Physics of LHC

Seongchan Park (SKKU)

10th Saga-Yonsei workshop on Particle Physics,
13-17 Jan, 2014

Ask questions!

Disclaimer

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- **Again, ask questions! Let’s discuss!**

Plan

- A theorist's introduction to LHC physics
- Physics learned from the LHC so far
- Some speculations about BSM
- Conclusion

LHC: Large Hadron Collider

Q. Why large?

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LHC: Large Hadron Collider

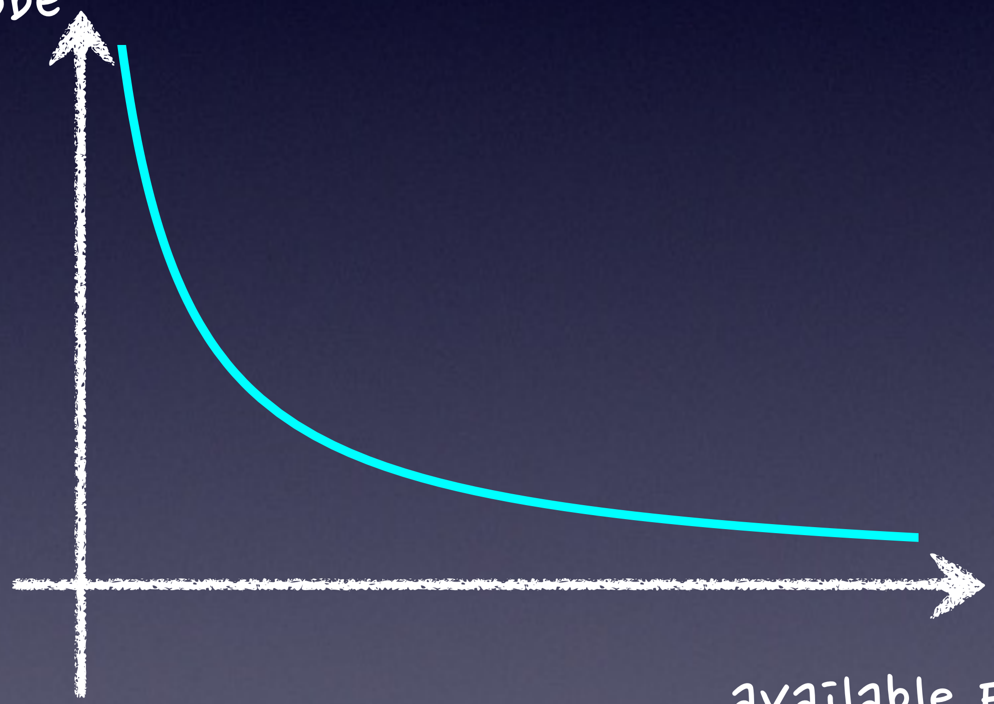
Q. Why not electron?

Why large?

The uncertainty principle

$$\Delta x \geq \hbar / \Delta p$$

Why large?



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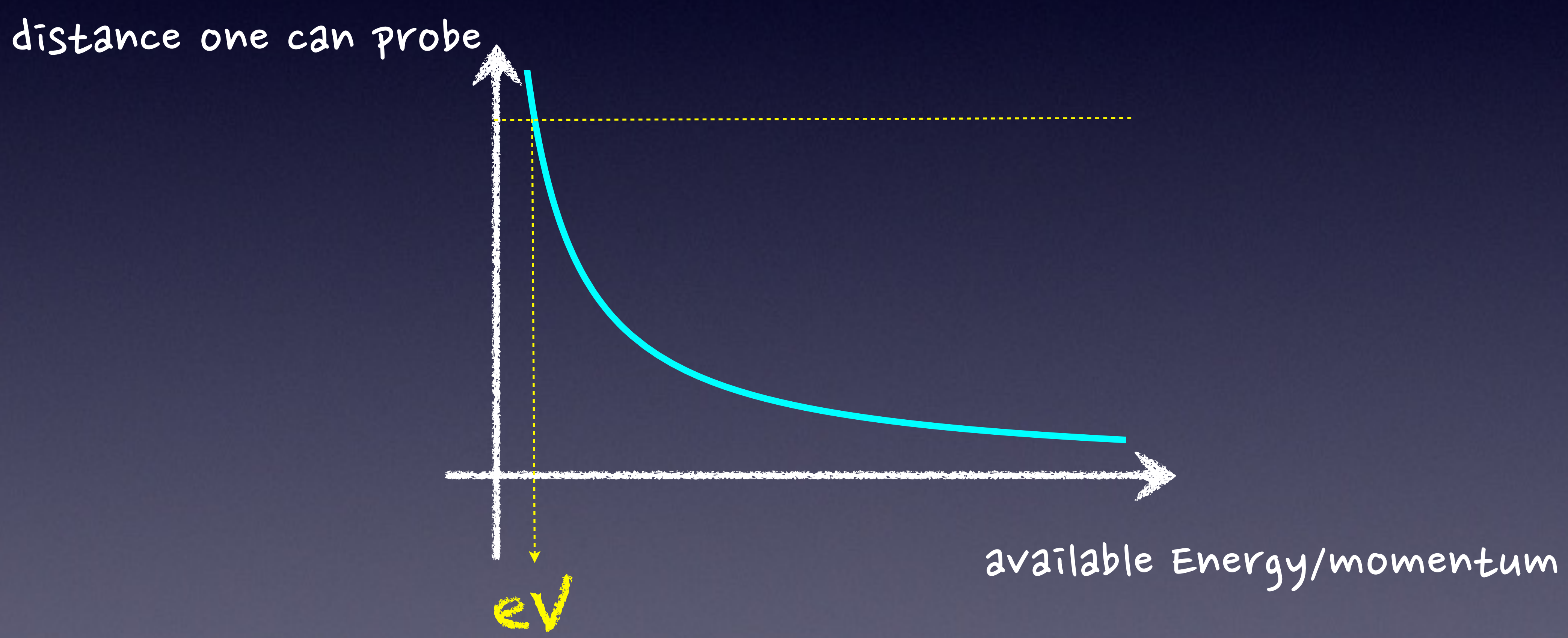
★~1900 reached atomic scale 10^{-8}cm≈$1/(\alpha^2 m_e)$



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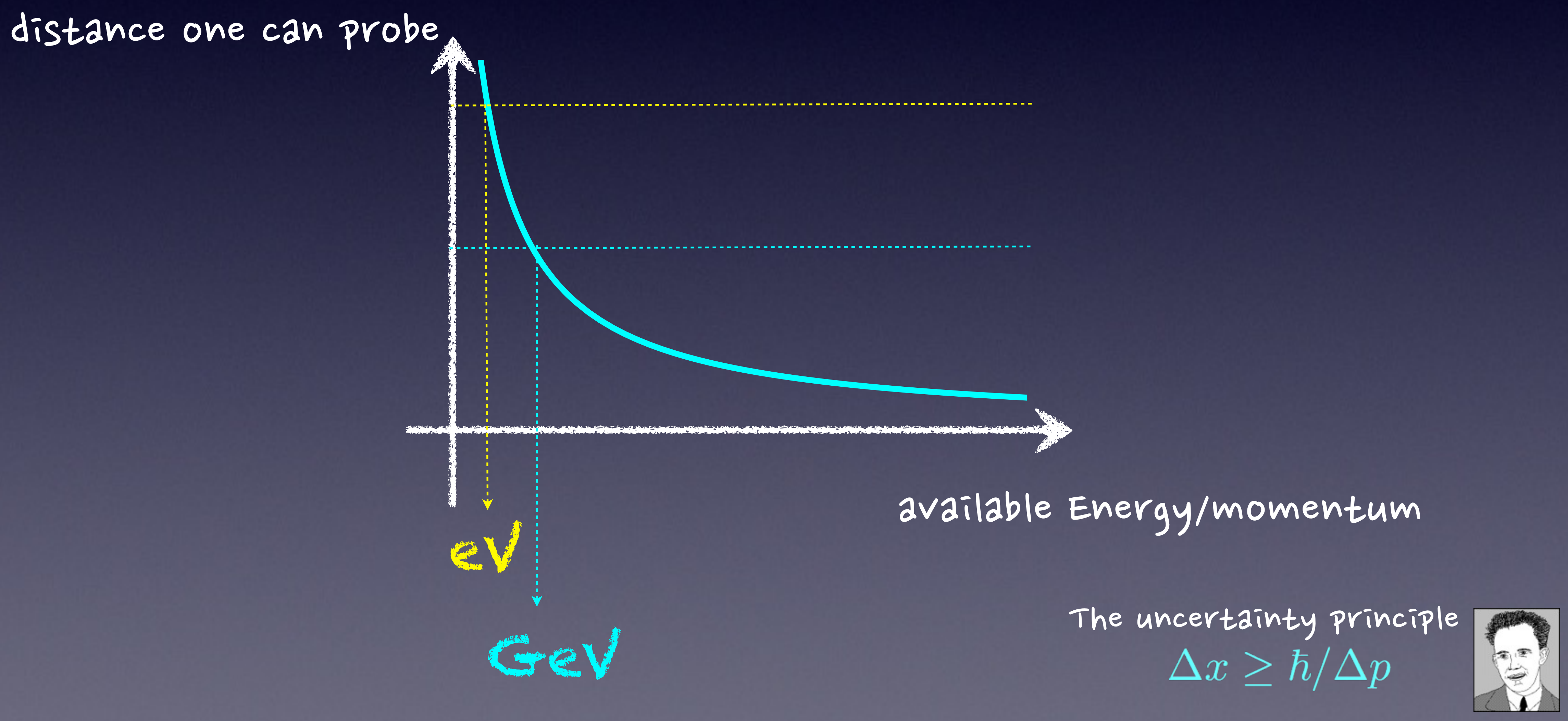

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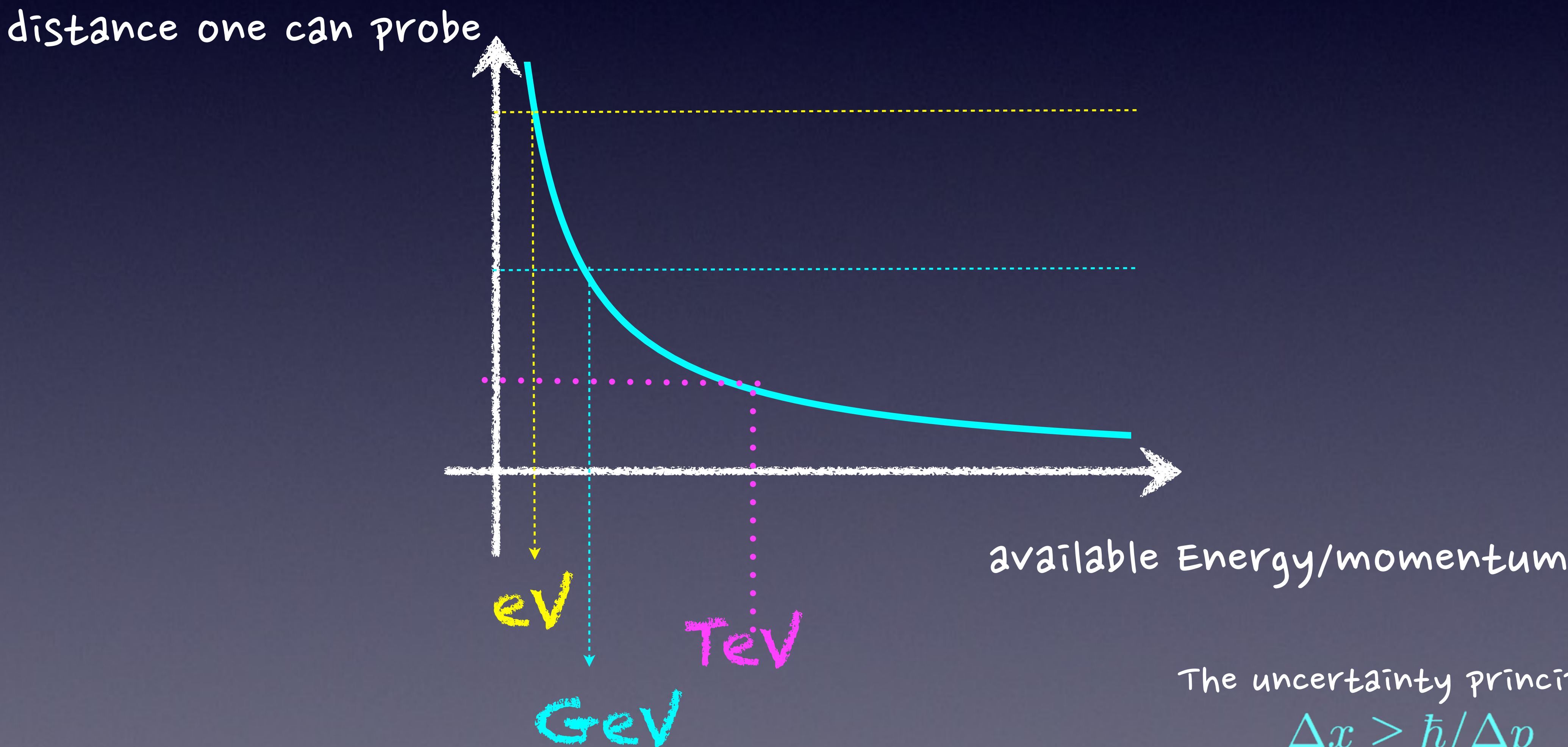
★~1970 reached strong scale 10^{-13}cm≈$(1/M)\ e^{-2pi/as\ b0}$

★~2011 reach weak scale 10^{-17}cm ⇐LHC here!



The uncertainty principle

$$\Delta x \geq \hbar/\Delta p$$

Why hadron?

$$P = ke^2a^2$$

$$P = ke^4\frac{\gamma^4 v^4}{r^2}$$

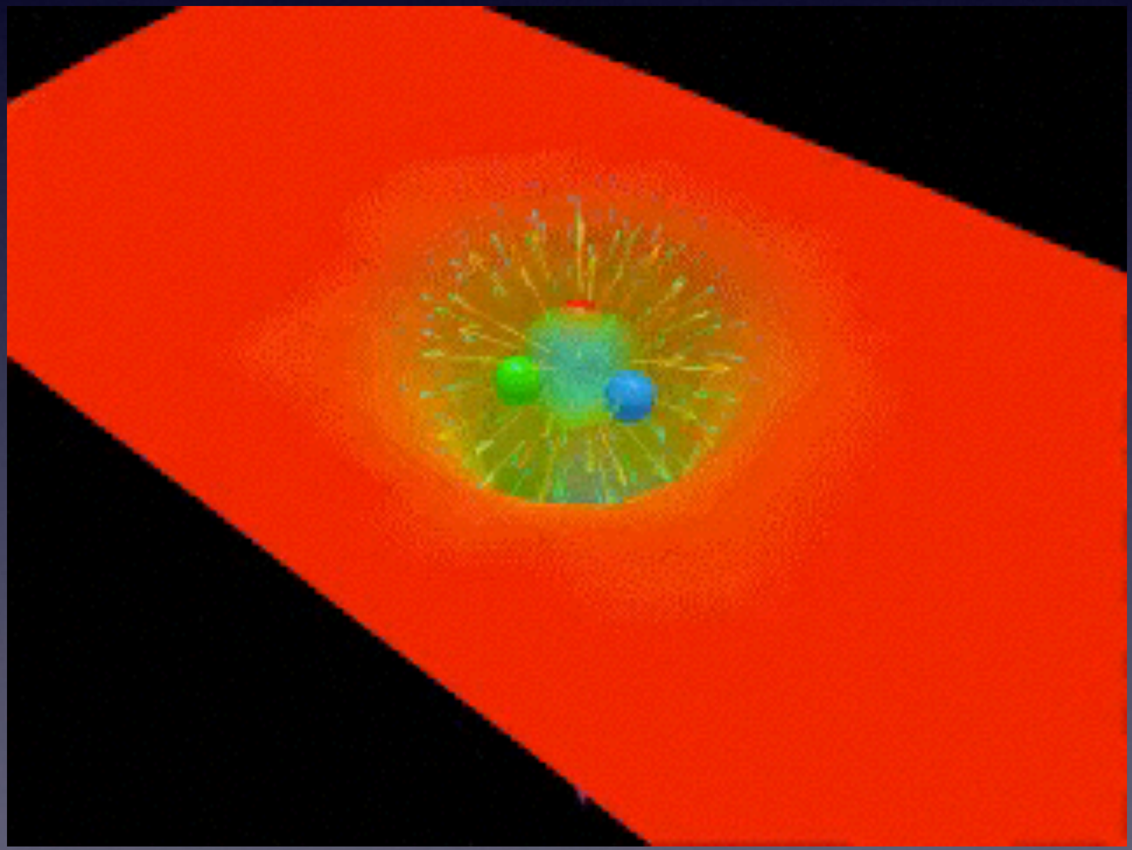
$$v \sim c, \gamma = E/m$$

$$P \propto 1/m^4$$ lighter, more efficient!

Q. Why proton rather than electron?

Proton

- proton is NOT an elementary particle but a composite state of many colored particles
- p={u,d,s,g,ubar, dbar…}
- It is highly dynamical!
- Q. Is this good or bad?



F. Bissey et.al. Phys. Rev. D 76, 114512 (2007)

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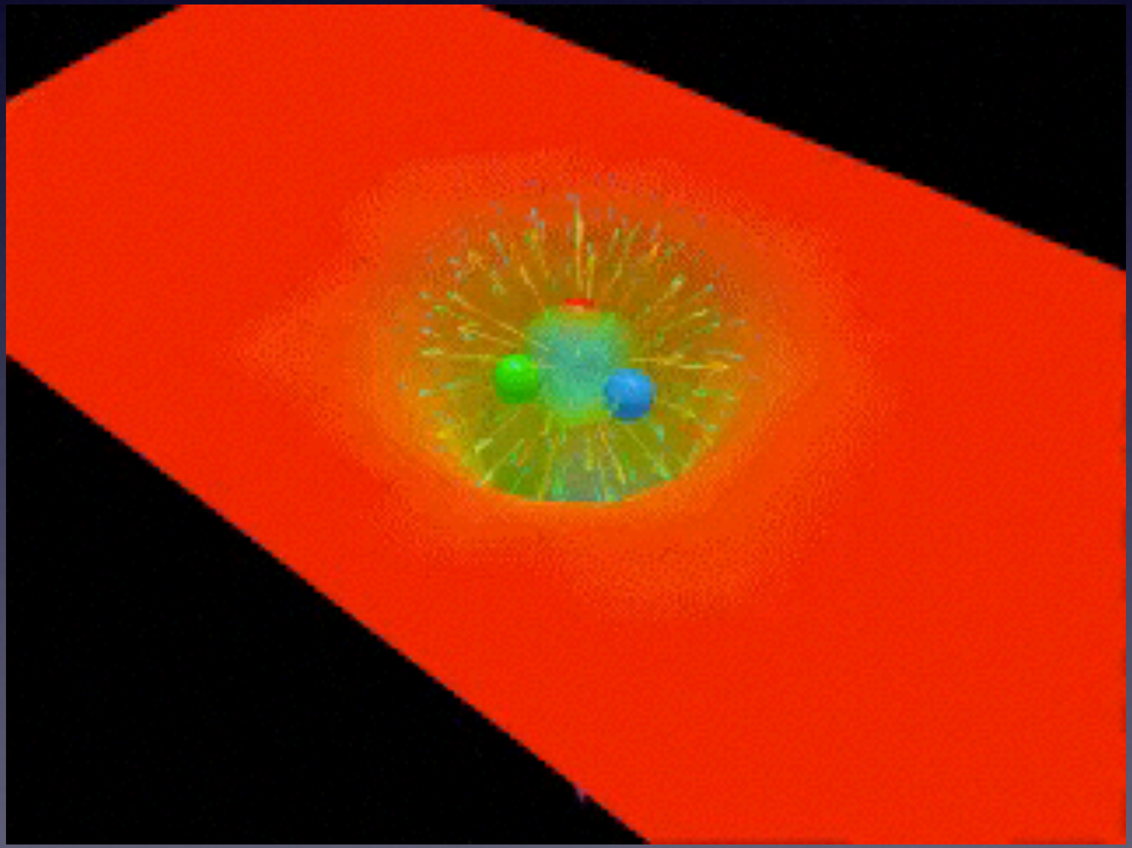

