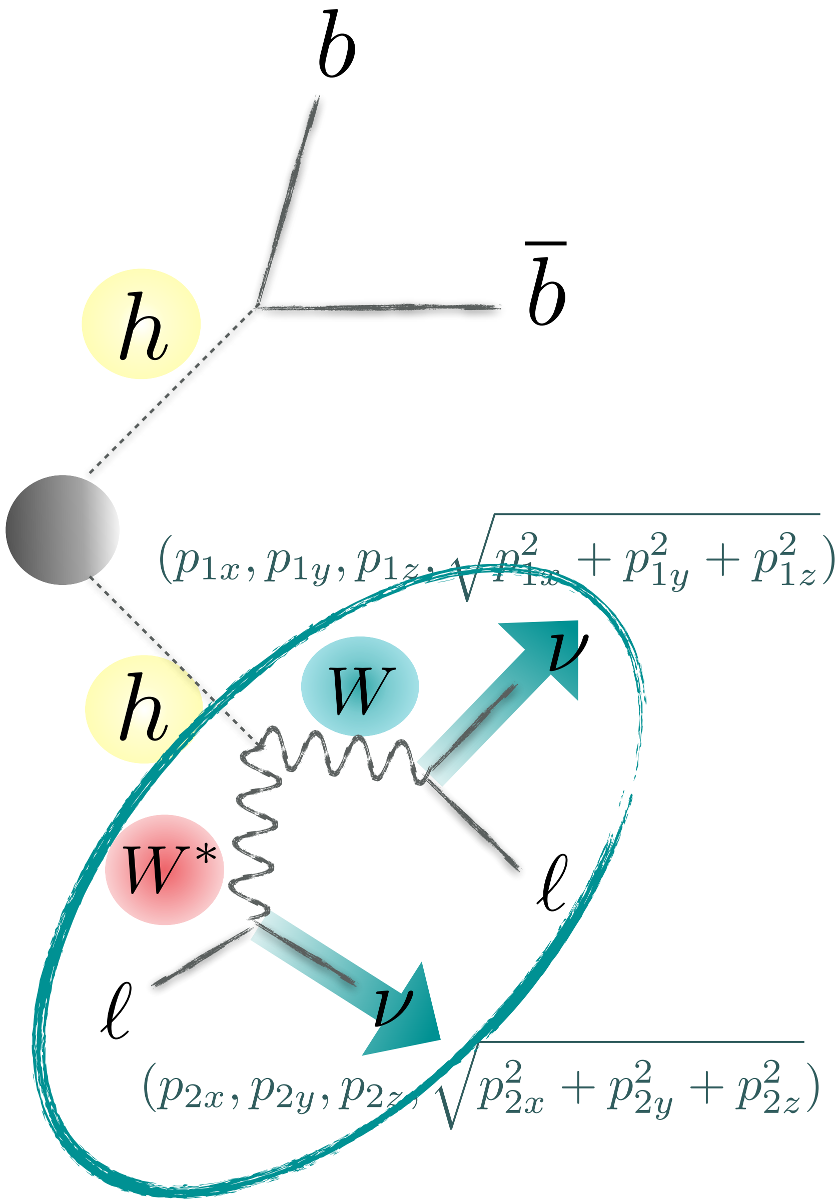
Higgsness (*H*)



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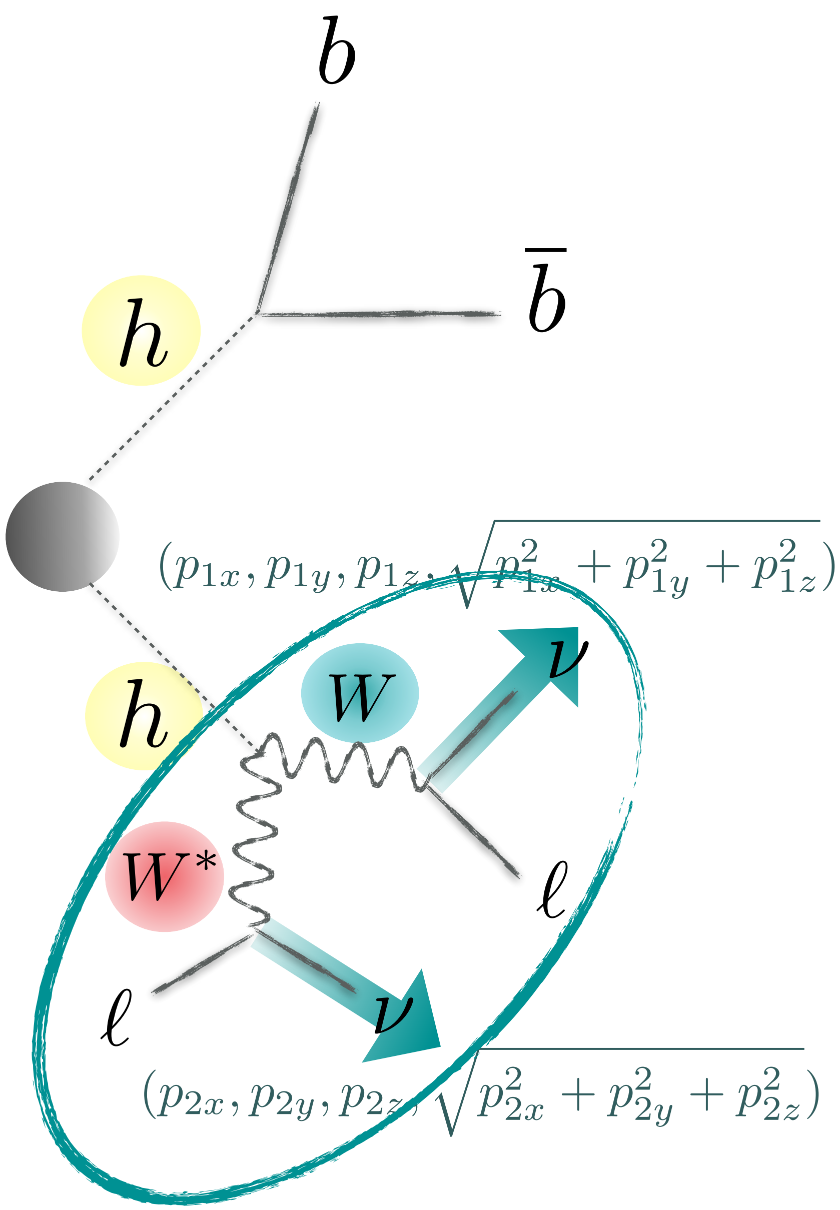

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two possible ways of paring ν and ℓ

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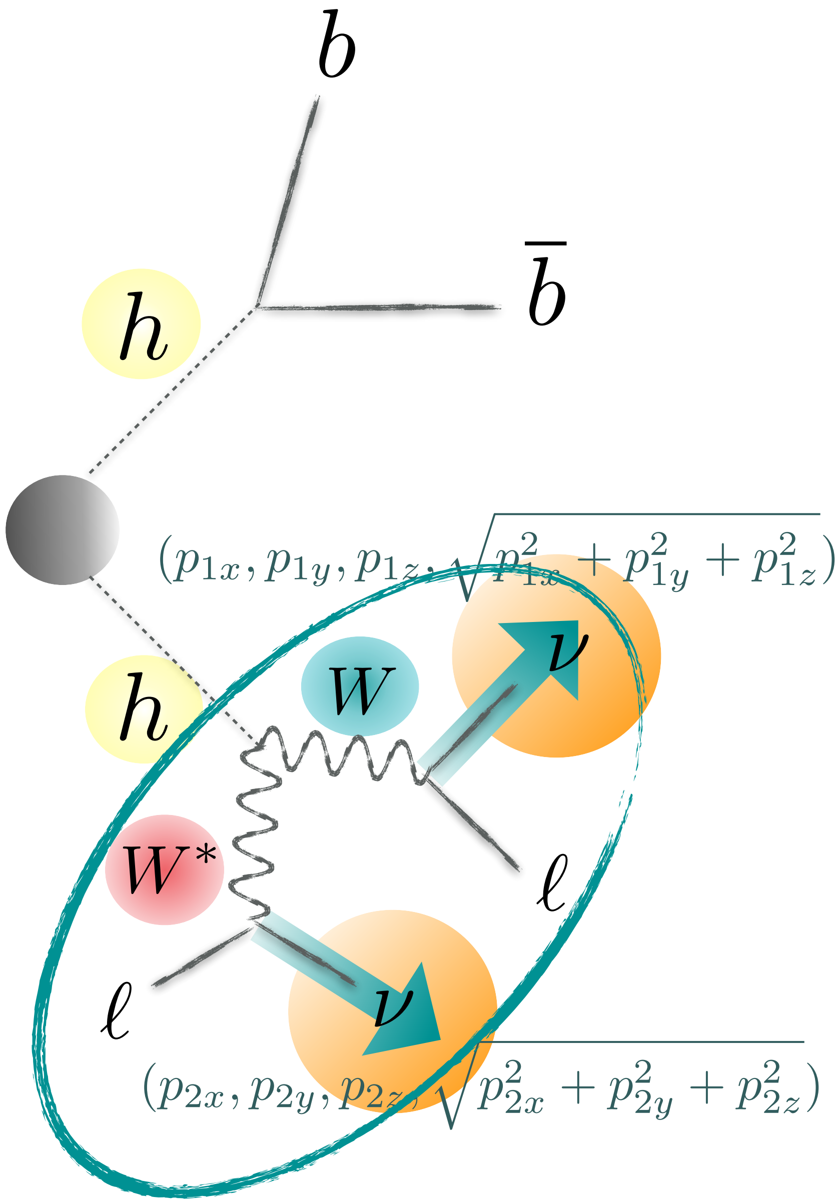

