Title: Bottom-up Naturalness

Date: Aug 27, 2013 01:00 PM

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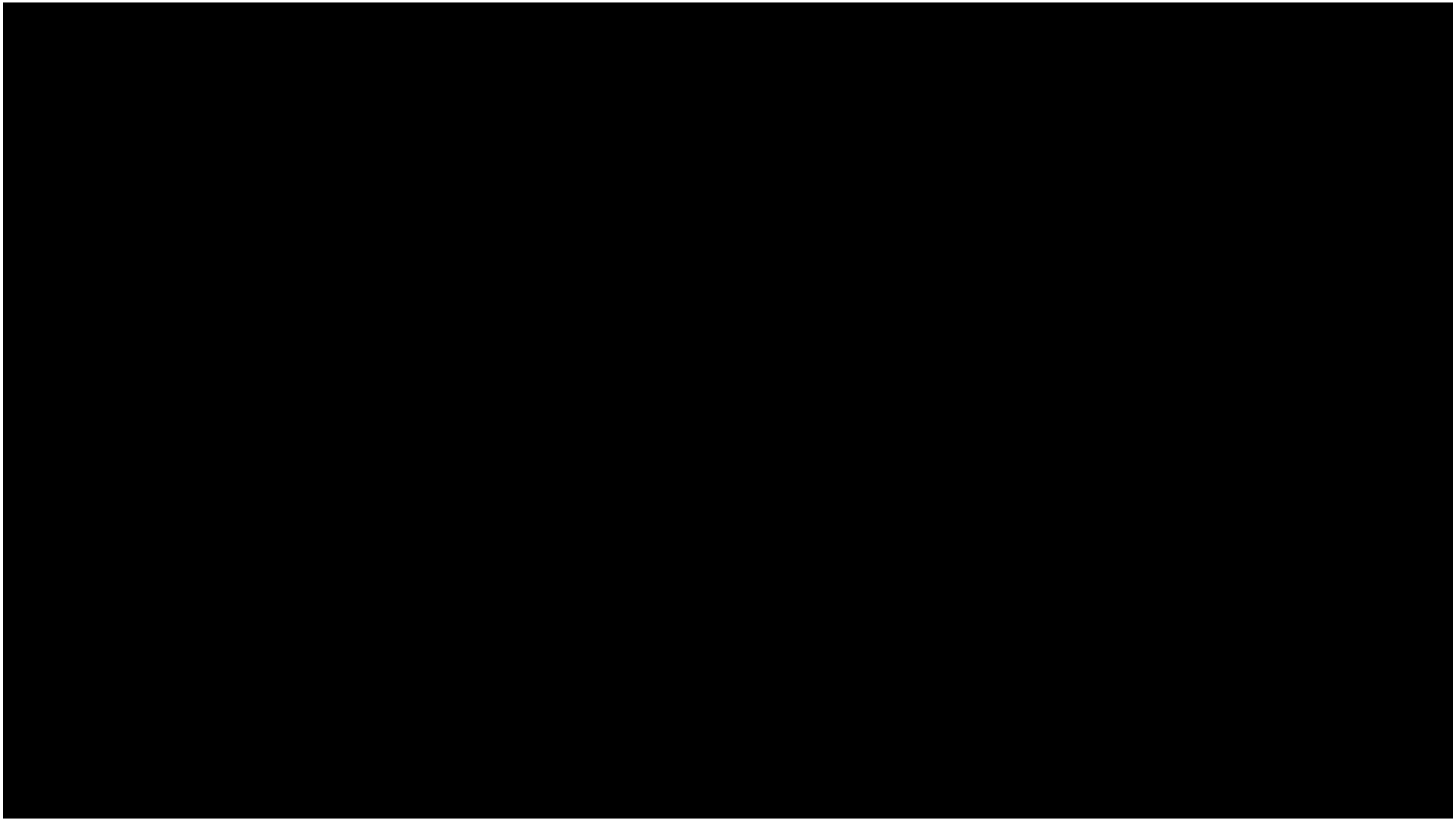
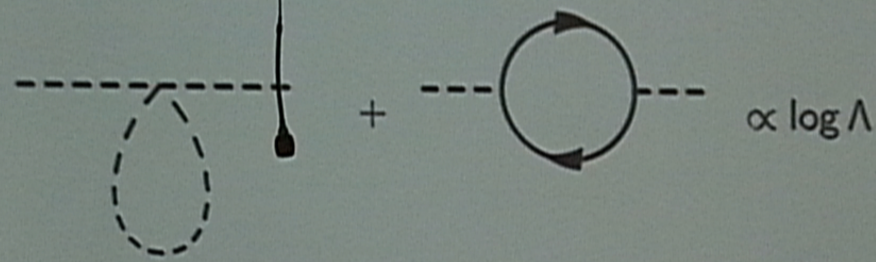
Abstract: We study the naturalness problem using a model independent bottom up approach by considering models where only the interaction terms needed to cancel the Higgs quadratic divergences are present. If quadratic divergences are canceled by terms linear in the Higgs field, then the collider phenomenology is well covered by current electroweakino and fourth generation searches. If quadratic divergences are canceled by terms bilinear in the Higgs field, then the signatures are highly dependent on the quantum numbers of the new particles. Precision Higgs measurements can reveal the presence of new particles with either vevs or Standard Model charges. If the new particles are scalar dark matter candidates, their direct and indirect detection signatures will be highly correlated and within the reach of XENON100 and Fermi. Observation at one of these experiments would imply observation at the other one. Observable LHC decay channels can also arise if the new particles mix with lighter states. This decay channel involves only the Higgs boson and not the gauge bosons. Observation of such decays would give evidence that the new particle is tied to the naturalness problem.

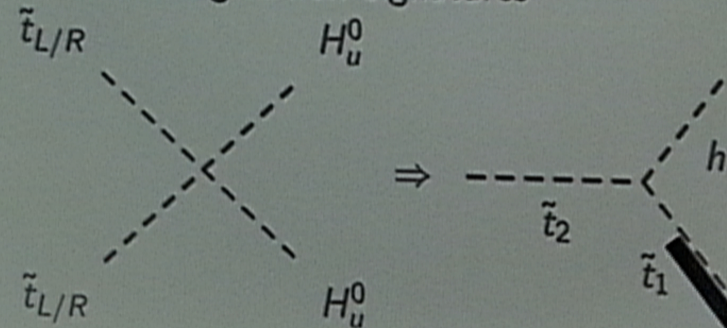


Traditional approaches

New particles running in loops

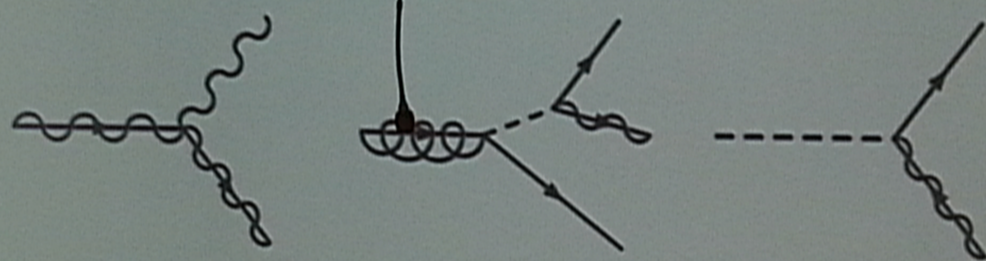


Cancellation terms give new signatures



Traditional approaches

But dominant signatures from other terms



Model dependent

Not directly related to the quadratic divergences

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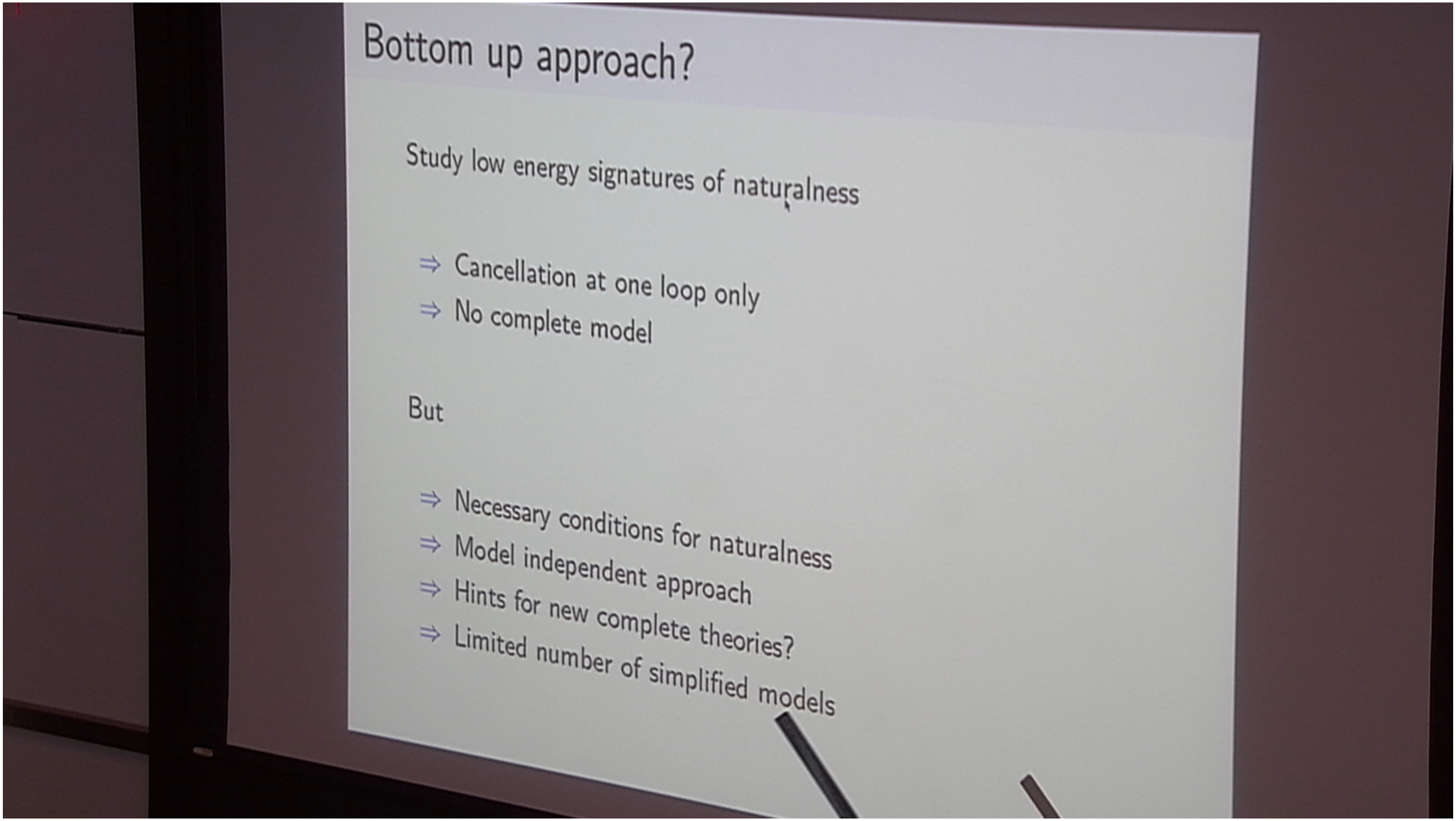
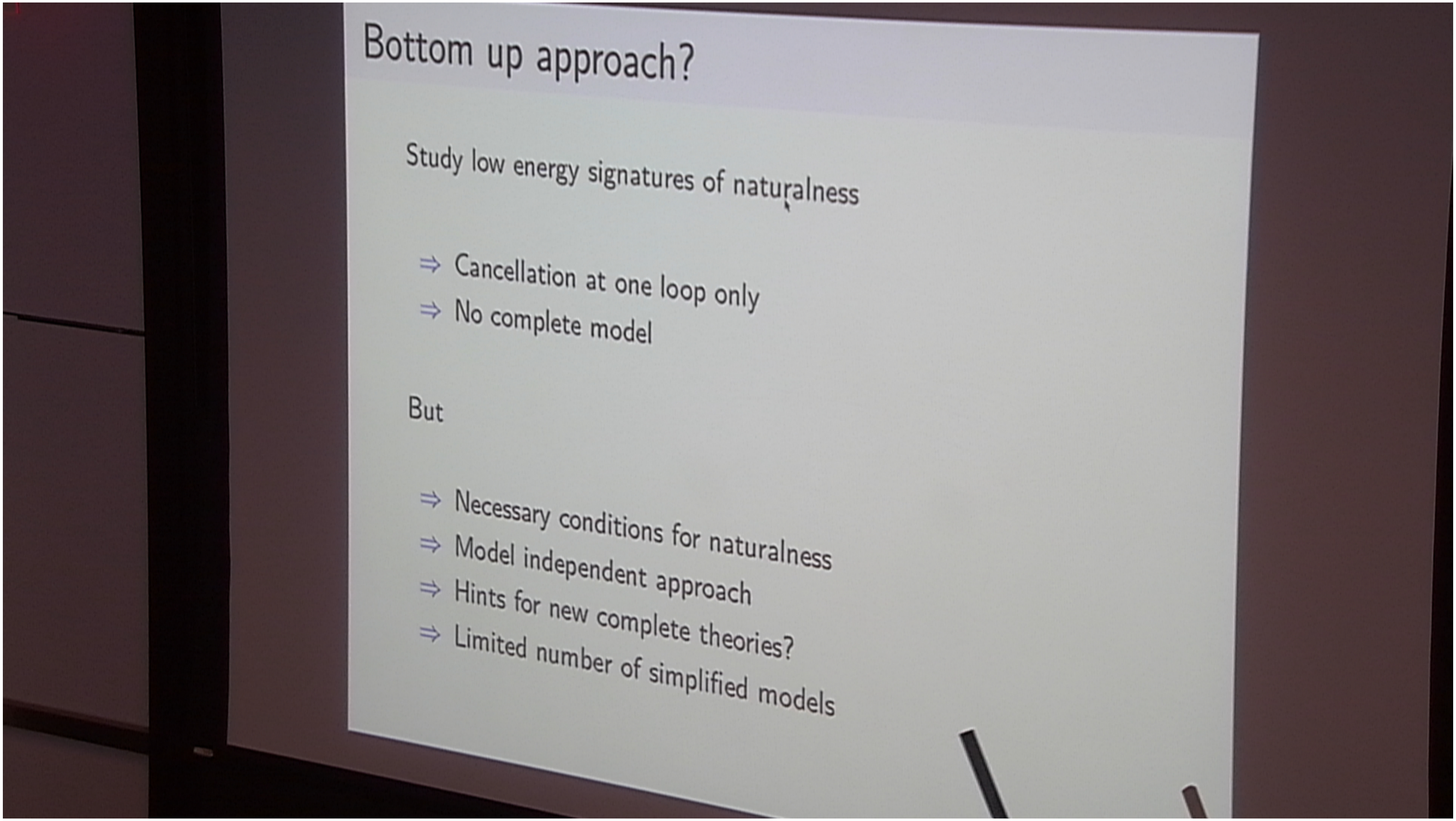

