Title: Physics beyond the standard model from Higgs Parity

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Series: Cosmology & Gravitation

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Abstract: The discovery of the Higgs boson has revealed that the quartic Higgs self-coupling becomes small at very high energy scales. Guided by this observation, I introduce Higgs Parity, which is a spontaneously broken symmetry exchanging the standard model Higgs with its parity partner. In addition to explaining the small Higgs quartic coupling, Higgs Parity can provide a dark matter candidate, solve the strong CP problem, and arise from an SO(10) grand unified gauge symmetry. I will show that the Higgs Parity symmetry breaking scale is determined by standard model parameters and predicts experimental signals such as the proton decay rate and the warmness of dark matter. As a result, Higgs Parity provides a tight correlation between future precision measurements of standard model parameters and these experimental signals.

05/19/2020

Perimeter Institute

Physics beyond the standard model from Higgs Parity

Keisuke Harigaya
(Institute for Advanced Study)

Hall and KH : 1803.08119, 1905.12722

Dror, Dunsky, Hall and KH: 2004.09511

Particle physics

is trying to answer questions such as

* What are the fundamental laws of physics?

  Particles, interactions among them, ...

* How did our universe begin and evolve?

  Inflation, cosmic perturbations,
  baryon asymmetry, dark matter, ...

Standard Model

(of particle physics)

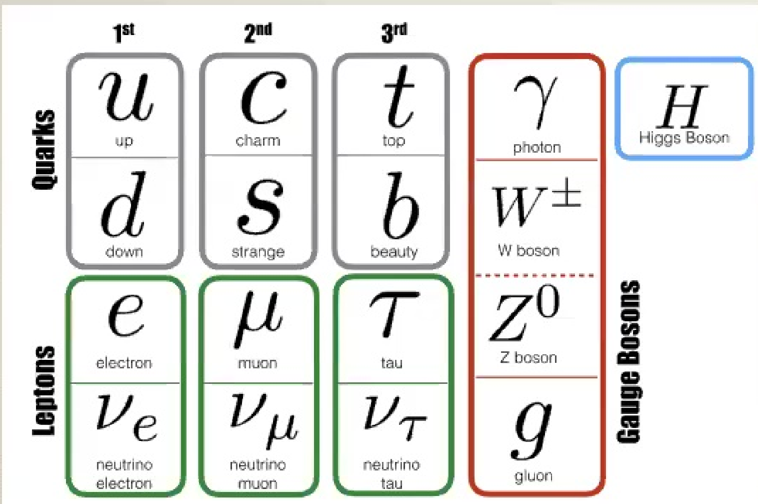
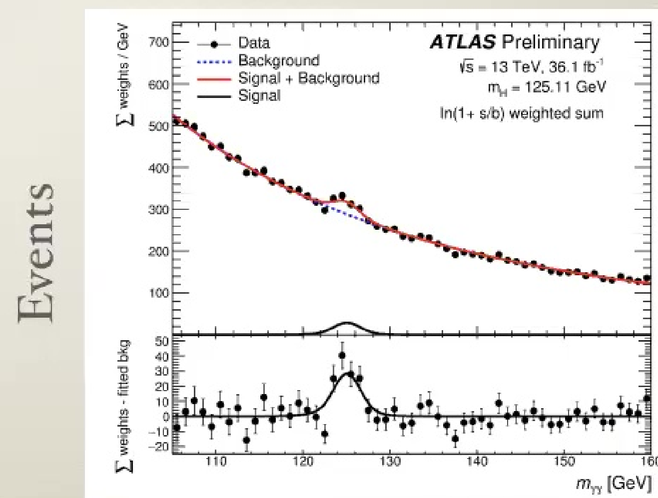


figure from www.physik.uzh.ch



Invariant mass

Precise measurements

- Higgs mass $m_h = 125.18 \pm 0.16$ GeV
- Top quark mass $m_t = 173.1 \pm 0.4$ GeV
- Strong coupling constant $\alpha_s(m_Z) = 0.1184 \pm 0.0011$
- ...

Can we learn something beyond the Standard Model ?

nature of dark matter, mass of new particles, rare decays, etc.

Precise measurement and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

New symmetry
Higgs Parity

* gives a dark matter candidate
* is part of a grand unified gauge symmetry
* solves the strong CP problem

Precise measurement and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

top quark mass
Higgs mass
strong coupling constant

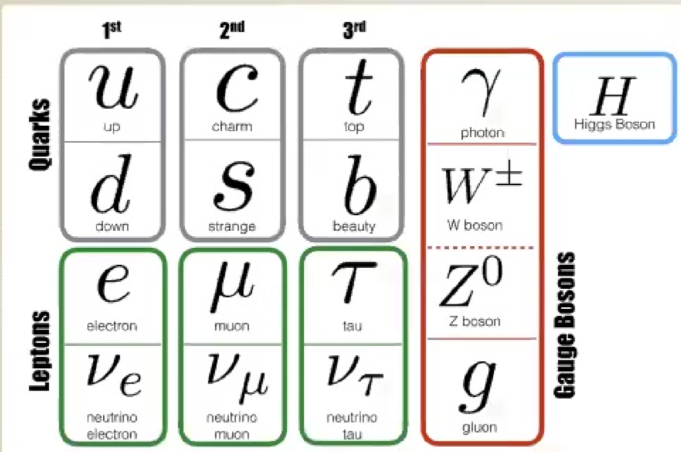
Higgs Parity
symmetry
breaking scale

Outline

* Introduction (continued)
* Higgs Parity
* Left-Right Higgs Parity and the strong CP problem
* Grand unification and proton decay
* Warm right-handed neutrino dark matter
* Summary and outlook

Introduction

Standard Model



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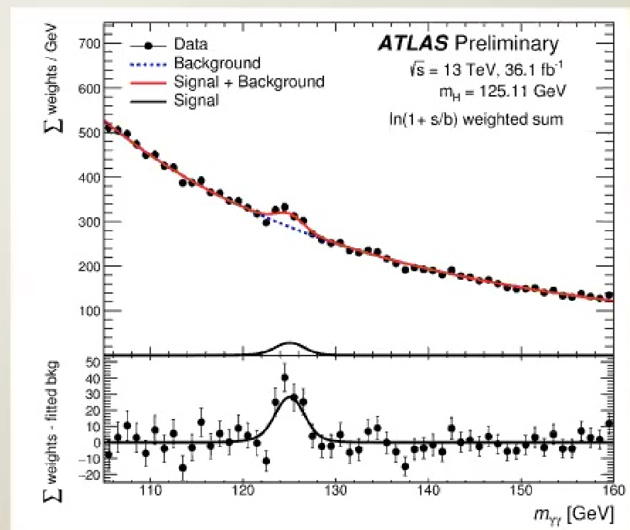

Picture from Recondito.org

We are far away from the goal

* What is dark matter?
* How did cosmic inflation occur?
* How was the baryon asymmetry of the universe created?
* Why does QCD preserve CP symmetry?
* What sets the Higgs potential parameters?

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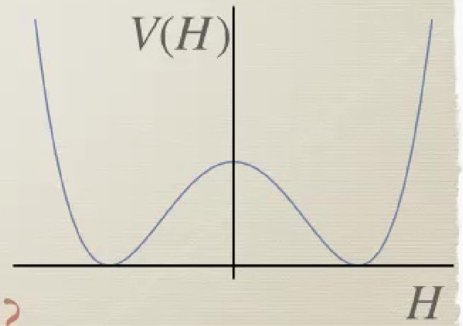
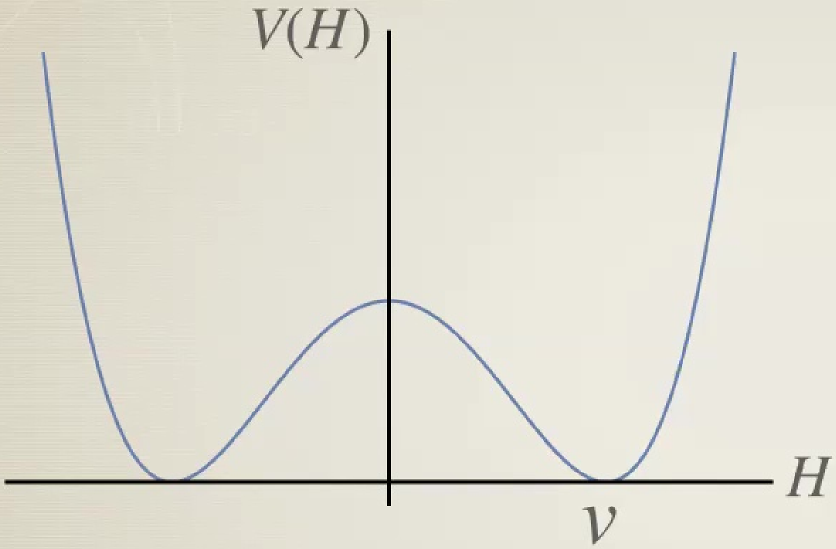


$$V(H) = \lambda_{\rm SM}\left(|H|^2 - v^2\right)^2$$

Higgs potential



$$V(H) = \lambda_{SM} \left(|H|^2 - v^2 \right)^2$$

A question of few decades:
What sets the mass scale of Higgs?

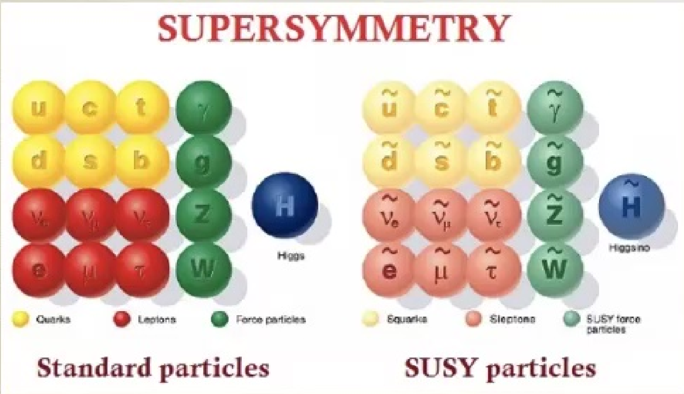
$v = 173$ GeV $\ll$ (Planck scale, GUT scale)

Hierarchy problem

Higgs potential

What sets the small mass scale of Higgs?

Ex. Supersymmetry



CERN & IES de SAR

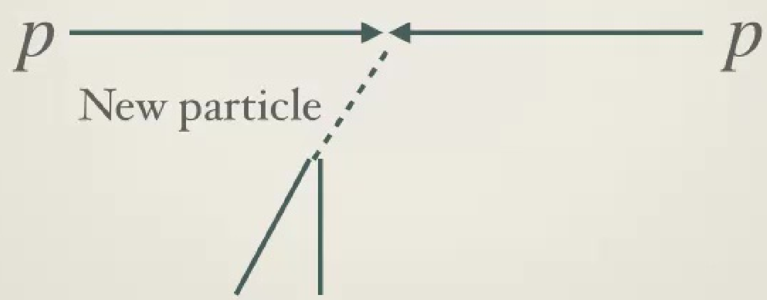
Higgs mass scale is naturally much smaller than the Planck scale

Maiani (1979), Veltman (1979), Witten (1981)

predict new particles with masses around 100 GeV

100 GeV scale new physics

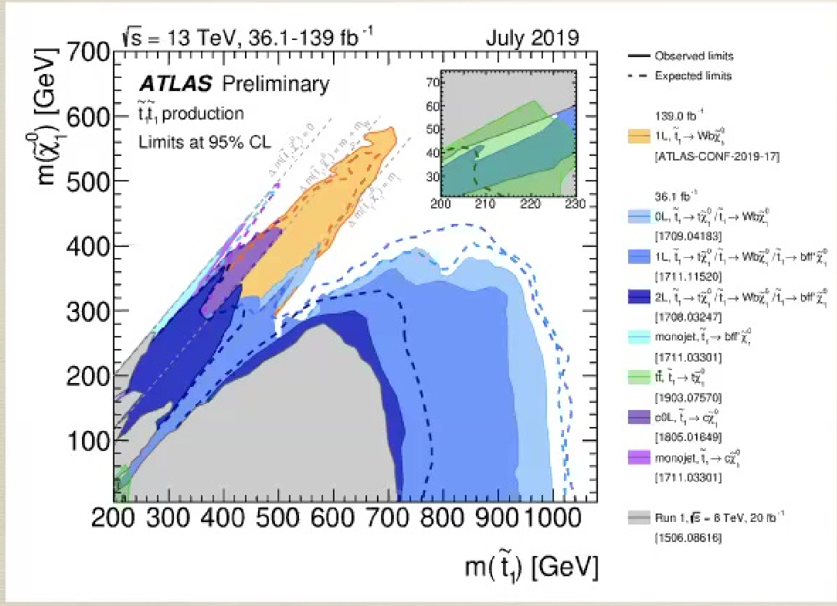
Searches for new particles at colliders

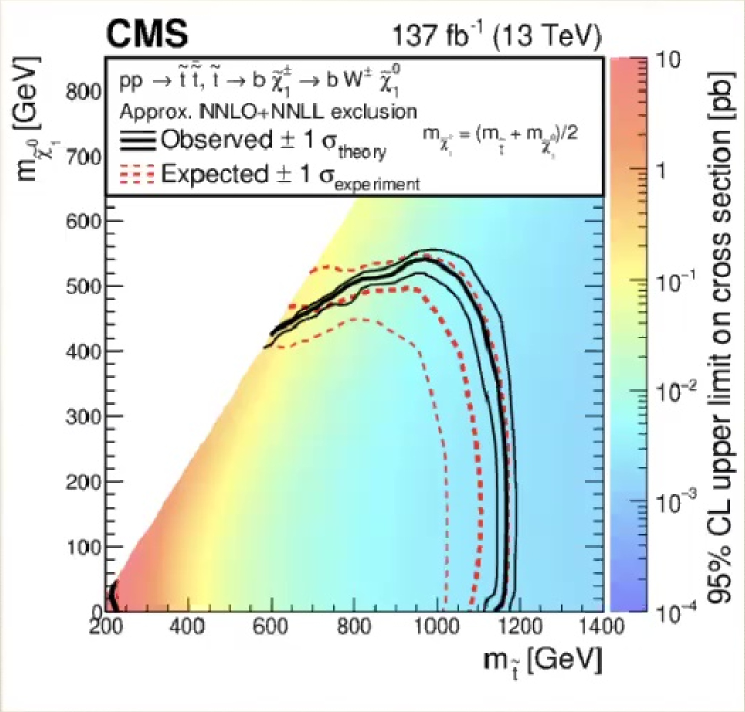


100 GeV scale new physics

New particles have not been found so far

Ex. Constraints on the masses of new particles
in supersymmetric theories





What to do?

$$V(H) = \lambda_{\rm SM}\left(|H|^2 - v^2\right)^2$$

We should keep trying to explain the small Higgs mass and seek experimental signatures of the explanation.

Recent effort includes, for example,

* Twin Higgs

Chacko, Goh and Harnik (2006), Falkowski, Pokorski and Schmaltz (2006), Chang, Hall and Weiner (2006), KH and Badziak (2017,2018), Barbieri, Hall and KH (2017,2018),

* Relaxion

Graham, Kaplan and Rajendran (2015), Espinosa et.al. (2015), Hook and Marques-Tavares (2016), Evans, Gherghetta, Nagata and Thomas (2016), Ibe, Shoji and Suzuki (2019), ...

We should also pursue complementary directions

Fine-tuned Higgs mass?

$$V(H) = \lambda_{\rm SM} \left(|H|^2 - v^2 \right)^2$$

We are not sure if the small Higgs mass is
a guiding principle to look for new physics

The small Higgs mass may be explained by theoretical ideas
which are difficult to probe experimentally

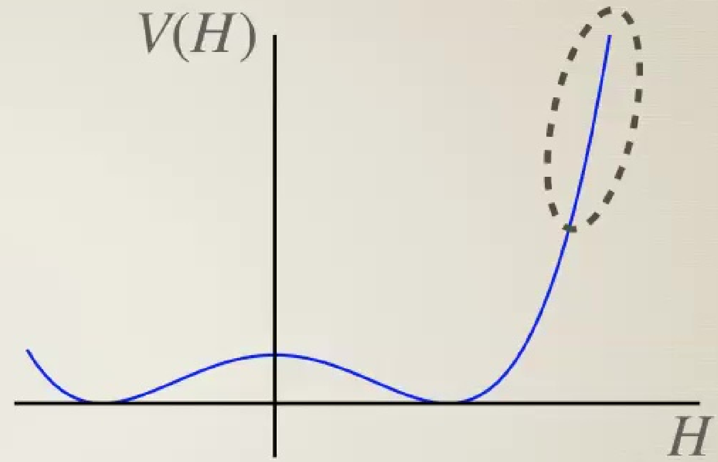
Ex. Multiverse and anthropic selection

Weinberg (1987), Susskind (2003), Agrawal, Barr, Donoghue and Seckel (1998), Clavelli and White (2006), Hall, Pinner and Ruderman (2014), ...

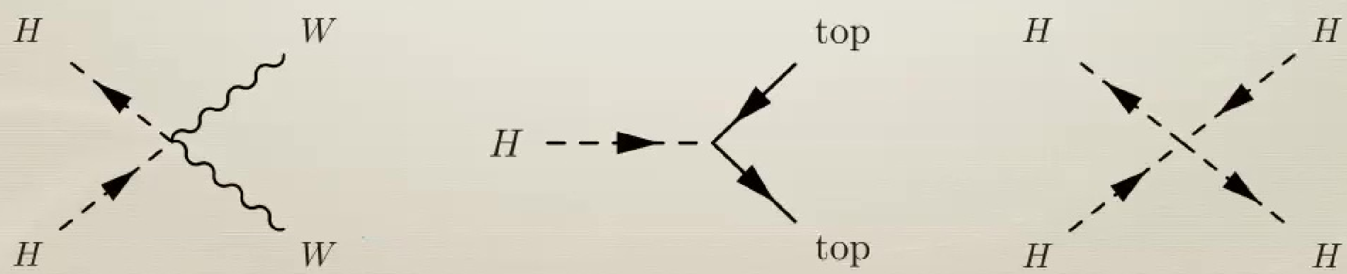
Higgs self-interaction?

$$V(H) = \lambda_{\rm SM}\left(\,|H|^2 - v^2\right)^2$$

$$m_h^2/(4v^2) \simeq 0.13$$



Let us examine the quartic coupling,
assuming that the standard model is valid up to high energy scales,
including quantum corrections

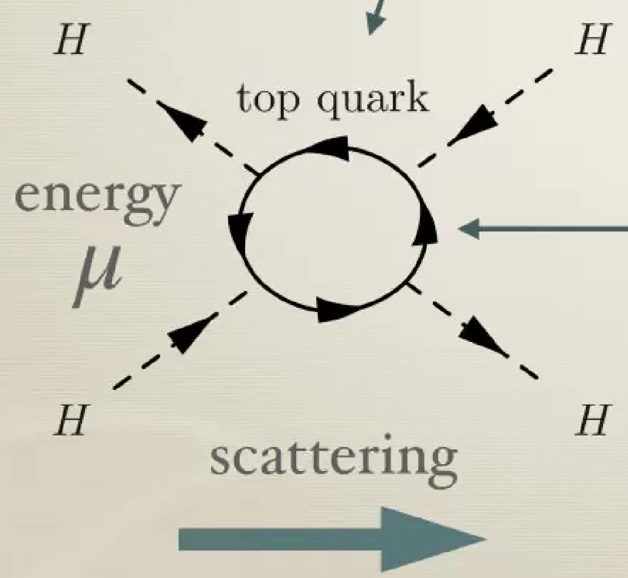


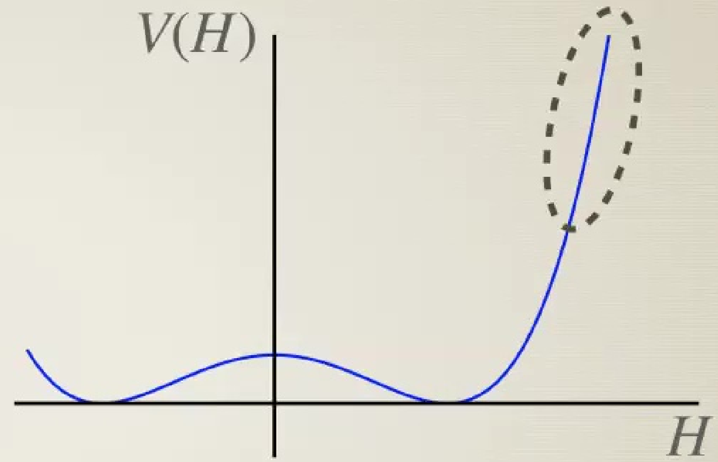
Energy-dependent quartic coupling

perturbation theory

$$\Delta\lambda_{SM} \sim \sum_i < HH|i > < i|HH >$$

sum over intermediate states

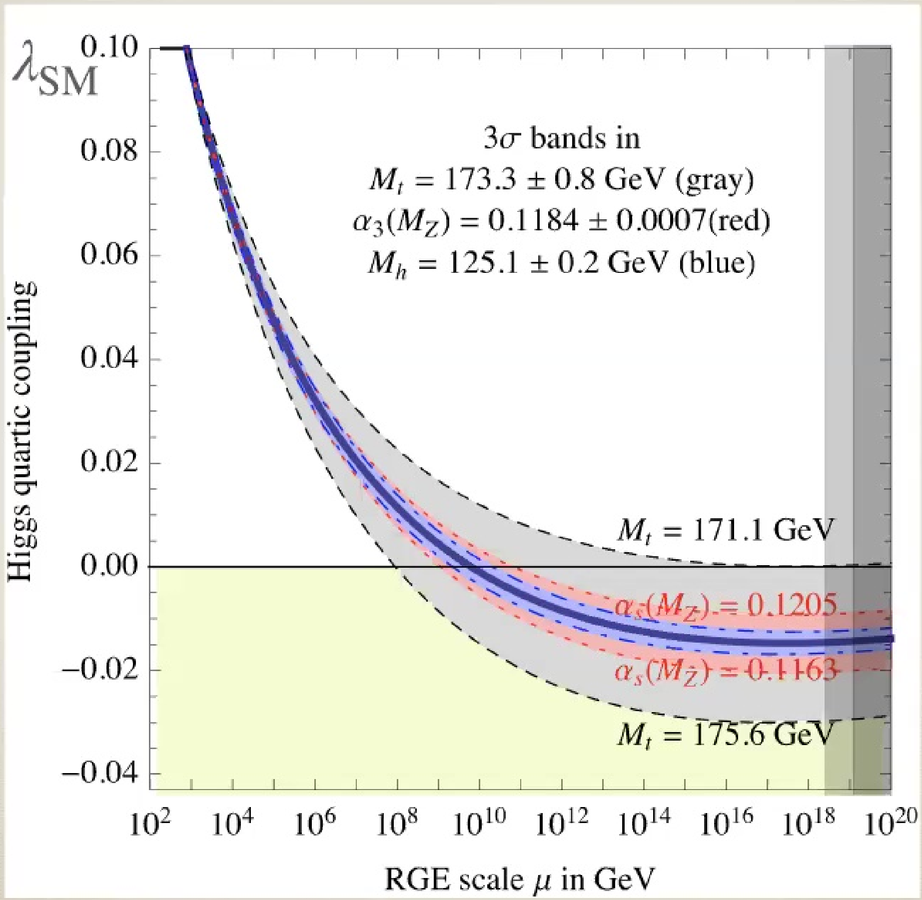




Intermediate states depend on energy μ

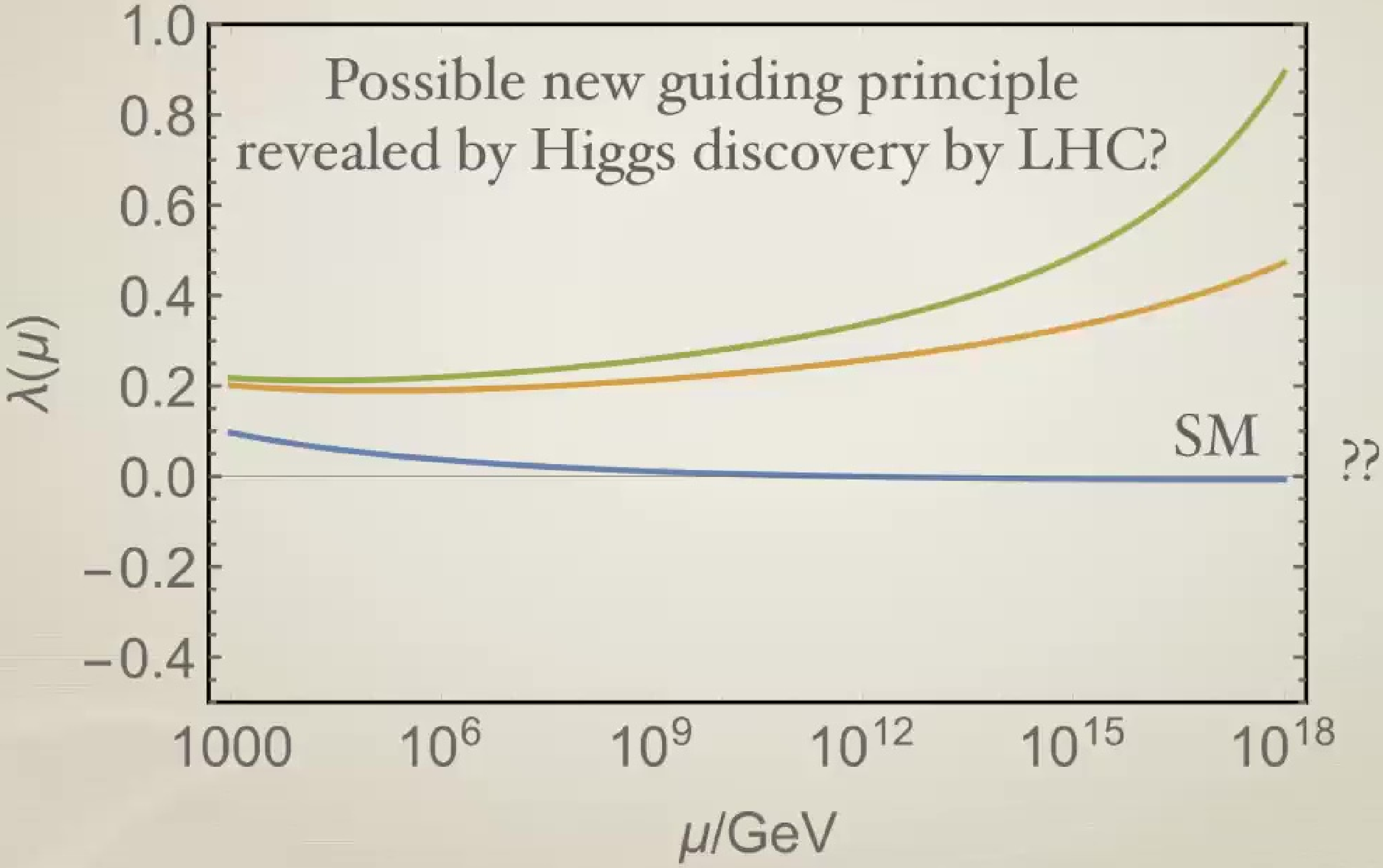
energy-dependent coupling

Small quartic coupling



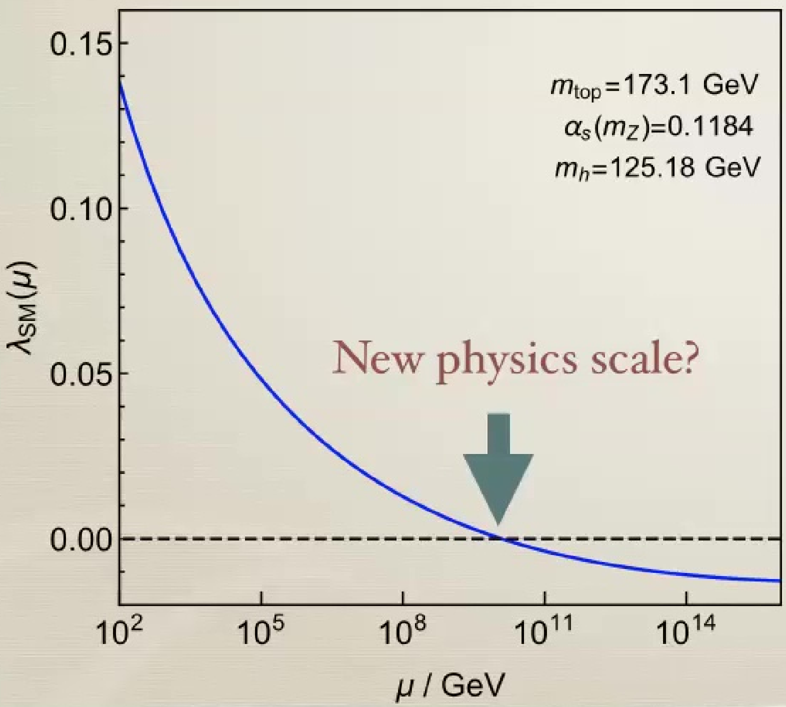
Buttazzo et.al (2013)

Small quartic coupling

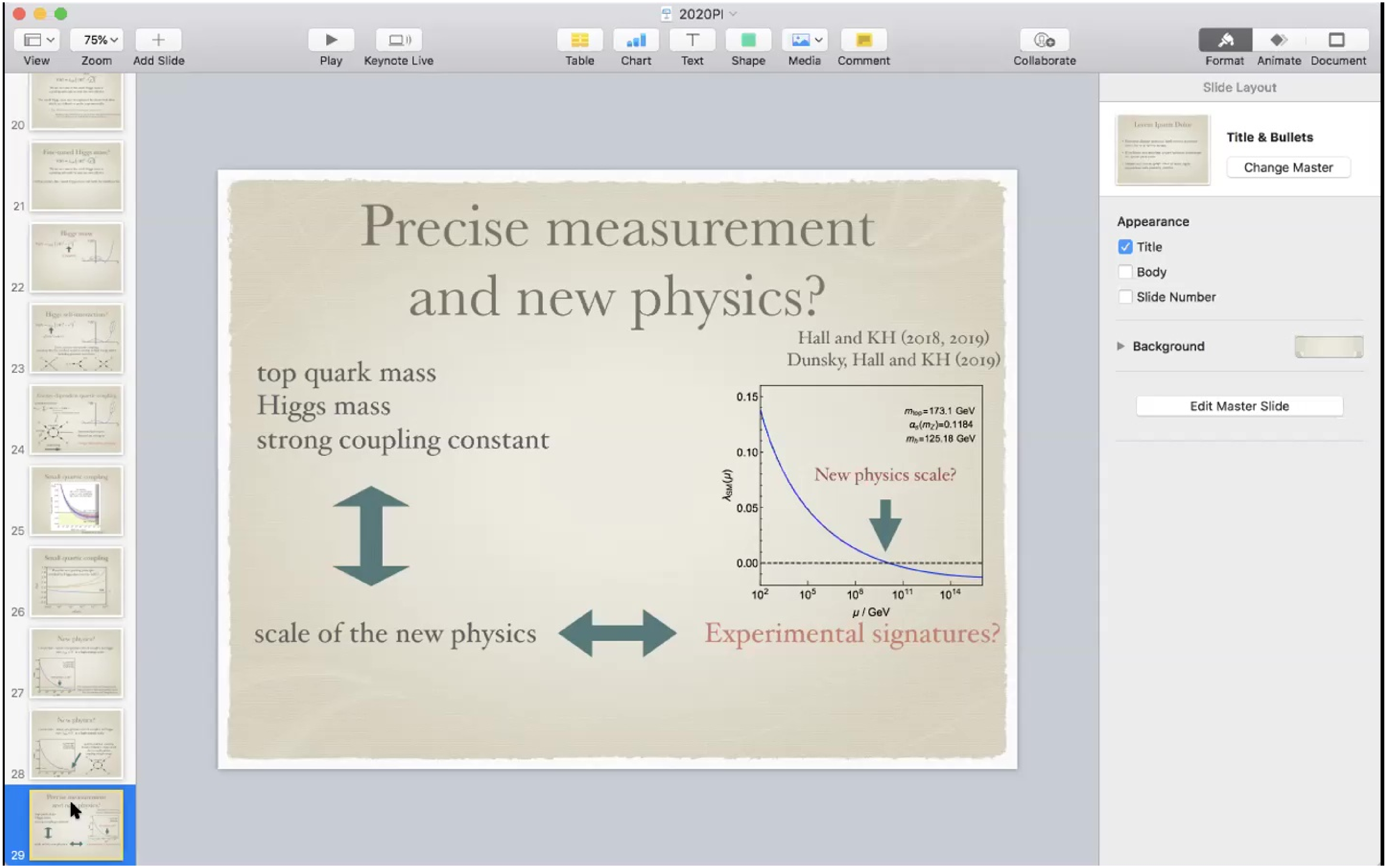


New physics?

