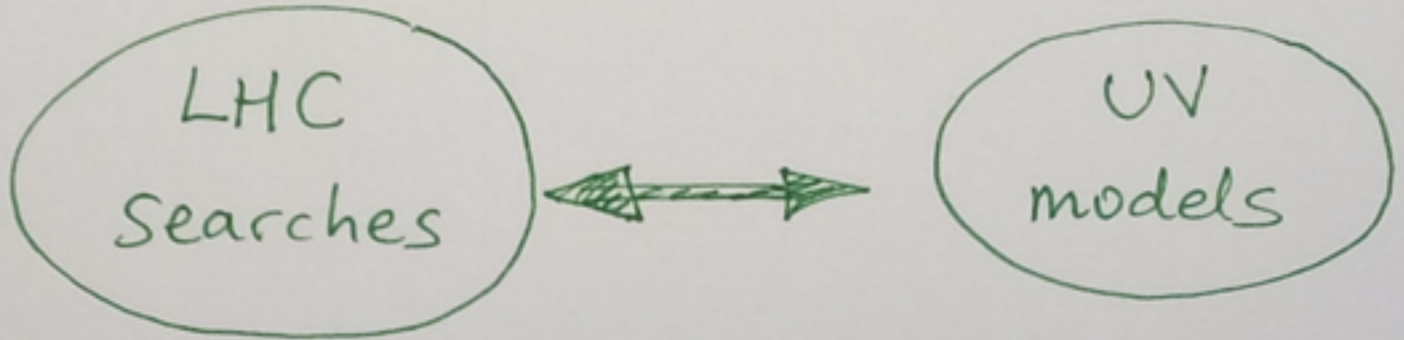
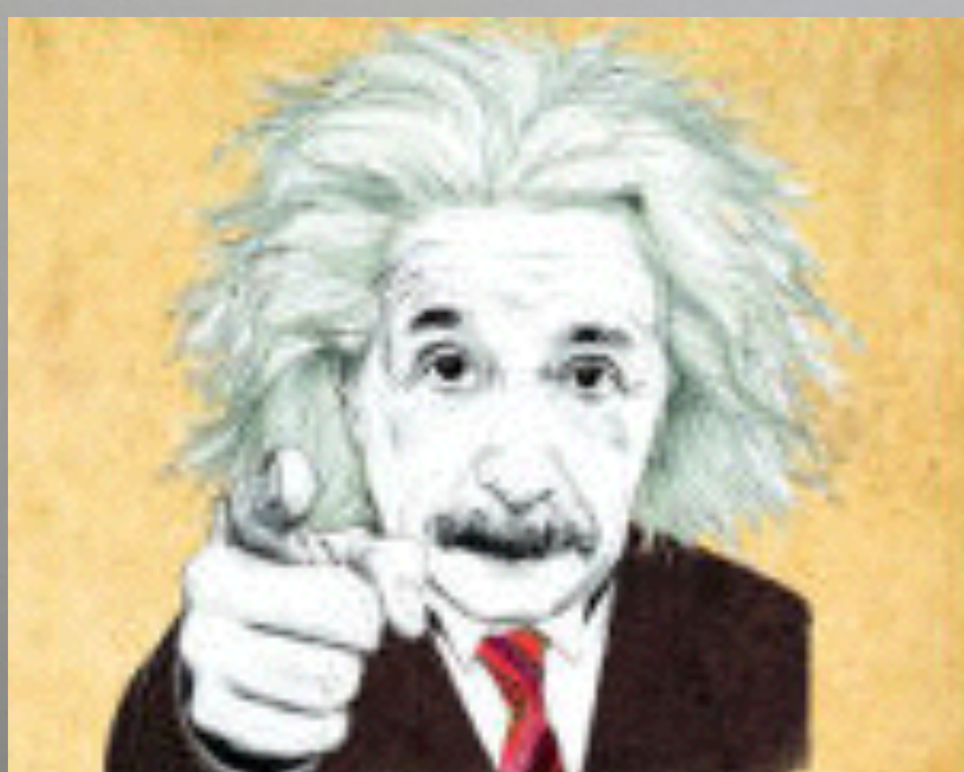
Models for the LHC & beyond

Veronica Sanz (Sussex)

MODELS FOR THE LHC & BEYOND



- Motivation : model, theory
- Search description : collider pheno
- Results : where do we stand



Hands-on, searches as a guide through models

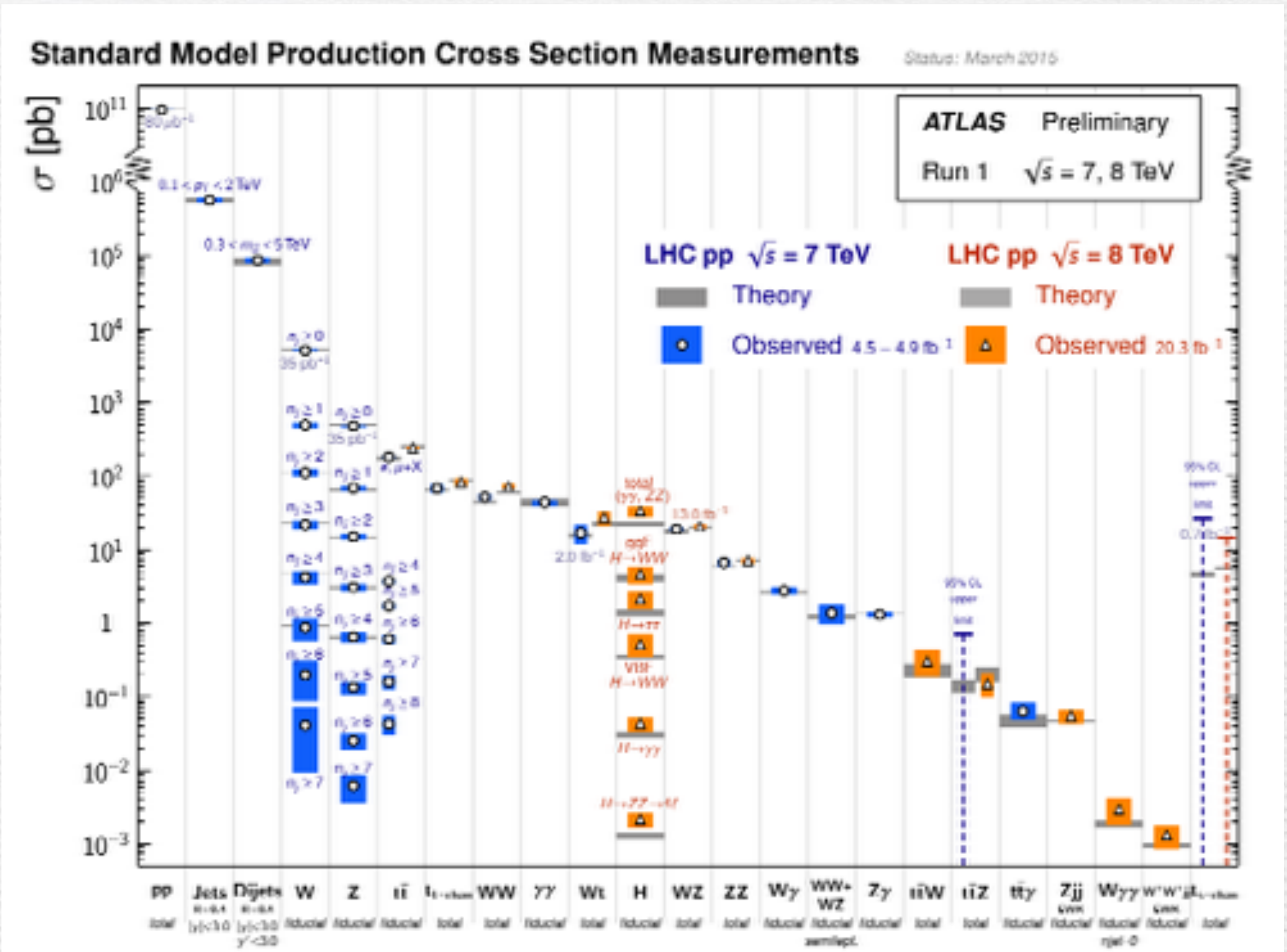
During these 50 mins

1. take lots of notes, hope to revise in the future (?)
2. ask lots of questions, engage and leave with ability to work in the subjelt.

Challenges

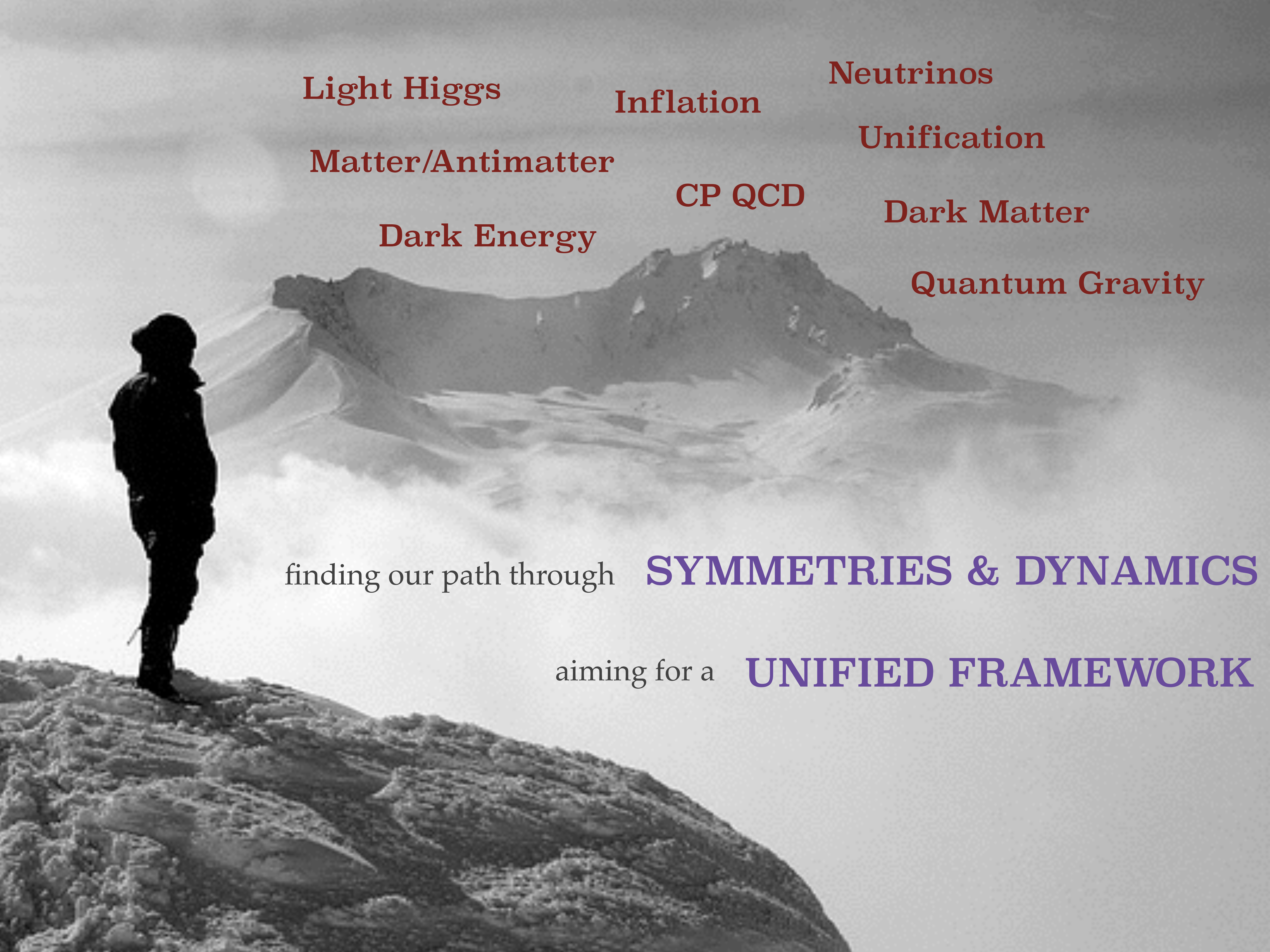
Standard Model of Particle Physics

Predictive, successful paradigm being tested to higher and higher precision at the LHC



Based on QFT, symmetries (global/gauge) and consistent ways to break them

Foundation from which we develop theories beyond the SM


Light Higgs
Inflation
Neutrinos
Unification
Matter/Antimatter
CP QCD
Dark Matter
Dark Energy
Quantum Gravity
finding our path through SYMMETRIES & DYNAMICS
aiming for a UNIFIED FRAMEWORK

Example of unified framework: Supersymmetry

Unifies concept of bosons and fermions

Light scalar bosons

Candidates for Dark Matter

Unification of strong/EM/weak forces

Matter/Antimatter asymmetry

Component of Quantum Gravity

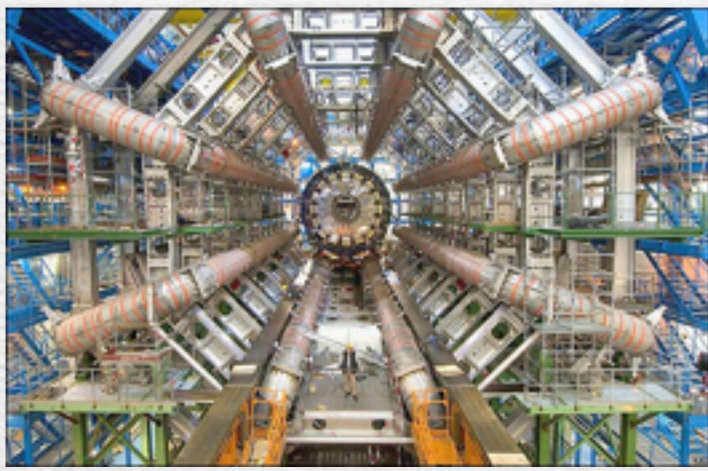
New mechanisms
Inflation, Neutrinos and Dark Energy

The discovery of SUSY at LHC
first step to understand many
aspects of Nature

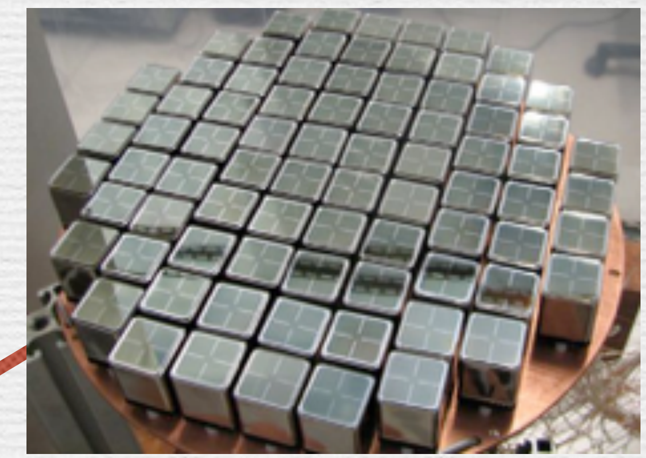
Example of multidimensional approach: Dark Matter

THEORY
Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…

COLLIDERS

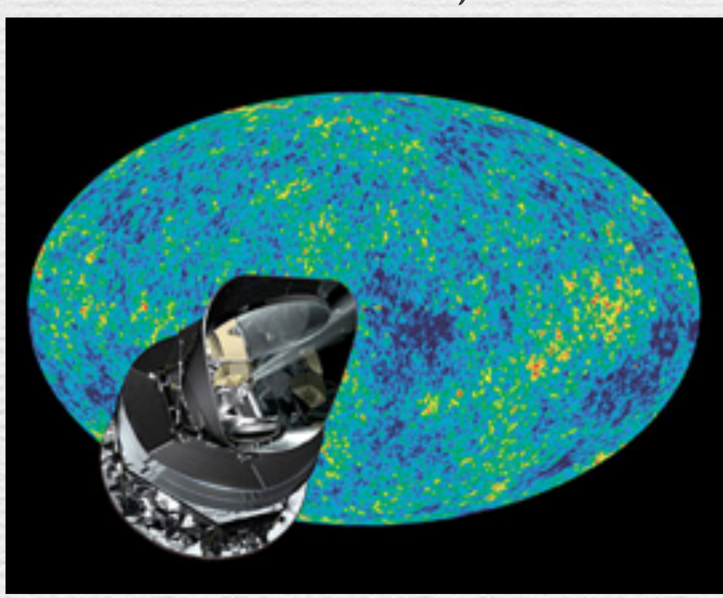


DIRECT DETECTION

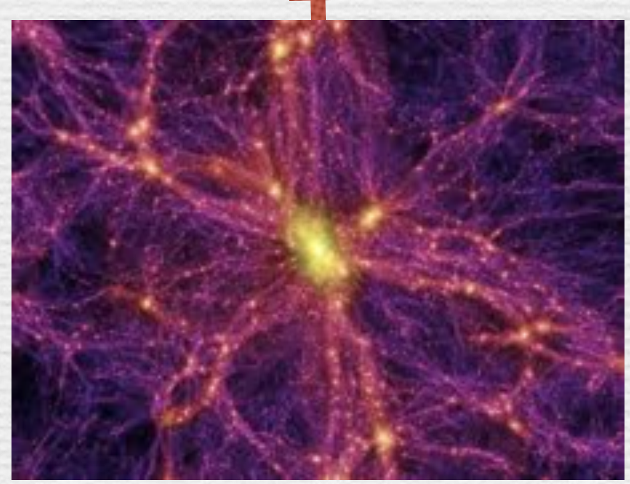


DARK MATTER

CMB: relic, tilt



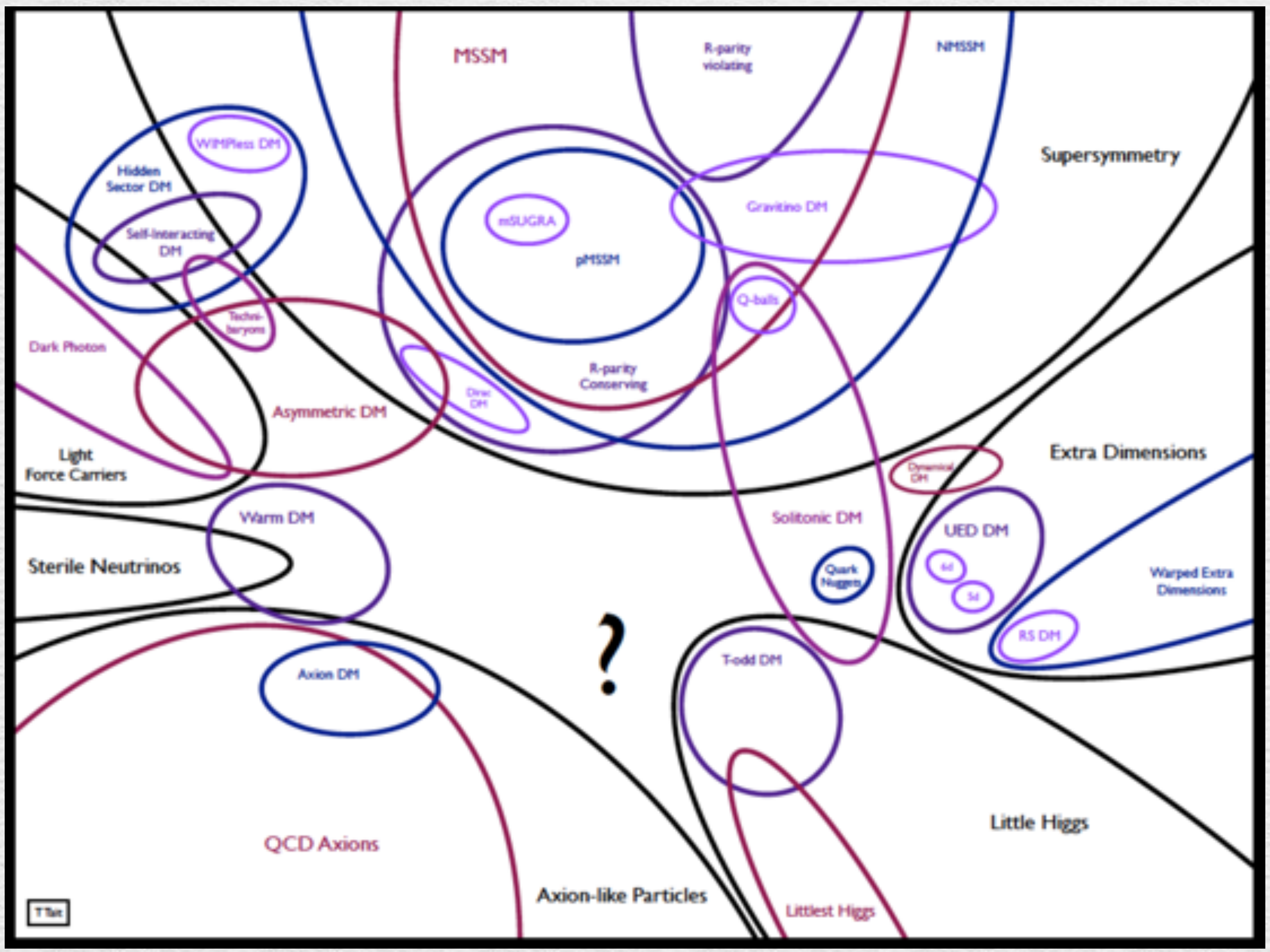
INDIRECT DETECTION



SIMULATIONS

The landscape

Each problem in the SM generates a plethora of new ideas
Example: **Dark Matter**



Thanks to Tim Tait

A snapshot of models for Dark Matter

Popular models = linked to solutions to other problems in the SM

Discovery to characterization of Dark Matter leading to new discoveries

Techniques in the landscape

Cancellations → Symmetries (often broken) → Relations Consistency: new states, new dimensions

e.g. Higgs potential

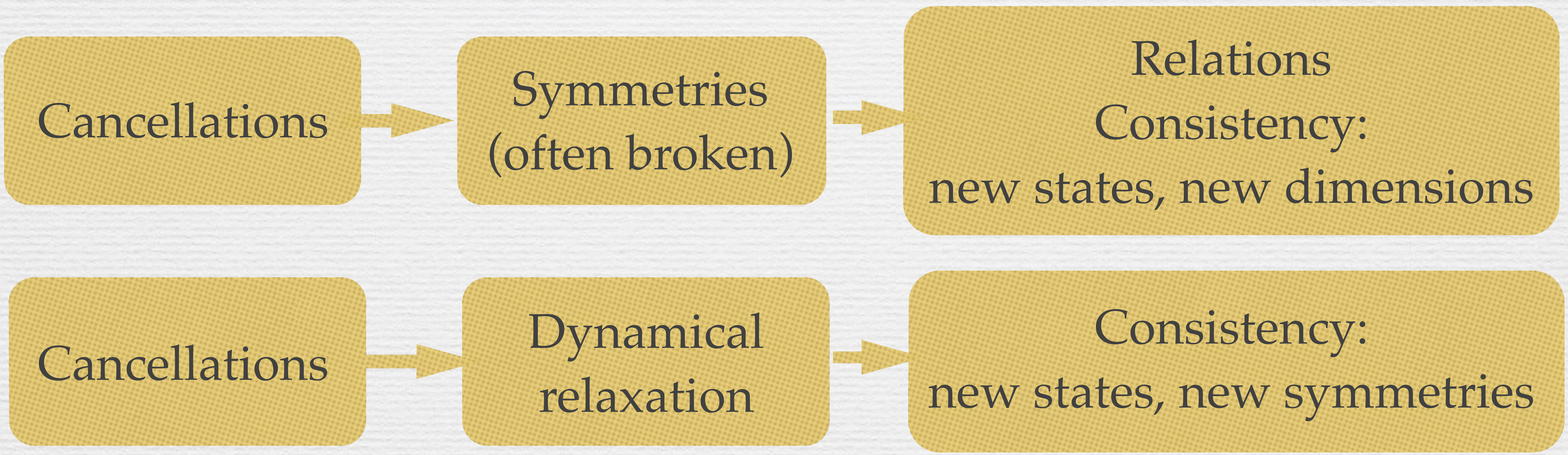
Global->Goldstone

Higgs as a Composite Higgs
new resonances W', T…

Global symmetry breaks spontaneously,
new massless scalars called Goldstone bosons
symmetry not exact-> pseudo-GBs
potential *protected* from UV physics

Higgs could be a pseudo-GB
of a spontaneously broken global symmetry
its potential (mass, interactions)
protected by Goldstone symmetry

Techniques in the landscape



e.g. QCD's CP problem

axion

coupling to photons, astro/cosmo
light shining through walls

Techniques in the landscape

Cancellations → Symmetries (often broken) → Relations; Consistency: new states, new dimensions

Cancellations → Dynamical relaxation → Consistency: new states, new symmetries

Stability → Symmetries or kinematic → Relations; rare processes

e.g. Dark Matter

new parities
continuous global symmetries

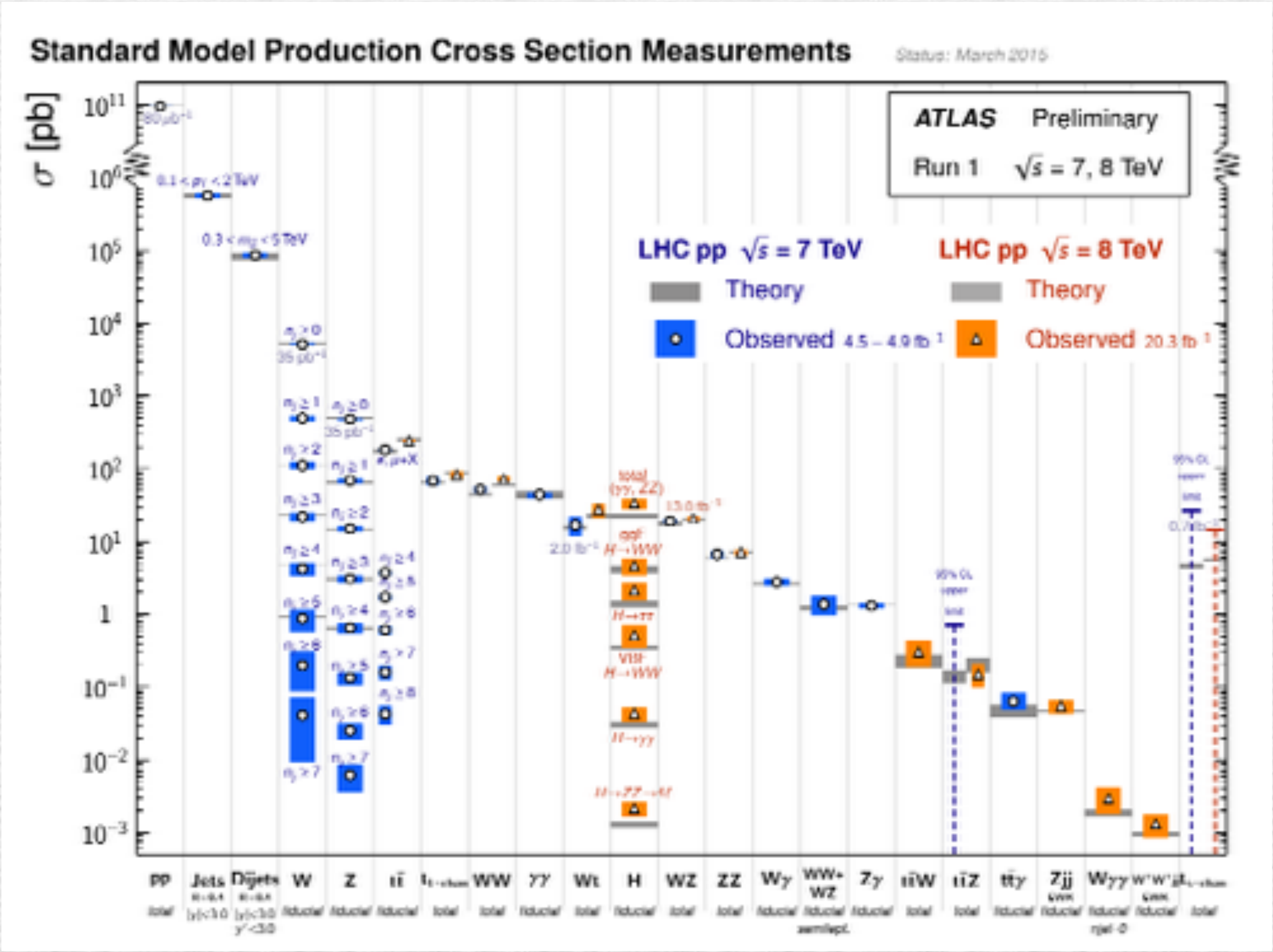
DM pair produced
if decay, displaced vertices

Techniques in the landscape

Weak coupling → Perturbation theory → Improvements: resummations, higher loops

e.g. SM gauge interactions

predictivity, testing small deviations possible



Techniques in the landscape

Weak coupling → Perturbation theory → Improvements: resummations, higher loops

Strong coupling → Non-perturbative perturb. another parameter, symmetries, dualities → lattice SUSY Holography, gravity

e.g. QCD at low-Energies
Composite Higgs,
Technicolor

lattice gauge theories, Seibergology, AdS/CFT,
instantons, large-N

Techniques in the landscape

Weak coupling → Perturbation theory → Improvements: resummations, higher loops

Strong coupling → Non-perturbative perturb. another parameter, symmetries, dualities → lattice, SUSY, Holography, gravity

Complexity → Effective Field Theories, Deformations from known theory, matching between theories → Separation of scales, universal behaviour based on symmetries

Techniques in the landscape

e.g. Flavour physics,
Higgs EFT

Deal with relevant degrees of freedom
Explore many known and unknown models in one go

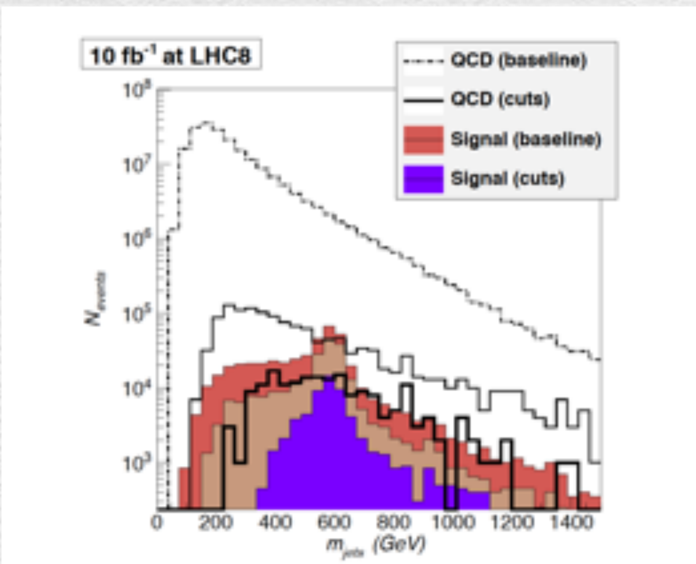
Complexity → Effective Field Theories
Deformations from known theory
matching between theories → Separation of scales
universal behaviour
based on symmetries

Today’s lectures

1. LHC: basic information
2. The Higgs

LHC: the experiment

Nowadays, pheno (collider, DM…) is very sophisticated



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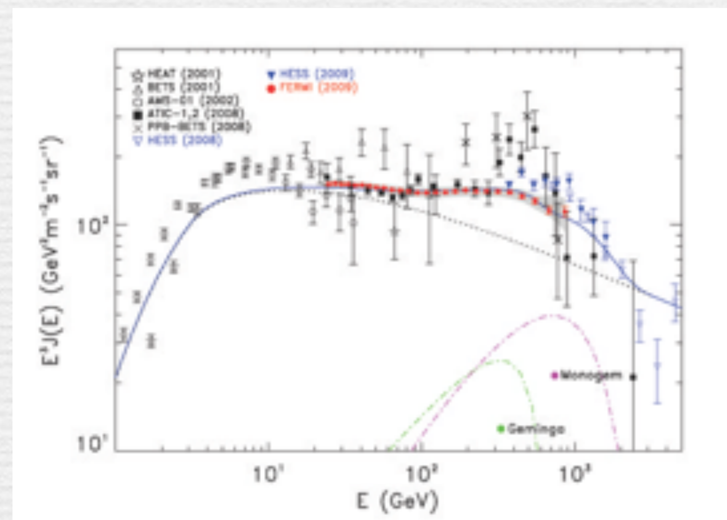


1305.0456

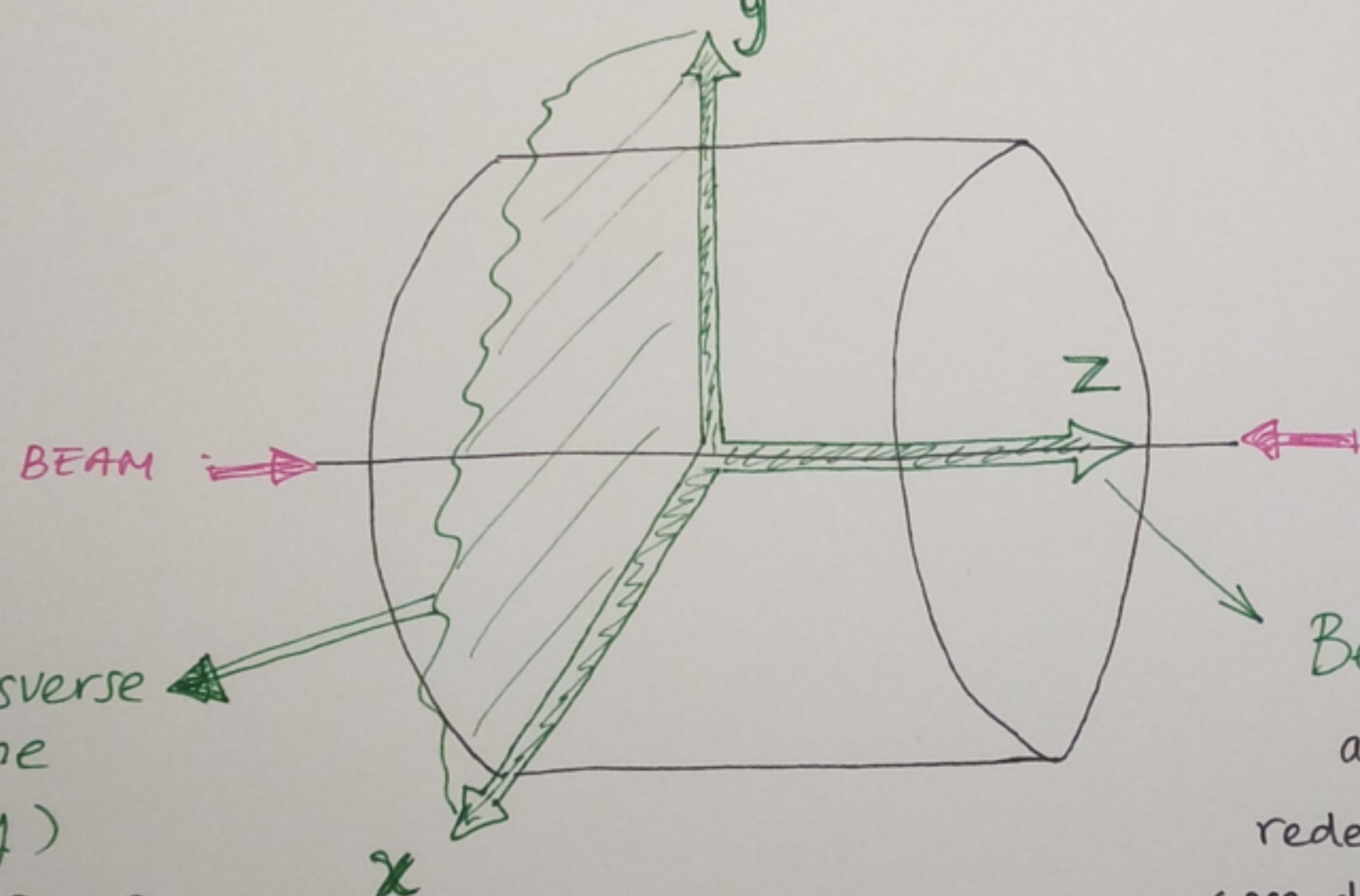
Why? experiments are running now! impact on models: full understanding of the capabilities

State-of-the-art, to remain for years to come

Run2: 100-120 ifb
Run3: 300 ifb
Run4 & 5 ends 2033

First we need to build some LHC vocabulary…

LHC: GEOMETRY



Transverse plane (x, y)