Bottom up approach?
Study low energy signatures of naturalness
⇒ Cancellation at one loop only
⇒ No complete model
But
⇒ Necessary conditions for naturalness
⇒ Model independent approach
⇒ Hints for new complete theories?
⇒ Limited number of simplified models


Bottom up approach?
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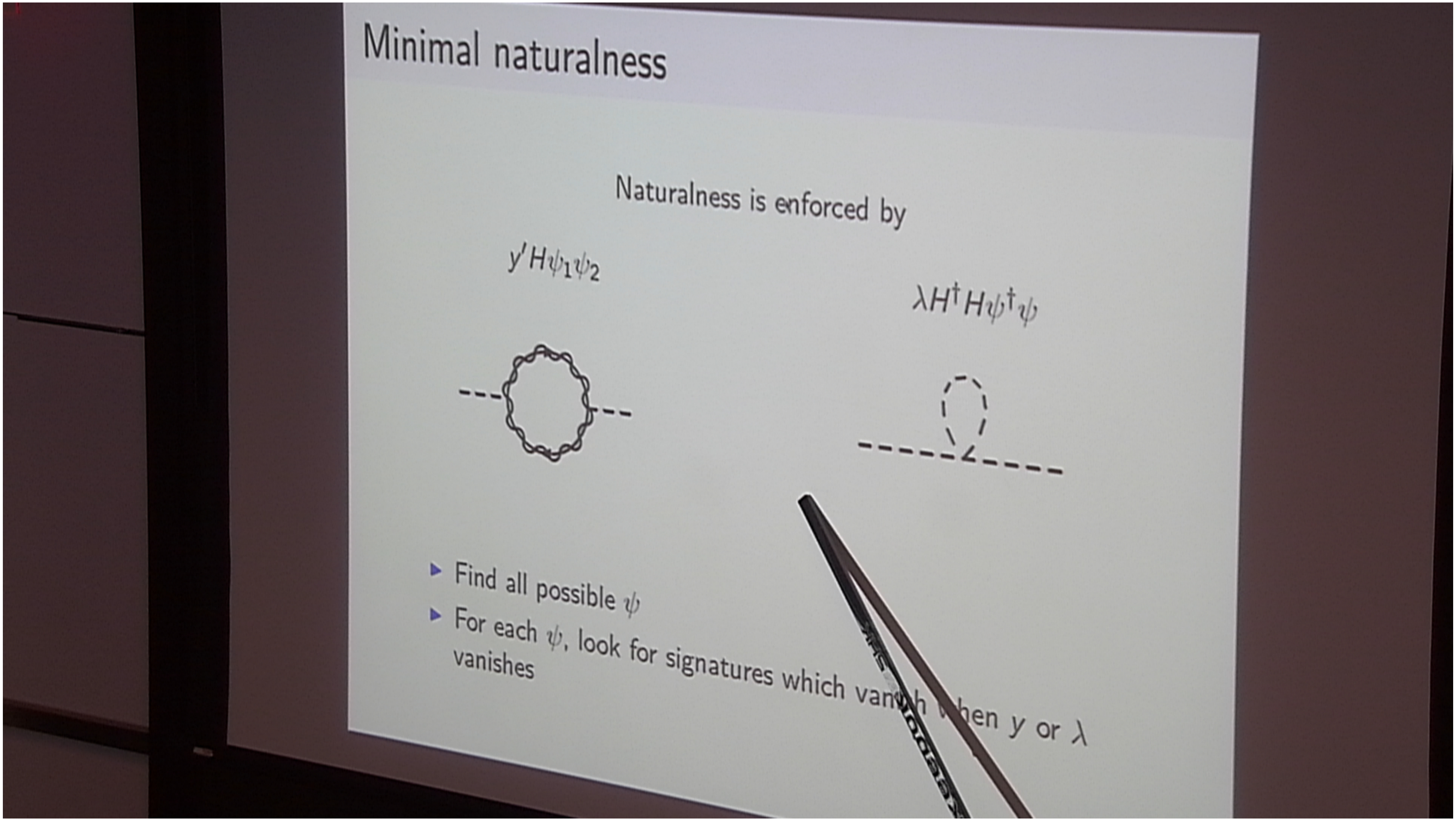
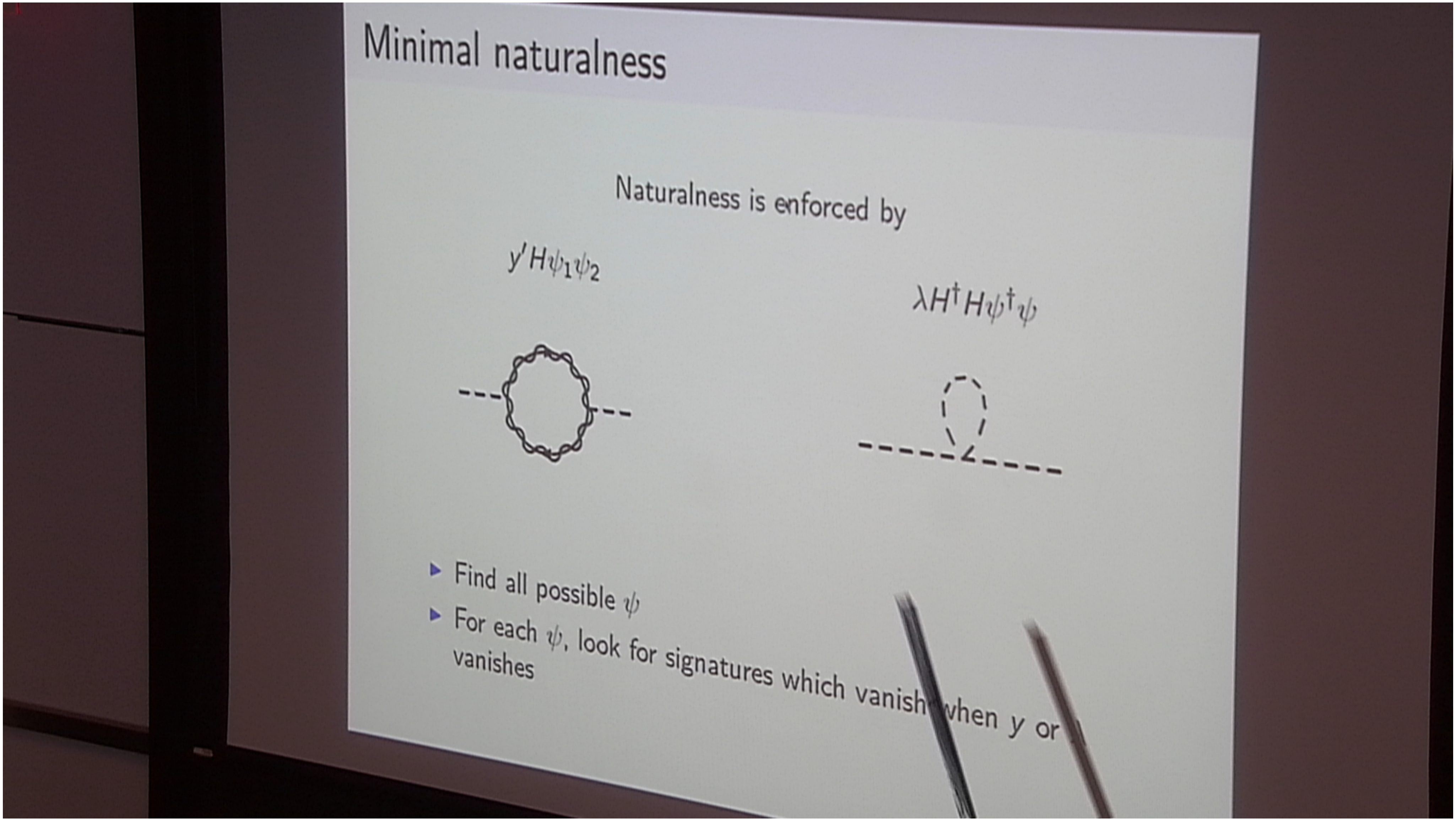


