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

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*University of Chicago*

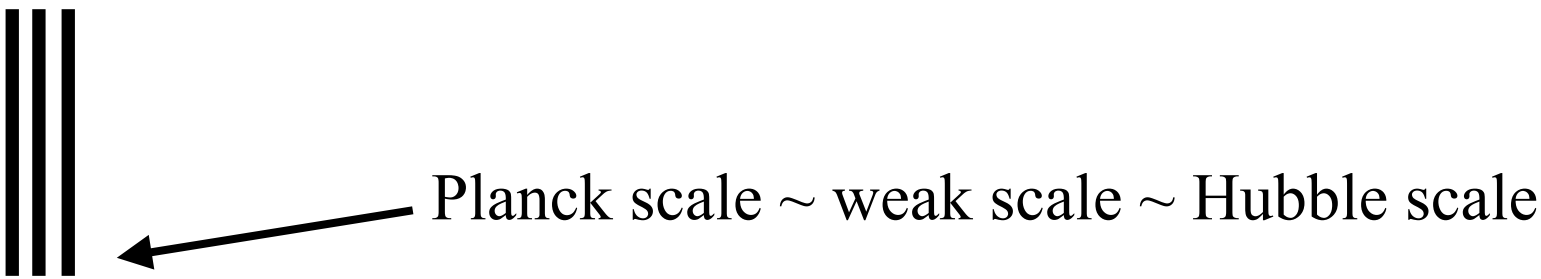
**http://hep.uchicago.edu/~johnda/ComptonLectures.html**

# Lecture Outline

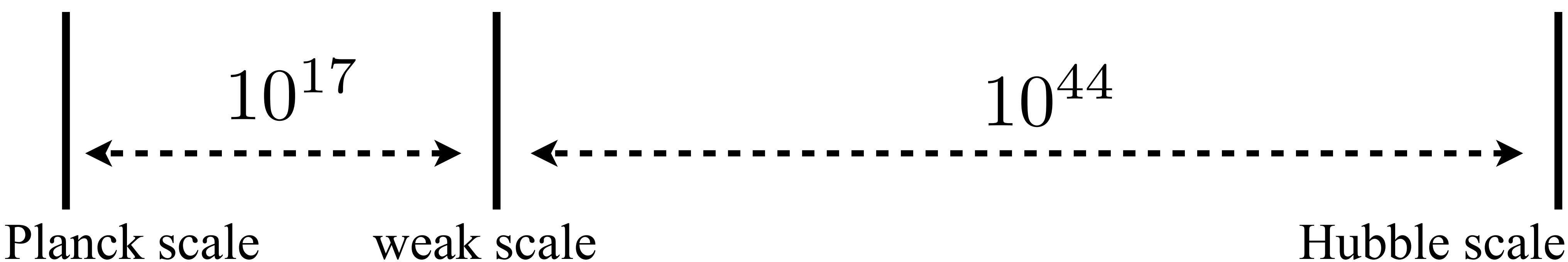
| | |
|---|---|
| **April 1st:** | **Newton's dream & 20th Century Revolution** |
| **April 8th:** | **Mission Barely Possible: QM + SR** |
| **April 15th:** | **The Standard Model** |
| **April 22nd:** | **Importance of the Higgs** |
| **April 29th:** | **Guest Lecture** |
| **May 6th:** | **The Cannon 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:




We observe:




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

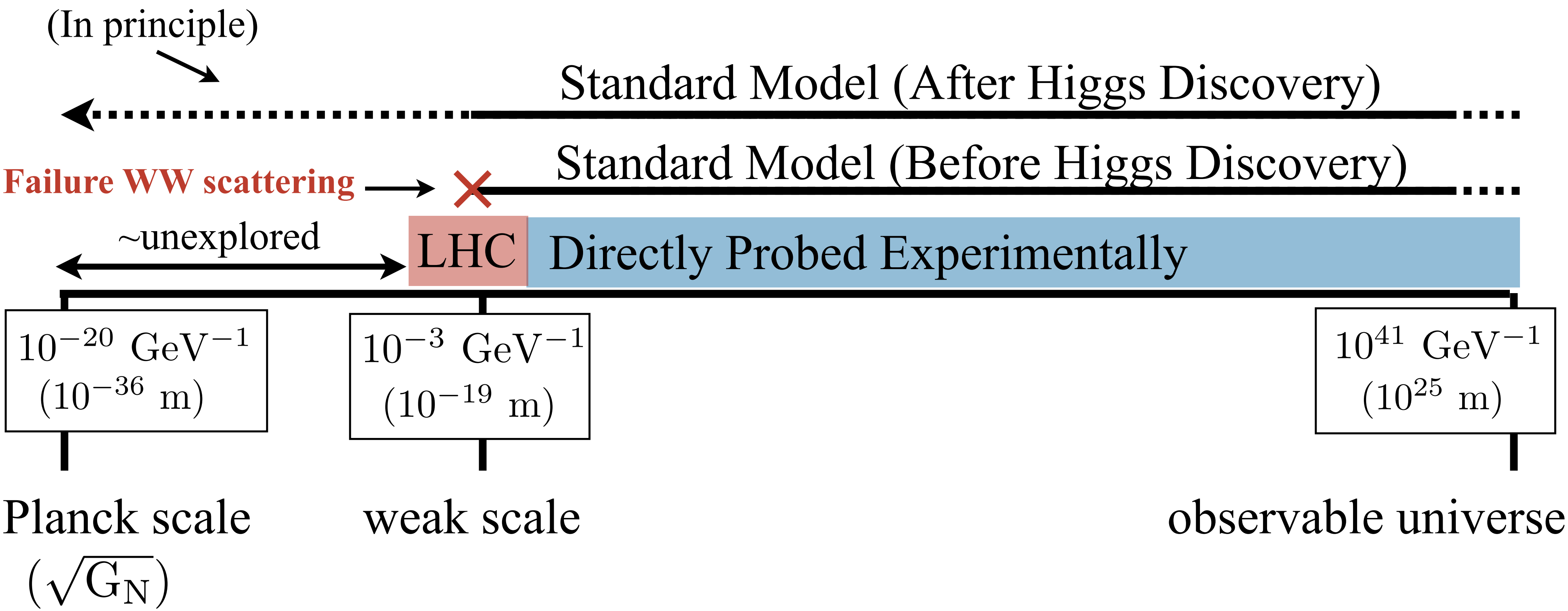
***Need modifications QM or Space-time to avoid fine tuning***

# Today's Lecture

Going beyond the Higgs Discovery:

*What comes next ?*

# Focus: Problem associated w/weak scale




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

(In principle)

**Failur**

$10^{-2}$

(10

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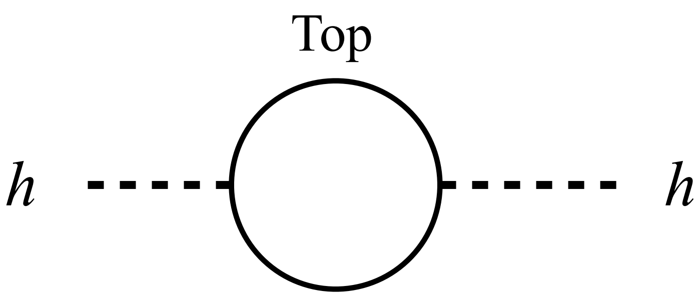
*Reminder*: Vacuum fluctuations of Higgs mass ($m_H^2$)




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

Very different type problem than we discussed before:

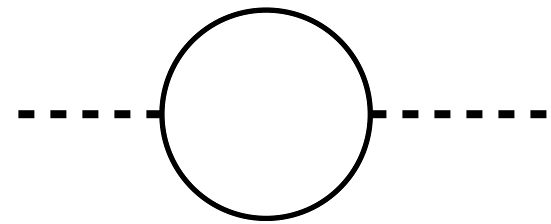
*"Naturalness" Problem:*

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

Un-like situation before Higgs where theory broke down

*P(ωω→ωω) > 1 / Inconsistent mass description*

# What scale do we need Modification?

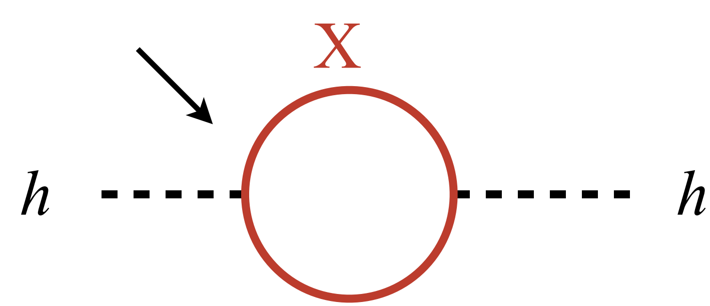
$m_H^2 \quad = $  $\quad + \quad$ 

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

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

**new particle** $\qquad m_X \sim 1000$ GeV

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

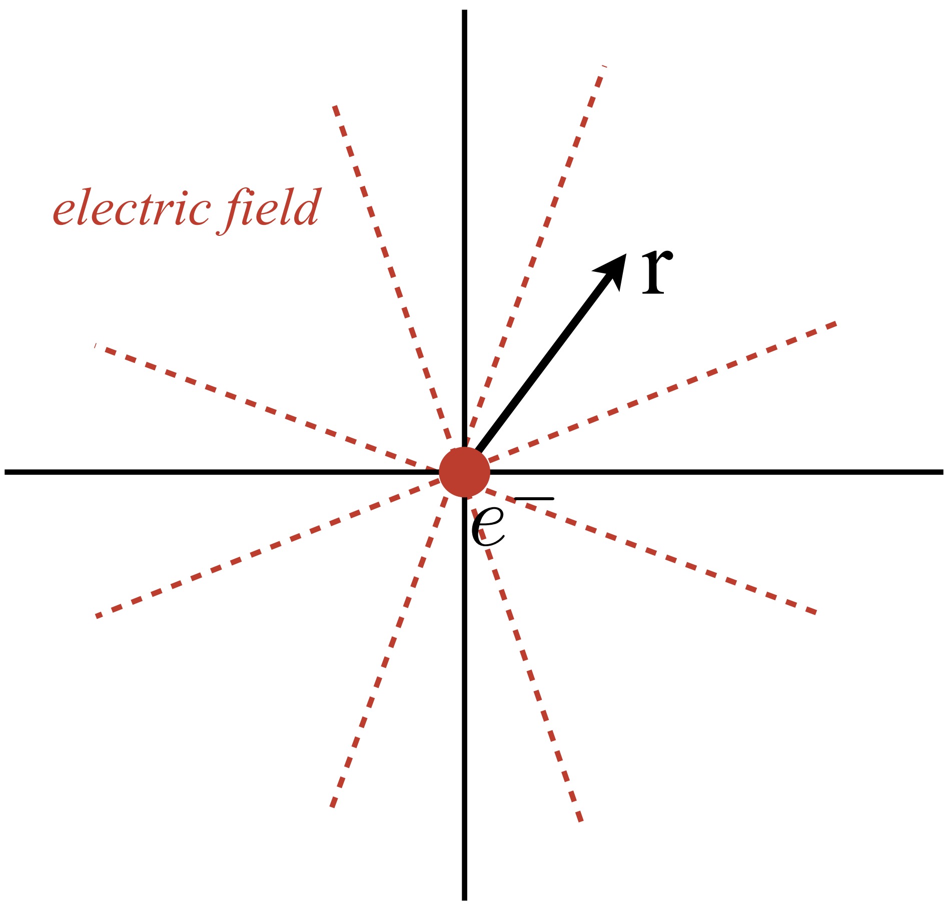



*(Pencil metaphor: analogous to the pencil glue/string)*

# 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




$$E \sim \frac{\alpha}{r} \sim \frac{\alpha}{\Lambda}$$

*Naively seems infinite*

Energy of electron at rest: ~ $m_e$

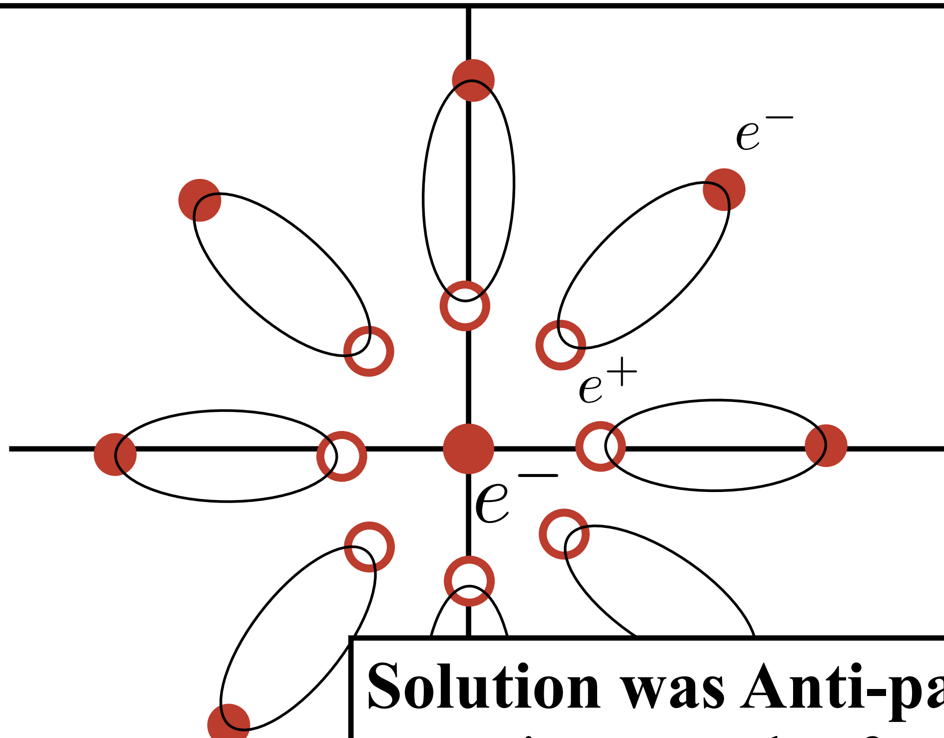
Introduce cut off

Need $\Lambda \geq \alpha/E$ to avoid fine tuning

# Naturalness Problems in History

Same type of problems have occurred before in history of physics

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



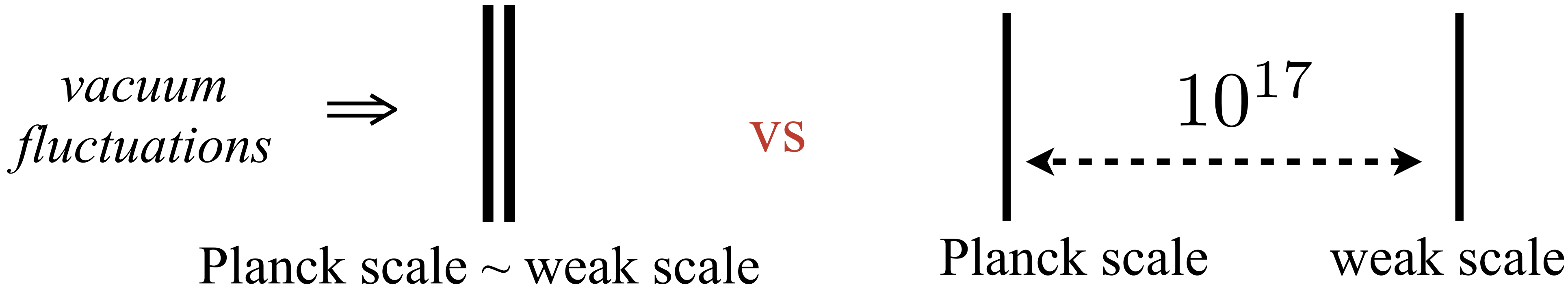

***Exactly what happens !***

At scale $\Lambda$~1/me start seeing particle-anti-particle cloud

**Solution was Anti-particles :**

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

# Potential Solutions




“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

Extra dimensions

Planck scale is really at the weak scale

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

Supersymmetry

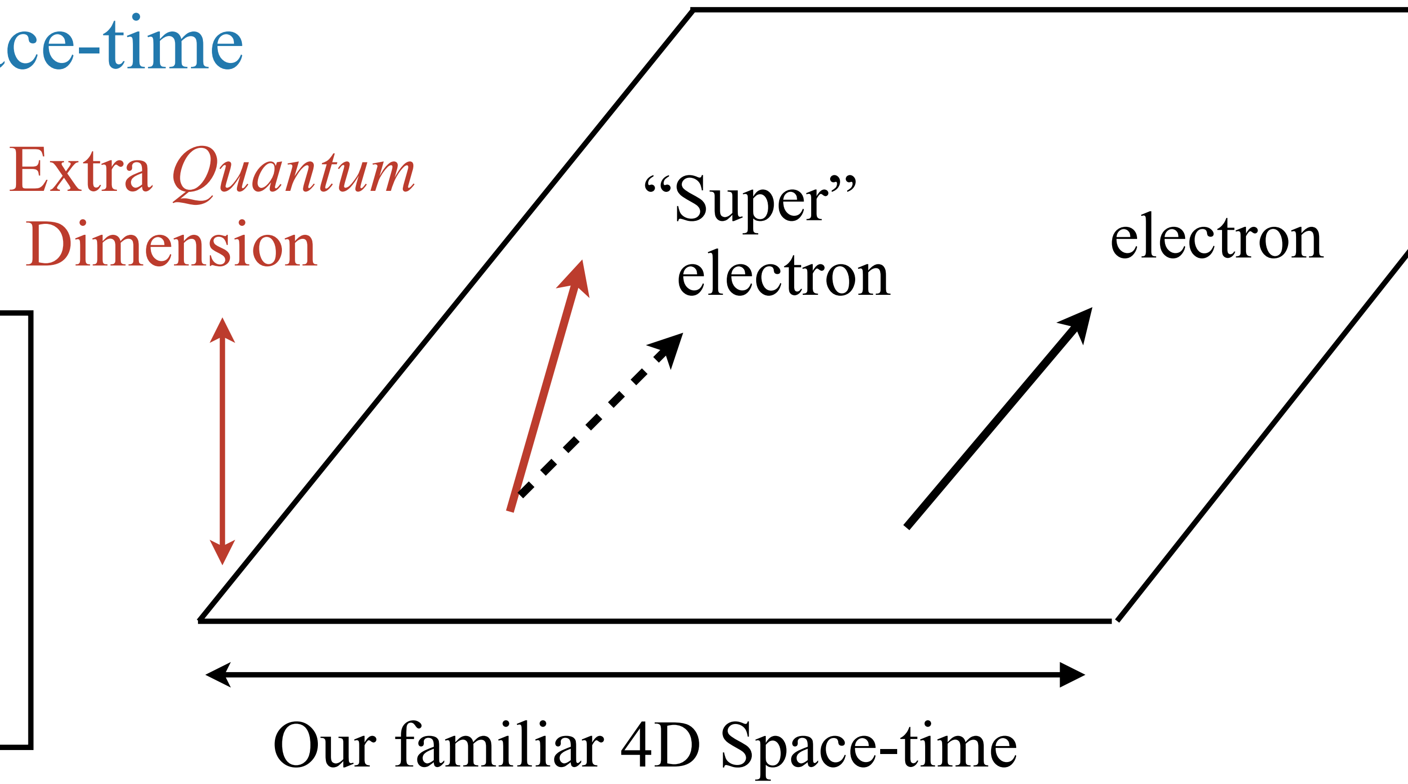
***Go through example of how works in detail***

***Has been a favorite within the field***

Vacuum corrections suppressed below weak scale

# Super Symmetry

## Modification of Space-time




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

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

<u>Doubles number of particles:</u>

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

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

# Super Symmetry

## Modification of Space-time

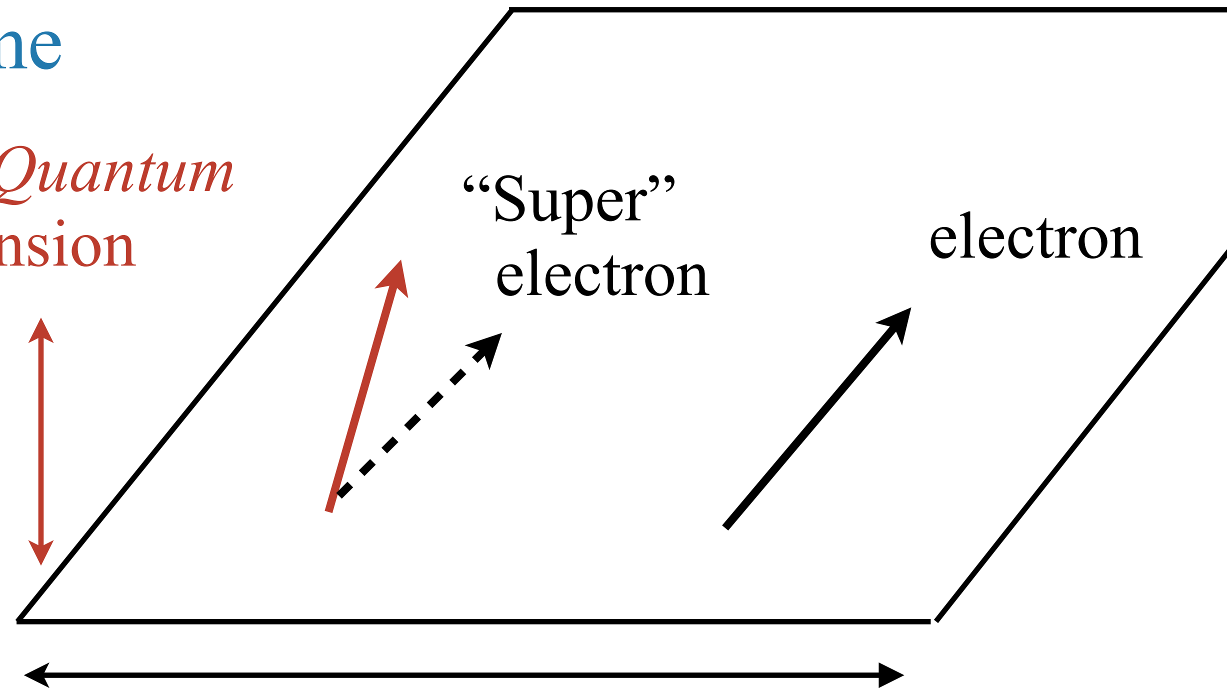
Extra *Quantum* Dimension

Distance measured in "quantum" numbers:

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

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

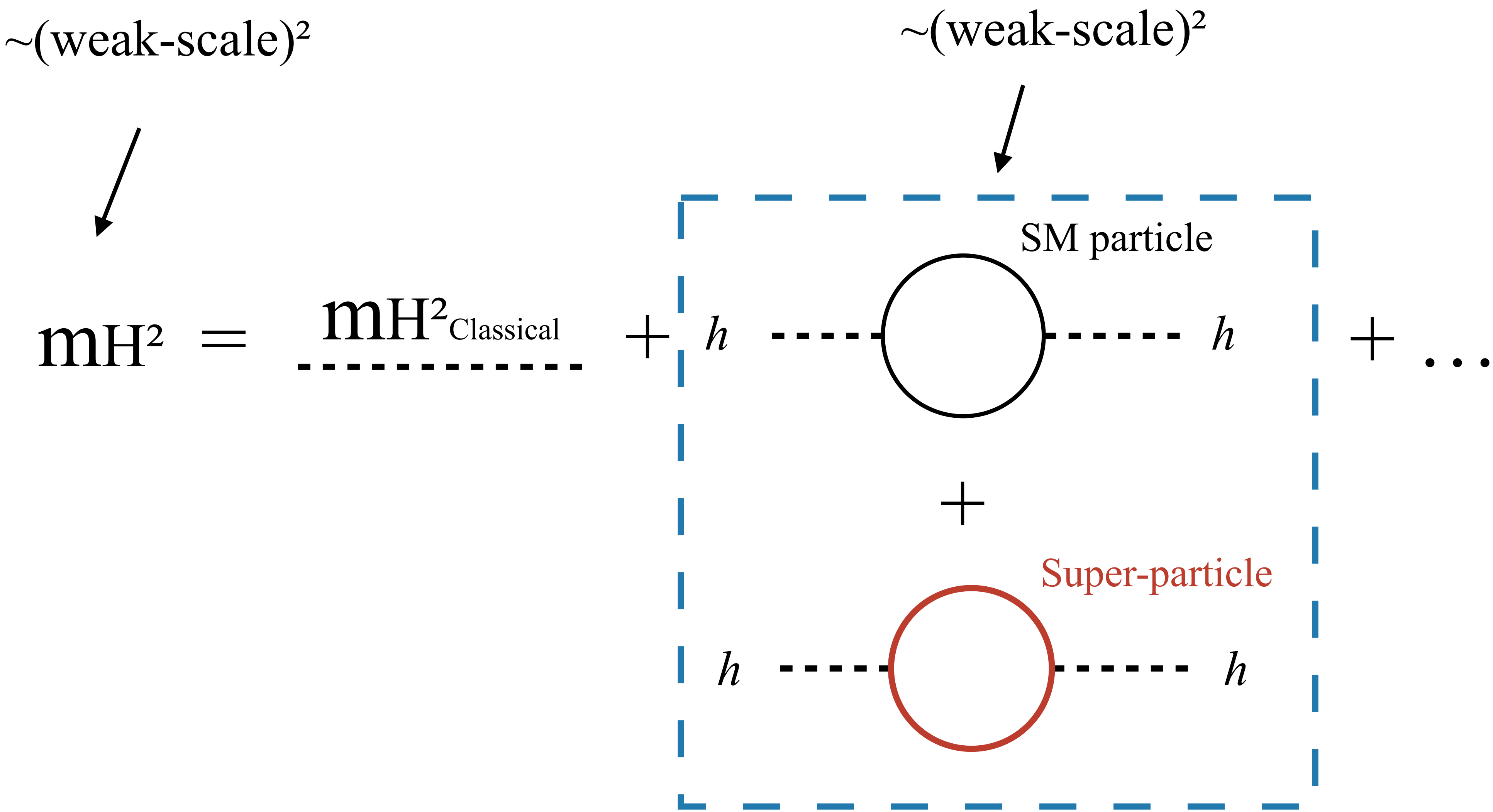
Can only take one step



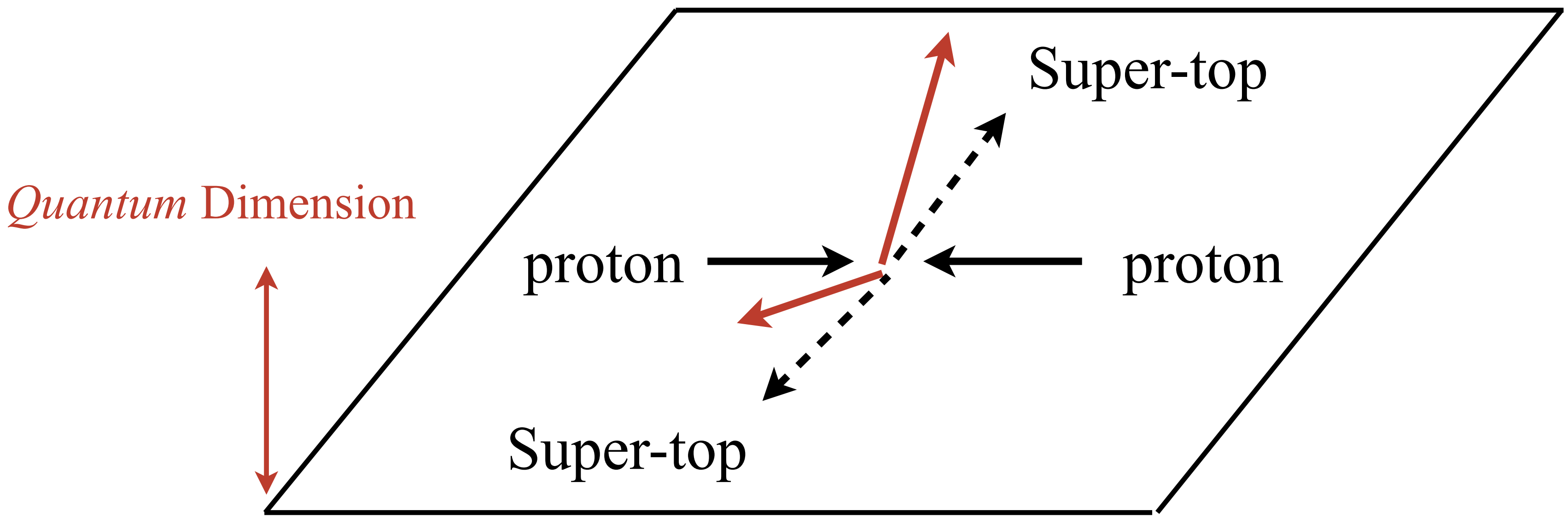

- Havent seen super-partners
- Could be another example of long-distance illusion:
  *eg: difference between forces*
- Idea: going to short enough distances start seeing symmetry
- To avoid fine-tuning needs to happen around weak scale

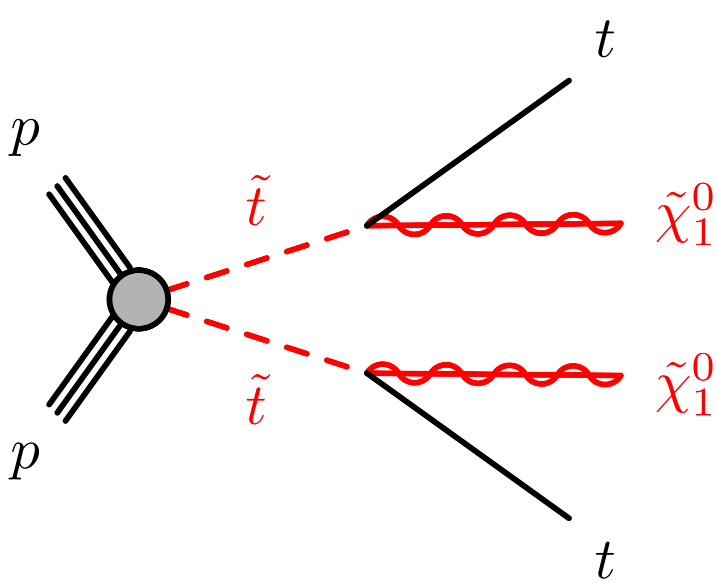
All regular rules of QFT apply / Symmetry relating particles/Super particles

# How Does This Help ?



# Super Symmetry at the LHC

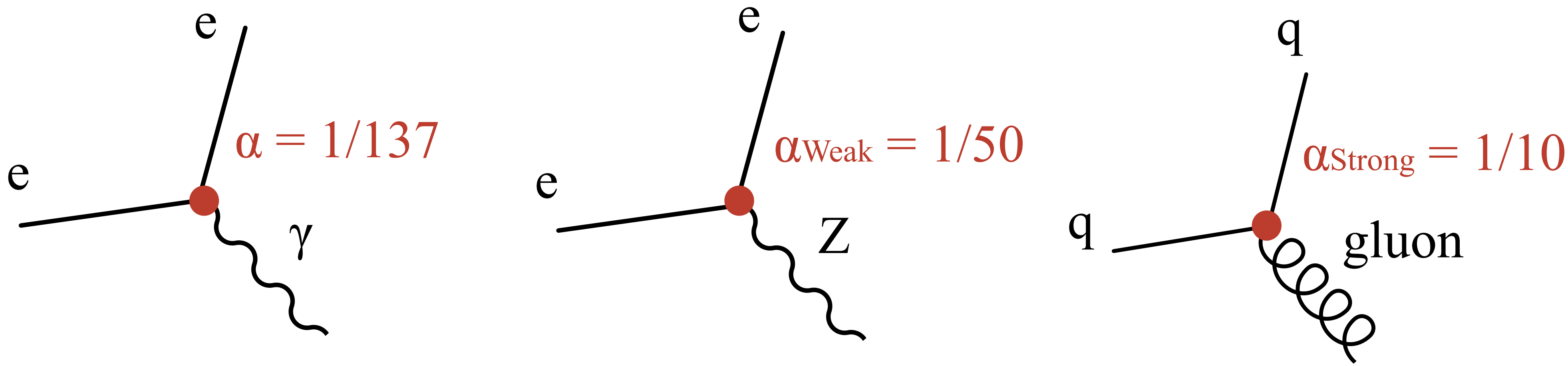


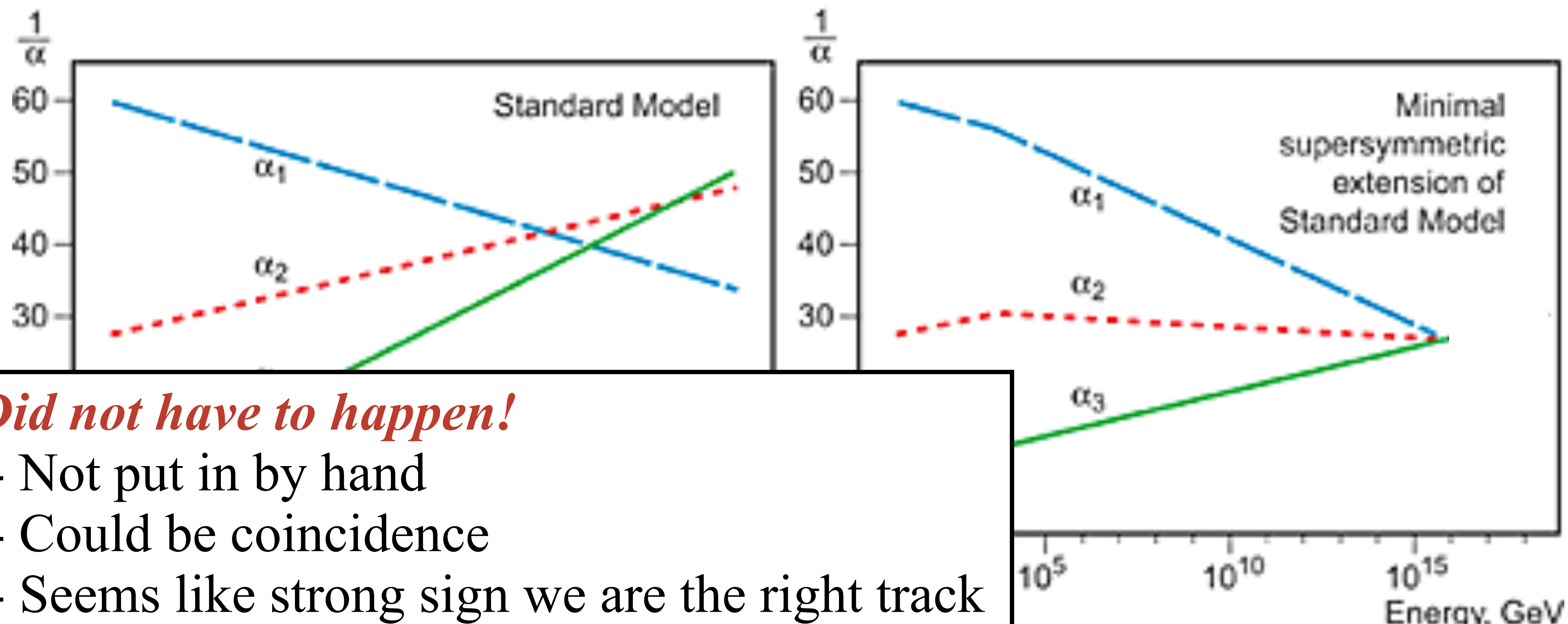




"Super-photon"
- Massive
- Stable
- Weakly interacting

***Perfect candidate for Dark Matter***

# Interaction Strengths




***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

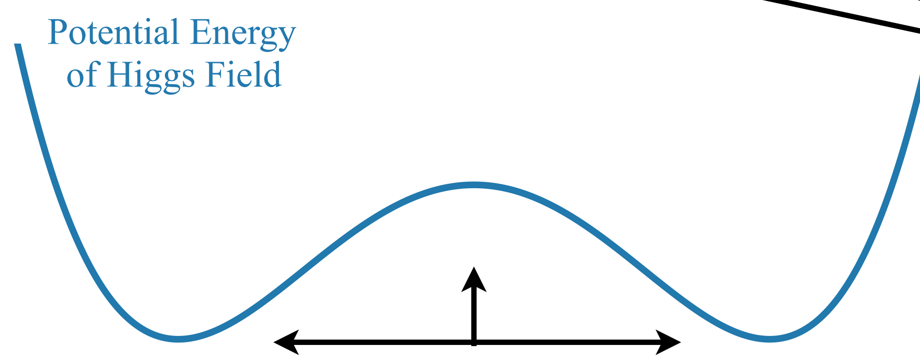
# Higgs as Window to New Physics

**Go through examples of each of these**

Higgs boson directly related to a… …tions

Problem fundamentally related to Higgs ne…

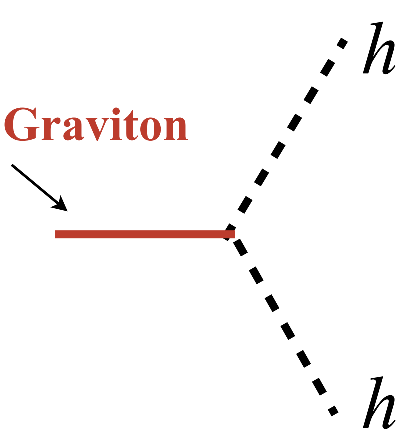
Higgs Boson is the harbinger of the Higgs field (how we…



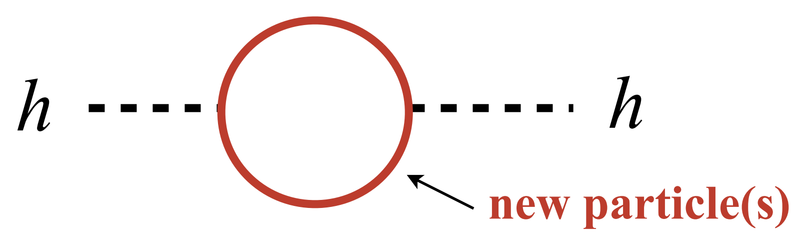

## Compositeness:

- Deeper origin for shape of potential
  (probe experimentally with *hh* events)

