How and Why to go Beyond the Discovery of the Higgs Boson

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University of Chicago

http://hep.uchicago.edu/~johnda/ComptonLectures.html

Lecture Outline

April 1st: **Newton's dream & 20th Century Revolution**

April 8th: **Mission Barely Possible: QM + SR**

April 15th: **The Standard Model**

April 22nd: **Importance of the Higgs**

April 29th: **Guest Lecture**

May 6th: **The Cannon and the Camera**

May 13th: **The Discovery of the Higgs Boson**

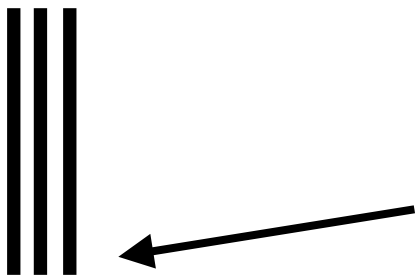
May 20th: **Problems with the Standard Model**

May 27th: **Memorial Day: No Lecture**

June 3rd: ***Going beyond the Higgs: What comes next ?***

Reminder: Last Week

Quantum Mechanics + Space-time leads us to expect:



Planck scale ~ weak scale ~ Hubble scale

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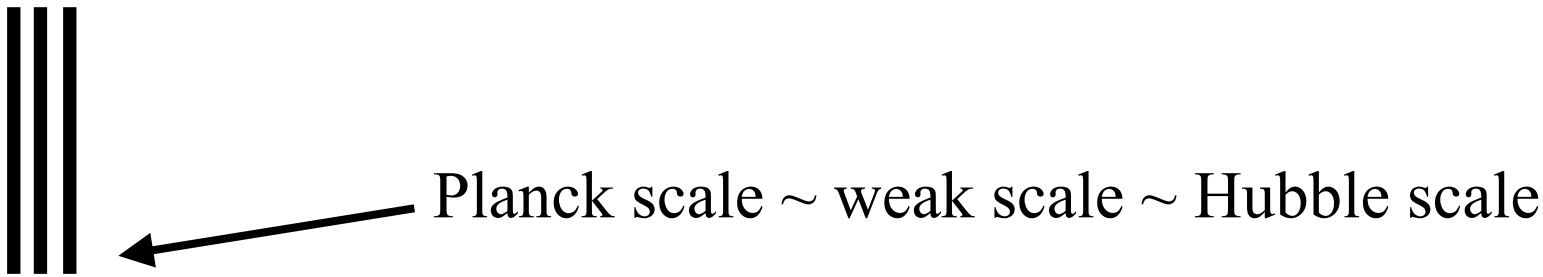
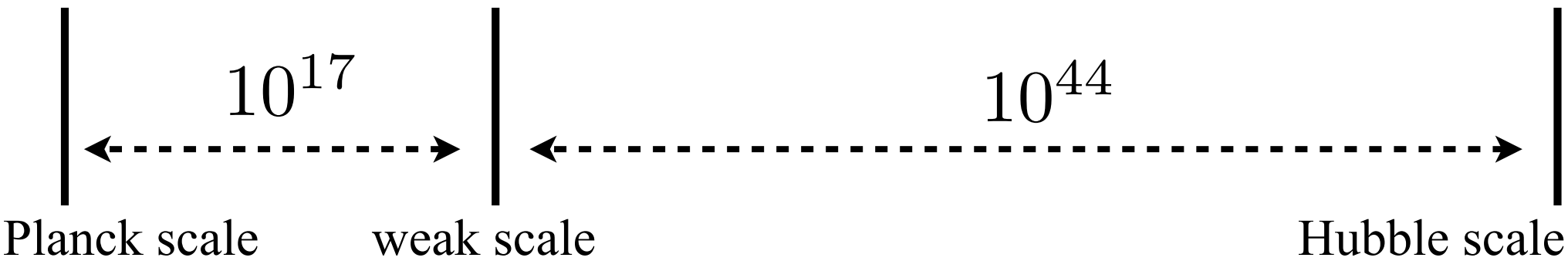


We observe:



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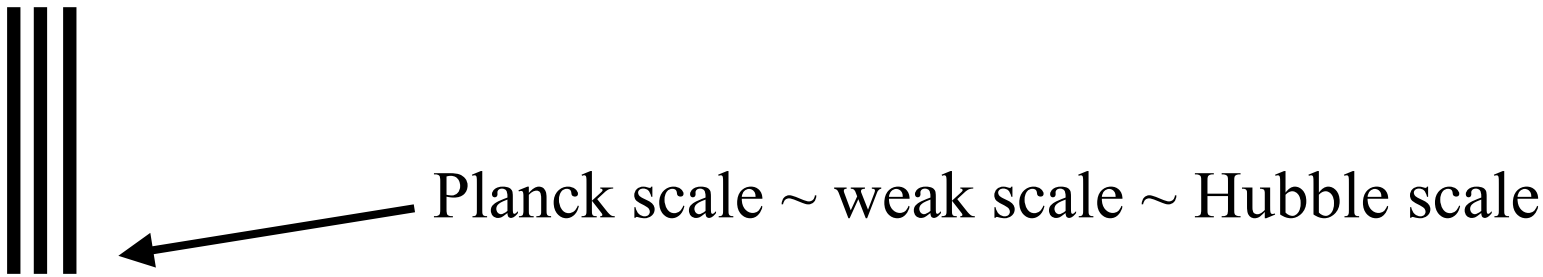

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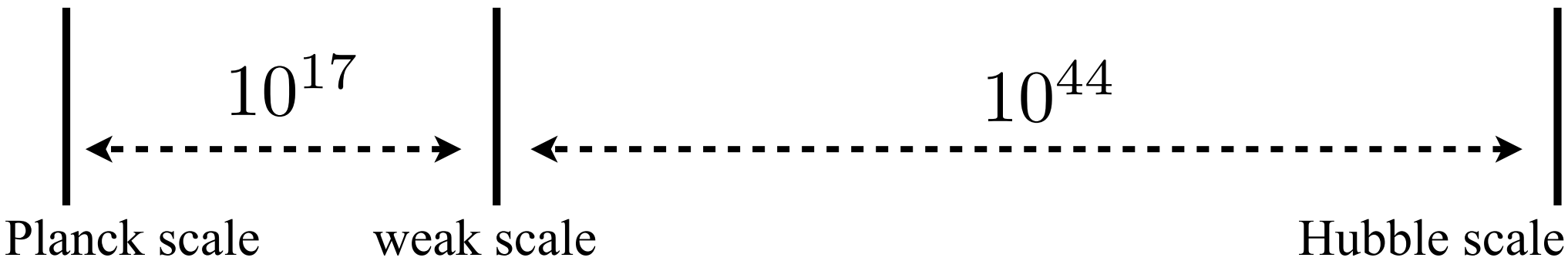

Current theory accounts for huge difference w/implausible cancellation

Need modifications QM or Space-time to avoid fine tuning

Reminder: Last Week

Problems associated to each fundamental scale.

Planck Scale:

What replaces spacetime ? ("Quantum Gravity")

Weak Scale:

Why is Gravity so weak ? ("Hierarchy Problem")

Hubble Scale:

Why is the universe so big ? ("Cosmological Constant Problem")

Current theory accounts for huge difference w/implausible cancellation

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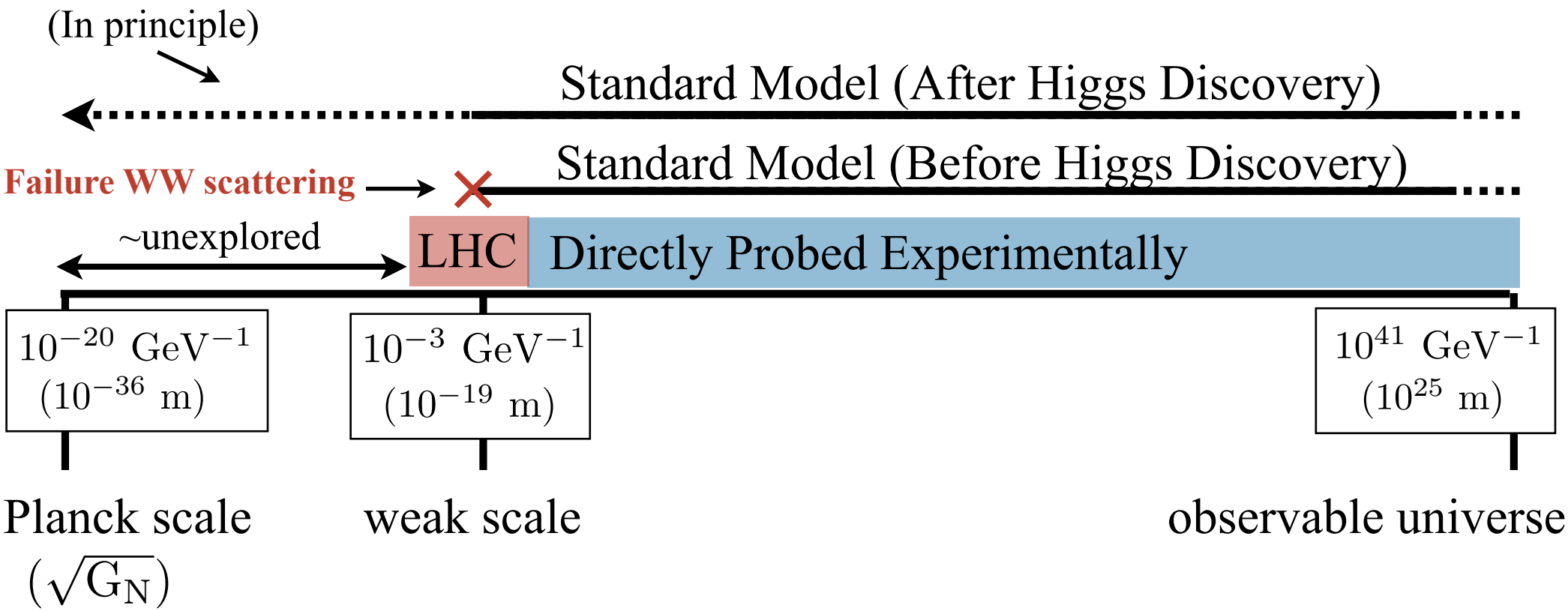
Today's Lecture

Going beyond the Higgs Discovery:

What comes next ?

Focus: Problem associated w/weak scale



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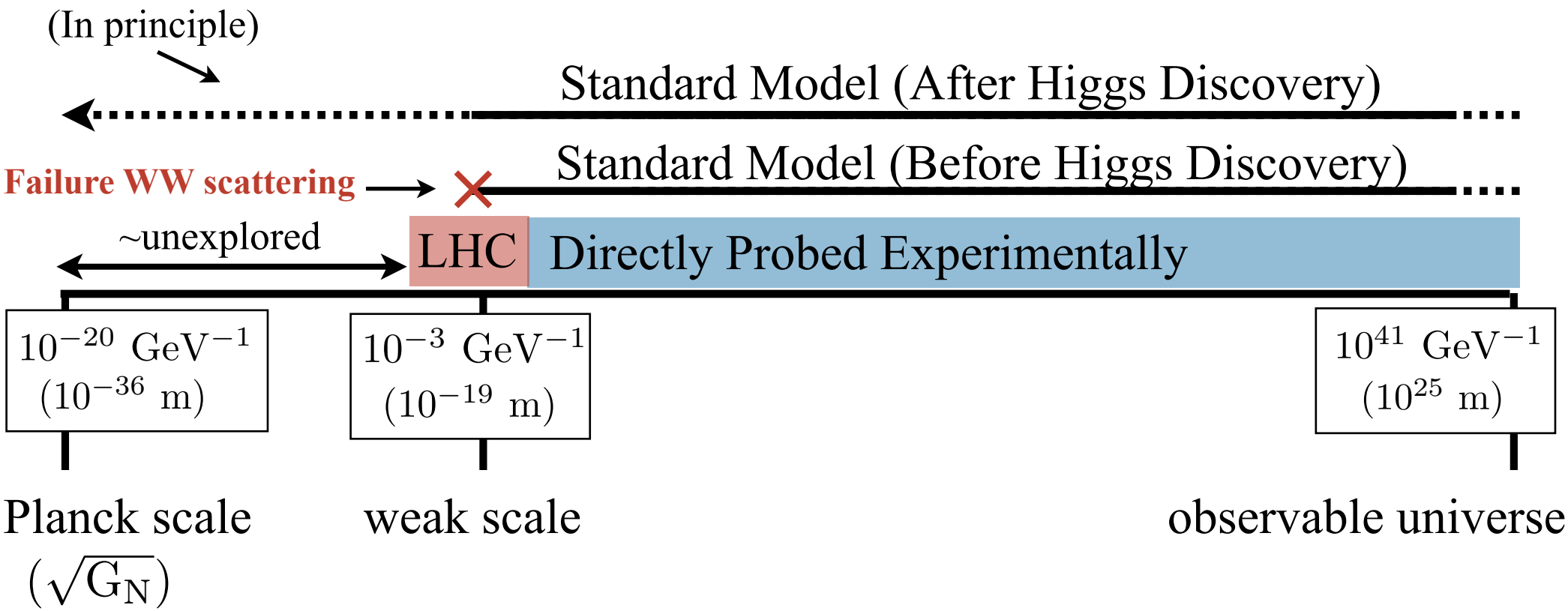


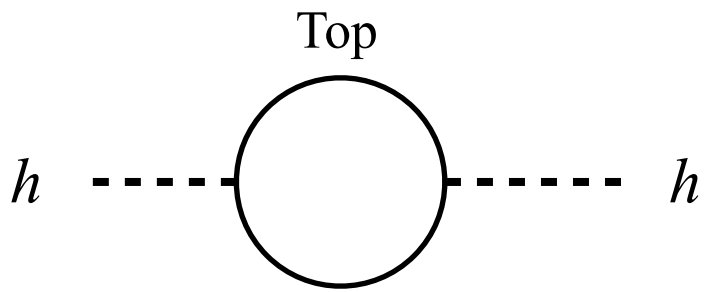
Most tractable now:

- Currently directly probing this scale with the LHC
- Understand the physics at this scale incredibly well

Working theory thats been verified experimentally

Focus: Problem associated w/weak scale

Reminder: Vacuum fluctuations of Higgs mass (m_H^2)



$\sim \Lambda^2 \Rightarrow$ mH $\sim 10^{20}$ GeV

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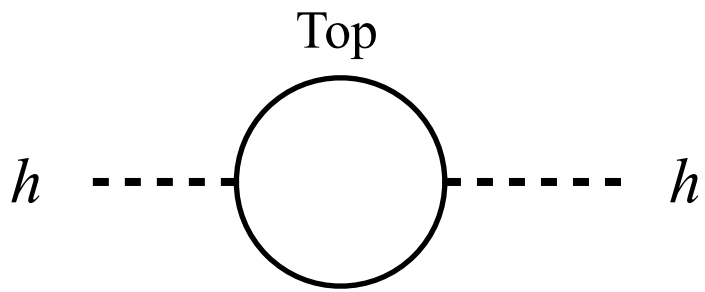

$\sim \Lambda^2 \Rightarrow$ mH $\sim 10^{20}$ GeV

$$mH^2 = 2.569678321 \ldots 554\ldots \times \ell_{Pl}{}^2$$

$$+ \quad \text{30 digits}$$

$$- 2.569678321 \ldots 453\ldots \times \ell_{Pl}{}^2$$

30 digits

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Focus: Problem associated w/weak scale

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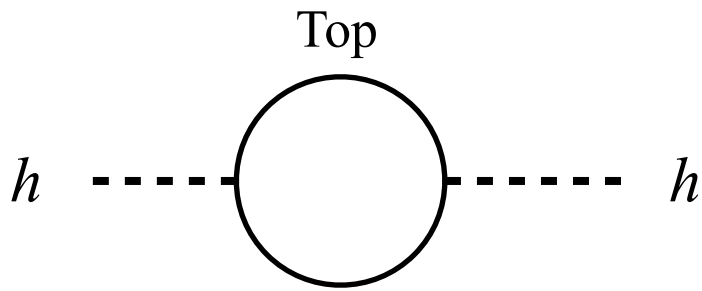


$\sim \Lambda^2 \Rightarrow$ mH $\sim 10^{20}$ GeV

Very different type problem than we discussed before:

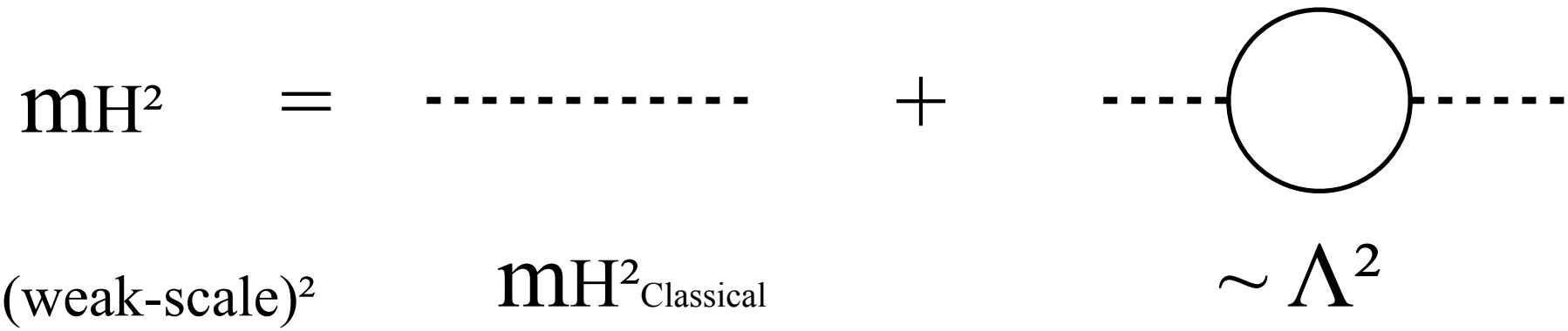
"Naturalness" Problem:

- Theory is fully logically consistent
- Need bizarre (un-natural) choice of input parameters

Un-like situation before Higgs where theory broke down

$P(\omega\omega \rightarrow \omega\omega) > 1$ / Inconsistent mass description

What scale do we need Modification?



Can avoid need for fine tuning only if $\Lambda \sim$ weak-scale.

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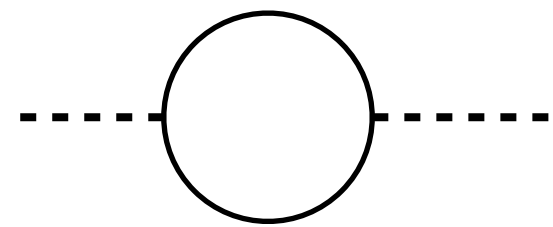
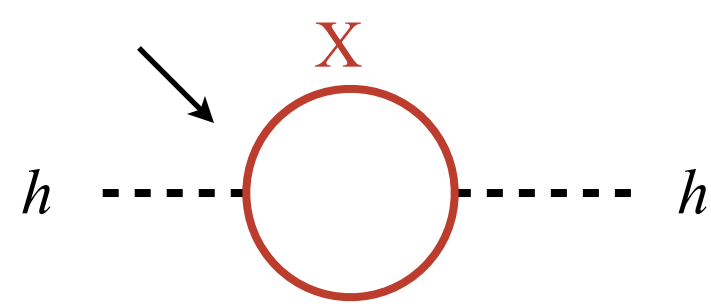
m_H^2 = + 

~ (weak-scale)^2 $m_{H^2\text{Classical}}$ $\sim \Lambda^2$

Can avoid need for fine tuning only if Λ ~ weak-scale.

Need changes to stop vacuum fluctuations below: 10^{-3} GeV^{-1} (10^{-19} m)

new particle mX ~ 1000 GeV

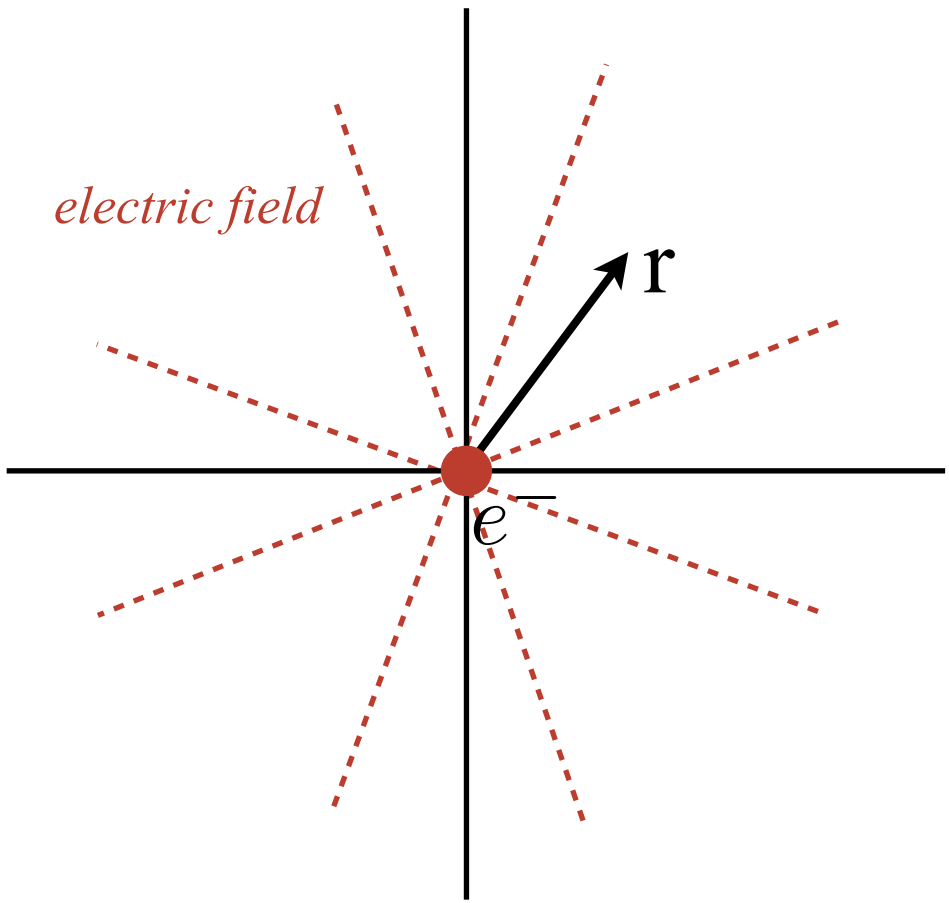


(Pencil metaphor: analogous to the pencil glue/string)

Naturalness Problems in History

Same type of problems have occurred before in history of physics
Same types of arguments for scale of new physics worked

Example: Energy stored in the electric field around electron



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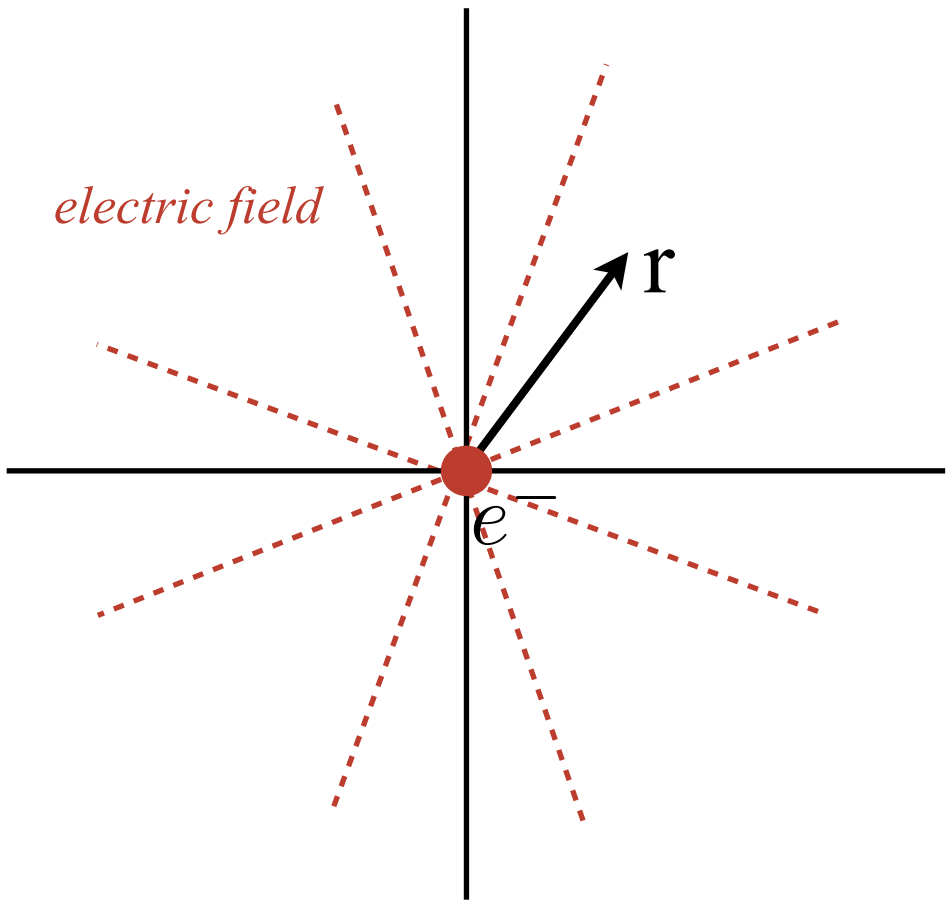

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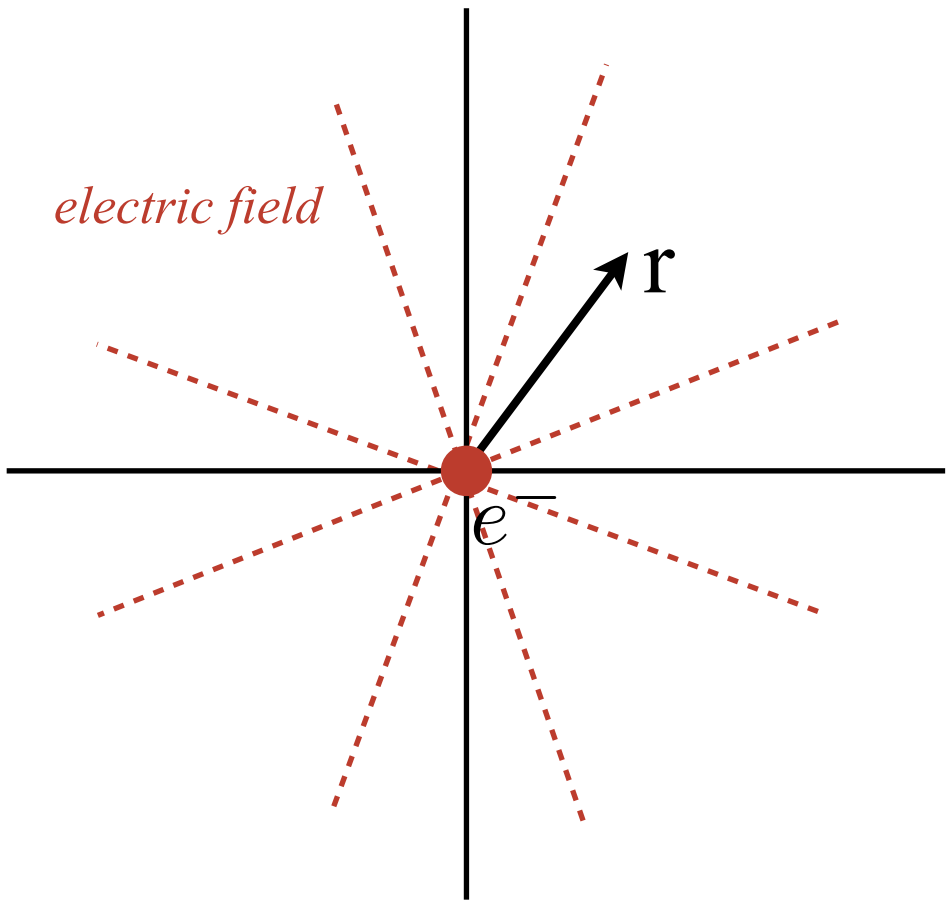

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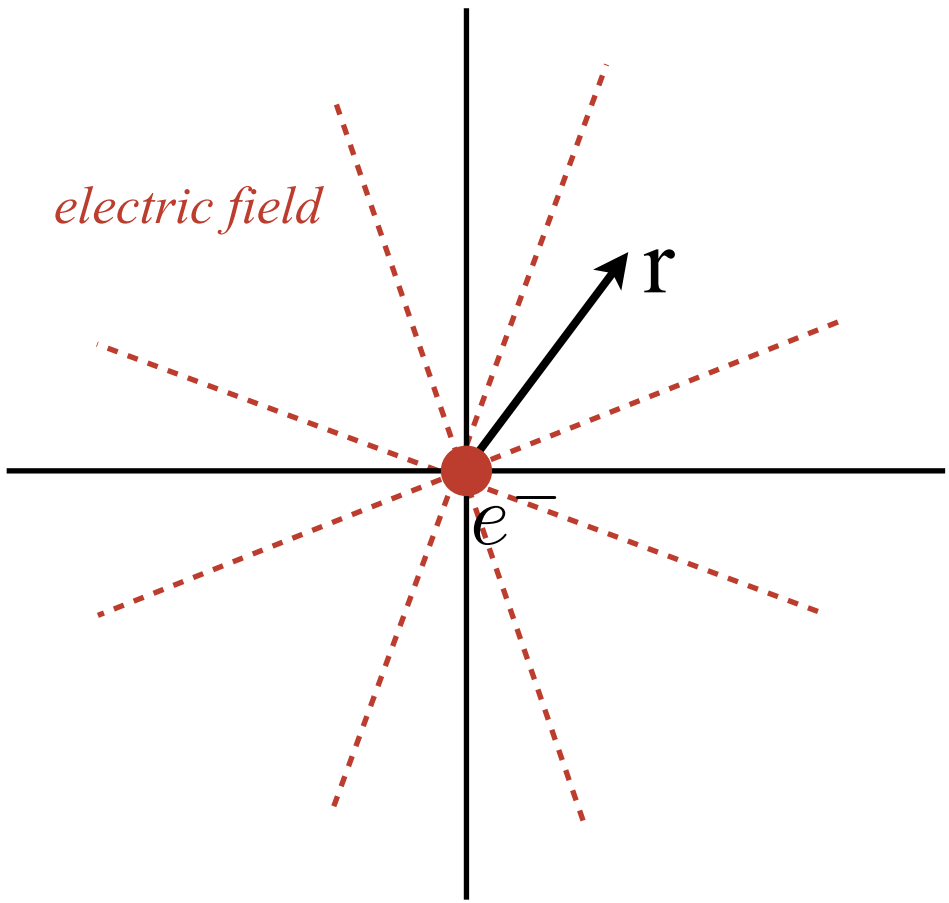

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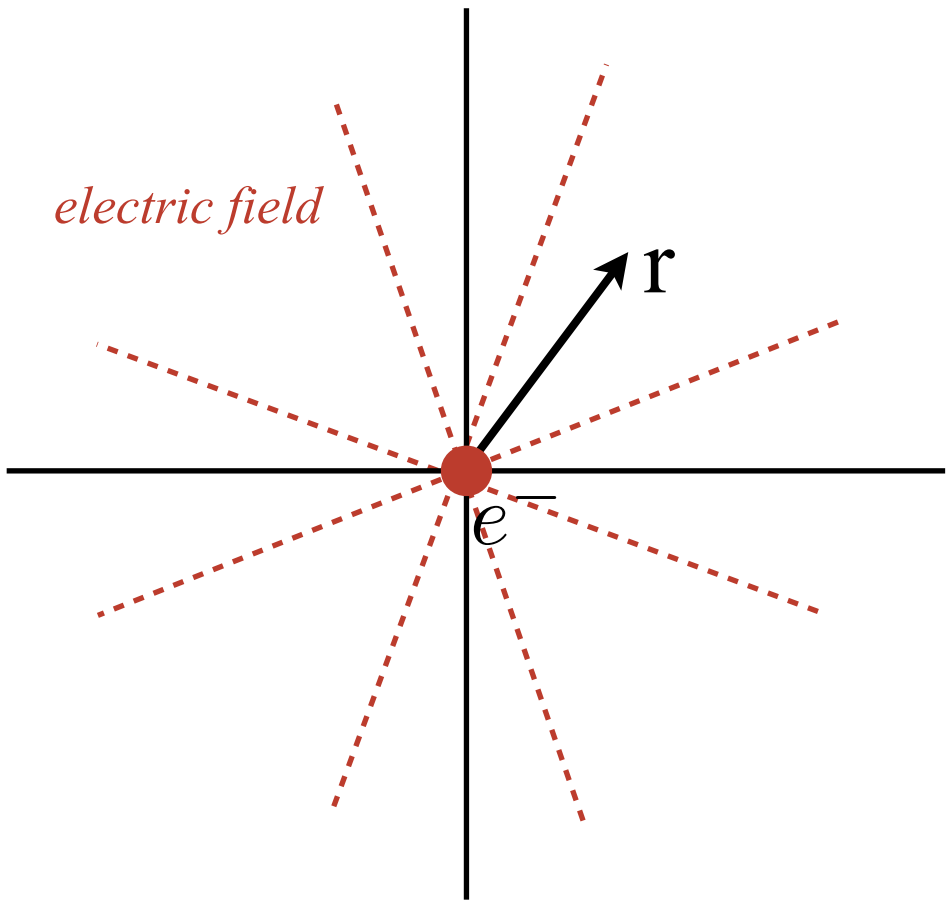

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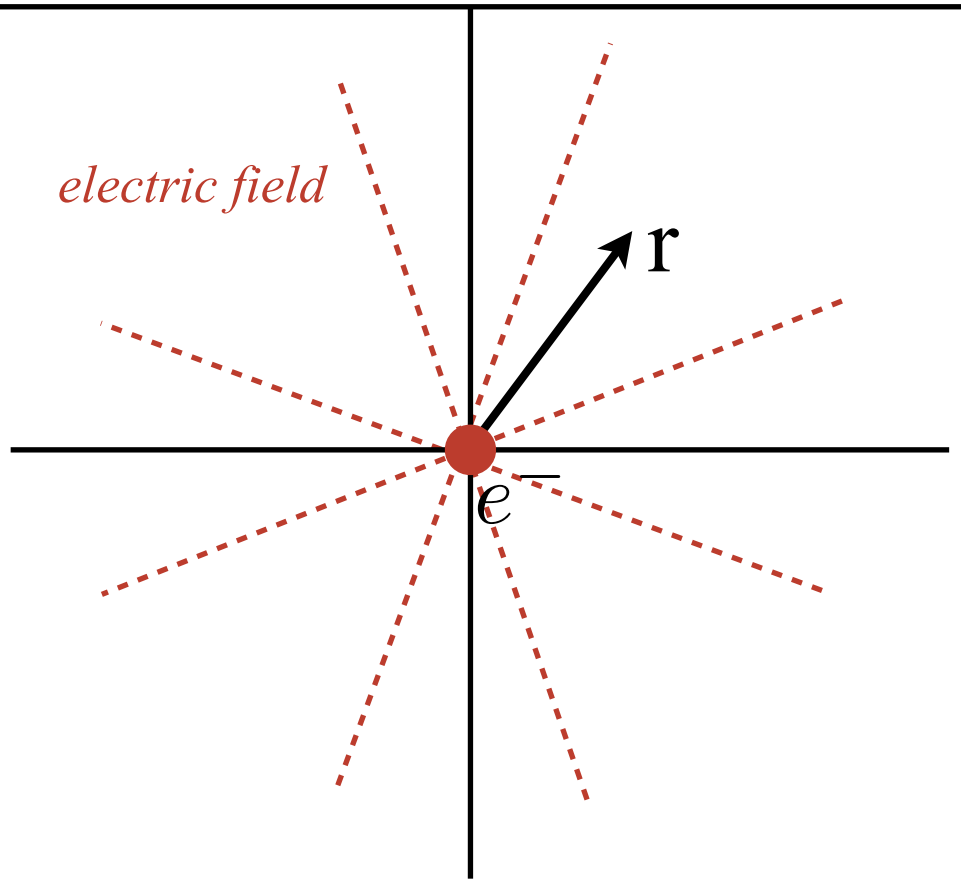
Naturalness requires new physics kick in $\Lambda \geq \alpha/m_e$
Picture of point like electron must break down at this scale



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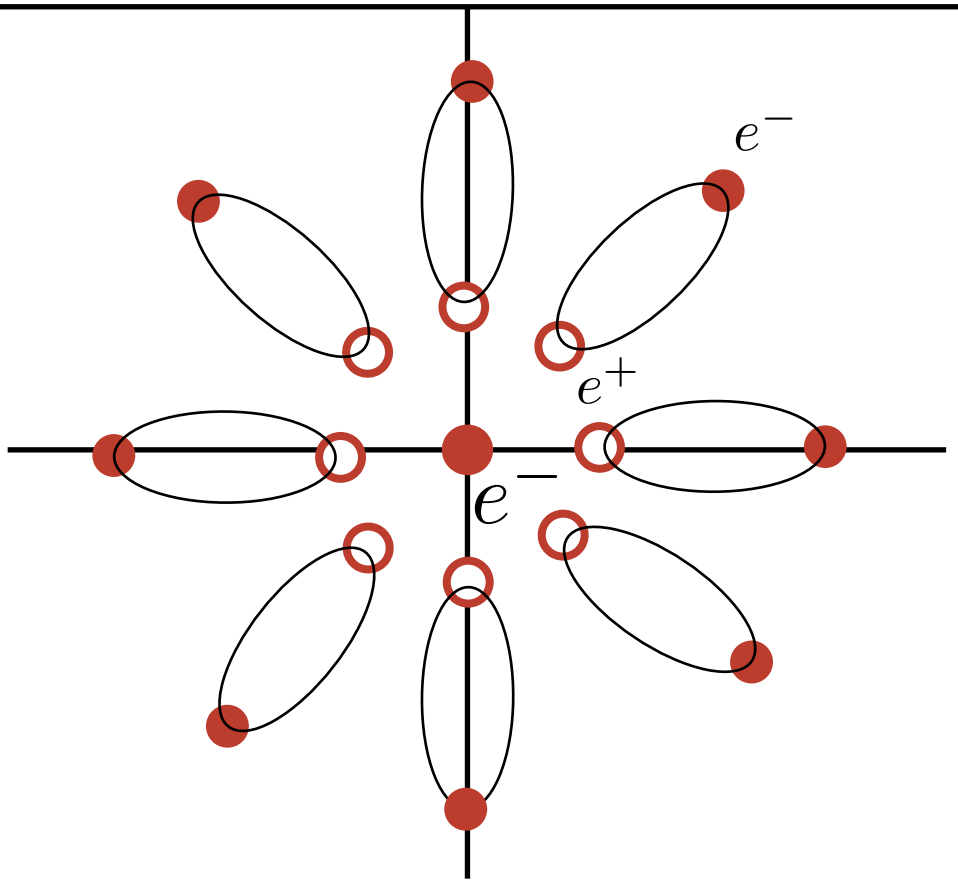

Exactly what happens !

