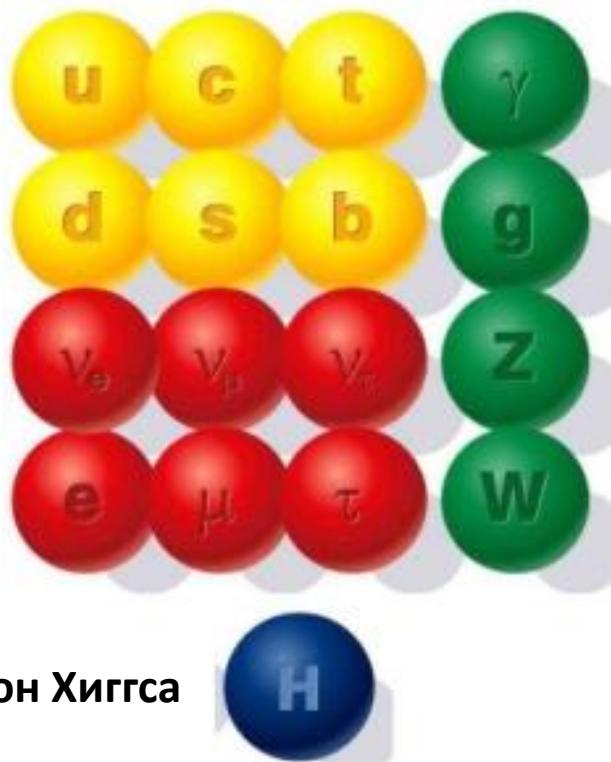


Проблемы физики фундаментальных взаимодействий после открытия бозона Хиггса

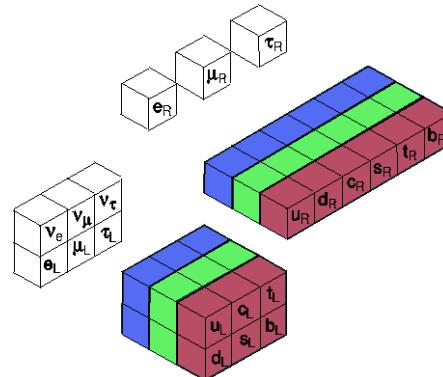
**Э.Э.Боос
НИИЯФ МГУ**

Стандартная модель

Поколения частиц
1-ое 2-ое 3-е

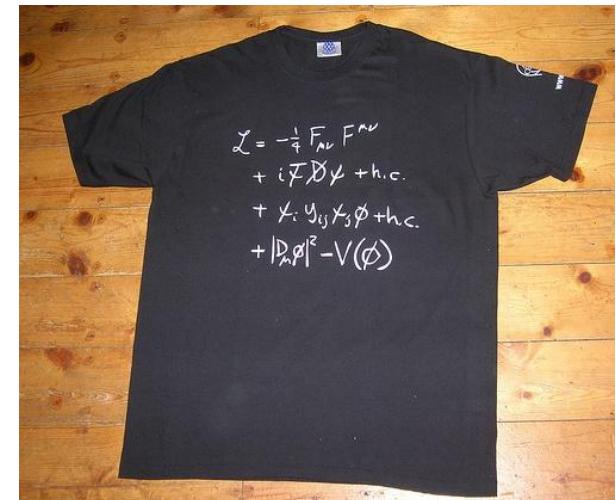


Переносчики
взаимодействий



Калибровочная симметрия

$$\mathbf{SU(2)_L} \times \mathbf{U(1)_Y} \times \mathbf{SU(3)_c}$$



Бозон Хиггса



СМ - элегантная теоретическая конструкция,
одно из наиболее важных интеллектуальных достижений последних 50 лет

In Ginzburg-Landau theory

The free energy in terms of the temperature T and the magnetization M

$$F(\mathbf{M}, T) \simeq F_0(T) + 1/2 \mu^2(T) \mathbf{M}^2 + 1/4 \lambda(T) (\mathbf{M}^2)^2 + \dots$$

F is invariant under rotations

The minimum condition for F

$$\partial F / \partial M_i = 0, \quad [\mu^2(T) + \lambda(T) \mathbf{M}^2] \mathbf{M} = 0$$

$$\mu^2(T_{\text{crit}}) = 0$$

If $\mu^2 > 0$ the only solution is $\mathbf{M} = 0$

If $\mu^2 < 0$ the solution is $|\mathbf{M}_0|^2 = -\mu^2 / \lambda$

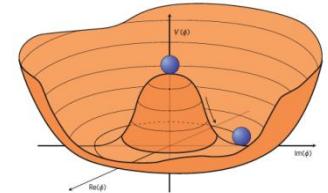
A particular direction chosen by the vector \mathbf{M}_0 leads to a breaking of the rotation symmetry.

Brout-Engelrt-Higgs mechanism (БЕН)

Массы W и Z бозонов

$$L_\Phi = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$\Phi(x) = \exp\left(-i\frac{\xi^i(x)t^i}{v}\right) \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$



Массы夸克ов и лептонов, матрица смешивания СКМ

$$L_{Yukawa} = -\Gamma_d^{ij} \bar{Q}_L^i \Phi d_R'^j + h.c. - \Gamma_u^{ij} \bar{Q}_L^i \Phi^C u_R'^j + h.c. - \Gamma_e^{ij} \bar{L}_L^i \Phi e_R'^j + h.c. \quad (1)$$

Унитарное поведение и переномируемость СМ

Пропагатор массивного векторного бозона

Унитарная калибровка

$$D_{\mu\nu}(p) = \frac{-i}{p^2 - M_V^2} \left[g_{\mu\nu} - \frac{p_\mu p^\nu}{M_V^2} \right]$$

Ковариантная калибровка

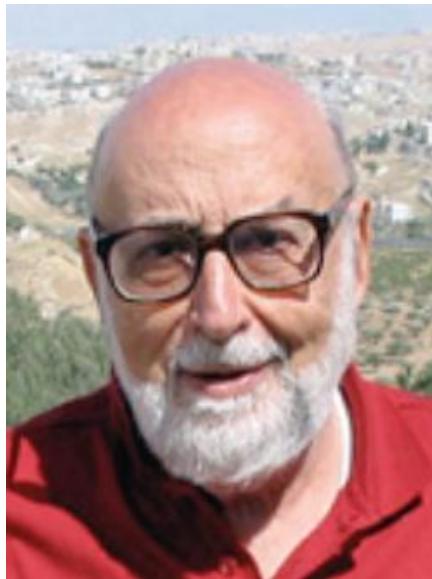
$$D_{\mu\nu}^\xi = \frac{-i}{k^2 - M_V^2} \left[g_{\mu\nu} - (1 - \xi) \frac{k_\mu k_\nu}{k^2 - \xi M_V^2} \right]$$

$$D^c = \frac{i}{p^2 - \xi M_V^2}$$

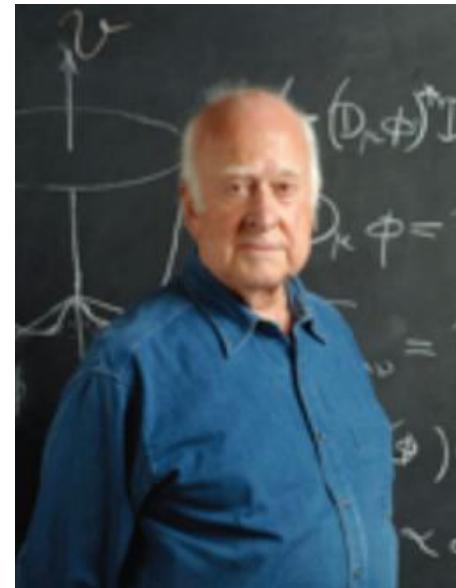
Пропагатор
голдстоуновского бозона

Нобелевская премия по физике 2013 года

Francios Englert



Peter Higgs



За теоретическое открытие механизма, который обогащает
наше понимание происхождения массы субатомных частиц
и который недавно был подтвержден открытием предсказанной
фундаментальной частицы в ходе экспериментов ATLAS и CMS
на Большом адронном коллайдере ЦЕРН

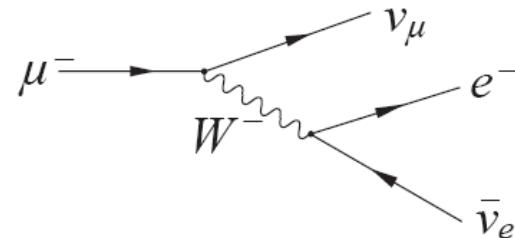
**Что нам было известно о бозоне Хиггса СМ
до его прямого обнаружения?**

Константа G_F извлекается с высокой точностью из данных по измерению времени жизни мюона

$$G_F = 1.166\,378\,7(6) \times 10^{-5} \text{ GeV}^{-2}$$

Поскольку $m_\mu \ll M_W$, в пропагаторе W можно пренебречь импульсами и получить:

$$\frac{g_2^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$$



Но в СМ масса W бозона обусловлена механизмом Хиггса и пропорциональна значению вакуумного среднего v

$$M_W^2 = \frac{1}{4} g_2^2 v^2$$

Из этих двух соотношений:

$$v = \frac{1}{\sqrt{\sqrt{2} G_F}} = 246.22 \text{ GeV}$$

Мощь принципа калибровочной инвариантности, g_2 – это одна и также калибровочная константа связи группы $SU_L(2)$

The Higgs field expectation value v is determined by the Fermi constant G_F introduced long before the Higgs mechanism appeared!

Только один свободный параметр – масса бозона Хиггса

$$\begin{aligned} L_H = & \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_h^2}{2}h^2 - \frac{M_h^2}{2v}h^3 - \frac{M_h^2}{8v^2}h^4 + \\ & + (M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu) \left(1 + \frac{h}{v}\right)^2 - \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right) \end{aligned}$$

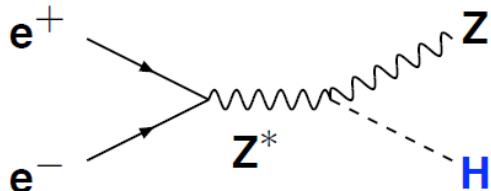
Предсказания для ширин распадов и сечений рождения по различным модам

Ограничения из условия унитарности и самосогласованности СМ

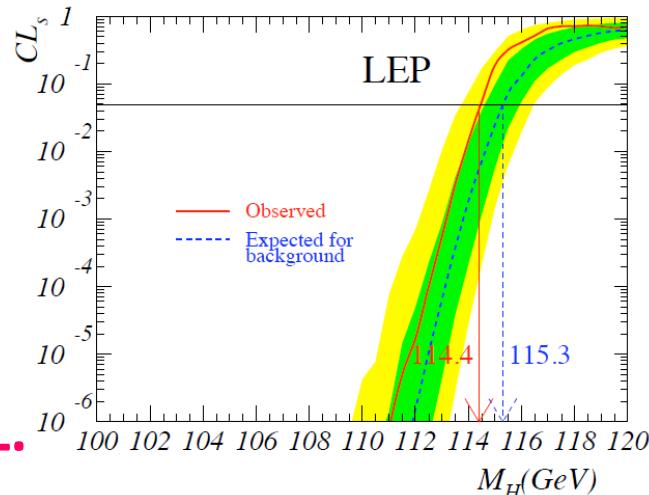
Ограничения из прямых поисков

Ограничения из сравнений петлевых вкладов с точными экспериментальными измерениями

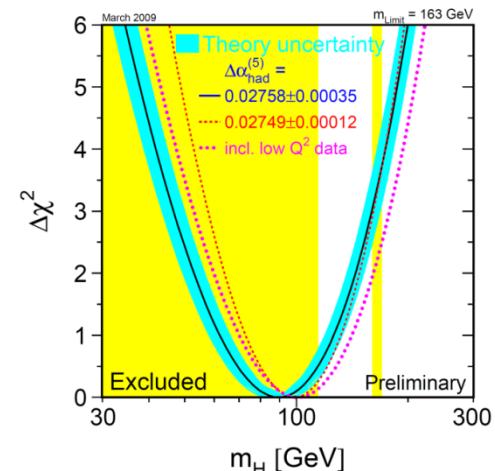
1. Прямые поиски:



$M_H > 114.4 \text{ GeV } 95\% \text{ C.L.}$



Tevatron (in gluon fusion with decay to WW):
Excluded region
 $M_H : 160-170 \text{ GeV}$



2. Ограничения из петлевых вкладов в массы:

$\sim M_{\text{top}}^2$

$$\sim \log(M_H^2/M_W^2)$$

Combination (LEP + Tevatron):

$$M_W = 80385 \pm 15 \text{ MeV} \quad 0.02\%$$

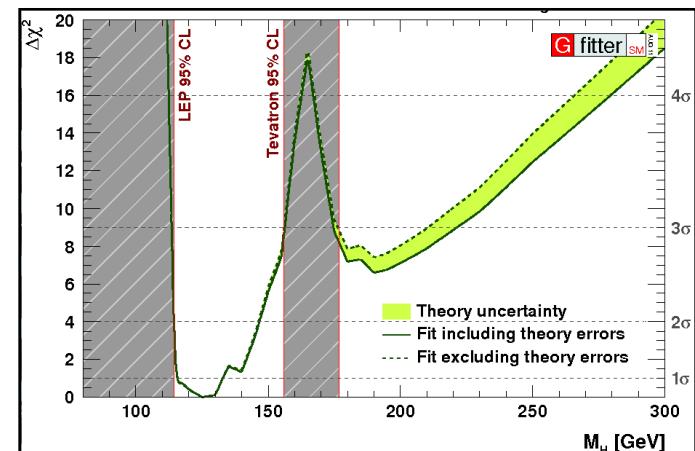
Tevatron

$$M_{\text{top}} = 173.18 \pm 0.56(\text{stat}) \pm 0.75 (\text{syst}) \text{ GeV}$$

LHC

$$M_{\text{top}} = 173.3 \pm 0.5(\text{stat.}) \pm 1.3(\text{syst.}) \text{ GeV}$$

Combining all direct and indirect constraints:

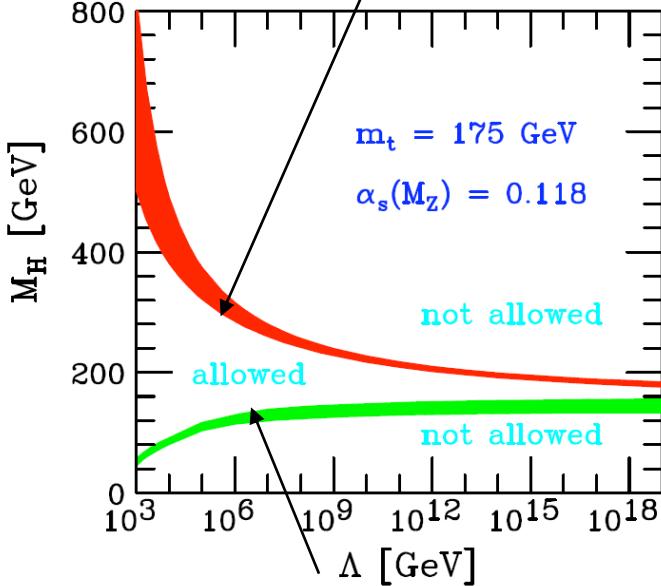


Gfitter collaboration, Aug. 2011

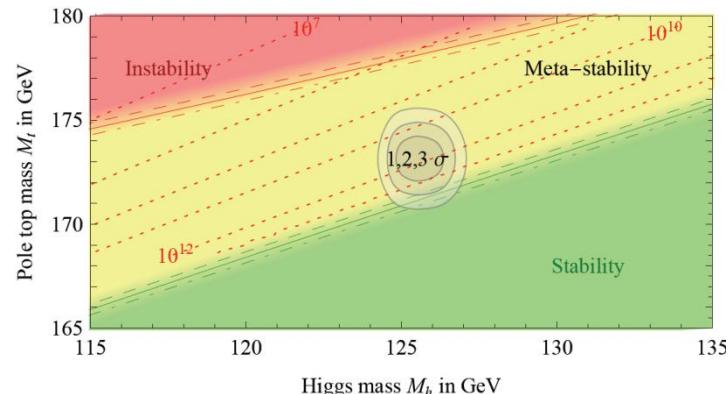
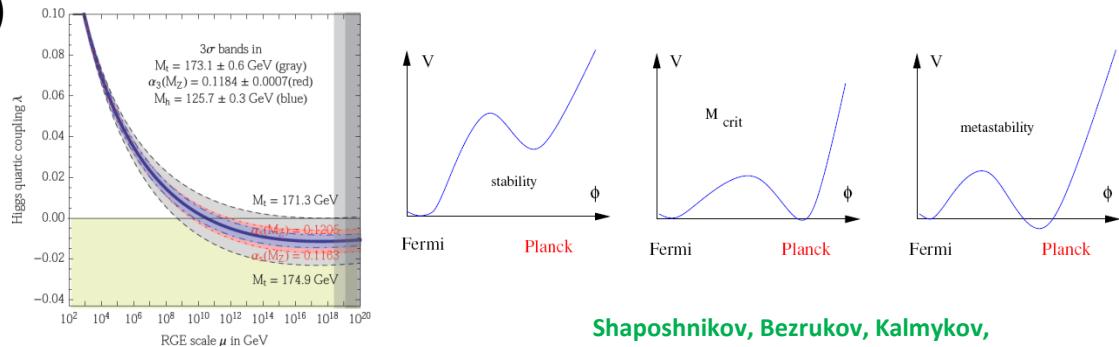
$$M_H = 125 \pm 10 \text{ GeV}$$

3. Самосогласованность СМ как квантовой теории поля

Отсутствие полюса Ландау (triviality)



Положительная констант самодействия
 (vacuum stability) $\lambda(Q^2) > 0$



4. Из требования унитарности для $VV \rightarrow VV$ ($V: W, Z$)

$$M_H \lesssim 710 \text{ GeV}$$

if $\sqrt{s} \gg M_H$

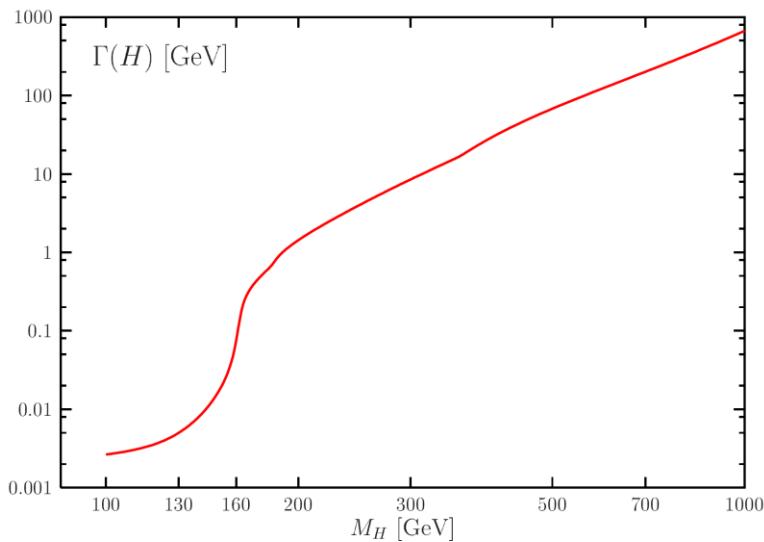
Либо легкий Хиггс

$$\sqrt{s} \lesssim 1.2 \text{ TeV}$$

if $\sqrt{s} \ll M_H$

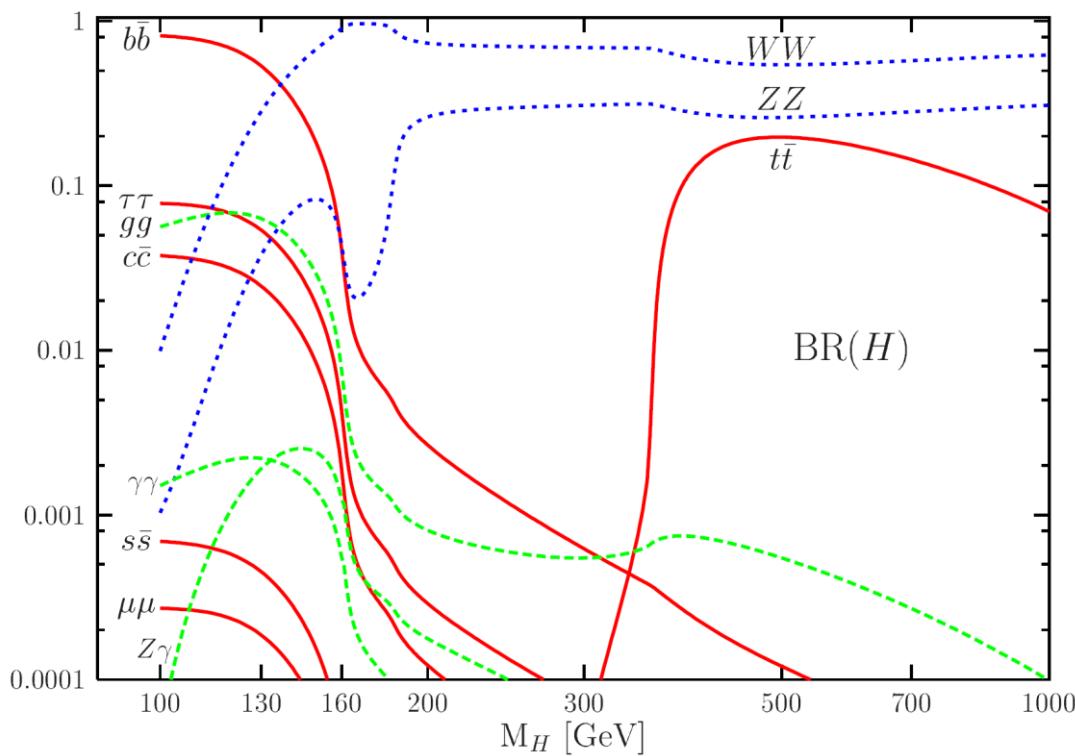
Либо «новая физика» на масштабе
 $\sim 1 \text{ TeV}$

No loose theorem!



Полная ширина мала для легкого бозона Хиггса и велика для тяжелого

Для массы $M_H \sim 1 \text{ TeV}$ ширина $\Gamma_H \sim 0.5 \text{ TeV}$



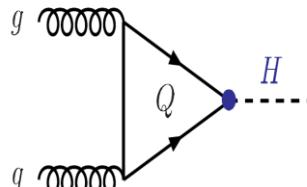
$M_H \lesssim 130 \text{ GeV}:$

- $H \rightarrow b\bar{b}$ dominant, $\text{BR} = 60\text{--}90\%$
- $H \rightarrow \tau^+\tau^-$, $c\bar{c}$, gg $\text{BR} = \text{a few \%}$
- $H \rightarrow \gamma\gamma$, γZ , $\text{BR} = \text{a few permille.}$

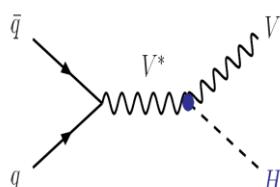
$M_H \gtrsim 130 \text{ GeV}:$

- $H \rightarrow WW^*$, ZZ^* up to $\gtrsim 2M_W$
- $H \rightarrow WW$, ZZ above ($\text{BR} \rightarrow \frac{2}{3}, \frac{1}{3}$)
- $H \rightarrow t\bar{t}$ for high M_H ; $\text{BR} \lesssim 20\%$.