$E_T^2 = p_T^2 + m^2$

$\vec{p}_T = (p_x, p_y, 0)$

angle φ

Beam axis z

angle θ

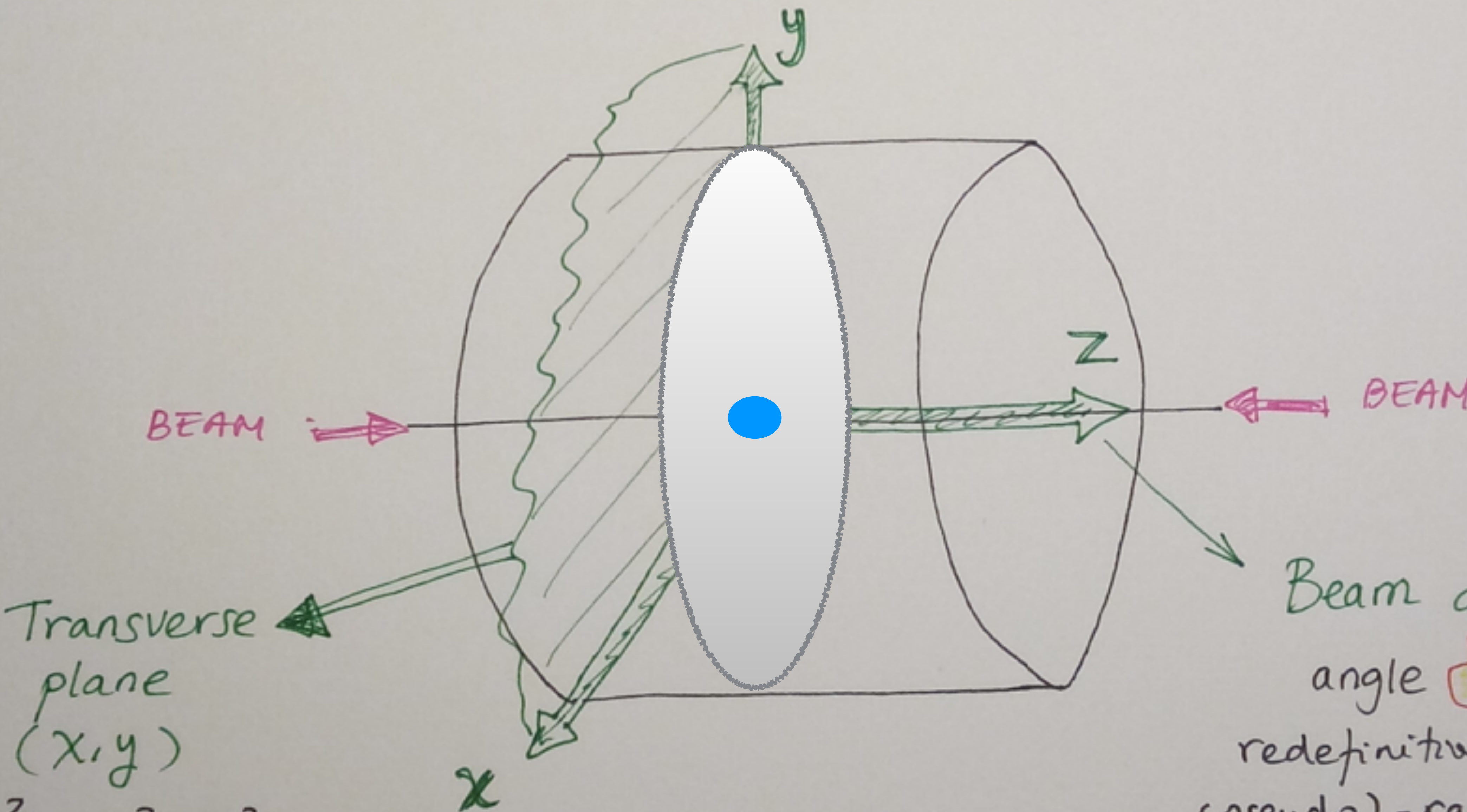
redefinition as (pseudo)-rapidity

$\eta = -\ln \tan \theta/2$

CENTRAL $\eta \to 0$ good coverage

FORWARD $\eta \to \infty$ bad coverage or "granularity"

LHC: GEOMETRY



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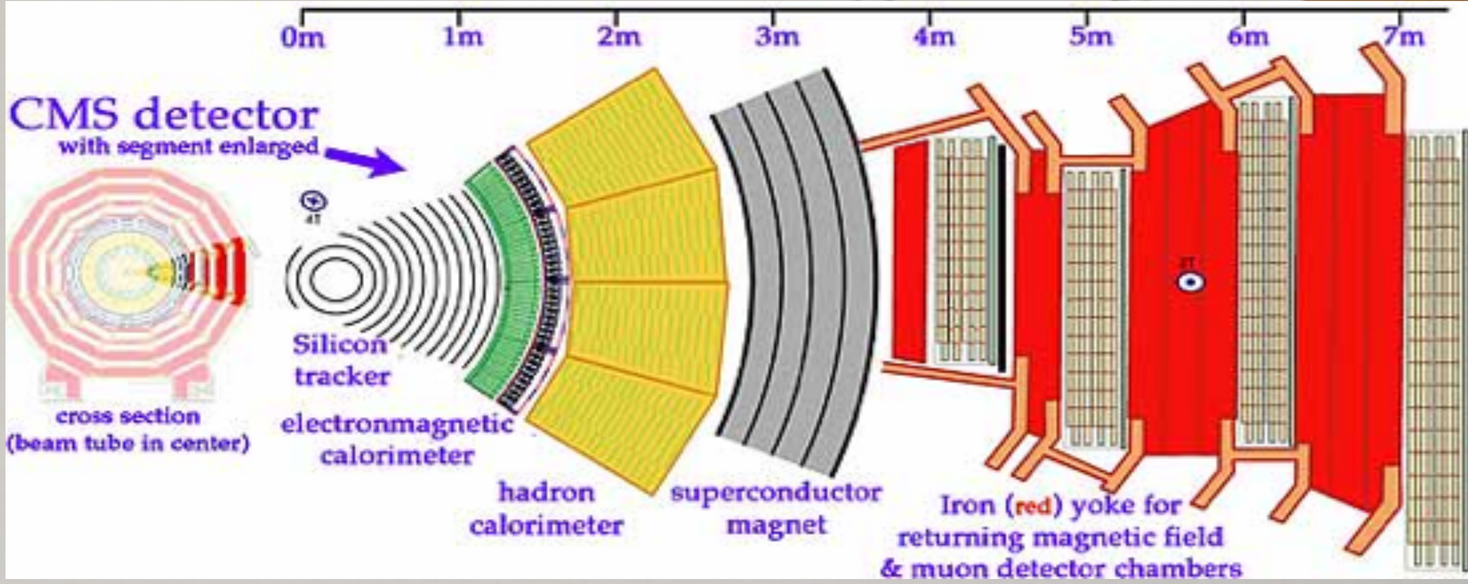
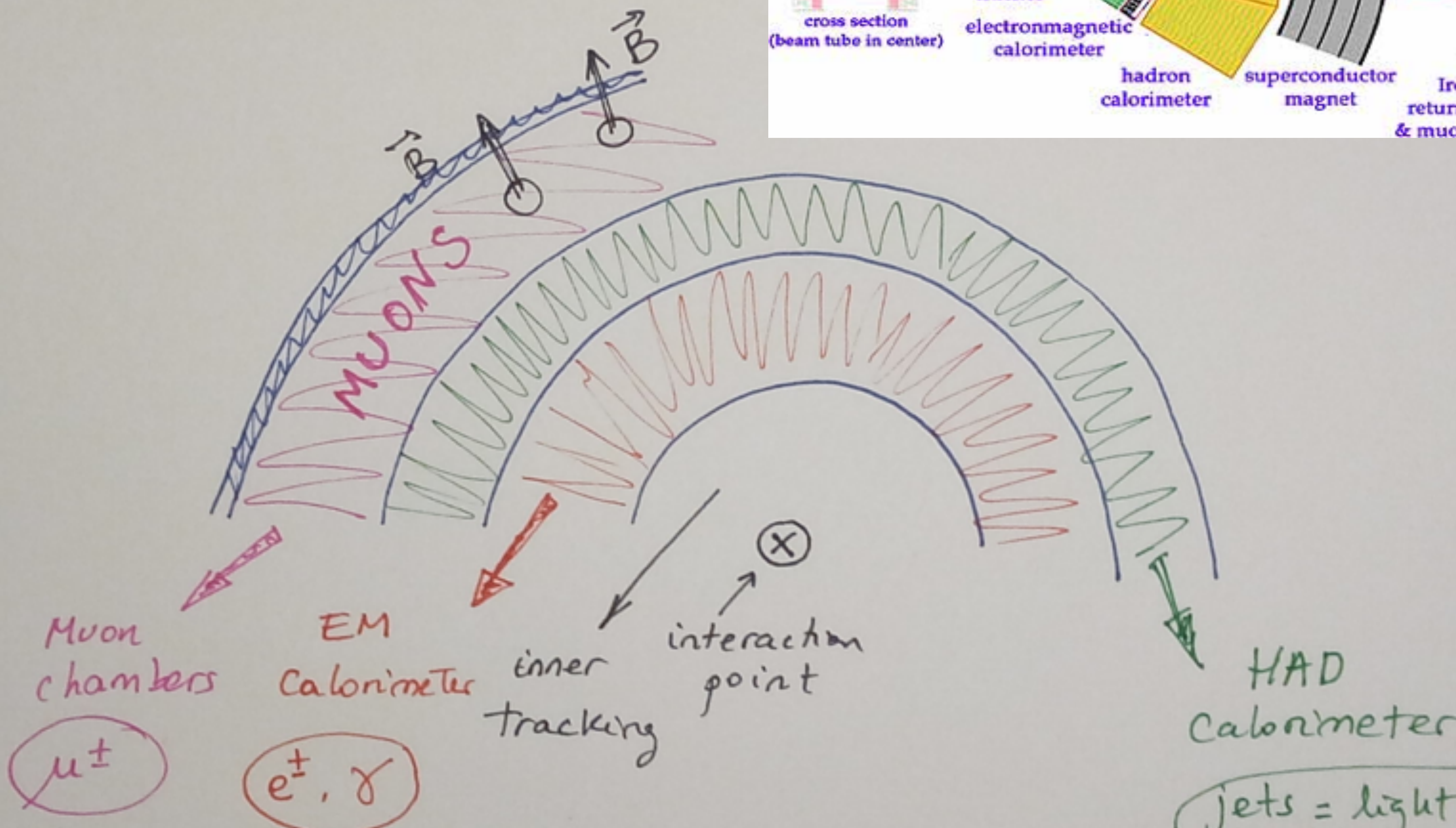
The detector



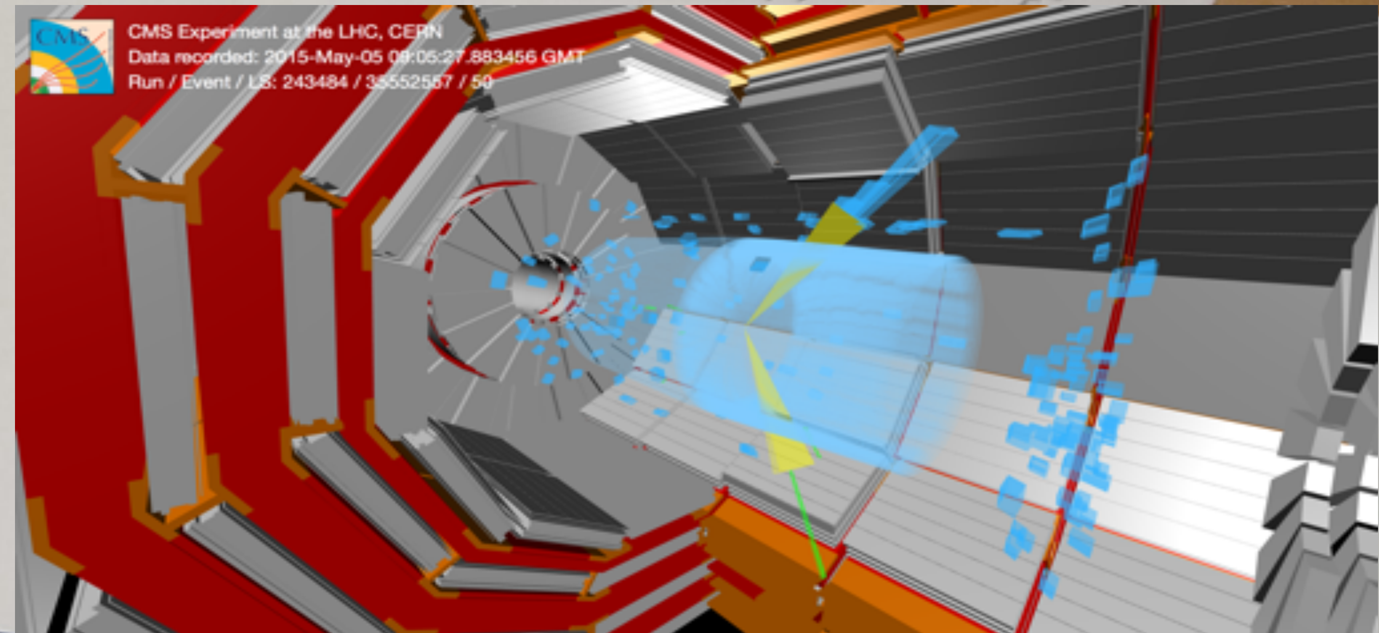


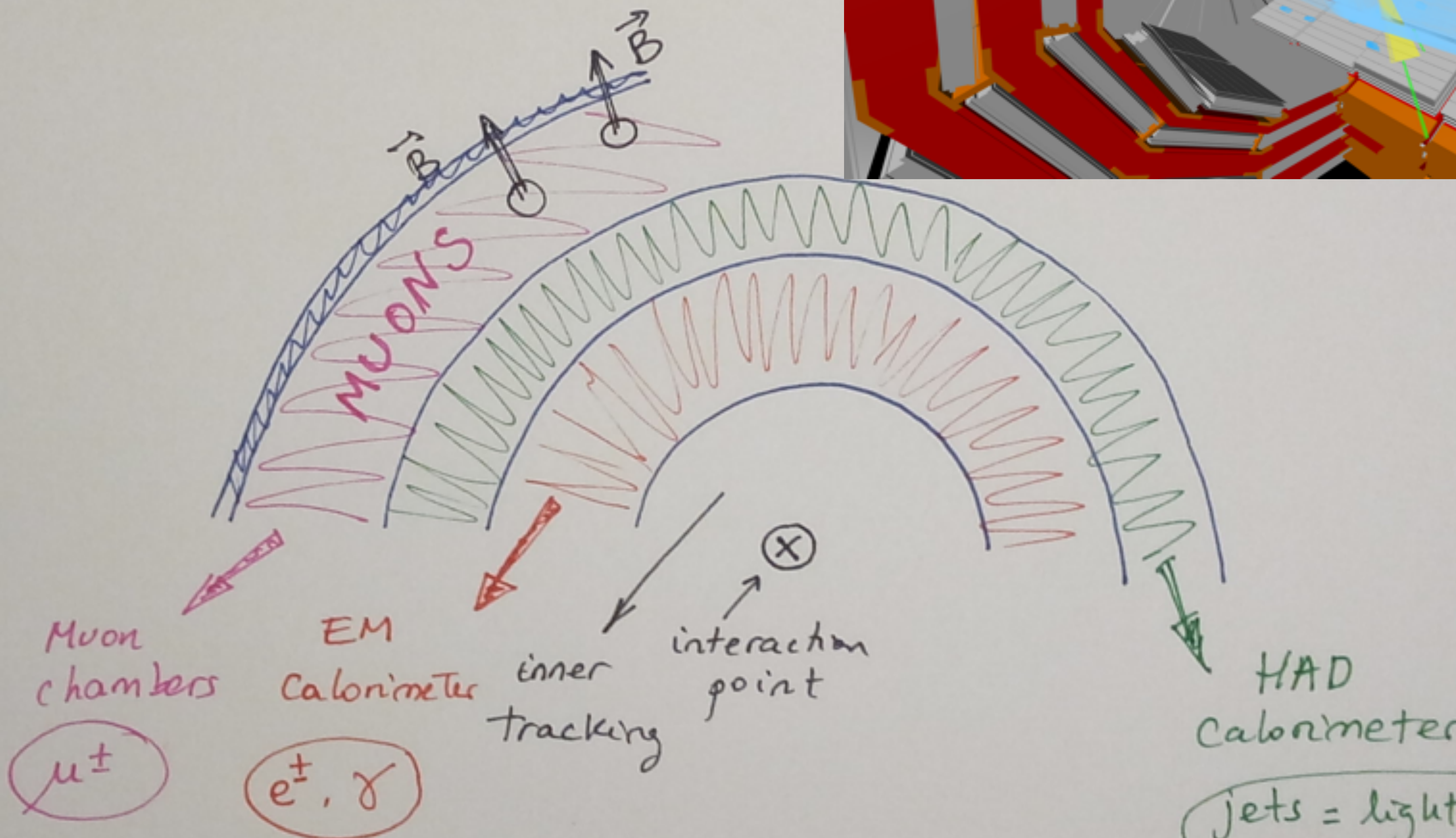
jets = light quarks and gluons

⊕ b-jets : displaced vertices
τ-jets, c-jets

⊕ top → b + W
Higgs → many ways

The detector





⊕ b-jets : displaced vertices
τ-jets, c-jets

⊕ top → b + W
Higgs → many ways

The Higgs

HIGGS SEARCHES

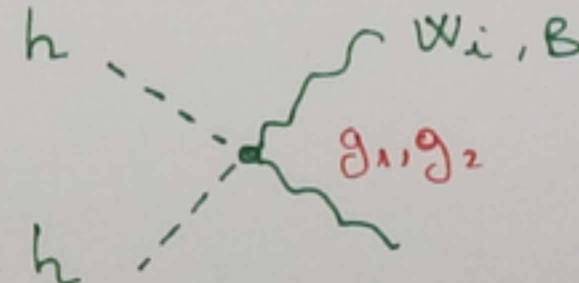
The Higgs was discovered in 2012, was it *the* SM Higgs?

in the SM $\Phi = \begin{pmatrix} -iG^+ \\ iG^0 + h + v \end{pmatrix}$ is a doublet of $SU(2)_L$ and $Y = 1/2$

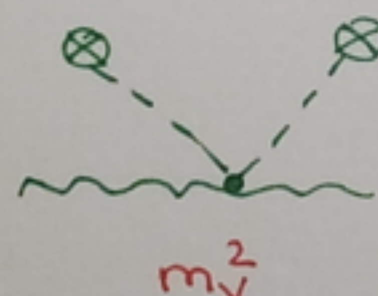
$\mathcal{L}(\Phi^\dagger \Phi)$ preserves $SU(3)_c \times SU(2)_L \times U(1)_Y$

before EWSB

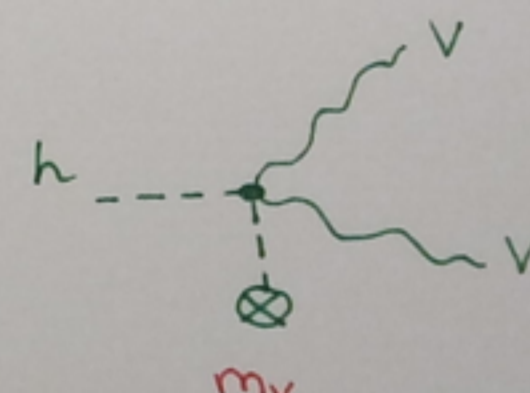
$|D_\mu \phi|^2 \Longrightarrow$

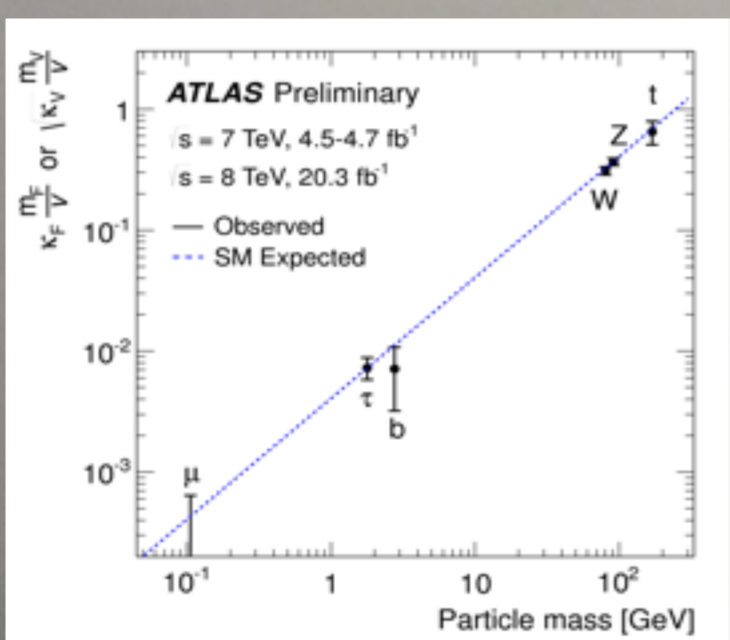


after EWSB

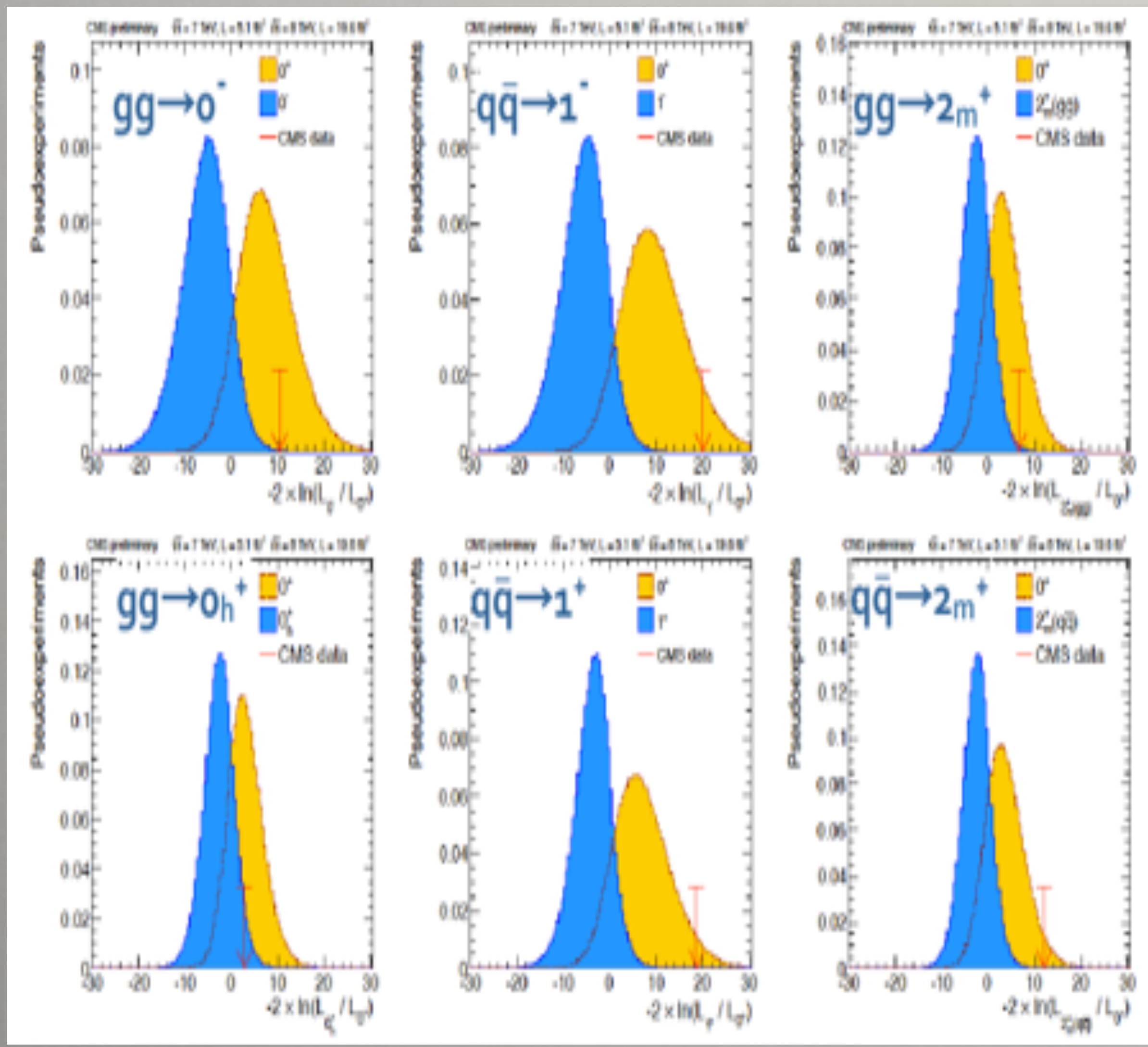


related to





Higgs is (MAYBE) the first fundamental scalar in Nature



Scalars in QFT are a difficult creature

Quantum corrections, e.g.

δm_ϕ^2 :

$\propto M_F^2$

as compared with

- fermions $\mathcal{L}_\psi \supset m_\psi \bar{\Psi} \Psi$

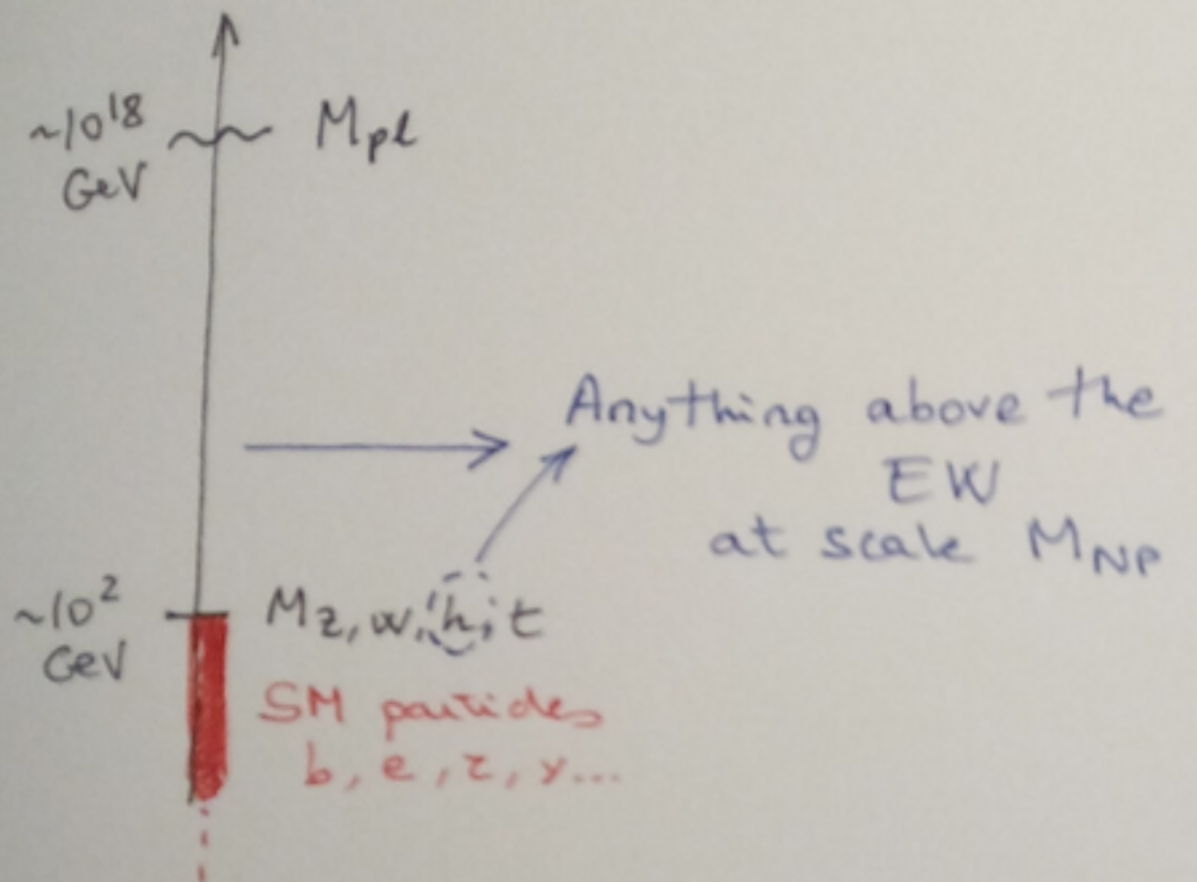
  symmetry: $\psi \to e^{i\alpha} \psi$

  corrections: $\delta m_\psi \propto m_\psi$

- gauge bosons $\mathcal{L}_{A_\mu} \not\supset m_A^2 A_\mu A^\mu$

  by symmetry: $A_\mu \to A_\mu - \partial_\mu \alpha$

NATURALNESS: Naturally, the scalar as heavy as the highest particle or phenomena it couples to. Higgs is 125 GeV.



$\delta M_h^2 \sim M_{NP}^2$ →

- **either** nothing above EW scale — DESERT
- **or** M_h^{phys} is kept low via:

① fine-tuning

$$M_{phys}^2 \simeq M_{bare}^2 + \delta M_Q^2$$

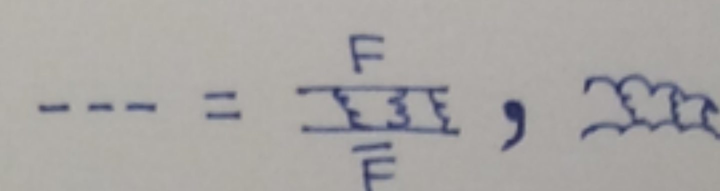
small = huge − huge

e.g. $(10^2)^2 = M_{bare}^2 - M_{pl}^2$

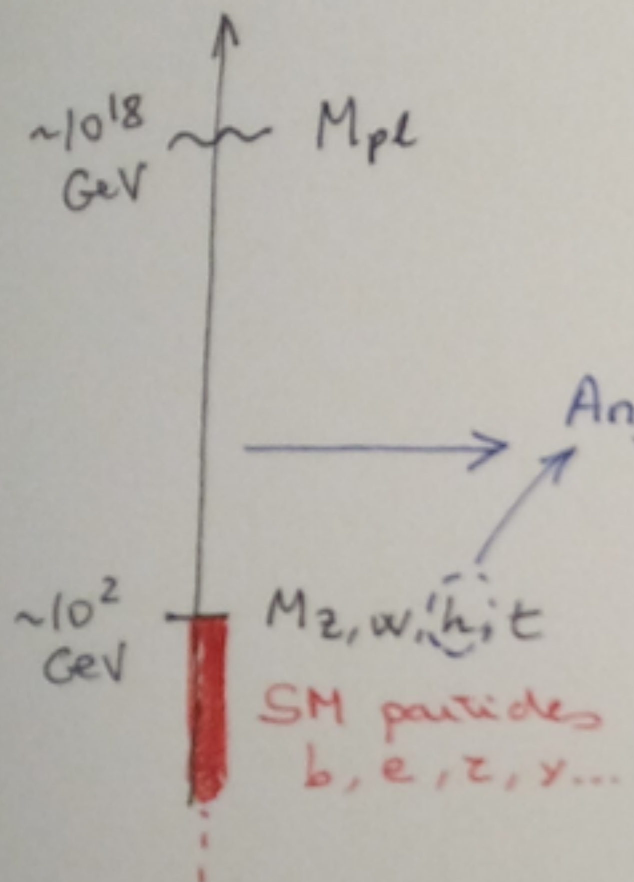
② symmetries

$\delta M_h^2 \propto$ parameter that breaks the symm.

③ dynamics — compositeness



Scalar = bound state of other fermions or gauge-fields



Anything above the EW at scale M_{NP}

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DESERT

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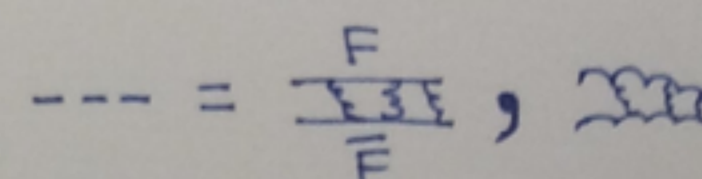
3. dynamics compositeness



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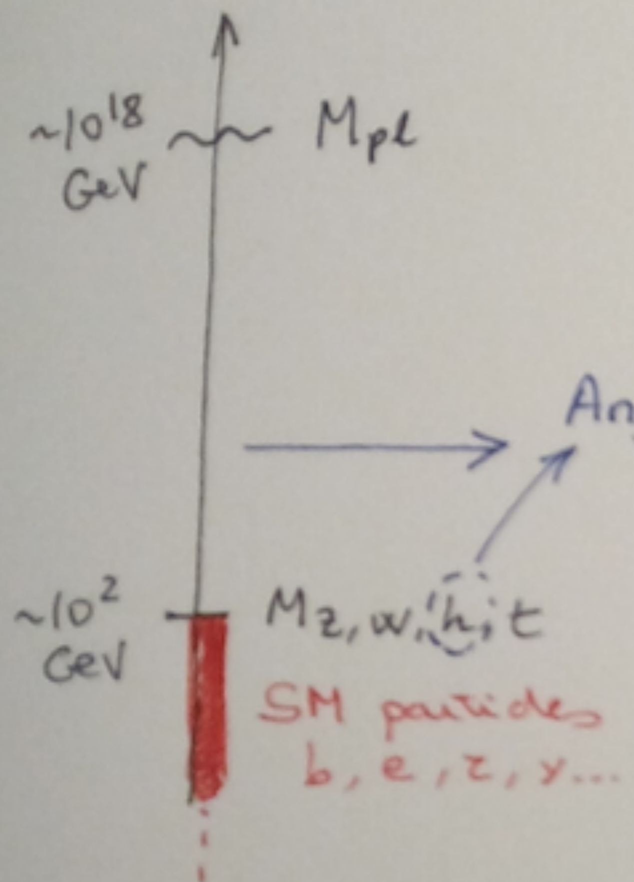

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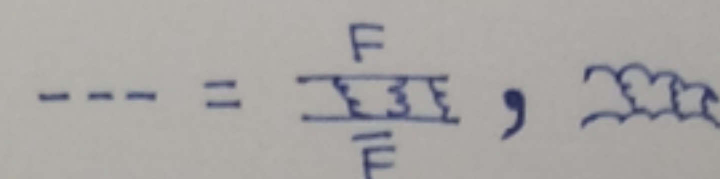


Scalar = bound state of other fermions or gauge fields

SUPERSYMMETRY (SUSY)

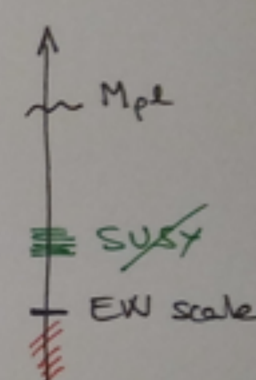
scalar ⟷ fermion

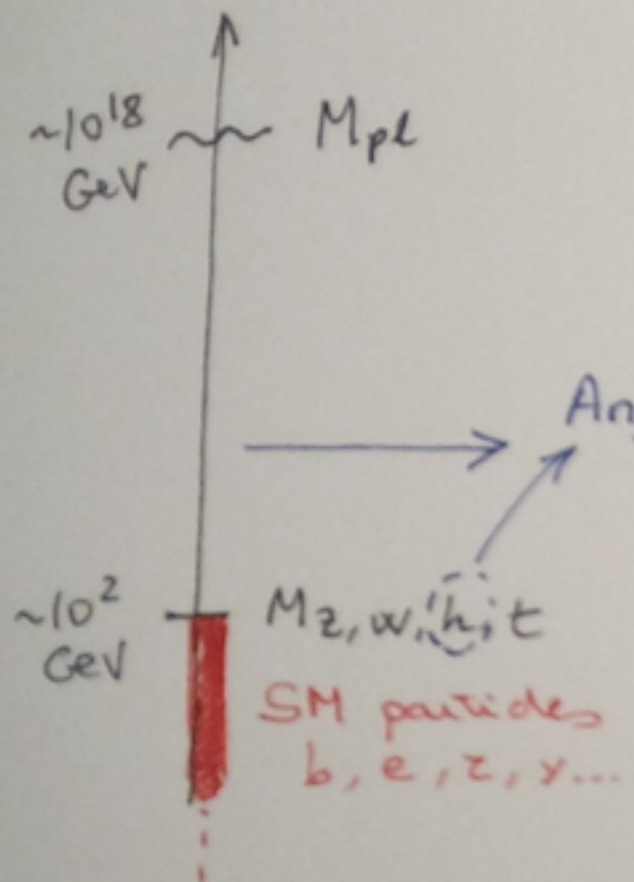
↙ inherits protection ↗ chiral symm

SUSY multiplet : $(H, \tilde{H})$ — higgs & higgsino

$\delta_Q M_h^2 = 0$ if SUSY exact

$\delta_Q M_h^2 \propto M_{SUSY}^2$





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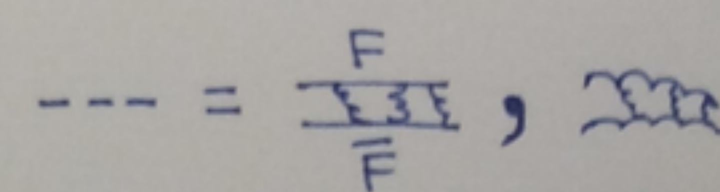

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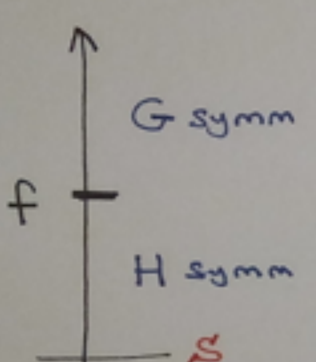
GOLDSTONE SYMM (AKA COMPOSITE HIGGS)

Global symm breaking $G \to H$ at scale f

new massless scalars : Goldstone bosons

symmetry : $S \to S + c$ shift symm.