At scale $\Lambda \sim 1/m_e$ start seeing particle-anti-particle cloud

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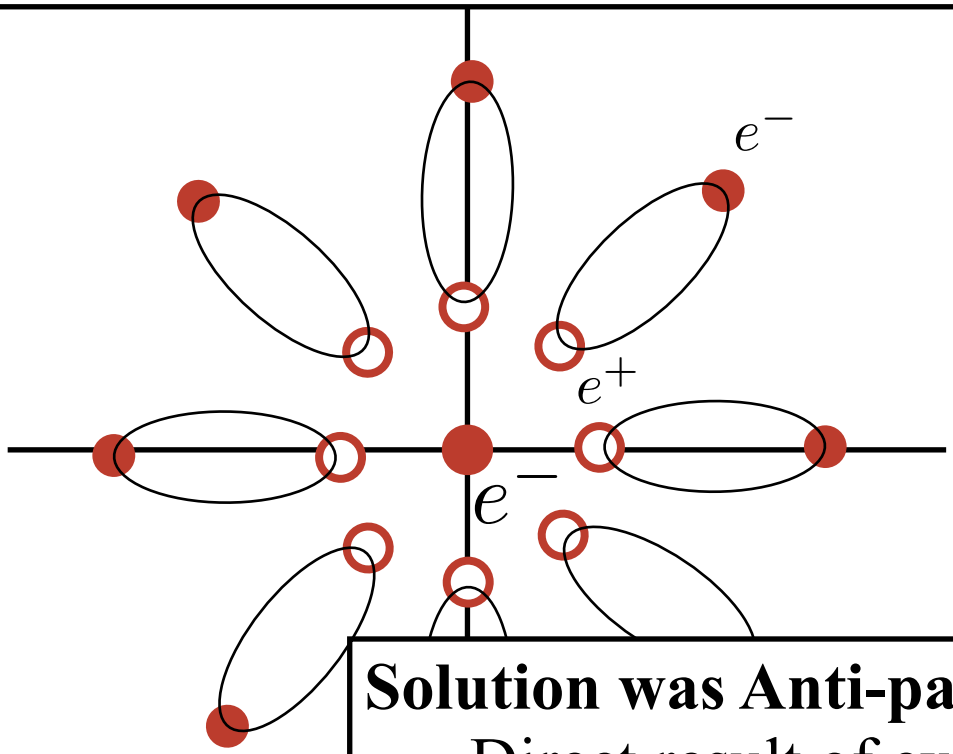

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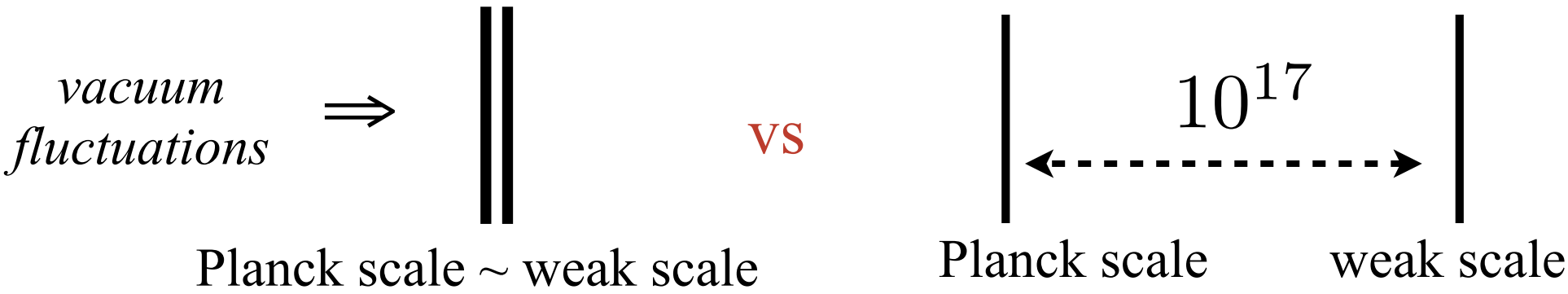
Solution was Anti-particles :
- Direct result of extension of Space-time (adding QM)
- Doubled the number of particles in the theory

Potential Solutions



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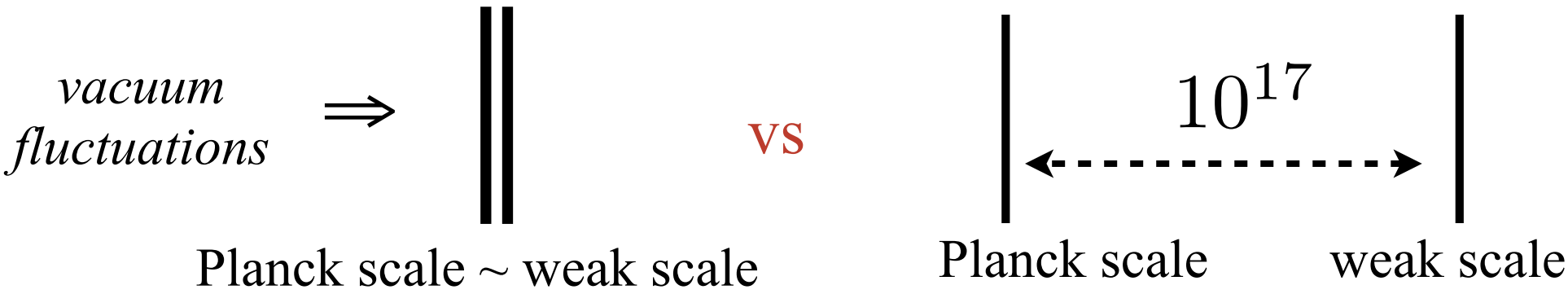
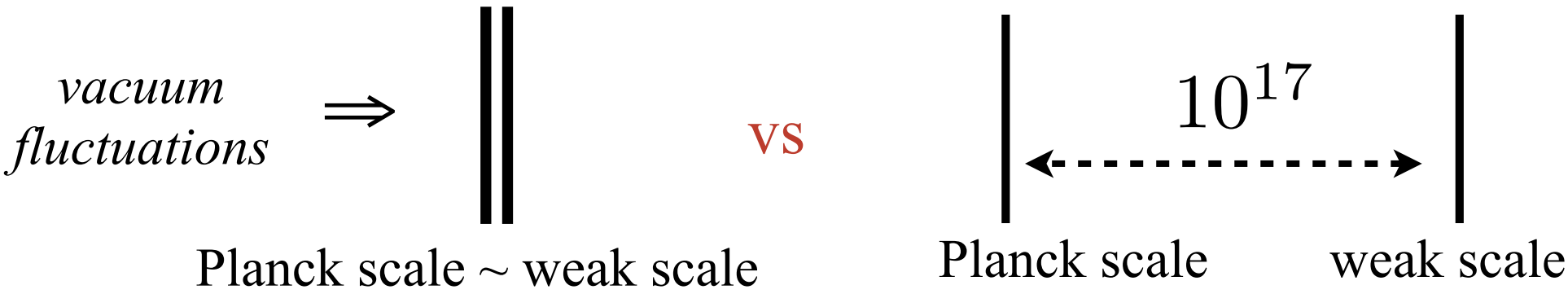


Expect any potential solutions to be dramatic
- Basic feature of space time get us in this mess
- Not like ωω scattering where could just add one new particle

Potential Solutions



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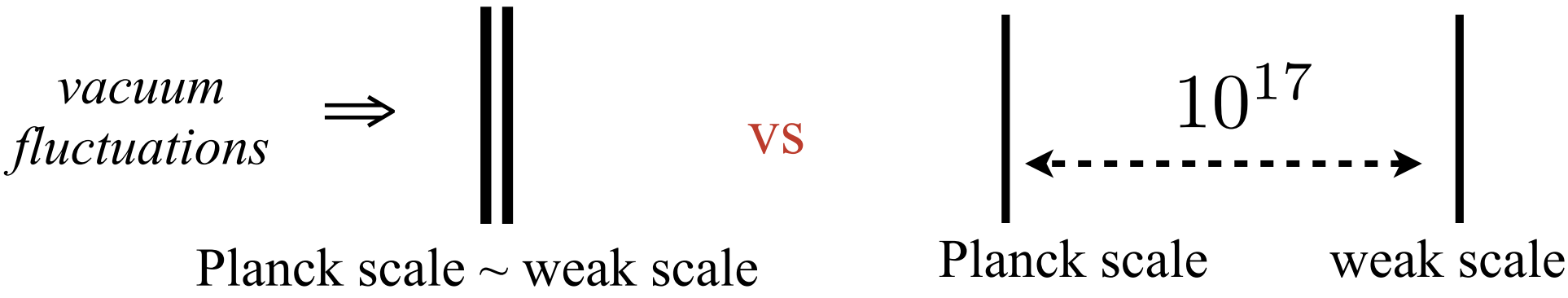

"Compositeness" Higgs made of smaller particles

Weak scale not fundamental / Similar to size of the proton

New underlying physics responsible for Higgs/Higgs potential

⇒ New forces / New matter

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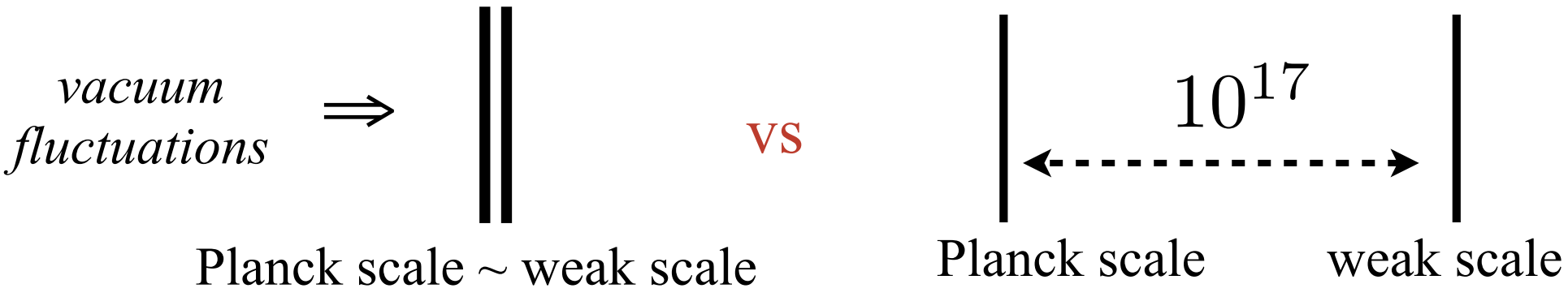

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Extra dimensions

Planck scale is really at the weak scale

Gravity appears weak b/c gravitons can propagate in extra dim.

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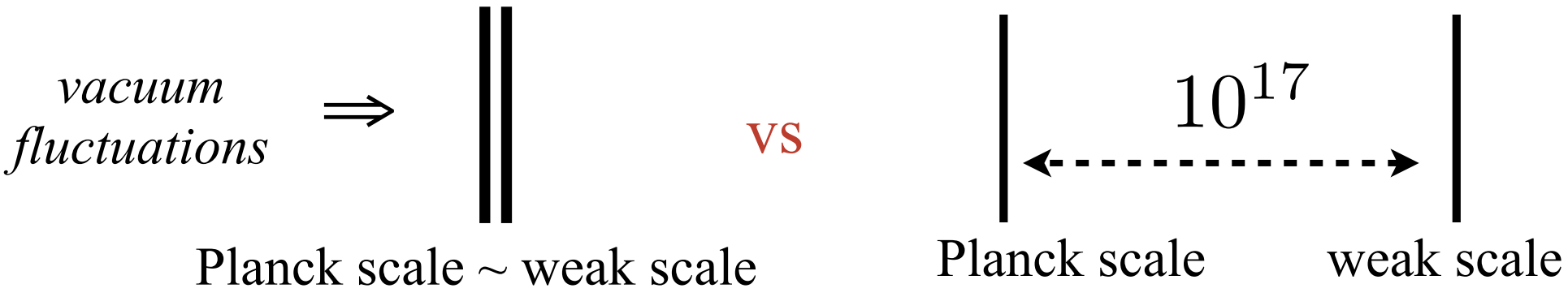

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Vacuum corrections suppressed below weak scale

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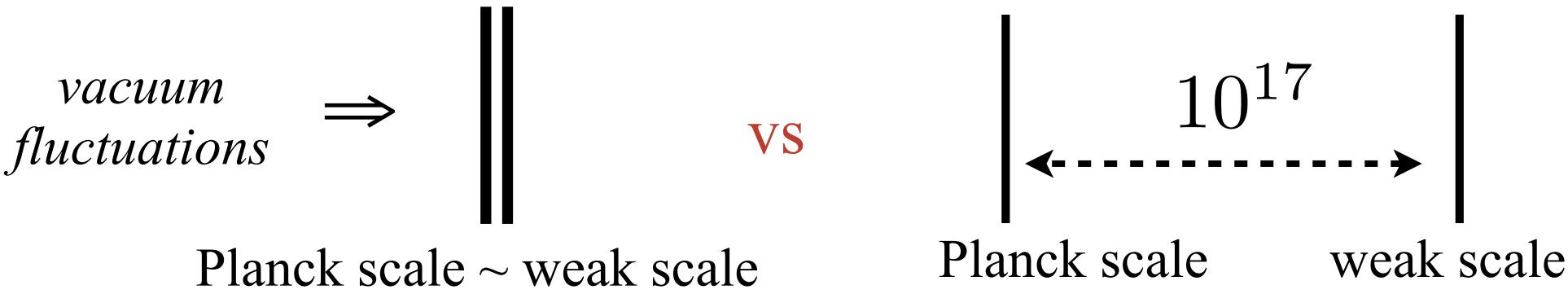

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Supersymmetry

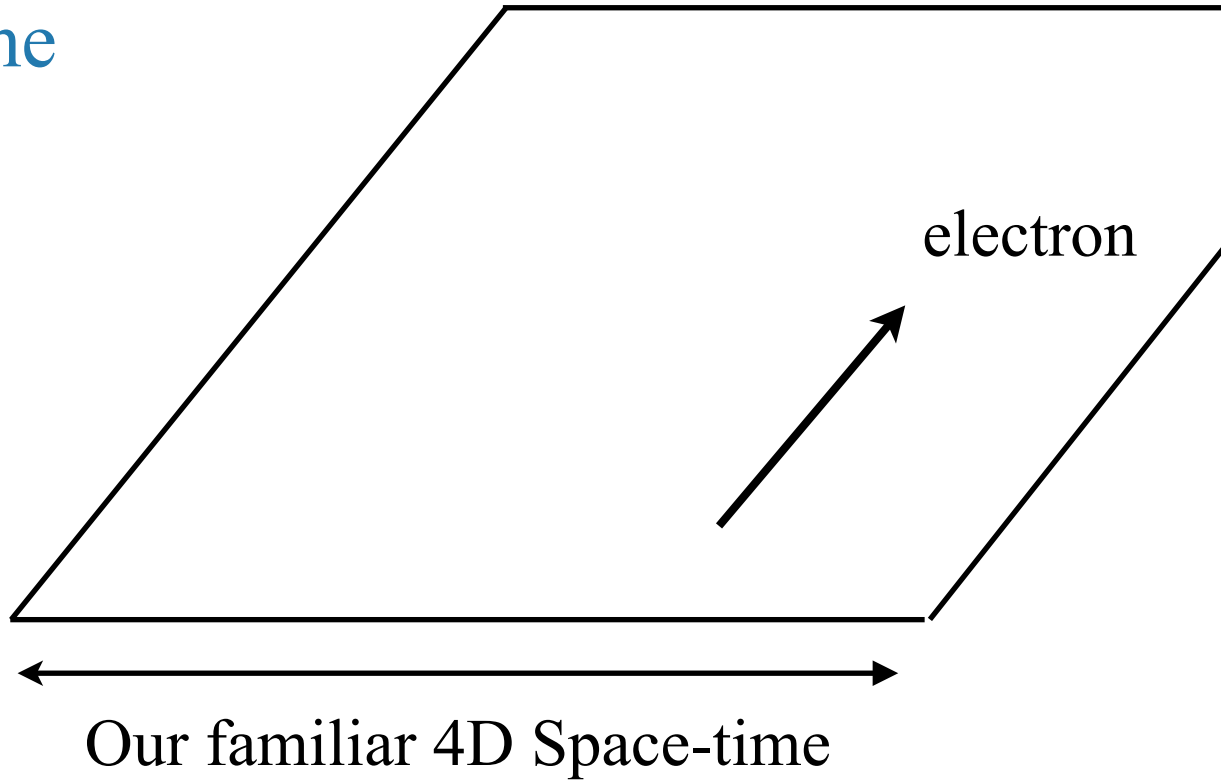
Go through example of how works in detail

Has been a favorite within the field

Vacuum corrections suppressed below weak scale

Super Symmetry

Modification of Space-time



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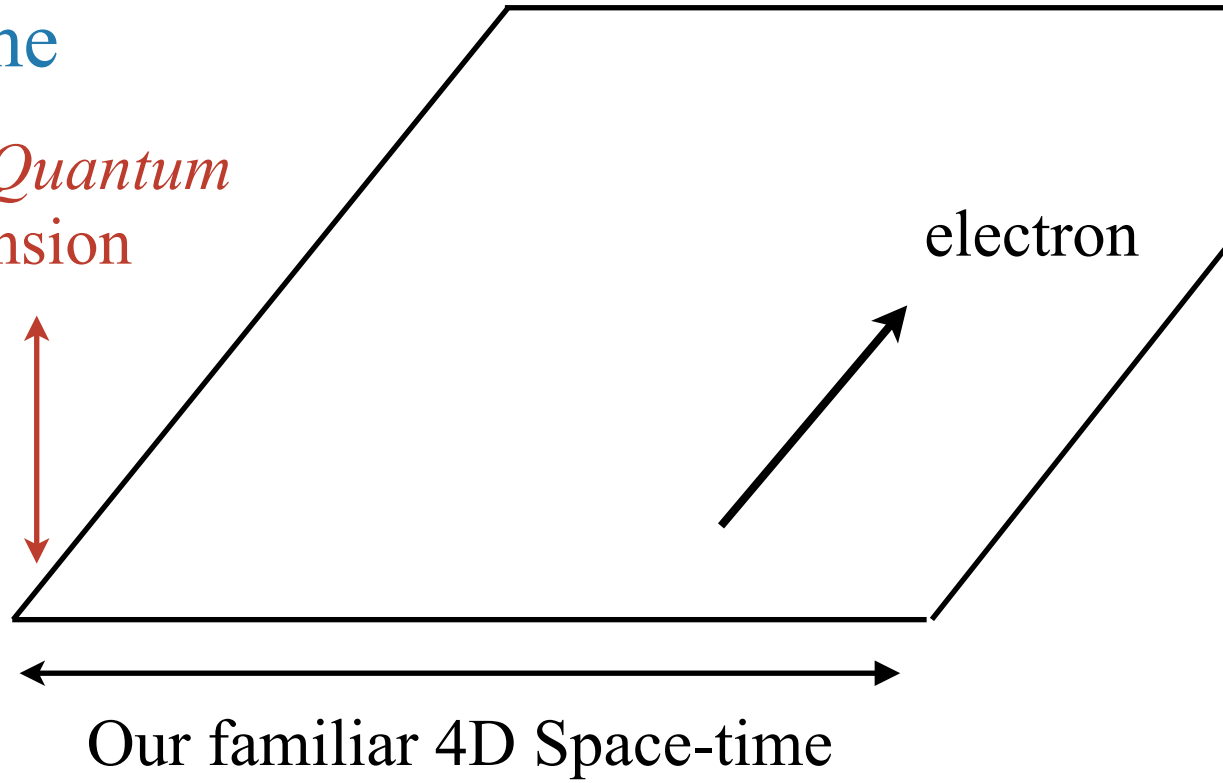

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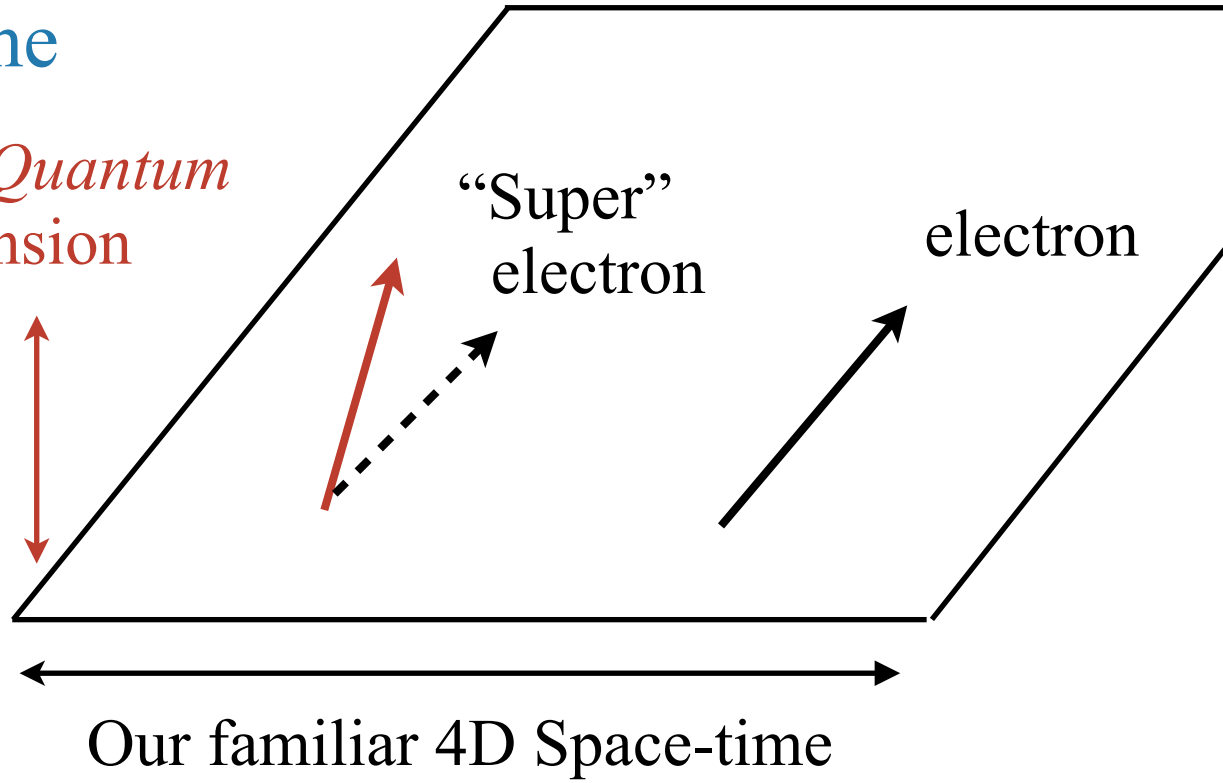

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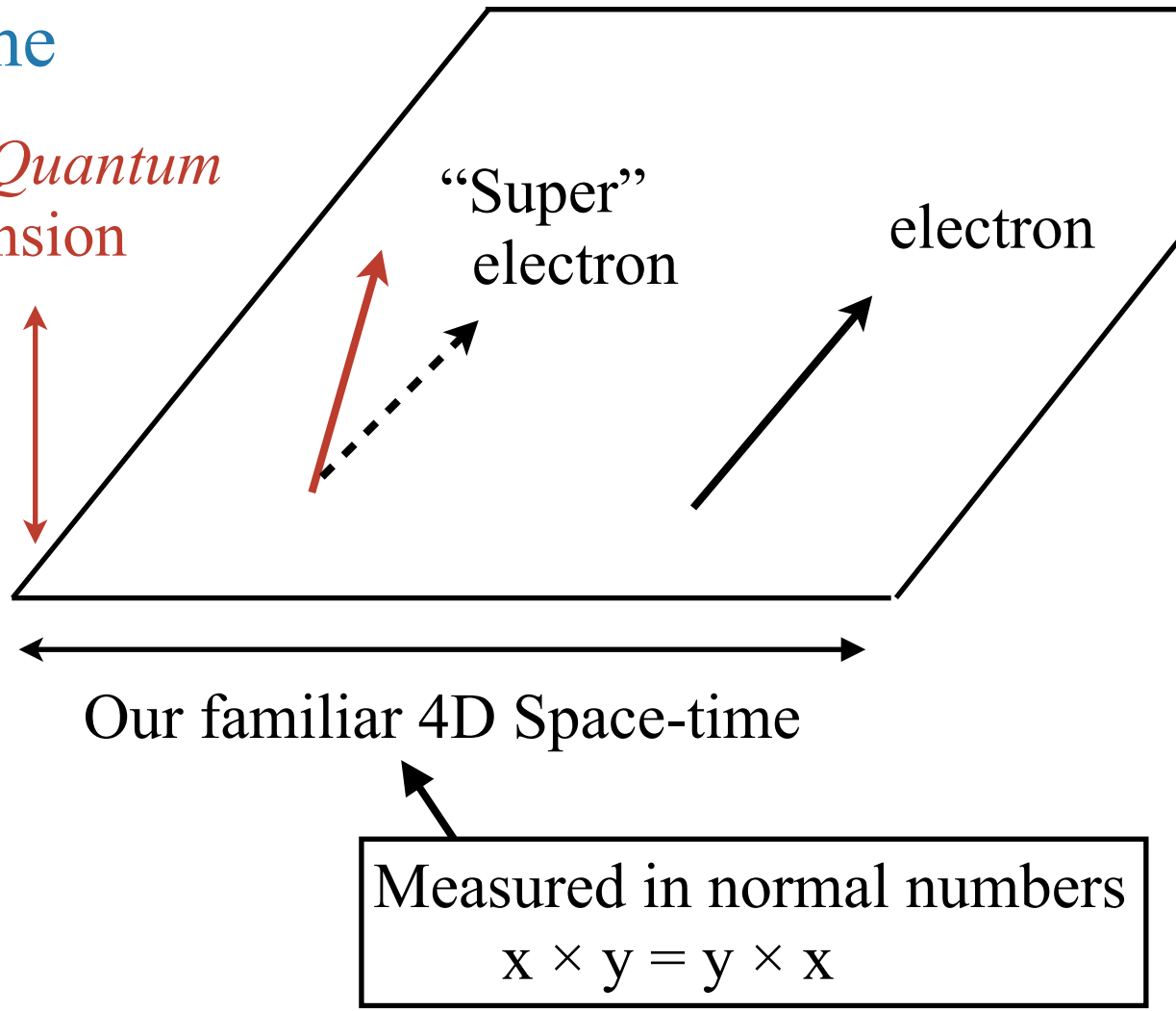

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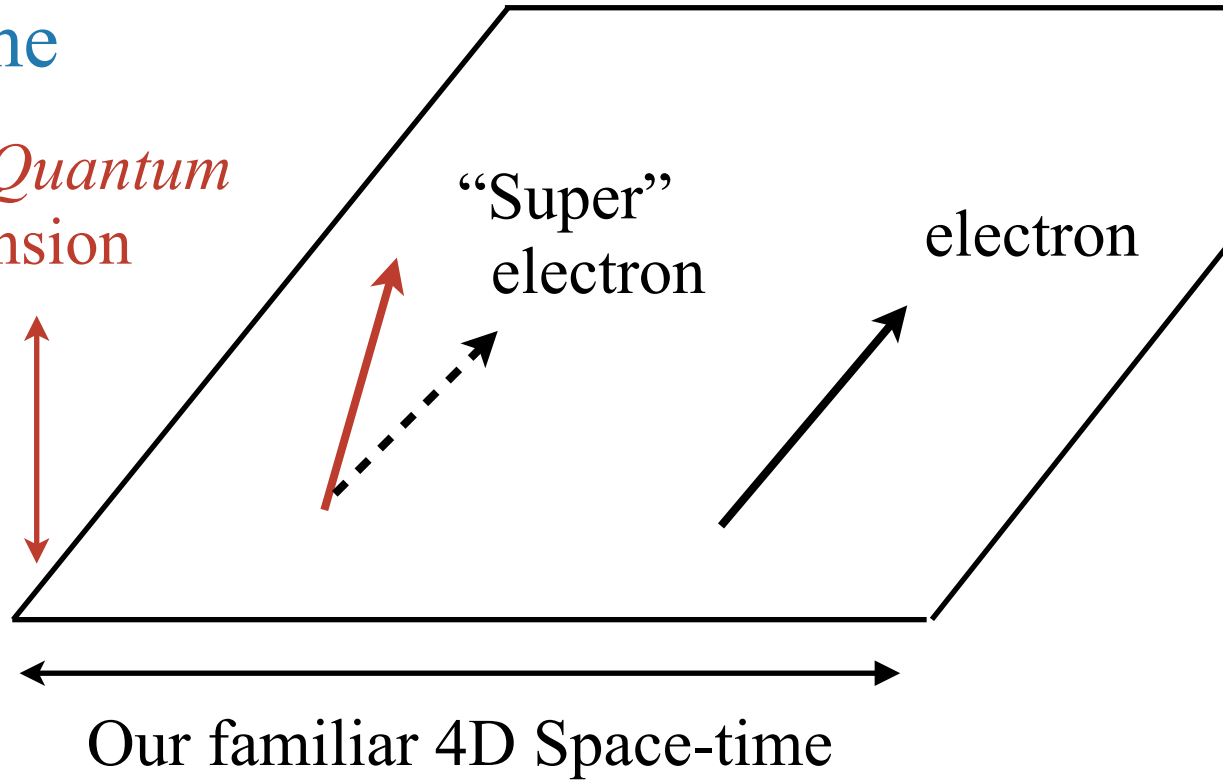