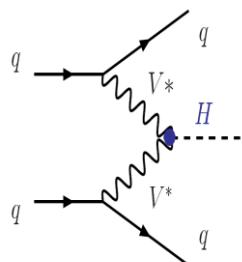
4 main SM Higgs production modes at LHC



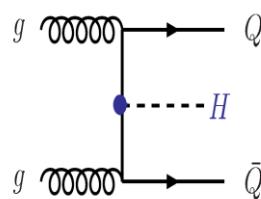
Gluon-gluon fusion



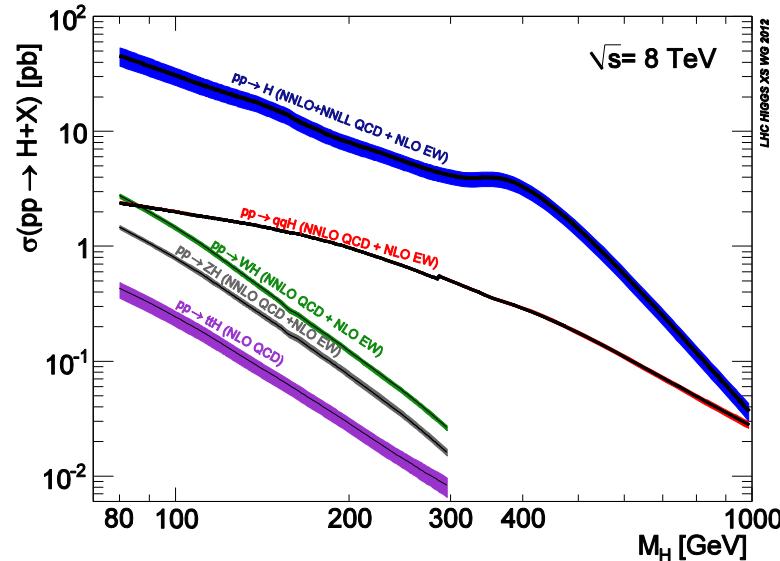
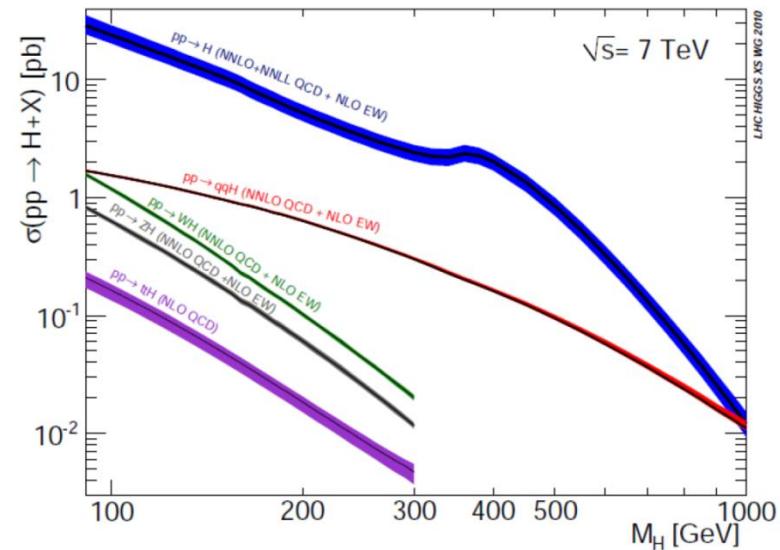
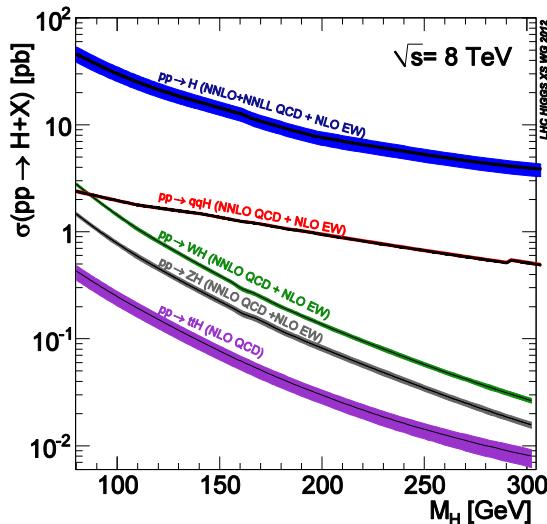
W/Z-Higgs associated



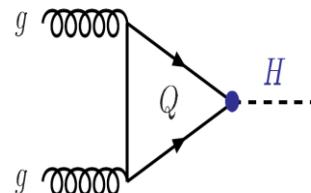
Vector boson fusion



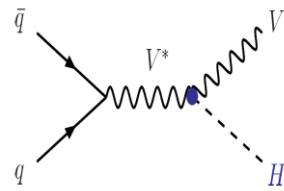
t t-bar Higgs associated



Основные механизмы рождения на Tevatron

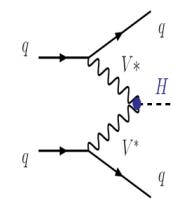


Gluon-gluon fusion

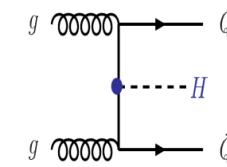


W/Z -Higgs associated

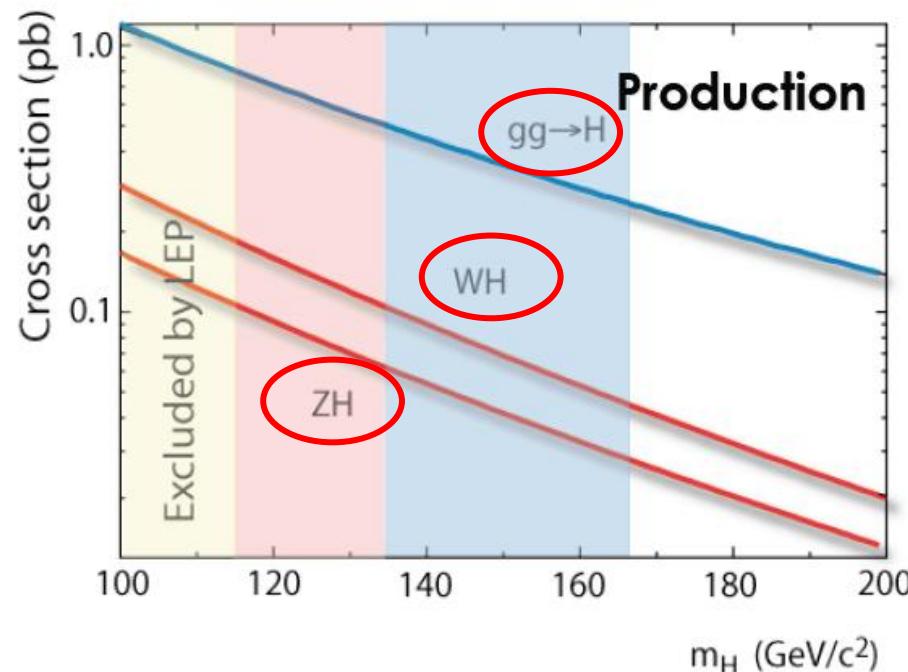
Недостижимые моды на Tevatron



Vector boson fusion



$t\bar{t}$ Higgs associated



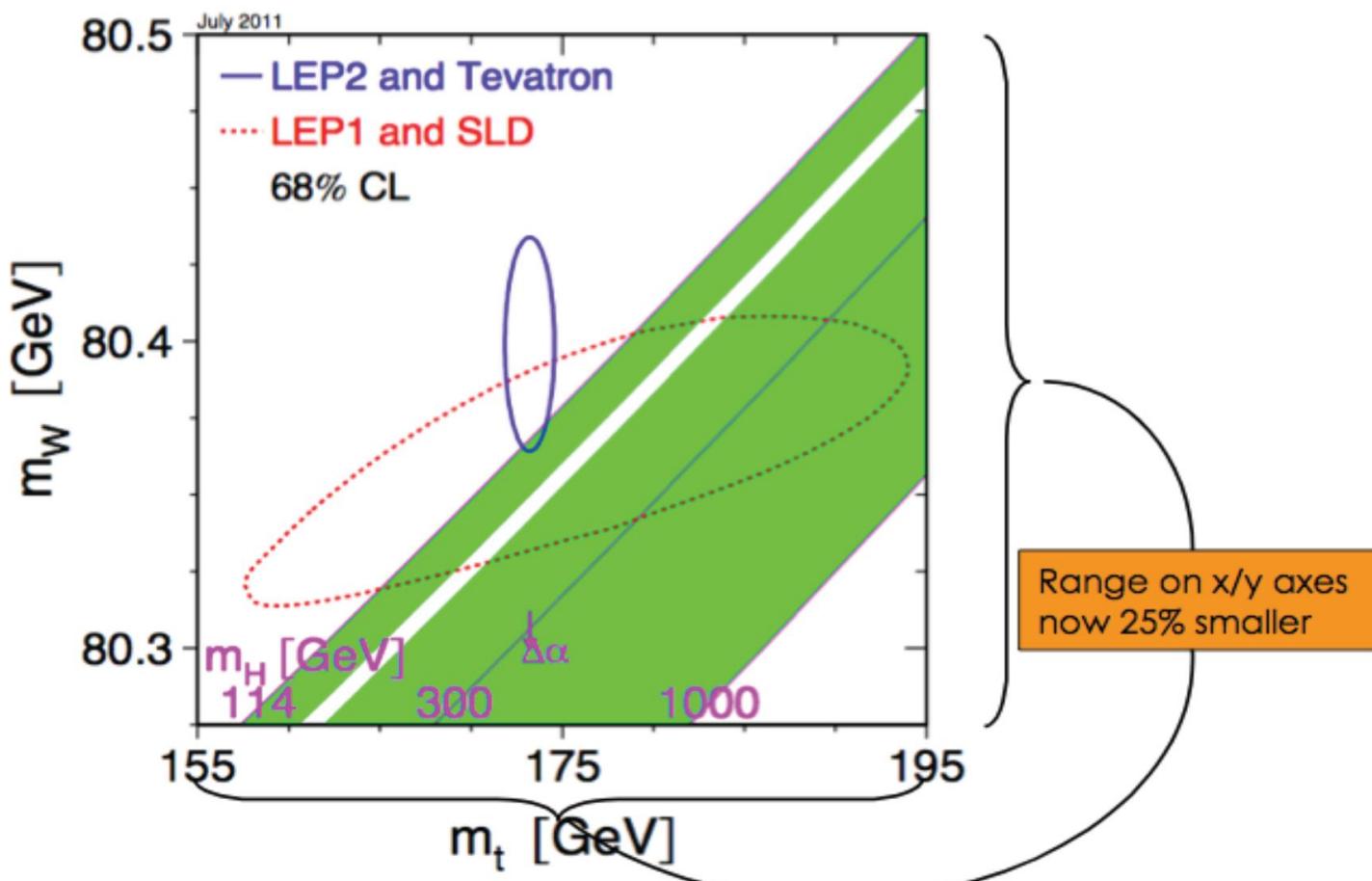
Search strategy:

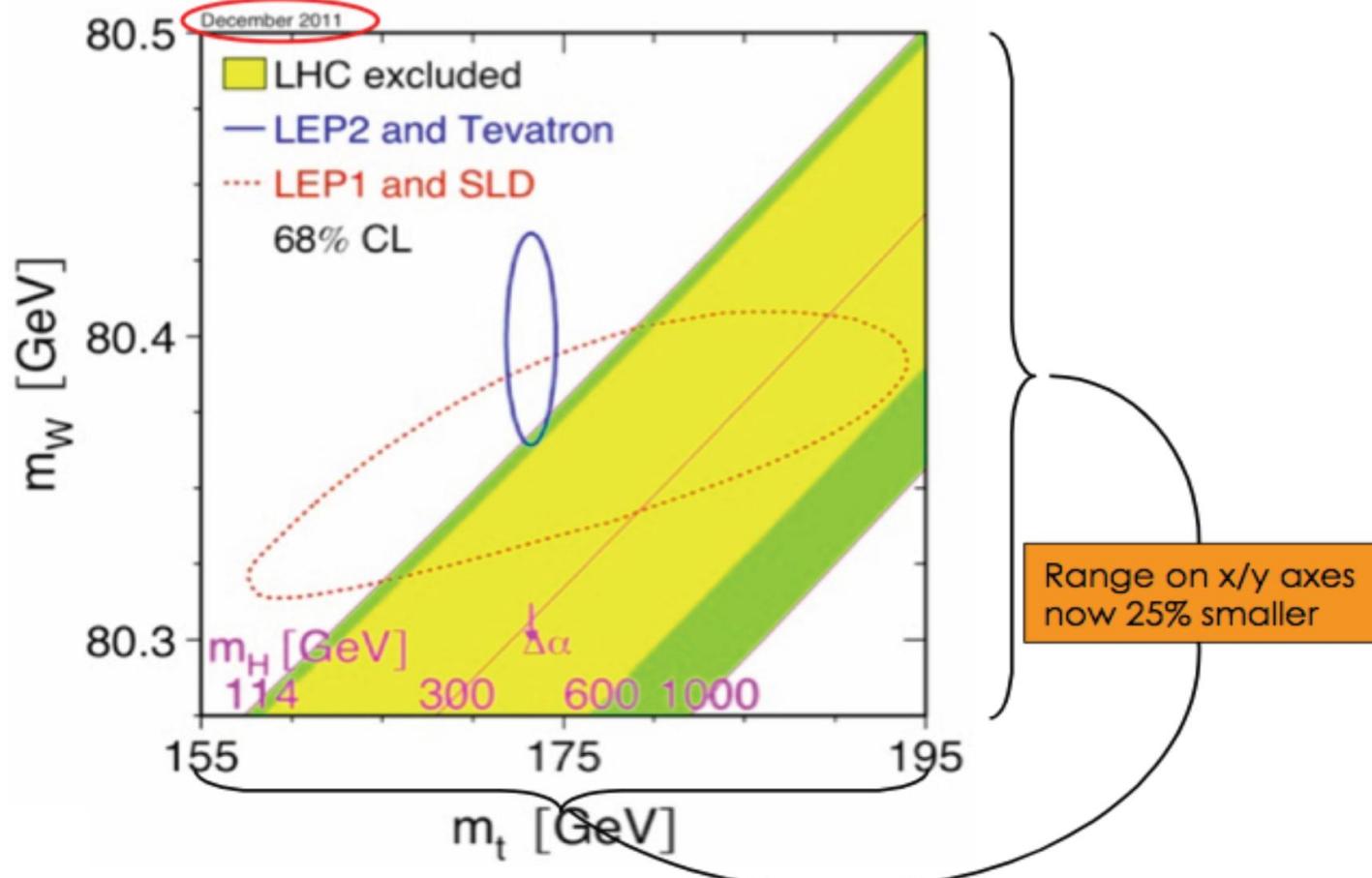
$M_H < 135$ GeV associated production and bb decay $W(Z)H \rightarrow l\nu(\ell\ell/\nu\nu) bb$

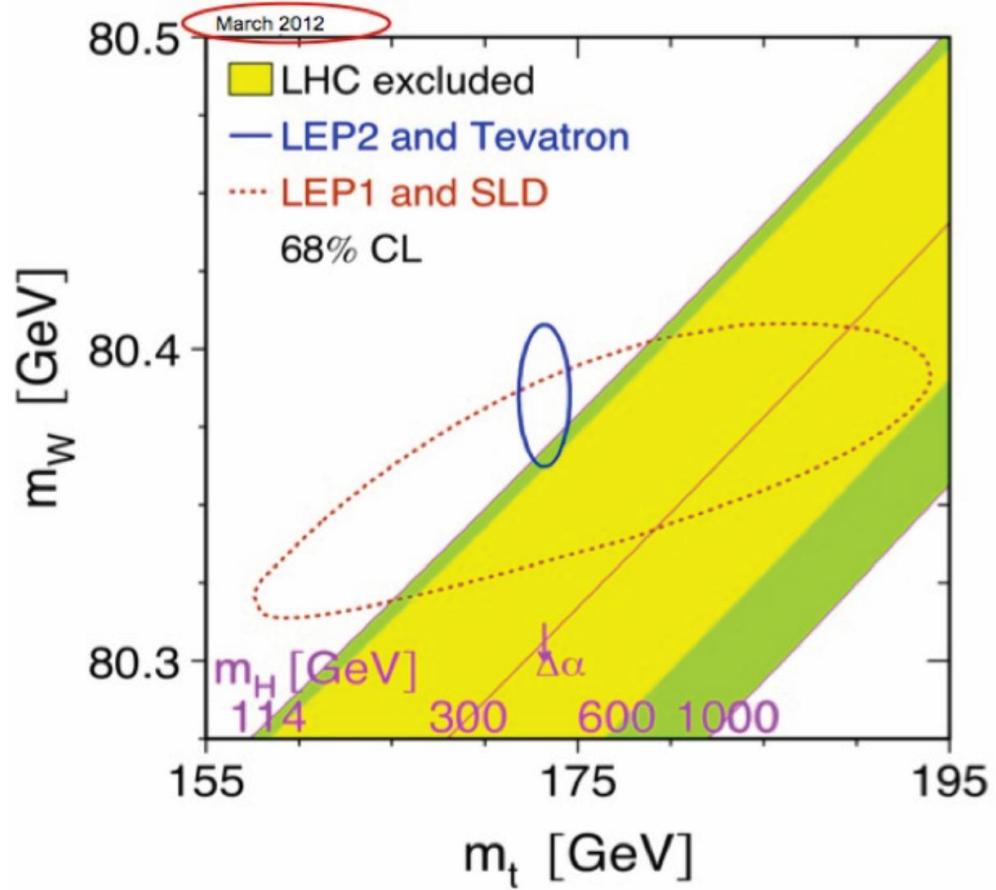
Main backgrounds: W/Zjj , top, Wbb , Zbb

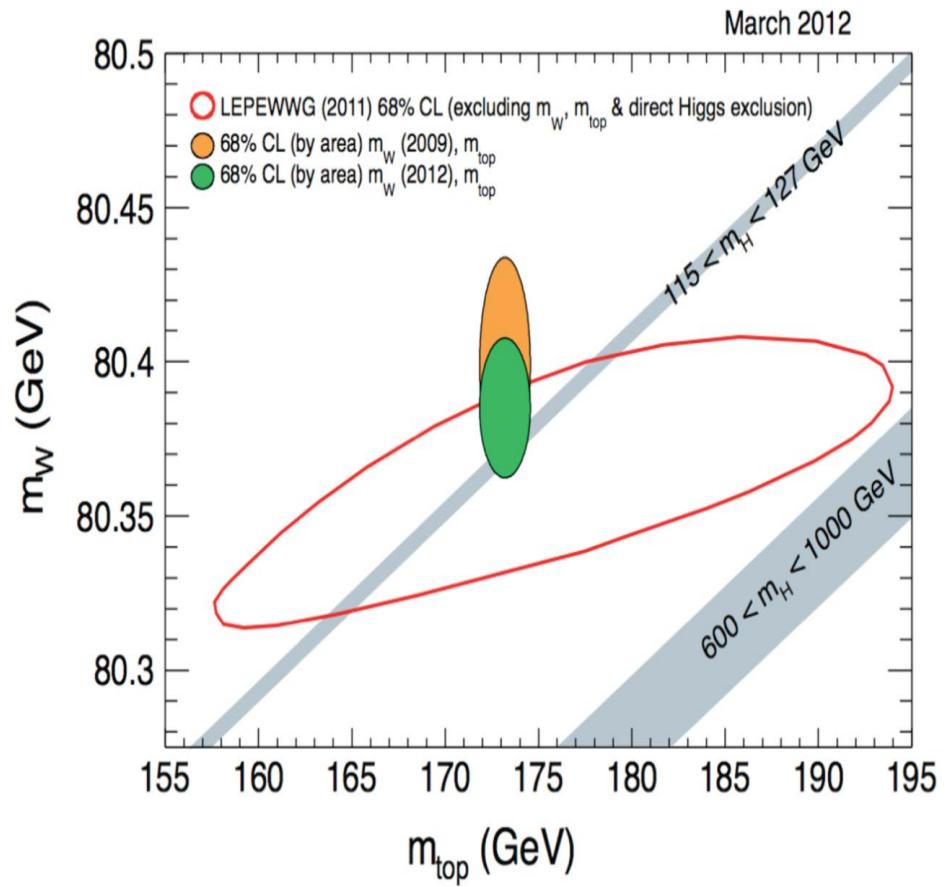
$M_H > 135$ GeV $gg \rightarrow H$ production with decay to WW^* , WW

Main background: electroweak WW production, W/Zjj

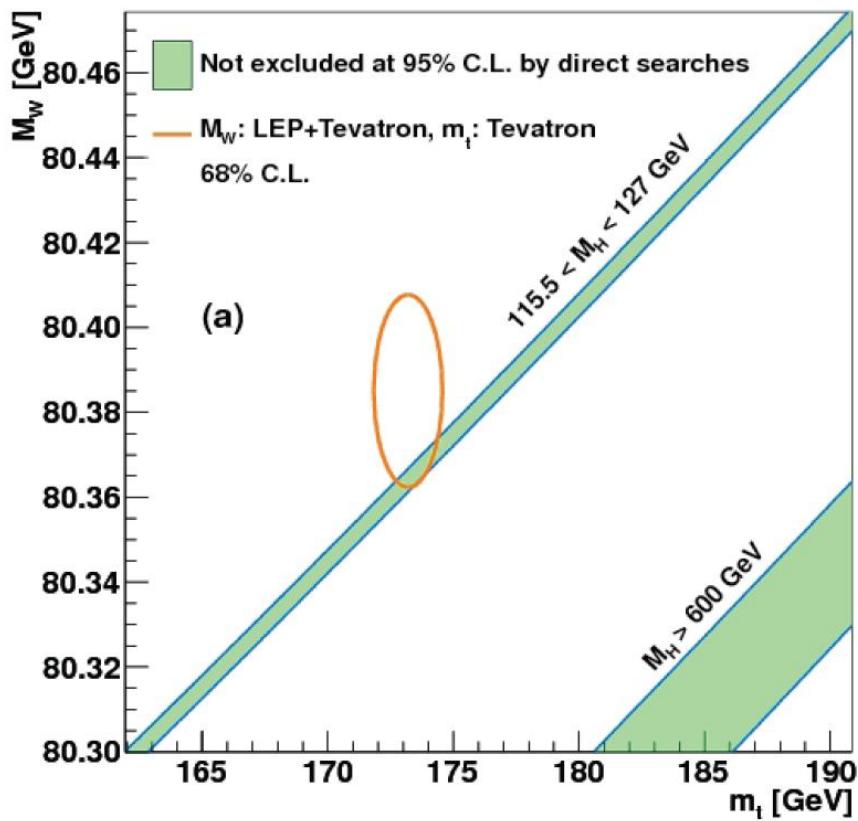




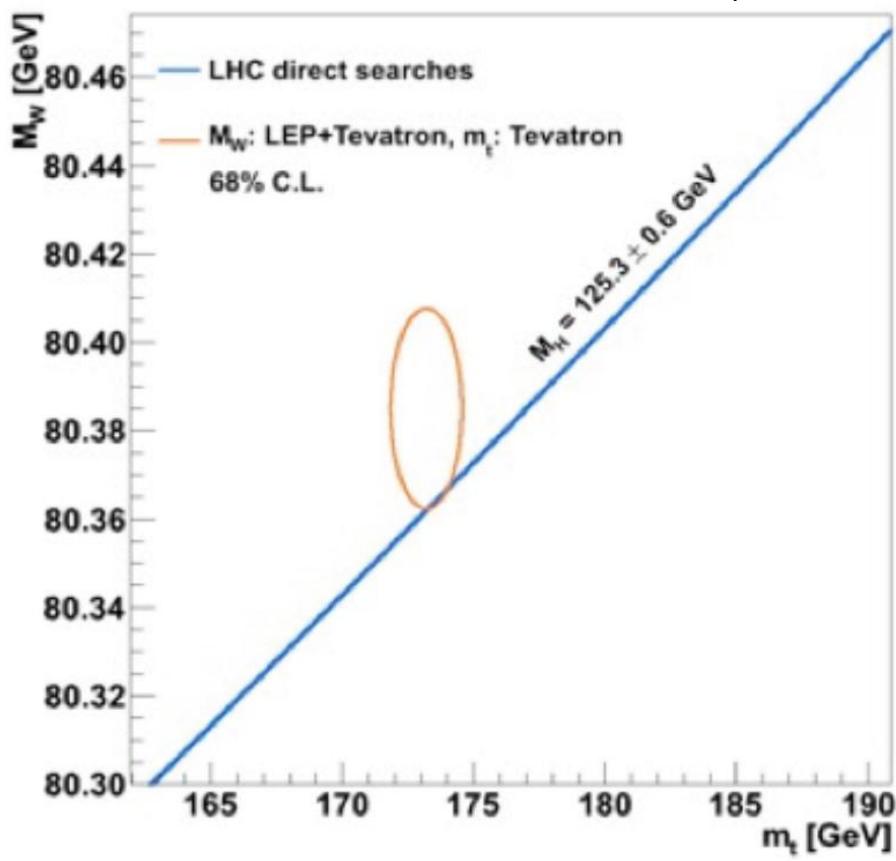




April 2012

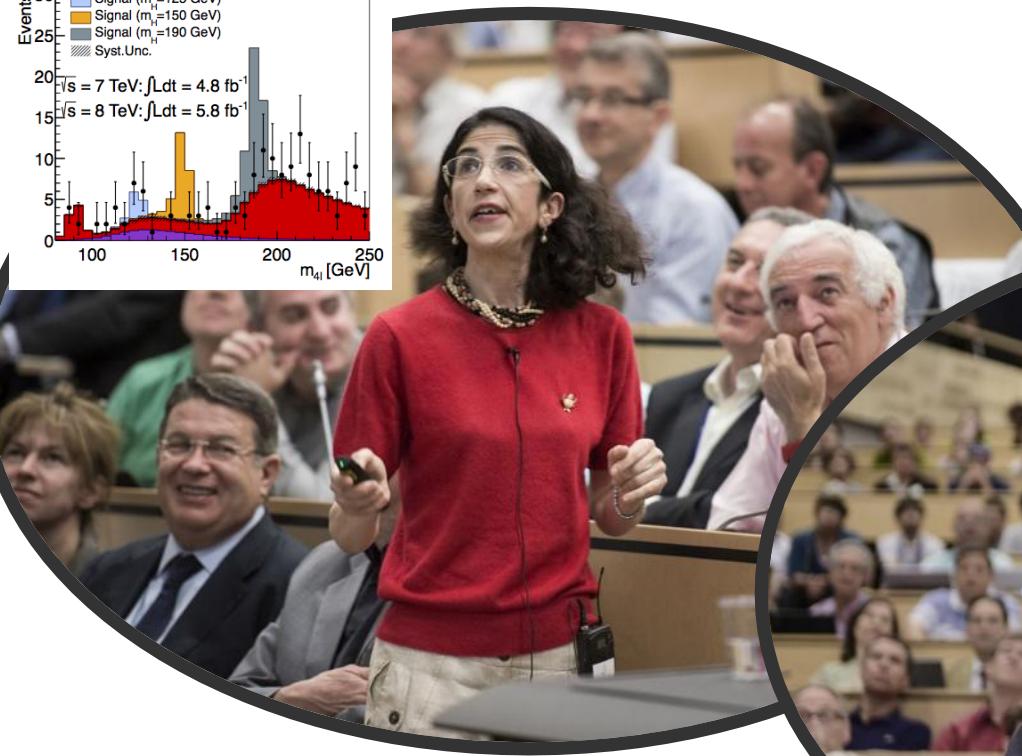
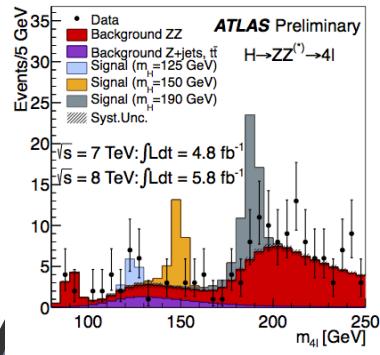


