Физика Большого Адронного Ускорителя

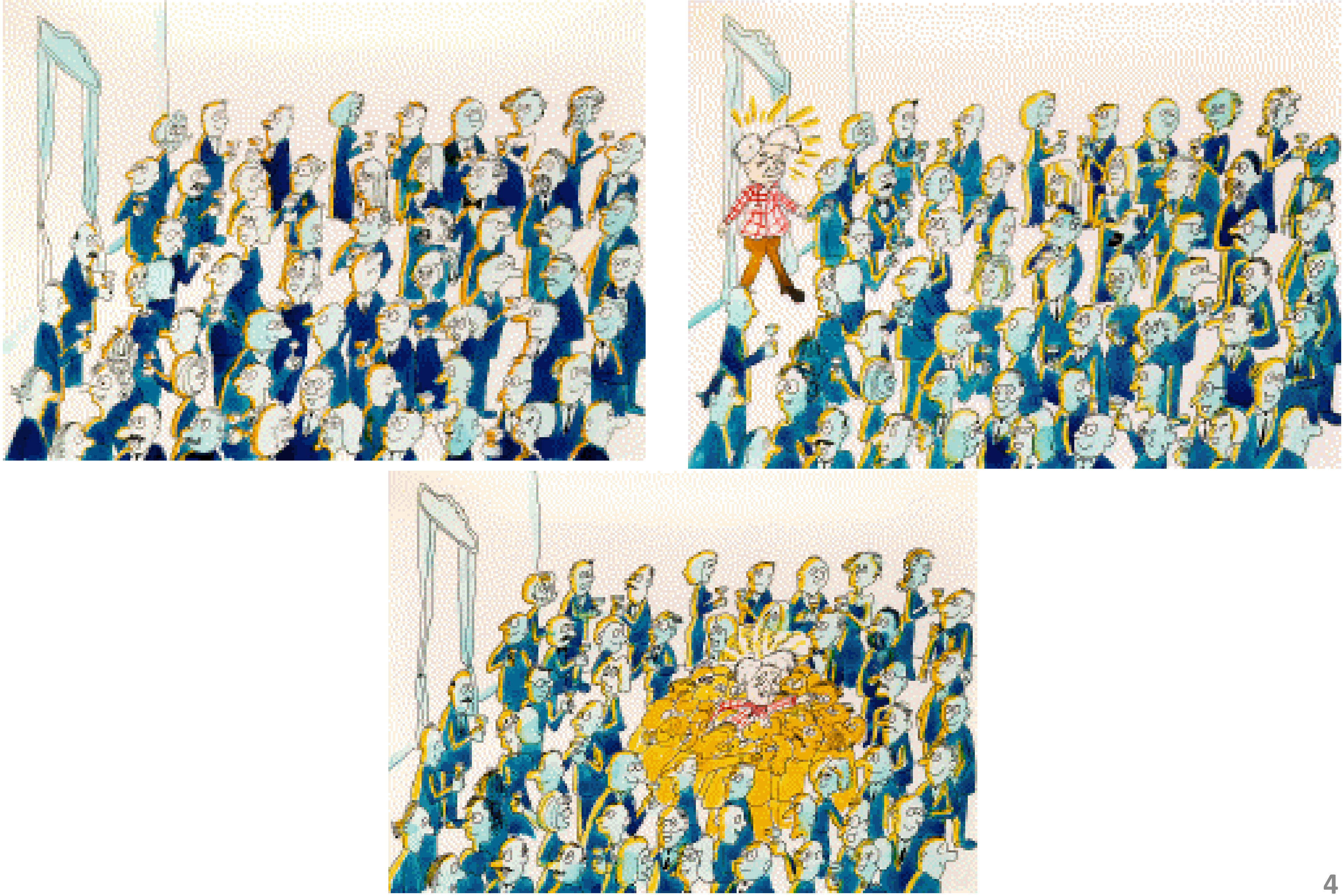
Татьяна Берже-Гринева
(LAPP Annecy, Франция)

Стандартная Модель (СМ)

1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: DESY g gluon
1968: SLAC d down quark	1947: Manchester Univ.. s strange quark	1977: Fermilab b bottom quark	1923: Washington Univ. γ photon
1956: Savannah River Plant ν_e electron neutrino	1982: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W *W* boson
1897: Cavendish Laboratory e electron	1937: Caltech & Harvard μ muon	1976: SLAC τ tau	1983: CERN Z *Z* boson
			2012: CERN H Higgs boson

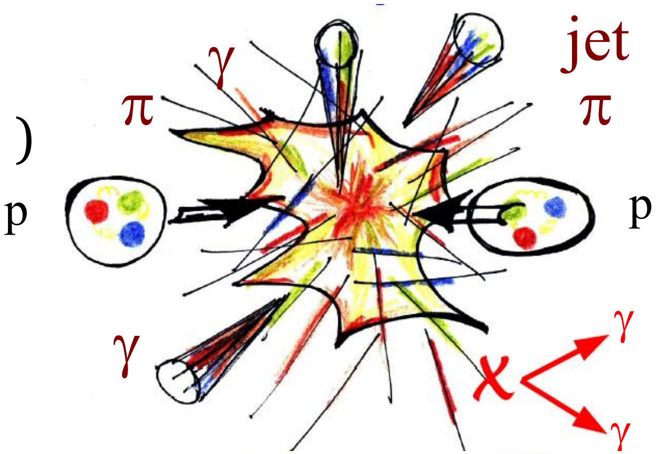
Higgs Physics

«Как частицы получают массу»

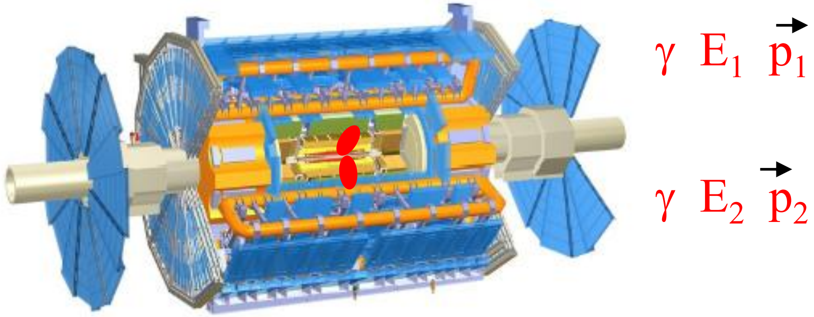


Как найти бозон Хиггса?