Distance measured in "quantum" numbers:

$$x \times y = - y \times x$$

$$\Rightarrow \quad x^2 = 0$$

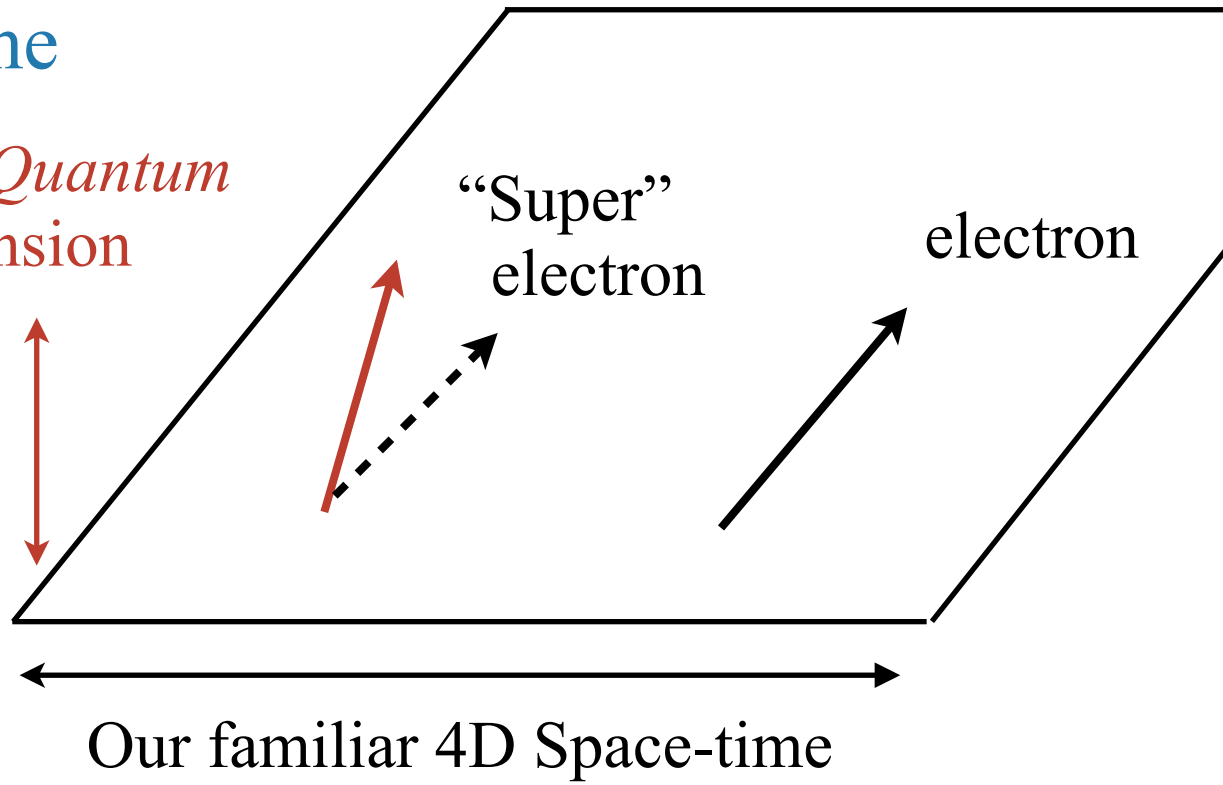
Can only take one step

Measured in normal numbers

$$x \times y = y \times x$$

Super Symmetry

Modification of Space-time



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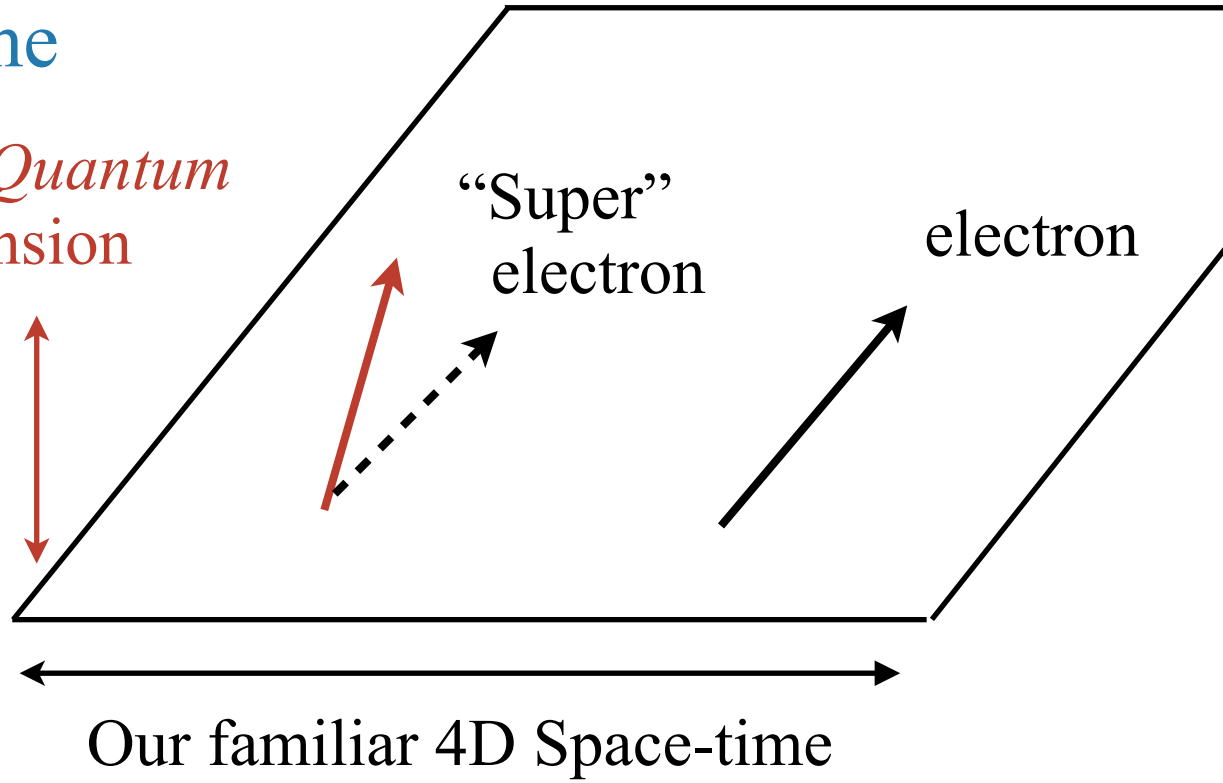
Doubles number of particles:

- Standard Model particles
- Super-partners w/step in extra dimension

Super Symmetry

Modification of Space-time



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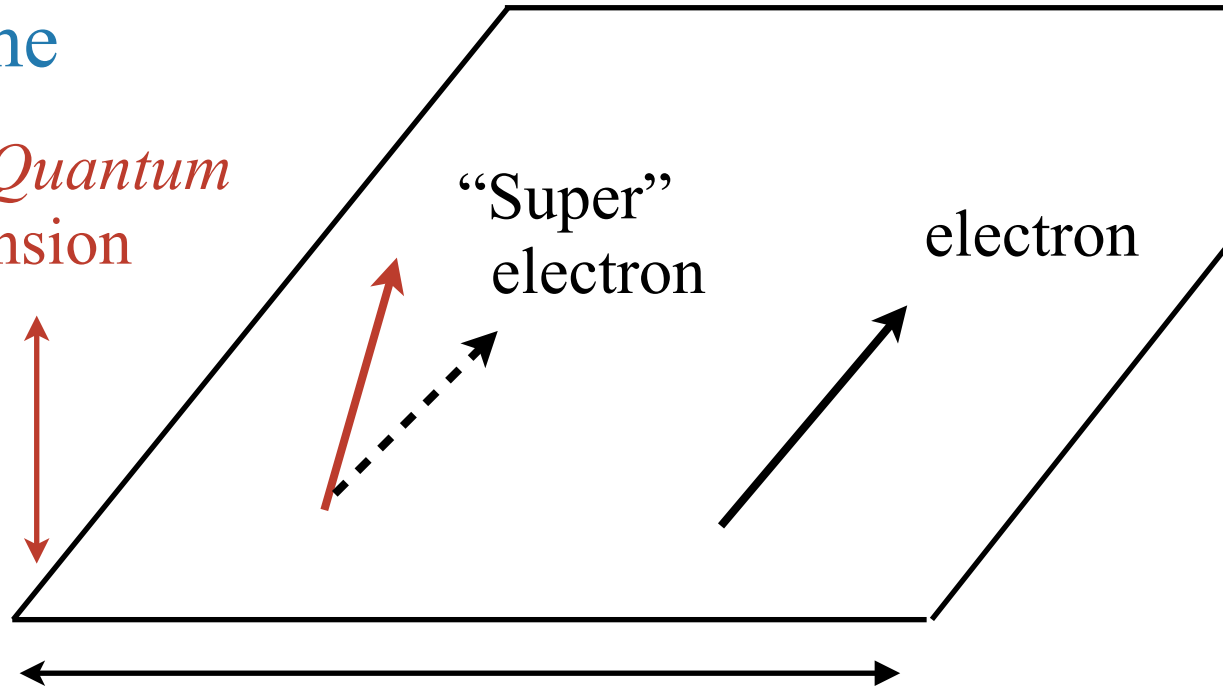
All regular rules of QFT apply / Symmetry relating particles/Super particles

Super Symmetry

Modification of Space-time

Extra *Quantum* Dimension



Distance measured in "quantum" numbers:

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Can only take one step

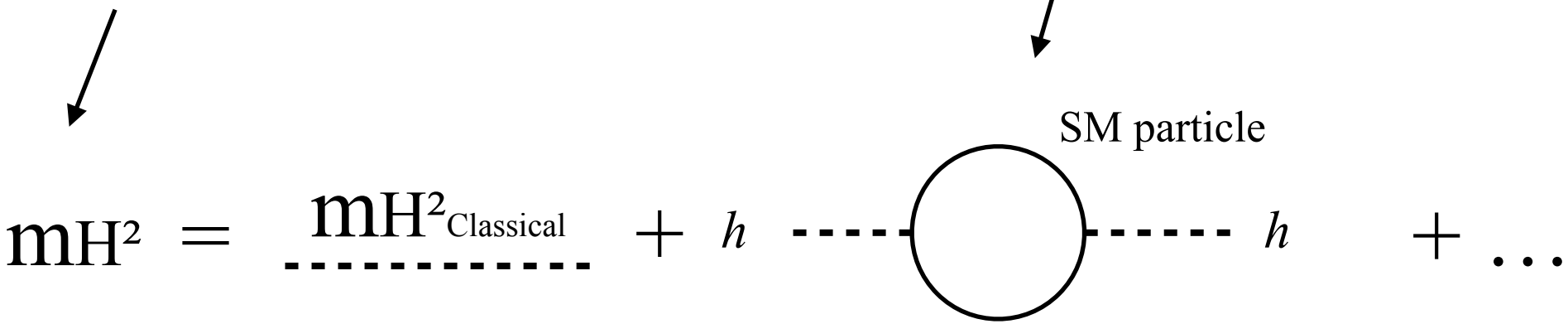
- Havent seen super-partners
- Could be another example of long-distance illusion:
  eg: difference between forces
- Idea: going to short enough distances start seeing symmetry
- To avoid fine-tuning needs to happen around weak scale

All regular rules of QFT apply + Symmetry relating particles/Super particles

How Does This Help ?

~(weak-scale)²

$\sim\Lambda^2$



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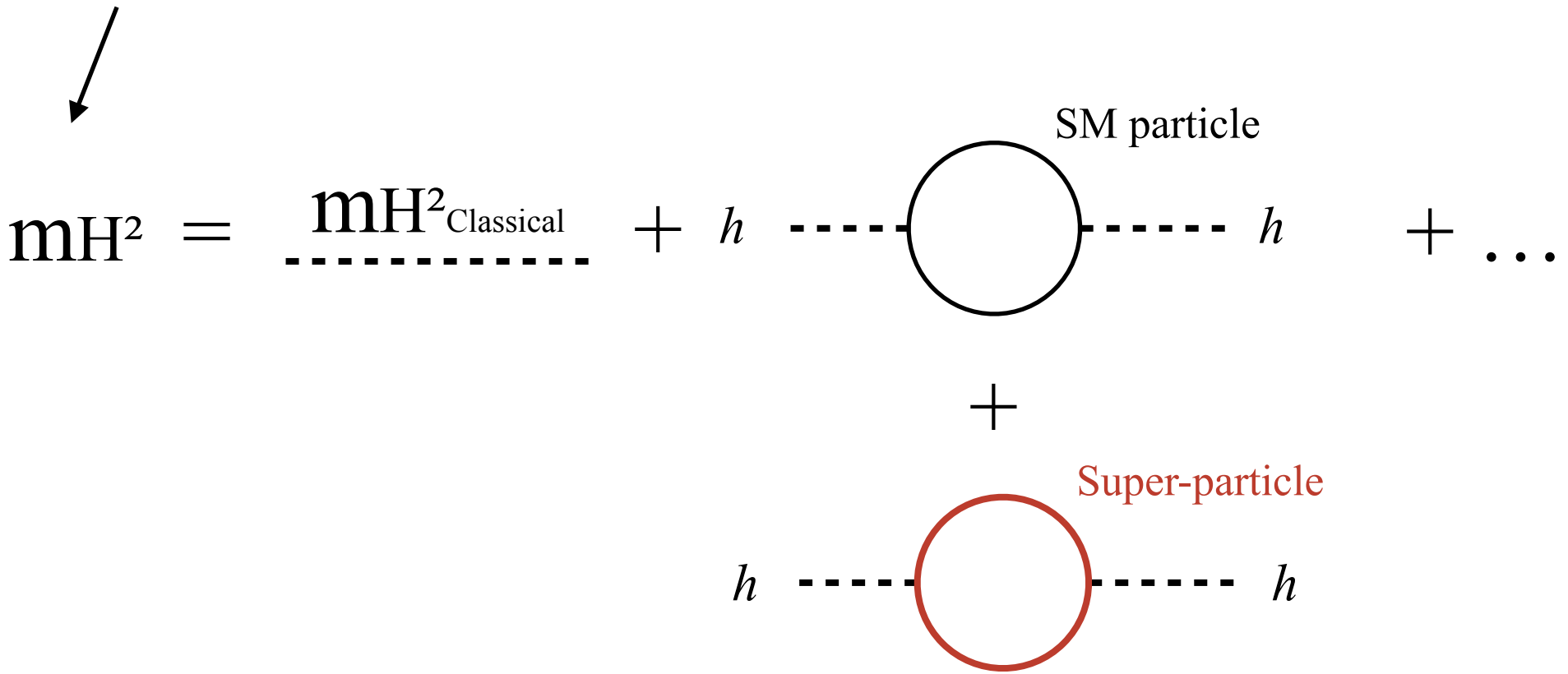

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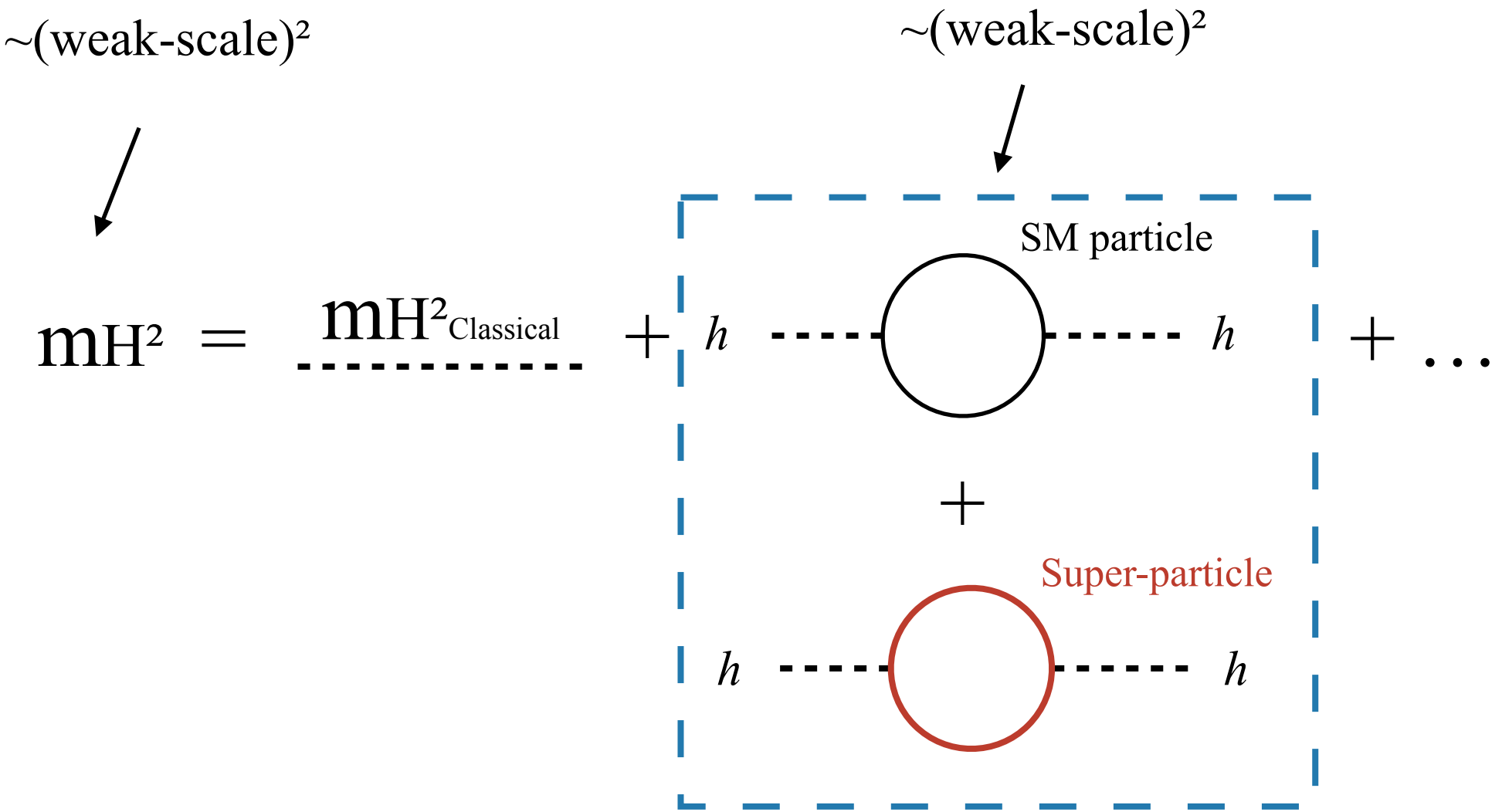
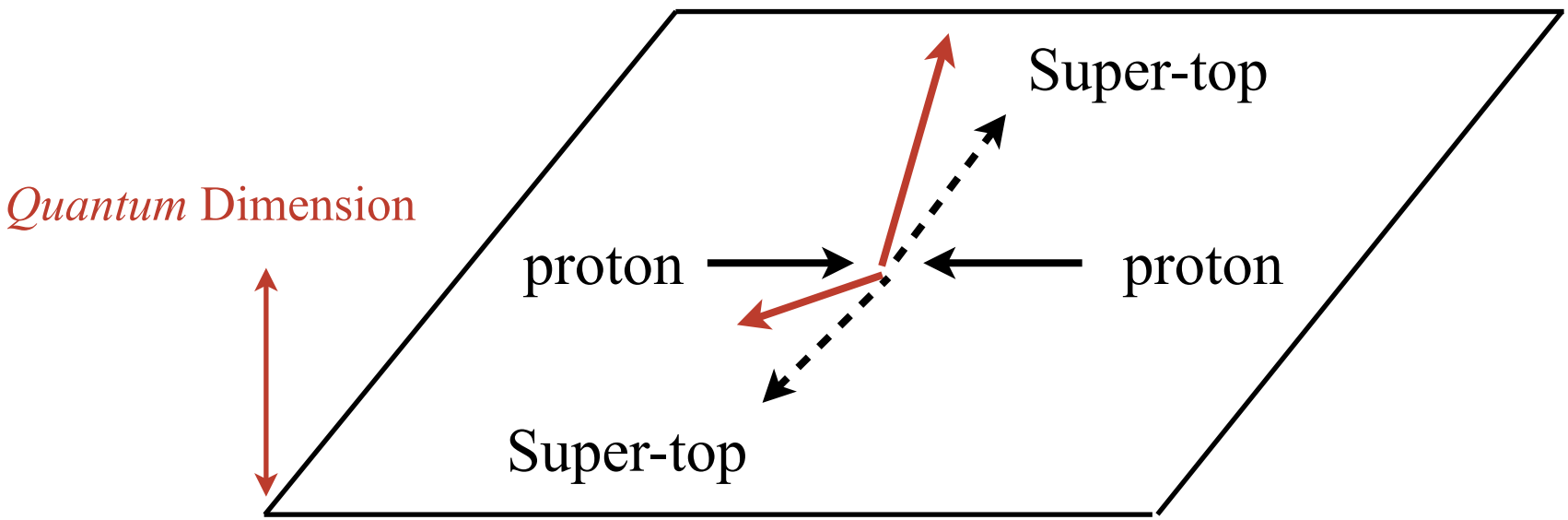


Super Symmetry at the LHC



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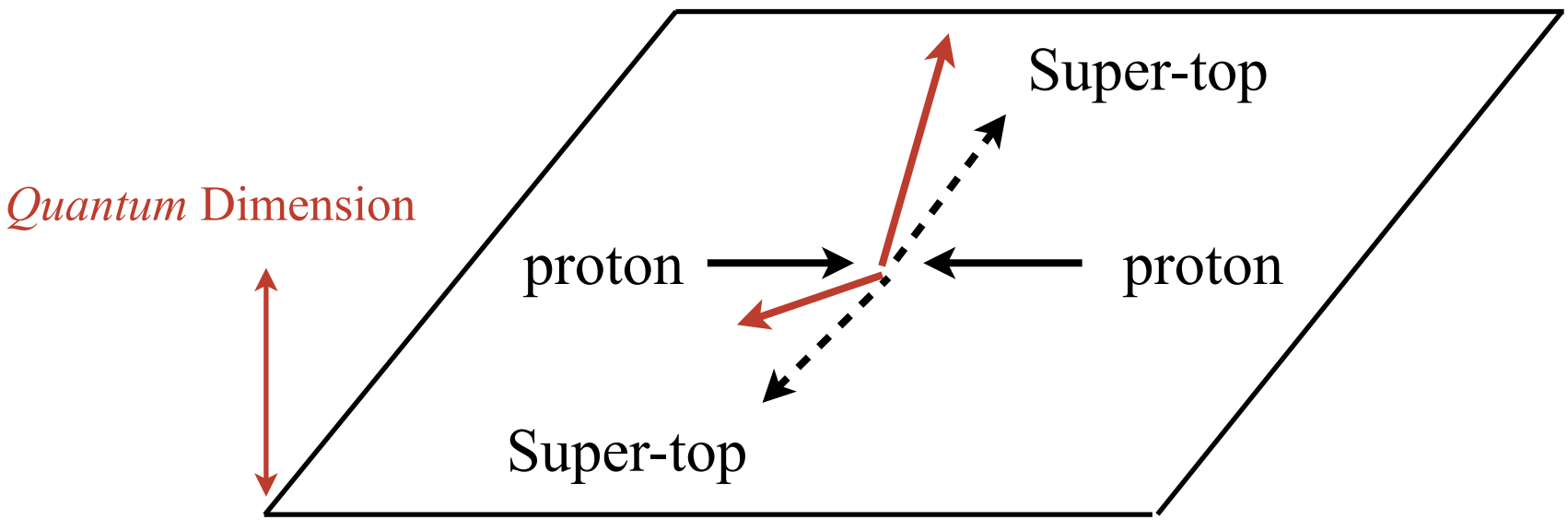

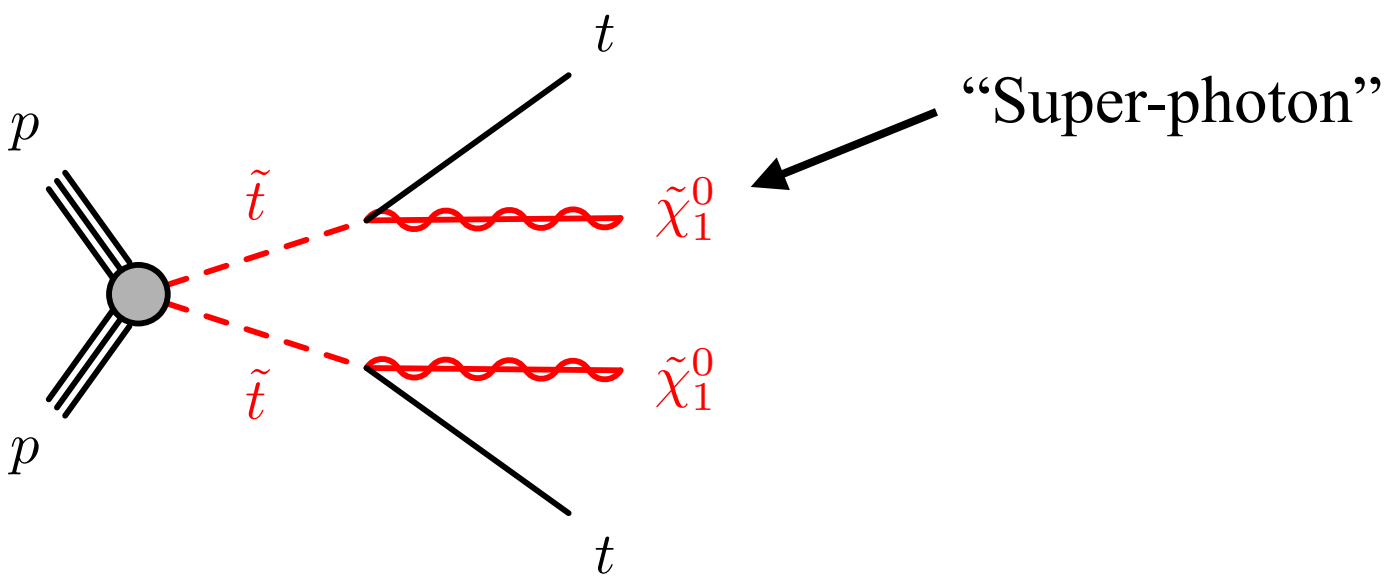

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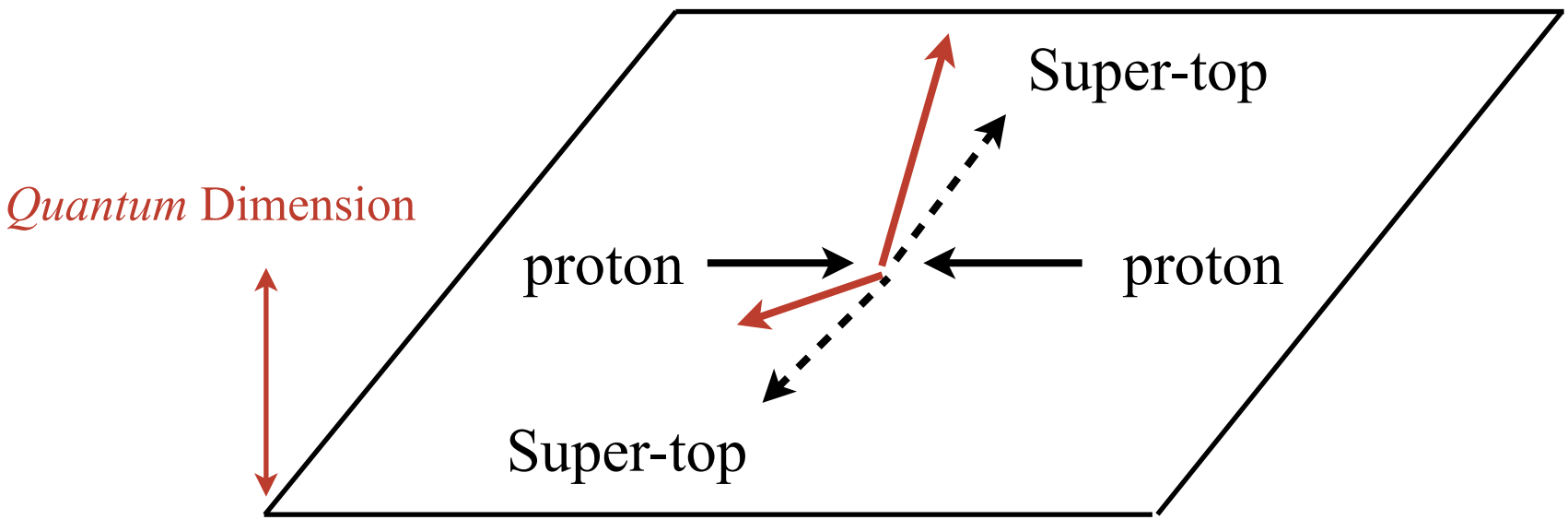
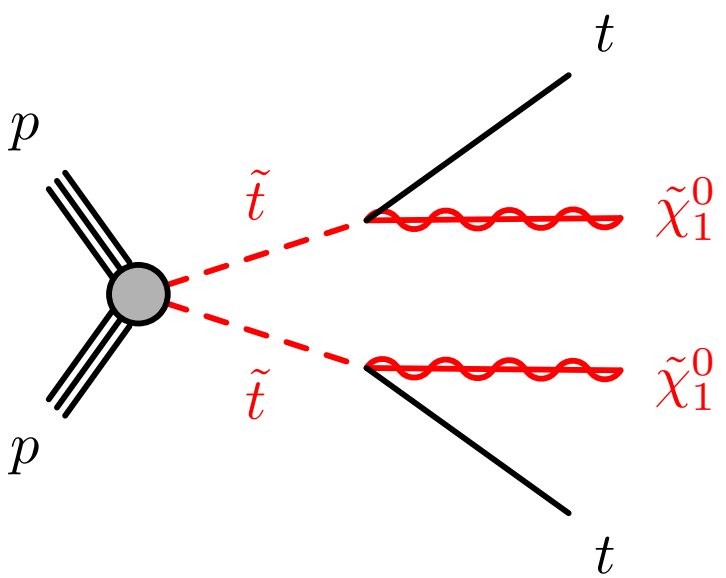
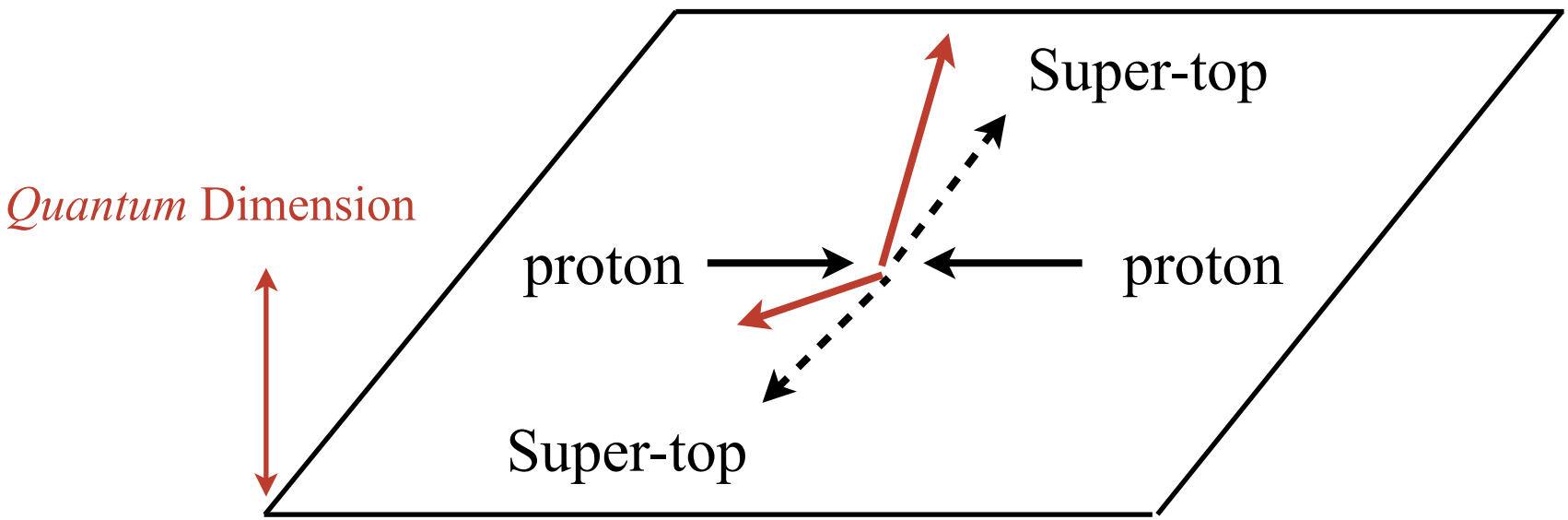
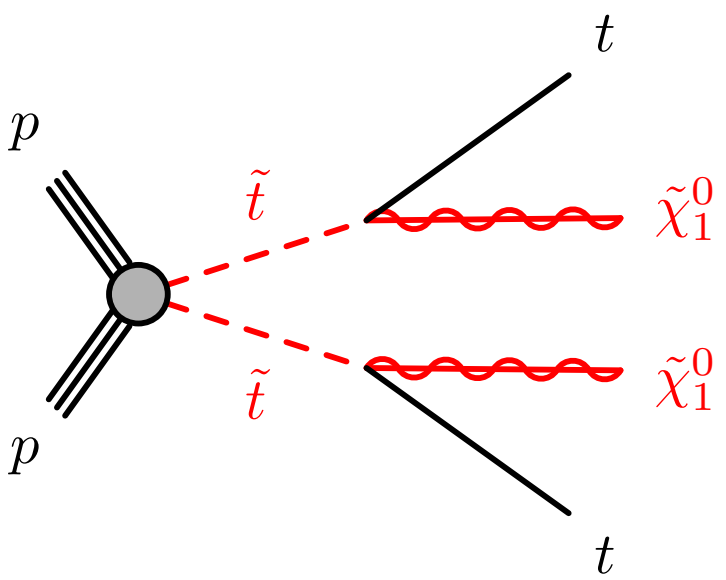




"Super-photon"
- Massive
- Stable
- Weakly interacting

Super Symmetry at the LHC

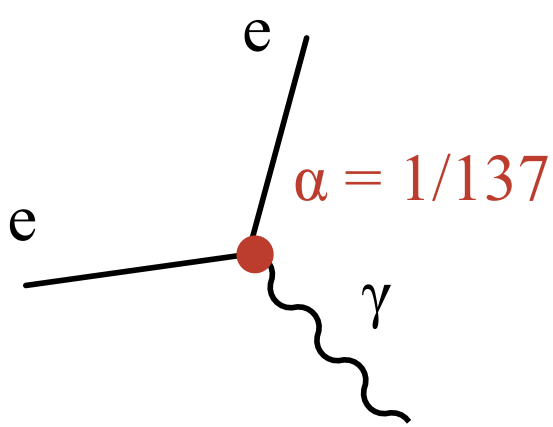


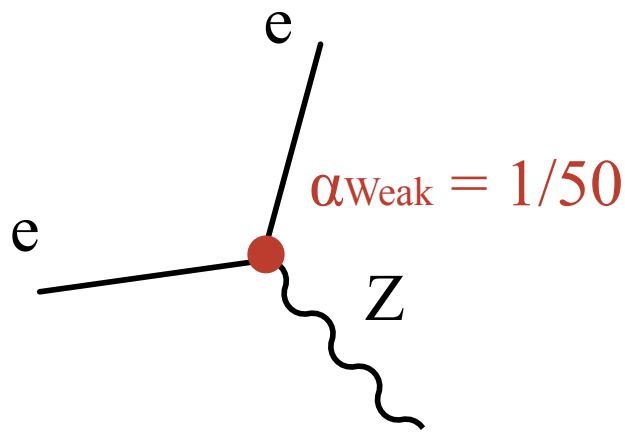


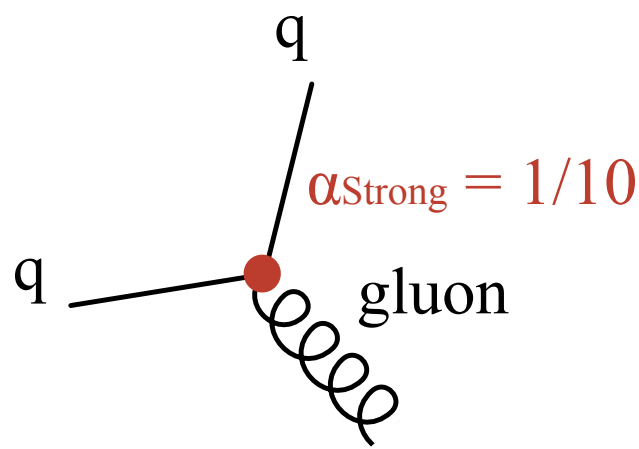
"Super-photon"
- Massive
- Stable
- Weakly interacting

Perfect candidate for Dark Matter

Interaction Strengths







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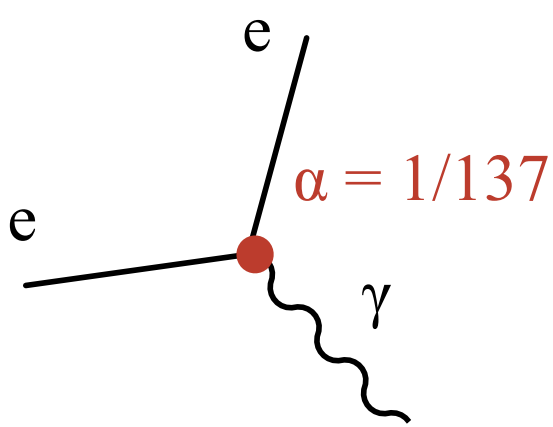
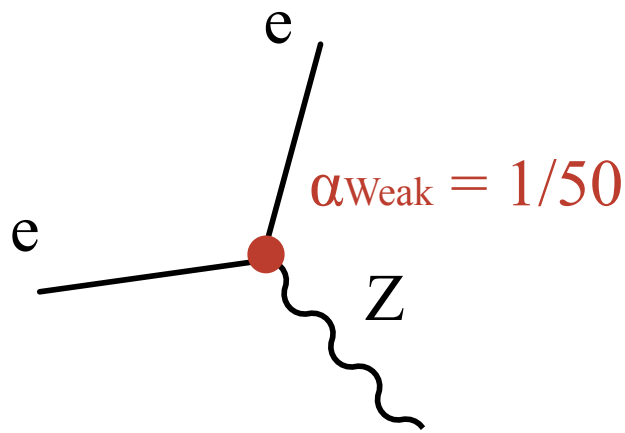
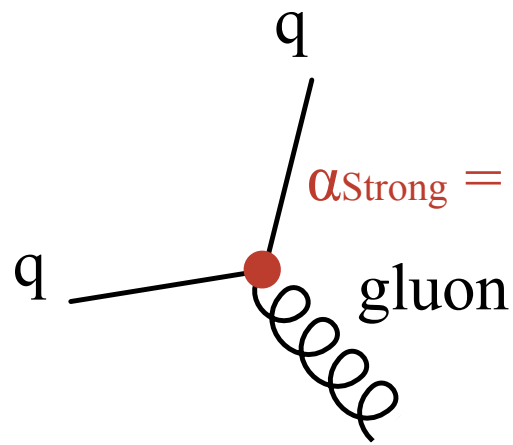