July 2012

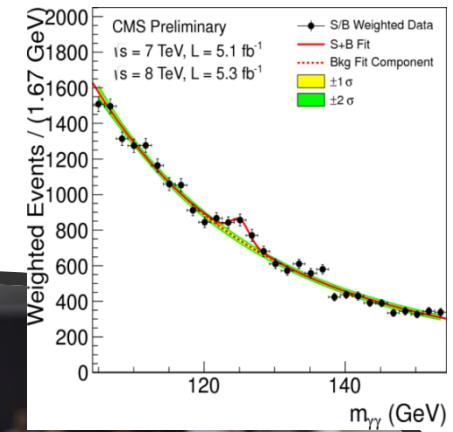


Доклады на семинаре в ЦЕРН

4 июля 2012 г.



Fabiola Gianotti
ATLAS Spokesperson 2010-2012



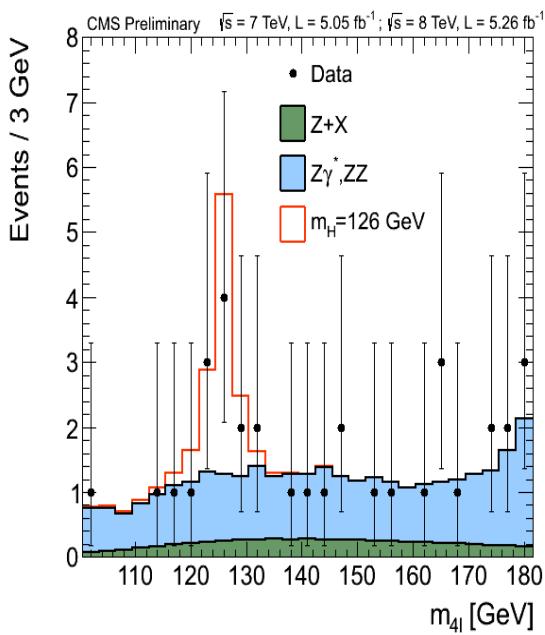
Joe Incandela
CMS Spokesperson 2012-2013

Исключительный день для мирового научного сообщества

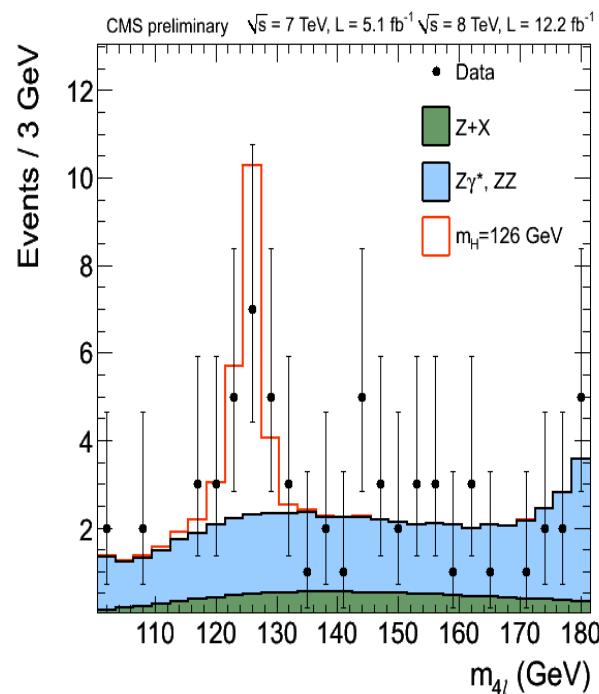


Все более четкий пик

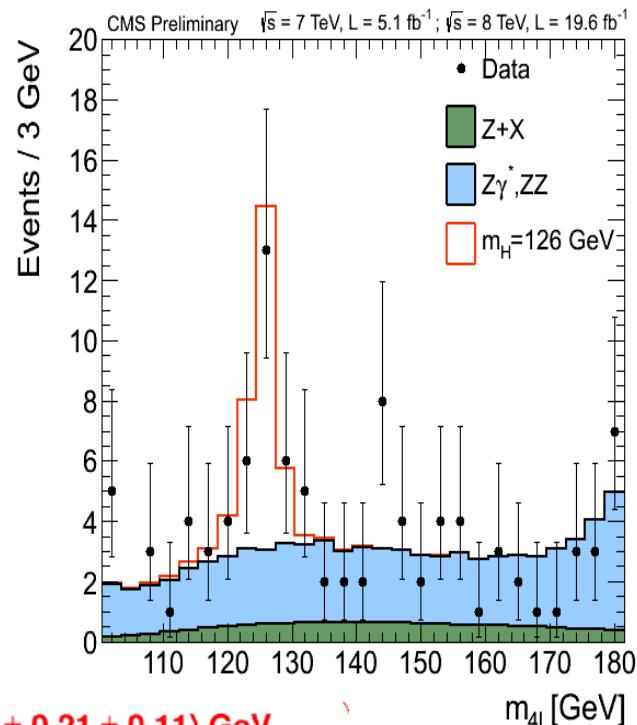
4 July



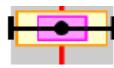
Nov 2012



RUN 1



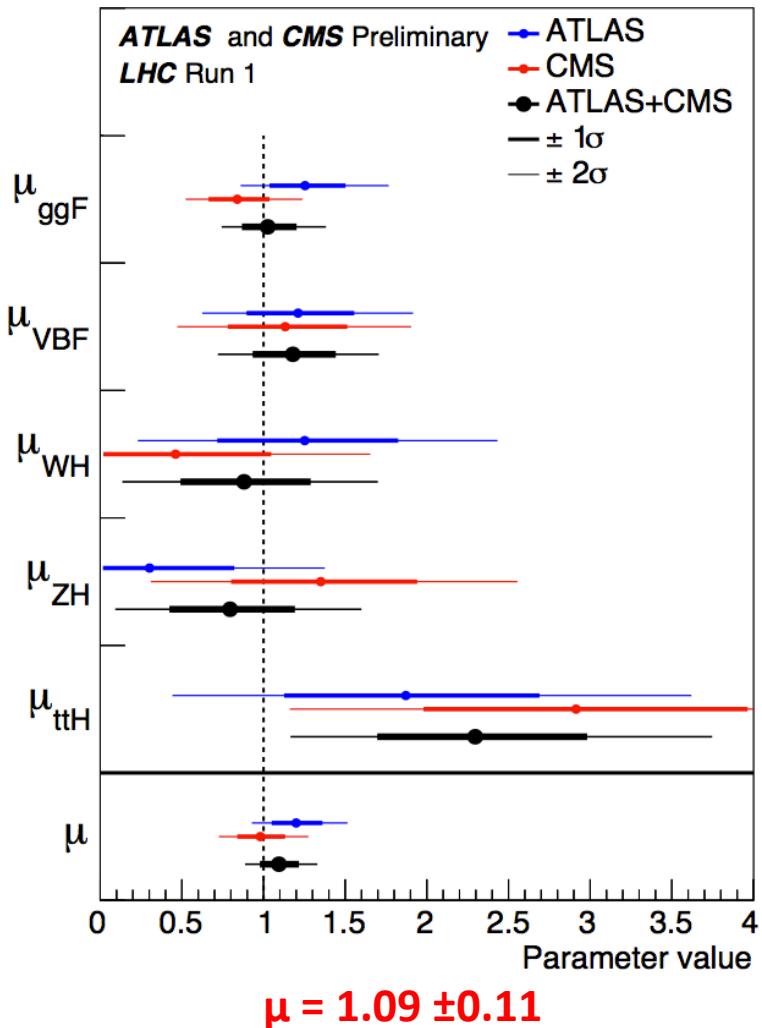
ATLAS+CMS $\gamma\gamma + 4l$



$125.09 \pm 0.24 (\pm 0.21 \pm 0.11) \text{ GeV}$

Квантовые числа 0^+ , константы взаимодействия пропорциональны массам, масса скалярного бозона измерена с высокой точностью

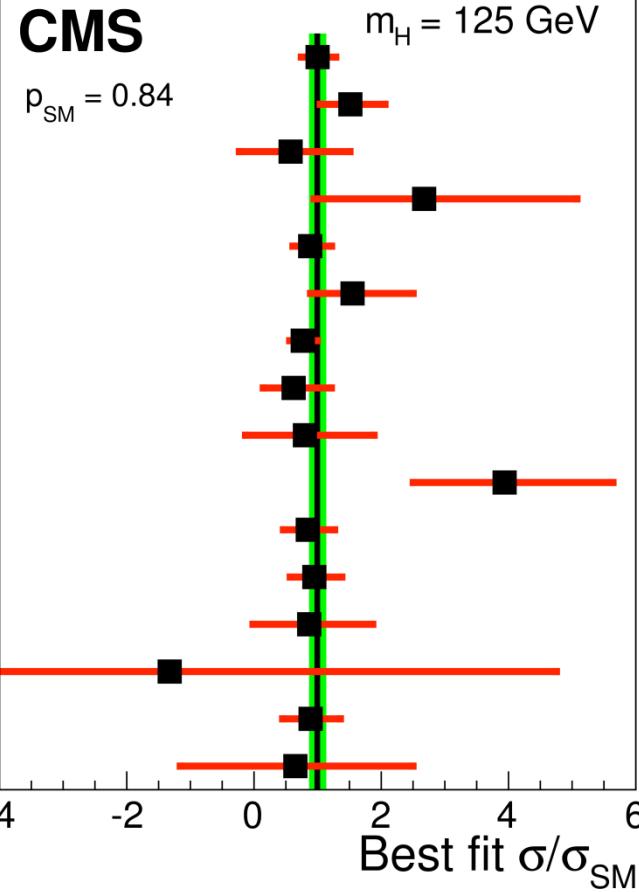
Согласие с предсказанием СМ



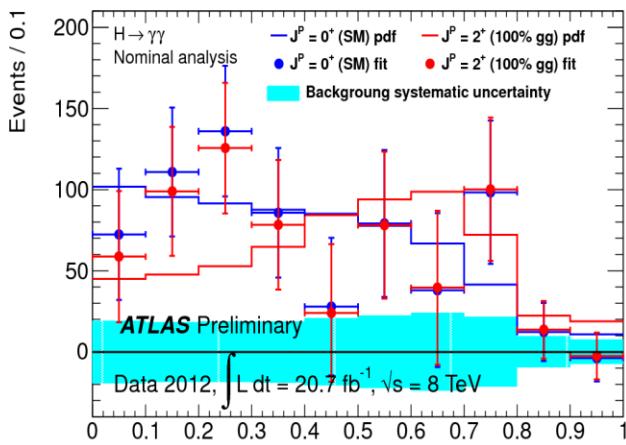
Combined
 $\mu = 1.00 \pm 0.14$

- $H \rightarrow \gamma\gamma$ (un-tagged)
- $H \rightarrow \gamma\gamma$ (VBF tag)
- $H \rightarrow \gamma\gamma$ (VH tag)
- $H \rightarrow \gamma\gamma$ (tH tag)
- $H \rightarrow ZZ$ (0/1-jet)
- $H \rightarrow ZZ$ (2-jet)
- $H \rightarrow WW$ (0/1-jet)
- $H \rightarrow WW$ (VBF tag)
- $H \rightarrow WW$ (VH tag)
- $H \rightarrow WW$ (tH tag)
- $H \rightarrow \tau\tau$ (0/1-jet)
- $H \rightarrow \tau\tau$ (VBF tag)
- $H \rightarrow \tau\tau$ (VH tag)
- $H \rightarrow \tau\tau$ (tH tag)
- $H \rightarrow bb$ (VH tag)
- $H \rightarrow bb$ (tH tag)

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)

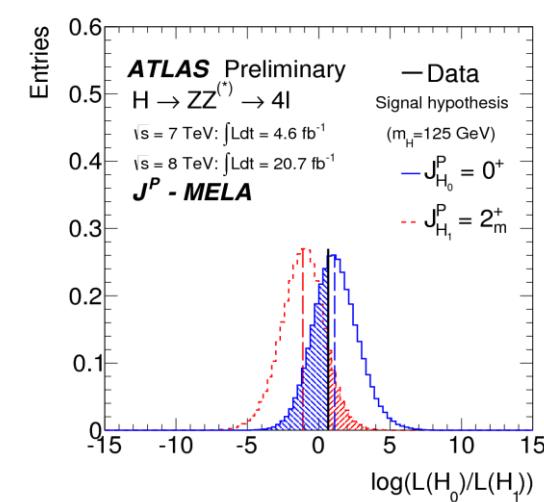
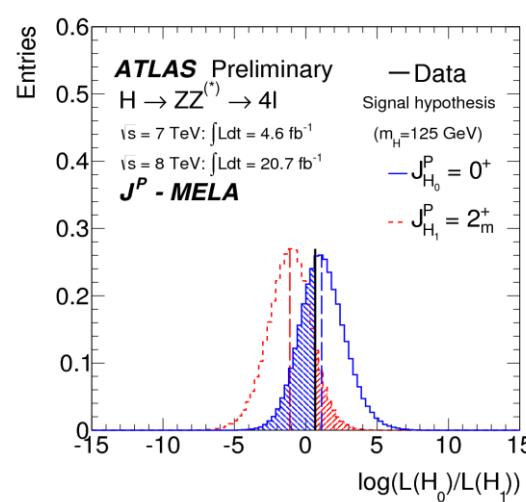
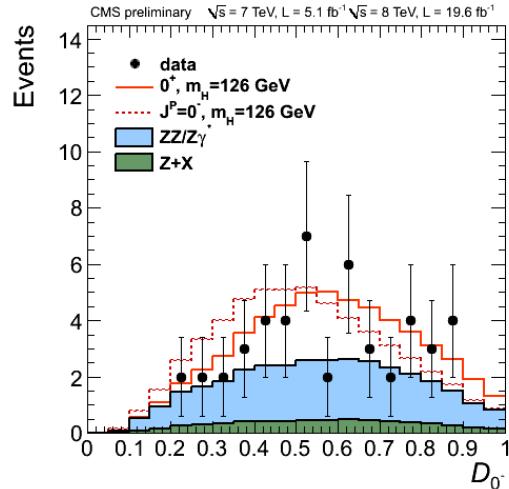


Still large errors in individual channels!



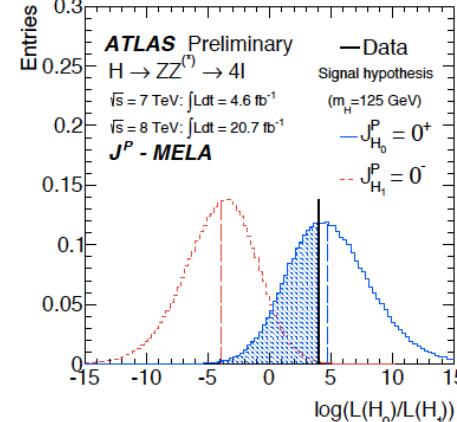
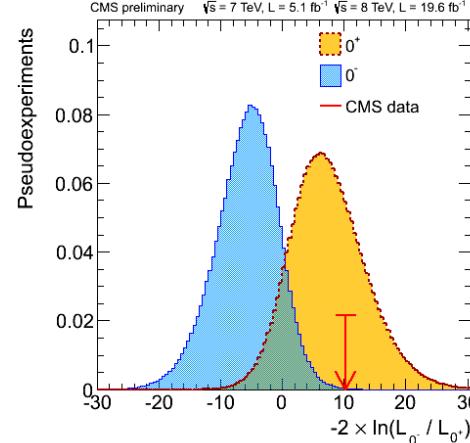
$$\cos \theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + (p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}}$$

$$\mathcal{D}_{J^p} = \frac{\mathcal{P}_{\text{SM}}}{\mathcal{P}_{\text{SM}} + \mathcal{P}_{J^p}} = \left[1 + \frac{\mathcal{P}_{J^p}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\text{SM}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})} \right]^{-1}$$

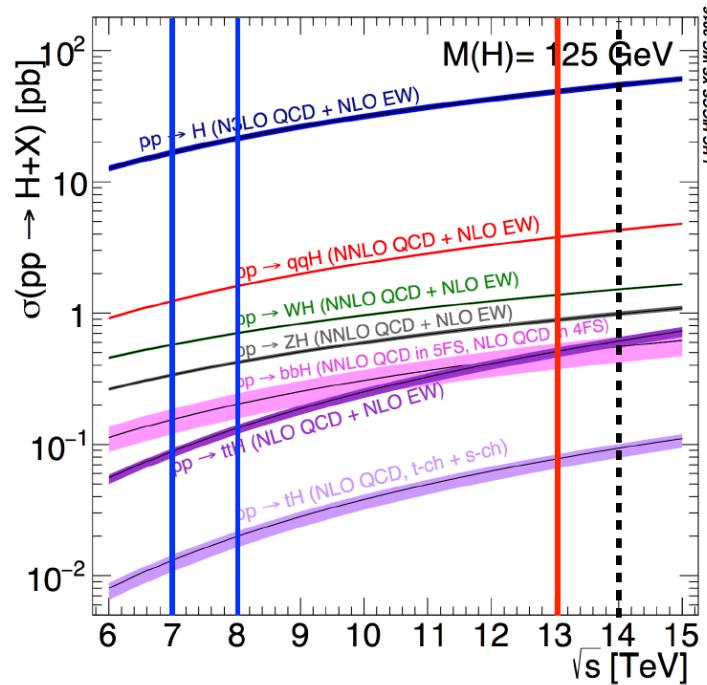
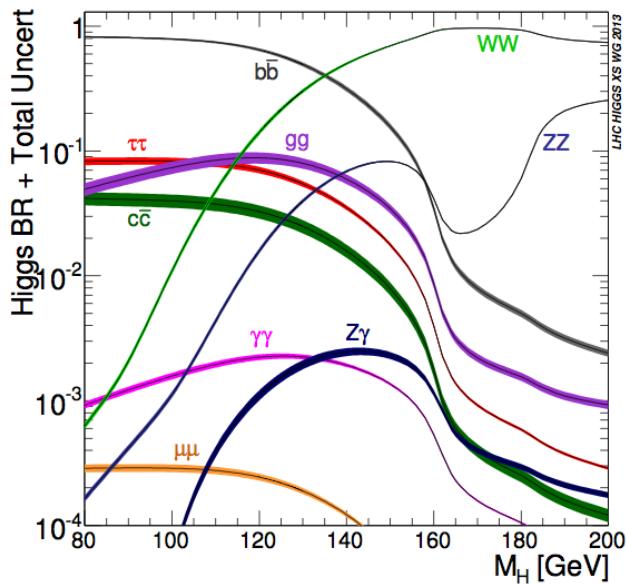
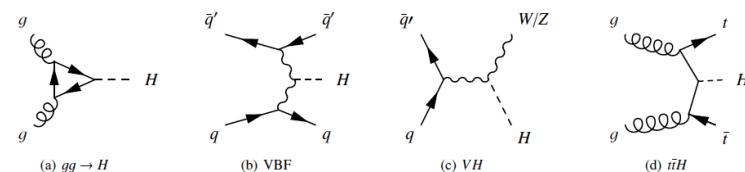
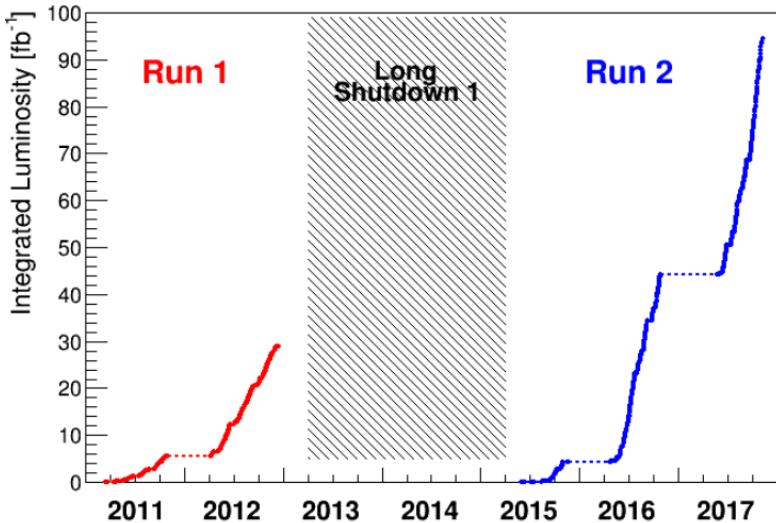


Graviton-like spin-2⁺ disfavoured at 99.9% CL

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1|m_{4\ell})} \right]^{-1}$$