Minimal naturalness
Naturalness is enforced by
$y' H \psi_1 \psi_2$
$\lambda H^\dagger H \psi^\dagger \psi$
Find all possible ψ
For each ψ, look for signatures which van h hen y or λ
vanishes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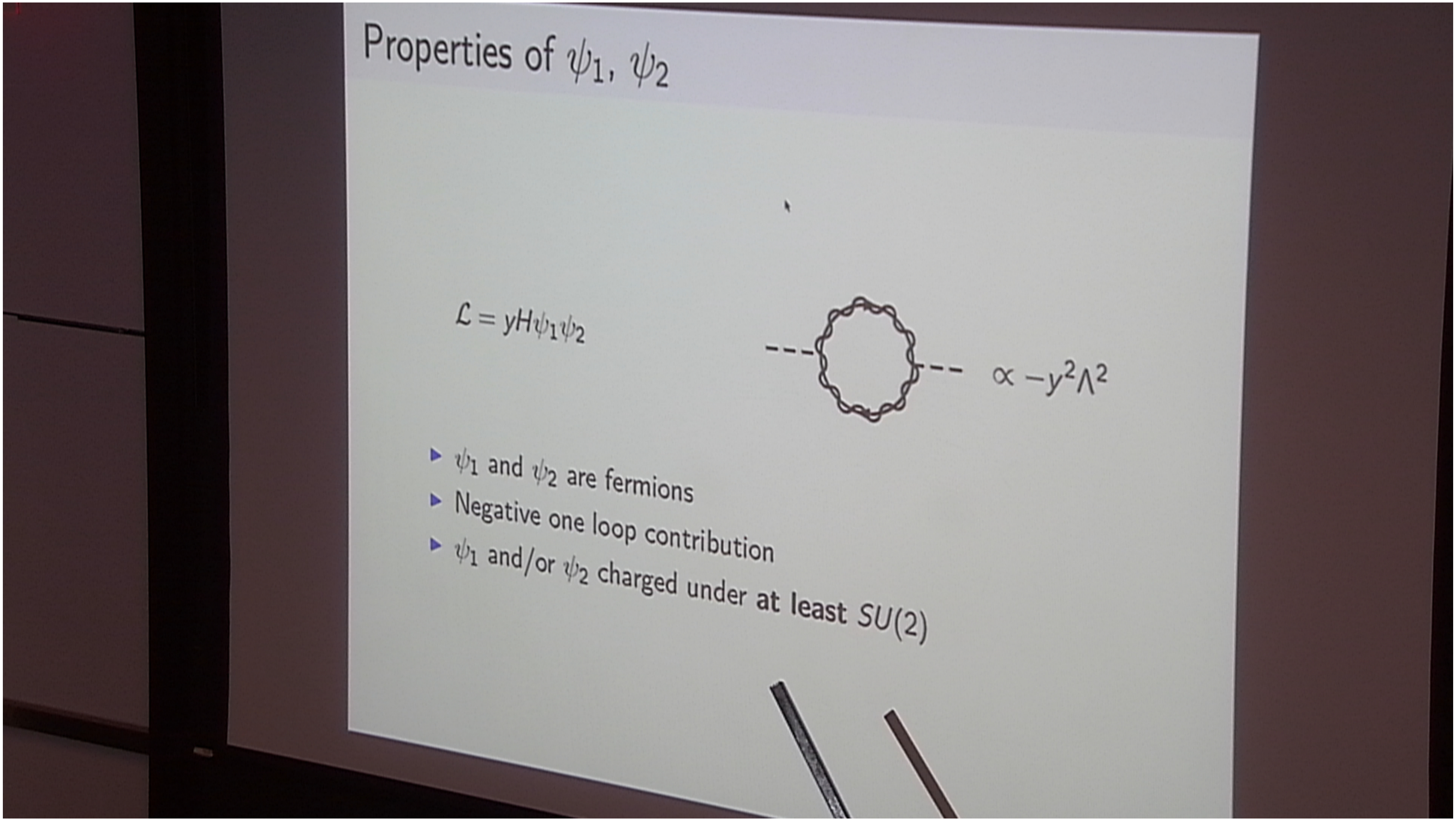
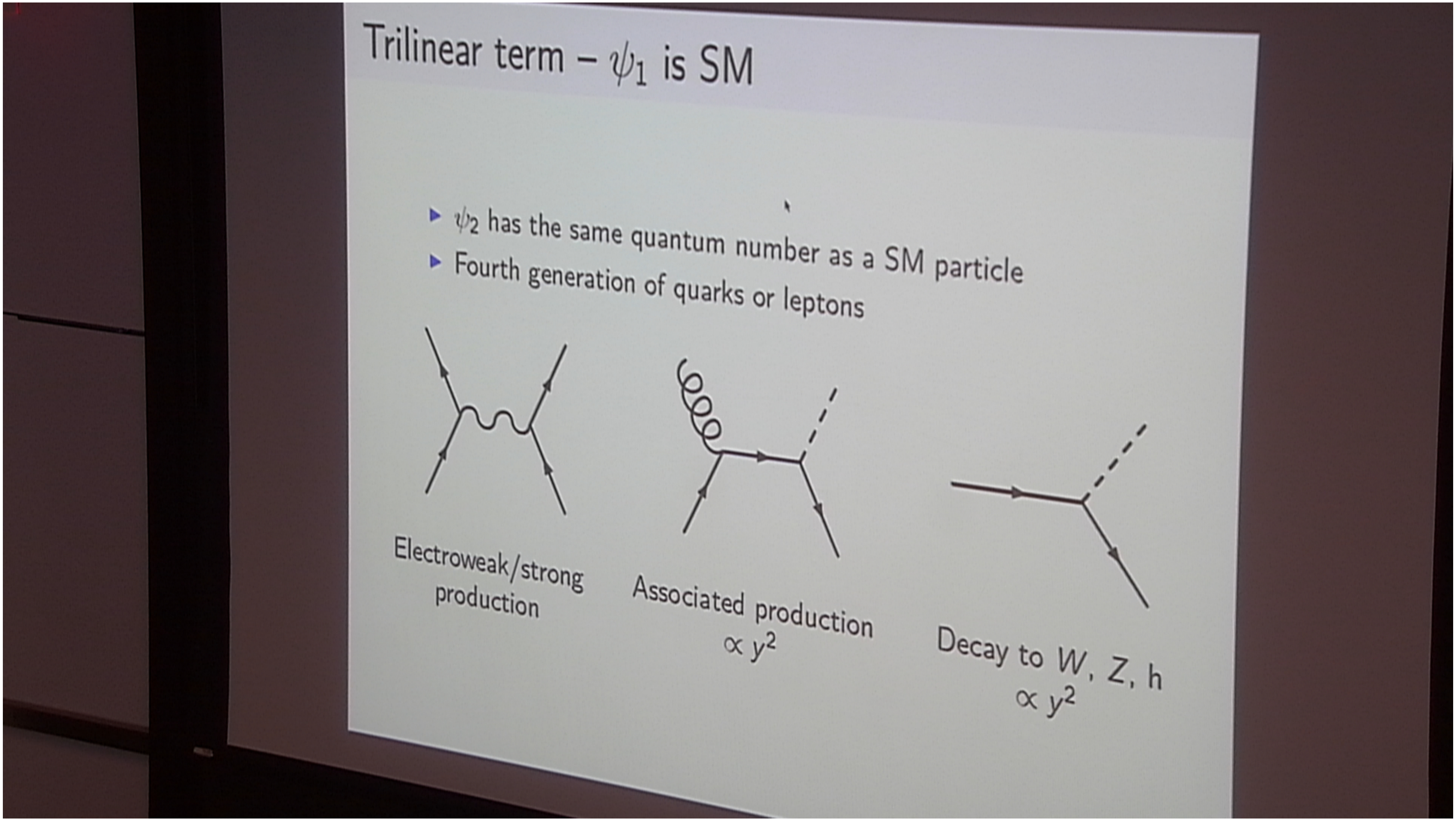
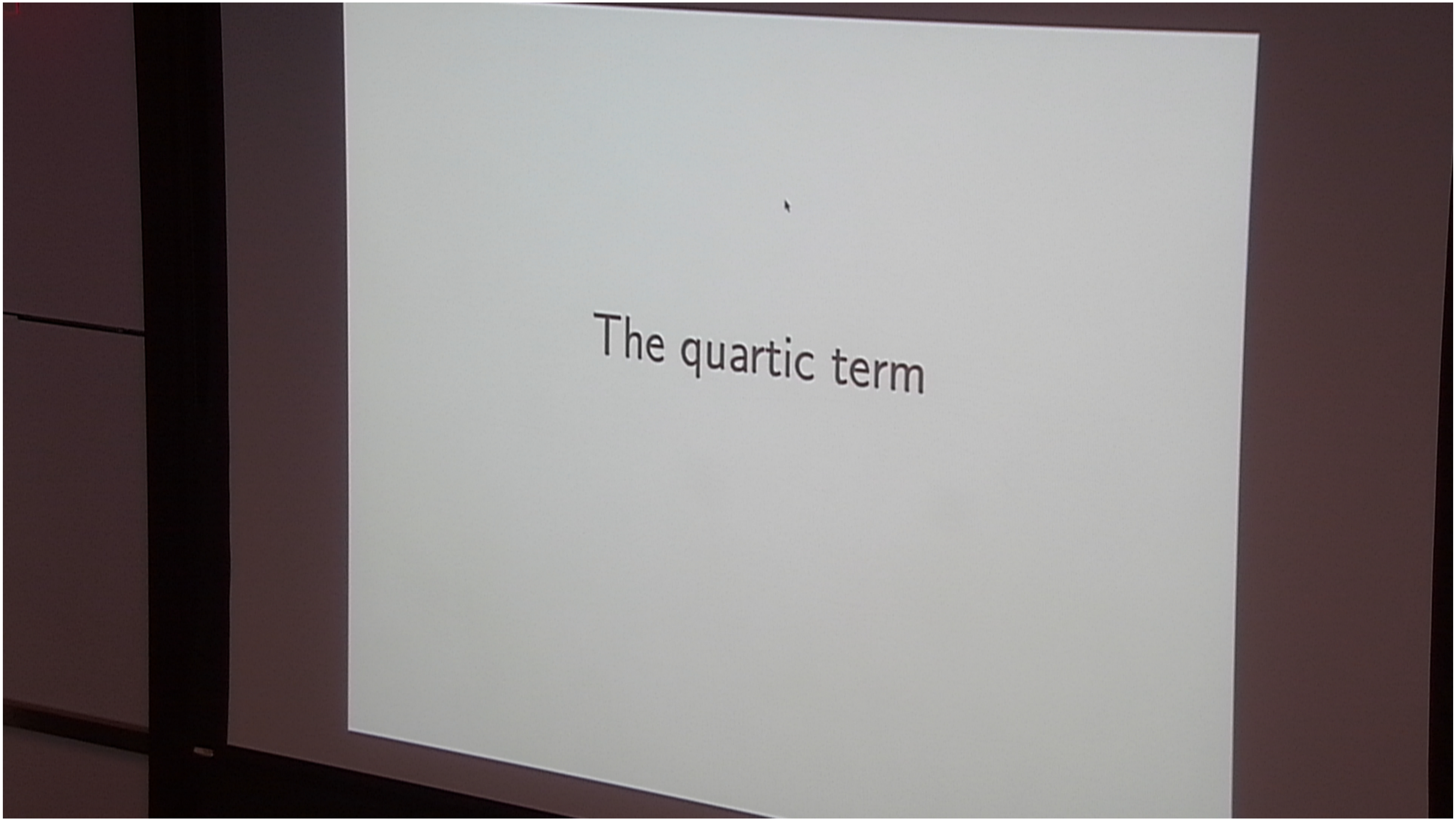
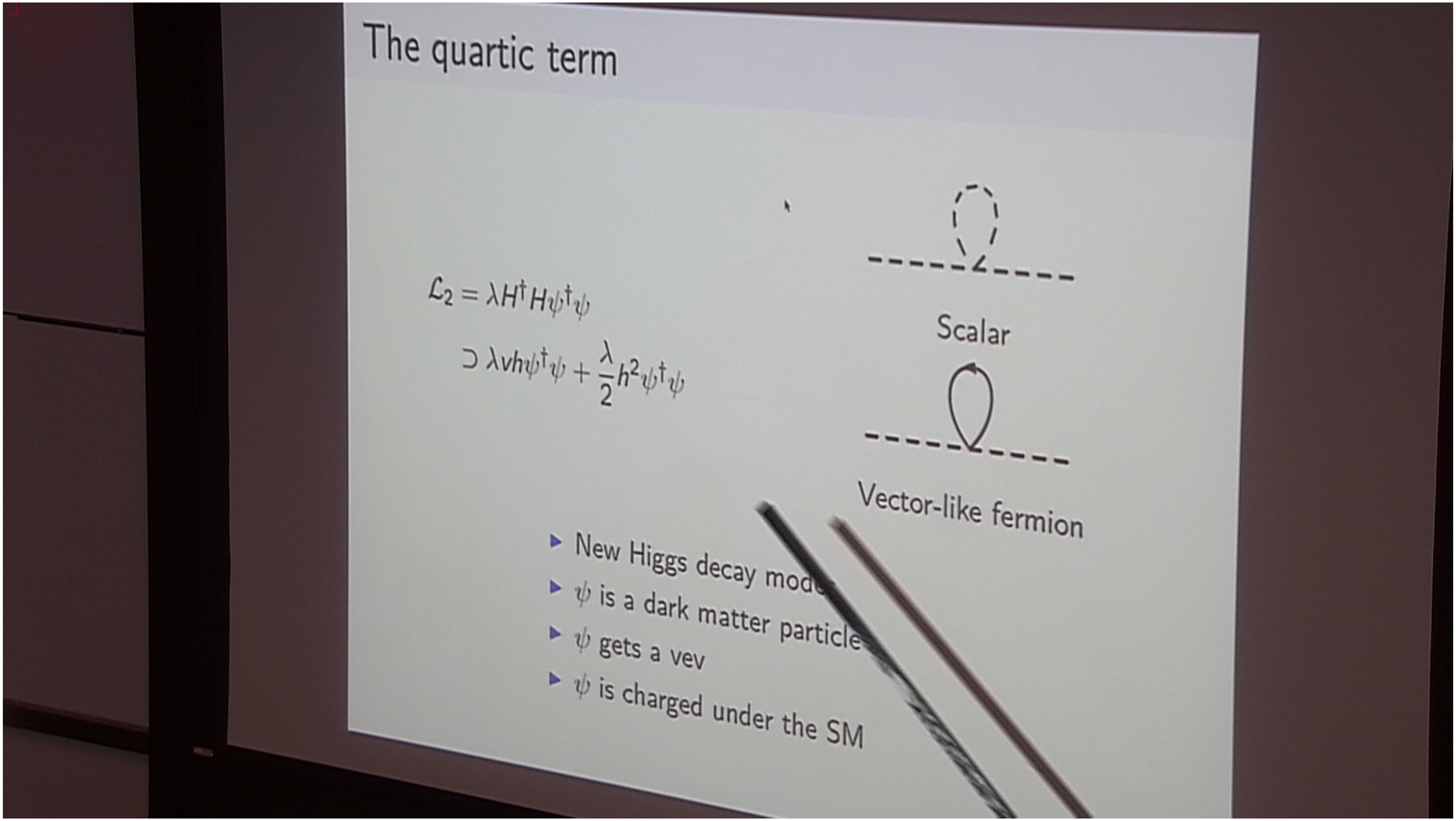

Properties of ψ_1, ψ_2
$\mathcal{L} = yH\psi_1\psi_2$
$\propto -y^2\Lambda^2$
ψ_1 and ψ_2 are fermions
Negative one loop contribution
ψ_1 and/or ψ_2 charged under **at least** $SU(2)$

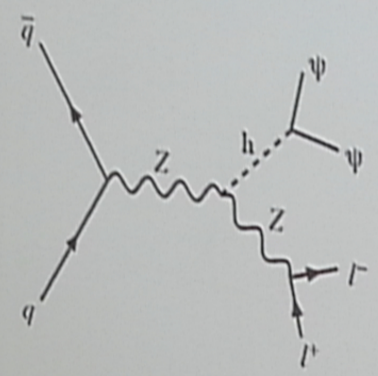

Trilinear term – ψ_1 is SM
ψ_2 has the same quantum number as a SM particle
Fourth generation of quarks or leptons
Electroweak/strong production
Associated production $\propto y^2$
Decay to W, Z, h $\propto y^2$

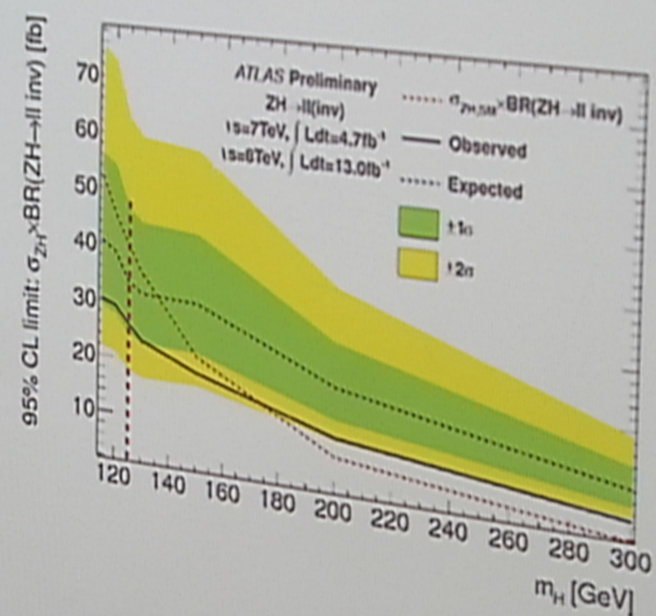

The quartic term


The quartic term
$\mathcal{L}_2 = \lambda H^\dagger H \psi^\dagger \psi$
$\supset \lambda v h \psi^\dagger \psi + \frac{\lambda}{2} h^2 \psi^\dagger \psi$
Scalar
Vector-like fermion
New Higgs decay mod
ψ is a dark matter particle
ψ gets a vev
ψ is charged under the SM

