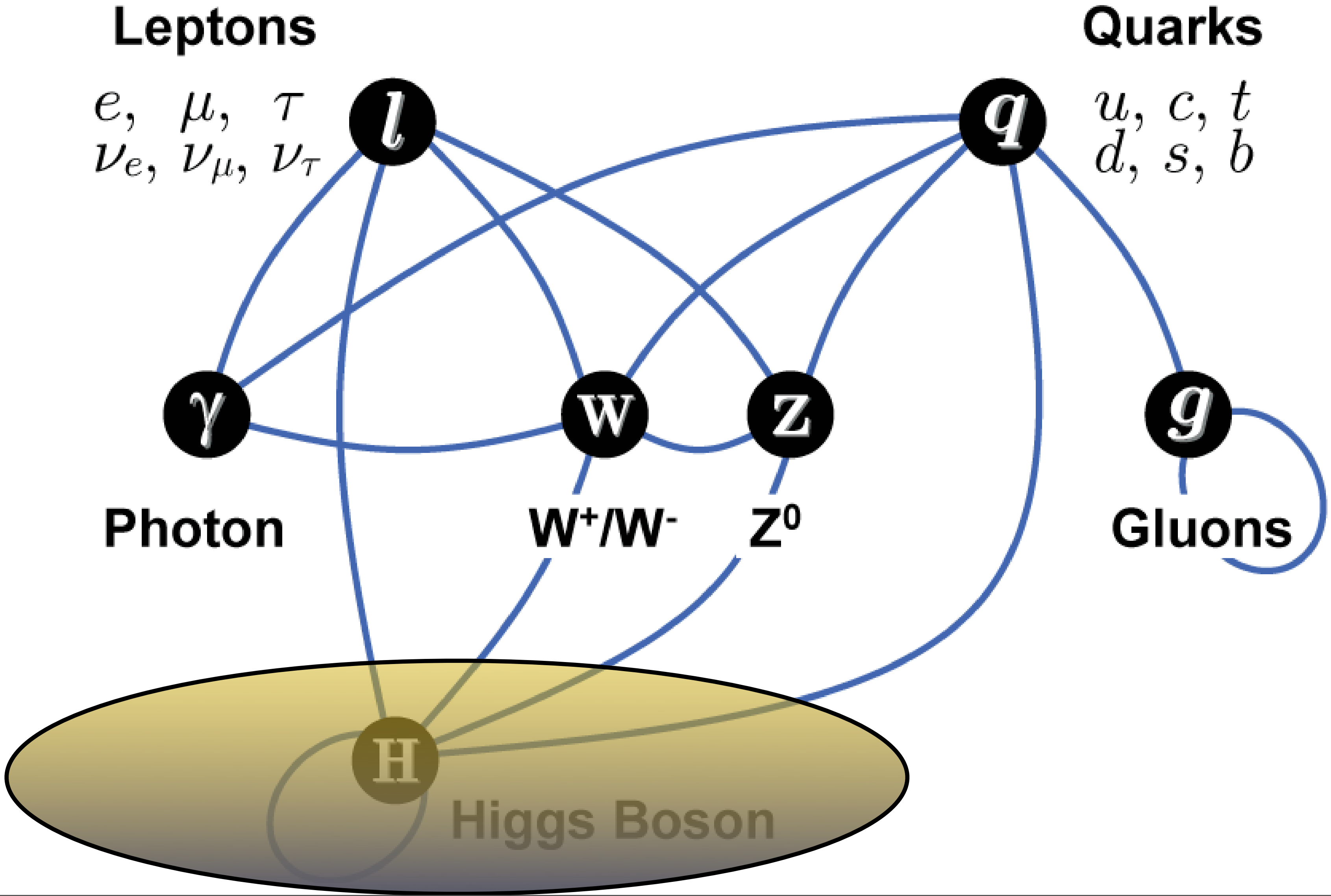
Exciting (the) Vacuum: *Possible Manifestations of the Higgs particle at the LHC*

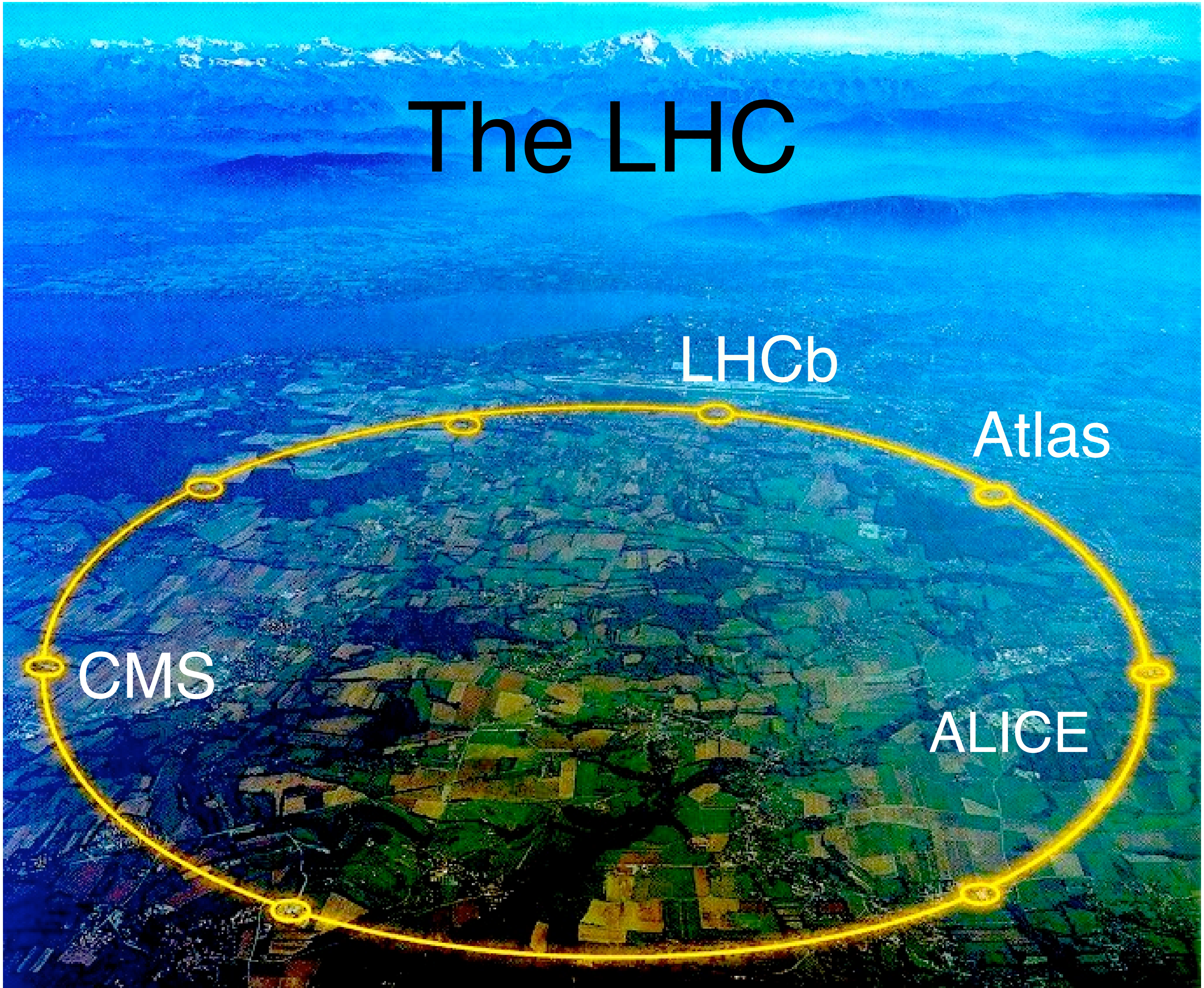
David E Kaplan

5 Aug 2009

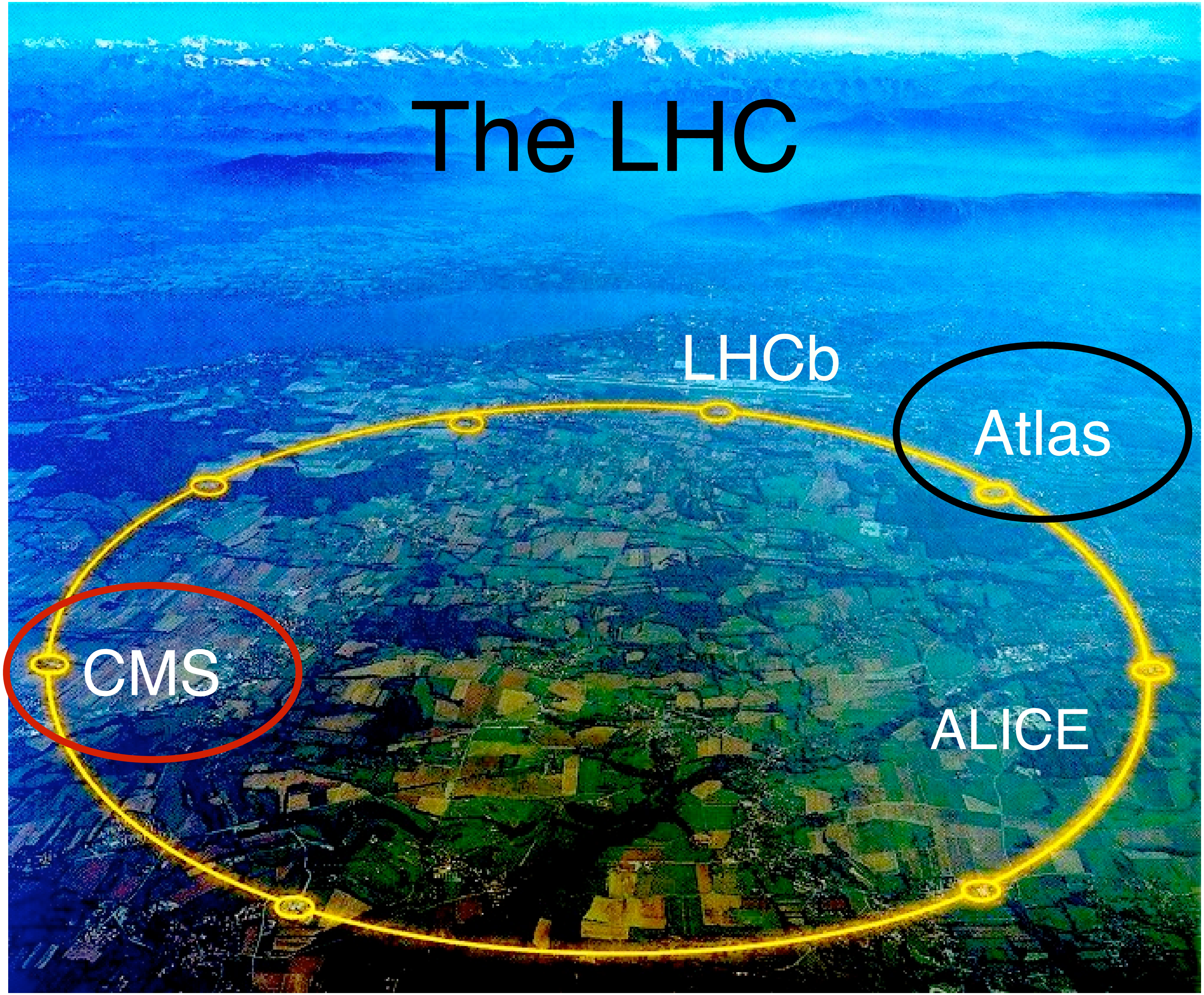
The standard model of particle physics



The LHC



The LHC



QM and SR

$$E = mc^2$$

Kinetic energy can be converted to mass.

Particles are excitations of (quantized) fields -- the fields are fundamental.

We are searching for the fields that fill spacetime by seeing what particle states can be excited.

$$\hbar = c = 1$$

Summary

- What is the Higgs Boson
- How do we find it (and why haven’t we)?
- What will it look like?

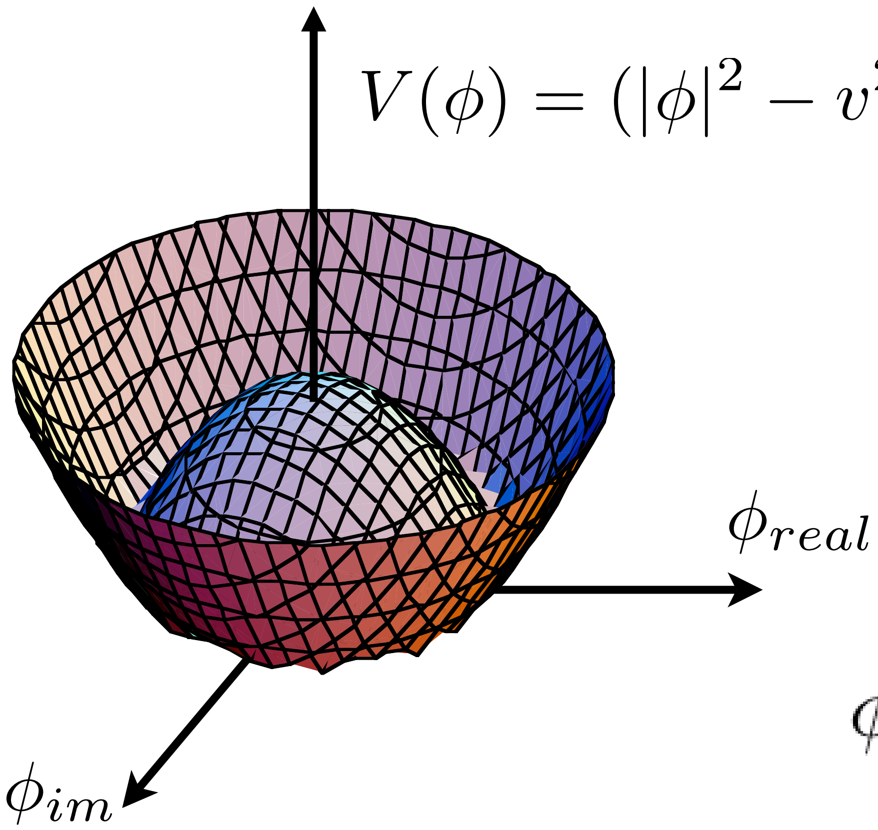
What is the Higgs?

- Differentiate Between the ‘Higgs Mechanism’ and the ‘Higgs Boson’

The *mechanism* is a consistent way to give spin-one particles a mass -- the Z and W bosons mass in the standard model (with quark/lepton masses as a bonus)

Internal Symmetry Breaking

$$V(\phi) = (|\phi|^2 - v^2)^2$$



The potential is independent of theta.

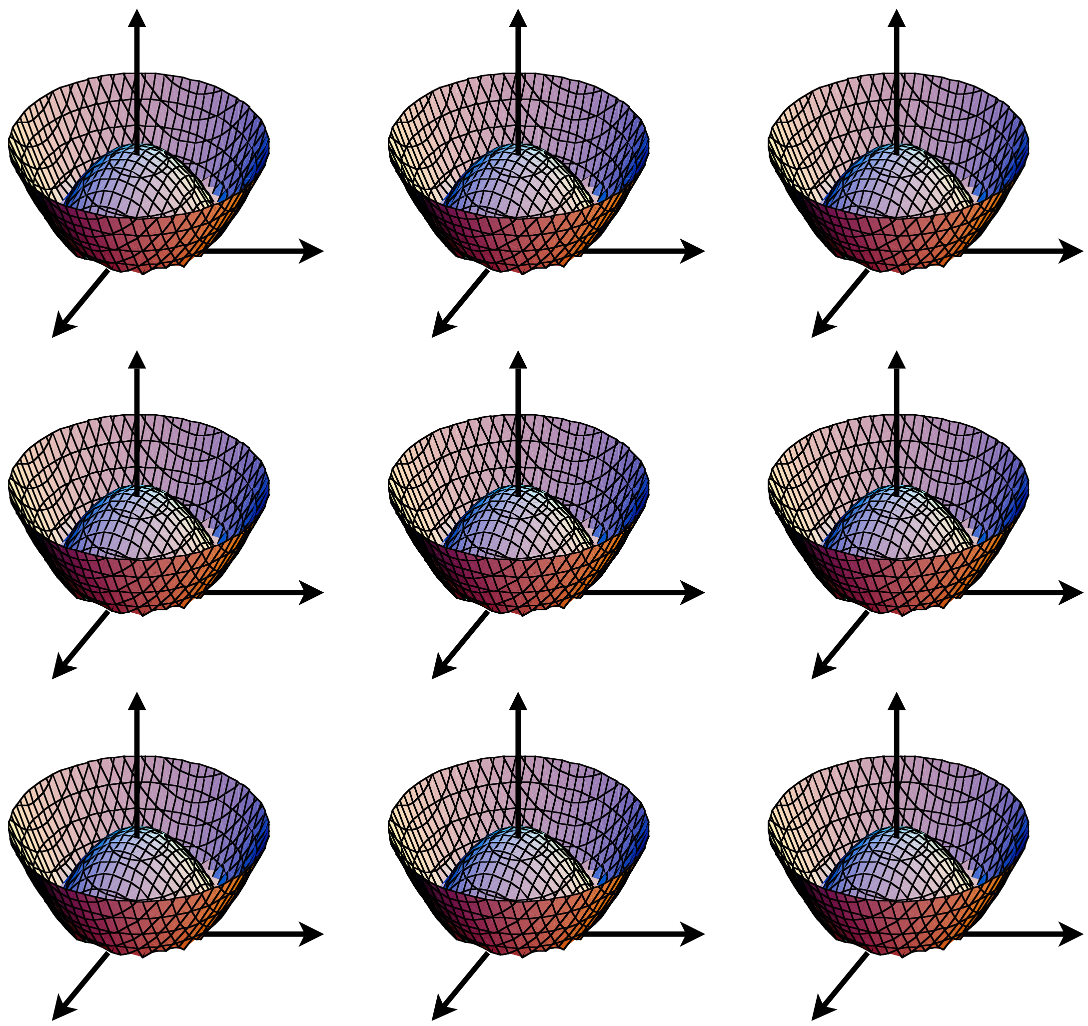
$$\phi \rightarrow e^{i\alpha}\phi(x)$$

$$|\phi_{min}| = v$$

$$\phi(x) = (v + \rho(x))e^{i\theta(x)}$$

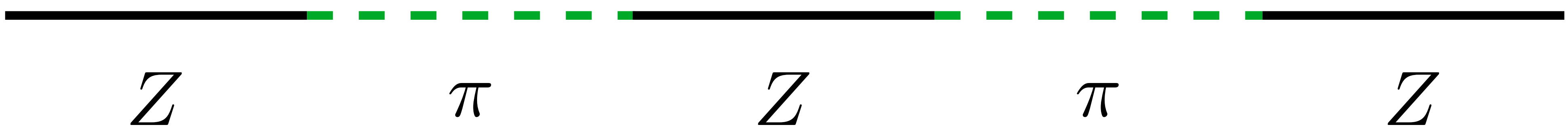
$$V = (2v\rho + \rho^2)^2$$

Internal Symmetry Breaking



The potentials live at every point in space and waves of fluctuations between vacua move through space

Gauge-Goldstone mixing

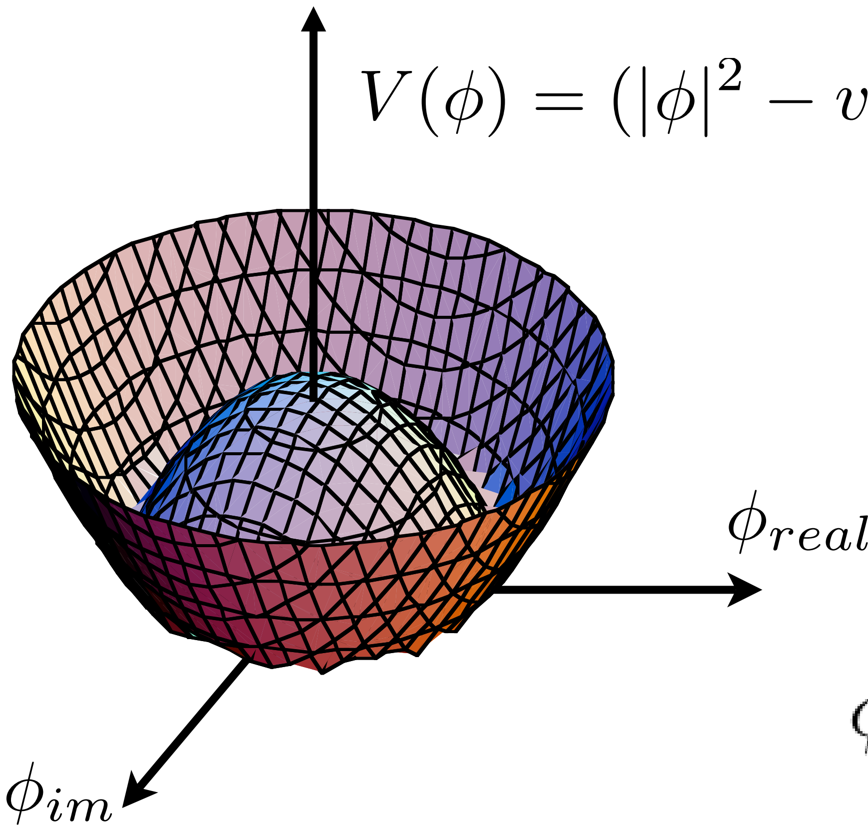


The pi-particle gets ‘eaten’ - is not an eigenstate of the Hamiltonian (not even approximate).

Lorentz invariance guarantees that this completes the spin-one multiplet.

Radial Excitations

$$V(\phi) = (|\phi|^2 - v^2)^2$$



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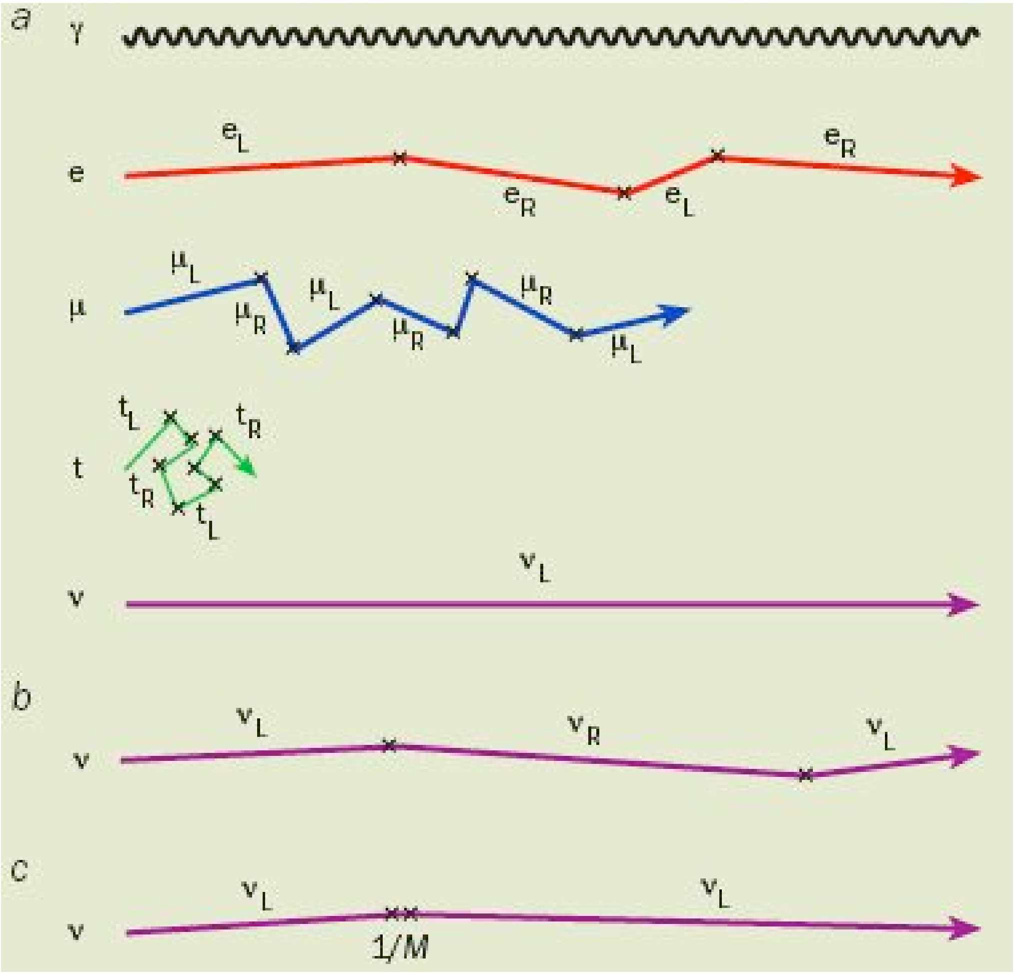
$$V = (2v\rho + \rho^2)^2$$

That's the Higgs field

Mass for everyone



What it 'adds' to those fields must be Lorentz invariant.

A rest mass.