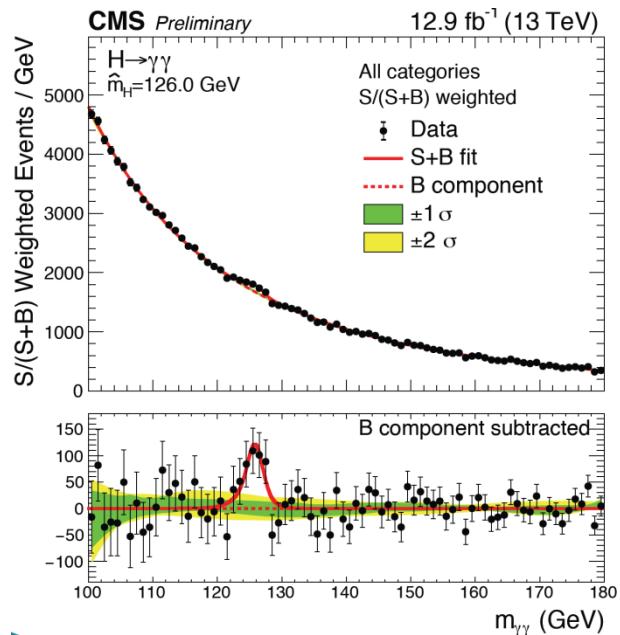


Pseudoscalar 0⁻ disfavoured at > 99% CL

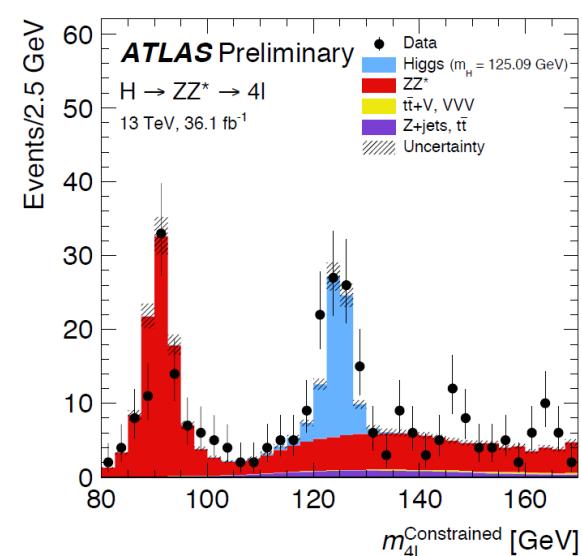
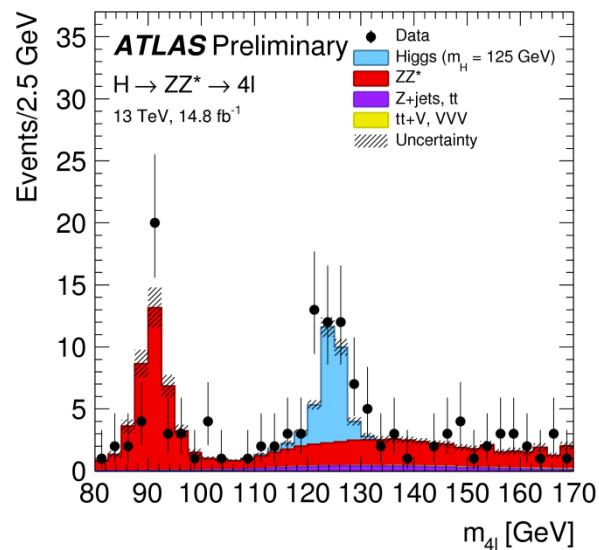
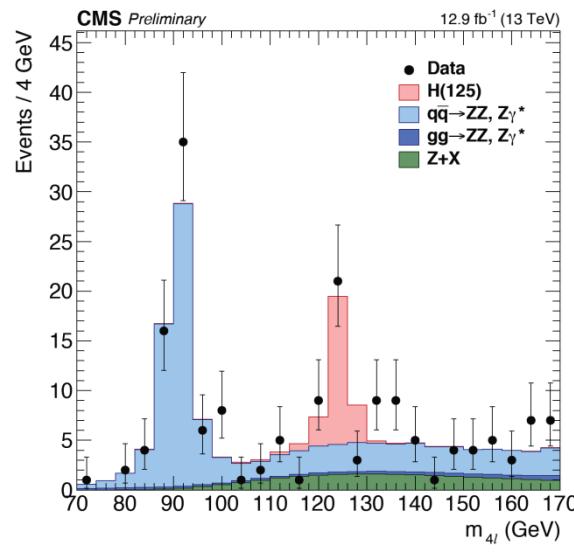


Регистрация бозона Хиггса при 13 TeV

$H \rightarrow \gamma\gamma$



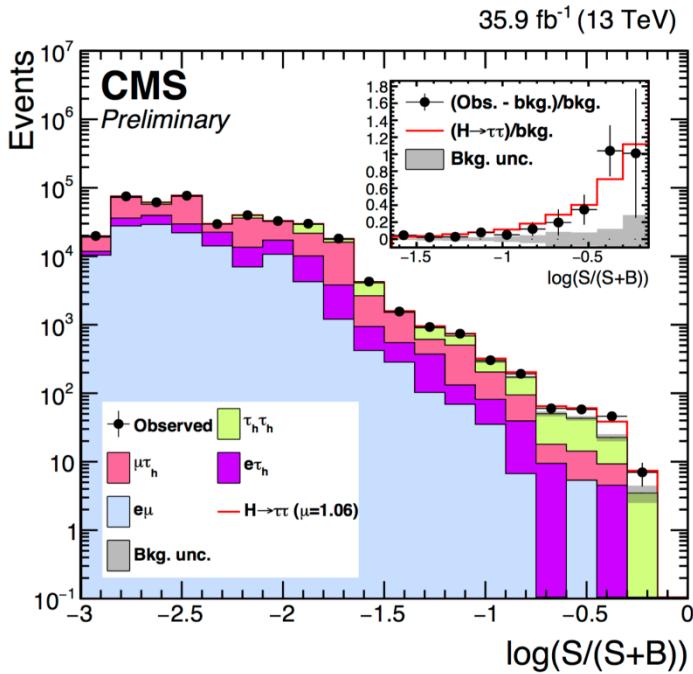
$H \rightarrow ZZ^*$



Регистрация новых мод

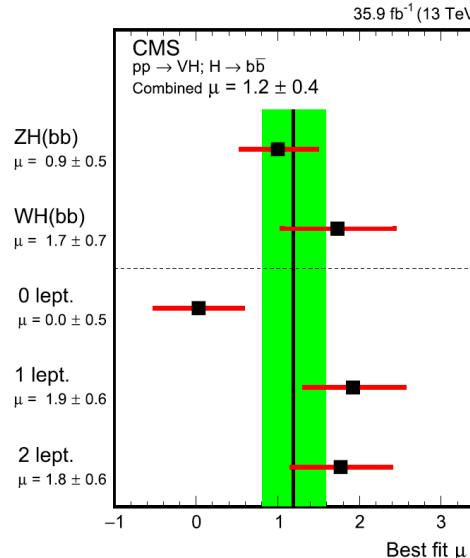
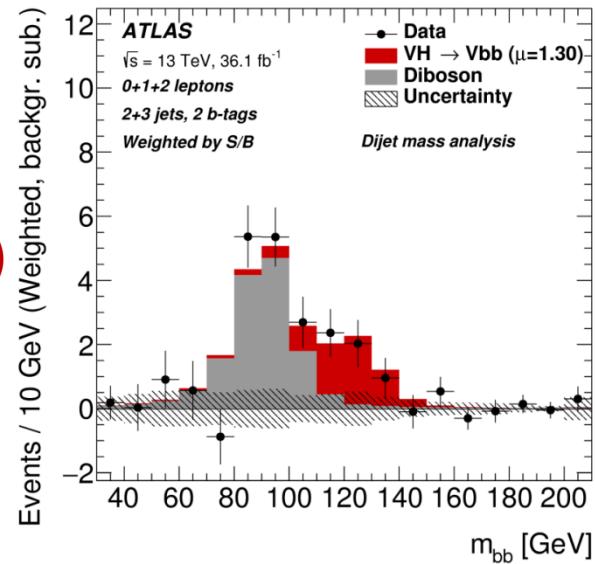
$H \rightarrow bb$

$H \rightarrow \tau\tau$



**5.9 σ (5.9 expected)
 $\mu=1.09 \pm 0.26$**

**3.5 σ (3.0 expected)
 $\mu=0.9 \pm 0.27$**



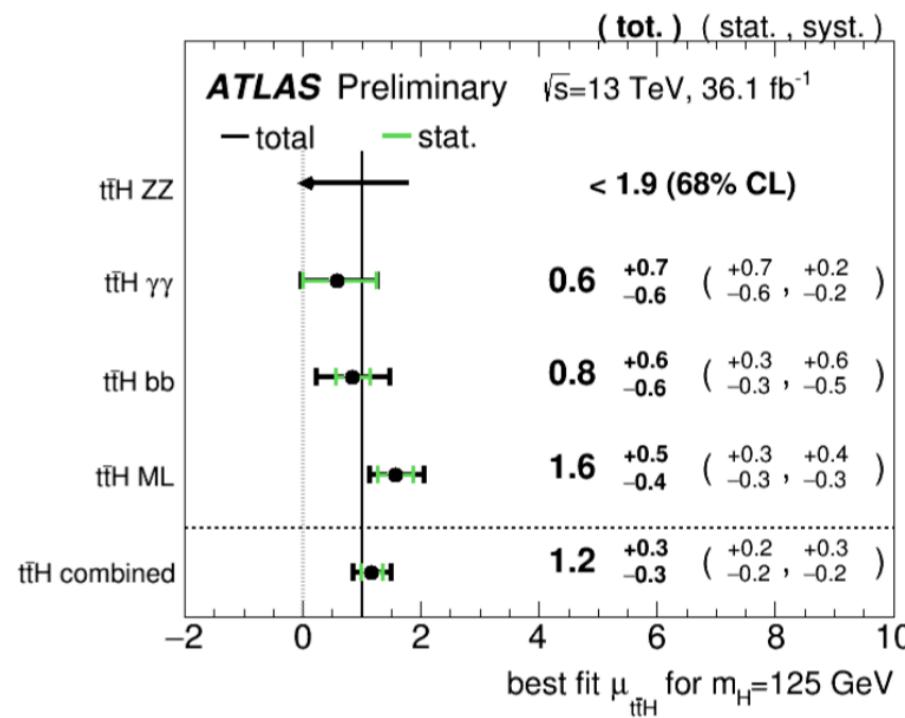
**3.3 σ (2.8 expected)
 $\mu=1.2 \pm 0.4$**

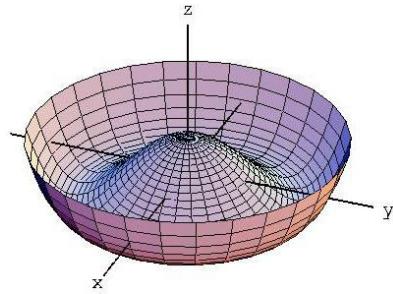
Точность далека от нужной $\sim v^2/\Lambda^2 \sim 10^{-2}$ или меньше

Сечения в определенных кинематических областях

$\sqrt{s} = 13 \text{ TeV}$	Channel	Measurement (fb)	SM prediction (fb)
ATLAS (13.3 fb^{-1})	$H \rightarrow \gamma\gamma$	$43.2 \pm 14.9 \text{ (stat)} \pm 4.9 \text{ (syst)}$	$62.7^{+3.4}_{-4.4} \text{ (N3LO+XH)}$
CMS (12.9 fb^{-1})	$H \rightarrow \gamma\gamma$	$69^{+16}_{-22} \text{ (stat)} {}^{+8}_{-6} \text{ (syst)}$	73.8 ± 3.8
ATLAS (14.8 fb^{-1})	$H \rightarrow ZZ^*$	$4.54^{+1.02}_{-0.90}$	$3.07^{+0.21}_{-0.25}$
CMS (12.9 fb^{-1})	$H \rightarrow ZZ^*$	$2.29^{+0.74}_{-0.64} \text{ (stat)} {}^{+0.30}_{-0.23} \text{ (syst)}$	2.53 ± 0.13

Мода рождения $t\bar{t}H$:
4.2 σ (3.8 expected)
 $\mu = 1.2 \pm 0.3$

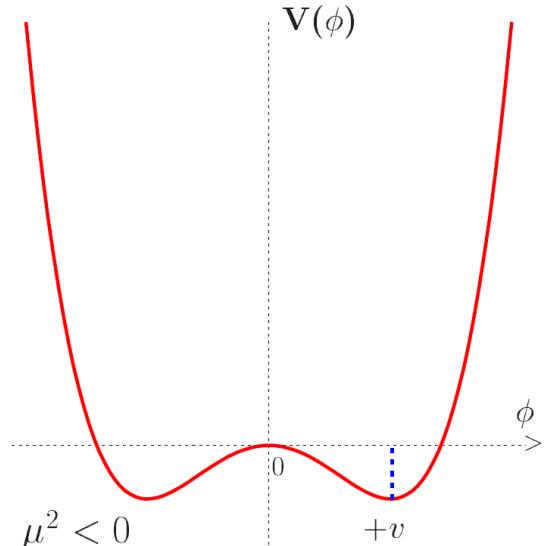




$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$\Phi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H+v \end{pmatrix}$$

$$\begin{aligned} L_H = & \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_h^2}{2}h^2 - \frac{M_h^2}{2v}h^3 - \frac{M_h^2}{8v^2}h^4 + \\ & + (M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu) \left(1 + \frac{h}{v}\right)^2 - \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right) \end{aligned}$$



$$M_H^2 = 2\lambda v^2 = -2\mu^2 \quad \lambda \cong 0.13$$

weakly-coupled theory

- Стандартная модель - перенормируемая, свободная от киральных аномалий квантовая калибровочная теория поля со спонтанным нарушением электрослабой симметрии. Впечатляющее согласие с большим числом экспериментальных данных.

* СМ (EW part) 17 параметров:

gauge-Higgs sector - 4 параметра:

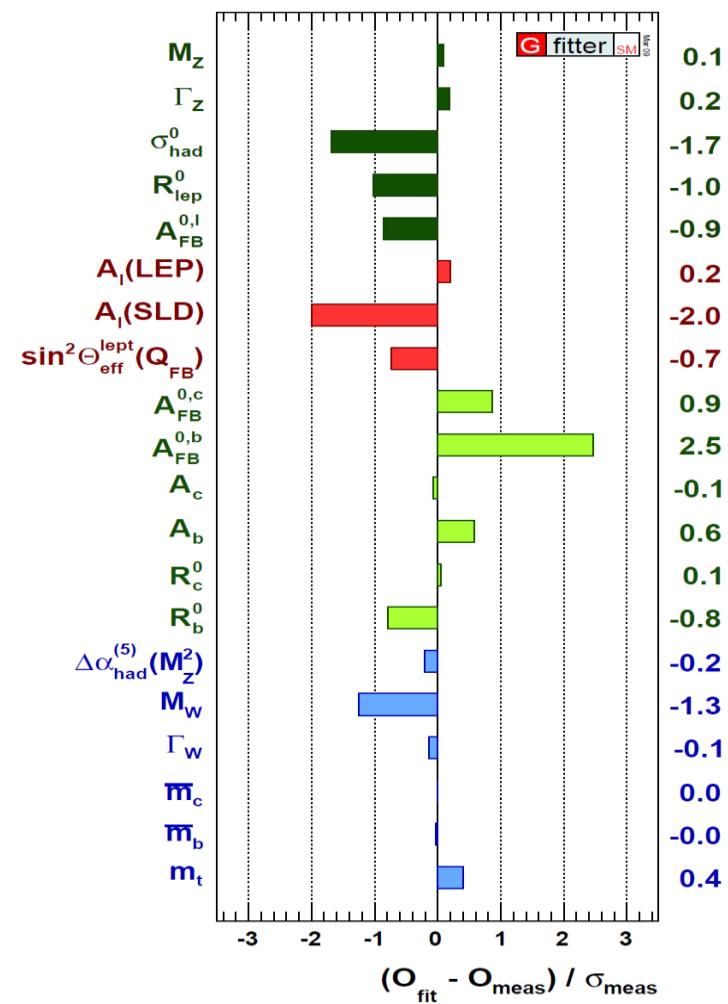
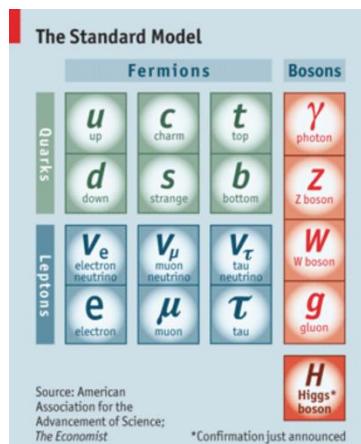
$g_1, g_2, \mu^2, \lambda \rightarrow$ best measured

$\alpha_{\text{em}}, G_F, M_Z$ (or $\alpha_{\text{em}}, s_W, M_W$) плюс M_H

В дополнение: 6 quarks masses, 3 lepton masses,
3 mixing angles, 1 phase of the CKM matrix

plus α_{QCD} \rightarrow 18 SM parameters

(+ may be masses and mixing parameters from neutrino sector)



Факты, которые не находят объяснения в Стандартной Модели

1. Механизм Хиггса наделяет бозоны и фемионы массами.

Но по какой причине массы фермионов столь различны ?

($M_{top} \approx 173$ GeV, $M_e \approx 0.5$ MeV, $\Delta M_\nu \approx 10^{-3}$ eV)

2. Темная материя во Вселенной

3. ($g-2)_\mu$ (about 3.5 σ)

4. Осцилляции нейтрино

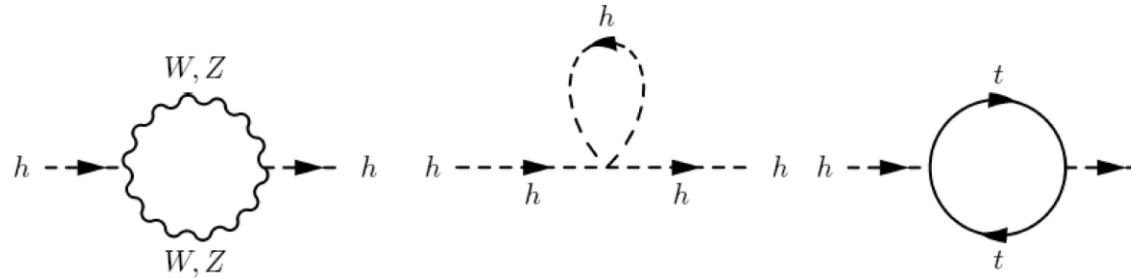
5. Асимметрия частицы-античастицы во Вселенной,
природа CP-нарушения

6. Гравитационные взаимодействия существенно слабее электрослабых.
В чем причина? Что представляет собой темная энергия и почему так
мала гравитационная постоянная ?

Остается множество вопросов

- Что такое поколение? Почему поколений только 3?
- Какова природа кварк-лептонной аналогии? Как соотносятся друг другу лептоны и кварки?
- Элементарны ли кварки и лептоны?
- Существуют ли новые кварки и лептоны?
- Что определяет калибровочные симметрии? Почему квантуются заряды частиц?
- Существуют ли новые калибровочные взаимодействия?
- Что формирует потенциал поля Хиггса?
- Почему электрослабый масштаб столь мал по сравнению с массой Планка?
- Почему гравитация столь слаба? Как ее включить в общую схему?
- Почему столь мала космологическая постоянная?
- Насколько точна СРТ-симметрия?
- Существуют ли новые симметрии в природе?
- Существуют ли дополнительные измерения пространства-времени?
- Что такое темная энергия и темная материя?
-

Простейший механизм Хиггса нестабилен по отношению к квантовым петлевым поправкам к массе бозона Хиггса (проблема иерархий, натуральности)



Поправка не должна превышать саму массу. Проблема “малых иерархий”

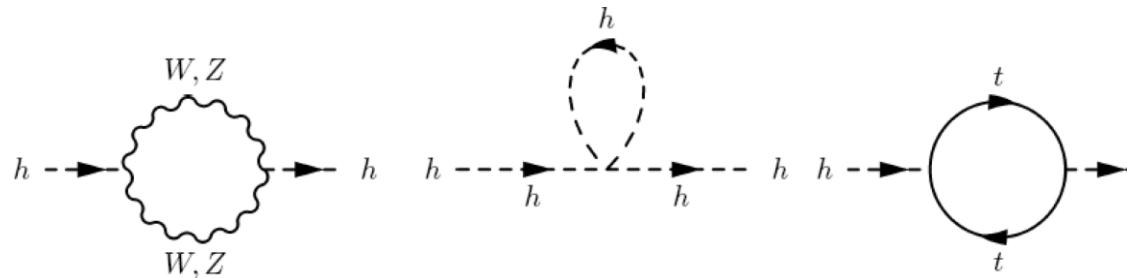
$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2} (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda^2 \approx -(0.2 \Lambda)^2$$

$$\delta m_H < m_H \quad \Lambda < \sim 1 \text{ TeV}$$

В СМ нет симметрии, которая бы запрещала столь сильную зависимость массы от возможного масштаба “новой физики”

Something is needed in addition to SM...

Простейший механизм Хиггса нестабилен по отношению к квантовым петлевым поправкам к массе бозона Хиггса (проблема иерархий, натуральности)



Поправка не должна превышать саму массу. Проблема “малых иерархий”

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2} (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda^2 \approx -(0.2 \Lambda)^2$$

$$\delta m_H < m_H \quad \Lambda < \sim 1 \text{ TeV}$$

Но СМ – перенормируемая теория. Рассмотрение в размерной регуляризации

$$M_H(\Lambda) = M_H(v) - C y_f^2 M_f^2 \ln(\Lambda^2/v^2) + \dots$$

В СМ нет симметрии, которая бы запрещала столь сильную зависимость массы от возможного масштаба “новой физики”

**(Если есть частица с массой $M_f^2 \sim \Lambda^2$ и
взаимодействие с бозоном Хиггса СМ y_f^2 достаточно сильно)**

**Something is needed in addition to SM...
but one can not predict a scale...**

Main options beyond SM

1. Fundamental Higgs:

- Supersymmetric models
(MSSM, NMSSM...)



More Higgses practically in all BSM models

2. Composite Higgs:

- Models with new strong dynamics
(Chiral Lagrangians from holography, latest technicolor variants, Little Higgs...)



3. Mixed cases:

- Models with extra space dimensions
- Partially composite models...