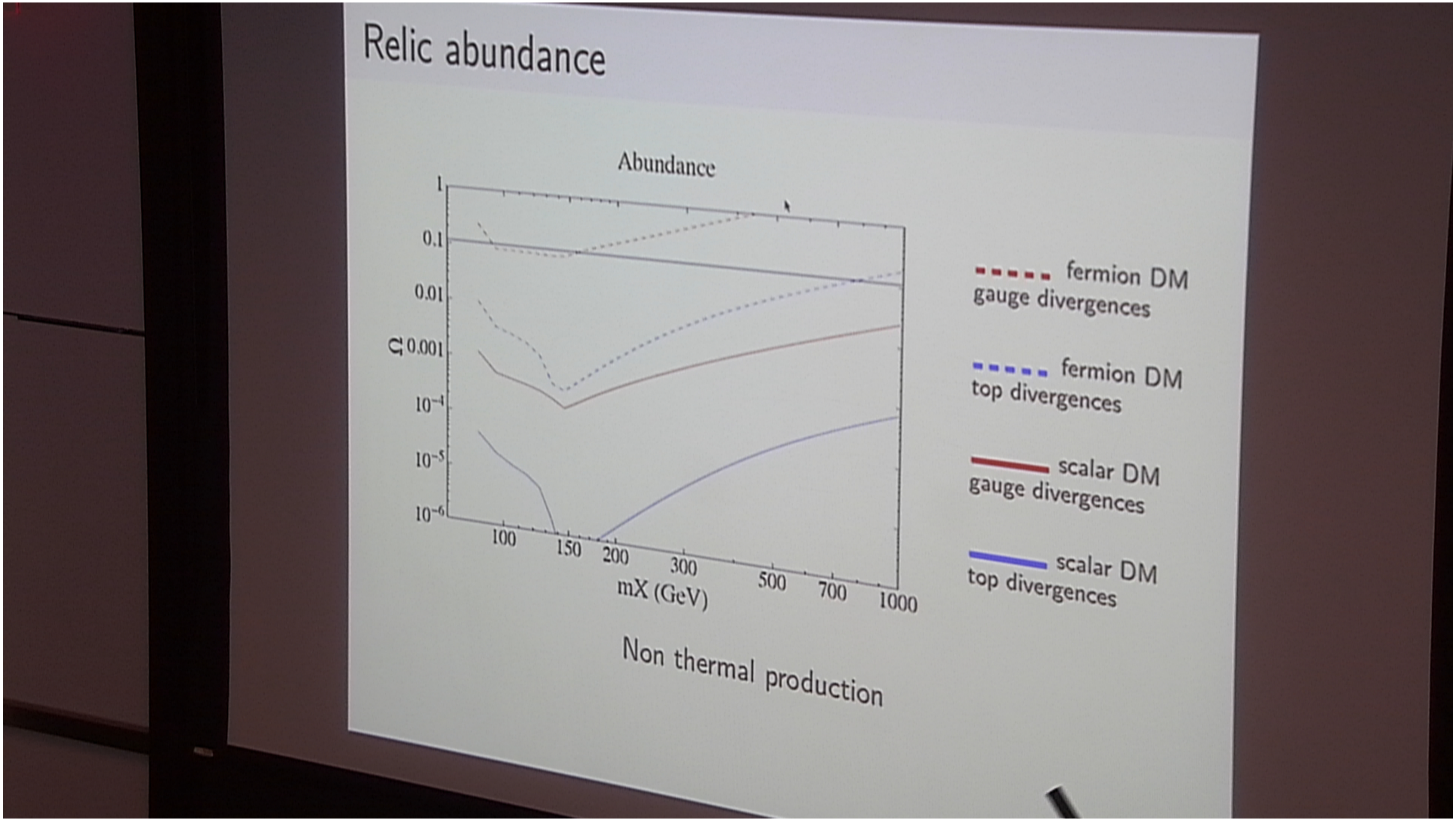
Higgs decays to $\psi^\dagger\psi$

ATLAS-CONF-2013-011





- Invisible decay modes
- Top and gauge divergences ⇒ Excluded
- Other divergences ⇒ Effect too small


Relic abundance
Abundance
1
0.1
0.01
0.001
10^-4
10^-5
10^-6
Ω
100
150
200
300
500
700
1000
mX (GeV)
fermion DM
gauge divergences
fermion DM
top divergences
scalar DM
gauge divergences
scalar DM
top divergences
Non thermal production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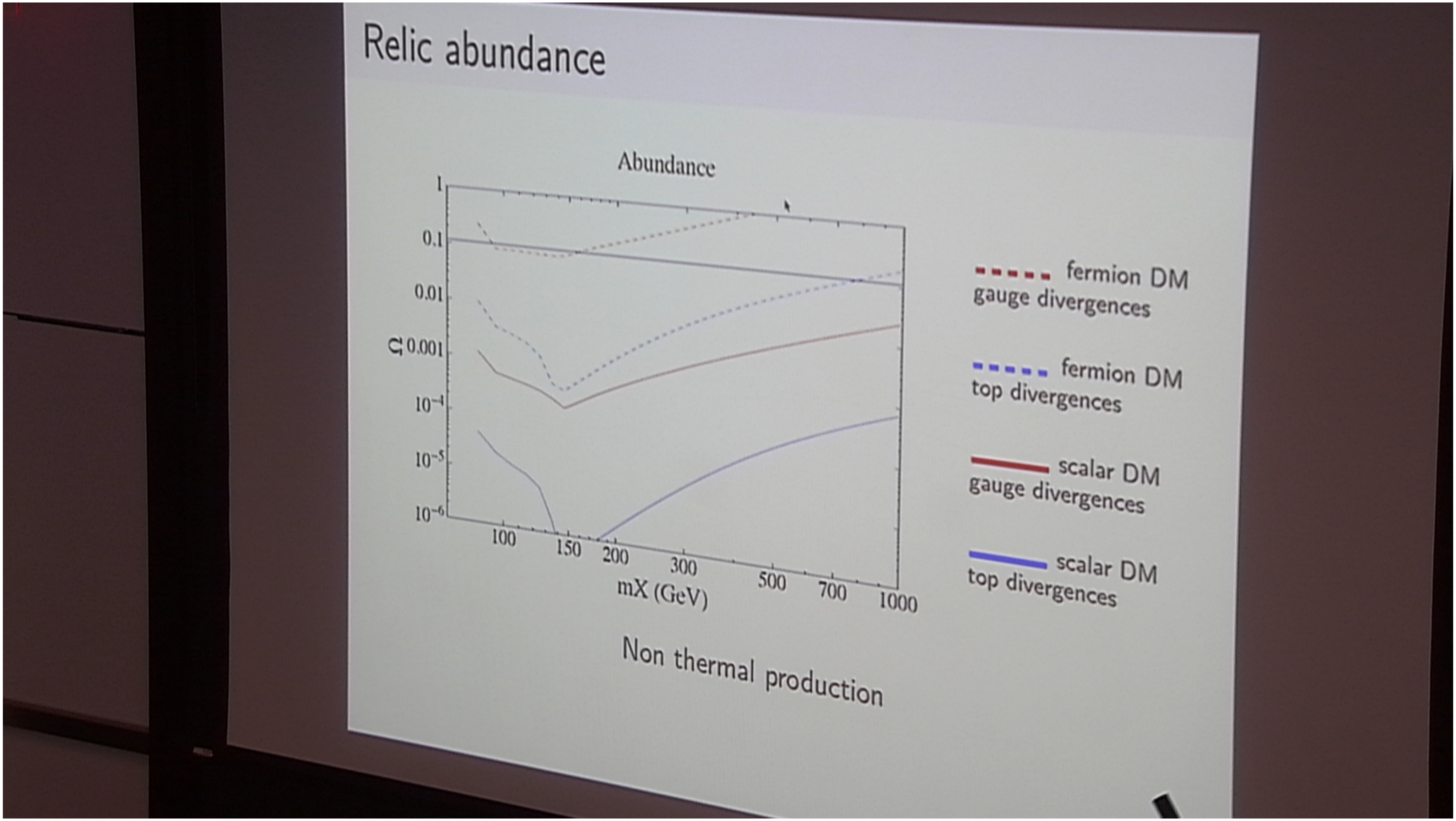
Relic abundance
Abundance
Ω
1
0.1
0.01
0.001
10⁻⁴
10⁻⁵
10⁻⁶
100
150
200
300
500
700
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mX (GeV)
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scalar DM
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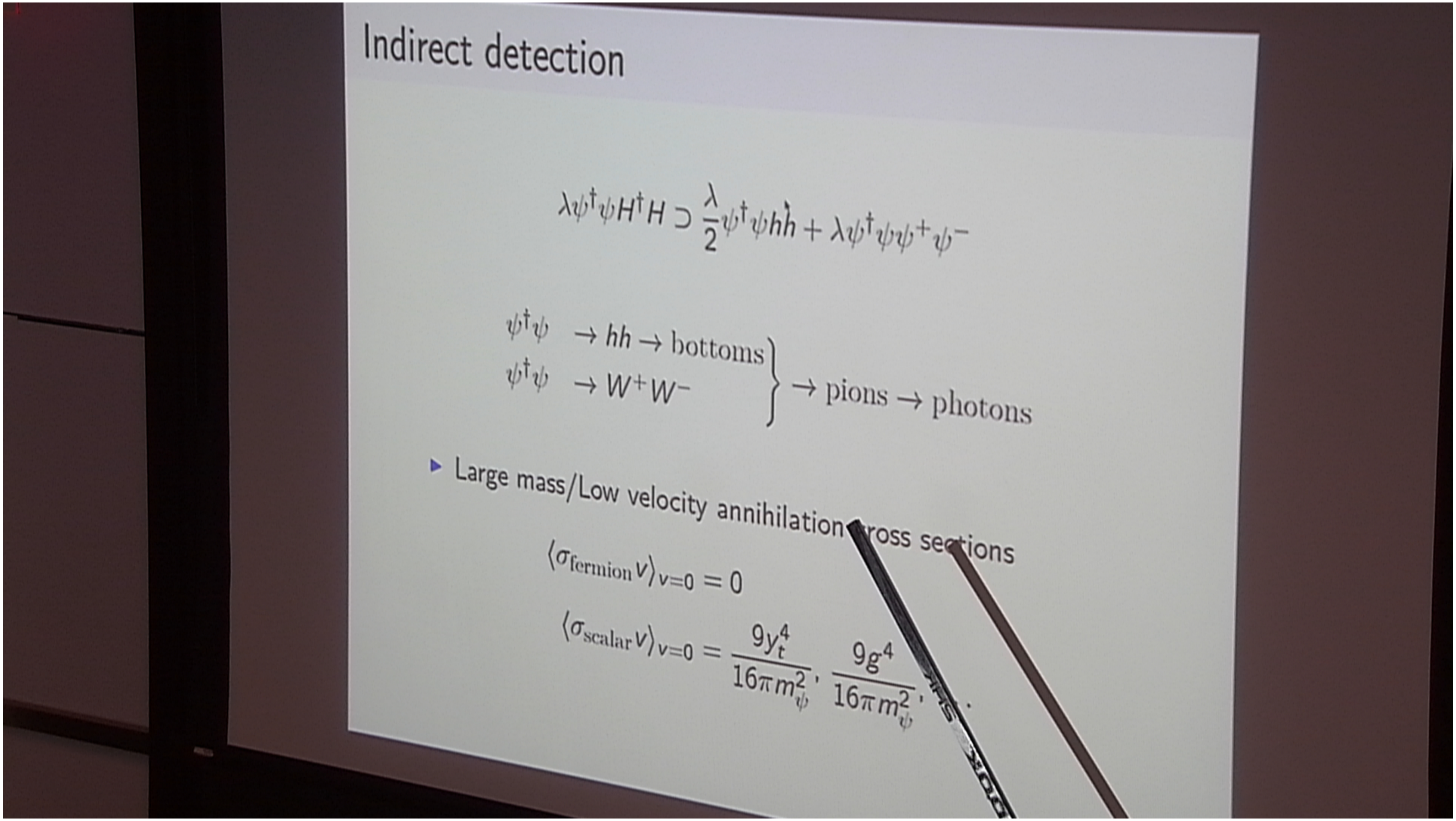
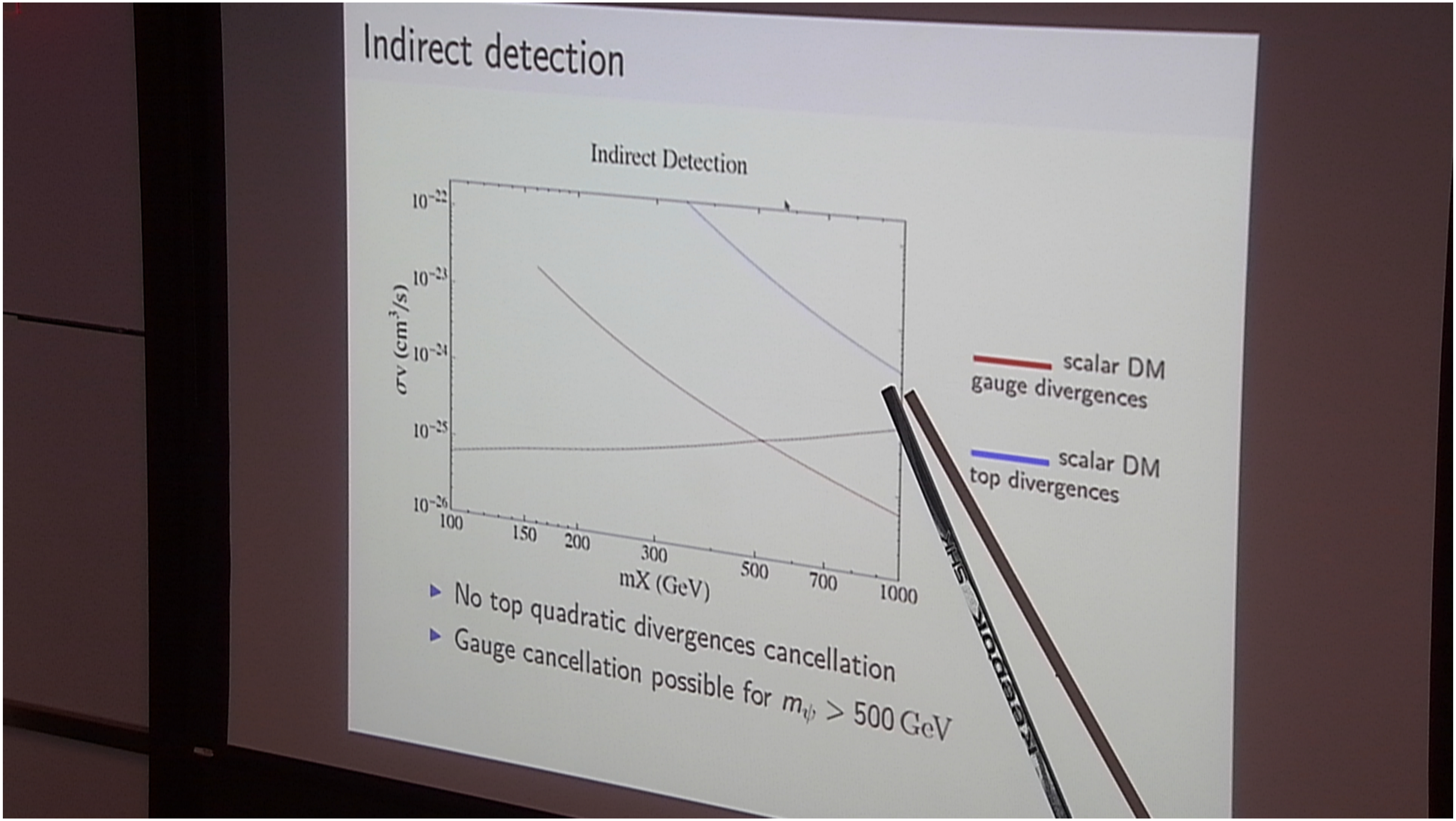
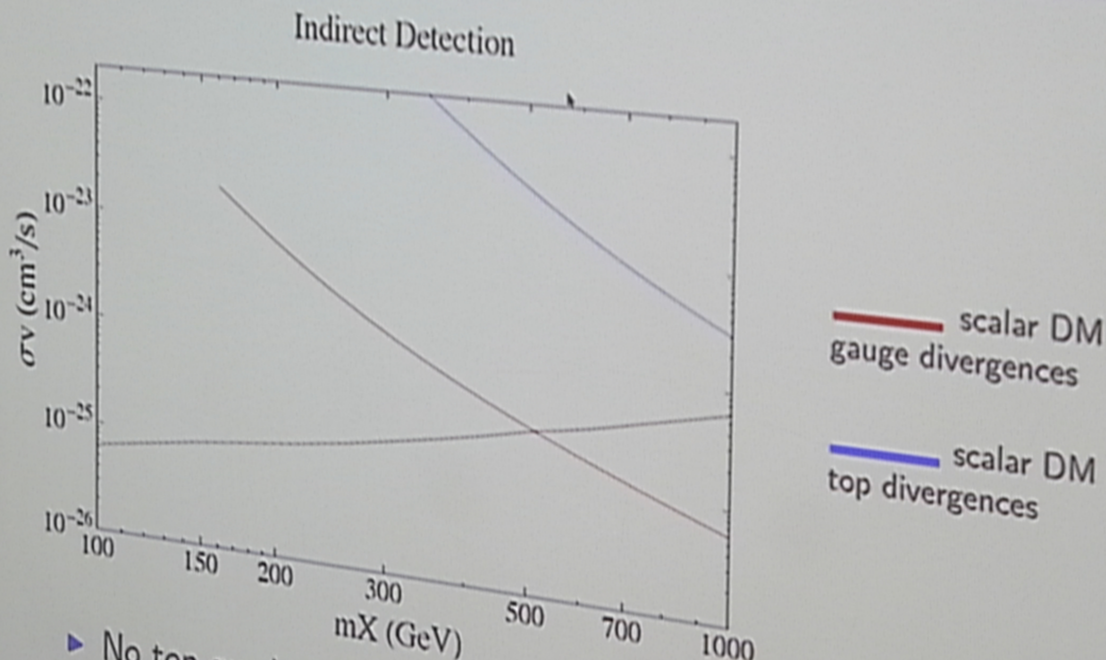
Non thermal production