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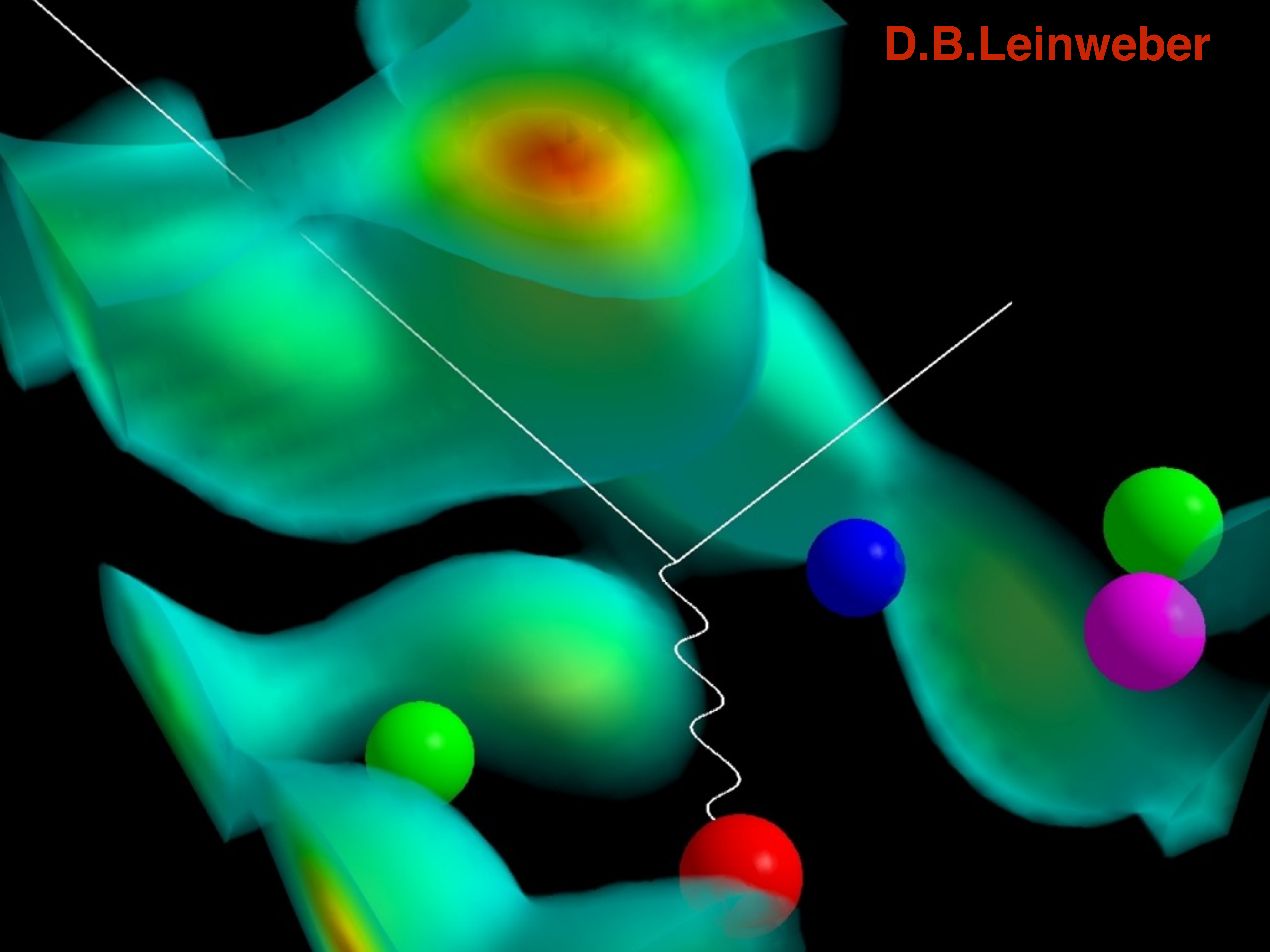
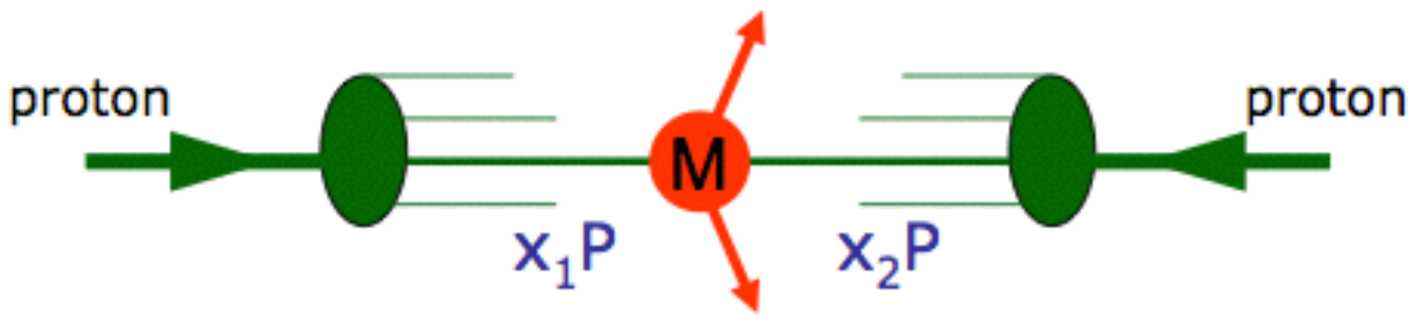


D.B.Leinweber

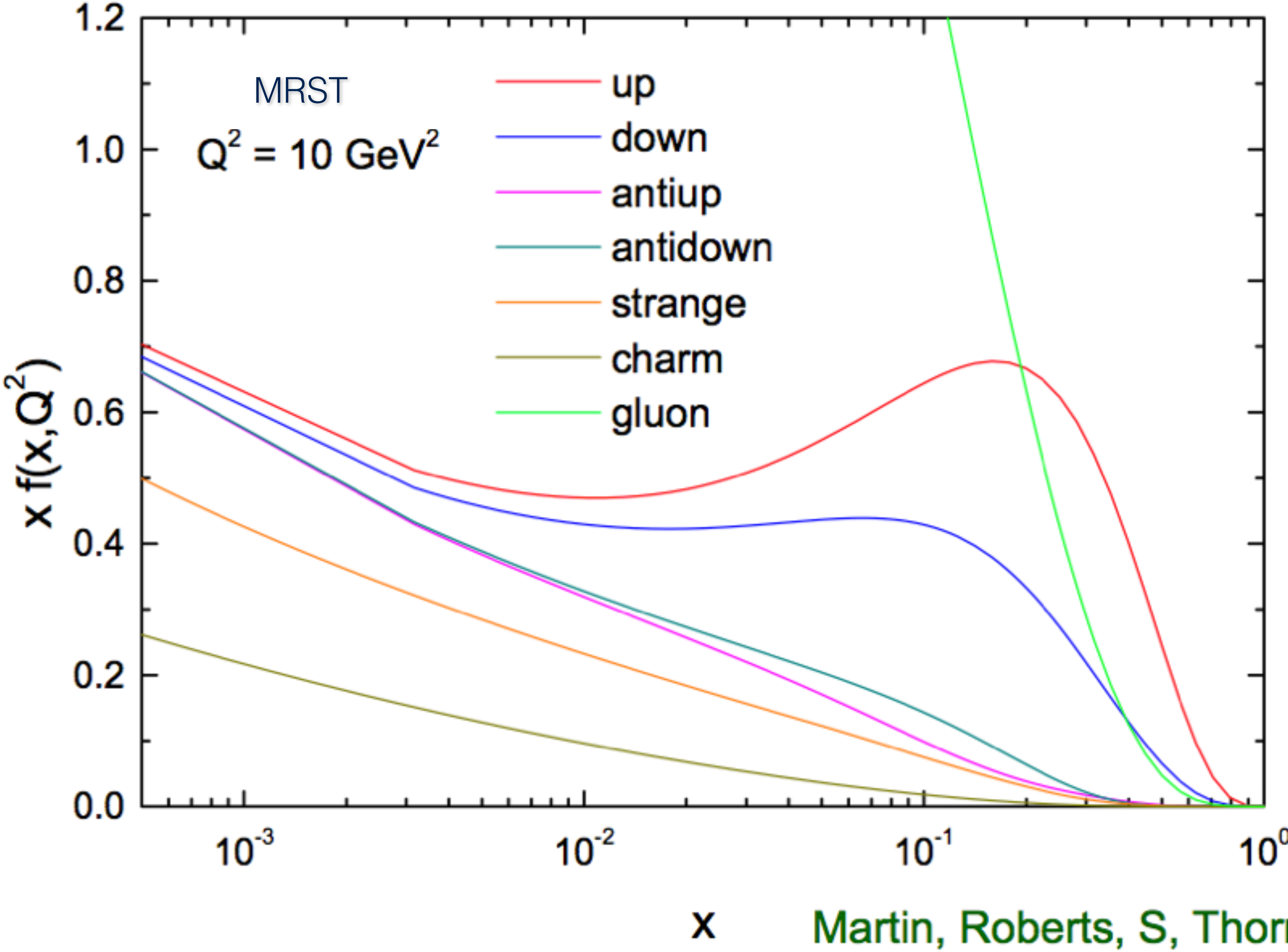
Only a small fraction of the proton energy is actually participating the scattering processes ..

kinematics



- collision energy: $\sqrt{s}$
- parton momenta: $$p_1^\mu = x_1\sqrt{s}/2\,(1,0,0,1)$$ $$p_2^\mu = x_2\sqrt{s}/2\,(1,0,0,-1)$$
- invariant mass: $M^2 = (p_1 + p_2)^2 \equiv \hat{s} = x_1 x_2 s$

(MRST) parton distributions in the proton



Martin, Roberts, S, Thorne

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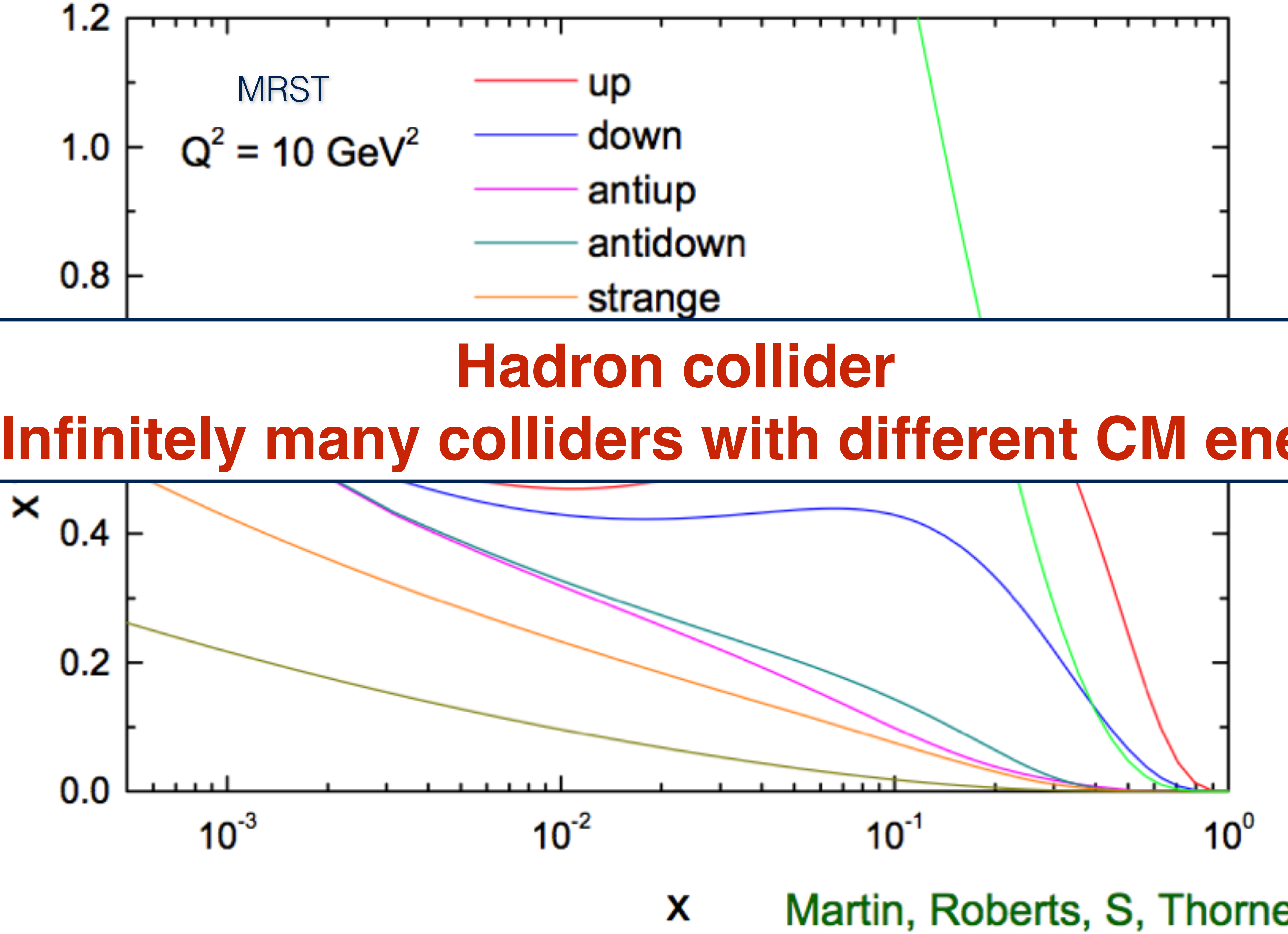
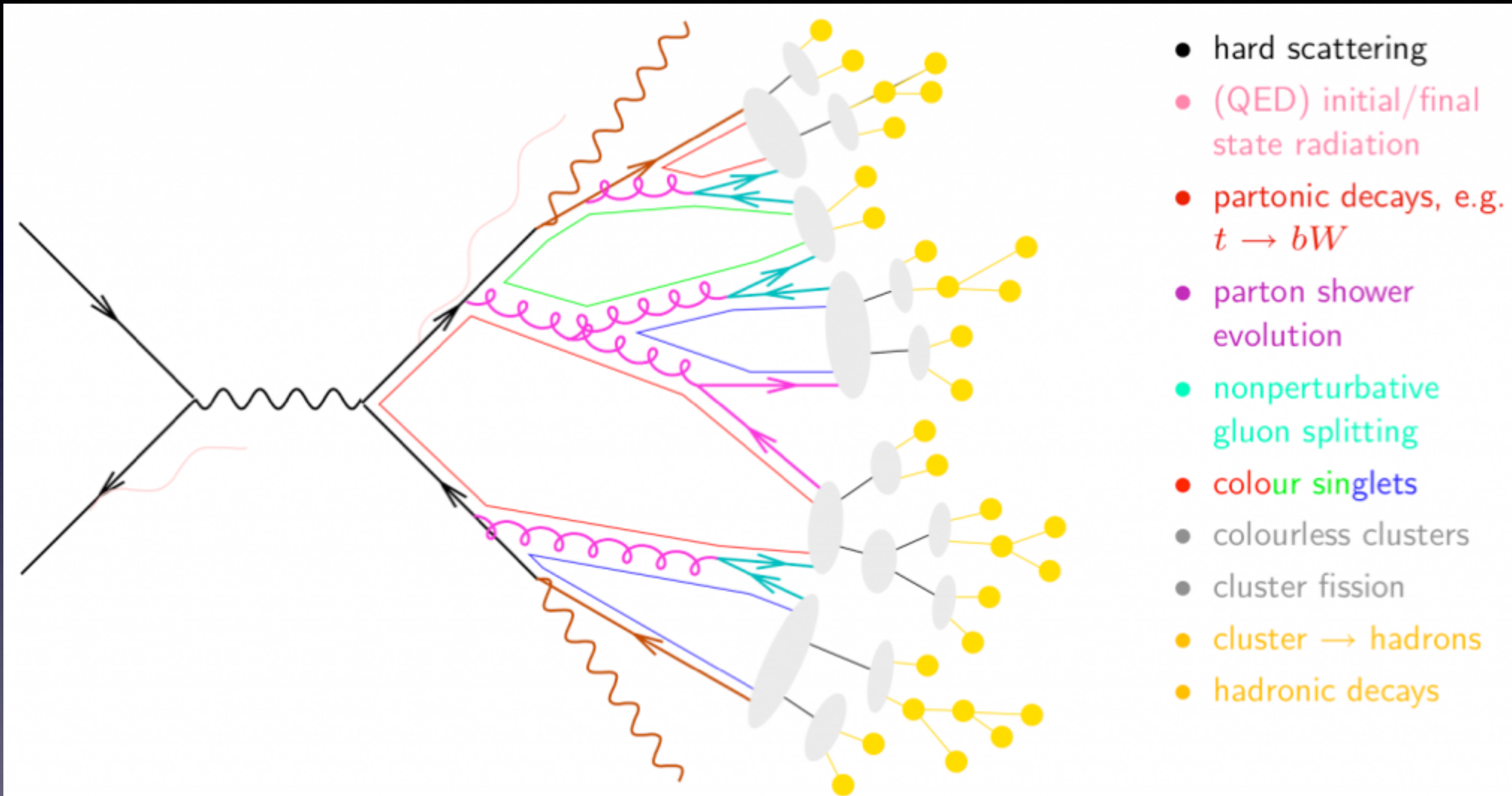


Hadron collider
= Infinitely many colliders with different CM energy

but complicated.....



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Answer:

$$\hbar c \approx 200\ \text{MeV} \cdot \text{fm}$$

$$\Rightarrow 1\text{TeV} \approx \frac{1}{2 \times 10^{-17}\text{cm}}$$

$$14\text{TeV} \times 20\% = 2.8\text{TeV}$$

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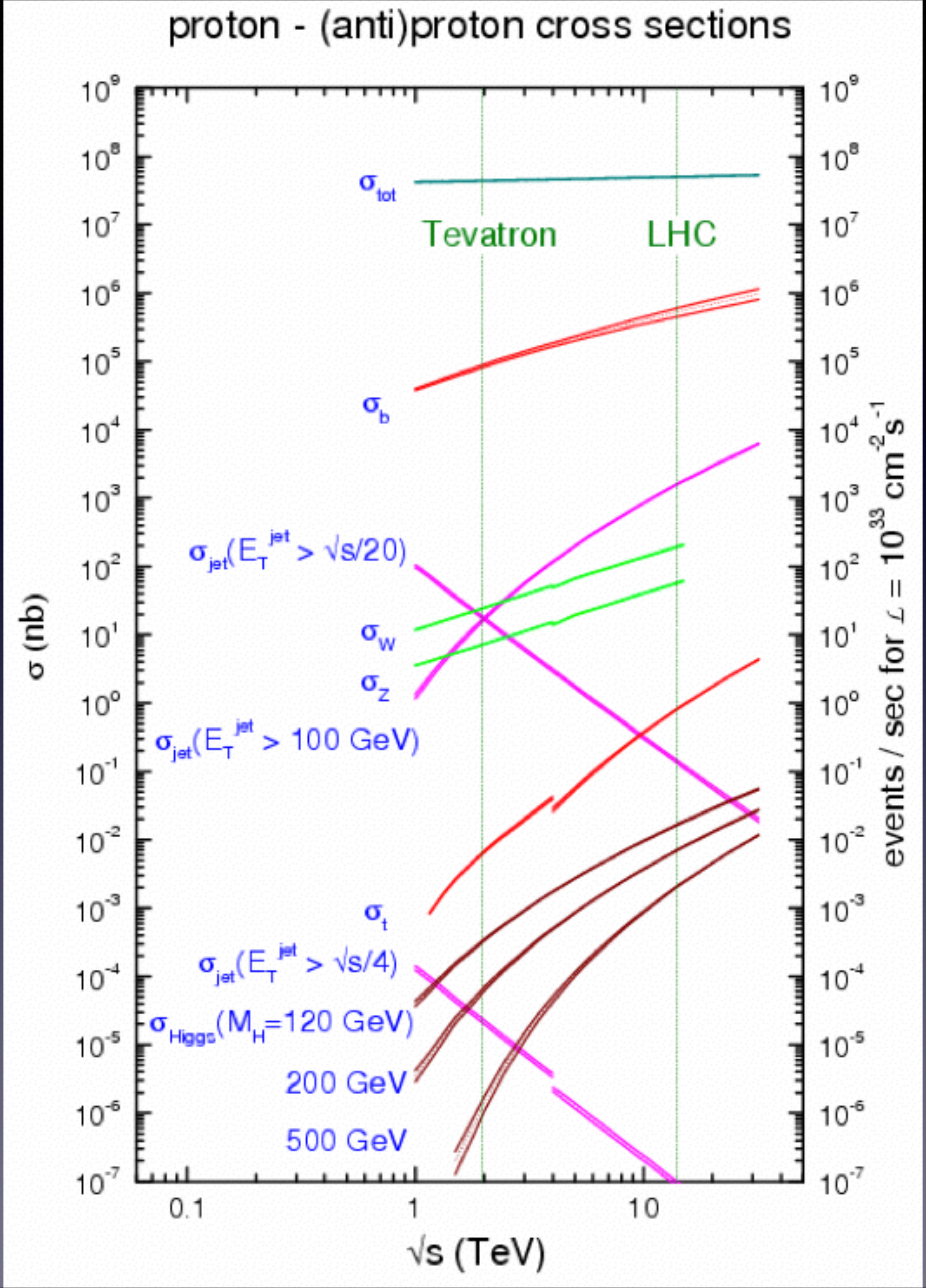
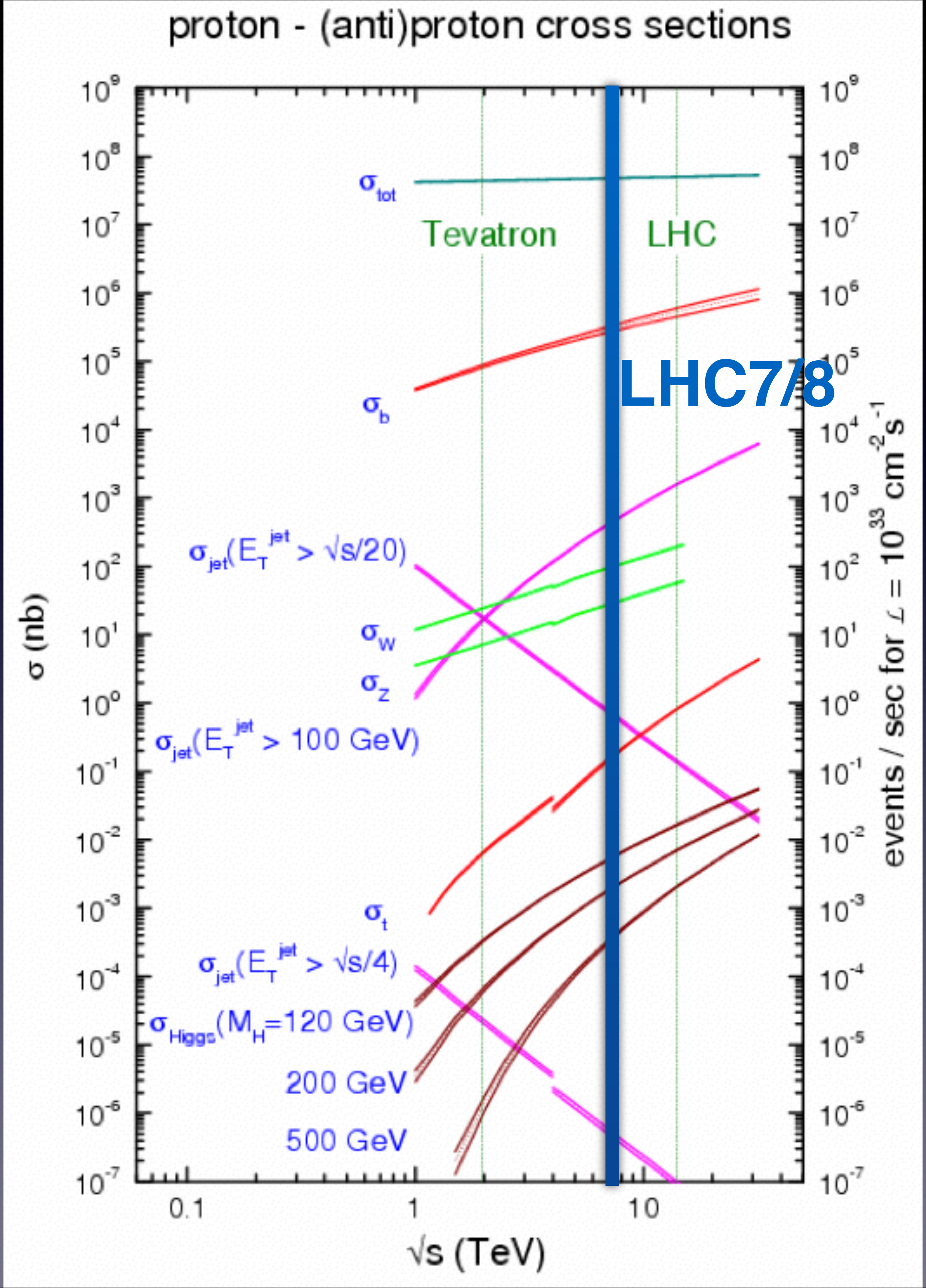
Q. why can we use hbar=c=1?