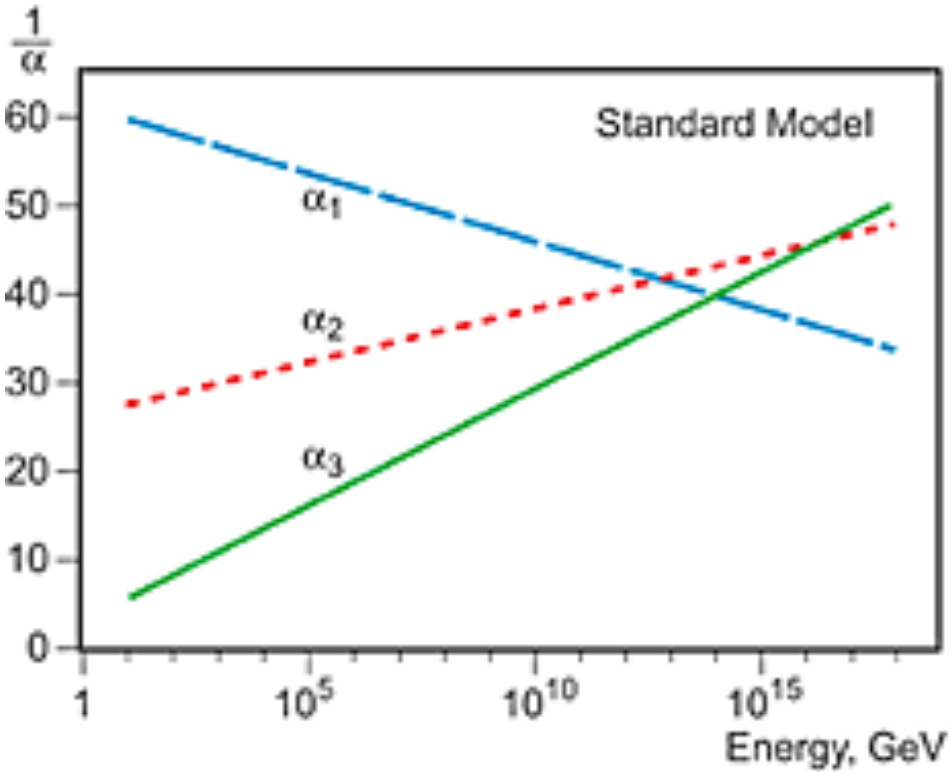
$\alpha = 1/137$



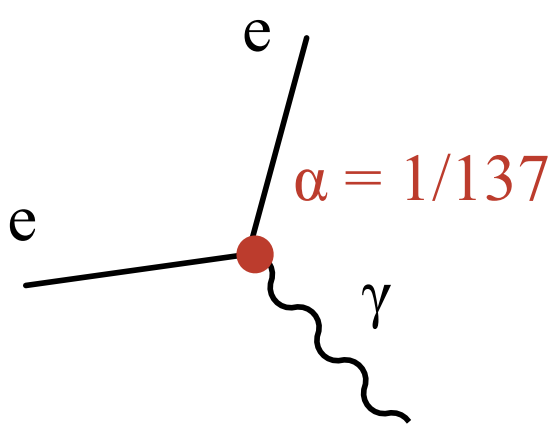
$\alpha_{Weak} = 1/50$

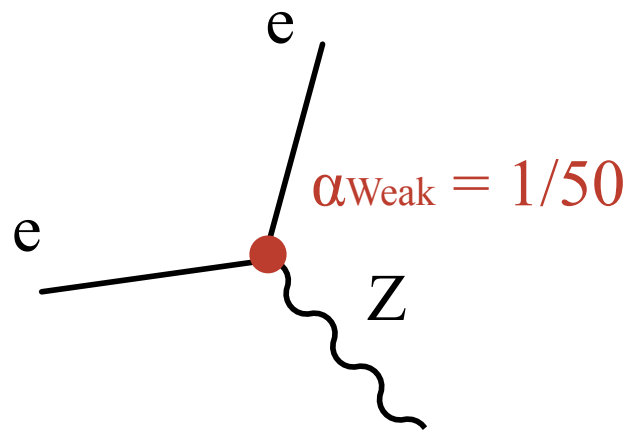


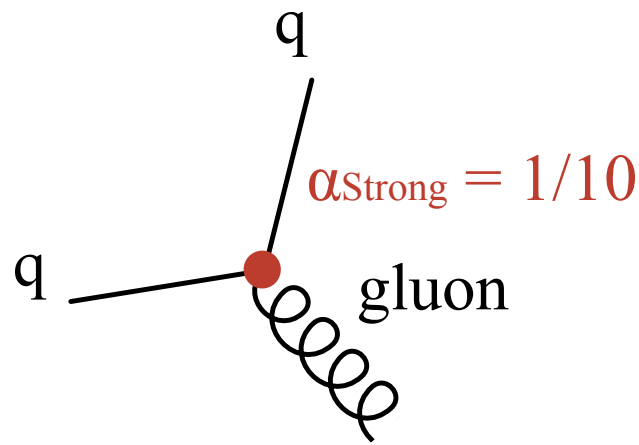
$\alpha_{Strong} = 1/10$

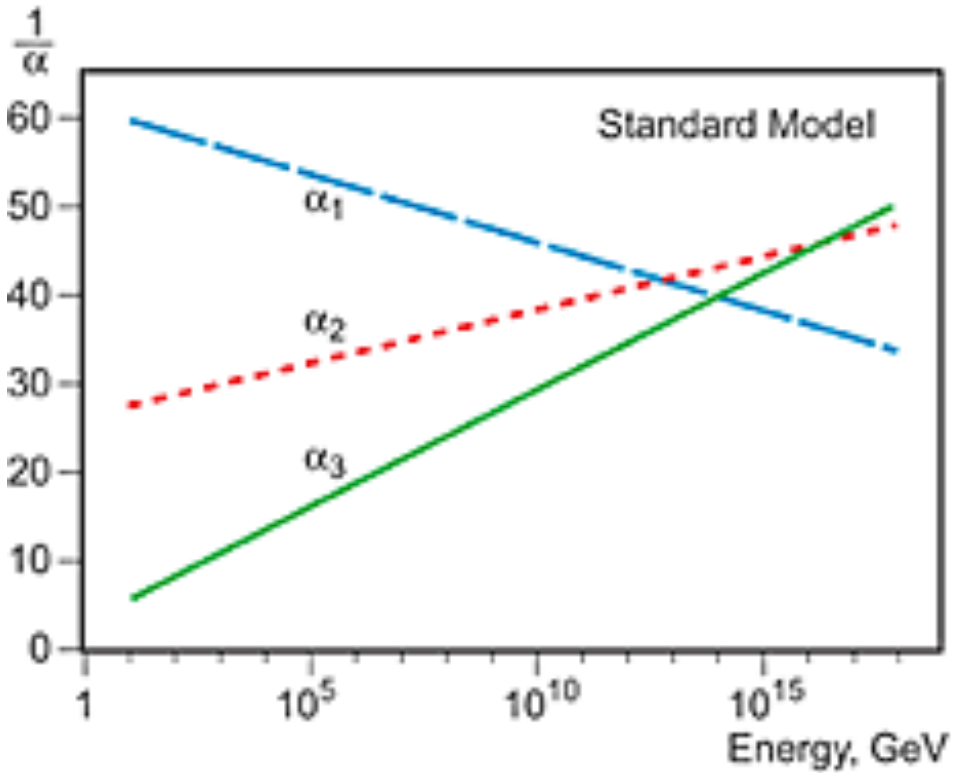


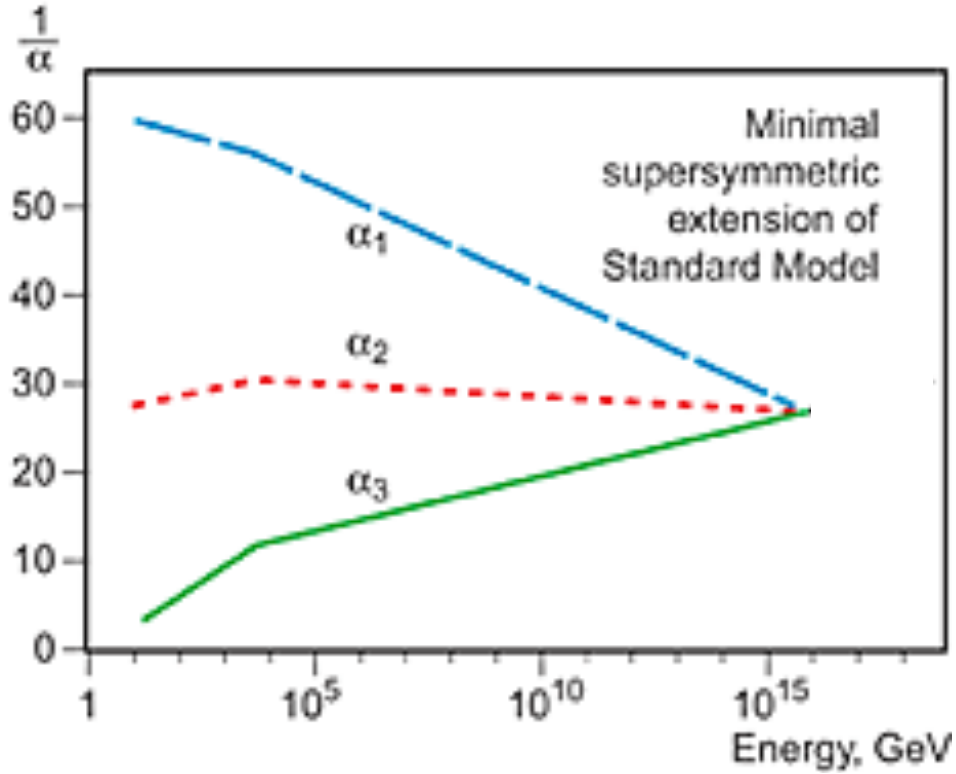
Interaction Strengths











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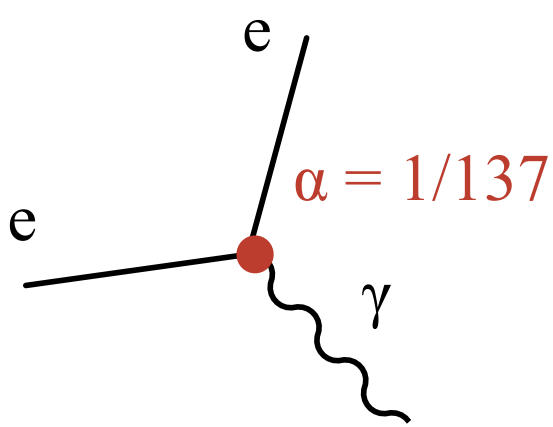

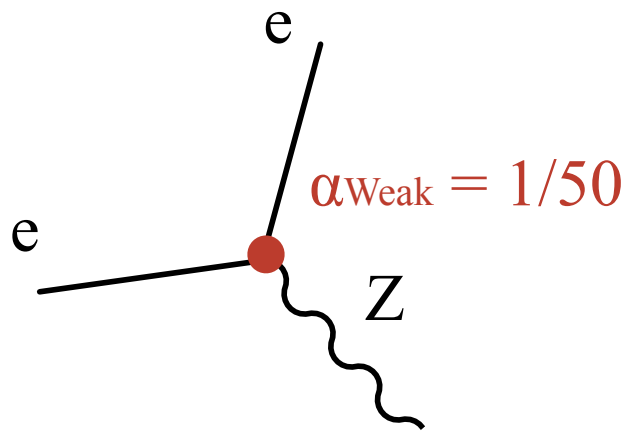

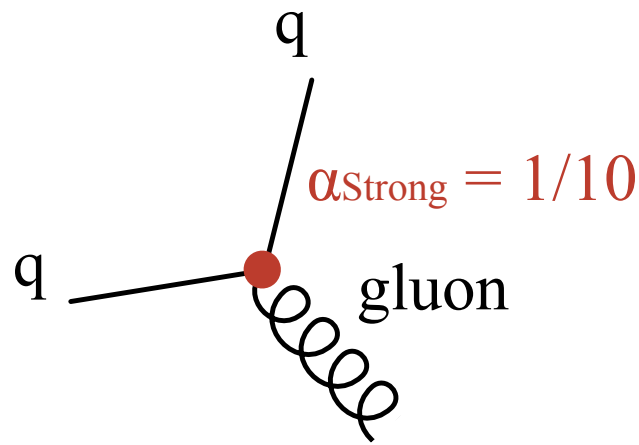

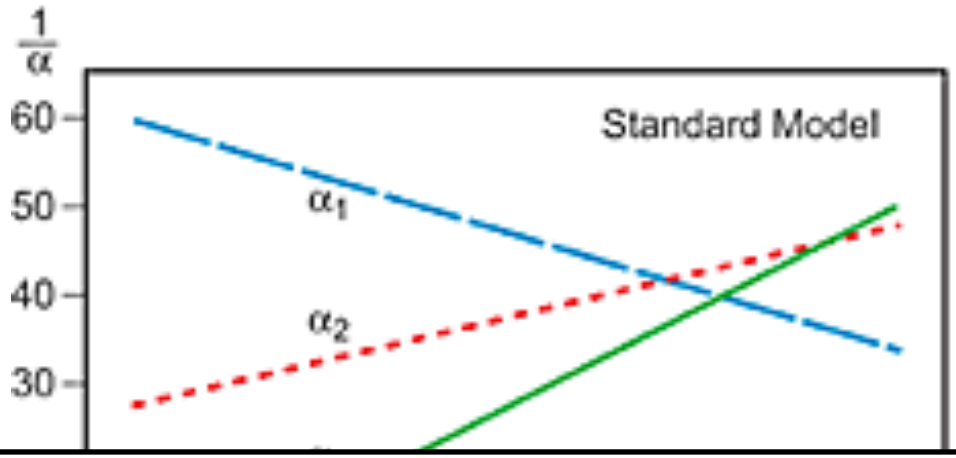

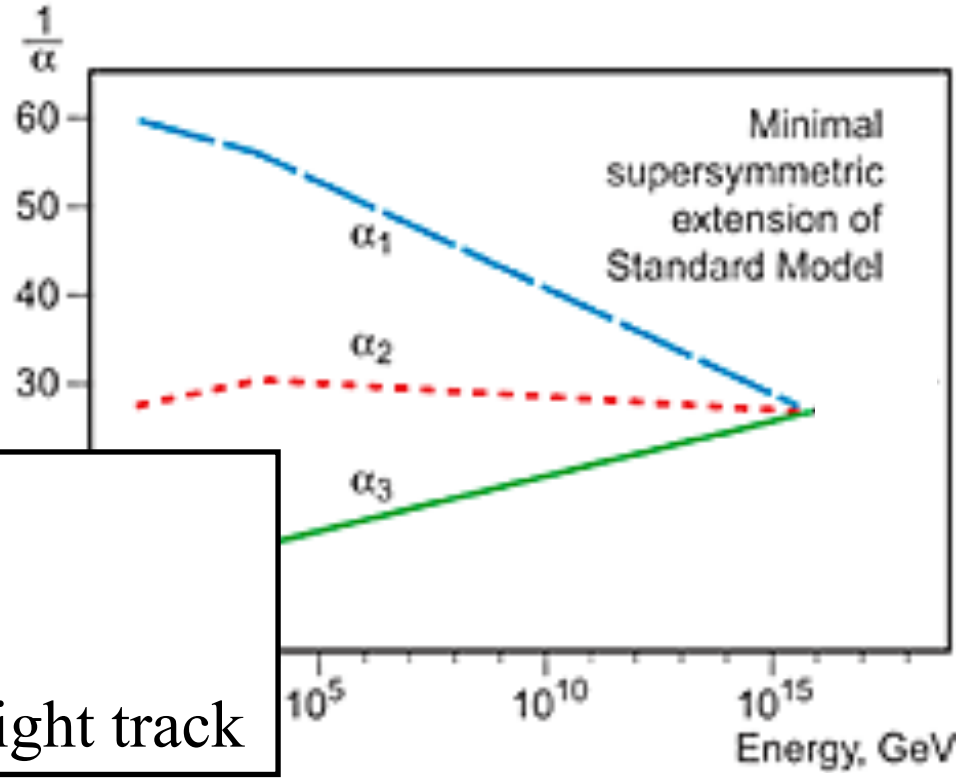

Did not have to happen!

- Not put in by hand
- Could be coincidence
- Seems like strong sign we are the right track

Searching For Solutions at the LHC

Higgs as Window to New Physics

Higgs boson directly related to all potential solutions

- Problem fundamentally related to Higgs field
- Higgs Boson is the harbinger of the Higgs field (how we study it)

Higgs as Window to New Physics

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Compositeness:

- Deeper origin for shape of potential
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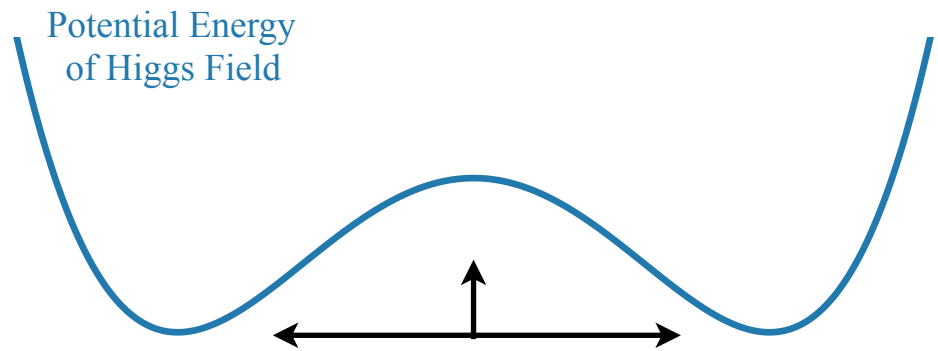

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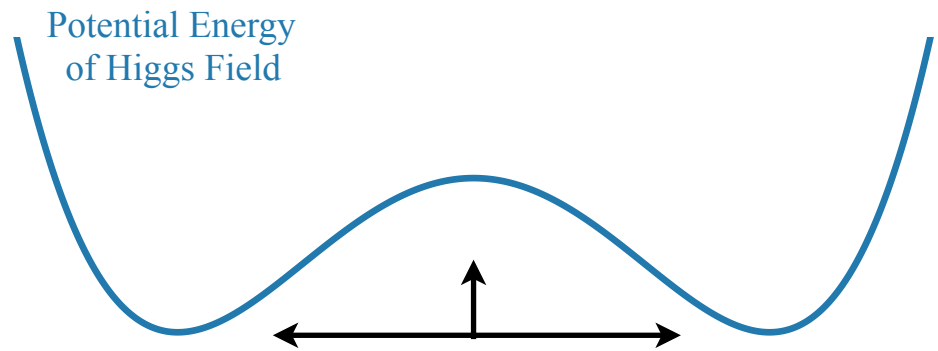

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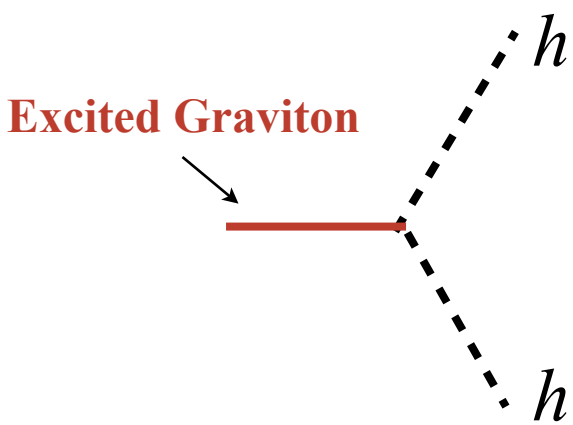
Extra Dimensions:



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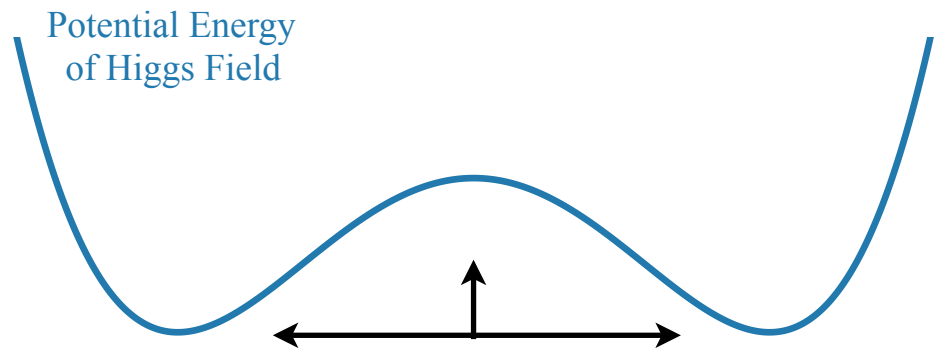

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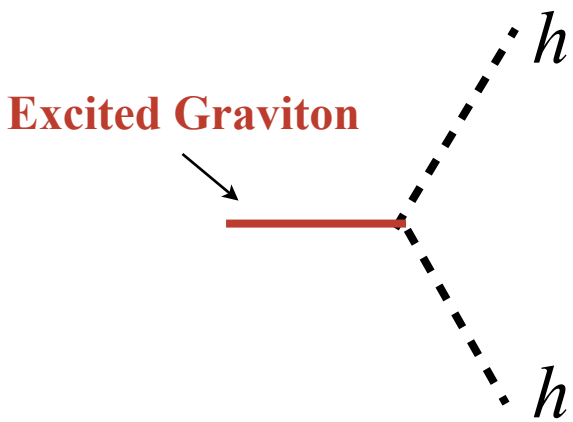
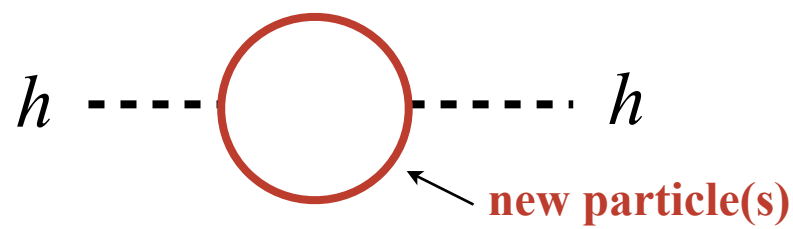


SuperSymmetry:



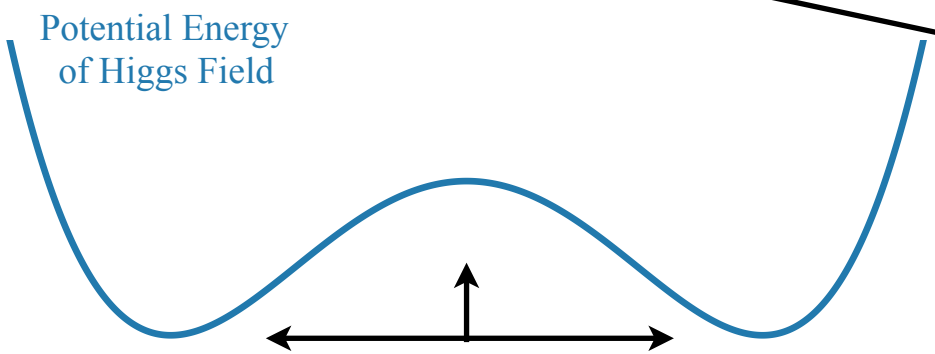
Higgs as Window to New Physics

Higgs boson directly related to [illegible]tions

Problem fundamentally related to Higgs [illegible]

Higgs Boson is the harbinger of the Higgs field (how [illegible]

Go through examples of each of these



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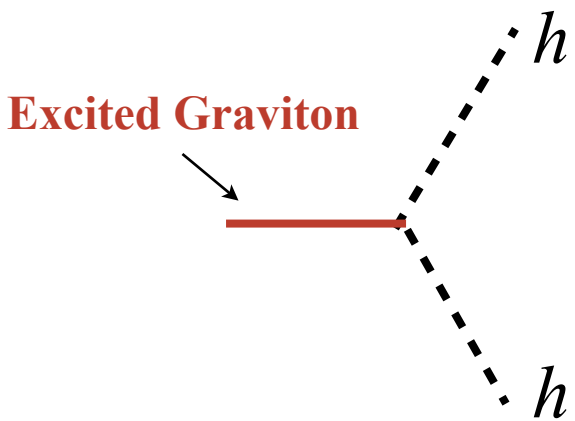

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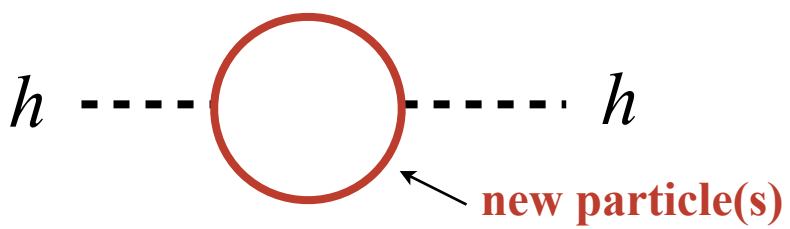

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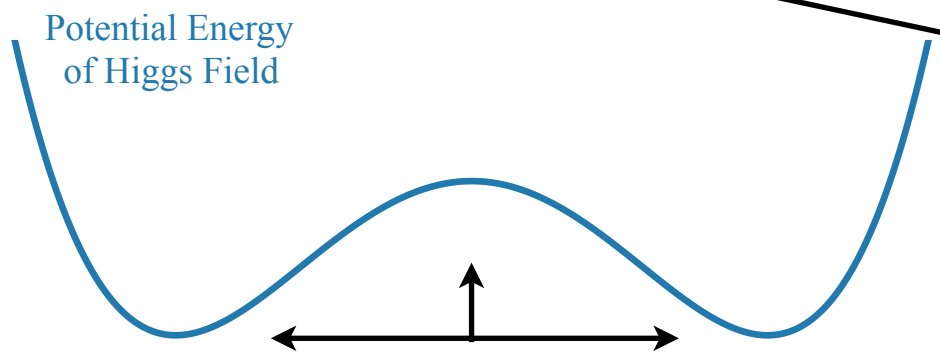

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Extra Dimensions:

SuperSymmetry:

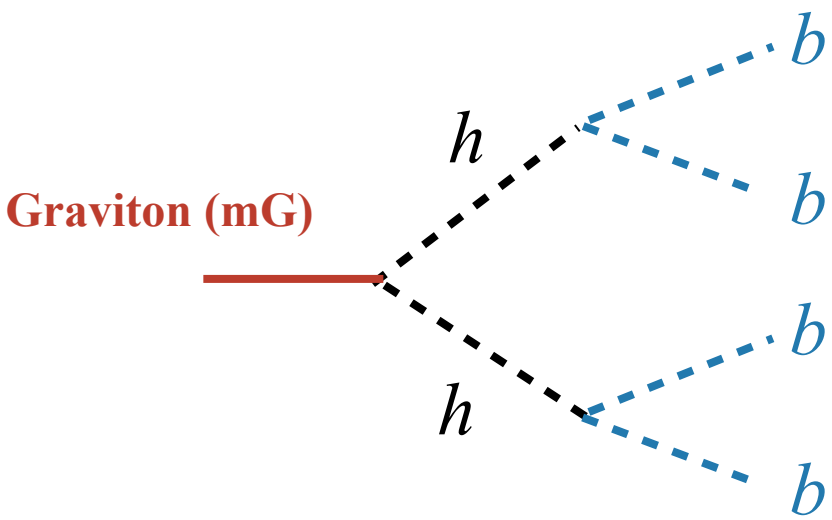
This is what the Higgs boson is good for ! (Deeper level-answer)

Studying Higgs boson production/decays addresses why gravity is so weak.

Not a boring technical detail ! Responsible for ~all structure that around us.

Enhanced Higgs Production

Signal:



Enhanced Higgs Production

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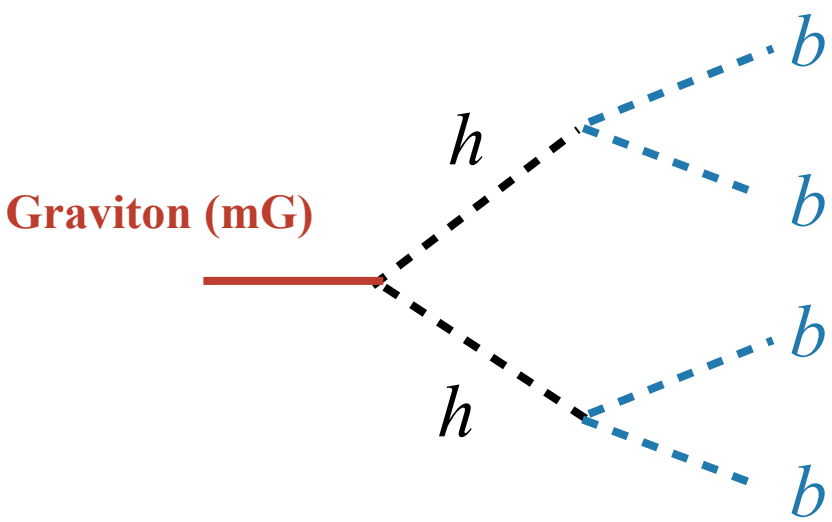
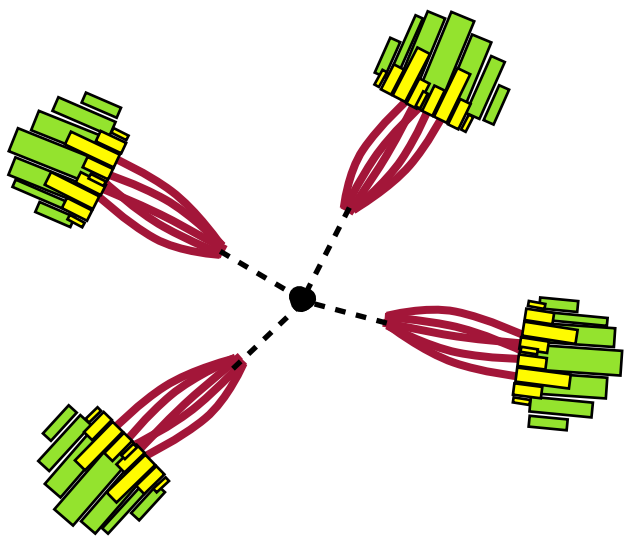


Event Selection:



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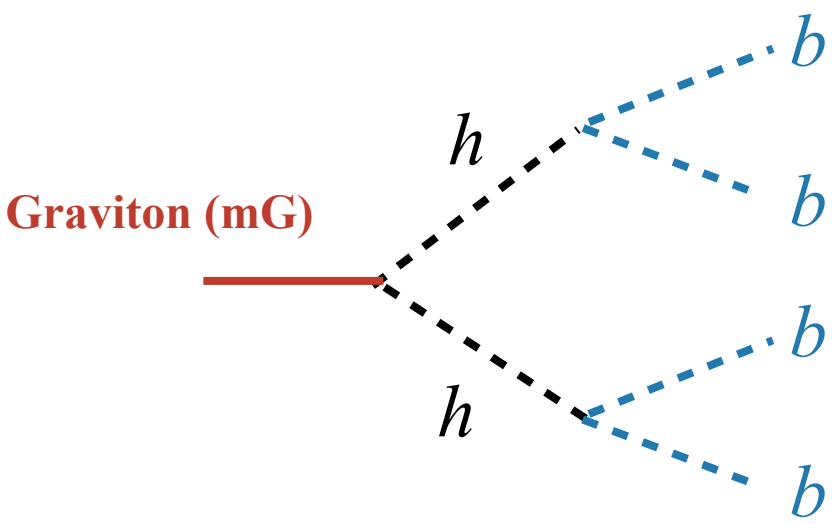

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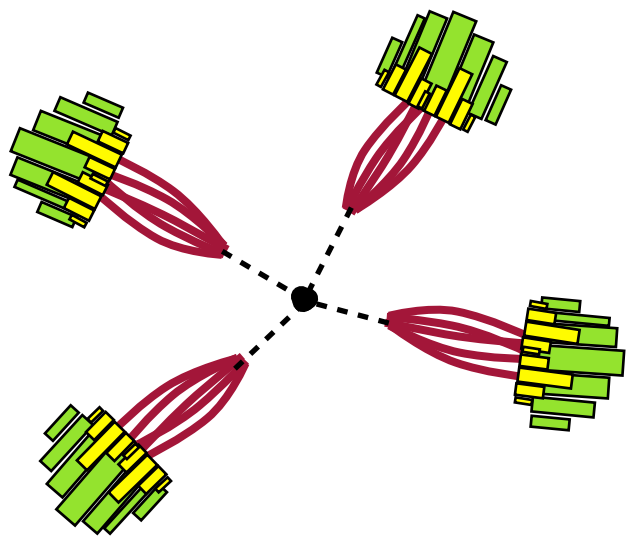


Reconstructed the event from the observed b-jets

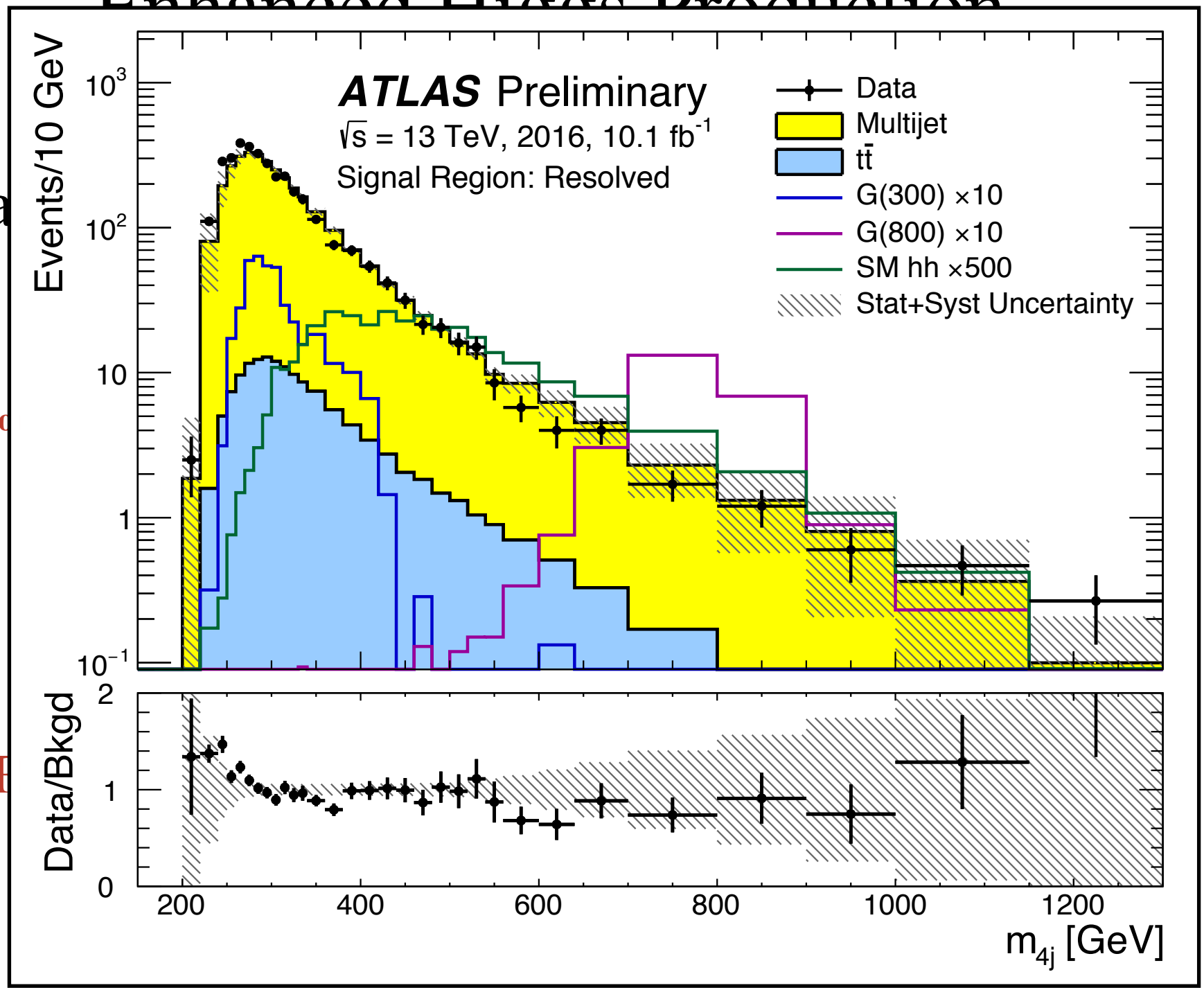
- Work backward from 4b → 2h → G
- Study the "reconstructed" graviton mass

Enhanced Higgs Production

Signa

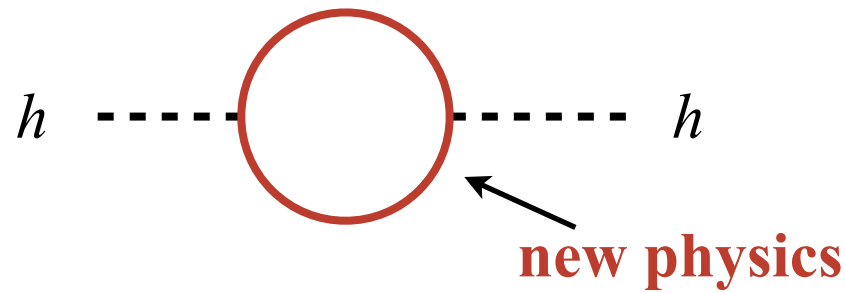
Gravito

H



Modified Higgs Couplings

Expect contributions from new physics to correct higgs mass:



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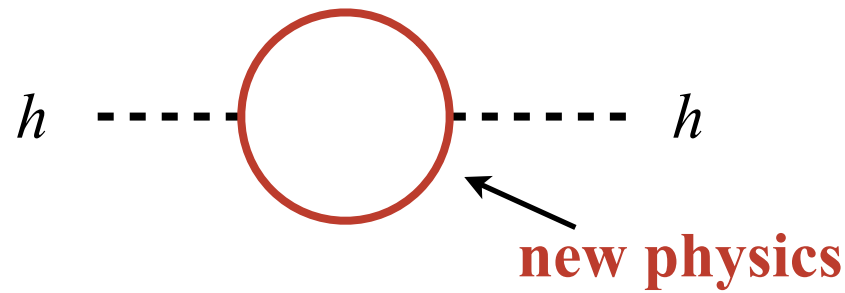
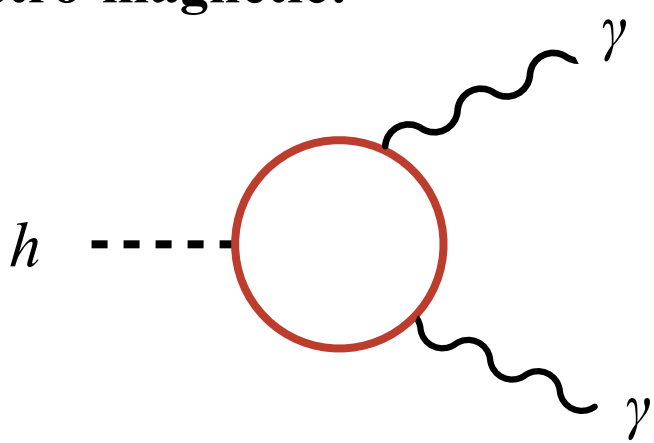


If new physics interacts with the **electro-magnetic:**



Modifies rate a which higgs bosons decay to photons.