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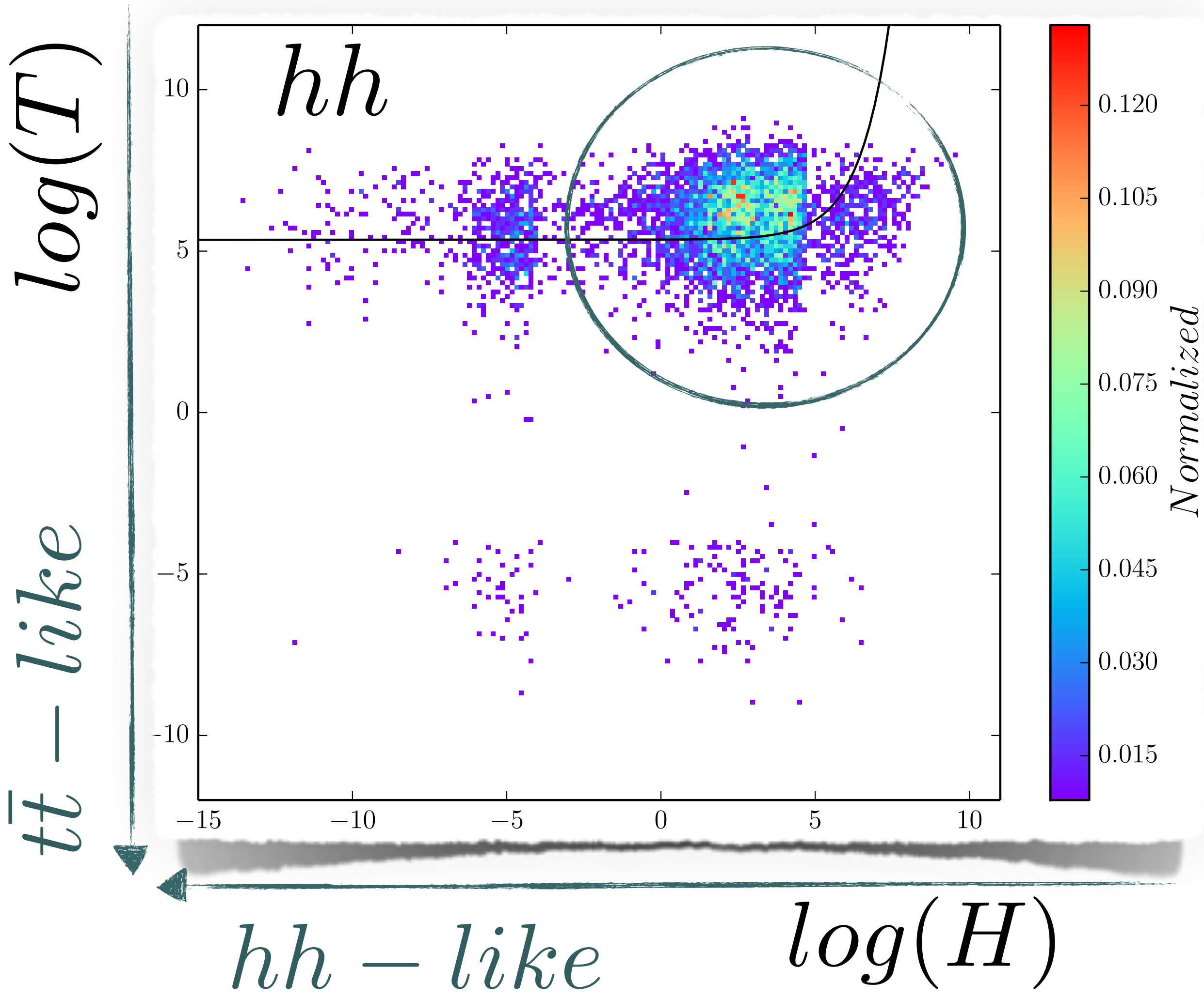
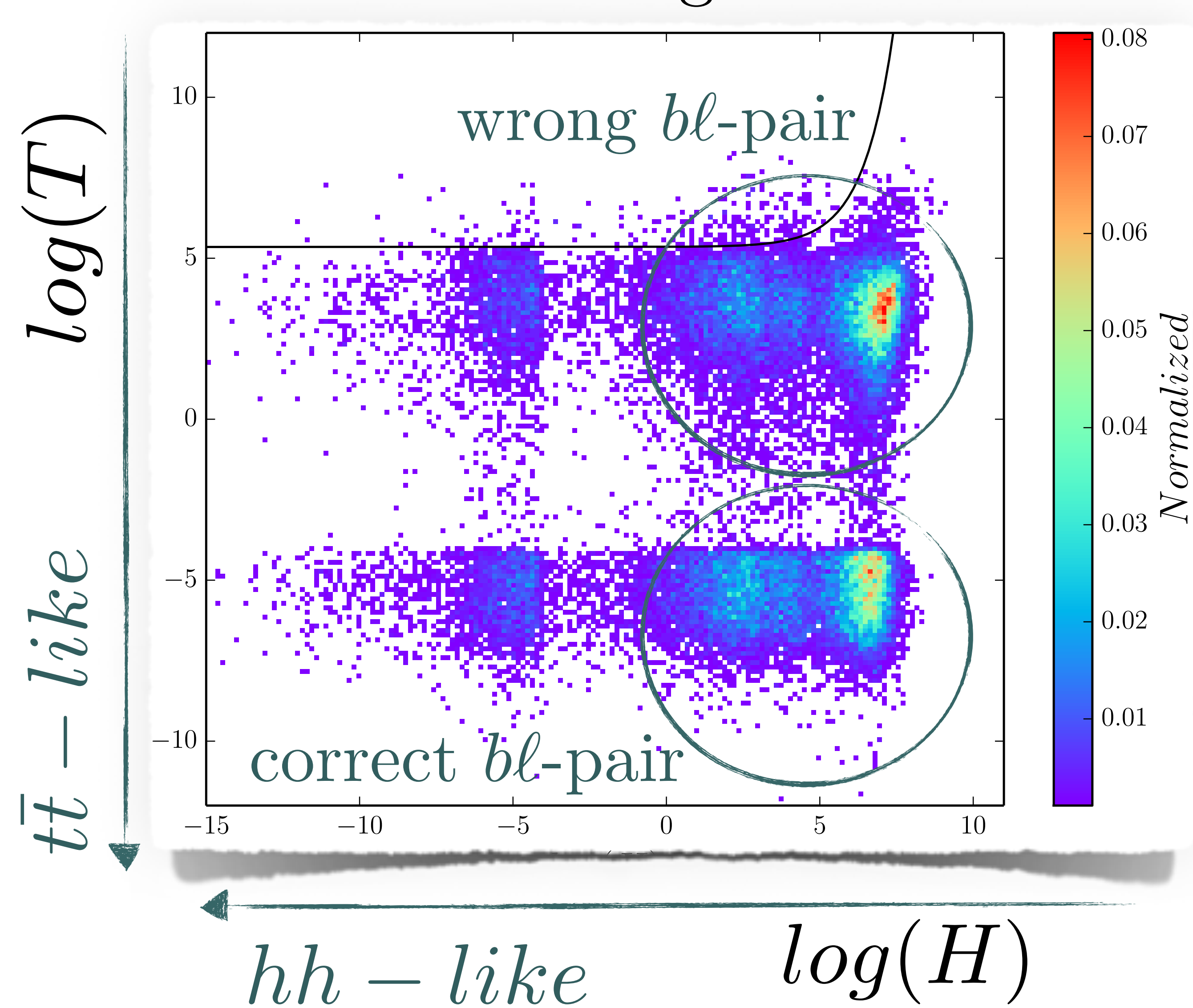
Distributions of (*log H* , *log T*) after baseline selection cuts



- A clear separation between *hh* and backgrounds ($t\bar{t}$ is dominant)