- Поизвести в столкновениях (напр. pp)
  ⇒ Среди других известных частиц может быть X



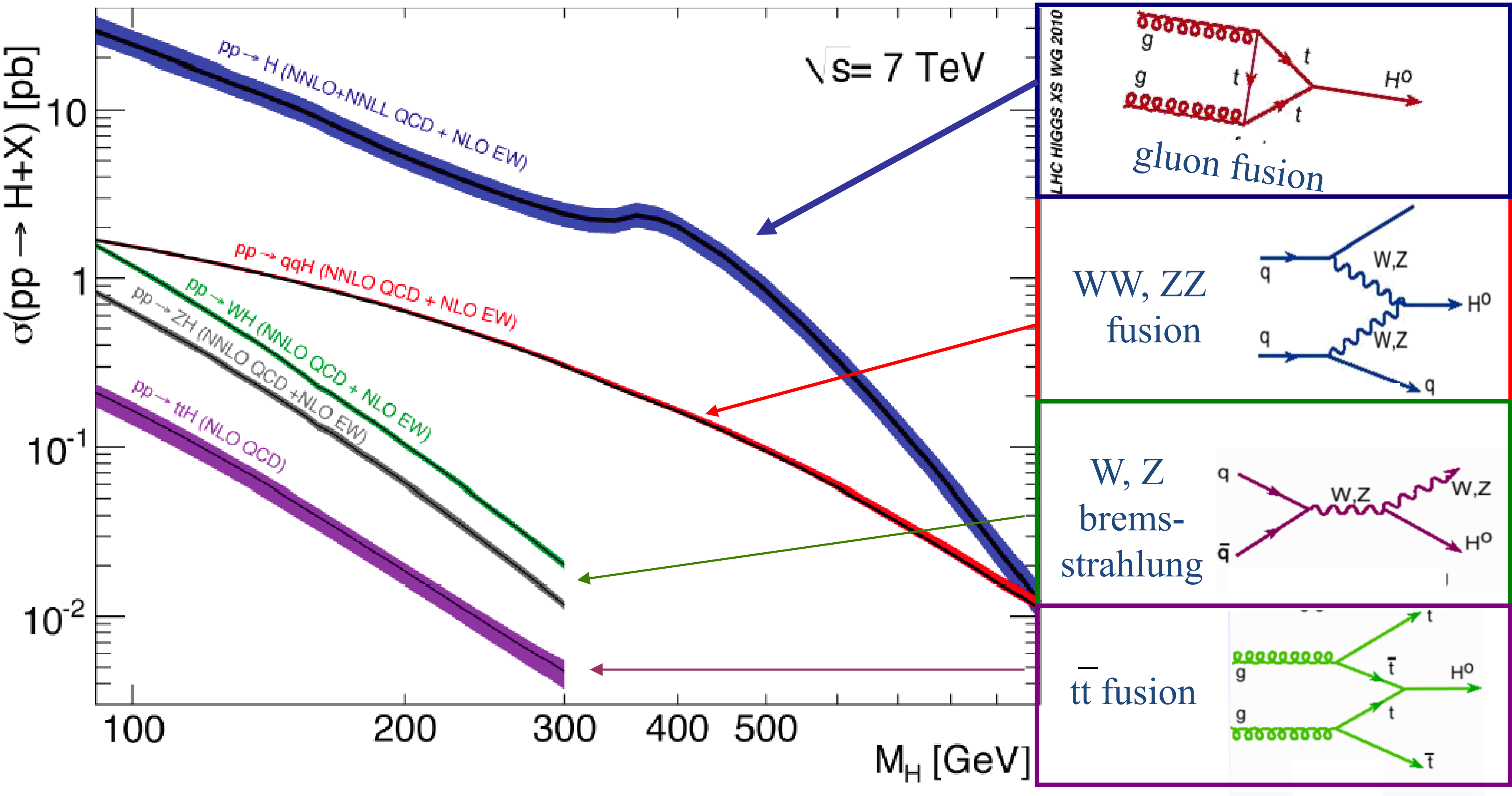
- Идентифицировать и измерить свойства частиц, особенно тех , что получаются при распадах X



- Чаще всего, бозон Хиггса проявится как пик в распределении инвариантной массы ($m_{\gamma\gamma}$).

$$M_{\gamma\gamma}^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

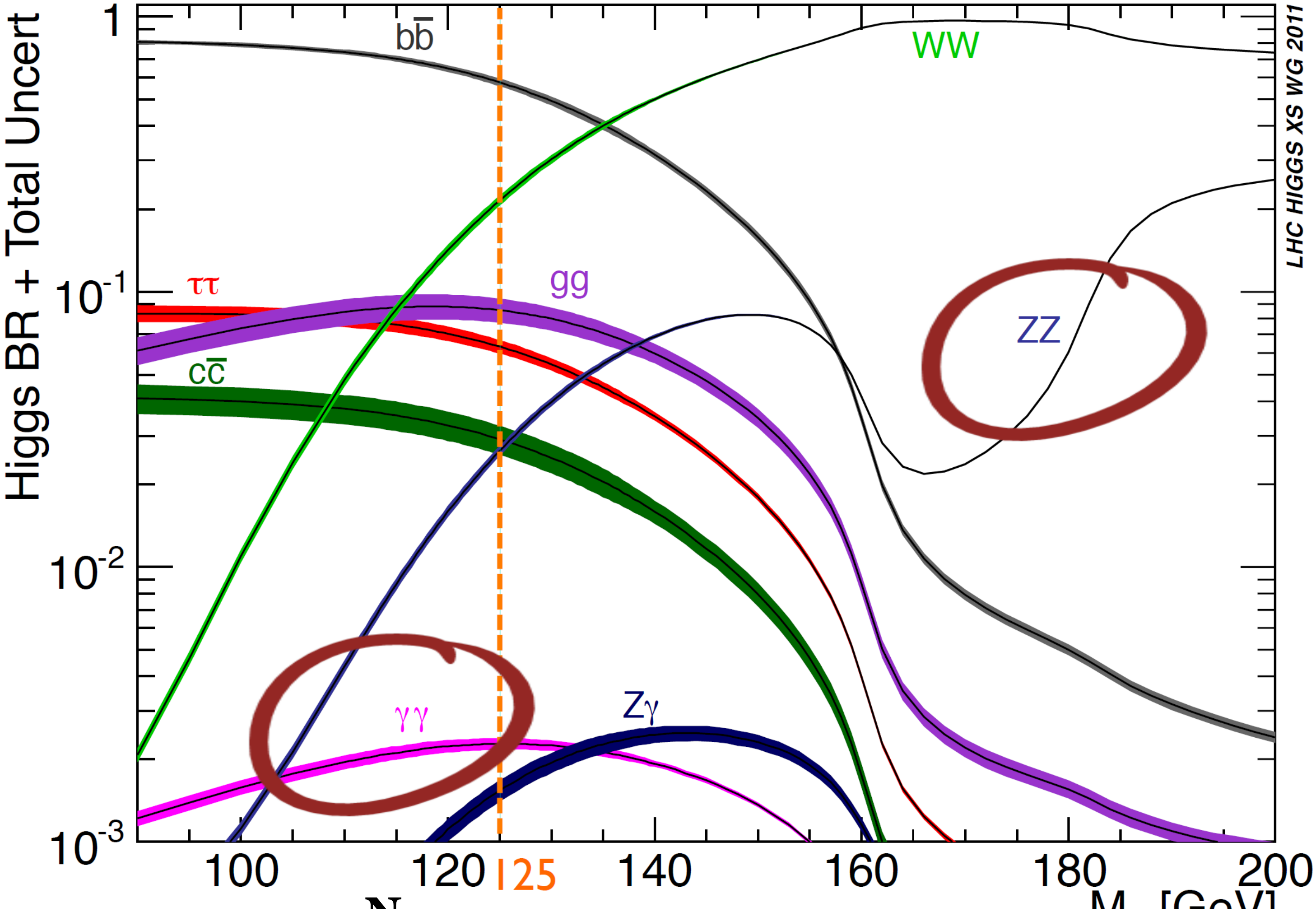
Как производится бозон Хиггса?



Главный канал: глюонный синтез.