Conjecture : some new physics which couples to Higgs sets $\lambda_{SM} \simeq 0$ at a high energy scale



PQ symmetry? Redi and Strumia (2012)
Supersymmetry? Hall and Nomura (2013), Ibe, Matsumoto and Yanagida (2013)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Precise measurement and new physics?
Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)
top quark mass
Higgs mass
strong coupling constant
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
New physics scale?
$\lambda_{SM}(\mu)$
μ / GeV
scale of the new physics
Experimental signatures?
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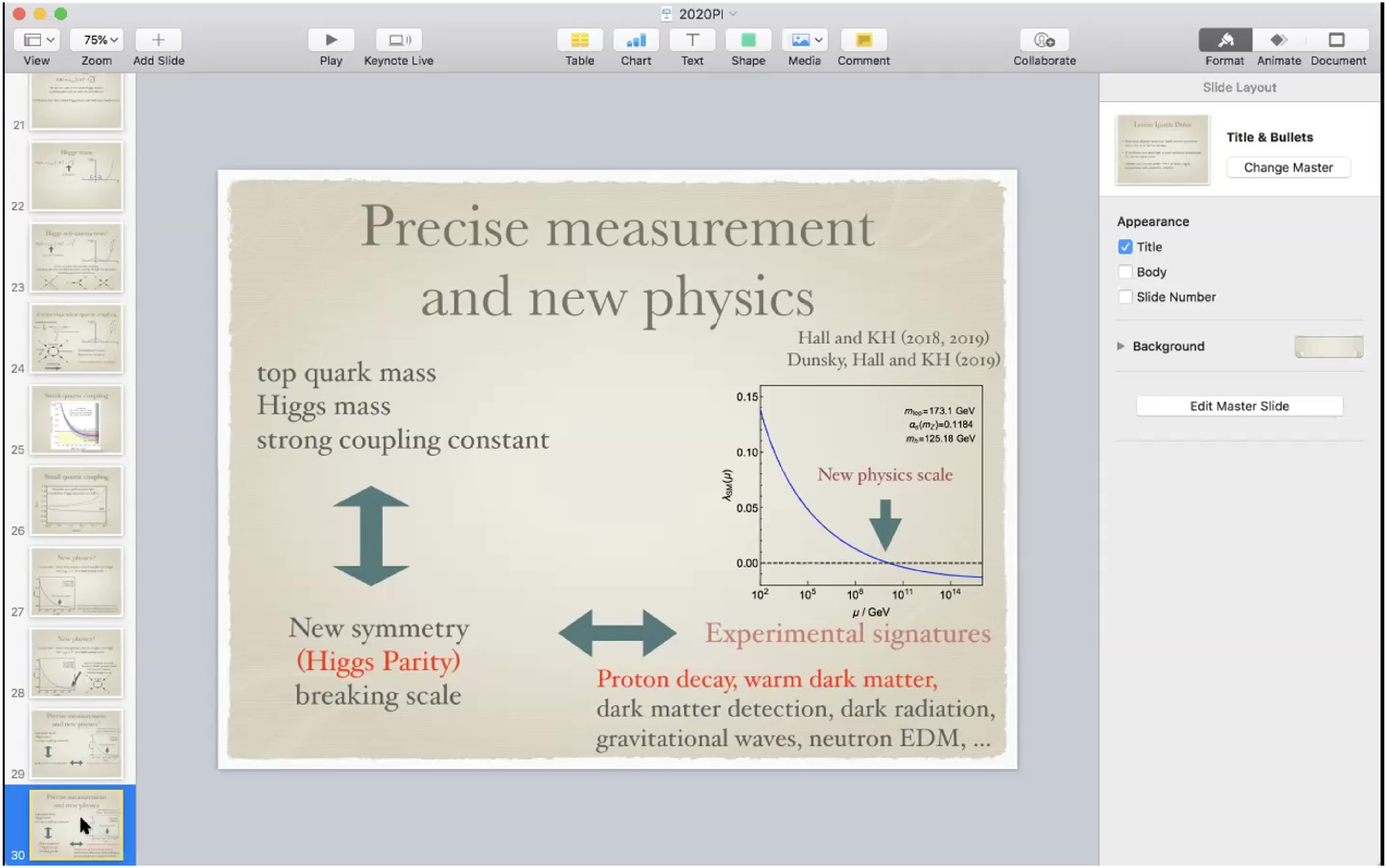
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Precise measurement
and new physics
Hall and KH (2018, 2019)
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top quark mass
Higgs mass
strong coupling constant
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
New physics scale
$\lambda_{SM}(\mu)$
μ / GeV
New symmetry
(Higgs Parity)
breaking scale
Experimental signatures
Proton decay, warm dark matter,
dark matter detection, dark radiation,
gravitational waves, neutron EDM, ...
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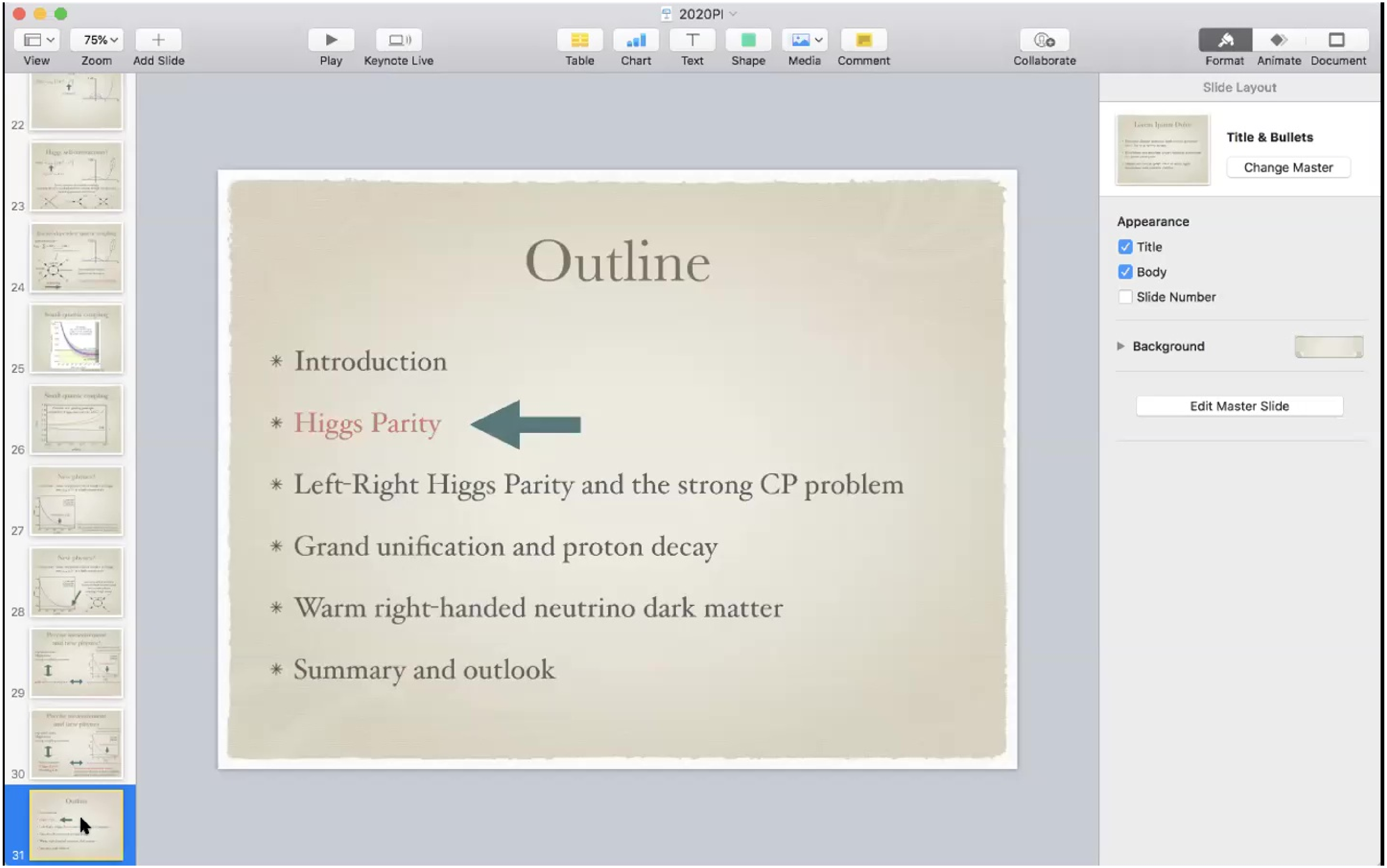
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Symmetry

Symmetry has been playing the central role in physics

Dictate relations among masses
and interaction rates of particles

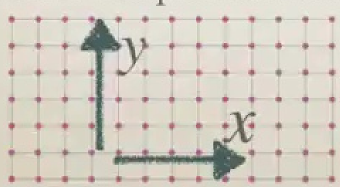
* Symmetry of hadrons

  Explain why the proton mass is similar to the neutron mass

  938.27 MeV　　　　939.57 MeV

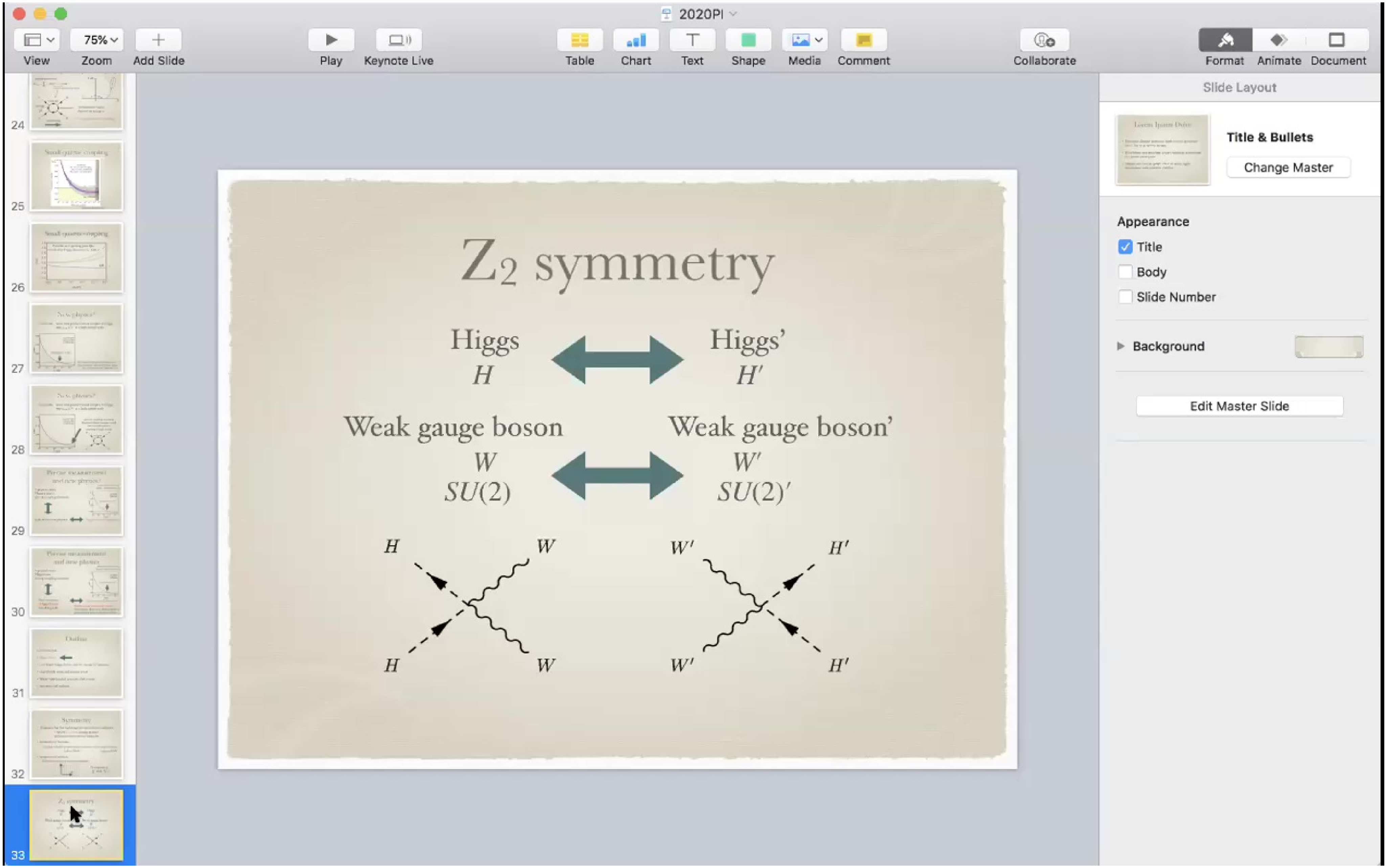
* Symmetry of crystals

  Relation between phonon excitations



Z2 symmetry

$$x \leftrightarrow y$$



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Z2 symmetry
Higgs
H
Higgs'
H'
Weak gauge boson
W
SU(2)
Weak gauge boson'
W'
SU(2)'
H W H W
W' H' W' H'
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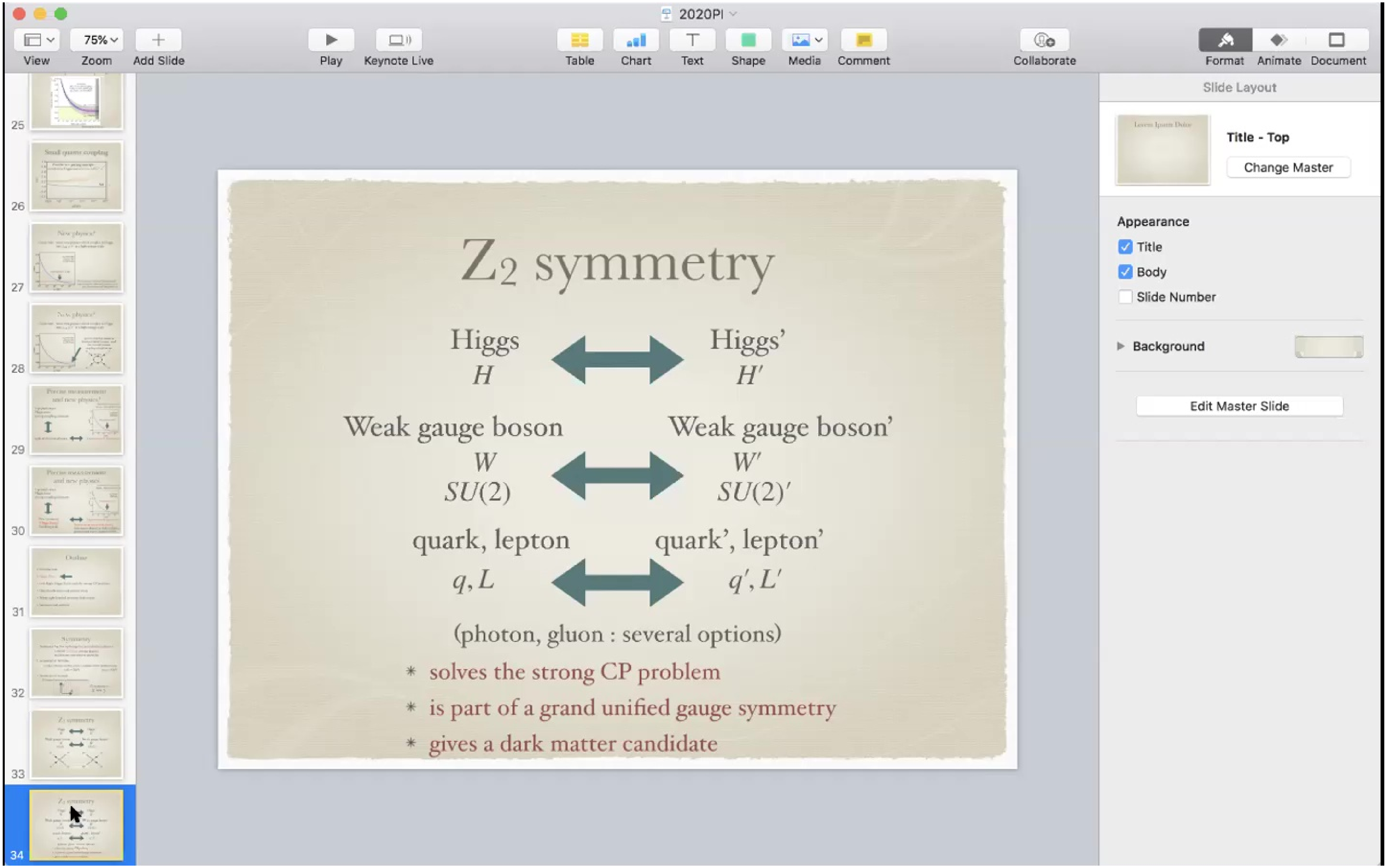
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Z2 symmetry
Higgs
H
Higgs'
H'
Weak gauge boson
W
SU(2)
Weak gauge boson'
W'
SU(2)'
quark, lepton
q, L
quark', lepton'
q', L'
(photon, gluon : several options)
* solves the strong CP problem
* is part of a grand unified gauge symmetry
* gives a dark matter candidate
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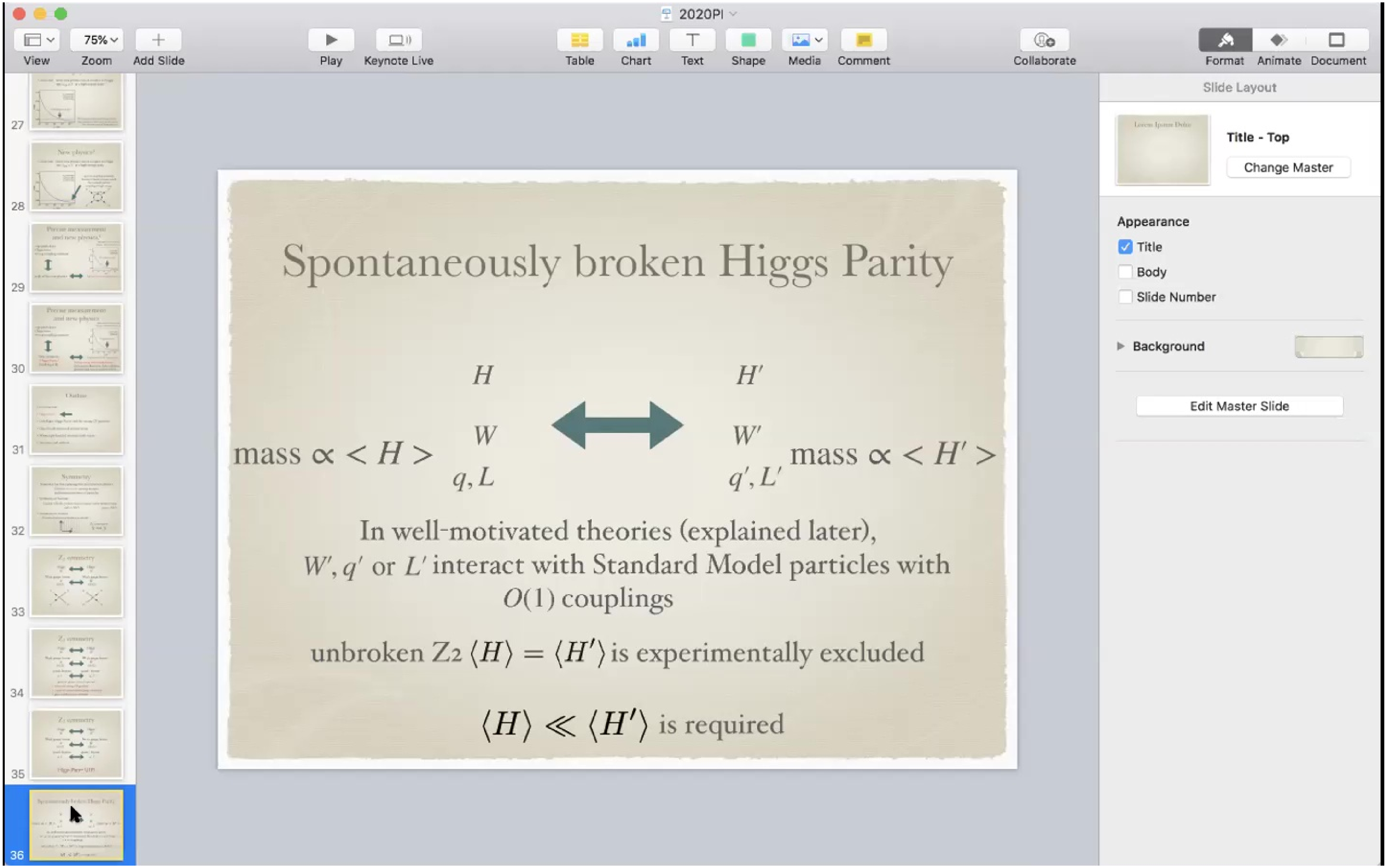
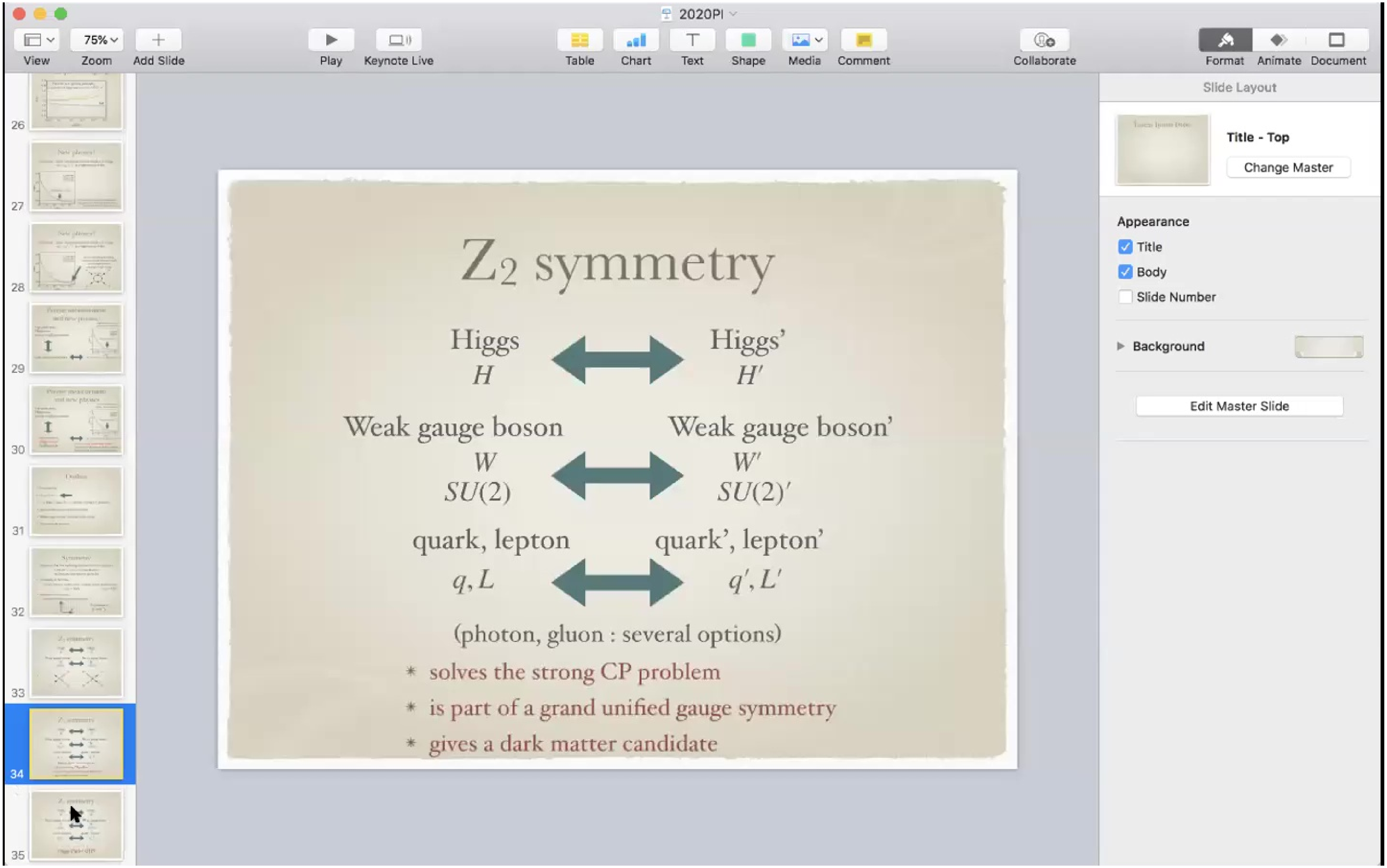

Spontaneously broken Higgs Parity
H
H′
W
W′
mass ∝ < H >
q, L
q′, L′
mass ∝ < H′ >
In well-motivated theories (explained later),
W′, q′ or L′ interact with Standard Model particles with
O(1) couplings
unbroken Z2 ⟨H⟩ = ⟨H′⟩ is experimentally excluded
⟨H⟩ ≪ ⟨H′⟩ is required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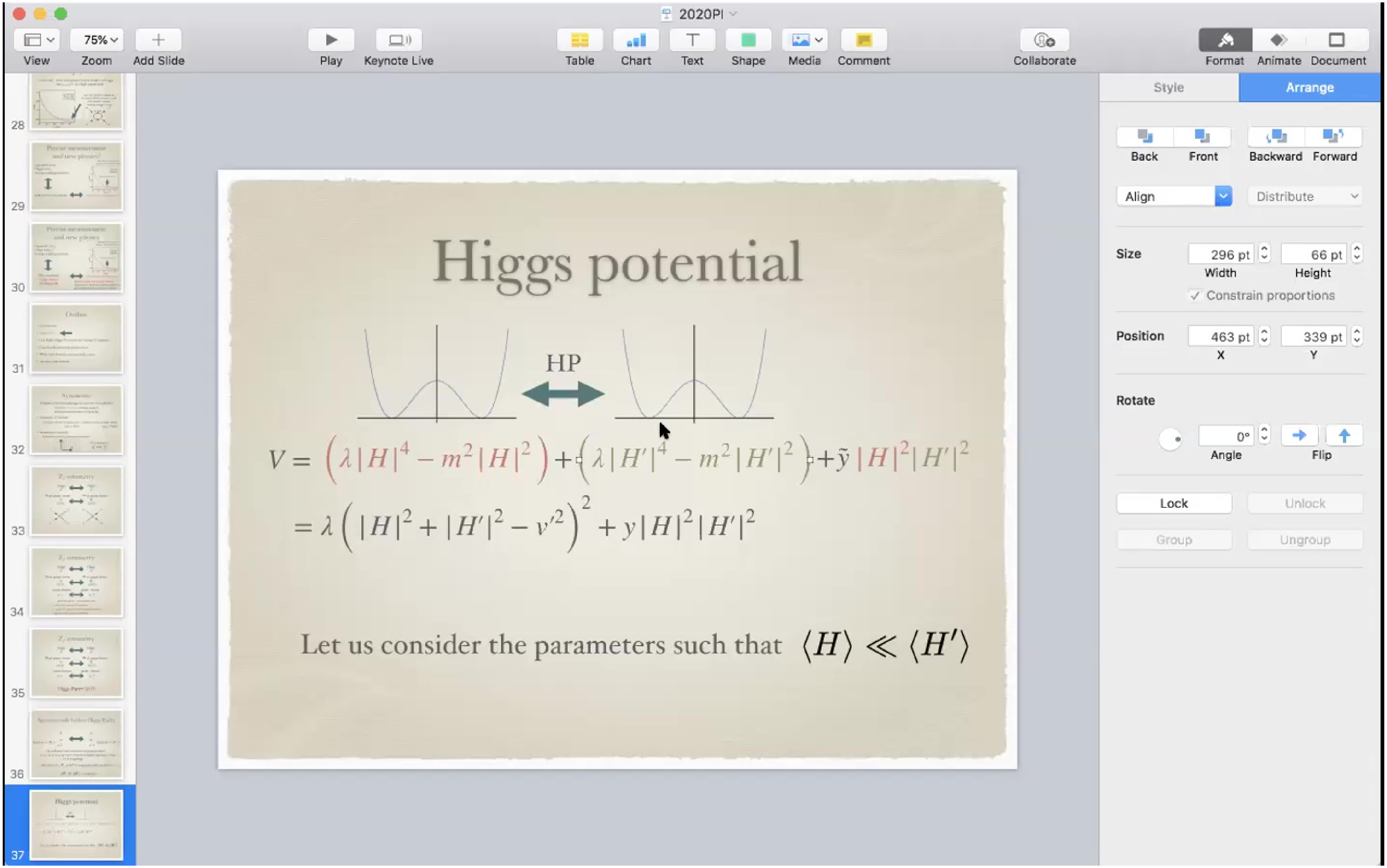
Z2 symmetry
Higgs
H
Higgs'
H'
Weak gauge boson
W
SU(2)
Weak gauge boson'
W'
SU(2)'
quark, lepton
q, L
quark', lepton'
q', L'
(photon, gluon : several options)
* solves the strong CP problem
* is part of a grand unified gauge symmetry
* gives a dark matter candidate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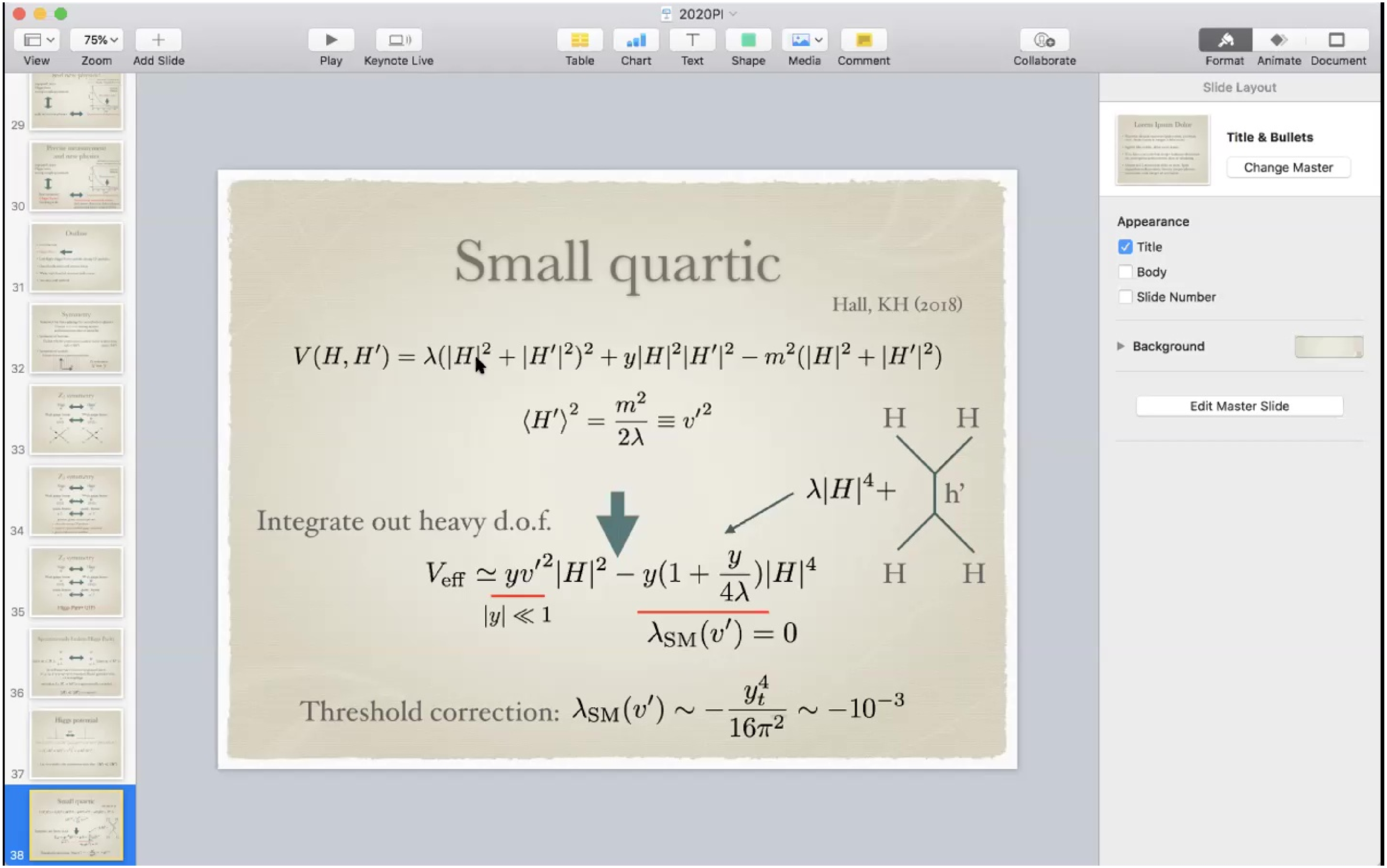
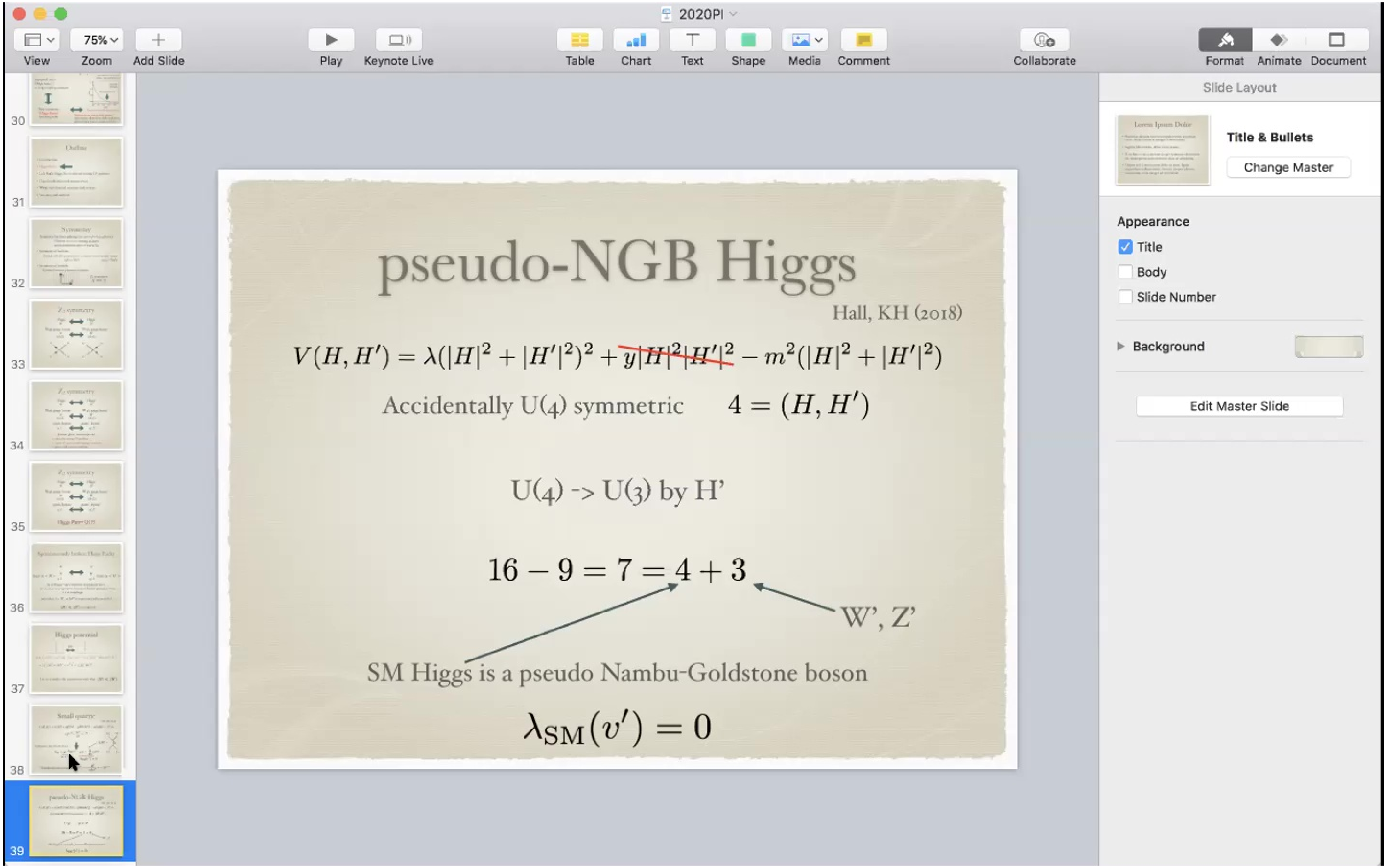
Higgs potential
HP
$V = \left(\lambda |H|^4 - m^2 |H|^2\right) + \left(\lambda |H'|^4 - m^2 |H'|^2\right) + \tilde{y}\, |H|^2 |H'|^2$
$= \lambda \left(|H|^2 + |H'|^2 - v'^2 \right)^2 + y\, |H|^2 |H'|^2$
Let us consider the parameters such that $\langle H \rangle \ll \langle H' \rangle$