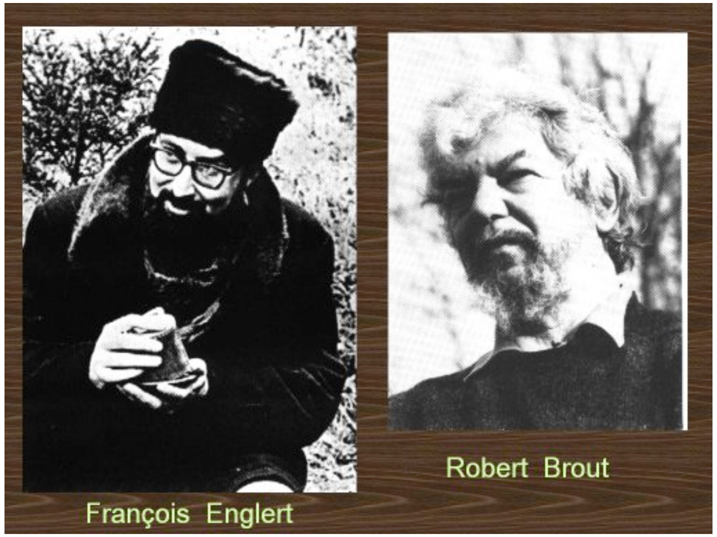
the history of the mechanism...

Julian Schwinger, in 1961, had shown that particles with spin 1 could be massive in a consistent theory (i.e., not break gauge invariance), despite the common wisdom that it was not so (shown in 1949 by Julian Schwinger)

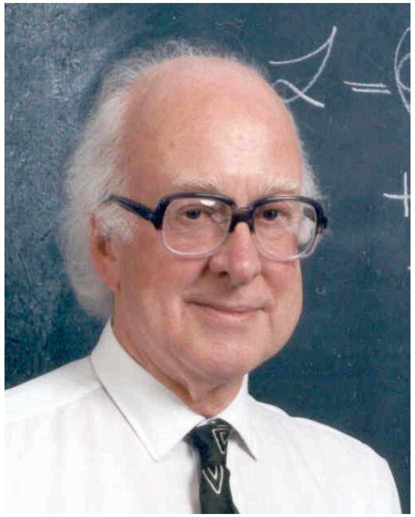
The next year, Philip W. Anderson, inspired by Schwinger's work, showed an explicit example in condensed matter in which a gauge excitation (effectively a spin-1 particle) gained a degree of freedom and was massive.

(They read each other's papers back then...)

... and the particle



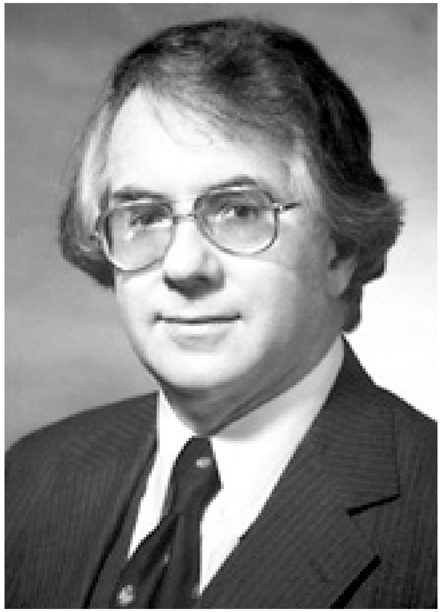
Englert and Brout wrote down a relativistic field theory where a scalar field condenses and spin one particles are massive (1964).



Peter Higgs, wrote a similar paper and submitted to the same journal two months later.

At the same time, G. S. Guralnick, C. R. Hagen, and T. W. B. Kibble produced the same mechanism independently (1964).

to the standard model

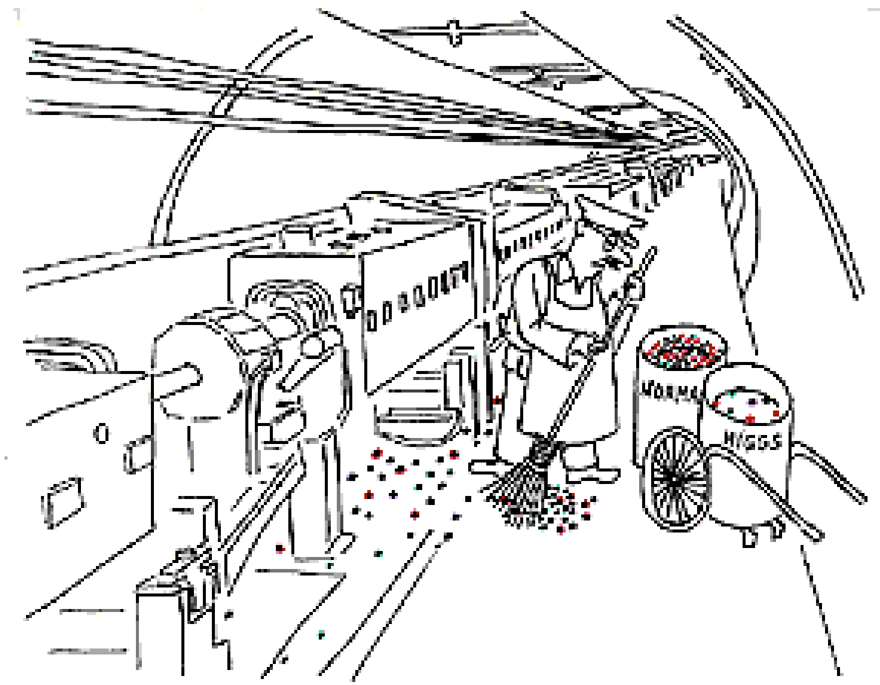


Glashow had a model with the right spin 1 particles, but no explanation for their mass (1961), based on an earlier project given to him by his advisor, Julian Schwinger.

Weinberg, and independently Salam, incorporated the mechanism in Glashow's model and could also give fermions their masses (1967).

The three shared the 1979 Nobel Prize.

How do we find it?

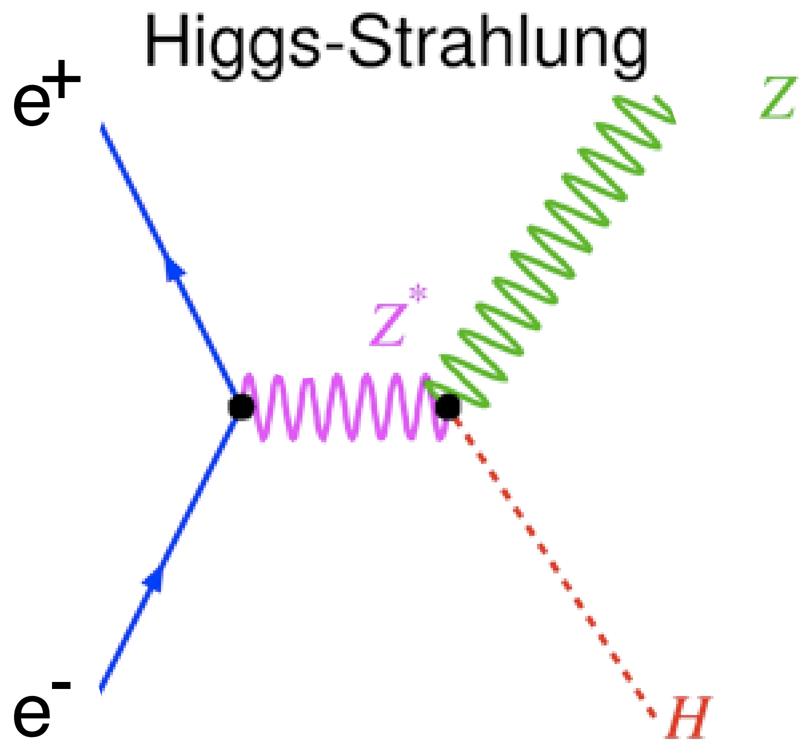


The Higgs couples strongly to heavy fields and weakly to light fields (interactions are proportional to mass).

Problem - light particles are what we collide (they don't decay).

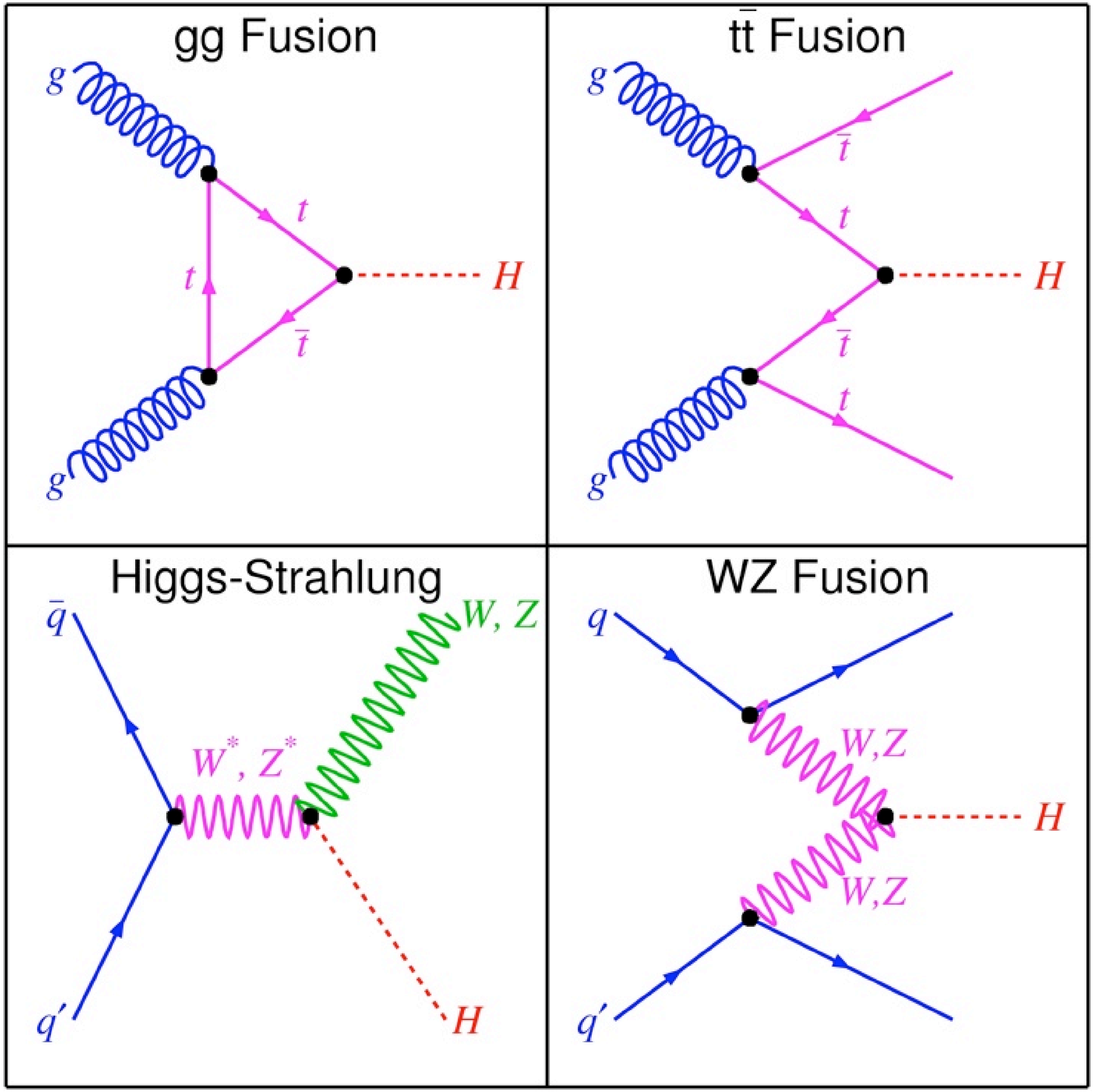
Original Searches

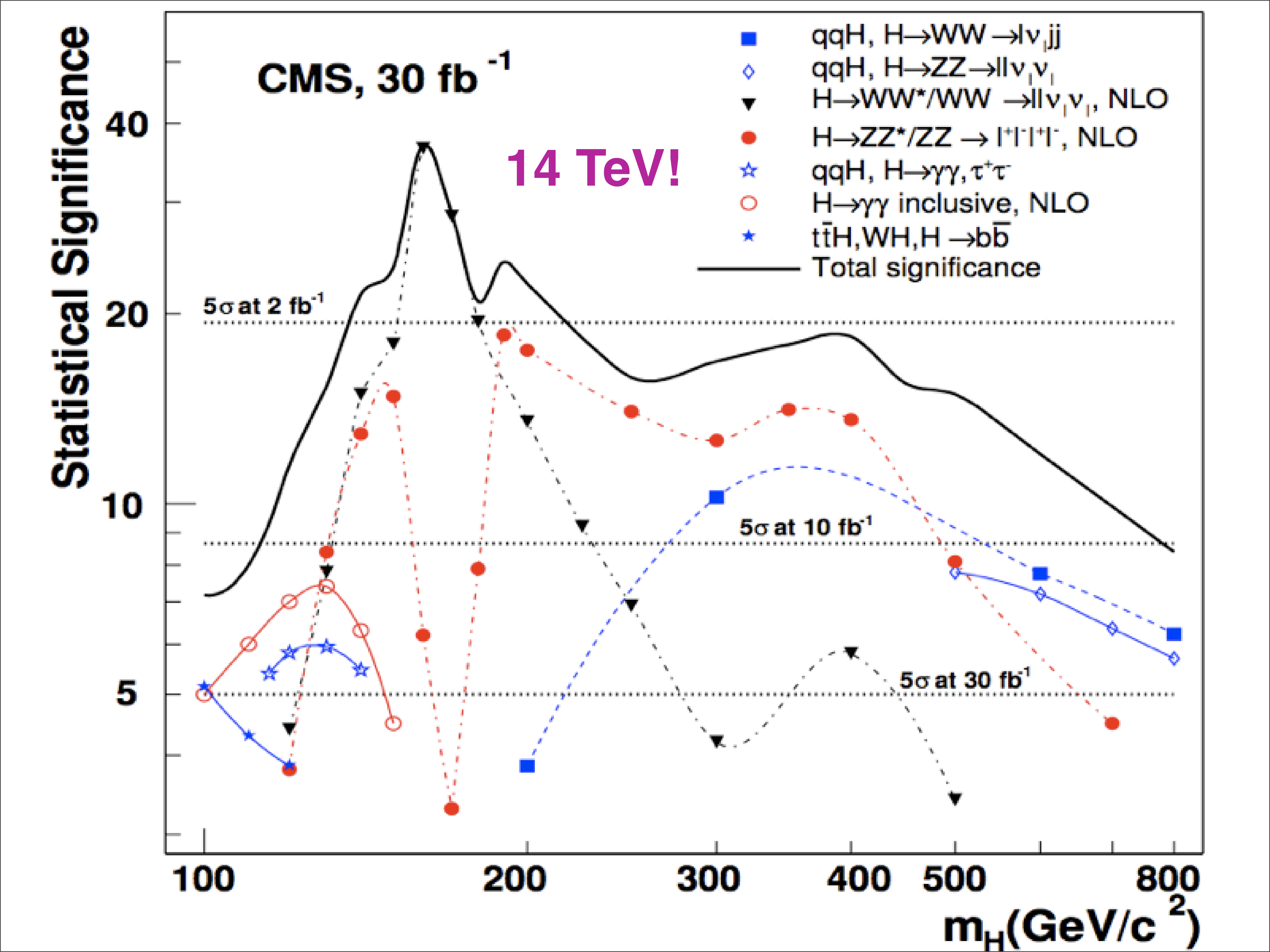
(1976) Linde/Weinberg: $m_h > 4$ GeV



(1989) LEP I: $m_h > 25$ GeV
(1997) LEP I: $m_h > 55$ GeV
(2002) LEP II: $m_h > 114$ GeV

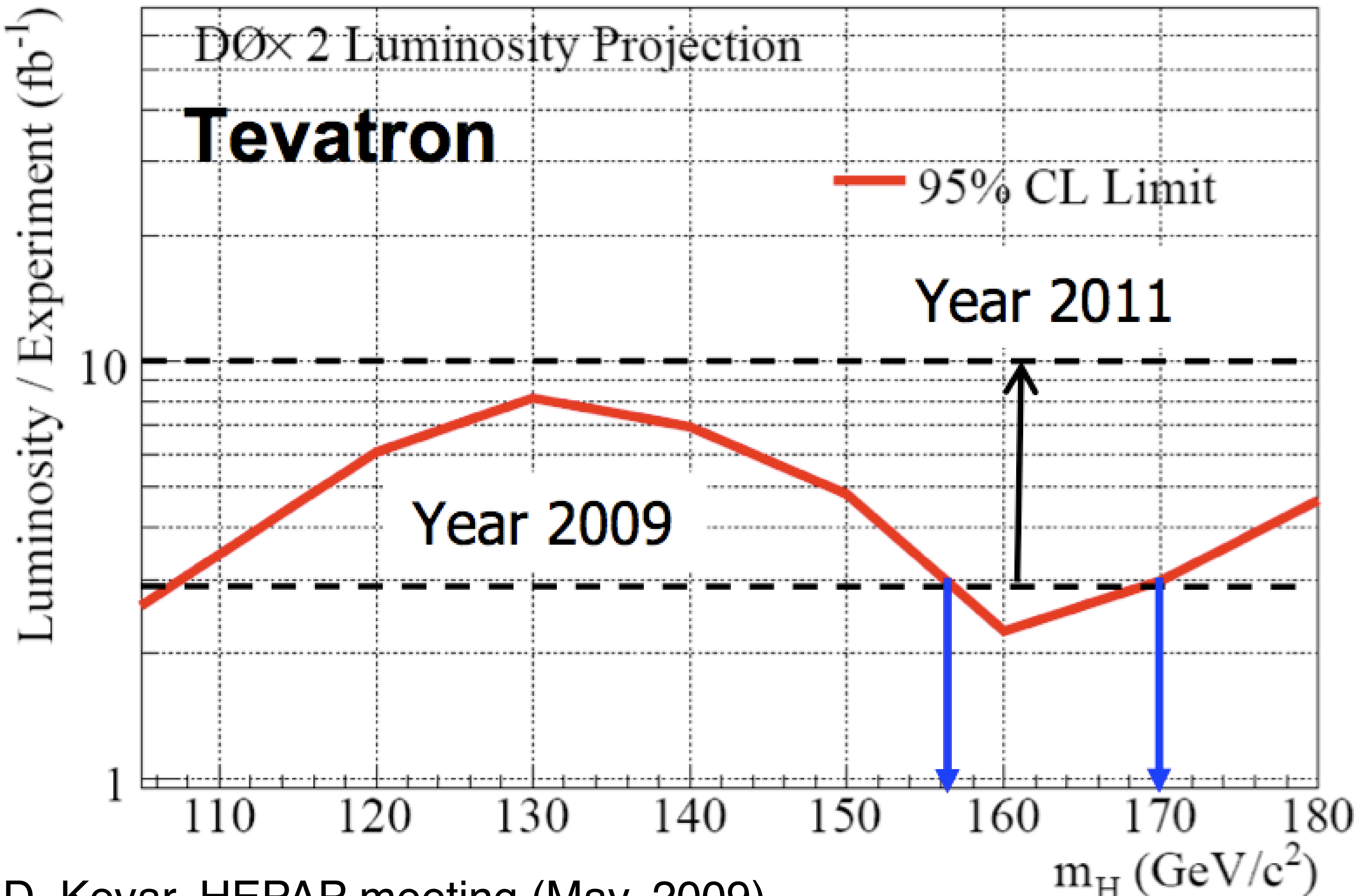
Production at 'Hadron' Colliders (Tevatron and the LHC)





CMS, 30 fb^{-1}
14 TeV!
qqH, H→WW→lν jj
qqH, H→ZZ→llνν
H→WW*/WW →llνν, NLO
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ,τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
Statistical Significance
40
20
10
5
100
200
300
400
500
800
mH(GeV/c²)

Here and Now

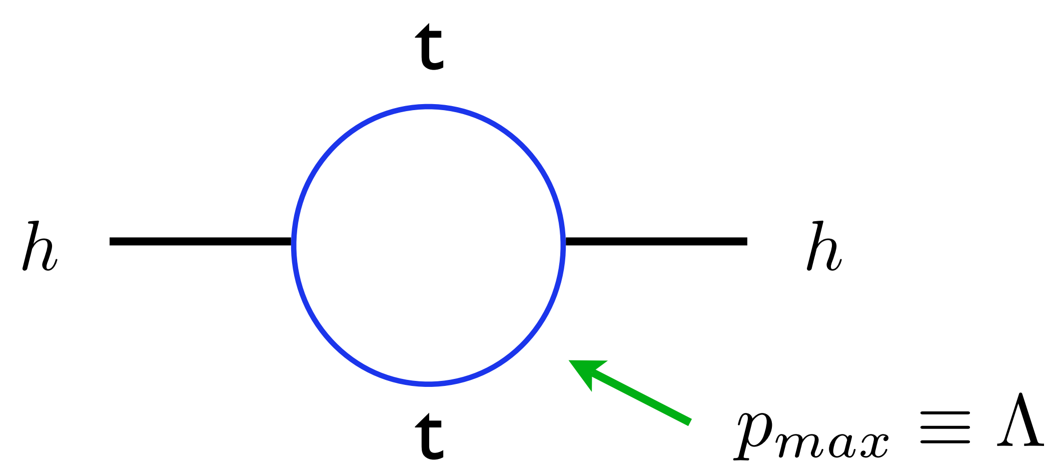


D. Kovar, HEPAP meeting (May, 2009)

If the standard model is wrong...

...will we still see the Higgs?

Regulating the Theory

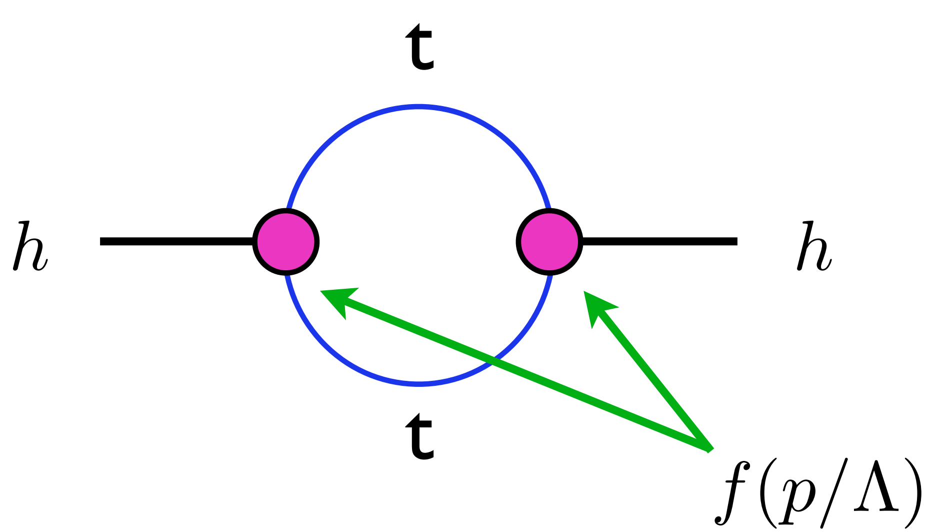


Whatever makes this finite becomes important at energies of order Λ

From the top loop,

$\delta m_h \sim (1/5)\Lambda$, and so the cutoff is $\Lambda \sim 1$ TeV

Regulating the Theory



Whatever makes this finite becomes important at energies of order Λ

Momentum-dependent couplings (compositeness)

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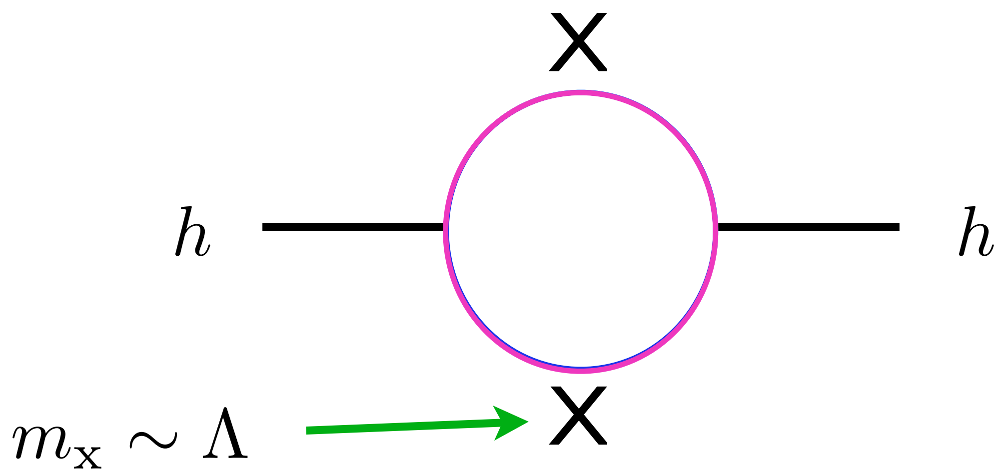
$\delta m_h \sim (1/5)\Lambda$, and so the cutoff is $\Lambda \sim 1$ TeV

Regulating the Theory



Whatever makes this finite becomes important at energies of order Λ

New particles in the loop

Fermions: top loop,

$\delta m_h \sim (1/5)\Lambda$, and so the cutoff is $\Lambda \sim 1$ TeV

Regulating the Theory

Supersymmetry: copies of the standard model particles with over 100 new parameters (but weakly coupled).