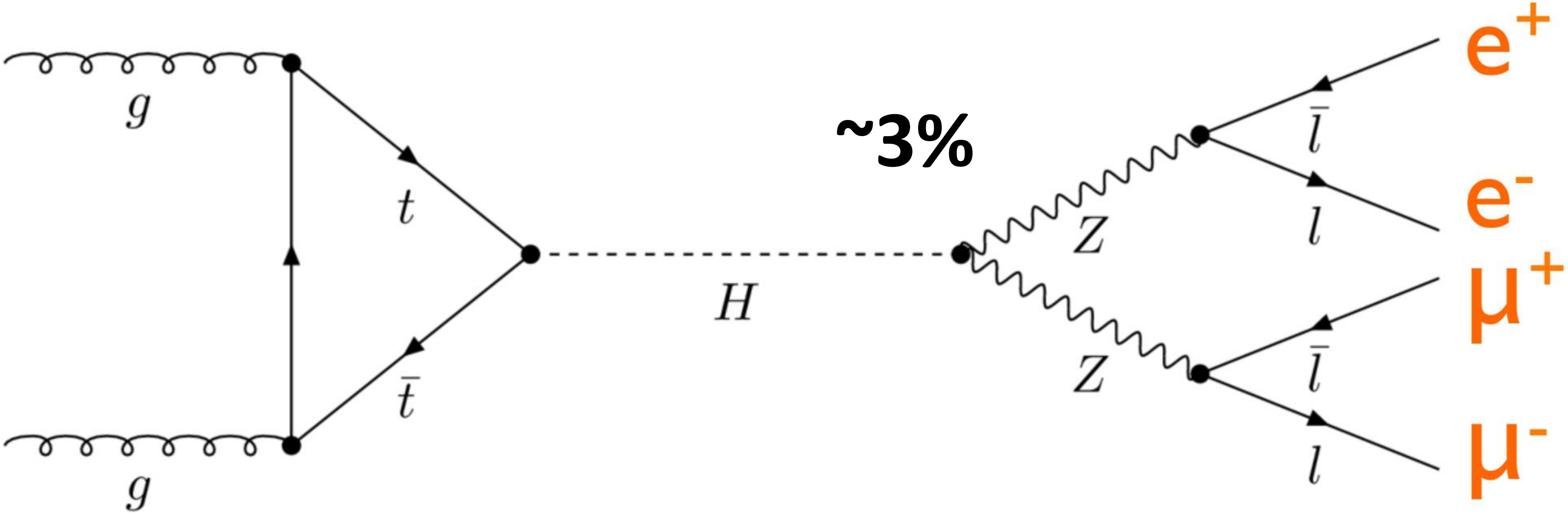
Каналы распада бозона Хиггса в СМ

Branching Ratio (BR) это процент распадов в заданное конечное состояние.