Indirect detection
$\lambda\psi^\dagger\psi H^\dagger H \supset \frac{\lambda}{2}\psi^\dagger\psi hh + \lambda\psi^\dagger\psi\psi^+\psi^-$
$\psi^\dagger\psi \to hh \to$ bottoms
$\psi^\dagger\psi \to W^+W^-$
$\to$ pions $\to$ photons
Large mass/Low velocity annihilation cross sections
$\langle\sigma_{\text{fermion}} v\rangle_{v=0} = 0$
$\langle\sigma_{\text{scalar}} v\rangle_{v=0} = \frac{9y_t^4}{16\pi m_\psi^2}, \frac{9g^4}{16\pi m_\psi^2}, \ldots$


Indirect detection
Indirect Detection
σv (cm³/s)
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
100
150
200
300
500
700
1000
mX (GeV)
scalar DM
gauge divergences
scalar DM
top divergences
No top quadratic divergences cancellation
Gauge cancellation possible for mψ > 500 GeV

Indirect detection



- No top quadratic divergences cancellation
- Gauge cancellation possible for $m_\psi > 500\,\mathrm{GeV}$

ψ dark matter

Correlated direct and indirect detection signatures

- If fermion, direct detection signature but no indirect detection signal
- If scalar,

$$\frac{\sigma_{\rm SI}}{\langle \sigma v \rangle_{v=0}} = \frac{16 f^2 m_p^2}{m_h^4} = 1.5 \times 10^{-19} \frac{\rm cm^2}{\rm cm^3/s}$$

Measurable at FERMI and XENON100

Sub-TeV ψ cannot cancel the top quadratic divergences

Small region still left for gauge quadratic divergences

ψ dark matter

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Measurable at FERMI and XENON100

Sub-TeV ψ cannot cancel the top quadratic divergences

Small region still left for gauge quadratic divergences

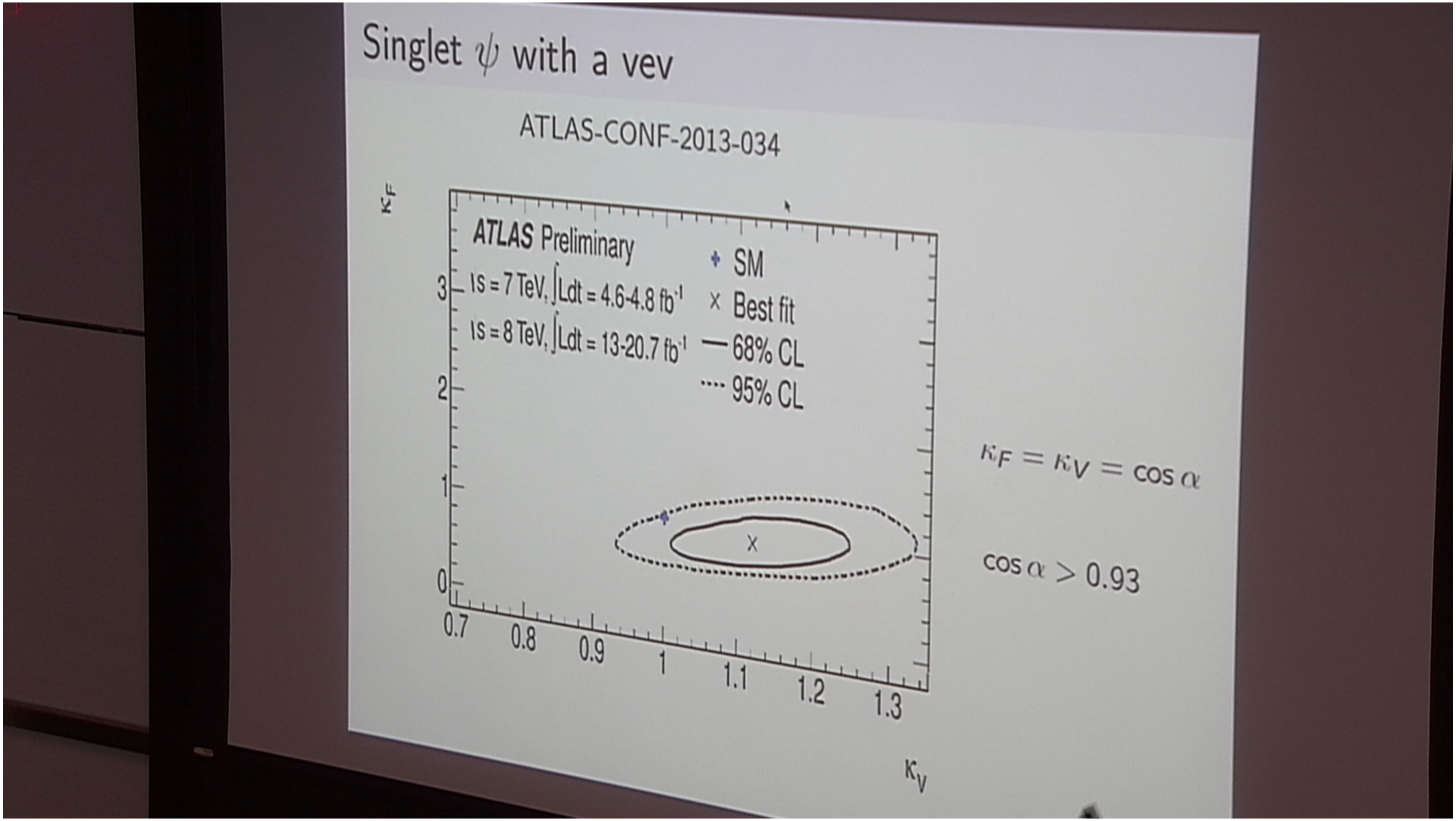
Scalar with a vev

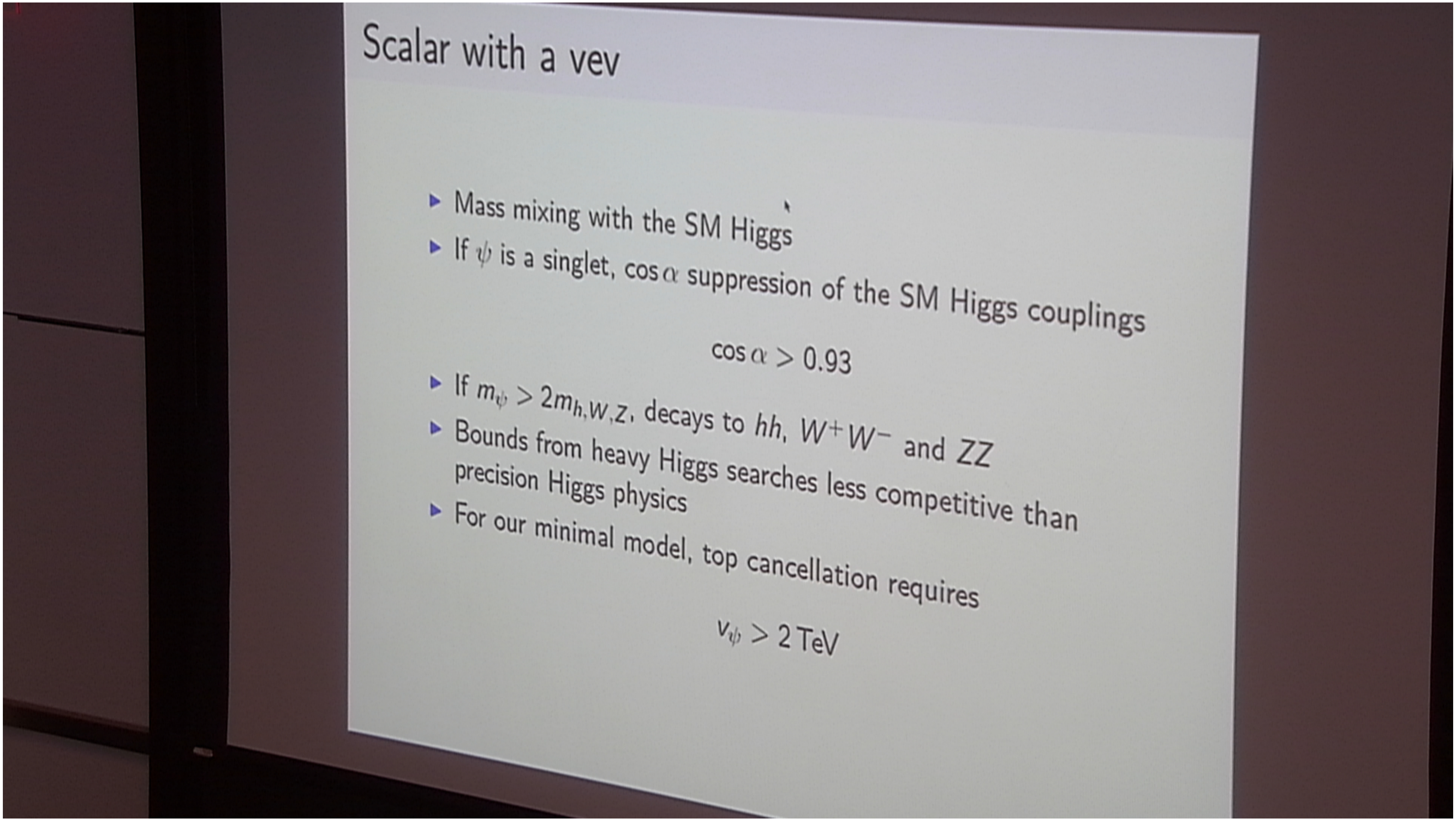
$$\mathcal{L} = \lambda v v_\psi h\psi + \frac{\lambda}{2} v_\psi \psi hh + \frac{\lambda}{2} v h\psi\psi + \dots$$

- Mixing with the Higgs
- ψ decays
- h decays (already studied)

If ψ is an $SU(2)$ doublet $\Rightarrow$ two Higgs doublet model

What about a singlet?