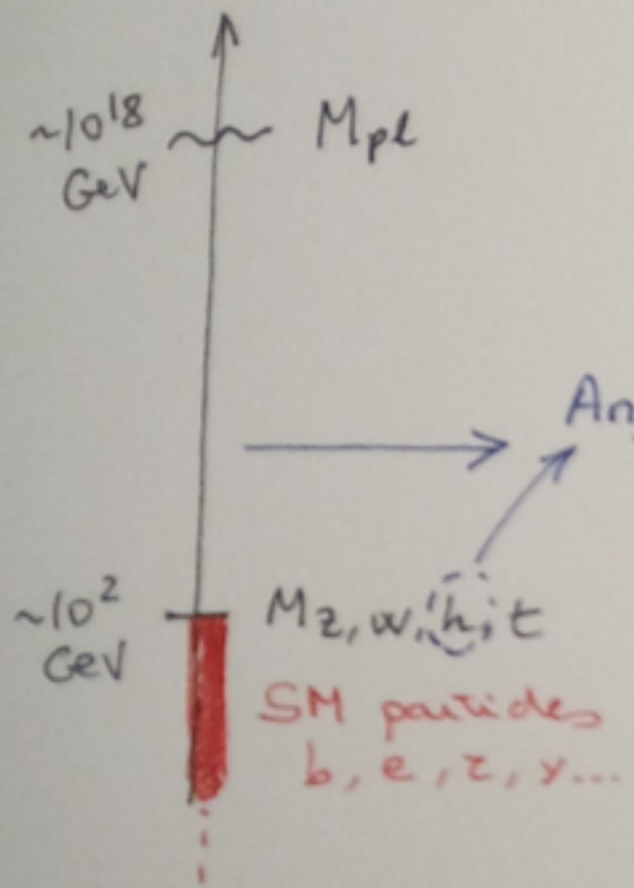


adding small explicit breaking of G generates a potential for S, small mass

Natural $m_S \sim g \cdot f \ll f$

g: parameter explicit breaking

f: only scale in the problem



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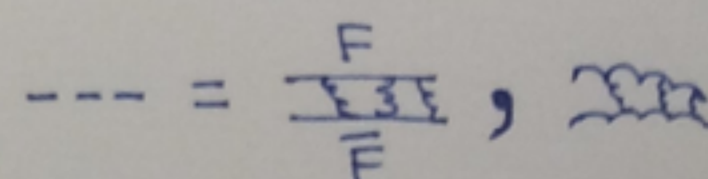
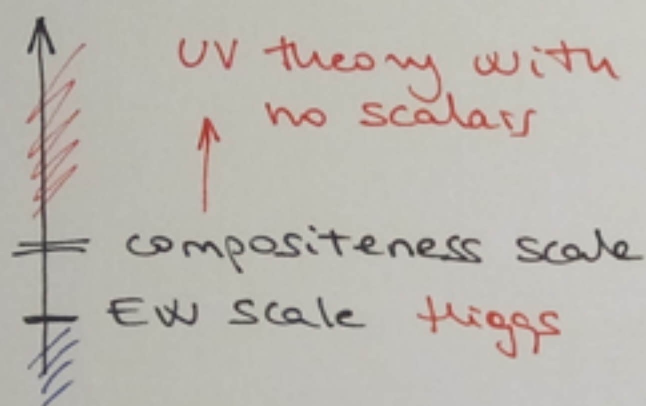


Scalar = bound state of other fermions or gauge fields

COMPOSITENESS (AKA COMPOSITE HIGGS)



As we probe Higgs @ higher energies Higgs is no longer a dof (e.g. pions in QCD)

even composite Higgs needs a symm protection (SUSY, Goldstone, scale ...)

otherwise $M_h \sim M_{other\ bound\ states}$ we haven't seen

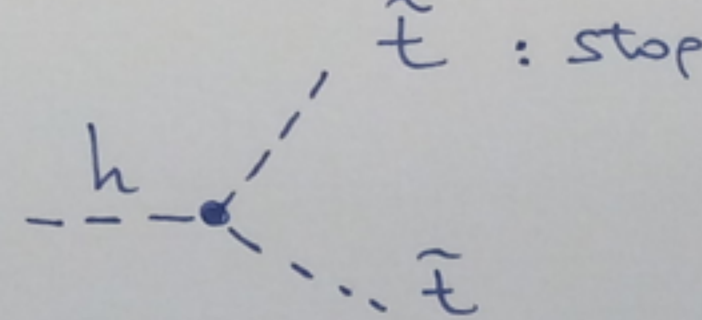
All these symmetry/dynamical protections for the Higgs lead to

① Scale of breaking/compositeness
~ close to the EW scale
(otherwise → fine-tuning again!)

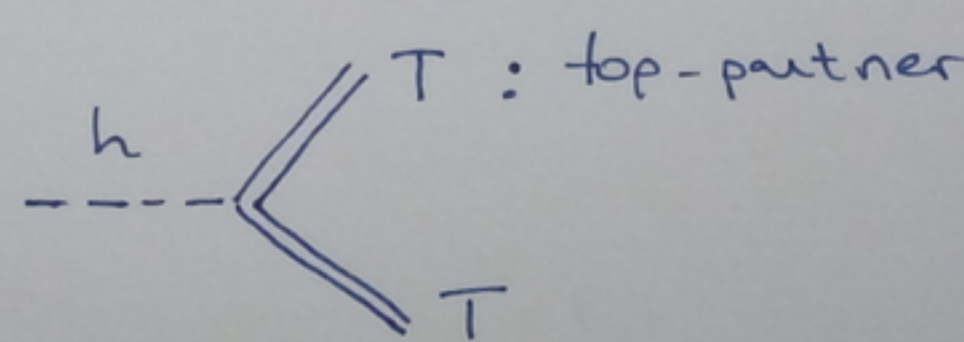
② New resonances, strongly coupled to the Higgs, at that scale

e.g.

SUSY



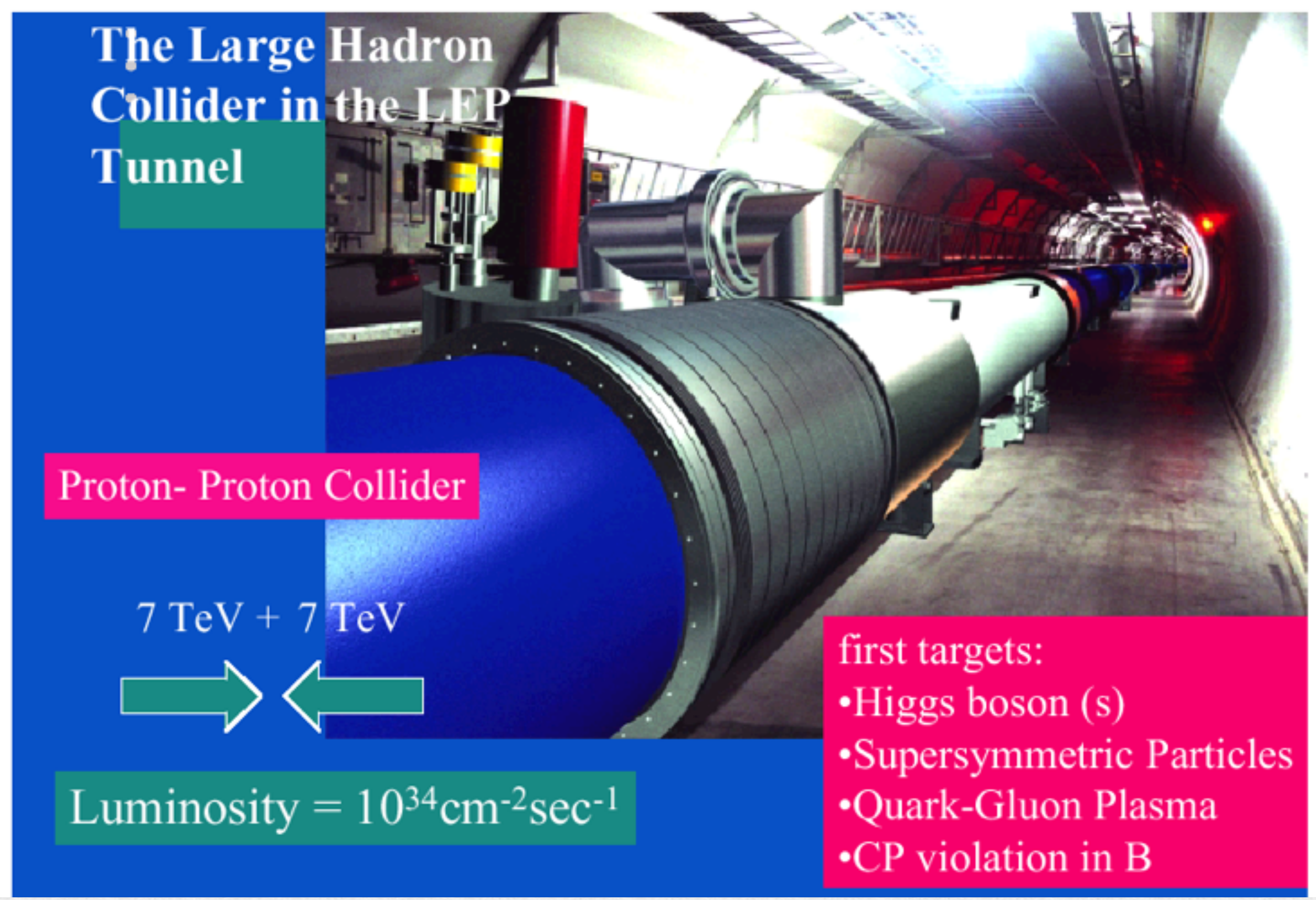
COMPOSITE HIGGS



③ Deviations of Higgs behaviour from SM.

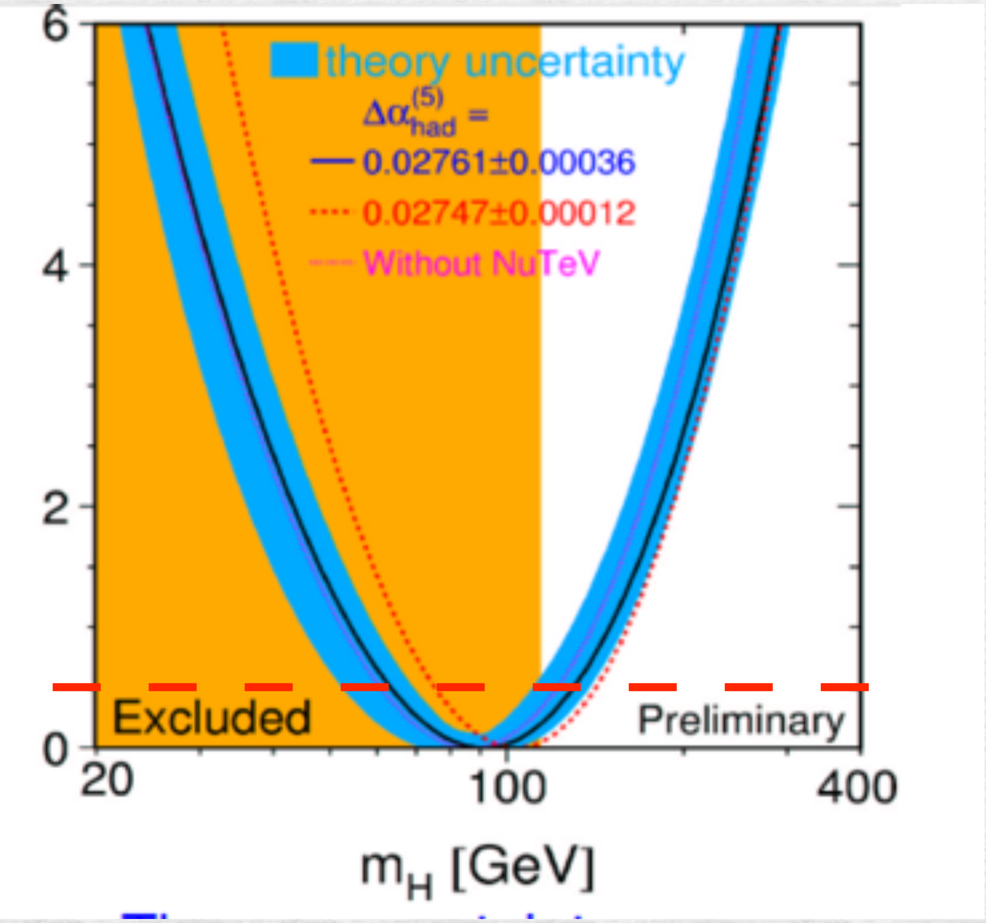
Naturalness: a qualifier

There was a clear case for the LHC



From CERN's education webpage, back before 2010

There was a clear case for the LHC



back in 2000's

EWSB via Higgs
missing piece

EWPTs: light Higss or
something rather similar

unitarization of WW scattering
something had to be around the
EW scale

And there is a clear case for BSM

Evidence

Dark Universe, neutrinos, baryogenesis

And there is a clear case for BSM

Evidence

Dark Universe, neutrinos, baryogenesis

but not of where/what BSM is

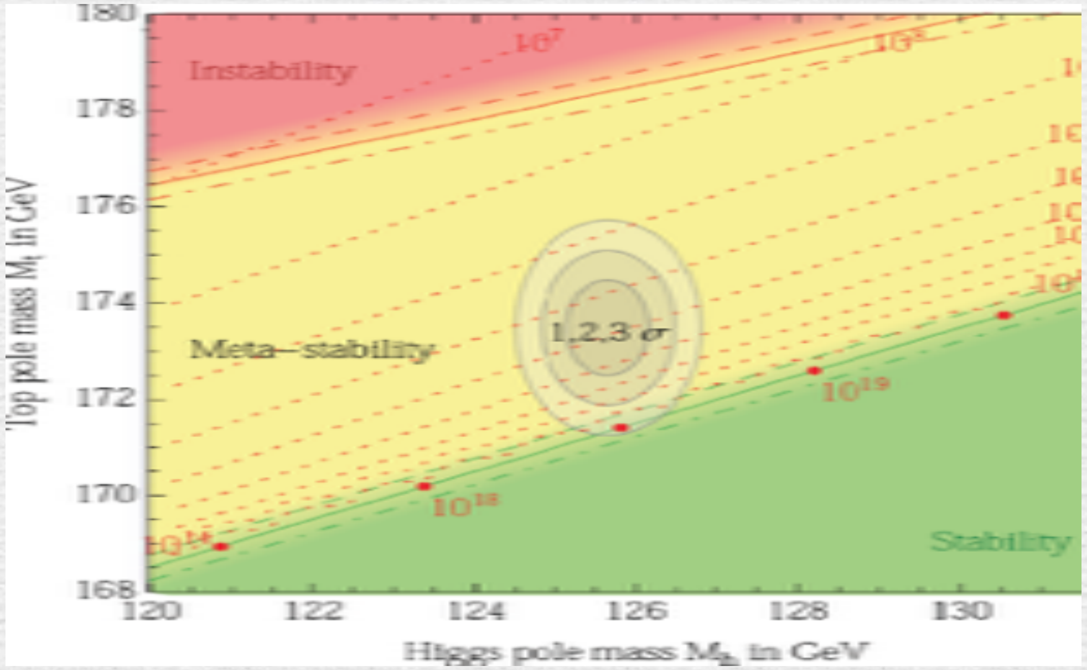
aesthetical arguments as naturalness/tuning are not on the same footing as violation of unitarity

precision tests are perfectly happy with no new physics at the EW scale

BSM models

(Unfortunately)

Higgs is not *evidence* for new physics



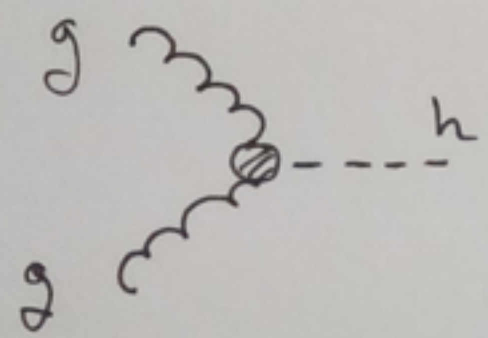
but a strong case for it comes from naturalness

As physicists, we must develop theories which *could*

The Higgs at the LHC

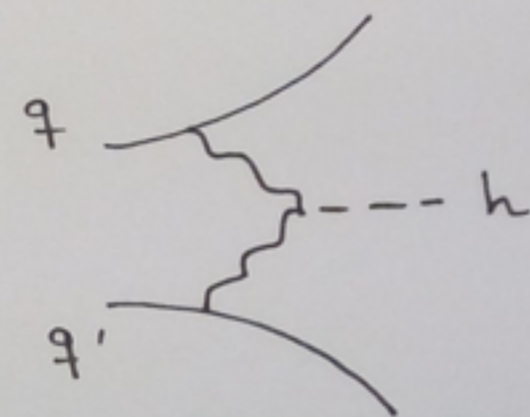
Higgs @ LHC : how do we search for it?

We produce it

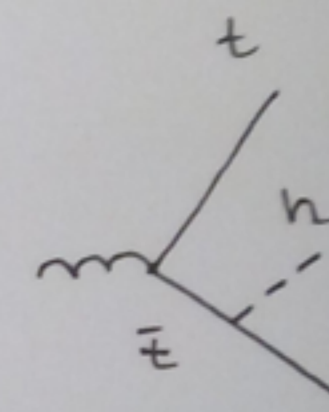


GLUON FUSION

HV



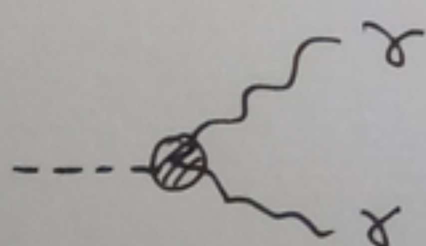
VECTOR BOSON FUSION (VBF)



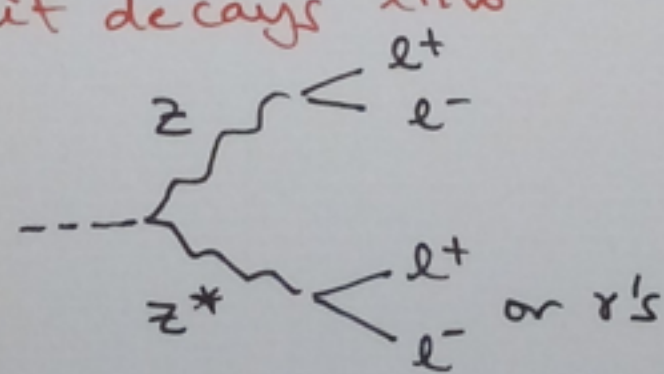
ttH

and then it decays into

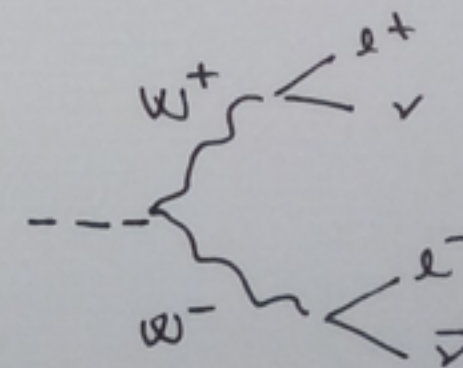
GAUGE BOSONS



rare, but clean

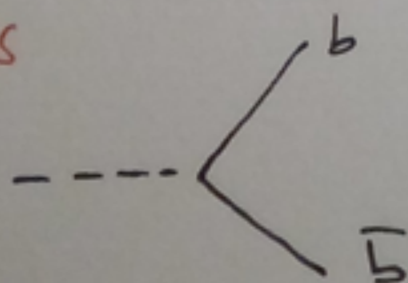


2L or 4L

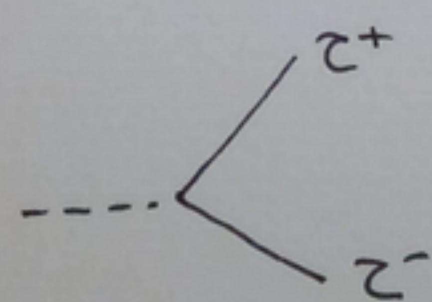


2L

FERMIONS



b-jets, only in HV



τ-jets, leptonic τ's

backgrounds to hadronic final states are enormous

HV, V goes into leptons

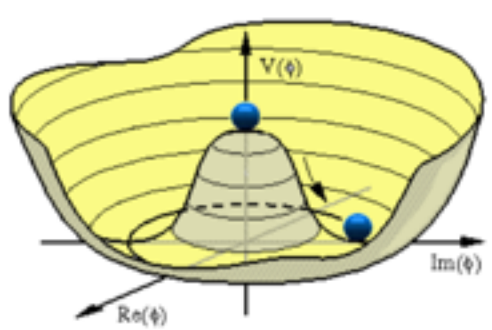
Let's talk about LHC Higgs data

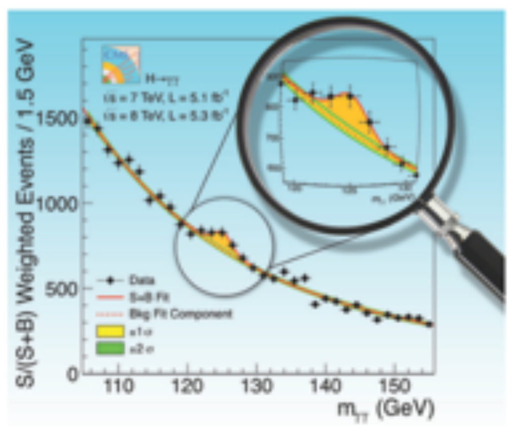
First of all, where?

google Higgs ATLAS (or CMS) public results

TWiki > CMSPublic Web > PhysicsResults > PhysicsResultsHIG (2015-08-14, AndreDavi

CMS Higgs Physics Results





in preliminary results

Compact Muon Solenoid
LHC, CERN

Visit CMS Public Website, CMS Physics ; Contact us: CMS Publications Committee

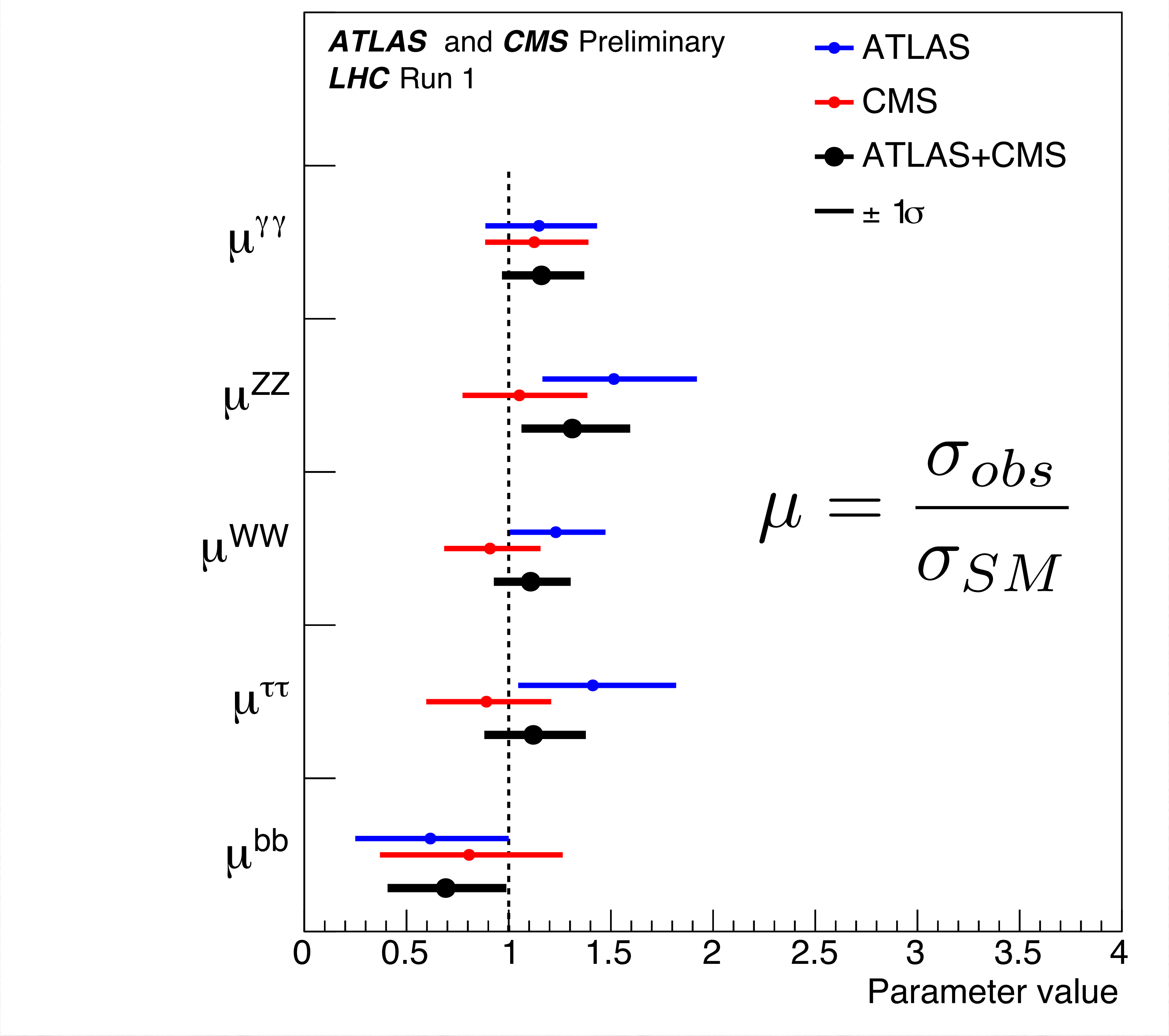
Recent Higgs Physics Preliminary Results

CMS-PAS-HIG-15-011	Search for the exotic decay of the Higgs boson to two light pseudoscalar bosons with two taus and two muons in the final state at $\sqrt{s}$ = 8 TeV	February 2016
CMS-PAS-HIG-14-039	Search for a doubly-charged Higgs boson with $\sqrt{s}$ = 8 TeV pp collisions at the CMS experiment	January 2016
CMS-PAS-HIG-15-010	Measurement of the transverse momentum spectrum of the Higgs boson produced in pp collisions at $\sqrt{s}$ = 8 TeV using the $H \to WW$ decays	December 2015
CMS-PAS-HIG-14-037	Search for new resonances in the diphoton final state in the mass range between 80 and 115 GeV in pp collisions at $\sqrt{s}$ = 8 TeV	October 2015
CMS-PAS-HIG-14-022	Search for Higgs decays to new light bosons in boosted tau final states	October 2015
CMS-PAS-HIG-15-012	A combination of searches for the invisible decays of the Higgs boson using the CMS detector	September 2015
CMS-PAS-HIG-15-002	Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}$ = 7 and 8 TeV	September 2015

How SM-like is the Higgs?

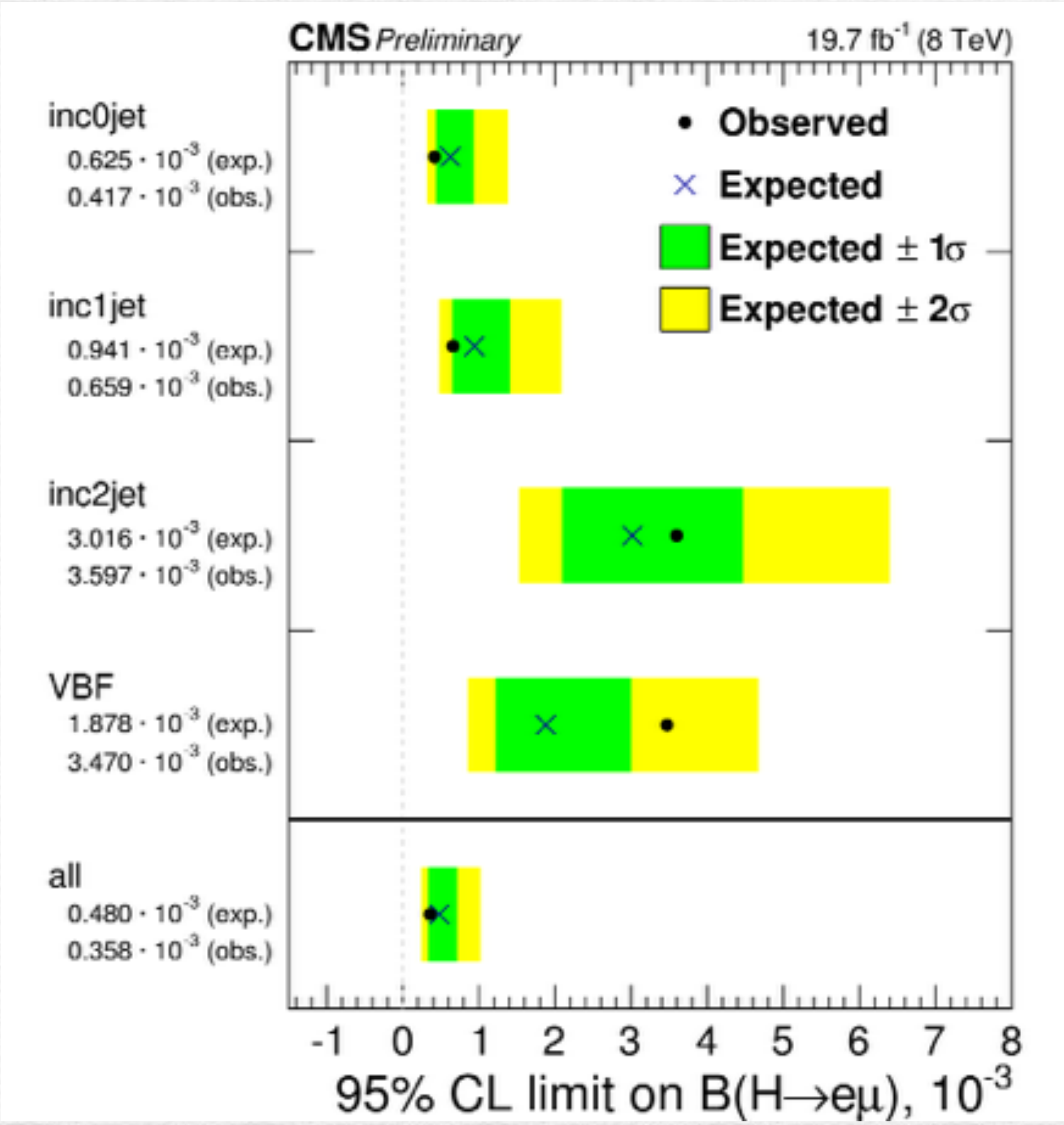
The rundown

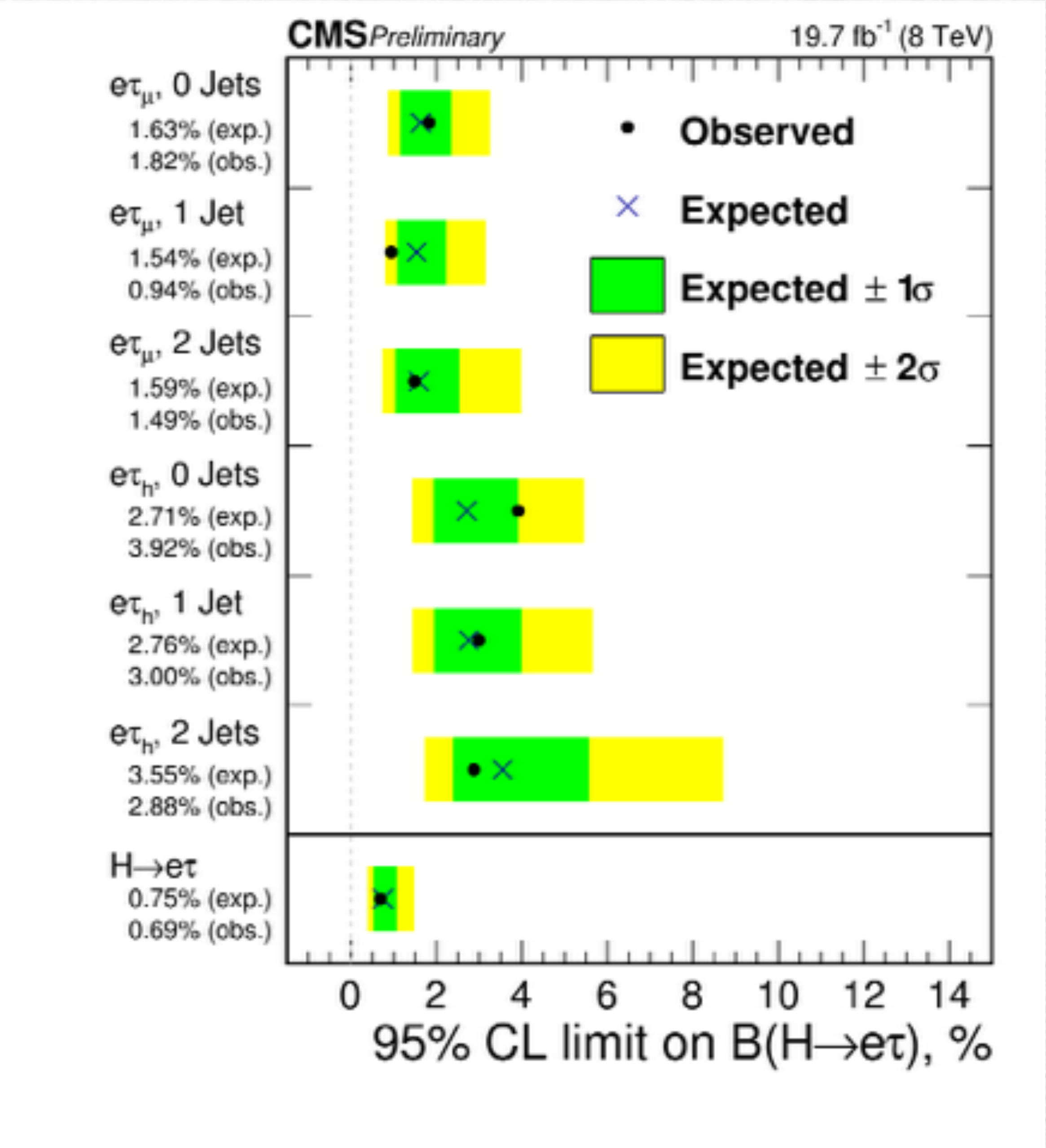
ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002



How SM-like is the Higgs?