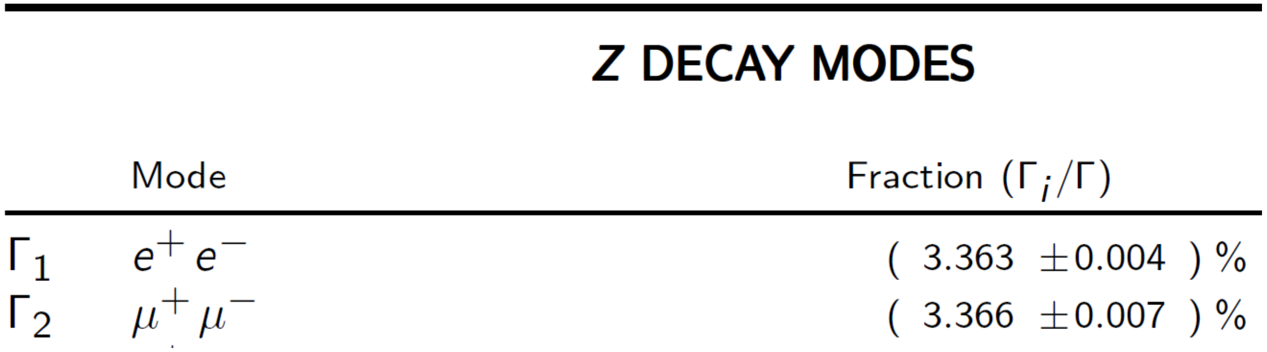


Branching ratio H-> γ γ $= \frac{N_{H\to\gamma\gamma}}{N_{H\to all}}$

H→ZZ→4l

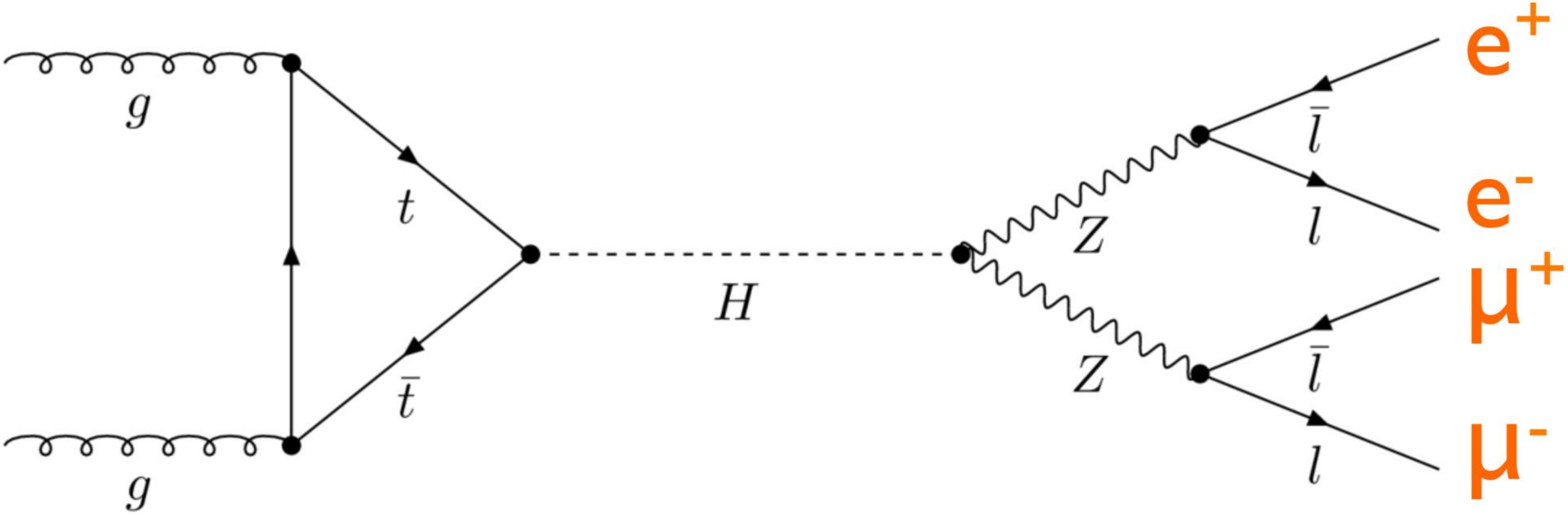


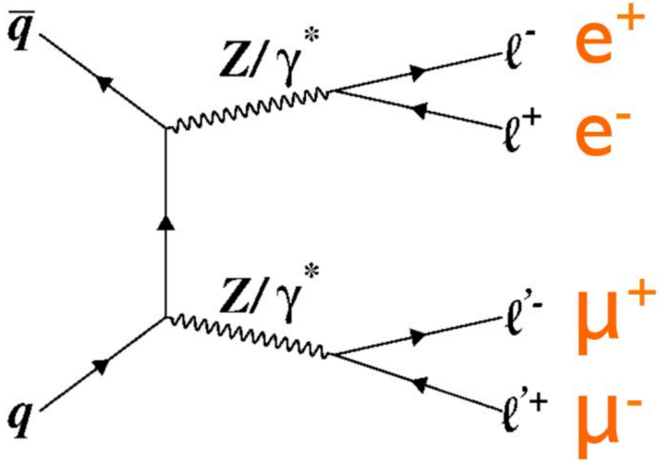
~3%

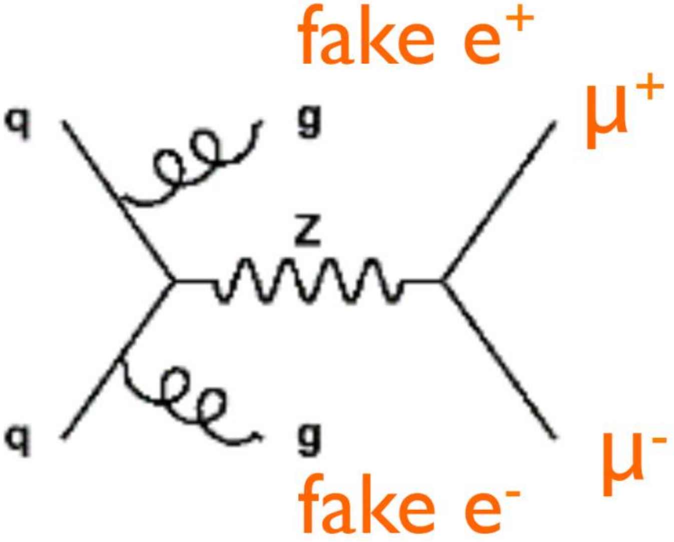


Z DECAY MODES

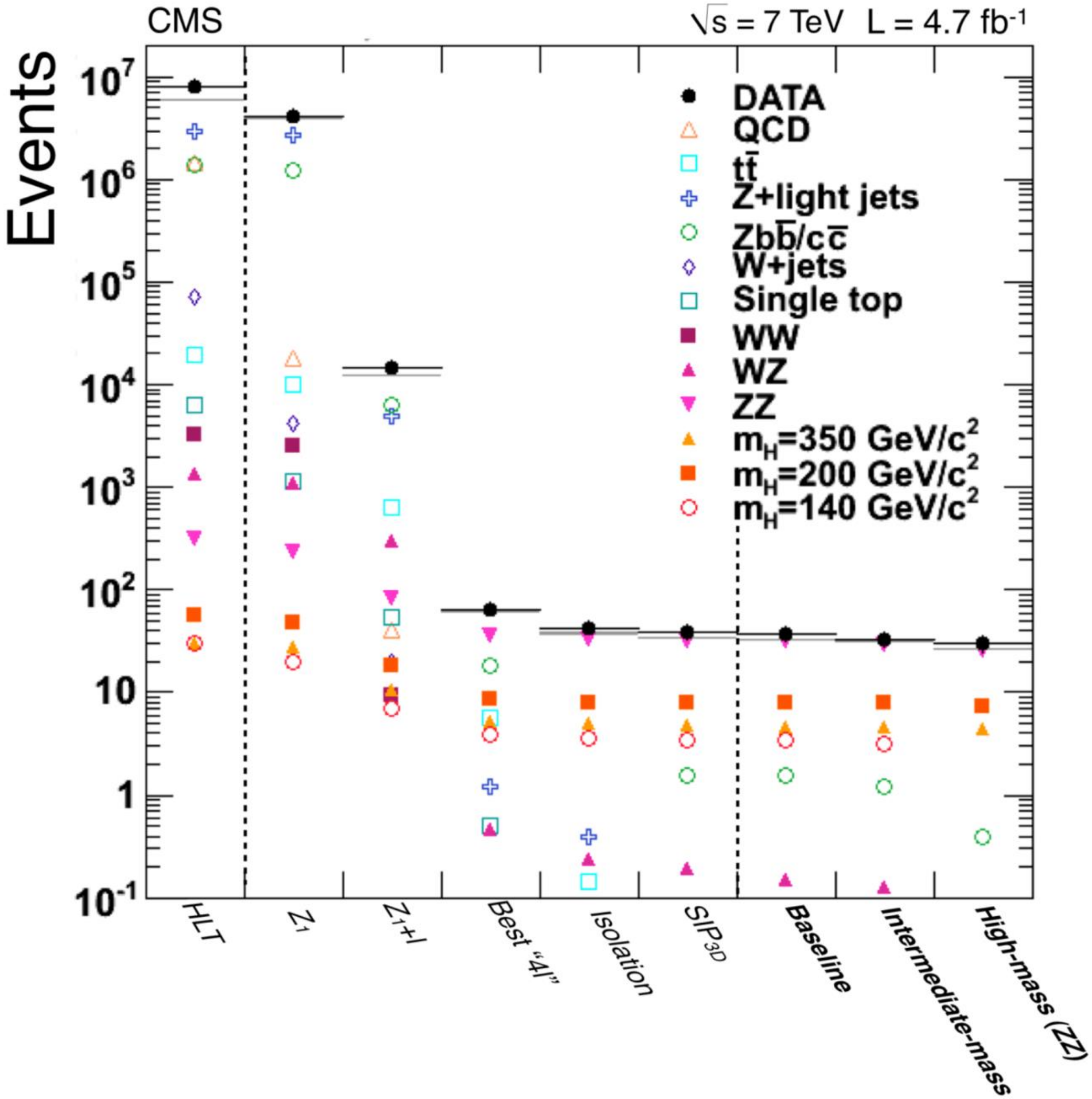
	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	(3.363 ±0.004) %
Γ_2	$\mu^+\mu^-$	(3.366 ±0.007) %