Singlet ψ with a vev
ATLAS-CONF-2013-034
ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV, ∫Ldt = 13-20.7 fb⁻¹
SM
Best fit
68% CL
95% CL
κ_F
κ_V
0
1
2
3
0.7
0.8
0.9
1
1.1
1.2
1.3
$\kappa_F = \kappa_V = \cos\alpha$
$\cos\alpha > 0.93$


Scalar with a vev
Mass mixing with the SM Higgs
If ψ is a singlet, $\cos\alpha$ suppression of the SM Higgs couplings
$\cos\alpha > 0.93$
If $m_\psi > 2m_{h,W,Z}$, decays to hh, W^+W^- and ZZ
Bounds from heavy Higgs searches less competitive than precision Higgs physics
For our minimal model, top cancellation requires
$v_\psi > 2\,\text{TeV}$

Scalar with a vev

- Mass mixing with the SM Higgs
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$$\cos\alpha > 0.93$$

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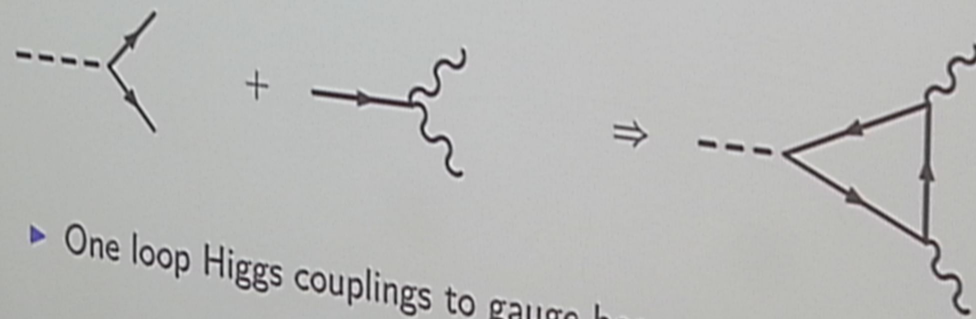
- For our minimal model, top cancellation requires

$$v_\psi > 2\,\text{TeV}$$

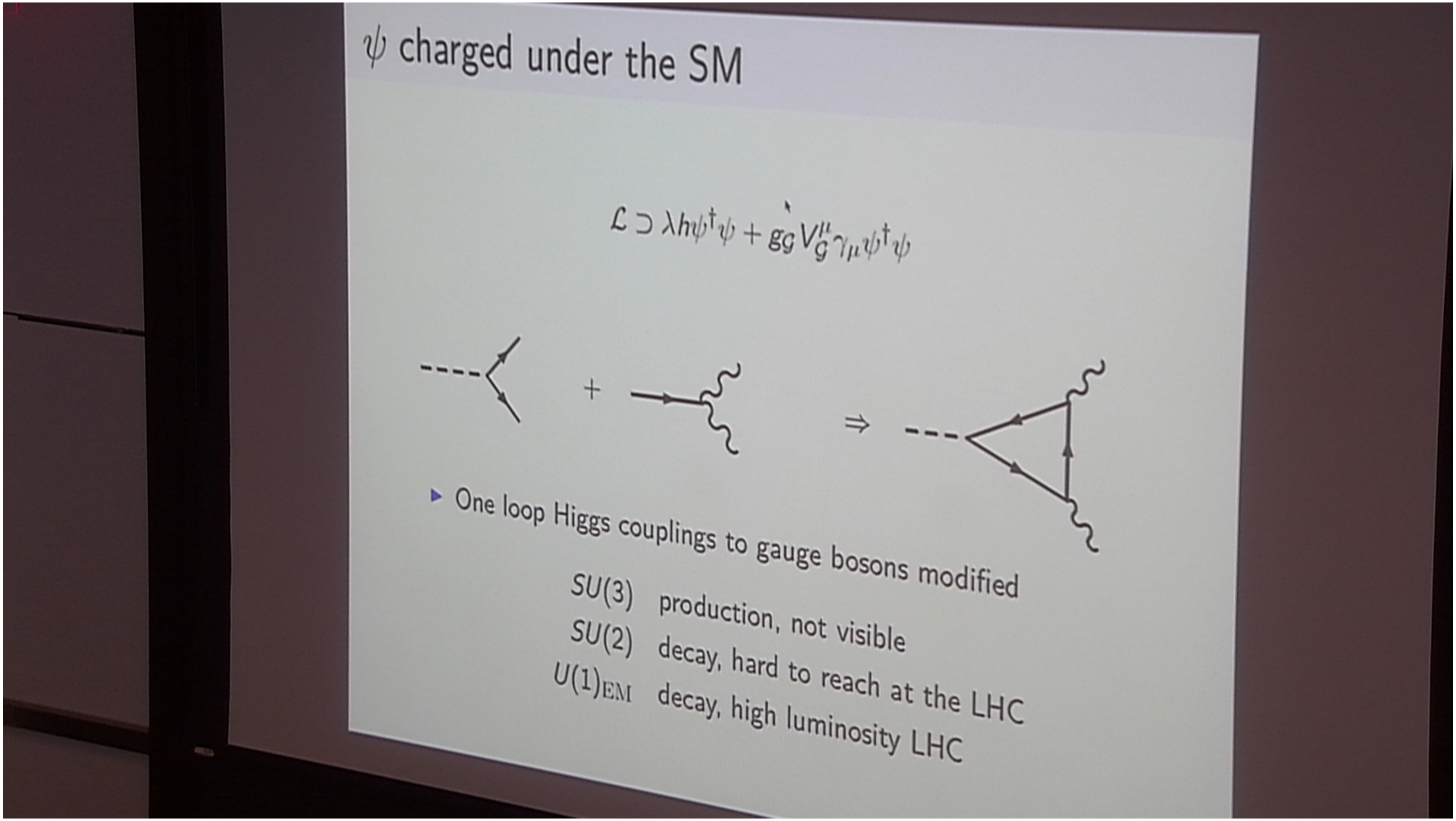
ψ charged under the SM

$$\mathcal{L} \supset \lambda h \psi^\dagger \psi + g_{\mathcal{G}} V^\mu_{\mathcal{G}} \gamma_\mu \psi^\dagger \psi$$



- One loop Higgs couplings to gauge bosons modified

$SU(3)$	production, not visible
$SU(2)$	decay, hard to reach at the LHC
$U(1)_{\mathrm{EM}}$	decay, high luminosity LHC


ψ charged under the SM
$\mathcal{L} \supset \lambda h \psi^\dagger \psi + g_G V_G^\mu \gamma_\mu \psi^\dagger \psi$
+
⇒
One loop Higgs couplings to gauge bosons modified
$SU(3)$ production, not visible
$SU(2)$ decay, hard to reach at the LHC
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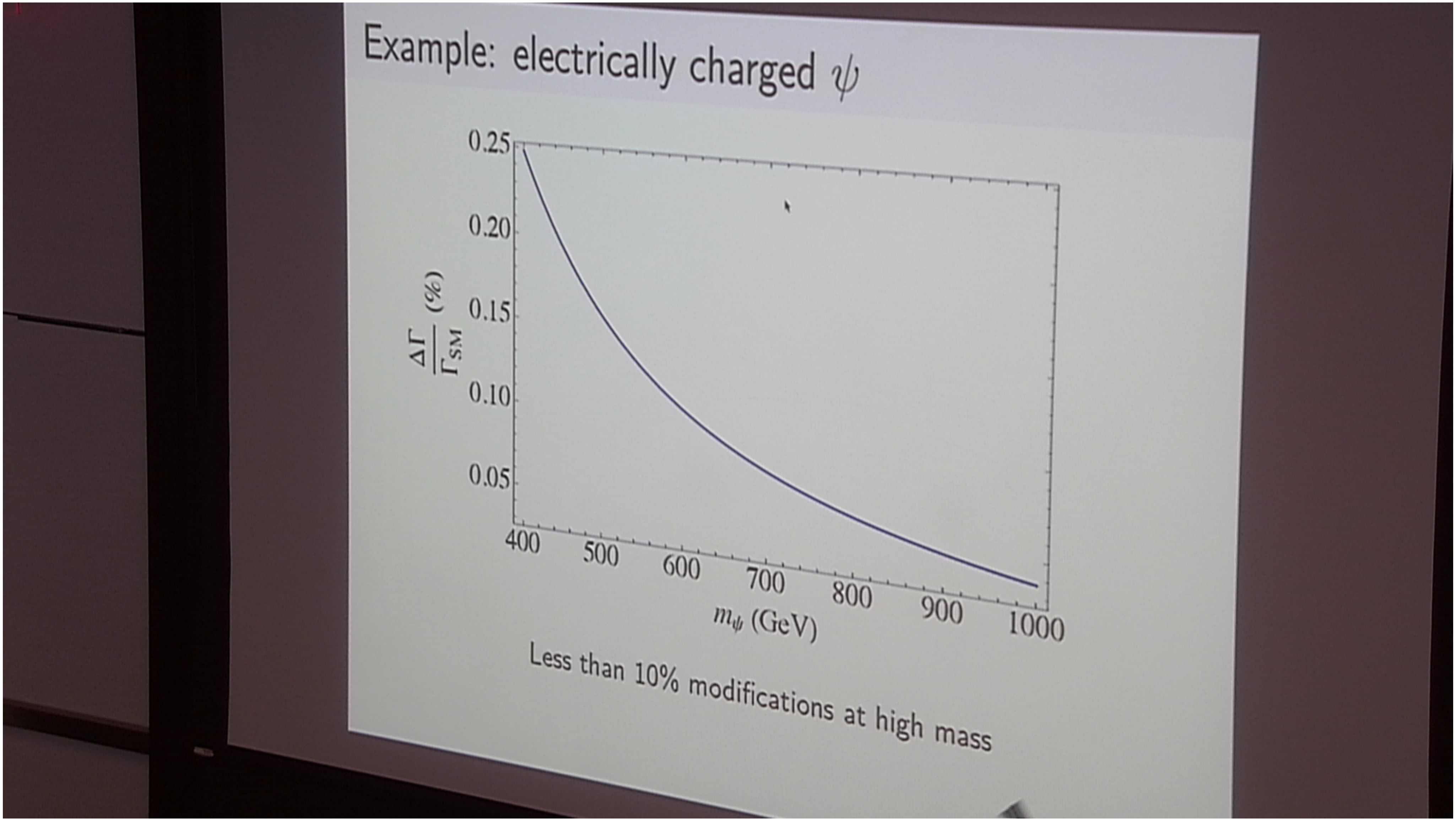
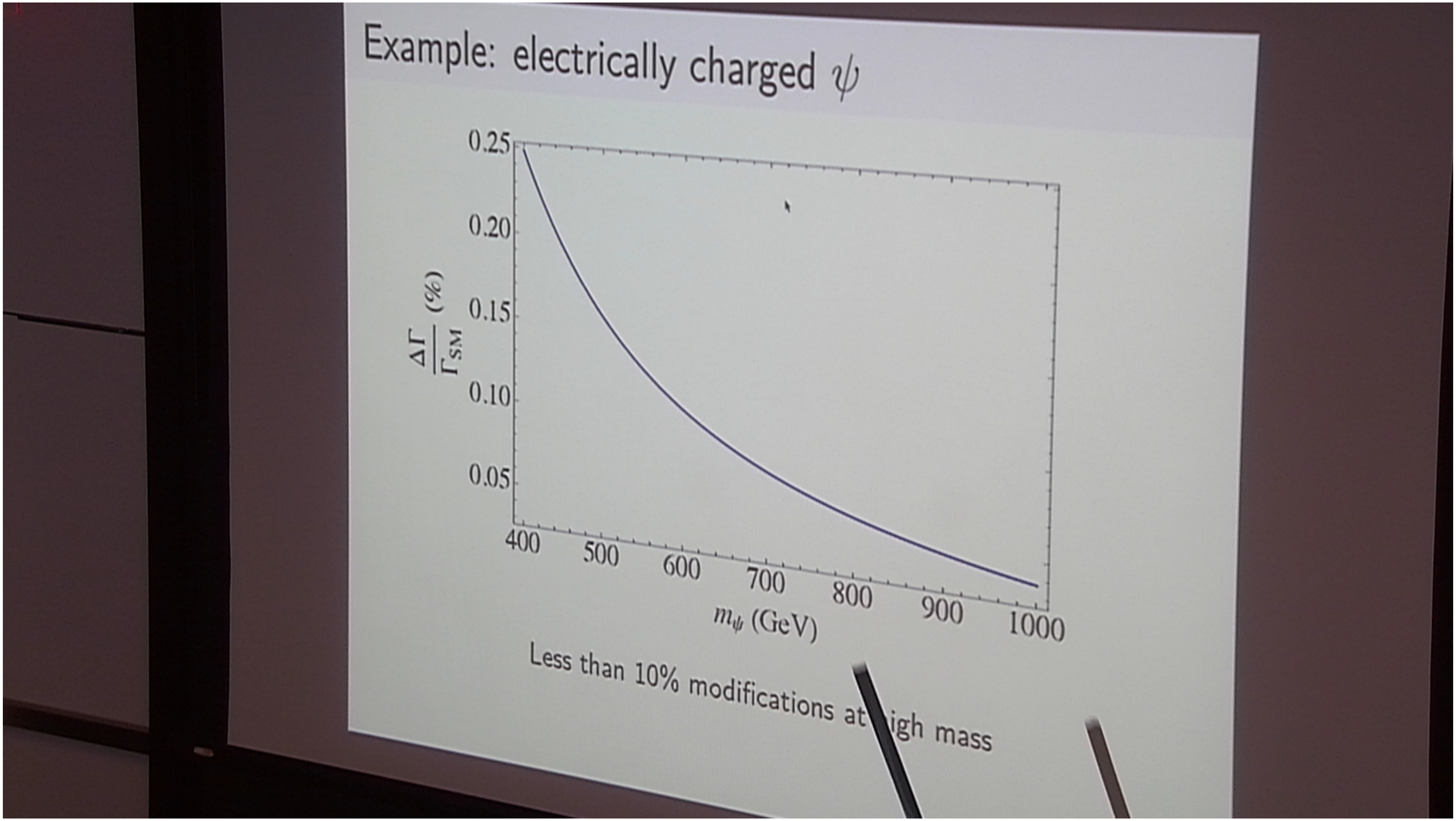