Small quartic
Hall, KH (2018)
$V(H,H') = \lambda(|H|^2 + |H'|^2)^2 + y|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$
$\langle H' \rangle^2 = \frac{m^2}{2\lambda} \equiv v'^2$
H H
h'
H H
$\lambda|H|^4 +$
Integrate out heavy d.o.f.
$V_{\rm eff} \simeq yv'^2|H|^2 - y(1 + \frac{y}{4\lambda})|H|^4$
$|y| \ll 1$
$\lambda_{\rm SM}(v') = 0$
Threshold correction: $\lambda_{\rm SM}(v') \sim -\frac{y_t^4}{16\pi^2} \sim -10^{-3}$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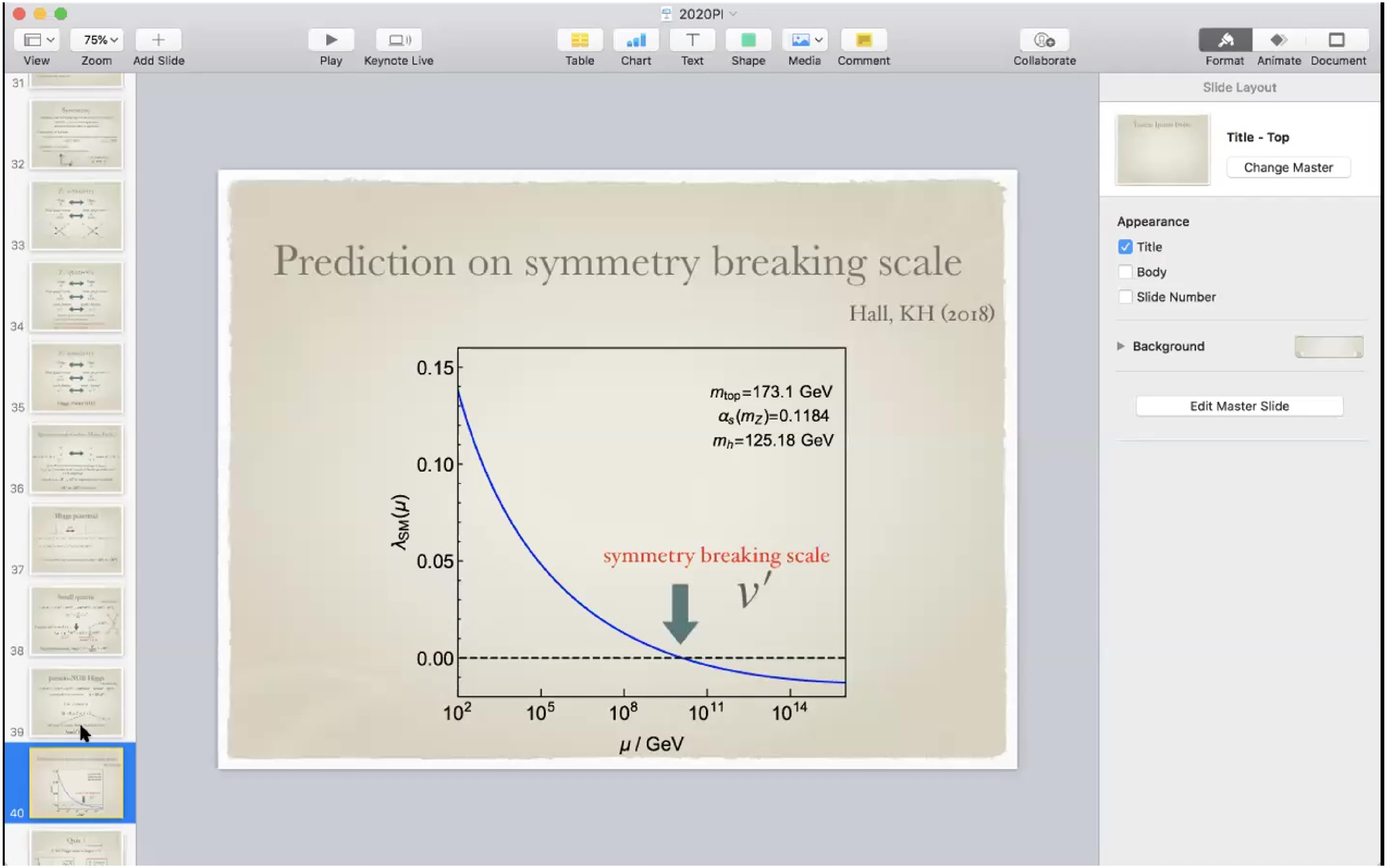
pseudo-NGB Higgs
Hall, KH (2018)
$V(H,H') = \lambda(|H|^2 + |H'|^2)^2 + y|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$
Accidentally U(4) symmetric $4 = (H, H')$
U(4) -> U(3) by H'
$16 - 9 = 7 = 4 + 3$
W', Z'
SM Higgs is a pseudo Nambu-Goldstone boson
$\lambda_{\rm SM}(v') = 0$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Prediction on symmetry breaking scale
Hall, KH (2018)
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
symmetry breaking scale
v'
0.15
0.10
0.05
0.00
$\lambda_{SM}(\mu)$
10^2
10^5
10^8
10^{11}
10^{14}
μ / GeV
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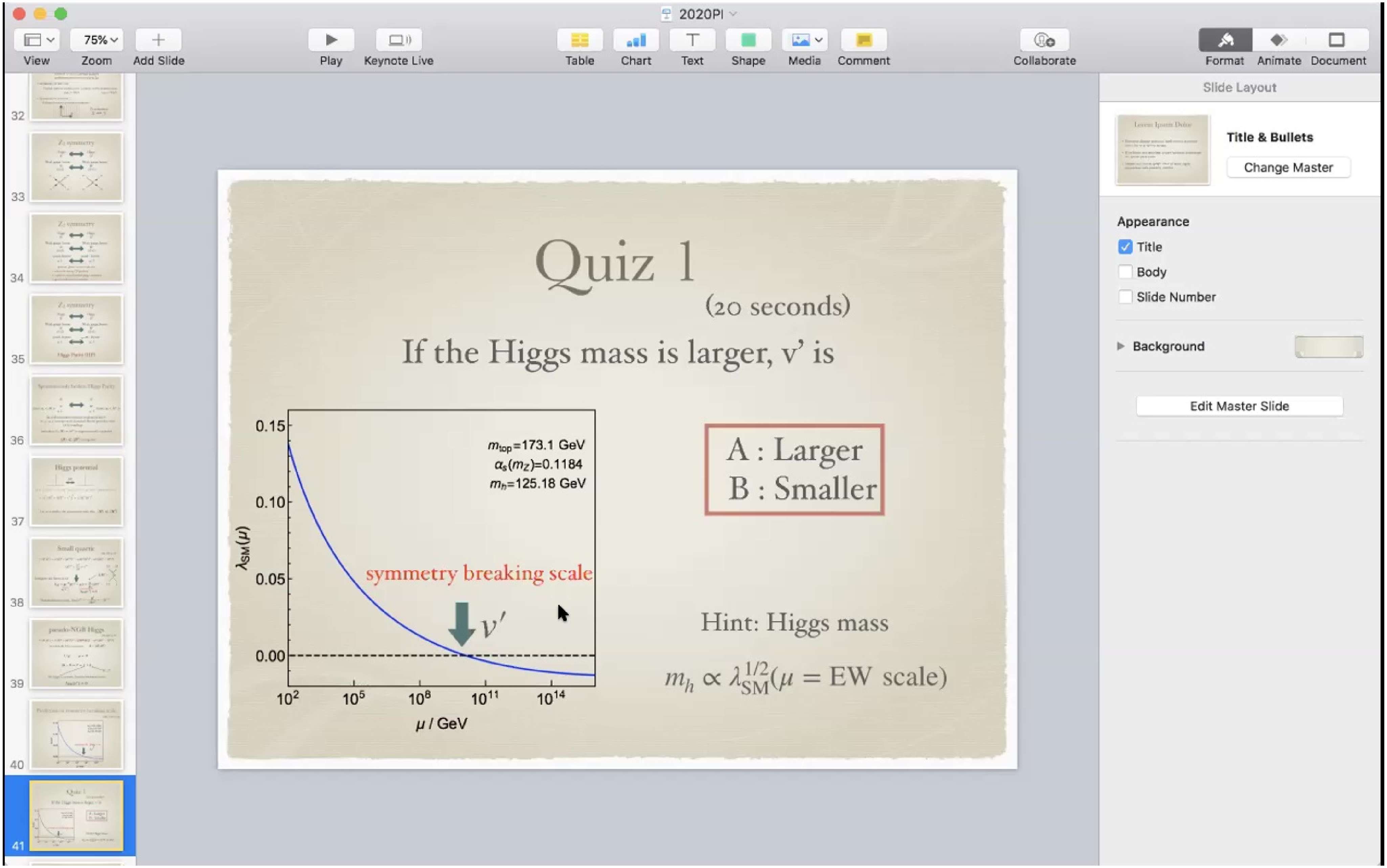
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Quiz 1
(20 seconds)
If the Higgs mass is larger, v' is
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
symmetry breaking scale
v'
$\lambda_{SM}(\mu)$
μ / GeV
A : Larger
B : Smaller
Hint: Higgs mass
$m_h \propto \lambda_{SM}^{1/2}(\mu = \text{EW scale})$
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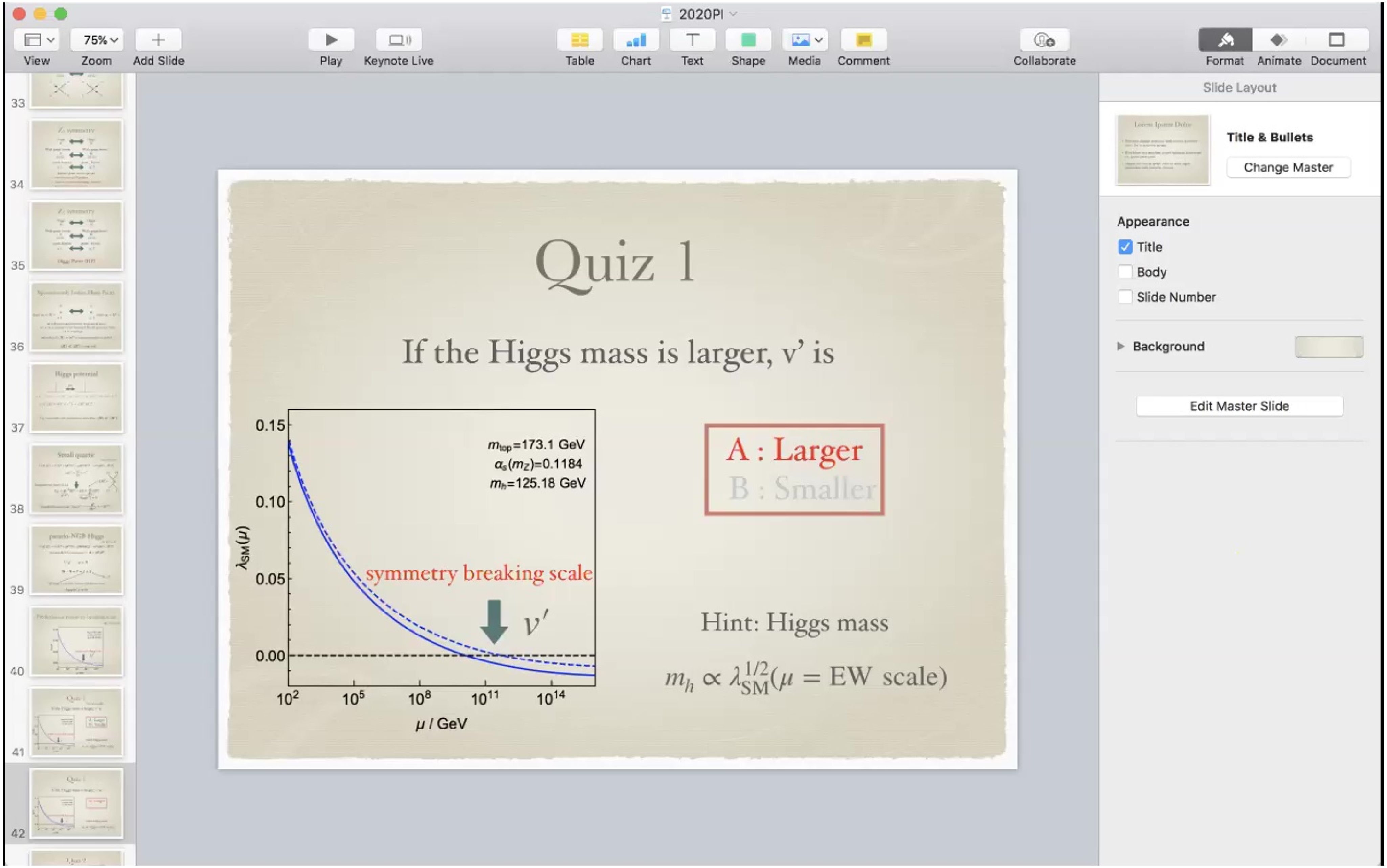
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Quiz 1
If the Higgs mass is larger, v' is
A : Larger
B : Smaller
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
symmetry breaking scale
v'
$\lambda_{SM}(\mu)$
μ / GeV
Hint: Higgs mass
$m_h \propto \lambda_{SM}^{1/2}(\mu = \text{EW scale})$
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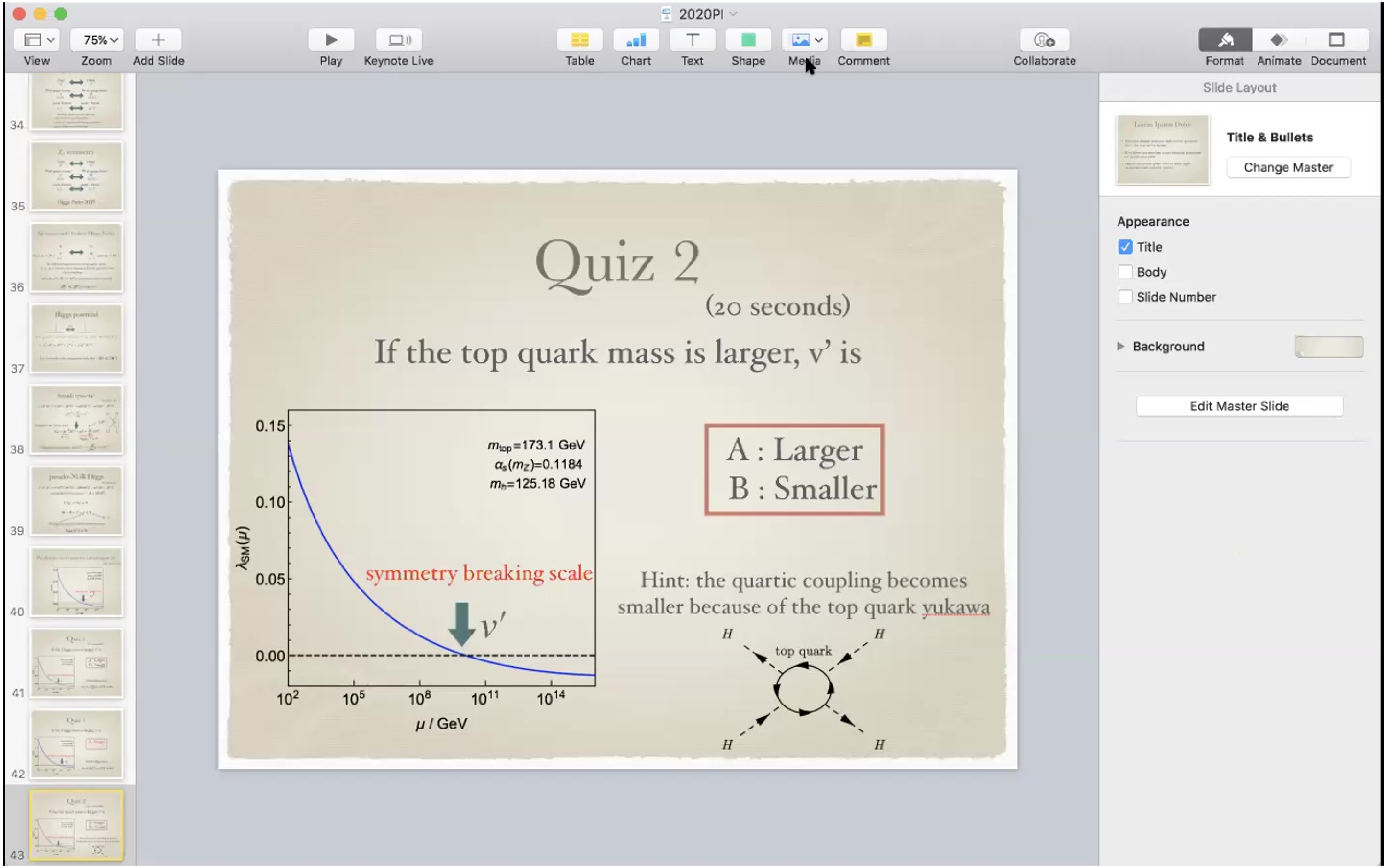
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Quiz 2
(20 seconds)
If the top quark mass is larger, v' is
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
$\lambda_{SM}(\mu)$
μ / GeV
symmetry breaking scale
v'
A : Larger
B : Smaller
Hint: the quartic coupling becomes smaller because of the top quark yukawa
H
H
top quark
H
H
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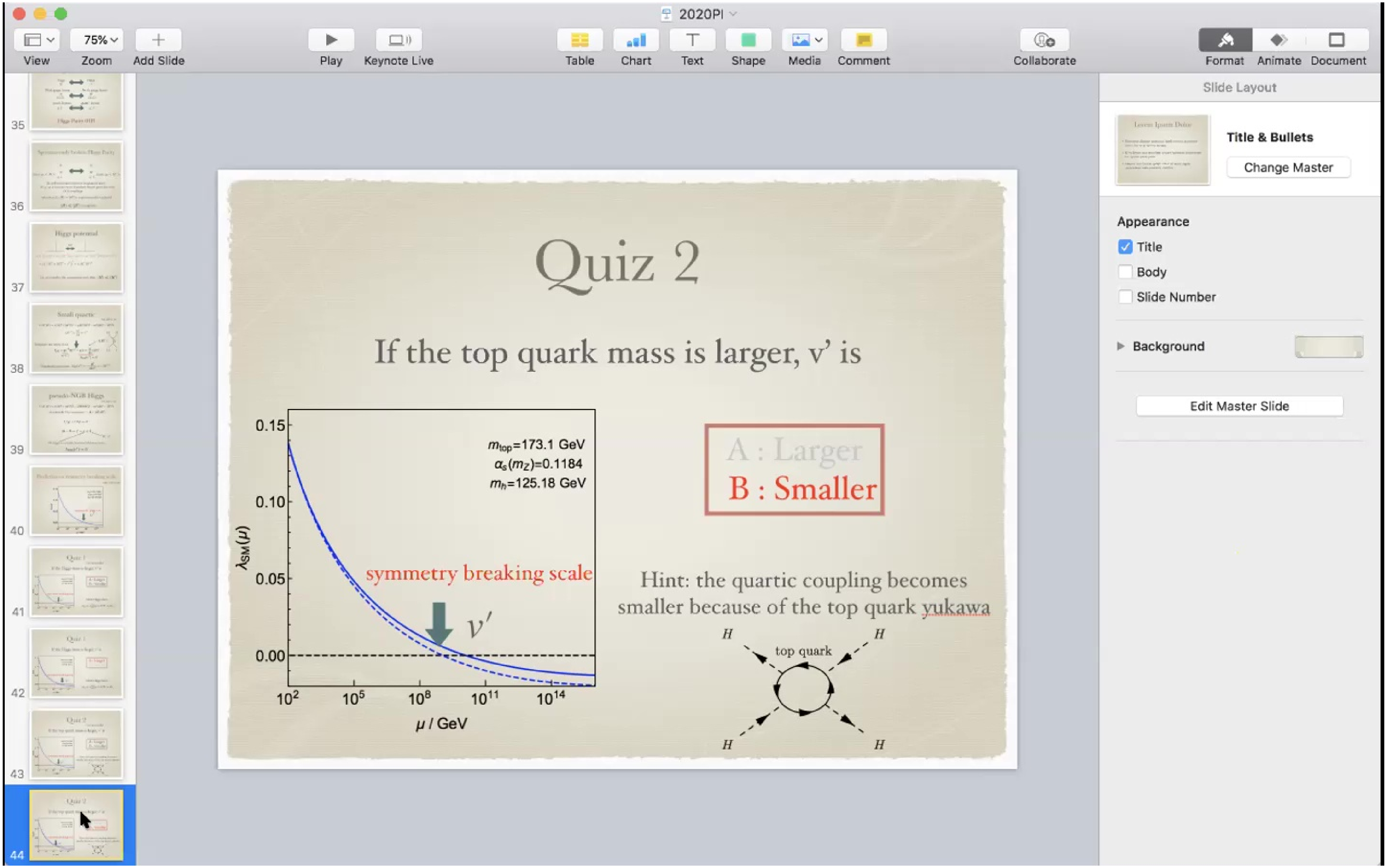
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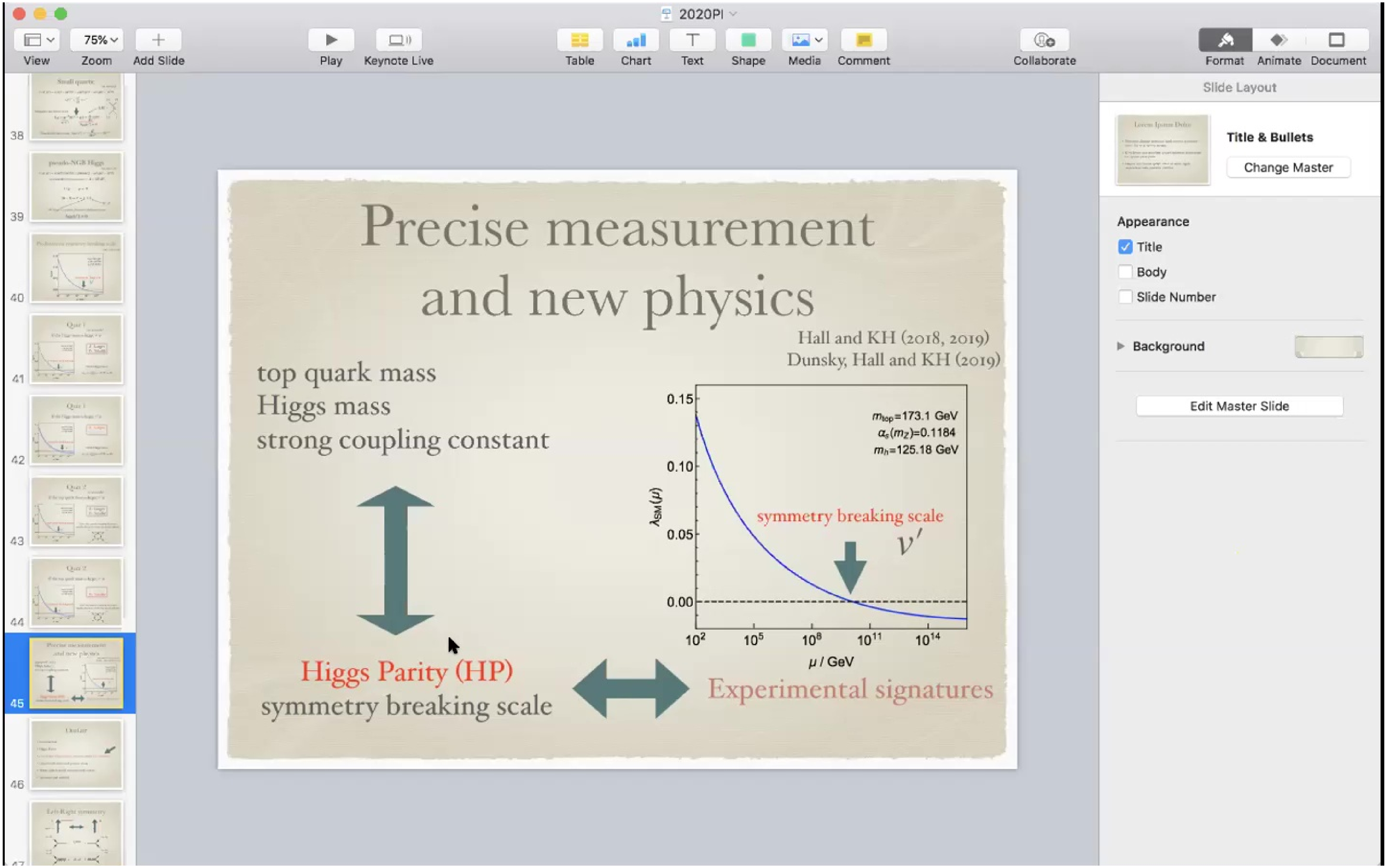
Hint: the quartic coupling becomes smaller because of the top quark yukawa
top quark
H
H
H
H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and new physics
Hall and KH (2018, 2019)
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top quark mass
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strong coupling constant
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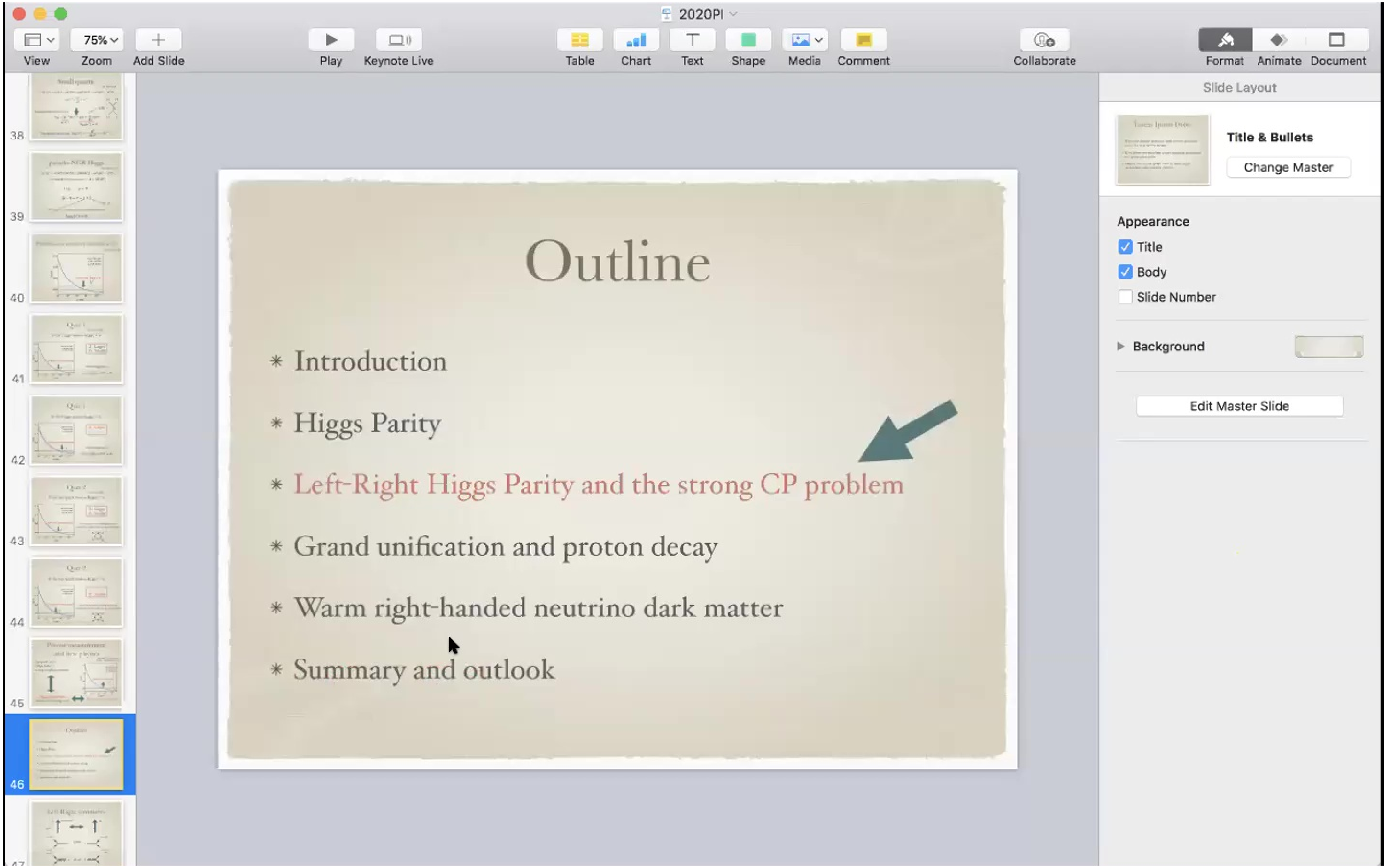
symmetry breaking scale
v'
$\lambda_{SM}(\mu)$
μ / GeV
Higgs Parity (HP)
symmetry breaking scale
Experimental signatures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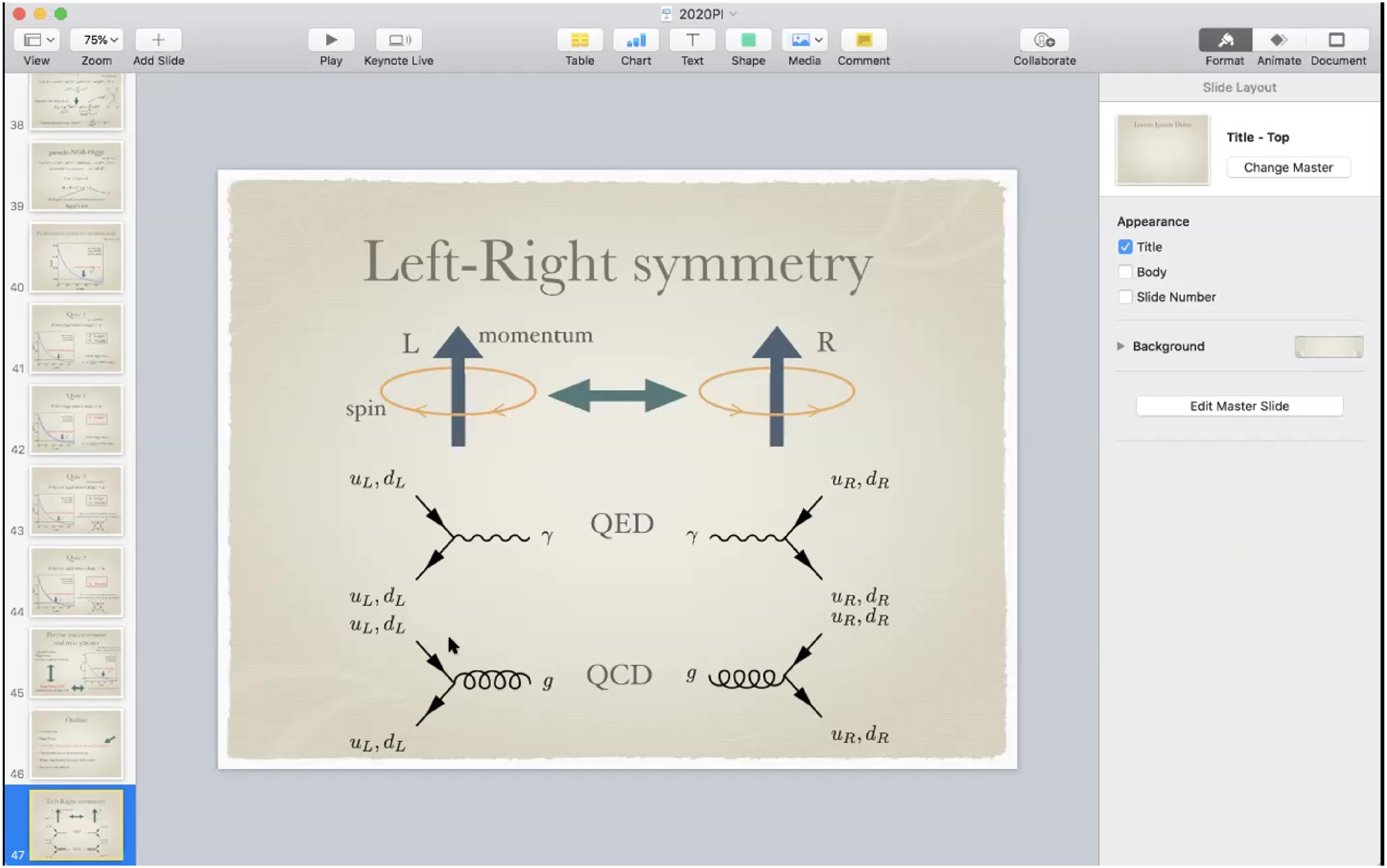
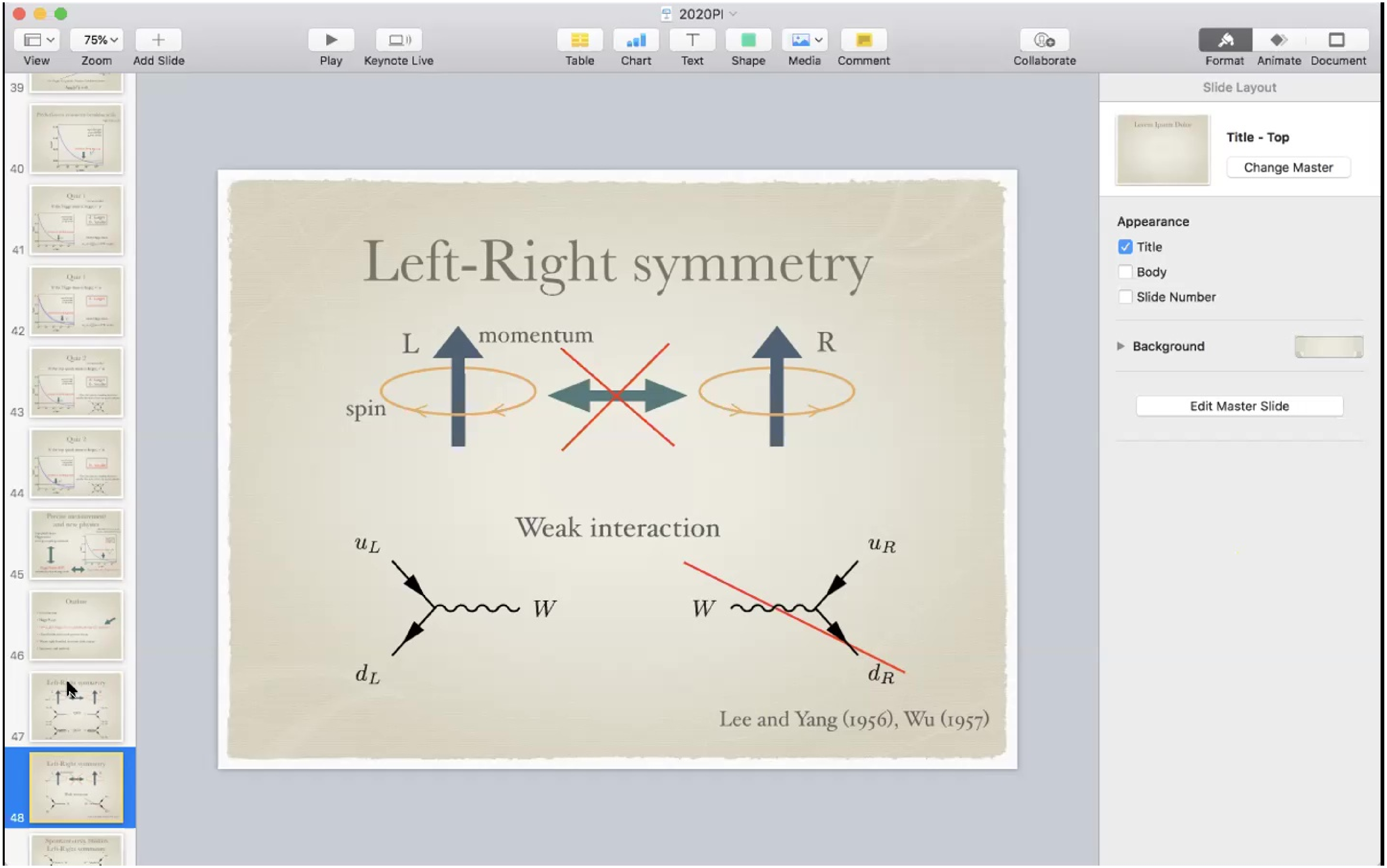