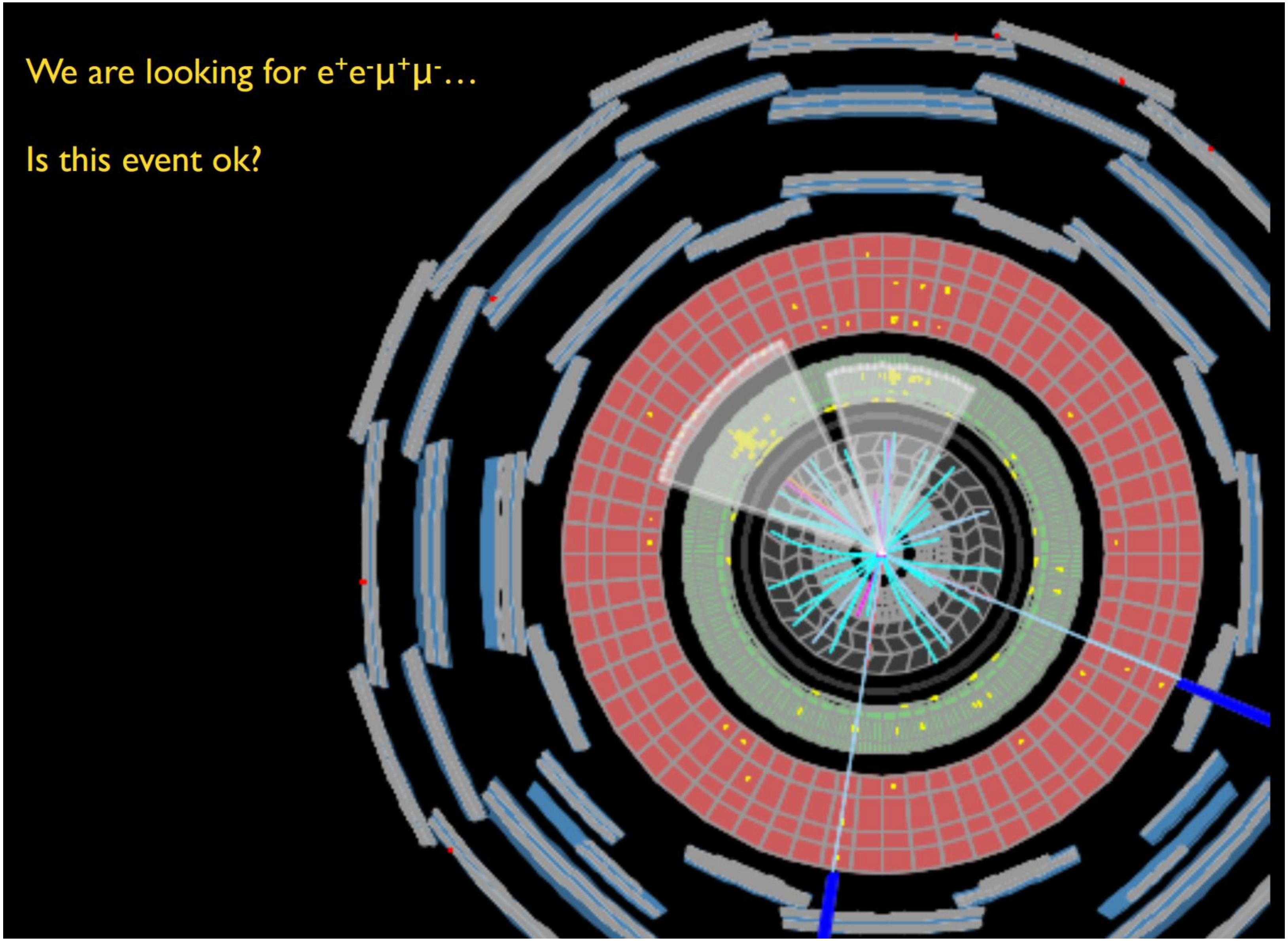

g
g
t
$\bar{t}$
H
Z
Z
$\bar{l}$
l
$\bar{l}$
l
e+
e-
μ+
μ-


$\bar{q}$
q
Z/γ*
Z/γ*
ℓ-
ℓ+
ℓ'-
ℓ'+
e+
e-
μ+
μ-


fake e+
q
g
Z
q
g
fake e-
μ+
μ-

Выбор событий



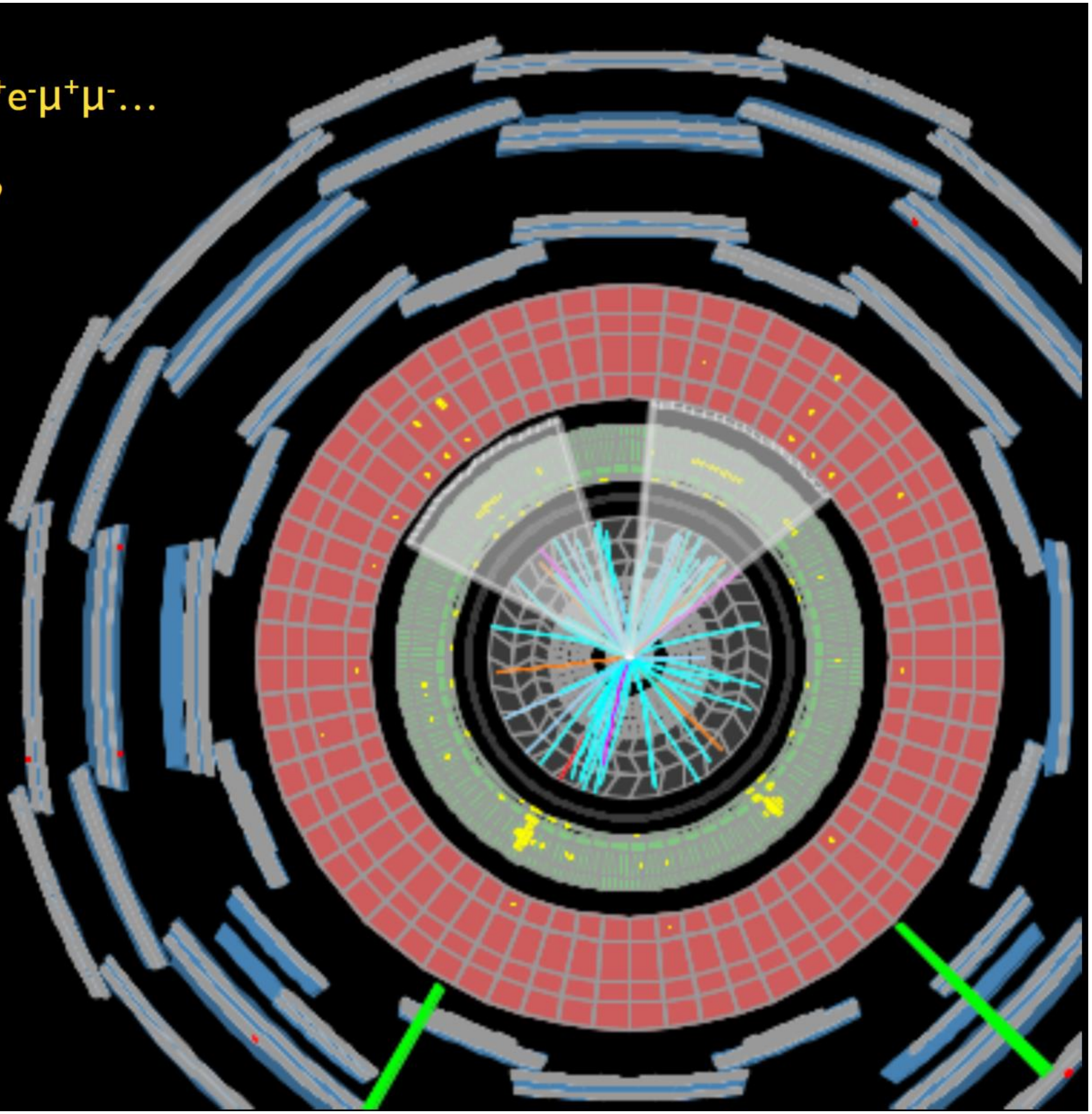


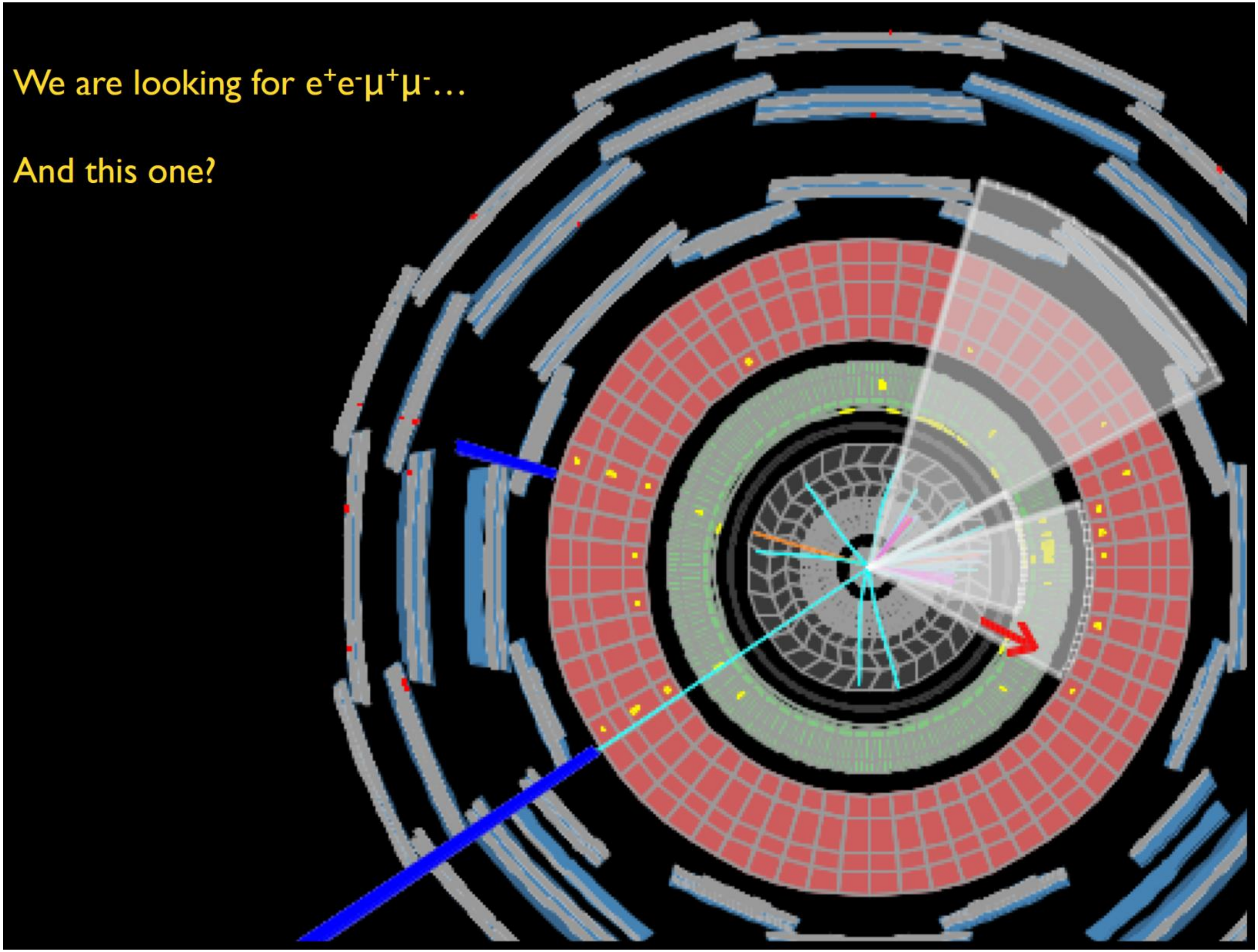