## Extra Dimensions:

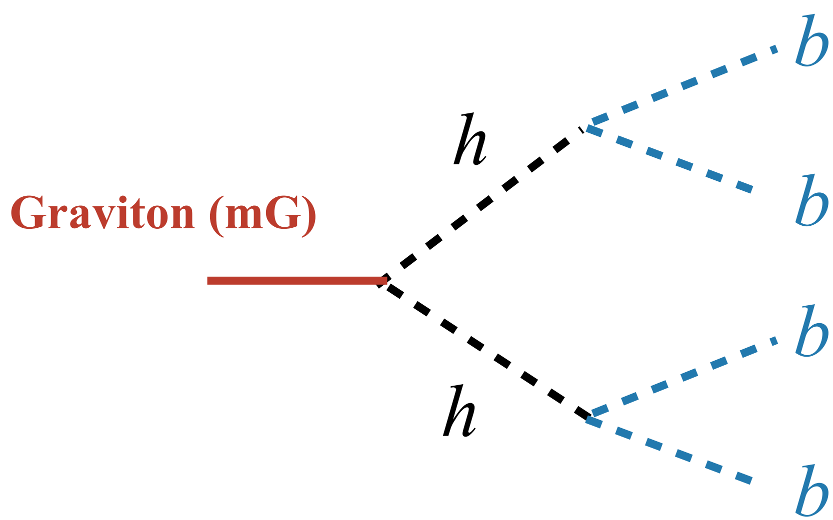



## SuperSymmetry:

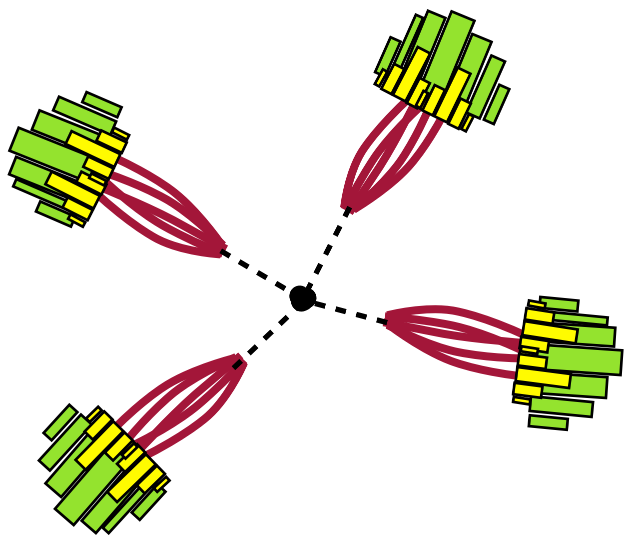


# Enhanced Higgs Production

Signal:




Event Selection:



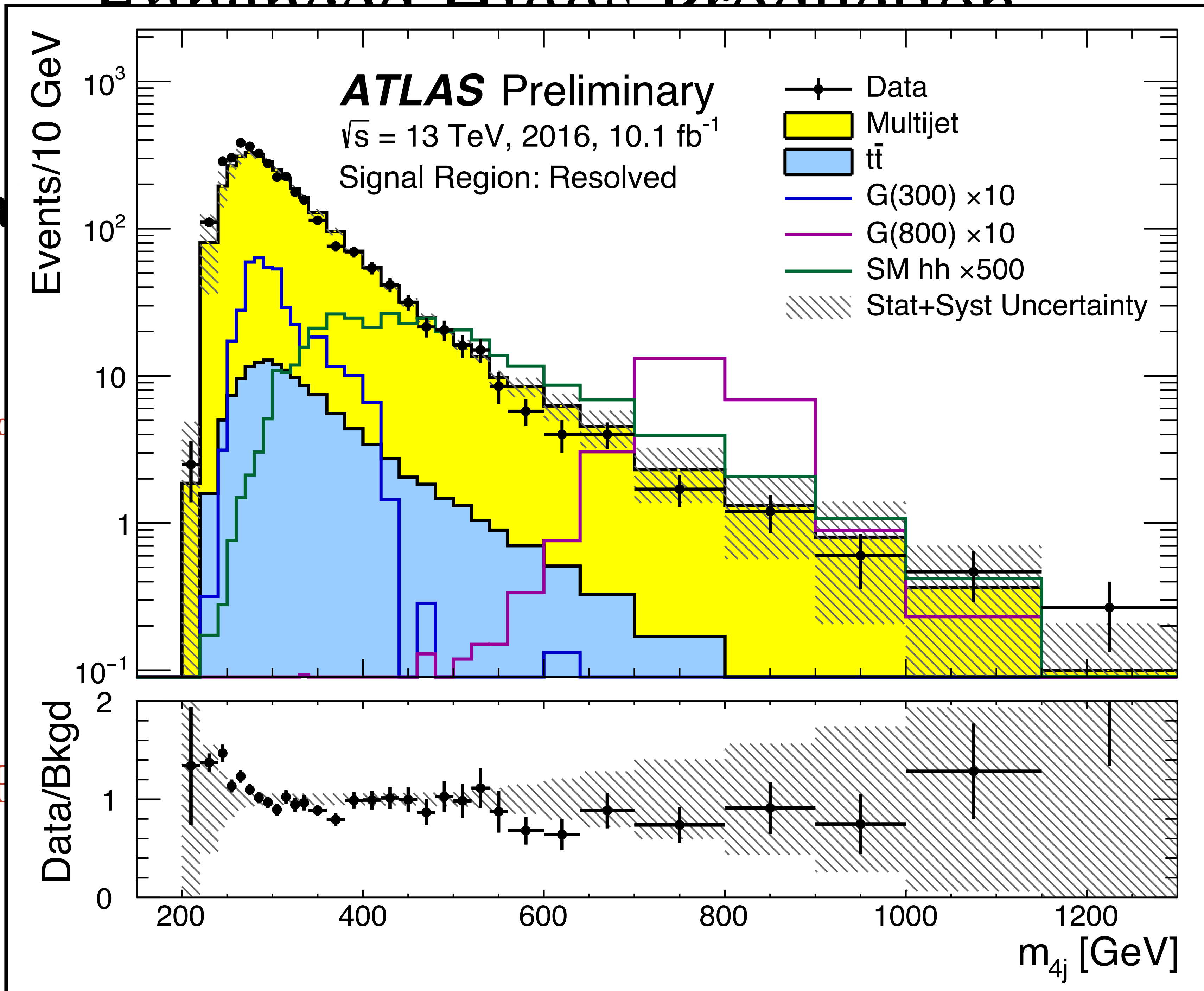
Reconstructed the event from the observed b-jets

- Work backward from $4b \rightarrow 2h \rightarrow G$
- Study the "reconstructed" graviton mass

# Enhanced Higgs Production

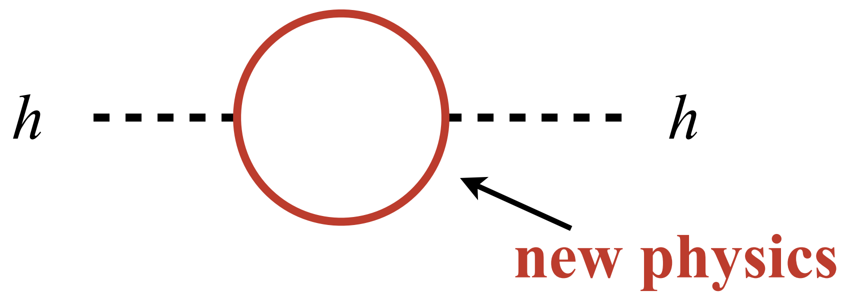
Signa

Gravito



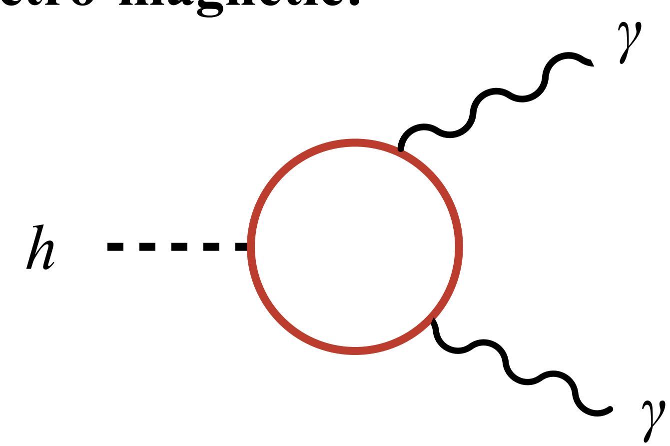
# Modified Higgs Couplings

Expect contributions from new physics to correct higgs mass:



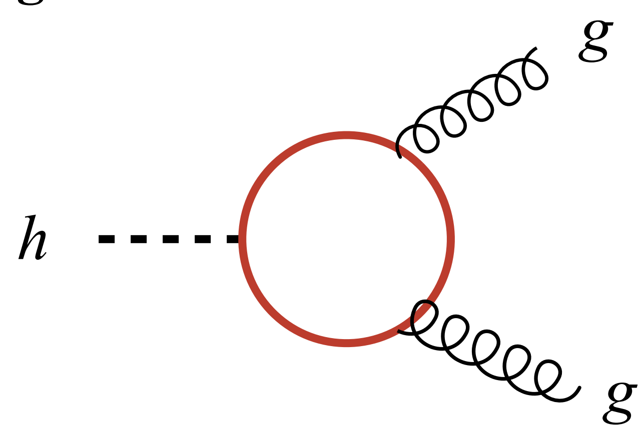

If new physics interacts with the

**electro-magnetic:**




Modifies rate a which higgs bosons decay to photons.

**strong force:**




Modifies rate a which higgs bosons are produced at LHC

# Modified Higgs Couplings

Exp

If ne
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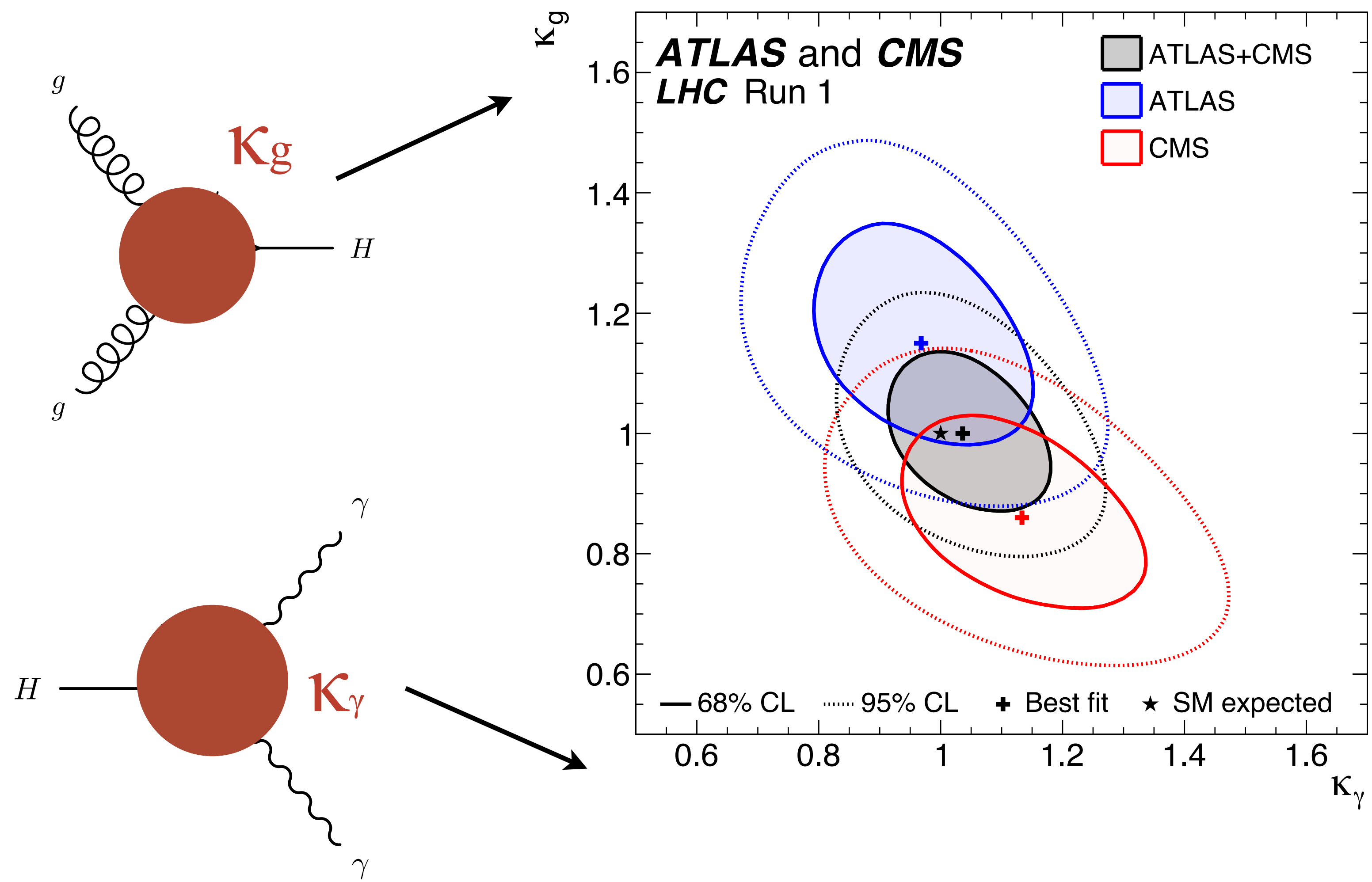
Why detailed Higgs measurements are so important:

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# Modified Higgs Couplings

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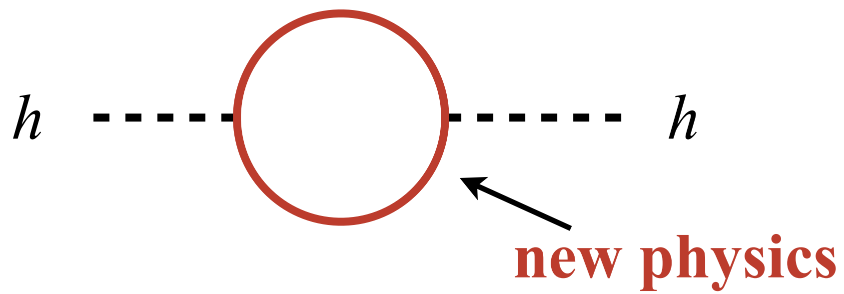
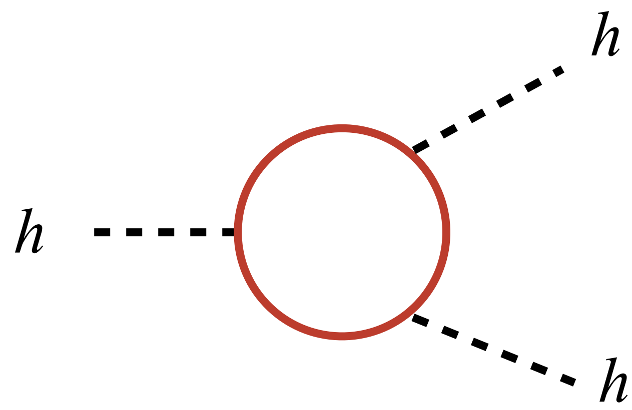



by construction, cannot avoid:

**Higgs interaction:**

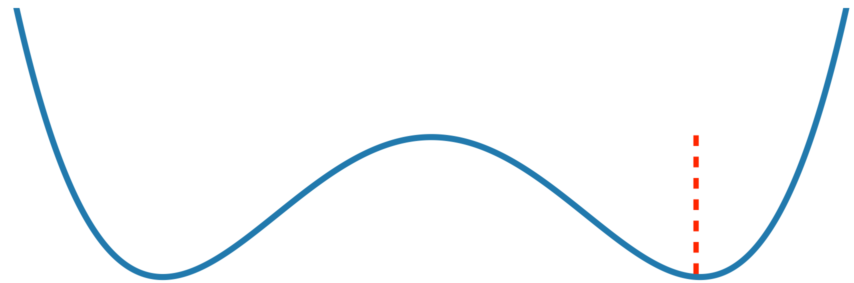



One of the reasons
Di-Higgs is a so important

Modifies Di-Higgs production

# Measuring Higgs Potential

Energy of Higgs field: *Higgs potential*



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

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

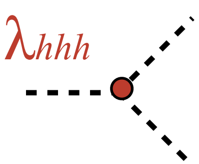
$$\frac{\mu}{\sqrt{\lambda}} \equiv v \ \sim \text{weak scale}$$

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

$$= V_0 + \frac{1}{2} m_h^2 h^2 + \underline{\frac{m_h^2}{2v^2}} v h^3 + \frac{1}{4} \underline{\frac{m_h^2}{2v^2}} h^4$$

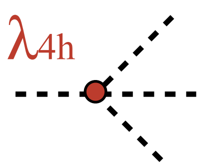
Higgs mass term

$\lambda_{hhh}$



*hh*-production

$\lambda_{4h}$

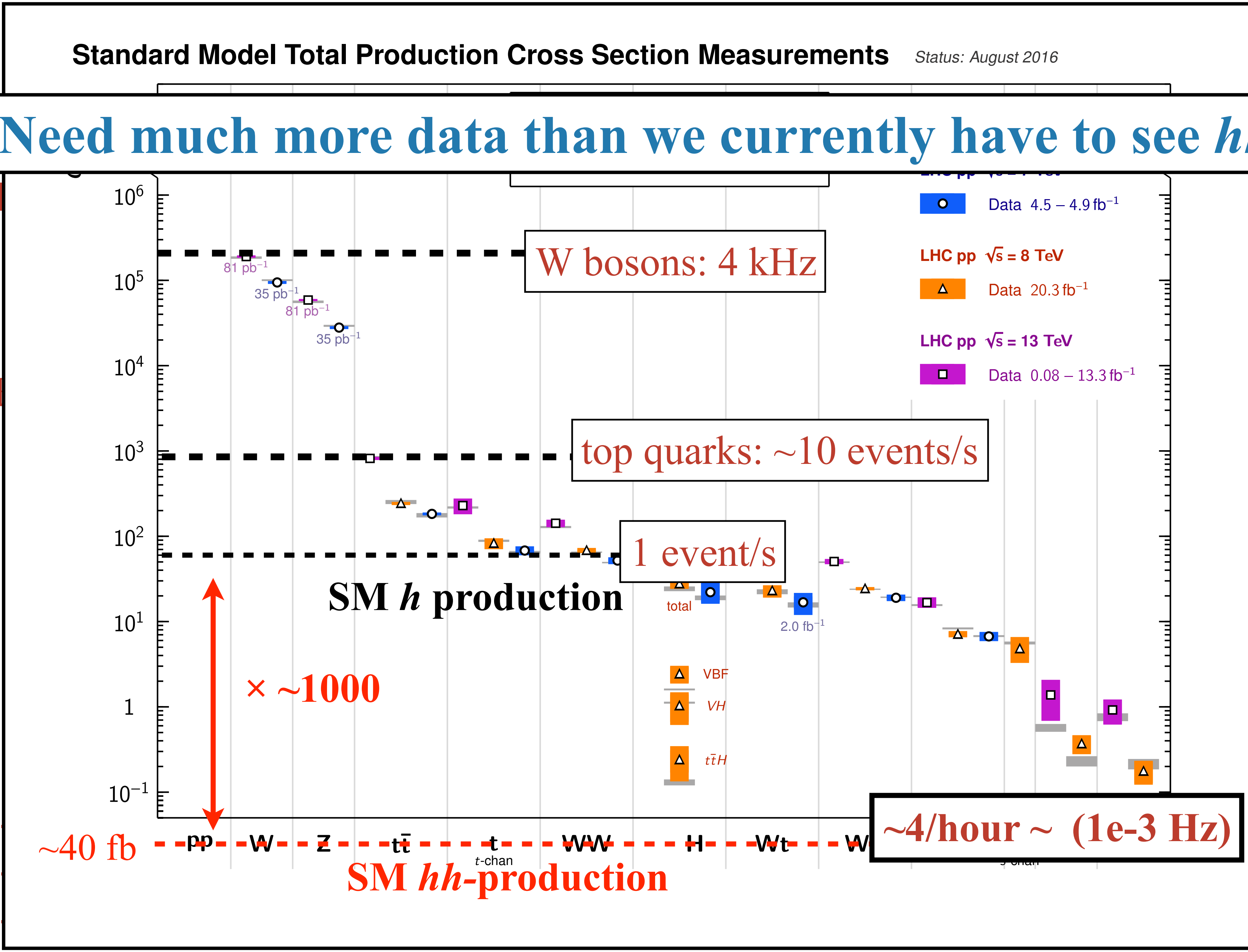


*hhh*-production

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

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

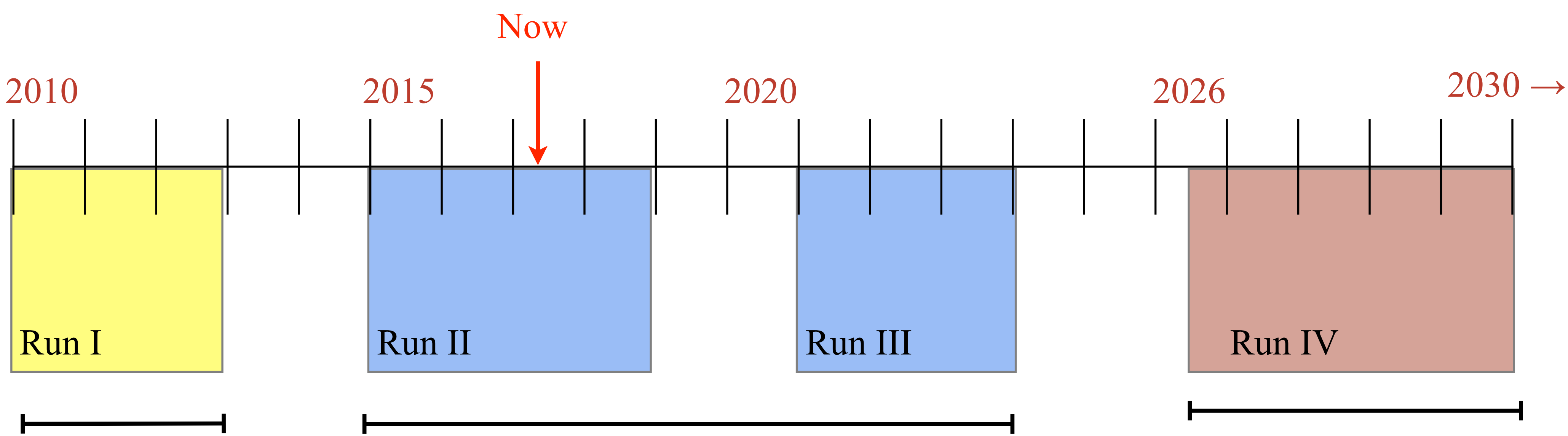
# Need much more data than we currently have to see *hh*