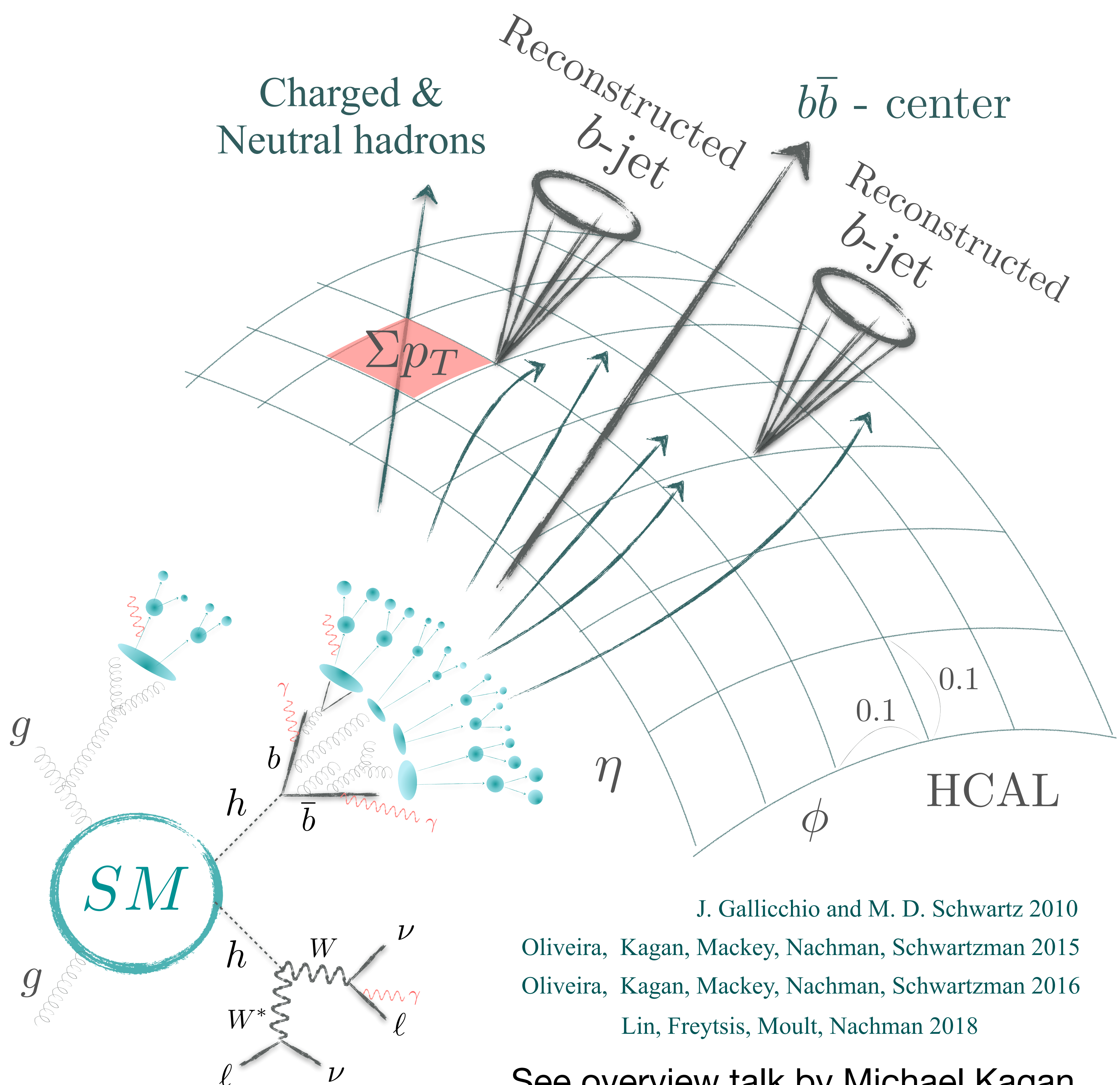
All backgrounds

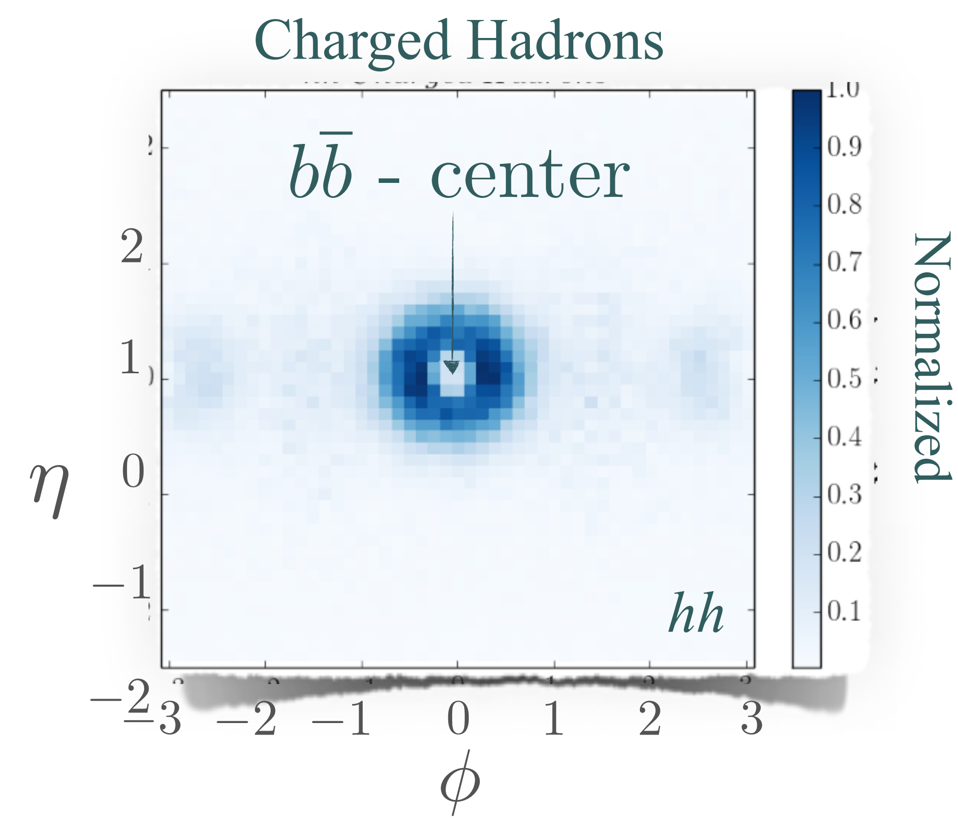


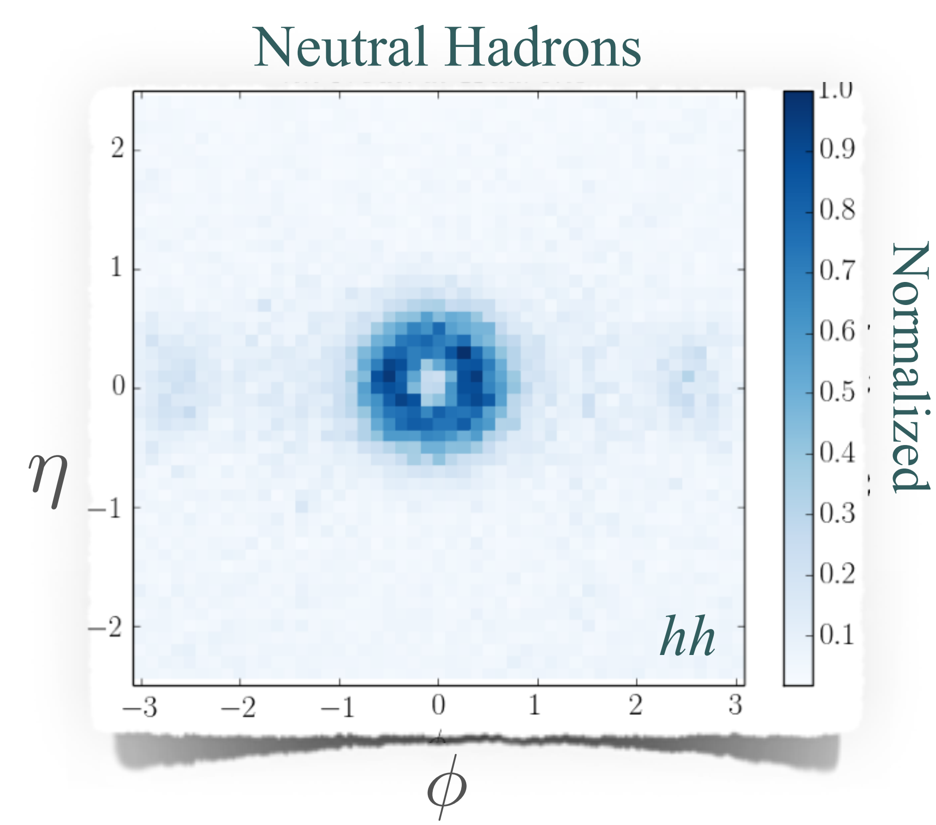
- The Topness (Higgsness) variable measures the degree of consistency of a given event with the kinematics of dilepton ttbar (hh) production.