LHC~TeV ~10^{-17} cm



proton - (anti)proton cross sections
σ (nb)
events / sec for L = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10
Tevatron
LHC
σtot
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σt
σjet(ET jet > √s/4)
σHiggs(MH=120 GeV)
200 GeV
500 GeV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σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
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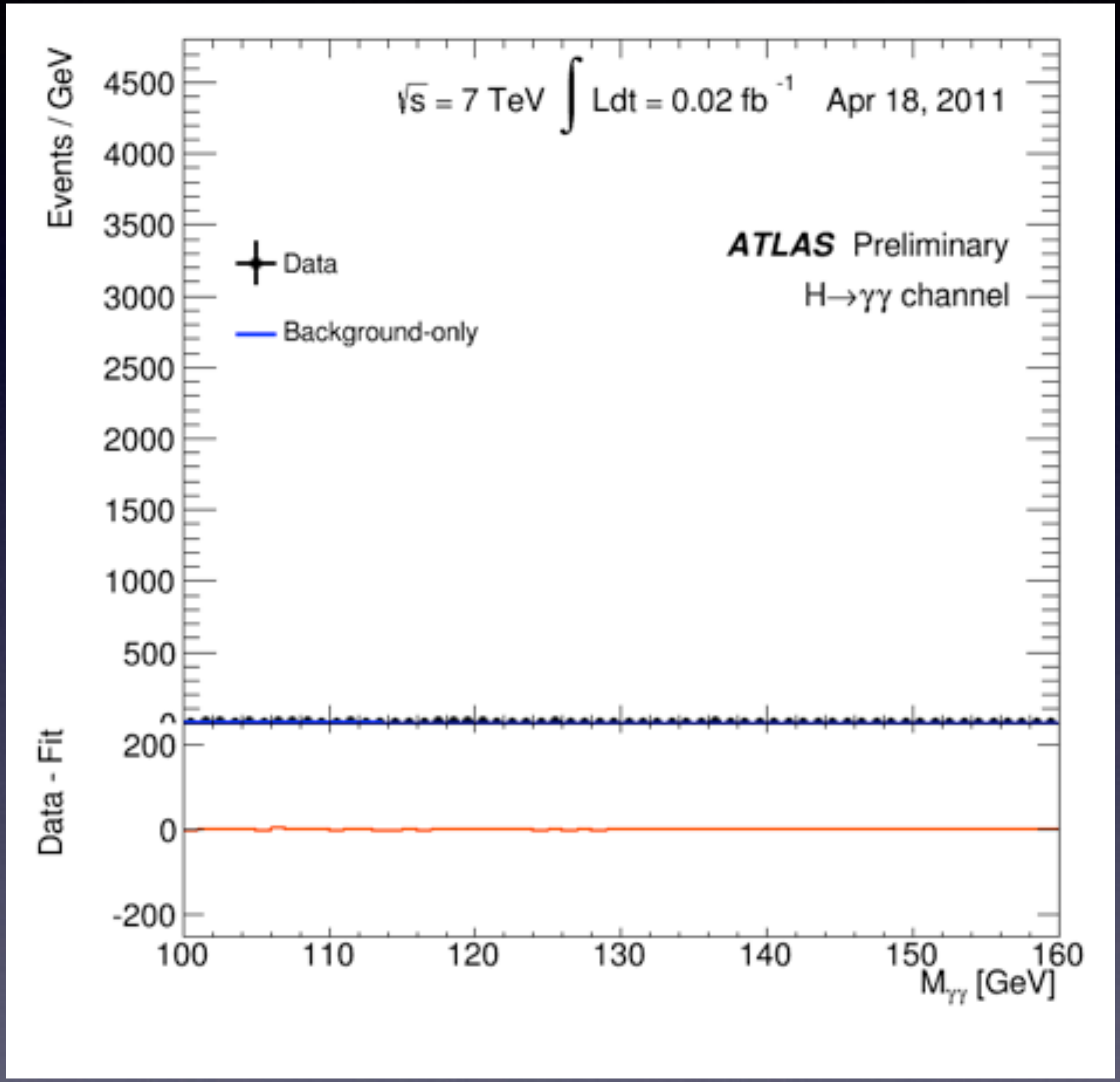
- The distance scale for electroweak symmetry breaking… (Q. what is EWSB?)
- In the SM, the Higgs mechanism is responsible for EWSB …(Q. any other idea?)
- => excitation of Higgs field (=Higgs particle) can be seen.
- The LHC discovered a Higgs boson!

$$PP \to \gamma\gamma$$



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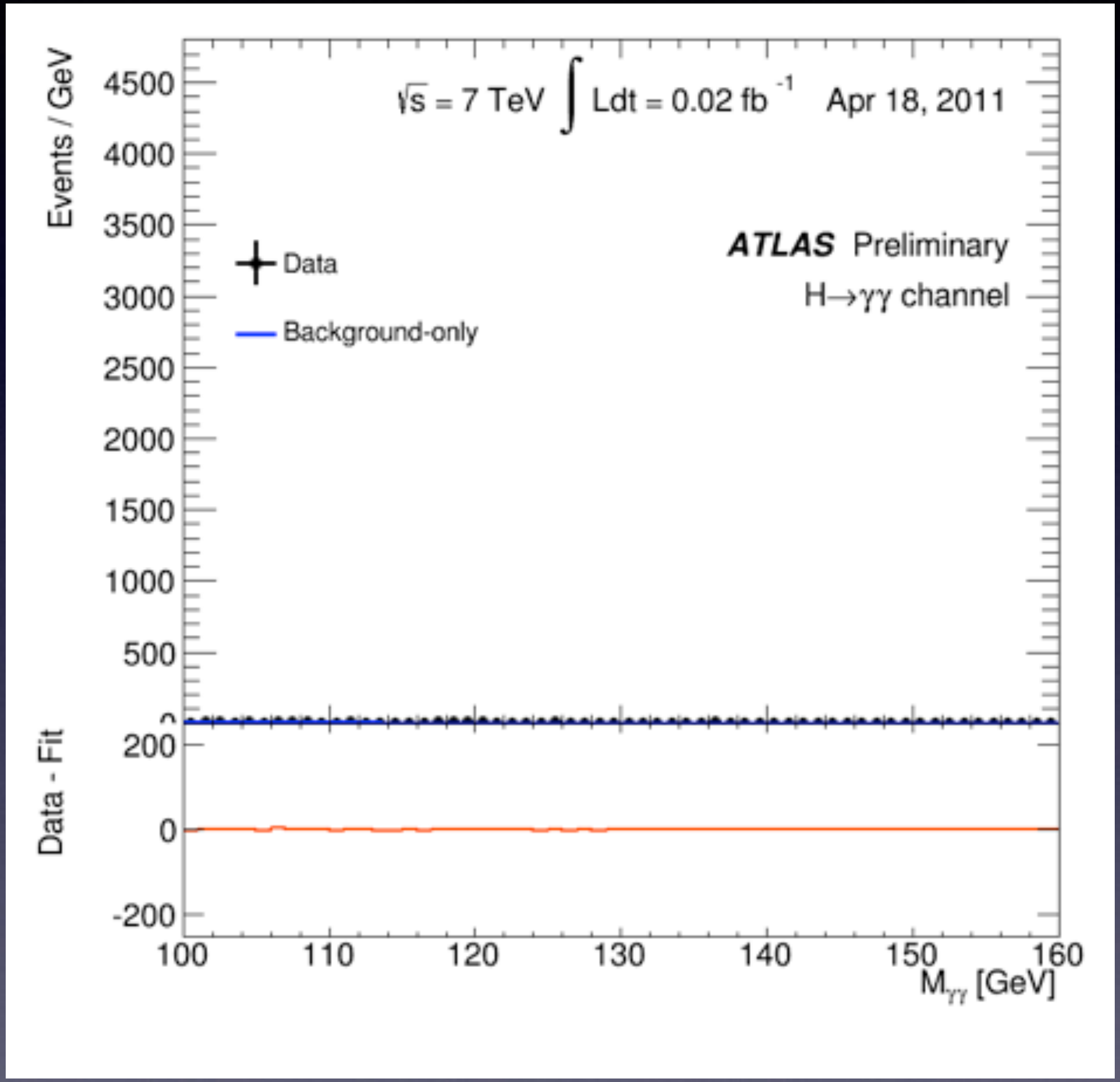

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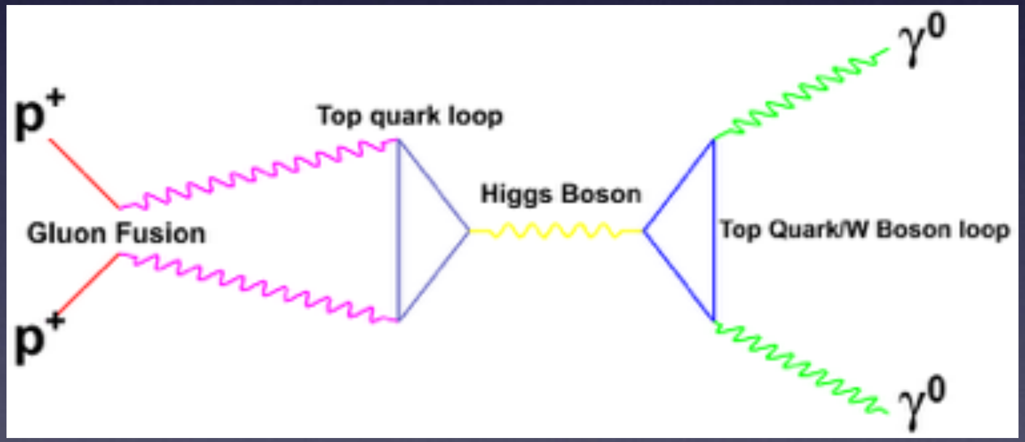

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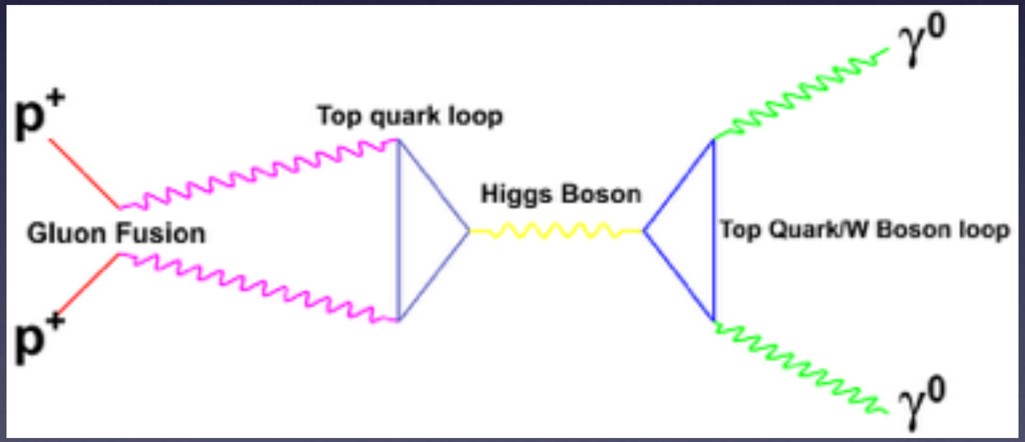

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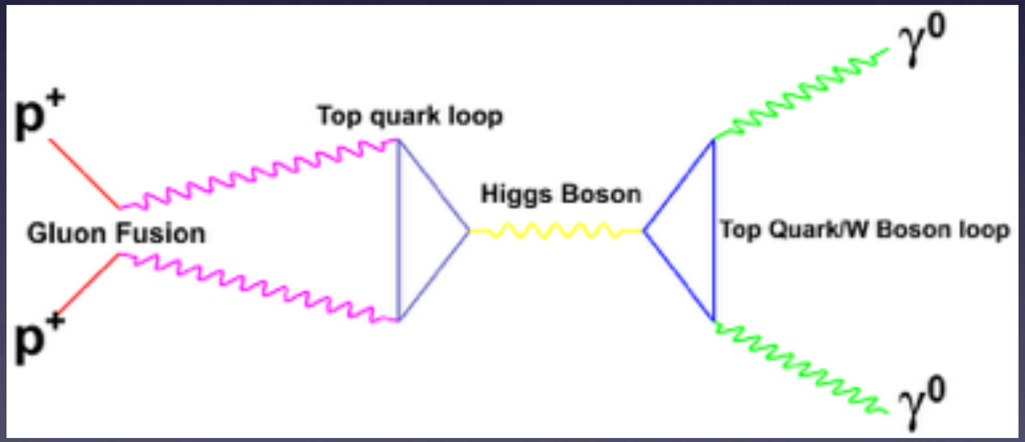
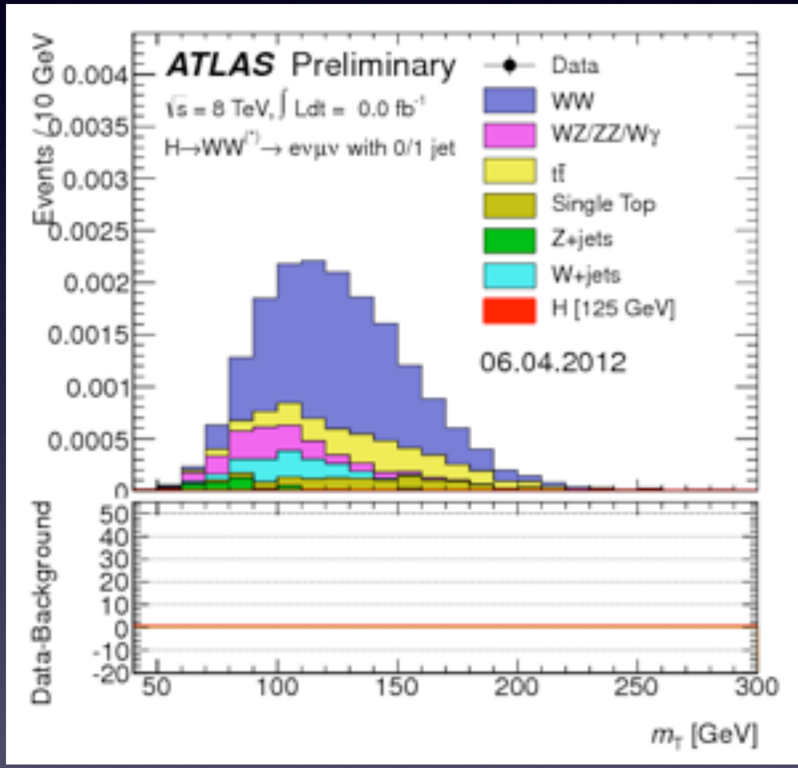


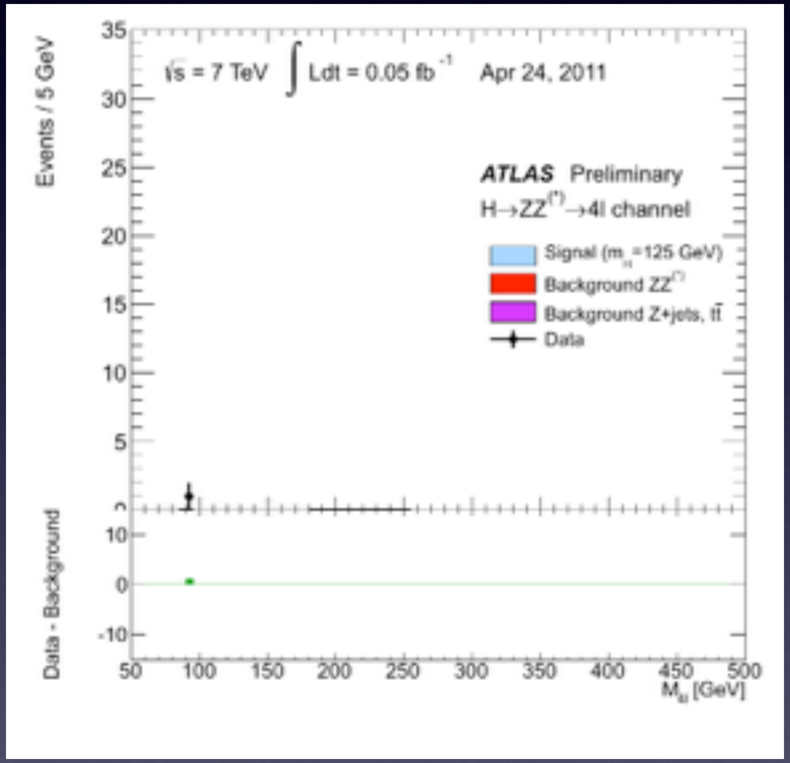
Q. Why only top-quark loop important?

$$\frac{A_t}{A_u} \approx \frac{y_t^2}{y_u^2}$$

$$PP \to W^+W^-$$

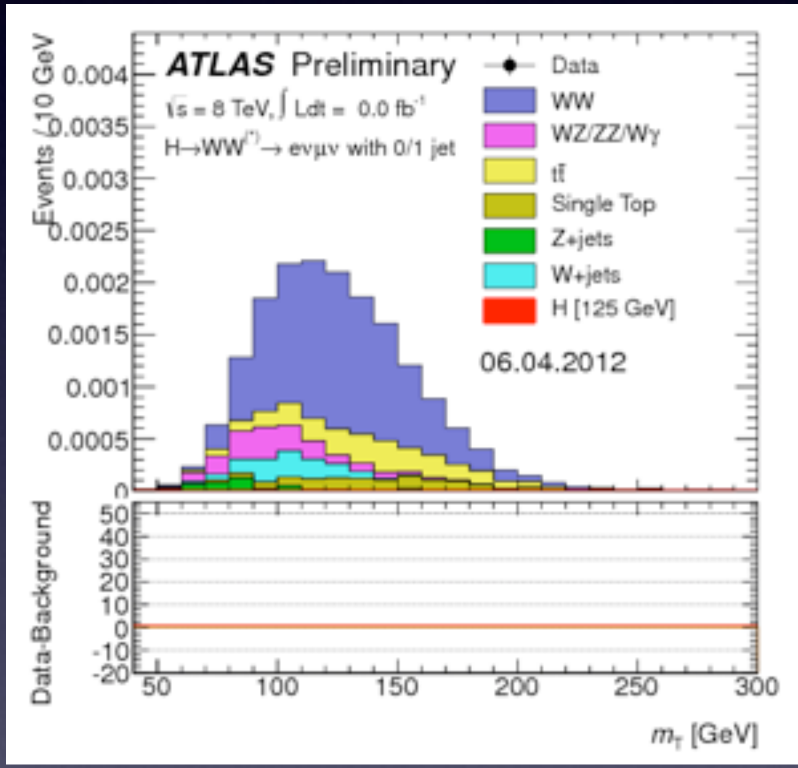


ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 0.0 fb⁻¹
H→WW(*)→ eνμν with 0/1 jet
Data
WW
WZ/ZZ/Wγ
tt̄
Single Top
Z+jets
W+jets
H [125 GeV]
06.04.2012
Events / 10 GeV
Data-Background
m_T [GeV]