## *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**

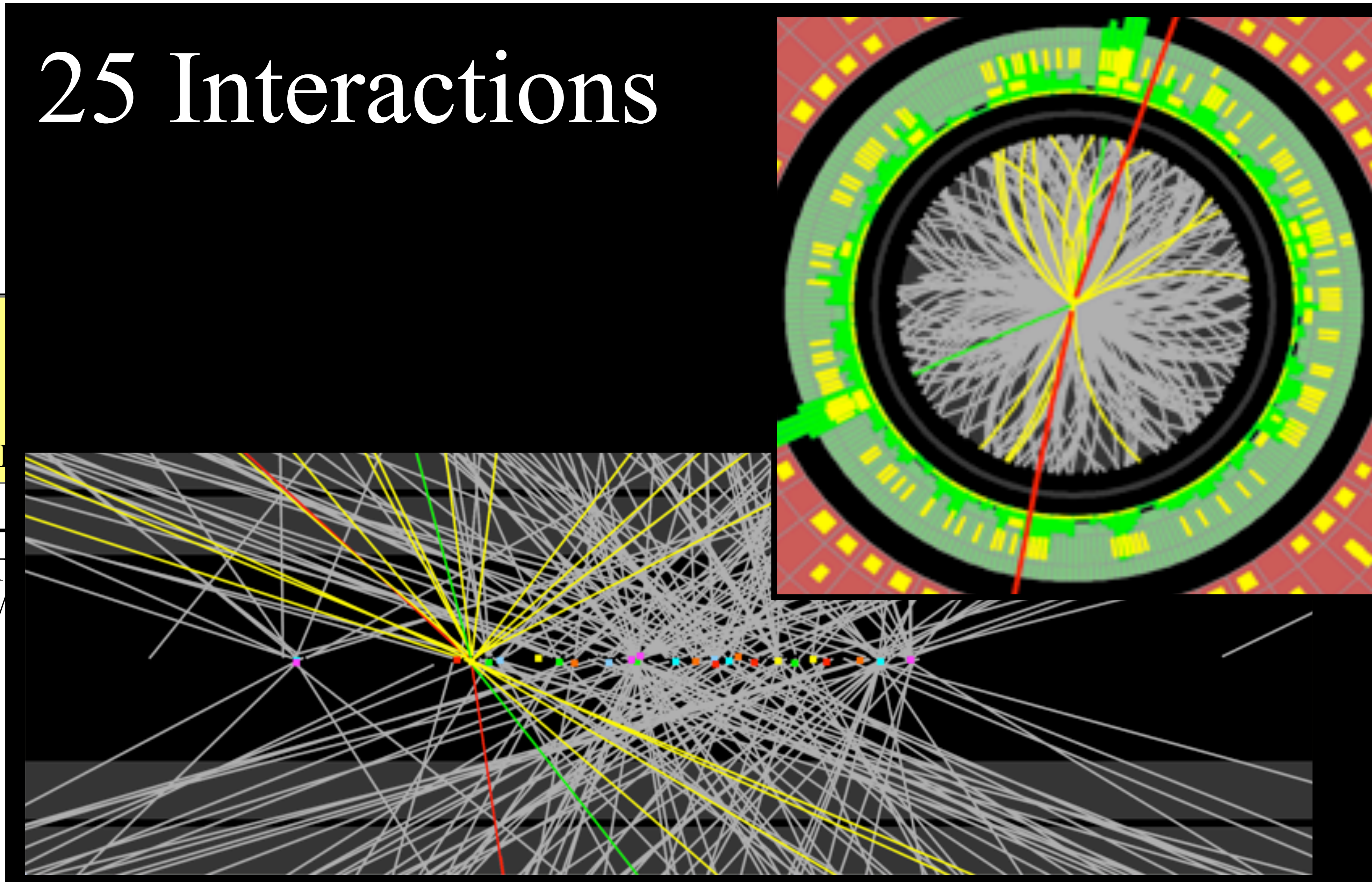
**×150 increase in dataset size**

# Future LHC Program

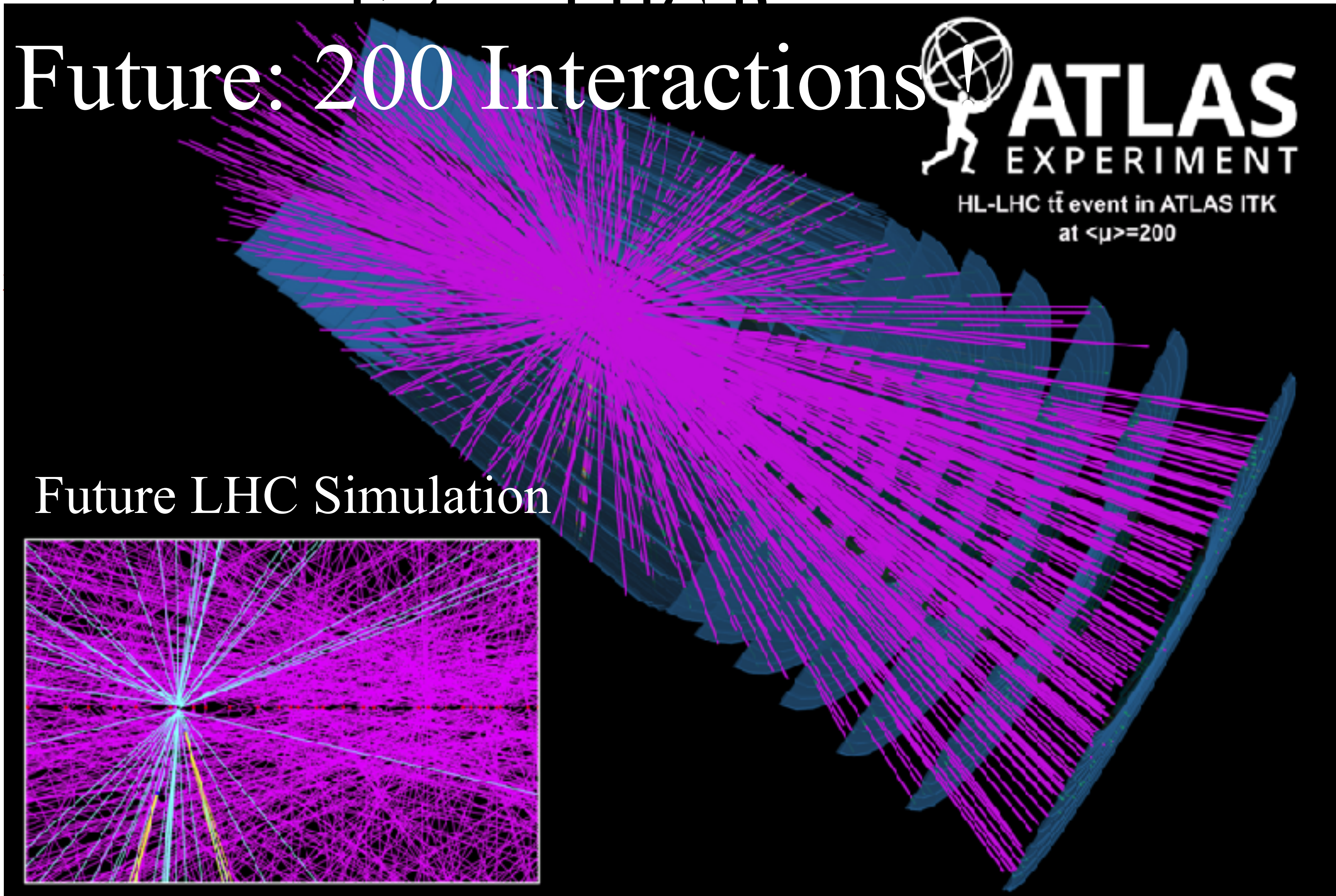
2010

Run I

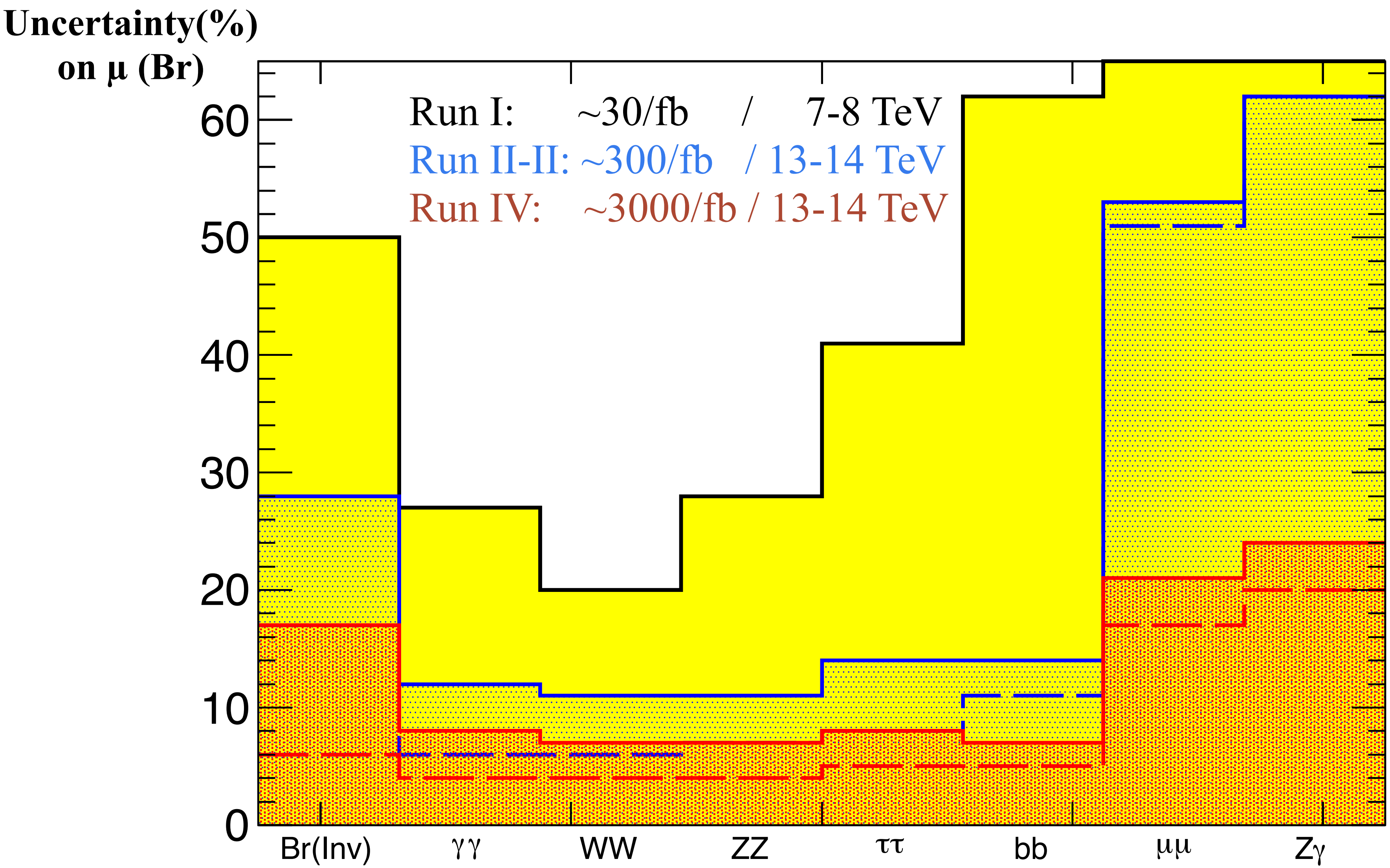
- 8 T
- 20/



# Future: 200 Interactions!

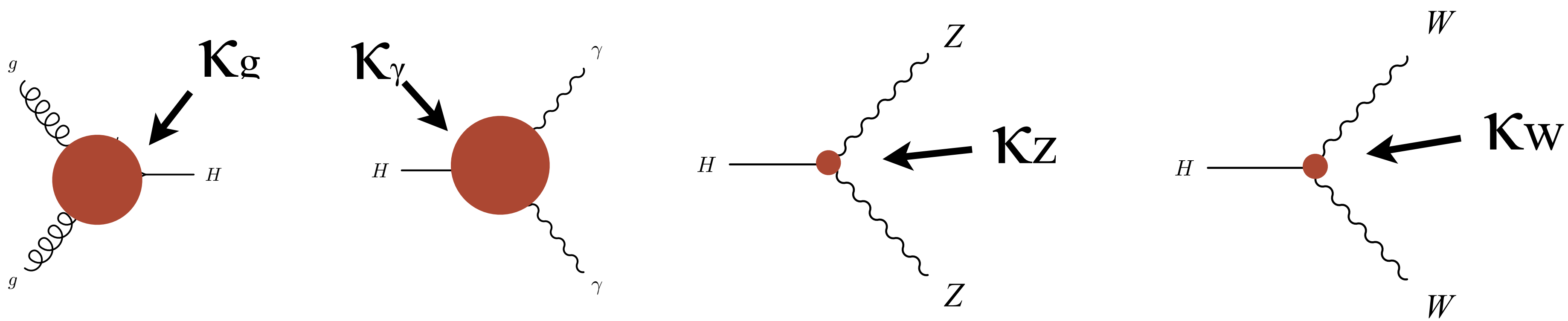


# Higgs at the LHC



# Benchmark Coupling Constraints

Sensitivity tested in model with 7 parameters

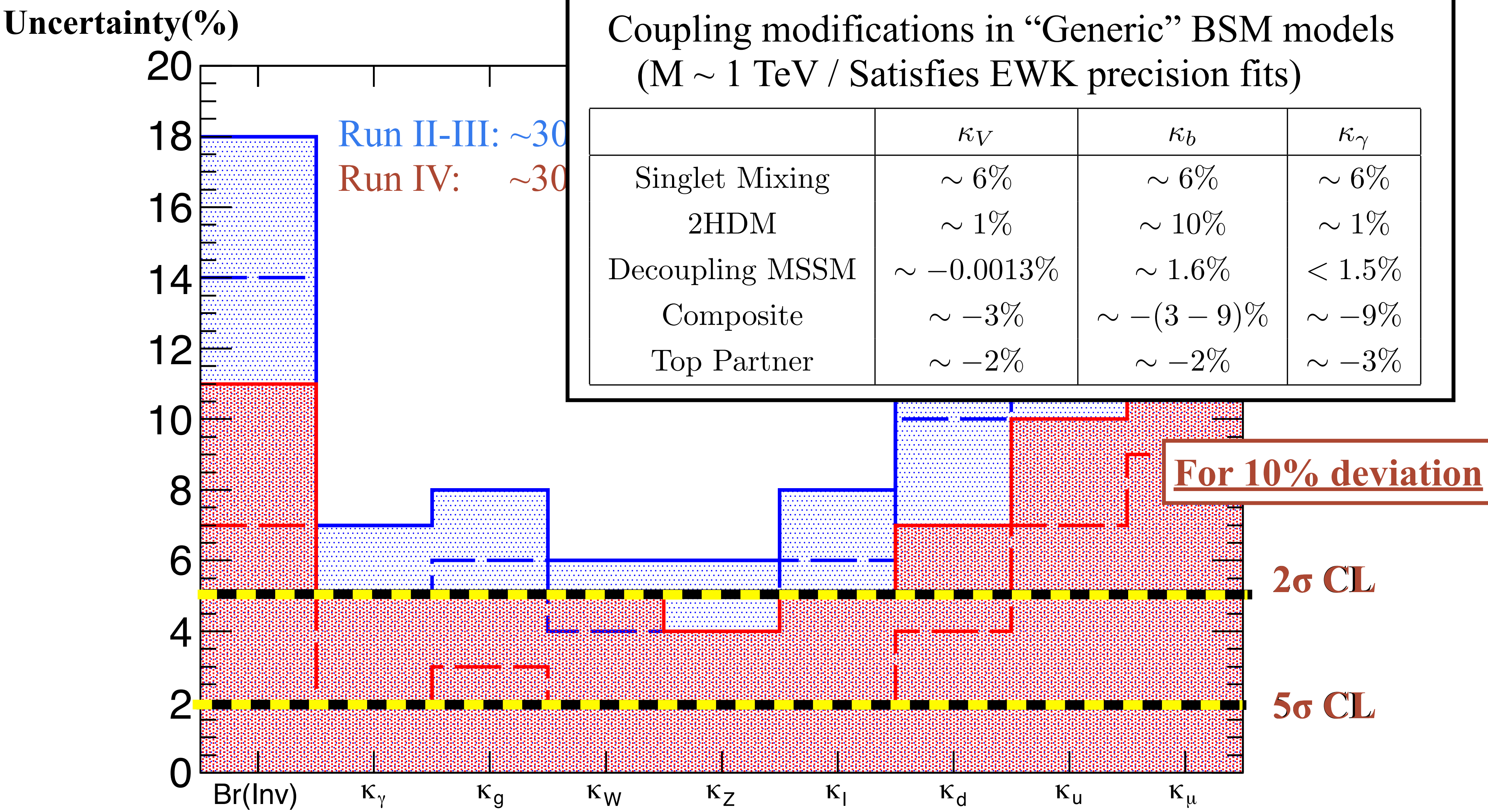



4 fermion couplings:

$\kappa_\tau$ / $\kappa_\mu$ / $\kappa_u \equiv \kappa_t = \kappa_c$ / $\kappa_d \equiv \kappa_b$