4. Many more (hidden valleys, landscape)

BSM searches

Collision energy > particle production threshold

-Searches for new particles

strongly interacting new particles with large cross sections (squarks, gluinos...)
top partners motivated by naturalness (stop, sbottom, vector like quarks, t* ...)
new resonances predicted by many BSM extensions (Z' , W' , π_T , ρ_T , KK states, ..)
extended Higgs sector (new neutral Higgses, charged Higgs)

Collision energy < particle production threshold

- Anomalous/new interactions of SM particles
(anom. gauge boson couplings, anom. Wtb couplings, FCNC ...)
- New particle contributions via quantum loops

Searches below threshold

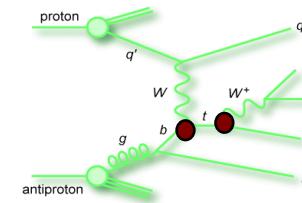
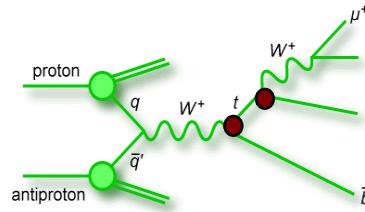
Effective field theory approach

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

c_i - dimensionless coefficients

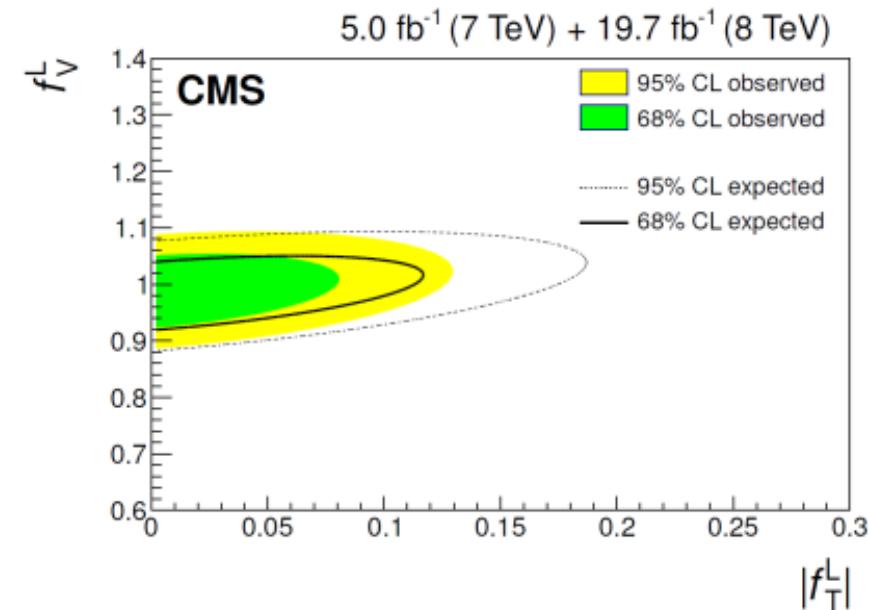
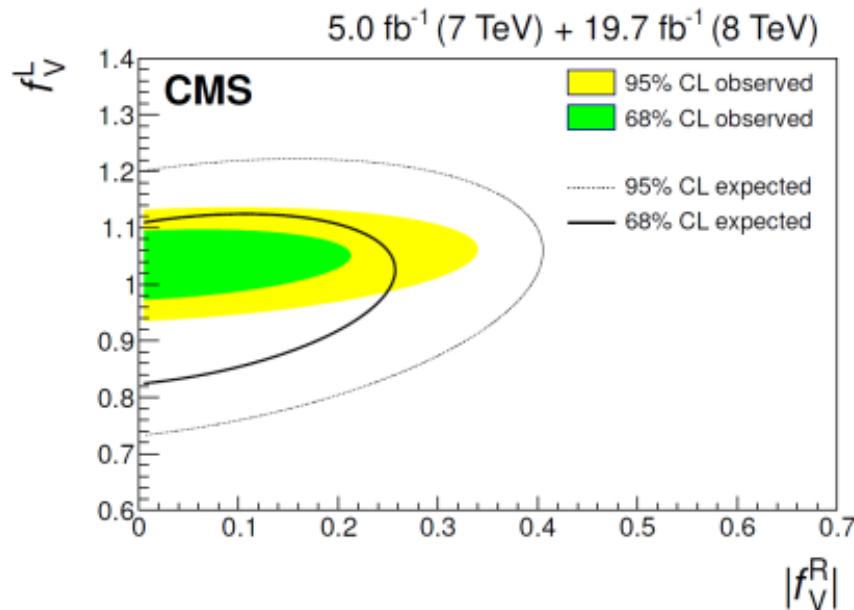
\mathcal{O}_i – operators constructed from SM fields preserving
SM gauge invariance

Anomalous Wtb couplings



$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu \left(f_V^L P_L + f_V^R P_R \right) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu} \partial_\nu W_\mu^-}{M_W} \left(f_T^L P_L + f_T^R P_R \right) t + \text{h.c.}$$

Natural size $|1-f_L^V|, f_R^V \sim v^2/\Lambda$ Natural size $f_L^T, f_R^T \sim M_W^* v^2/\Lambda^2$



SUSY

**Supersymmetry is one of the most favorite BSM ideas,
relating spin $\frac{1}{2}$ fermions with spin 0,1 bosons**

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle \quad Q^\dagger|\text{Boson}\rangle = |\text{Fermion}\rangle$$

Fermion degrees of freedom \leftrightarrow boson degrees of freedom

Minimal particle content

Gauge / Gaugino Sector

Standard Bosons	Supersymmetric Partners
$W^\pm \quad H^\pm$	Charginos $\chi_1^\pm \quad \chi_2^\pm$
$g \quad Z$ $h \quad H \quad A$	Neutralinos $\chi_1^0 \quad \chi_2^0 \quad \chi_3^0 \quad \chi_4^0$
g_i	Gluinos \tilde{g}_i

[Two Higgs doublets]

[All fermions]

And also ...

Graviton G	Gravitino \tilde{G}
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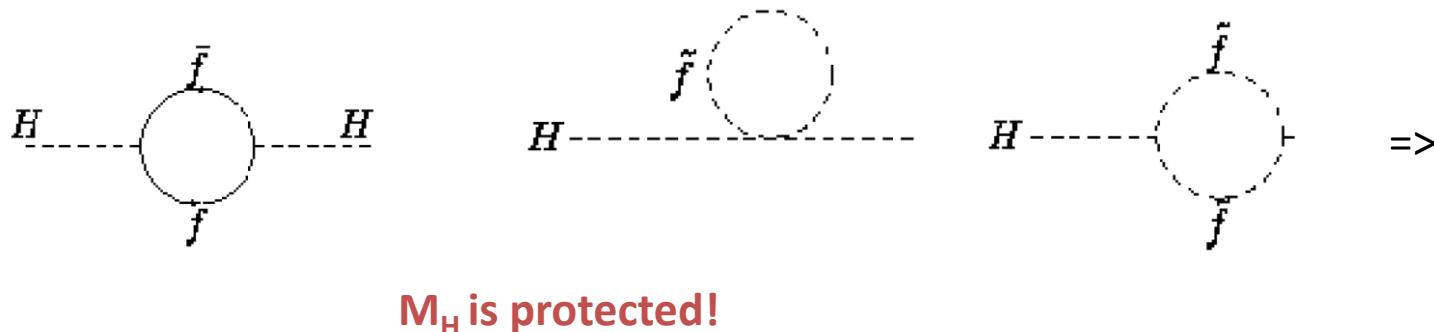
Particle / Sparticle Sector

Standard Particles	Supersymmetric Partners
Leptons ℓ	Sleptons $\tilde{\ell}_{R,L}$
Neutrinos ν_ℓ	Sneutrinos $\tilde{\nu}_\ell$
Quarks q	Squarks $\tilde{q}_{R,L}$

[All scalars]

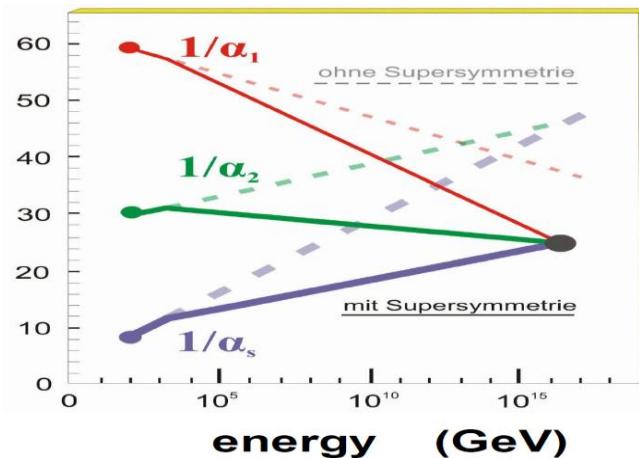
SUSY

1. Cancellation of the leading scale dependence

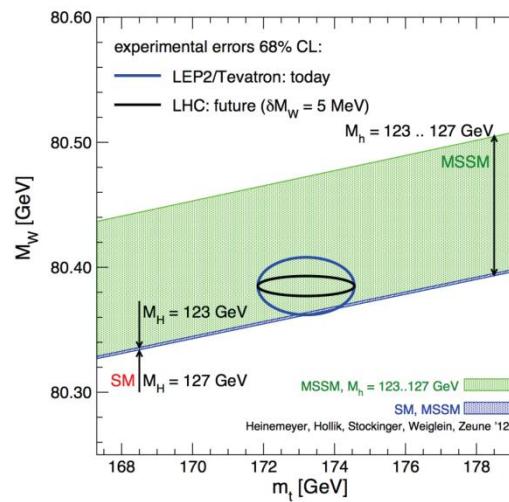


2. Lightest SUSY particle is stable (if R-parity) – Dark Matter candidate

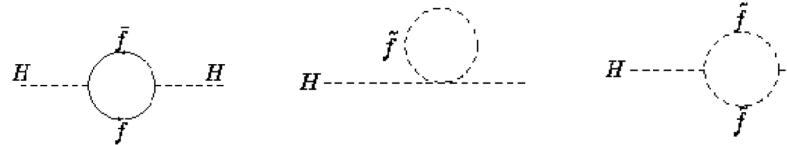
3. Unification of couplings in contrast to SM



4. Fit of EW precision data



M_H is protected due to cancellation of Λ^2 dependence!



($X_t = \sqrt{6} M_{\text{SUSY}}$ **Maximal mixing scenario**)

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2} \left[\ln \left(\frac{M_{\text{SUSY}}^2}{m_t^2} \right) + \frac{X_t^2}{M_{\text{SUSY}}^2} \left(1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right) \right]$$

Large loop correction

$$M_{\text{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t = A_t - \mu \cot \beta$$

$$\tan \beta \equiv \frac{v_2}{v_1}, M_A$$

$$M_h^2 \leq M_Z^2 + \Delta m_h^2$$

↓

$(125 \text{ GeV})^2 \quad (91 \text{ GeV})^2 \quad (86 \text{ GeV})^2$

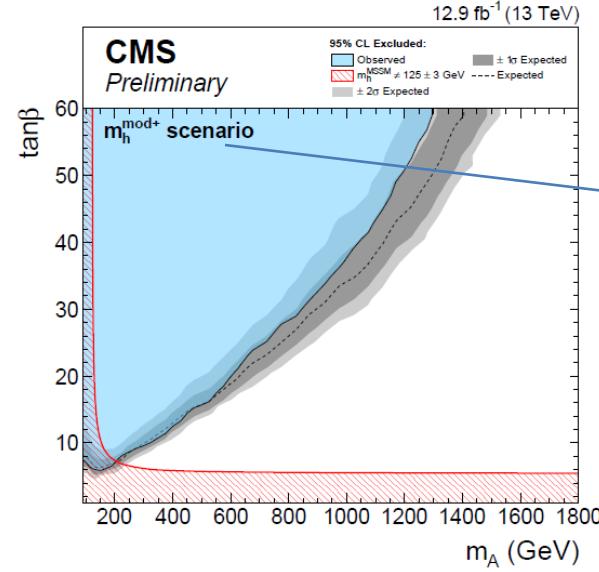
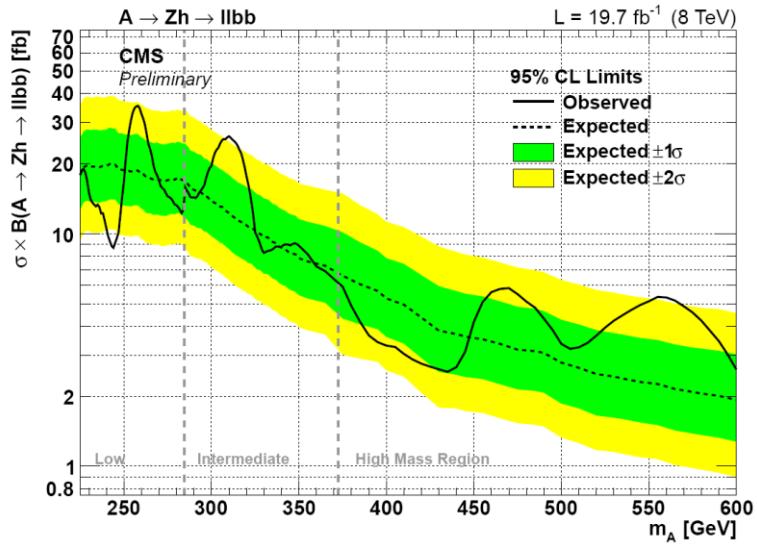
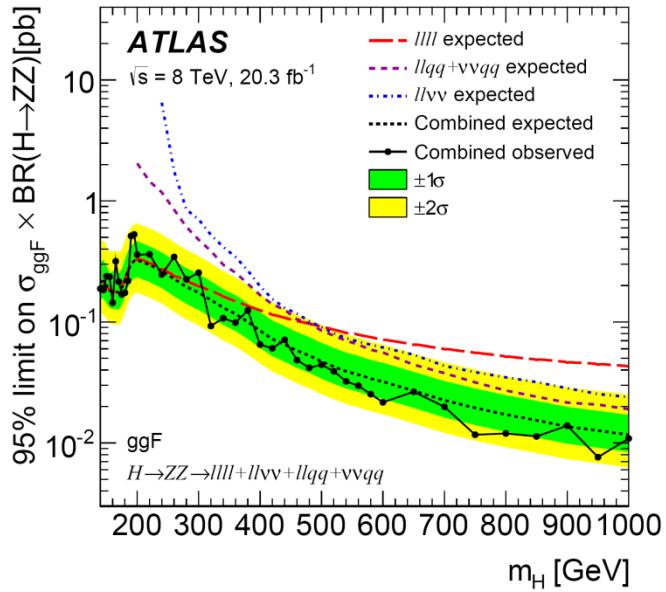
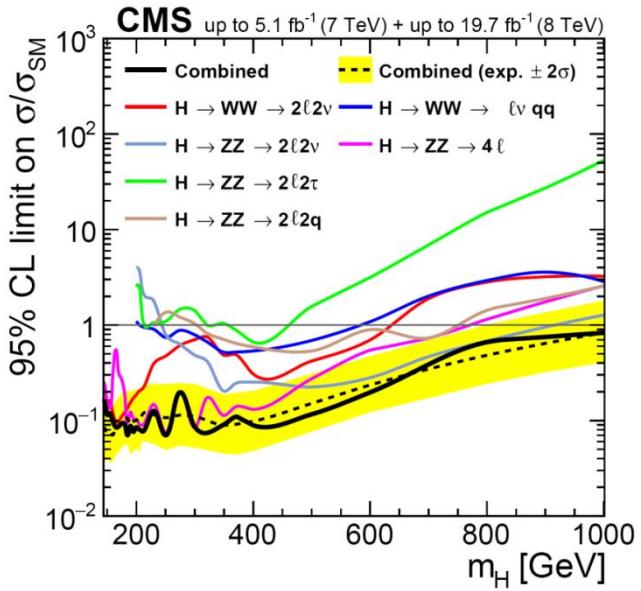
2 complex scalar doublets => 8 degrees of freedom

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a) / \sqrt{2} \end{pmatrix}, \quad a = 1, 2$$

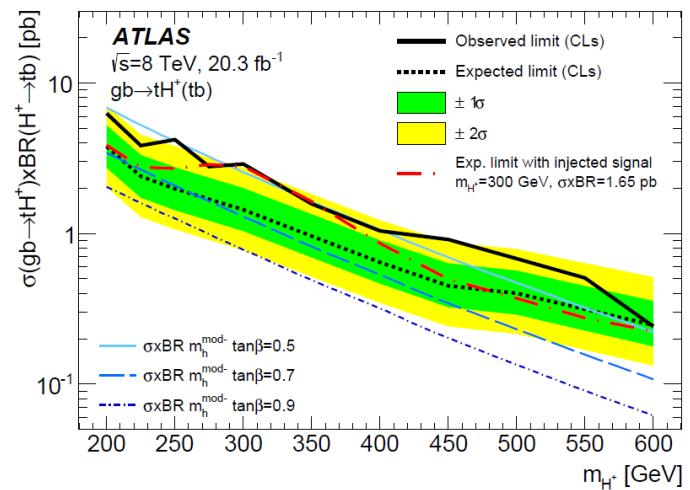
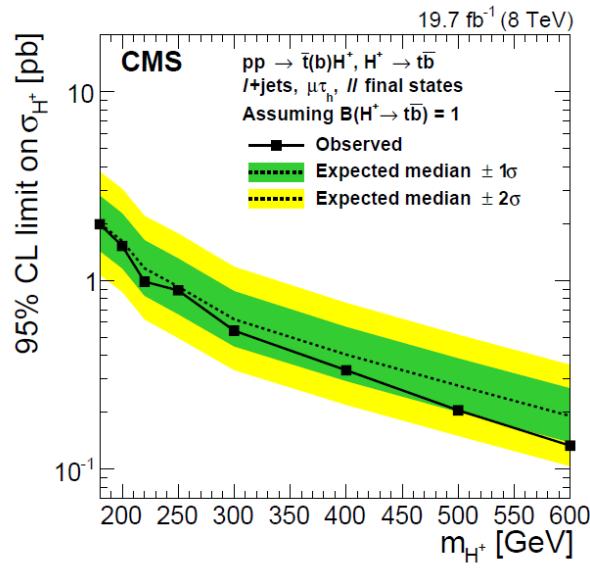
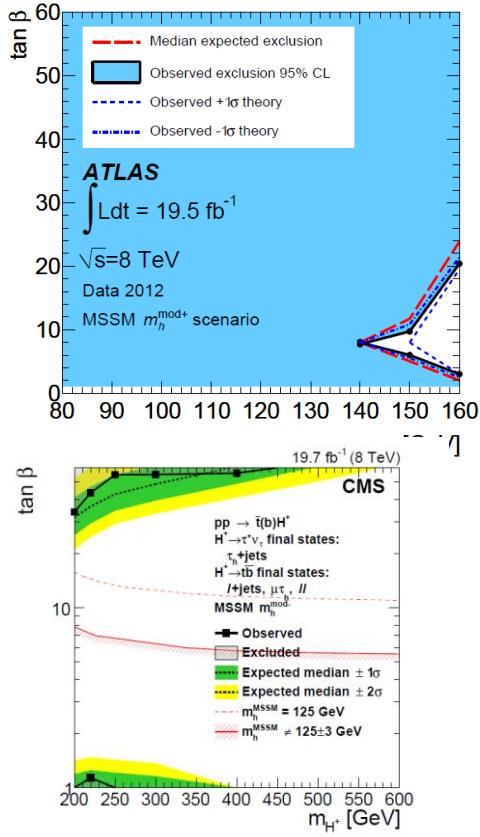
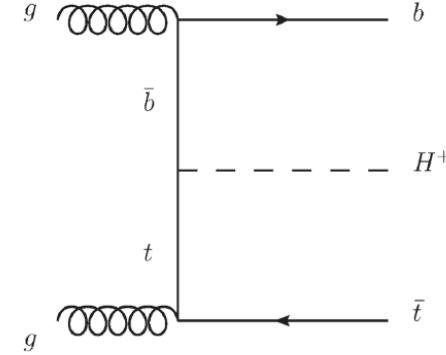
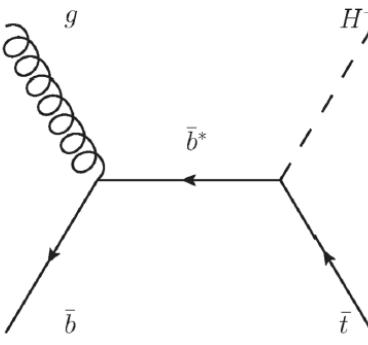
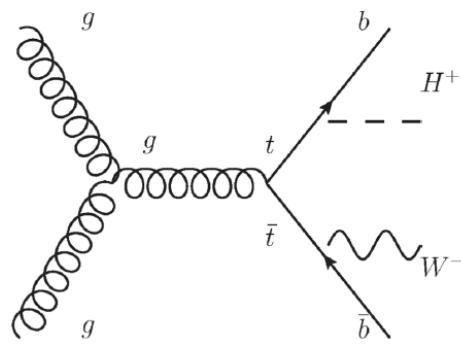
As in the SM 3 Goldstone bosons are absorbed (“eaten”) by W^\pm and Z

5 physics degrees of freedom

**h, H – CP even scalars,
A - CP odd scalar,
 H^\pm - charged scalars**



Поиски заряженного бозона Хиггса



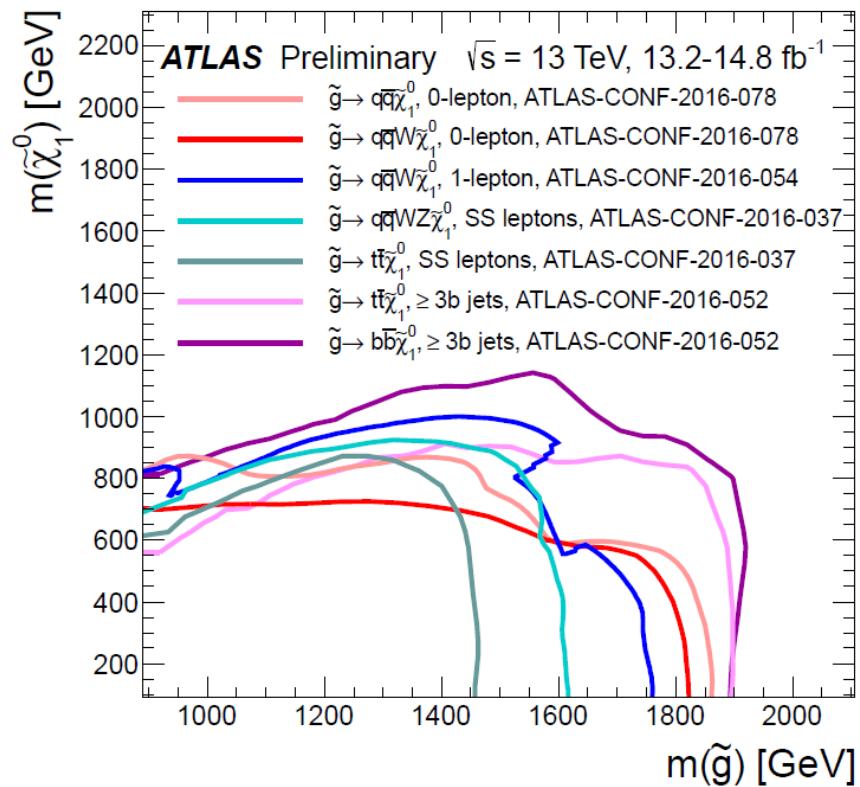
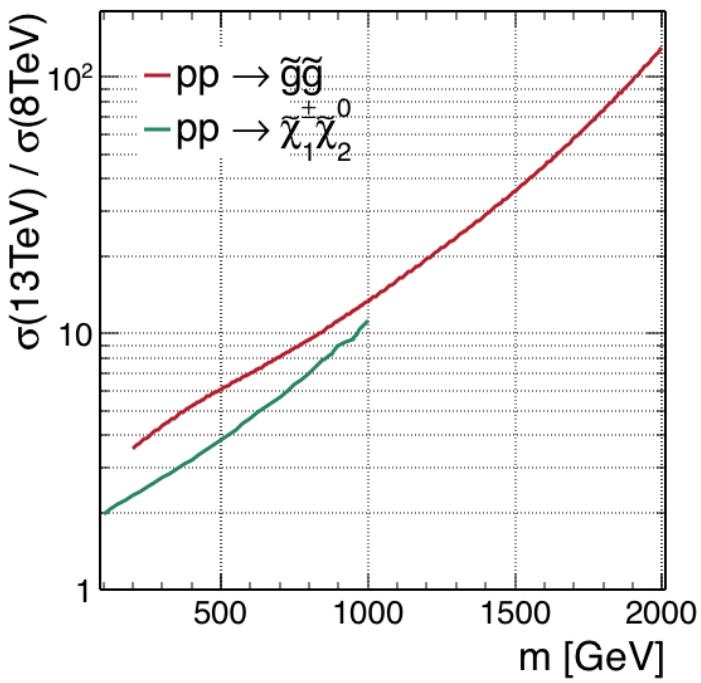
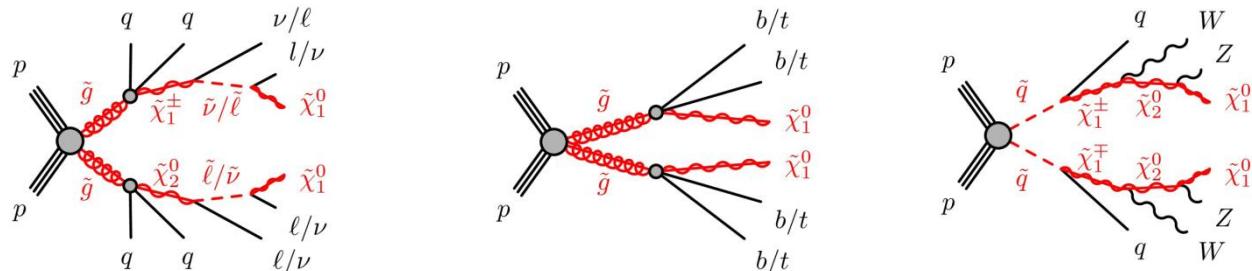
SUSY searches

In order to establish SUSY one needs:

- find superpartners
 - measure spins which should differ by $\frac{1}{2}$
 - demonstrate their couplings are the same
 - their quantum numbers are the same
- ...