√s = 7 TeV ∫ Ldt = 0.05 fb⁻¹ Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]

$$PP \to W^+W^-$$



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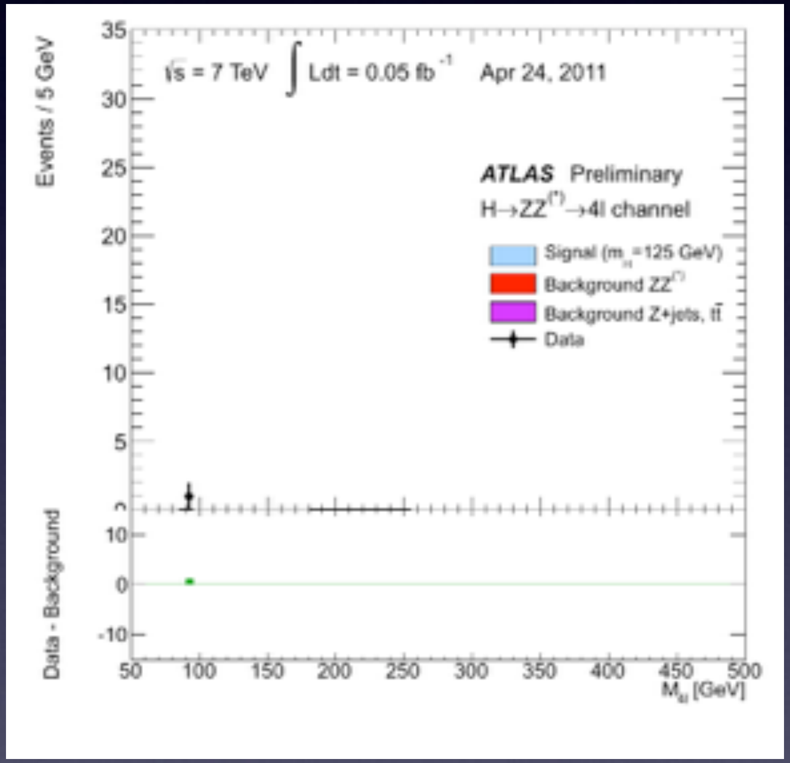
H→WW(*)→ eνμν with 0/1 jet
Data
WW
WZ/ZZ/Wγ
tt̄
Single Top
Z+jets
W+jets
H [125 GeV]
06.04.2012
Events / 10 GeV
Data-Background
m_T [GeV]



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Data
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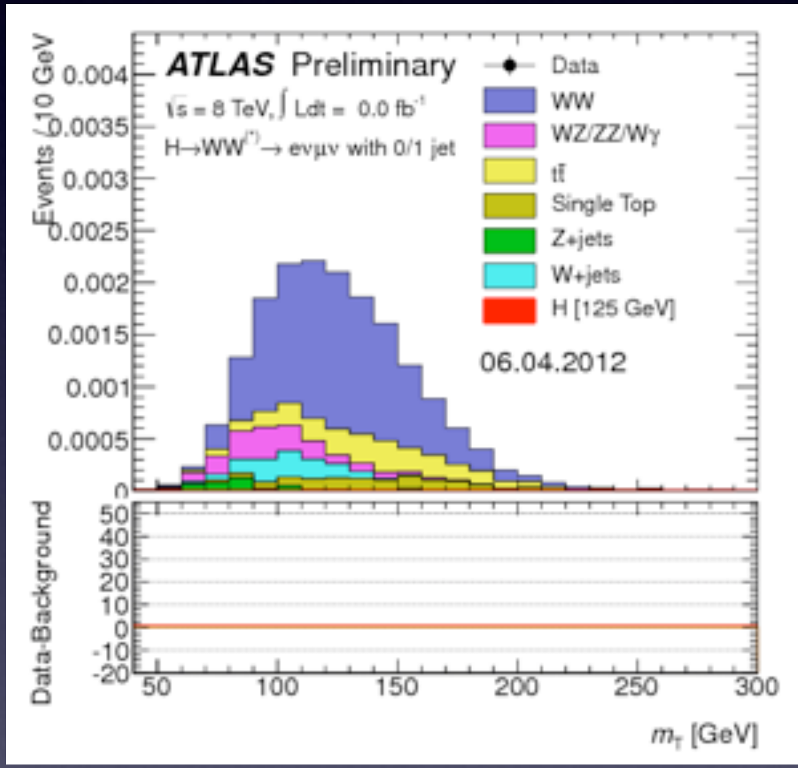
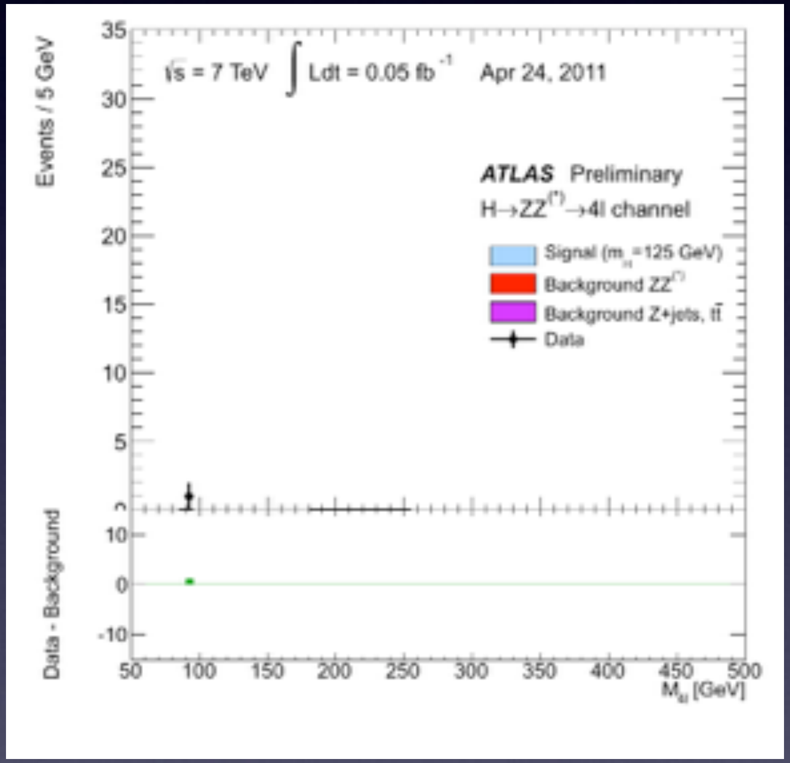
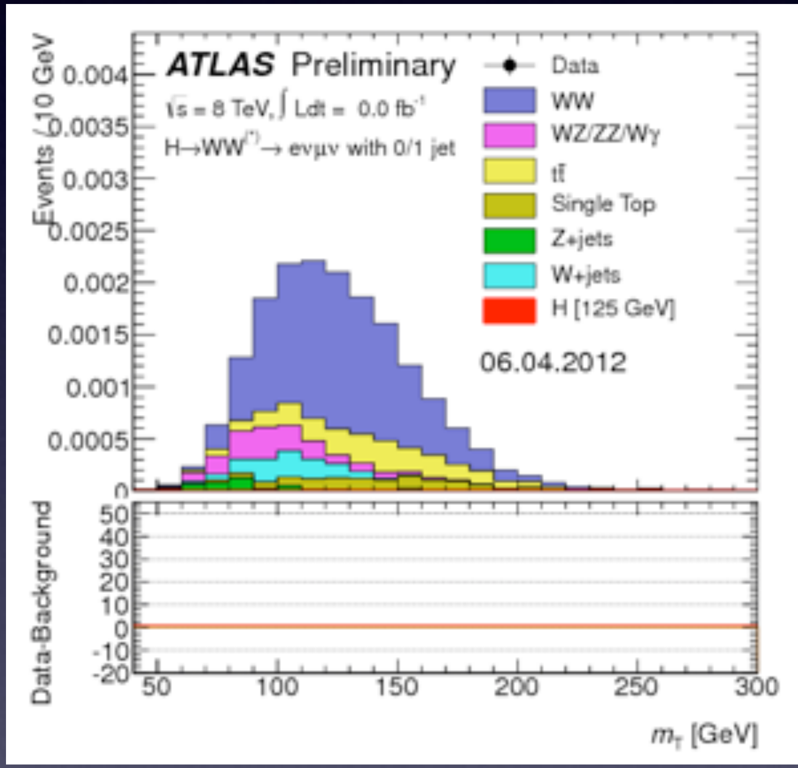
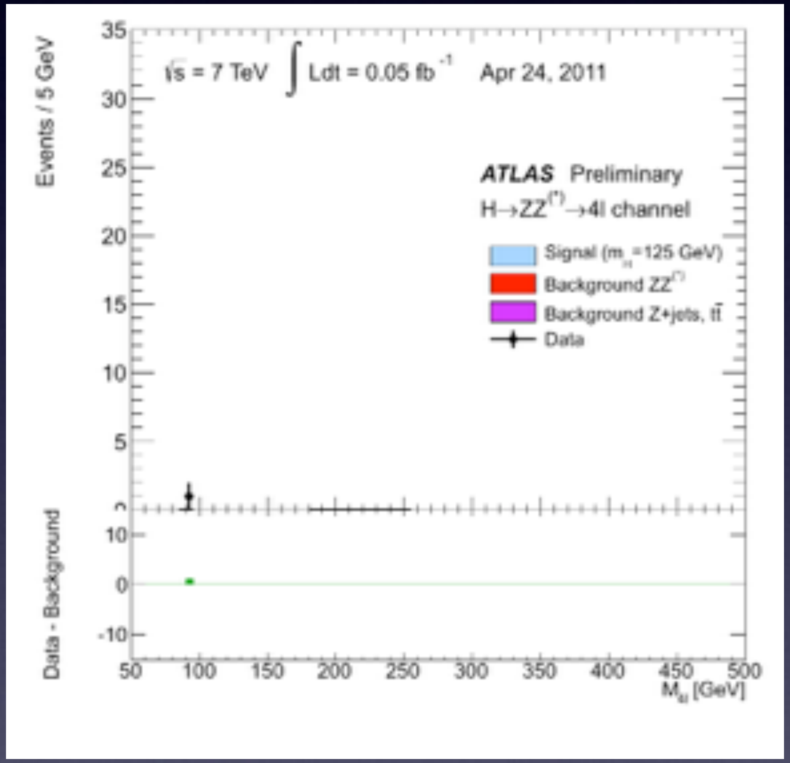
$$PP \to W^+W^-$$
$$PP \to H \to W^+W^-$$



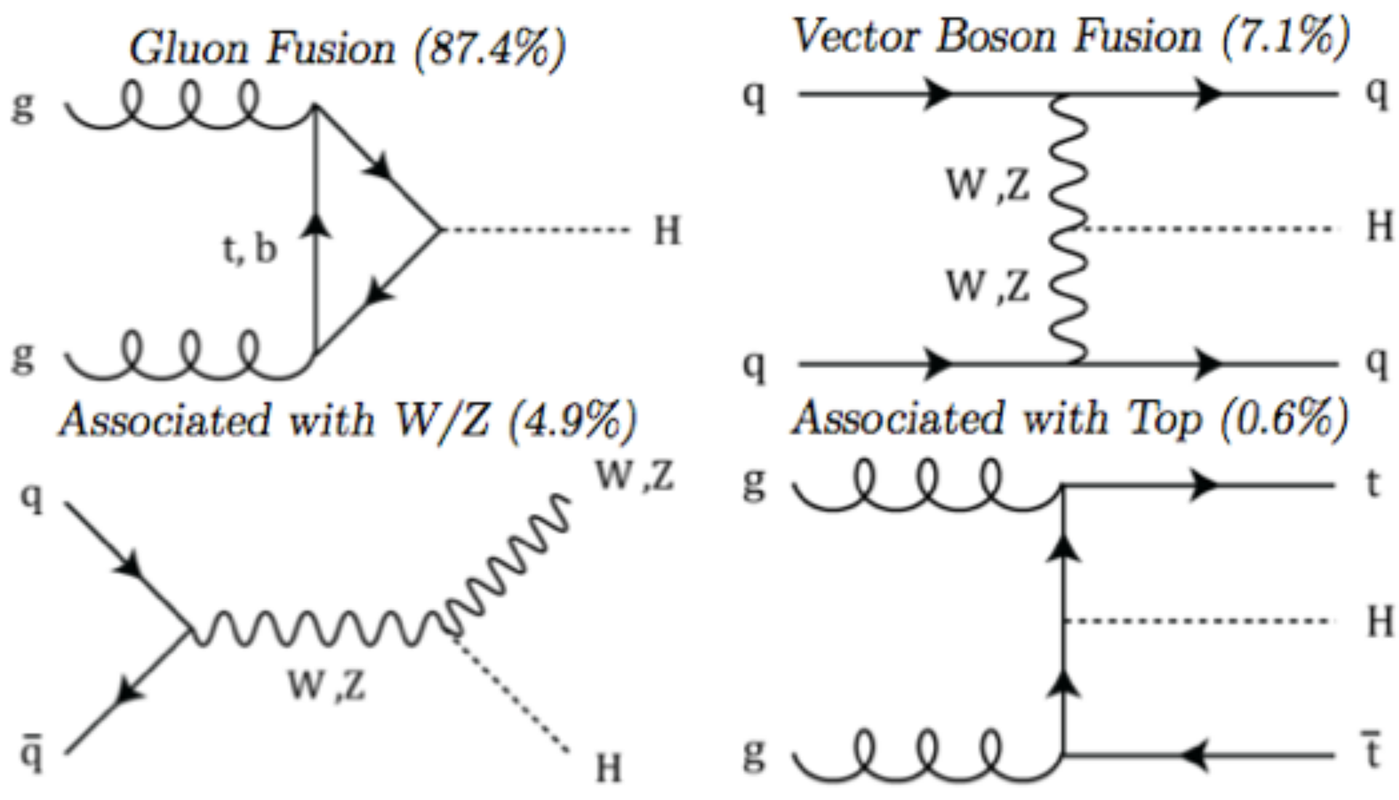


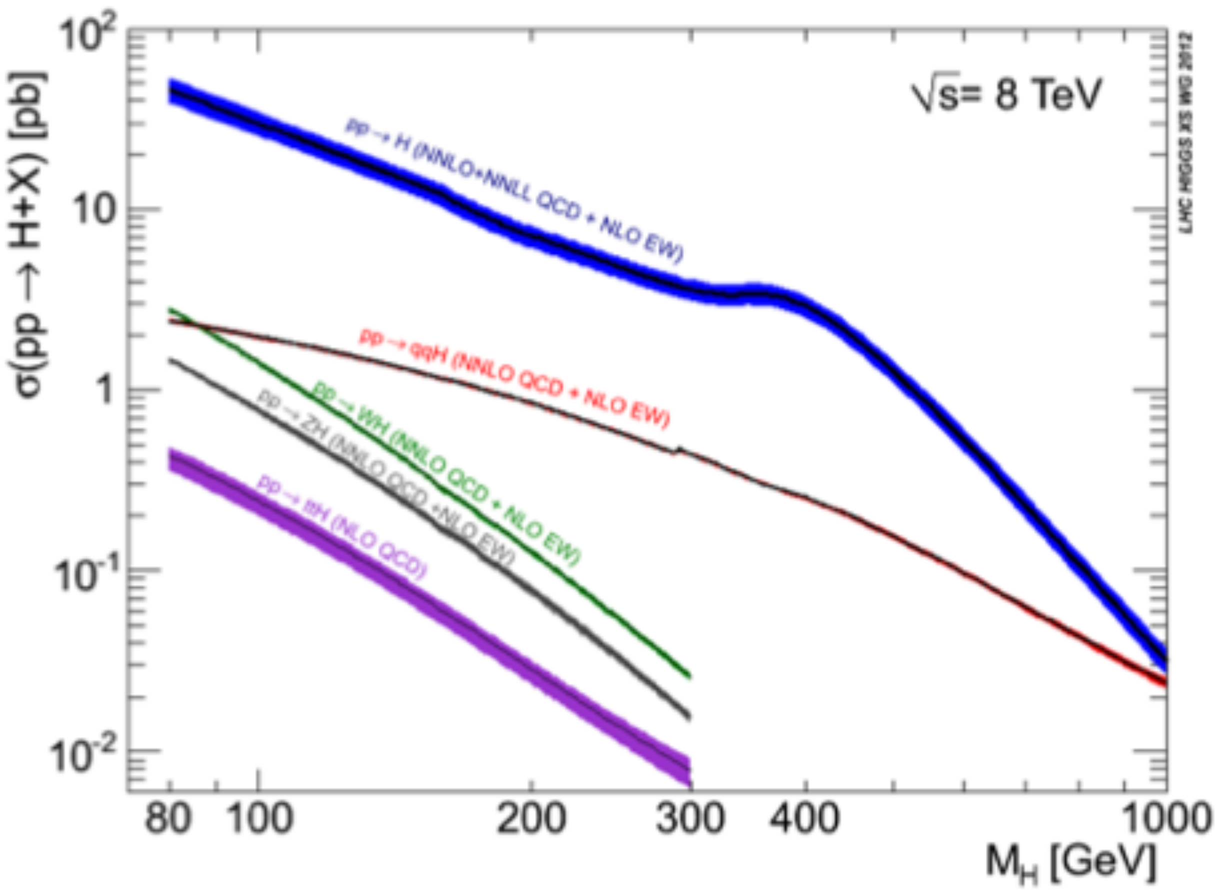
$$PP \to W^+W^-$$
$$PP \to H \to W^+W^-$$