Example: electrically charged ψ
$\frac{\Delta\Gamma}{\Gamma_{SM}}$ (%)
0.25
0.20
0.15
0.10
0.05
400
500
600
700
800
900
1000
m_ψ (GeV)
Less than 10% modifications at high mass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$\frac{\Delta\Gamma}{\Gamma_{SM}}$ (%)
400
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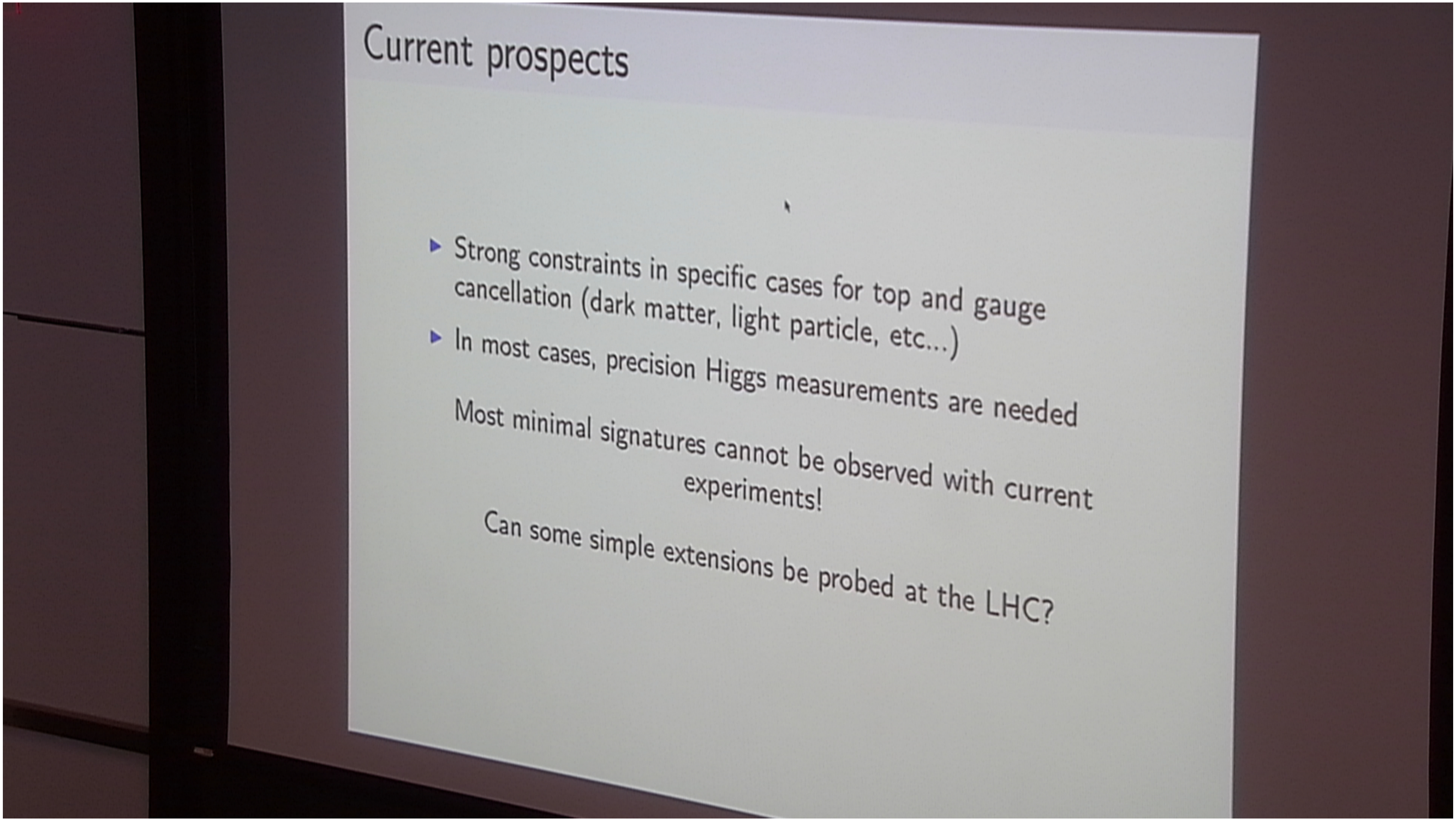
m_ψ (GeV)
Less than 10% modifications at igh mass

Quartic term: summary

$$\lambda\psi^\dagger\psi H^\dagger H \supset \begin{cases} \lambda v h \psi^\dagger\psi + \frac{\lambda}{2} hh\psi^\dagger\psi \\ \frac{\lambda}{2} v v_\psi h \psi + \lambda v h \psi^\dagger \psi + \lambda v_\psi \psi hh \end{cases}$$

- ψ light
  - Invisible Higgs decays
  - Cannot cancel top and gauge quadratic divergences
- ψ dark matter
  - Correlated direct and indirect detection signatures
  - Strong constraints on top and gauge divergences cancellation
- ψ scalar with a vev
  - Precision Higgs coupling measurements
  - Tight constraints on v_ψ
- ψ charged under the SM
  - One loop contributions to $h \to VV$
  - Modifications too small to observe with current sea


Current prospects
Strong constraints in specific cases for top and gauge cancellation (dark matter, light particle, etc...)
In most cases, precision Higgs measurements are needed
Most minimal signatures cannot be observed with current experiments!
Can some simple extensions be probed at the LHC?

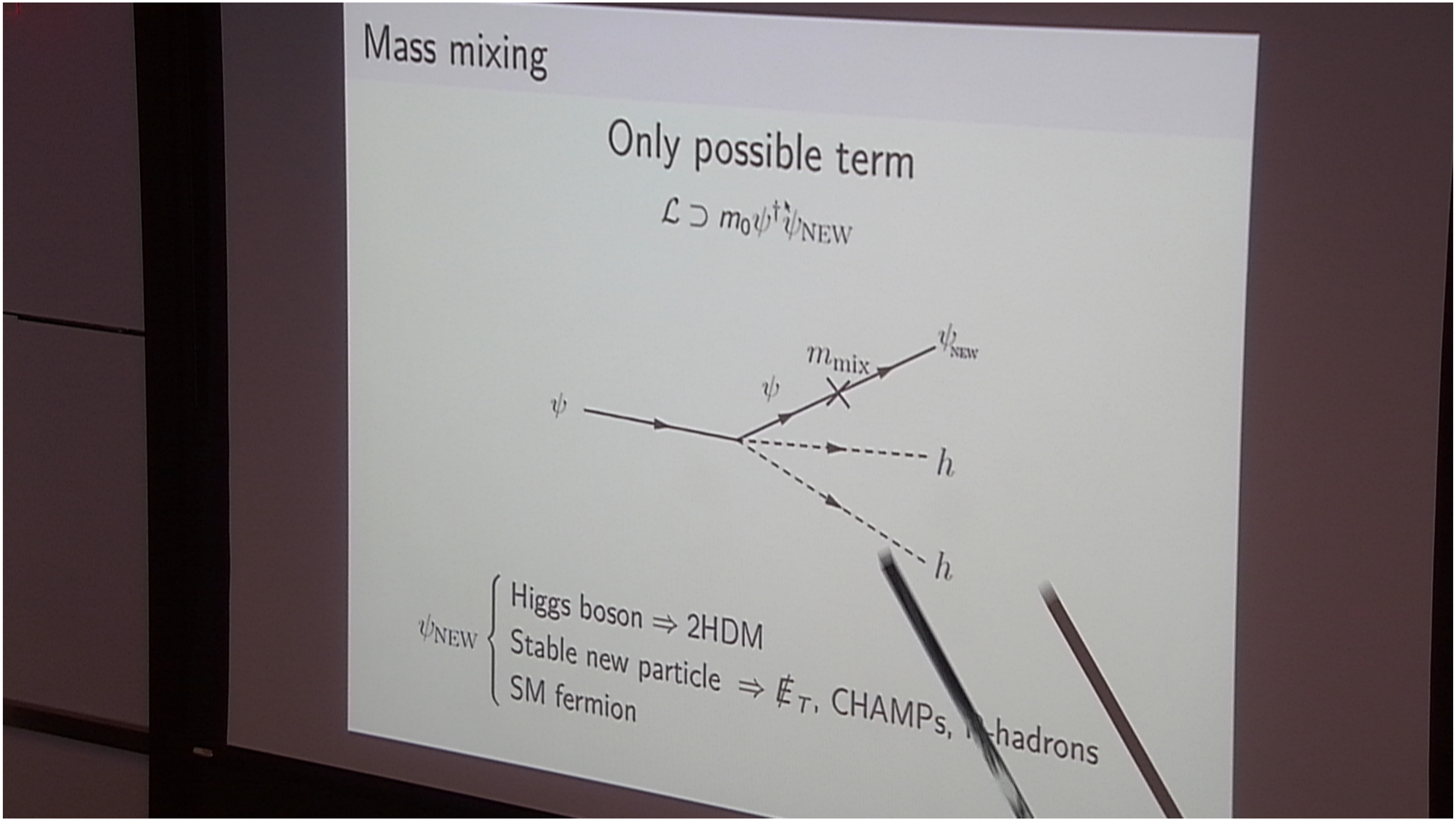
Finding minimal extensions

Minimal naturalness – Quartic term extension

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \lambda H^\dagger H \psi^\dagger \psi$$

Find additional terms:

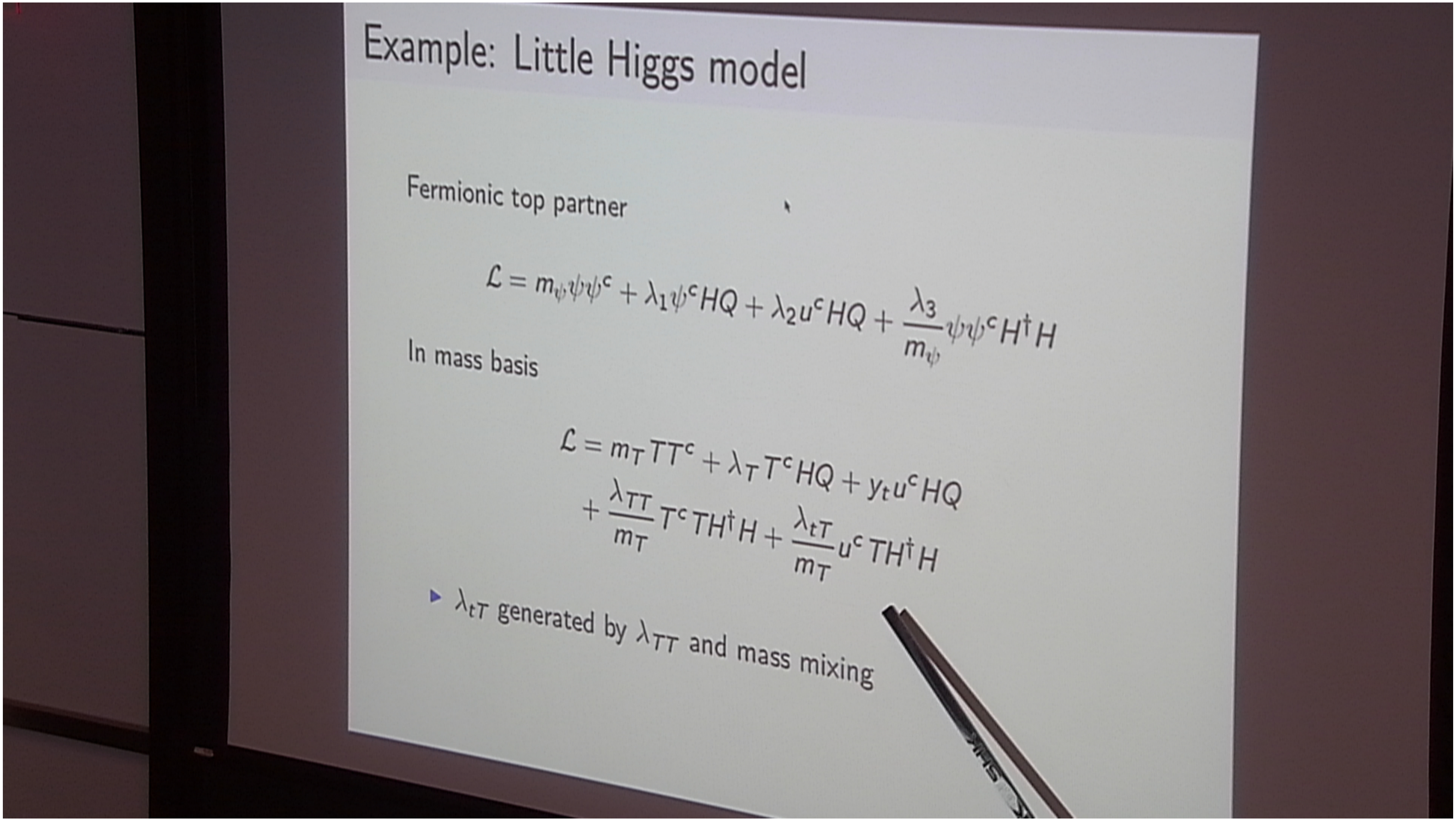
- IR effect
- No assumptions about the UV physics
- New decay modes for ψ, new LHC signatures
- **Signatures vanish when** $\lambda \to 0$

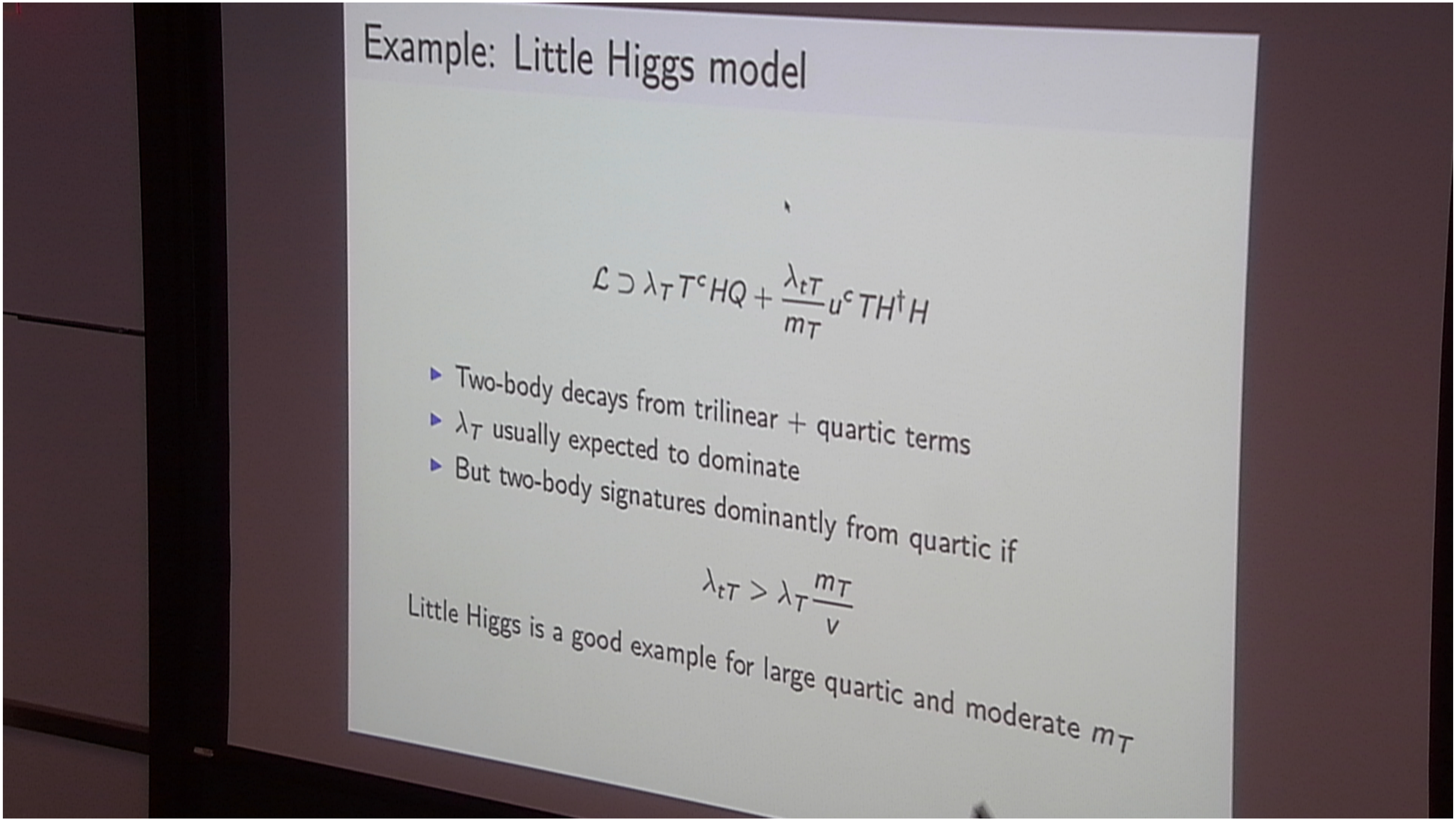

Mass mixing
Only possible term
$\mathcal{L} \supset m_0 \psi^\dagger \psi_{\rm NEW}$
ψ
ψ
$m_{\rm mix}$
$\psi_{\rm NEW}$
h
h
$\psi_{\rm NEW}$
Higgs boson ⇒ 2HDM
Stable new particle ⇒ $\not{E}_T$, CHAMPs, -hadrons
SM fermion