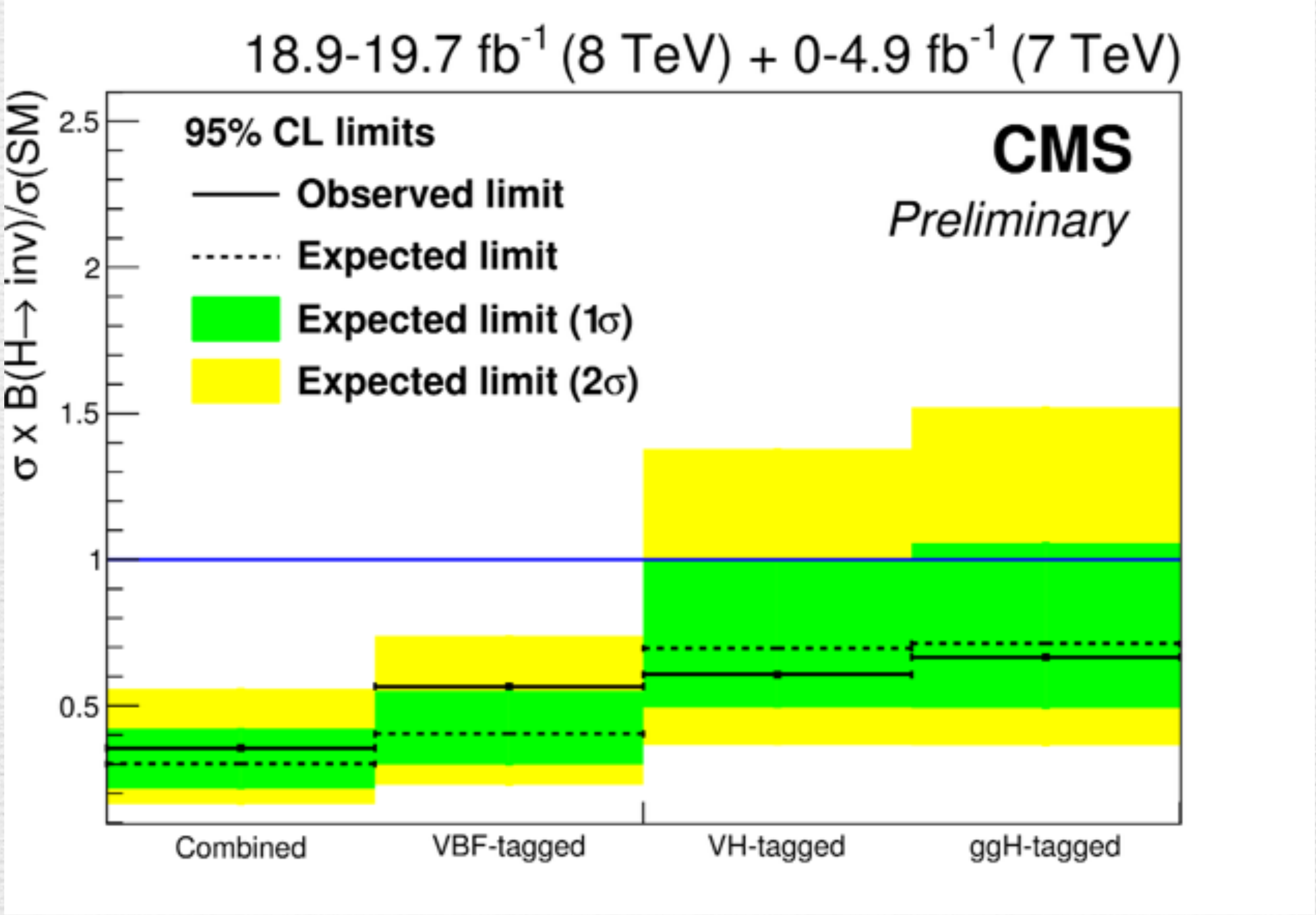
Lepton-flavour violation



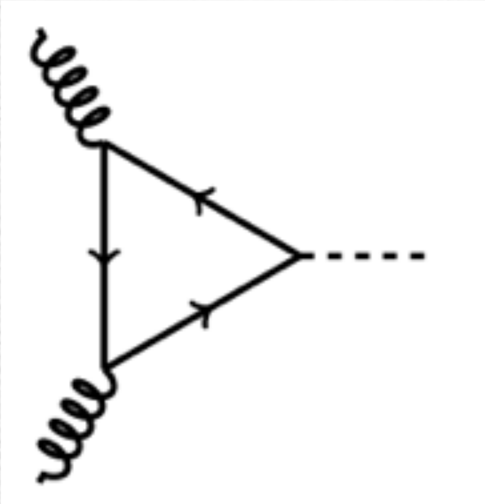


How SM-like is the Higgs?

Higgs to invisibles

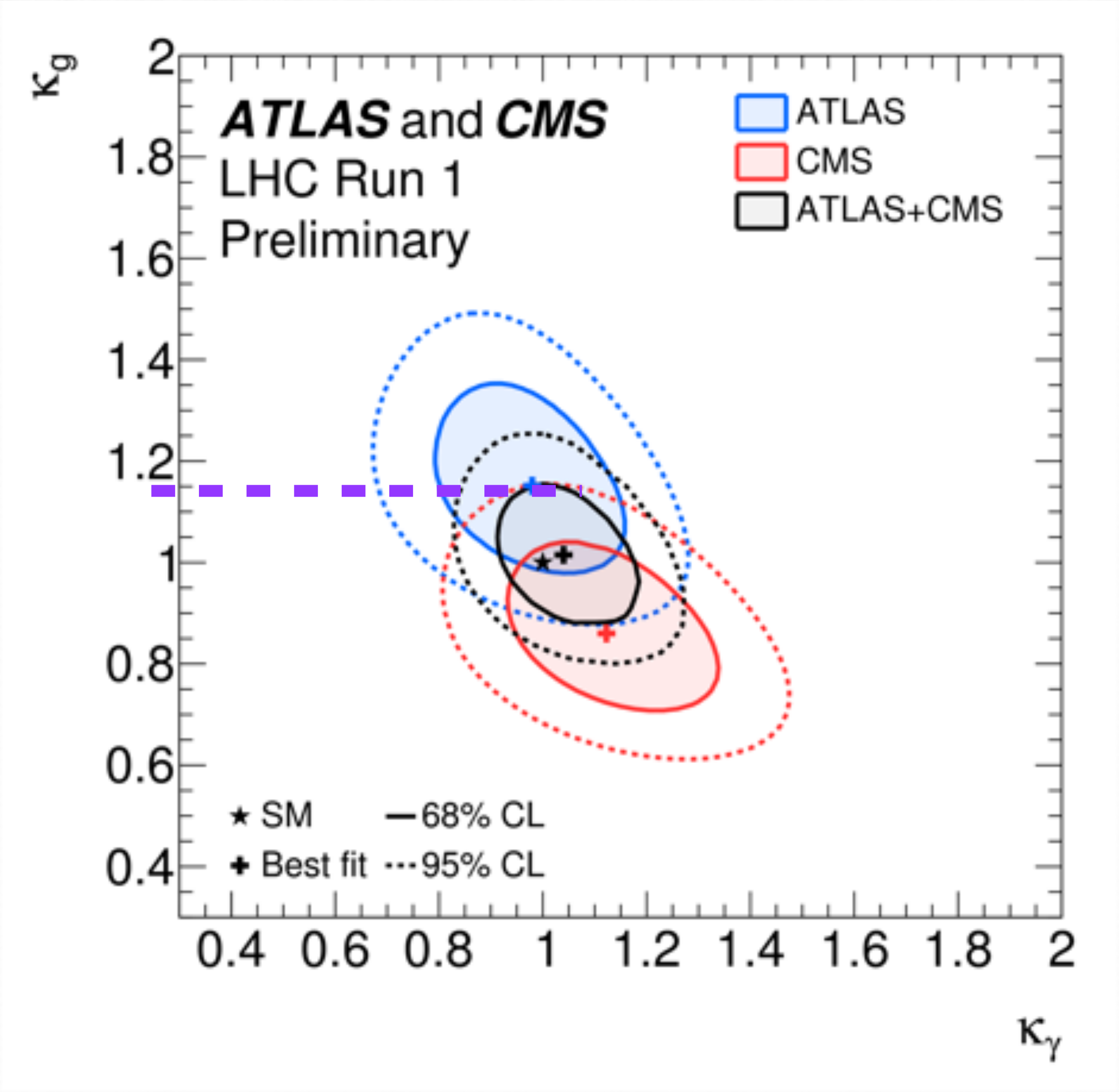


What are the implications for New Physics?



Supersymmetry

tops+stops



indirect searches for stops

$$\kappa_g \simeq 1 + \frac{m_t^2}{4m_{\tilde{t}}^2}$$

1207.7355

$$\Delta\kappa_g < 0.15$$

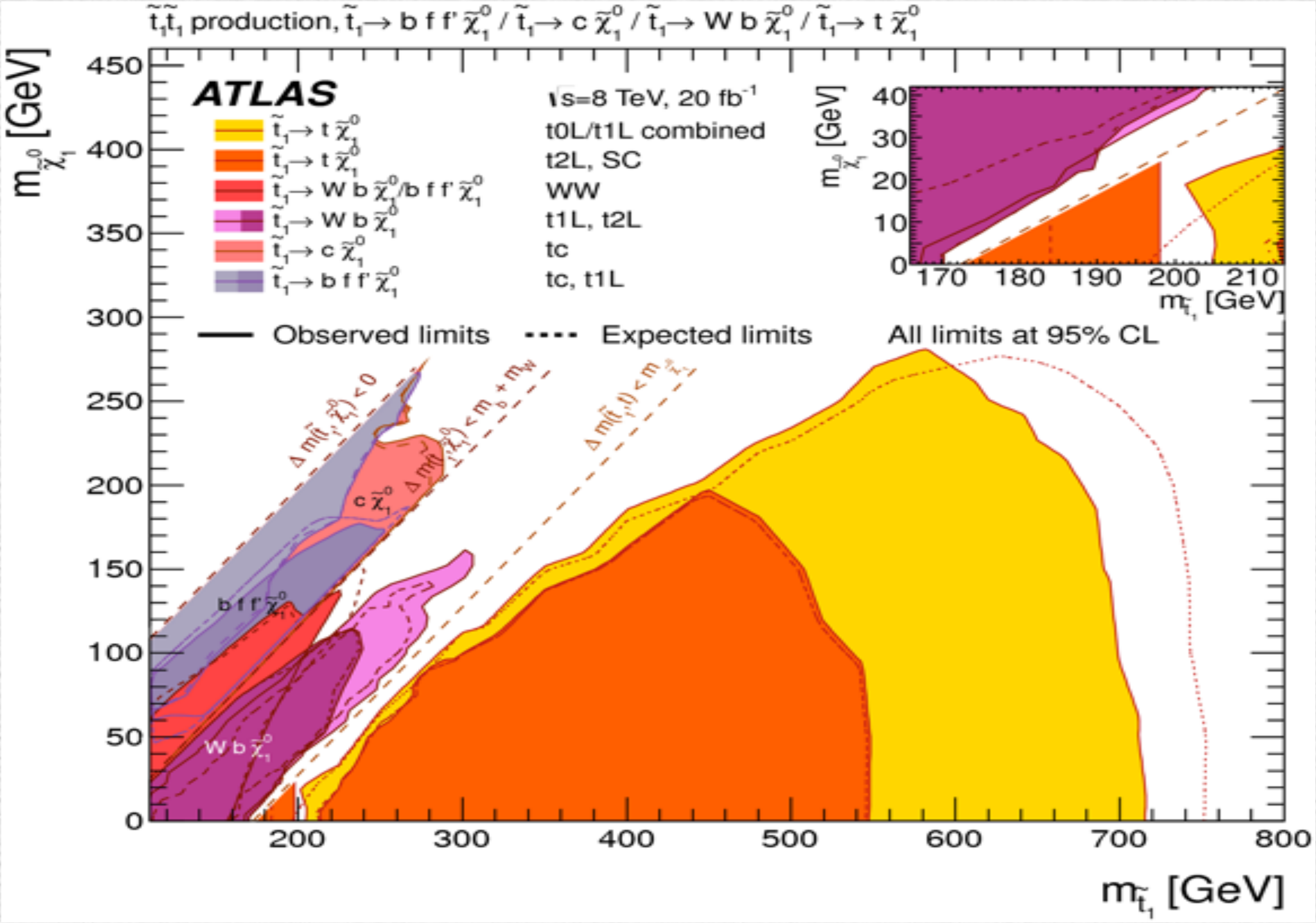
$$m_{\tilde{t}} > 940 \text{ GeV}$$

What are the implications for New Physics?

Supersymmetry

$m_{\tilde{t}} > 940$ GeV

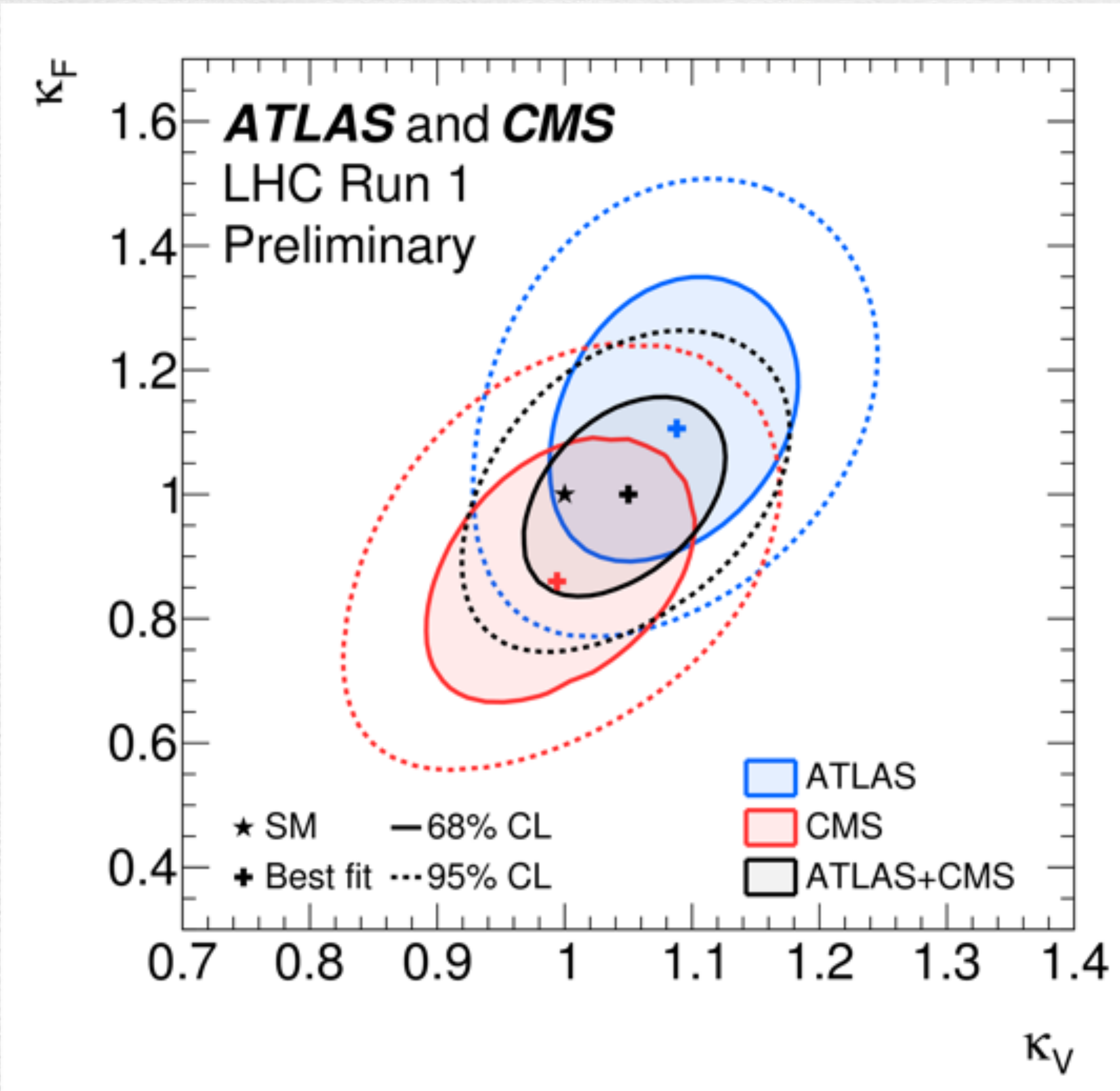
Higgs data vs direct searches for stops



complementary

What are the implications for New Physics?

Composite Higgs

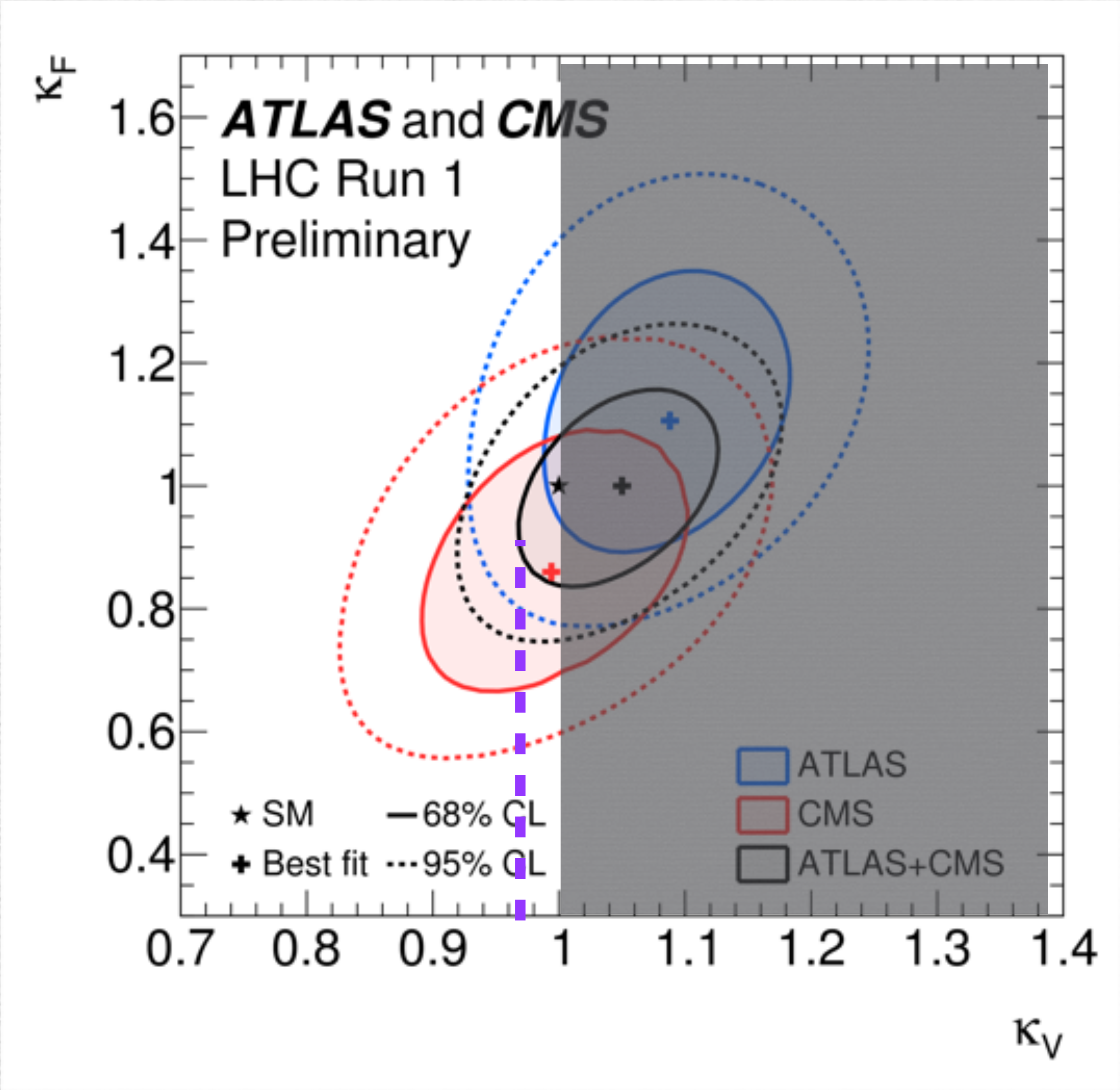


Non-linear realization breaking at scale f

$$\kappa_V \sim \sqrt{1 - v^2/f^2}$$

What are the implications for New Physics?

Composite Higgs



Non-linear realization breaking at scale f

$$\kappa_V \sim \sqrt{1 - v^2/f^2}$$

$$\kappa_V > 0.97$$

$$f \gtrsim 1 \text{ TeV}$$

What are the implications for New Physics?

Model-independent approaches

Expansion in inverse powers of NP scale

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i \mathcal{O}_i$$

dim6, dim8, …

coupling HWW
at dim-6

$$\frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\right] D^\nu W^k_{\mu\nu}$$

$$\frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu \Phi^\dagger T_{2k} D^\nu \Phi\right] W^k_{\mu\nu}$$

What are the implications for New Physics?

HEFT

Write down Lagrangian at a given order, consistent with symmetries and particle content of the SM, basis

$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
+\ & \frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\ \bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
+\ & \frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
+\ & \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R\,.
\end{aligned}
$$

What are the implications for New Physics?

Higgs anomalous couplings

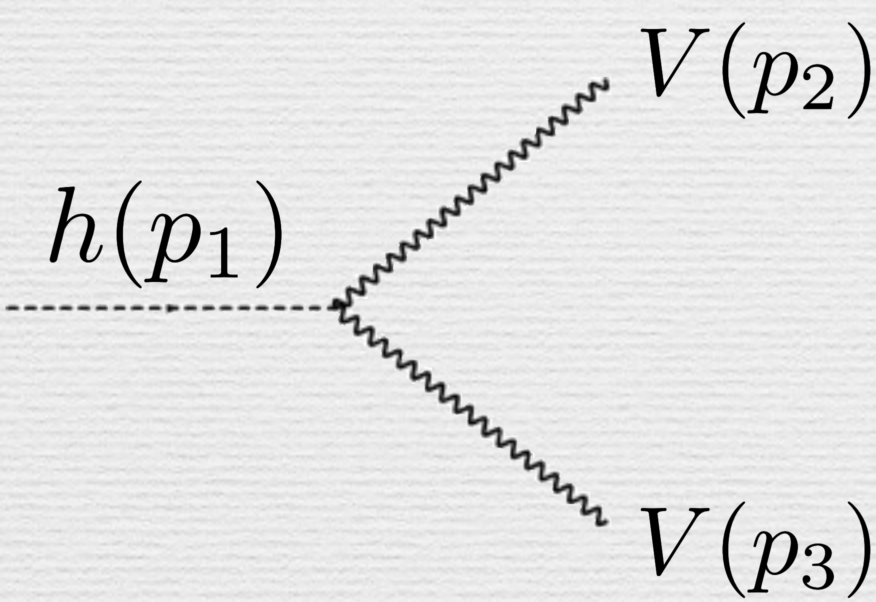
HDOs generate HVV interactions with more derivatives

$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu}$$

$$-h\, g^{(2)}_{hVV} V_{\nu} \partial_{\mu} V^{\mu\nu}$$

$$-\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$

ex. Feynman rule if mh>2mV



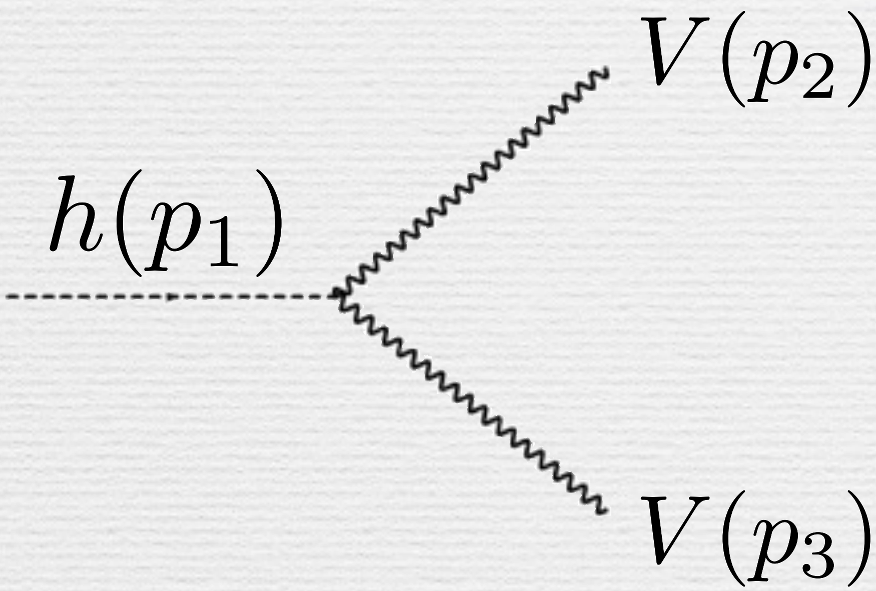
$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

$$-i g^{(1)}_{hVV} p_3^{\mu} p_2^{\nu}$$

$$-i \tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

What are the implications for New Physics?

Higgs anomalous couplings



$$i\eta_{\mu\nu}\left(g^{(1)}_{hVV}\left(\frac{\hat{s}}{2}-m_V^2\right)+2g^{(2)}_{hVV}m_V^2\right)$$

$$-ig^{(1)}_{hVV}p_3^{\mu}p_2^{\nu}$$

$$-i\tilde{g}_{hVV}\epsilon^{\mu\nu\alpha\beta}p_{2,\alpha}p_{3,\beta}$$

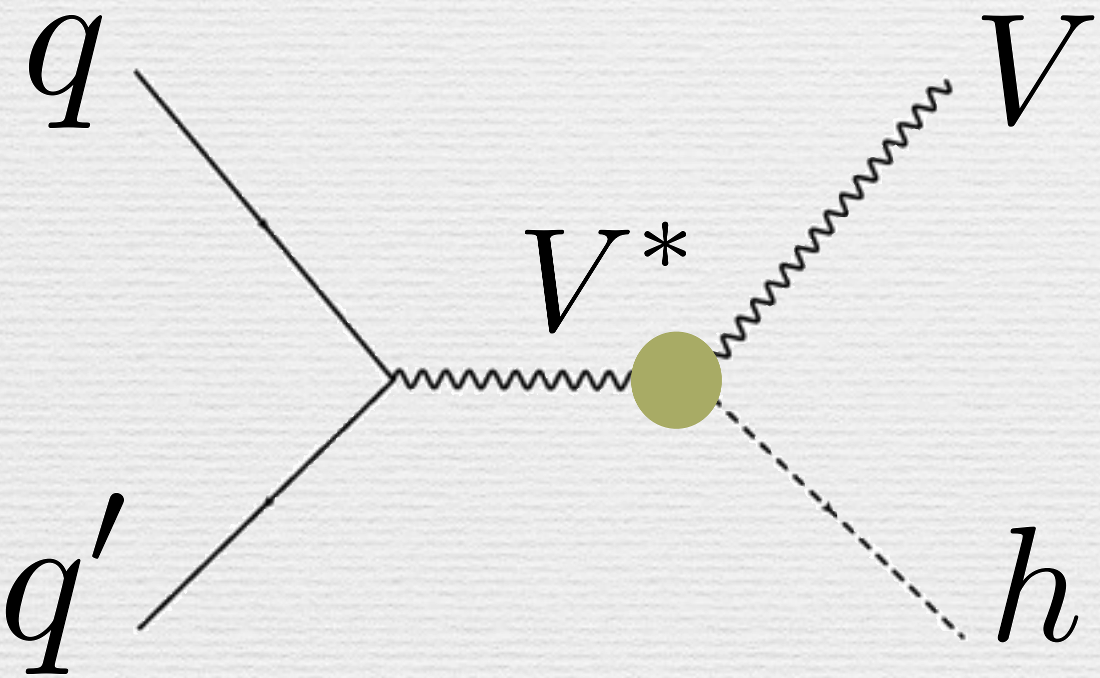
Changes in

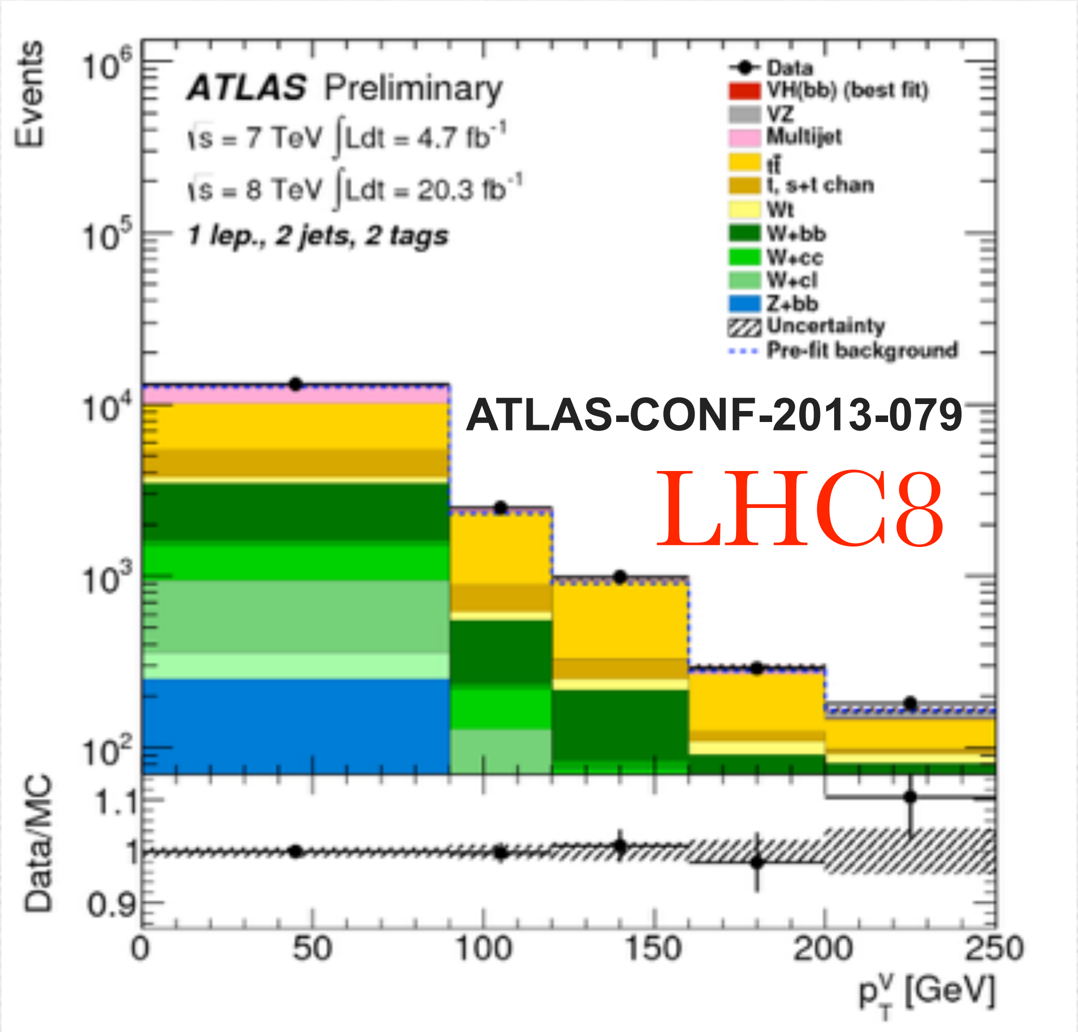
total rates and differential information

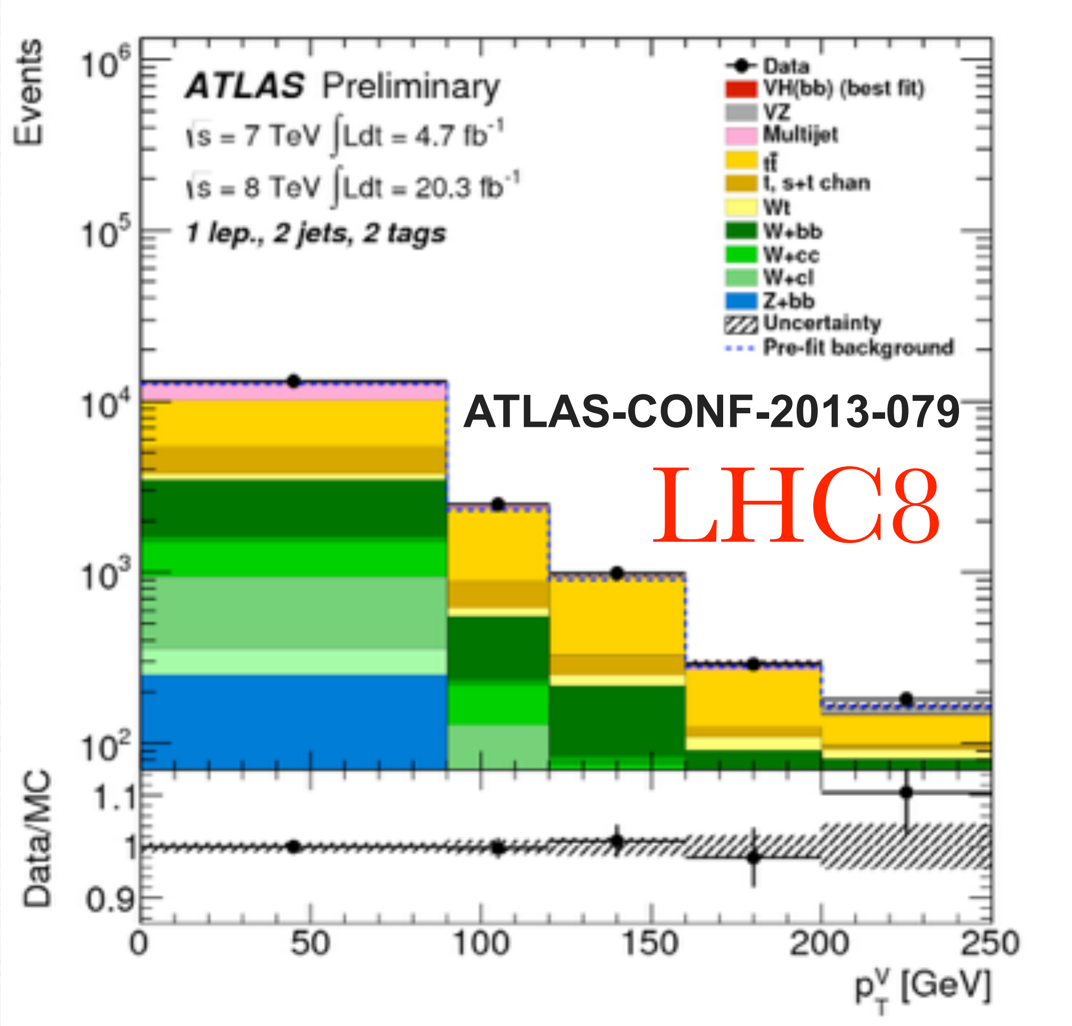
Pushing the limits: Differential information