Left-Right symmetry
L
momentum
R
spin
u_L, d_L
u_R, d_R
QED
γ
γ
u_L, d_L
u_R, d_R
u_L, d_L
u_R, d_R
QCD
g
g
u_L, d_L
u_R, d_R


2020PI
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Keynote Live
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Media
Comment
Collaborate
Format
Animate
Document
Left-Right symmetry
L
momentum
R
spin
Weak interaction
u_L
d_L
W
W
u_R
d_R
Lee and Yang (1956), Wu (1957)
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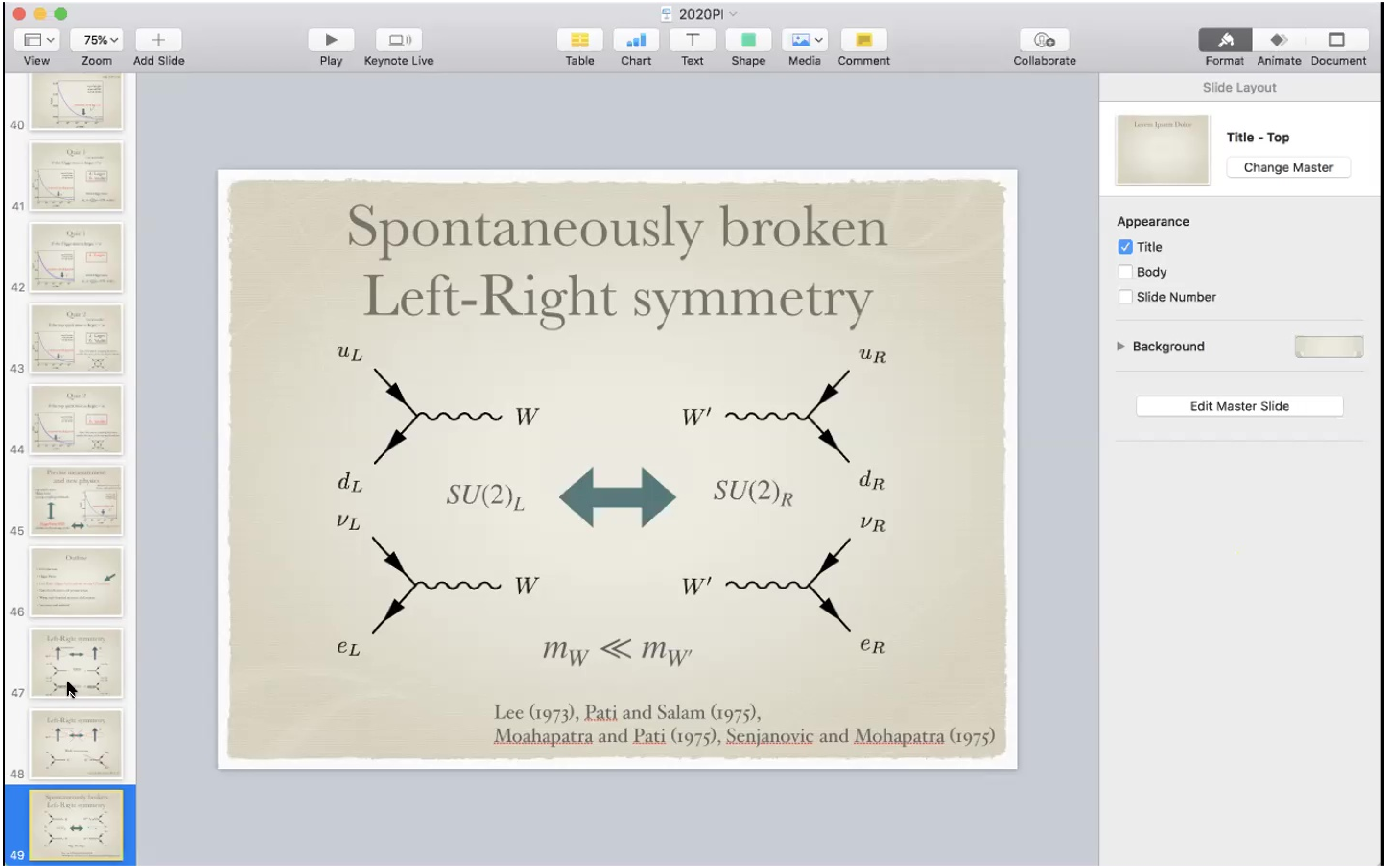
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Document
Spontaneously broken
Left-Right symmetry
u_L
d_L
W
ν_L
e_L
W
$SU(2)_L$
$SU(2)_R$
u_R
d_R
W'
ν_R
e_R
W'
$m_W \ll m_{W'}$
Lee (1973), Pati and Salam (1975),
Moahapatra and Pati (1975), Senjanovic and Mohapatra (1975)
Slide Layout
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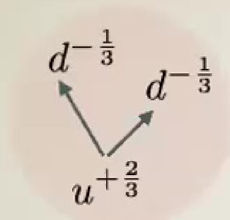
The strong CP problem



Neutron Electric Dipole Moment

$$H = d_n \vec{E} \cdot \vec{S}$$

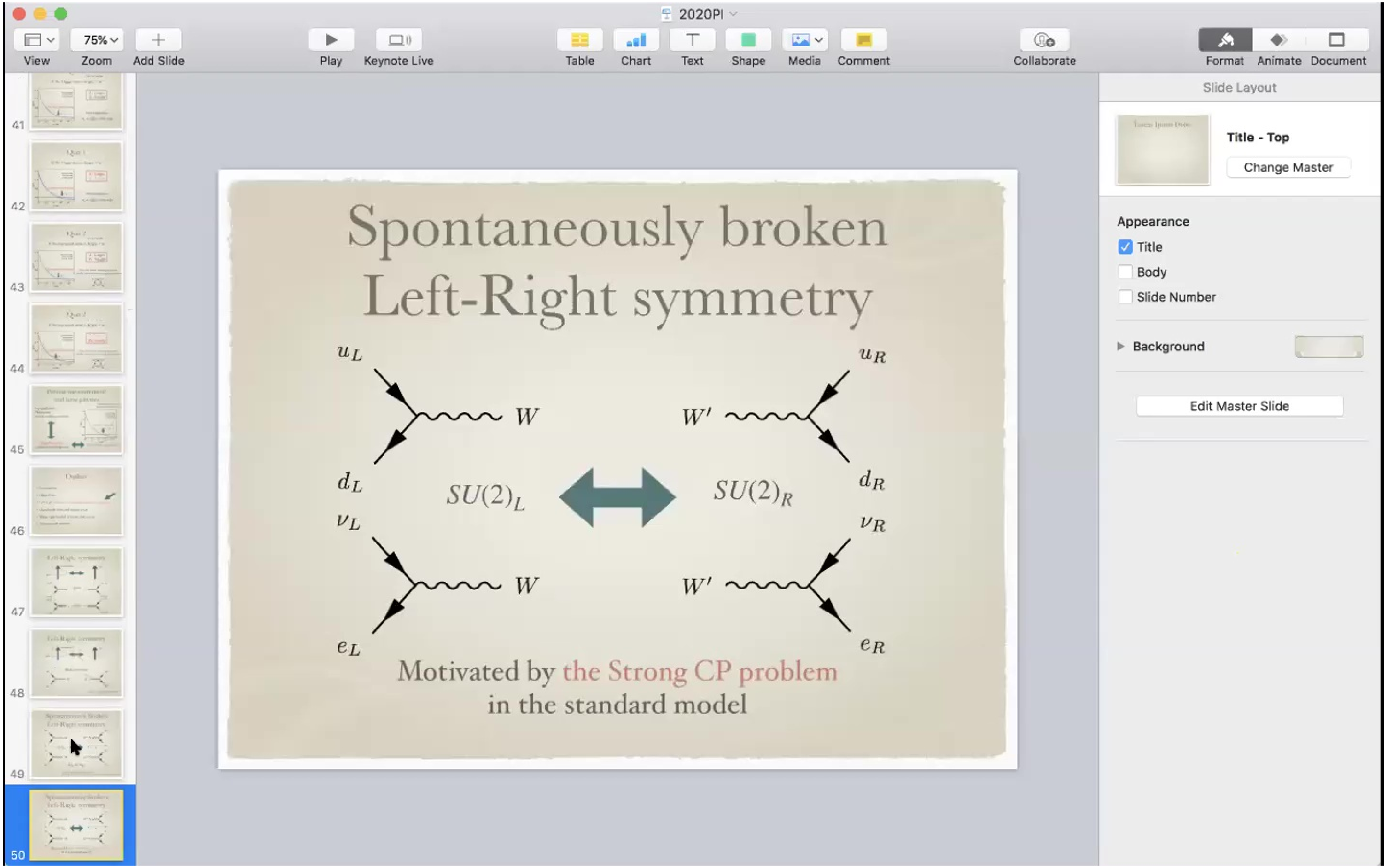
$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm ?}$$

$$d_n/e < 2.9 \times 10^{-26} \text{ cm}$$ Baker et.al (2006)

Suggests CP symmetry forbidding $H = d_n \vec{E} \cdot \vec{S}$

But CP violation from quark masses is essential for CKM phase

Strong CP problem 't Hooft (1976)


2020PI
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Keynote Live
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Comment
Collaborate
Format
Animate
Document
Spontaneously broken
Left-Right symmetry
u_L
d_L
W
$SU(2)_L$
ν_L
e_L
W
u_R
d_R
W'
$SU(2)_R$
ν_R
e_R
W'
Motivated by the Strong CP problem
in the standard model
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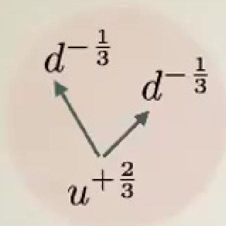
The strong CP problem



Neutron Electric Dipole Moment

$$H = d_n \vec{E} \cdot \vec{S}$$

$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm ?}$$

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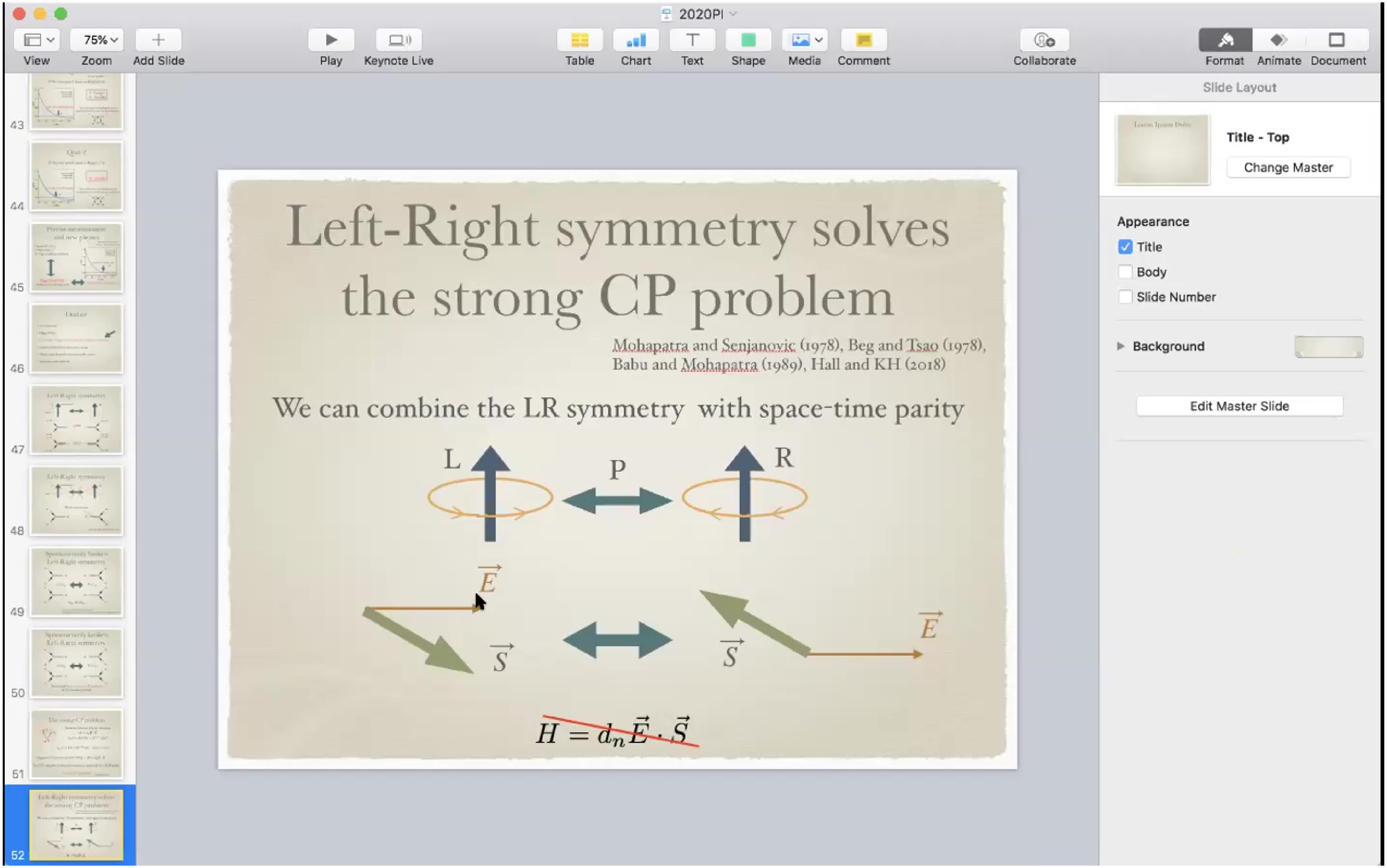
Suggests CP symmetry forbidding $H = d_n \vec{E} \cdot \vec{S}$

But CP violation from quark masses is essential for CKM phase

Strong CP problem 't Hooft (1976)


Left-Right symmetry solves the strong CP problem
Mohapatra and Senjanovic (1978), Beg and Tsao (1978), Babu and Mohapatra (1989), Hall and KH (2018)
We can combine the LR symmetry with space-time parity
L
P
R
$\vec{E}$
$\vec{S}$
$\vec{S}$
$\vec{E}$
$H = d_n \vec{E} \cdot \vec{S}$

Left-Right symmetry solves the strong CP problem

Mohapatra and Senjanovic (1978), Beg and Tsao (1978), Babu and Mohapatra (1989), Hall and KH (2018)

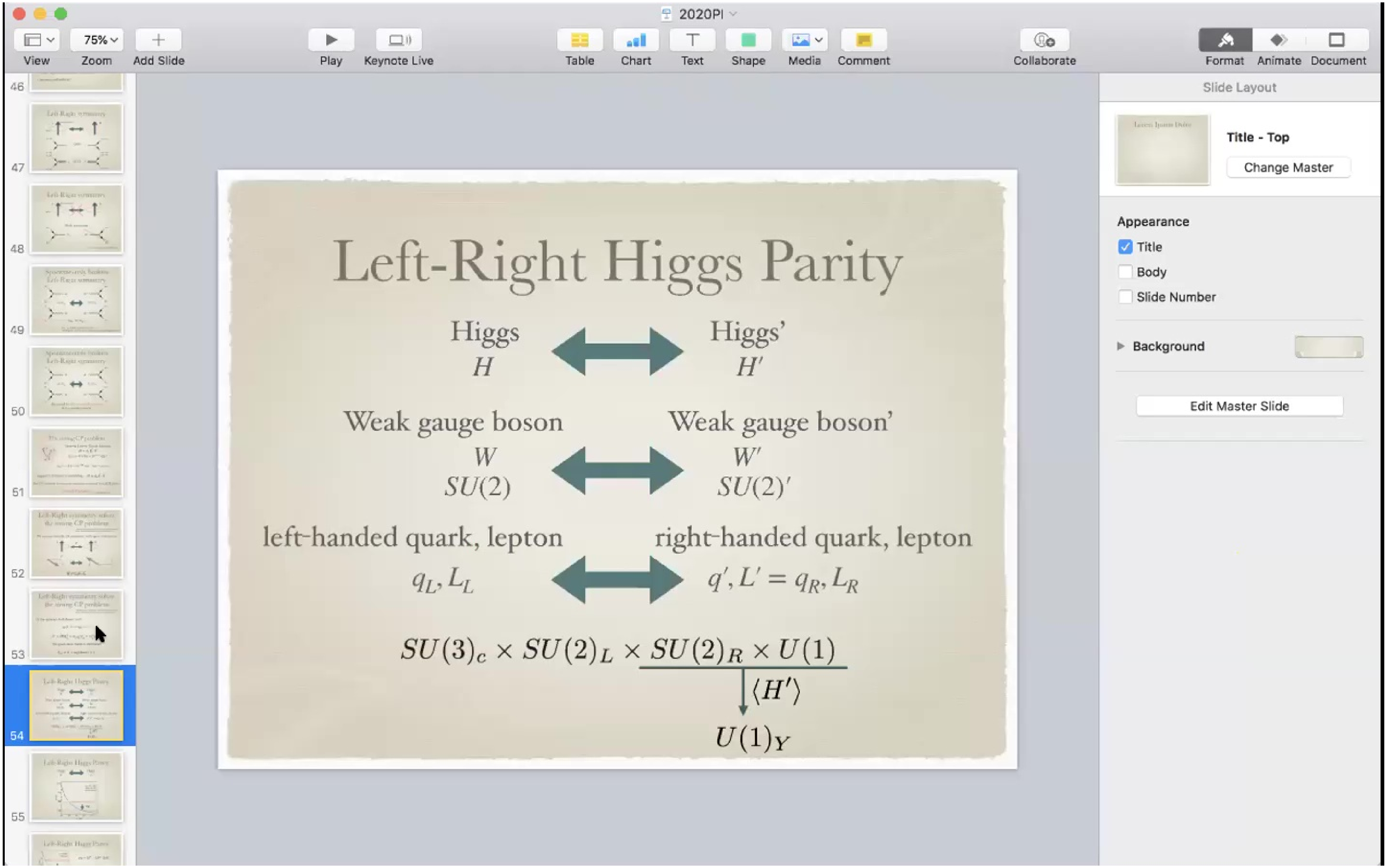
At the quantum field theory level,

$$q_L(x,t) \leftrightarrow q_R(-x,t)$$

$$\mathscr{L} = \cancel{\theta G\tilde{G}} + m_{ij} q_L^i \bar{q}_R^j + m_{ij}^* \bar{q}_L^i q_R^j$$

The quark mass matrix is Hermitian

$$\theta_{CP} = \theta + \arg(\det m) = 0$$


2020PI
Left-Right Higgs Parity
Higgs
H
Higgs'
H'
Weak gauge boson
W
$SU(2)$
Weak gauge boson'
W'
$SU(2)'$
left-handed quark, lepton
q_L, L_L
right-handed quark, lepton
$q', L' = q_R, L_R$
$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$
$\langle H' \rangle$
$U(1)_Y$
Slide Layout
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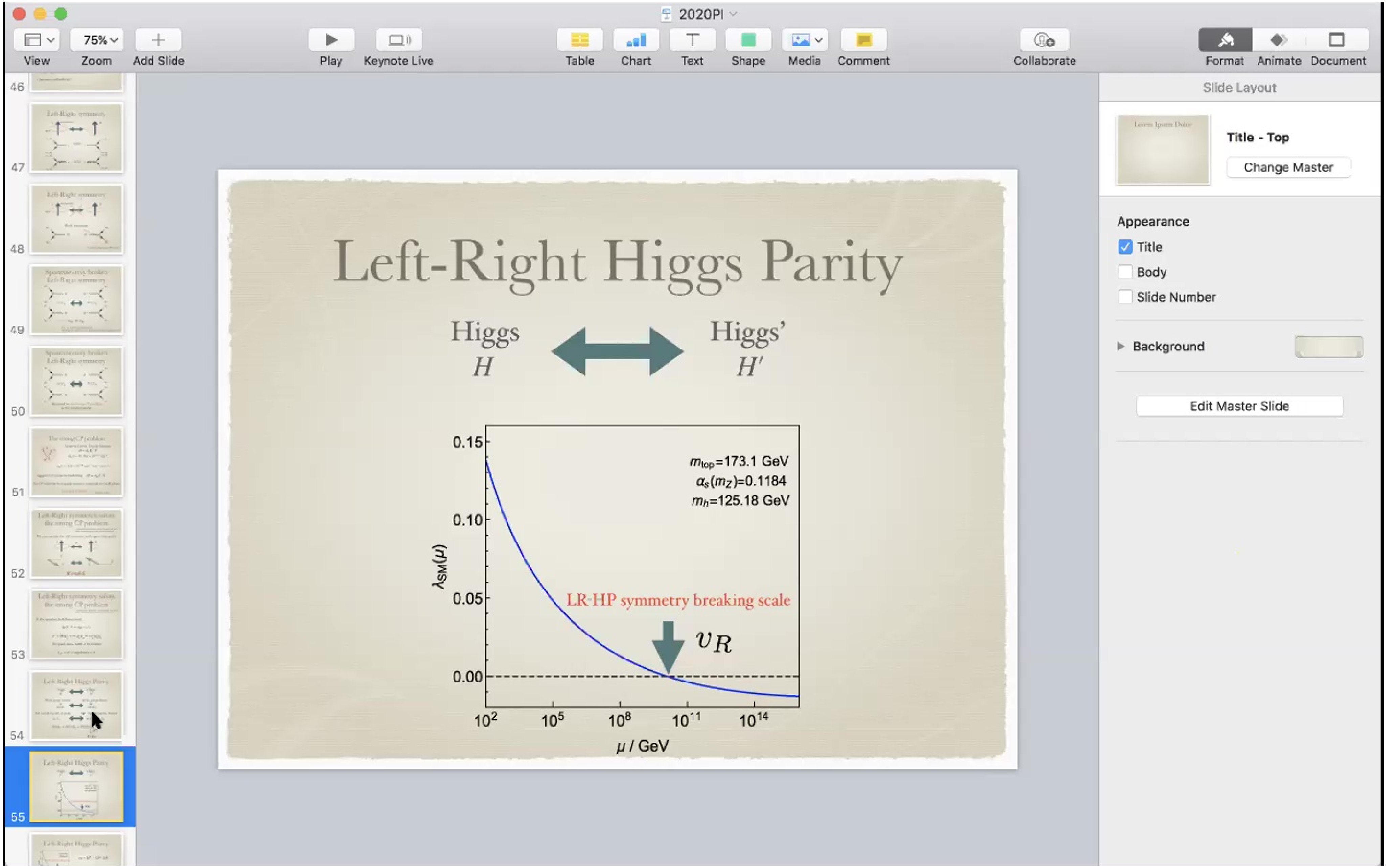
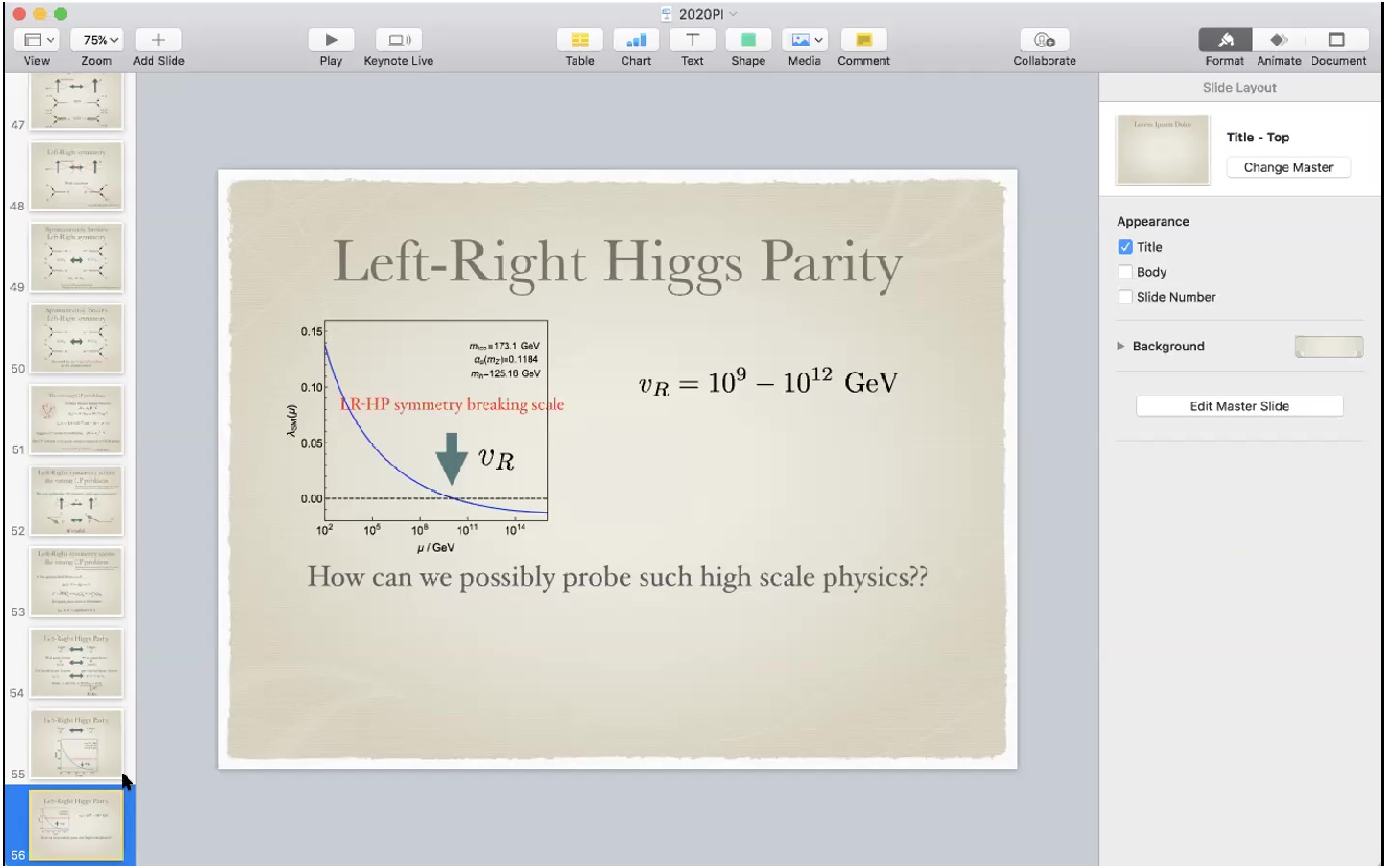
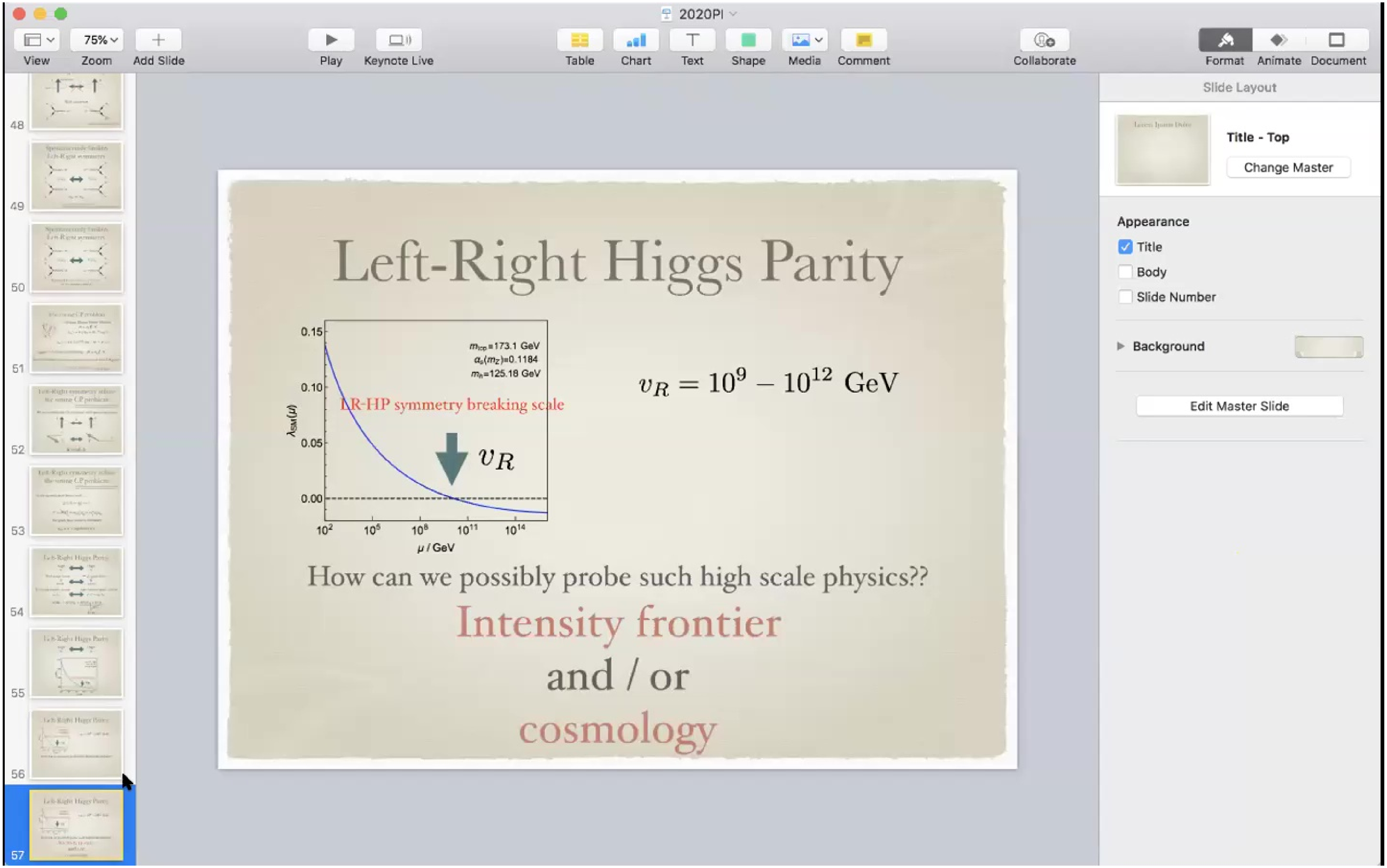
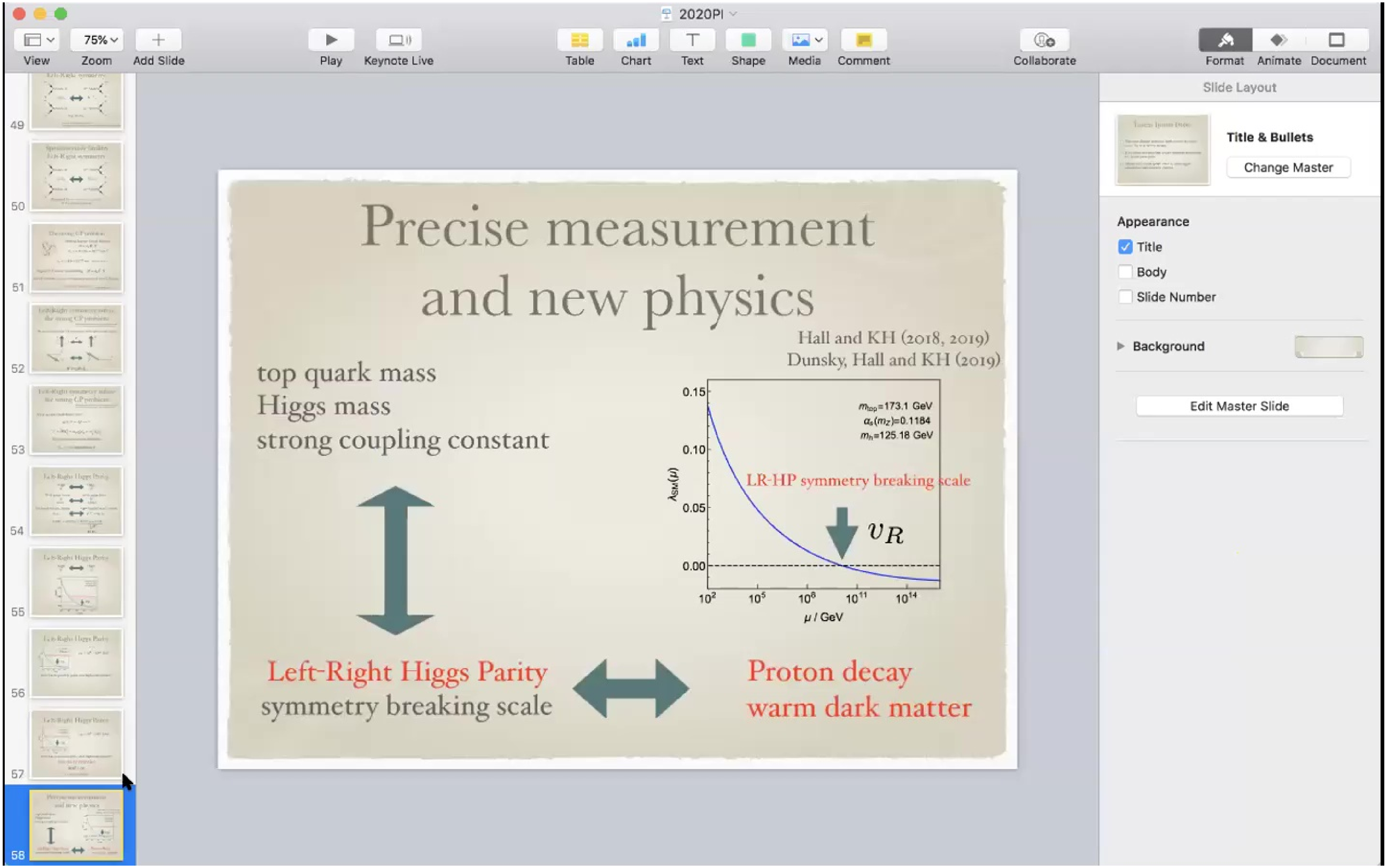
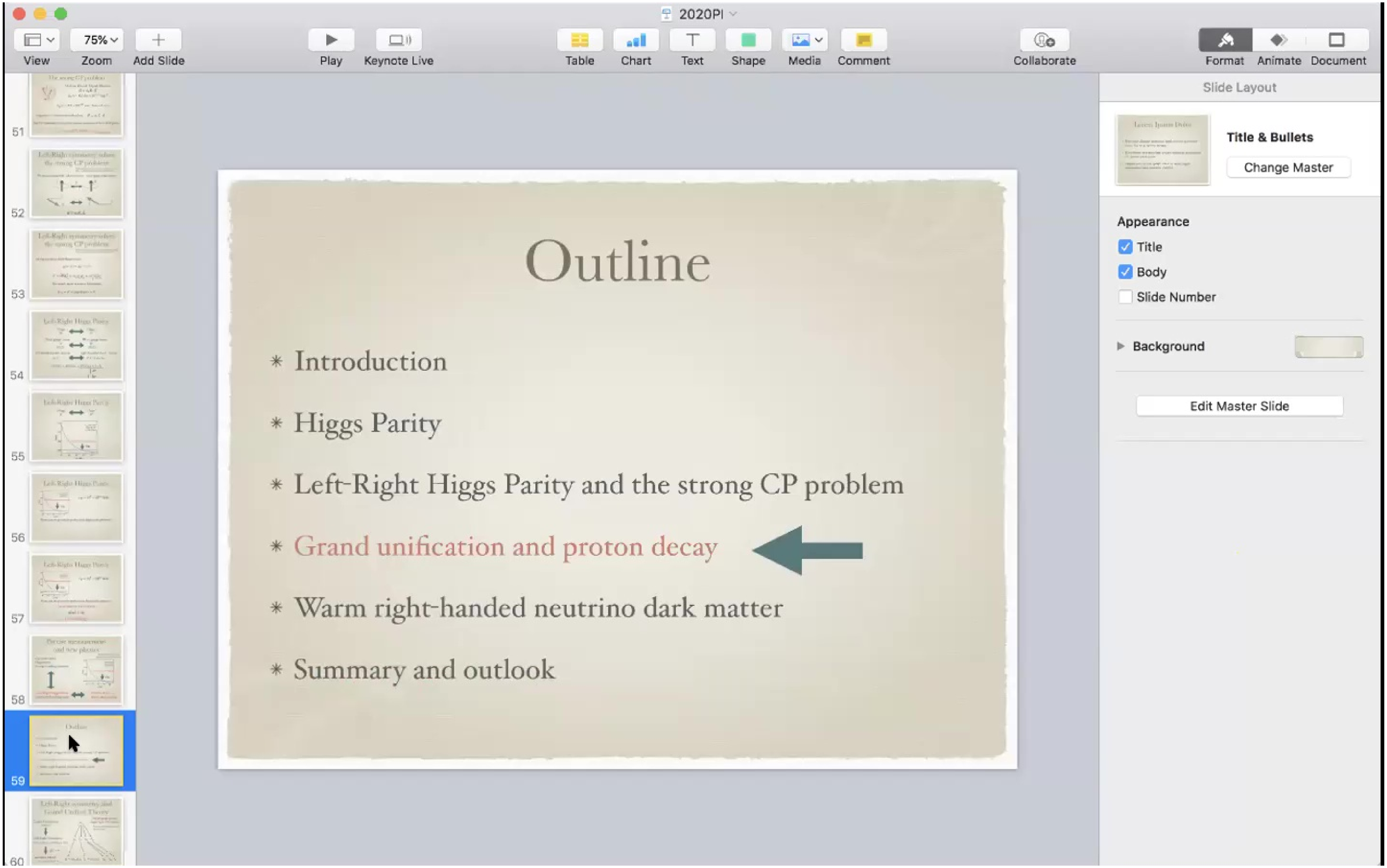

Left-Right Higgs Parity
Higgs
H
Higgs'
H'
m_top=173.1 GeV
α_s(m_Z)=0.1184
m_h=125.18 GeV
λ_SM(μ)
LR-HP symmetry breaking scale
v_R
μ / GeV
0.15
0.10
0.05
0.00
10^2
10^5
10^8
10^11
10^14


Left-Right Higgs Parity
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
LR-HP symmetry breaking scale
v_R
$\lambda_{SM}(\mu)$
μ / GeV
$v_R = 10^9 - 10^{12}$ GeV
How can we possibly probe such high scale physics??