Composite Higgs (Randall-Sundrum ultraviolet structure)/ Extra Dimensions

Technicolor (no Higgs)

I focus on supersymmetry as my example.

Variations on a Higgs

- Multiple Higgses (new light neutral particles)
- Higgs, but different production mechanism?
- Higgs, but different decay products?
- (No Higgs?)

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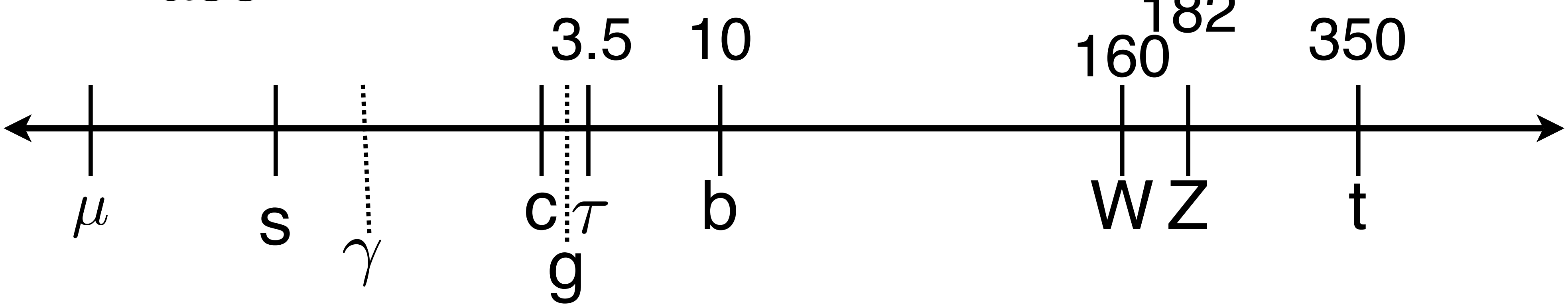
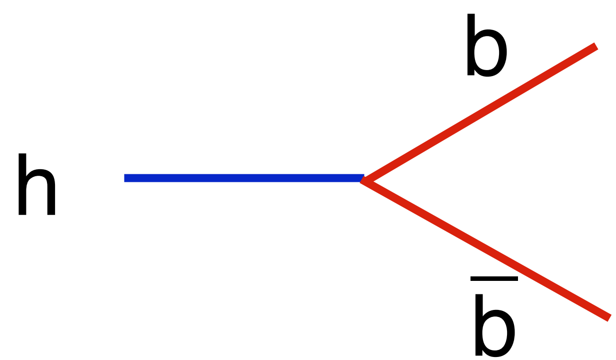
- Higgs, but different production mechanism?
- ★ Higgs, but different decay products?
- (No Higgs?)

New Higgs decays

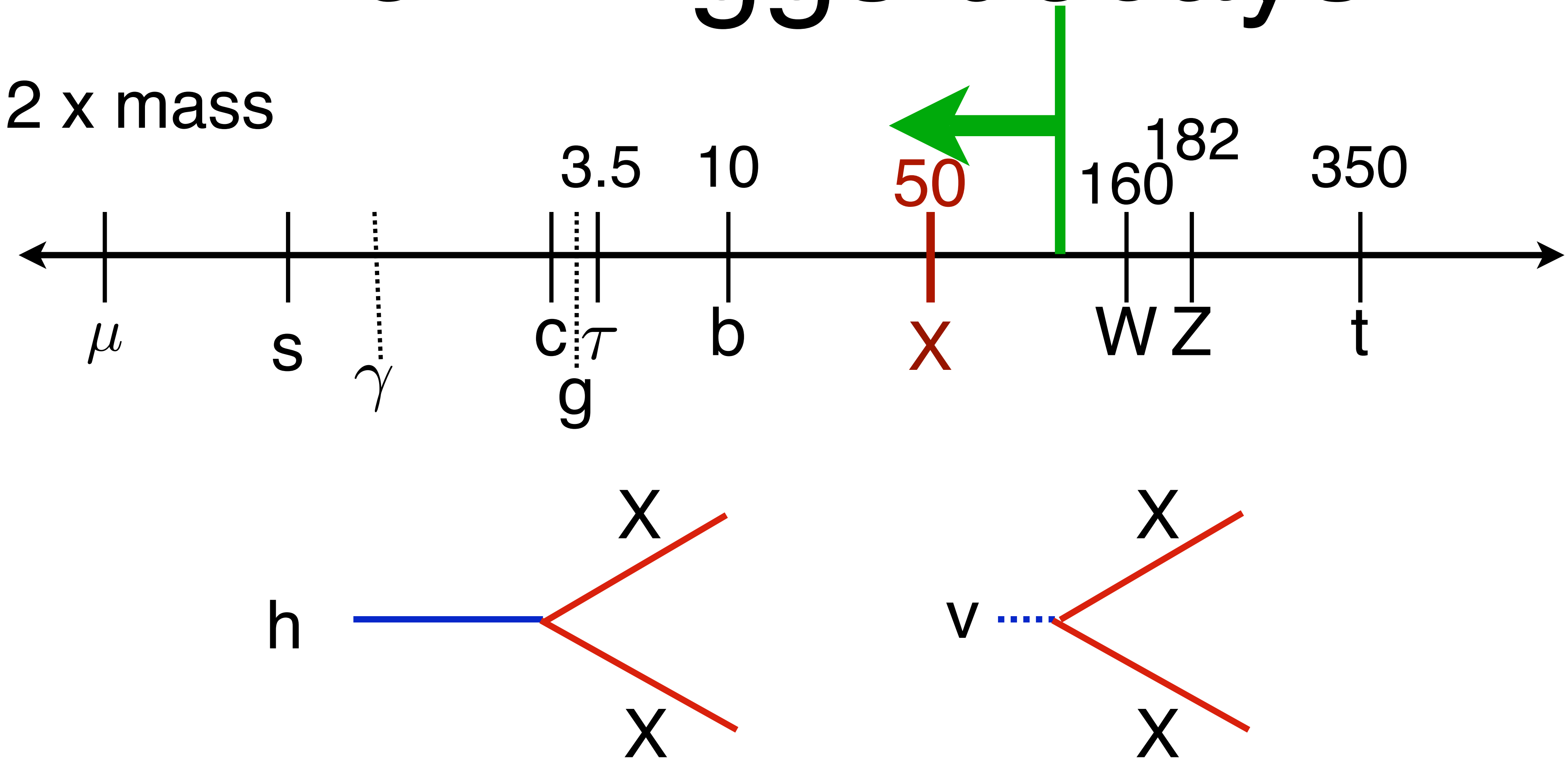
2 x mass





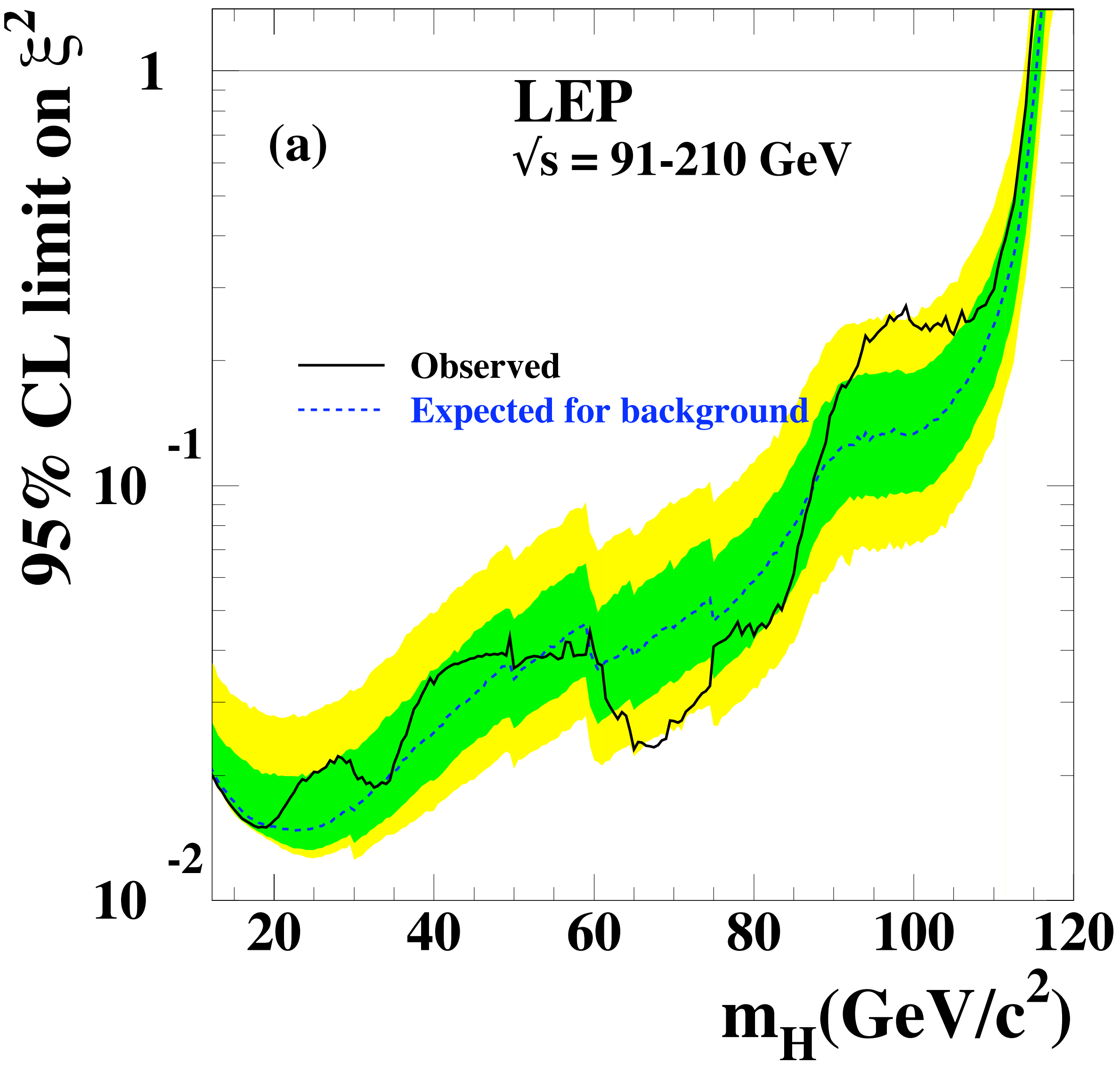
Decay rates are proportional to a positive power of the mass.

New Higgs decays

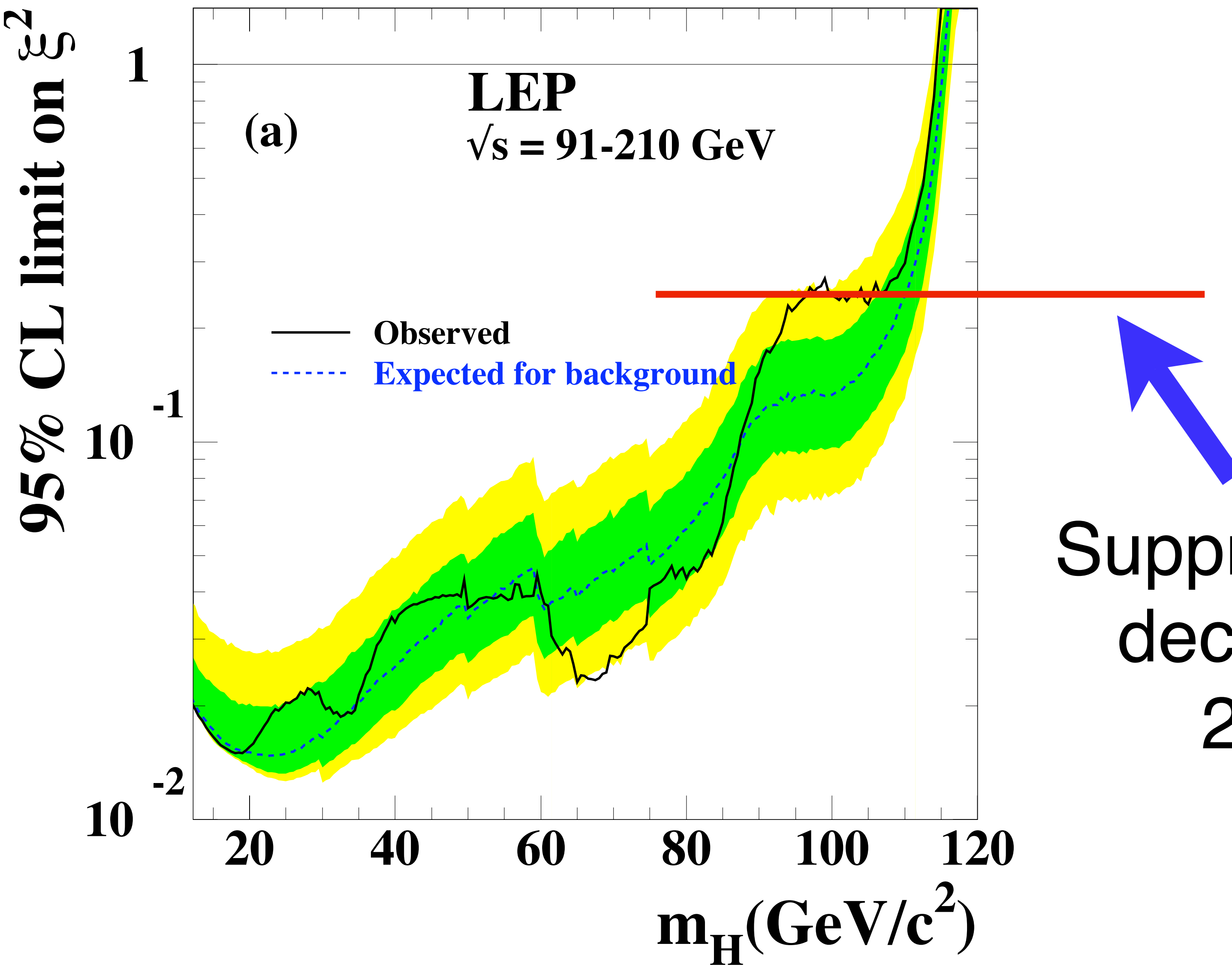


$$\Gamma \sim \frac{m_X^4}{m_h v^2}$$ for a scalar

Non-Standard Higgs?



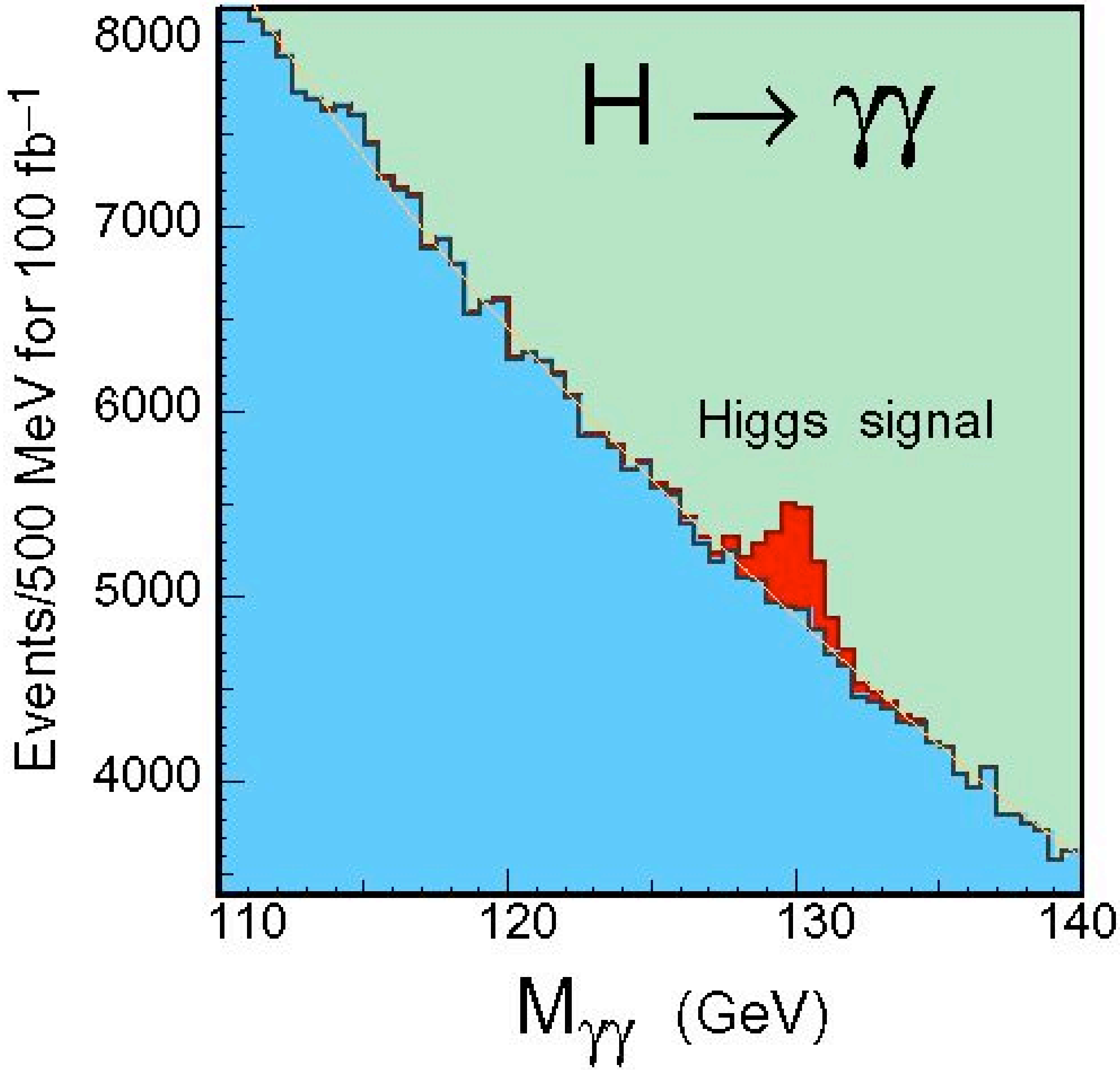
Non-Standard Higgs?



Suppress SM decays to 20%

Suppression of standard searches

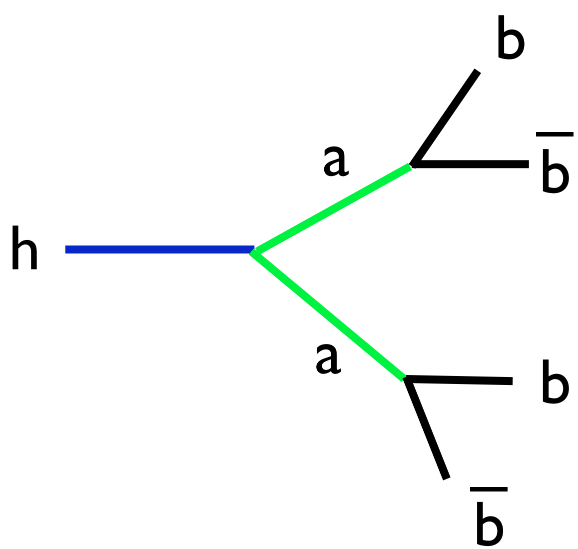
If the rate of Higgs boson decays to multiple jets is, for example, 5 times that into standard model modes, standard searches are dramatically weakened.



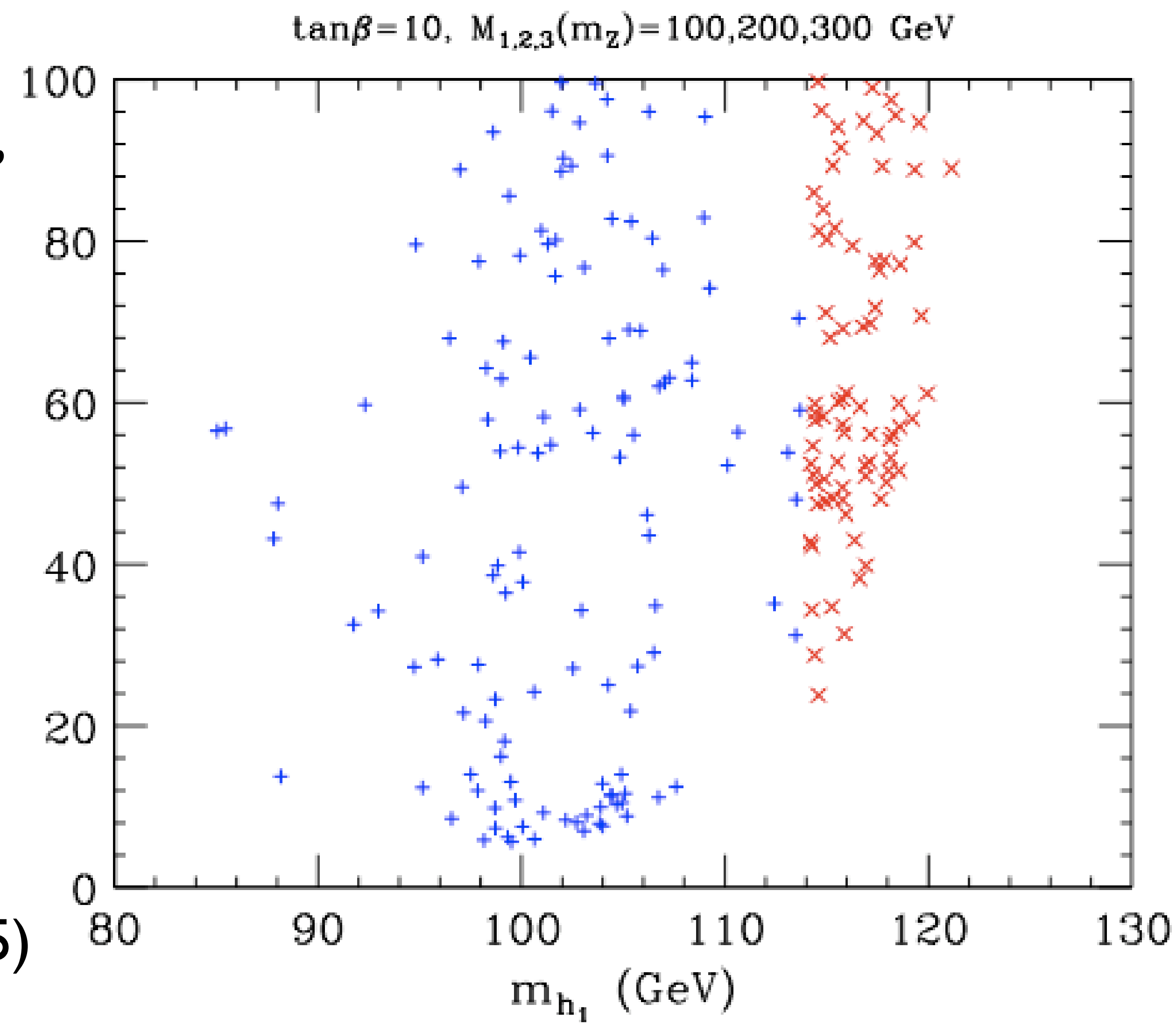
Supersymmetric examples

'NMSSM'

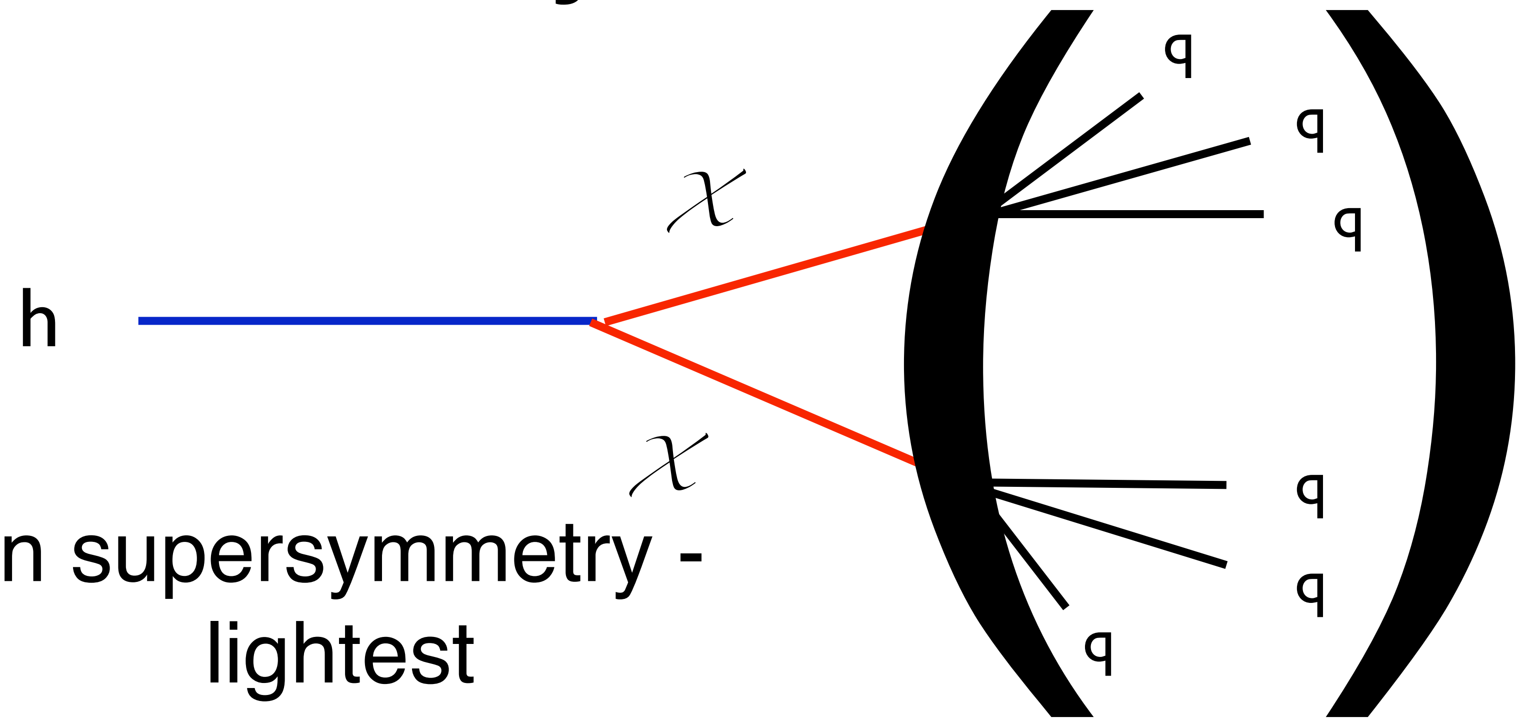
Nilles, Srednicki, Wyler (1983), Frere, Jones, Raby (1983), ...