Allow for decays to new particles

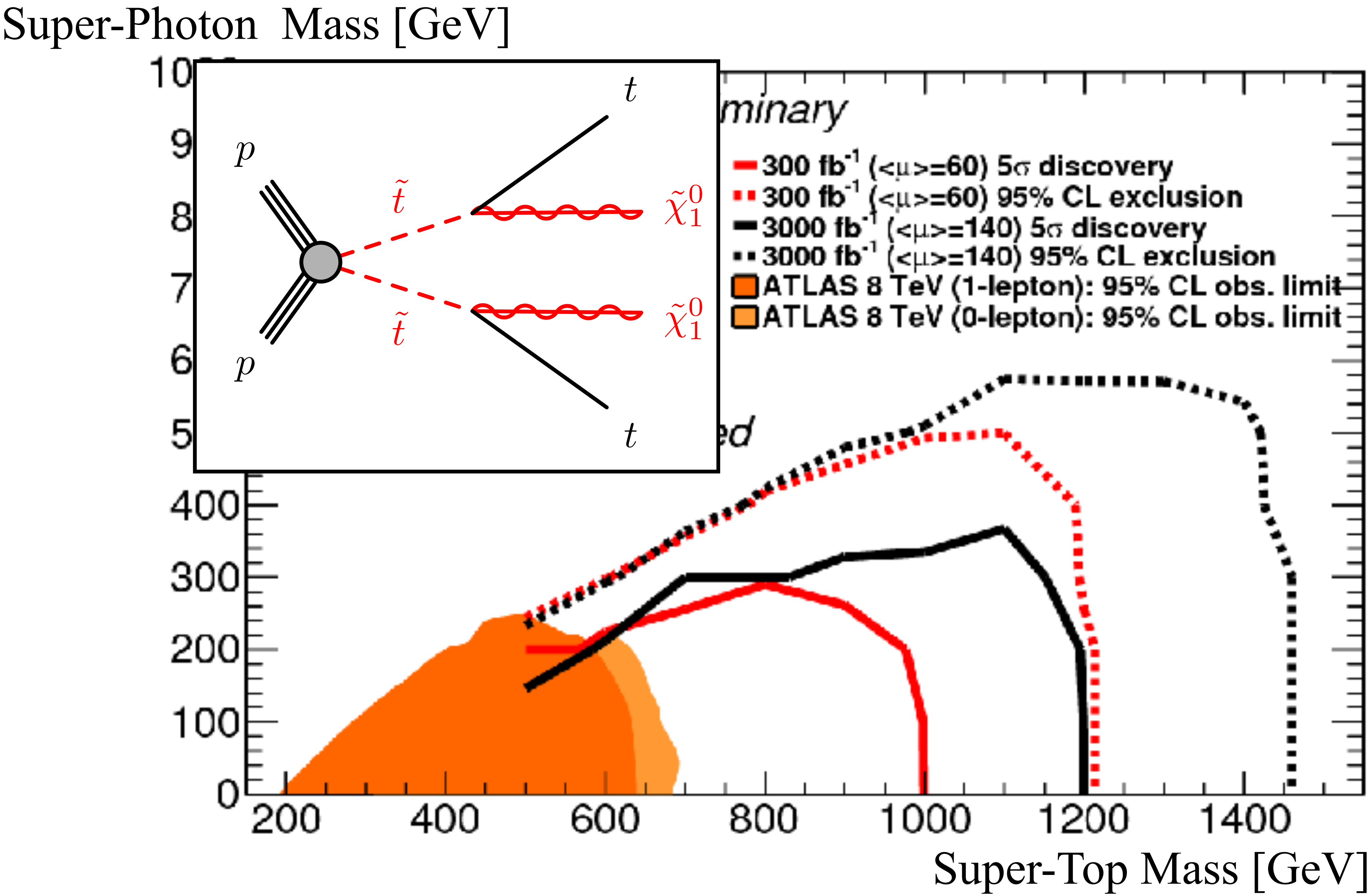
# Higgs at the LHC




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

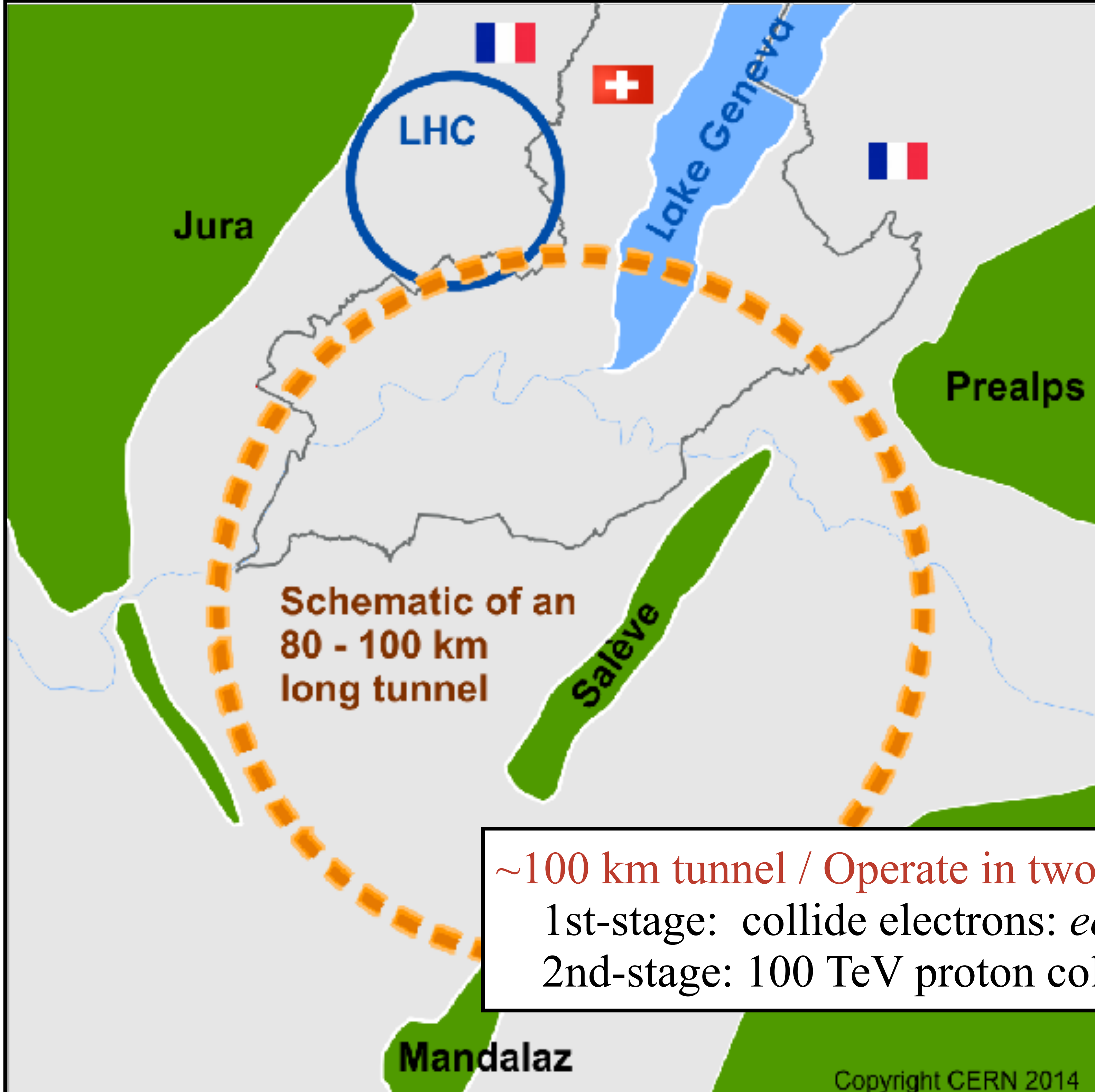
| | $\kappa_V$ | $\kappa_b$ | $\kappa_\gamma$ |
|---|---|---|---|
| Singlet Mixing | $\sim 6\%$ | $\sim 6\%$ | $\sim 6\%$ |
| 2HDM | $\sim 1\%$ | $\sim 10\%$ | $\sim 1\%$ |
| Decoupling MSSM | $\sim -0.0013\%$ | $\sim 1.6\%$ | $< 1.5\%$ |
| Composite | $\sim -3\%$ | $\sim -(3-9)\%$ | $\sim -9\%$ |
| 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