Left-Right Higgs Parity
0.15
0.10
0.05
0.00
$\lambda_{SM}(\mu)$
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
LR-HP symmetry breaking scale
v_R
10^2 10^5 10^8 10^{11} 10^{14}
μ / GeV
$v_R = 10^9 - 10^{12}$ GeV
How can we possibly probe such high scale physics??
Intensity frontier
and / or
cosmology


Precise measurement
and new physics
Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)
top quark mass
Higgs mass
strong coupling constant
m_{top}=173.1 GeV
$\alpha_s(m_Z)$=0.1184
m_h=125.18 GeV
LR-HP symmetry breaking scale
v_R
$\lambda_{SM}(\mu)$
μ / GeV
Left-Right Higgs Parity
symmetry breaking scale
Proton decay
warm dark matter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Format
Animate
Document
Outline
* Introduction
* Higgs Parity
* Left-Right Higgs Parity and the strong CP problem
* Grand unification and proton decay
* Warm right-handed neutrino dark matter
* Summary and outlook
Slide Layout
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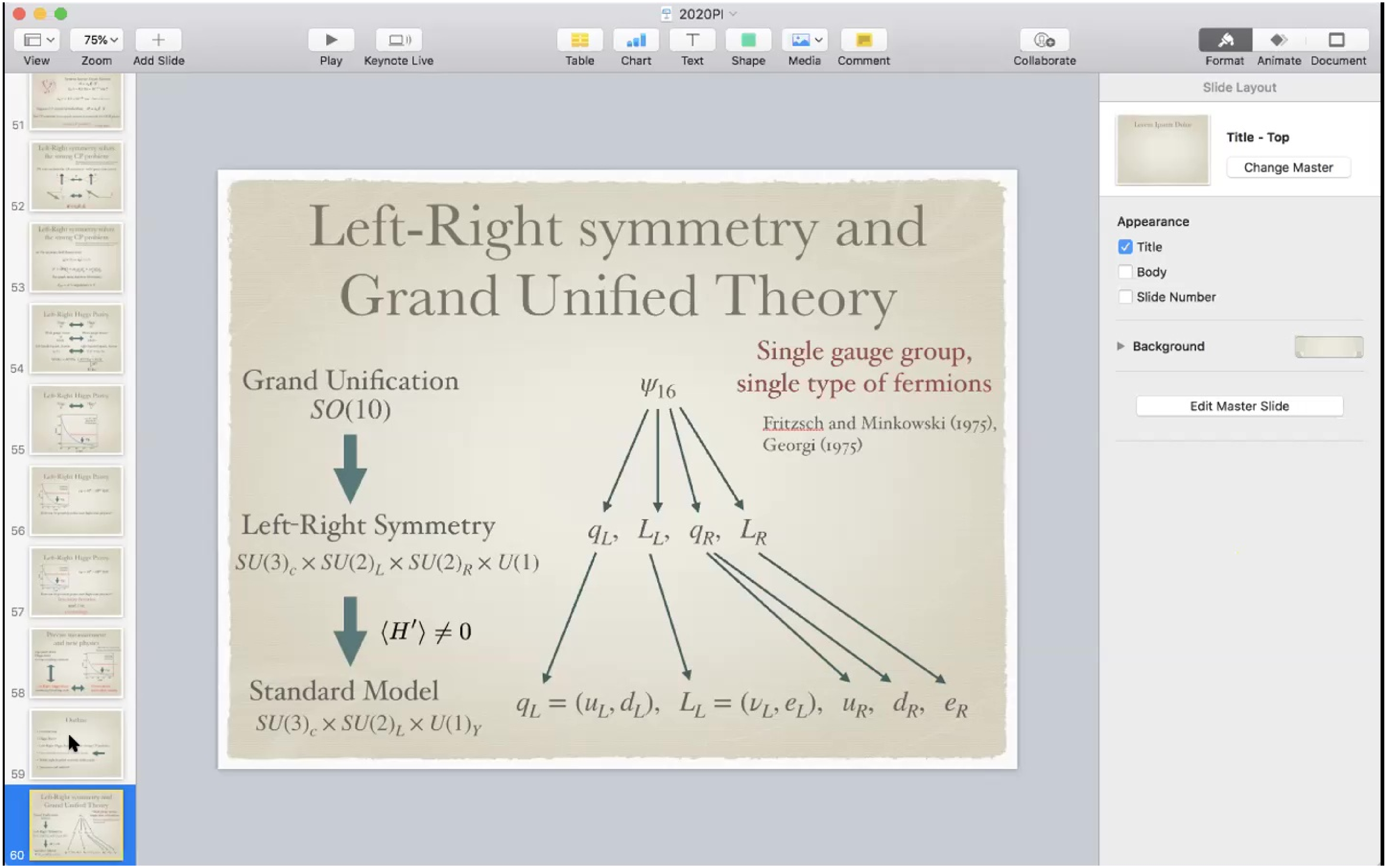
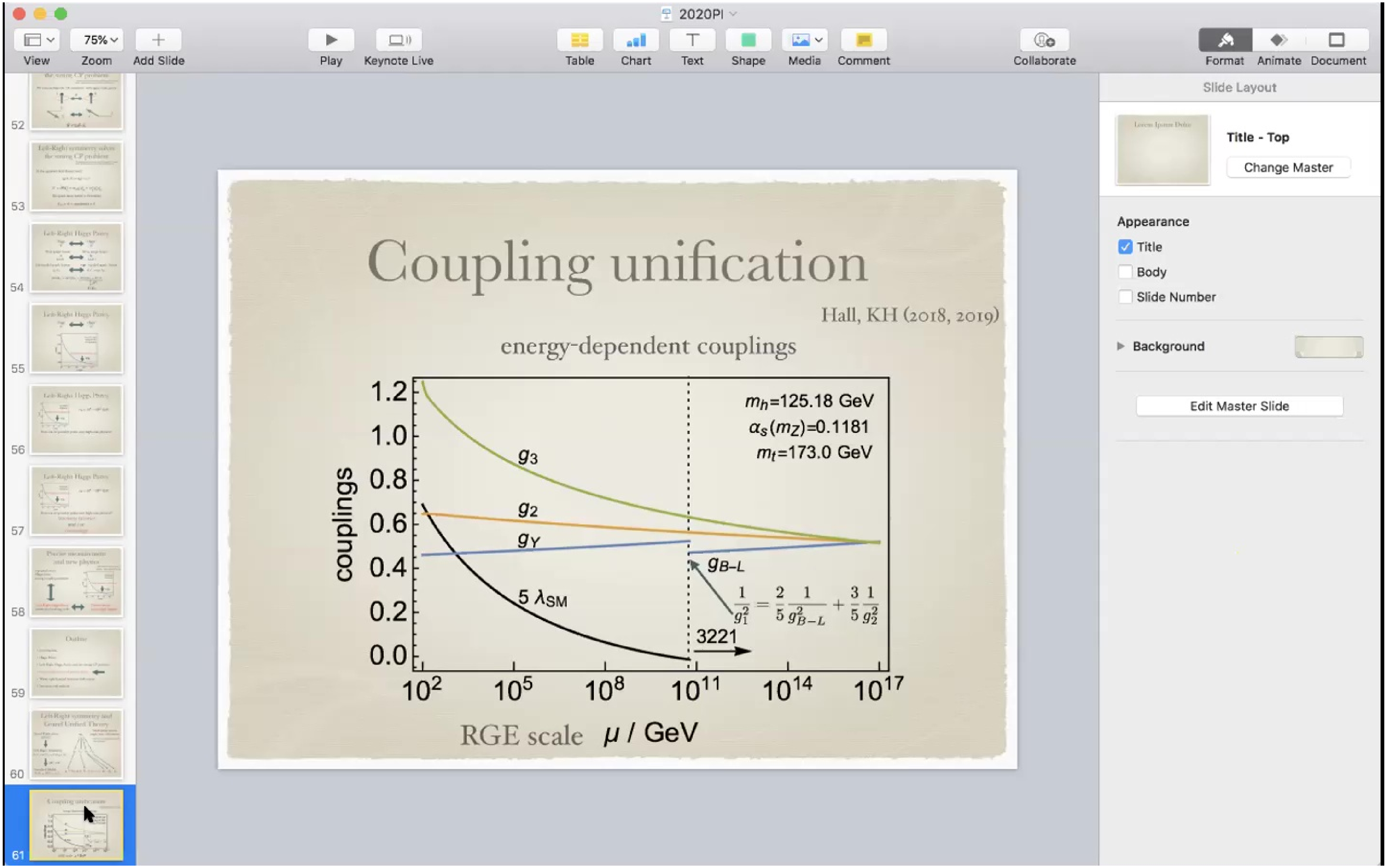
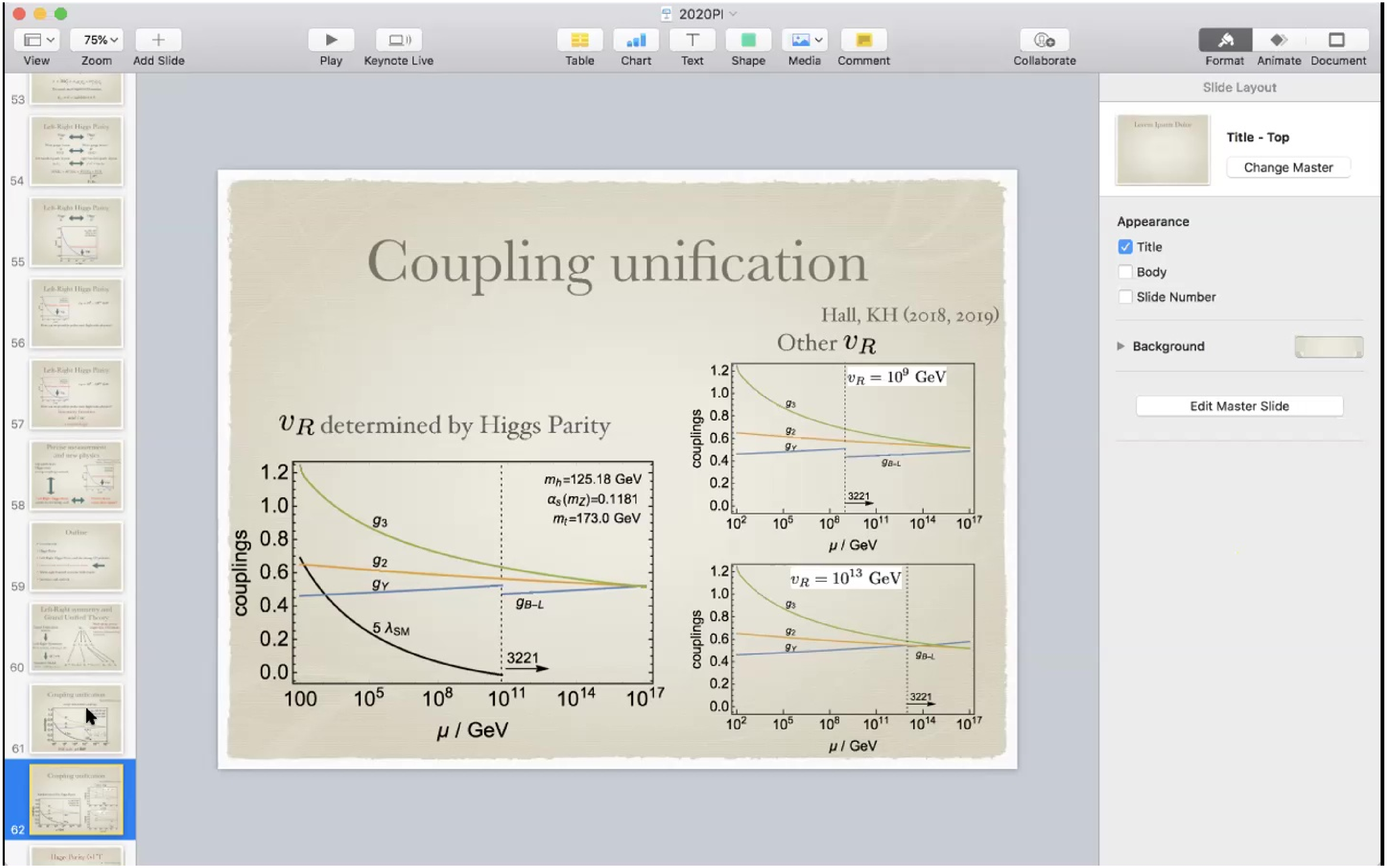

Left-Right symmetry and Grand Unified Theory
Grand Unification
$SO(10)$
Left-Right Symmetry
$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$
$\langle H' \rangle \neq 0$
Standard Model
$SU(3)_c \times SU(2)_L \times U(1)_Y$
ψ_{16}
$q_L,\ L_L,\ q_R,\ L_R$
$q_L = (u_L, d_L),\ L_L = (\nu_L, e_L),\ u_R,\ d_R,\ e_R$
Single gauge group, single type of fermions
Fritzsch and Minkowski (1975), Georgi (1975)


Coupling unification
Hall, KH (2018, 2019)
energy-dependent couplings
m_h=125.18 GeV
$\alpha_s(m_Z)$=0.1181
m_t=173.0 GeV
g_3
g_2
g_Y
g_{B-L}
$5\,\lambda_{SM}$
$\frac{1}{g_1^2} = \frac{2}{5}\frac{1}{g_{B-L}^2} + \frac{3}{5}\frac{1}{g_2^2}$
3221
couplings
RGE scale μ / GeV


Coupling unification
Hall, KH (2018, 2019)
v_R determined by Higgs Parity
m_h=125.18 GeV
$\alpha_s(m_Z)$=0.1181
m_t=173.0 GeV
g_3
g_2
g_Y
g_{B-L}
5 λ_{SM}
3221
couplings
μ / GeV
Other v_R
$v_R = 10^9$ GeV
$v_R = 10^{13}$ GeV
Slide Layout
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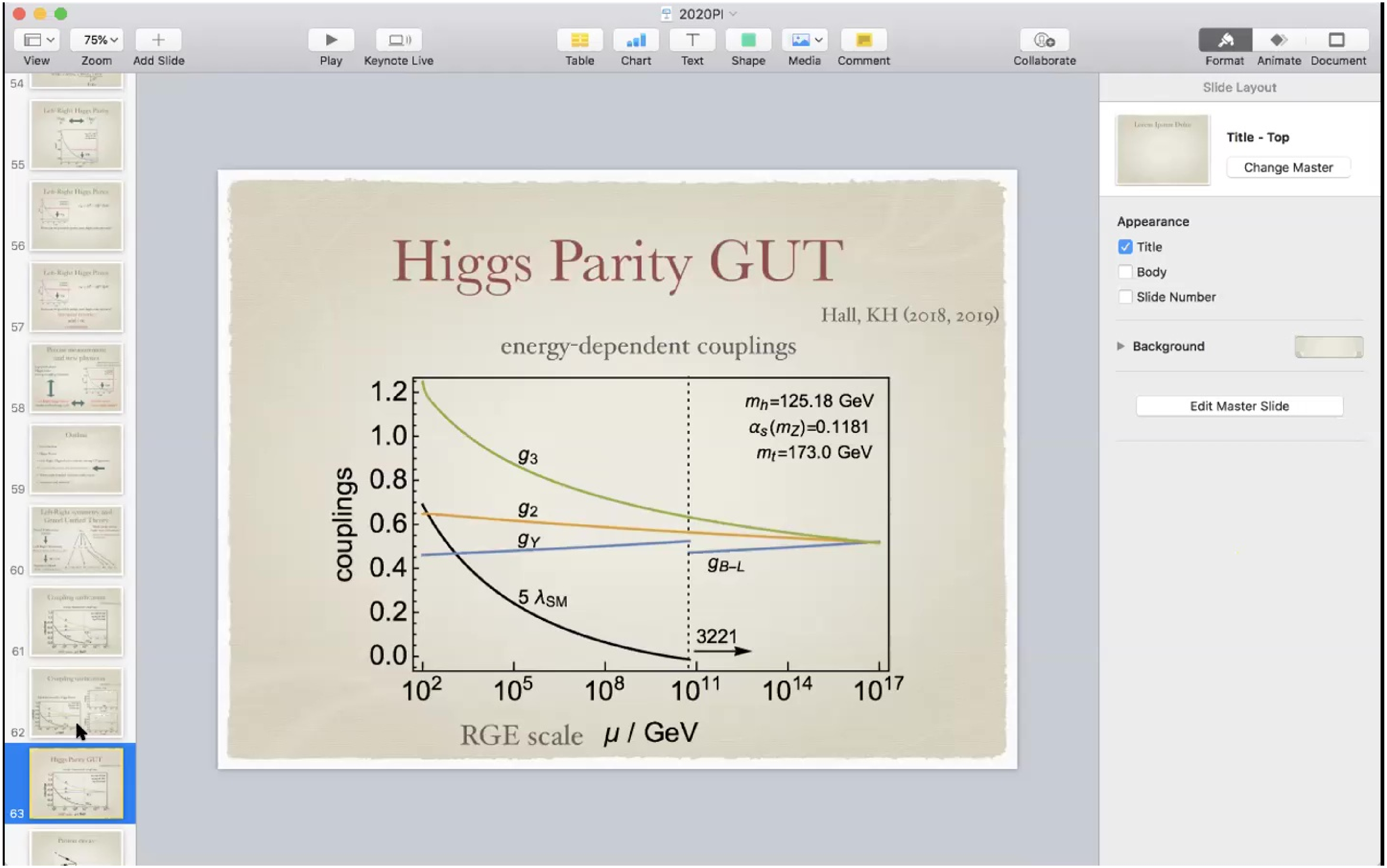
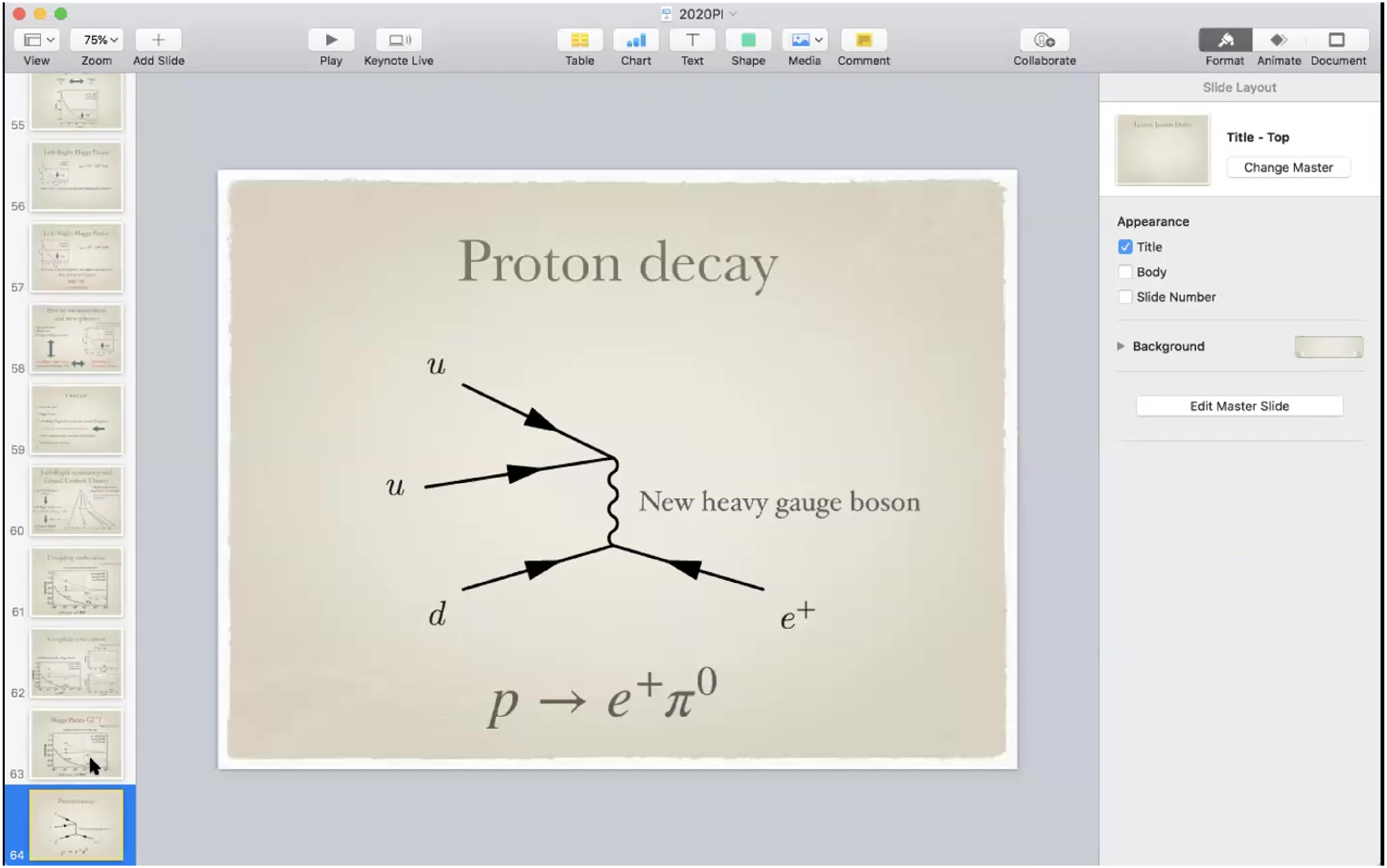

Higgs Parity GUT
Hall, KH (2018, 2019)
energy-dependent couplings
m_h=125.18 GeV
$\alpha_s(m_Z)$=0.1181
m_t=173.0 GeV
g_3
g_2
g_Y
g_{B-L}
5 λ_{SM}
3221
couplings
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^2 10^5 10^8 10^{11} 10^{14} 10^{17}
RGE scale μ / GeV


2020PI
Proton decay
u
u
d
New heavy gauge boson
e+
p → e+π0
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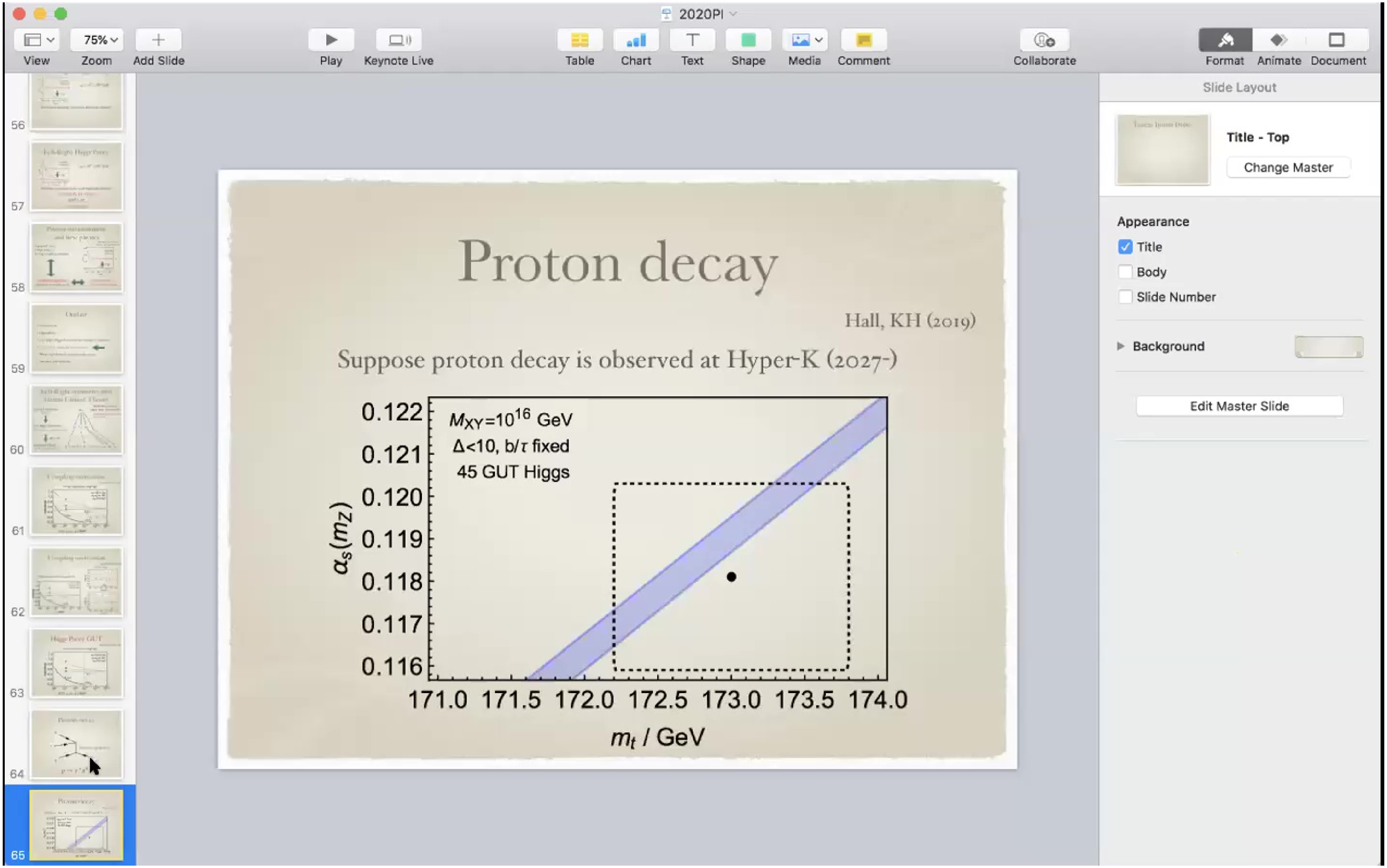
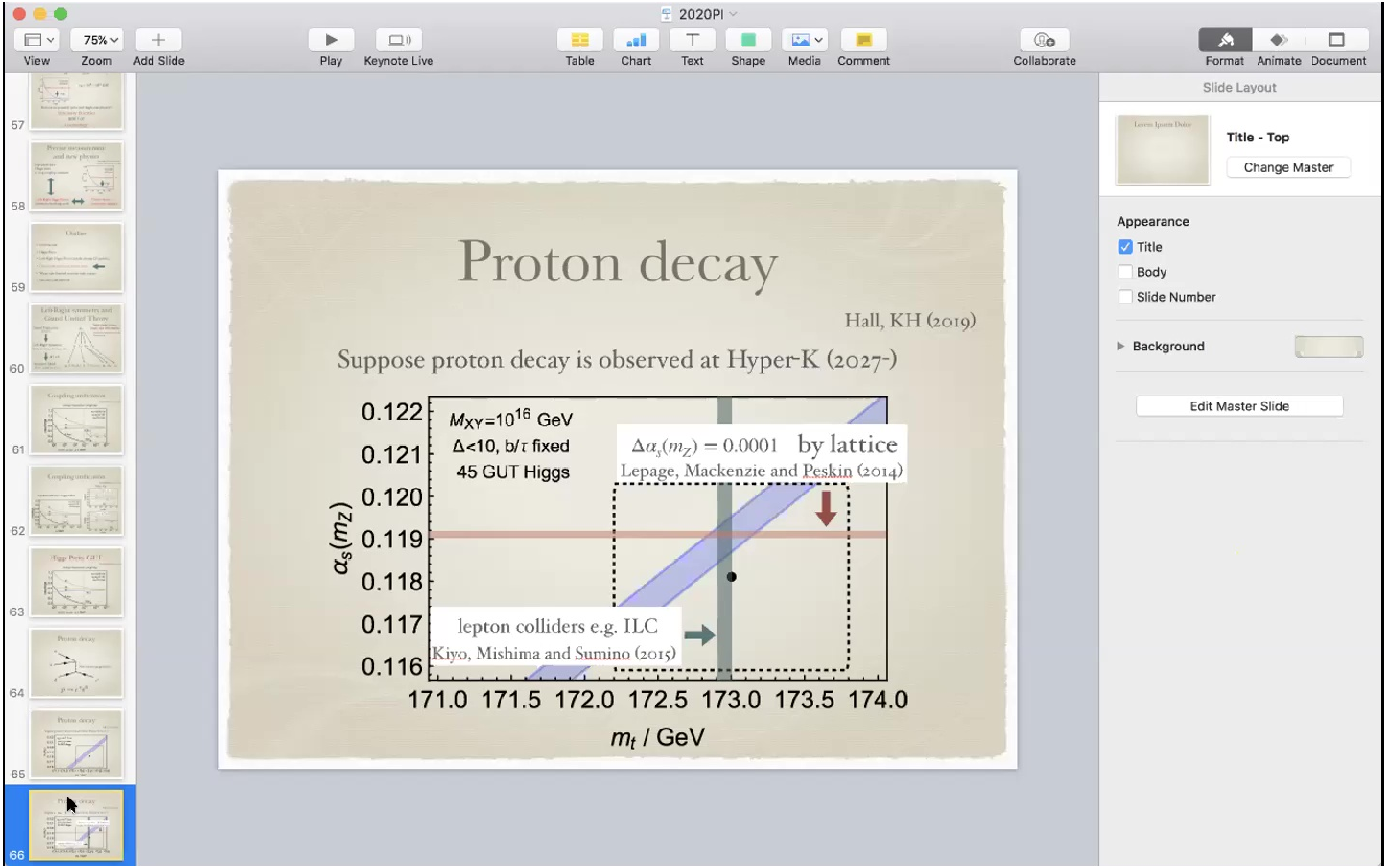