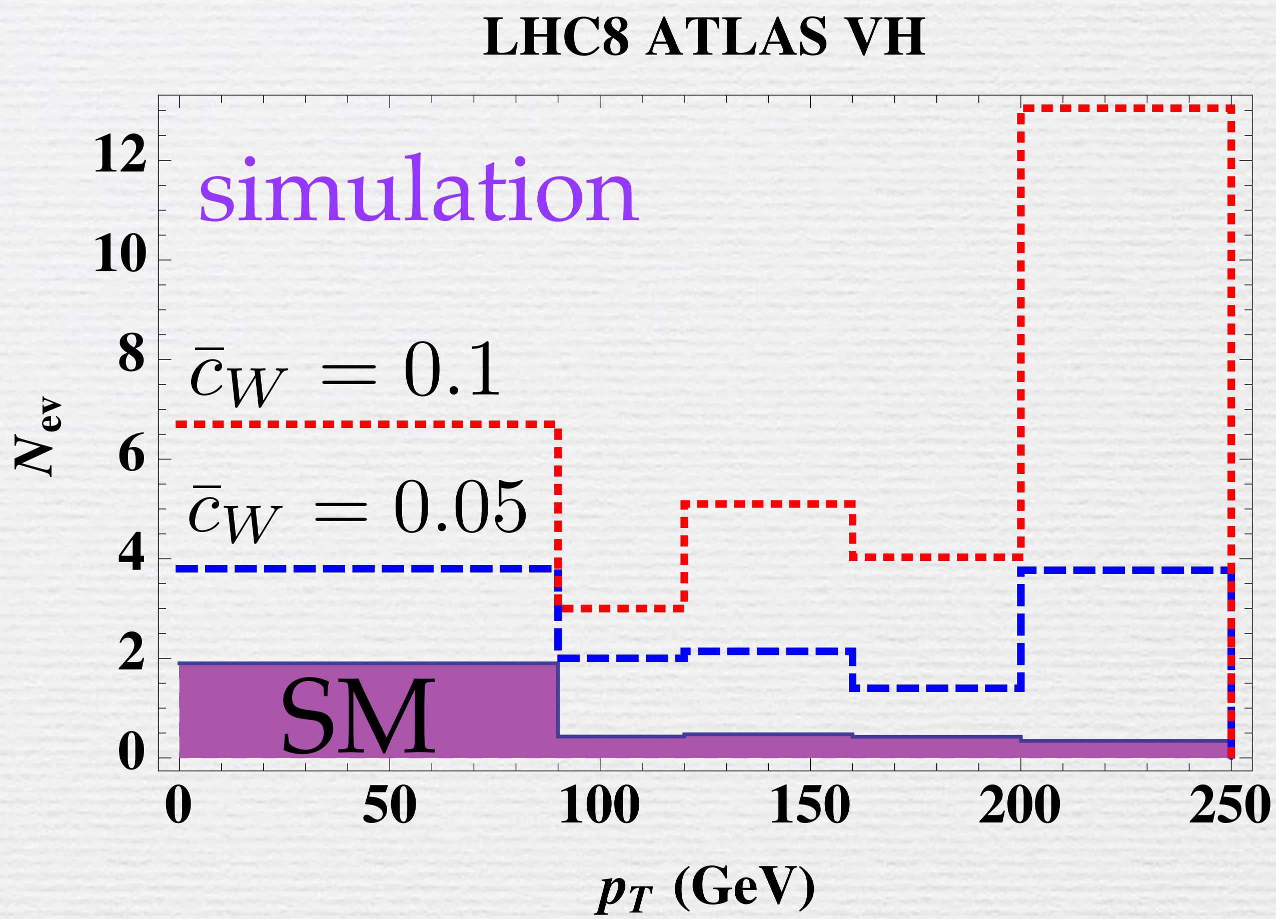
channels which probe a large kinematic regime

e.g. VH and H+j





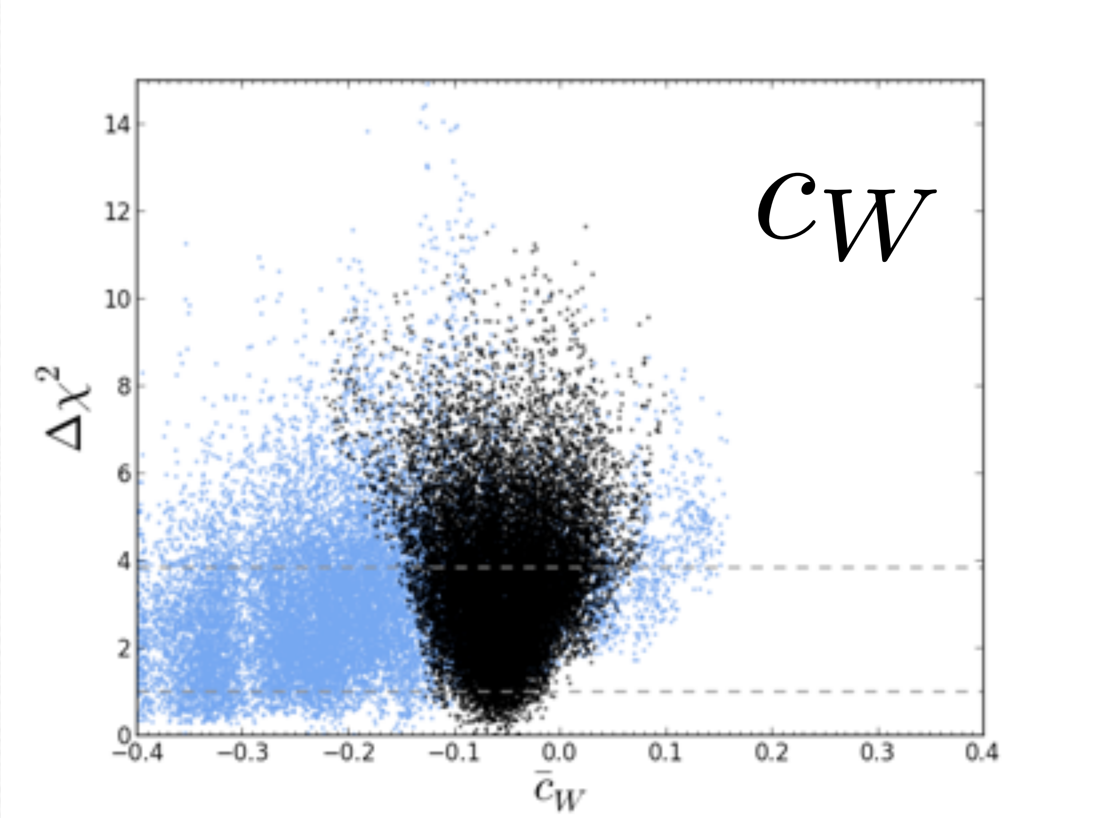




Ellis, VS and You. 1404.3667, 1410.7703

Feynrules -> MG5-> pythia->Delphes3

verified for SM/BGs => expectation for EFT



Global fit

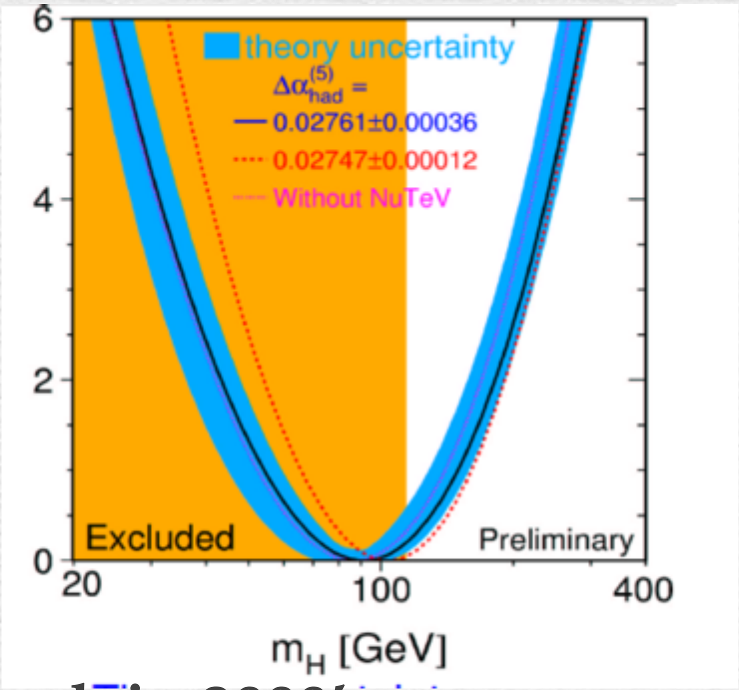
inclusive cross section is less sensitive than distribution

EFT approach

If New Physics thresholds above
the energy scale @ channel
EFT suitable to look for new physics
alternative to direct searches

Exp. signatures: deviations in
total rates or distribution (not a resonance)

Pathway: push theoretical and experimental limits in indirect searches



back in 2000's

Data consistent with mh~125 GeV at 1sigma

What are the implications for New Physics?

EFT: Current status

LEP+Run1 LHC data (including VV)

Operator	Coefficient	LHC Constraints Individual	LHC Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HW}$	$(-0.042, 0.008)$	$(-0.035, 0.015)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HB}$	$(-0.053, 0.044)$	$(-0.045, 0.075)$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$	$\frac{m_W^2}{\Lambda^2} c_{3W}$	$(-0.083, 0.045)$	$(-0.083, 0.045)$
$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_g$	$(0, 3.0) \times 10^{-5}$	$(-3.2, 1.1) \times 10^{-4}$
$\mathcal{O}_\gamma = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_\gamma$	$(-4.0, 2.3) \times 10^{-4}$	$(-11, 2.2) \times 10^{-4}$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$	$\frac{v^2}{\Lambda^2} c_H$	$(-0.14, 0.194)$	$(-, -)$
$\mathcal{O}_f = y_f \lvert H\rvert^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2} c_f$	$(-0.084, 0.155)(c_u)$ $(-0.198, 0.088)(c_d)$	$(-, -)$ $(-, -)$

one-by-one global

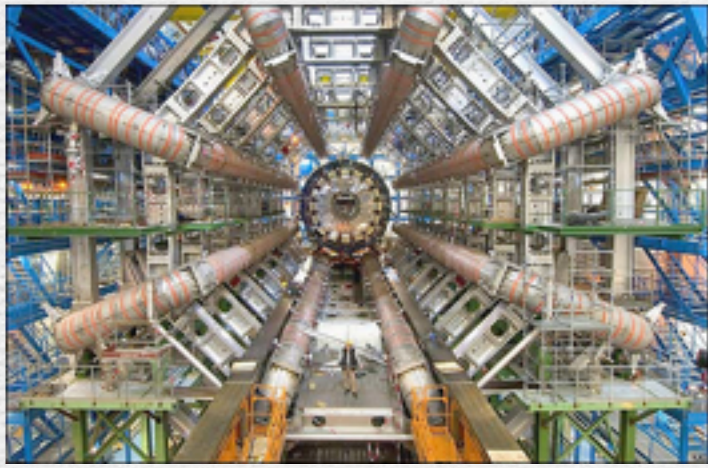
1410.7703

Dark Matter at the LHC

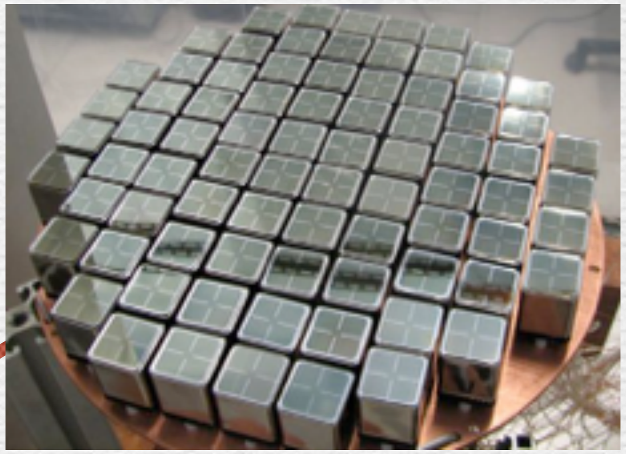
Dark Matter

THEORY
Discrete symmetries
Dynamical stability
self-interactions
Link to Higgs…

COLLIDERS

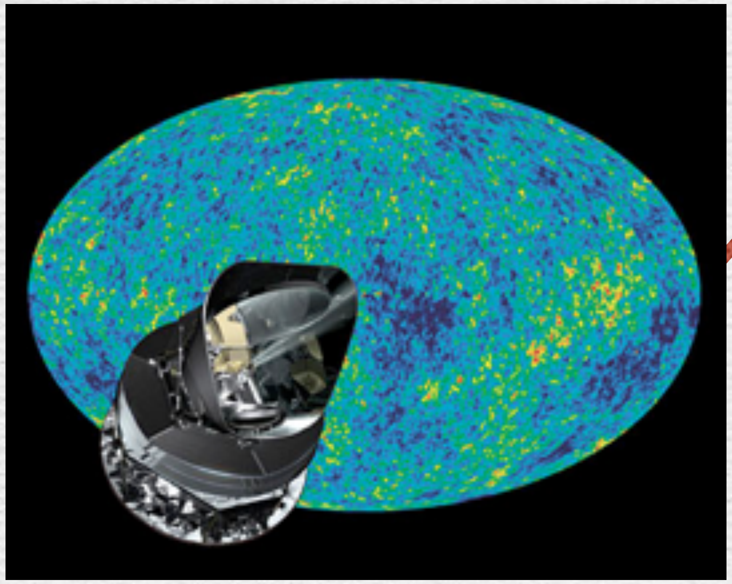


DIRECT DETECTION



DARK MATTER

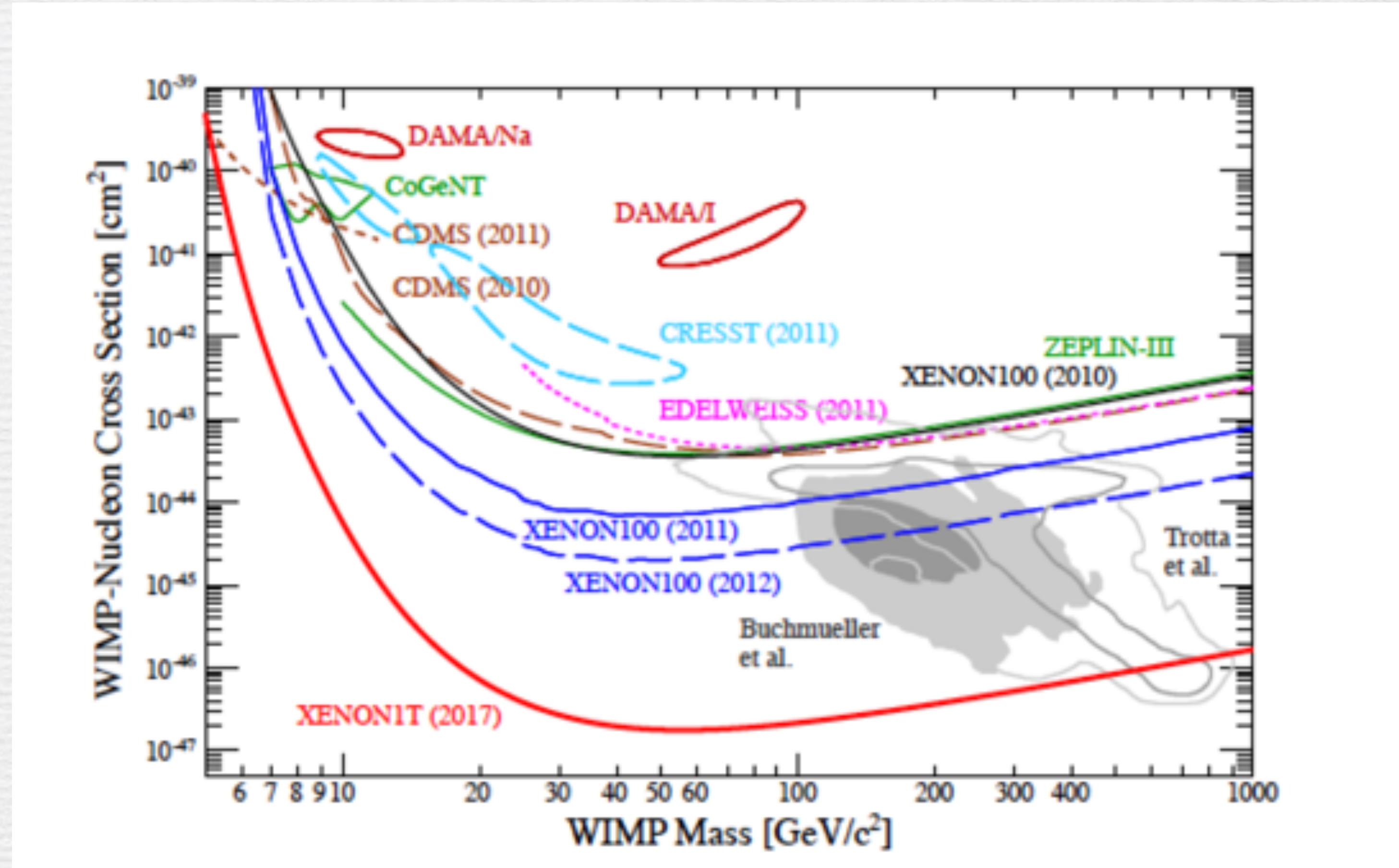
CMB: relic, tilt



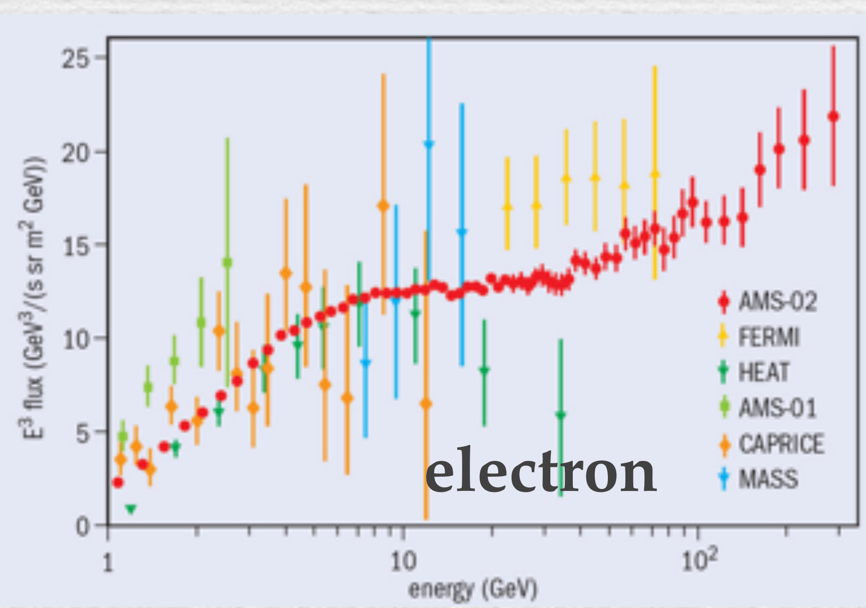
INDIRECT DETECTION

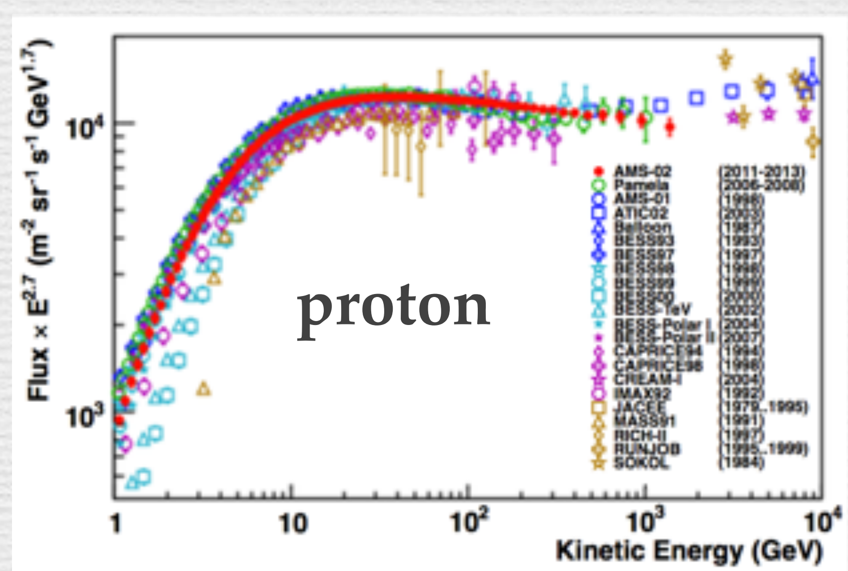
SIMULATIONS

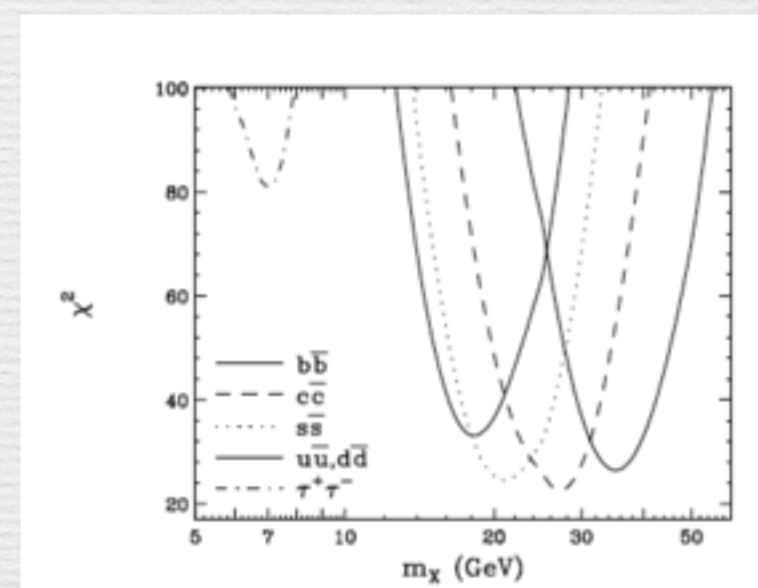
Direct detection



Indirect detection

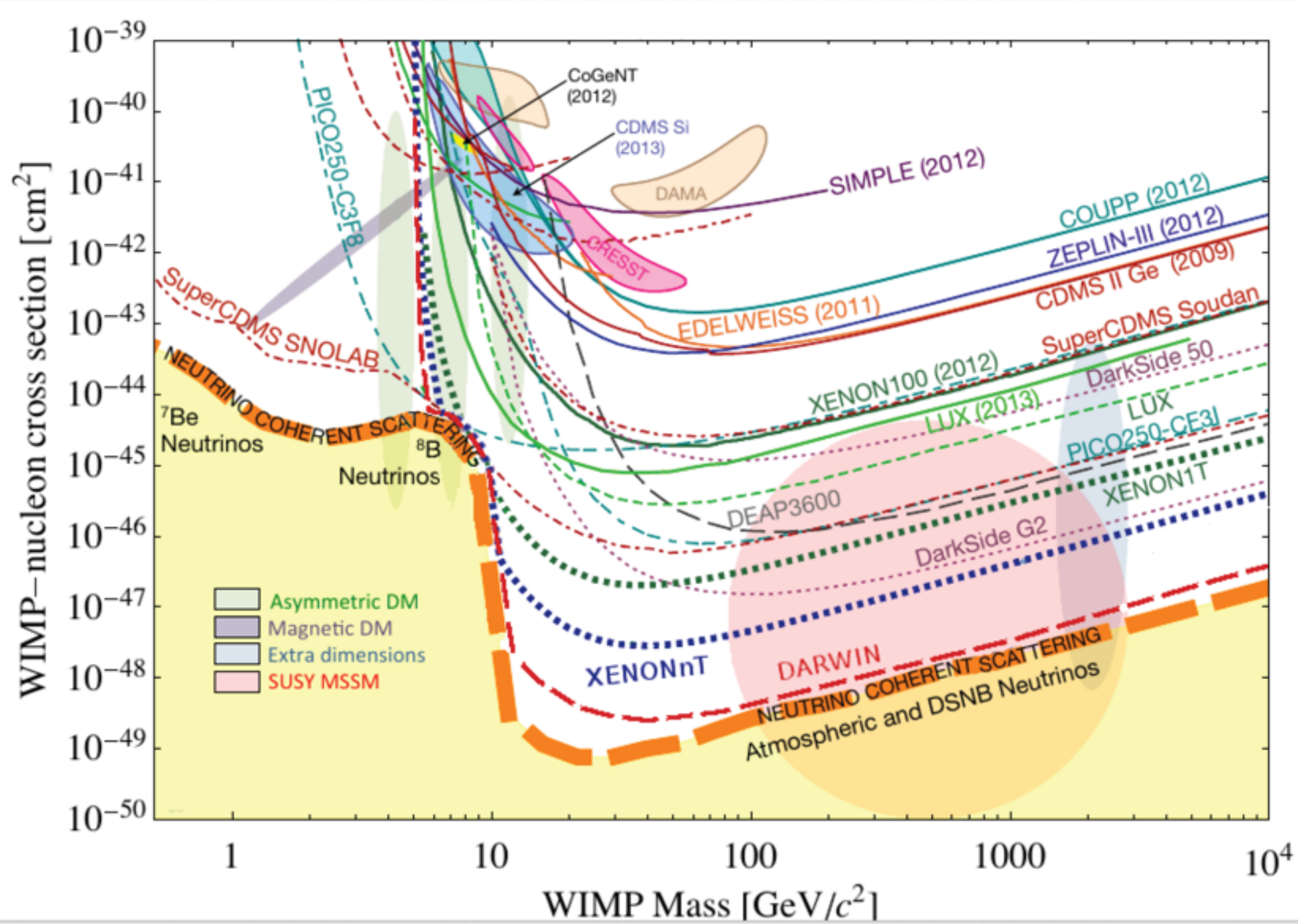






1402.6703

Direct detection

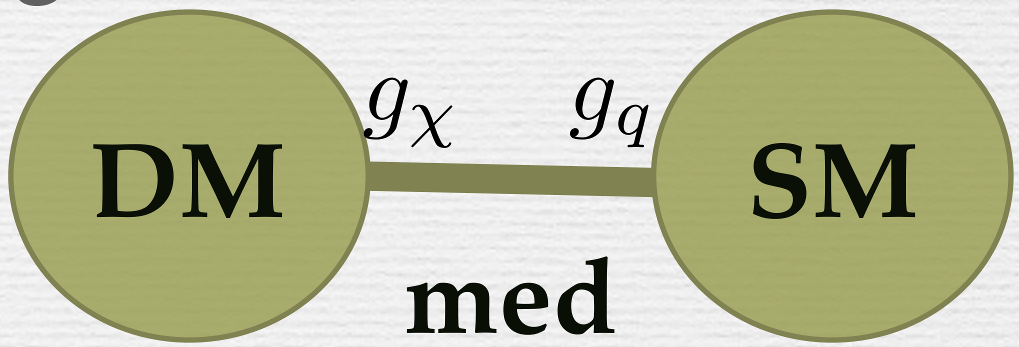


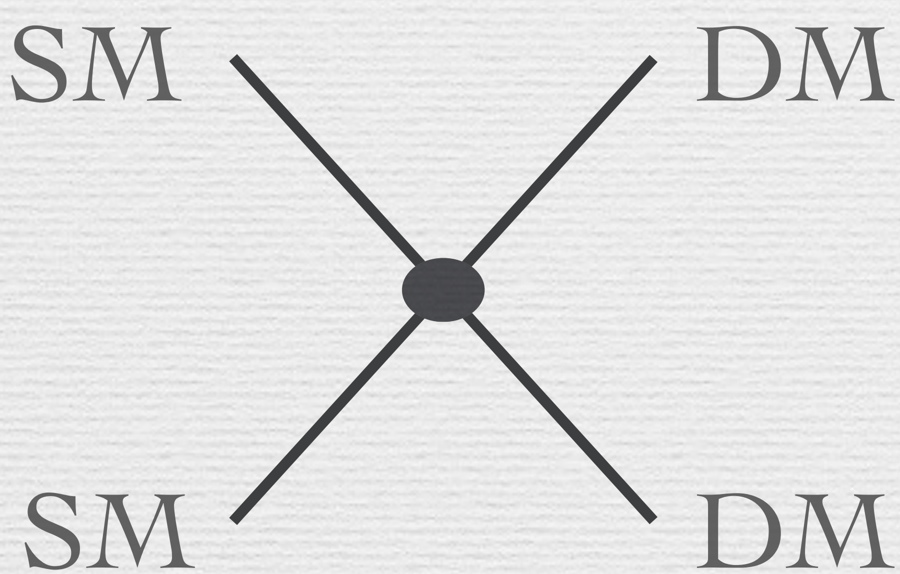
1408.4371

LHC searches for DM

DM is a neutral
likely collider-stable particle
production via weak couplings
or via a mediator

e.g.



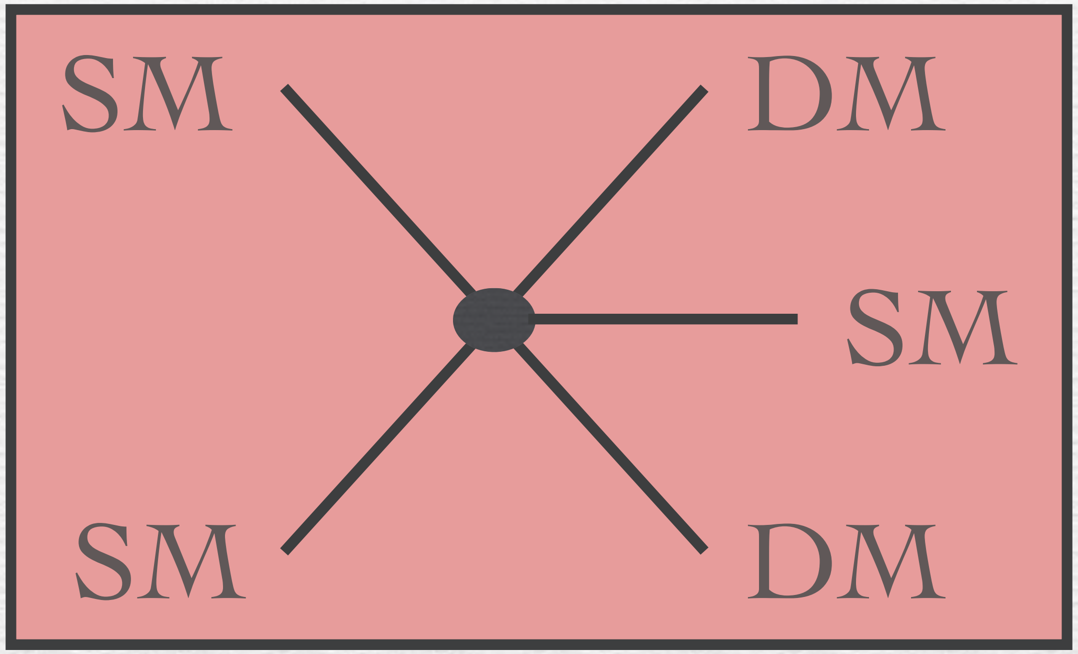


LHC signature?

protons producing
invisible particles

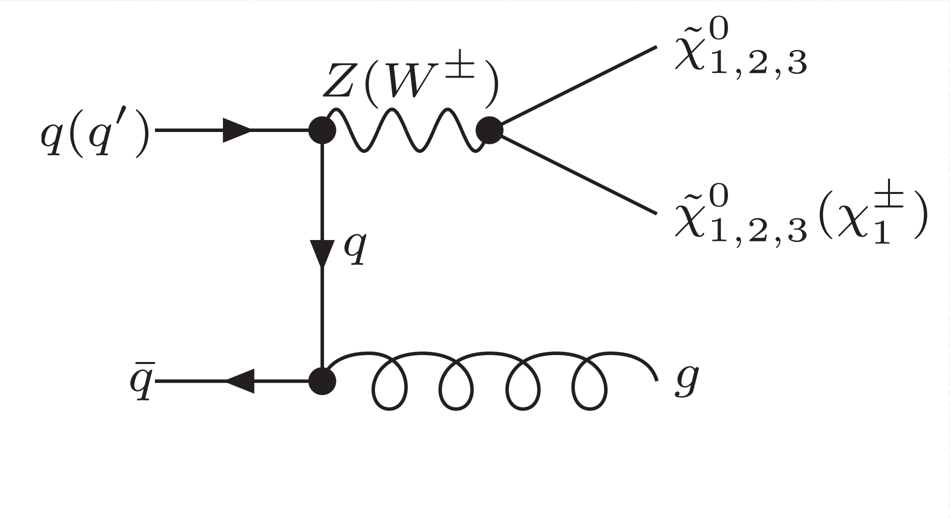
=nothing to trigger on

LHC searches for DM

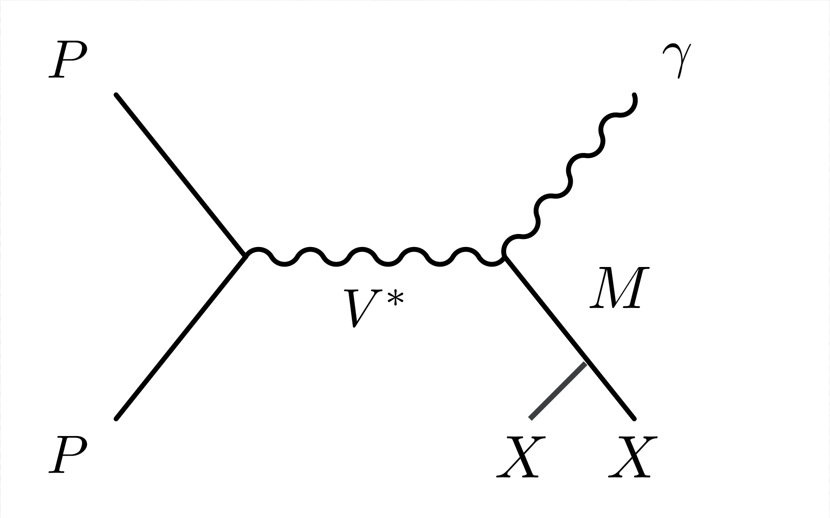


examples:

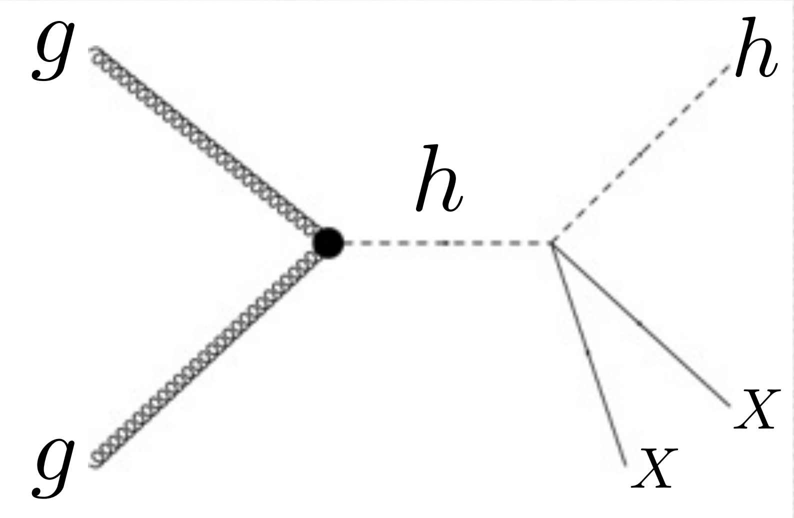
SUSY neutralino



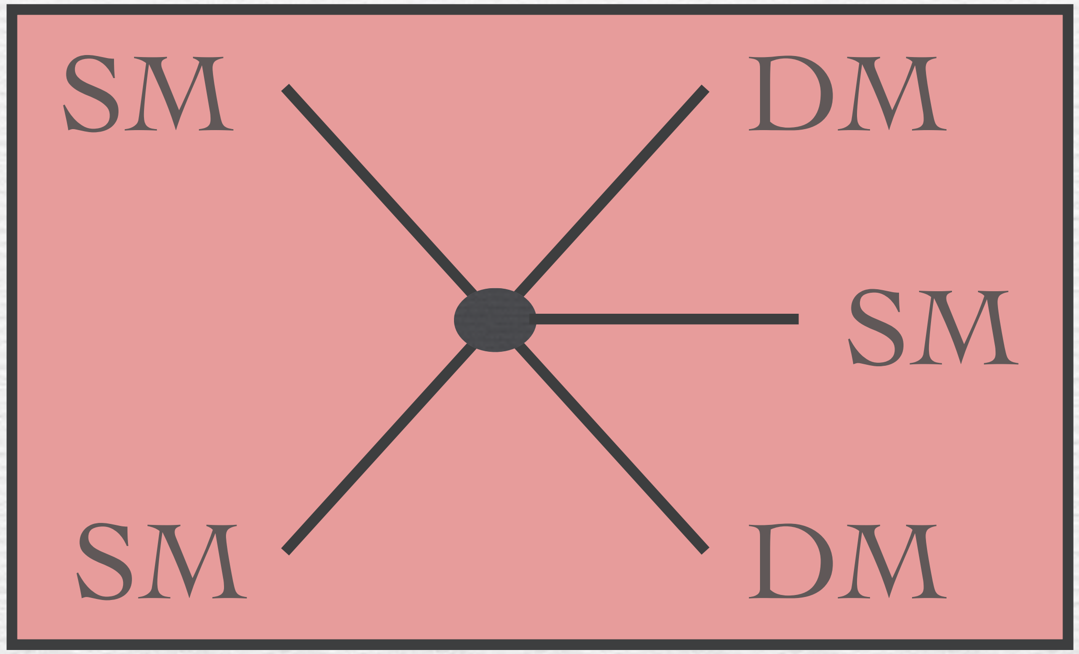
Mediator (axion,Z')



Higgs portal

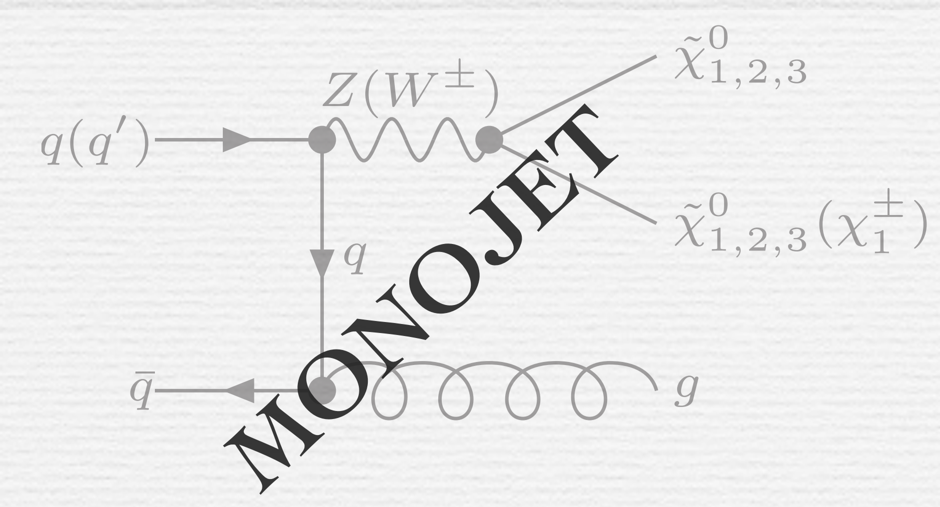


LHC searches for DM

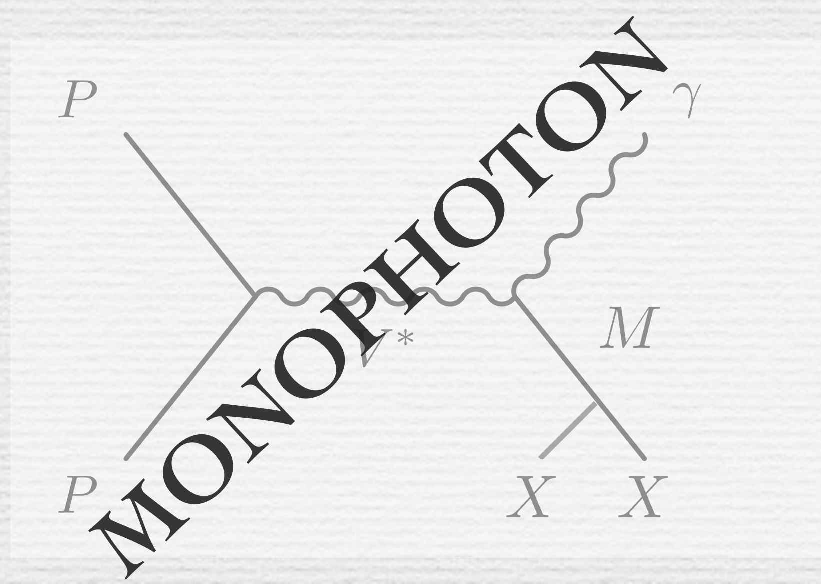


examples:

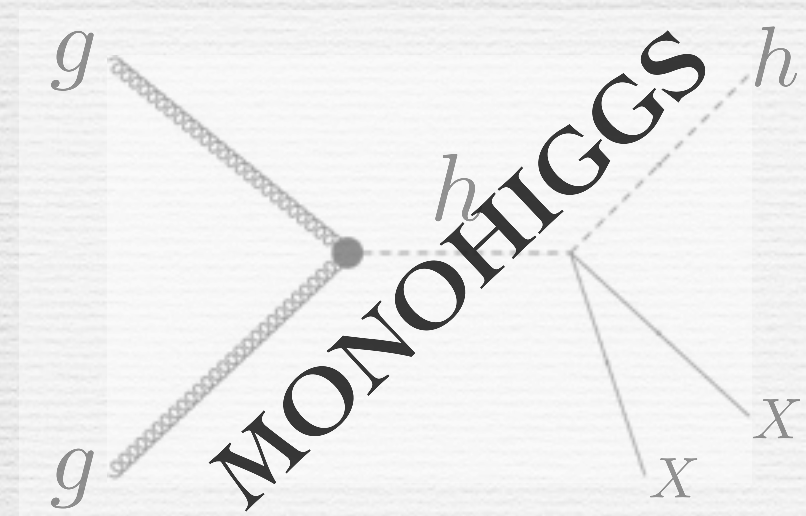
SUSY neutralino



Mediator (axion,Z')

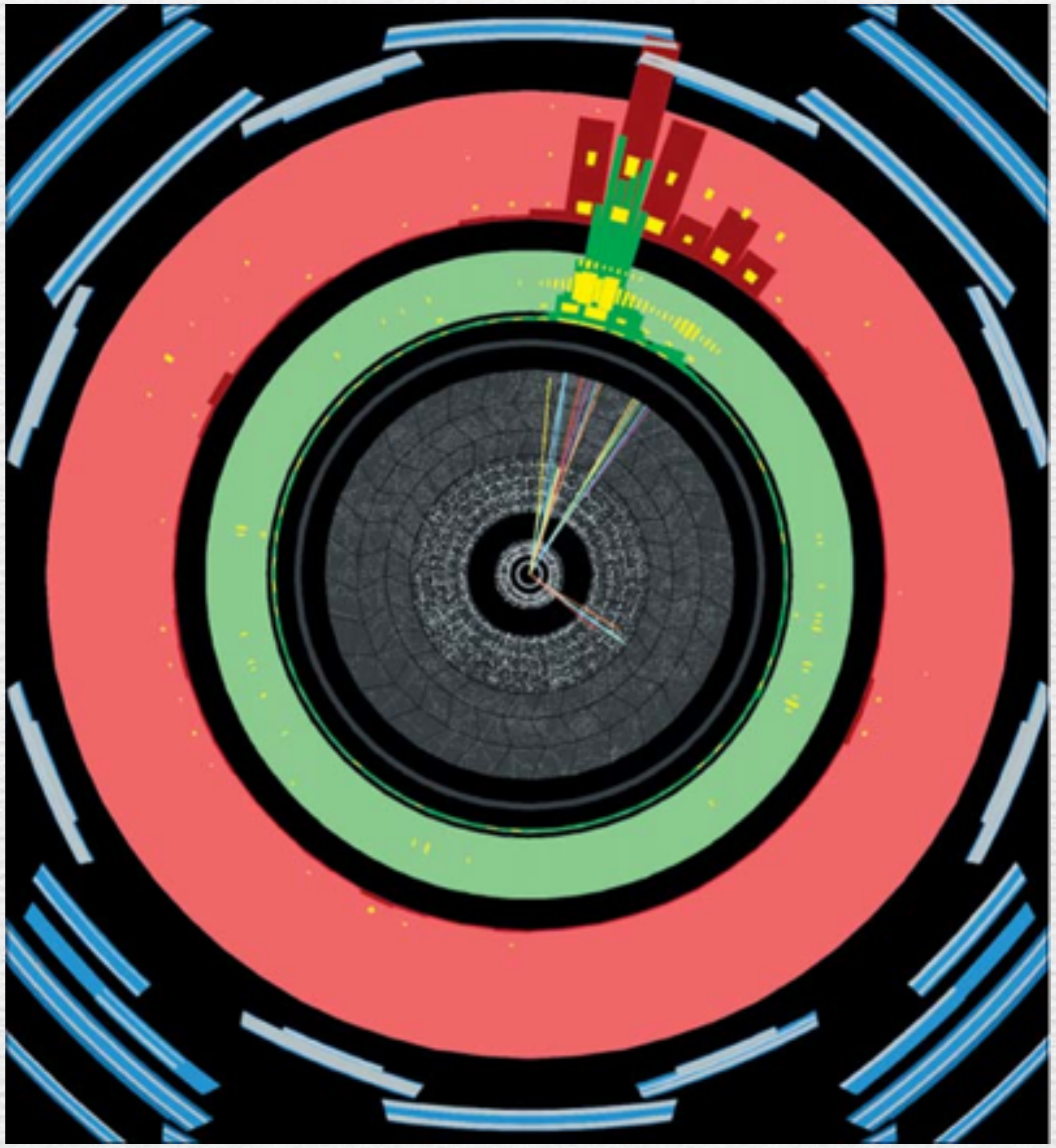


Higgs portal

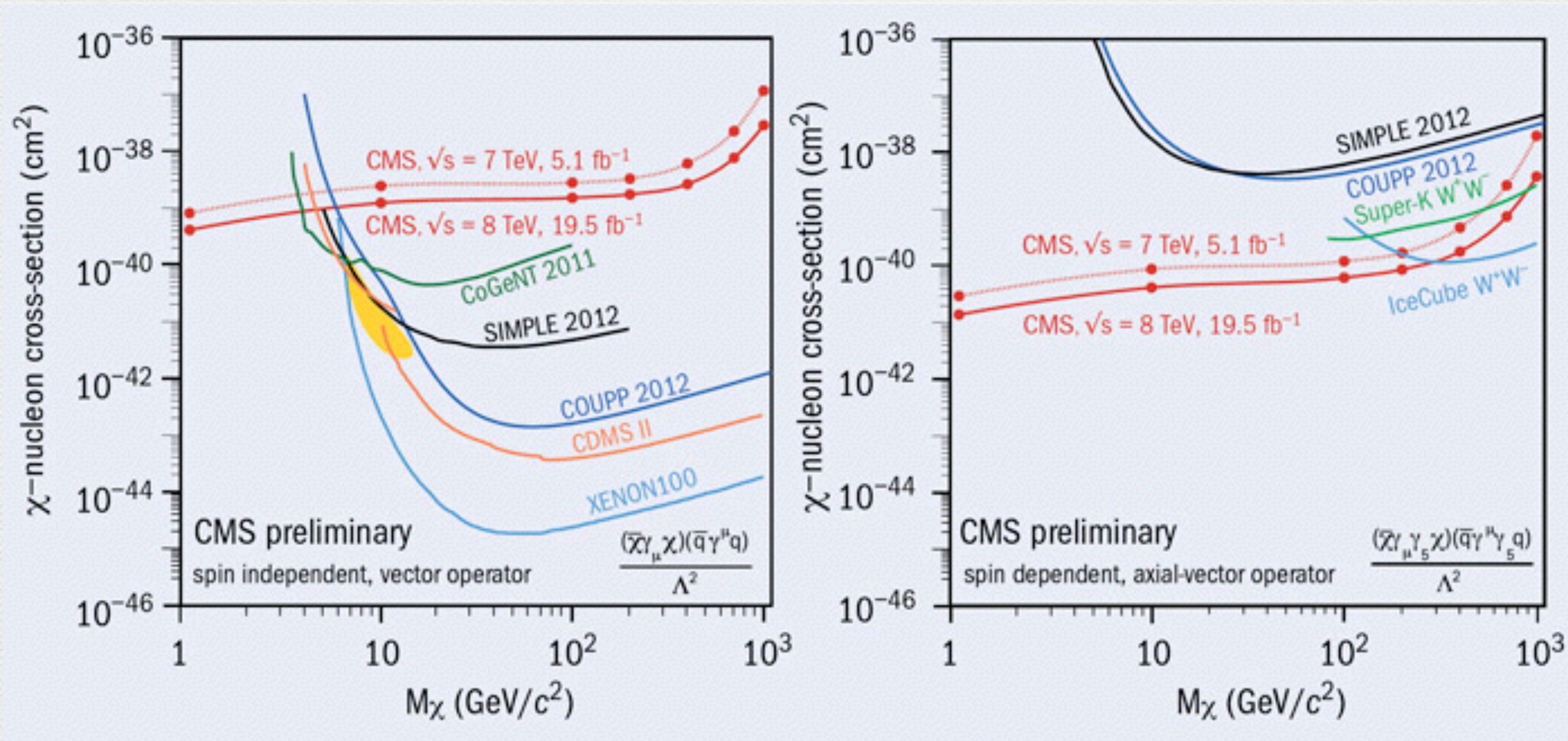


Signature for DM:

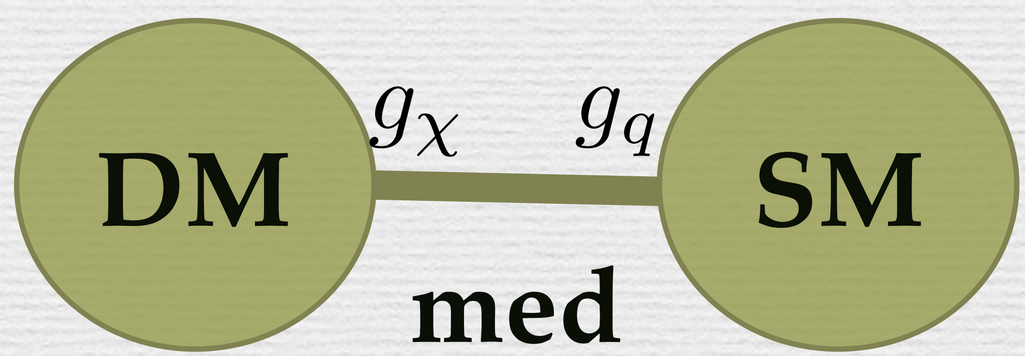
A visible object (X=jet, higgs, lepton, top…)
recoiling against missing energy



LHC vs direct detection

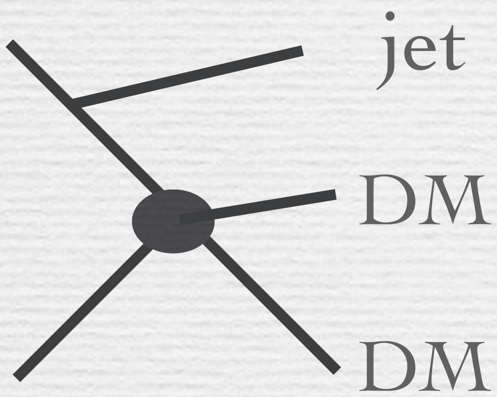


$$\frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$



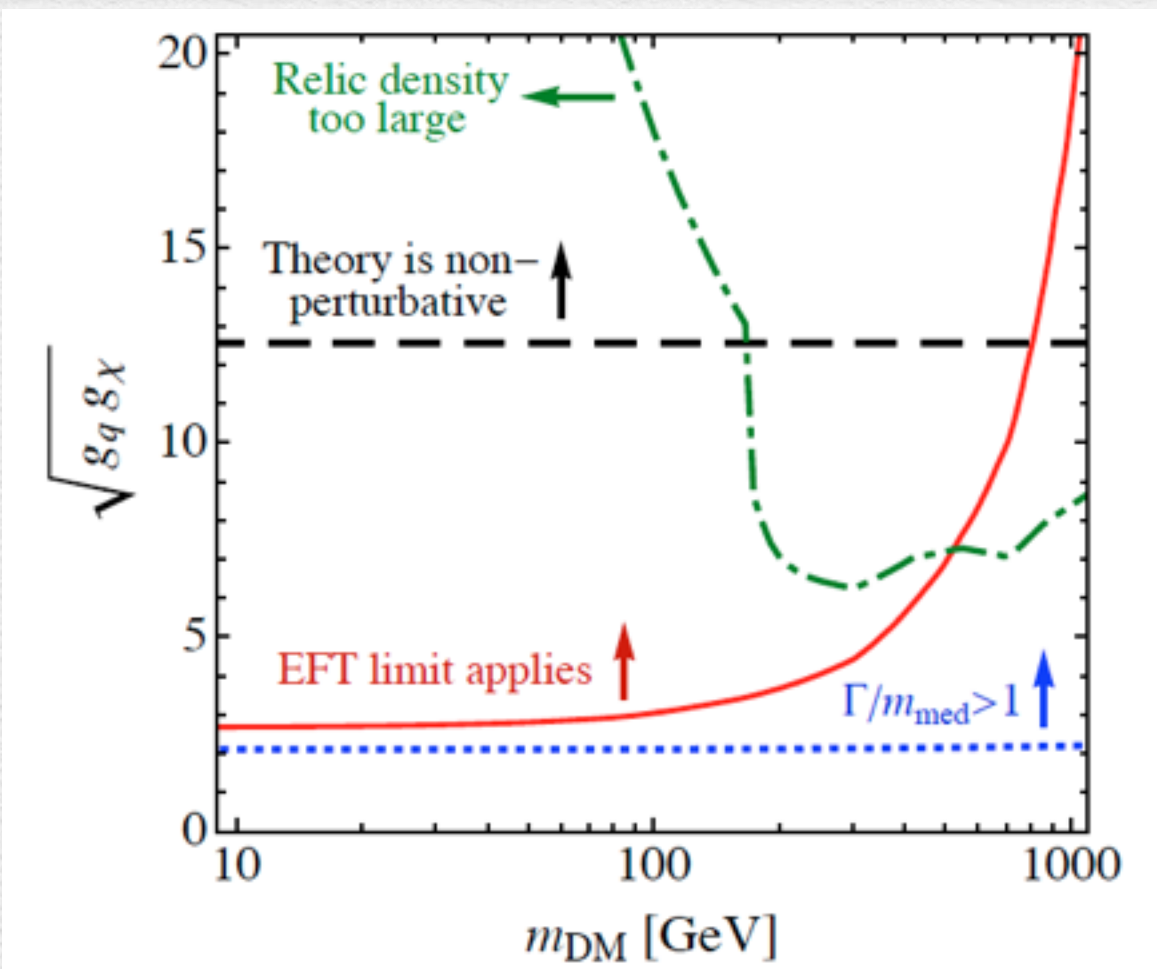
LHC vs direct detection

Heavy criticism to this approach



strength of the signal $\dfrac{g_\chi g_q}{M_{med}^2}$

validity of the EFT $M_{med} > E \simeq p_{T,cut}$



and $\Gamma_{med} \sim \dfrac{g_\chi^2}{8\pi} M_{med}$

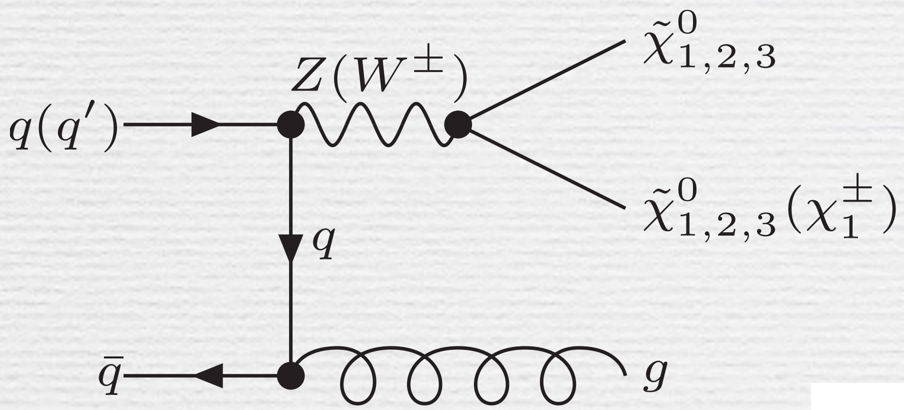
$$\Gamma_{med} > M_{med}$$

no meaning of a mediator

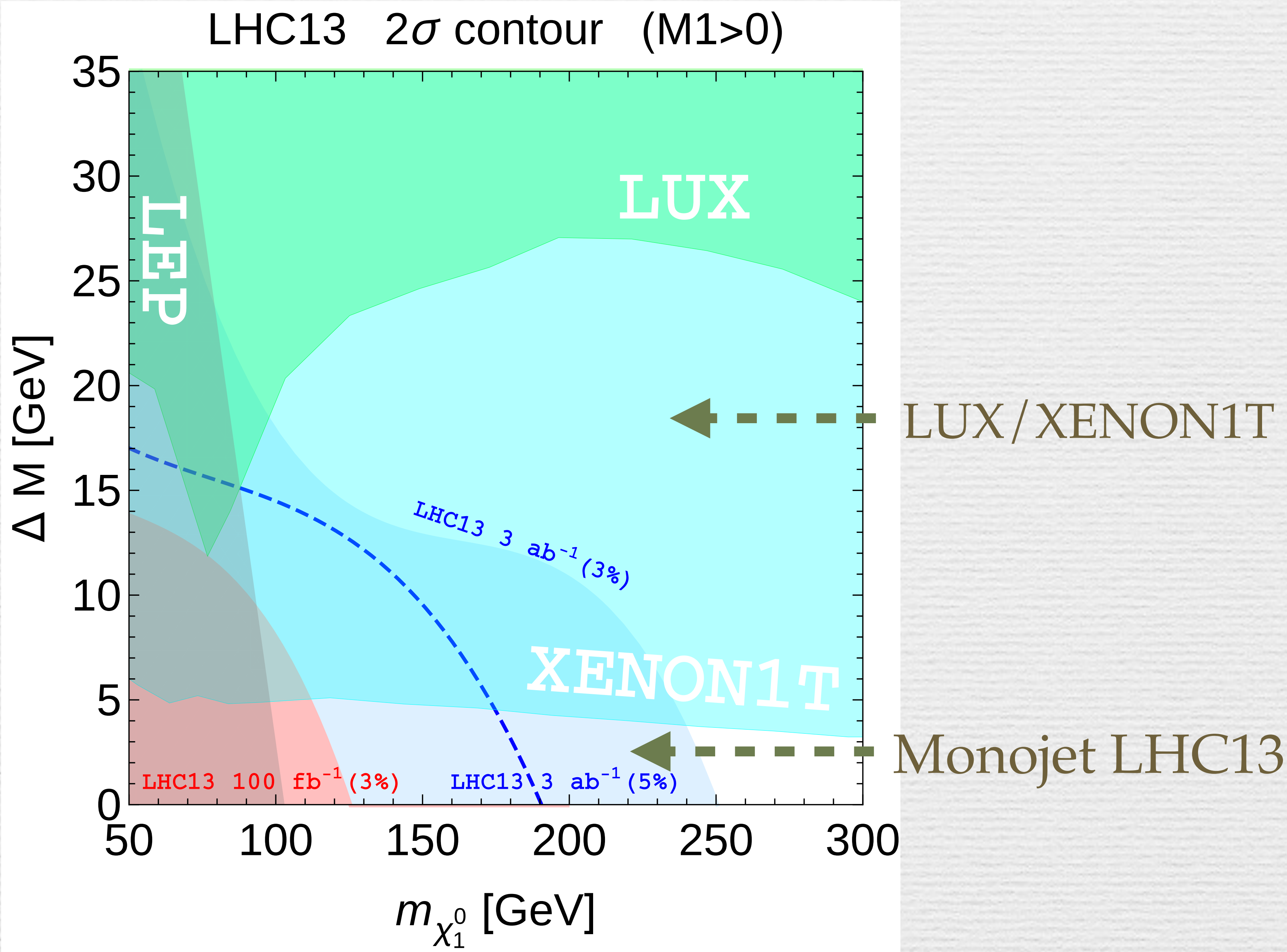
Buchmueller, Dolan and McCabe. 1308.6799

movement towards
simplified models
full models

LHC vs direct detection



Natural SUSY, Higgsino-like DM
difficult small mass splittings



1504.02472

LHC searches for DM

Focused on signatures of MET with very energetic, visible objects

Reach is complementary to direct detection and constrained by relic abundance

LHC may provide the first direct discovery of Dark Matter, or the LHC could adapt their program if XENON1T would claim discovery

LHC DM searches: more luminosity Run3-4-5 useful

Tomorrow's lecture (last)

A case study:
the diphoton excess at 750 GeV

aka an example of how the
LHC could change our view
of particle physics any time

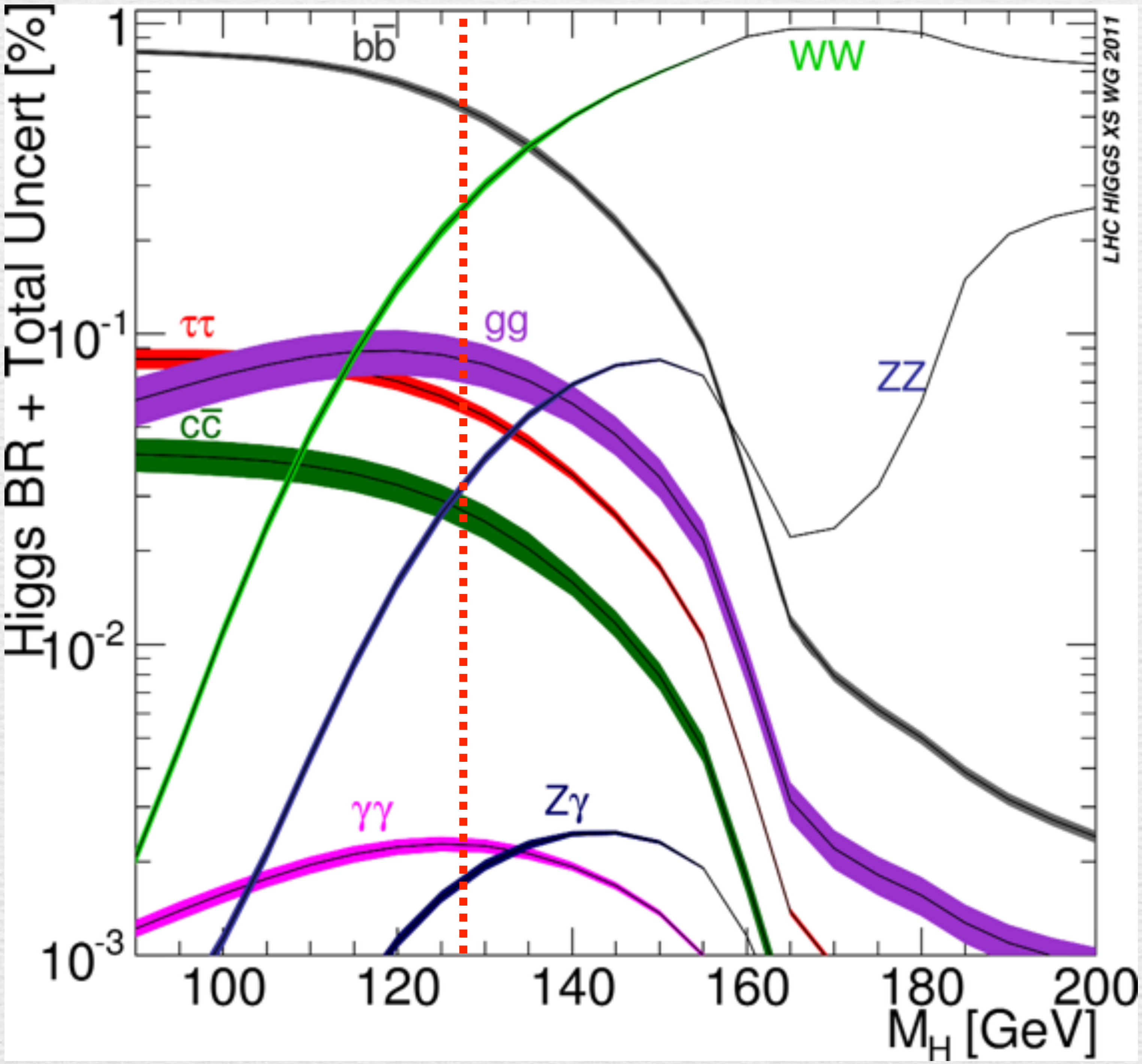
The diphoton excess

Warning! this talk
contains some distressing images

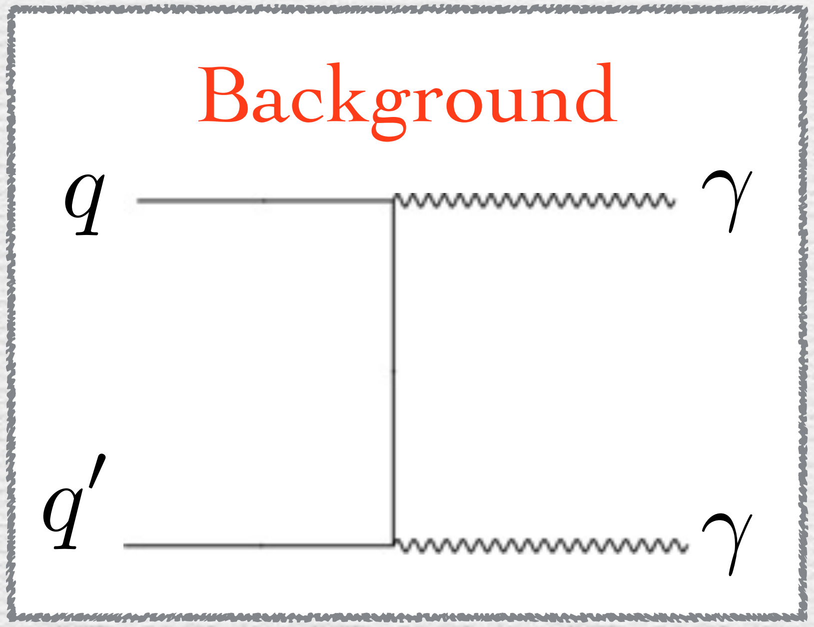
Let's go back to 2012
The discovery of the Higgs