We are looking for $e^+e^-\mu^+\mu^-$…

Is this event ok?

We are looking for $e^+e^-\mu^+\mu^-$…

What about this one?



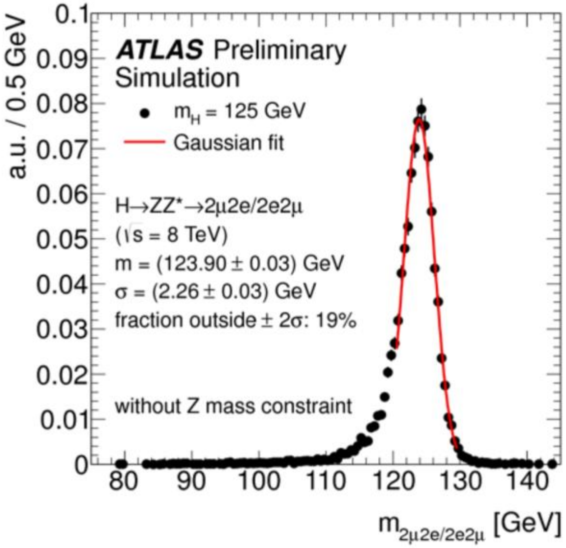


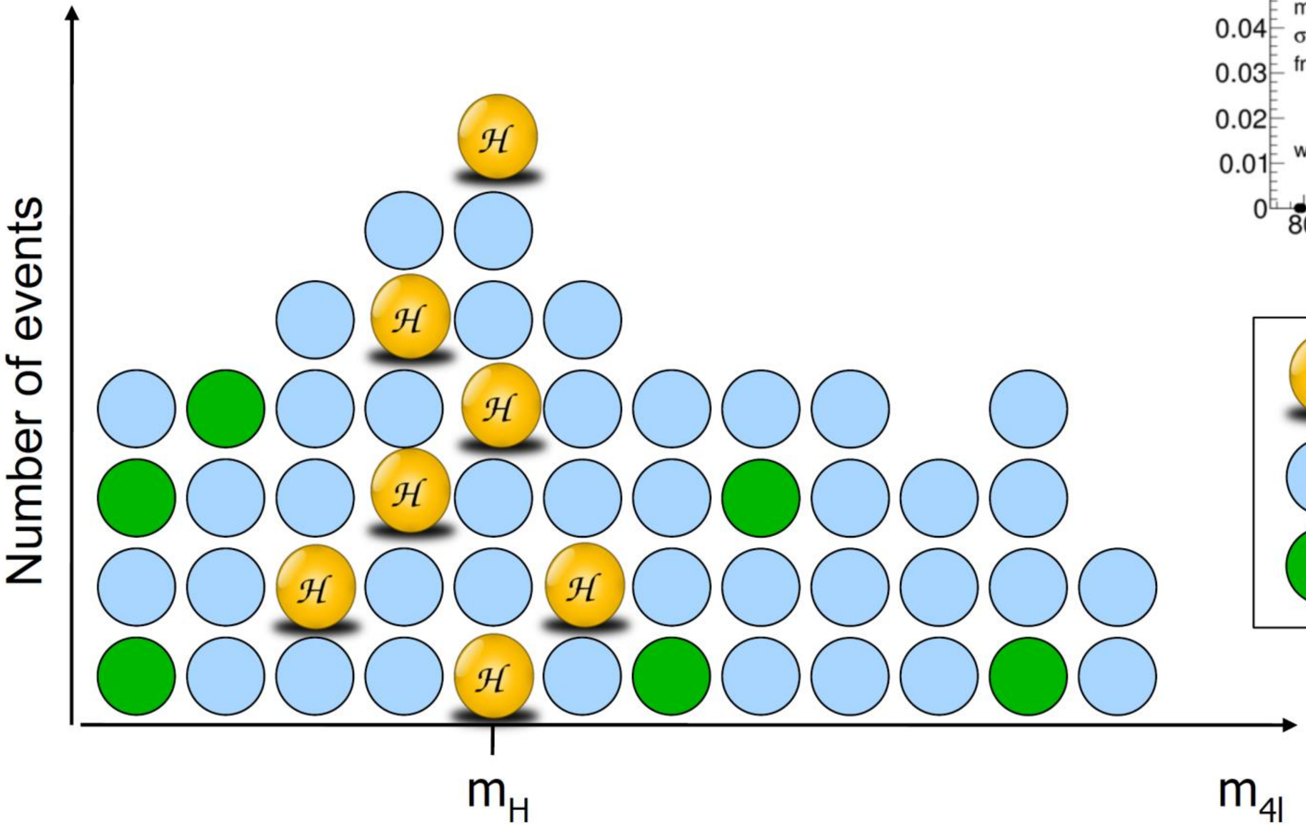
We are looking for $e^+e^-\mu^+\mu^-$…

And this one?