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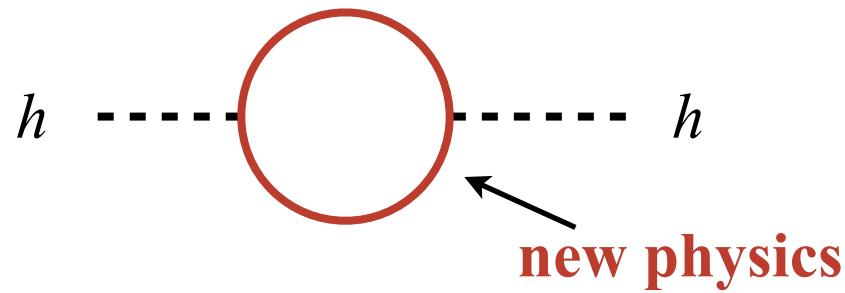

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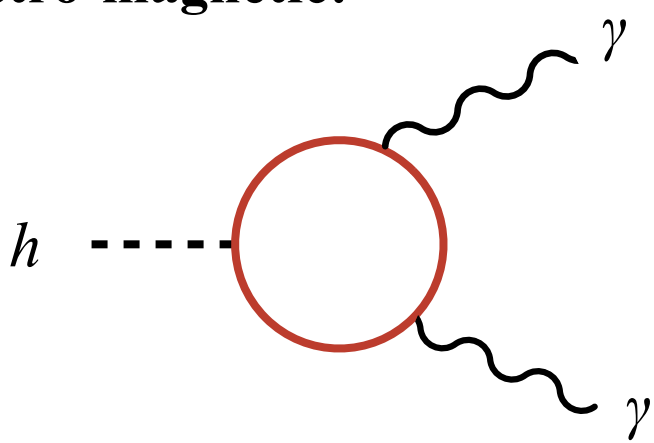

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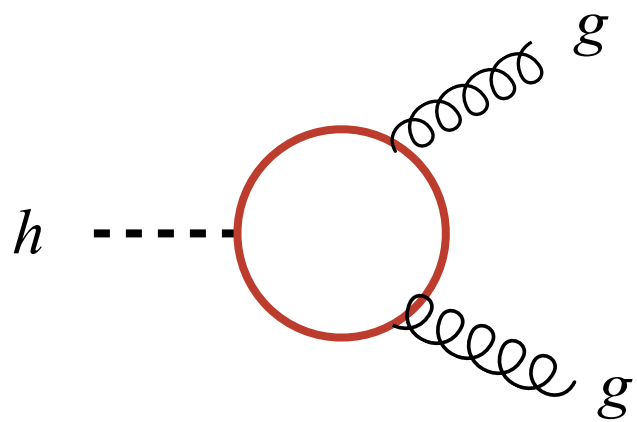

Modifies rate a which higgs bosons are produced at LHC

Modified Higgs Couplings

Exp

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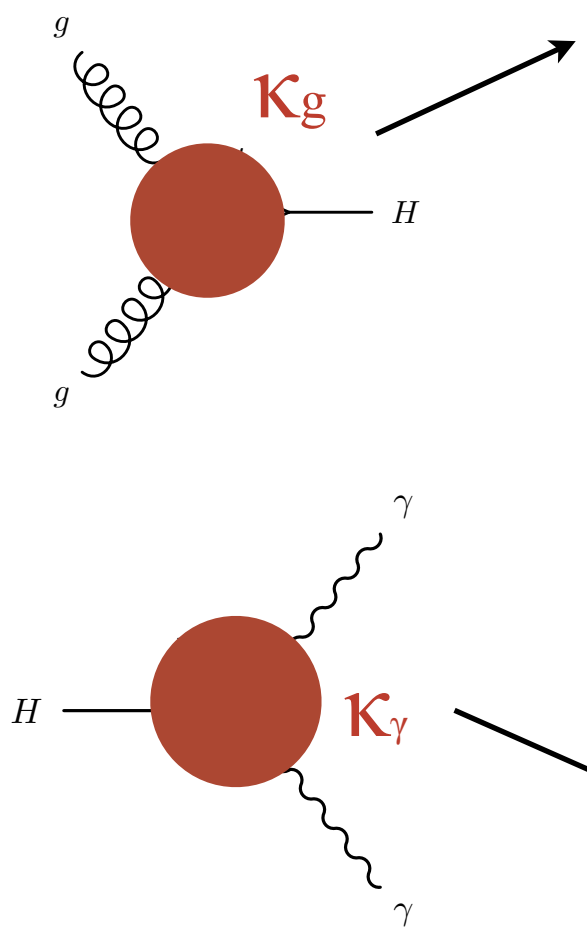
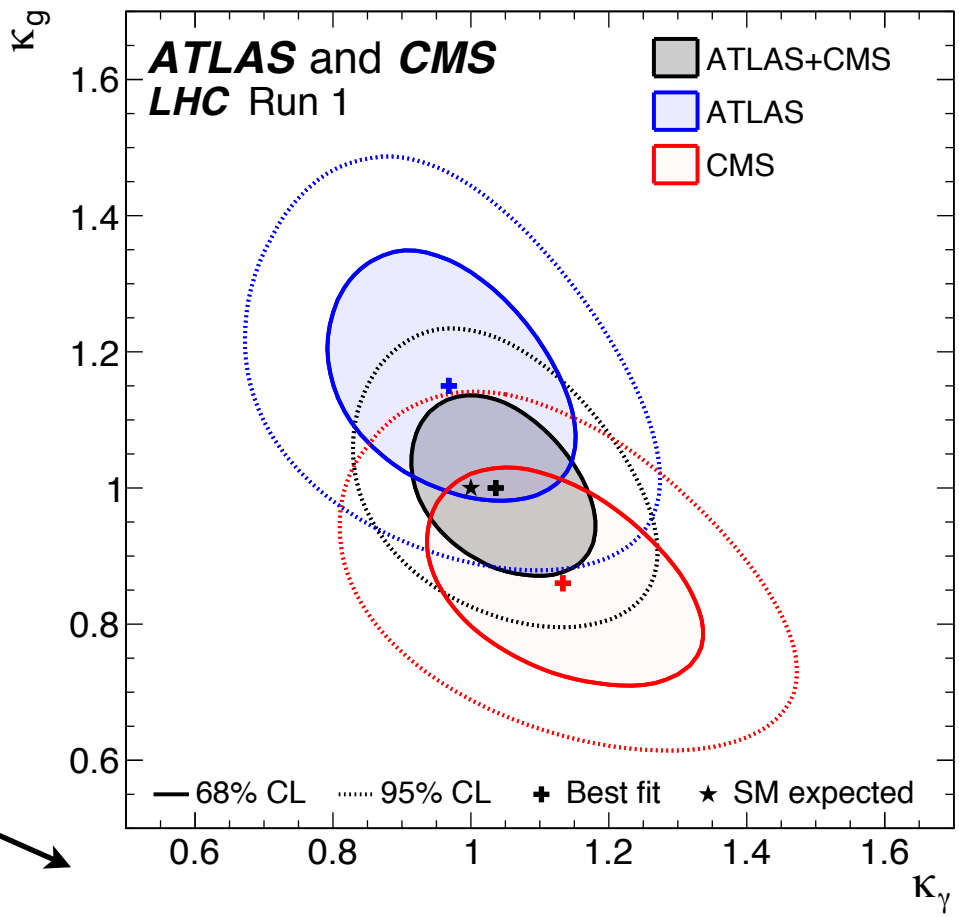
Why detailed Higgs measurements are so important:





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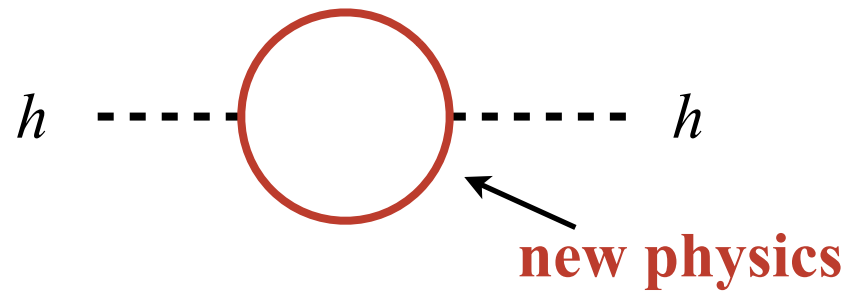

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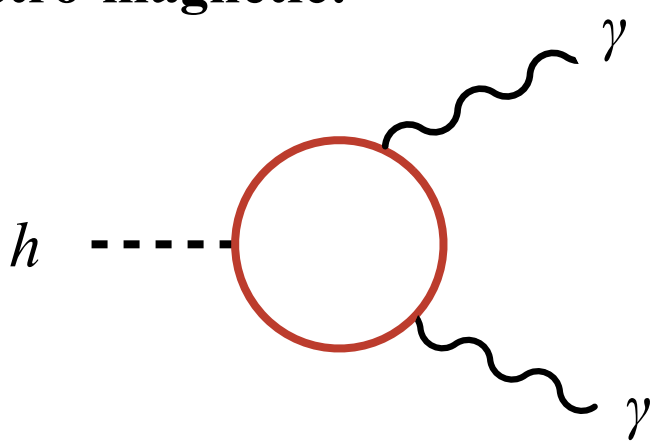

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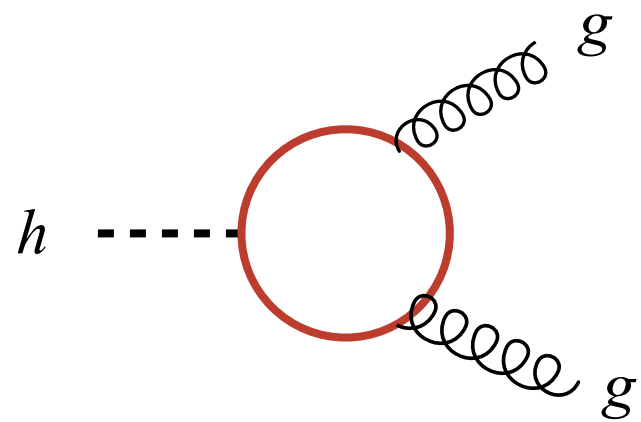

Modifies rate a which higgs bosons are produced at LHC

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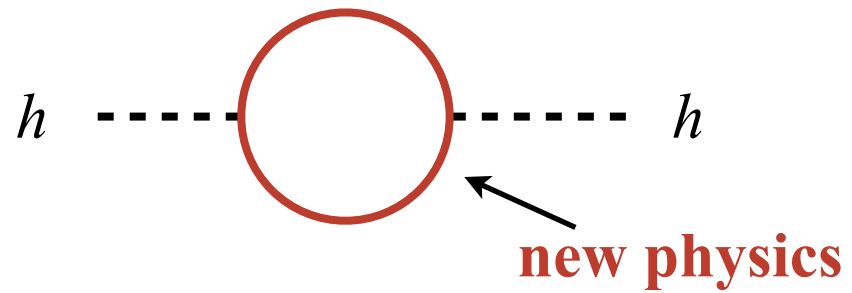
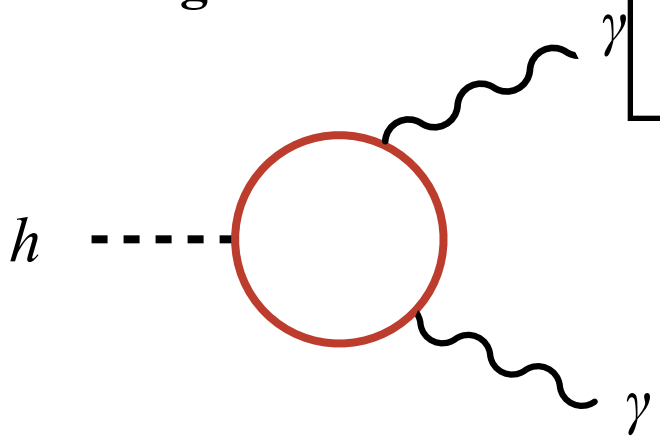


If new physics interacts with the **electro-magnetic:**

Can play Devil's advocate:
- Add particle stabilize Higgs mass, but
- Not feel strong or electromagnetic force



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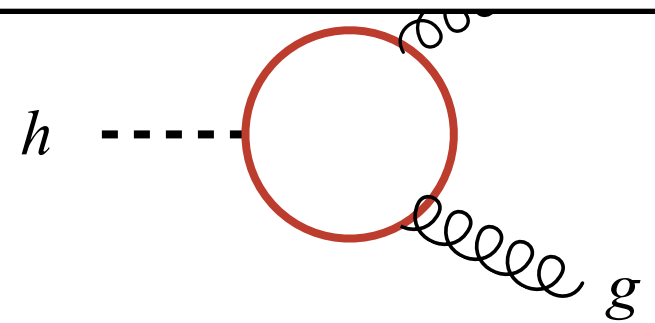

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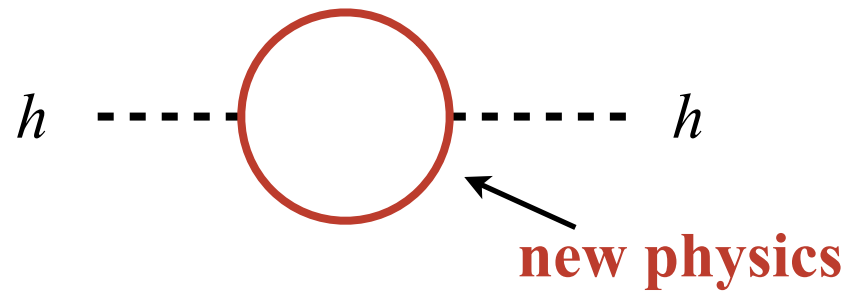
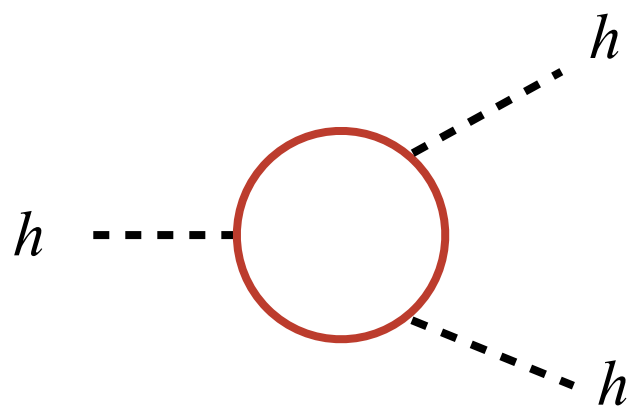


by construction, cannot avoid:

Higgs interaction:



Modifies Di-Higgs production

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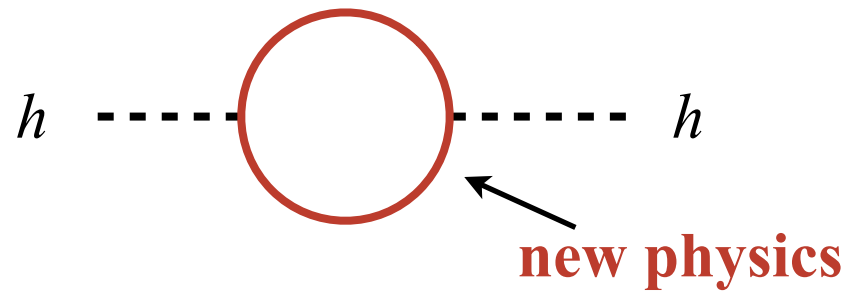
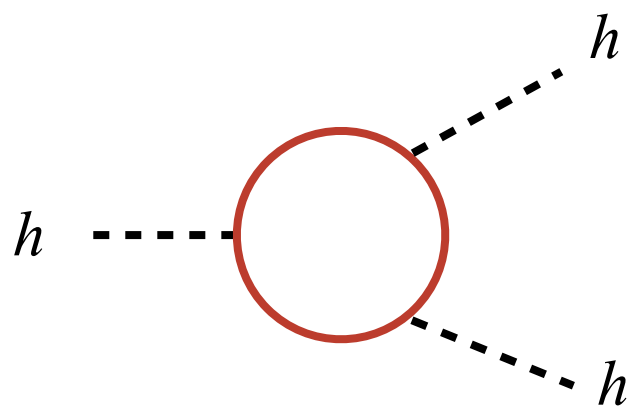


by construction, cannot avoid:

Higgs interaction:



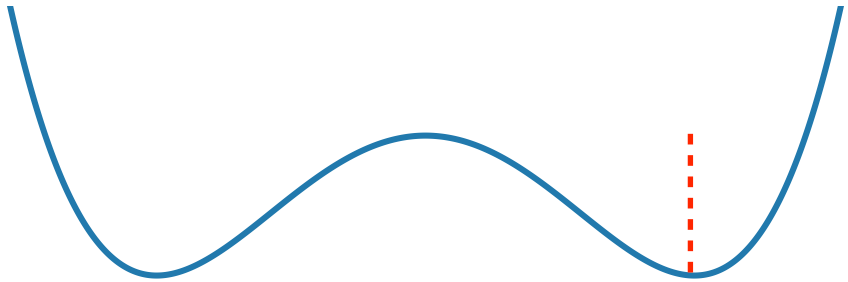
One of the reasons
Di-Higgs is a so important

Modifies Di-Higgs production

Measuring Higgs Potential

Energy of Higgs field: *Higgs potential*

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



$\frac{\mu}{\sqrt{\lambda}} \equiv v$ ~ weak scale

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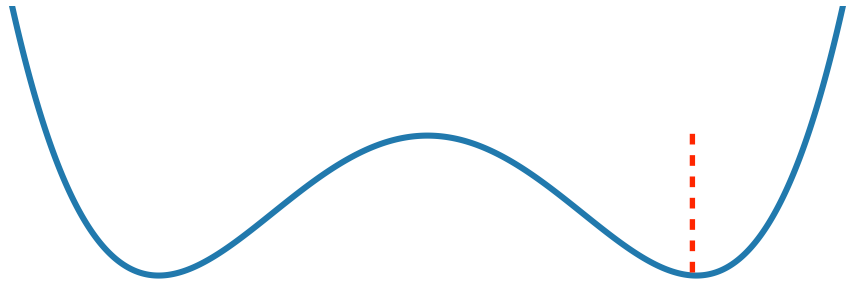

Expanding about minimum: $V(\phi) \to V(v+h)$

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

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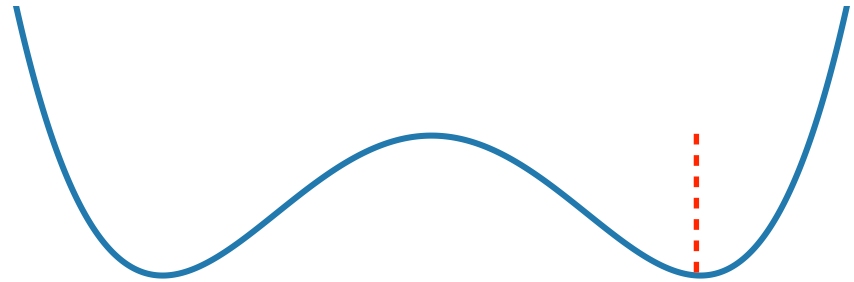

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Higgs mass term

Measuring Higgs Potential

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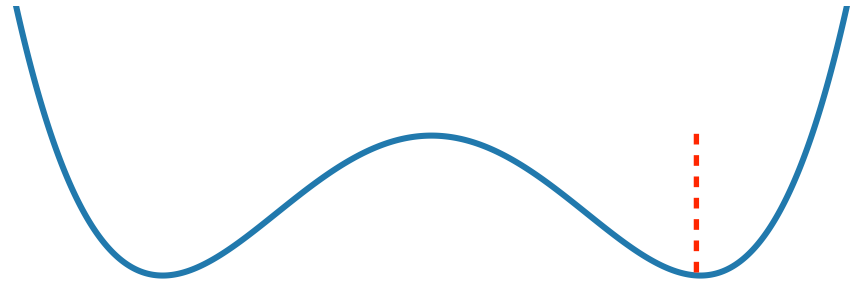

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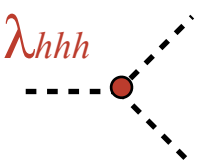
Higgs mass term

λ_{hhh}



hh-production

Measuring Higgs Potential

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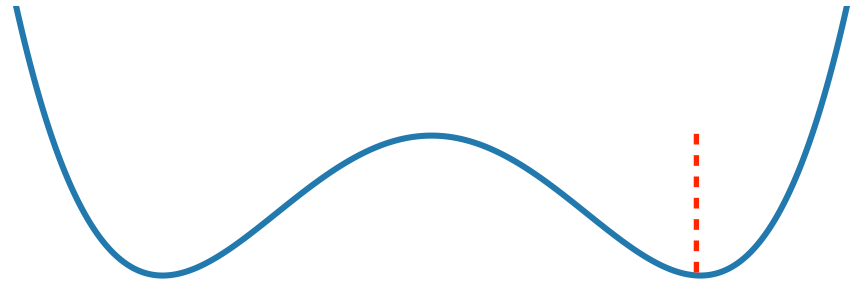

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Higgs mass term

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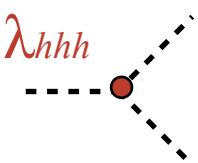
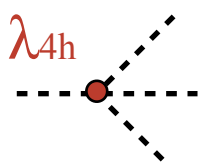


hh-production

λ_{4h}



hhh-production

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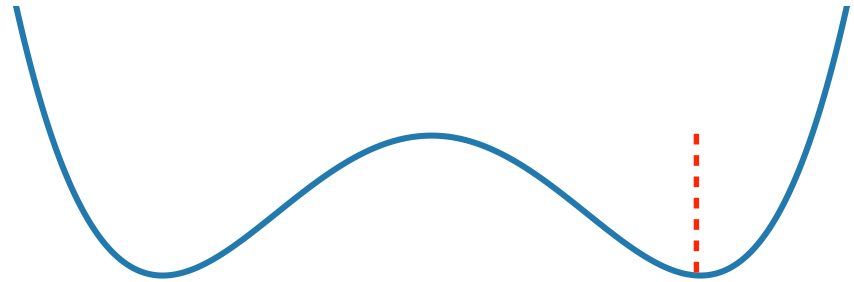

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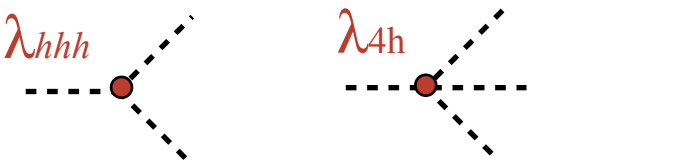
Higgs mass term

λ_{hhh} λ_{4h}



hh-production *hhh*-production

Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

- Shape of potential gives relationship between λ_{hhh} and m_h, v

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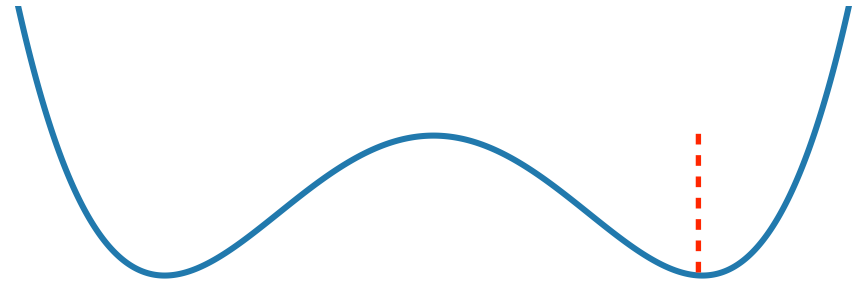

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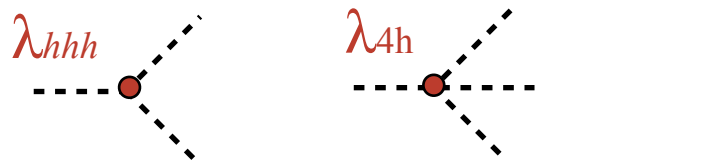

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Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

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- Measuring λ_{hhh} important probes the shape of the Higgs potential

Measuring Higgs Potential

Energy of Higgs field: *Higgs potential*

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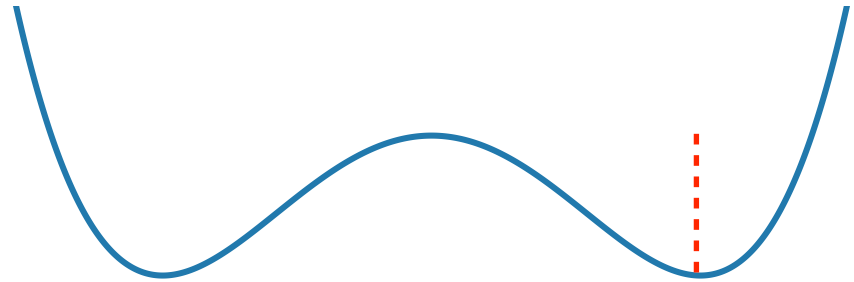

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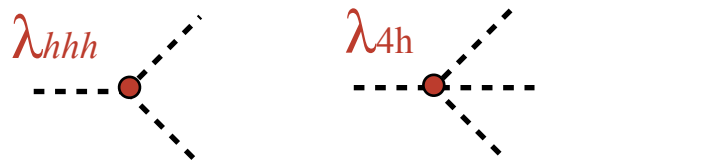

hh-production

hhh-production

Standard Model:

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

- Shape of potential gives relationship between λ_{hhh} and m_h, v
- Measuring λ_{hhh} important probes the shape of the Higgs potential
- *hh* production interesting because it measures λ_{hhh}

Measuring Higgs Potential

Energy of Higgs field: *Higgs potential*

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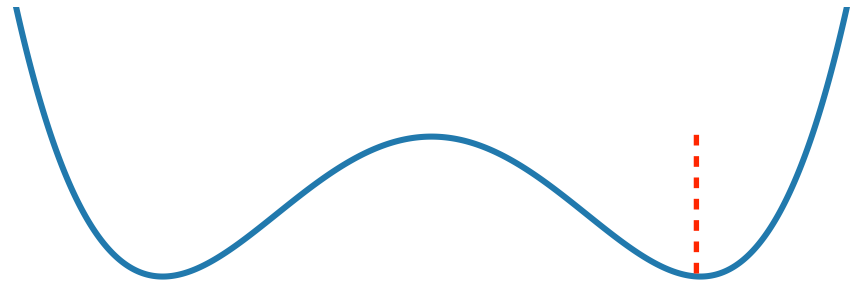

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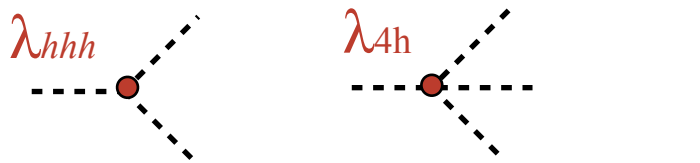
Higgs mass term



hh-production

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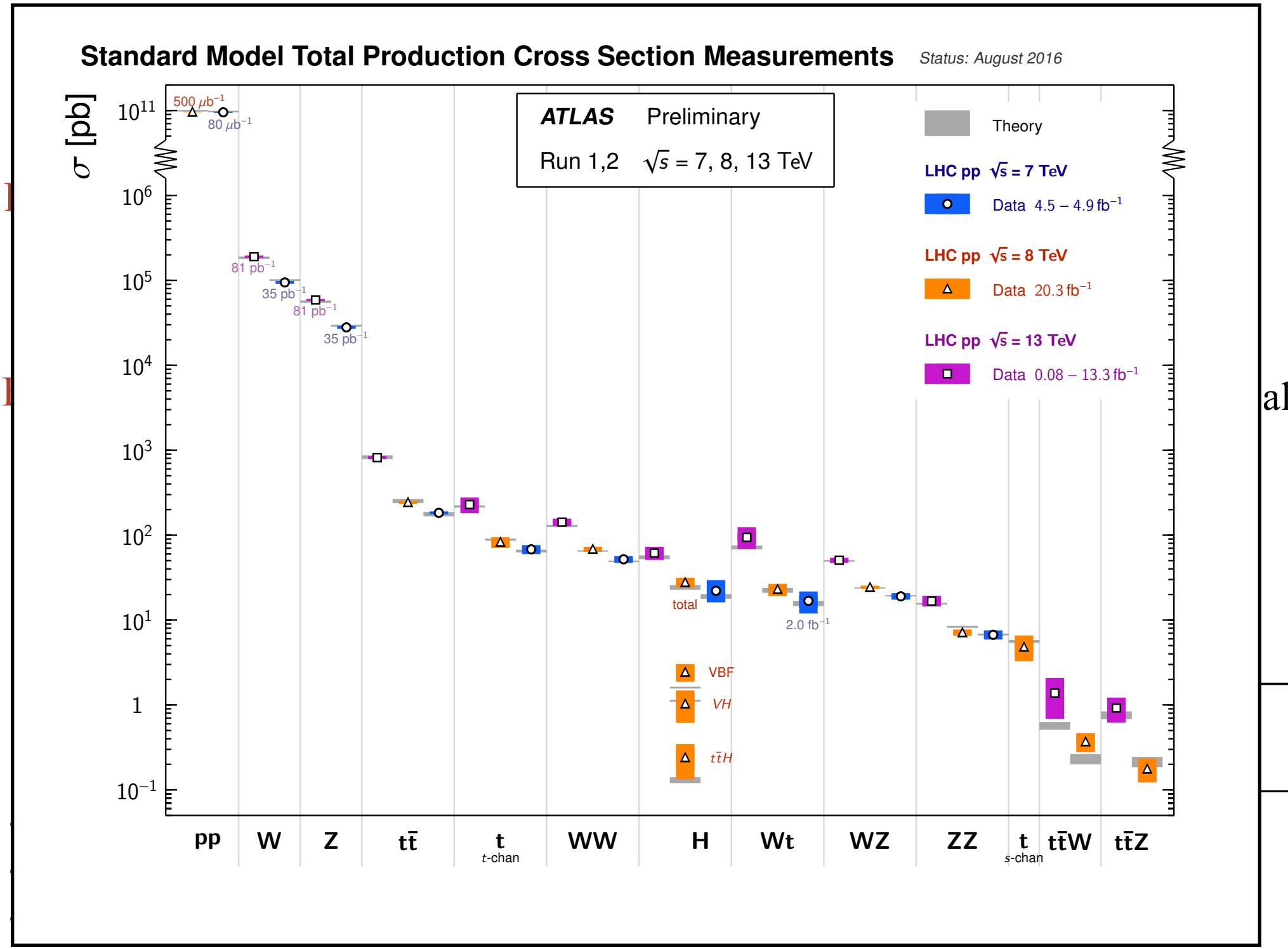
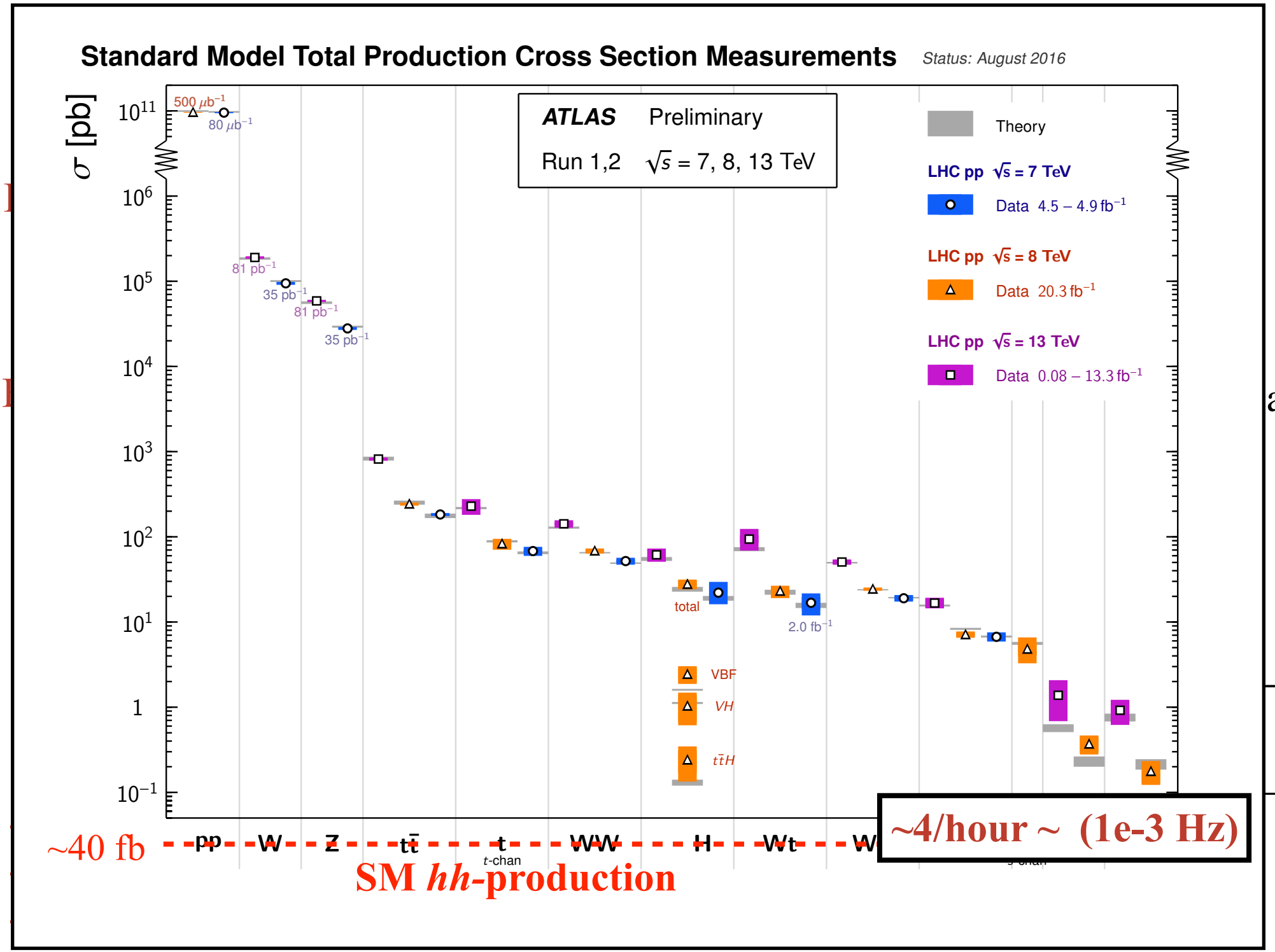
Another reason Di-Higgs is a so important