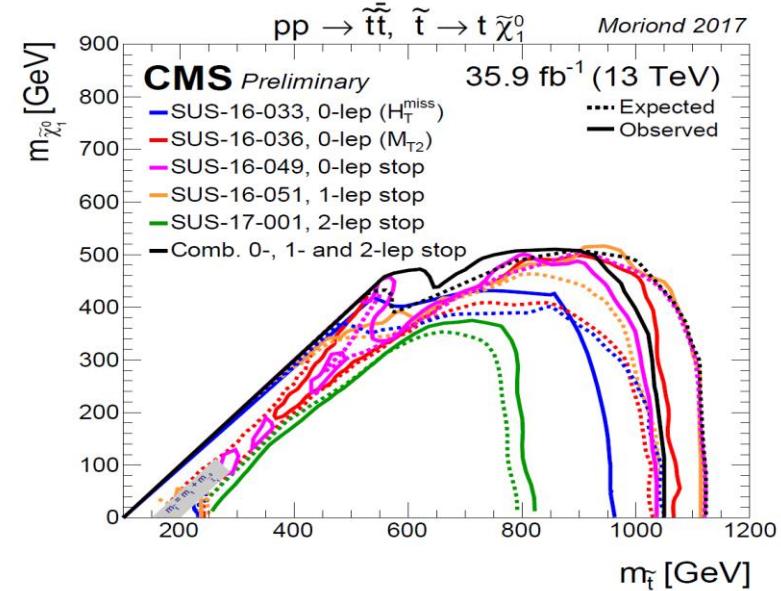
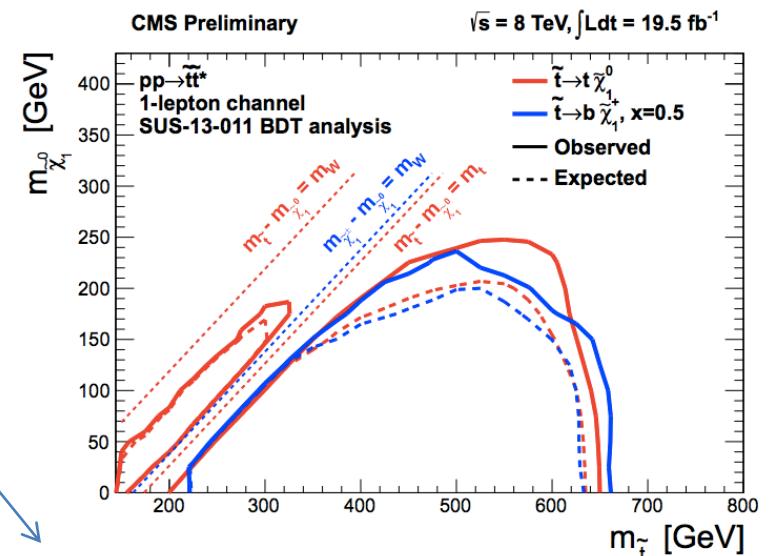
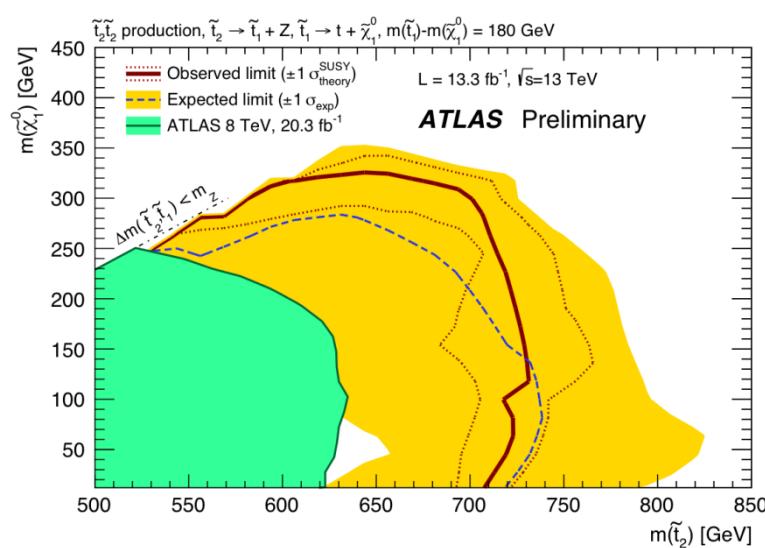
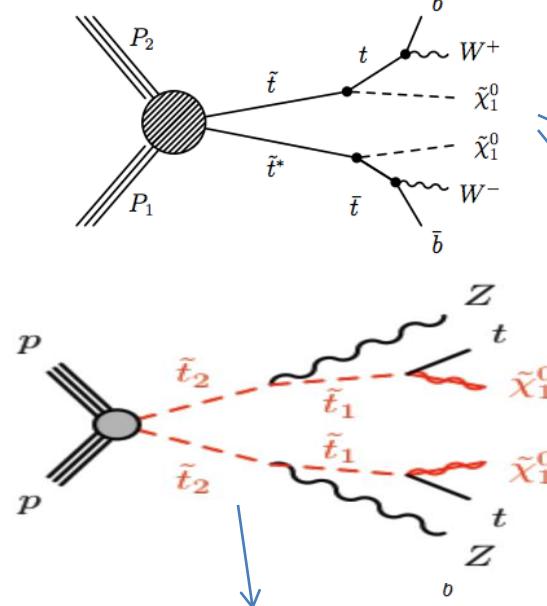
Searches for strongly interacting superpartners

Gluino and squark
signatures:



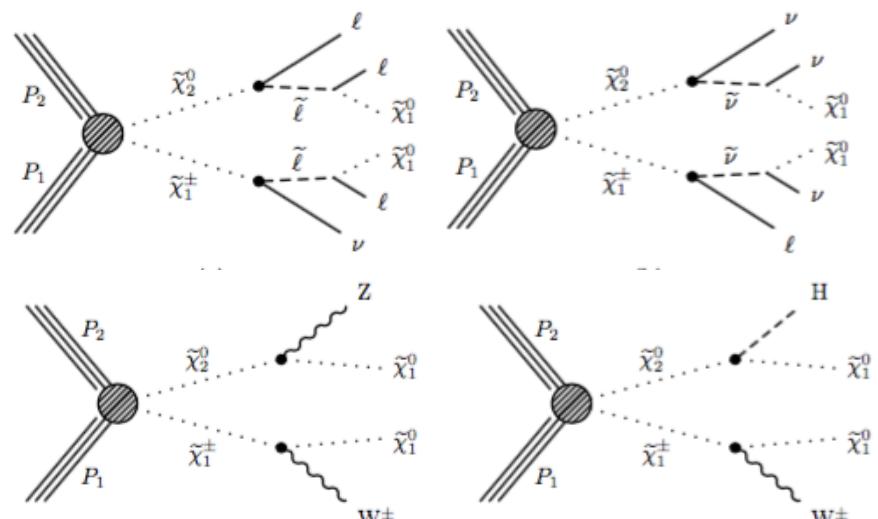
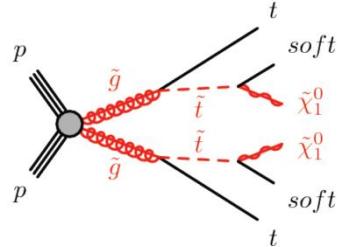
$$\tilde{t}\tilde{t} \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Searches for Stops

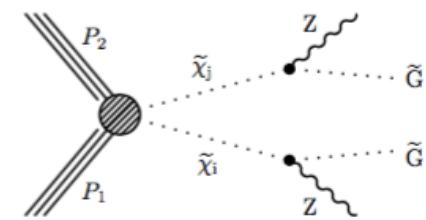
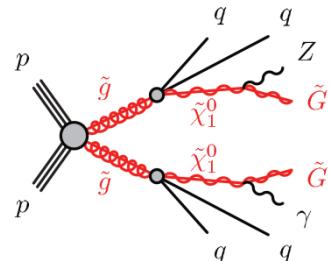


Many other searches for superpartners

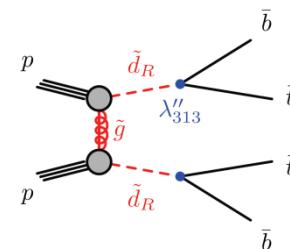
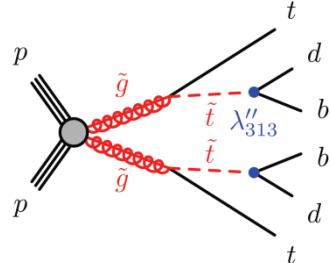
R-parity conserving scenarios



Gauge mediated scenarios



R-parity violating scenarios



Selected CMS SUSY Results* - SMS Interpretation

ICHEP '16 - Moriond '17

Glino

Squark

EWK Gauginos

CMS Preliminary

$\sqrt{s} = 13\text{TeV}$

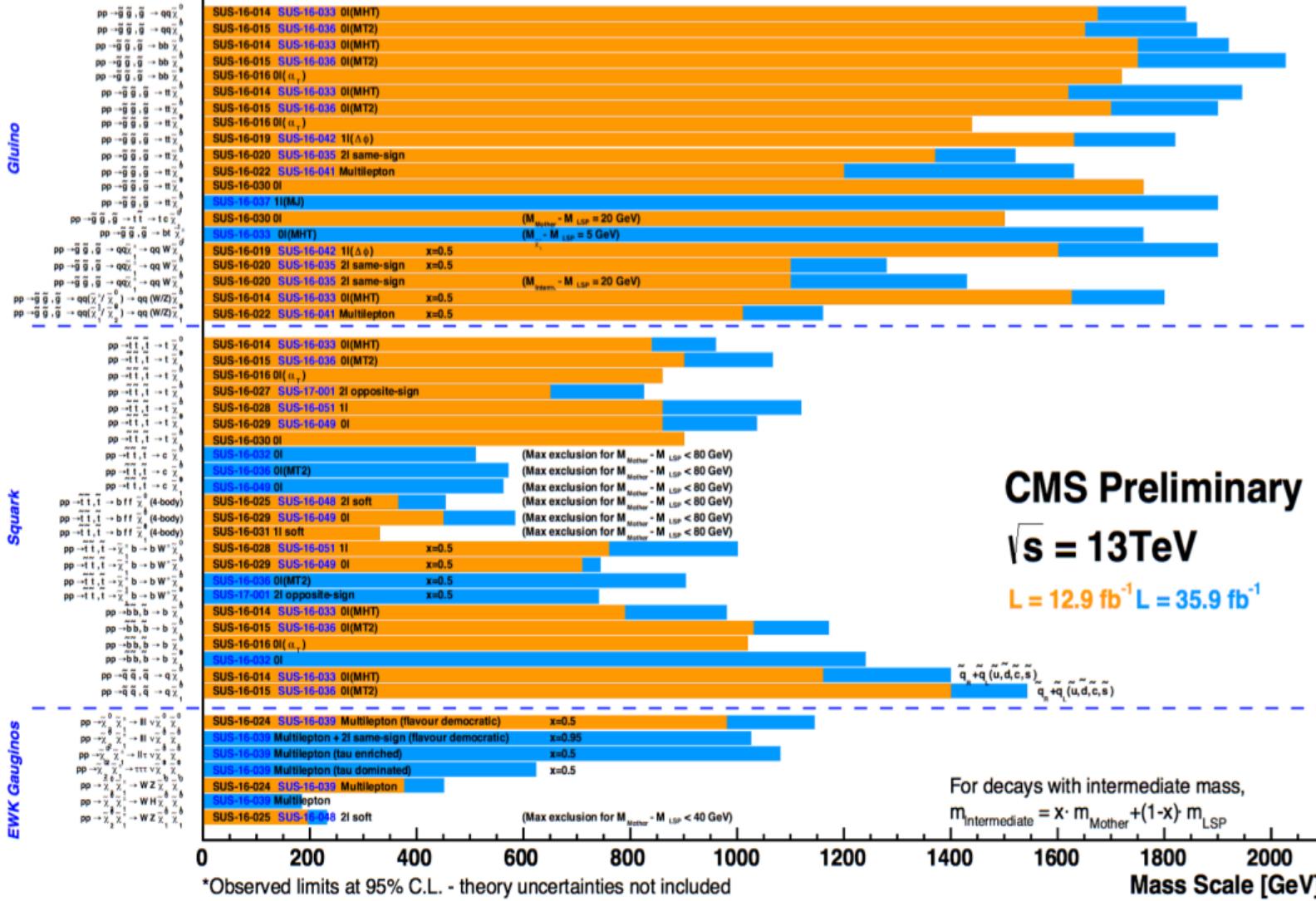
$L = 12.9 \text{ fb}^{-1}$ $L = 35.9 \text{ fb}^{-1}$

$\tilde{q}, \tilde{q}, (\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s})$

$\tilde{q}, \tilde{q}, (\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s})$

For decays with intermediate mass,

$$m_{\text{intermediate}} = x \cdot m_{\text{Mother}} + (1-x) \cdot m_{\text{LSP}}$$



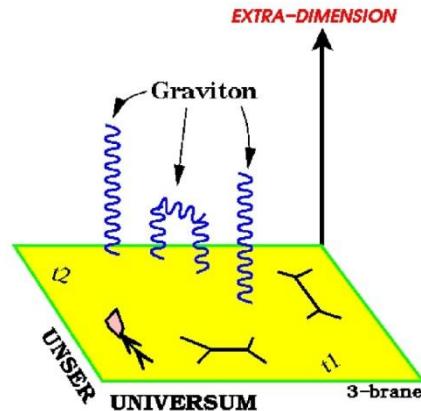
*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{\text{LSP}} \sim 0 \text{ GeV}$ unless stated otherwise

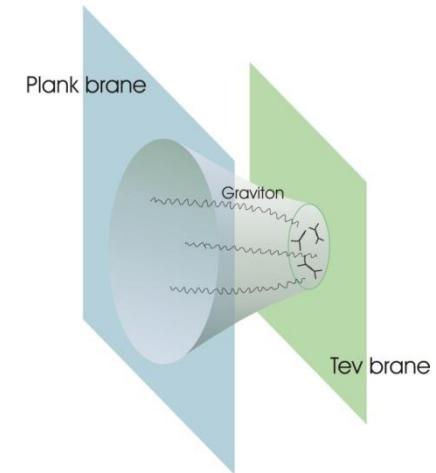
Models with extra space dimensions

we are confined on some 4-dim. brane imbedded into higher dim. bulk

ADD type models



RS type models



UED type scenarios

with SM fields in ADD or RS bulk

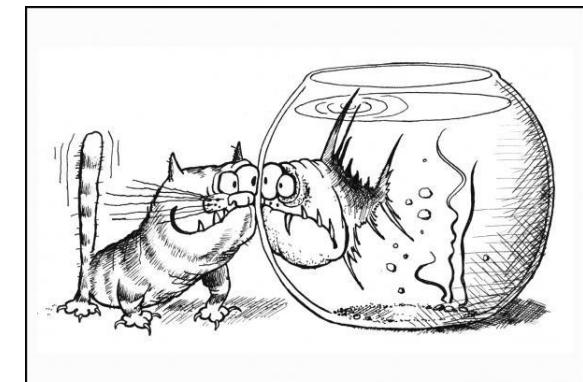
KK-parity ->
LKKP is a good DM candidate

Can unify the forces

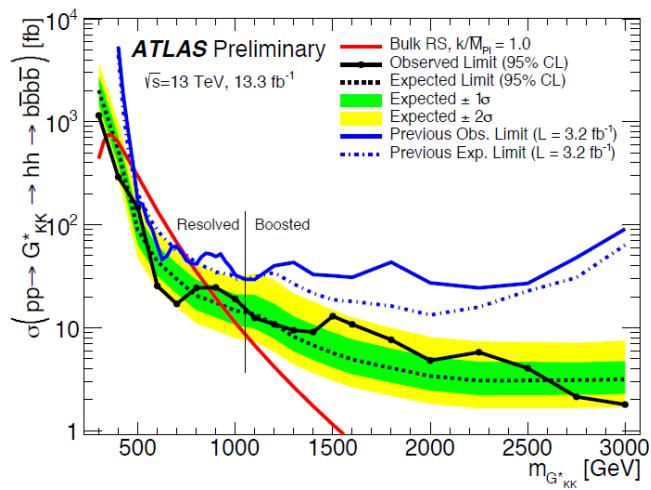
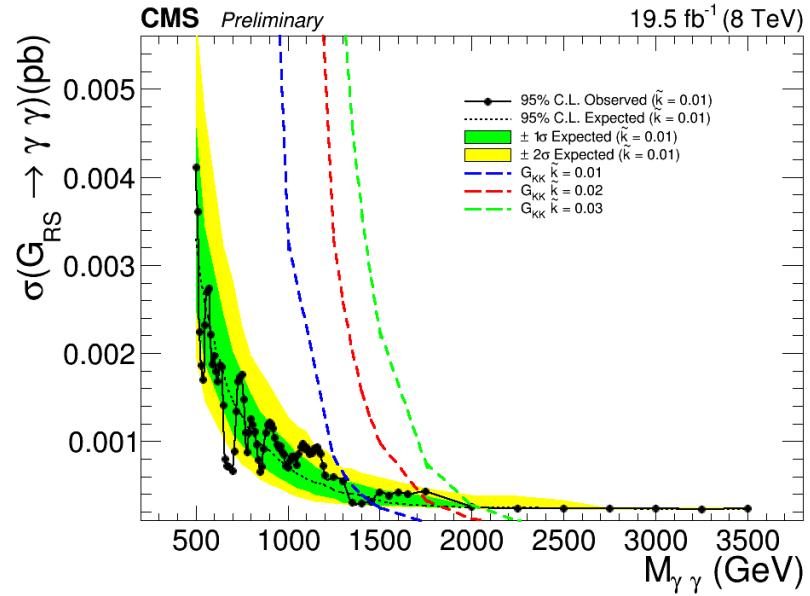
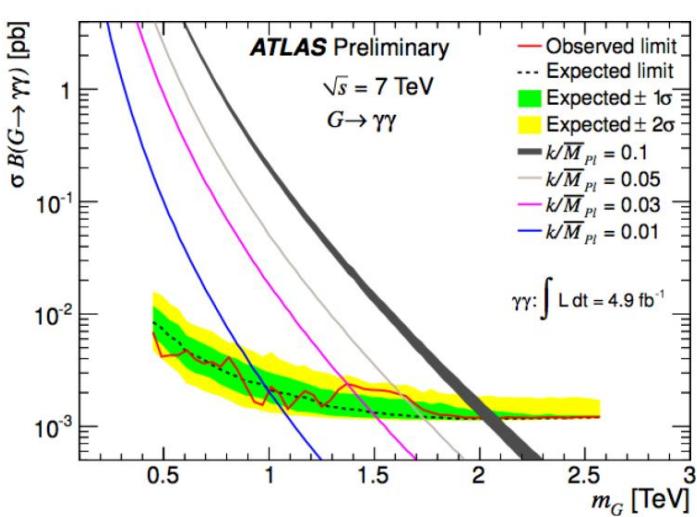
Can explain why gravity is weak (solve hierarchy problem)

Contain Dark Matter Candidates

Can generate neutrino masses



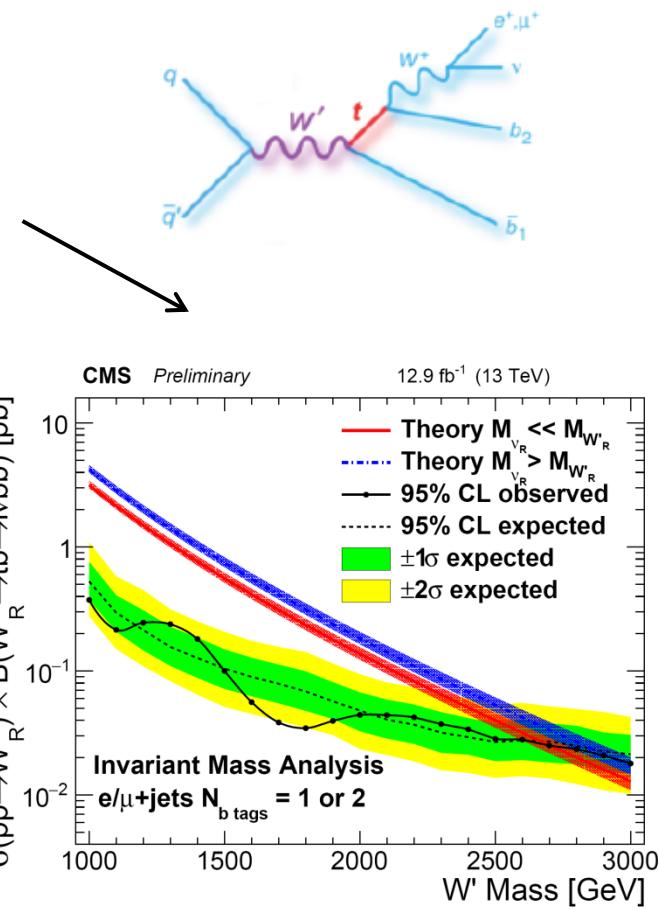
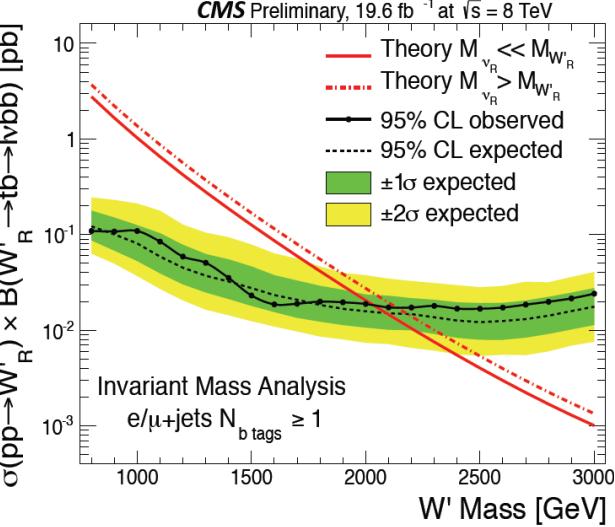
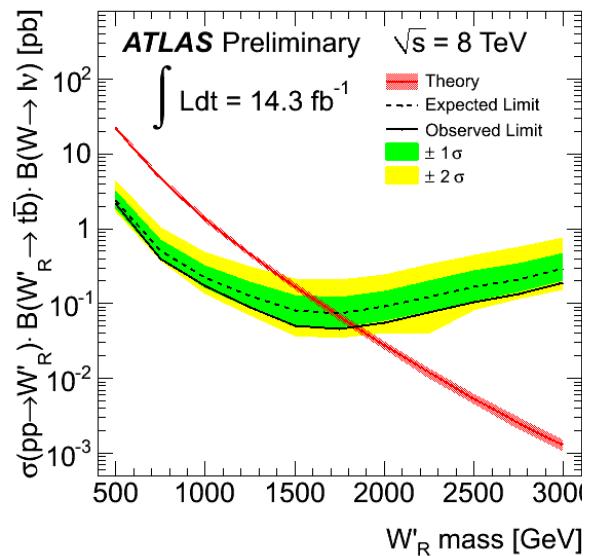
Searches for RS gravitons



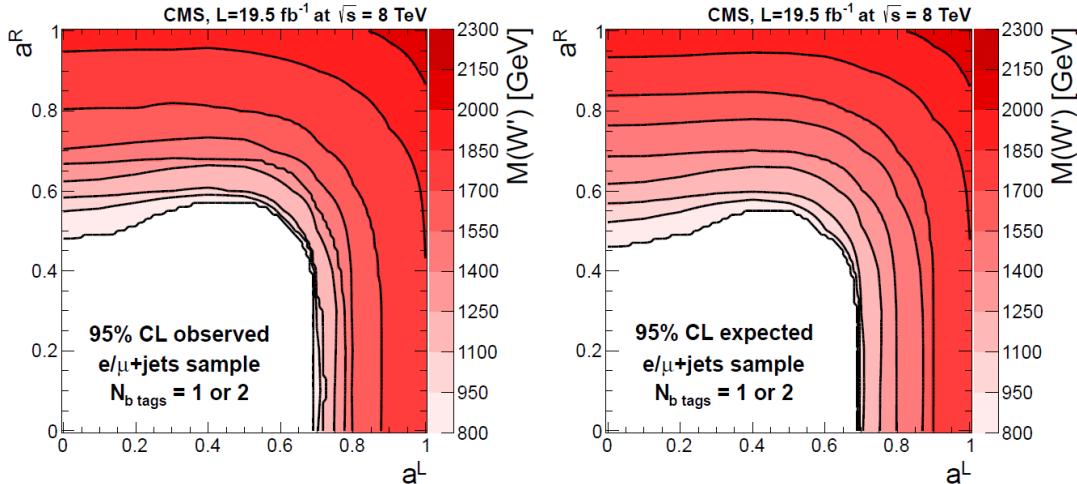
Searches for various resonances

Simplified models

Searches for W' in top+b

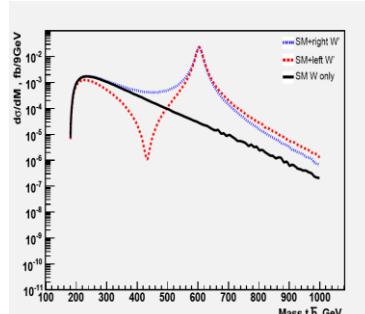


$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu (a_{f_i f_j}^R (1 + \gamma^5) + a_{f_i f_j}^L (1 - \gamma^5)) W'^\mu f_j + \text{h.c.}$$