Dermisek, Gunion (2005)



Decays into fermions



In supersymmetry - lightest superpartner is stable

Haber, Kane (1984)

Or not...

Carpenter, DEK, Rhee (2006)

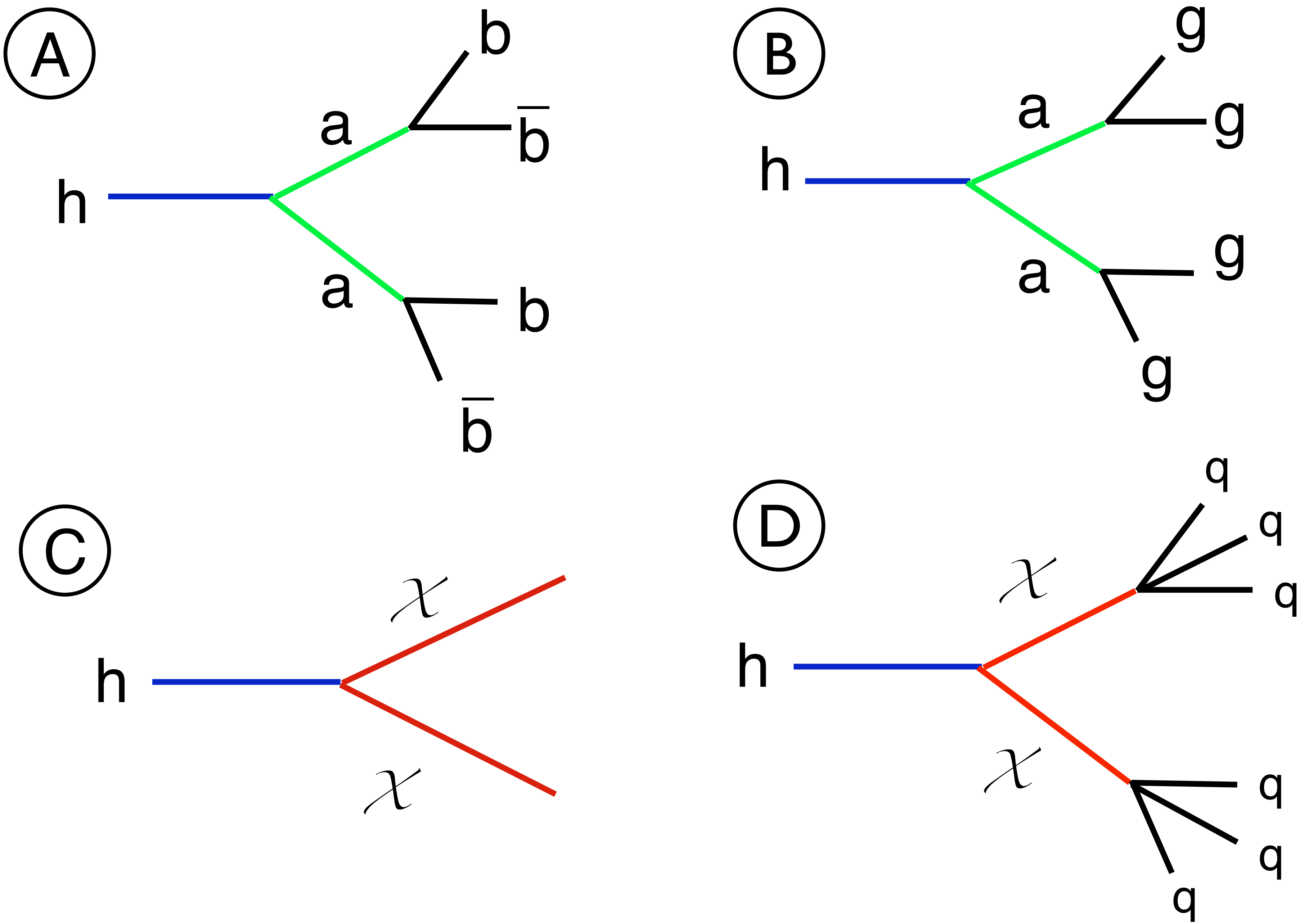
Other scalar decays in supersymmetry

LEP Bounds

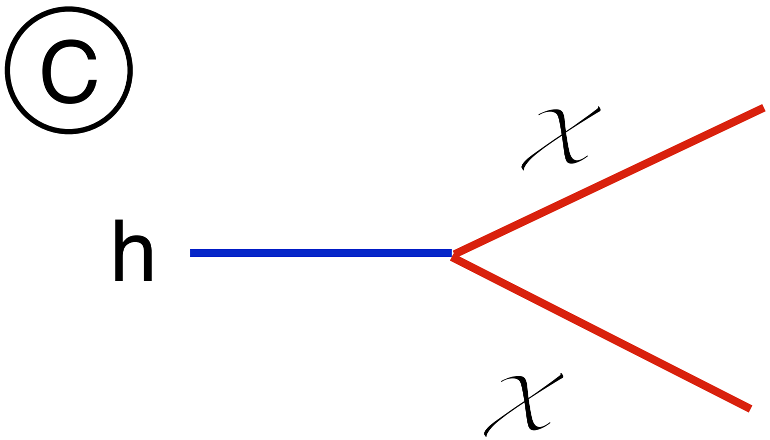
$h \to aa \to \bar{b}b\bar{b}b$	$m_h > 110\,\mathrm{GeV}$
$h \to aa \to \bar{\tau}\tau\bar{\tau}\tau$	$m_h > 86\,\mathrm{GeV}$
$h \to aa \to gggg$	$m_h > 82 - 95\,\mathrm{GeV}$?
$h \to ss \to aaaa \to \bar{b}b\bar{b}b\bar{b}b\bar{b}b$	$m_h > 82\,\mathrm{GeV}$????

Dermisek, Gunion, Dobrescu, Matchev, Landsberg, Chang, Fox, Weiner, Graham, Pierce, Wacker, (2000-2007), plus plenty of older literature.

Typical decays

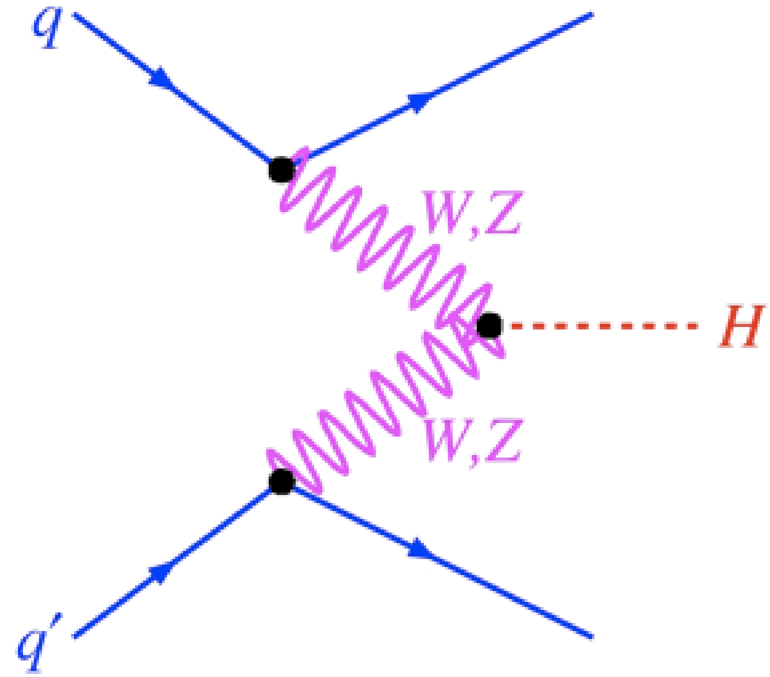


Need to look at the new decay modes



The invisible Higgs

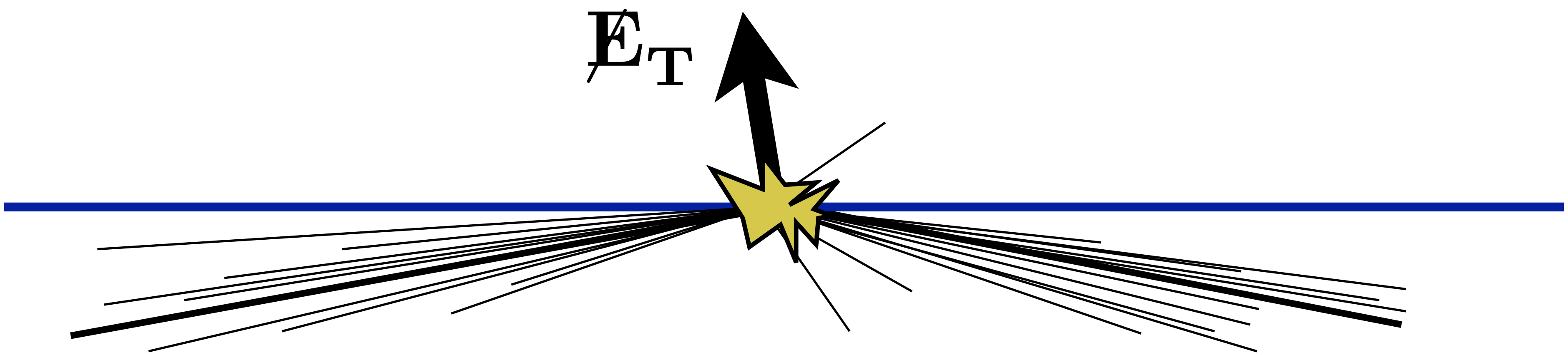
Two forward jets



M_H (GeV)	110	120	130	150	200	300	400
10 fb^{-1}	12.6%	13.0%	13.3%	14.1%	16.3%	22.3%	30.8%
100 fb^{-1}	4.8%	4.9%	5.1%	5.3%	6.2%	8.5%	11.7%

Eboli, Zeppenfeld (2007)

Two forward jets



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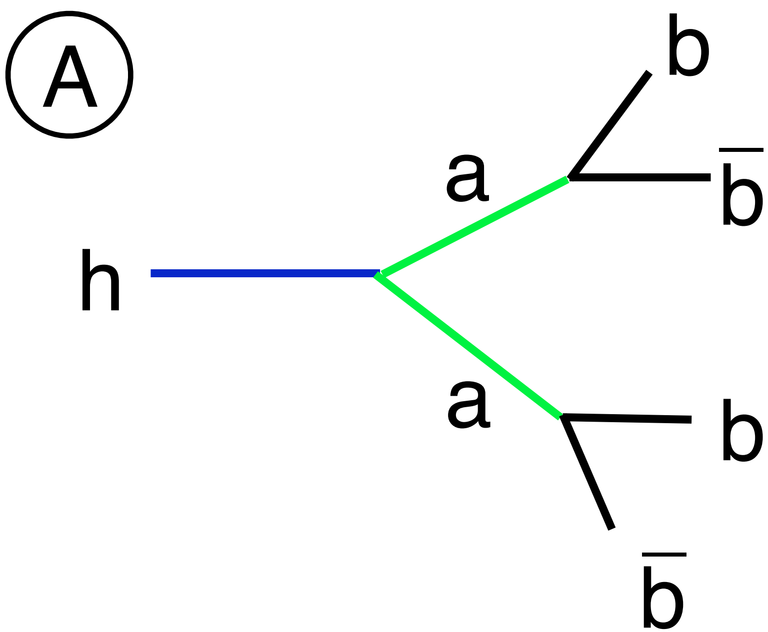
Hadronic decays



Much harder.

Signal:

$\sigma \sim 25\text{pb}$

5×10^4 events

Background:

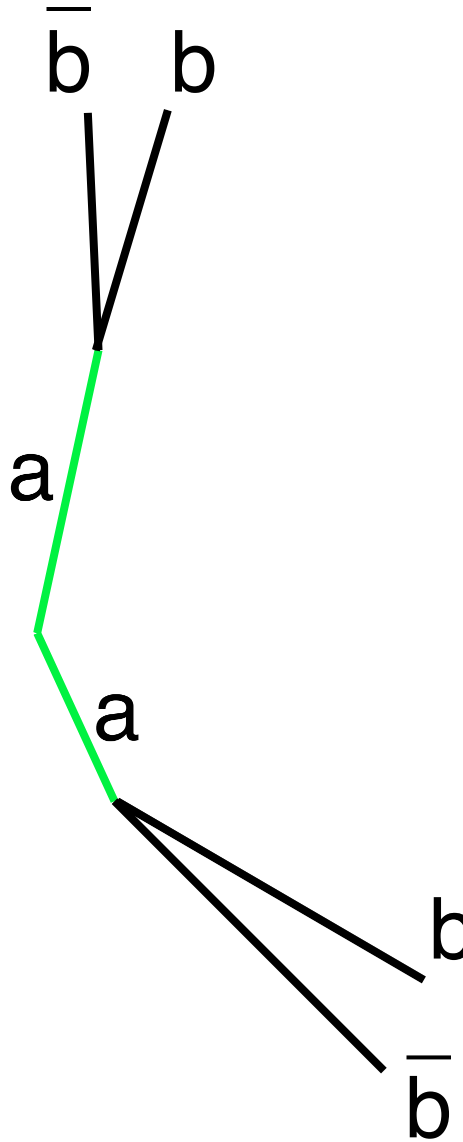
$\sigma \sim 0.5\mu\text{b}$

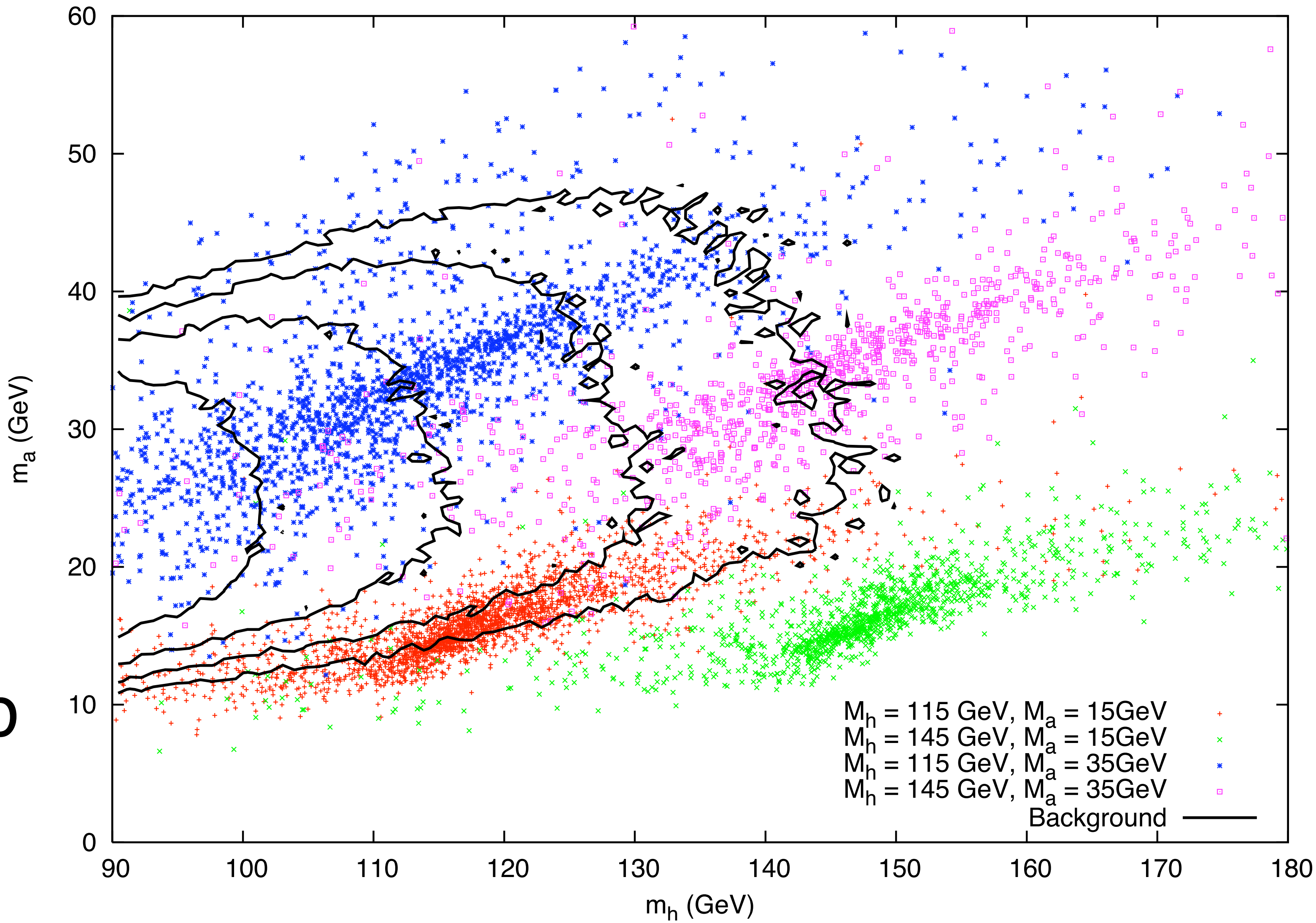
$\sim 500,000\text{pb}$

10^9 events

P_T cuts help!

Nice kinematic regions





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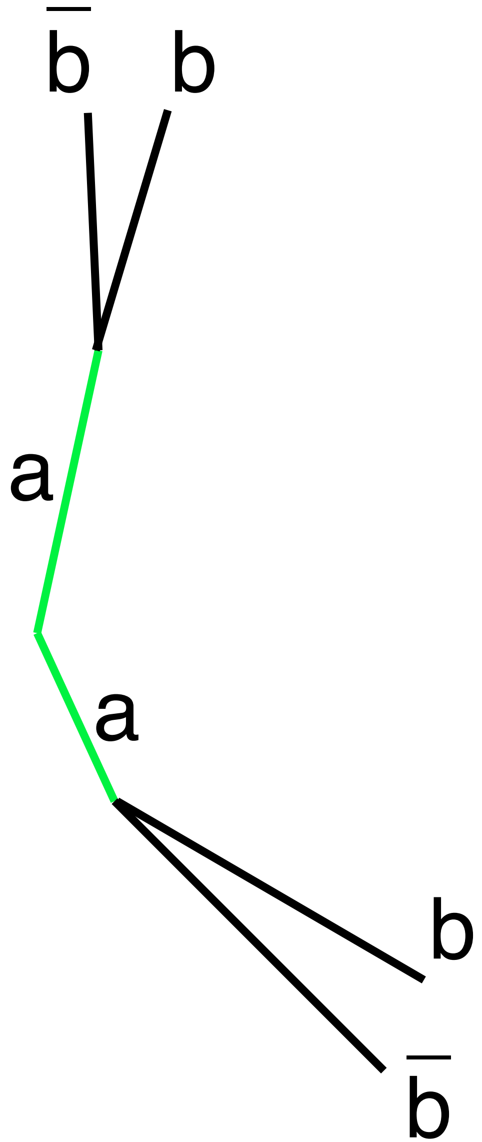
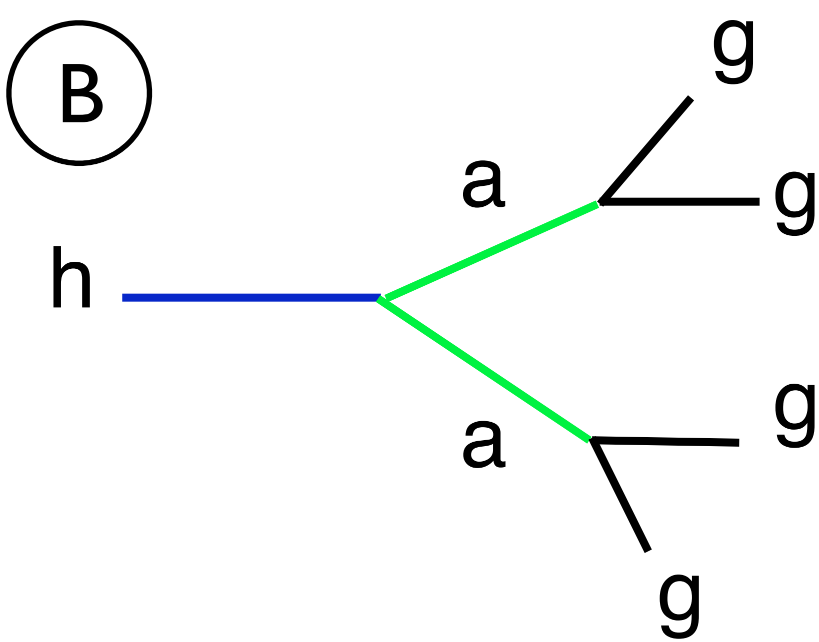


m_h	m_a	q^+	q^-	ϵ_{req}	S/B
115	15	105	72.5	0.06	0.11
115	20	135	57.5	0.24	0.023
115	25	135	42.5	0.39	0.016
115	30	135	27.5	0.69	0.012
115	35	135	12.5	1.15	0.009
130	15	125	87.5	0.05	0.175
130	20	145	72.5	0.24	0.034
130	25	155	57.5	0.39	0.025
130	30	155	42.5	0.59	0.020
130	35	155	27.5	0.88	0.017
145	15	135	102.5	0.05	0.38
145	20	155	87.5	0.22	0.052
145	25	165	72.5	0.46	0.029
145	30	165	57.5	0.78	0.022
145	35	165	42.5	1.00	0.020

For all gluons



Background at least 1,000 times larger - no tricks yet...

Why believe in light scalars?

Interlude: Nambu-Goldstone Bosons

Let's see the classical phenomenon using the wave description.

An infinite straight rope breaks translation invariance in directions perpendicular to the rope. The transverse waves are the Goldstone modes.

$$\mathcal{L} = \frac{1}{2}\sigma\left(\frac{\partial\phi}{\partial t}\right)^2 - \frac{1}{2}\tau\left(\frac{\partial\phi}{\partial x}\right)^2 \longrightarrow \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = \frac{\partial^2\phi}{\partial x^2}$$

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Fourier transform:

$$\phi(x,t) = \int \frac{dk\,d\omega}{4\pi^2}\tilde{\phi}(k,\omega)\,e^{i(kx-\omega t)} \longrightarrow \omega^2 = k^2c^2$$

Can have waves with arbitrarily low frequency.