Standard Model Total Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 13.3 fb⁻¹
σ [pb]
500 μb⁻¹
80 μb⁻¹
81 pb⁻¹
35 pb⁻¹
81 pb⁻¹
35 pb⁻¹
total
2.0 fb⁻¹
VBF
VH
ttH
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
ttW
ttZ

ale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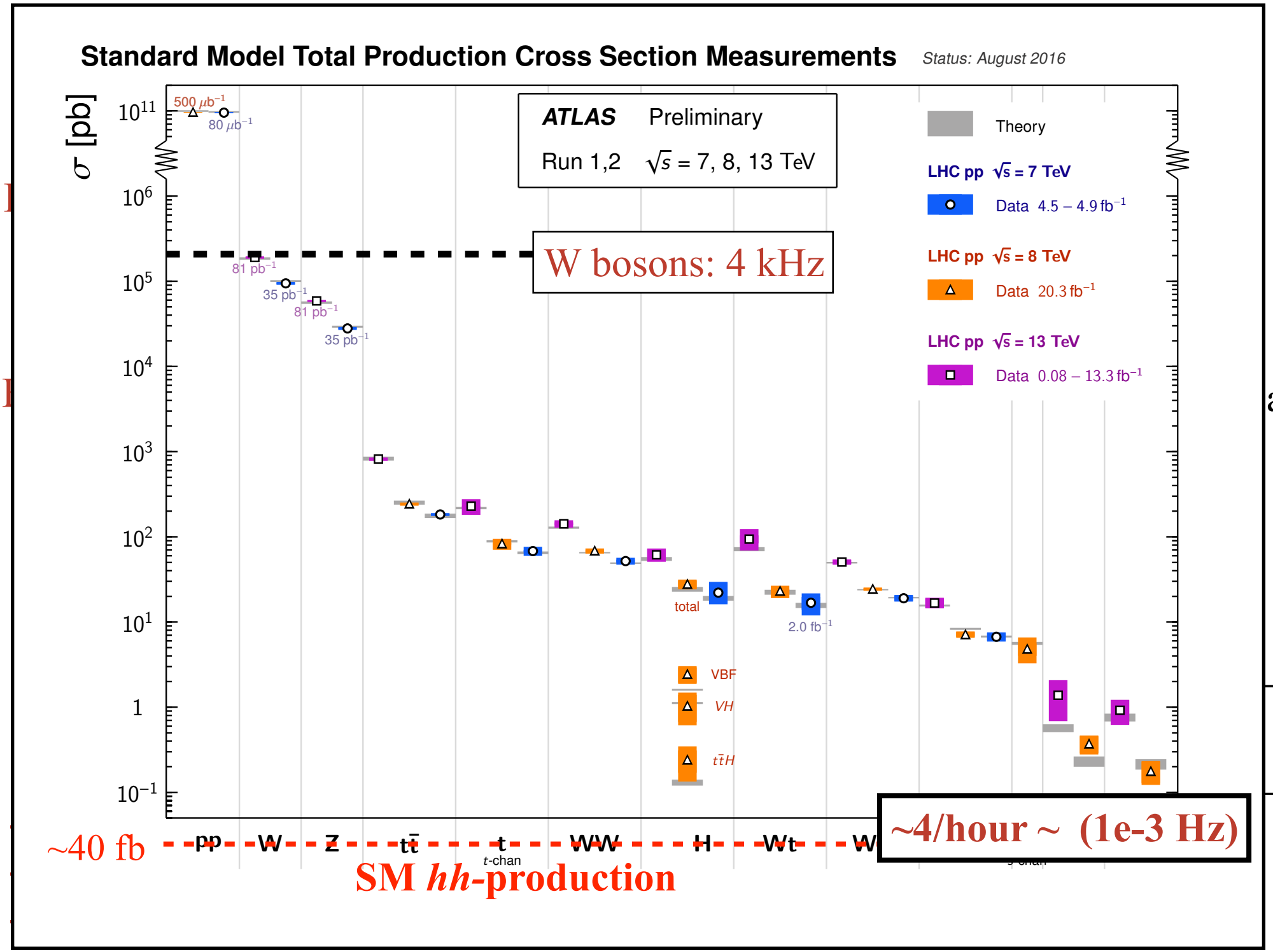
σ [pb]
total
VBF
VH
tt̄H
2.0 fb⁻¹
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
~40 fb
~4/hour ~ (1e-3 Hz)
SM hh-production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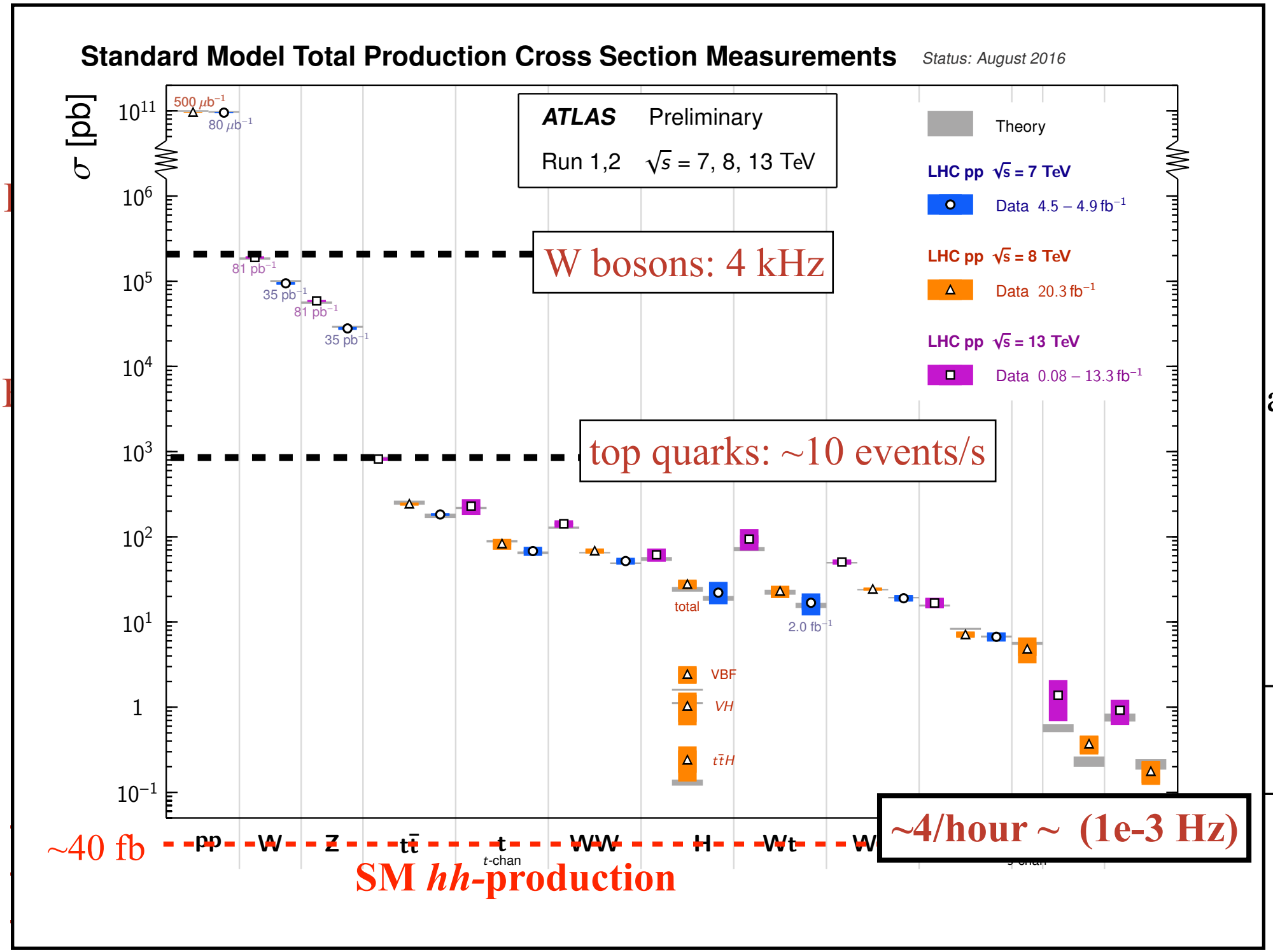
LHC pp √s = 13 TeV
Data 0.08 – 13.3 fb⁻¹
σ [pb]
W bosons: 4 kHz
~4/hour ~ (1e-3 Hz)
~40 fb
SM hh-production
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
total
VBF
VH
ttH
2.0 fb⁻¹


Standard Model Total Production Cross Section Measurements
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Data 0.08 – 13.3 fb⁻¹
W bosons: 4 kHz
top quarks: ~10 events/s
~4/hour ~ (1e-3 Hz)
~40 fb
SM hh-production
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
total
VBF
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ttH
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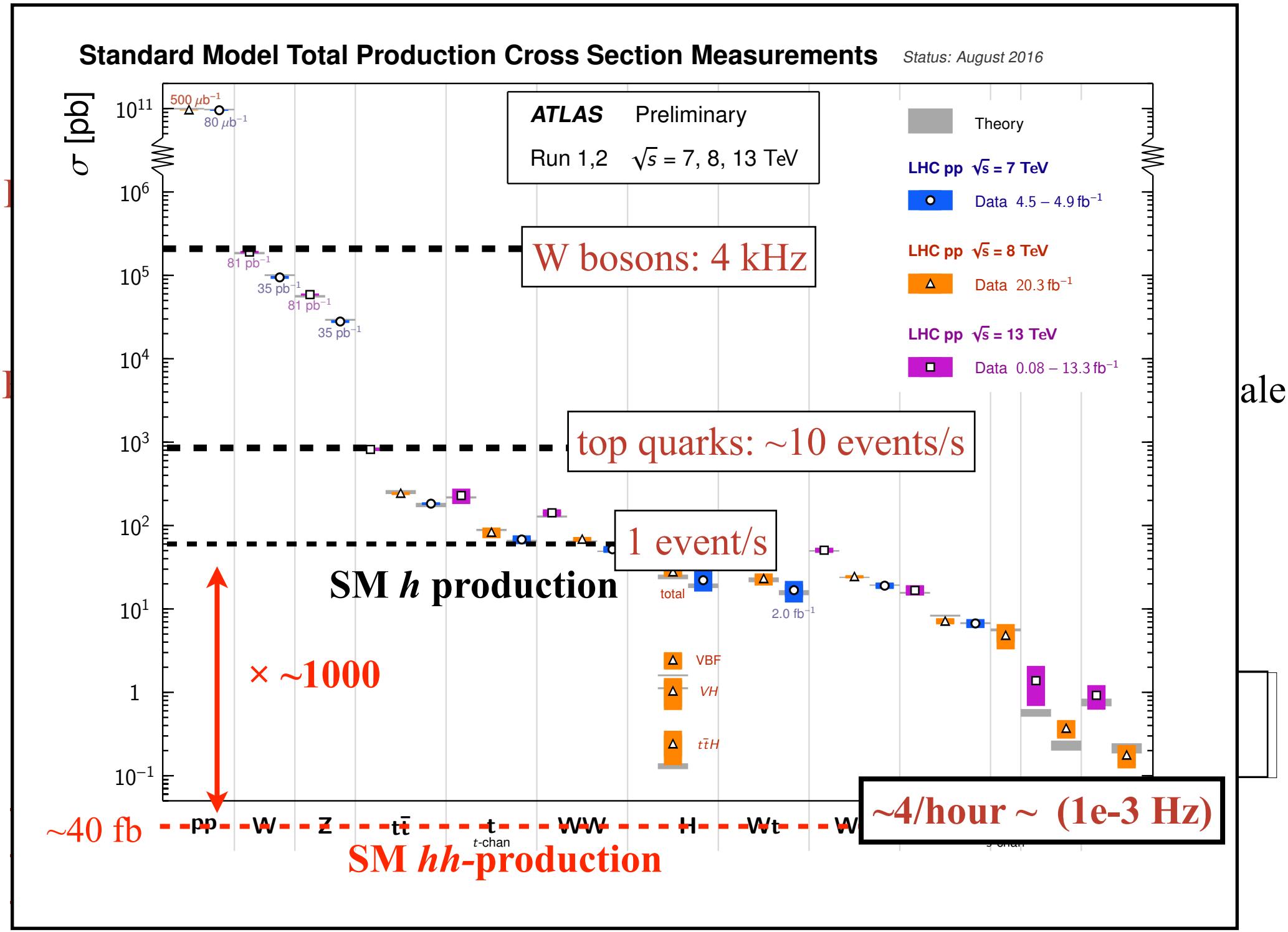
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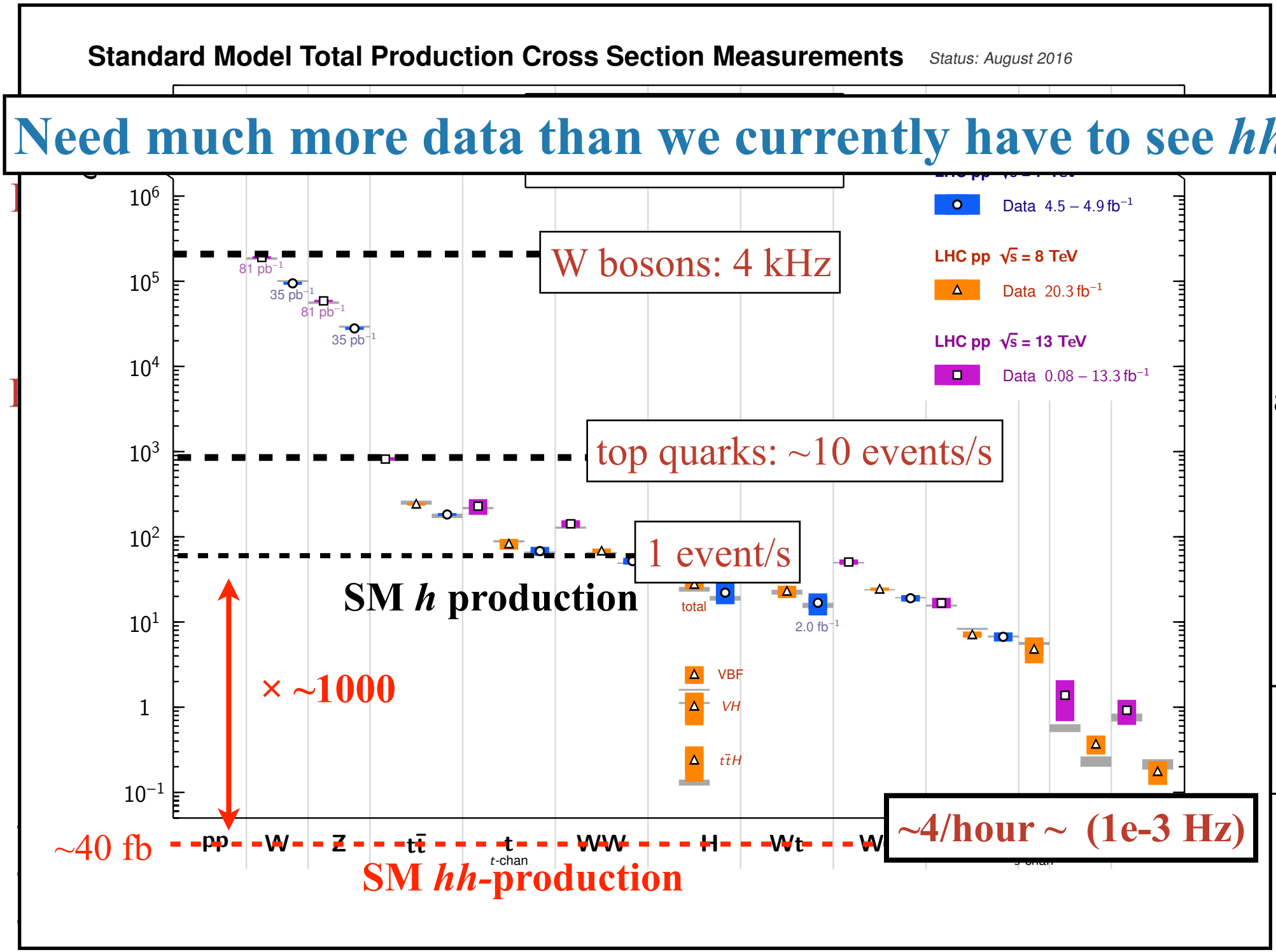
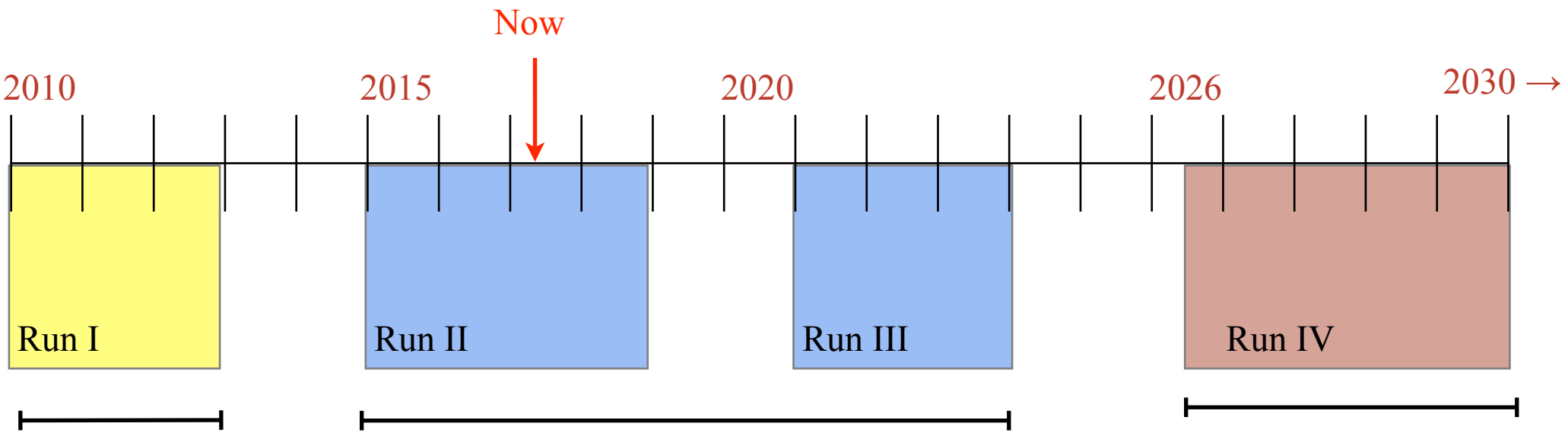
σ [pb]
W bosons: 4 kHz
top quarks: ~10 events/s
1 event/s
SM h production
× ~1000
~40 fb
~4/hour ~ (1e-3 Hz)
SM hh-production
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
total
VBF
VH
tt̄H


Standard Model Total Production Cross Section Measurements
Status: August 2016
Need much more data than we currently have to see hh
W bosons: 4 kHz
top quarks: ~10 events/s
1 event/s
SM h production
× ~1000
~40 fb
SM hh-production
~4/hour ~ (1e-3 Hz)
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 13.3 fb⁻¹
total
VBF
VH
ttH
pp
W
Z
tt̄
t
t-chan
WW
H
Wt

Outlook for the Future

What we might know by 2035…

Future LHC Program



- 8 TeV
- 20/fb

- Get to 300/fb of 13-14 TeV data
- Up to 75 interactions per crossing

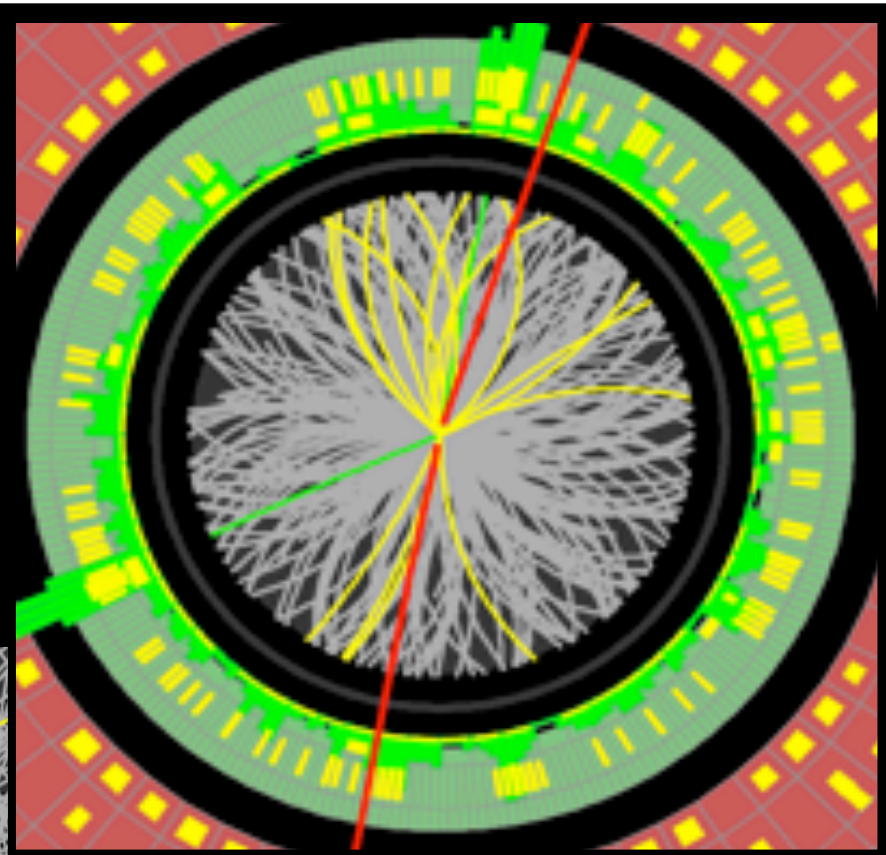
×15 increase in size of dataset

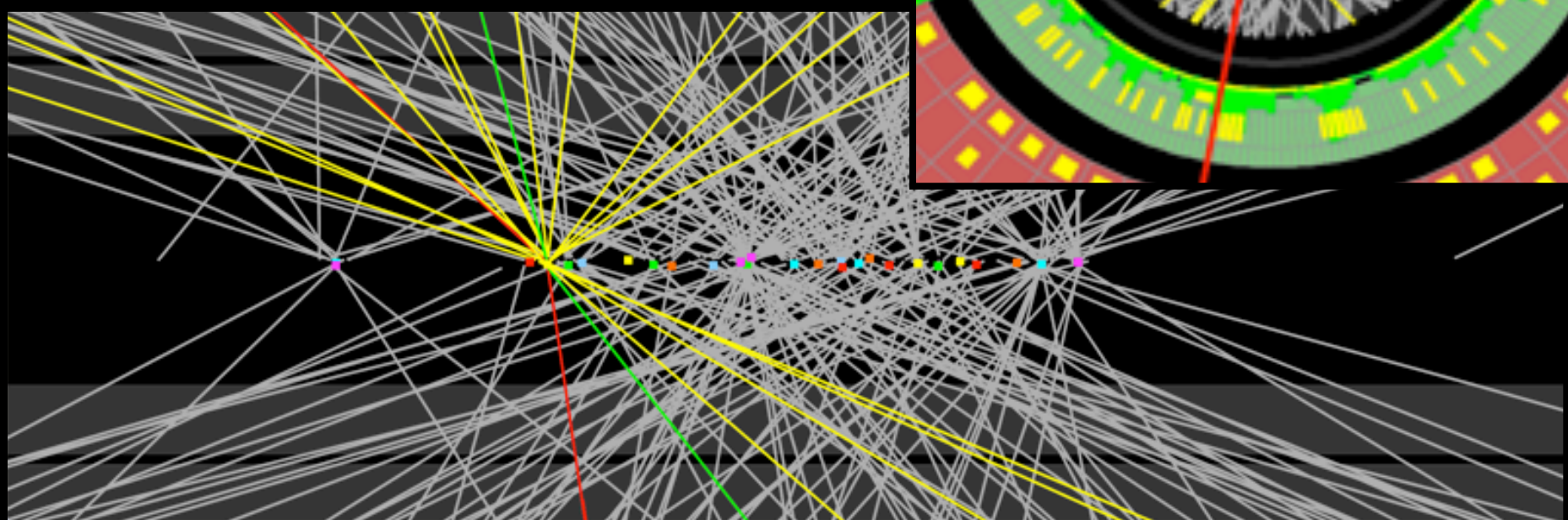
- 3000/fb of 13-14 TeV data
- Pile-up of up to **150-200**

×150 increase in dataset size

Future LHC Program

25 Interactions



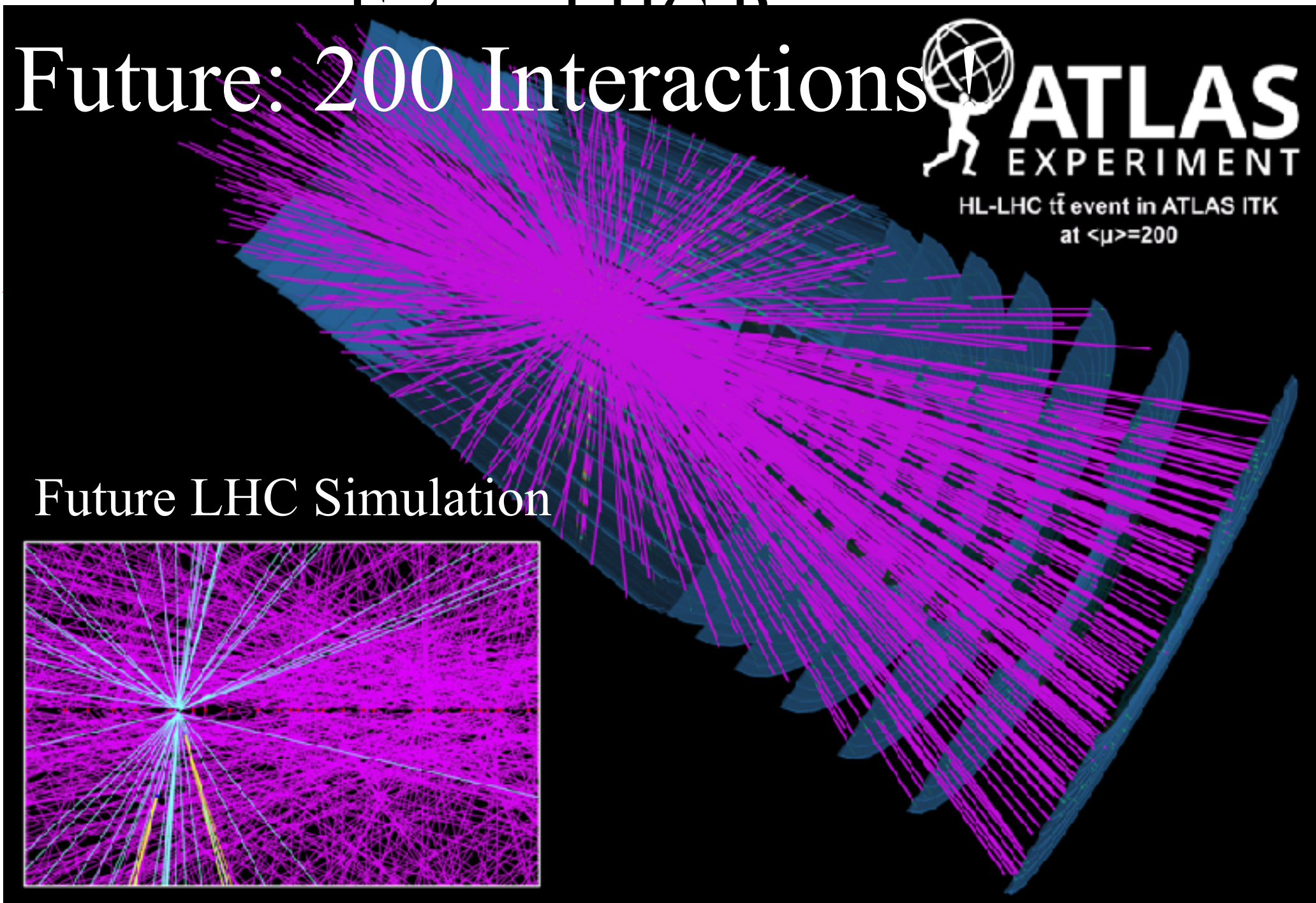


2010

Run I

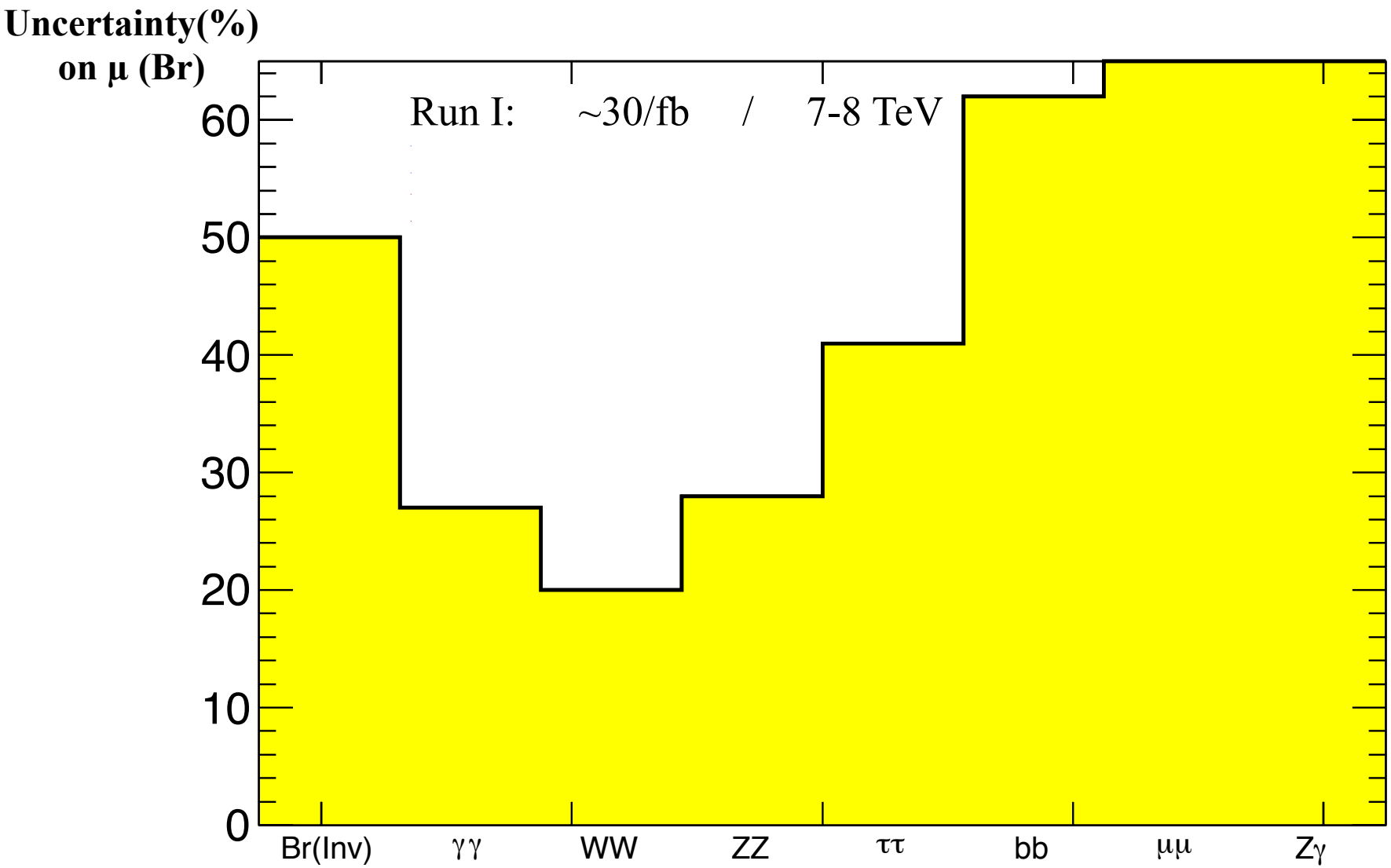
- 8 T
- 20/

Future: 200 Interactions!