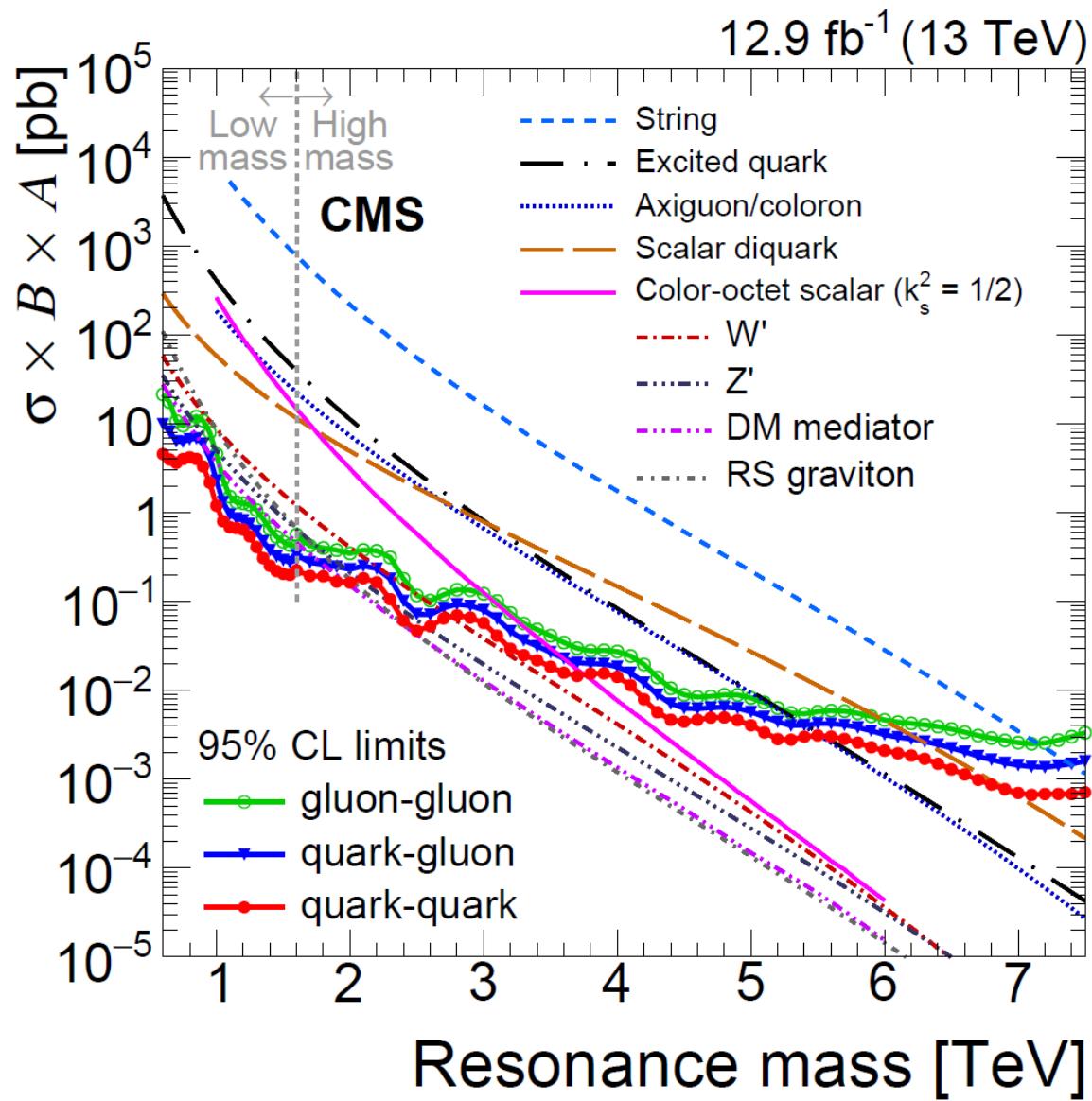


E.B., Bunichev, Dudko, Perfilov

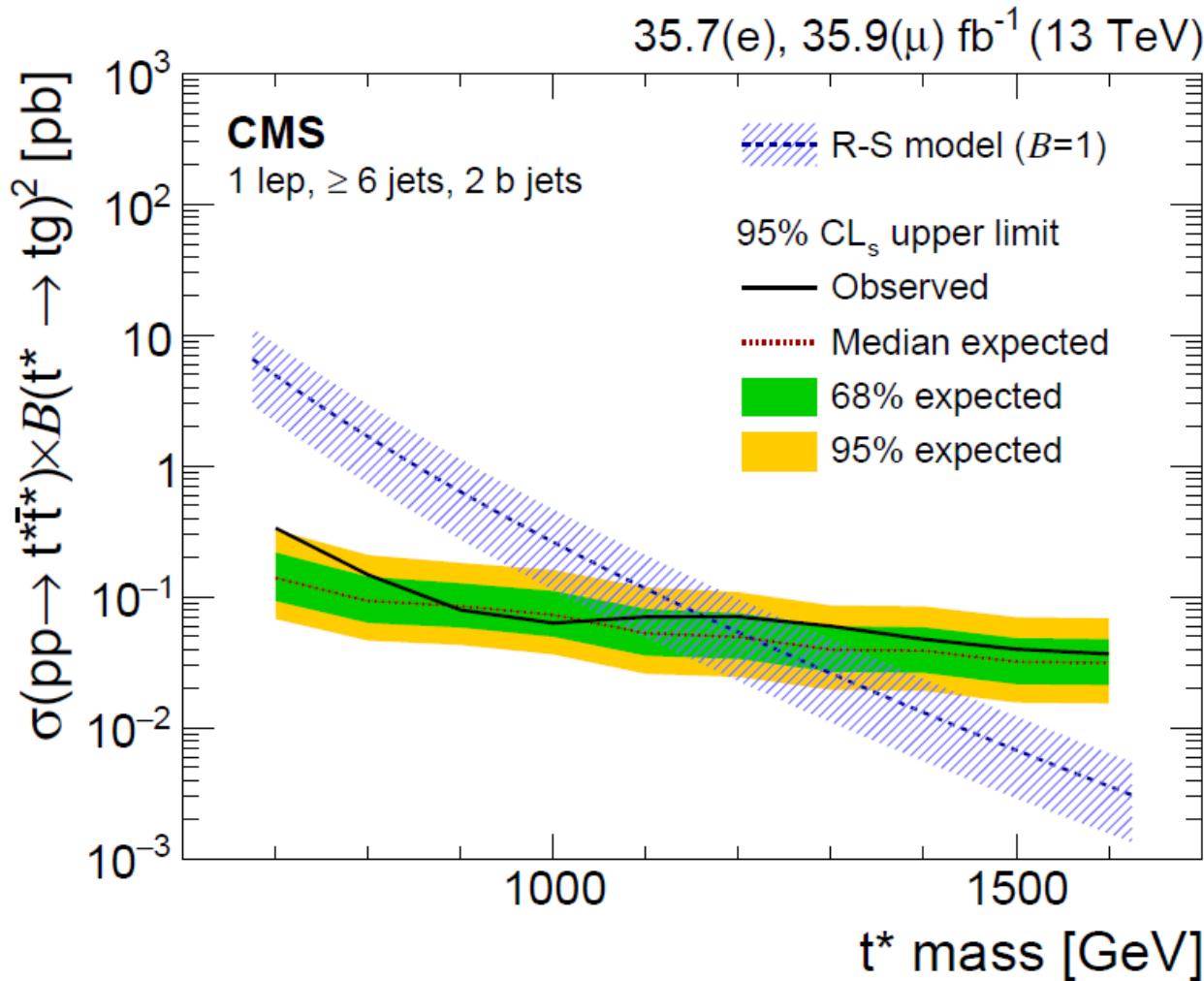
Negative interference



Поиск резонансов, распадающихся в две легкие струи



Возбужденный топ-кварк



Vector like top partners

Vector-like quarks - spin 1/2 particles with the same color and electroweak quantum numbers for left and right components

Masses not from the BEH mechanism

$Q_L Q_R$ mass terms are allowed by EW gauge symmetry

VLQ appear in many BSM extensions

Matsedonskyia, Panicob, Wulzer

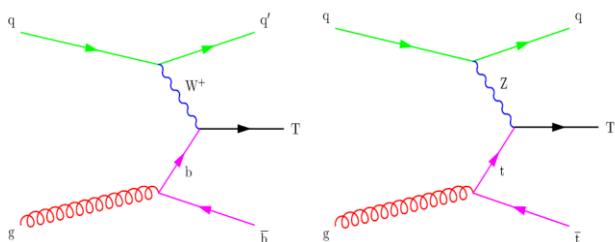
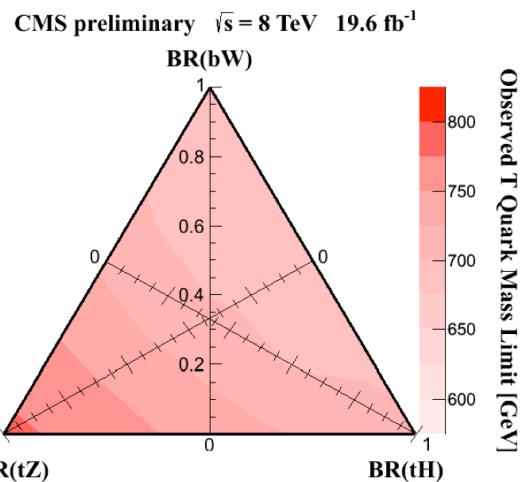
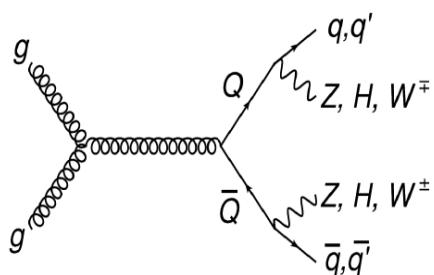
partner (MG name)	Q	W^\pm	Z	h	$W^\pm W^\pm$
$T_{2/3}$ (T23)	2/3	c_L^{TW}, c_R^{TW}	c_L^{TZ}, c_R^{TZ}	c_L^{Th}, c_R^{Th}	—
$B_{1/3}$ (B13)	-1/3	c_L^{BW}, c_R^{BW}	c_L^{BZ}, c_R^{BZ}	c_L^{Bh}, c_R^{Bh}	—
$X_{5/3}$ (X53)	5/3	c_L^{XW}, c_R^{XW}	—	—	—
$Y_{4/3}$ (Y43)	-4/3	c_L^{YW}, c_R^{YW}	—	—	—
$V_{8/3}$ (V83)	8/3	—	—	—	c_L^{VW}, c_R^{VW}

**Example of the simplified model Lagrangian
(after mixing and mass matrix diagonalization)**

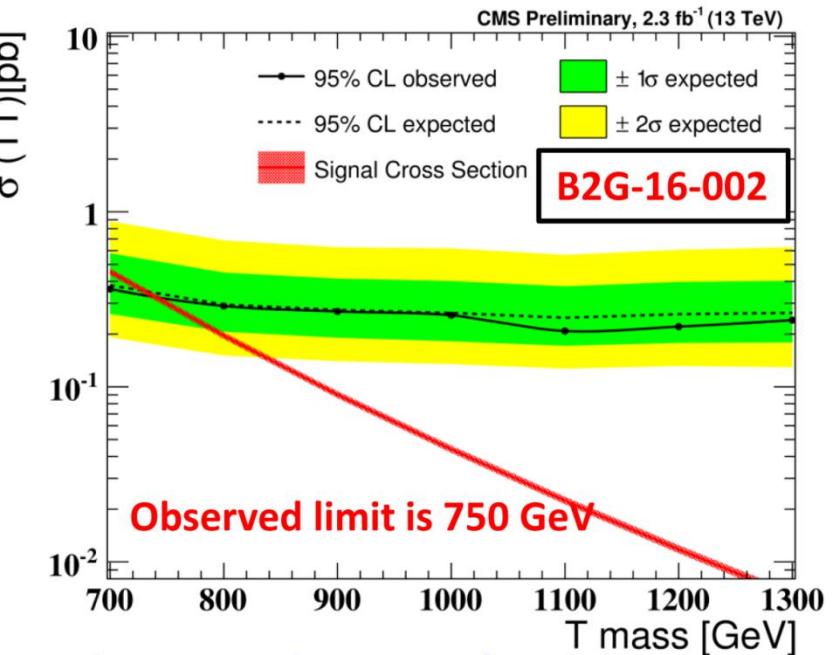
$$\frac{g_w}{2} c_L^{TW} [\bar{T}_L \gamma_\mu b_L W^\mu] + h.c.$$

$$c_L^{Th} [\bar{T}_R t_L h] + h.c.$$

Similar limit at 13 TeV with just 2.3 fb^{-1} integrated luminosity



$T \rightarrow Zt, T \rightarrow Wb, T \rightarrow Ht$ for $Q_T=2/3$

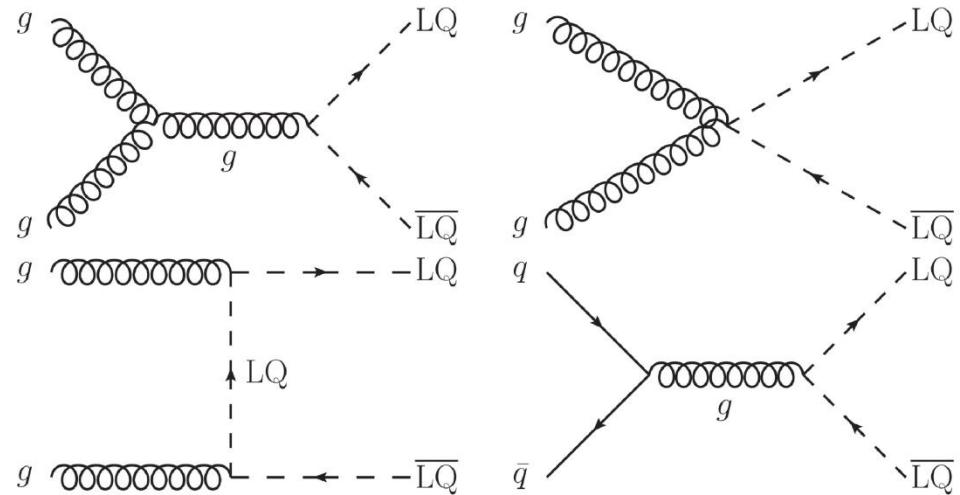


Also some limits are set on couplings and masses from single VLQ production

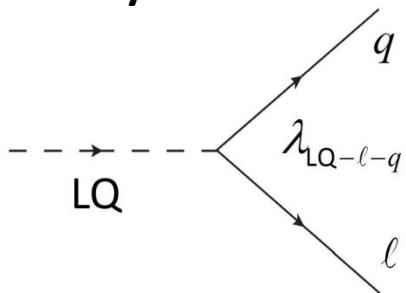
Leptoquark searches

LQs are predicted by composite models, GUT ...

Production channels



Decays

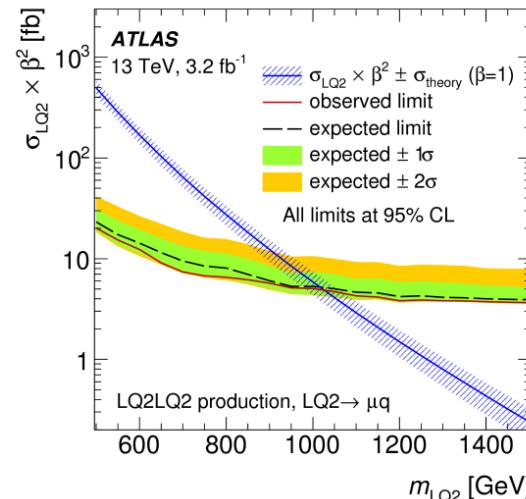
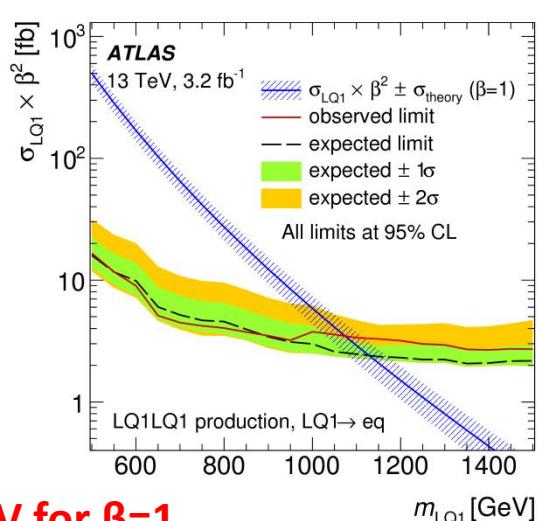


Final states for leptoquarks of three generations

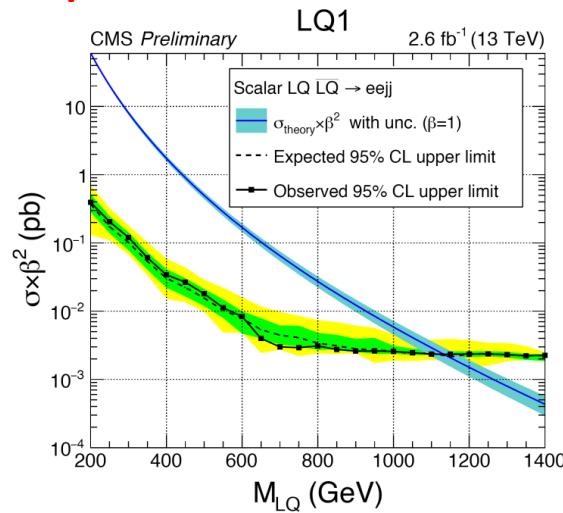
- LQ1 $\rightarrow e u, e d, v_e u, v_e d$**
- LQ2 $\rightarrow \mu c, \mu s, v_\mu c, v_\mu s$**
- LQ3 $\rightarrow \tau t, \tau b, v_\tau t, v_\tau b$**

1st generation LQ mass limit for $\beta=1$
 2nd generation LQ mass limit for $\beta=1$

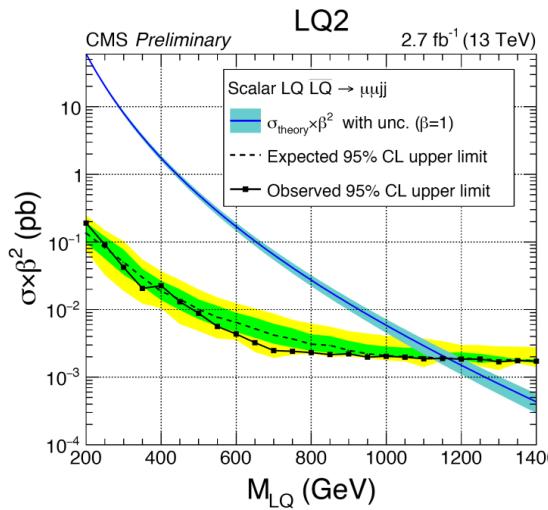
RUN1 • CMS: 1010 GeV; ATLAS 1060 GeV
 RUN1 • CMS: 1080 GeV; ATLAS 1050 GeV



1130 GeV for $\beta=1$



1165 GeV for $\beta=1$



Sensitivity is similar for ~ 20 fb⁻¹ at $\sqrt{s} = 8$ TeV and for ~ 3 fb⁻¹ at $\sqrt{s} = 13$ TeV

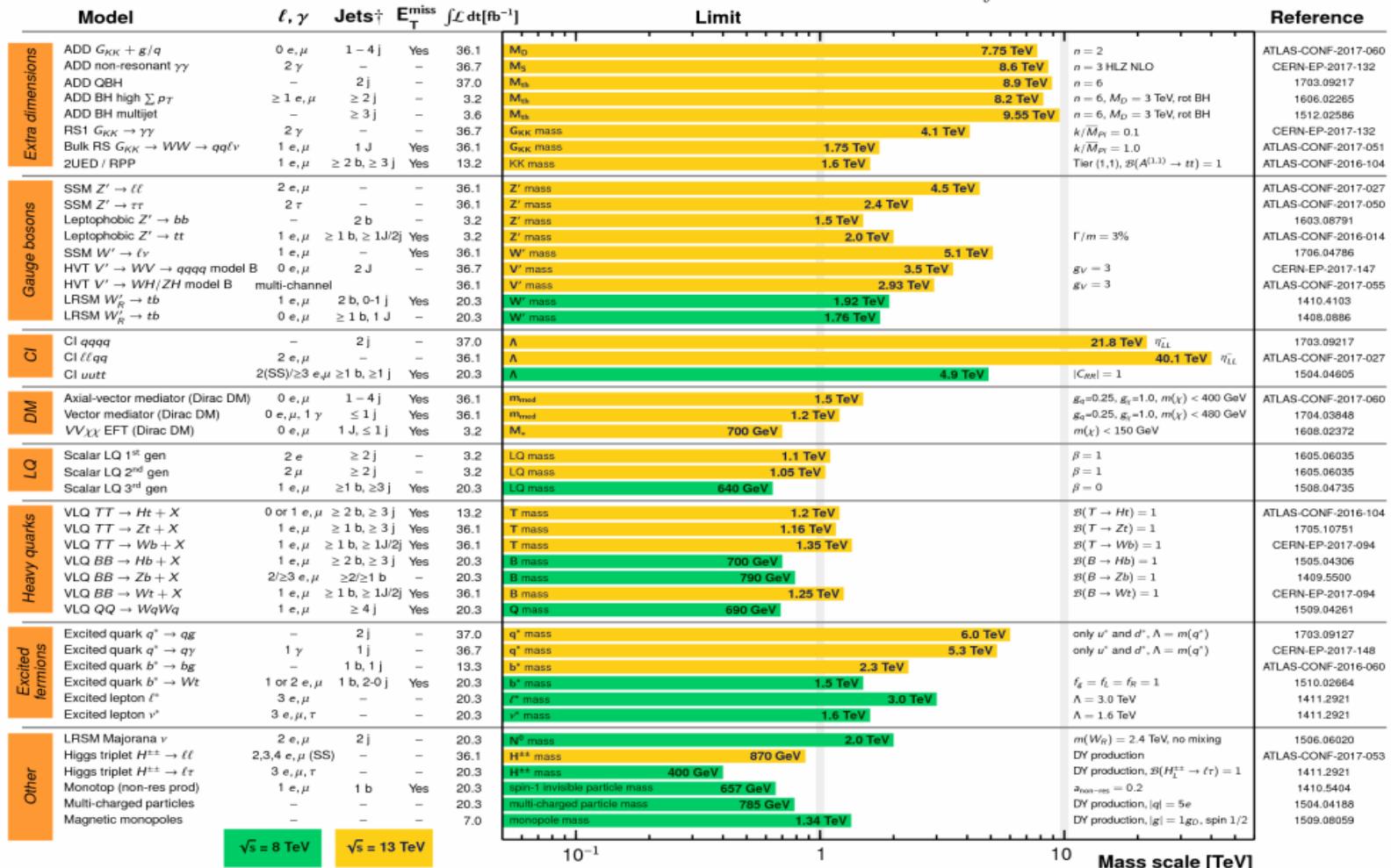
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

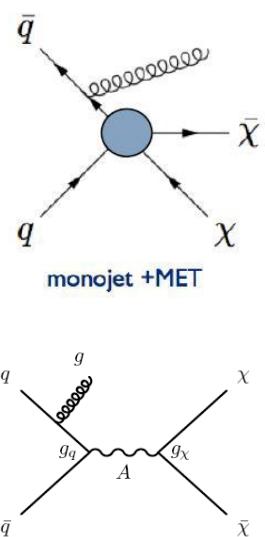
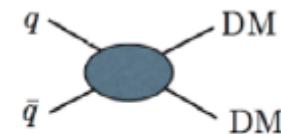
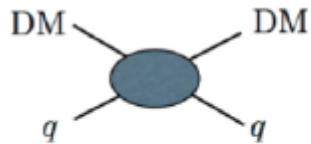


*Only a selection of the available mass limits on new states or phenomena is shown.