Извлечение сигнала из фона

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$





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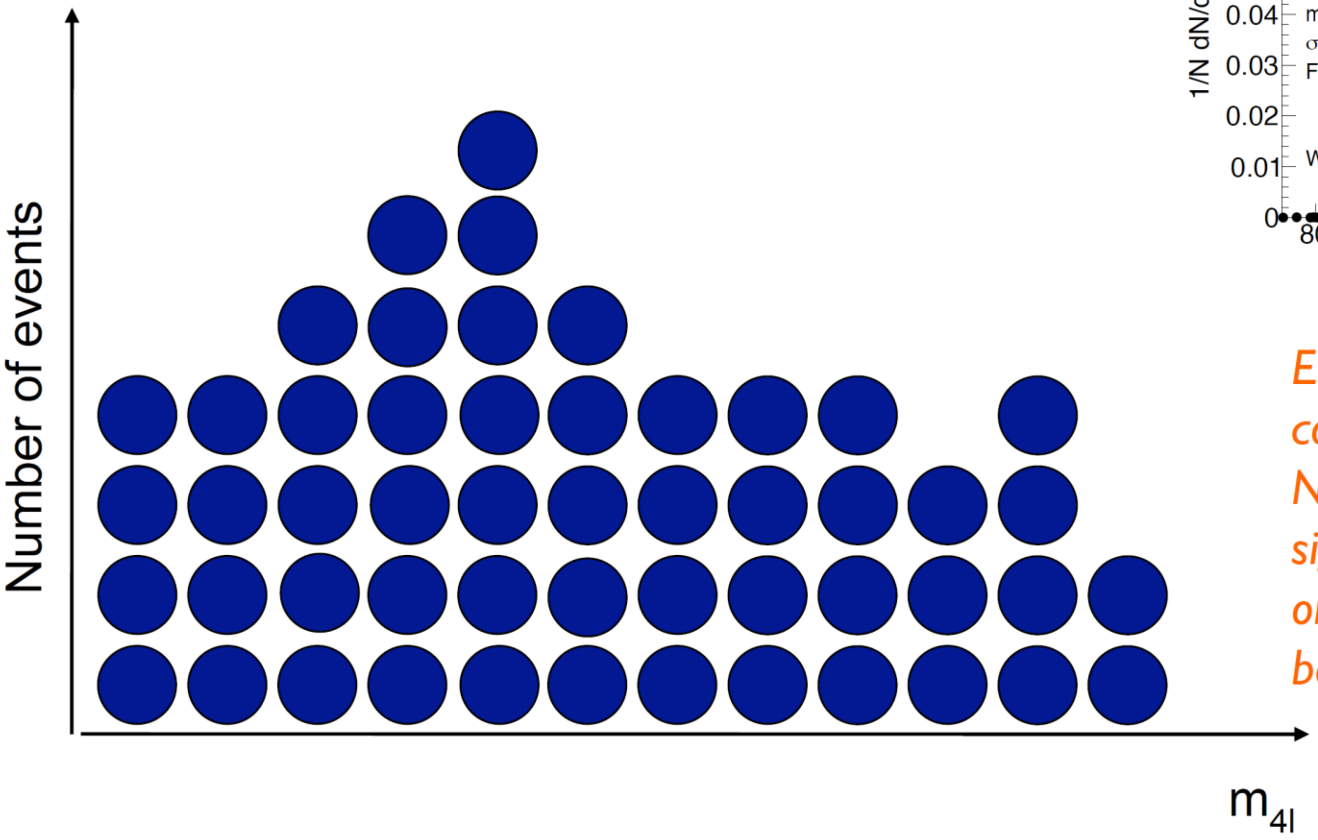
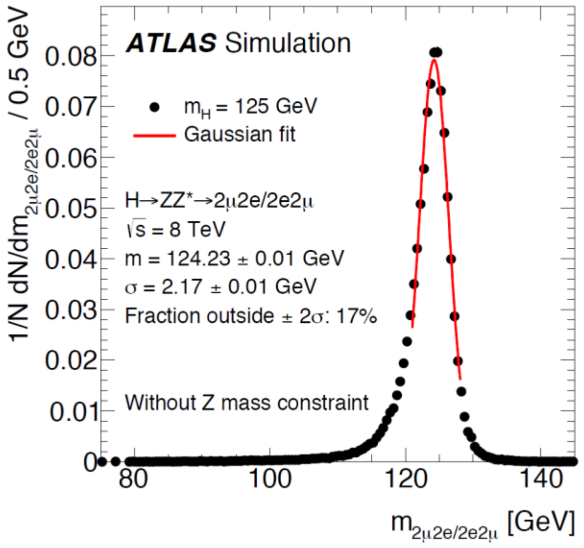
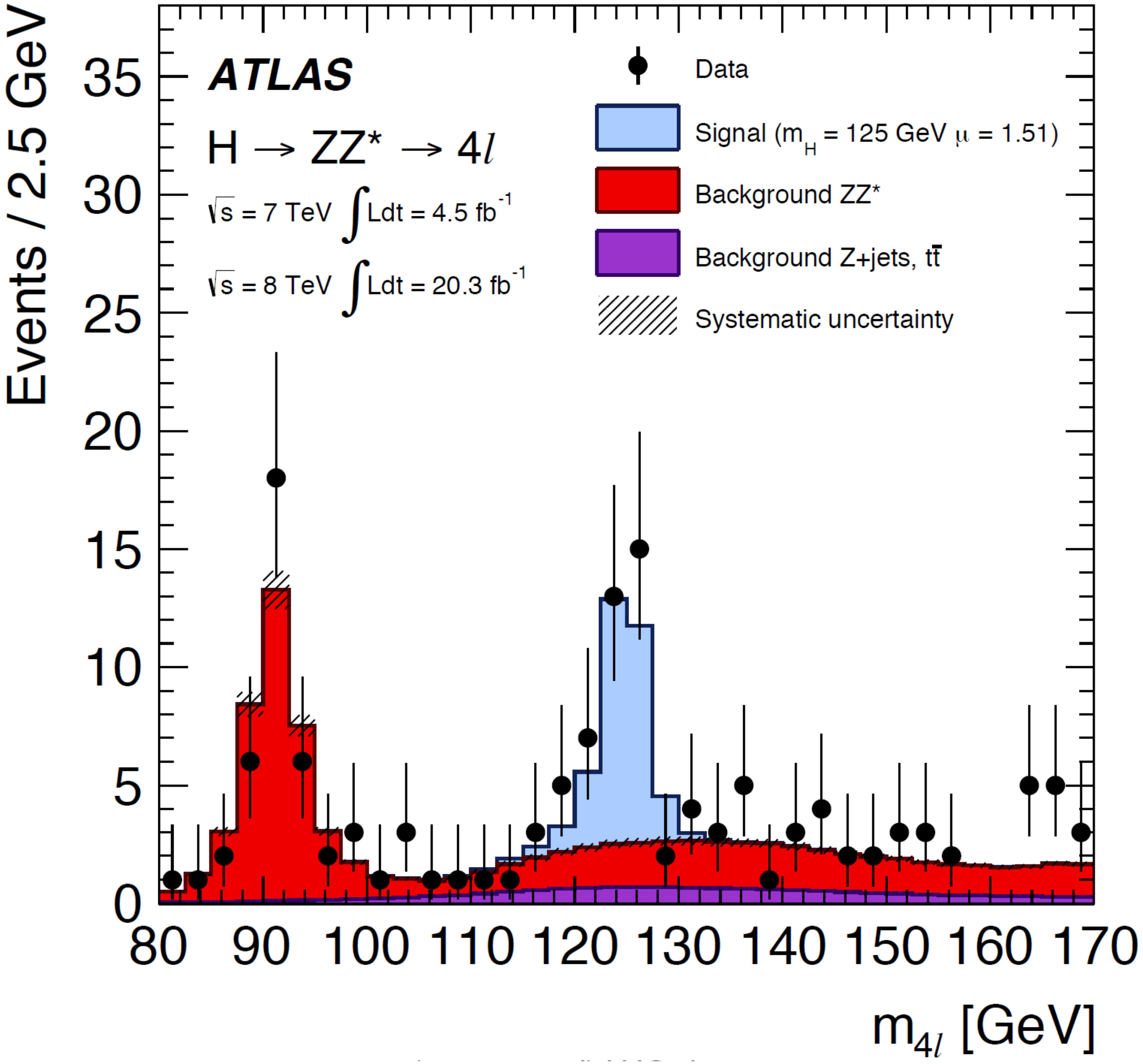
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$