Kim, Kong, Matchev, Park, PRL 2019

Processing Hadron Images (hh)







J. Gallicchio and M. D. Schwartz 2010

Oliveira, Kagan, Mackey, Nachman, Schwartzman 2015

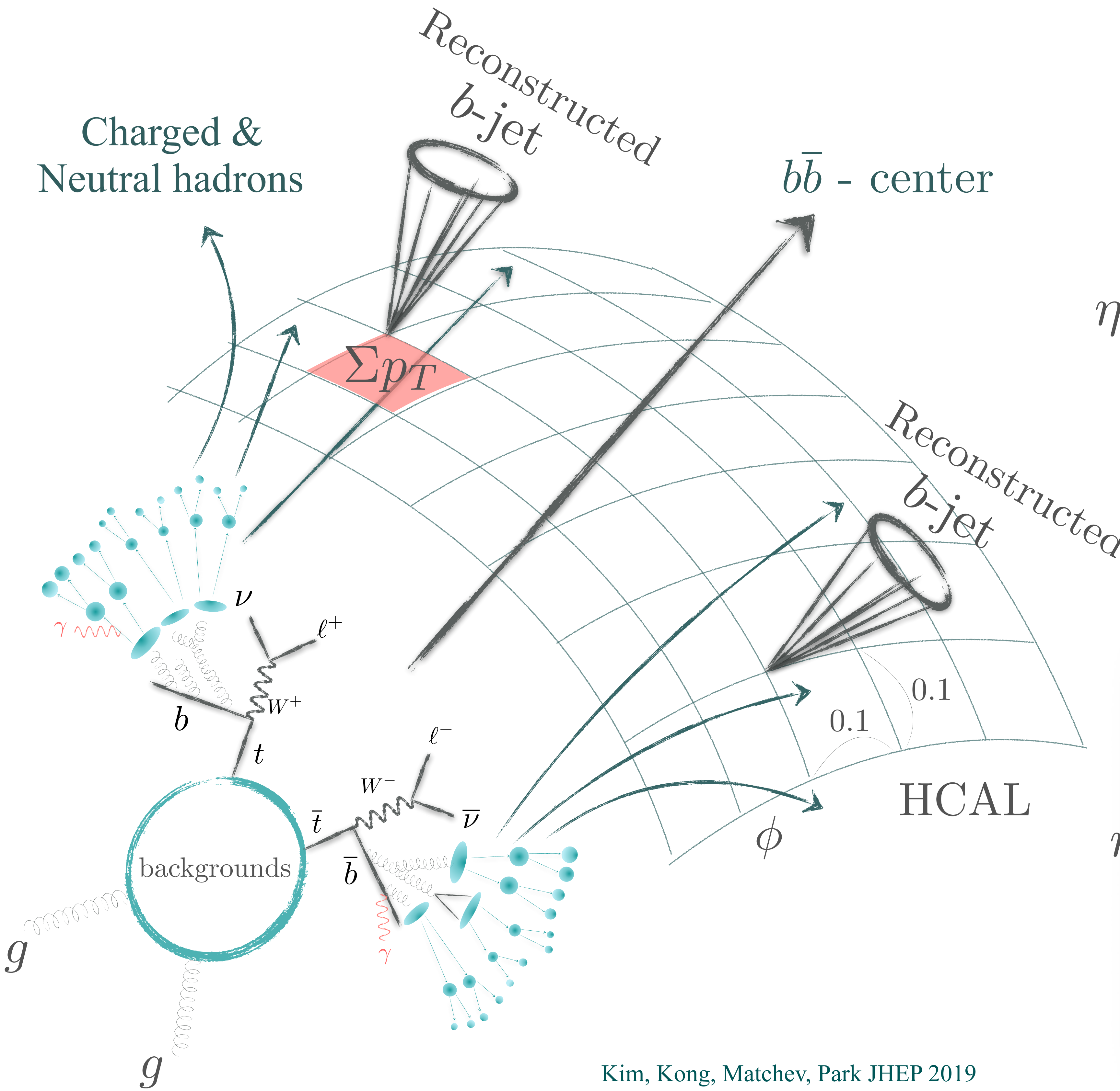
Oliveira, Kagan, Mackey, Nachman, Schwartzman 2016

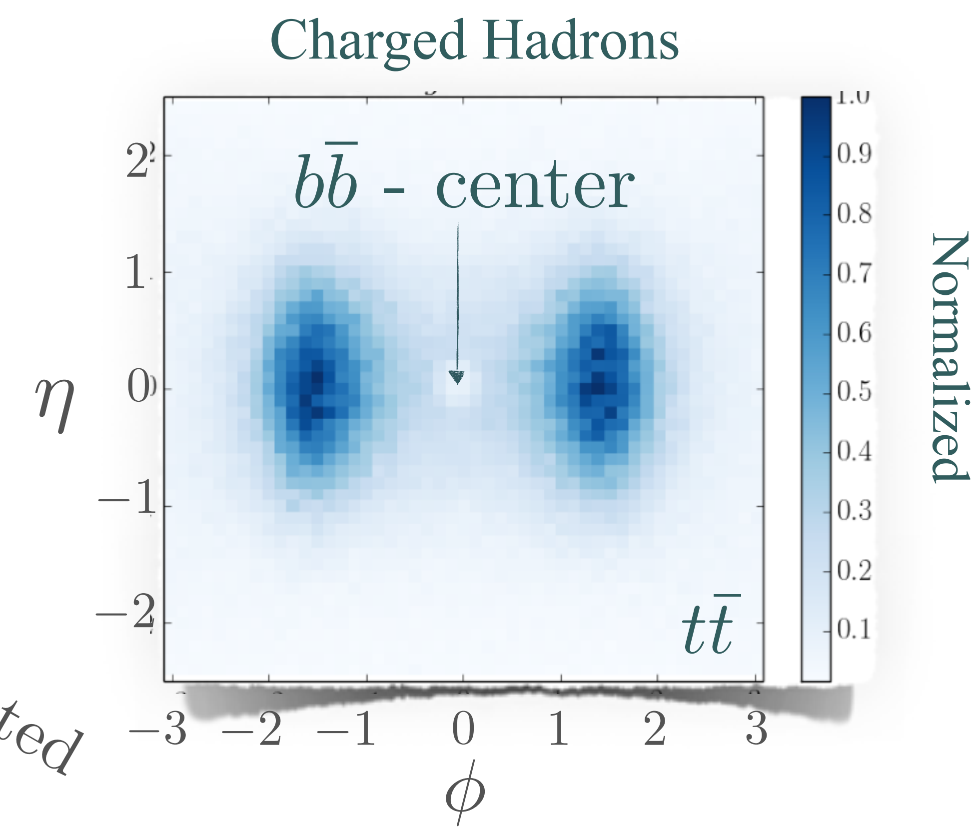
Lin, Freytsis, Moult, Nachman 2018

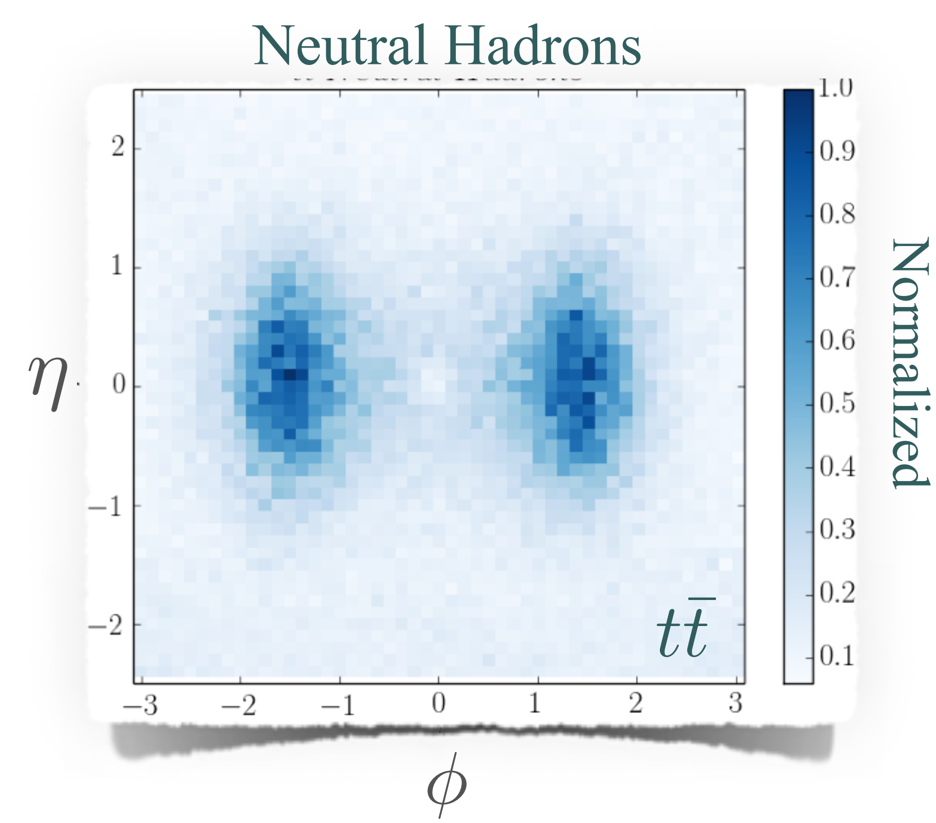
See overview talk by Michael Kagan

Kim, Kong, Matchev, Park JHEP 2019

Processing Hadron Images (tt)