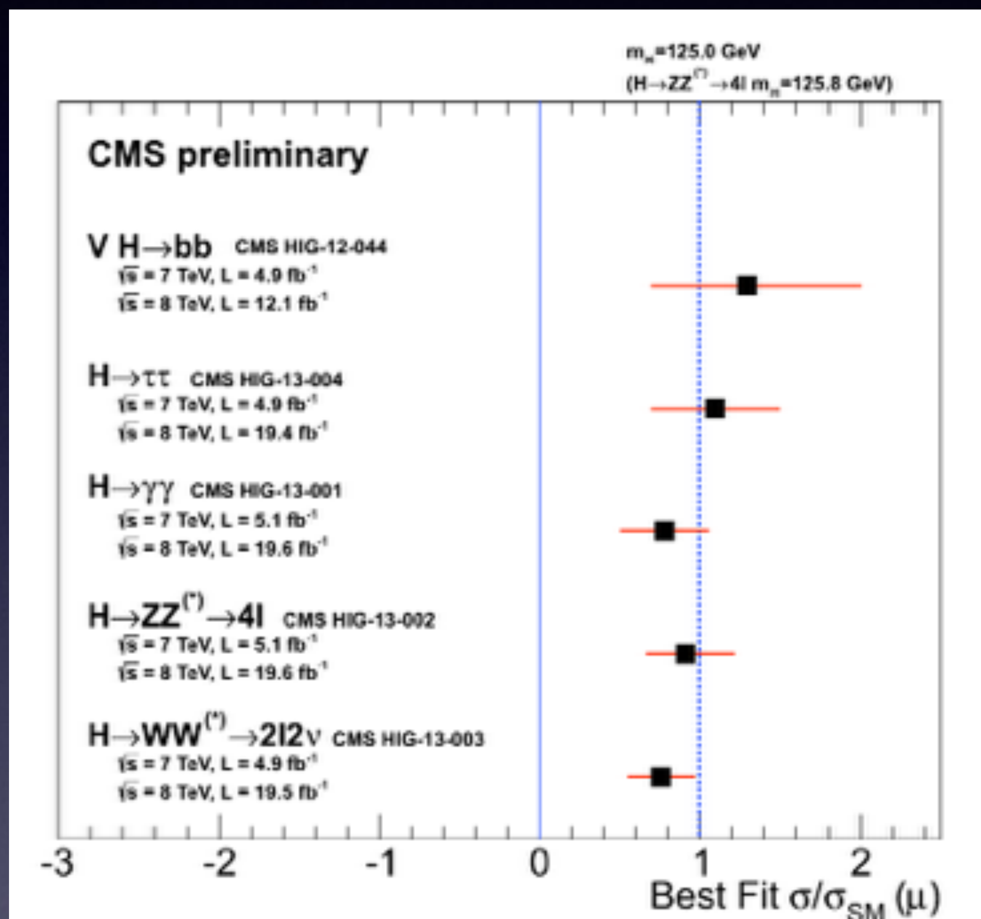


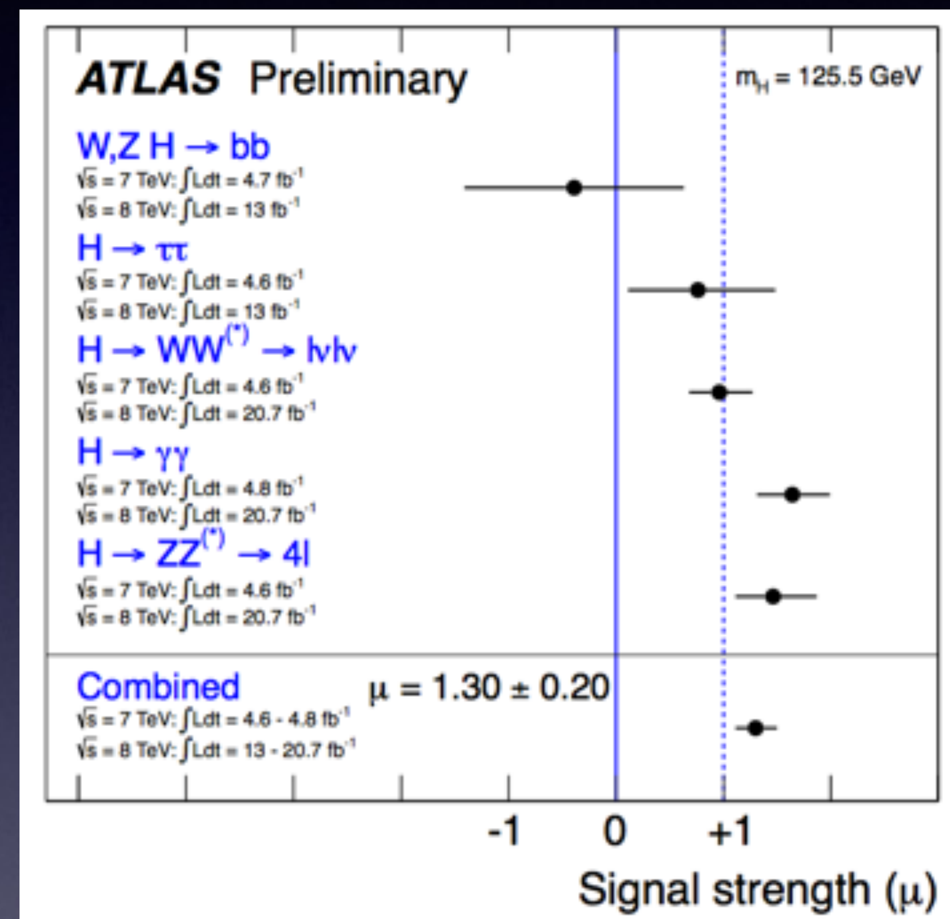
Various Higgs production mechanisms





Data vs SM

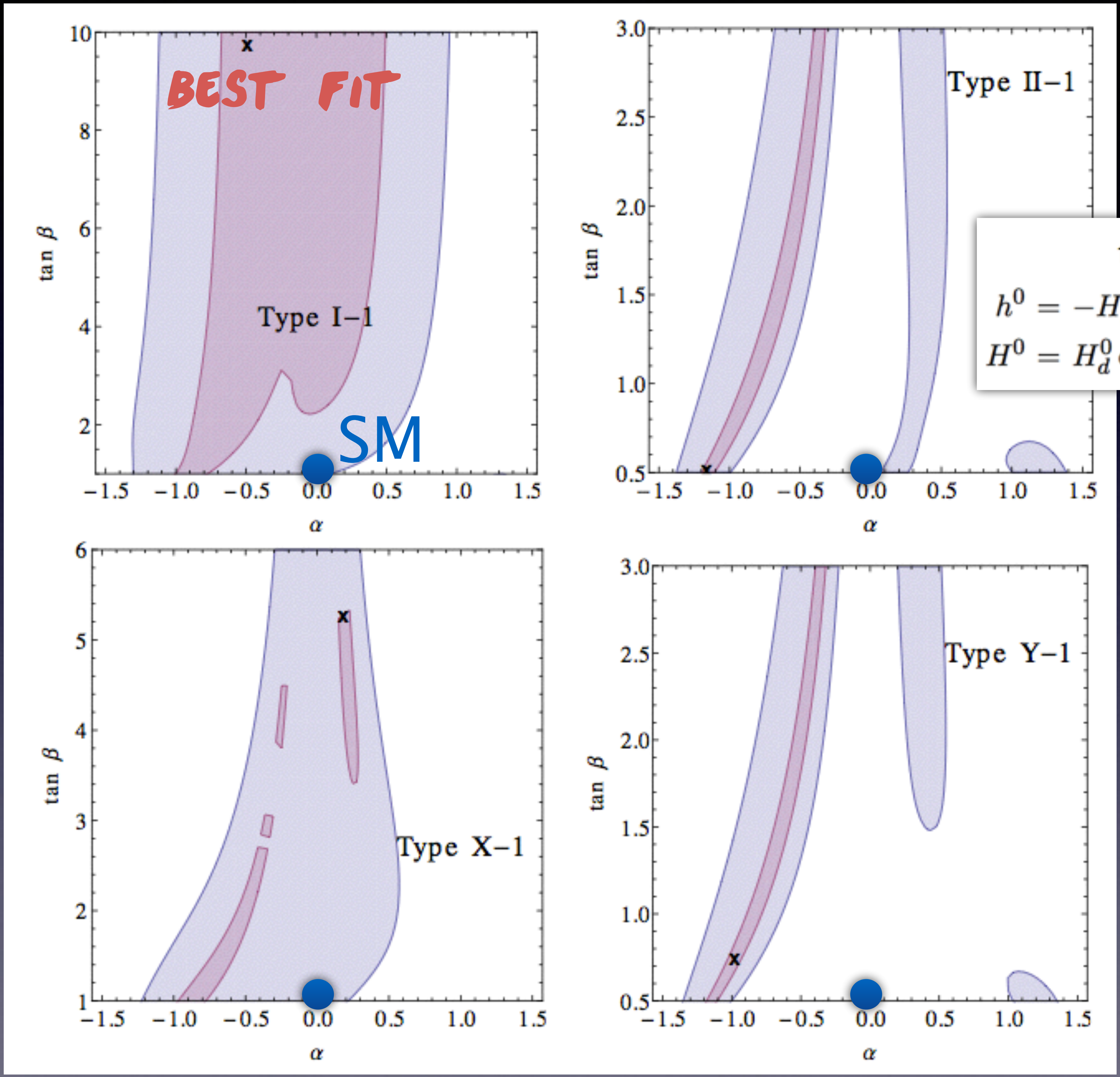




$$\mu_{\gamma\gamma} = \begin{cases} 1.65^{+0.34}_{-0.30} \ \mathrm{ATLAS} \\ 0.78^{+0.28}_{-0.26} \ \mathrm{CMS\ (MVAmass - factorized)} \\ 1.11^{+0.32}_{-0.30} \ \mathrm{CMS\ (Cut - based)} \end{cases}$$

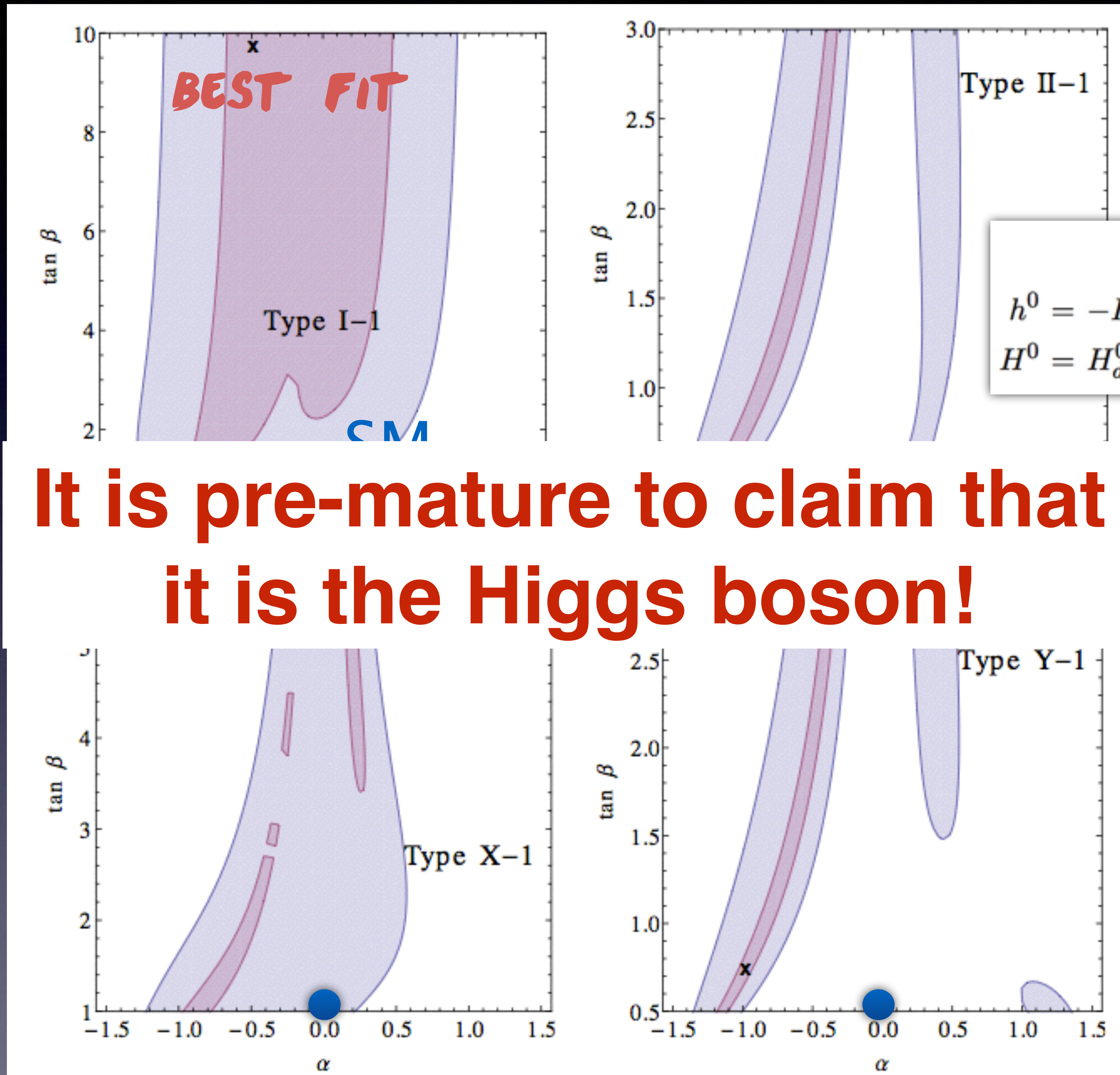
The Higgs or a Higgs?

- In the minimal SM, only one Higgs doublet field is introduced ..
- ..actually it is enough to count EWSB as well as the masses for fermions & gauge bosons
- Good and economical
- However, many extended models including multi-Higgs doublets are introduced to count other physics.. (e.g. 2HDM, MSSM, LH..etc)
- It is worth checking if only the SM limit is consistent with the observed data! (in any case H-AA is not the same in DATA)



$$\tan\beta = v_u/v_d.$$
$$h^0 = -H_d^0 \sin\alpha + H_u^0 \cos\alpha,$$
$$H^0 = H_d^0 \cos\alpha + H_u^0 \sin\alpha,$$

Chang, Kang, LeeX2, Park, Song [arXiv:1210.3439, JHEP 1305 (2013) 075], [arXiv:1310.3374]



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It is pre-mature to claim that it is the Higgs boson!

Chang, Kang, LeeX2, Park, Song [arXiv:1210.3439, JHEP 1305 (2013) 075], [arXiv:1310.3374]

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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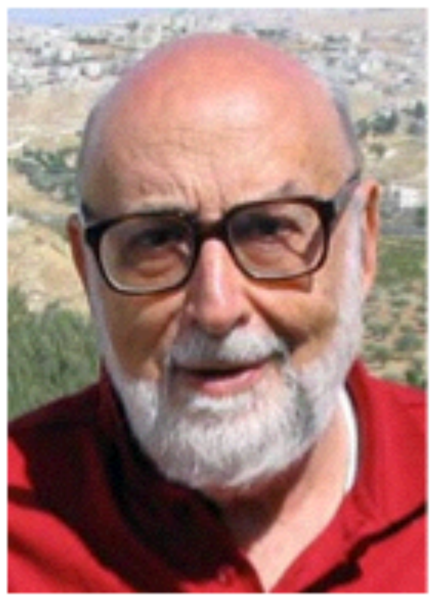
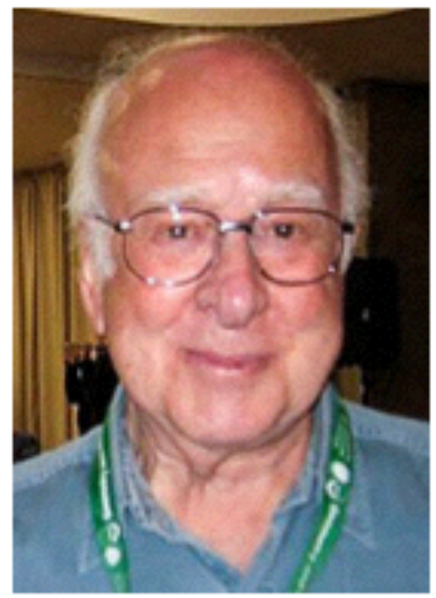


Photo: Pnicolet via Wikimedia Commons

François Englert



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Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

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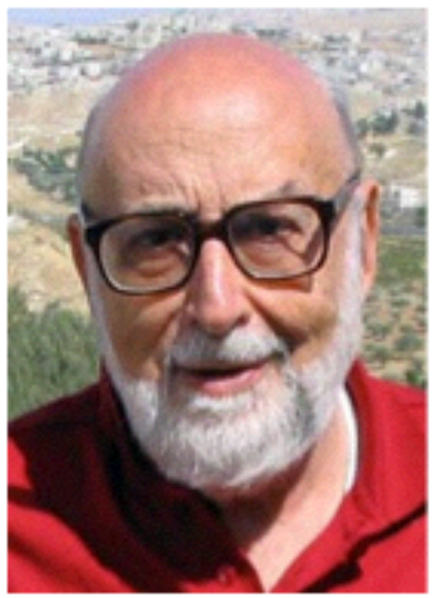
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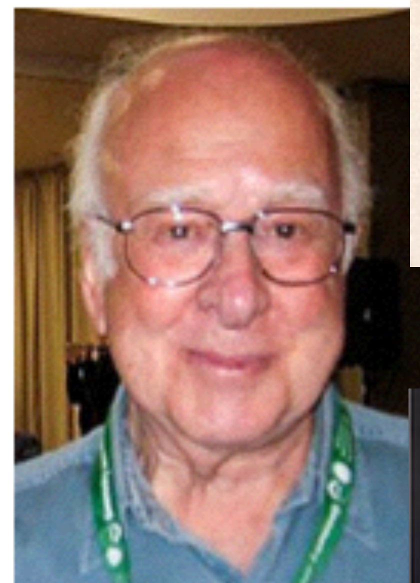
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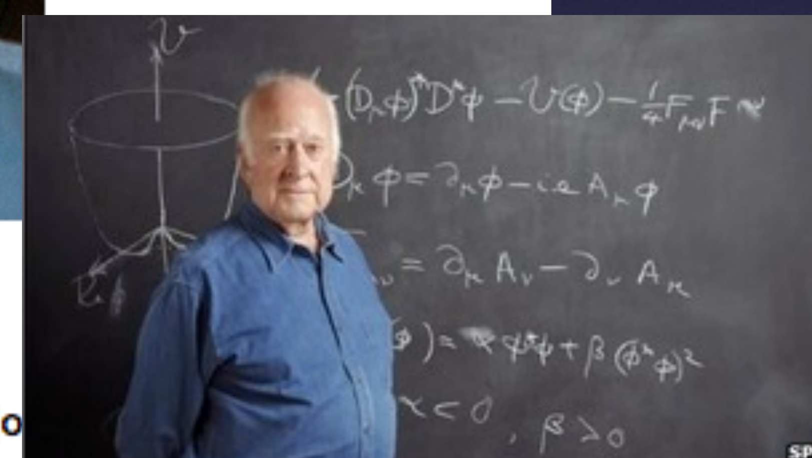

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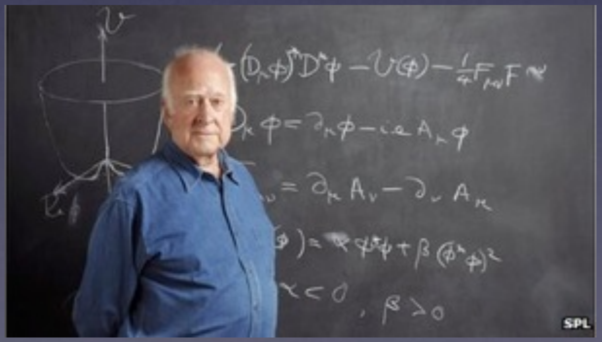
Why coined the name? (1)

"1972년 로체스터 대학에서의 한 파티장에서 함께 와인과 샌드위치를 들었던 벤 리(=이휘소 선생님)가 이 내용 (=힉스의 논문)을 알게된 후 내 이름(=힉스)을 대칭성의 자발적 깨짐 현상과 관련된 모든 곳에 붙이면서 다른 이들(앙글레어-브라우트 ...)은 각주 정도로 밀려나게 되었다"

"In 1972 Ben Lee, who had learnt about it first at a party in the University of Rochester at which we were both holding a glass of wine and a plate of sandwiches, then plastered my name over everything connected with spontaneous symmetry breaking, and other people were relegated to a footnote."

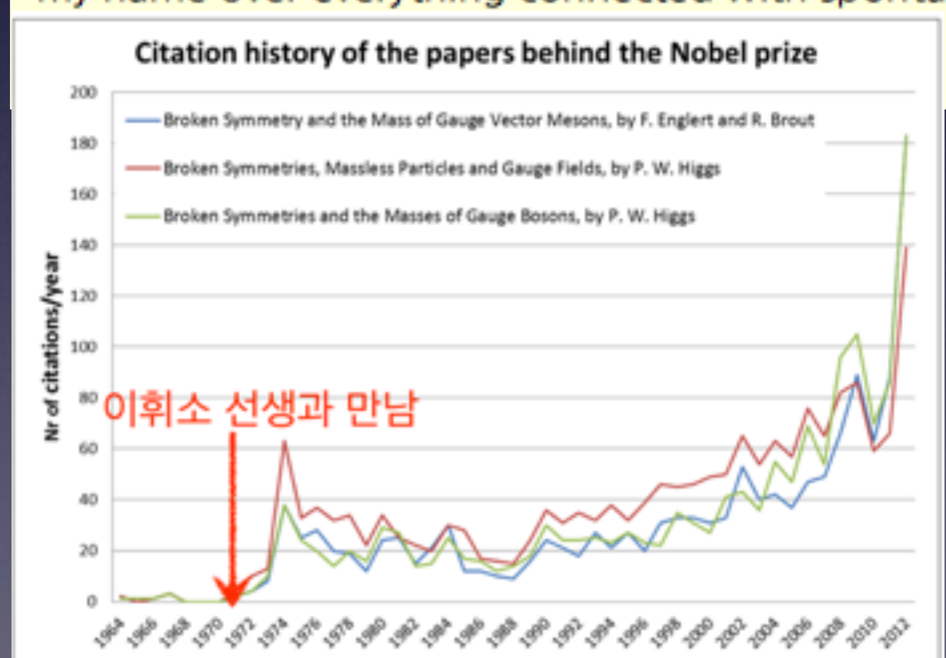
P. Higgs "My life as a boson" (2010)



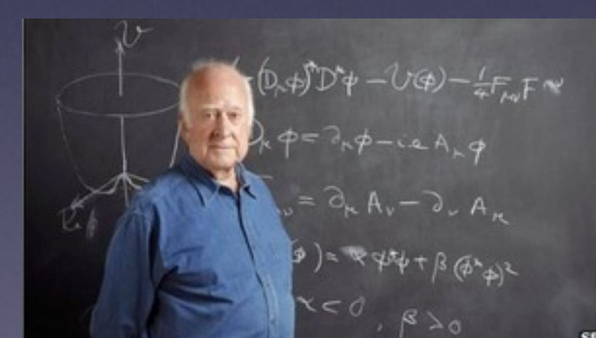
Why coined the name? (1)

"1972년 로체스터 대학에서의 한 파티장에서 함께 와인과 샌드위치를 들었던 벤 리(=이휘소 선생님)가 이 내용 (=힉스의 논문)을 알게된 후 내 이름(=힉스)을 대칭성의 자발적 깨짐 현상과 관련된 모든 곳에 붙이면서 다른 이들(앙글레어-브라우트 ...)은 각주 정도로 밀려나게 되었다"

"In 1972 Ben Lee, who had learnt about it first at a party in the University of Rochester at which we were both holding a glass of wine and a plate of sandwiches, then plastered my name over everything connected with spontaneous symmetry breaking, and other



P. Higgs "My life as a boson" (2010)



Who coined the name? (2)

Steven Weinberg..

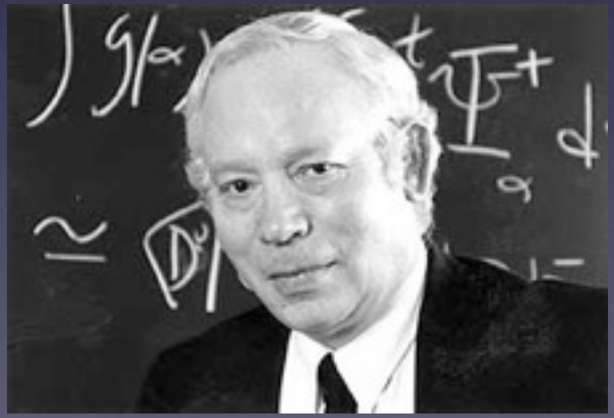
As to my responsibility for the name "Higgs boson," because of a mistake in reading the dates on these three earlier papers, I thought that the earliest was the one by Higgs, so in my 1967 paper I cited Higgs first, and have done so since then. Other physicists apparently have followed my lead. But as Close points out, the earliest paper of the three I cited was actually the one by Robert Brout and François Englert. In extenuation of my mistake, I should note that Higgs and Brout and Englert did their work independently and at about the same time, as also did the third group (Gerald Guralnik, C.R. Hagen, and Tom Kibble). But the name "Higgs boson" seems to have stuck. ↩

S. Weinberg (2012) The New York Book Review

wrong order..

[2]J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).
[3]P. W. Higgs, Phys. Letters 12, 132 (1964), Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964).

Refs in S. Weinberg [Model of Leptons] 1967



The value of discovery of a Higgs

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- => theoretically problematic..(later more)
- Completion of the SM
- => does not mean that particle physics ends.. (later more)

[reminder]
The SM in a single page

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- keep only relevant (D=<4) operators. Why?)

What did we learn?