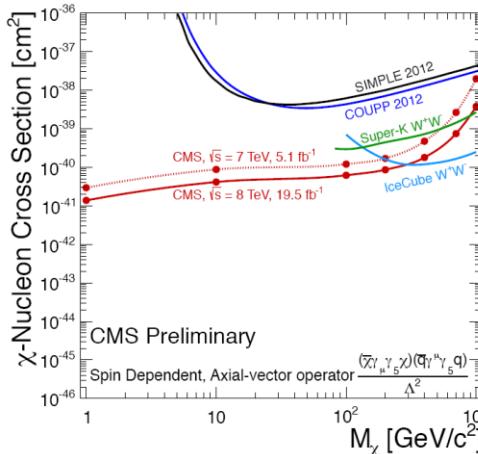
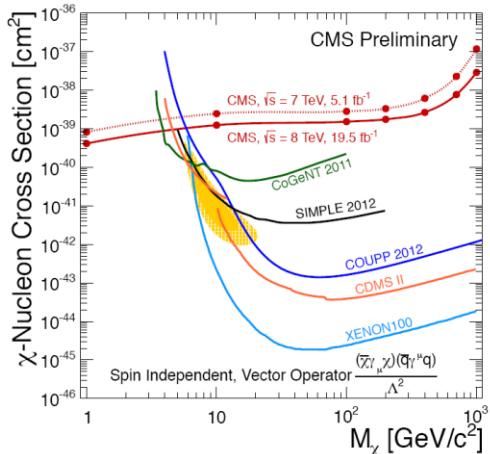
†Small-radius (large-radius) jets are denoted by the letter j (J).

"There are more things in heaven and earth,
Horatio, than are dreamt of in your philosophy."
-- Hamlet

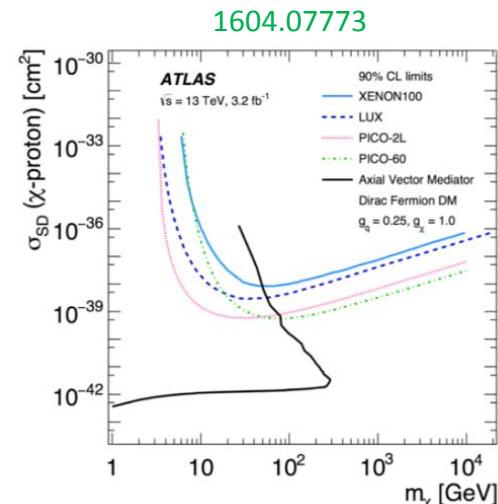
Dark Matter searches



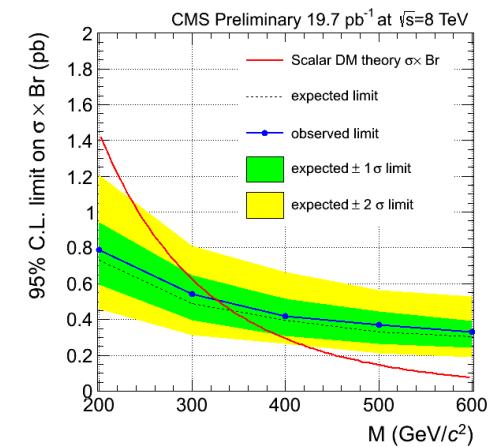
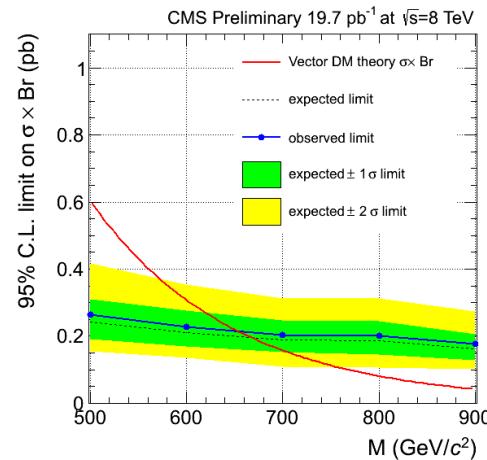
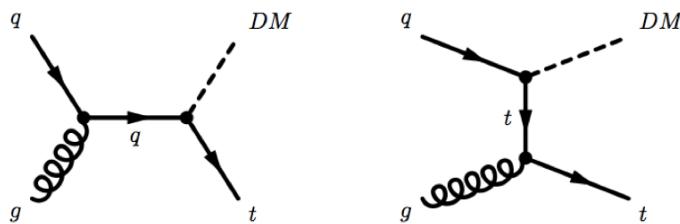
Direct Detection (t-channel)



Collider Searches (s-channel)



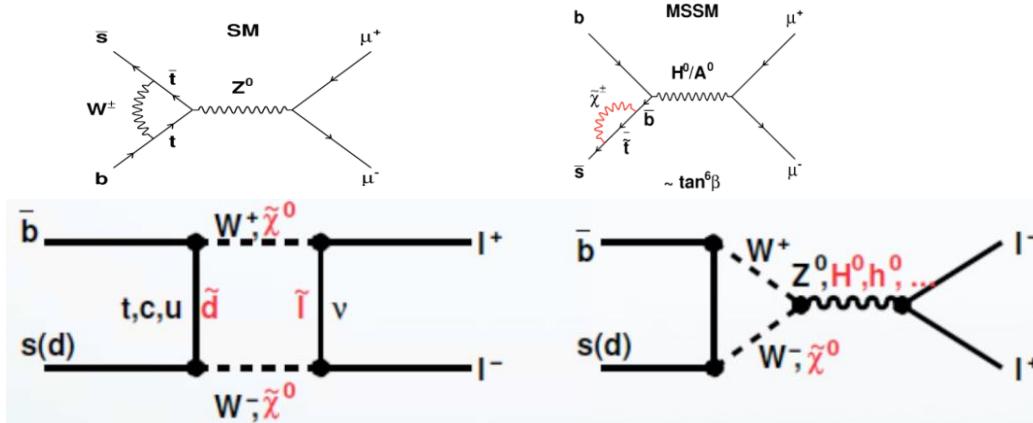
Dark Matter searches in association with single top



Mass of vector (scalar) DM candidate less than 655 (327) is excluded at 95% C.L.

Наблюдение редкого распада B_s^0 – мезона в пару мюонов $\mu^+\mu^-$ на основе совместного анализа данных детекторов CMS и LHCb на БАК

Публикация в журнале: **Nature 522 (2015) 68** (импакт фактор 41)



B_s^0 – мезон состоит из s -кварка и анти- b -кварка.

Измеренная экспериментально относительная вероятность распада B_s^0 – мезона в пару мюонов $\mu^+\mu^-$

$$\text{Br}(B_s^0 \rightarrow \mu^+\mu^-)_{\text{exp}} = (2.8^{+0.7}_{-0.8}) \times 10^{-9}$$

Пик от распада B_s^0

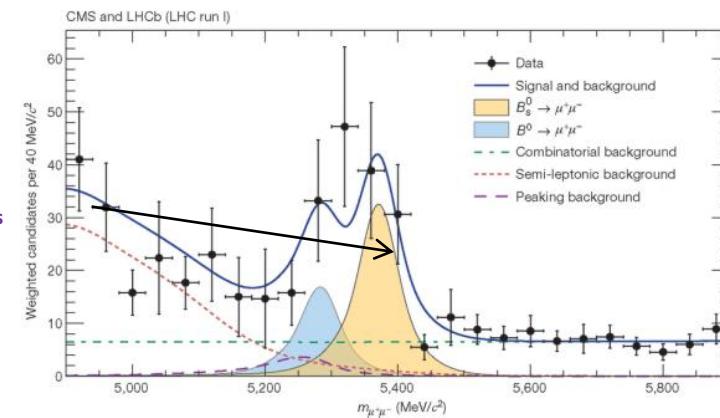
В полном согласии с теоретическим расчетом в рамках Стандартной модели

$$\text{Br}(B_s^0 \rightarrow \mu^+\mu^-)_{\text{theory}} = (3.66 \pm 0.23) \times 10^{-9}$$

Впервые прямо наблюдался этот редкий распад !

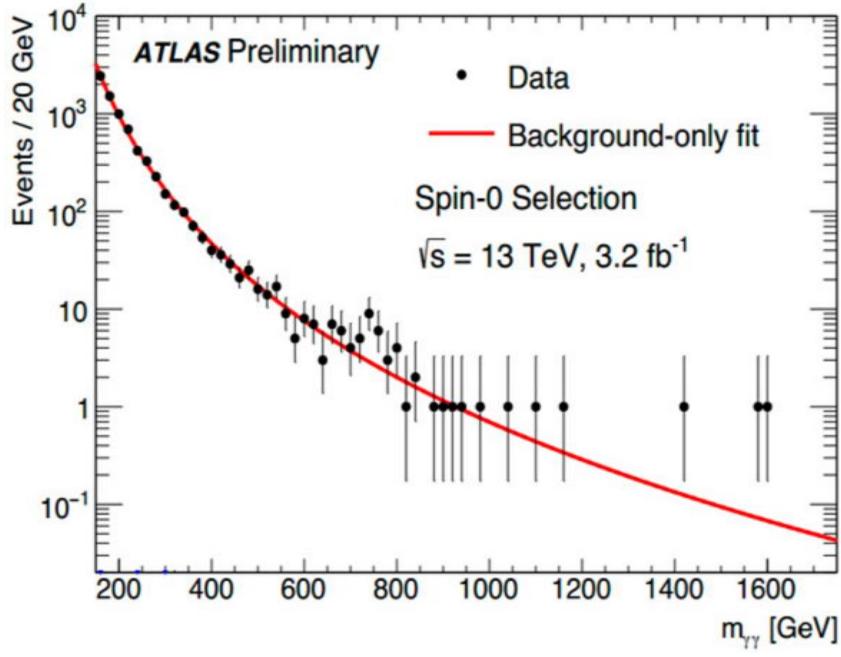
Многие модели за рамками Стандартной модели предсказывали усиление этого распада. Эти модели либо закрыты, либо область параметров этих моделей теперь резко ограничена.

Распределение по инвариантной массе $\mu^+\mu^-$

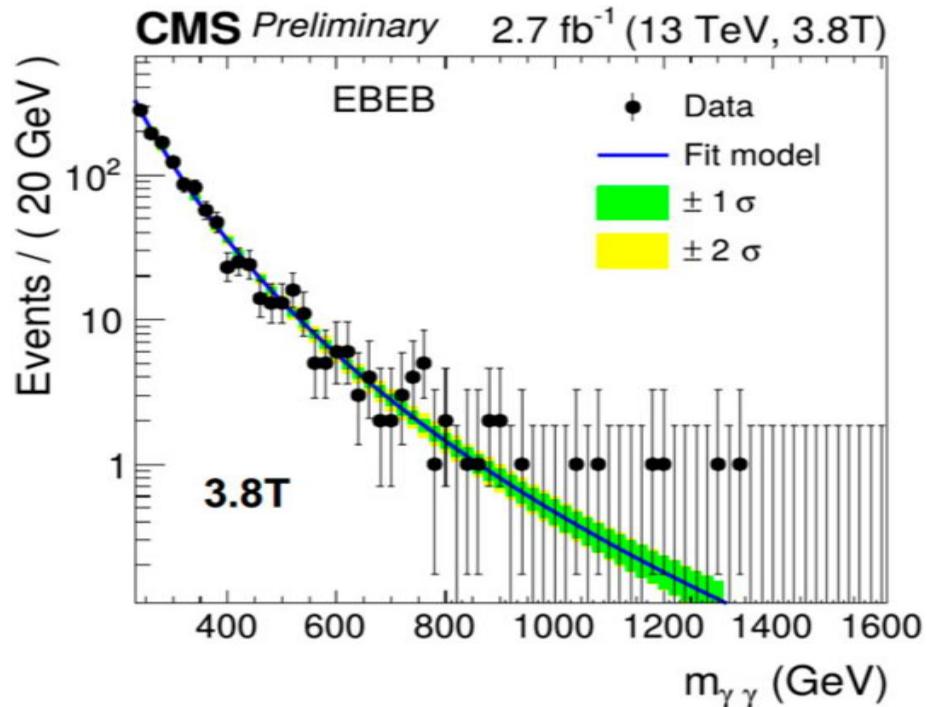


**Но пока не найдены достоверно
ни новые частицы и взаимодействия,
ни отклонения во взаимодействиях,
предсказанных Стандартной моделью**

The 750 GeV diphoton excess – поучительный пример не оправдавшихся открытий

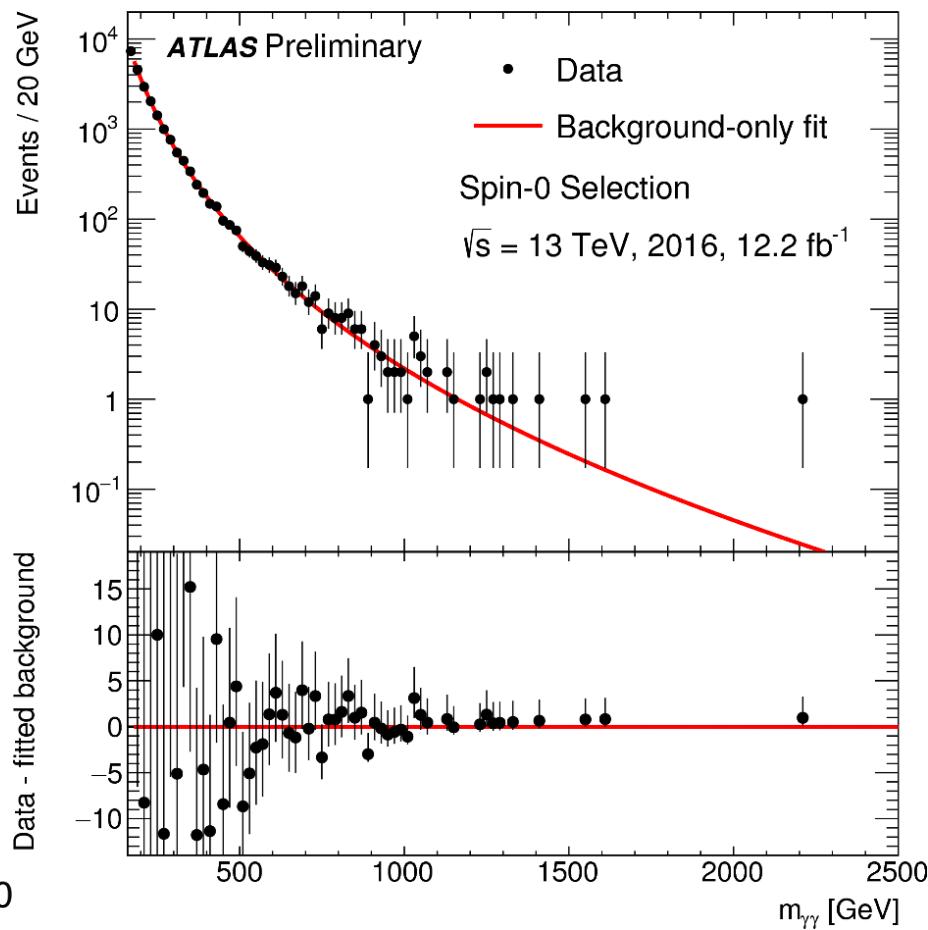
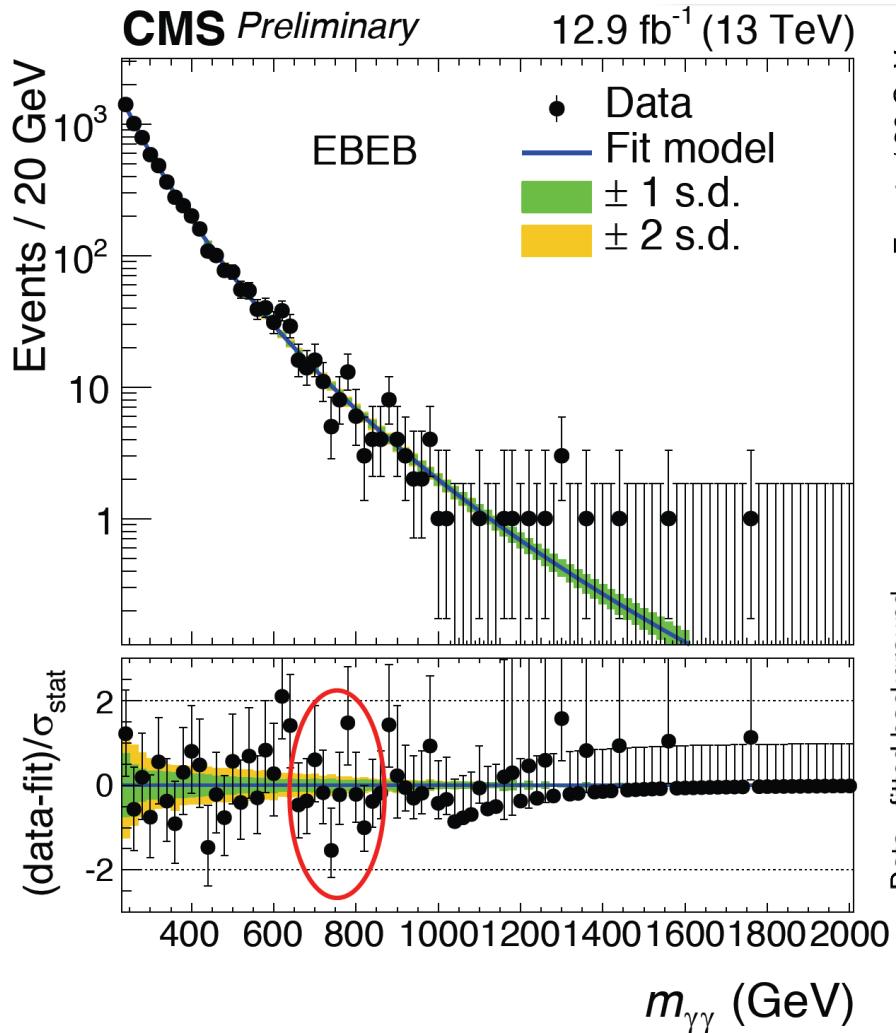


*Local significance = 3,9 σ
Global significance = 2 σ*



*Local significance = 3.4 σ
Global significance = 1.6 σ*

No signal with new much larger data set



Statistical fluctuation !

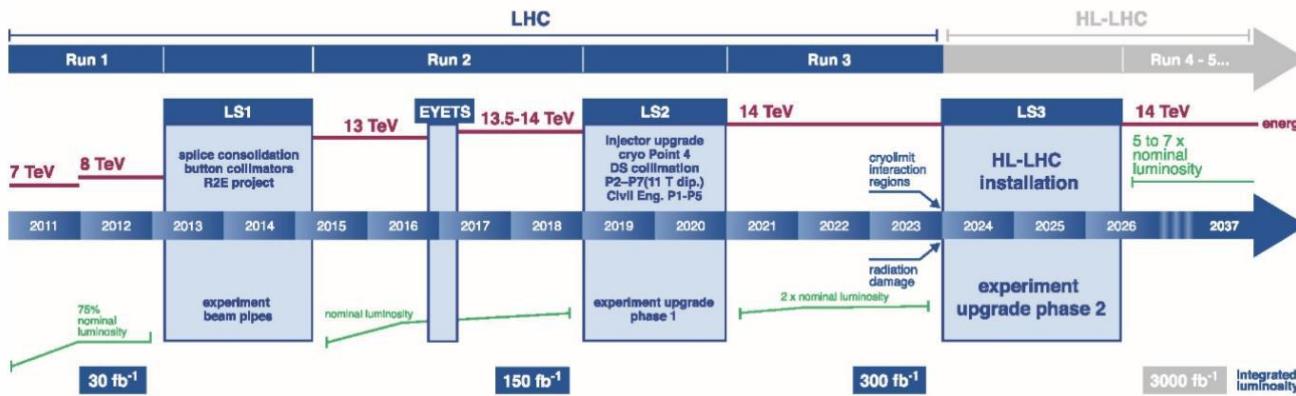
Nominal LHC: $\sqrt{s} = 14 \text{ TeV}$, $L = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (Note: $1.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ achieved already)

Integrated luminosity to ATLAS and CMS: 300 fb^{-1} by 2023 (end of Run-3)

HL-LHC: $\sqrt{s} = 14 \text{ TeV}$, $L = 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Integrated luminosity to ATLAS and CMS: 3000 fb^{-1} by ~ 2035

Fabiola Gianotti



Conceptual design study of a $\sim 100 \text{ km}$ ring:

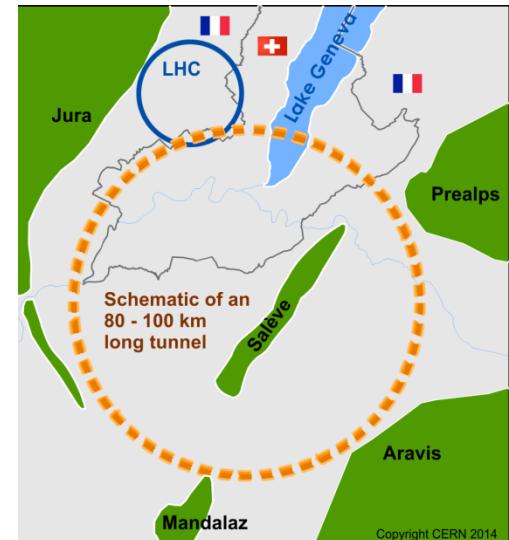
pp collider (FCC-hh): ultimate goal

$\sqrt{s} \sim 100 \text{ TeV}$, $L \sim 2 \times 10^{35}$; 4 IP, $\sim 20 \text{ ab}^{-1}/\text{expt}$

e+e-collider (FCC-ee): possible first step

$\sqrt{s} = 90 \div 350 \text{ GeV}$, $L \sim 200 \div 2 \times 10^{34}$; 2 IP

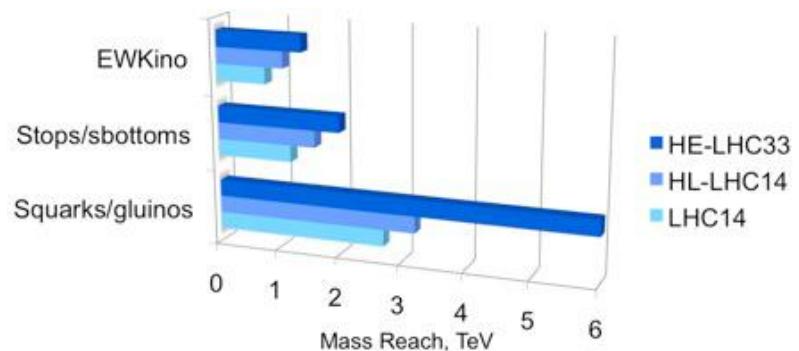
ep collider (FCC-he): option $\sqrt{s} \sim 3.5 \text{ TeV}$, $L \sim 10^{34}$



Expected precisions for Higgs couplings

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
\sqrt{s} (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L} dt$ (fb $^{-1}$)	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	-/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

$$\begin{aligned} \mathcal{L} = & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H \end{aligned}$$



- Нет общепринятого объяснения ряда явлений (DM, CP, иерархия масс, осцилляции ν ...)
 - Нет аргументов для величины масштаба Новой физики в ТэВ-ной области
 - Не измерен профиль потенциала Хиггса
 - Не достигнуто естественных точностей в измерениях констант взаимодействия Хиггса
 - Не оправдались надежды на наиболее естественные суперсимметричные сценарии
 - Не найдено значимых и общепризнанных отклонений во взаимодействиях
 - Не найдено новых частиц на ТэВ-ных масштабах
- ...

Надо продолжать поиски по всем возможным направлениям !



“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong”.

Richard P. Feynman