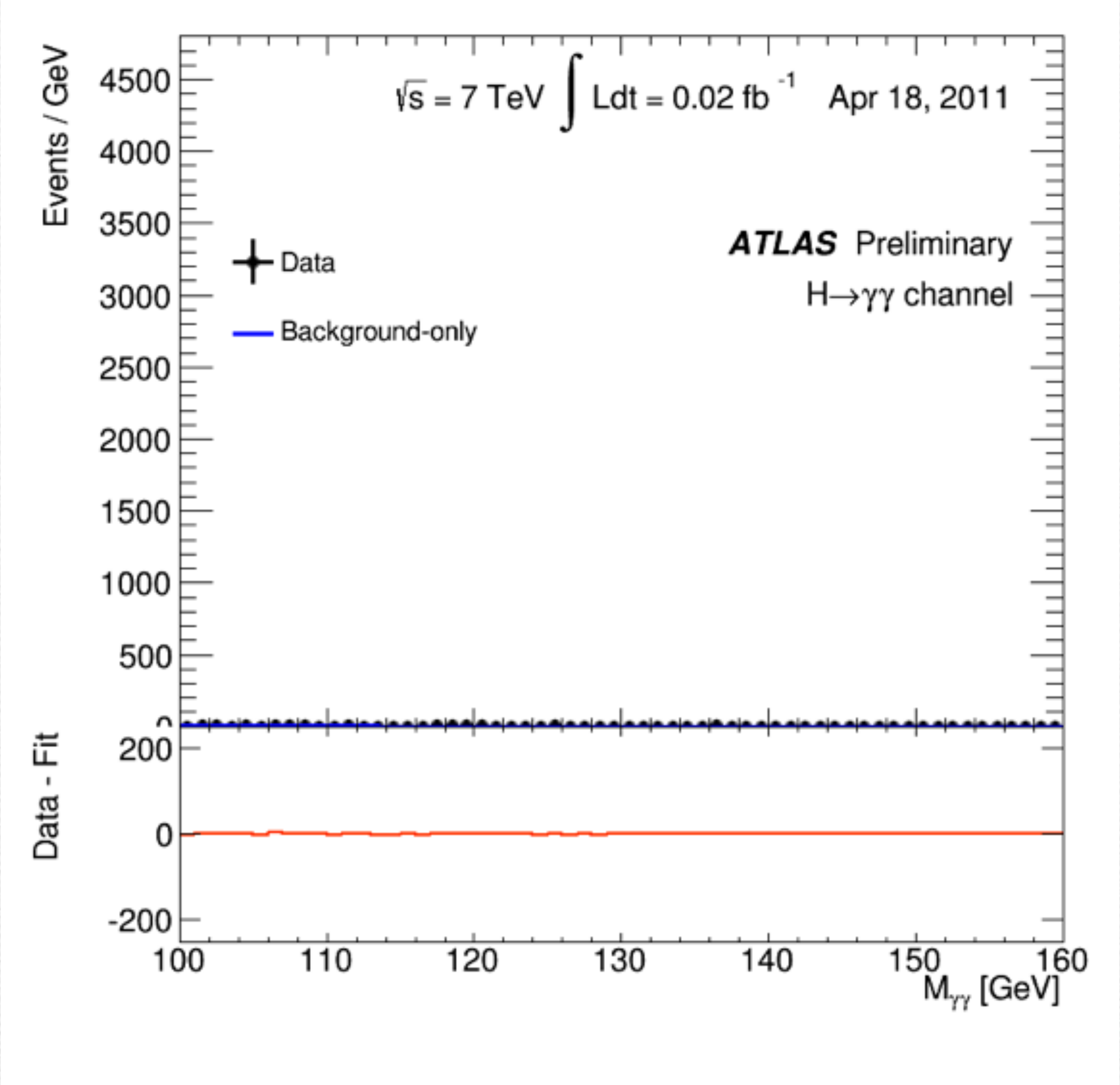
The discovery of the Higgs

diphoton channel

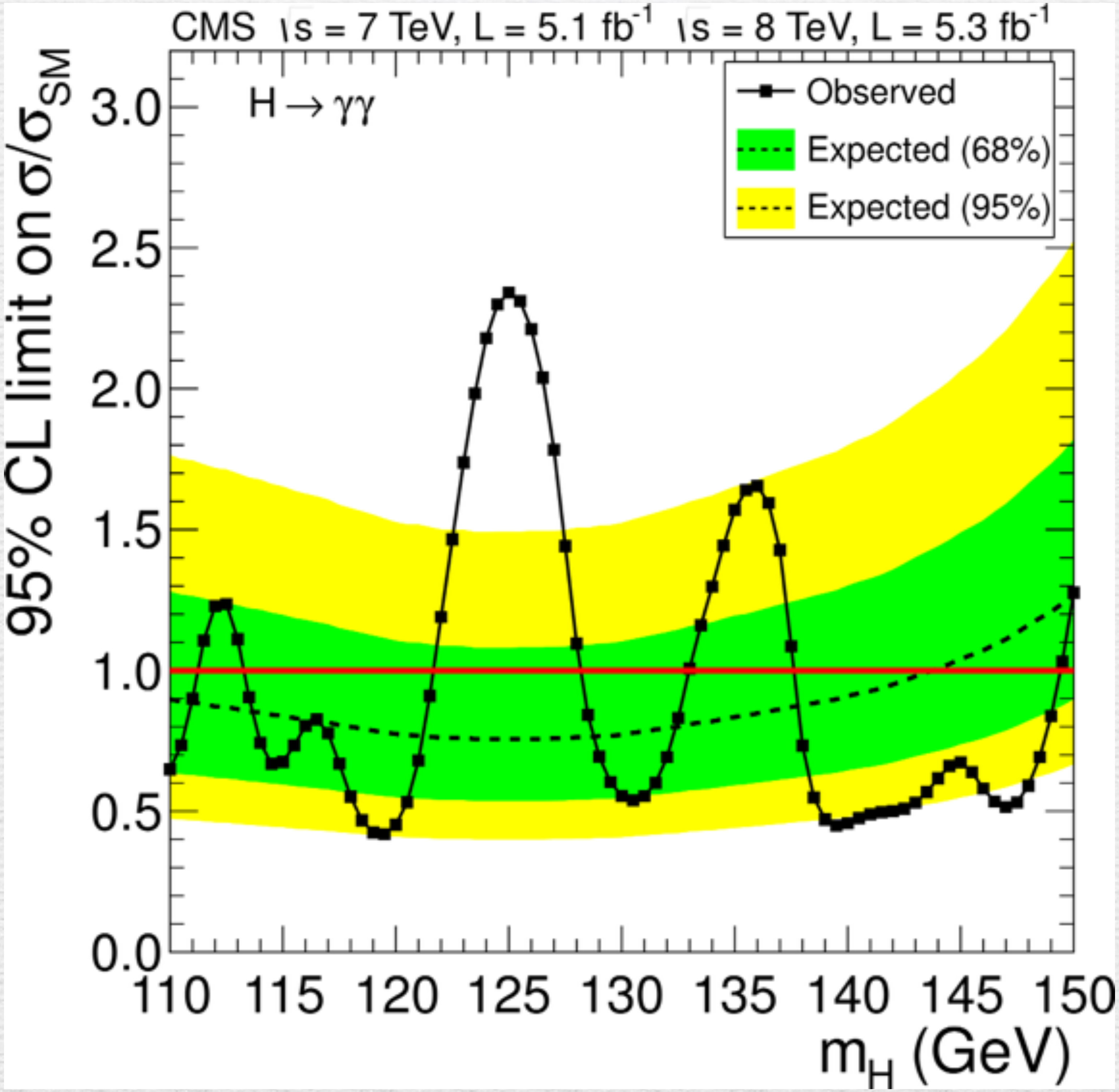


The discovery of the Higgs
diphoton channel





The discovery of the Higgs
brazilian plot

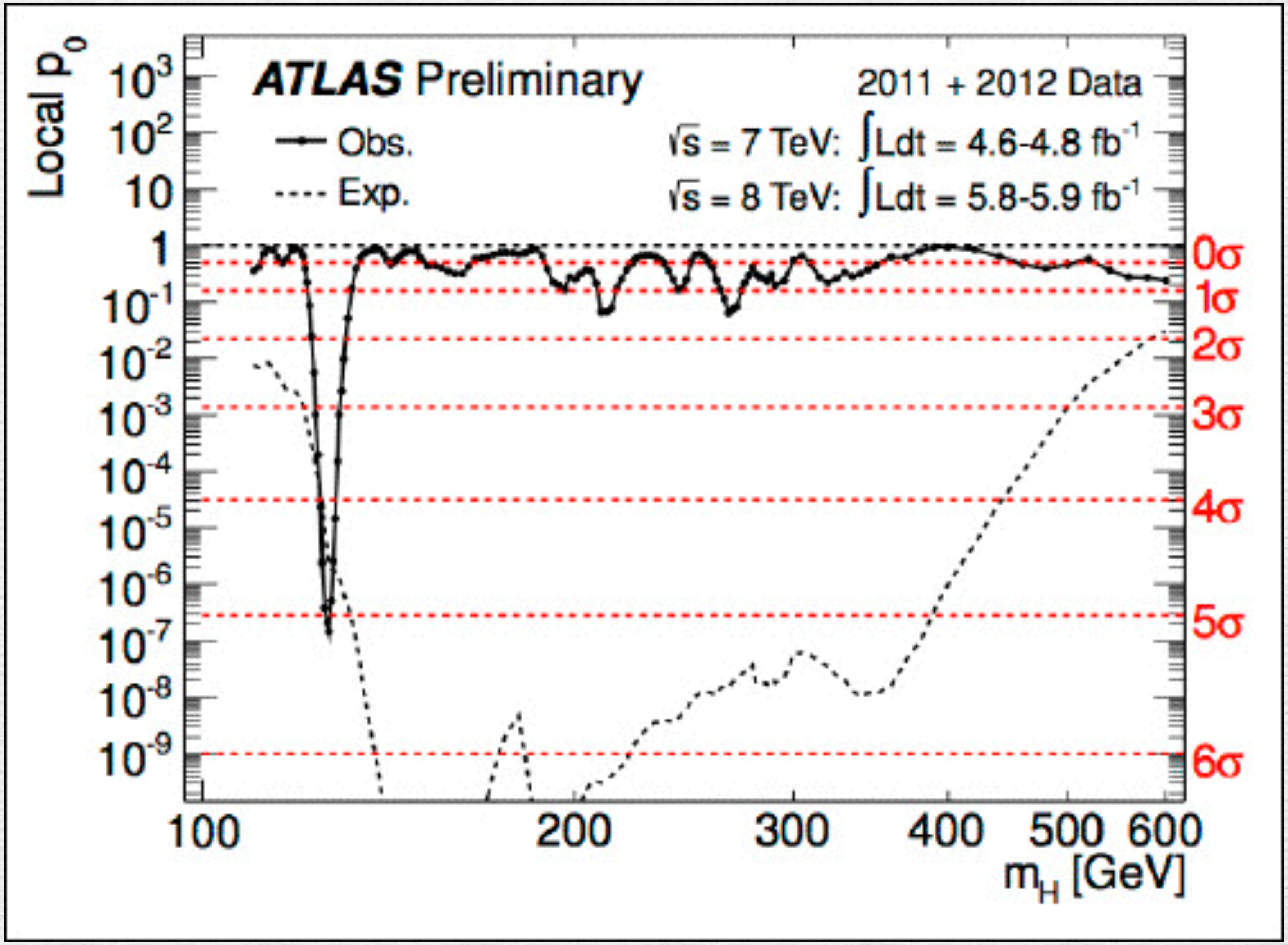


Sigmas

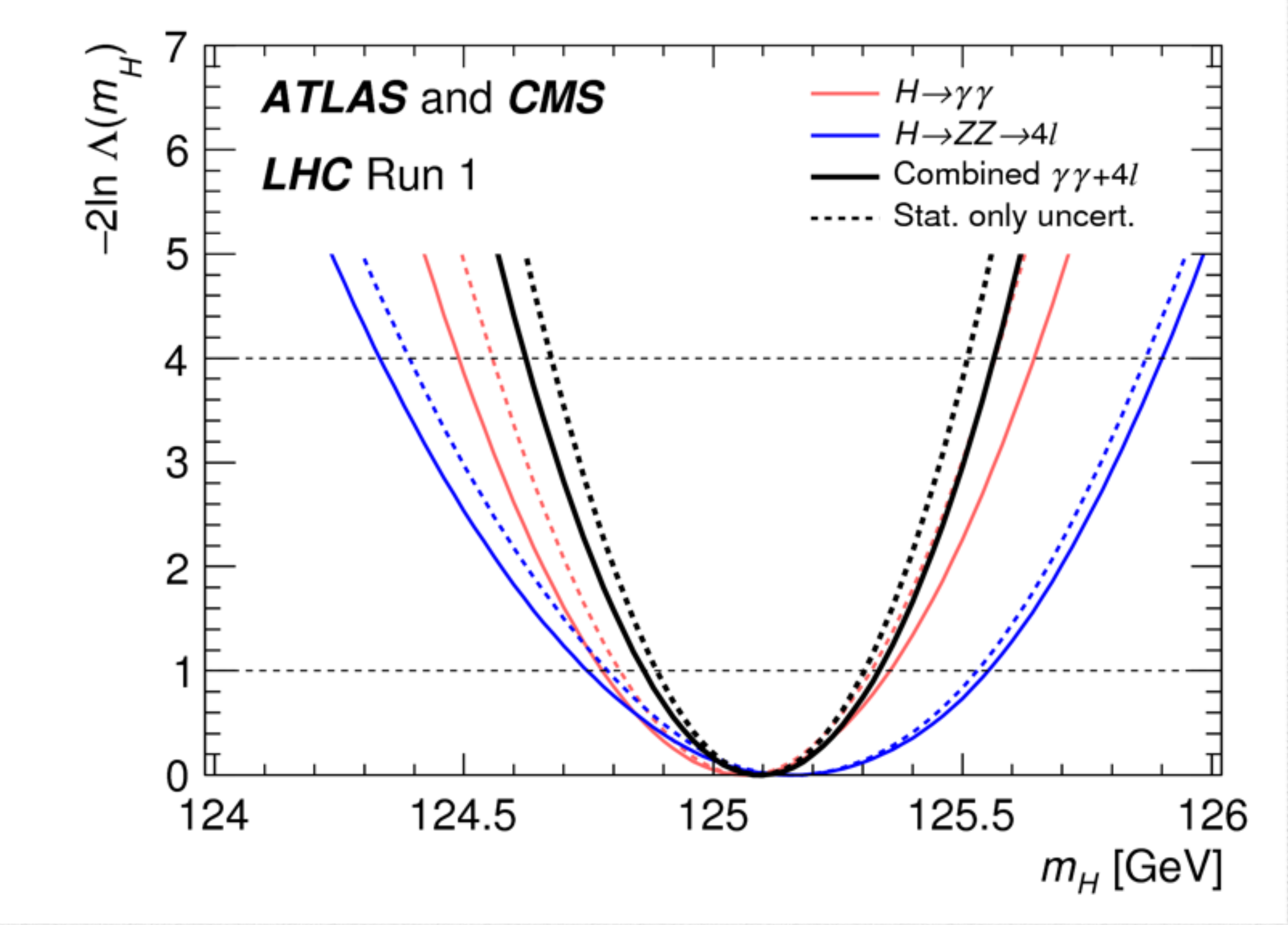
Statistical significance:

probability of some observed data compatible with the null hypotesis

one-sigma:
three-sigma:
five-sigma:



Resolution

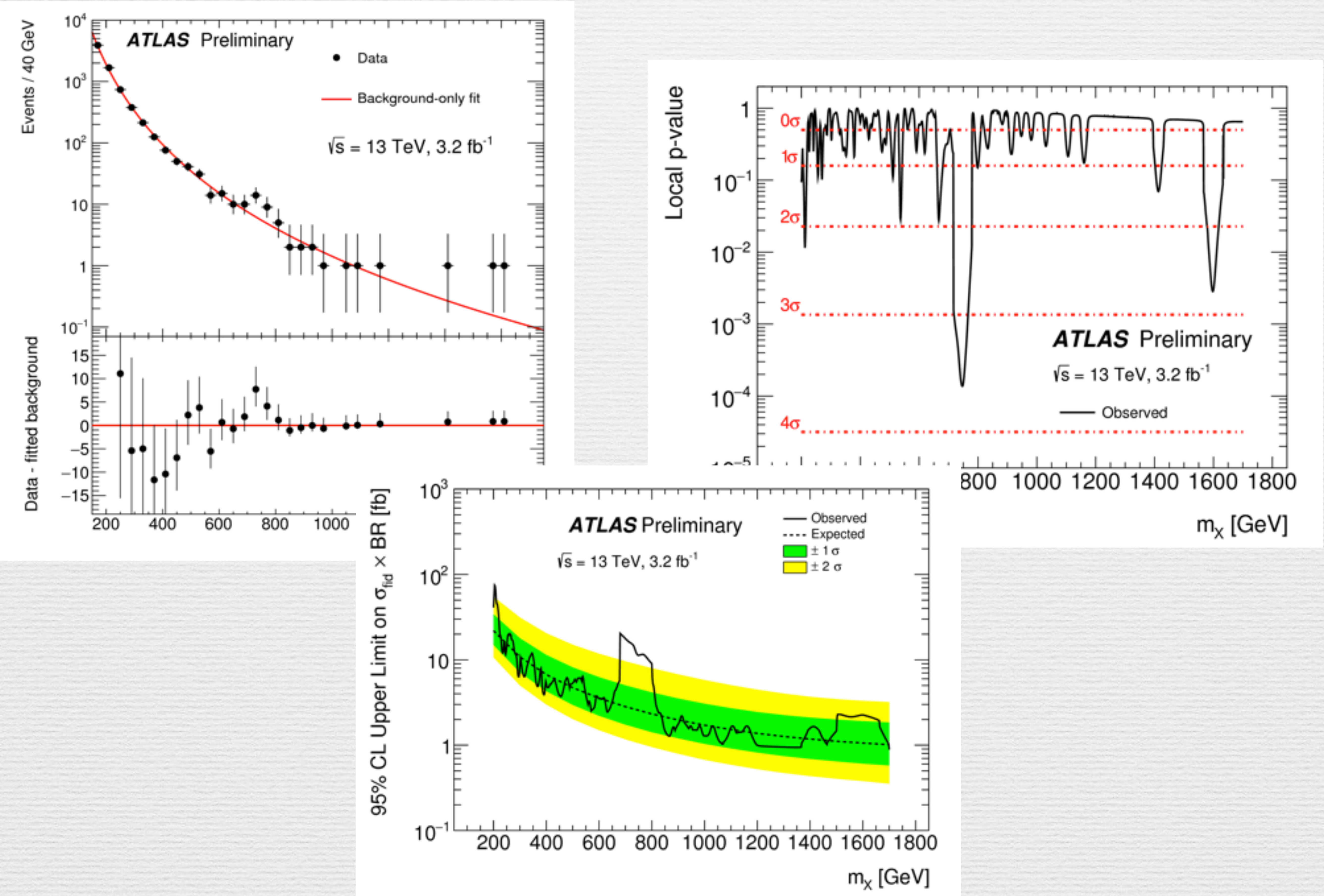


ATLAS and CMS
LHC Run 1
H→γγ
H→ZZ→4l
Combined γγ+4l
Stat. only uncert.
−2ln Λ(m_H)
m_H [GeV]
0
1
2
3
4
5
6
7
124
124.5
125
125.5
126

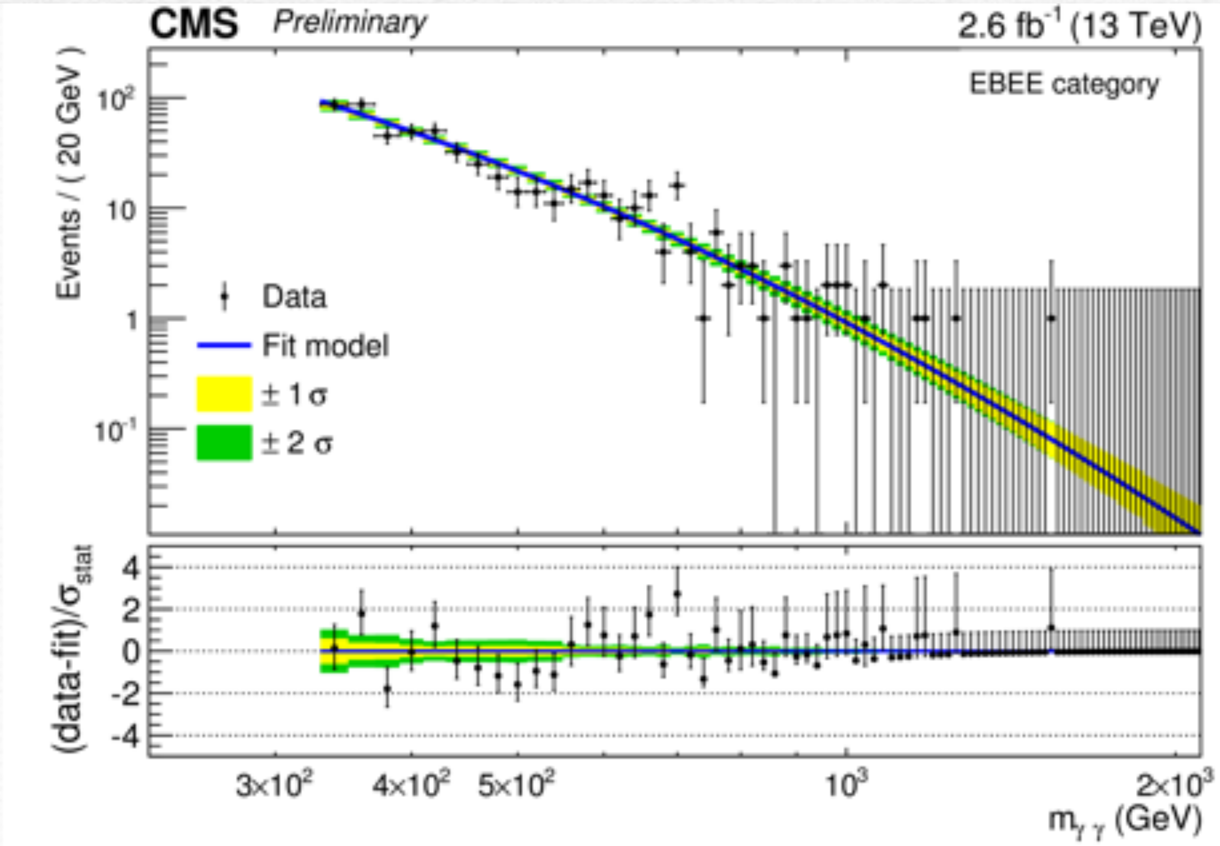
That was in 2012…

Two months ago
CERN council meeting Dec 15th

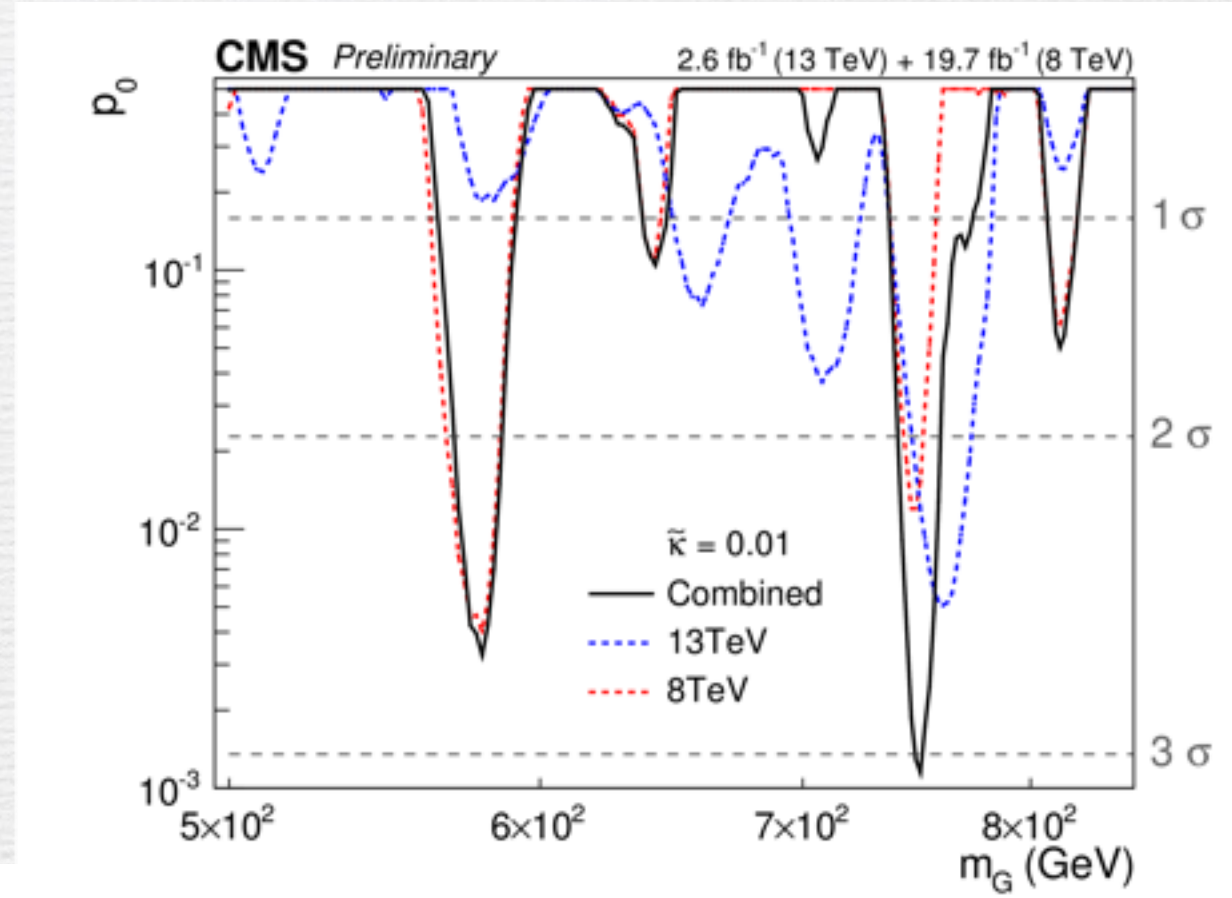
ATLAS


ATLAS Preliminary
Data
Background-only fit
√s = 13 TeV, 3.2 fb-1
Events / 40 GeV
Data - fitted background
Local p-value
0σ
1σ
2σ
3σ
4σ
Observed
mX [GeV]
Expected
± 1 σ
± 2 σ
95% CL Upper Limit on σfid × BR [fb]

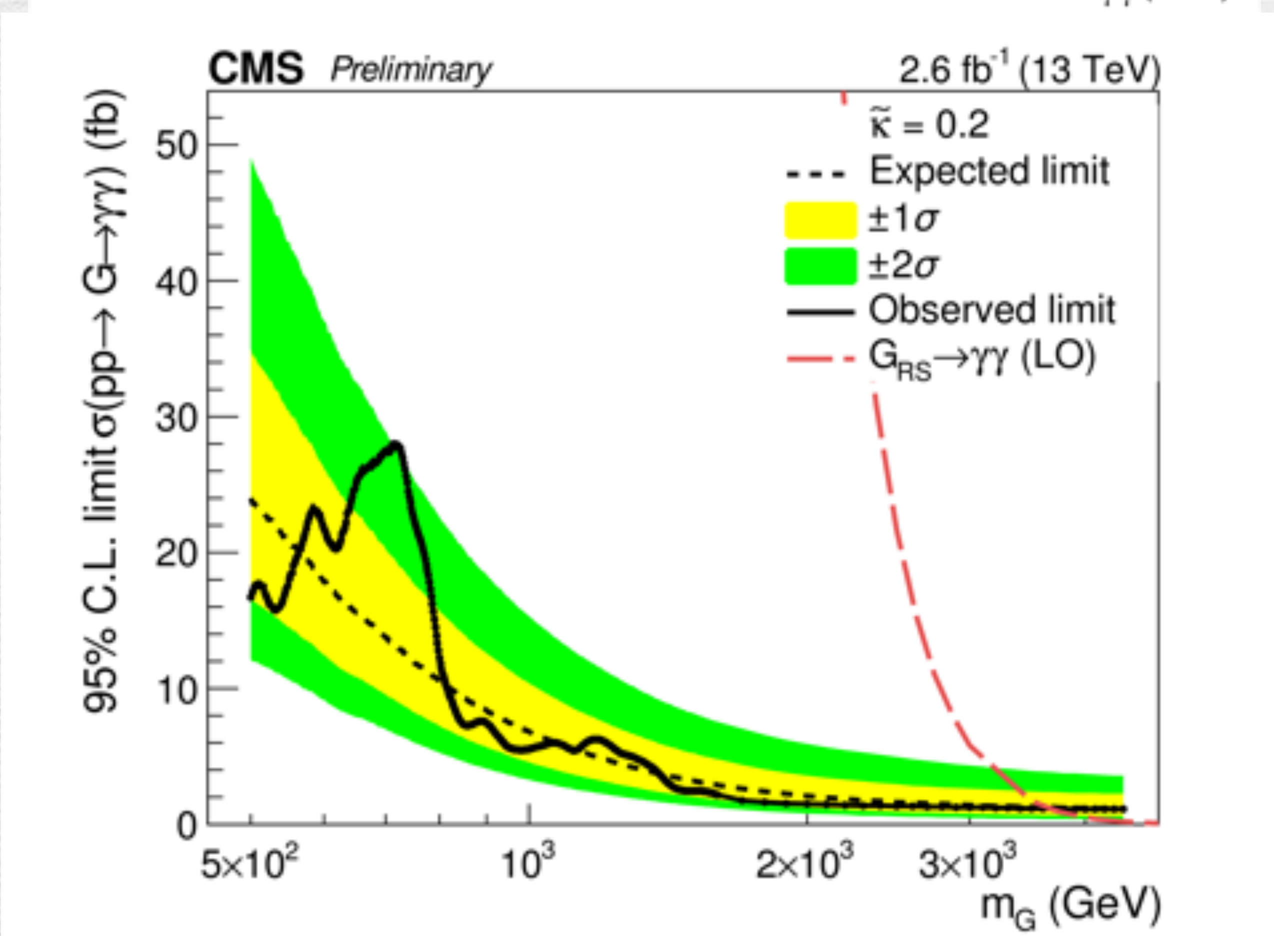
CMS



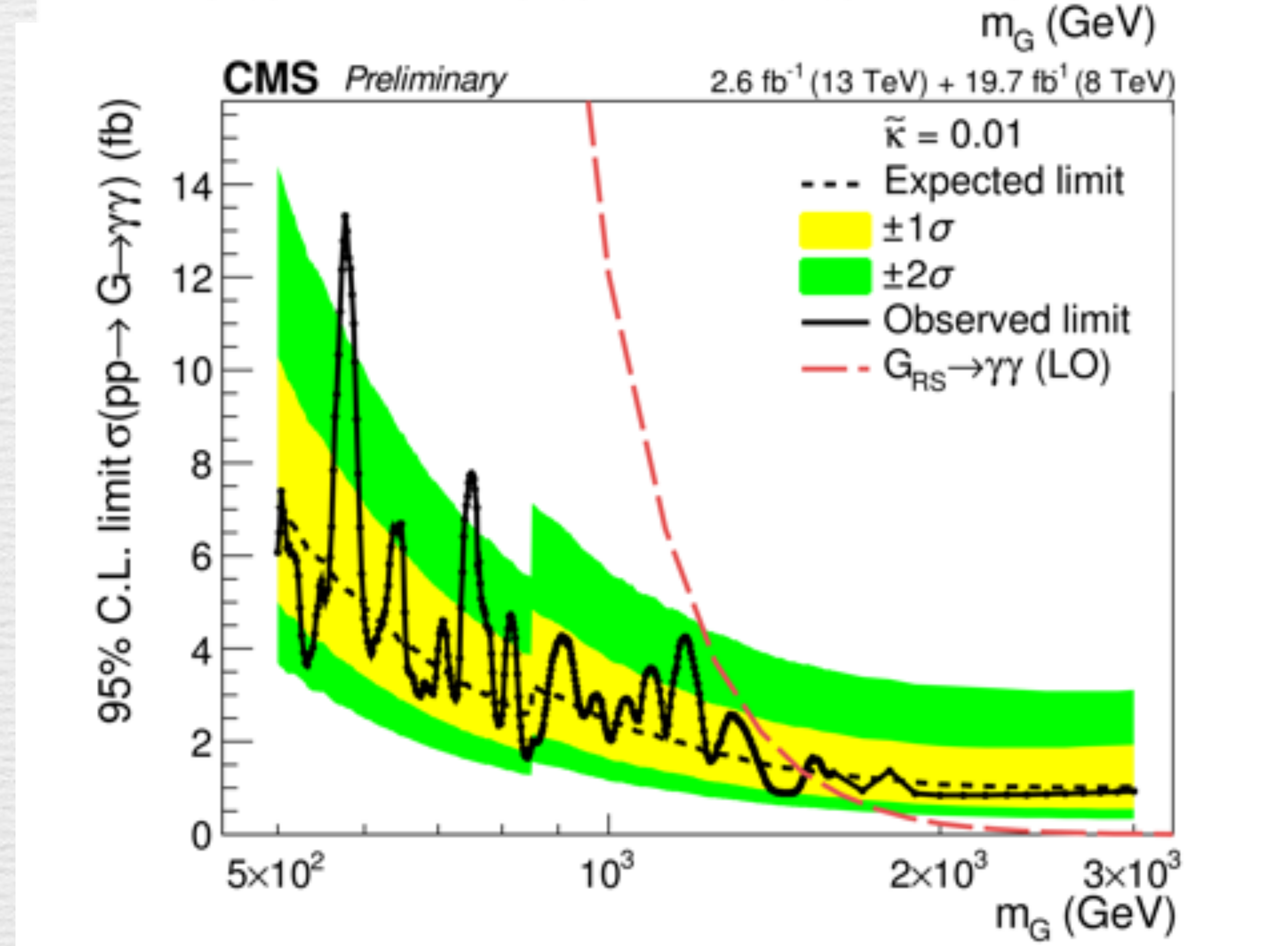
CMS Preliminary
2.6 fb-1 (13 TeV)
EBEE category
Events / (20 GeV)
Data
Fit model
± 1 σ
± 2 σ
(data-fit)/σstat
3×10²
4×10²
5×10²
10³
2×10³
mγγ (GeV)



CMS Preliminary
2.6 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
p0
1 σ
2 σ
3 σ
κ̃ = 0.01
Combined
13TeV
8TeV
5×10²
6×10²
7×10²
8×10²
mG (GeV)



CMS Preliminary
2.6 fb-1 (13 TeV)
κ̃ = 0.2
Expected limit
±1σ
±2σ
Observed limit
GRS→γγ (LO)
95% C.L. limit σ(pp→ G→γγ) (fb)
5×10²
10³
2×10³
3×10³
mG (GeV)



CMS Preliminary
2.6 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
κ̃ = 0.01
Expected limit
±1σ
±2σ
Observed limit
GRS→γγ (LO)
95% C.L. limit σ(pp→ G→γγ) (fb)
5×10²
10³
2×10³
3×10³
mG (GeV)

CMS

quite different

CMS

ATLAS

CMS

different treatment of backgrounds

Are CMS and ATLAS excesses compatible?

position of the peak: yes
strength of the peak?

Are CMS and ATLAS excesses compatible?

position of the peak: yes
strength of the peak?

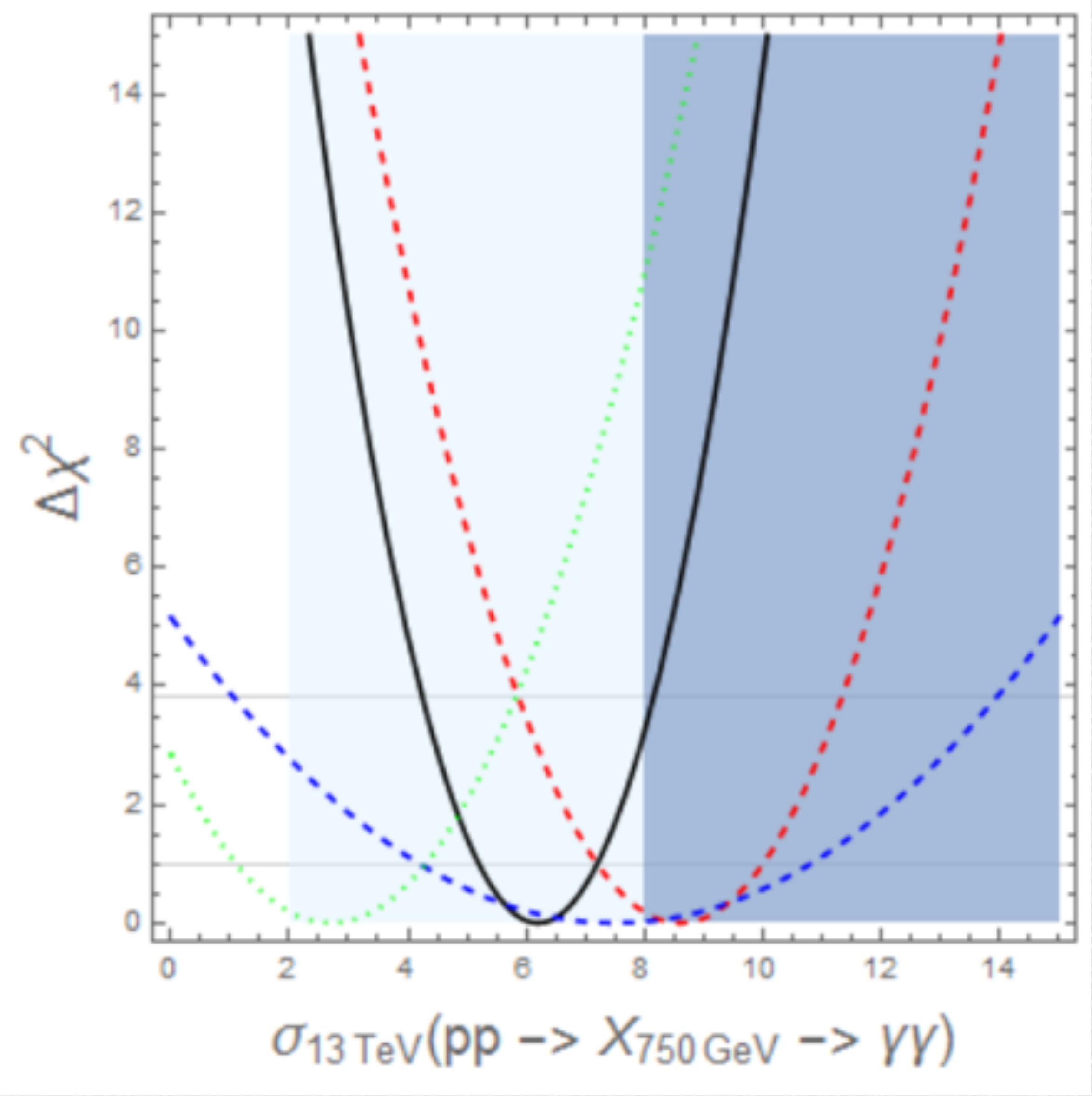
ATLAS
Run2

theorist's combination
local significance

best fit

6.2 ± 1.0 (fb)

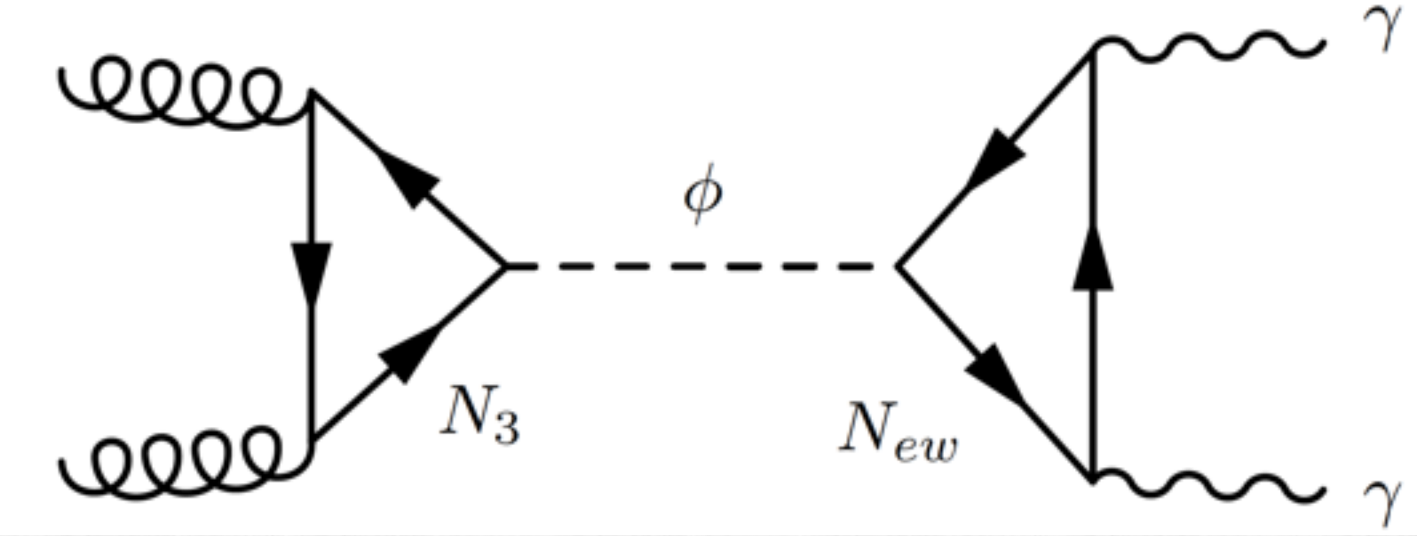
which means $> 5\sigma$



1512.05327

What is it, if anything?

maybe a scalar coupled to vector-like fermions?



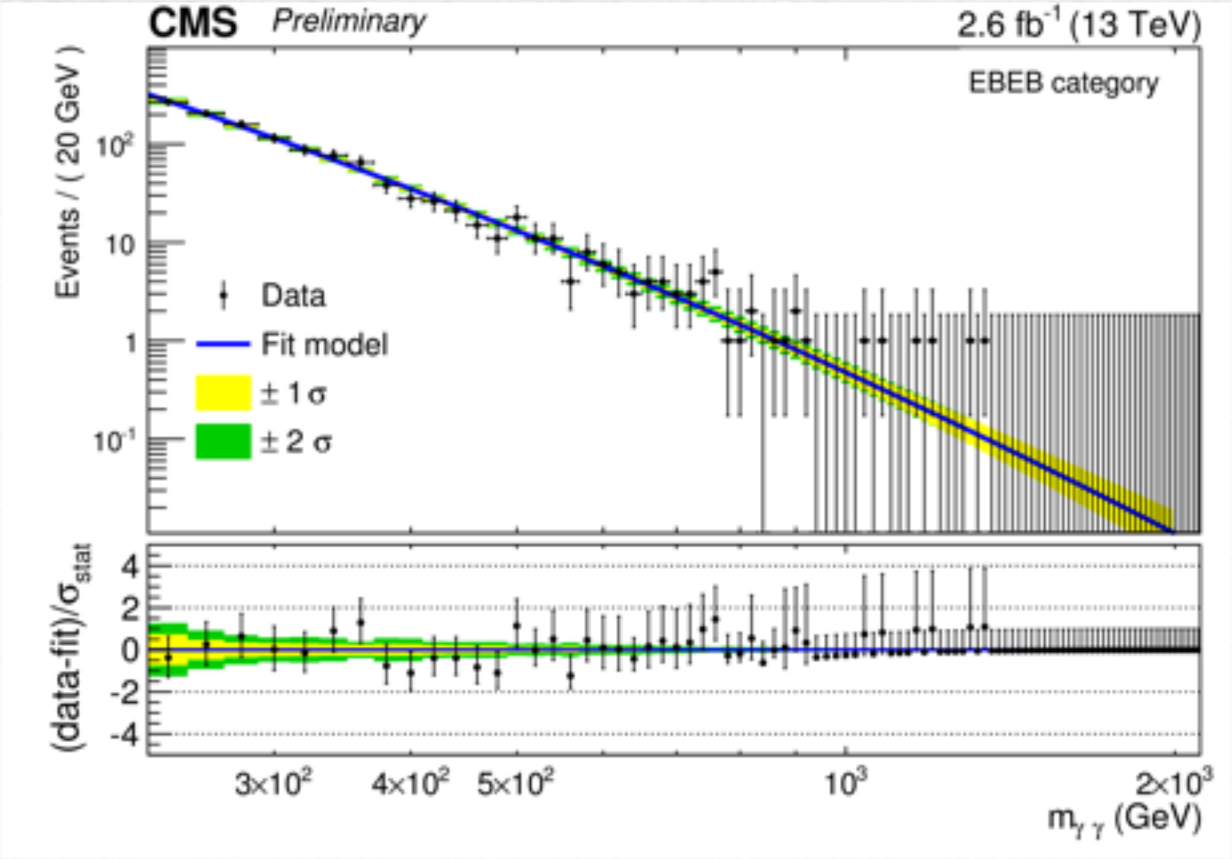
SUSY, Composite scalar?