Proton decay
Hall, KH (2019)
Suppose proton decay is observed at Hyper-K (2027-)
$M_{XY}=10^{16}$ GeV
Δ<10, b/τ fixed
45 GUT Higgs
$\alpha_s(m_Z)$
0.122
0.121
0.120
0.119
0.118
0.117
0.116
171.0 171.5 172.0 172.5 173.0 173.5 174.0
m_t / GeV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Proton decay
Hall, KH (2019)
Suppose proton decay is observed at Hyper-K (2027-)
$M_{XY}=10^{16}$ GeV
Δ<10, b/τ fixed
45 GUT Higgs
$\Delta\alpha_s(m_Z) = 0.0001$ by lattice
Lepage, Mackenzie and Peskin (2014)
lepton colliders e.g. ILC
Kiyo, Mishima and Sumino (2015)
$\alpha_s(m_Z)$
0.122
0.121
0.120
0.119
0.118
0.117
0.116
171.0 171.5 172.0 172.5 173.0 173.5 174.0
m_t / GeV
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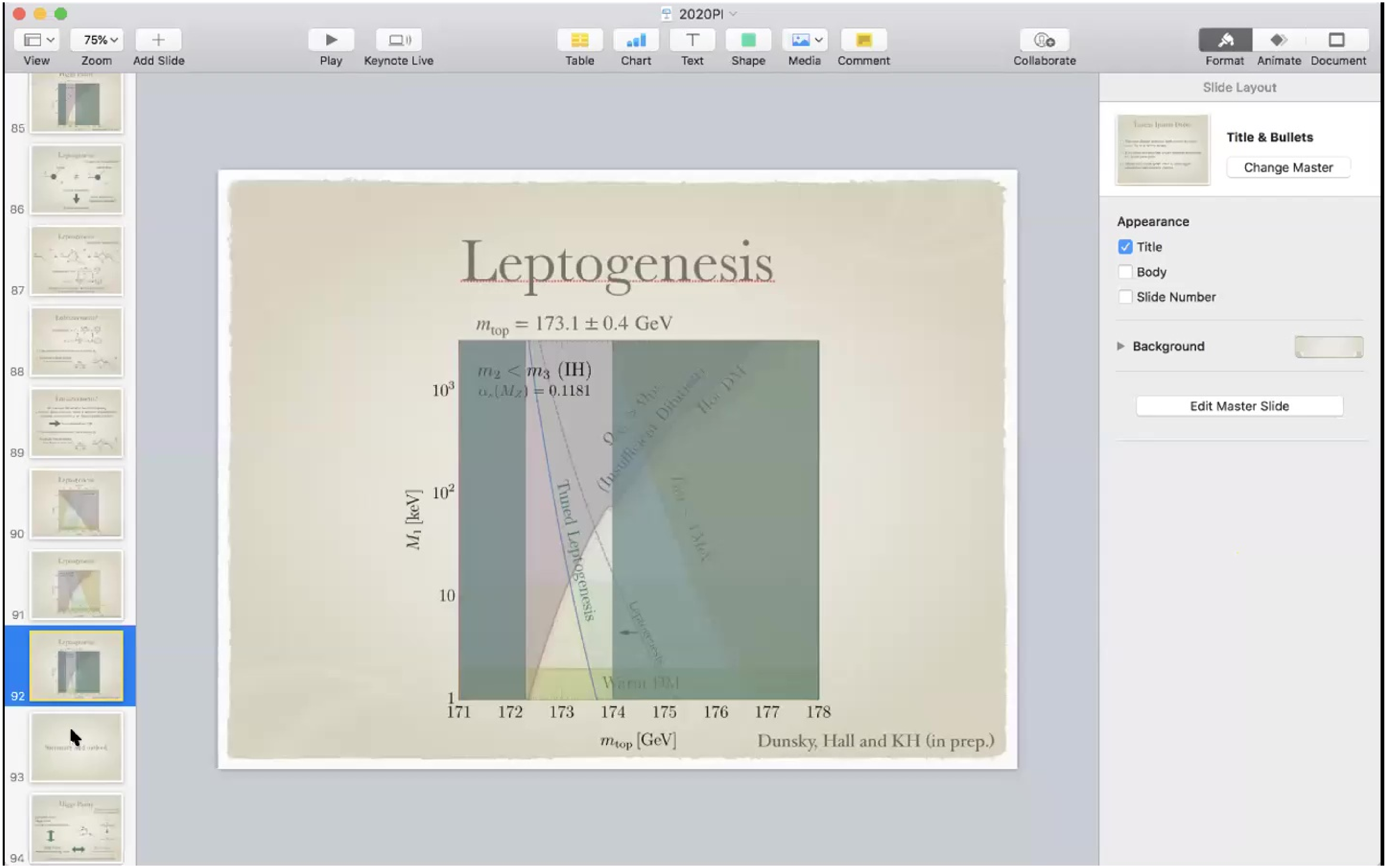
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Document
Leptogenesis
m_top = 173.1 ± 0.4 GeV
m2 < m3 (IH)
αs(MZ) = 0.1181
Tuned Leptogenesis
Hot DM
Warm DM
M1 [keV]
10^3
10^2
10
1
171 172 173 174 175 176 177 178
m_top [GeV]
Dunsky, Hall and KH (in prep.)
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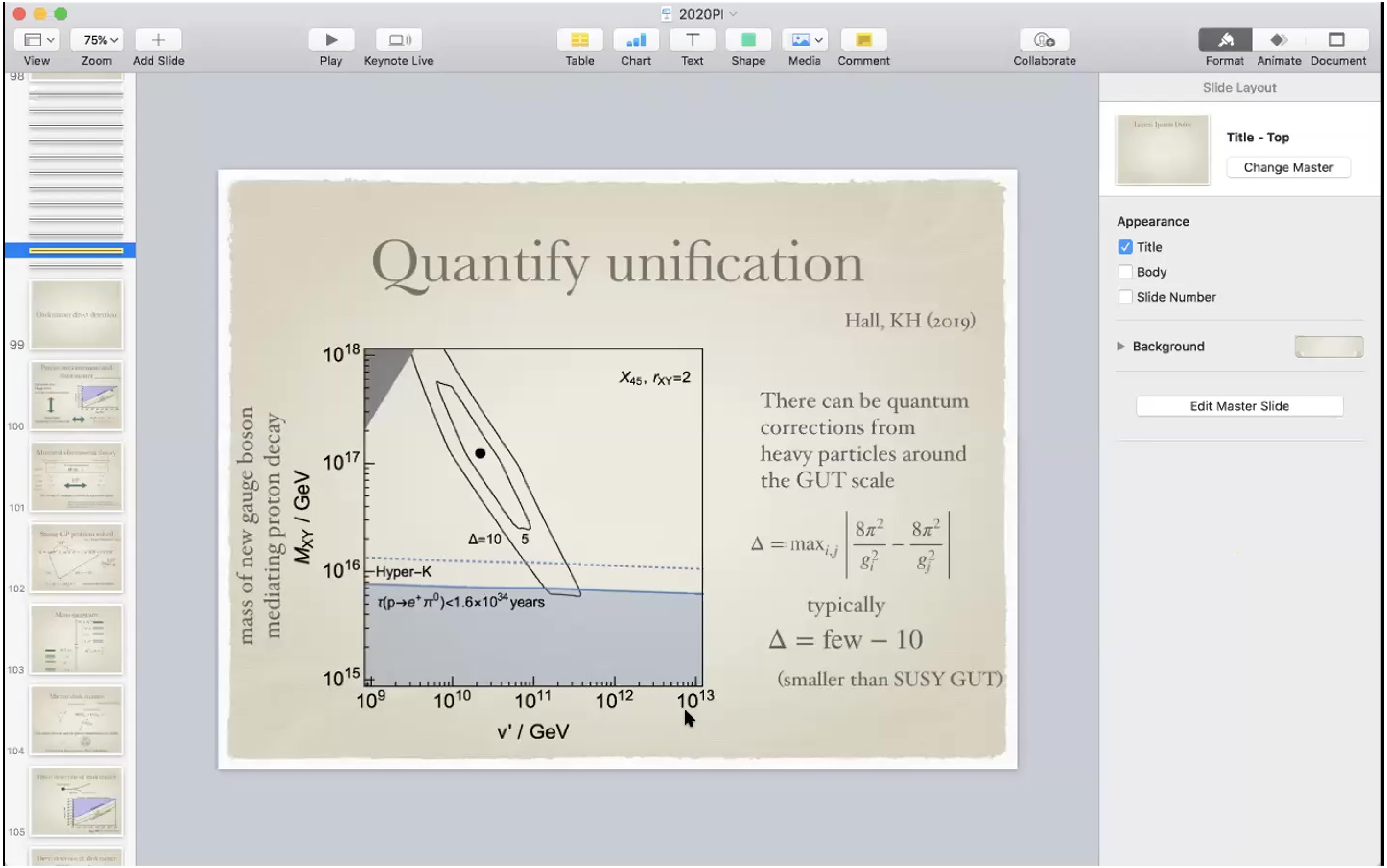
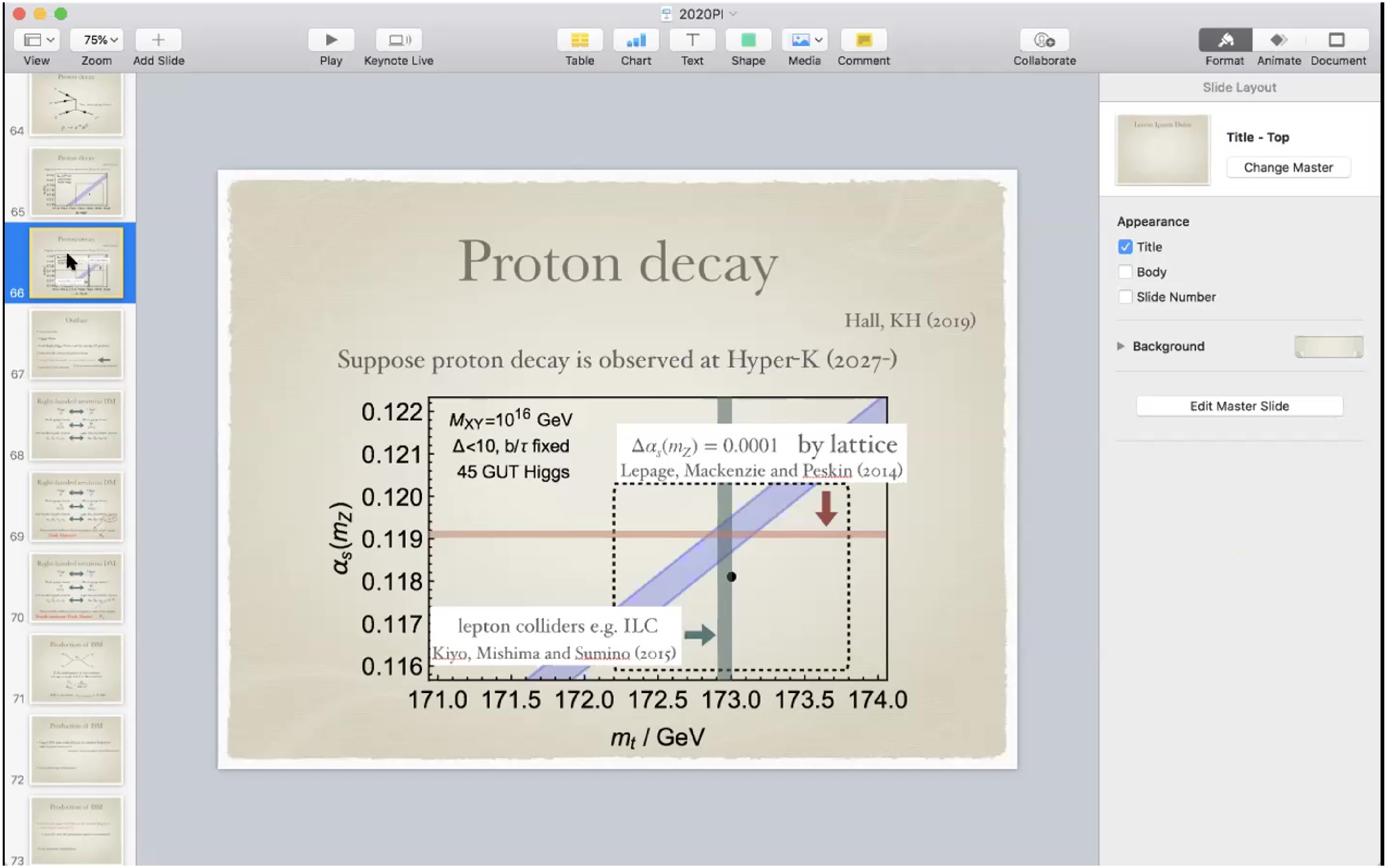
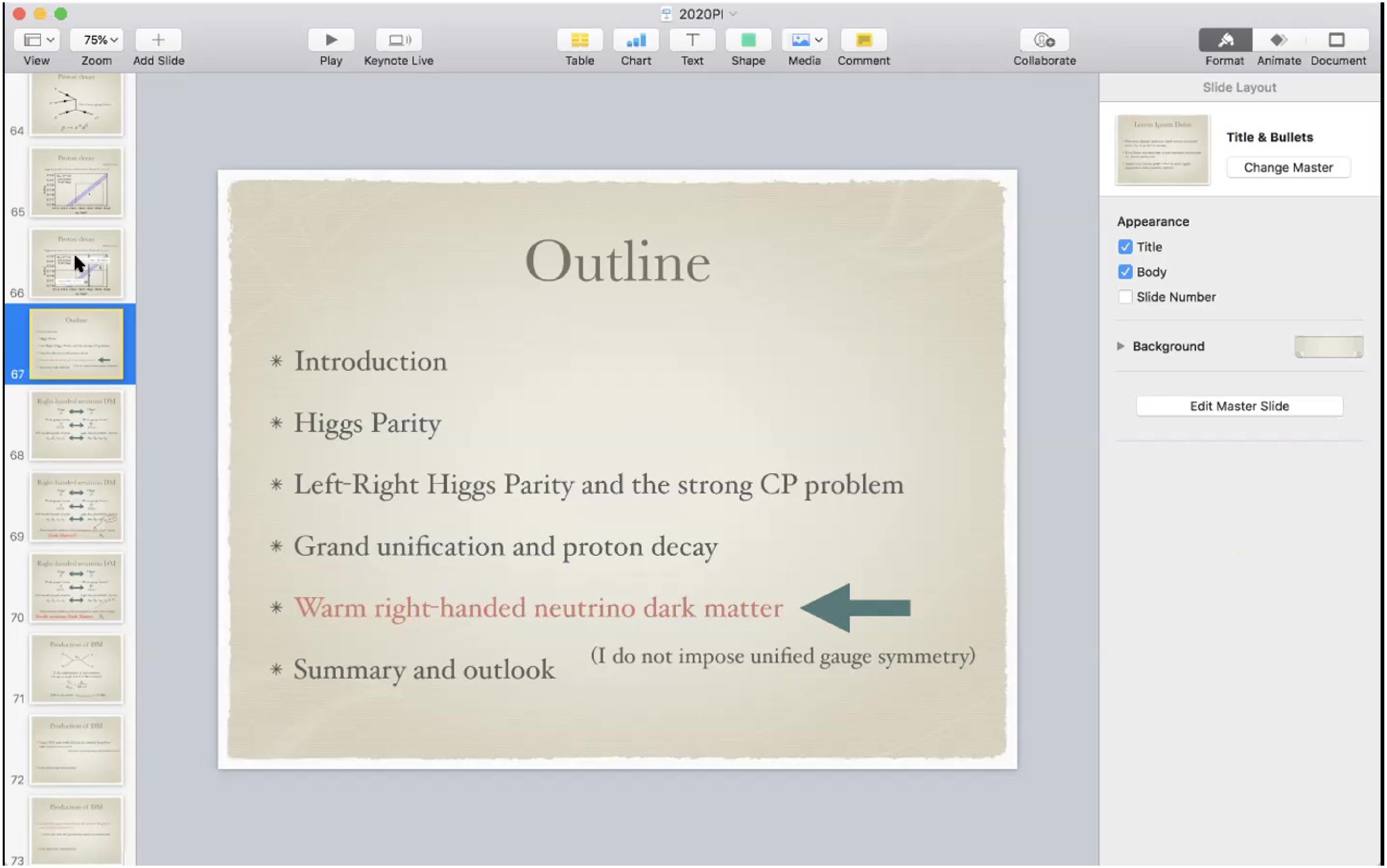

Quantify unification
Hall, KH (2019)
mass of new gauge boson mediating proton decay
M_{XY} / GeV
10^{18}
10^{17}
10^{16}
10^{15}
X_{45}, r_{XY}=2
Δ=10
5
Hyper−K
$\tau(p \to e^+ \pi^0) < 1.6 \times 10^{34}$ years
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
v' / GeV
There can be quantum corrections from heavy particles around the GUT scale
$\Delta = \max_{i,j} \left| \frac{8\pi^2}{g_i^2} - \frac{8\pi^2}{g_j^2} \right|$
typically
Δ = few − 10
(smaller than SUSY GUT)


Proton decay
Hall, KH (2019)
Suppose proton decay is observed at Hyper-K (2027-)
$M_{XY}=10^{16}$ GeV
Δ<10, b/τ fixed
45 GUT Higgs
$\Delta\alpha_s(m_Z) = 0.0001$ by lattice
Lepage, Mackenzie and Peskin (2014)
lepton colliders e.g. ILC
Kiyo, Mishima and Sumino (2015)
$\alpha_s(m_Z)$
0.122
0.121
0.120
0.119
0.118
0.117
0.116
171.0 171.5 172.0 172.5 173.0 173.5 174.0
m_t / GeV


2020PI
Outline
* Introduction
* Higgs Parity
* Left-Right Higgs Parity and the strong CP problem
* Grand unification and proton decay
* Warm right-handed neutrino dark matter
* Summary and outlook
(I do not impose unified gauge symmetry)
Slide Layout
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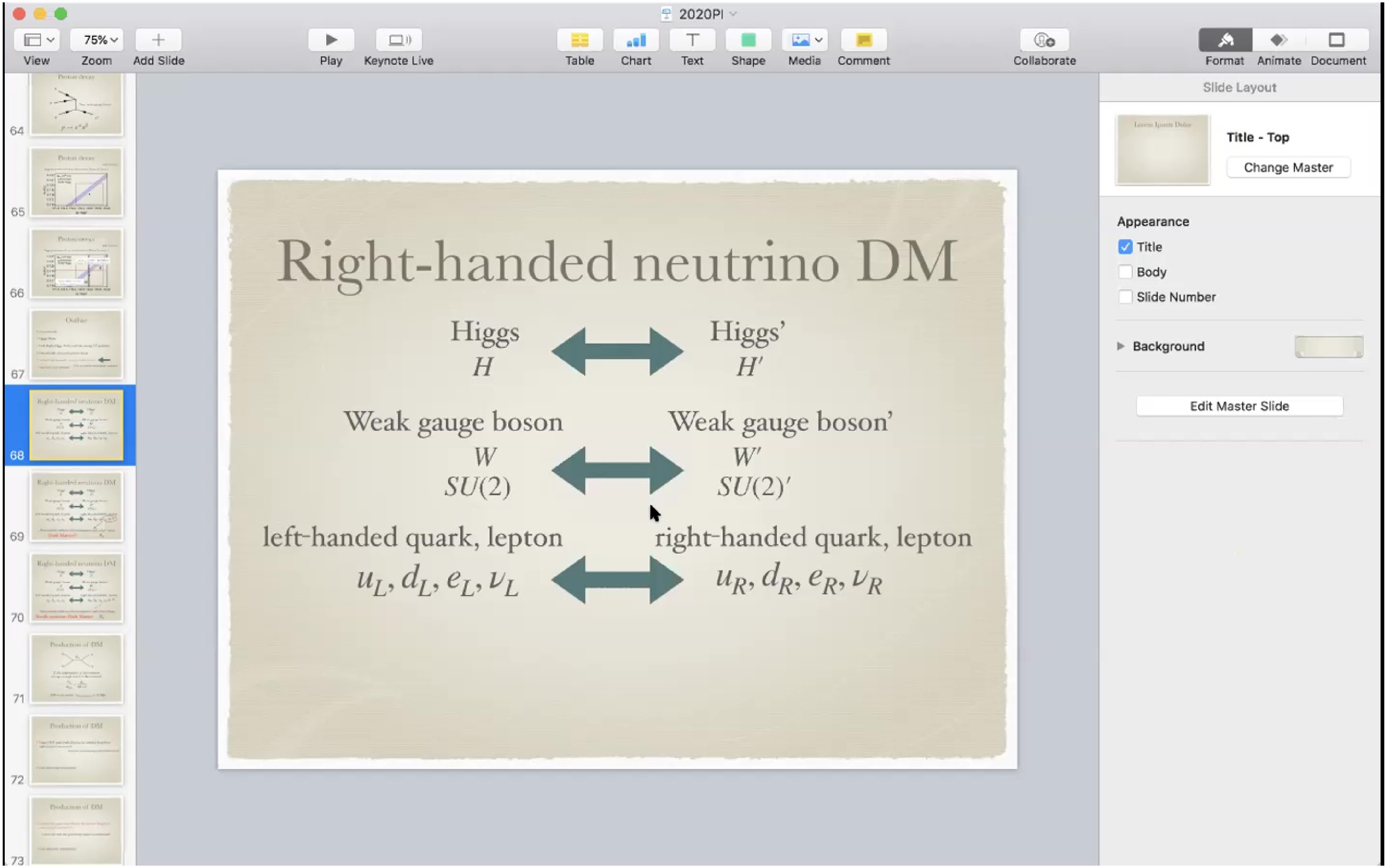
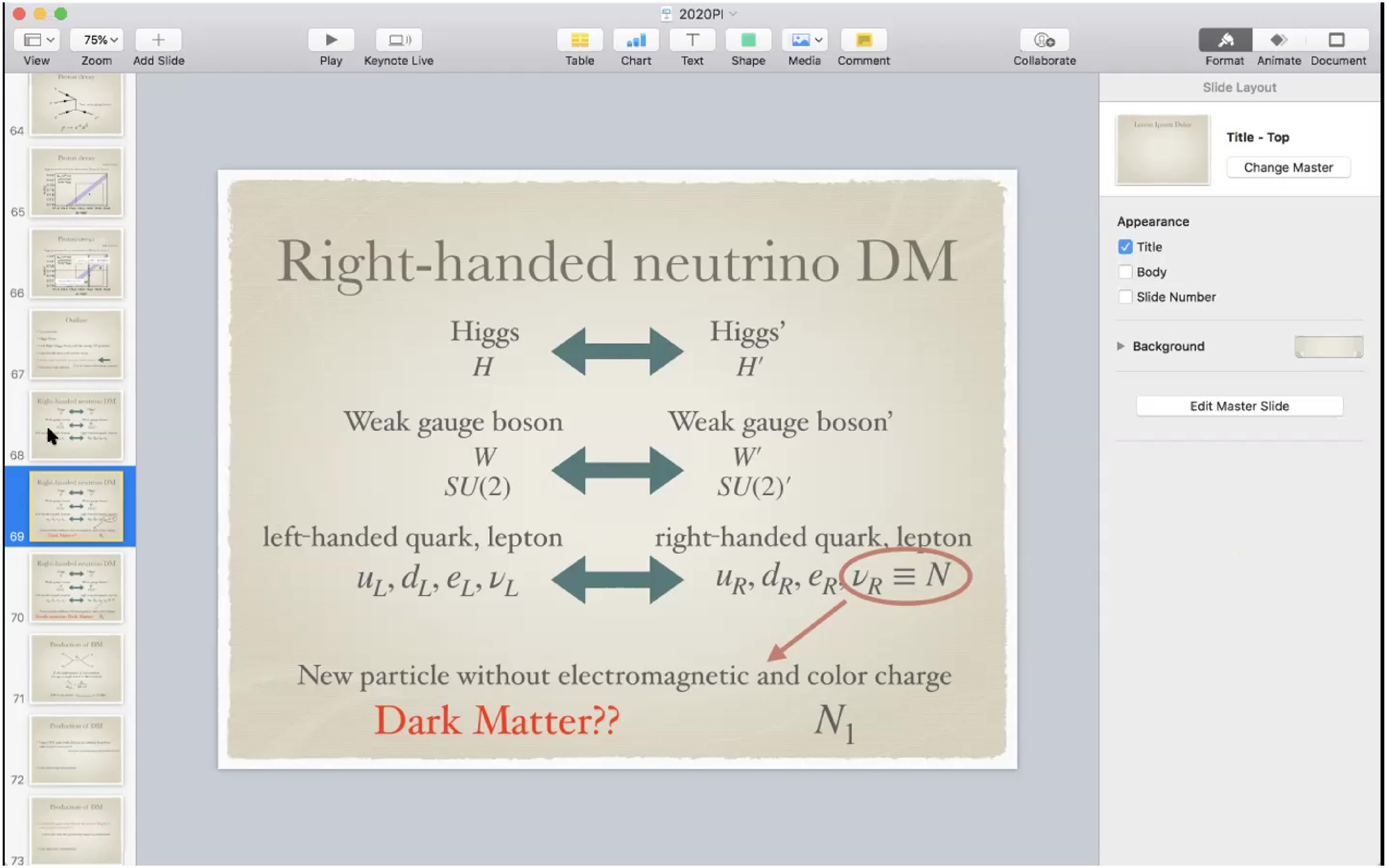
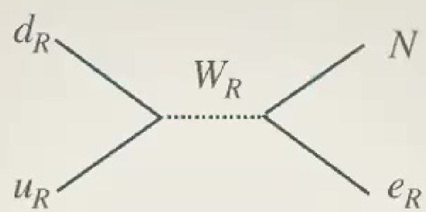

Right-handed neutrino DM
Higgs
H
Higgs'
H′
Weak gauge boson
W
SU(2)
Weak gauge boson'
W′
SU(2)′
left-handed quark, lepton
u_L, d_L, e_L, ν_L
right-handed quark, lepton
u_R, d_R, e_R, ν_R


Right-handed neutrino DM
Higgs
H
Higgs'
H'
Weak gauge boson
W
$SU(2)$
Weak gauge boson'
W'
$SU(2)'$
left-handed quark, lepton
u_L, d_L, e_L, ν_L
right-handed quark, lepton
$u_R, d_R, e_R, \nu_R \equiv N$
New particle without electromagnetic and color charge
Dark Matter??
N_1

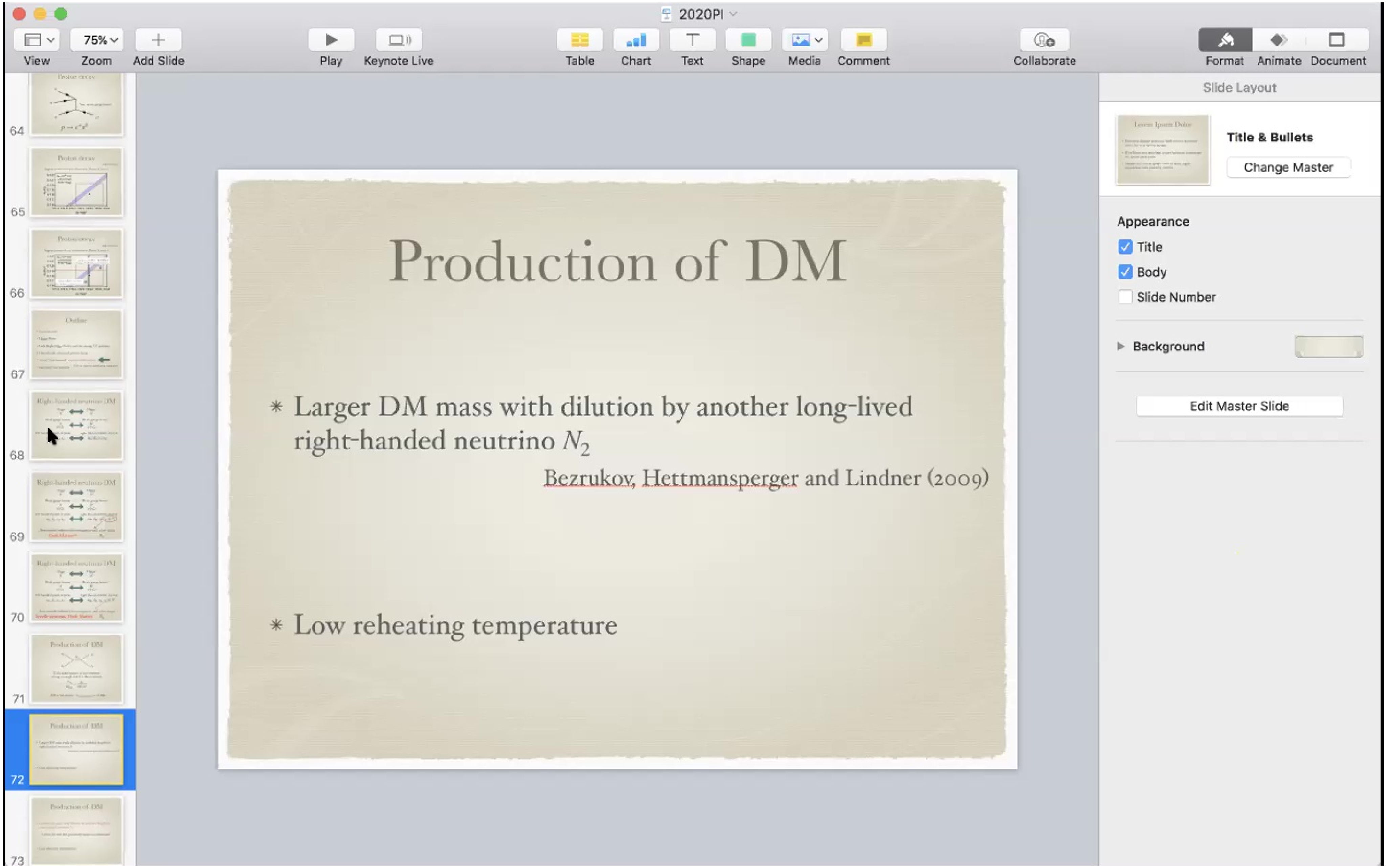
Production of DM



If the temperature of the universe
is large enough that N is thermalized,

$$\frac{\Omega_{N_1}}{\Omega_{\rm DM}} \simeq \frac{M_1}{100\ \rm eV}$$

DM is too warm: $\lambda_{\rm Free-streaming} \simeq 10\ \rm Mpc$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Document
Production of DM
* Larger DM mass with dilution by another long-lived right-handed neutrino N_2
Bezrukov, Hettmansperger and Lindner (2009)
* Low reheating temperature
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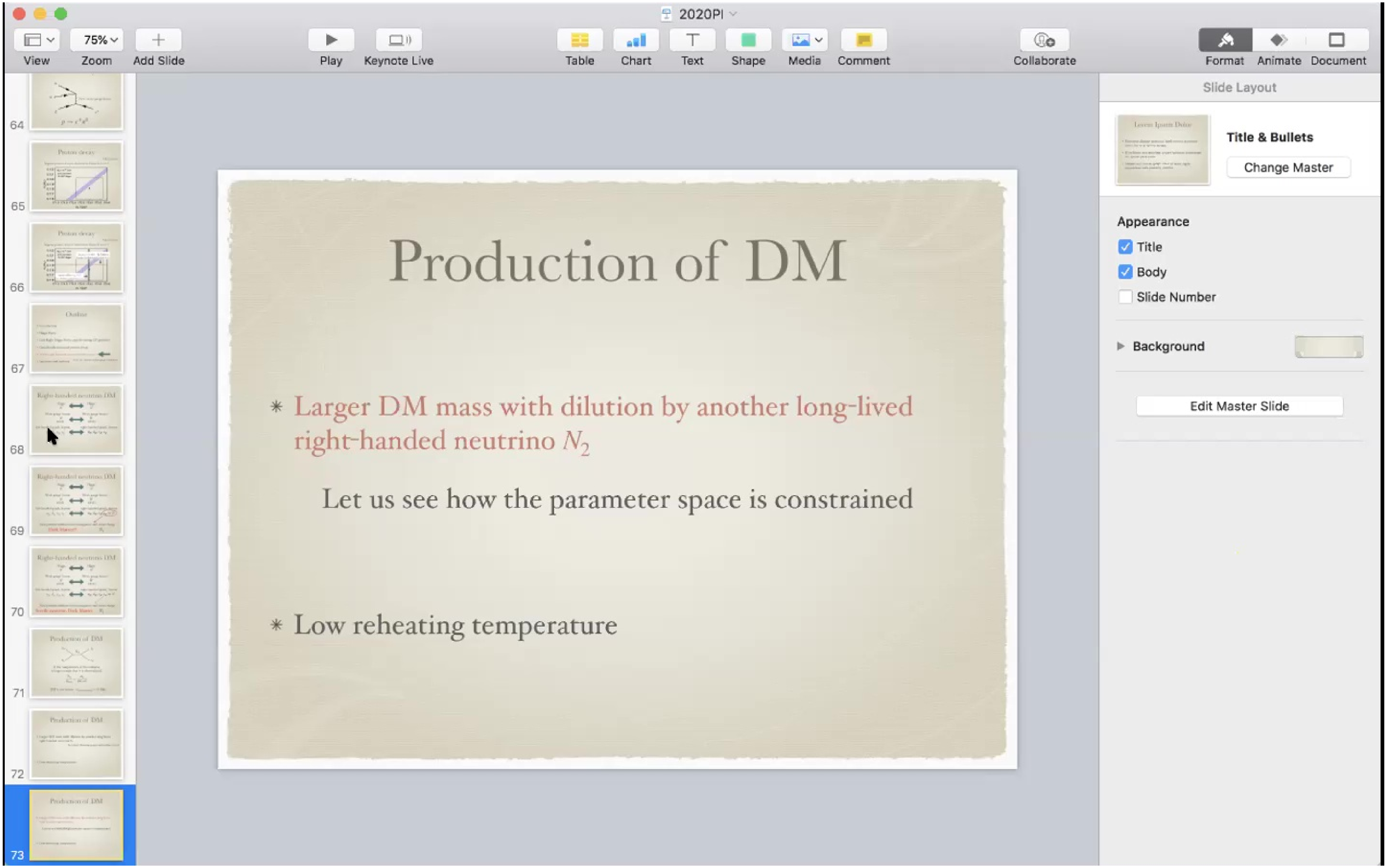
2020PI
Production of DM
* Larger DM mass with dilution by another long-lived right-handed neutrino N_2
Let us see how the parameter space is constrained
* Low reheating temperature
Slide Layout
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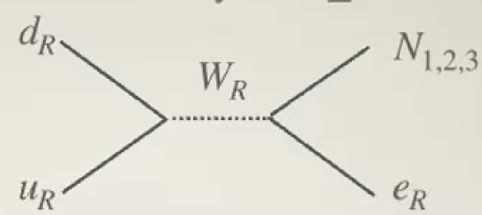
Dilution by N_2

$$n_{N_1} = n_{N_2}$$



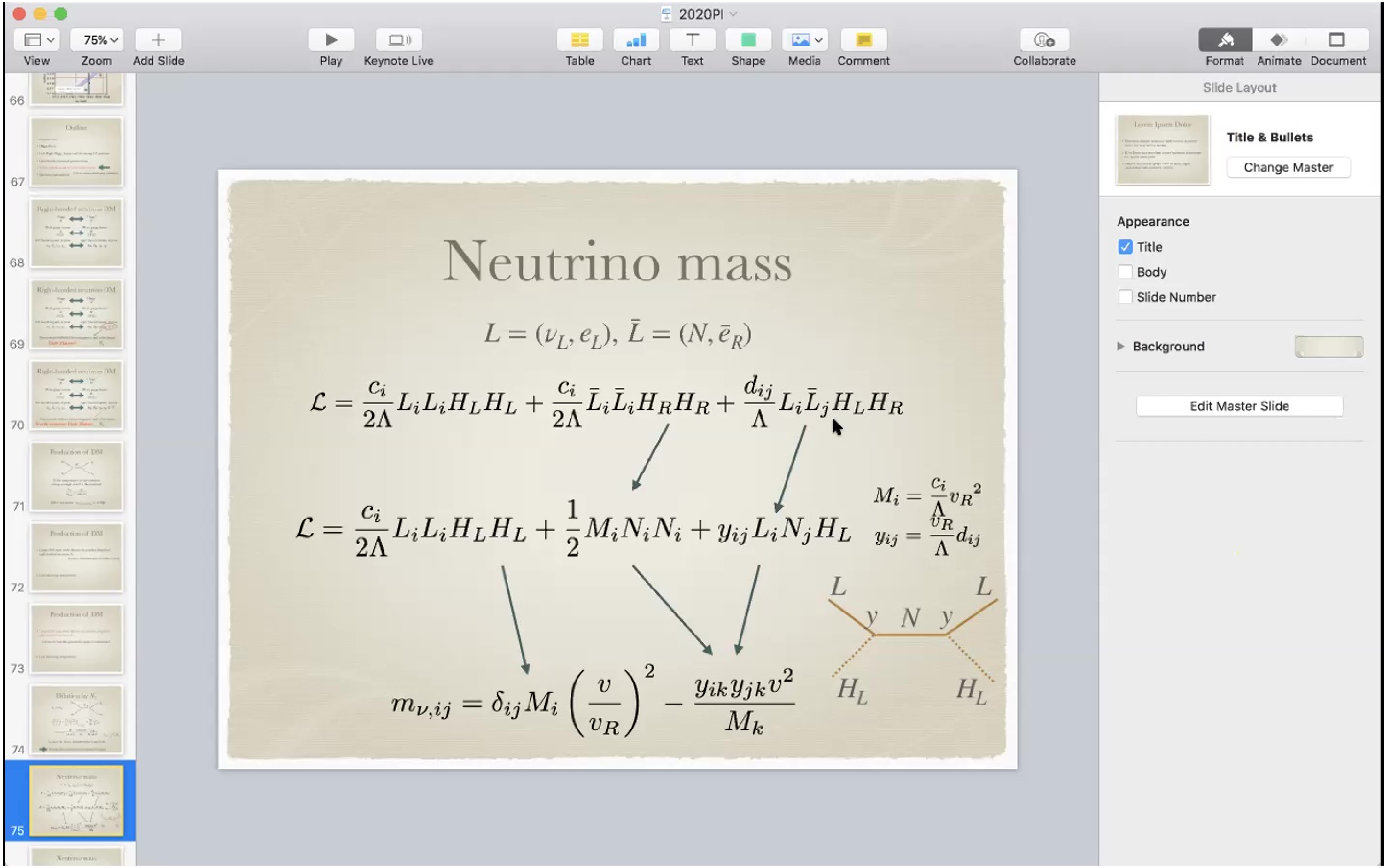
$$\left(\frac{\rho_{N_1}}{s}\right) = \frac{\rho_{N_1}}{\rho_{N_2}}\left(\frac{\rho_{N_2}}{s}\right)_{N_2 \text{ decay}} = \frac{M_1}{M_2}\frac{3}{4}T_{\rm RH}$$

$$= 0.4 \text{ eV}\frac{M_1}{10 \text{ keV}}\frac{300 \text{ GeV}}{M_2}\frac{T_{\rm RH}}{10 \text{ MeV}}$$

$$T_{\rm RH} \sim \sqrt{\Gamma_{N_2} M_{\rm pl}}$$

N_2 must be heavy enough while long-lived

➡ Strong constraints on the parameter space


2020PI
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Animate
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Neutrino mass
$L = (\nu_L, e_L),\ \bar{L} = (N, \bar{e}_R)$
$\mathcal{L} = \frac{c_i}{2\Lambda} L_i L_i H_L H_L + \frac{c_i}{2\Lambda} \bar{L}_i \bar{L}_i H_R H_R + \frac{d_{ij}}{\Lambda} L_i \bar{L}_j H_L H_R$
$\mathcal{L} = \frac{c_i}{2\Lambda} L_i L_i H_L H_L + \frac{1}{2} M_i N_i N_i + y_{ij} L_i N_j H_L$
$M_i = \frac{c_i}{\Lambda} v_R{}^2$
$y_{ij} = \frac{v_R}{\Lambda} d_{ij}$
$m_{\nu,ij} = \delta_{ij} M_i \left(\frac{v}{v_R}\right)^2 - \frac{y_{ik} y_{jk} v^2}{M_k}$
L
L
y
N
y
H_L
H_L
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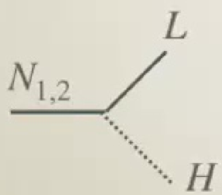
Neutrino mass

$$m_{\nu,ij} = \delta_{ij} M_i \left(\frac{v}{v_R}\right)^2 - \frac{y_{ik} y_{jk} v^2}{M_k}$$