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$$\begin{aligned}
\lambda^{(1)}(\mu) = \frac{1}{2} G_\mu^2 \frac{1}{(4\pi)^2} \Bigg\{ & \frac{6(L_H - L_W) M_h^6}{M_h^2 - M_W^2} - 8\left(2M_W^4 + M_Z^4\right) - 2(-3 + 6L_T) M_h^2 M_t^2 \\
& + M_h^4 \left(19 - 15L_H + 6L_W - 3\sqrt{3}\pi\right) + 12(M_h^2 - 4M_t^2) M_t^2 B_0(M_t, M_t, M_h) \\
& + 2\left(M_h^4 - 4M_h^2 M_W^2 + 12 M_W^4\right) B_0(M_W, M_W, M_h) \\
& + \left(M_h^4 - 4M_h^2 M_Z^2 + 12 M_Z^4\right) B_0(M_Z, M_Z, M_h) \\
& + M_h^2 \left[2(8L_W - 7) M_W^2 + (8L_Z - 7) M_Z^2 - \frac{6 M_Z^2 M_W^2}{M_Z^2 - M_W^2}(L_Z - L_W)\right] \Bigg\} ,
\end{aligned}$$

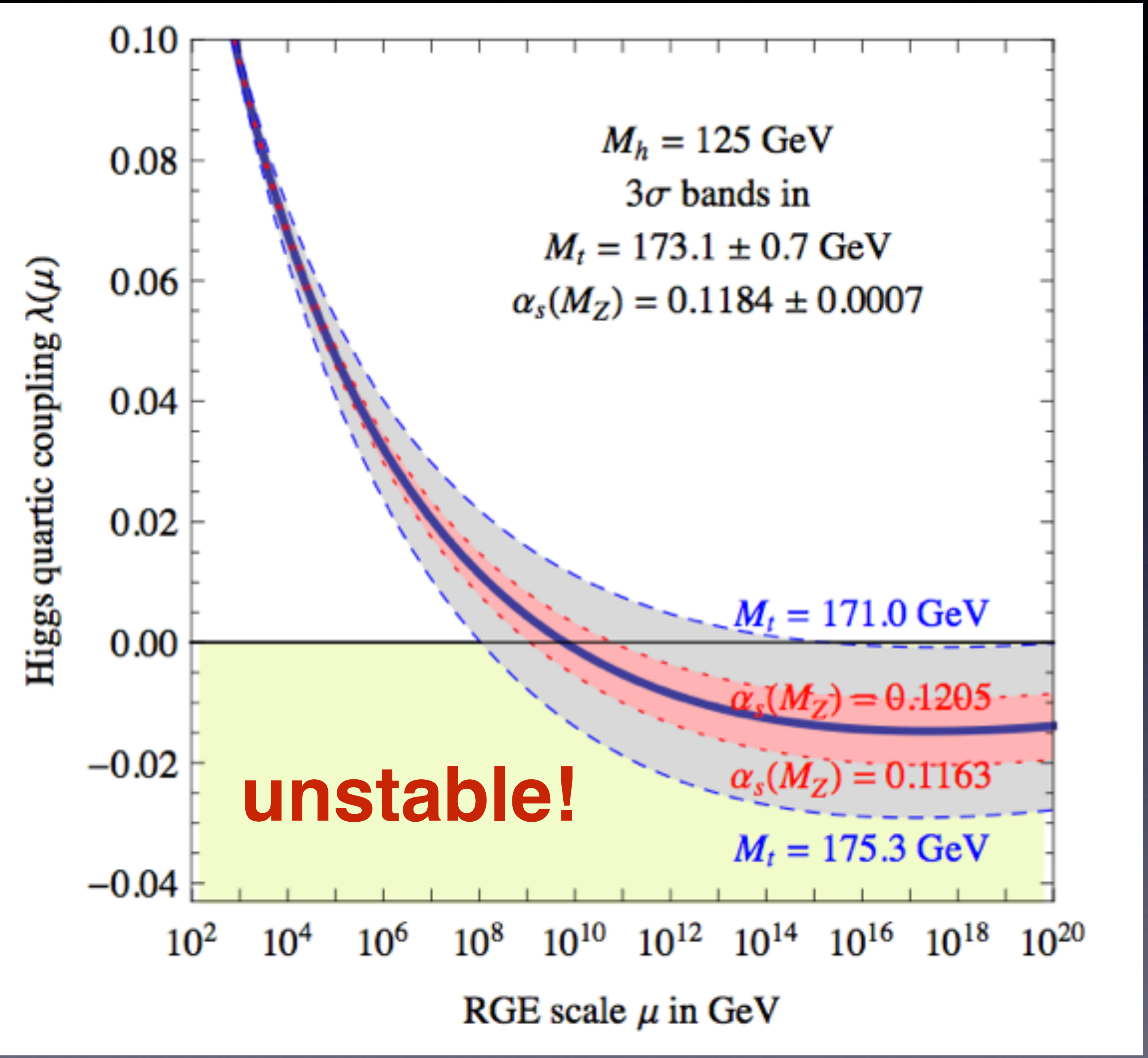
d the leading two loop QCD and Yukawa terms are **@2-loop**

$$\lambda^{(2)}_{\text{QCD,lead.}}(\mu) = \frac{G_\mu^2 M_t^4}{(4\pi)^4} 64 g_s^2(\mu) \left(-4 - 6L_T + 3L_T^2\right) ,$$

$$\lambda^{(2)}_{\text{Yuk,lead.}}(\mu) = \frac{8\sqrt{2} G_\mu^3 M_t^6}{(4\pi)^4} \left(30 + \pi^2 + 36 L_T - 45 L_T^2\right) .$$

[arXiv:1205.6497]

If the SM is true all the way …



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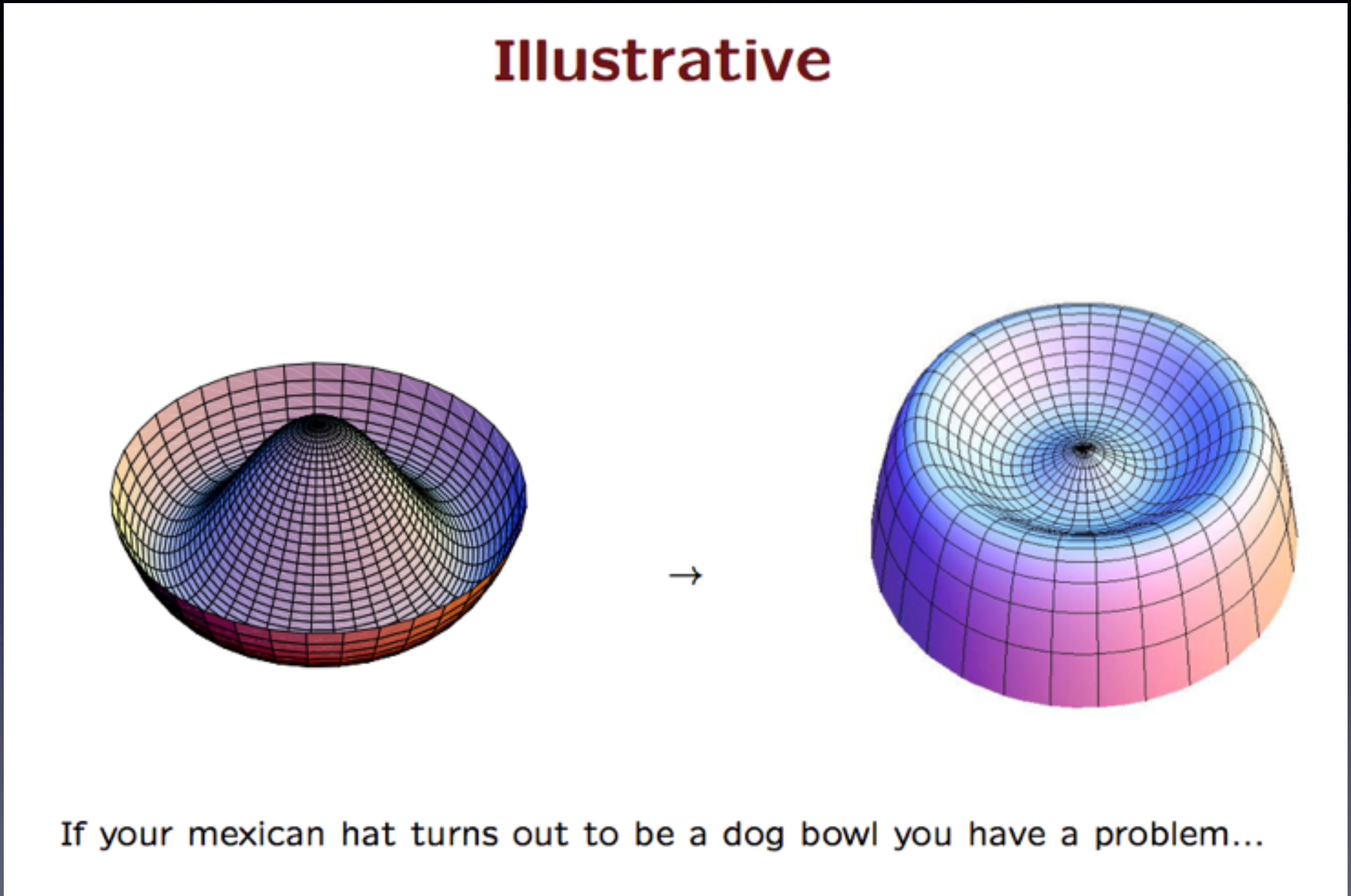

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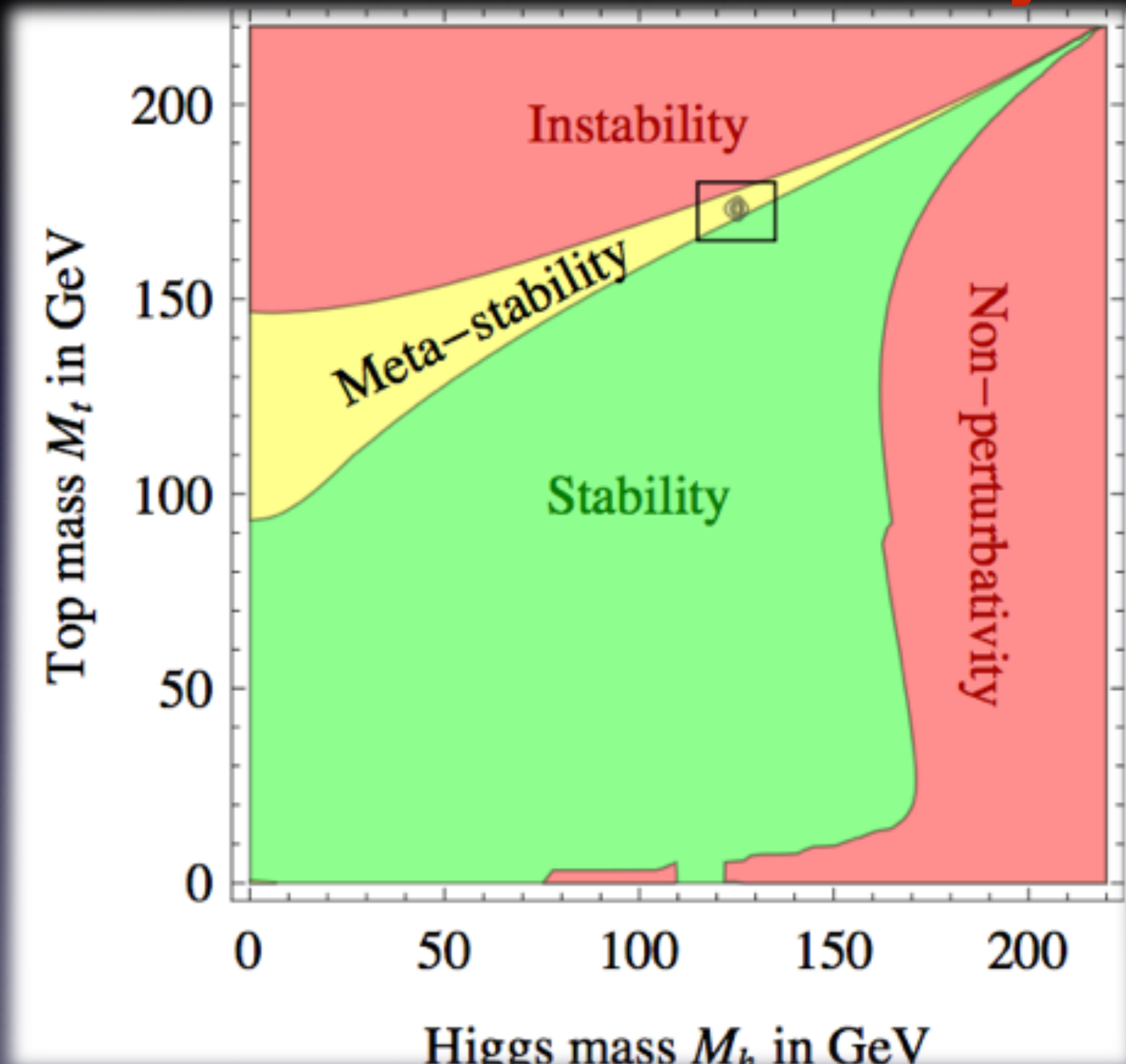

We live at the boarder of stability and metastability!

New (& old) questions

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- This is inconsistent with conventional picture with (SUSY) GUT, which takes place $10^{13\text{-}15}$ GeV ..??
- Does it indicate the break down of the SM below 10^{8} GeV??
- Any reason why we need to think of BSM at 1 TeV? => The hierarchy problem

A big beautiful hierarchical structure

SM: $\left(\frac{M_P}{M_W}\right)^2 \sim 10^{30}$

what's wrong with this?

A big hierarchical structure

tends to collapse

unless there is a mechanism protecting the structure

⇒New Physics

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- (Food for thought: is it really numerology?)

The hierarchy problem in the Higgs sector

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- The Higgs mass is quadratically sensitive to UV physics unless new physics comes in at ~TeV to soften the sensitivity
- The naturalness problem is often stated in terms of the one-loop corrections to the scalar mass

The 1-loop Higgs mass

$$M_H^2 = (M_H^0)^2 - \frac{c}{16\pi^2}\Lambda^2$$

physical

bare parameter
(in Lagrangian)

cutoff

$$(125\mathrm{GeV})^2 = (M_H^0)^2 - \frac{c}{16\pi^2}(10^{19}\mathrm{GeV})^2$$

~17 digits tuned

$$(125\mathrm{GeV})^2 = (M_H^0)^2 - \frac{c}{16\pi^2}(1000\mathrm{GeV})^2$$

~natural!

The 1-loop Higgs mass in dimensional regularization

only sees "log divergence" not "power divergence"

$$\int^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \sim \Lambda^2$$

$$\int \frac{d^dk}{(2\pi)^d} \frac{1}{k^2 - m^2} \sim m^2\left(\frac{1}{\epsilon} - \log m^2\right)$$

Q. where is the quadratic divergence?

Criticality

$$S \ni \int d^d x \lambda_i \frac{\mathcal{O}_i^{\delta_i}}{\Lambda^{\delta_i - d}} \qquad [\lambda_i] \sim 1$$

scattering at E*: $A \sim \lambda_i \left(\frac{E_*}{\Lambda}\right)^{\delta_i - d}$

for scalar mass: $S_\phi \sim \int d^d x \lambda_\phi \Lambda^2 \phi^2 \qquad \delta_\phi = 2$

$$m_\phi^2 \sim \lambda \times \frac{\Lambda_\phi^2}{100^2} \times (100\text{GeV})^2 \qquad E_* \sim 100 \text{ GeV}$$

$\lambda_\phi \sim (10^{-17})^2$ Why so small?

BSM at TeV

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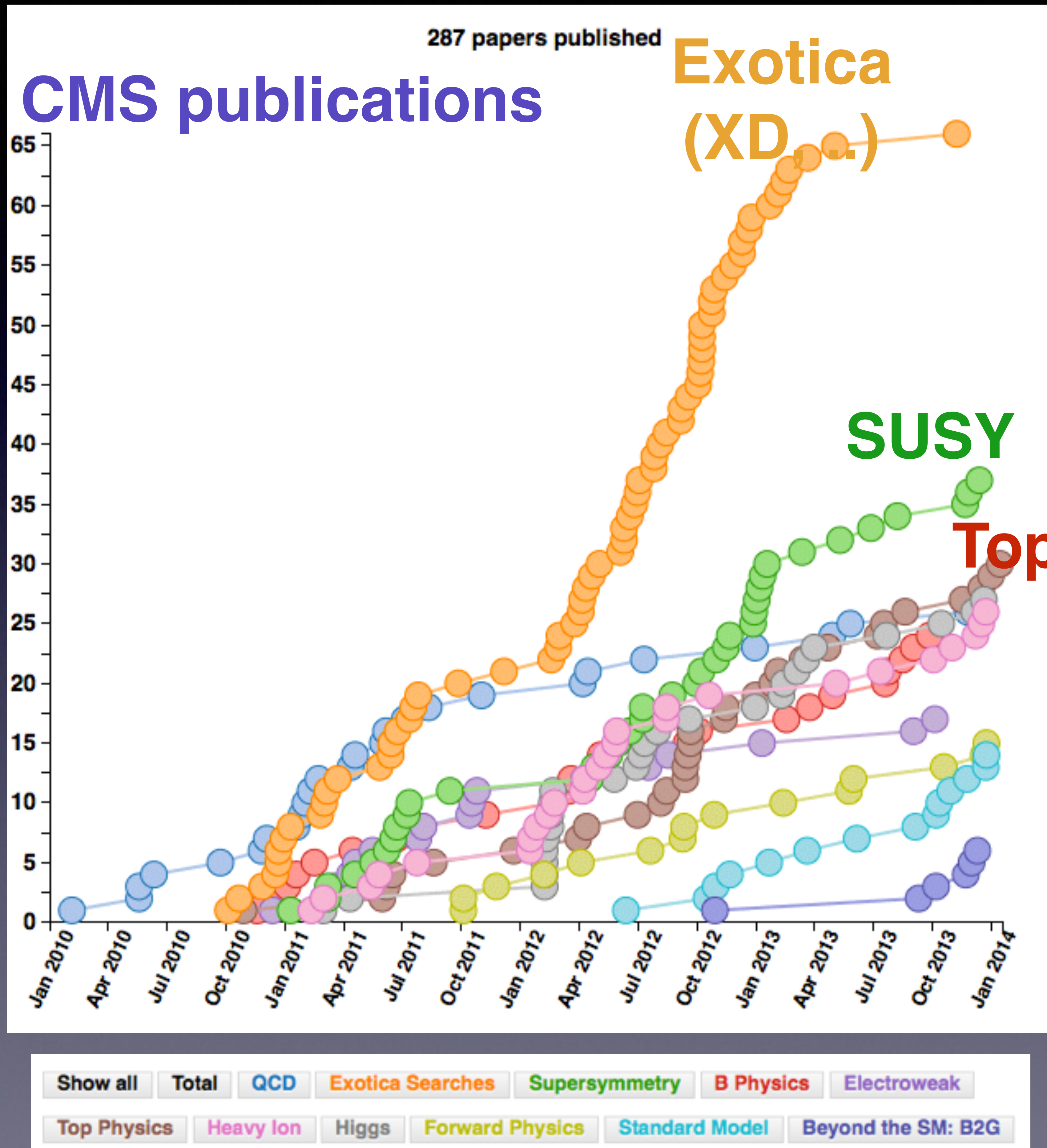
- Most of them predicted new particles at around TeV


287 papers published
CMS publications
Exotica
(XD, ..)
SUSY
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Electroweak
Top Physics
Heavy Ion
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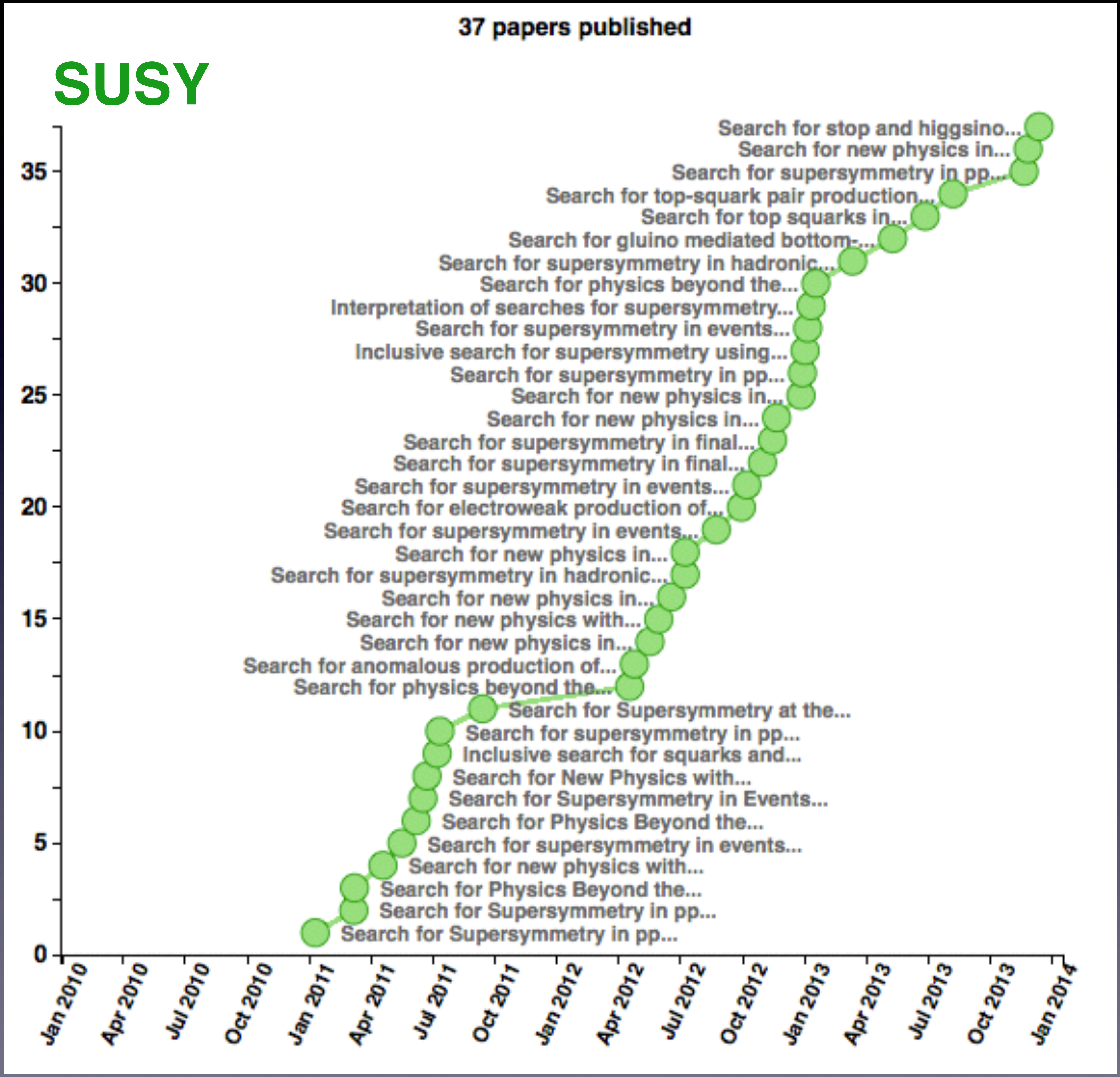
Forward Physics
Standard Model
Beyond the SM: B2G