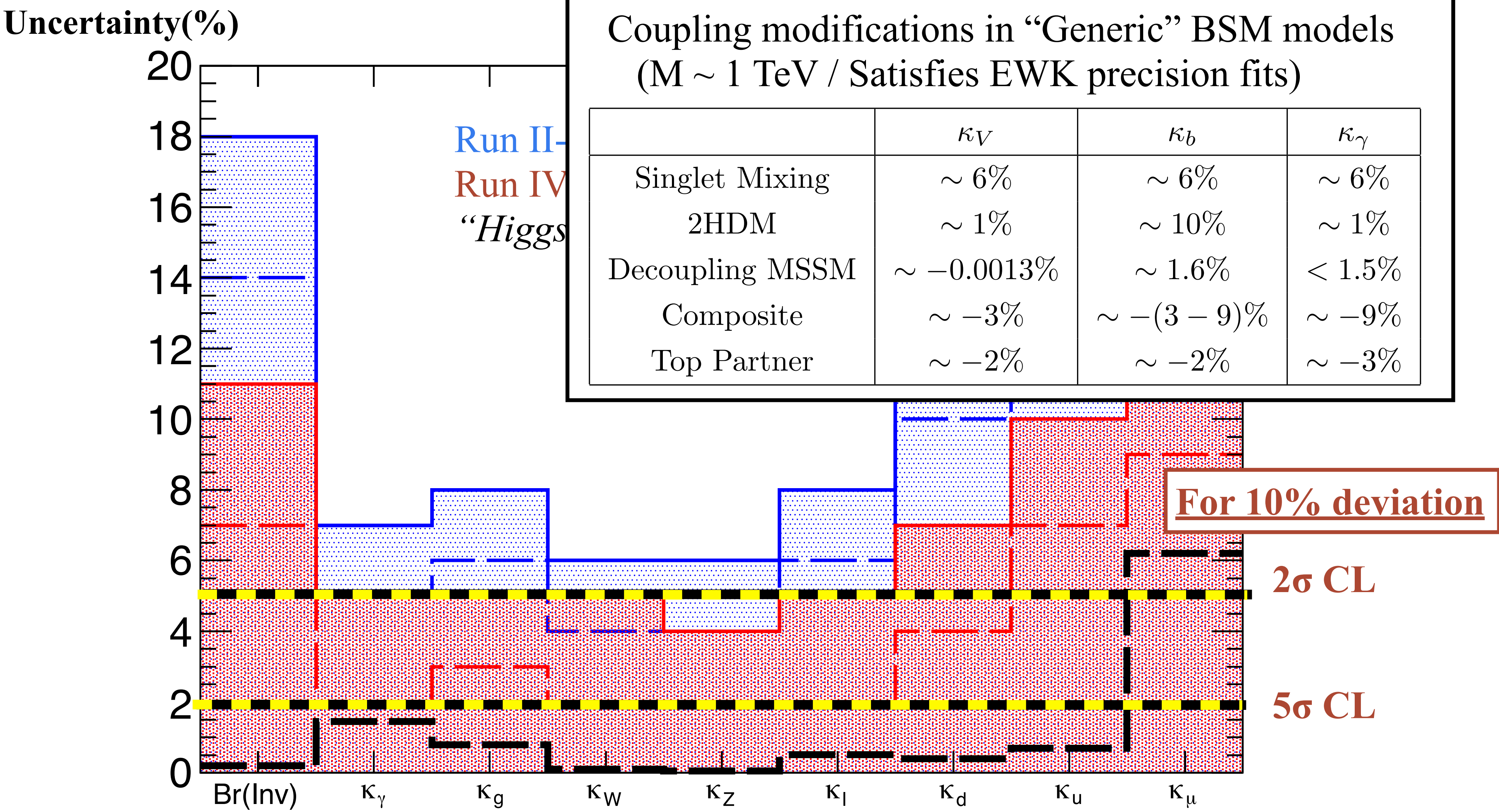

Would Also operate in two modes

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

2nd-stage: 50 TeV proton collider

Could be faster time scale if approved

# Beyond the LHC

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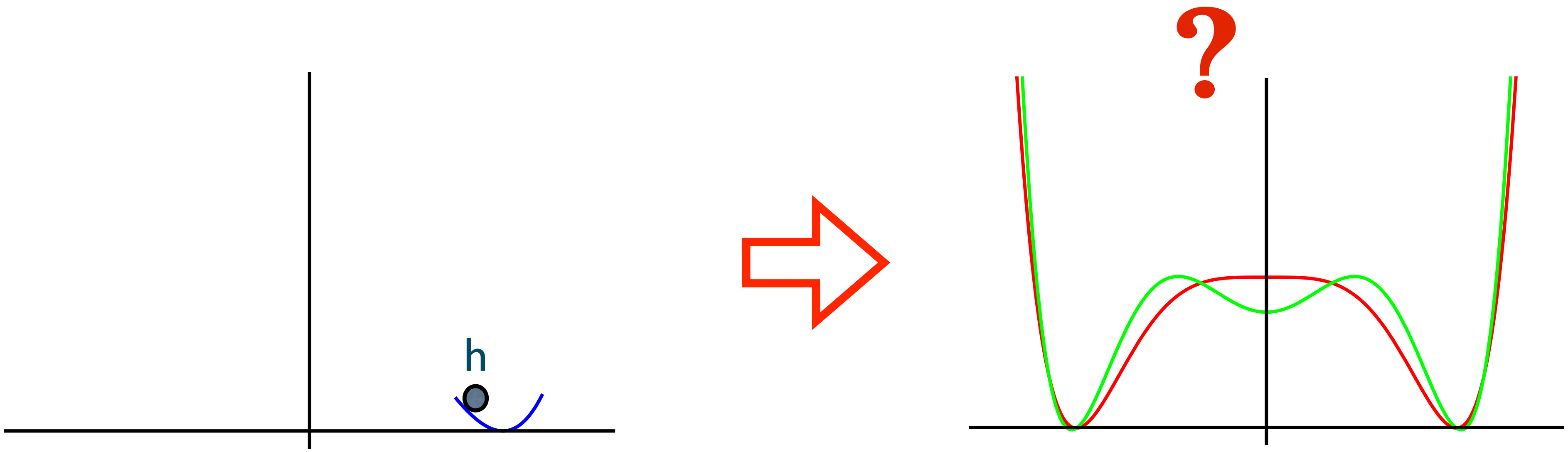
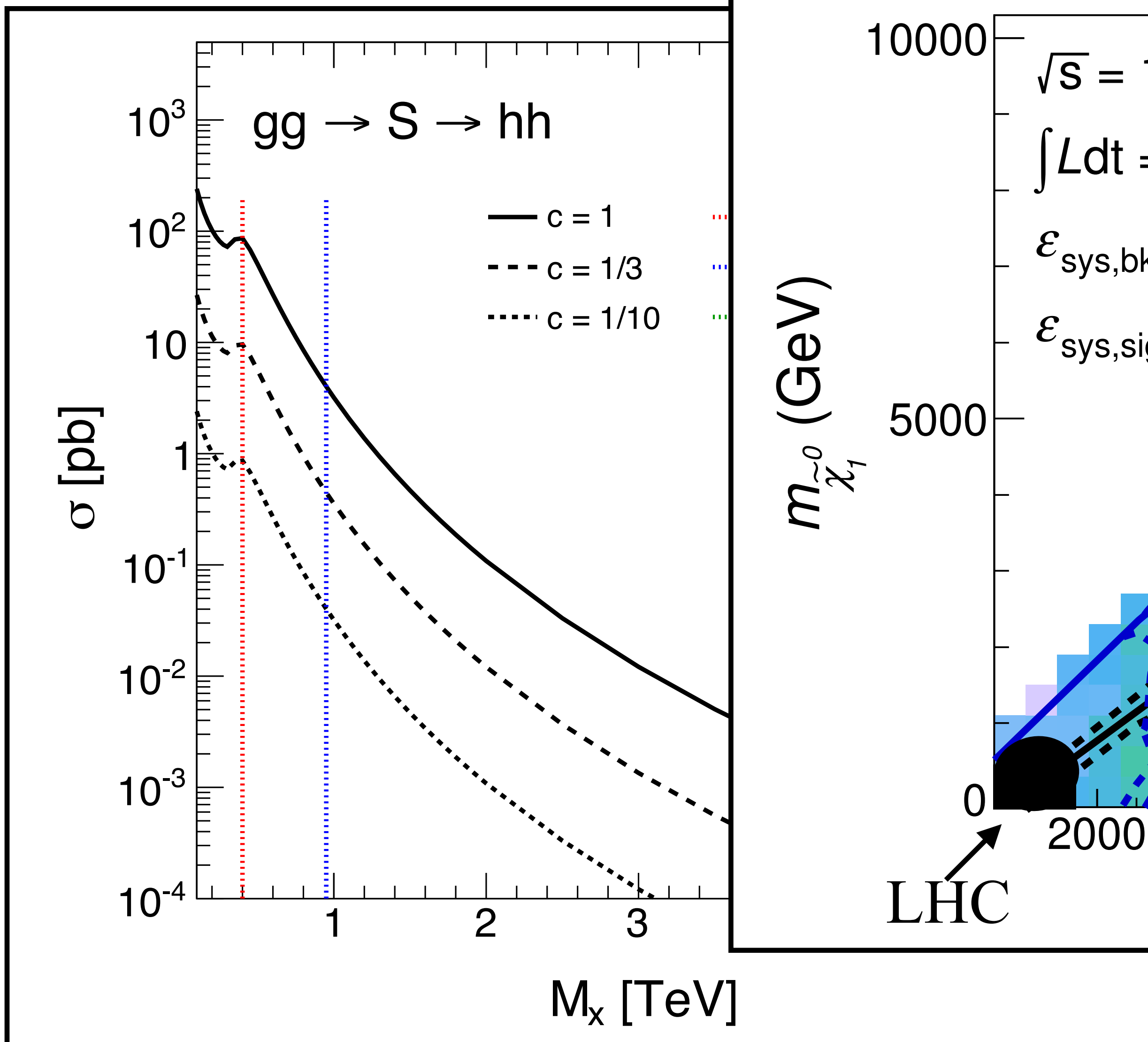
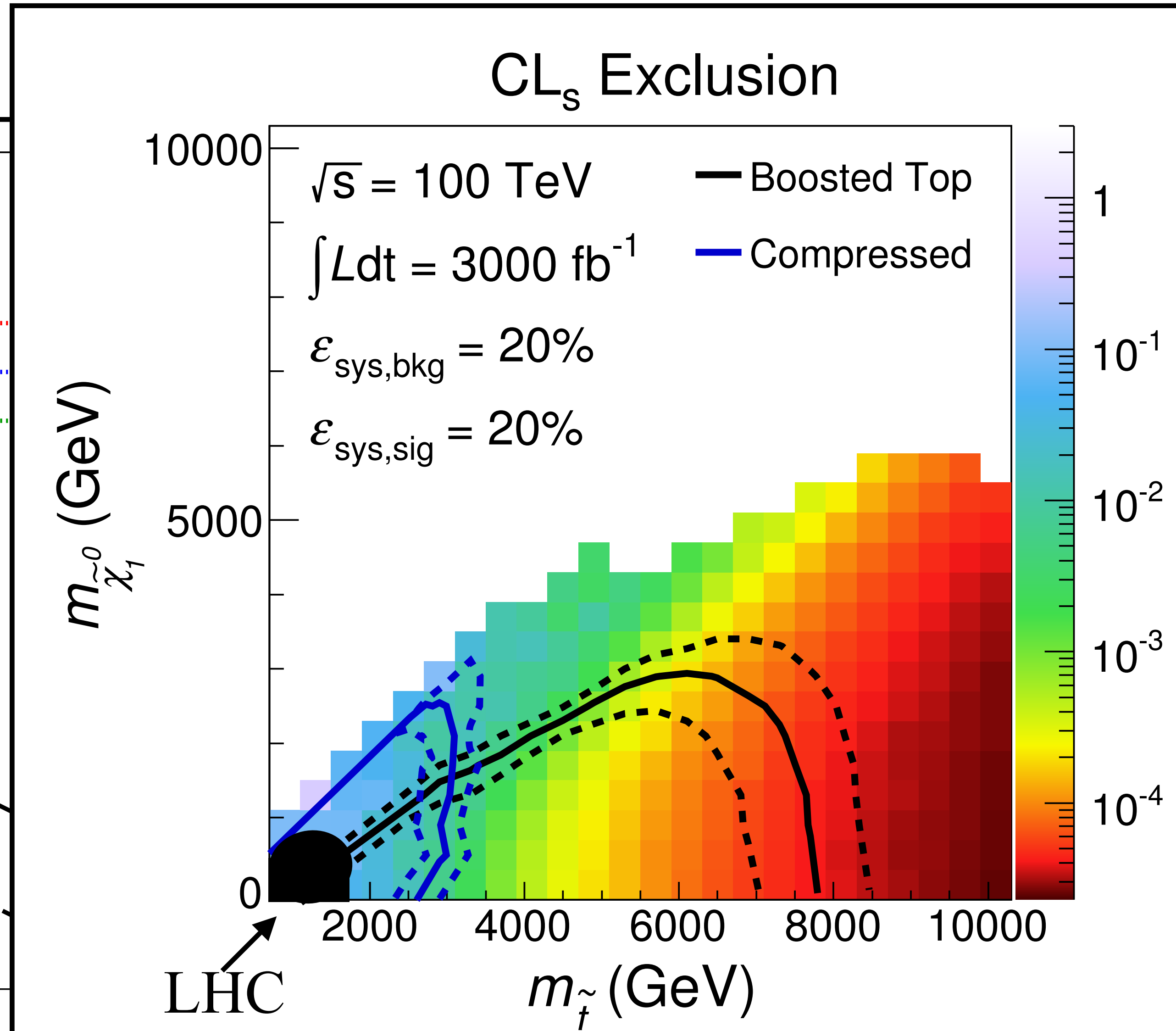
# 100 TeV proton collider

Measure Higgs self-coupling to ~10%



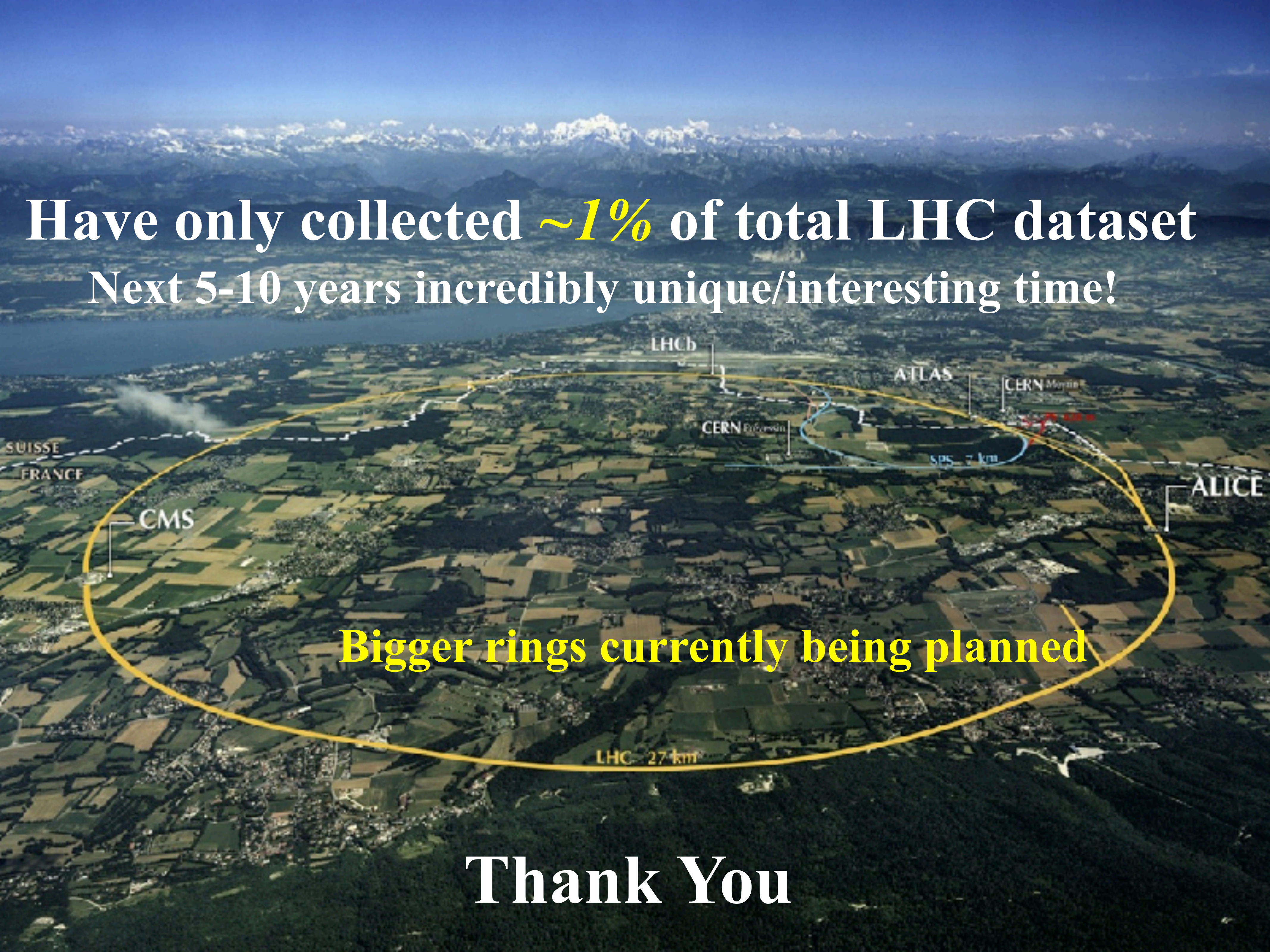
# 100 TeV proton collider



# Have only collected *~1%* of total LHC dataset

## Next 5-10 years incredibly unique/interesting time!




**Bigger rings currently being planned**

# Thank You