The second term is strongly constrained from the stability of $N_{1,2}$



y_{i1}, y_{i2} are required to be small

$$y_{ij} L_i N_j H$$

Right-handed neutrino mass

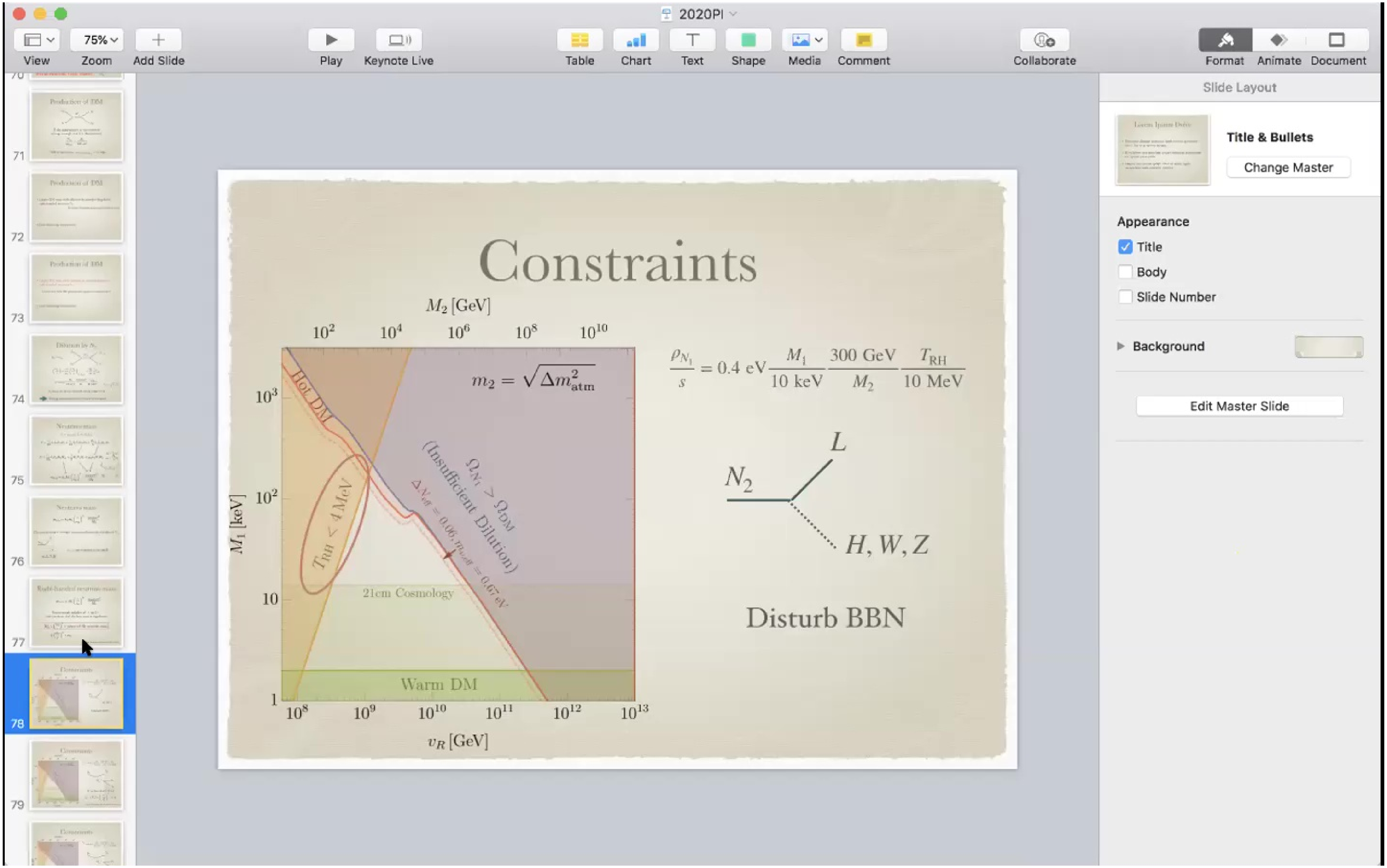
$$m_{\nu,22} = M_2 \left(\frac{v}{v_R} \right)^2 - \frac{y_{2k} y_{2k} v^2}{M_k}$$

From enough stability of N_1 and N_2,
one can show that the first term is significant

$$M_2 = \left(\frac{v_R}{v} \right)^2 \times (\text{observed SM neutrino mass})$$

$$\equiv \left(\frac{v_R}{v} \right)^2 \times m_2$$

Dror, Dunsky, Hall and KH (2020)



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Constraints
M_2 [GeV]
$m_2 = \sqrt{\Delta m^2_{\rm atm}}$
Hot DM
$T_{\rm RH} < 4$ MeV
$\Omega_{N_1} > \Omega_{\rm DM}$
(Insufficient Dilution)
$\Delta N_{\rm eff} = 0.06, m_{\nu, {\rm eff}} = 0.67$ eV
21cm Cosmology
Warm DM
M_1 [keV]
v_R [GeV]
$\frac{\rho_{N_1}}{s} = 0.4\ {\rm eV} \frac{M_1}{10\ {\rm keV}} \frac{300\ {\rm GeV}}{M_2} \frac{T_{\rm RH}}{10\ {\rm MeV}}$
N_2
L
H, W, Z
Disturb BBN
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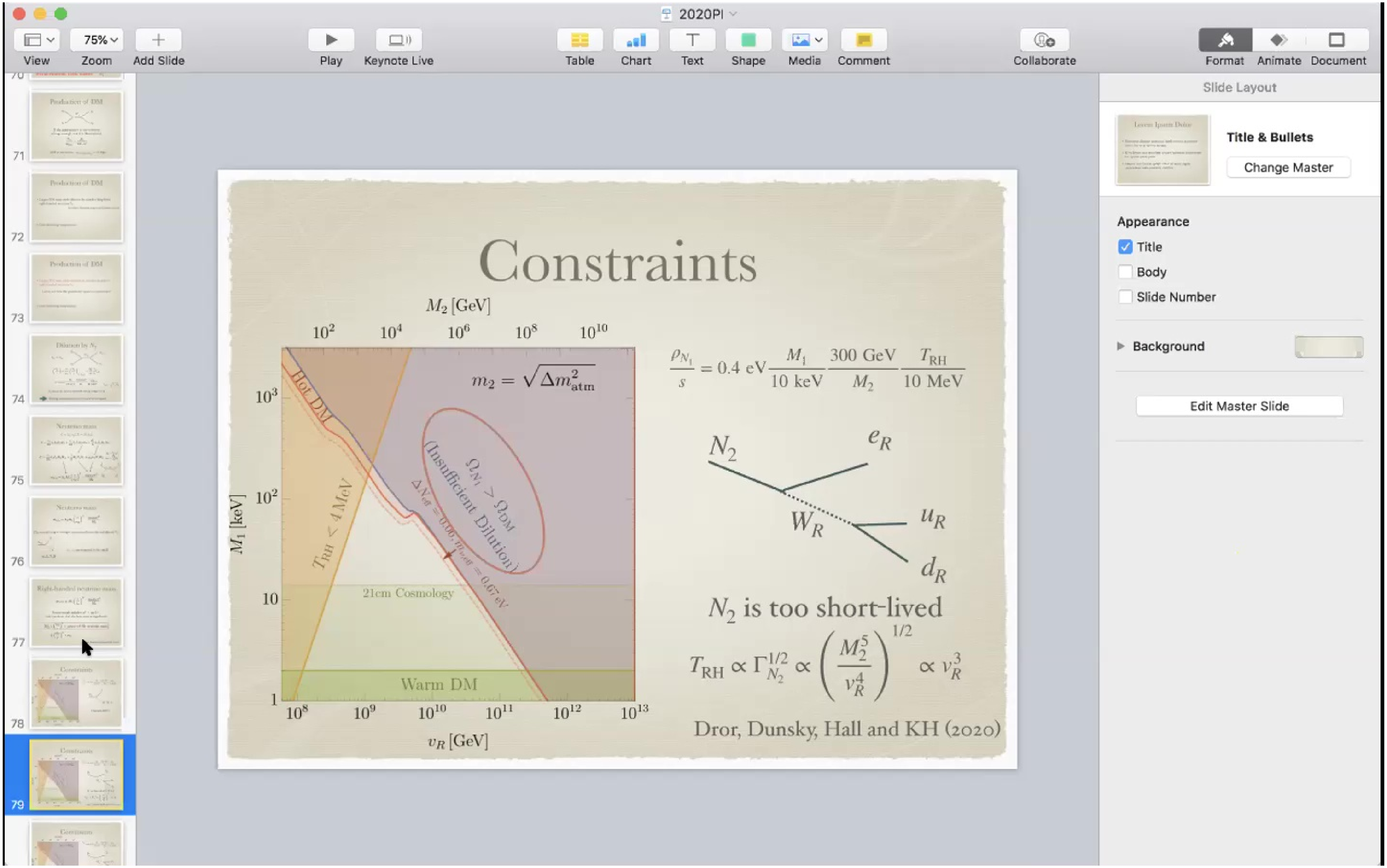
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Document
Constraints
M_2 [GeV]
m_2 = √Δm²_atm
Hot DM
T_RH < 4 MeV
Ω_N1 > Ω_DM
(Insufficient Dilution)
ΔN_eff = 0.06, m_eff = 0.67 eV
21cm Cosmology
Warm DM
M_1 [keV]
v_R [GeV]
ρ_N1 / s = 0.4 eV (M_1 / 10 keV)(300 GeV / M_2)(T_RH / 10 MeV)
N_2
e_R
W_R
u_R
d_R
N_2 is too short-lived
T_RH ∝ Γ^{1/2}_{N_2} ∝ (M_2^5 / v_R^4)^{1/2} ∝ v_R^3
Dror, Dunsky, Hall and KH (2020)
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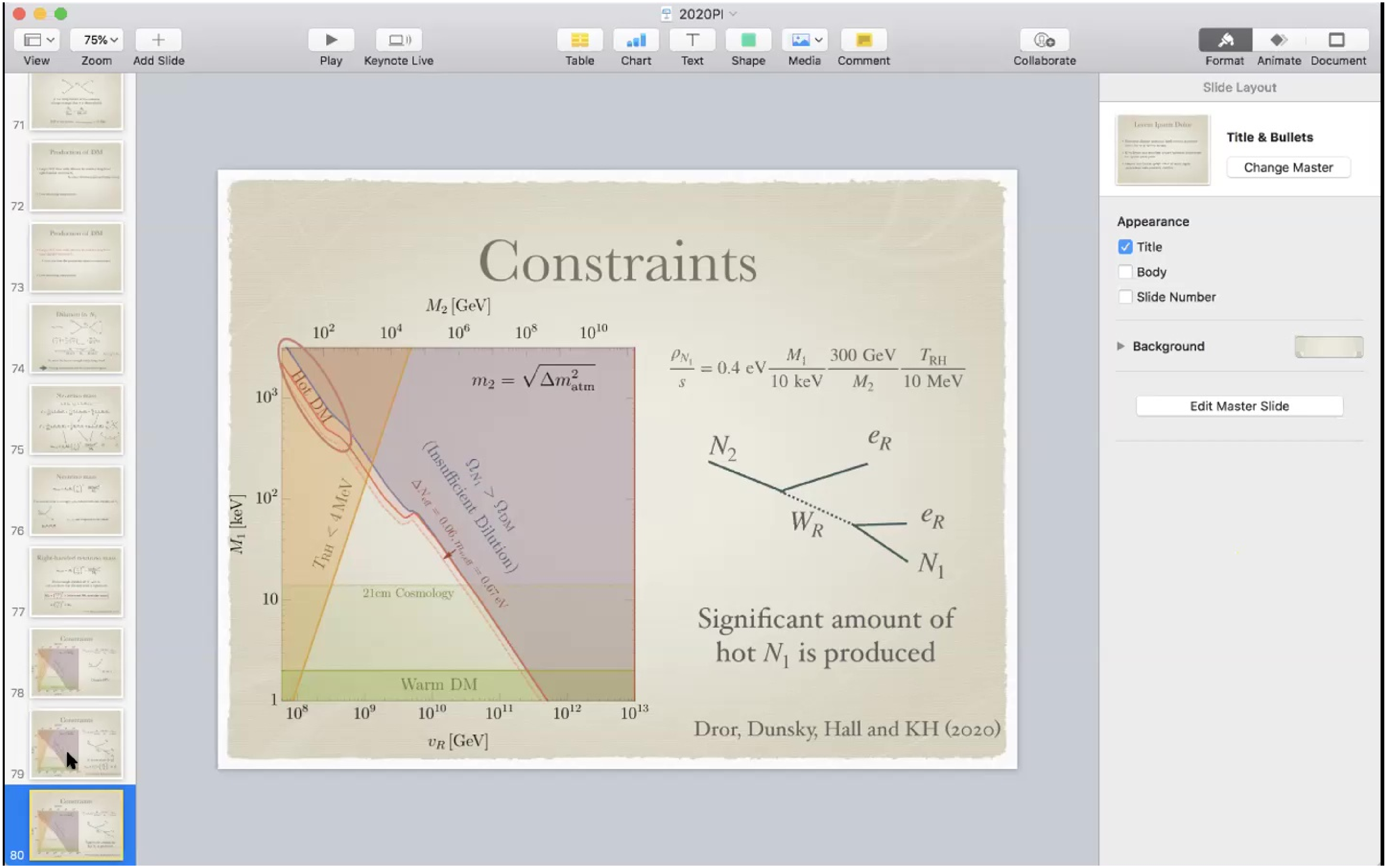
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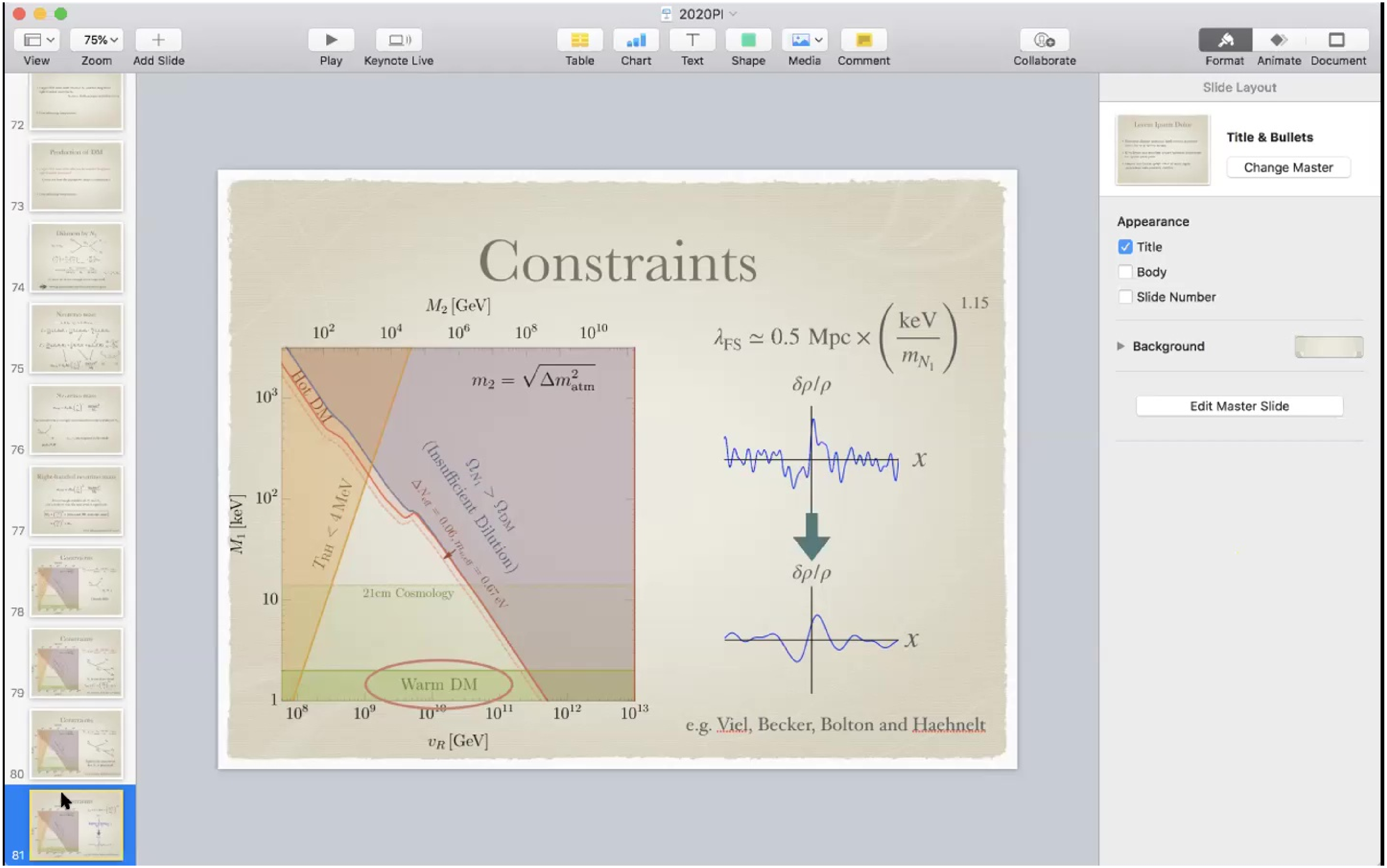
Constraints
M_2 [GeV]
10^2 10^4 10^6 10^8 10^{10}
$m_2 = \sqrt{\Delta m^2_{\rm atm}}$
Hot DM
$T_{\rm RH} < 4$ MeV
$\Omega_{N_1} > \Omega_{\rm DM}$
(Insufficient Dilution)
$\Delta N_{\rm eff} = 0.06, m_{\rm eff} = 0.67$ eV
21cm Cosmology
Warm DM
M_1 [keV]
1 10 10^2 10^3
10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13}
v_R [GeV]
$\frac{\rho_{N_1}}{s} = 0.4\ {\rm eV} \frac{M_1}{10\ {\rm keV}} \frac{300\ {\rm GeV}}{M_2} \frac{T_{\rm RH}}{10\ {\rm MeV}}$
N_2 e_R W_R e_R N_1
Significant amount of hot N_1 is produced
Dror, Dunsky, Hall and KH (2020)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Constraints
M_2 [GeV]
$m_2 = \sqrt{\Delta m^2_{atm}}$
Hot DM
$T_{RH} < 4$ MeV
$\Omega_{N_1} > \Omega_{DM}$
(Insufficient Dilution)
$\Delta N_{eff} = 0.06, m_{\nu,eff} = 0.67$ eV
21cm Cosmology
Warm DM
M_1 [keV]
v_R [GeV]
$\lambda_{FS} \simeq 0.5 \text{ Mpc} \times \left(\frac{\text{keV}}{m_{N_1}}\right)^{1.15}$
$\delta\rho/\rho$
x
$\delta\rho/\rho$
x
e.g. Viel, Becker, Bolton and Haehnelt
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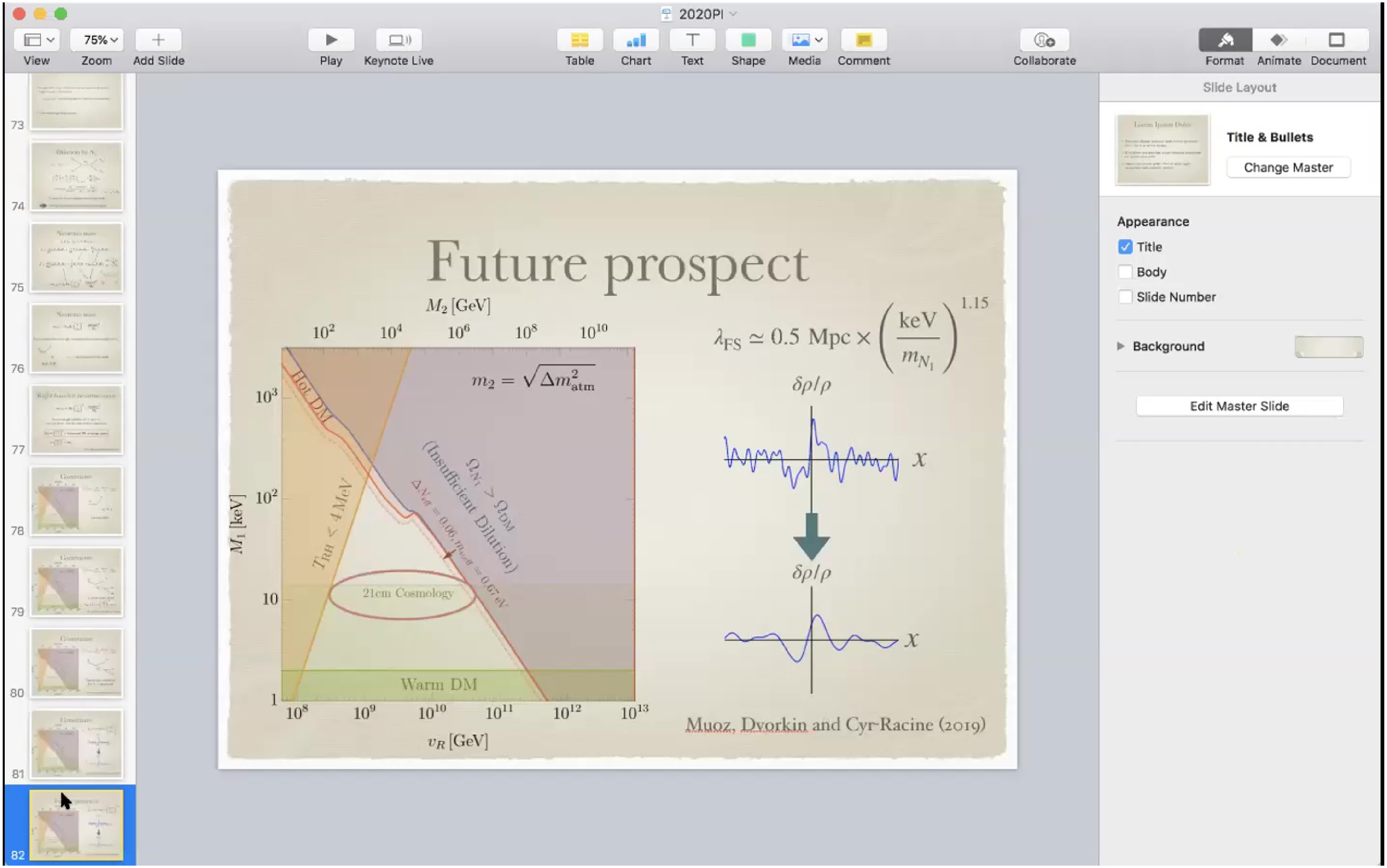
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Future prospect
M_2 [GeV]
$m_2 = \sqrt{\Delta m^2_{atm}}$
Hot DM
$T_{RH} < 4$ MeV
$\Omega_{N_1} > \Omega_{DM}$
(Insufficient Dilution)
21cm Cosmology
Warm DM
M_1 [keV]
v_R [GeV]
$\lambda_{FS} \simeq 0.5\ \mathrm{Mpc} \times \left(\frac{\mathrm{keV}}{m_{N_1}}\right)^{1.15}$
$\delta\rho/\rho$
x
$\delta\rho/\rho$
x
Muoz, Dvorkin and Cyr-Racine (2019)
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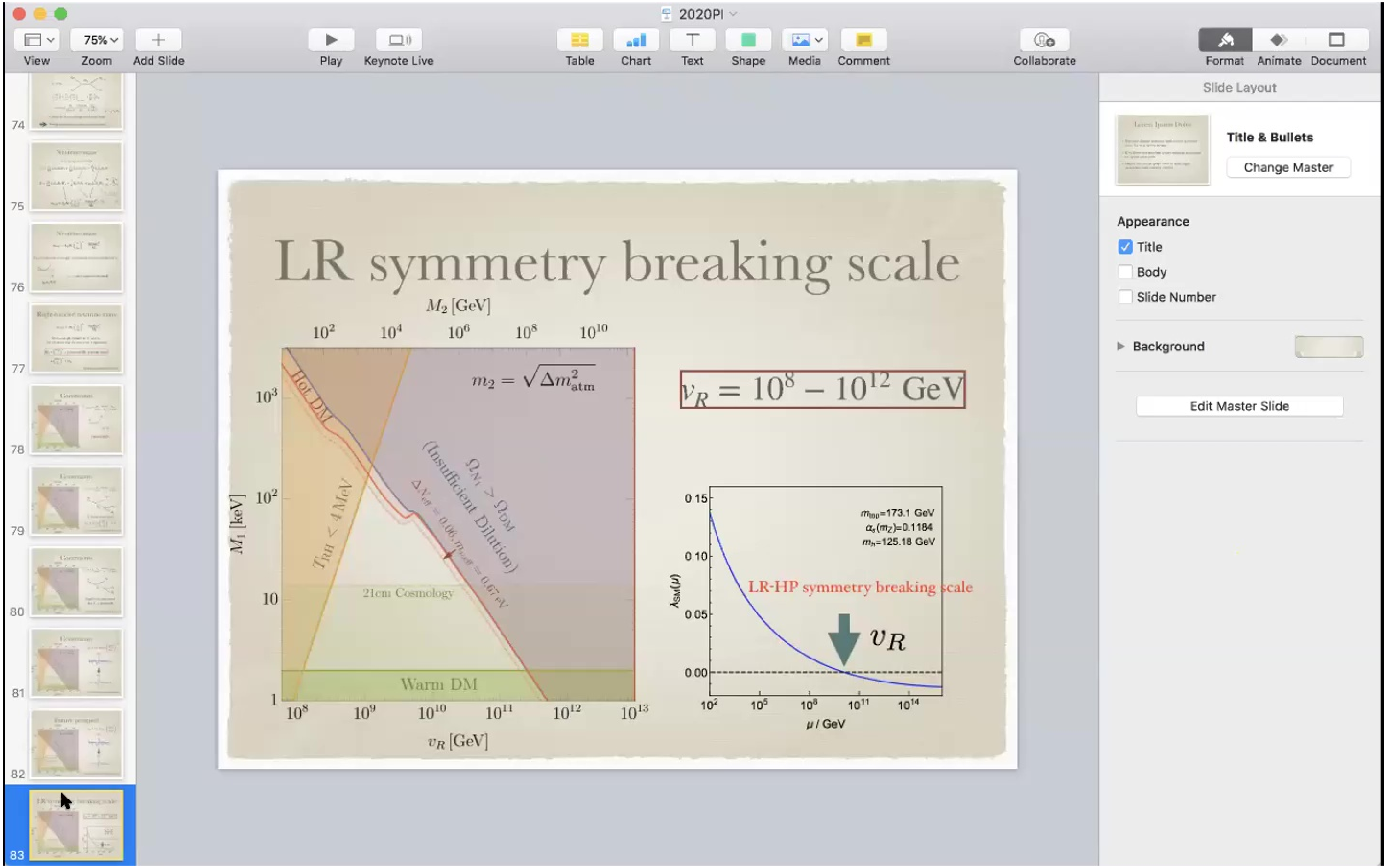
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LR symmetry breaking scale
M₂ [GeV]
m₂ = √Δm²atm
Hot DM
T_RH < 4 MeV
Ω_N1 > Ω_DM
(Insufficient Dilution)
21cm Cosmology
Warm DM
M₁ [keV]
v_R [GeV]
v_R = 10⁸ – 10¹² GeV
m_top=173.1 GeV
α_s(m_Z)=0.1184
m_h=125.18 GeV
LR-HP symmetry breaking scale
v_R
λ_SM(μ)
μ / GeV
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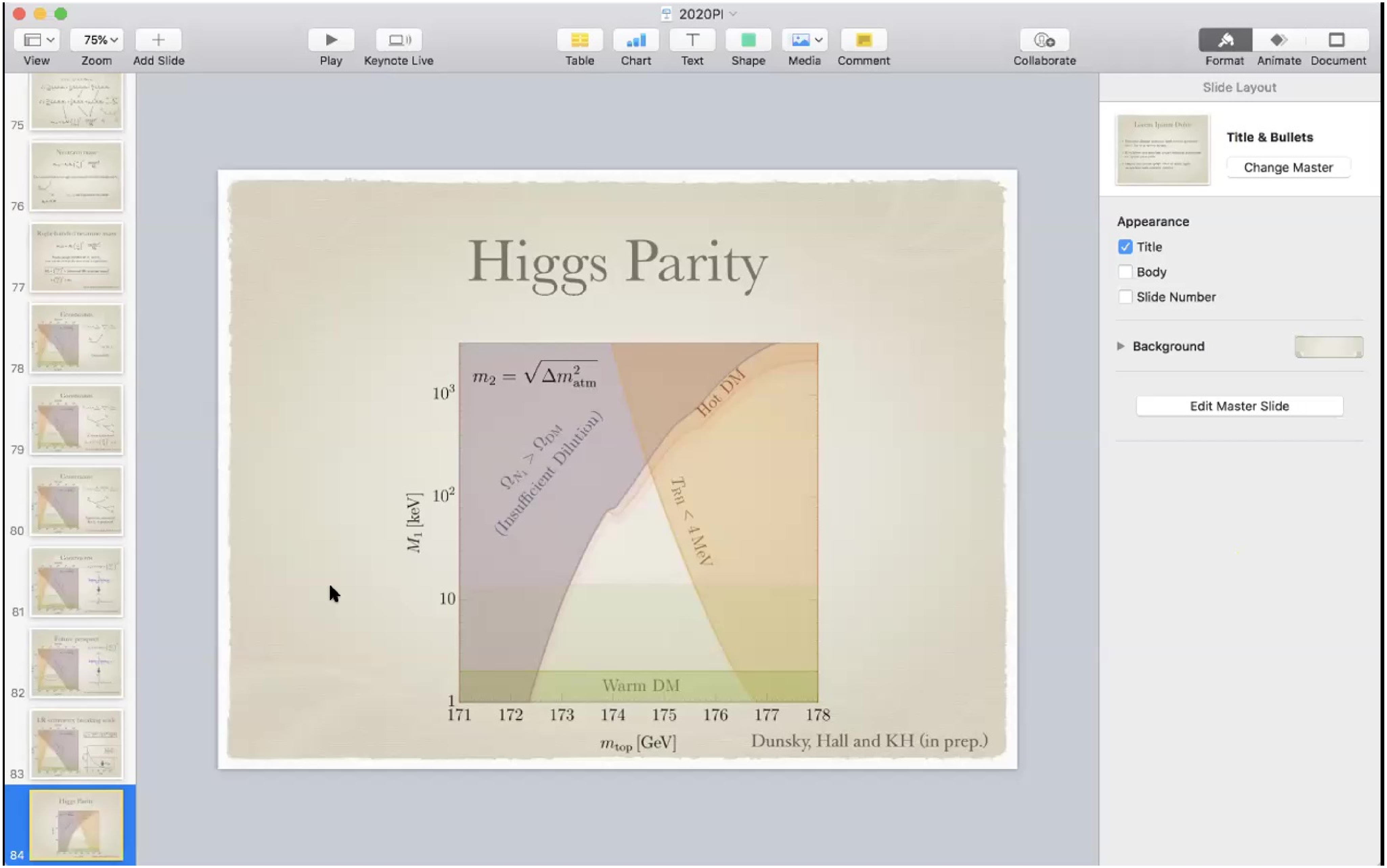
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Higgs Parity
$m_2 = \sqrt{\Delta m^2_{\rm atm}}$
$\Omega_{N_1} > \Omega_{DM}$ (Insufficient Dilution)
Hot DM
$T_{\rm RH} < 4$ MeV
Warm DM
M_1 [keV]
$m_{\rm top}$ [GeV]
Dunsky, Hall and KH (in prep.)
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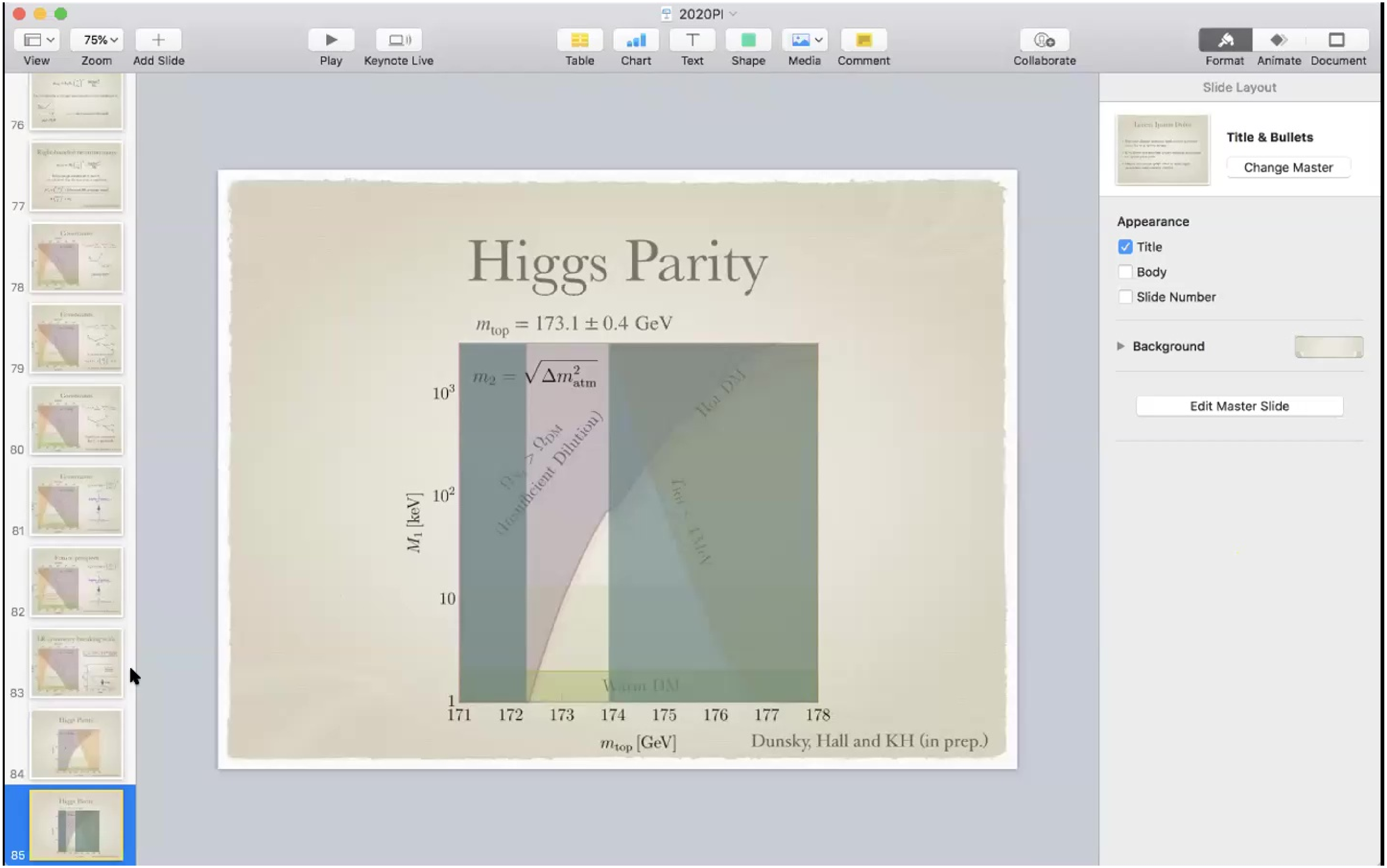
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Higgs Parity
$m_{\rm top} = 173.1 \pm 0.4$ GeV
$m_2 = \sqrt{\Delta m^2_{\rm atm}}$
M_1 [keV]
10^3
10^2
10
1
171
172
173
174
175
176
177
178
$m_{\rm top}$ [GeV]
Dunsky, Hall and KH (in prep.)
(Insufficient Dilution)
Hot DM
Warm DM
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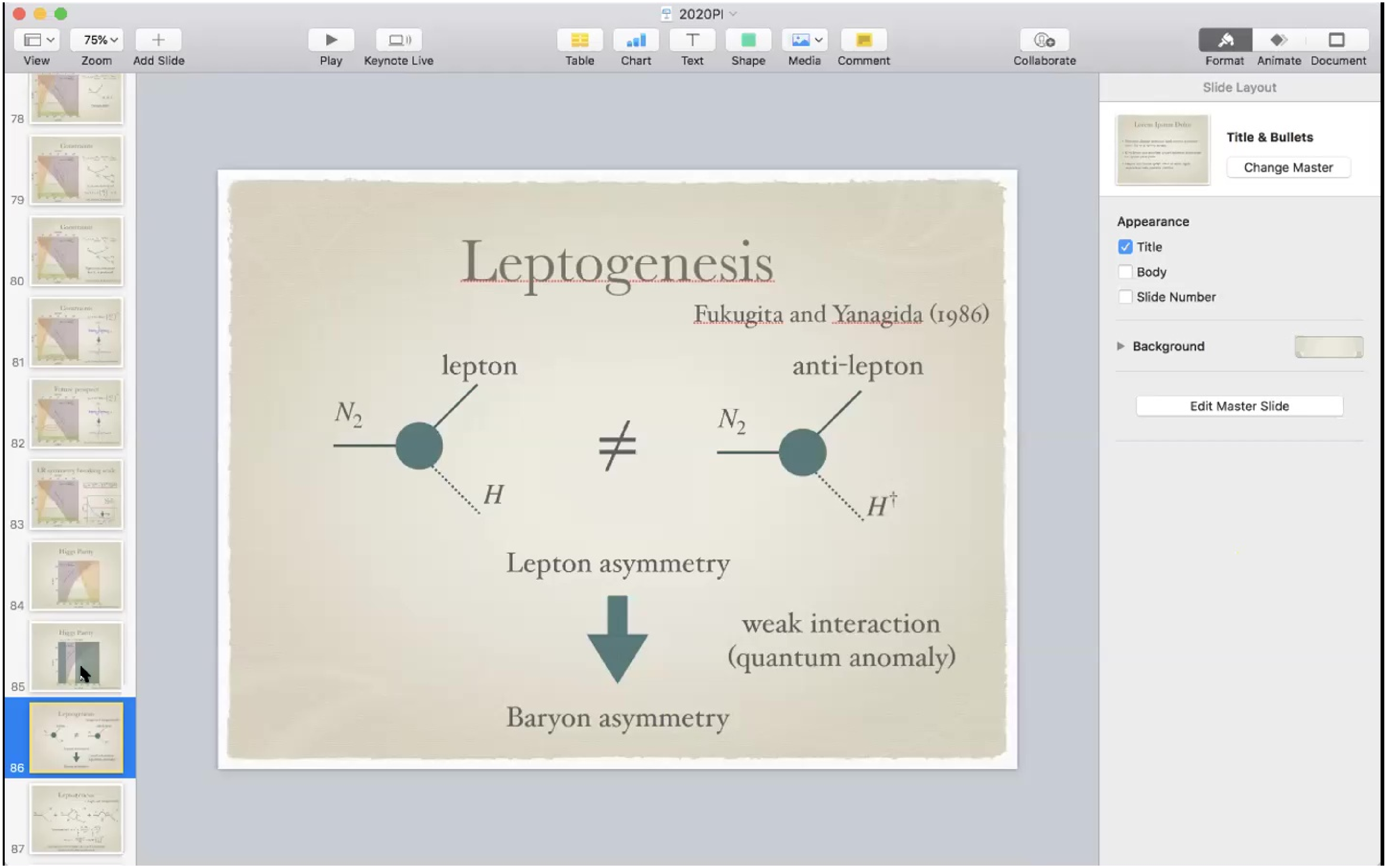
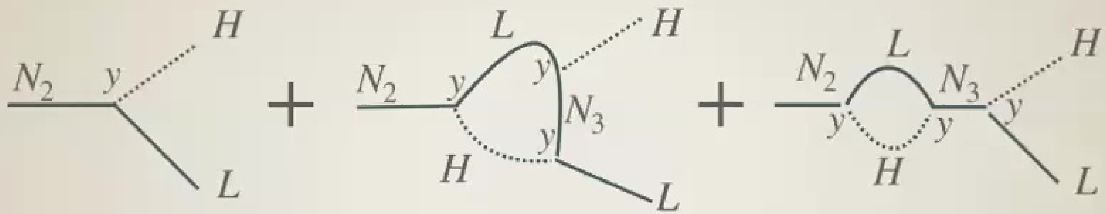