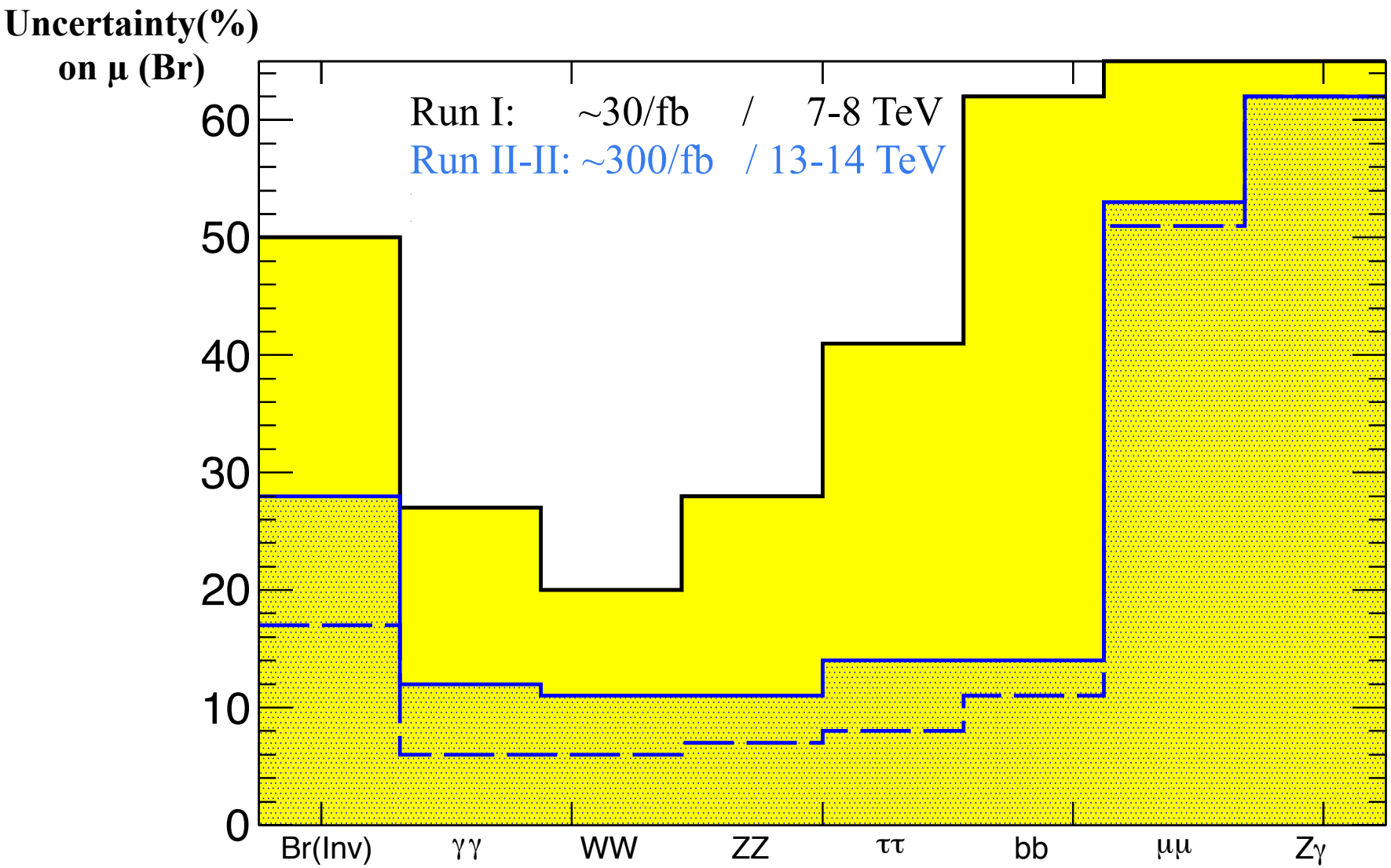


Future LHC Simulation

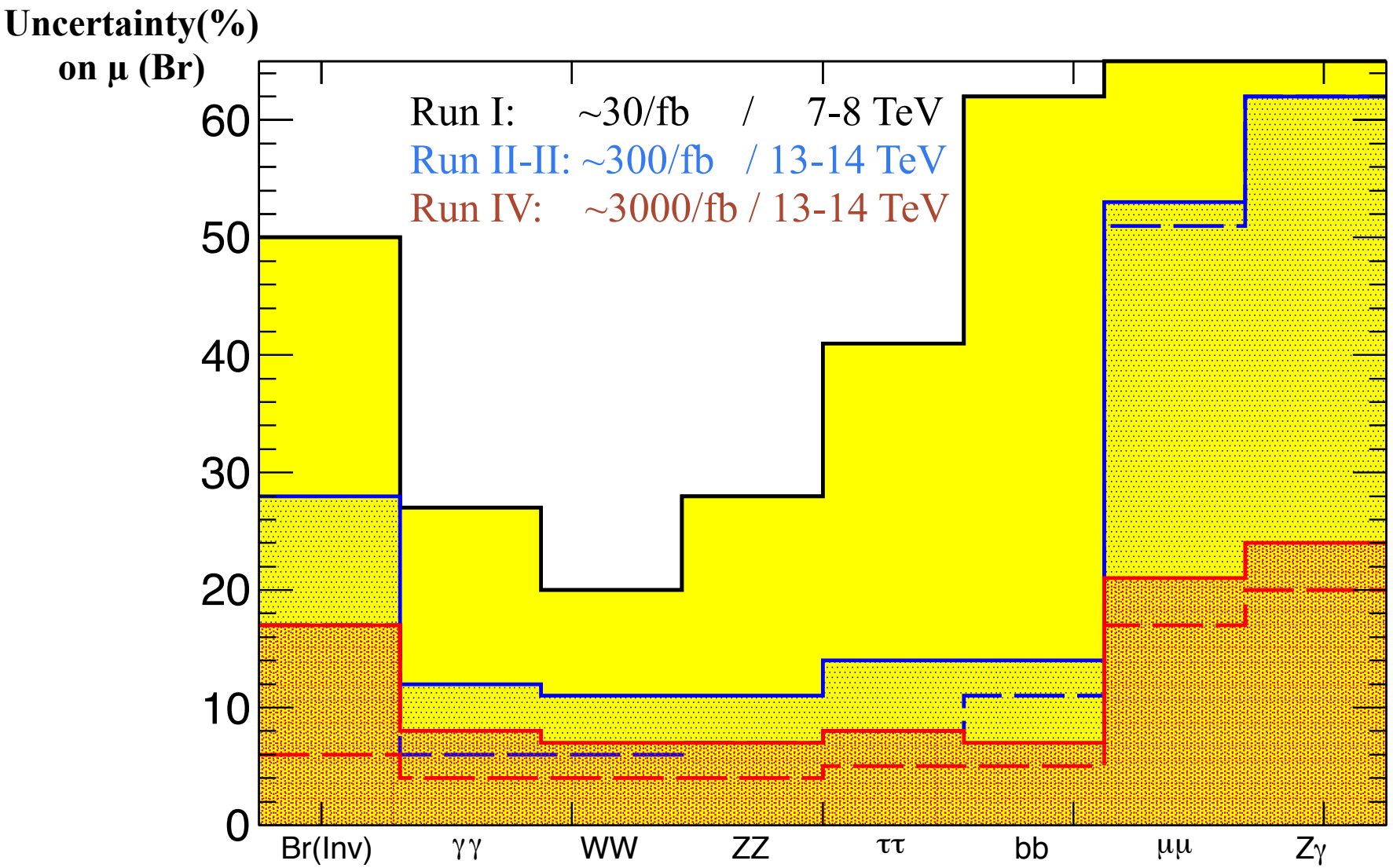
Higgs at the LHC



Higgs at the LHC

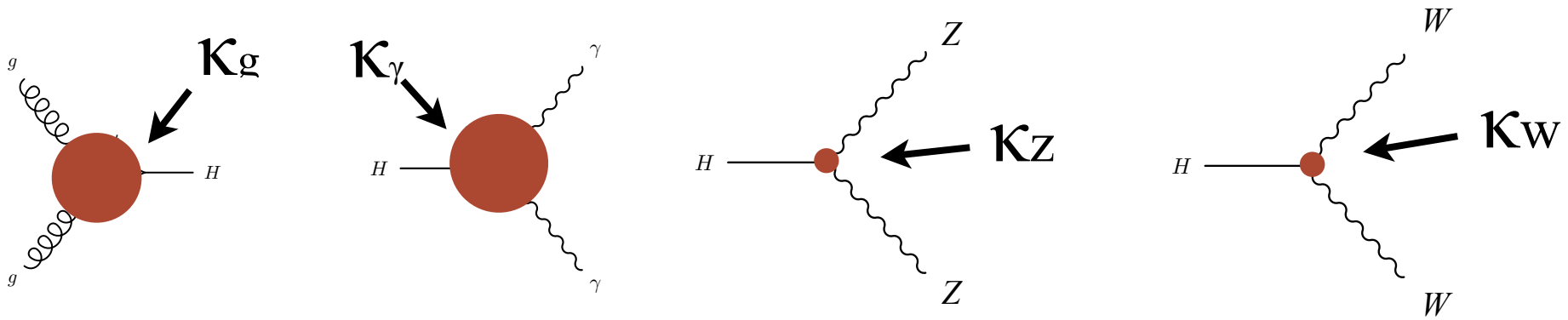


Higgs at the LHC



Benchmark Coupling Constraints

Sensitivity tested in model with 7 parameters

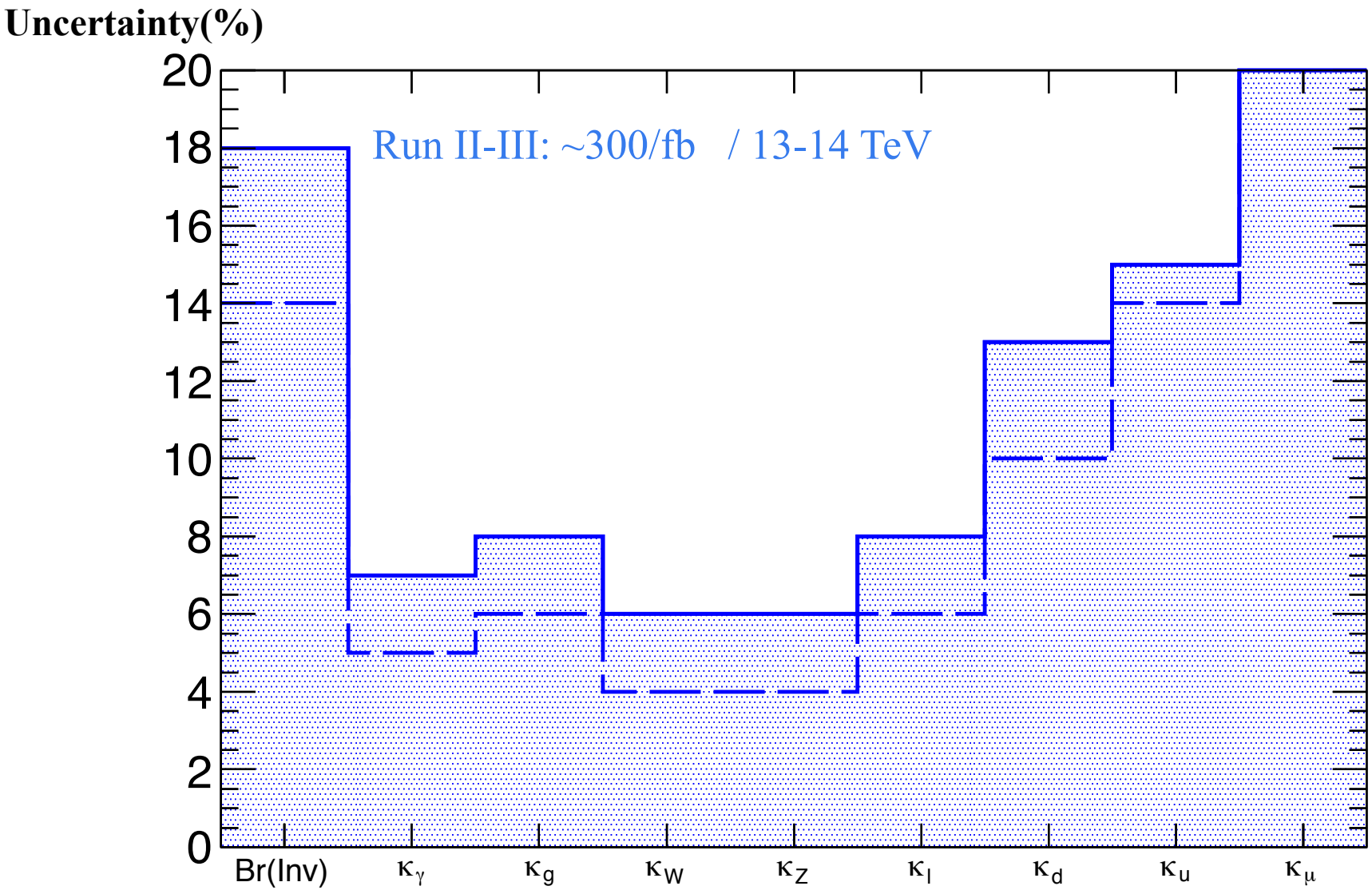


4 fermion couplings:

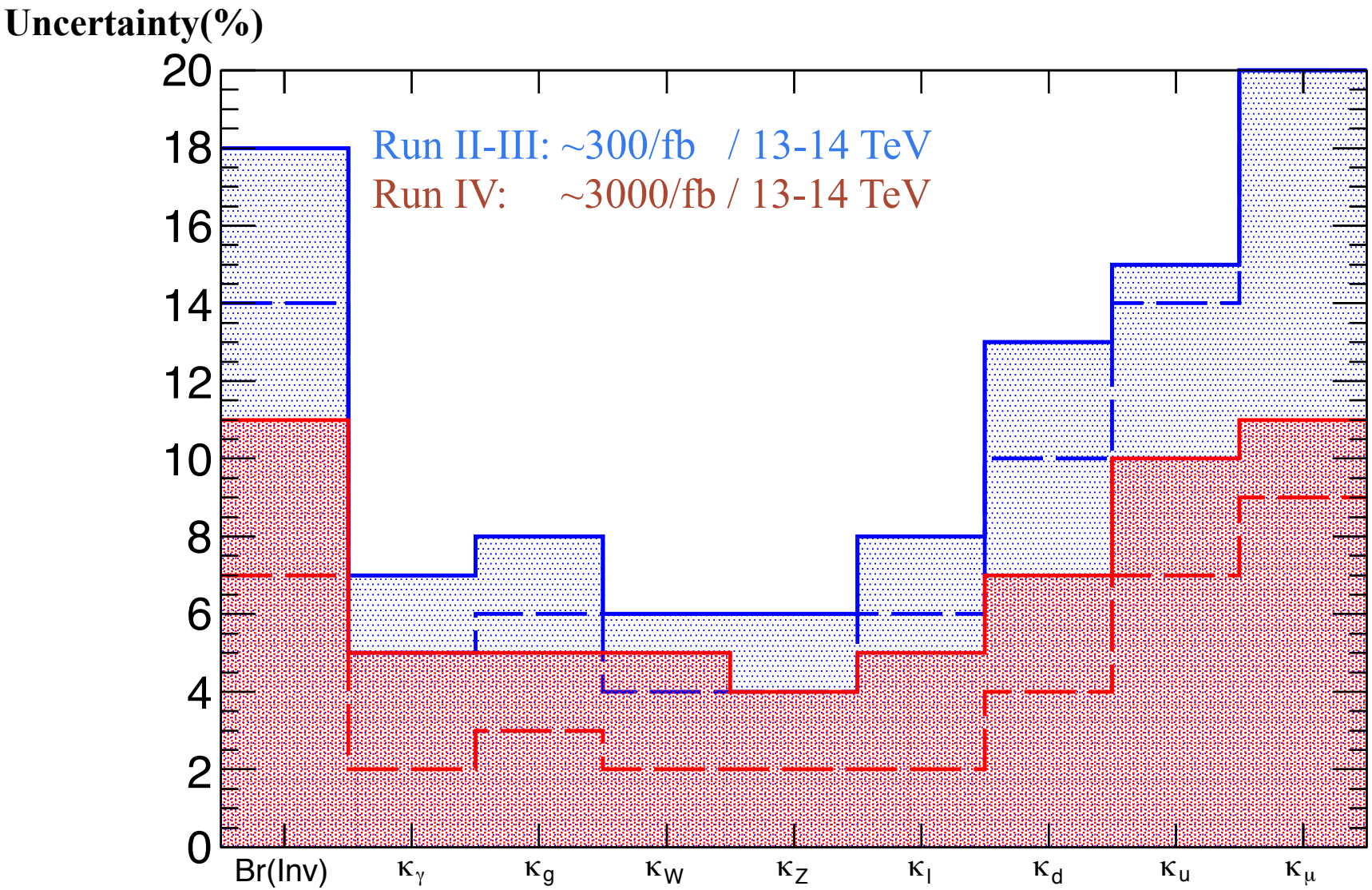
κ_τ / κ_μ / $\kappa_u \equiv \kappa_t = \kappa_c$ / $\kappa_d \equiv \kappa_b$

Allow for decays to new particles

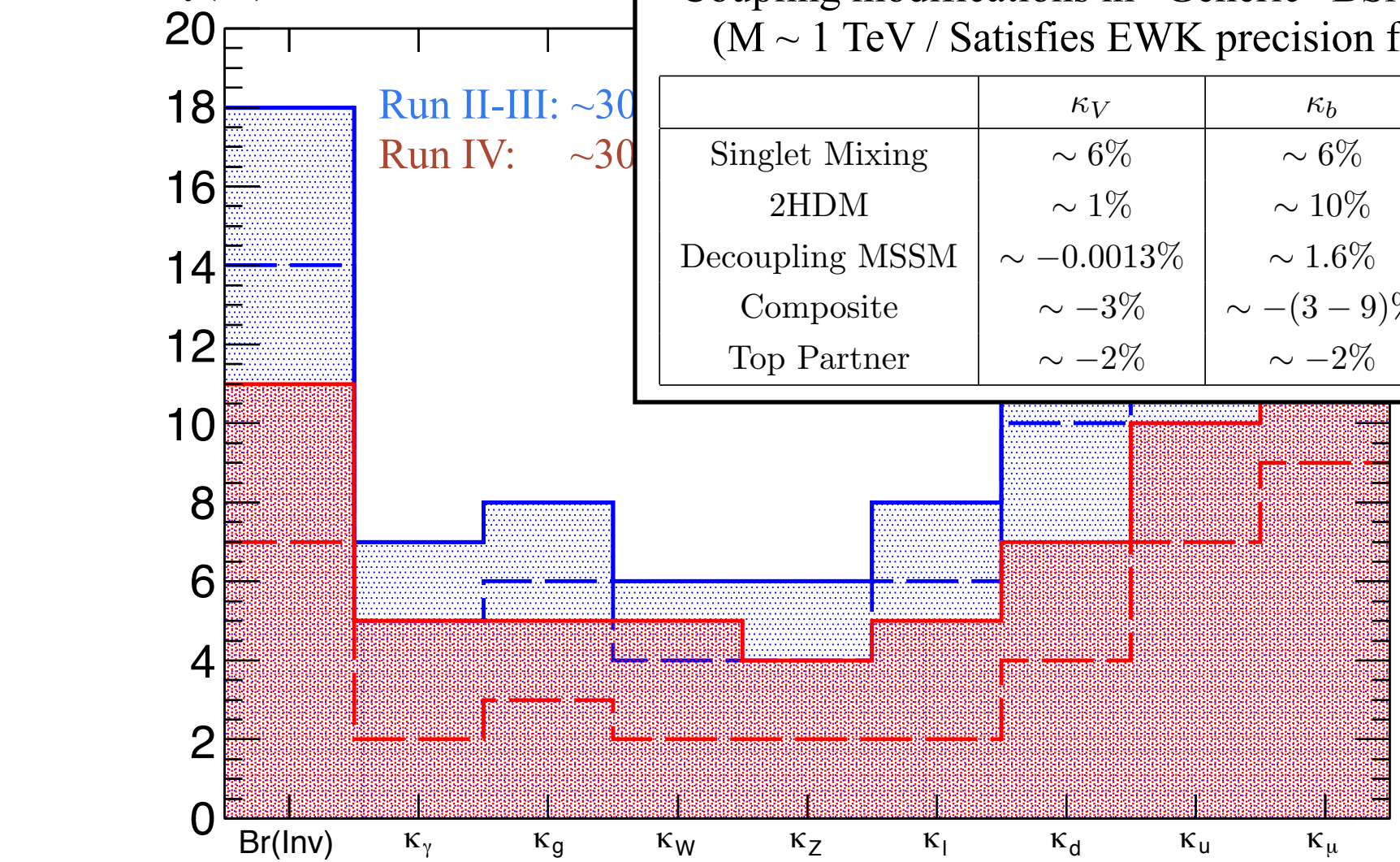
Higgs at the LHC



Higgs at the LHC



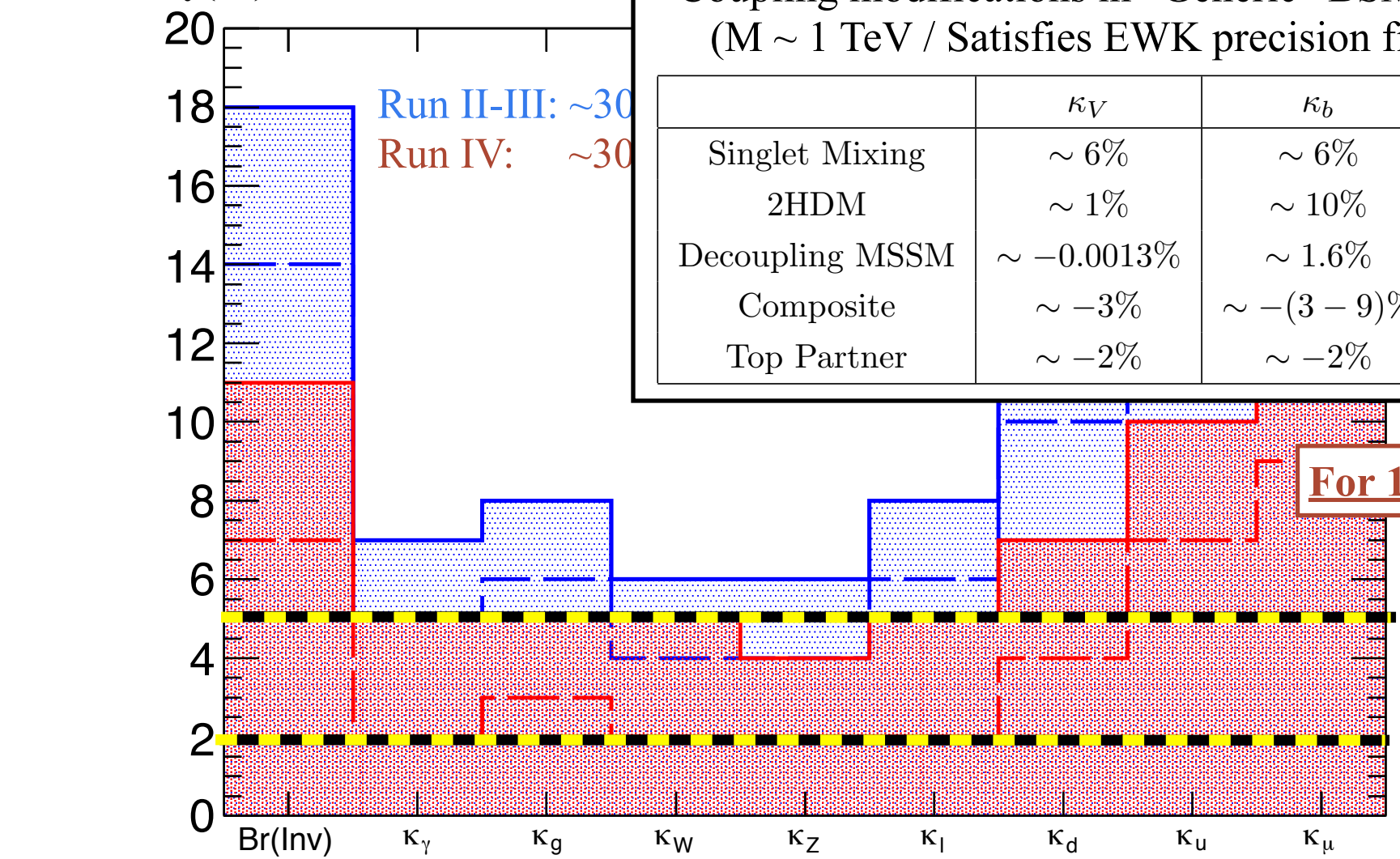
Higgs at the LHC



Coupling modifications in "Generic" BSM models
(M ~ 1 TeV / Satisfies EWK precision fits)

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

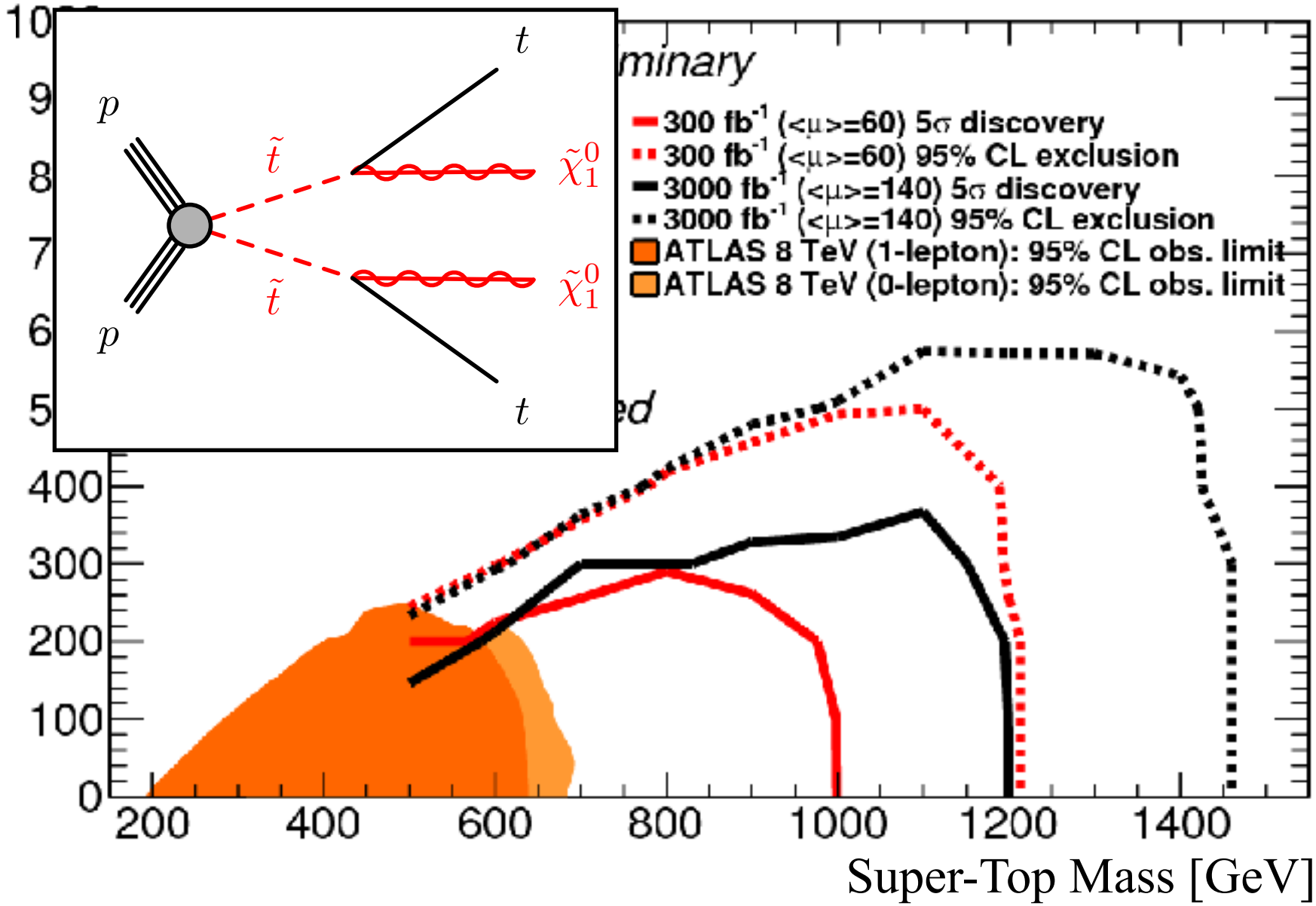
Higgs at the LHC



Coupling modifications in "Generic" BSM models
(M ~ 1 TeV / Satisfies EWK precision fits)

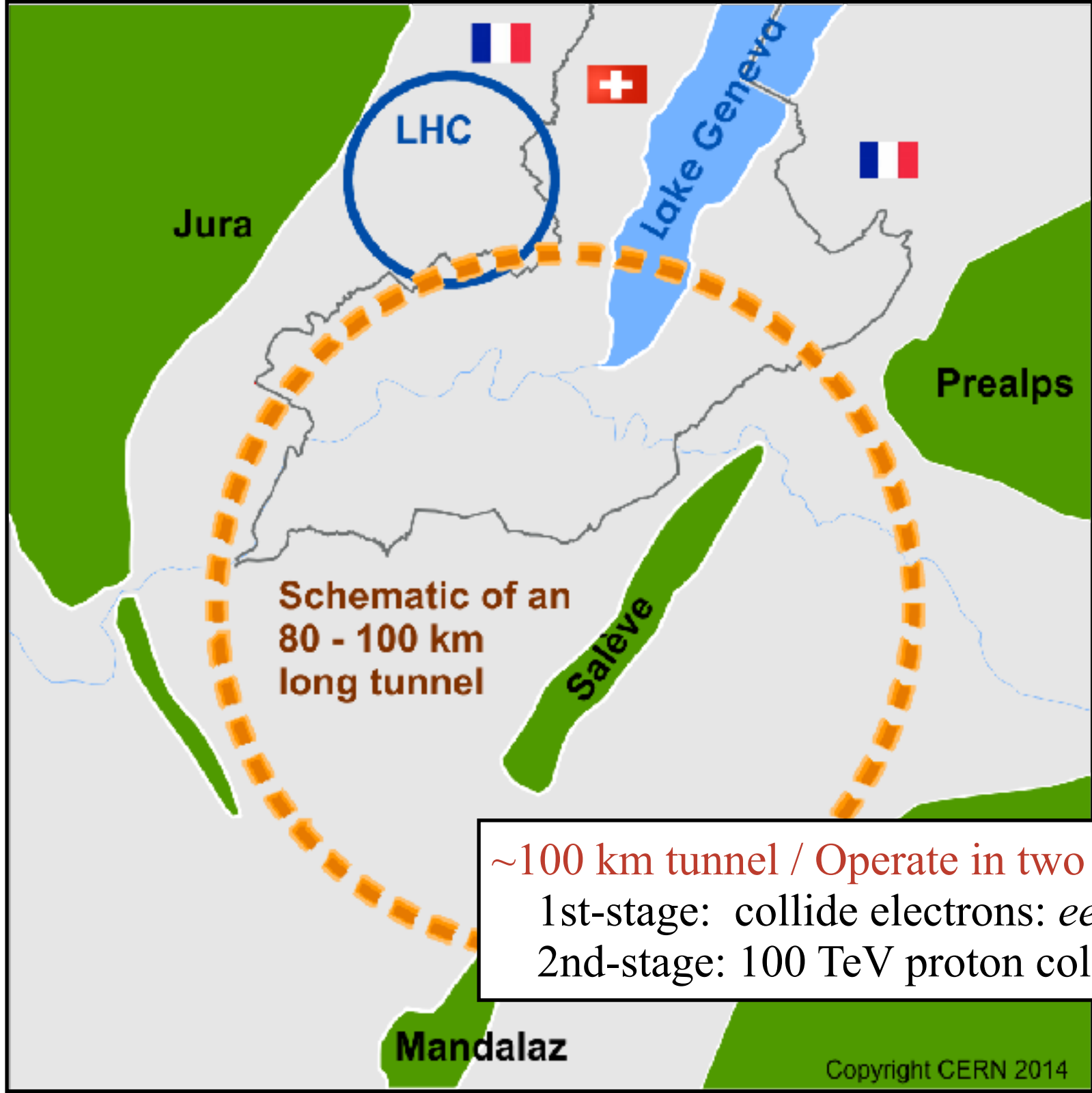
	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Direct search for Super Symmetry