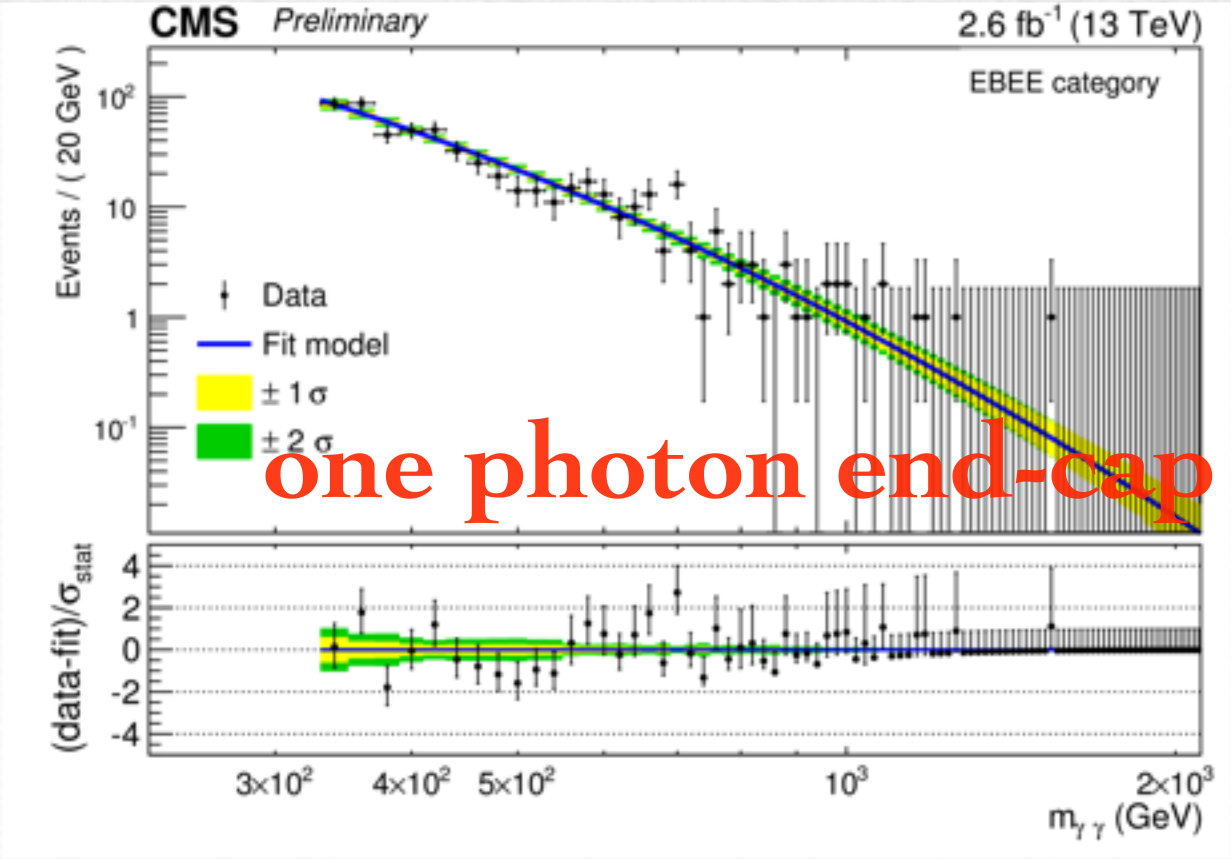
maybe it is not a scalar?

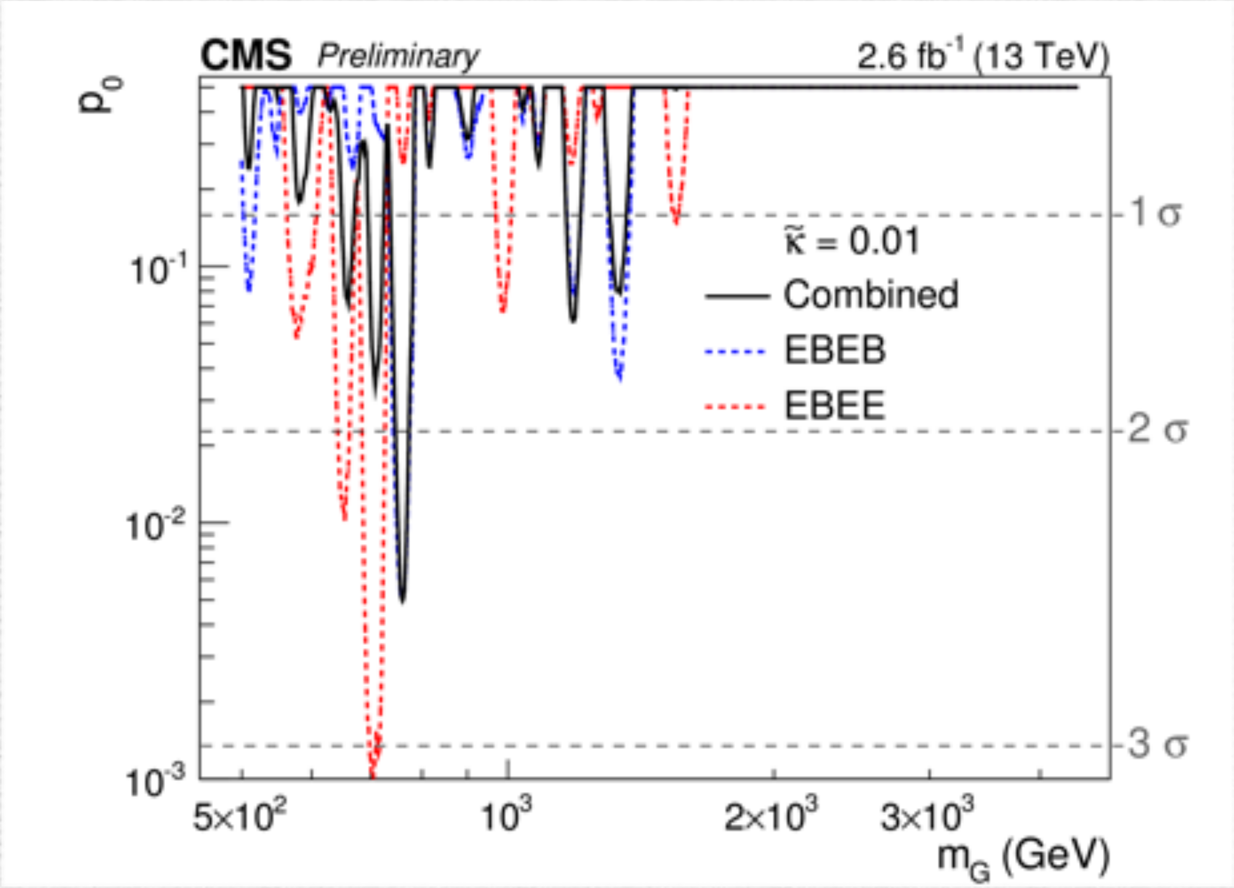
most likely, it is not a heavy higgs
from a 2HDM (SUSY or otherwise)

many theory explanations,
need more information to advance

Things to keep in mind

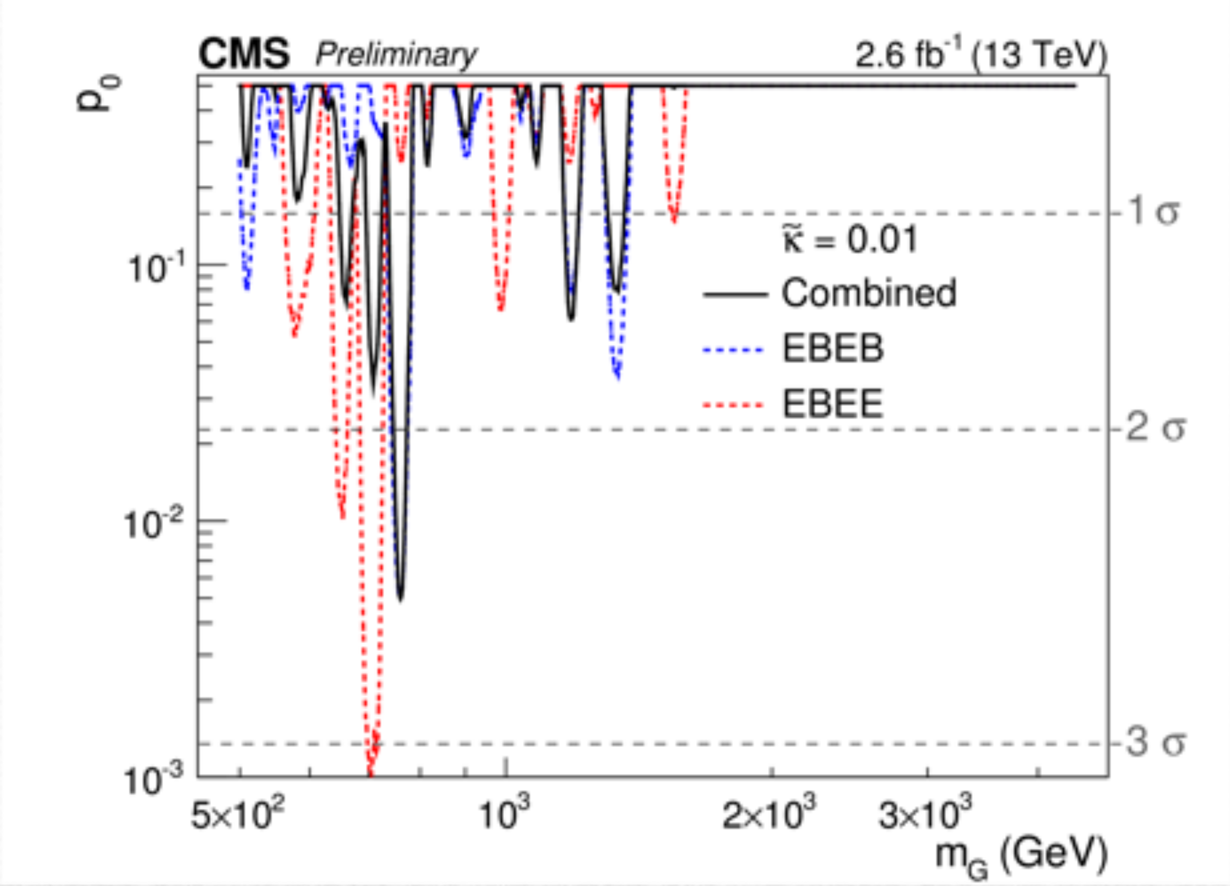






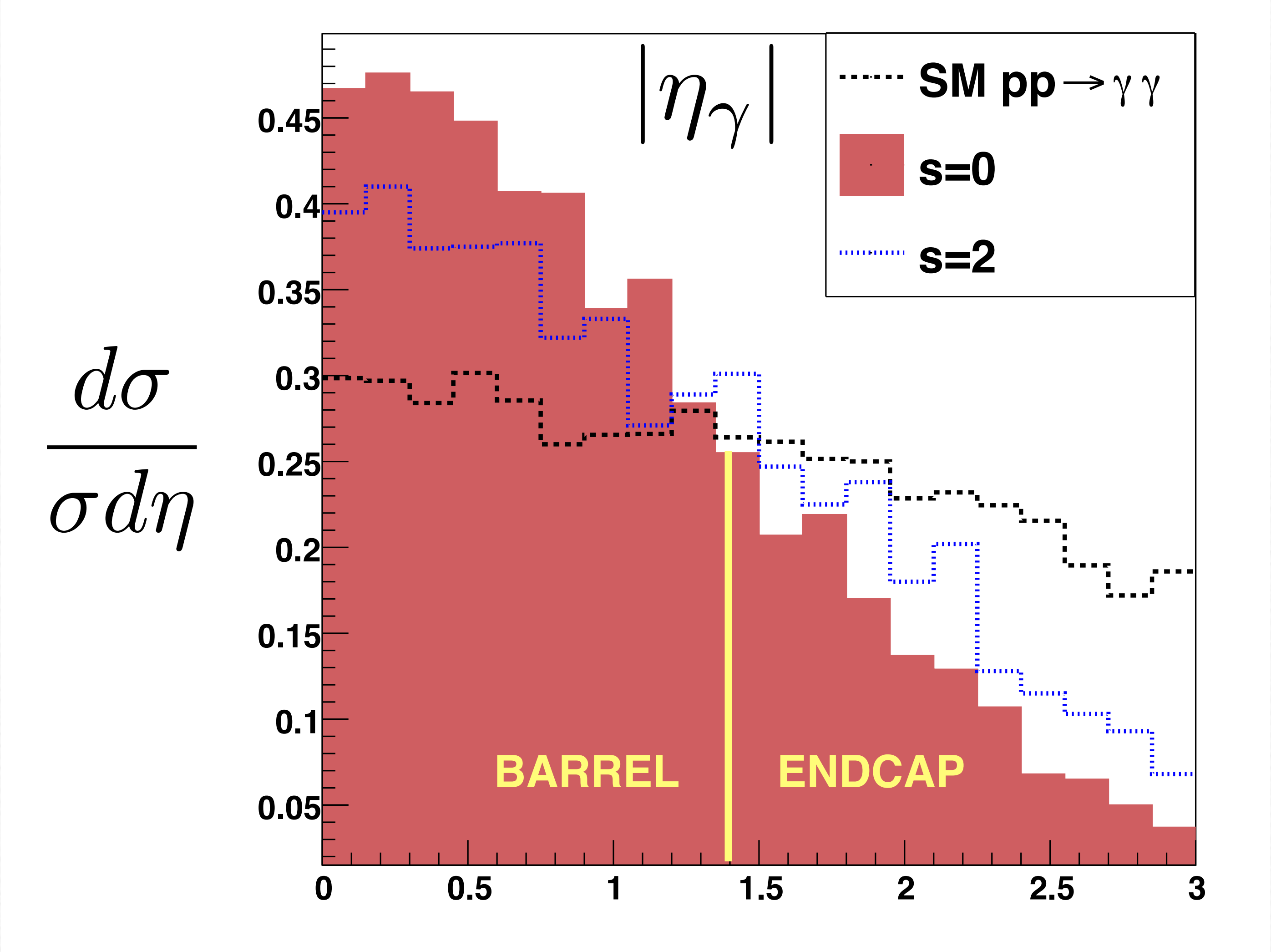
ATLAS
no public results

Things to keep in mind

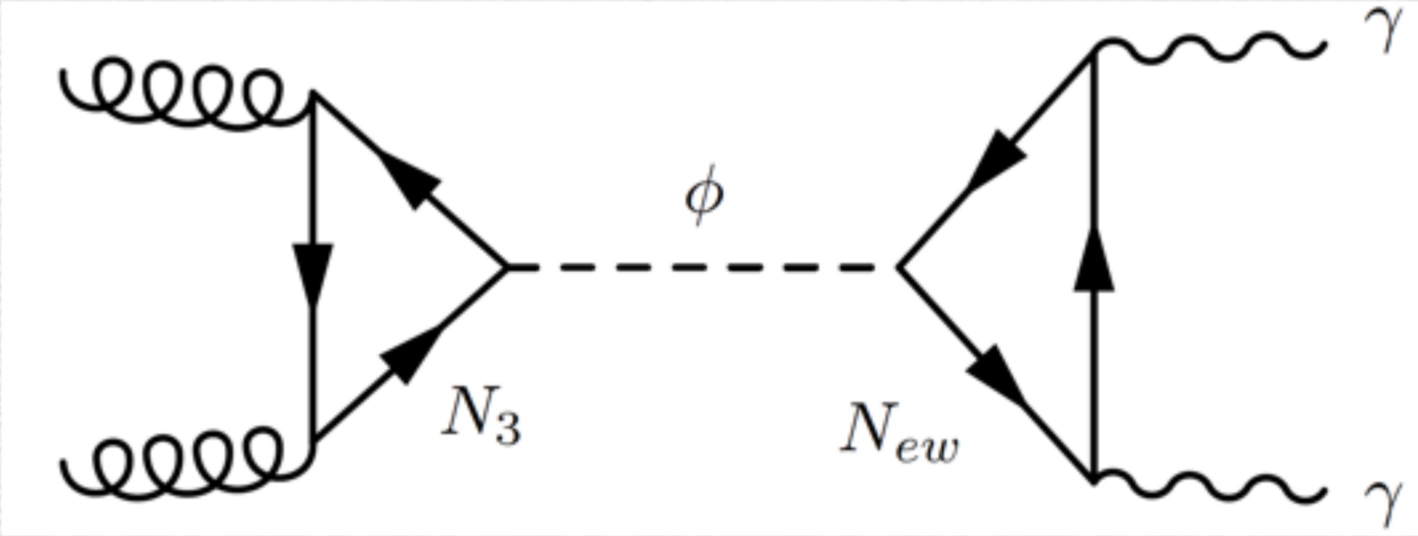


maybe a signature of spin

1512.06376



Things to keep in mind



likely to be seen it in other channels with vector bosons
WW, ZZ, Z-photon
compatible with diphoton first

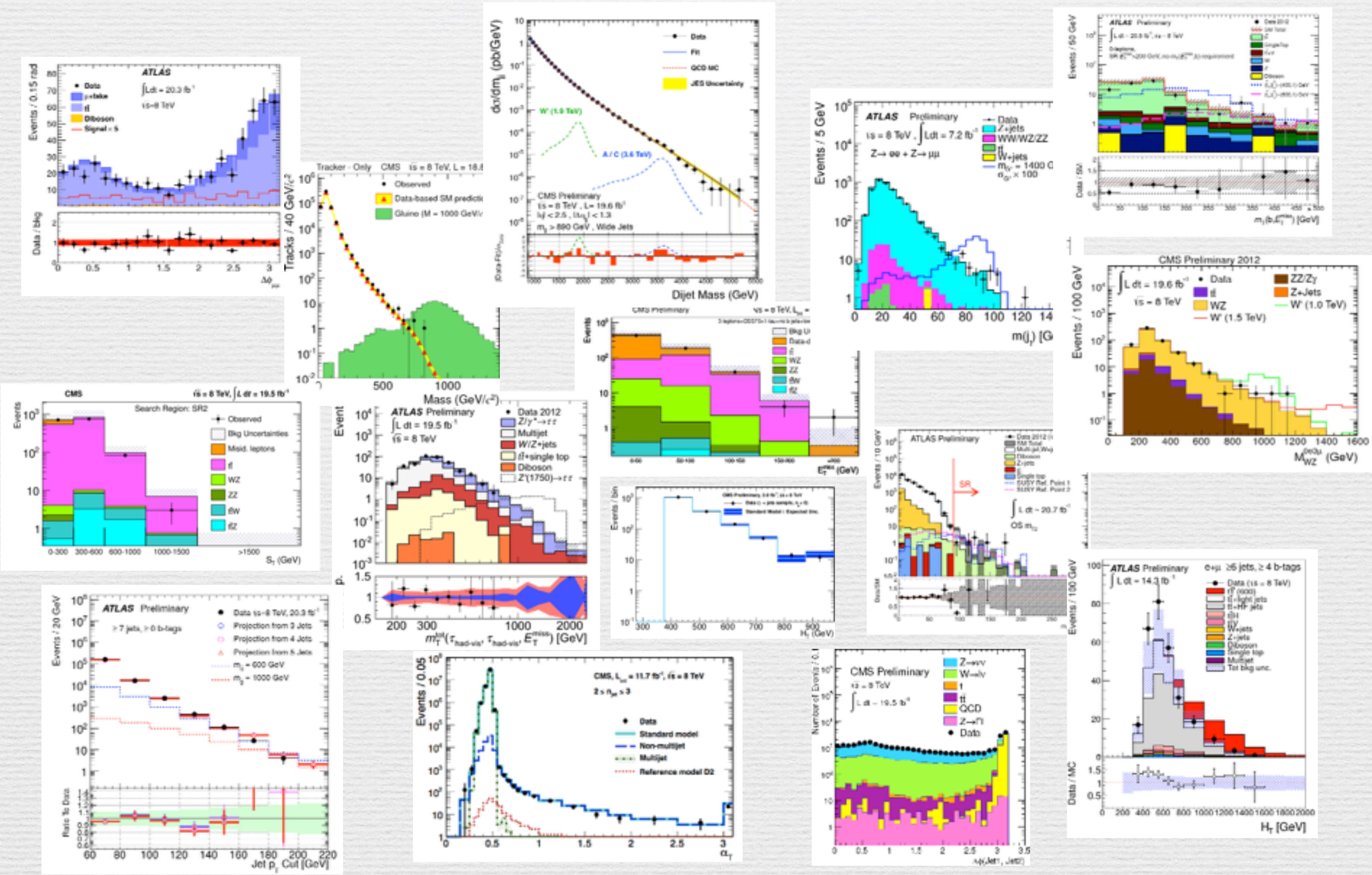
update in Moriond? (end of March)

and, new data Easter-Summer: ICHEP August 2-9

Things to keep in mind

local

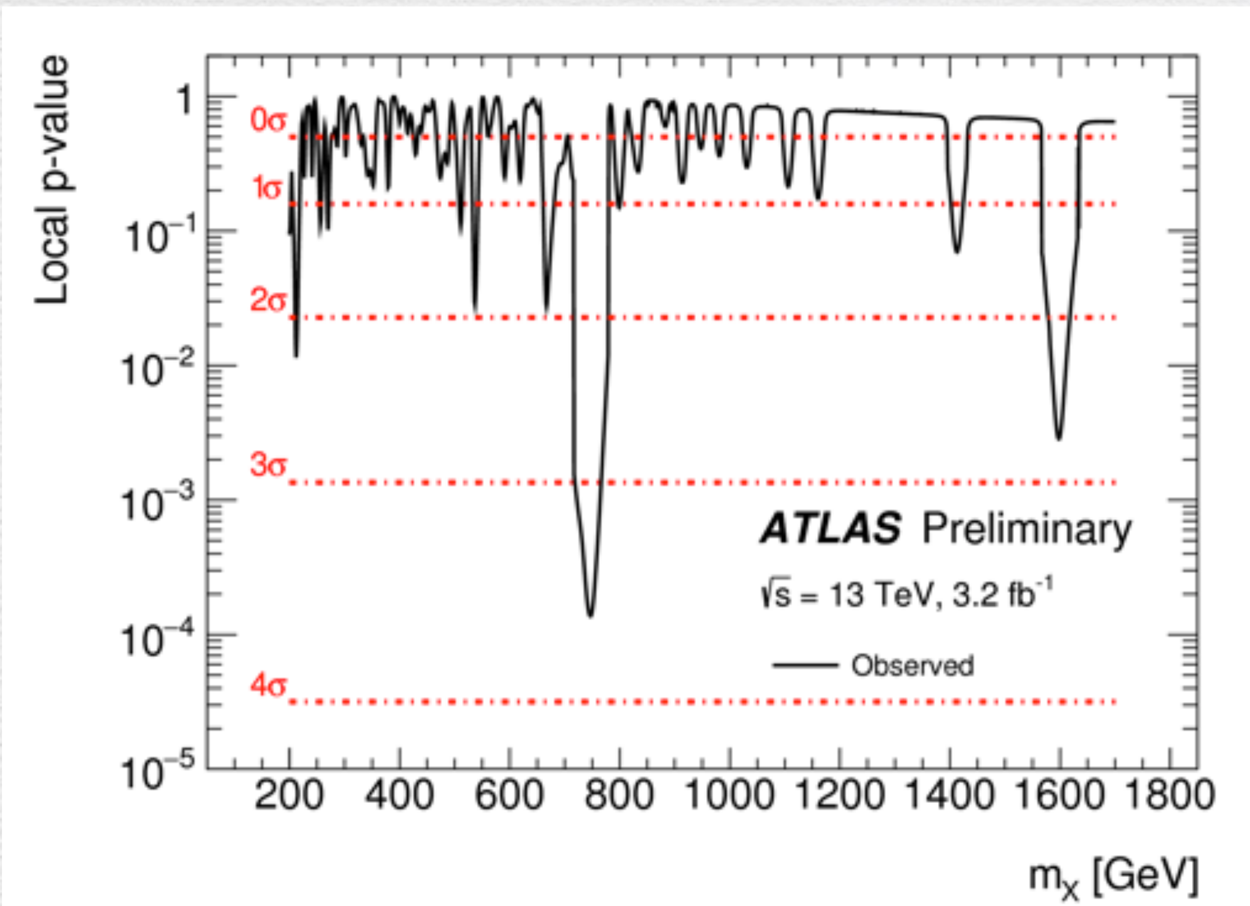
Look elsewhere effect (LEE)

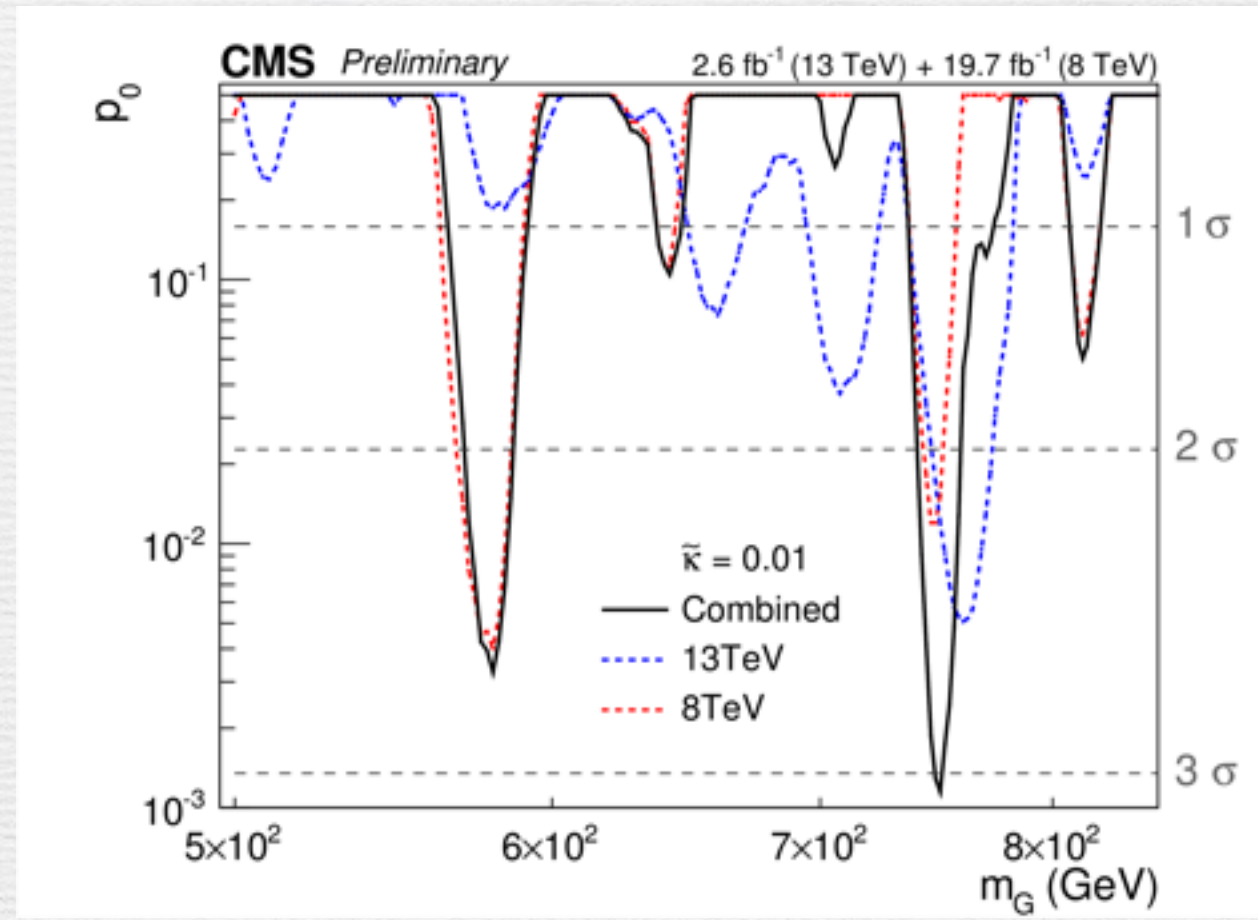


Things to keep in mind

local

Look elsewhere effect (LEE)





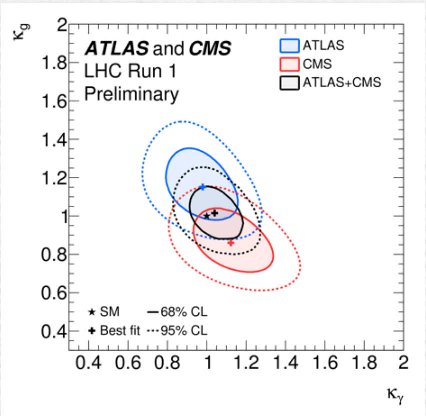
local significance to global
LEE: apply it to the combination

best fit

$$6.2 \pm 1.0 \ (\text{fb})$$

which means $> 5\sigma$

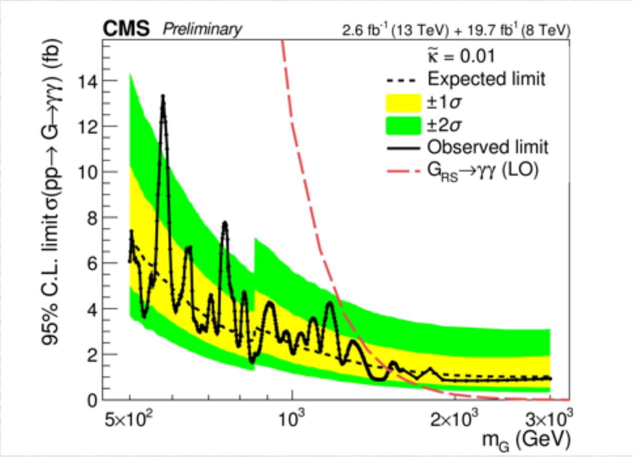
Models at the LHC



LHC Run1

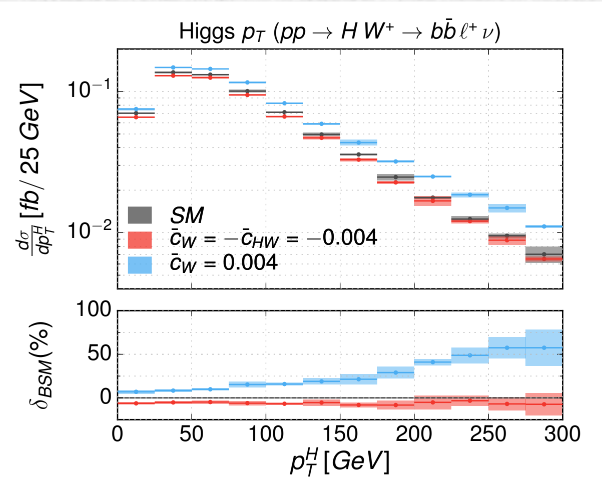
discovery of the Higgs

strong constraints on NP



LHC Run2

energy increase, heavy resonances



LHC now and beyond

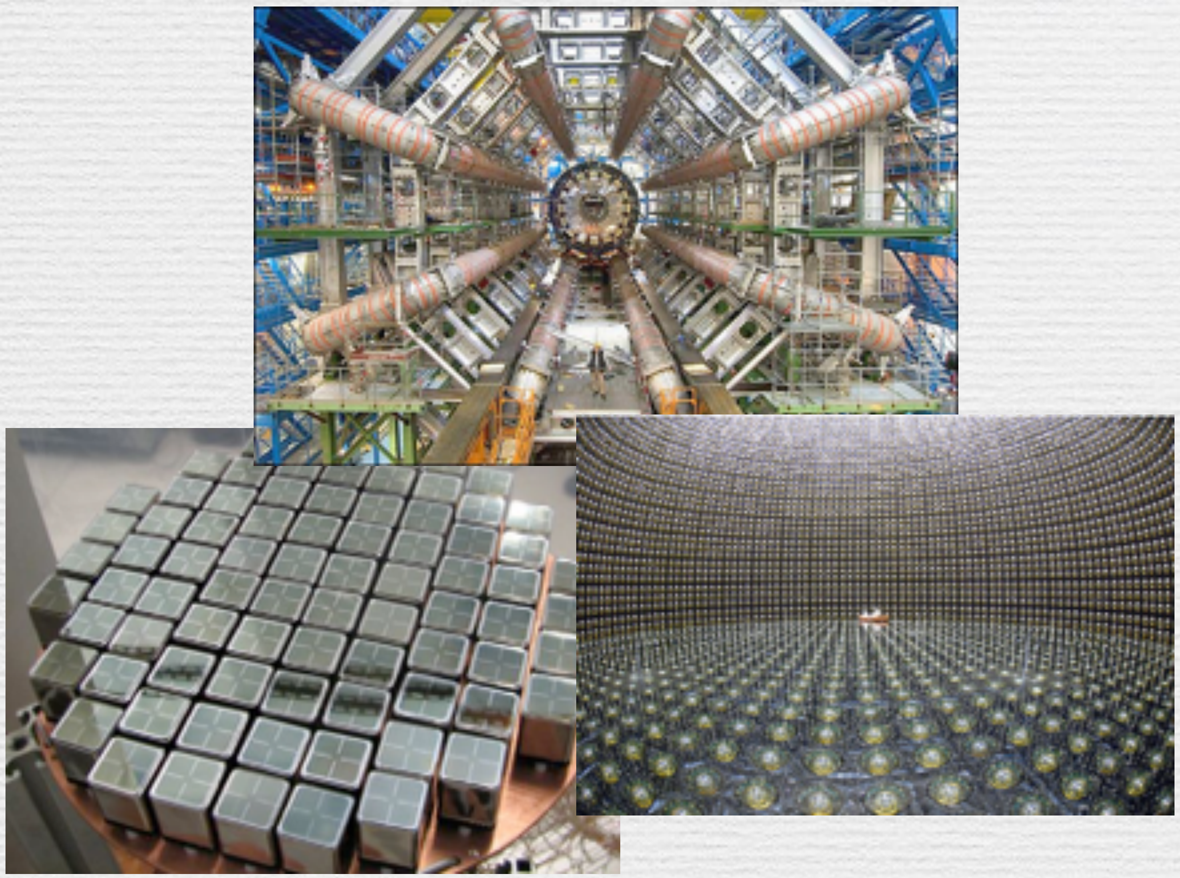
precision-> indirect searches (EFT)

Higgs as a messenger of NP

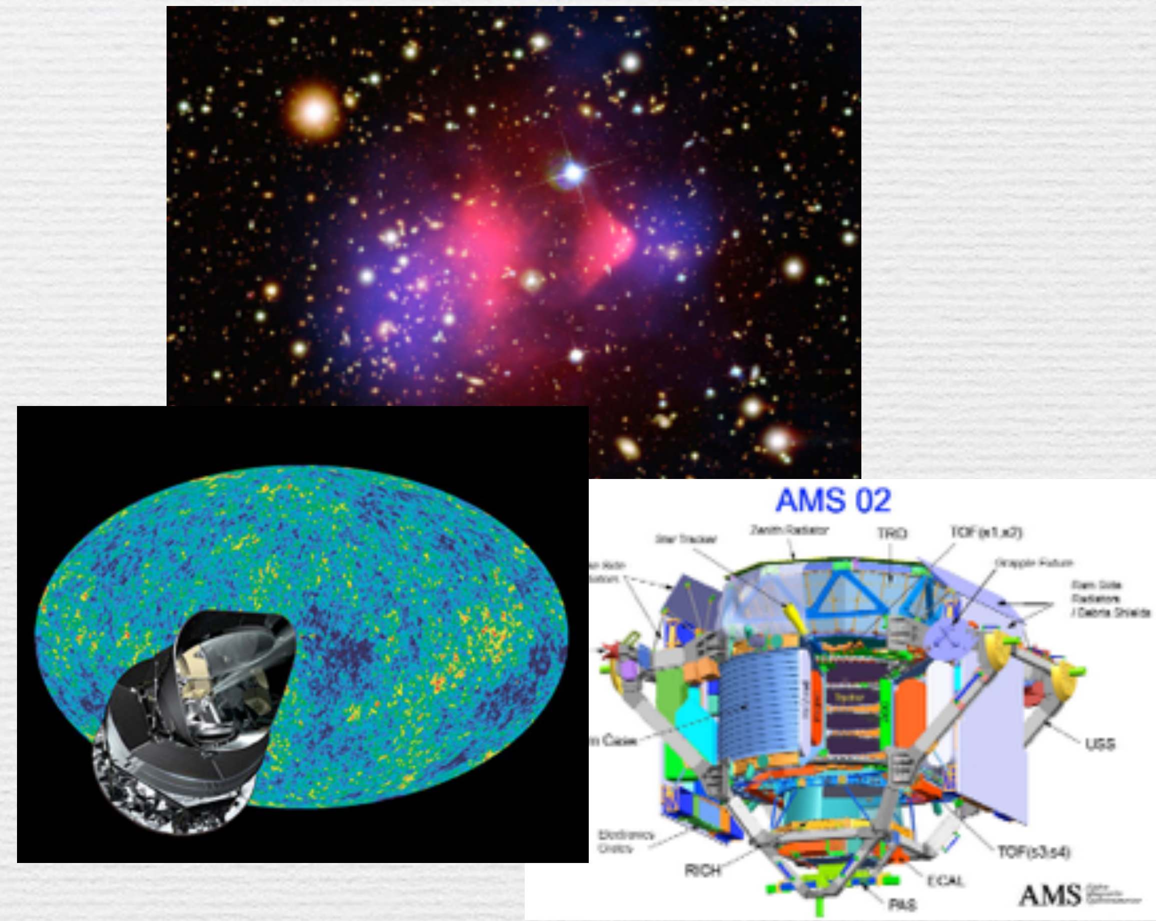
Dark Matter

Models at the LHC and beyond

EARTH



SPACE



next discovery may come from any front

understand discovery in a unified framework

characterization will use all sources of data