Leptogenesis
Fukugita and Yanagida (1986)
lepton
anti-lepton
N_2
H
$\neq$
N_2
$H^\dagger$
Lepton asymmetry
weak interaction
(quantum anomaly)
Baryon asymmetry

Leptogenesis

Fukugita and Yanagida (1986)



$$(\text{asymmetry}) \propto y^2 < \frac{m_\nu M_{2,3}}{v^2} < \frac{m_\nu^2 v_R^2}{v^4}$$

$$m_{\nu,ij} = -\frac{y_{ik} y_{jk} v^2}{M_j} + \delta_{ij} M_i \left(\frac{v}{v_R}\right)^2$$

Leptogenesis favors large v_R, which is however disfavored by DM production

Enhancement?

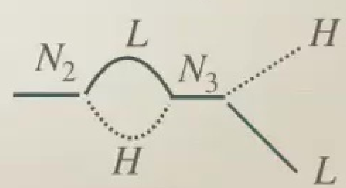
$$\text{(asymmetry)} \propto y^2 < \frac{m_\nu M_{2,3}}{v^2} < \frac{m_\nu^2 v_R^2}{v^4}$$

$$m_{\nu,ij} = -\frac{y_{ik} y_{jk} v^2}{M_j} + \delta_{ij} M_i \left(\frac{v}{v_R}\right)^2$$

* Cancellation between the two terms in m_ν
* Resonant enhancement

  Flanz, Paschos and Sarkar (1995)

$$\frac{M_{2,3}}{M_2 - M_3}$$



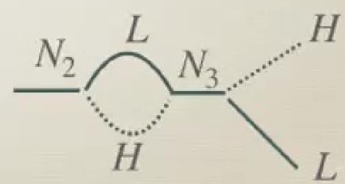
Enhancement?

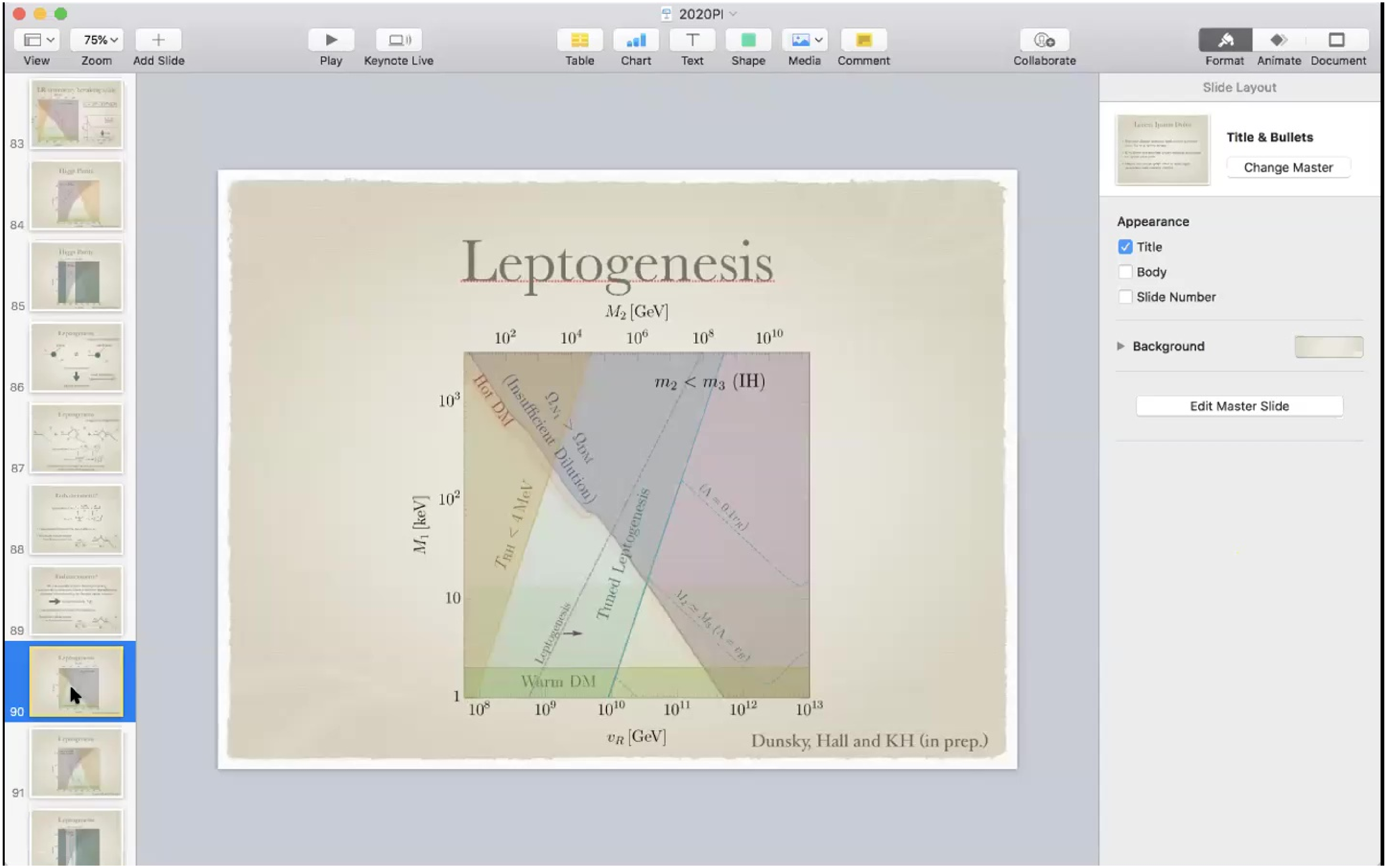
We can naturally achieve them by imposing a neutrino flavor structure, which is however destabilized by quantum corrections (e.g. by charged lepton yukawa)

→ Lower bound on v_R

* Cancellation between the two terms in m_ν
* Resonant enhancement
  Flanz, Paschos and Sarkar (1995)

$$\frac{M_{2,3}}{M_2 - M_3}$$

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Leptogenesis
M_2 [GeV]
m_2 < m_3 (IH)
Hot DM
(Insufficient Dilution)
Tuned Leptogenesis
Leptogenesis
Warm DM
M_1 [keV]
v_R [GeV]
Dunsky, Hall and KH (in prep.)
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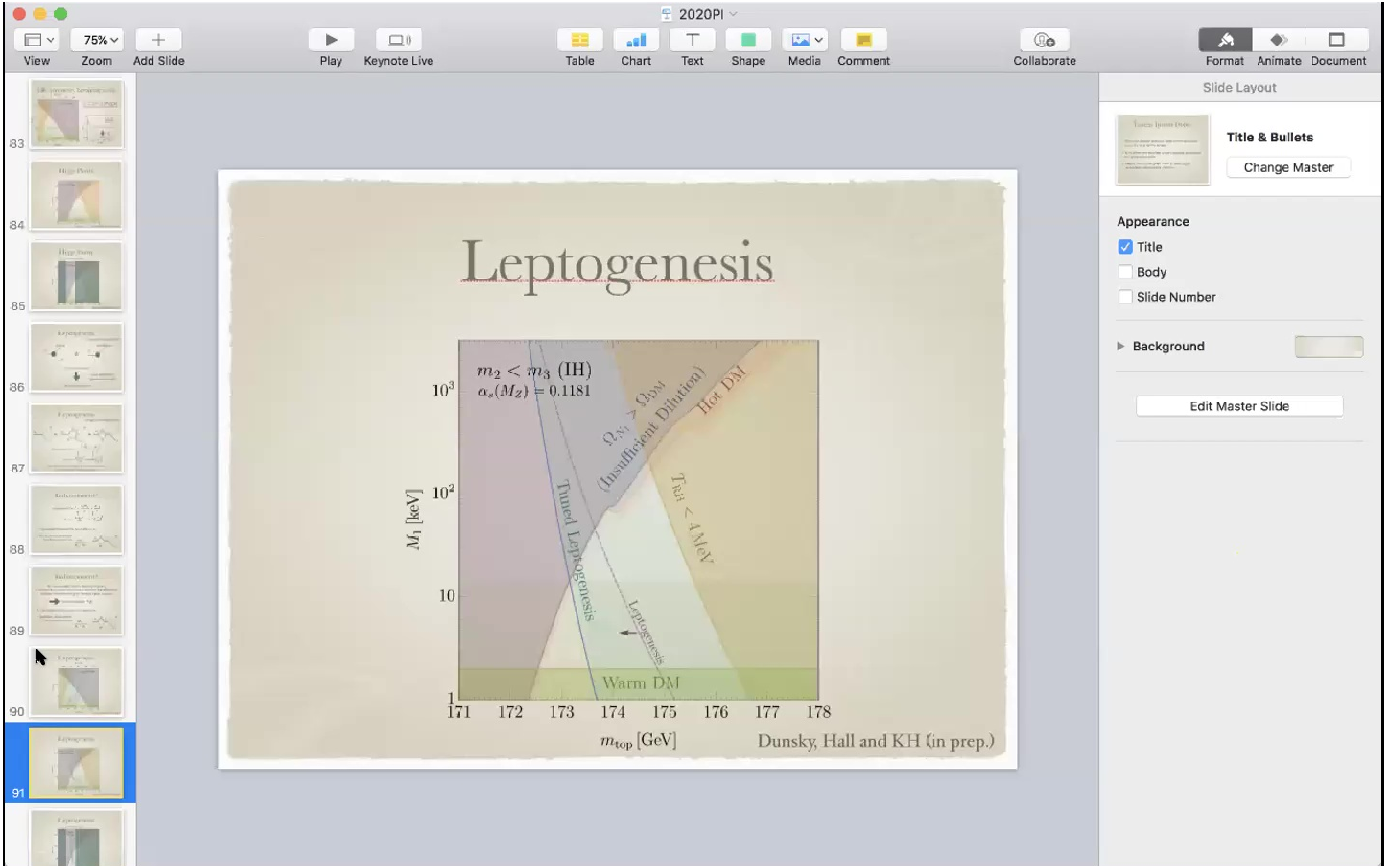
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Leptogenesis
$m_2 < m_3$ (IH)
$\alpha_s(M_Z) = 0.1181$
$\Omega_{N_1} > \Omega_{DM}$
(Insufficient Dilution)
Hot DM
Tuned Leptogenesis
$T_{RH} < 4$ MeV
Leptogenesis
Warm DM
M_1 [keV]
10^3
10^2
10
1
171
172
173
174
175
176
177
178
m_{top} [GeV]
Dunsky, Hall and KH (in prep.)
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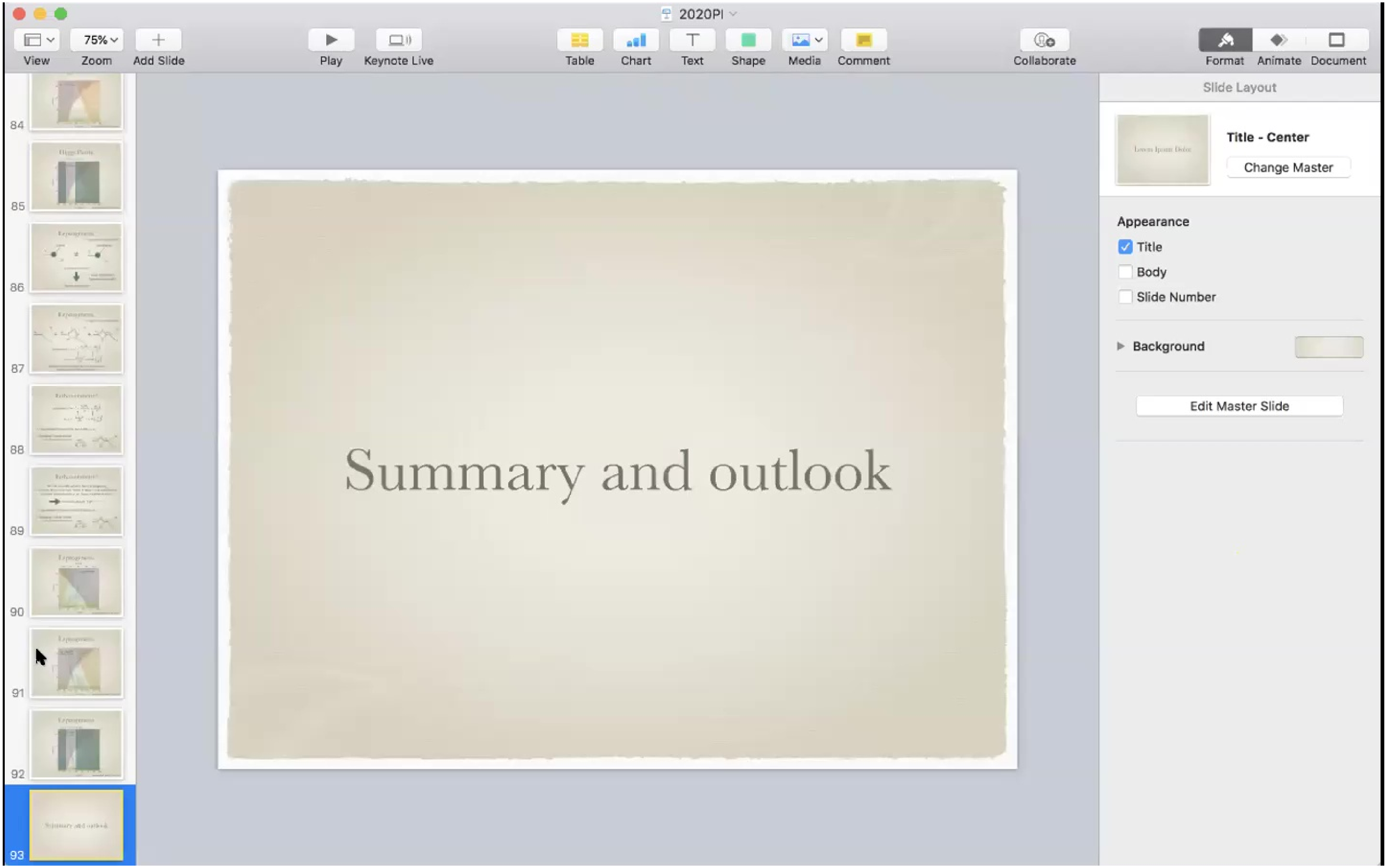
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Summary and outlook
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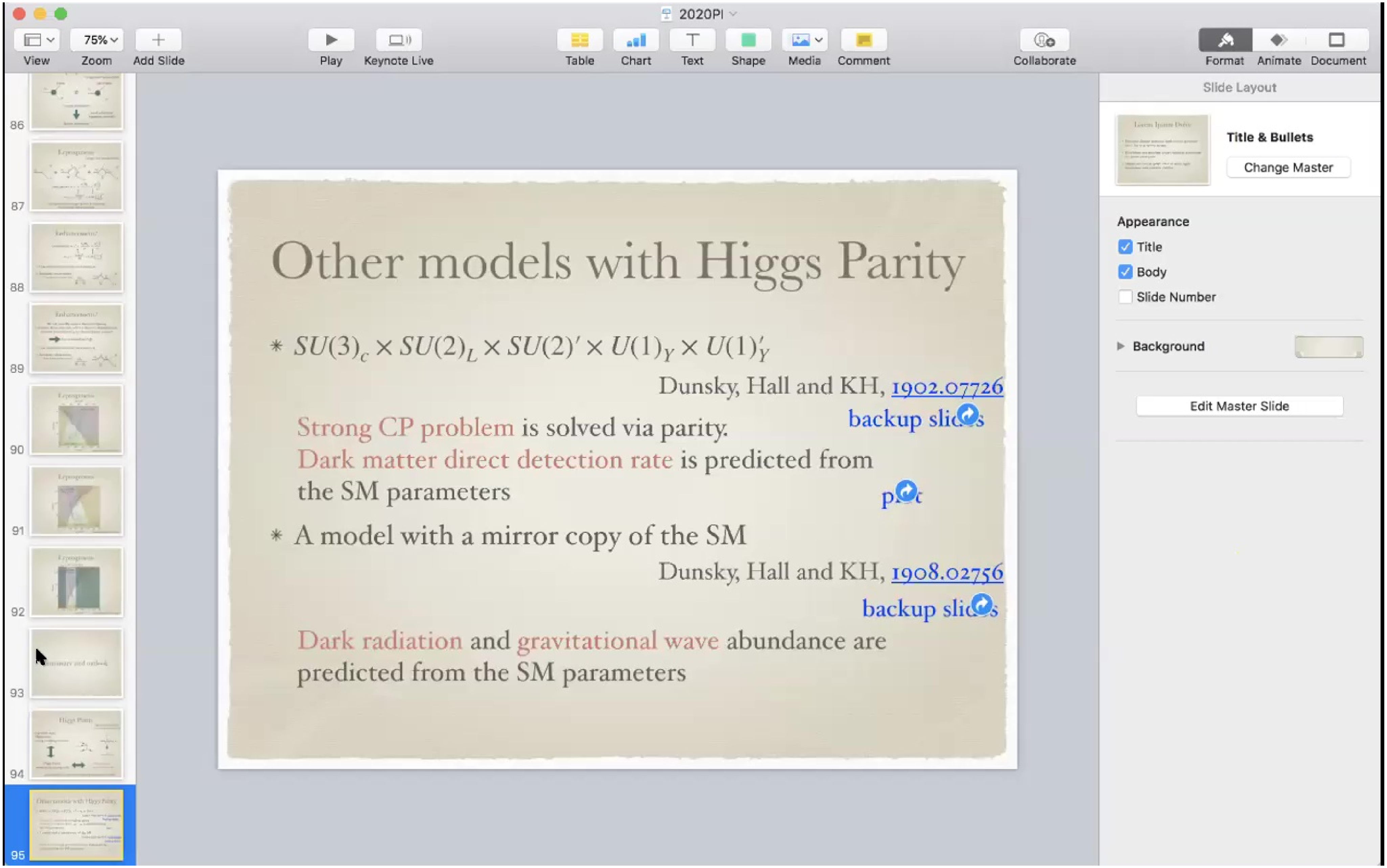
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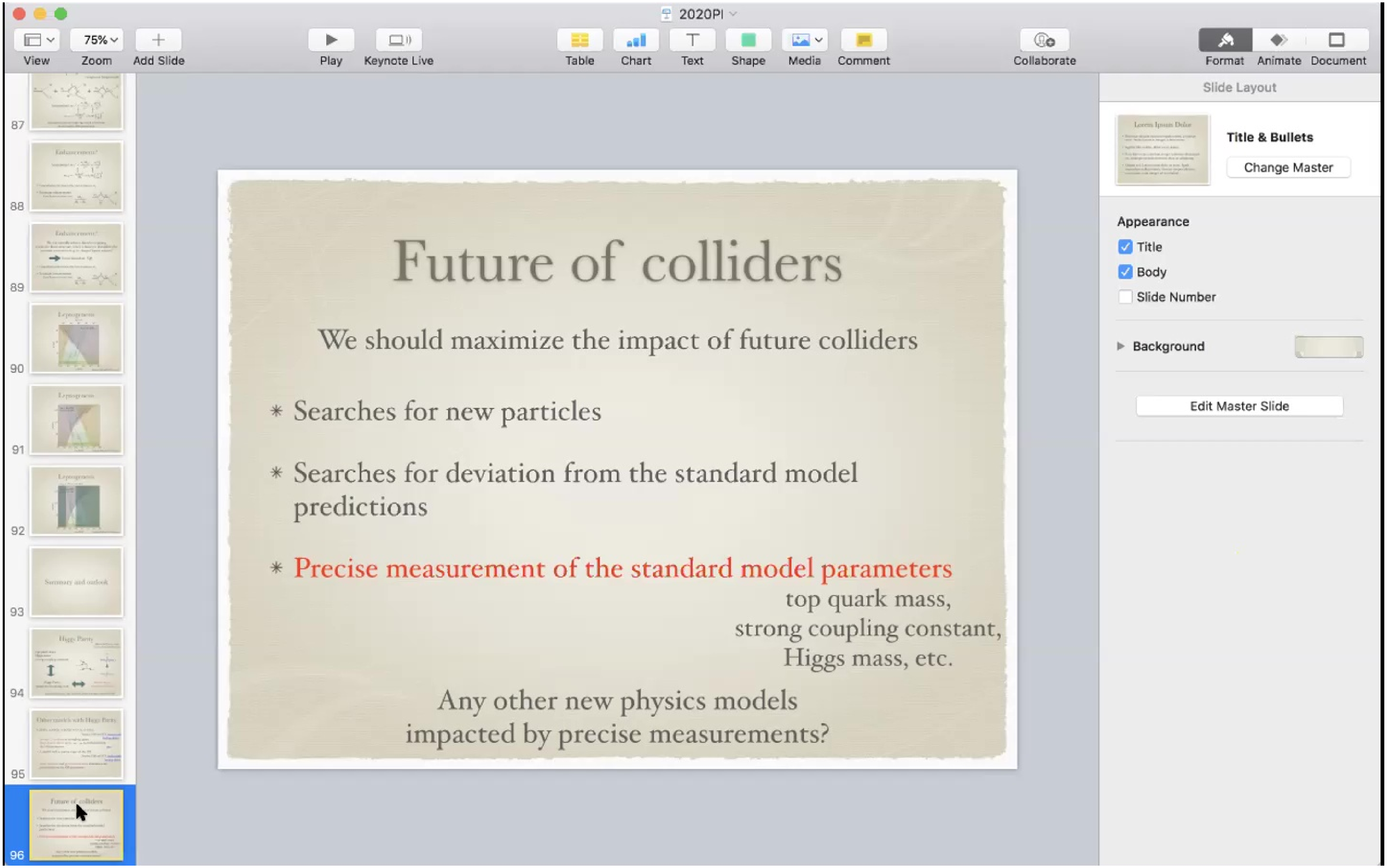
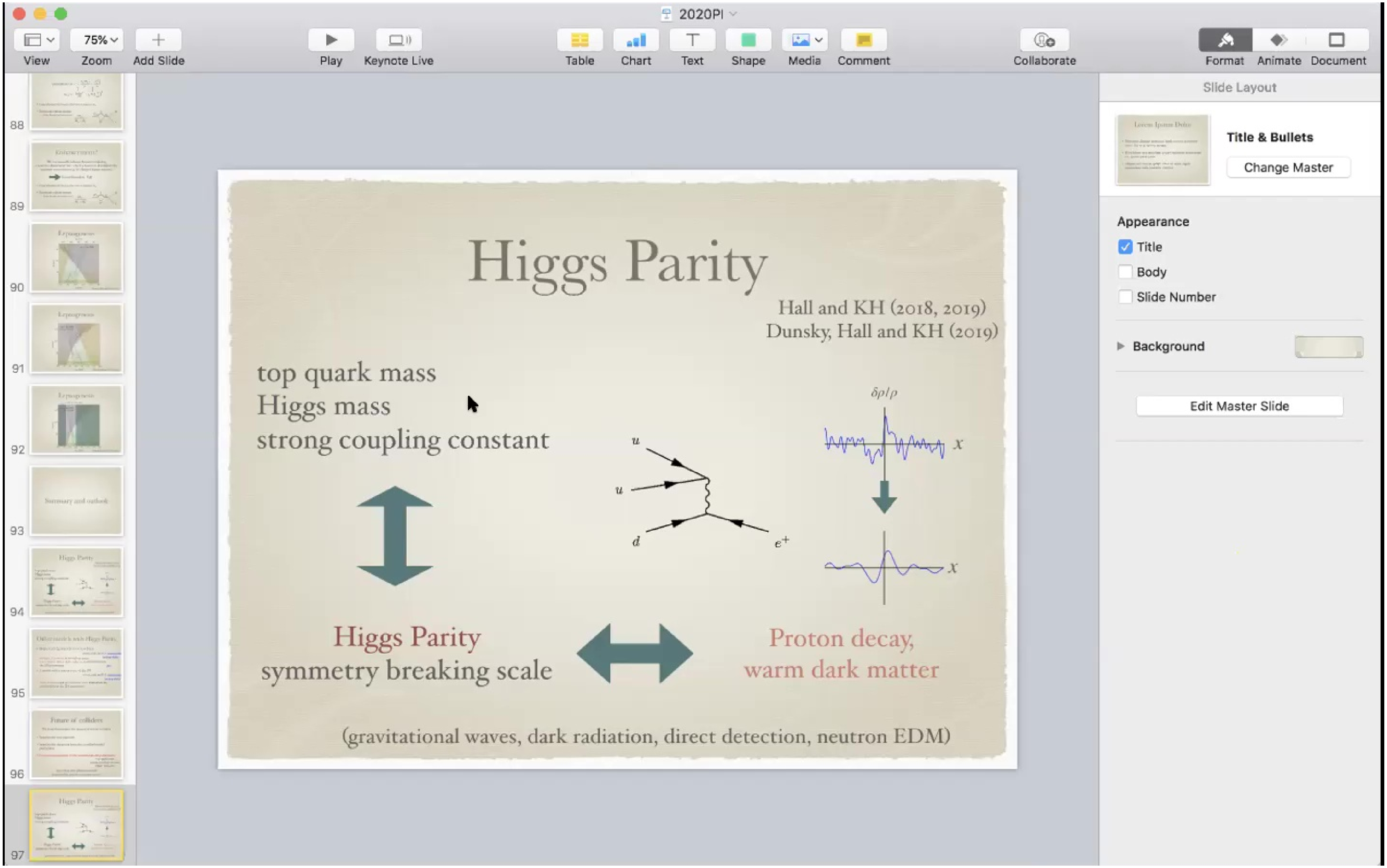
Other models with Higgs Parity
* $SU(3)_c \times SU(2)_L \times SU(2)' \times U(1)_Y \times U(1)'_Y$
Dunsky, Hall and KH, 1902.07726
backup slides
Strong CP problem is solved via parity.
Dark matter direct detection rate is predicted from the SM parameters
* A model with a mirror copy of the SM
Dunsky, Hall and KH, 1908.02756
backup slides
Dark radiation and gravitational wave abundance are predicted from the SM parameters


Future of colliders
We should maximize the impact of future colliders
* Searches for new particles
* Searches for deviation from the standard model predictions
* Precise measurement of the standard model parameters
top quark mass,
strong coupling constant,
Higgs mass, etc.
Any other new physics models
impacted by precise measurements?


2020PI
Higgs Parity
Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)
top quark mass
Higgs mass
strong coupling constant
u
u
d
e+
δρ/ρ
x
x
Higgs Parity
symmetry breaking scale
Proton decay,
warm dark matter
(gravitational waves, dark radiation, direct detection, neutron EDM)
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