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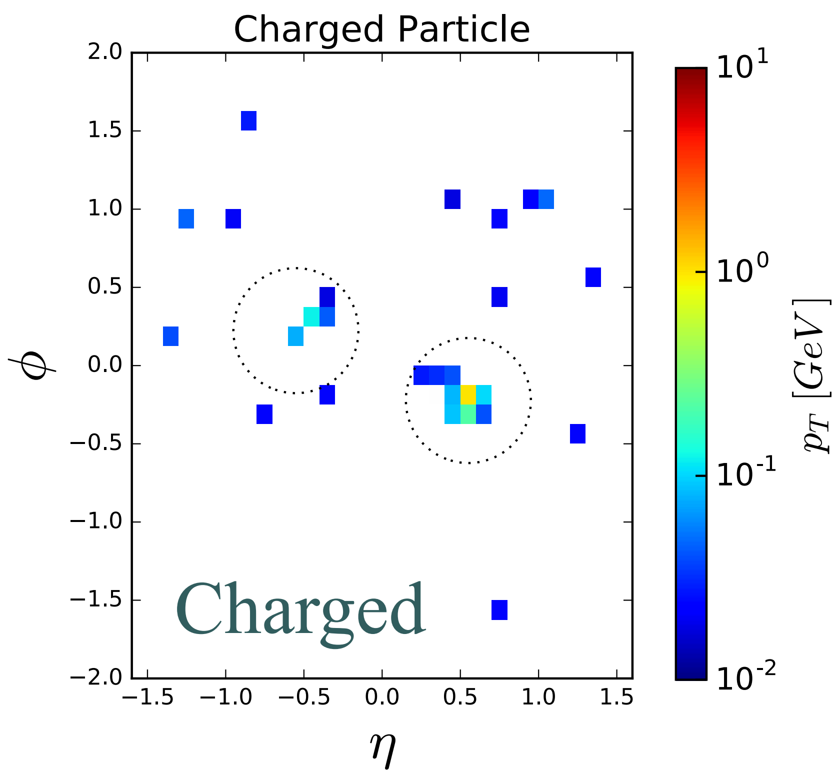
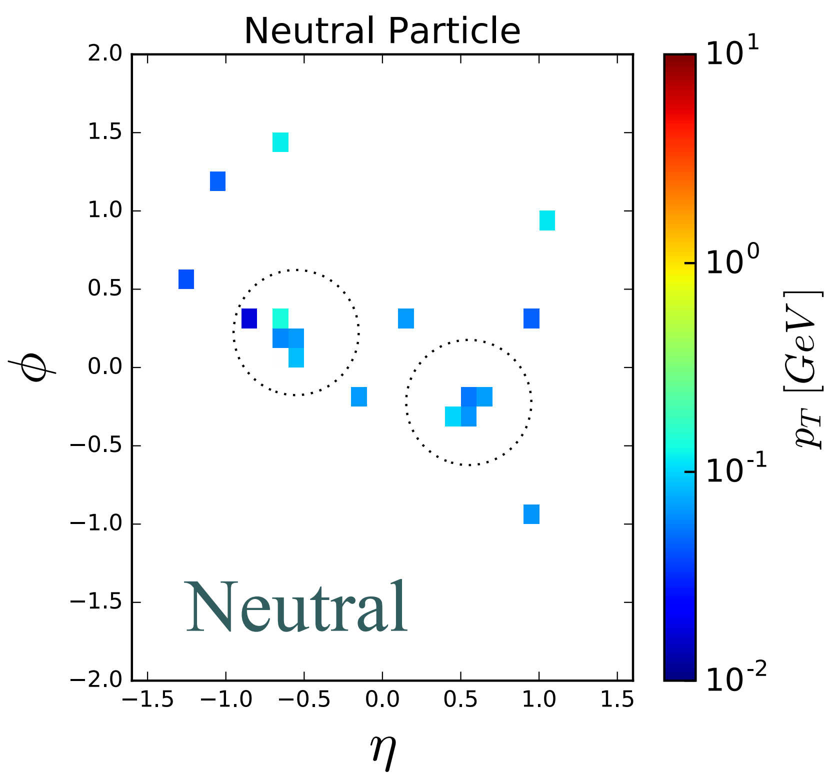
*J*et images: event-by-event

Each *hh* event

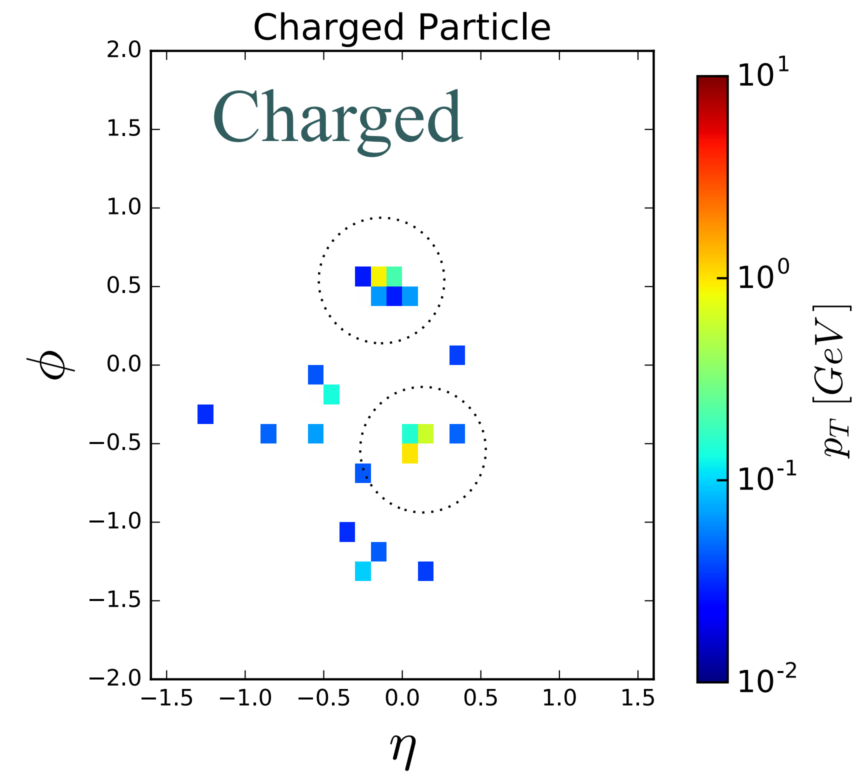


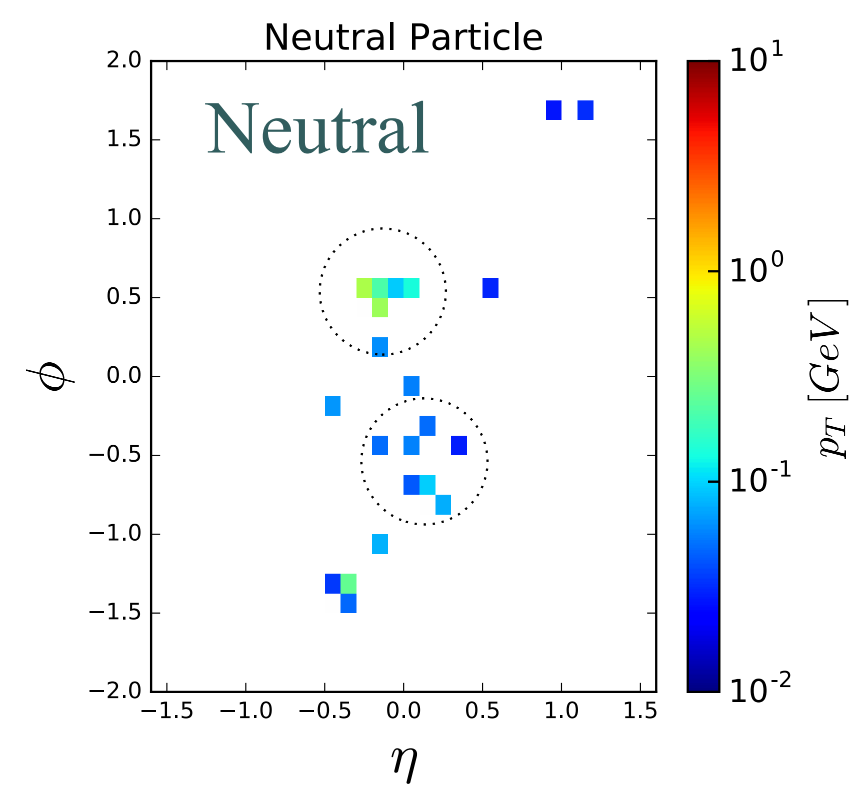


- It is difficult to distinguish them using the cut-and-count method…

- We train the machine using Deep Neural Network (DNN) architecture.