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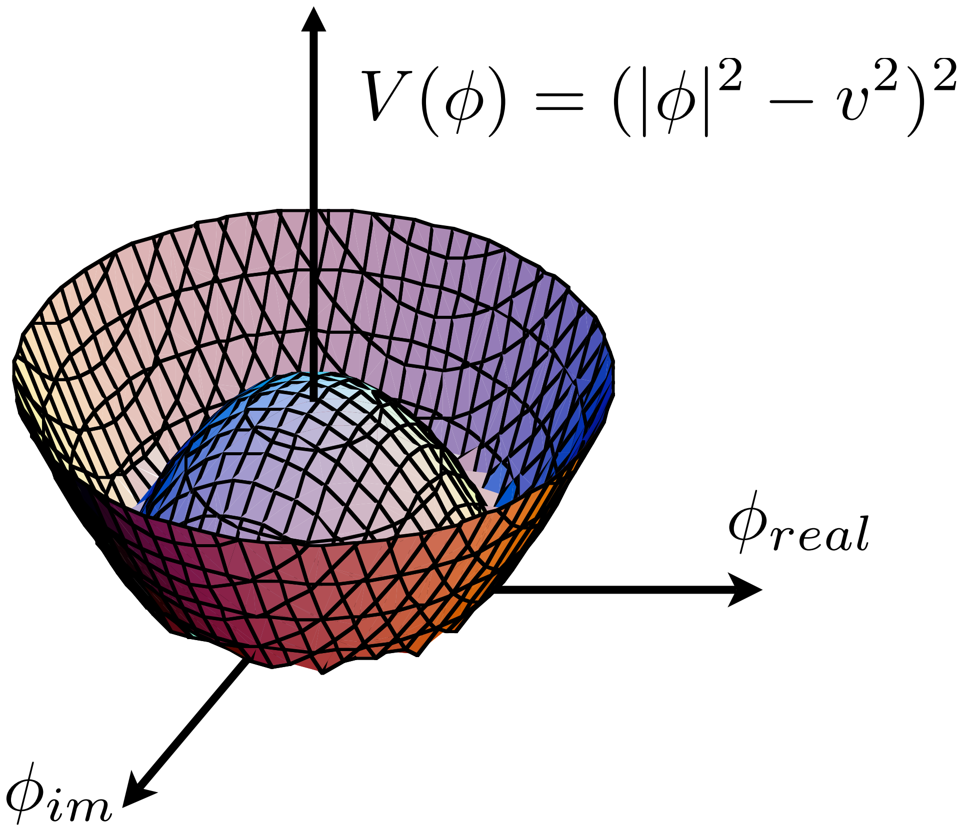
quantize: Particles with arbitrarily low energy $\longrightarrow$ massless particles

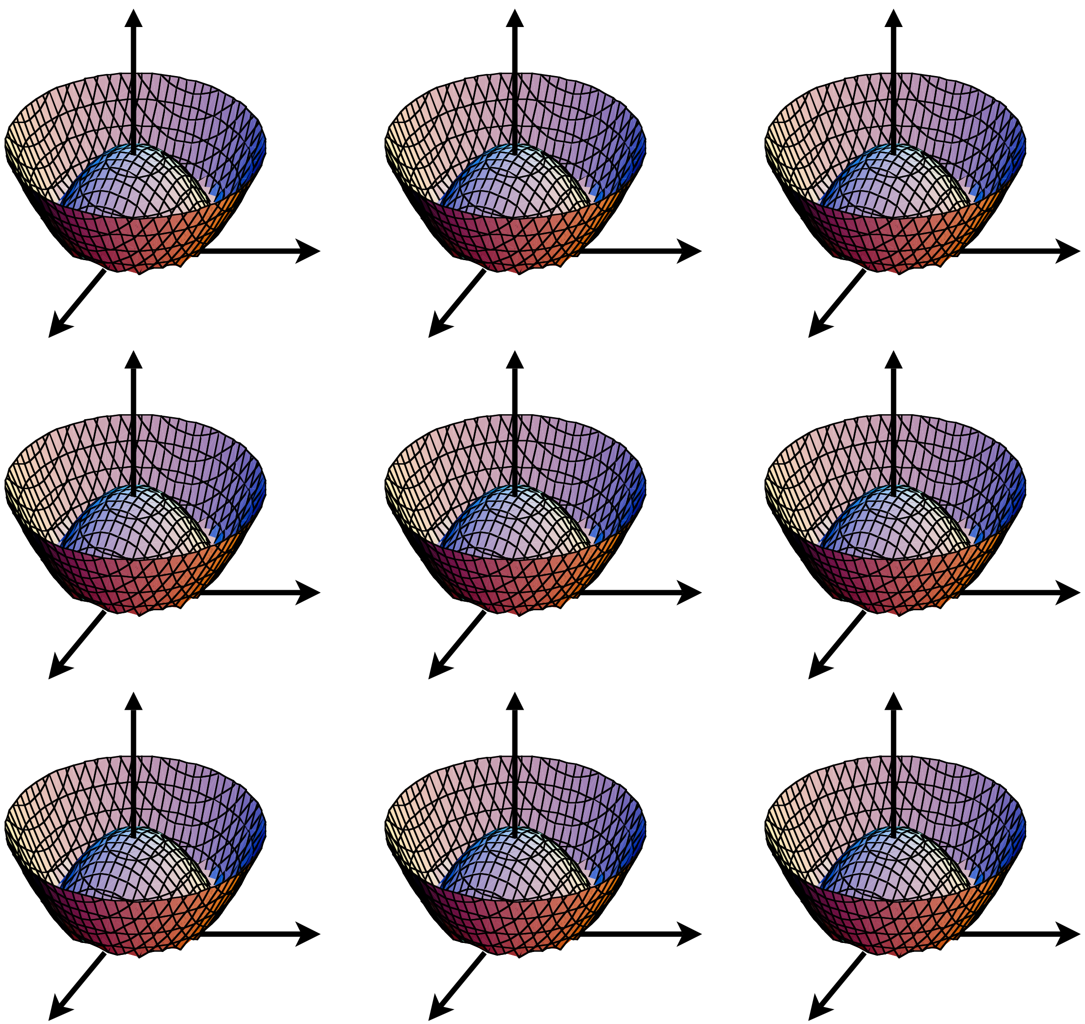
$$E^2 = p^2$$

Internal Symmetry Breaking



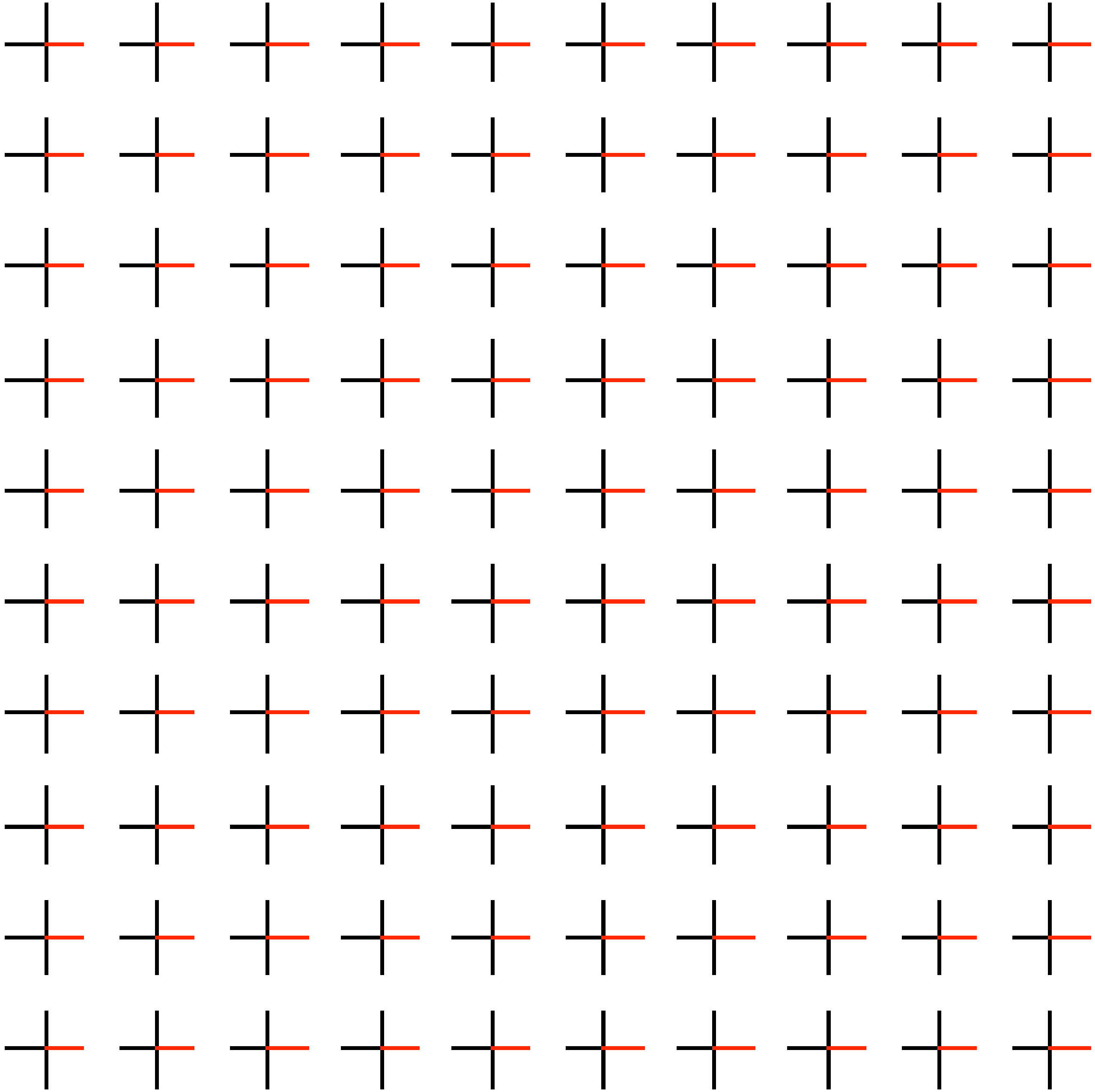
This again...

Internal Symmetry Breaking



The potentials live at every point in space and waves of fluctuations between vacua move through space

Propagating Goldstones



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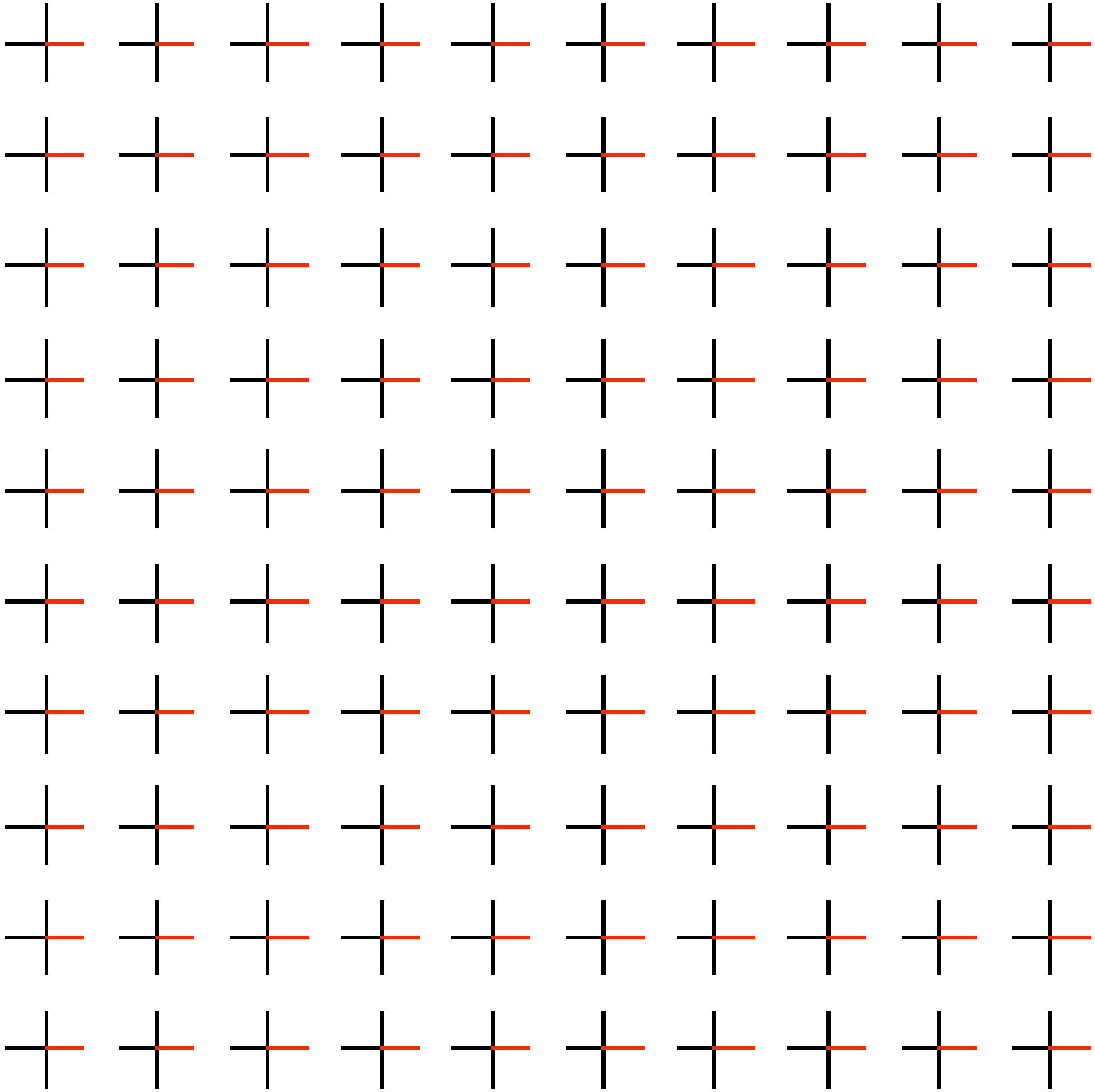

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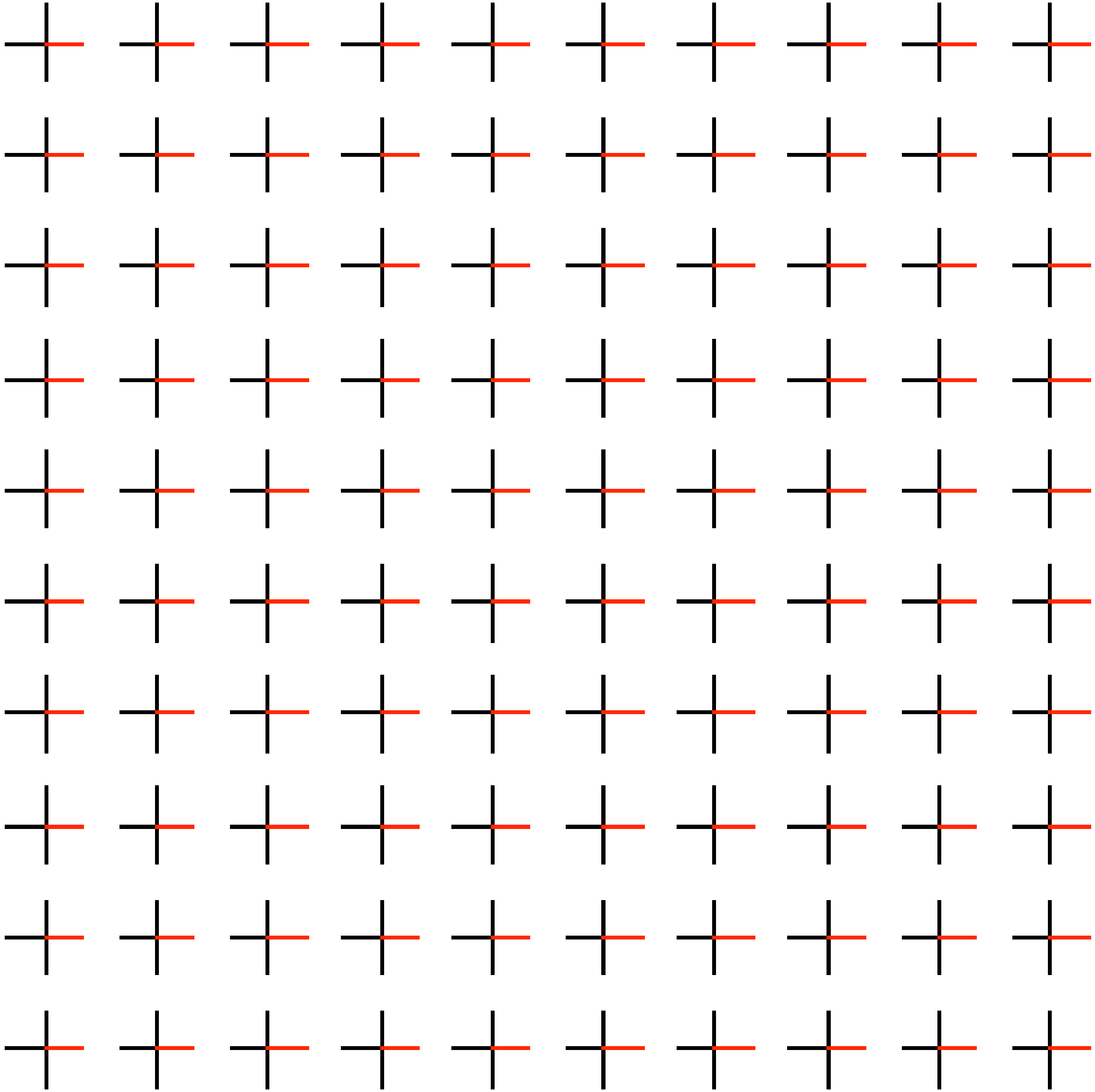

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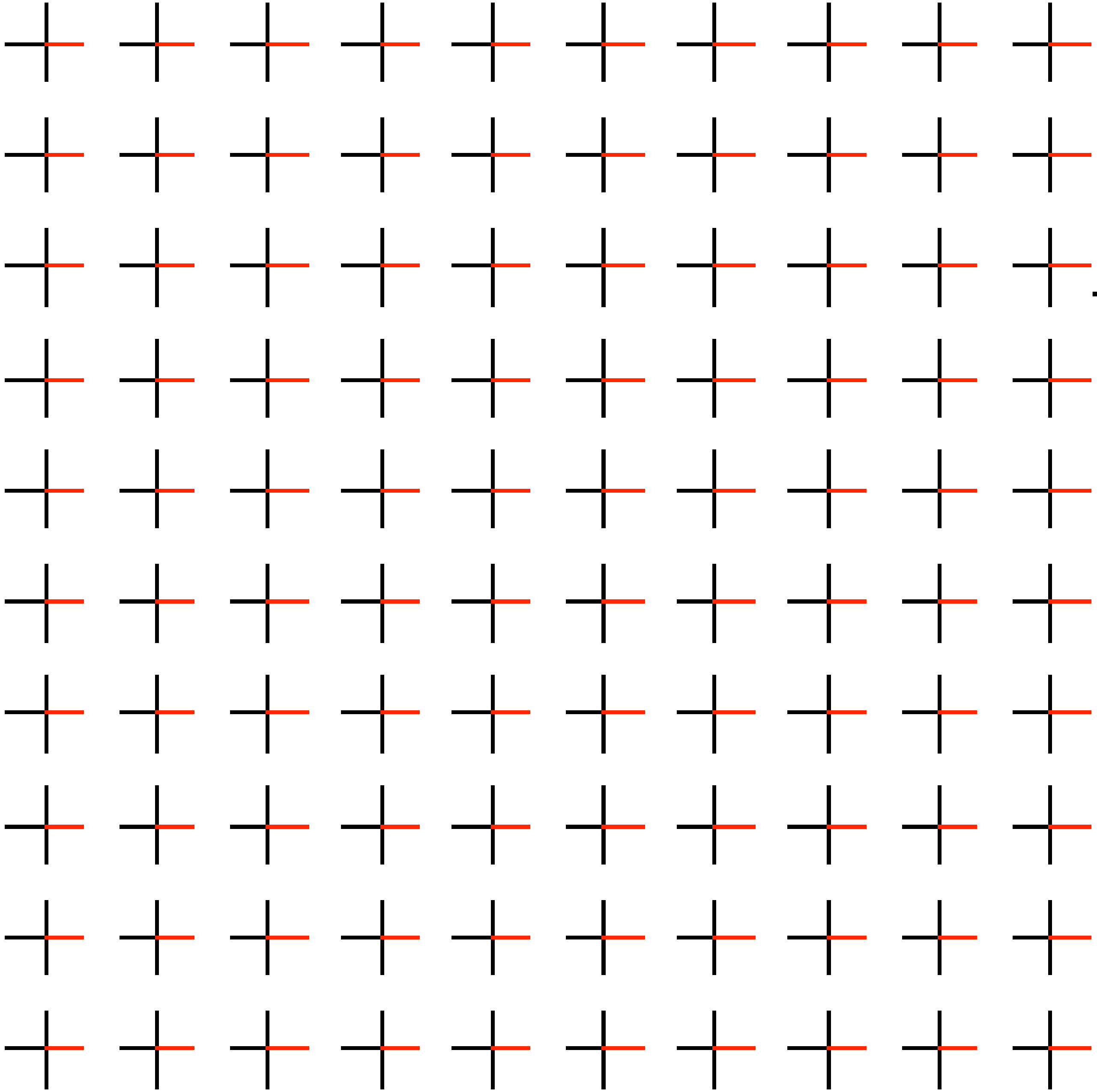
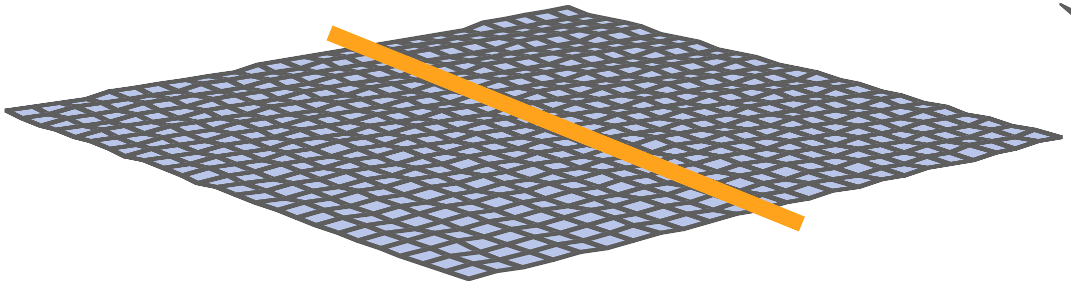
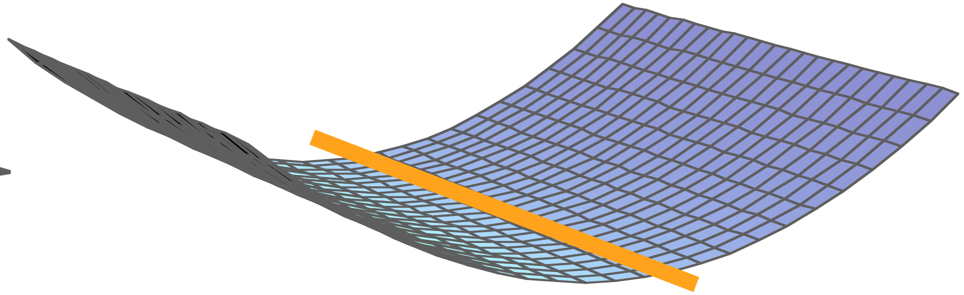


These particles have no potentials and no interactions (at long wavelengths)

Pseudo-Goldstone Bosons



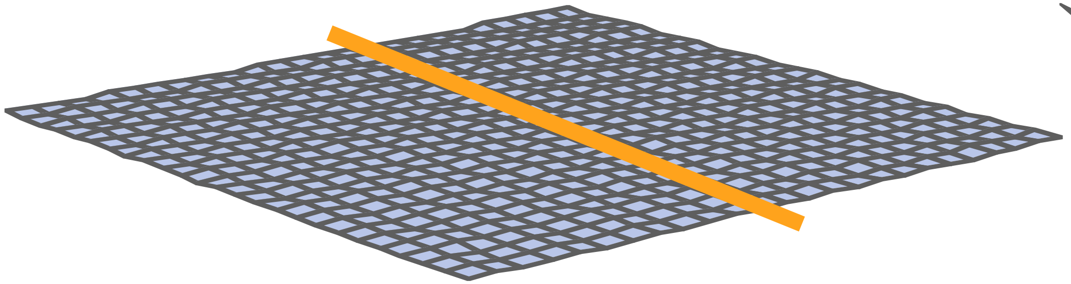


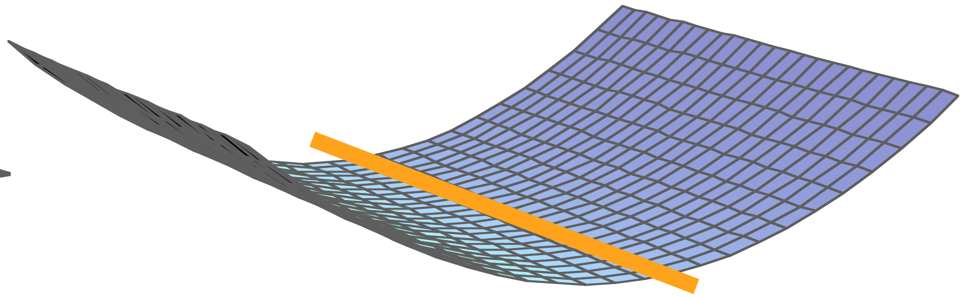
$$\mathcal{L} = \frac{1}{2}\sigma\left(\frac{\partial y}{\partial t}\right)^2 - \frac{1}{2}\tau\left(\frac{\partial y}{\partial x}\right)^2 - \frac{1}{2}\eta^2 y^2$$

Equation of motion:

$$\frac{1}{c^2}\frac{\partial^2 y}{\partial t^2} = \frac{\partial^2 y}{\partial x^2} - \mu^2 c^2 y^2$$