37 papers published
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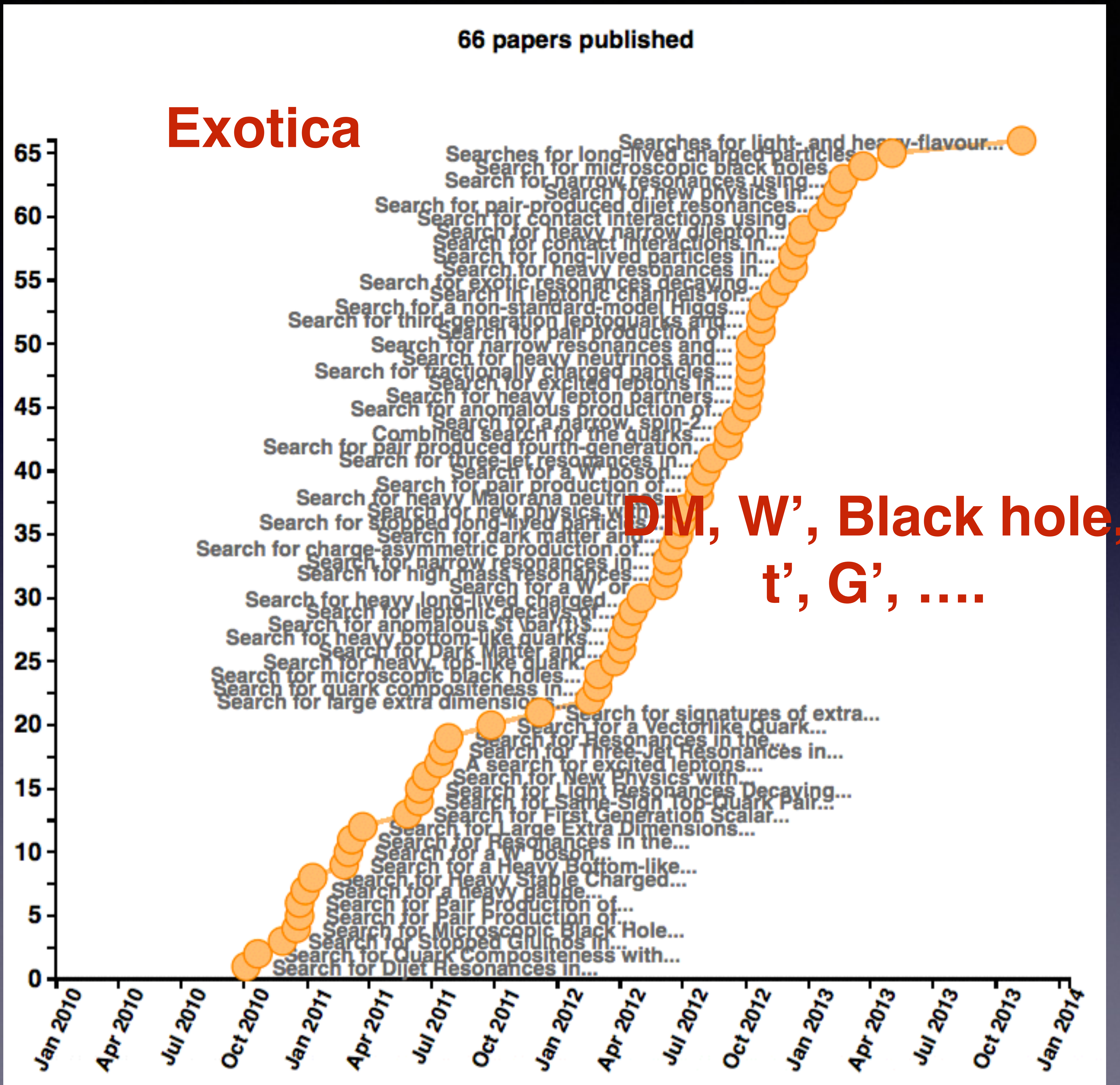
66 papers published
Exotica
DM, W', Black hole,
t', G', ….
Searches for light- and heavy-flavour...
Searches for long-lived charged particles...
Search for microscopic black holes...
Search for narrow resonances using...
Search for new physics in...
Search for pair-produced dijet resonances...
Search for contact interactions using...
Search for heavy narrow dilepton...
Search for contact interactions in...
Search for long-lived particles in...
Search for heavy resonances in...
Search for exotic resonances decaying...
Search in leptonic channels for...
Search for a non-standard-model Higgs...
Search for third-generation leptoquarks and...
Search for pair production of...
Search for narrow resonances and...
Search for heavy neutrinos and...
Search for fractionally charged particles...
Search for excited leptons in...
Search for heavy lepton partners...
Search for anomalous production of...
Search for a narrow, spin-2...
Combined search for the quarks...
Search for pair produced fourth-generation...
Search for three-jet resonances in...
Search for a W' boson...
Search for pair production of...
Search for heavy Majorana neutrinos...
Search for new physics with...
Search for stopped long-lived particles...
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Search for narrow resonances in...
Search for high mass resonances...
Search for a W' or...
Search for heavy long-lived charged...
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Search for anomalous $t \bar{t}$...
Search for heavy bottom-like quarks...
Search for Dark Matter and...
Search for heavy, top-like quark...
Search for microscopic black holes...
Search for quark compositeness in...
Search for large extra dimensions...
Search for signatures of extra...
Search for a Vectorlike Quark...
Search for Resonances in the...
Search for Three-Jet Resonances in...
A search for excited leptons...
Search for New Physics with...
Search for Light Resonances Decaying...
Search for Same-Sign Top-Quark Pair...
Search for First Generation Scalar...
Search for Large Extra Dimensions...
Search for Resonances in the...
Search for a W' boson...
Search for a Heavy Bottom-like...
Search for Heavy Stable Charged...
Search for a heavy gauge...
Search for Pair Production of...
Search for Pair Production of...
Search for Microscopic Black Hole...
Search for Stopped Gluinos in...
Search for Quark Compositeness with...
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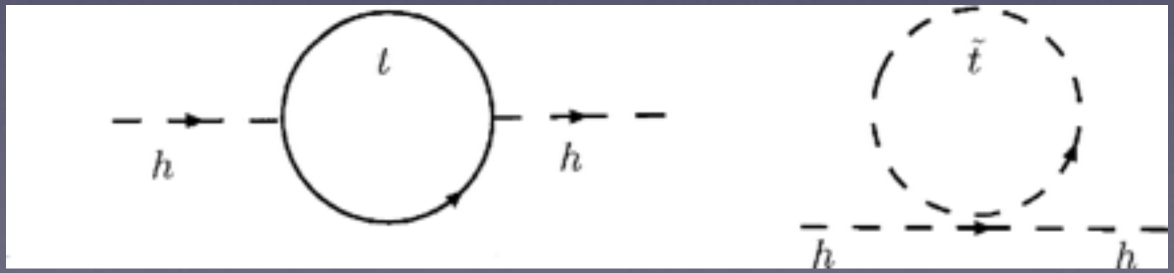
Supersymmetry

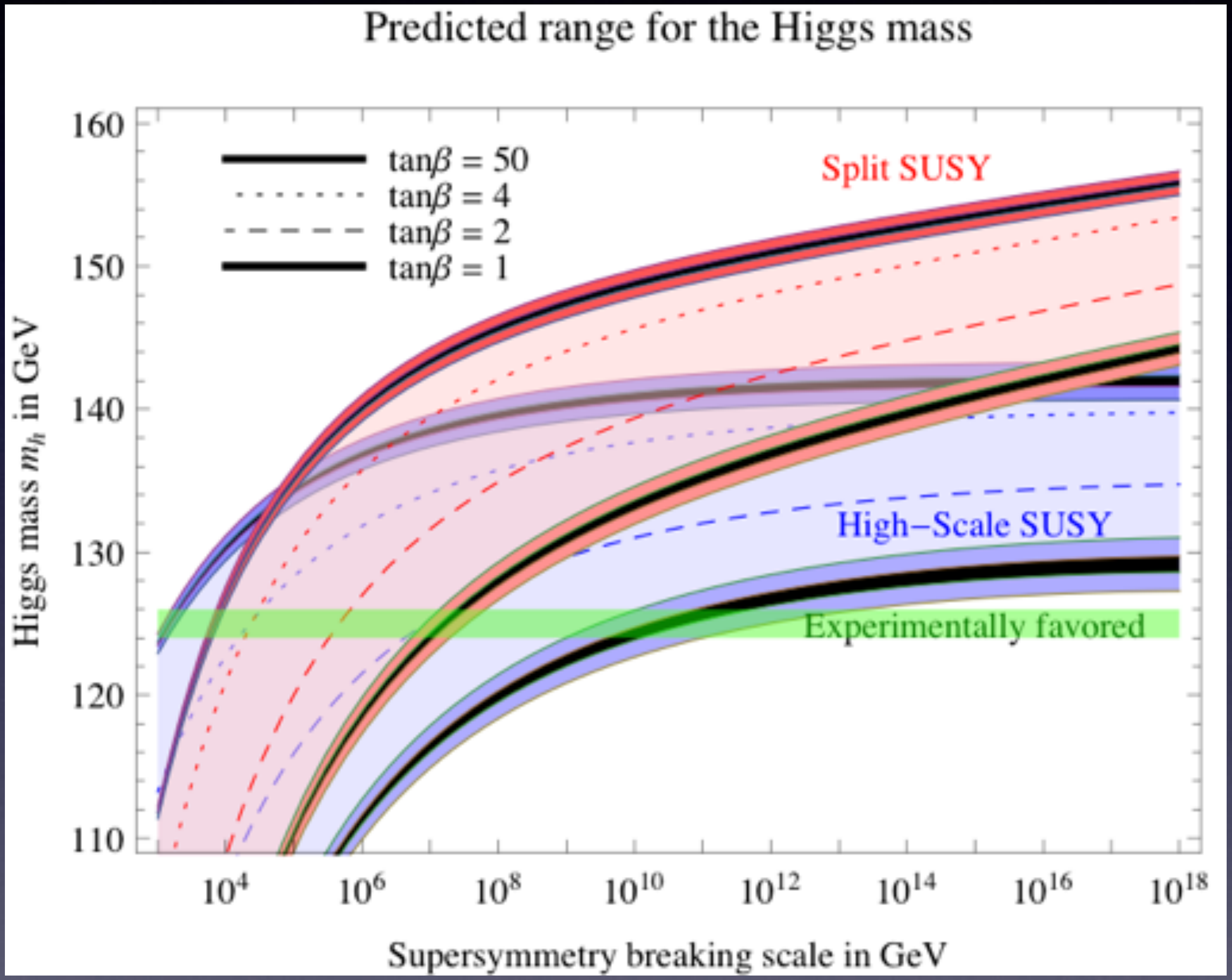
- Make a scalar and its (chiral)fermion partner in a same symmetry multiplet .. (S, F)
- If SUSY exact: $M_F = M_S$
- A symmetry forbids the fermion mass term => A scalar mass term (=the counter term for 1-loop correction) is also forbidden by SUSY
- Ms is associated with the SUSY breaking scale below which SUSY does not protect the scalar any more!

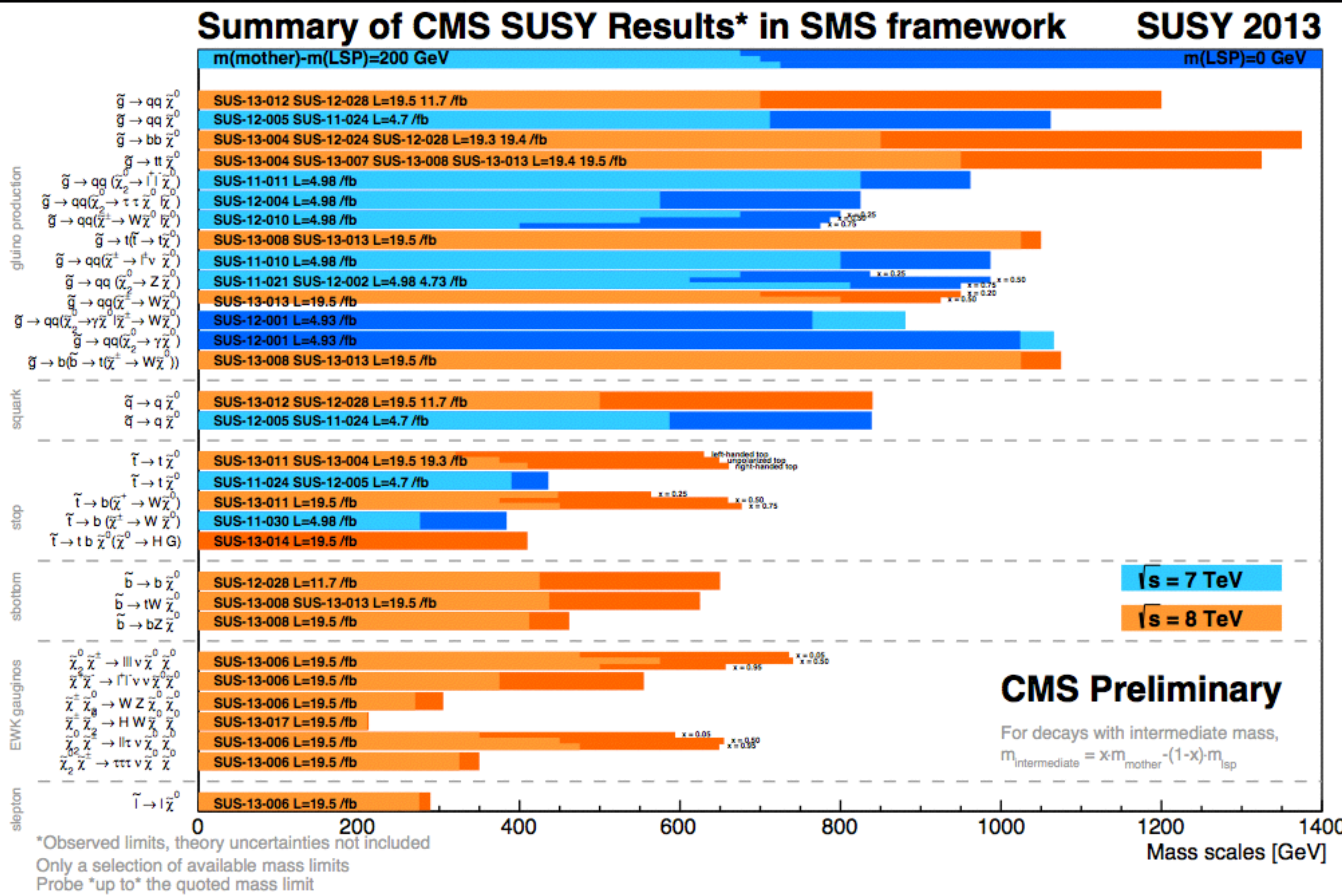
$$1+(-1)^F = 0$$



$$m_H^2 \approx m_Z^2[1 + \frac{3m_t^2}{2\pi^2 m_Z^2}\log(m_{stop}/m_t)]$$

1. Minimal SUSY without fine-tuning predicts the Higgs mass close to the Z boson mass, that is about 90 GeV. (ruled out)
2. Minimal SUSY ignoring fine-tuning predicts the Higgs boson lighter than 160 GeV. (fine-tuned)
3. Non-minimal SUSY in general makes no predictions about the Higgs mass. (many people are trying now..)





Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
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SUS-11-030 L=4.98 /fb
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SUS-12-028 L=11.7 /fb
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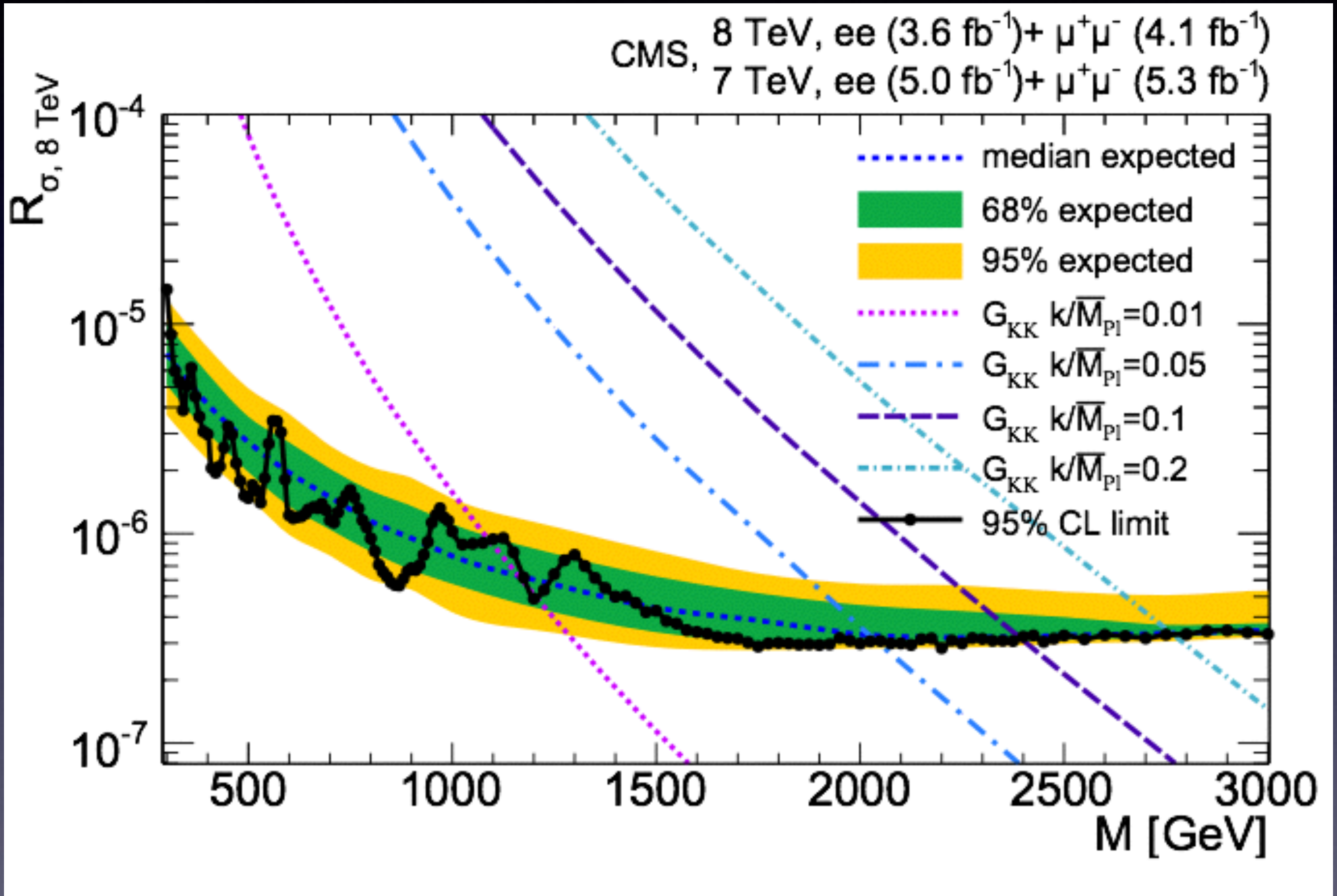
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother-(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Higgs=PNGB

- Higgs mass is protected by a global symmetry
- A la AdS/CFT, the model can be naturally implemented in 5D
- Bulk gauge symmetry ~ global symmetry @ boundary
- In Randall-Sundrum model, large warping factor provides a reason for light Higgs.

$$E_{\mathrm{weak}}/M_P = e^{-kL}$$

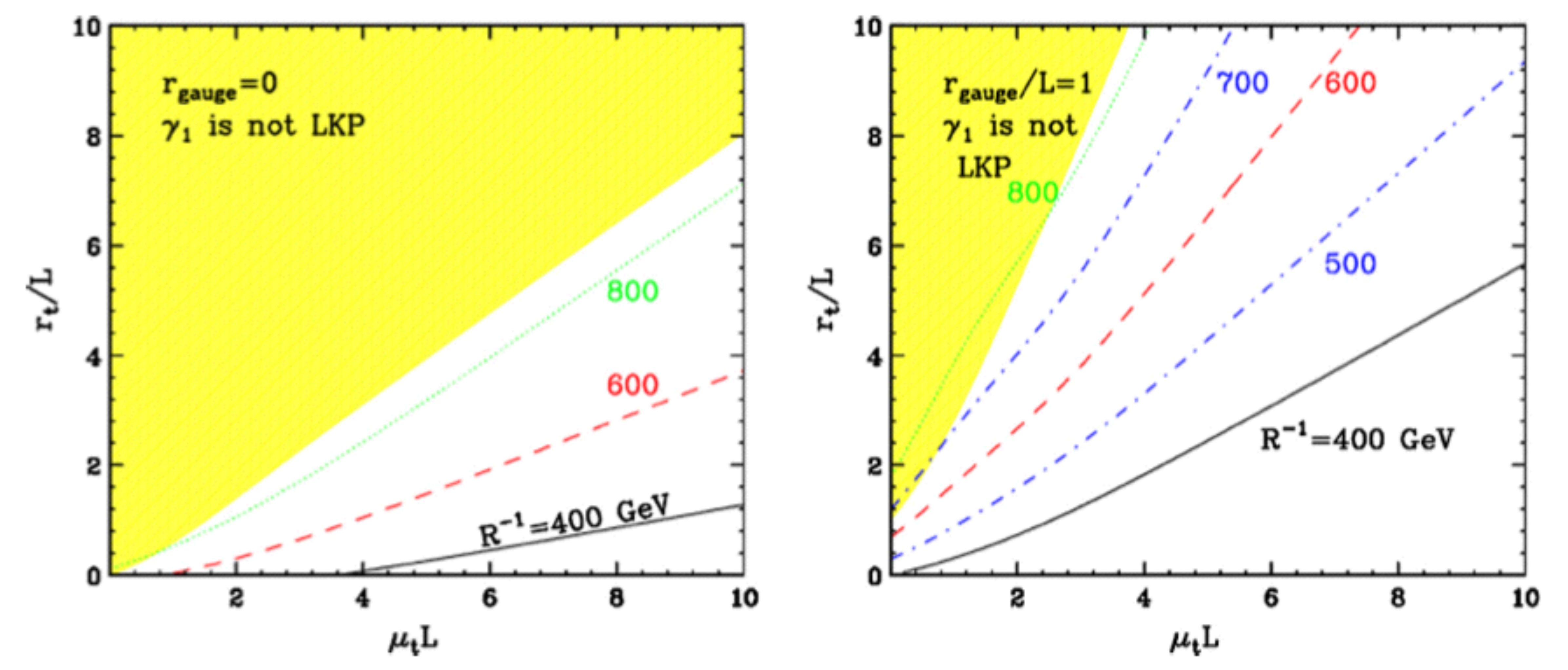
- L=size of XD, k=curvature of AdS
- Predicting KK excitation of the SM particles + KK gravitons