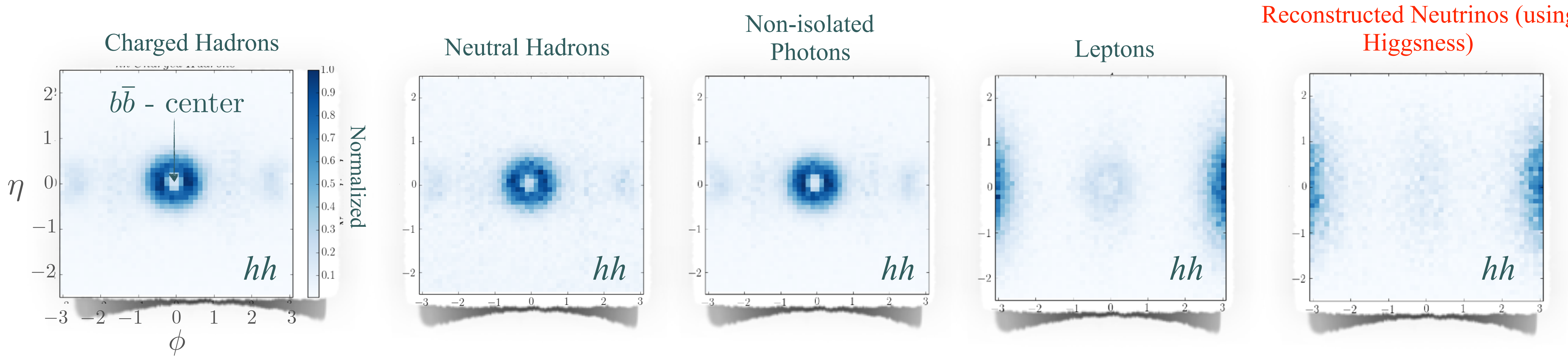
Each *tt* event



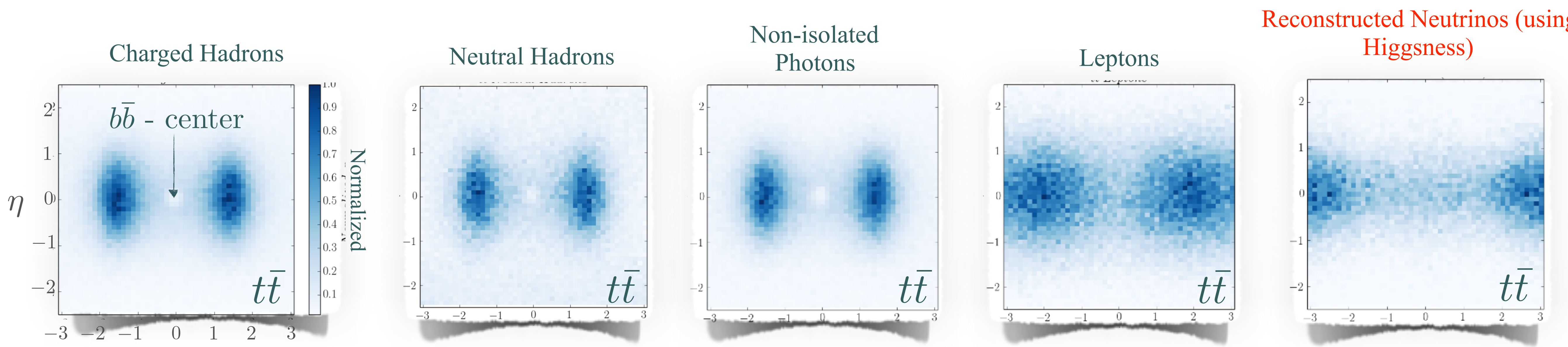


The Di-Higgs Photography

- Totally hadrons, lepton, photon, and neutrino images are shown for *hh*.



- Analogous five images are shown for $t\bar{t}$ background.



- A sharp difference between *hh* and $t\bar{t}$.

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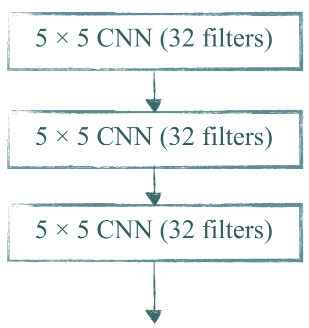
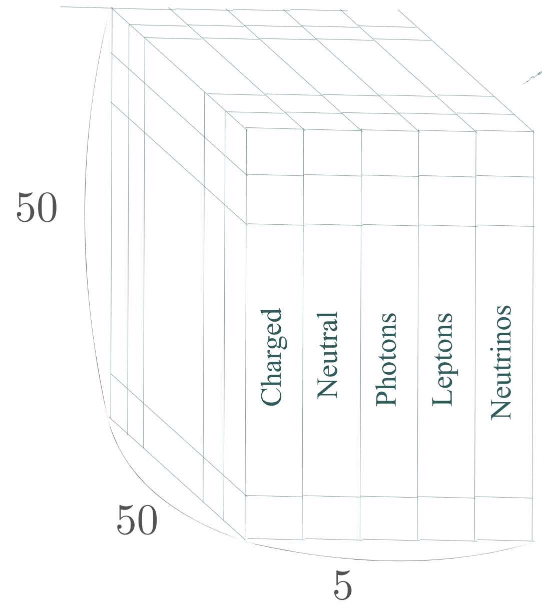
Our ResNet

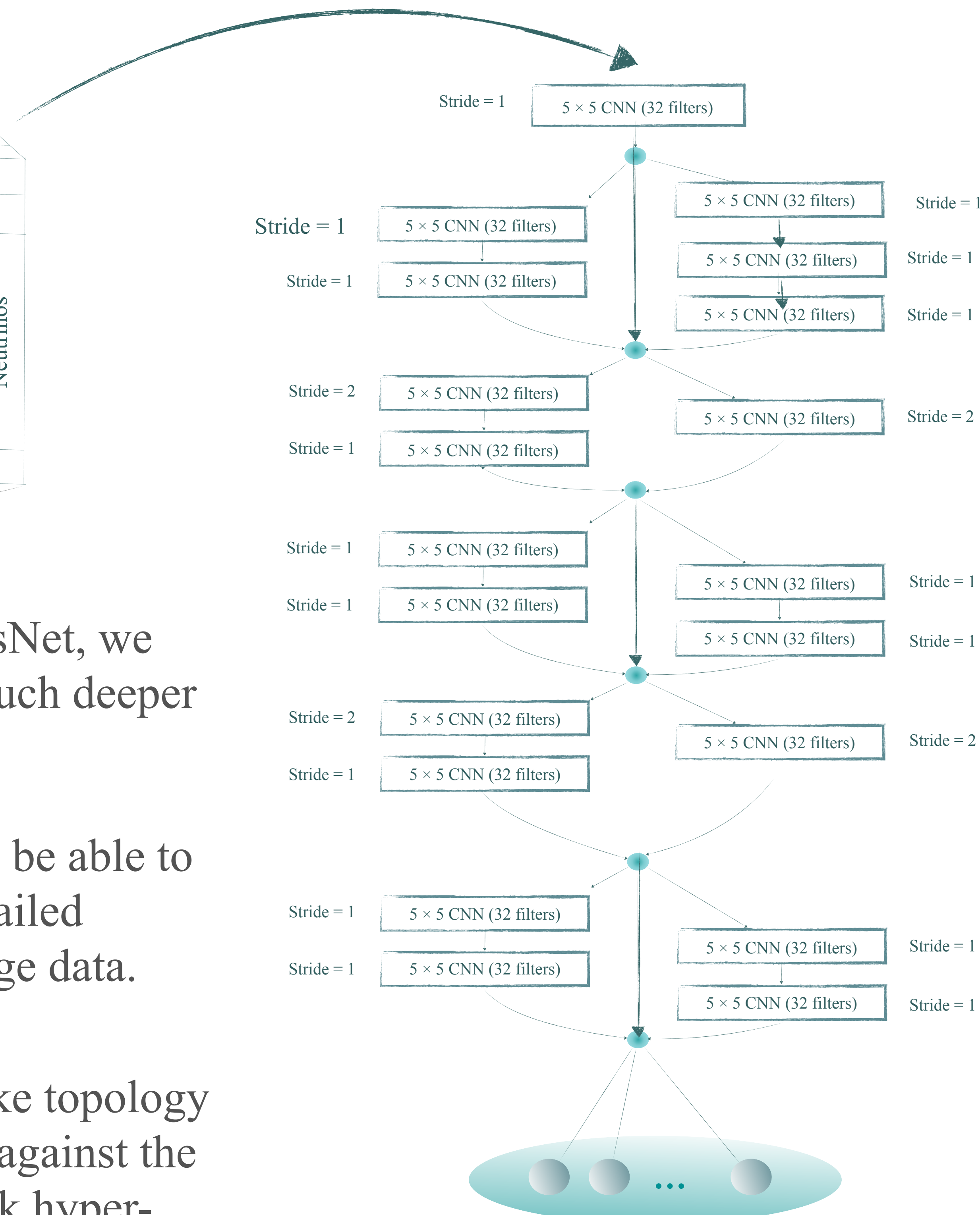
Classic CNN



- As the network becomes deeper, the performance of CNN gets saturated or even starts degrading rapidly.
- The classic CNN starts to degrade after 3 layers, with our 5-image data.
- Absolutely not suitable.