Pseudo-Goldstone Bosons



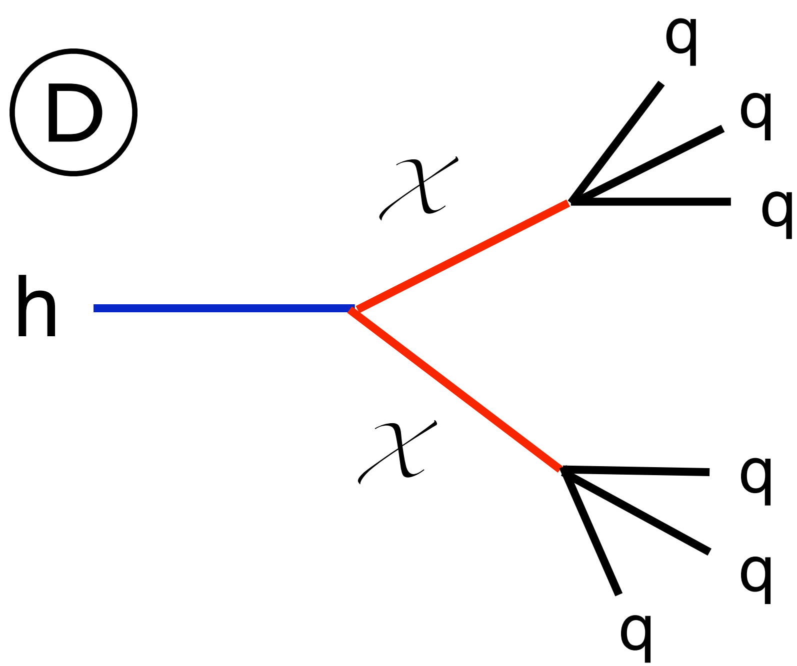


$$\mathcal{L} = \frac{1}{2}\sigma\left(\frac{\partial y}{\partial t}\right)^2 - \frac{1}{2}\tau\left(\frac{\partial y}{\partial x}\right)^2 - \frac{1}{2}\eta^2 y^2$$

A mass gap appears:

$$\omega^2 = k^2 + \mu^2$$

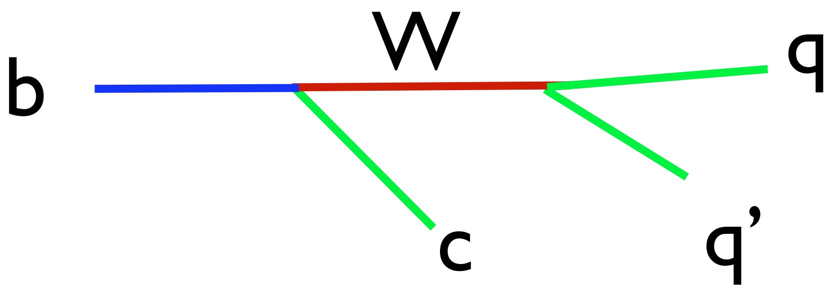
Decaying fermion



6 jets in principle has a smaller background, but these jets are of very low energy

Macroscopic lifetimes

What allows us to distinguish jets with bottom quarks is their decay length:



3-body decay

$$\Gamma \sim \frac{m_b^5}{v^4} \times \epsilon^2$$

$$\ell_b = c\tau_b \simeq 0.5 \text{ mm}$$

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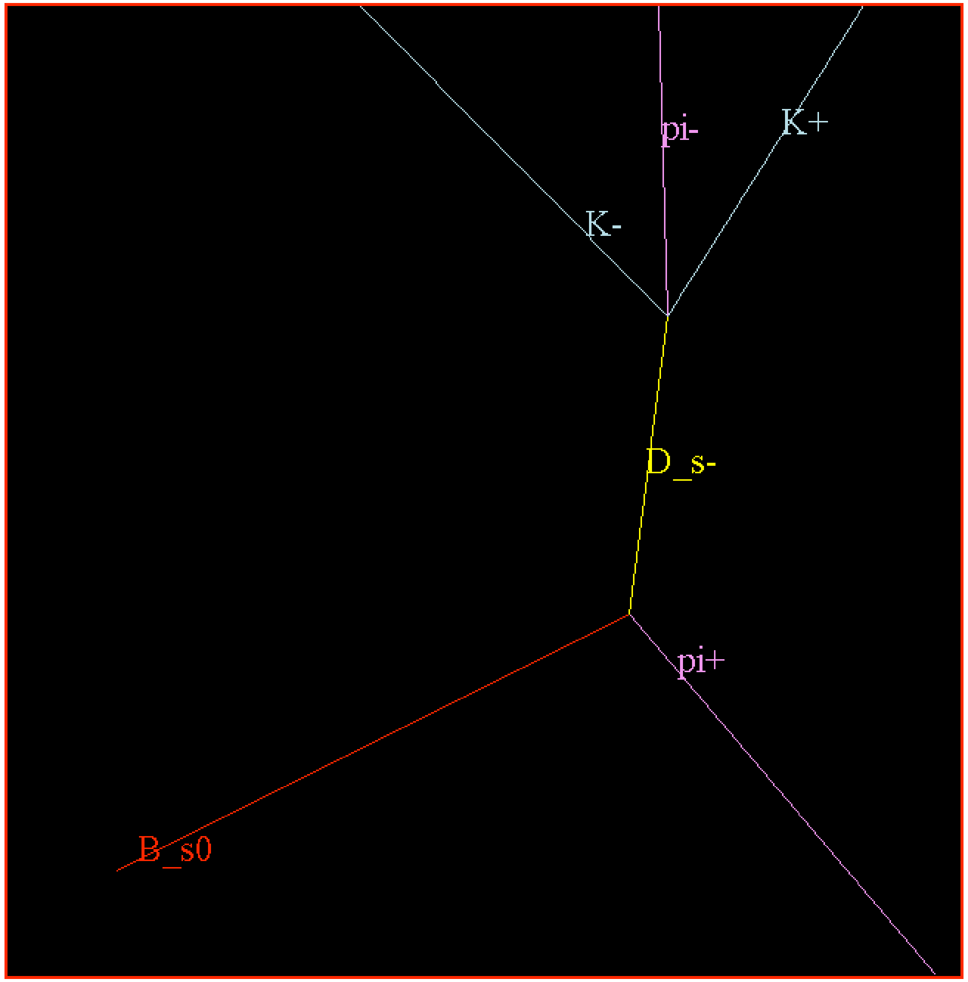

3-body decay

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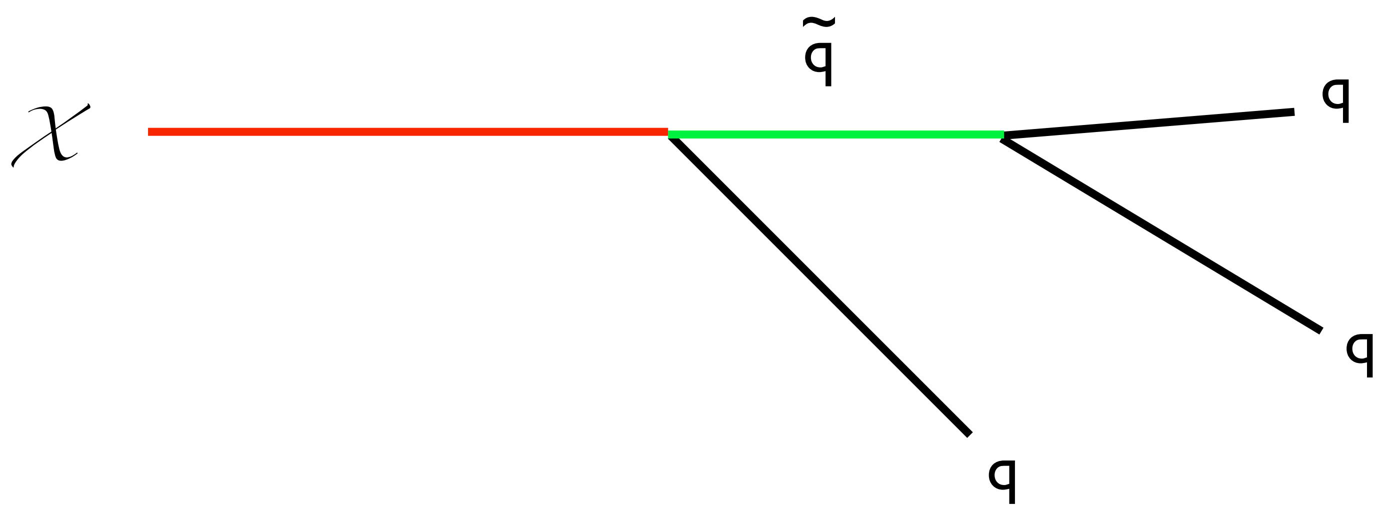
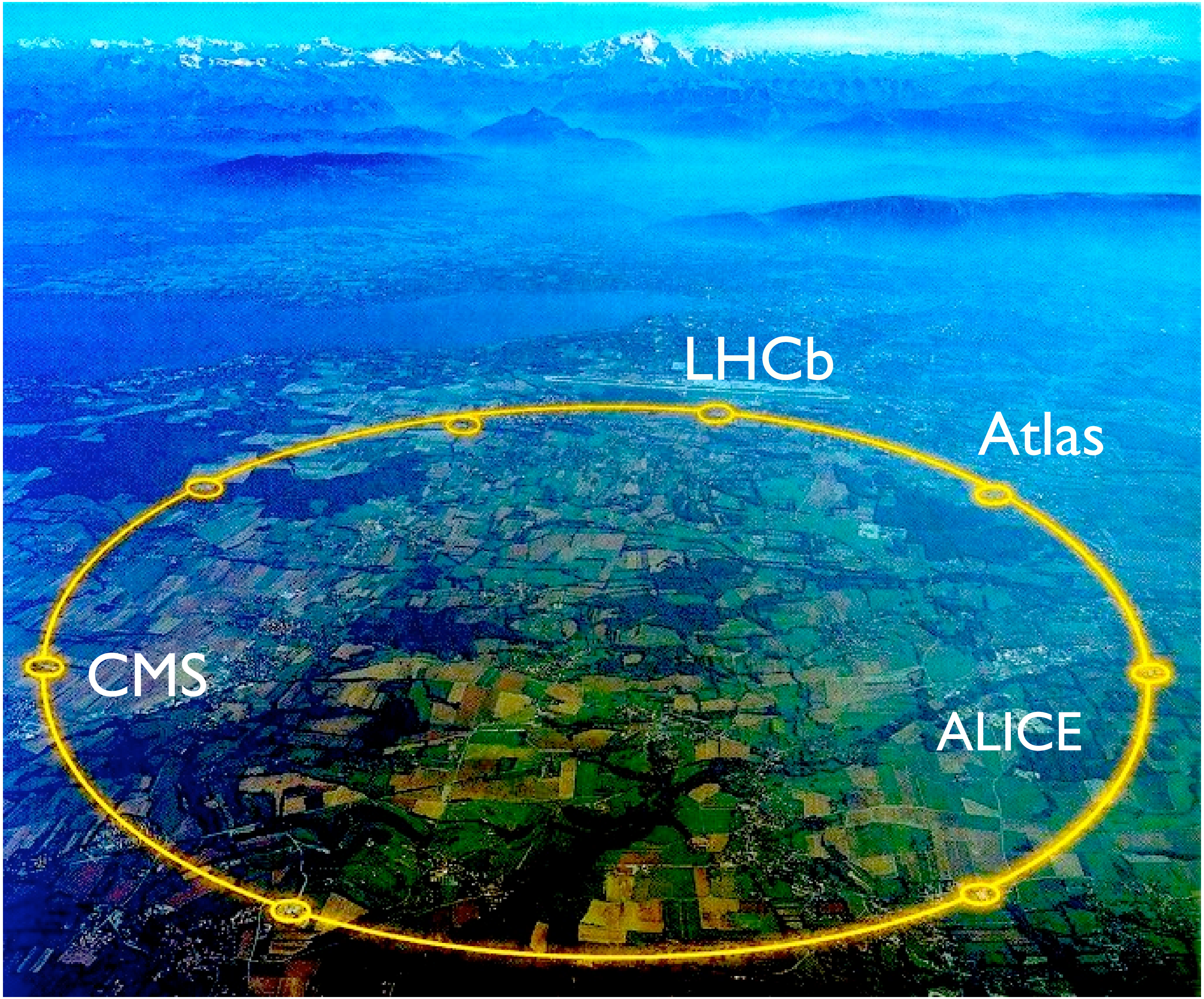
Neutralino decay

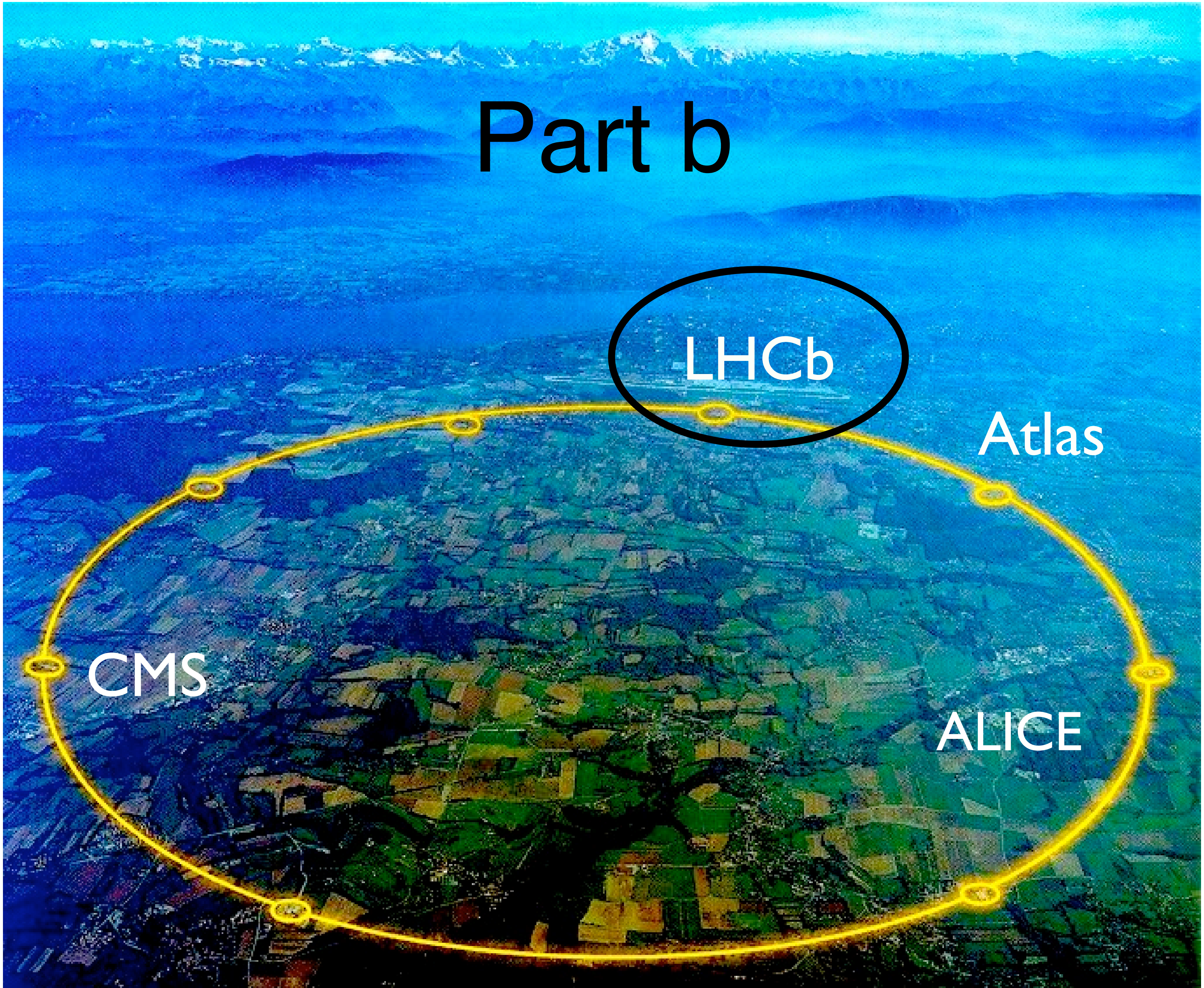


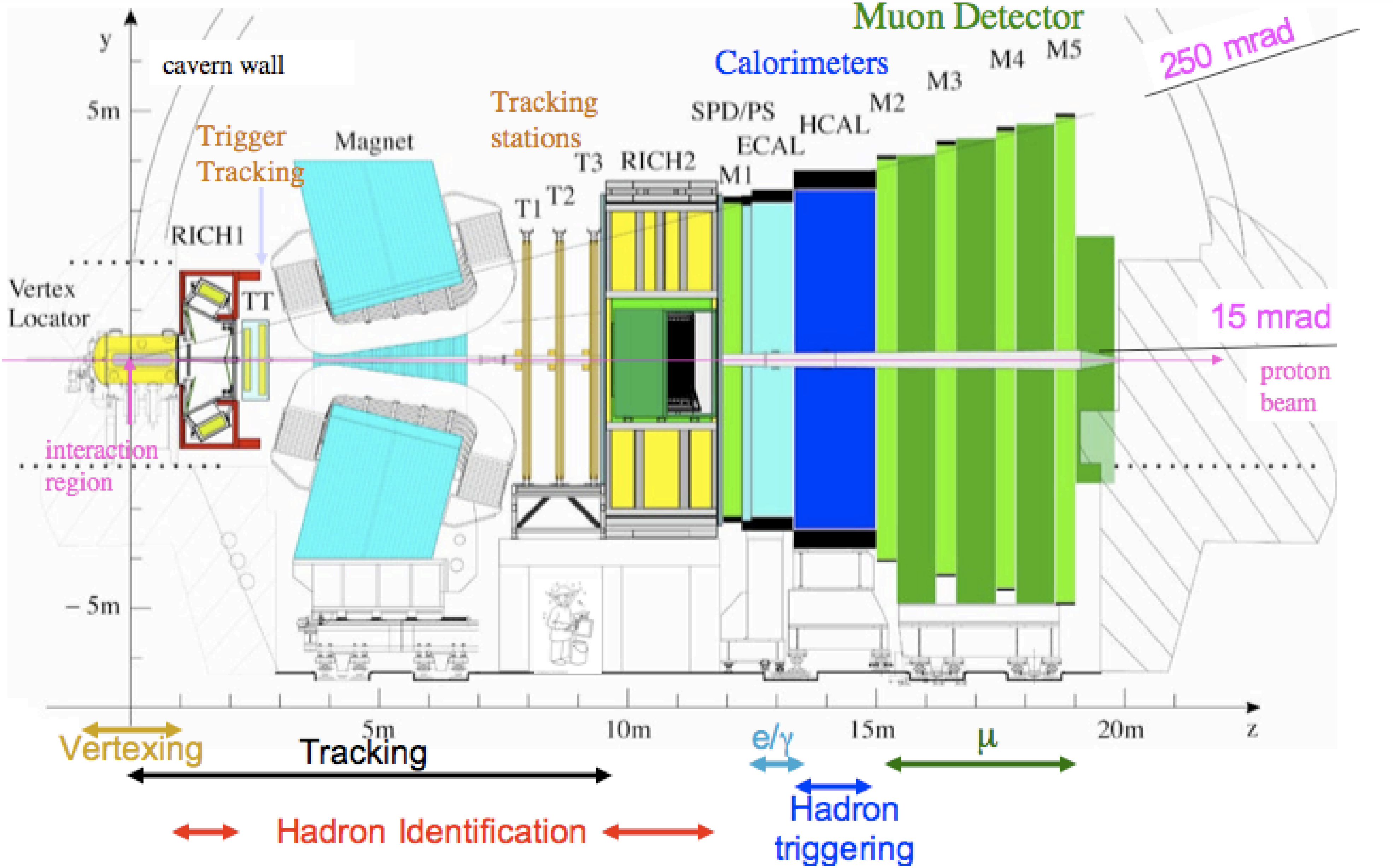
Neutralinos may have a long decay length.

$$L \sim 3\mu m \left(\frac{10^{-2}}{\lambda''}\right)^2 \left(\frac{m_{\tilde{q}}}{100\ \mathrm{GeV}}\right)^4 \left(\frac{30\ \mathrm{GeV}}{m_\chi}\right)^5$$

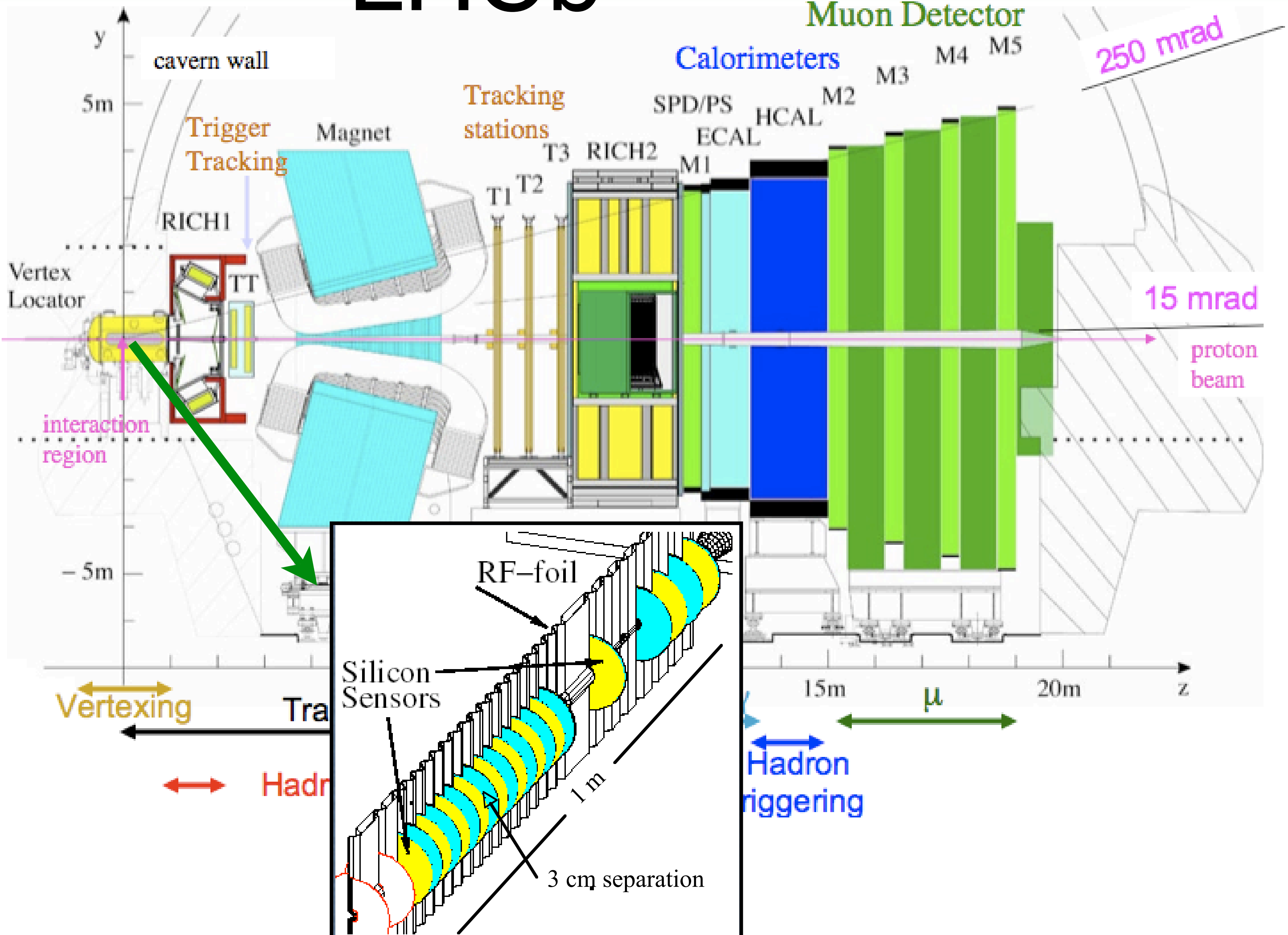

LHCb
Atlas
CMS
ALICE

Part b




Muon Detector
Calorimeters
250 mrad
cavern wall
y
5m
Trigger
Tracking
Magnet
Tracking
stations
SPD/PS
HCAL
ECAL
M1
M2
M3
M4
M5
T1
T2
T3
RICH2
RICH1
TT
Vertex
Locator
15 mrad
proton
beam
interaction
region
− 5m
5m
10m
15m
20m
z
Vertexing
Tracking
e/γ
μ
Hadron
triggering
Hadron Identification