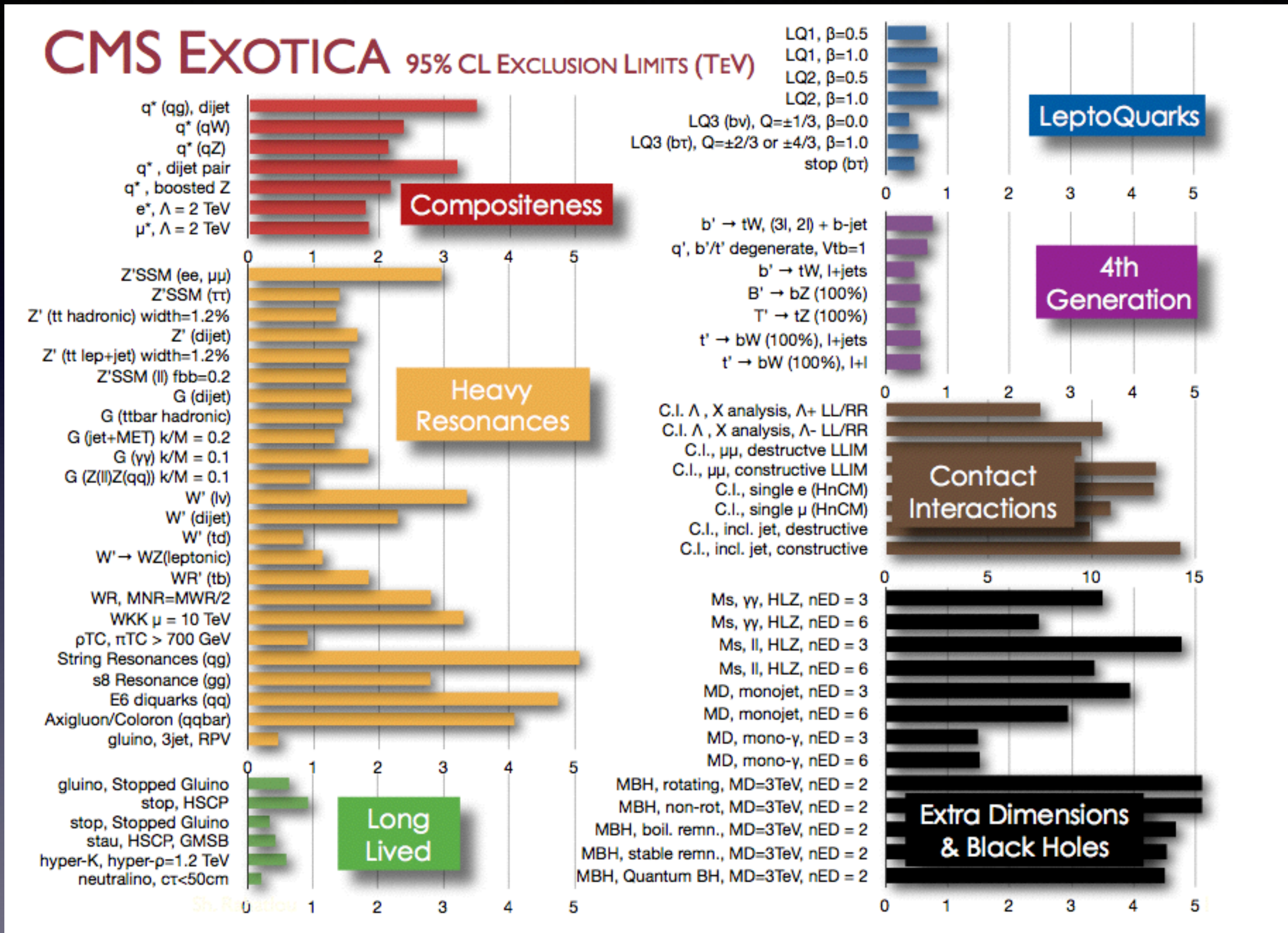
CMS collab. Phys. Lett. B 720 (2013) 63-82

KK-top effect and Higgs physics

ATLAS/CMS combined



Flacke, Kong, SCP [Physics Letters B 728 (2014) 262–267]


CMS Exotica 95% CL Exclusion Limits (TeV)
q* (qg), dijet
q* (qW)
q* (qZ)
q*, dijet pair
q*, boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W' → WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
LeptoQuarks
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
4th Generation
C.I. Λ, X analysis, Λ+ LL/RR
C.I. Λ, X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes

so..

- Impressive progress in NP searches..
- but the LHC only excluded a big chunk of parameter spaces in these models..
- what's the interpretation?

Interpretation-1

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- New physics is just around the corner, once again… LHC13 and LHC14 will see new particles! Q. why LHC7/LHC8 didn't see anything other than the Higgs boson?

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- Maybe the new physics has so degenerate spectrum so that the LHC detector could not identify the soft signals.. (e.g. stop/top degeneracy) Q. Why so degenerate? Is it simply due to that GOD is cruel to us?

Interpretation-2

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- $(Mp/Mw)^2$ vs $(Mp/cc)^4$ $\sim(Mp/M_v)^4$
- Can anthropic argument be the (only possible) solution to the CC problem ?
- Maybe we have not reach the proper level to understand these problems?

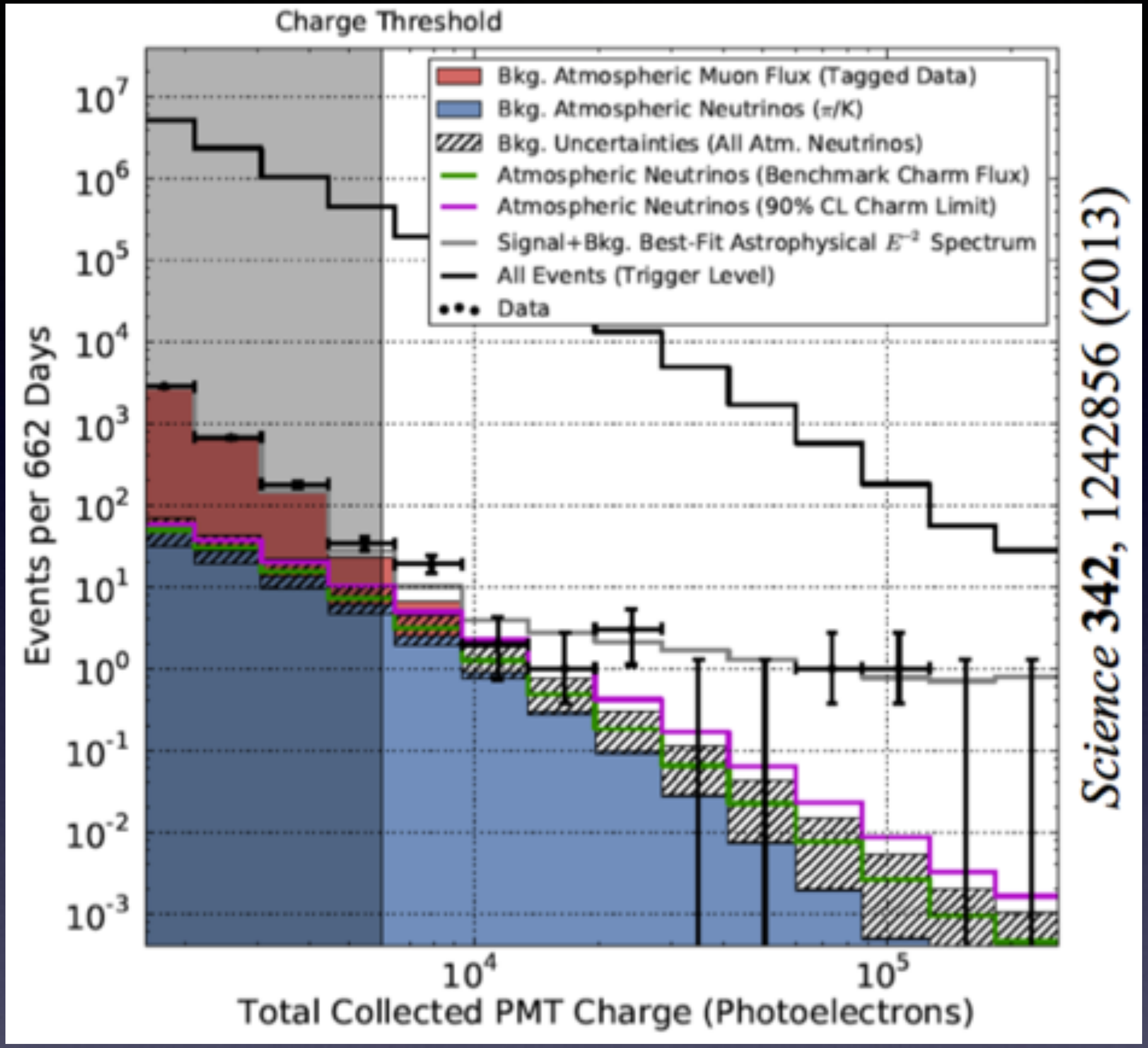
other clues

- We still have empirical reasons why BSM exists..
- Dark matter : no candidate for CDM exist in the SM => indicating ~TeV physics
- Baryon asymmetry: CKM picture does not provide enough CP violation
- Neutrino oscillations : may need RH neutrinos?

Interplay with astrophysics

- New generation of astrophysical observations based on cosmic-ray detection and CMBR measurement started to give us new data about our universe..
- IceCube (neutrino), Fermi-Lat(photon), Planck (CMBR) etc..
- Very interestingly, newly obtained data often suggests that what we know is only a small fraction of the whole story
- (Energy of unknown source)/(Energy of known source)~(95%)/(5%) …the SM is only responsible for this 5%!
- New source for cosmic ray may call for our attention..

IceCube PeV neutrinos



No Bert & Ernie (26 events)	With Bert & Ernie (2+26 events)	A posteriori 28 Events
3.3σ	**4.1σ**	**4.8σ**

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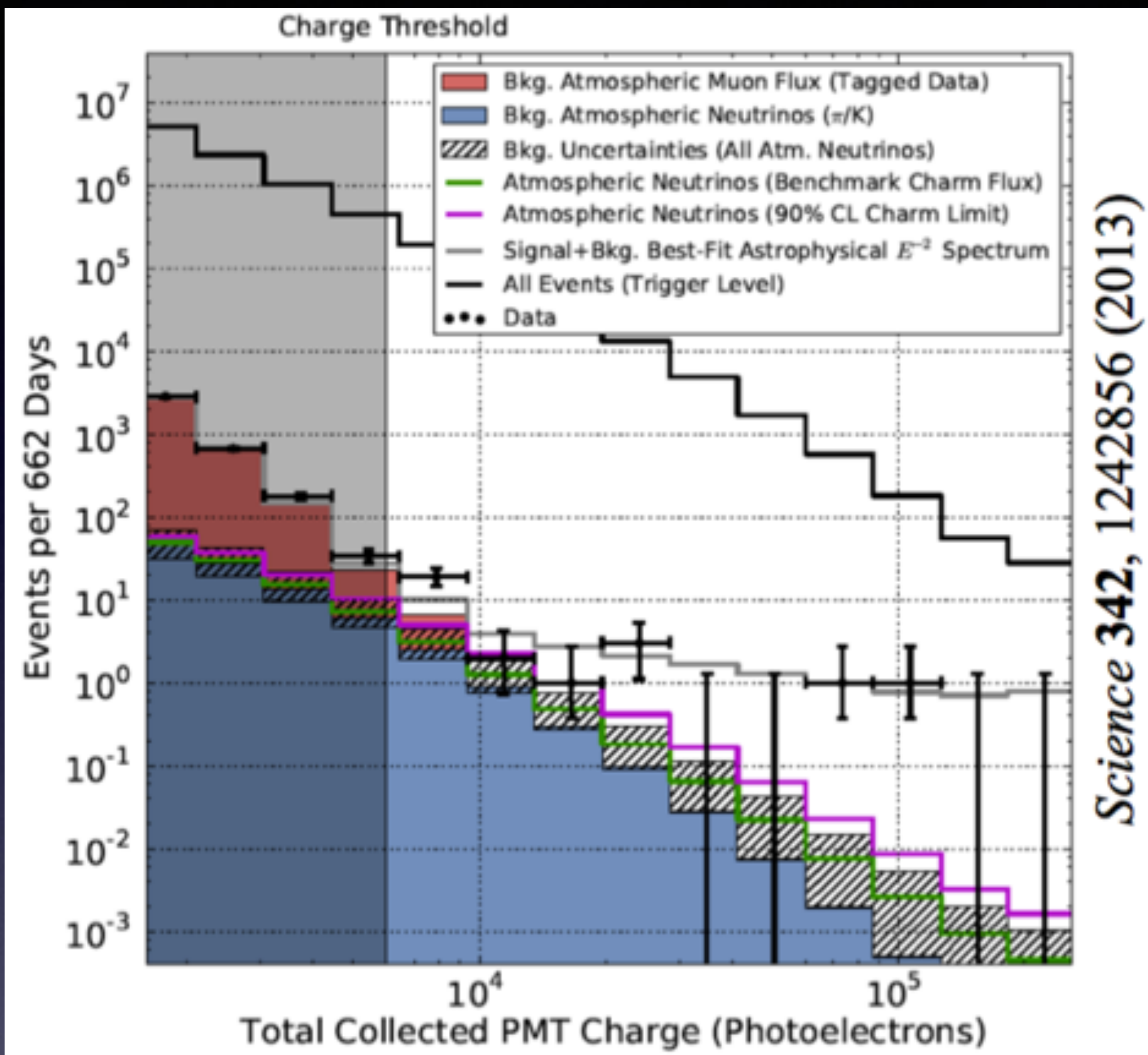

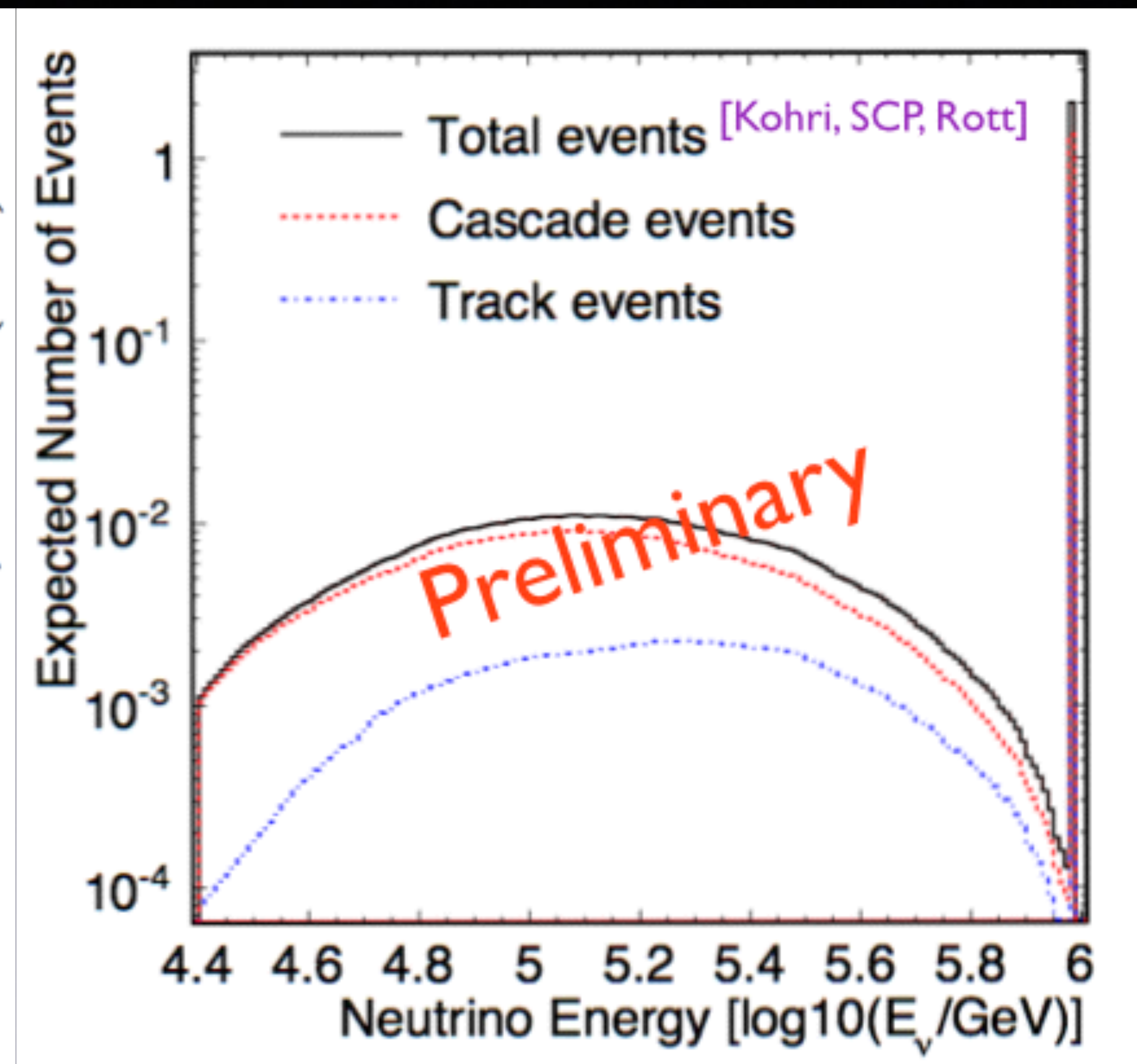

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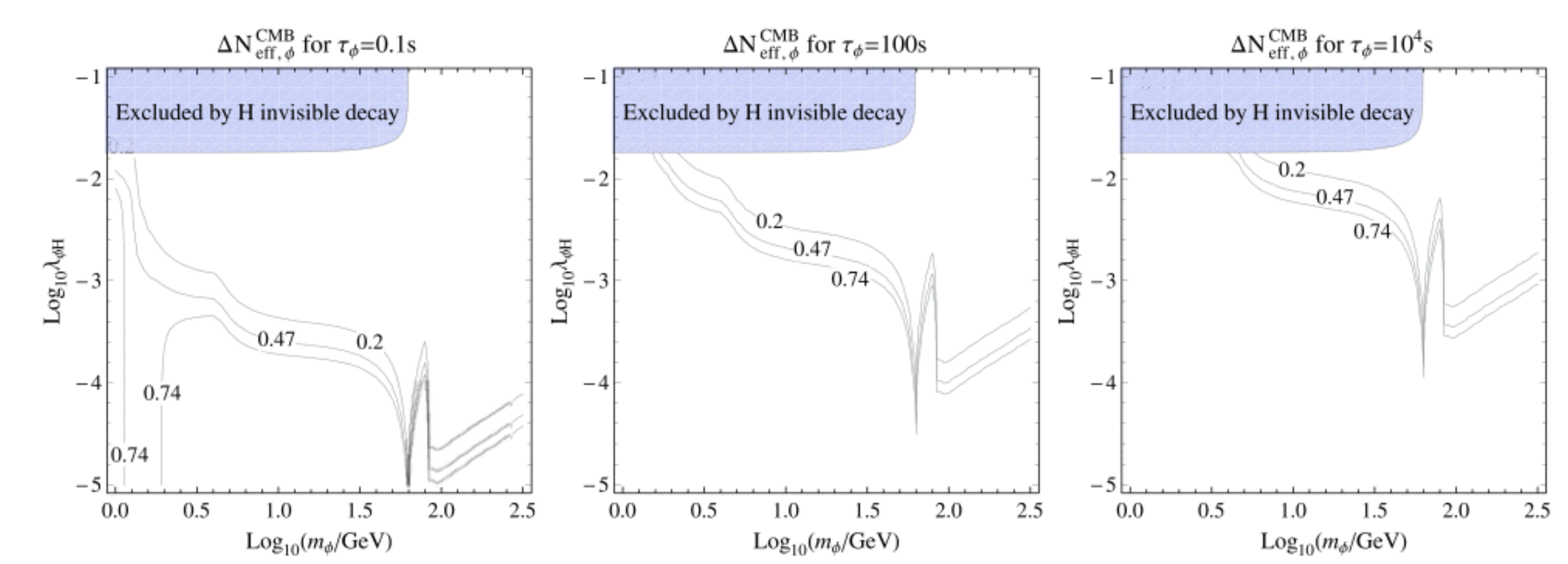
Superheavy Dark matter and Dark radiation



J.C.Park, SCP, [Physics Letters B 728 (2014) 41–44]

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- Also the hierarchy problem (still) lead us BSM at 1TeV scale ..
- ..LHC already ruled out a big chunk of parameter spaces for BSM@TeV

- However, we already know that the SM is not the end of the story!
- DM, Baryogenesis, neutrino masses …
- DM, in particular, seems to indicate NP at around TeV in the framework of Big-Bang cosmology..
- The LHC13/14 + new Astro/Cosmo observation may be able to see some clues to BSM soon
- Let’s be optimistic!