Beyond the LHC

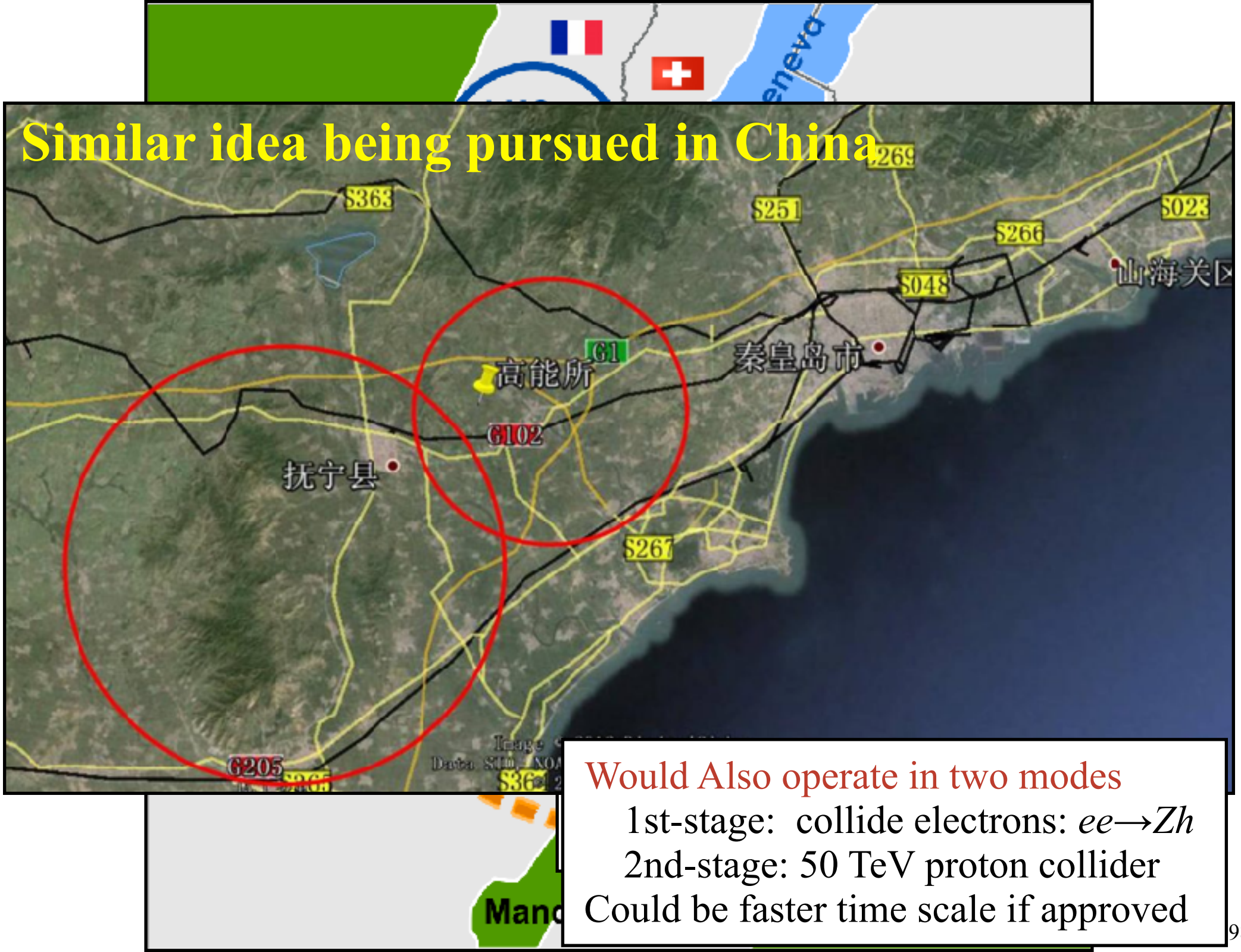
What we might know by 2055…



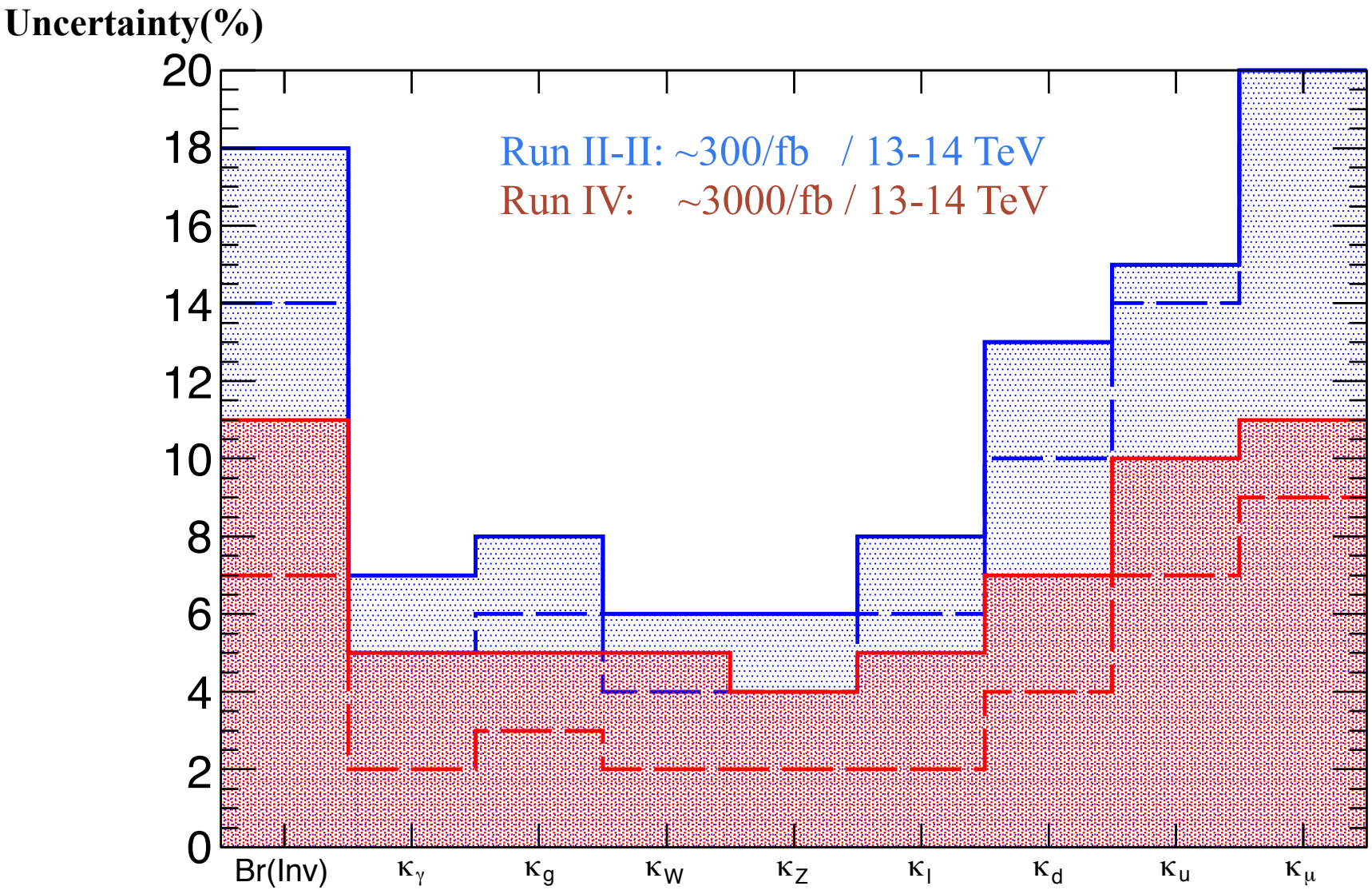
~100 km tunnel / Operate in two modes

1st-stage: collide electrons: $ee \rightarrow Zh$

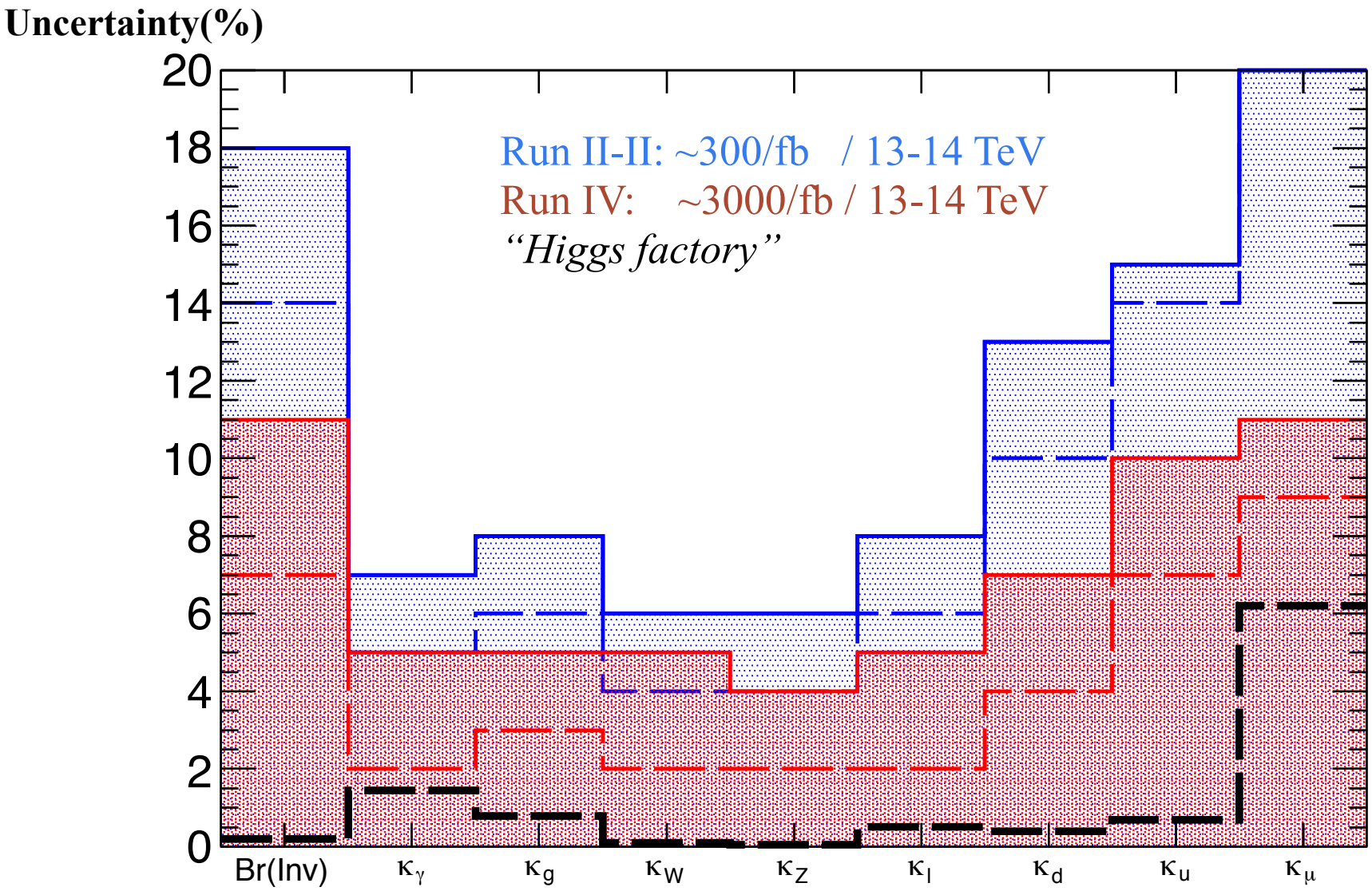
2nd-stage: 100 TeV proton collider


Similar idea being pursued in China
S363
S269
S251
S023
S266
S048
山海关区
秦皇岛市
高能所
G1
G102
抚宁县
S267
G205
Would Also operate in two modes
1st-stage: collide electrons: $ee \rightarrow Zh$
2nd-stage: 50 TeV proton collider
Could be faster time scale if approved

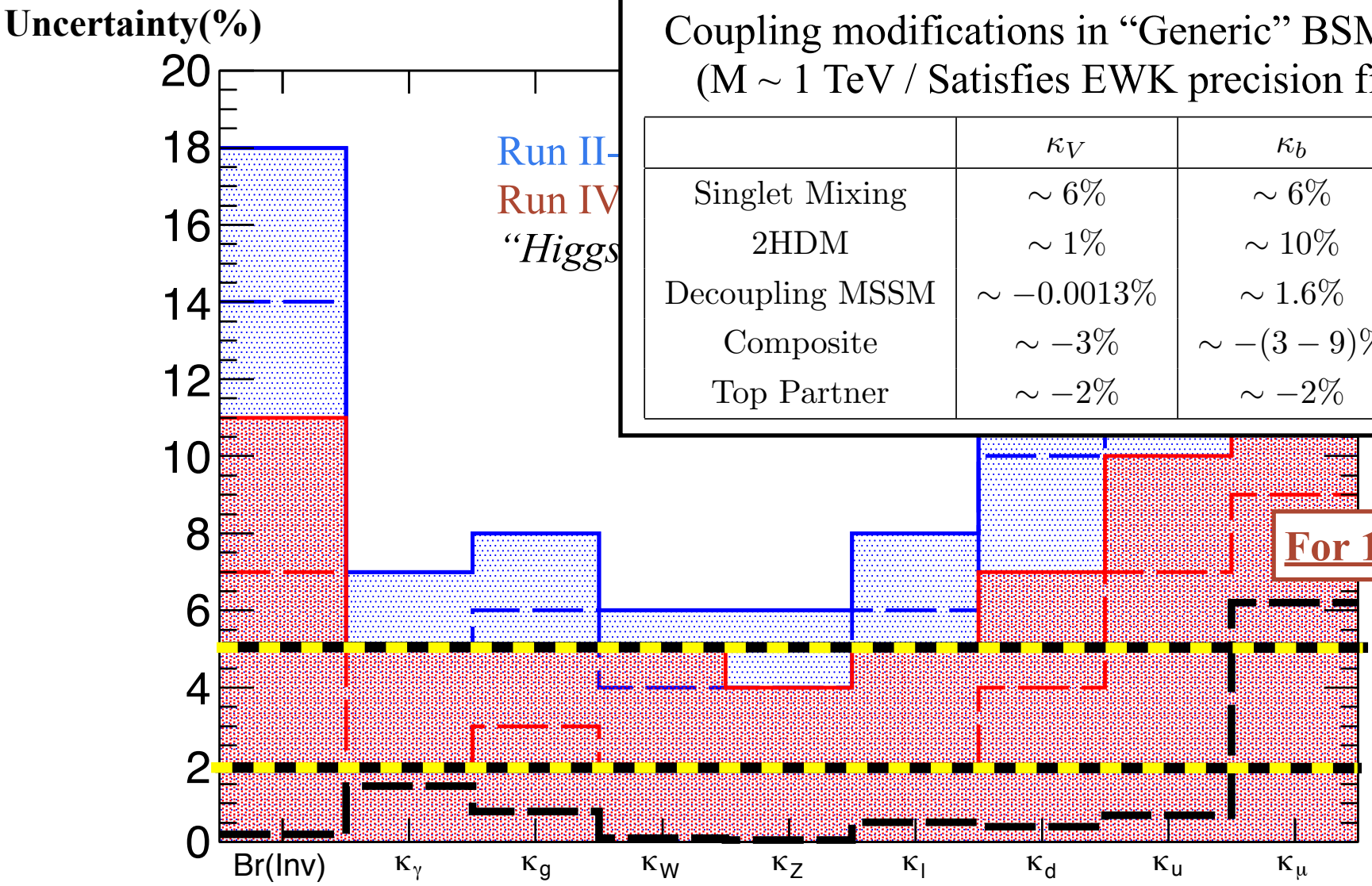
Beyond the LHC



Beyond the LHC



Beyond the LHC



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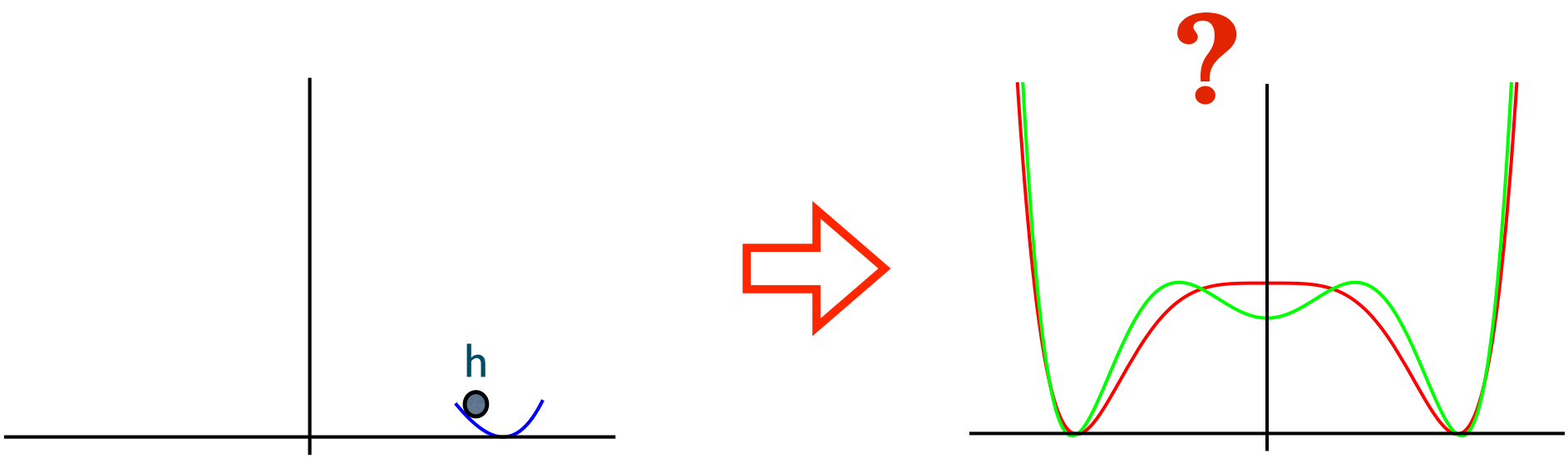
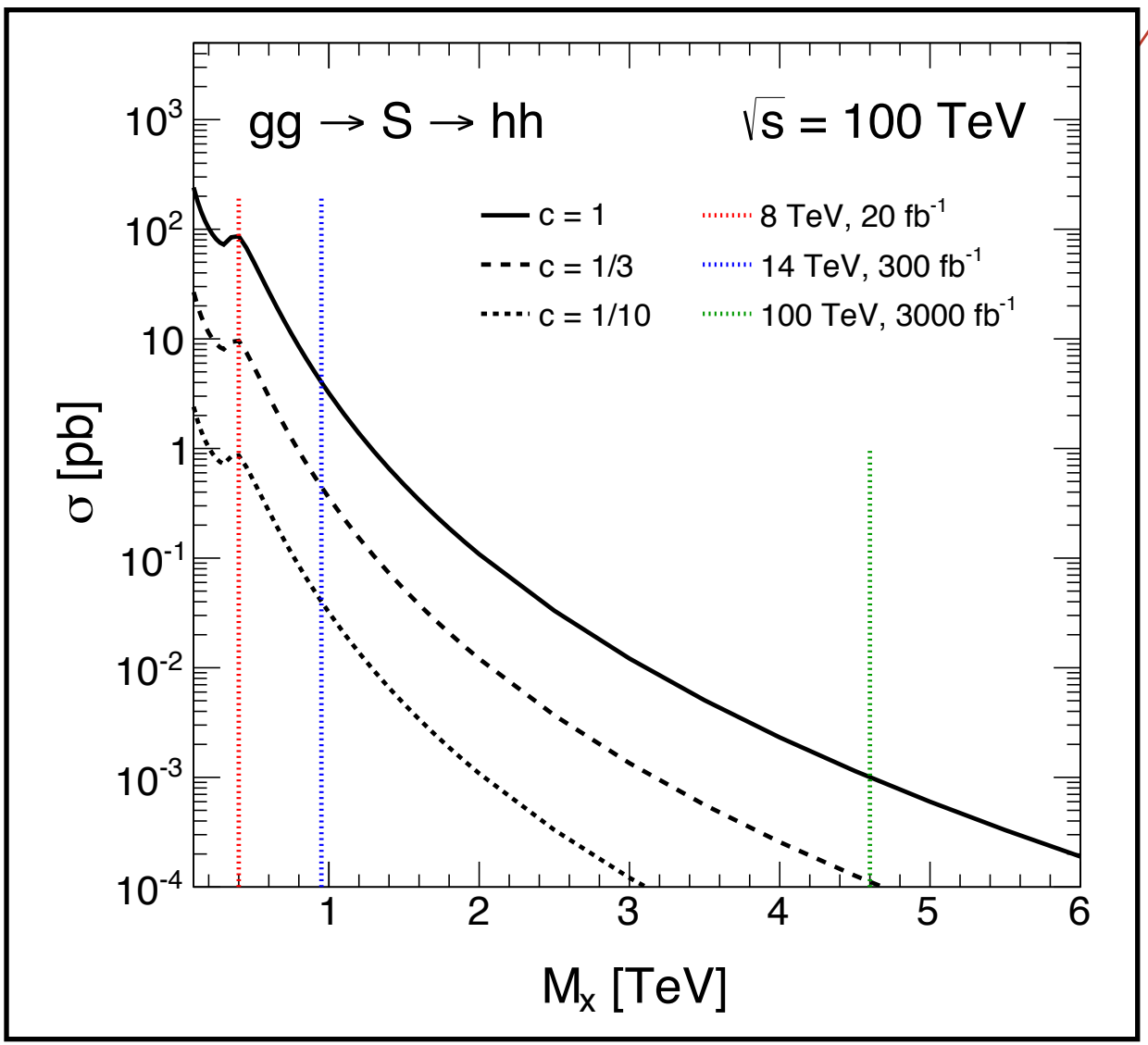
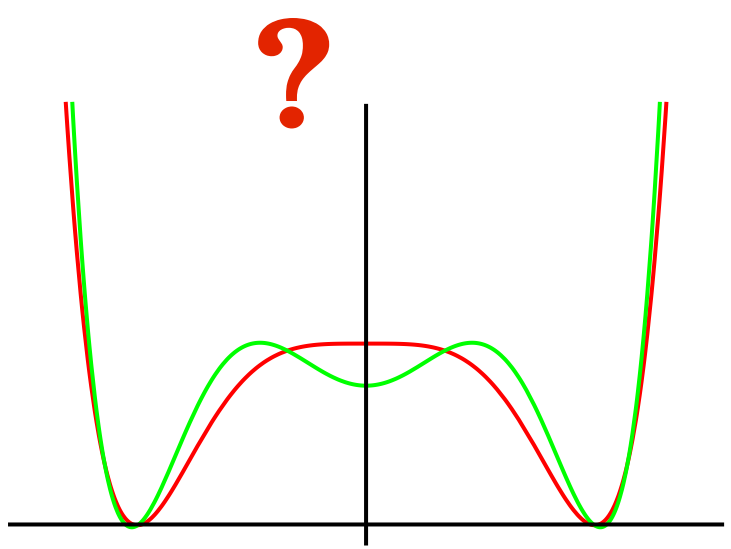
100 TeV proton collider

Measure Higgs self-coupling to ~10%

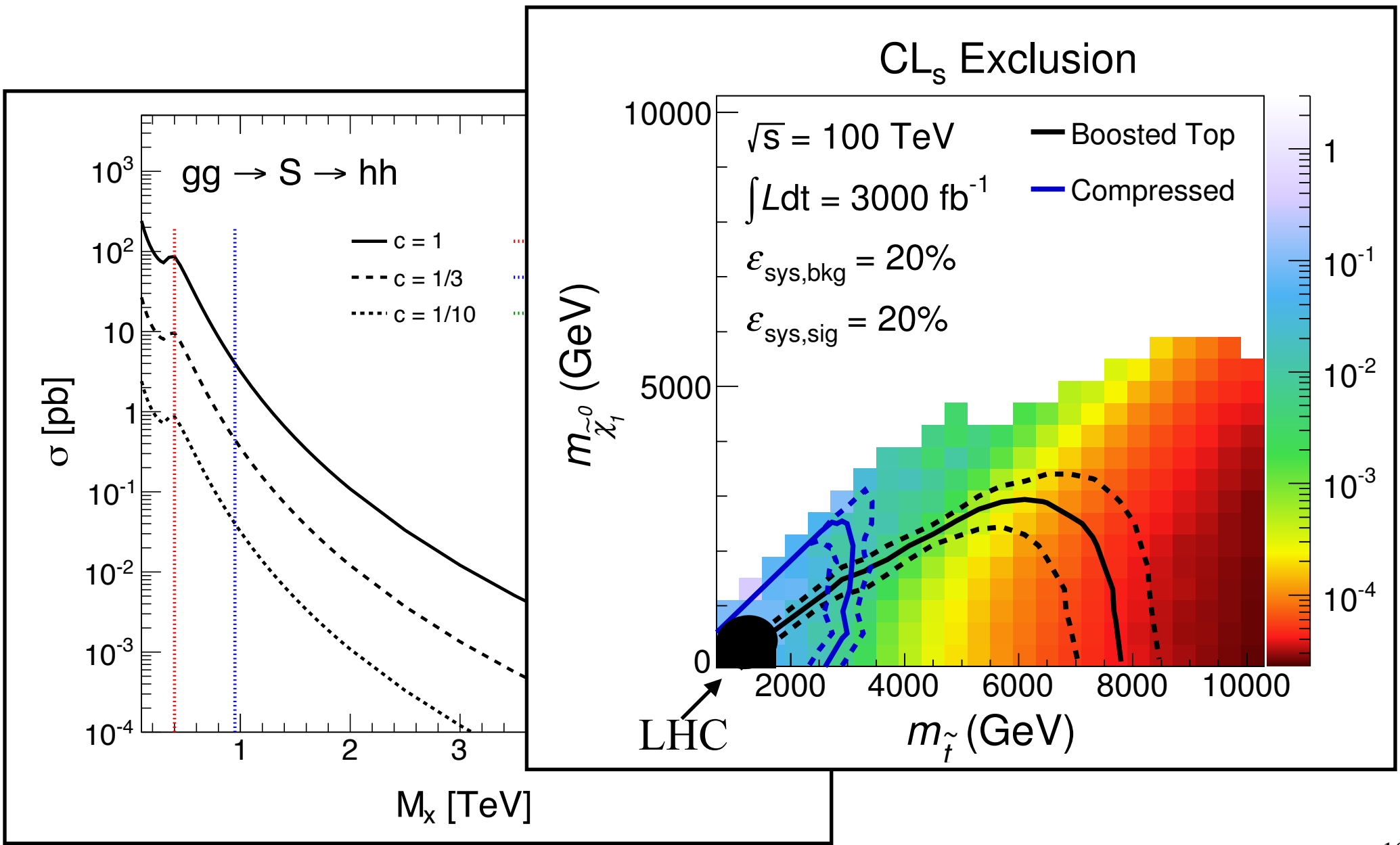


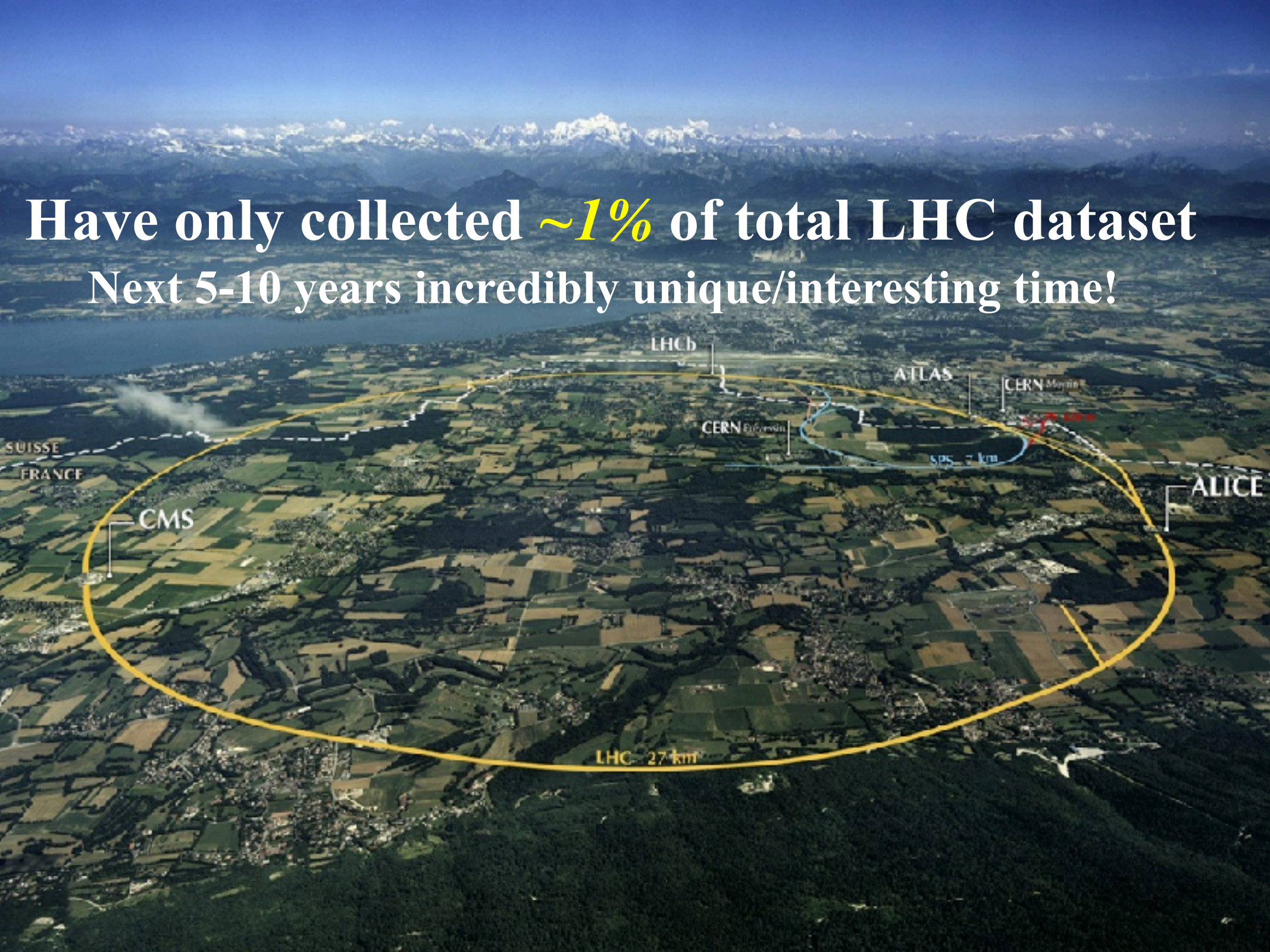
100 TeV proton collider

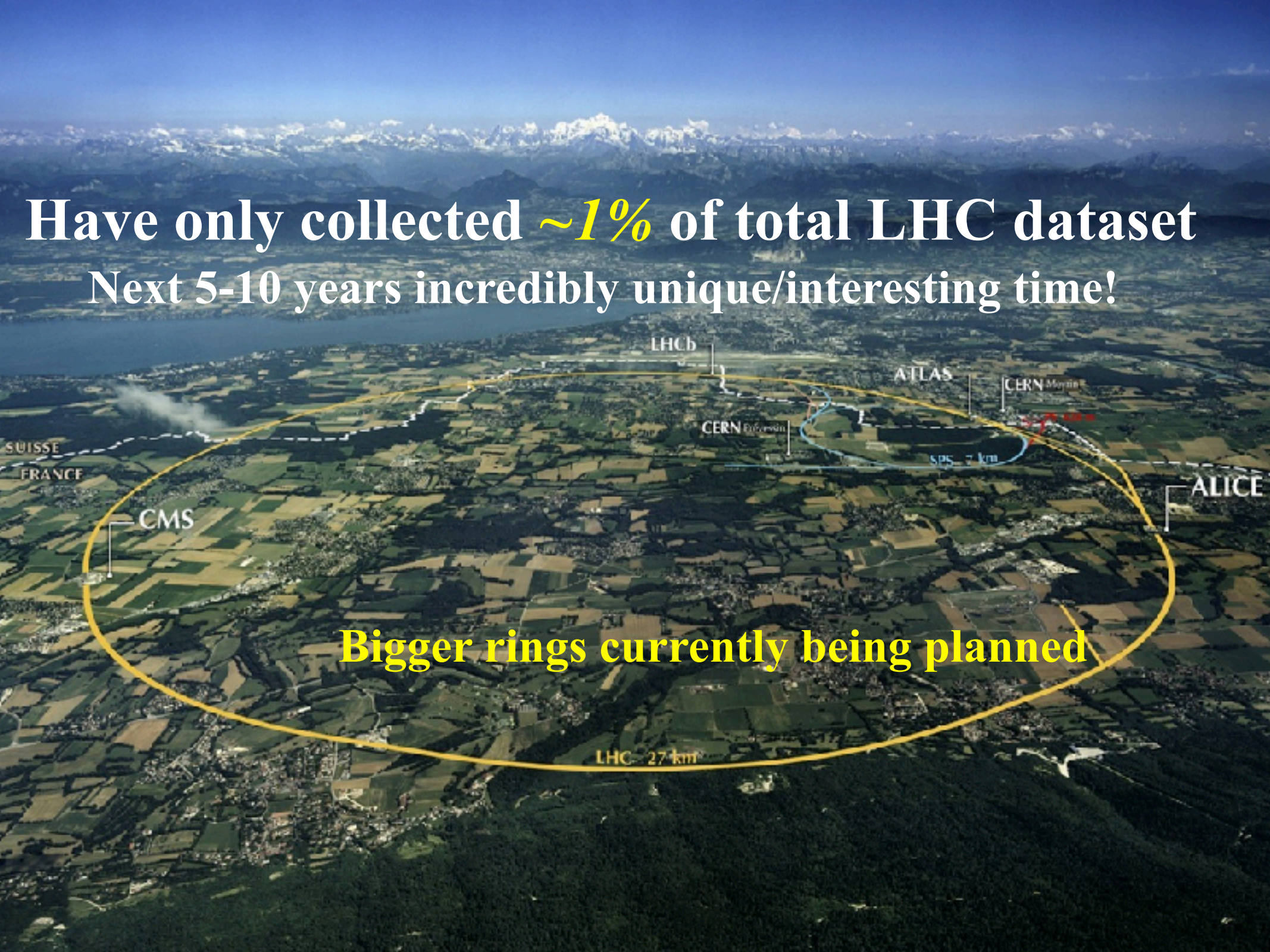




100 TeV proton collider




Have only collected ~1% of total LHC dataset
Next 5-10 years incredibly unique/interesting time!
LHCb
ATLAS
CERN Meyrin
CERN
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km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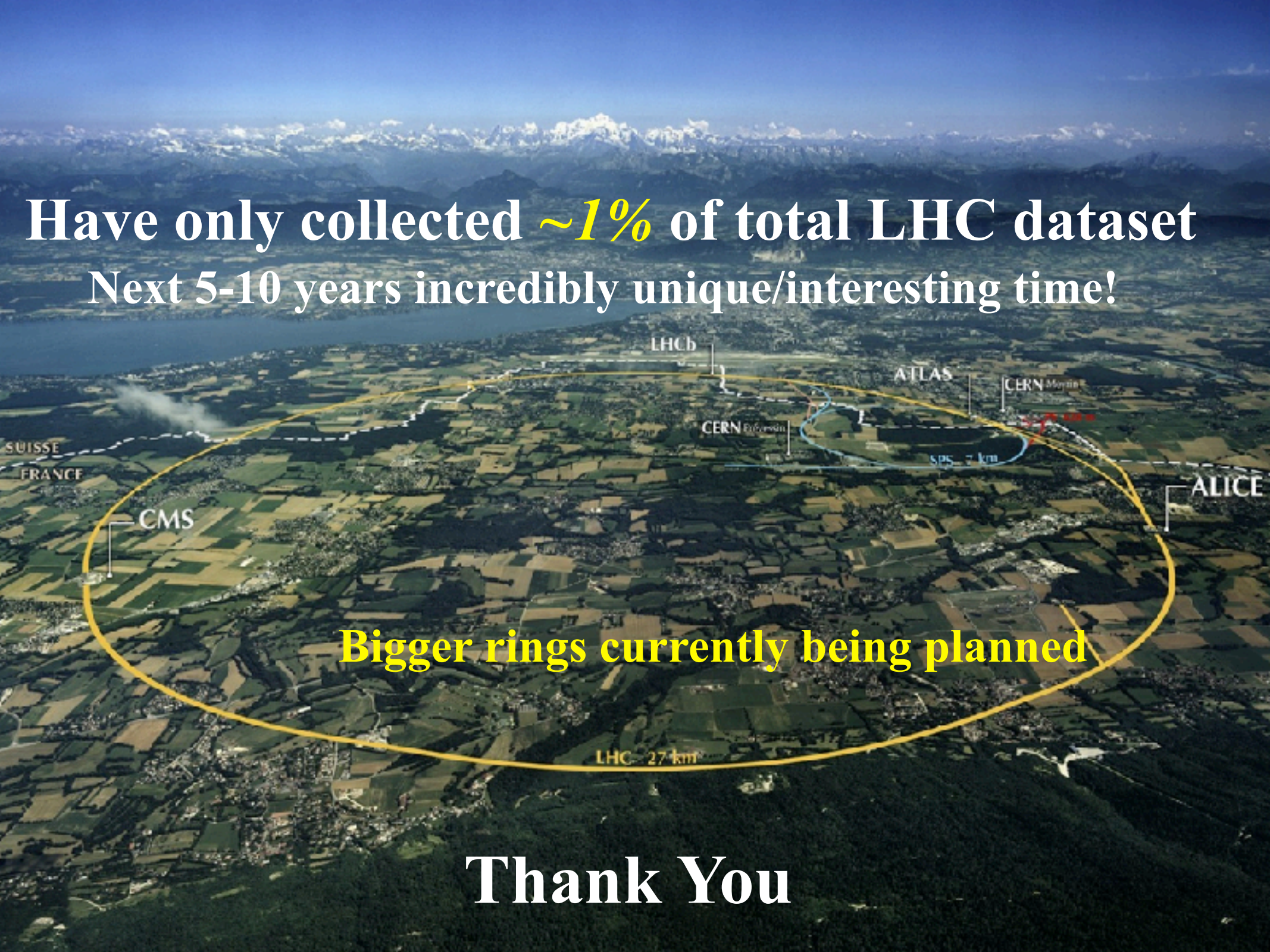
Bigger rings currently being planned
LHC 27 km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Thank You