LHCb


Muon Detector
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Vertexing
Tra
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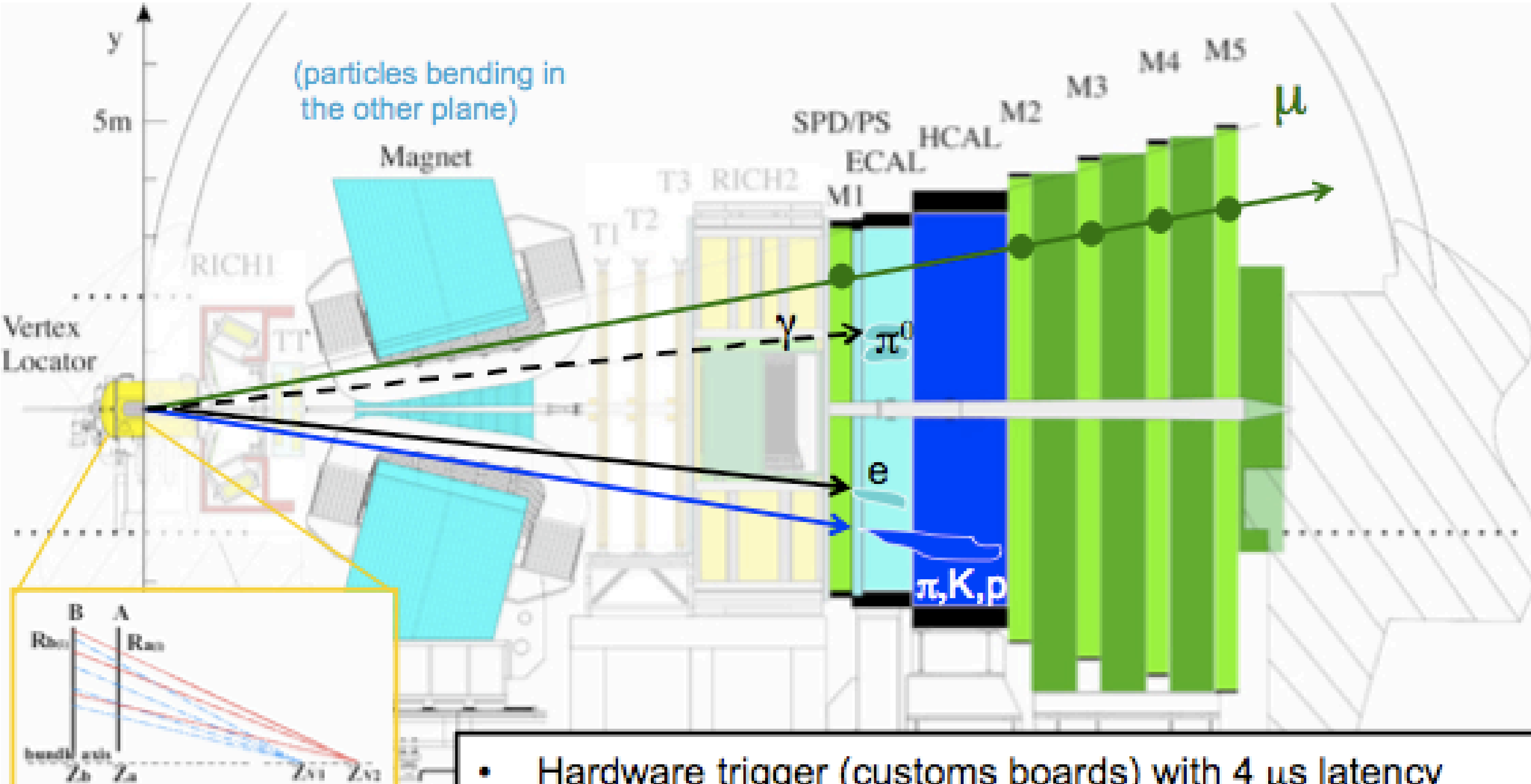
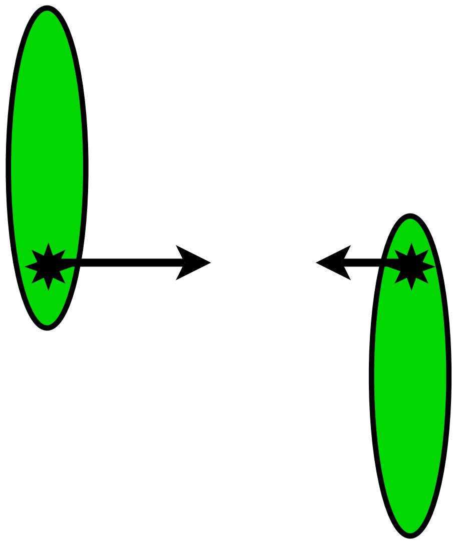
riggering
Hadr
1 m
3 cm separation



Pile-up veto:
Remove bunch crossings with too many beam-beam interactions
(not applied to μ-trigger)

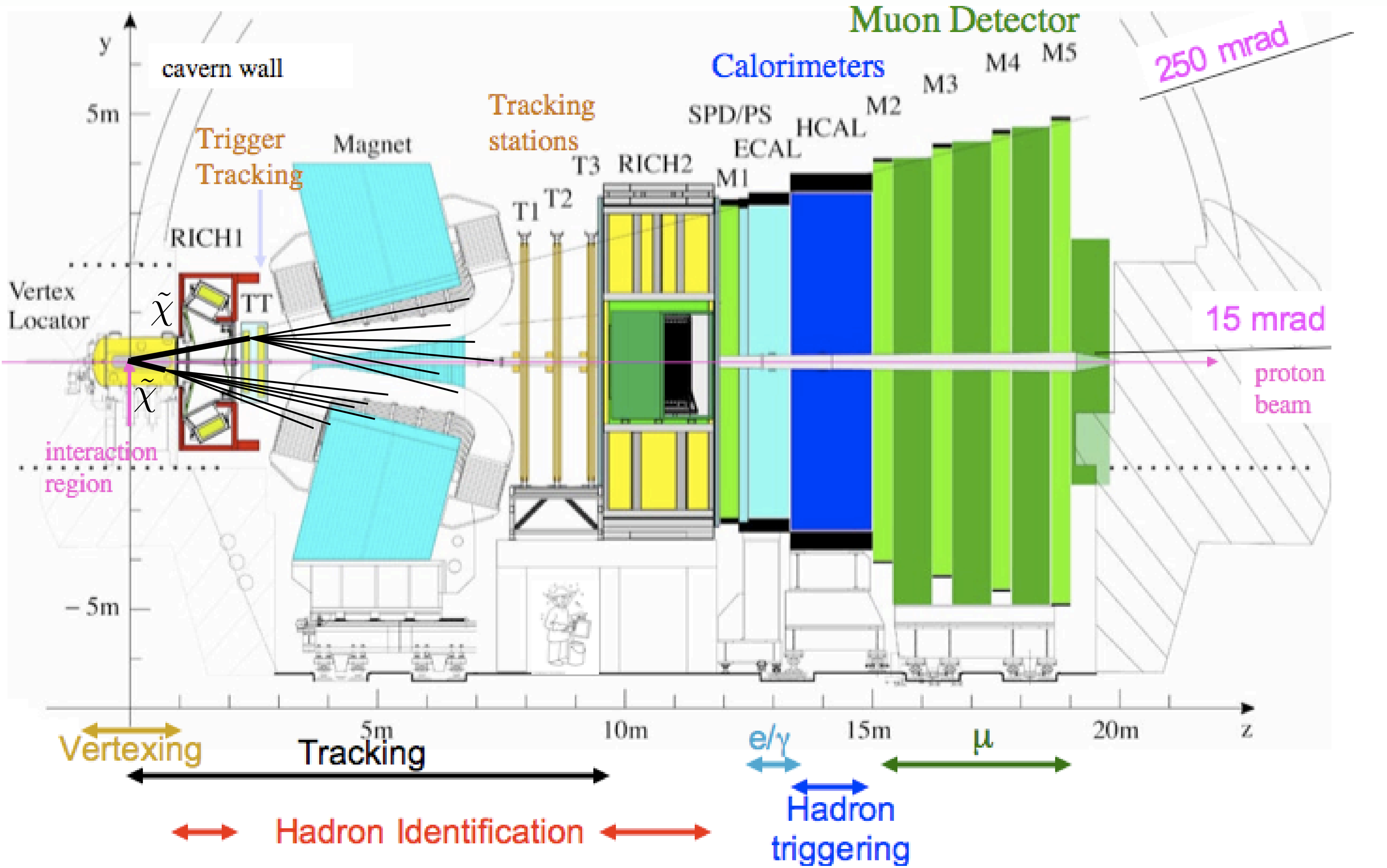
- Hardware trigger (customs boards) with 4 μs latency
- Reduces 10 MHz inelastic collision rate to 1 MHz:
  - $Pt_{\mu 1}$ (+ $Pt_{\mu 2}$) > 1.3 GeV
  - Et_e > 2.8 GeV Et_γ > 2.6 GeV Et_{π^0} > 4.0 GeV
  - $Et_{\pi,K,p}$ > 3.6 GeV

Boosted frames



Event typically boosted w.r.t. the lab frame. Allows for the spreading out of b-decays due to time dilation.

Hard partons inside protons typically carry small fractions of the total momentum.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Vertexing
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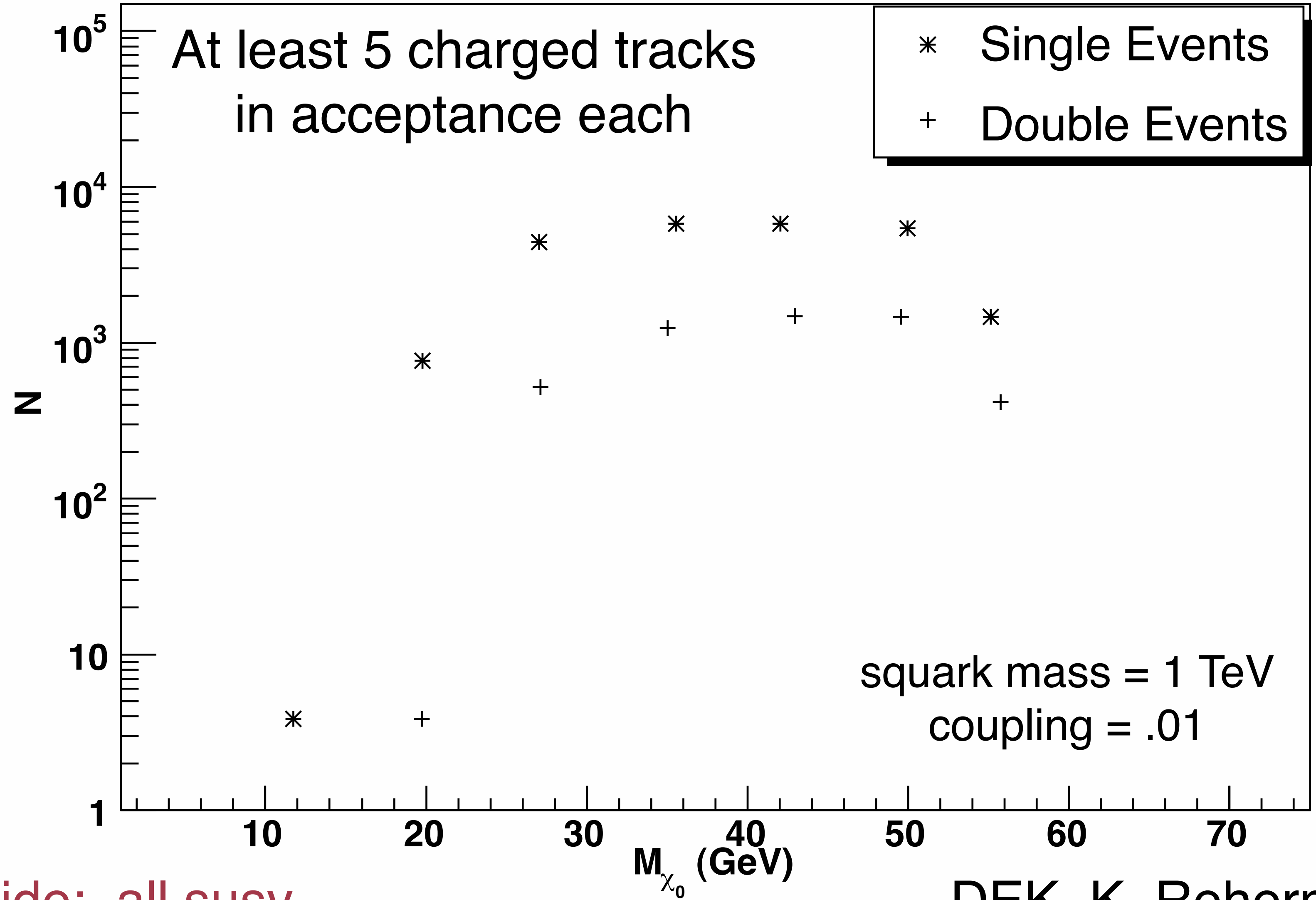
e/γ
μ
Hadron
triggering
Hadron Identification

Higgs/Neutralino search at LHCb

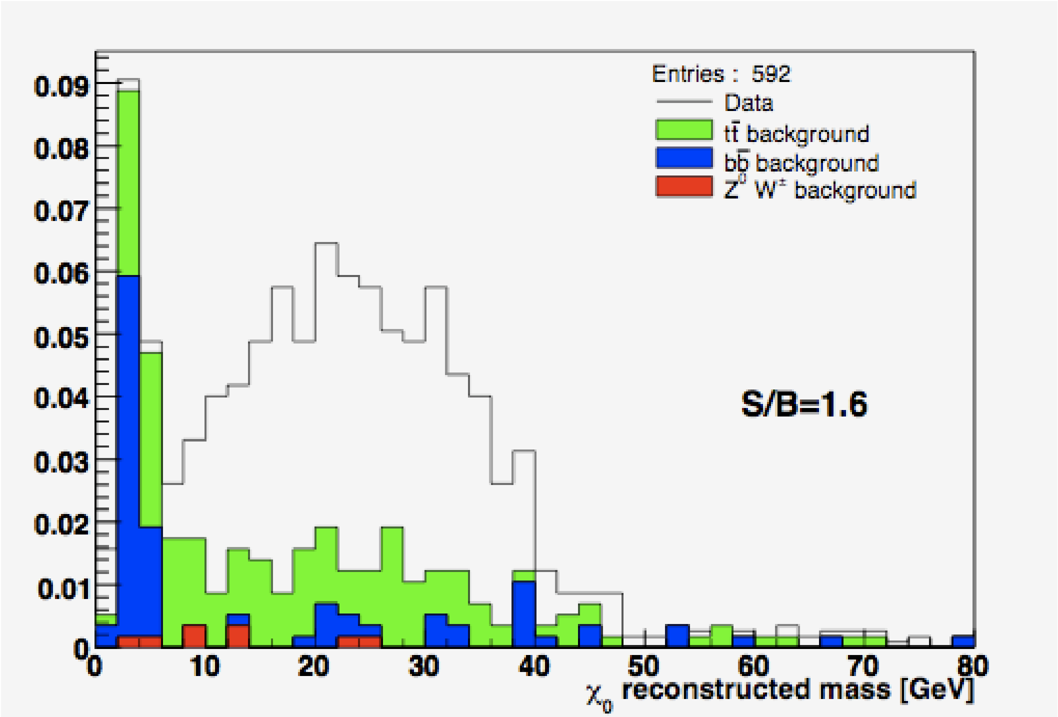


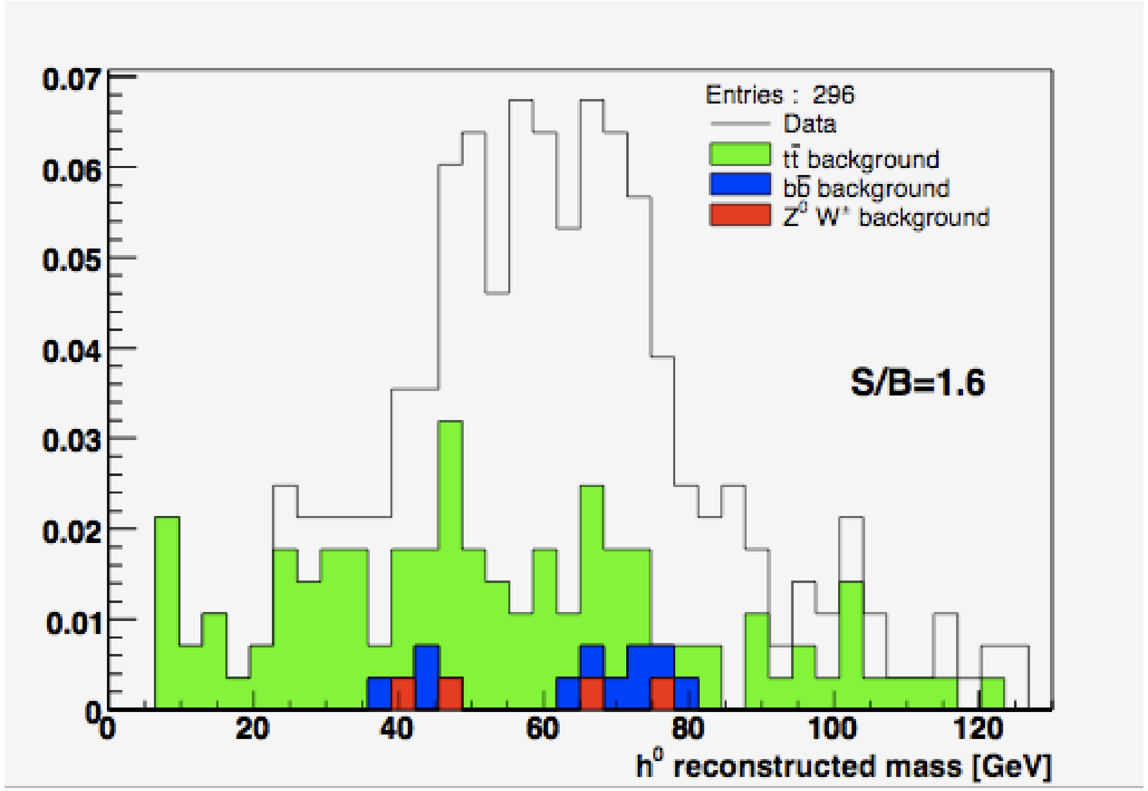
1 year of running

Aside: all susy

DEK, K. Rehermann (2007)

LHCb simulated data after acceptance requirements and cuts:





Could reconstruct the Higgs and measure its mass with ~10% accuracy.

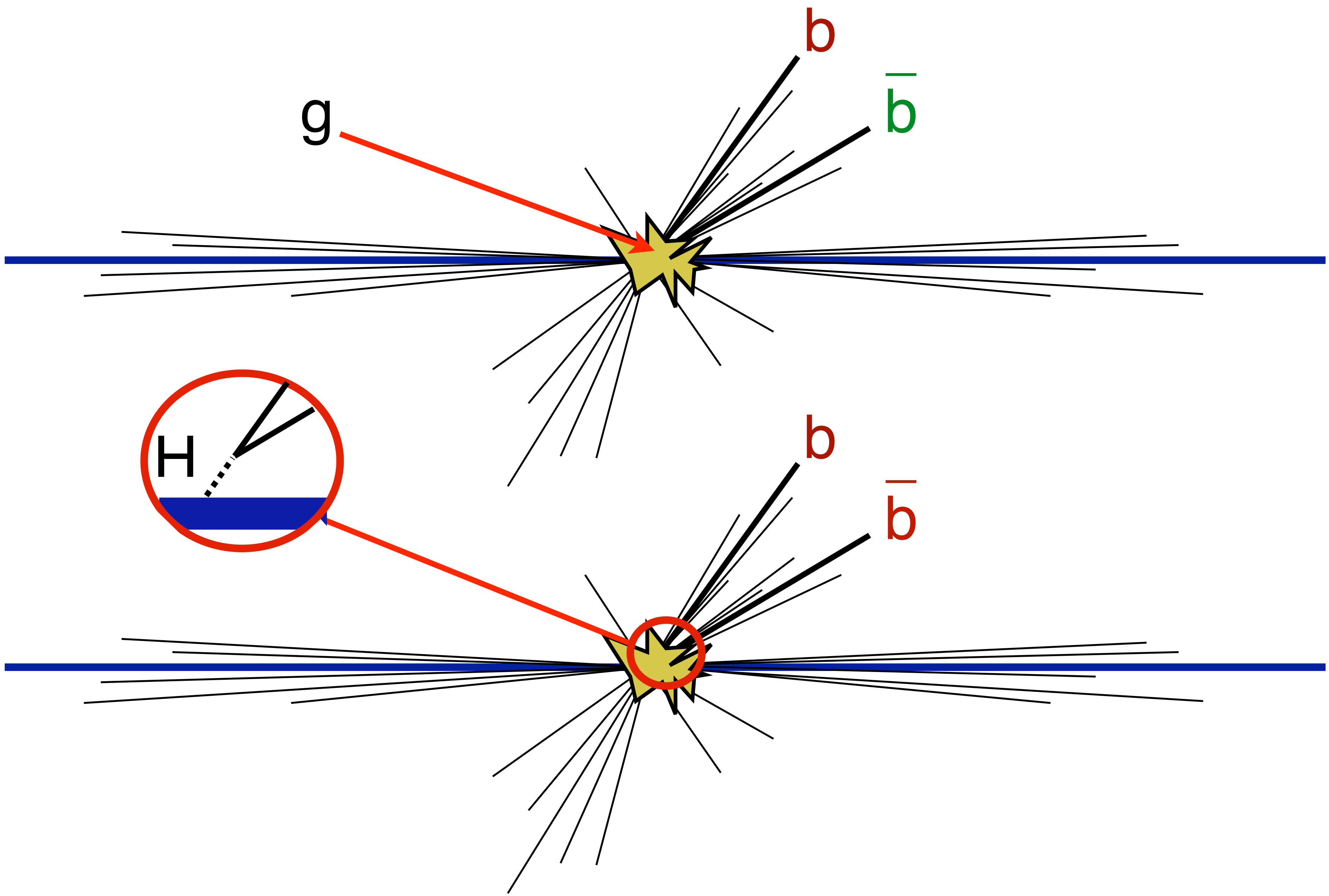
N. Gueissaz, (2007)
CERN-THESIS-2007-038

Other discriminants

So macroscopic decays (‘displaced vertices’) and special kinematics allow for distinguishing above background.

We need more generic observables if possible...

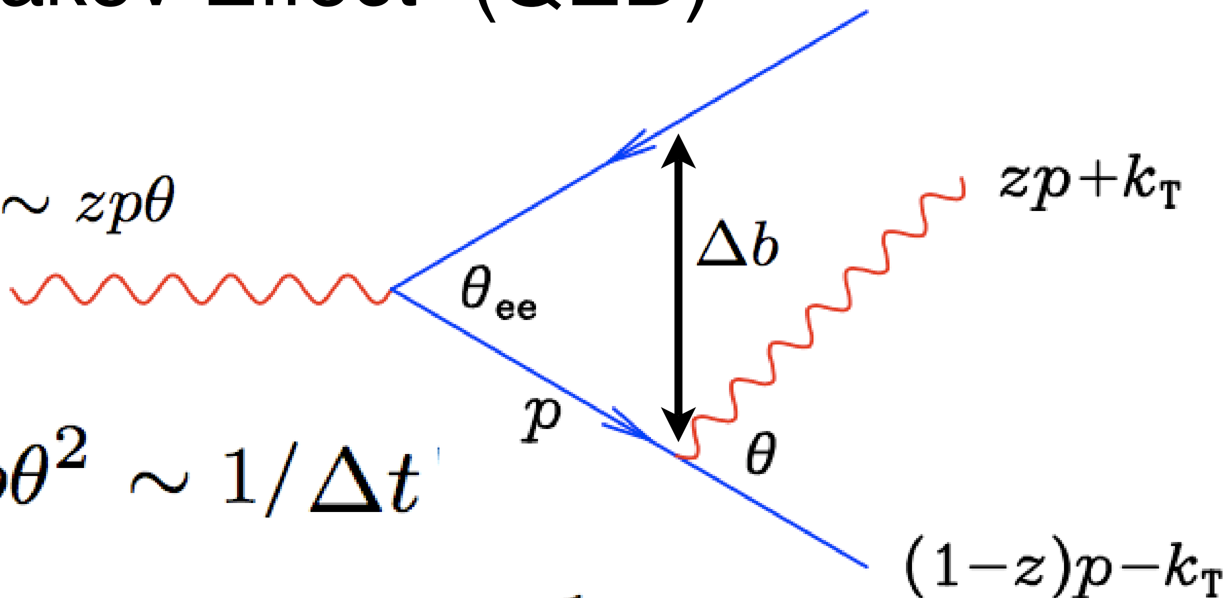
Color flow



Showering differences

The "Chudakov Effect" (QED)

$$\theta_{ee}, \theta \ll 1 \longrightarrow k_T \sim zp\theta$$



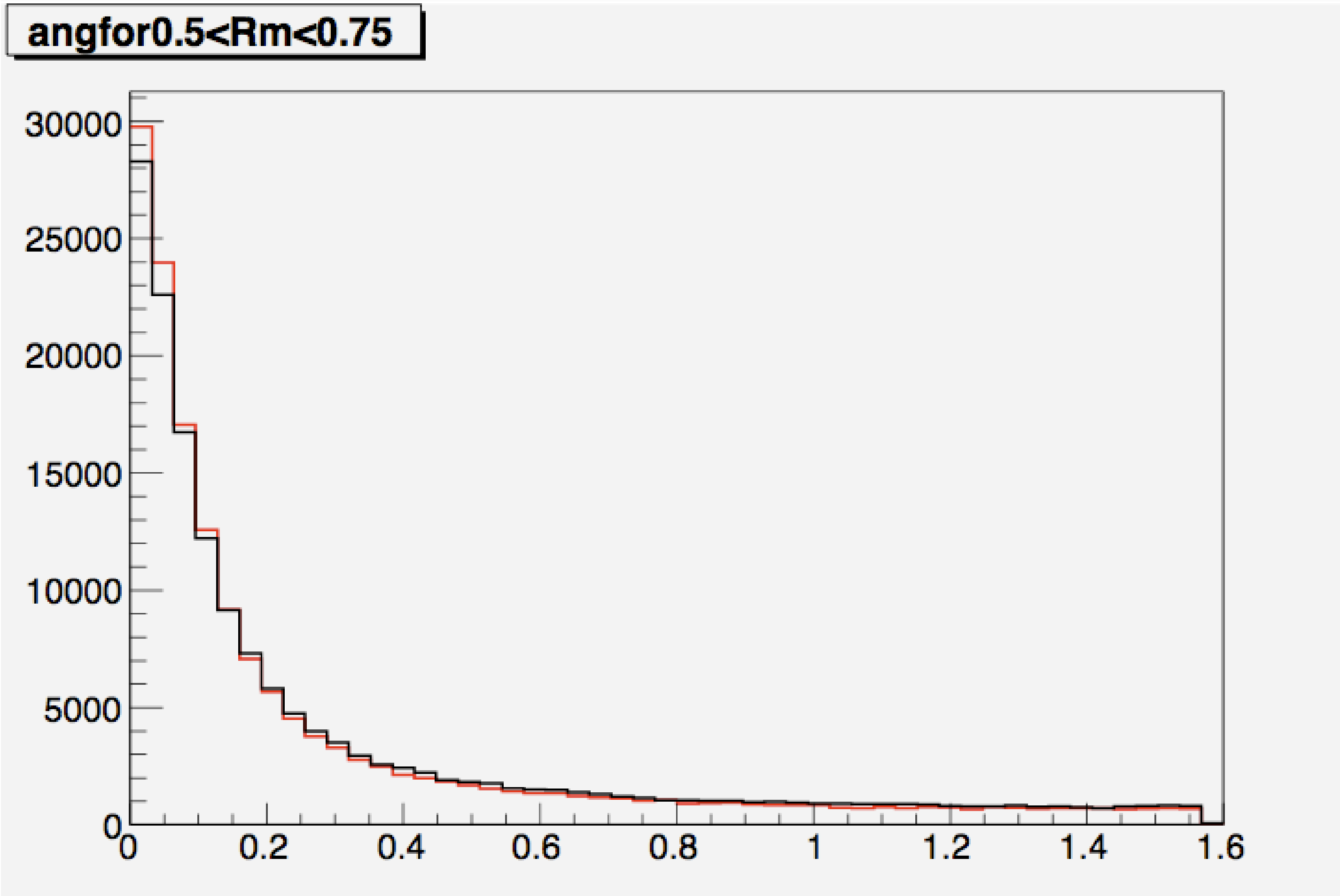
$$\Delta E \sim k_T^2/zp \sim zp\theta^2 \sim 1/\Delta t$$

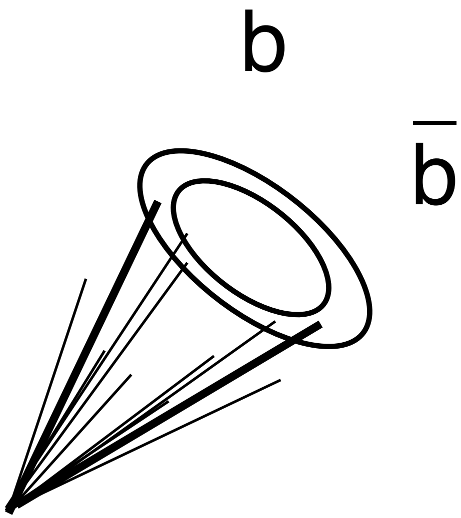
$$\Delta b \sim \theta_{ee}\Delta t > \lambda/\theta \sim (zp\theta)^{-1}$$

$$\theta_{ee}(zp\theta^2)^{-1} > (zp\theta)^{-1} \longrightarrow \theta_{ee} > \theta$$

Preliminary tests

Here is a simulation of Higgs production and QCD production of two b-jets boosted w.r.t. the lab frame.