- Motivated by ResNet, we could design a much deeper network.
- The machine will be able to resolve much detailed features of 5-image data.
- This ensemble-like topology is much resilient against the change in network hyper-parameter.



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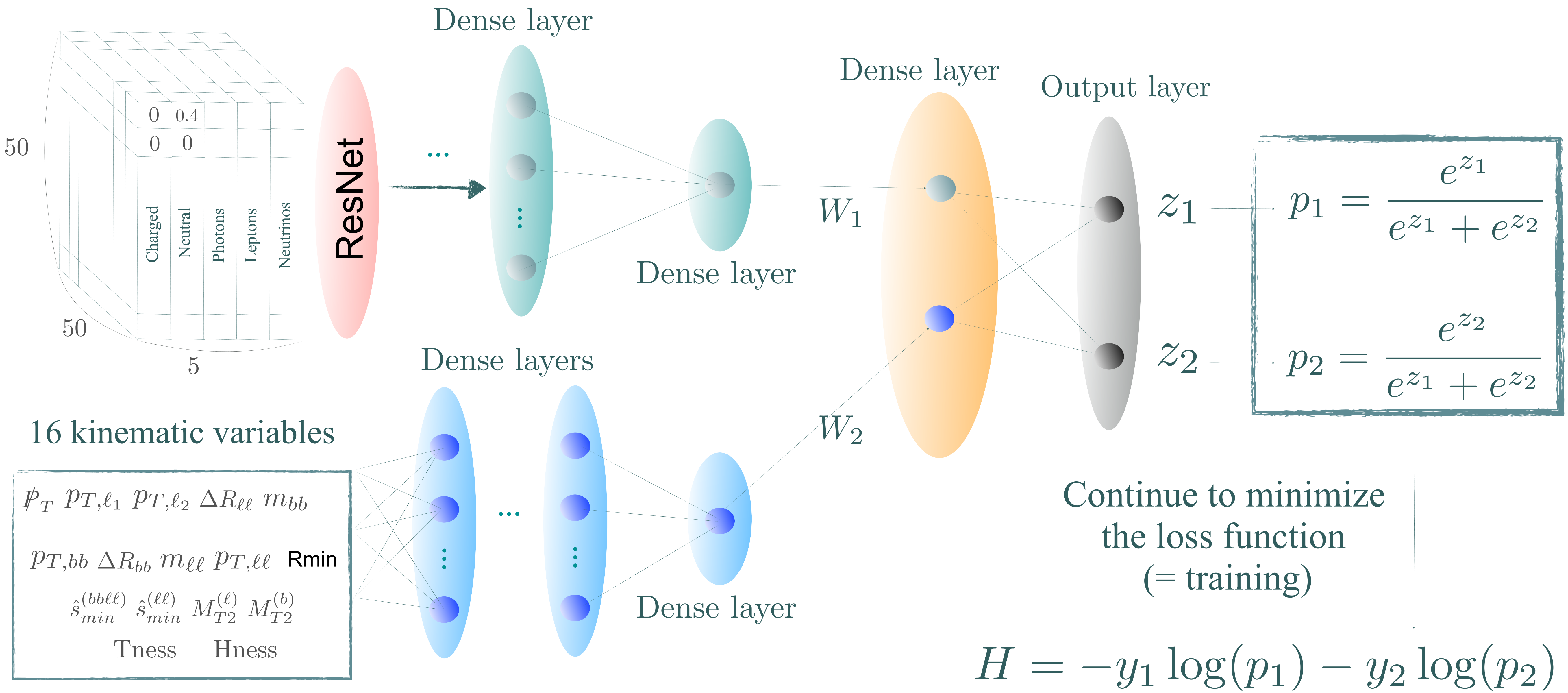
Combining image data and high level kinematic variables in dense neural networks



$$\text{Signal}: \quad (y_1, y_2) = (1, 0)$$

$$\text{Backgrounds}: \quad (y_1, y_2) = (0, 1)$$

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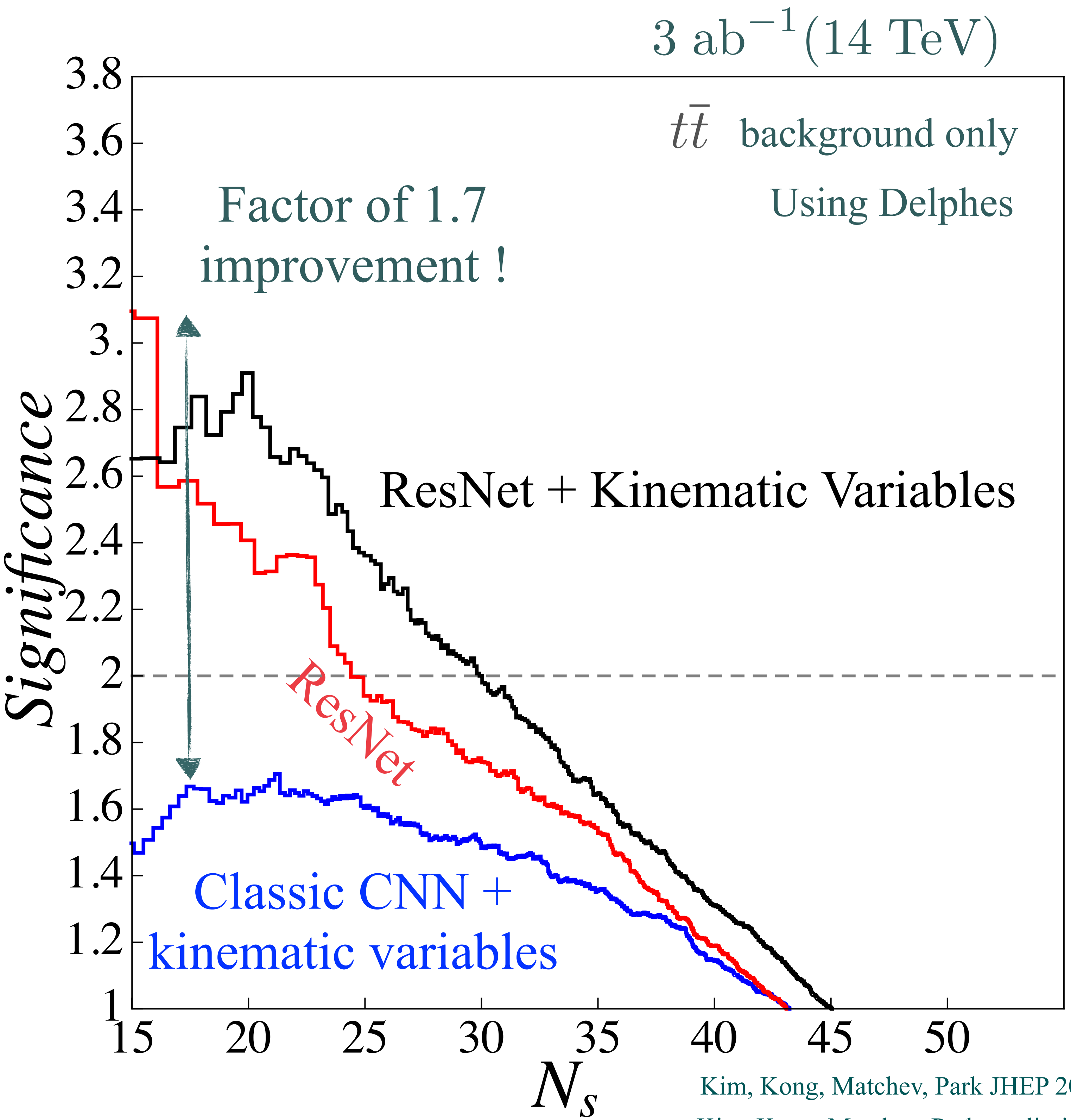
Preliminary Results