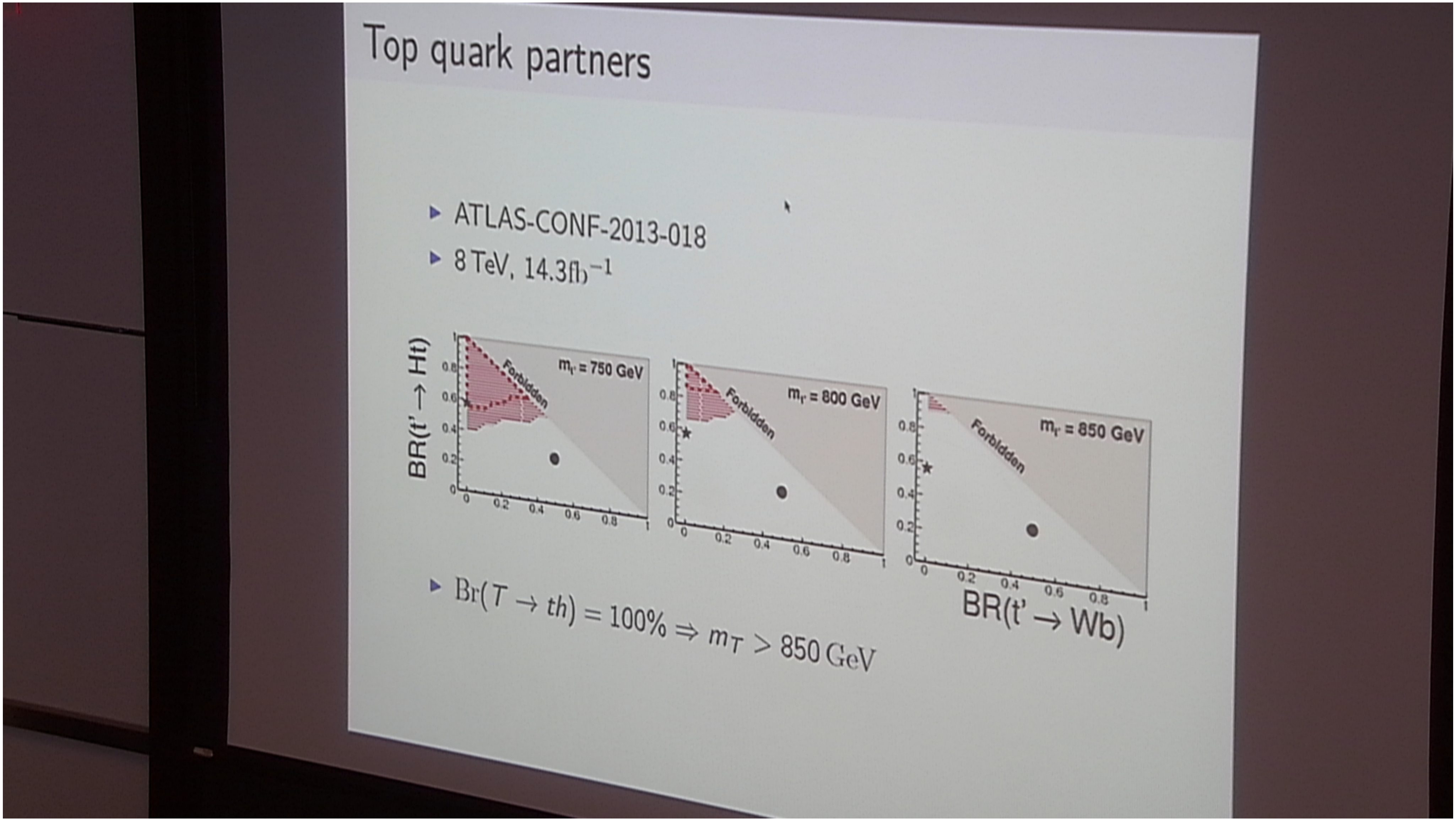
Mass mixing

$$\mathcal{L} \supset \lambda_1 \psi^\dagger \psi H^\dagger H + \lambda_2 \psi^\dagger \psi_{\mathrm{NEW}} H^\dagger H$$

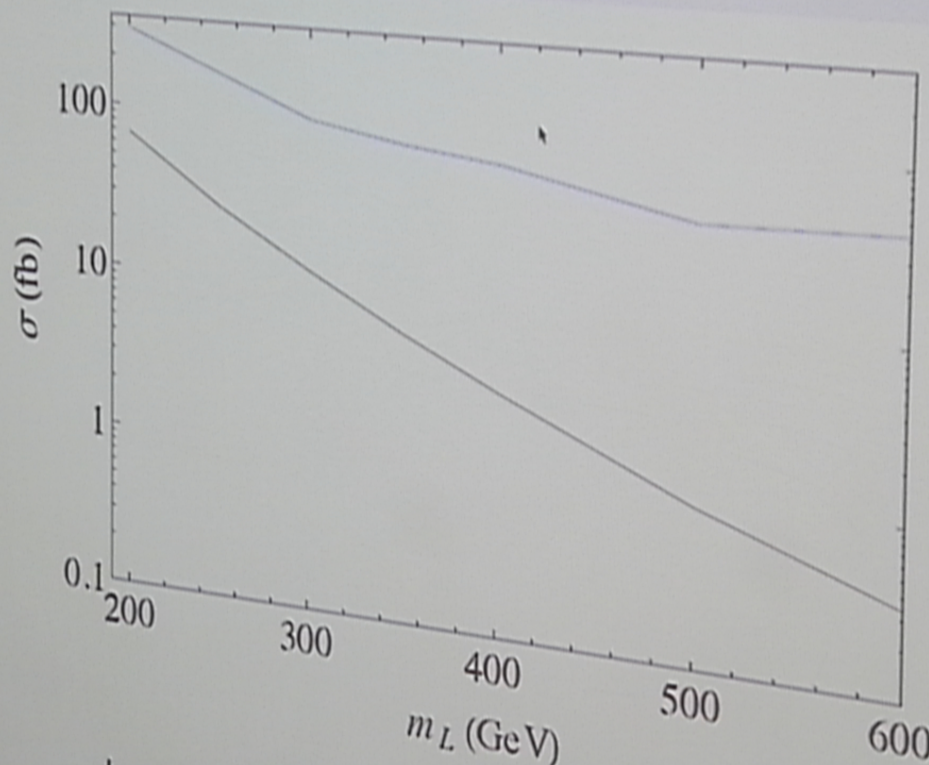
- Measuring λ_2
  - ⇒ **Indirect** evidence of λ_1
- Three-body decays to ψ_{NEW}, WW, hh and ZZ
- Two-body decay to ψ_{NEW} and h
- NO two-body decays to gauge bosons


Example: Little Higgs model
Fermionic top partner
$\mathcal{L} = m_\psi \psi \psi^c + \lambda_1 \psi^c HQ + \lambda_2 u^c HQ + \frac{\lambda_3}{m_\psi} \psi \psi^c H^\dagger H$
In mass basis
$\mathcal{L} = m_T T T^c + \lambda_T T^c HQ + y_t u^c HQ + \frac{\lambda_{TT}}{m_T} T^c T H^\dagger H + \frac{\lambda_{tT}}{m_T} u^c T H^\dagger H$
λ_{tT} generated by λ_{TT} and mass mixing

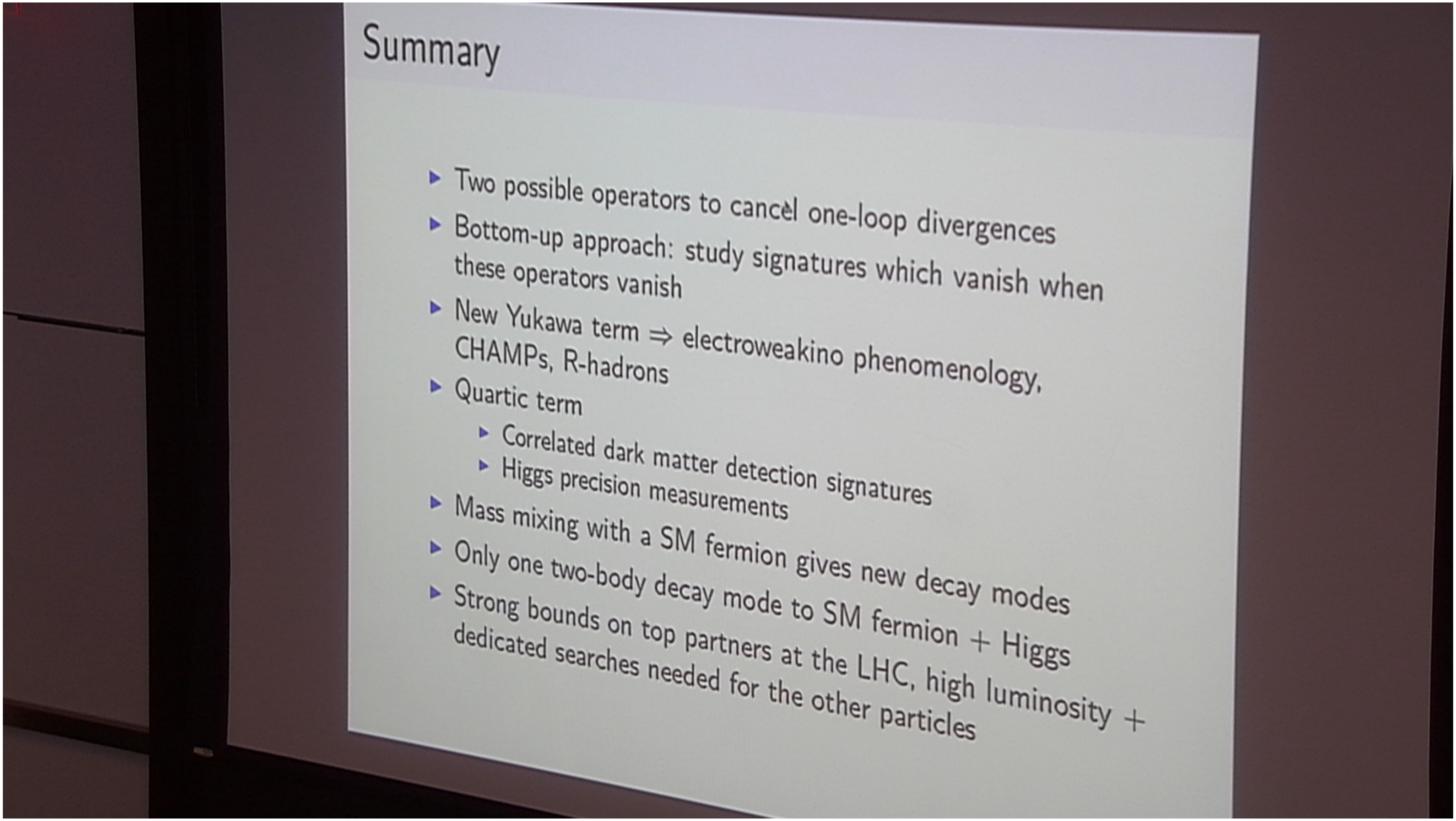

Example: Little Higgs model
$\mathcal{L} \supset \lambda_T T^c H Q + \frac{\lambda_{tT}}{m_T} u^c T H^\dagger H$
Two-body decays from trilinear + quartic terms
λ_T usually expected to dominate
But two-body signatures dominantly from quartic if
$\lambda_{tT} > \lambda_T \frac{m_T}{v}$
Little Higgs is a good example for large quartic and moderate m_T


Top quark partners
ATLAS-CONF-2013-018
8 TeV, 14.3fb^{-1}
$m_{t'}$ = 750 GeV
$m_{t'}$ = 800 GeV
$m_{t'}$ = 850 GeV
Forbidden
BR(t' → Ht)
BR(t' → Wb)
$\mathrm{Br}(T \to th) = 100\% \Rightarrow m_T > 850\,\mathrm{GeV}$

Lepton partner



Low production cross section ⇒ no exclusion bounds


Summary
Two possible operators to cancel one-loop divergences
Bottom-up approach: study signatures which vanish when these operators vanish
New Yukawa term ⇒ electroweakino phenomenology, CHAMPs, R-hadrons
Quartic term
Correlated dark matter detection signatures
Higgs precision measurements
Mass mixing with a SM fermion gives new decay modes
Only one two-body decay mode to SM fermion + Higgs
Strong bounds on top partners at the LHC, high luminosity + dedicated searches needed for the other particles