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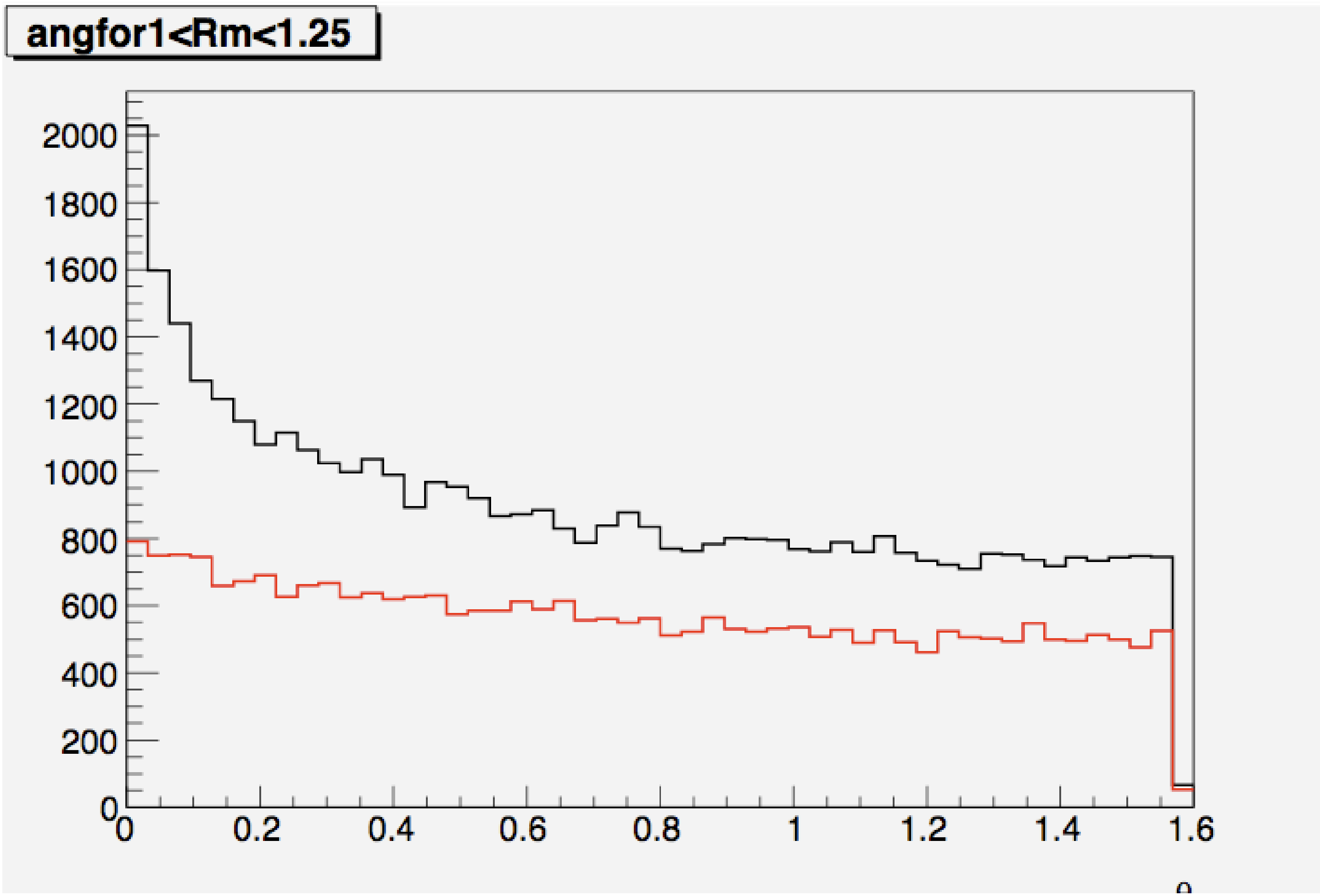
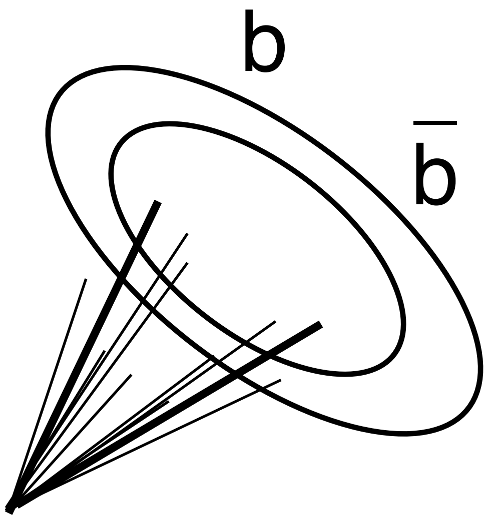


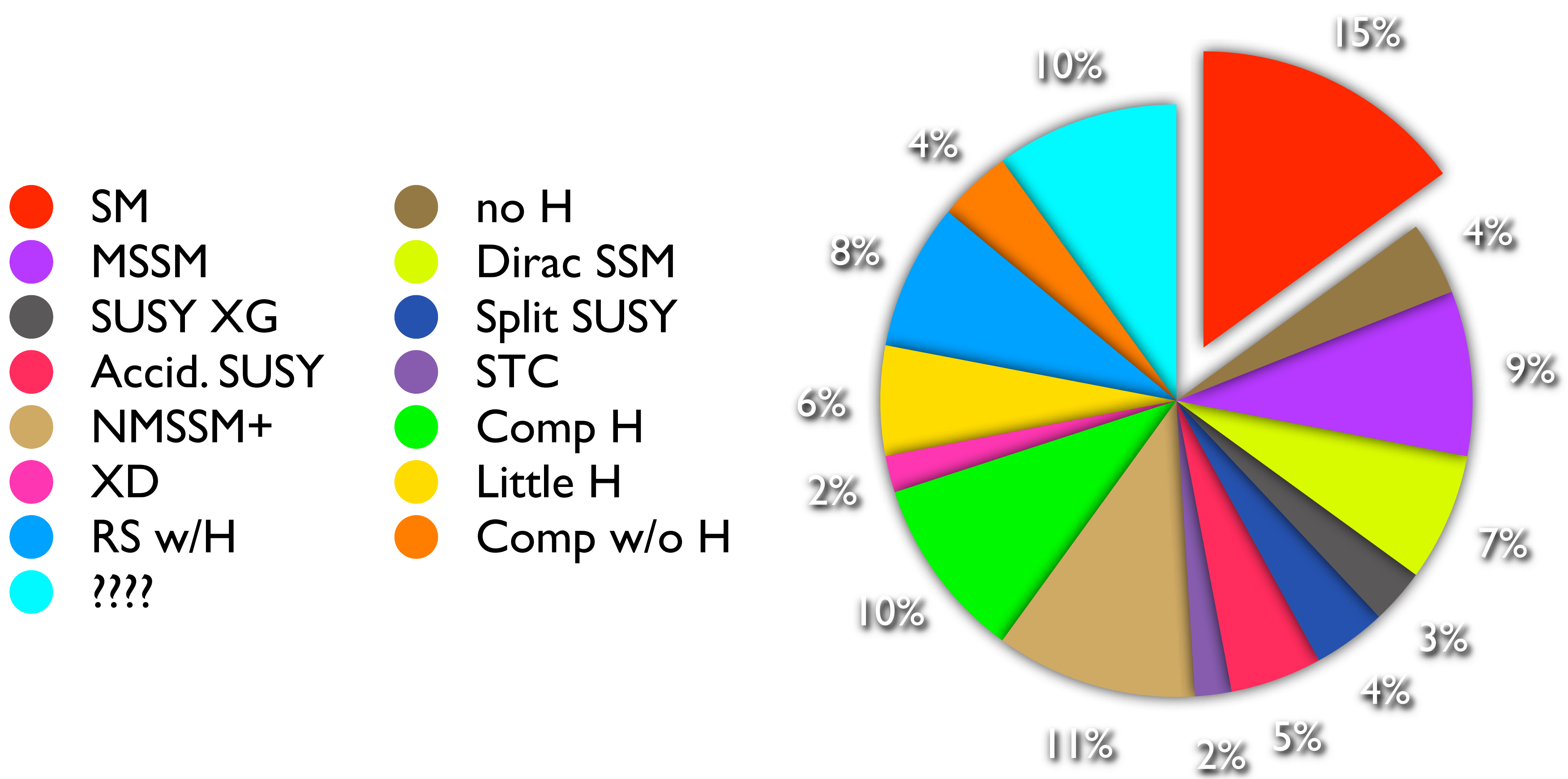


Conclusion

It has been 30 years since something unexpected happened at a collider

Conclusion

The Standard Model is our best guess



Conclusion

Theory strongly suggests physics beyond the standard model.

The Higgs is very susceptible to huge modifications in phenomenology

A broader range of search strategies is required to cover the possibilities for the Higgs

Excess...

Effects on Z-boson Data

LEP I made 17 million Z-bosons...

Precision Tests

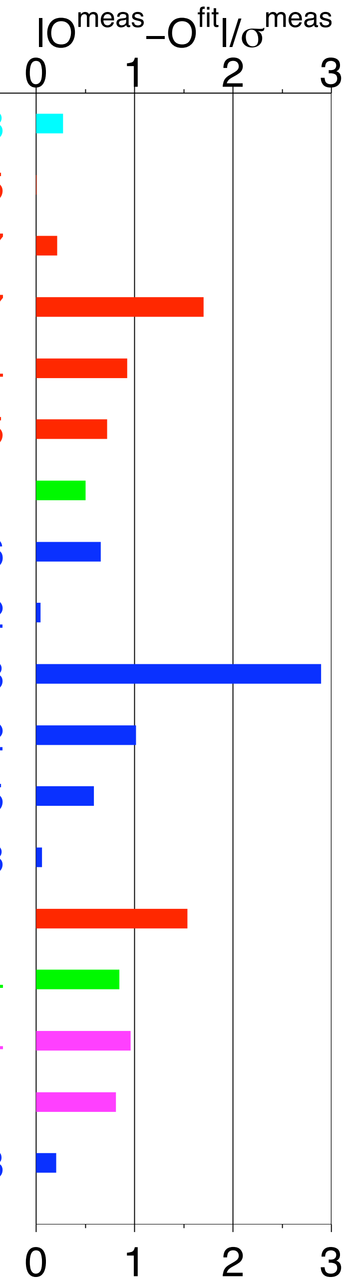
Precision measurements agree well

biggest discrepancy

$$\chi^2/\text{d.o.f.}=16.8/14$$

continuing updates

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



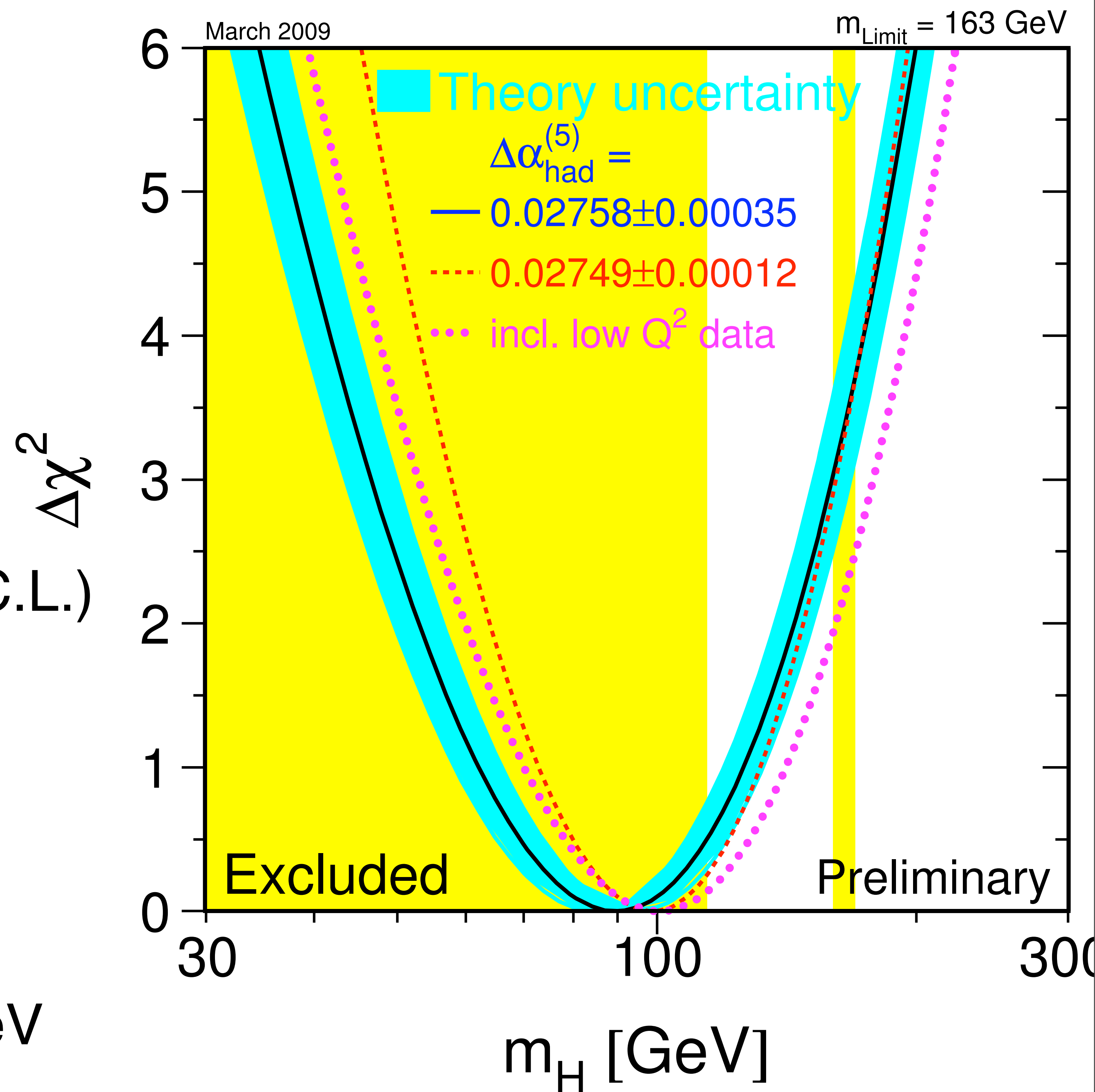
Higgs mass fit

90^{+36}_{-27} GeV

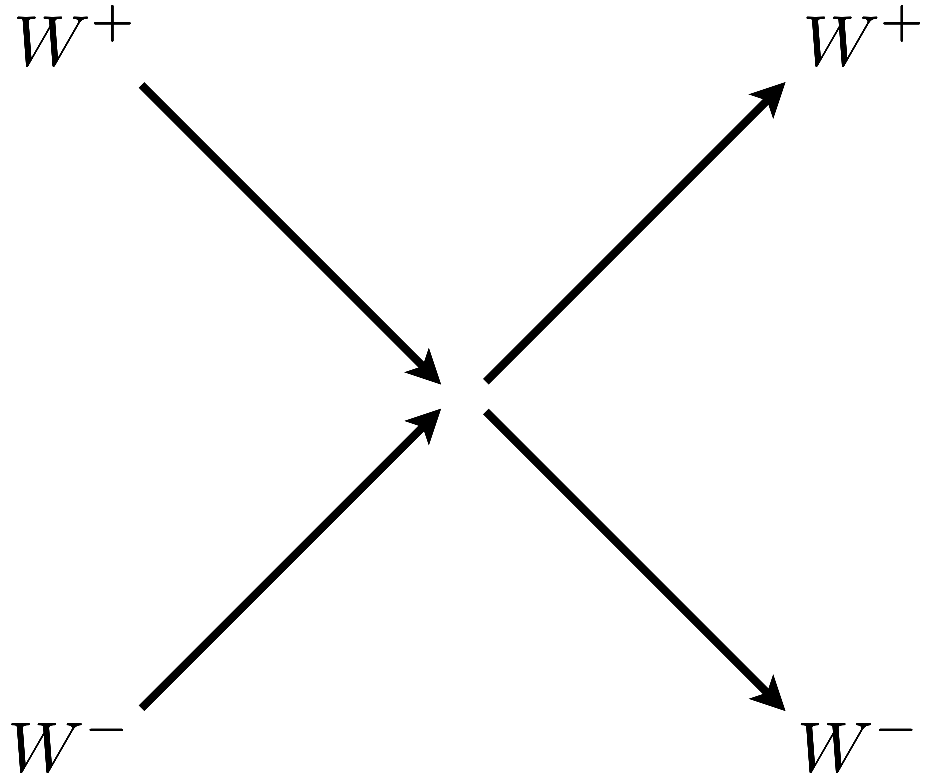
< 163 GeV (95% C.L.)

LEP II Bound:
> 114.4 GeV

Tevatron:
<160 or >170 GeV



The Higgs Completes the Standard Model

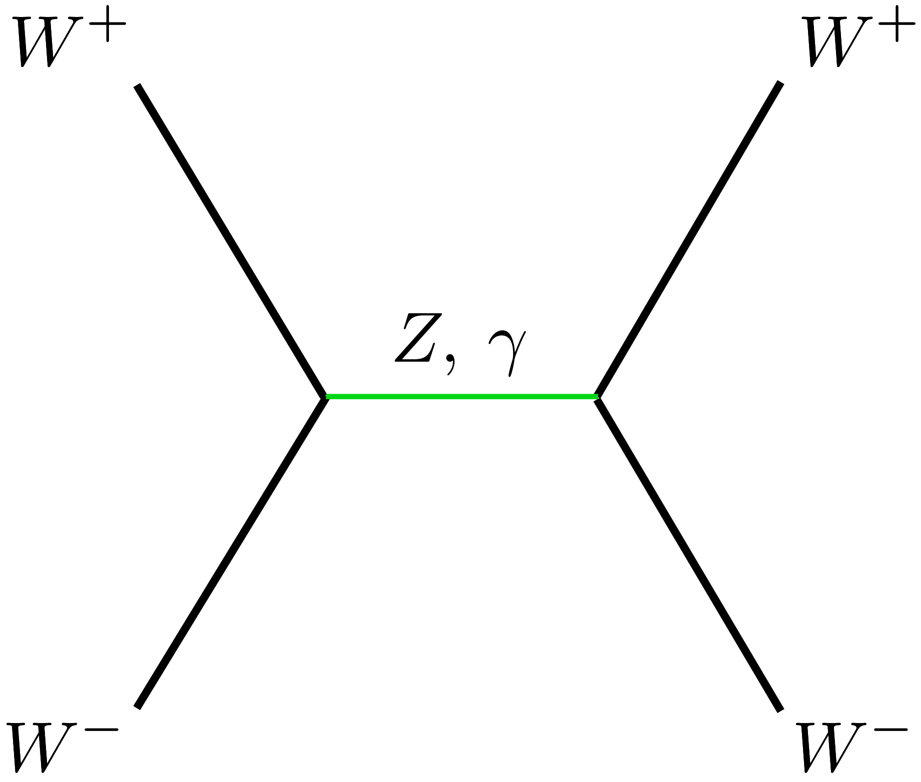


$$\lim_{E\to\infty} \mathcal{A} \propto E^2$$

At high energies, the probability of scattering is greater than one.

Theory breaks down at E ~ 1 TeV

The Higgs Completes the Standard Model



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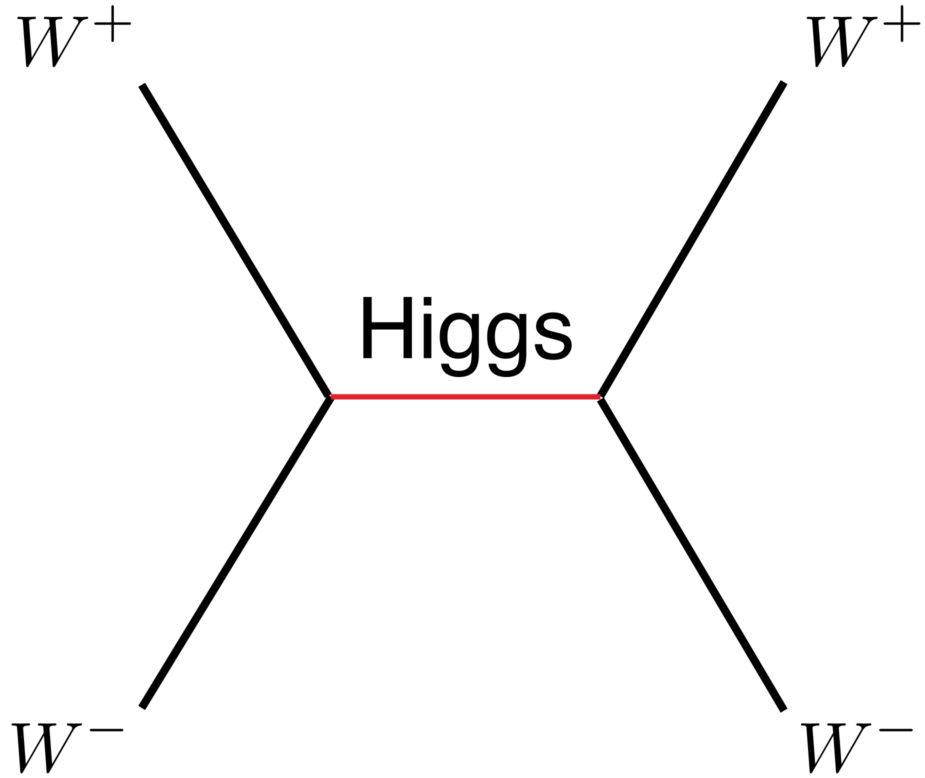

$$\lim_{E \to \infty} \mathcal{A} \propto \text{const.}$$

With the Higgs particle, the theory remains predictive.