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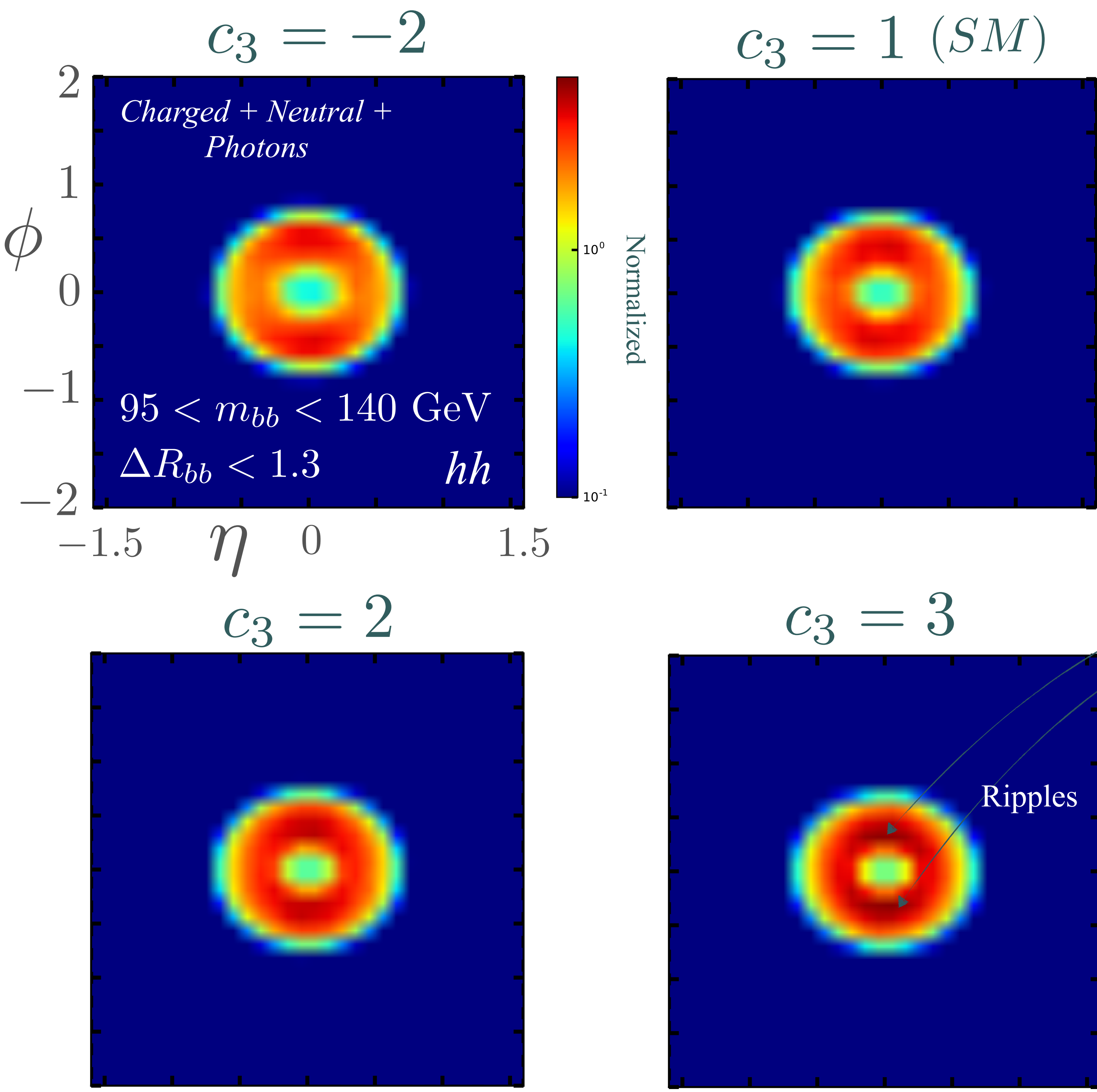
- As a preliminary study, we included only $t\bar{t}$ background.
- Significance with kinematic variables only or jet images only give signal significance below 1.
- We find that the classic CNN + kinematic variables can reach at most 1.7 sigma.
- Our ResNet can reach up to 2.9 sigma (factor of ~1.7 improvement)
- Our ResNet can be further reinforced by combining reconstructed kinematic variables.
- More recent architecture, Capsule Nets also provides a similar performance.

Shifting the Higgs triple coupling c_3

- How does the *hh* image vary by shifting the Higgs triple coupling c_3 ?

$$\mathcal{L} \supset -c_3 \frac{m_h^2}{2v} h^3$$



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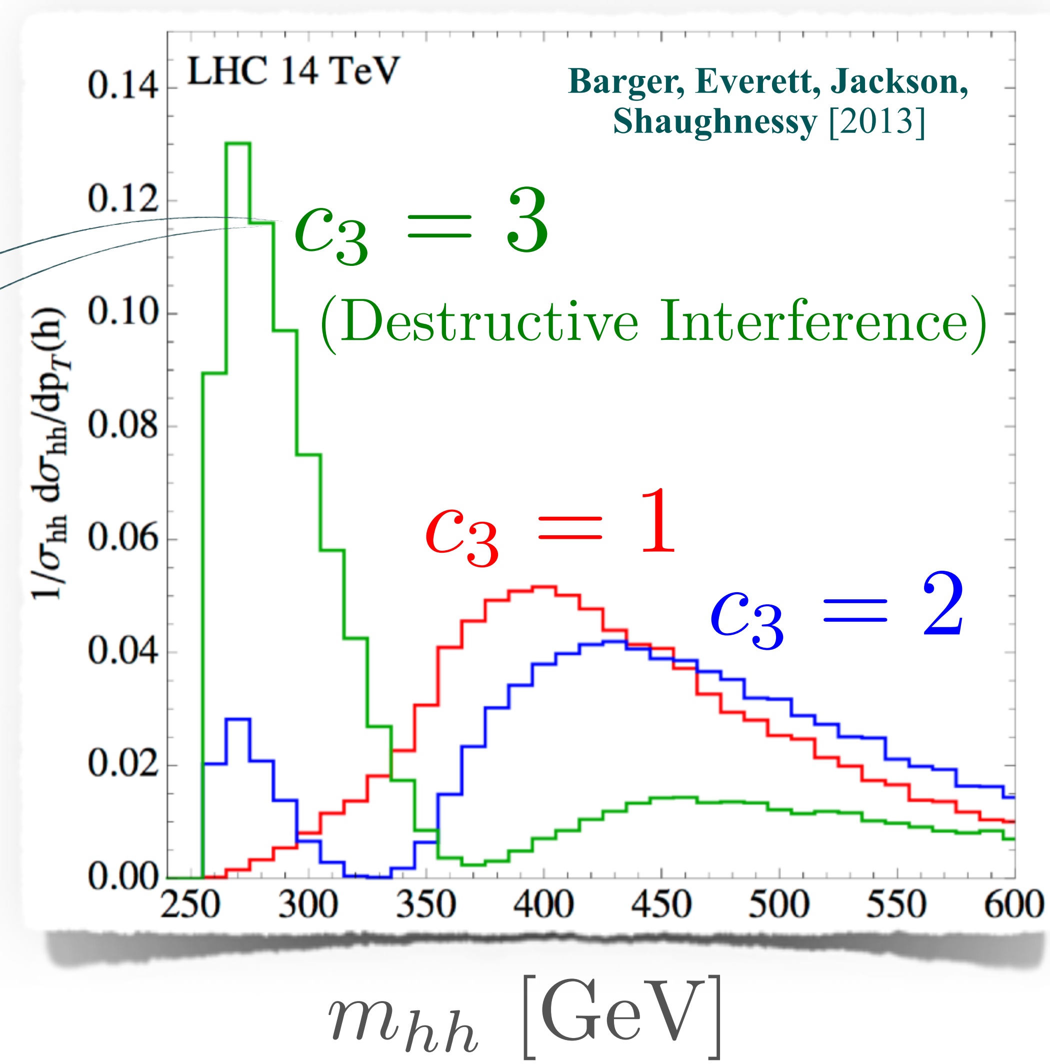
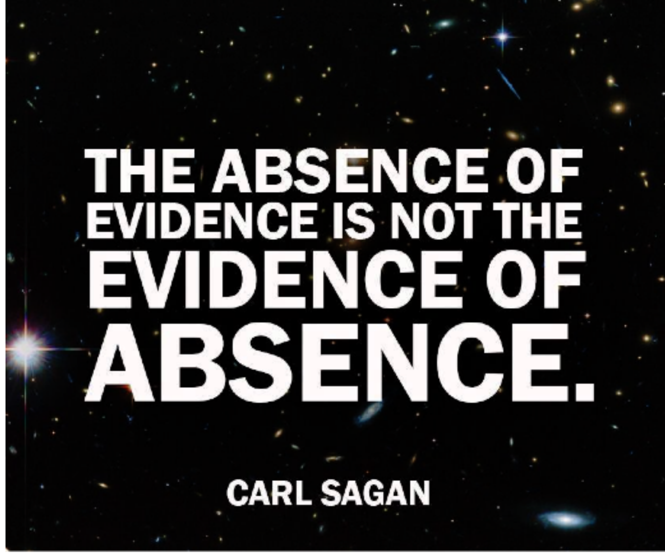
- Interestingly, the gradient of images change as moving into the region of a destructive interference.
- We are working on how much neural network can be sensitive to this change (we don't know yet, sorry).



Summary



- LHC has great opportunity to study new physics beyond the SM.
- Measurement of triple Higgs self coupling reveals the nature of electroweak symmetry breaking.
- Double Higgs production is challenging due to small signal cross section / large SM backgrounds, and strong correlation among many kinematic variables.
- Multivariate analysis could benefit from deep neural networks using jet images and Topness / Higgsness with mass information.
- bbWW dilepton channel would make a significant contribution in triple Higgs coupling measurement. There is room for further improvement.
- Semi-leptonic channel would be similar.