Events in real life do not come with a label! No way to distinguish signal from background on an event-by-event base…

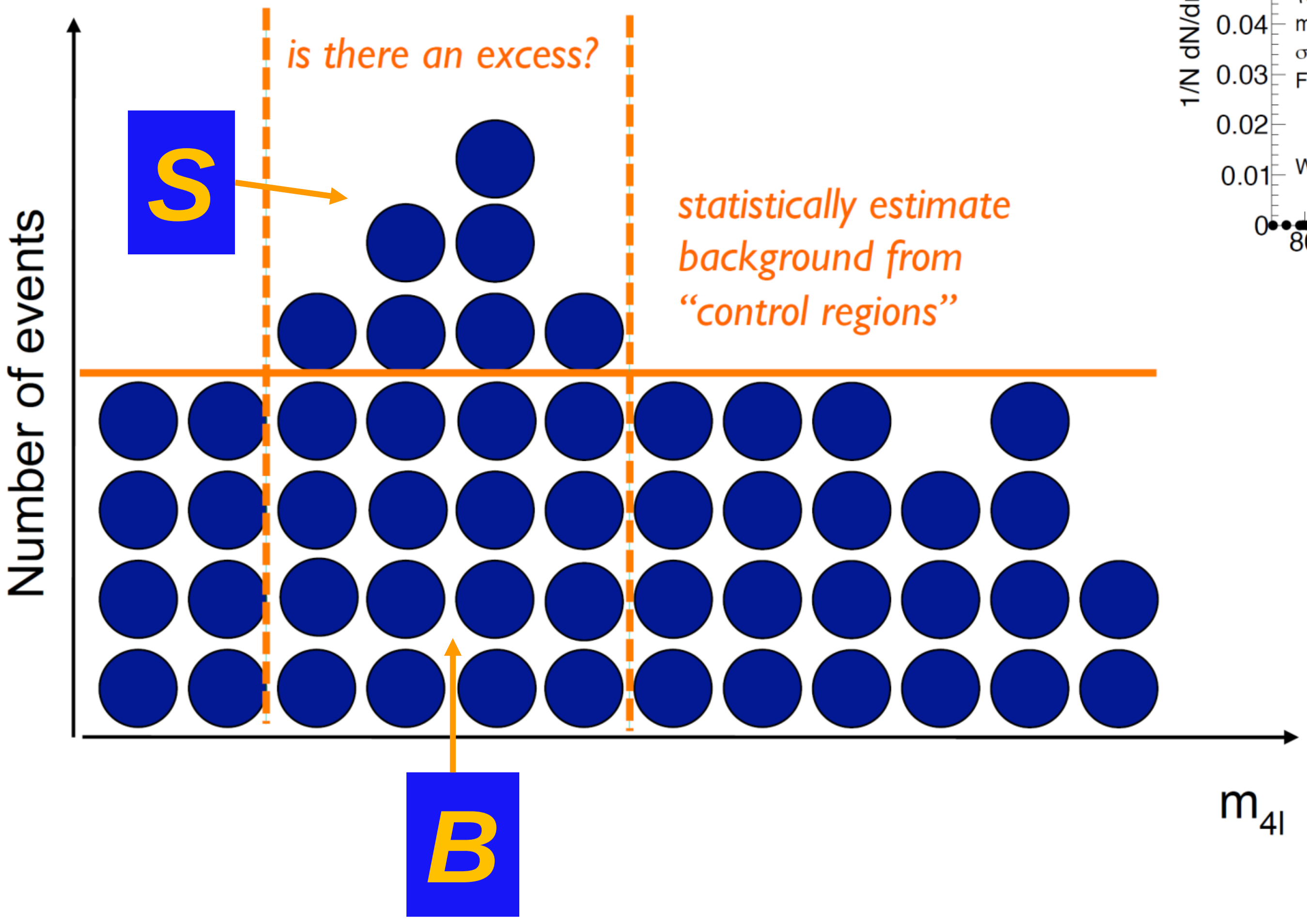
Измерение фона



- моделирование методом Монте-Карло
- измерение с помощью боковых полос

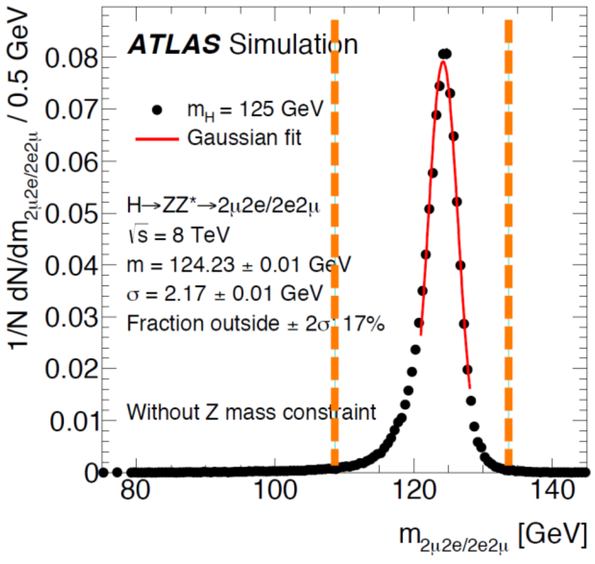
Извлечение сигнала из фона

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



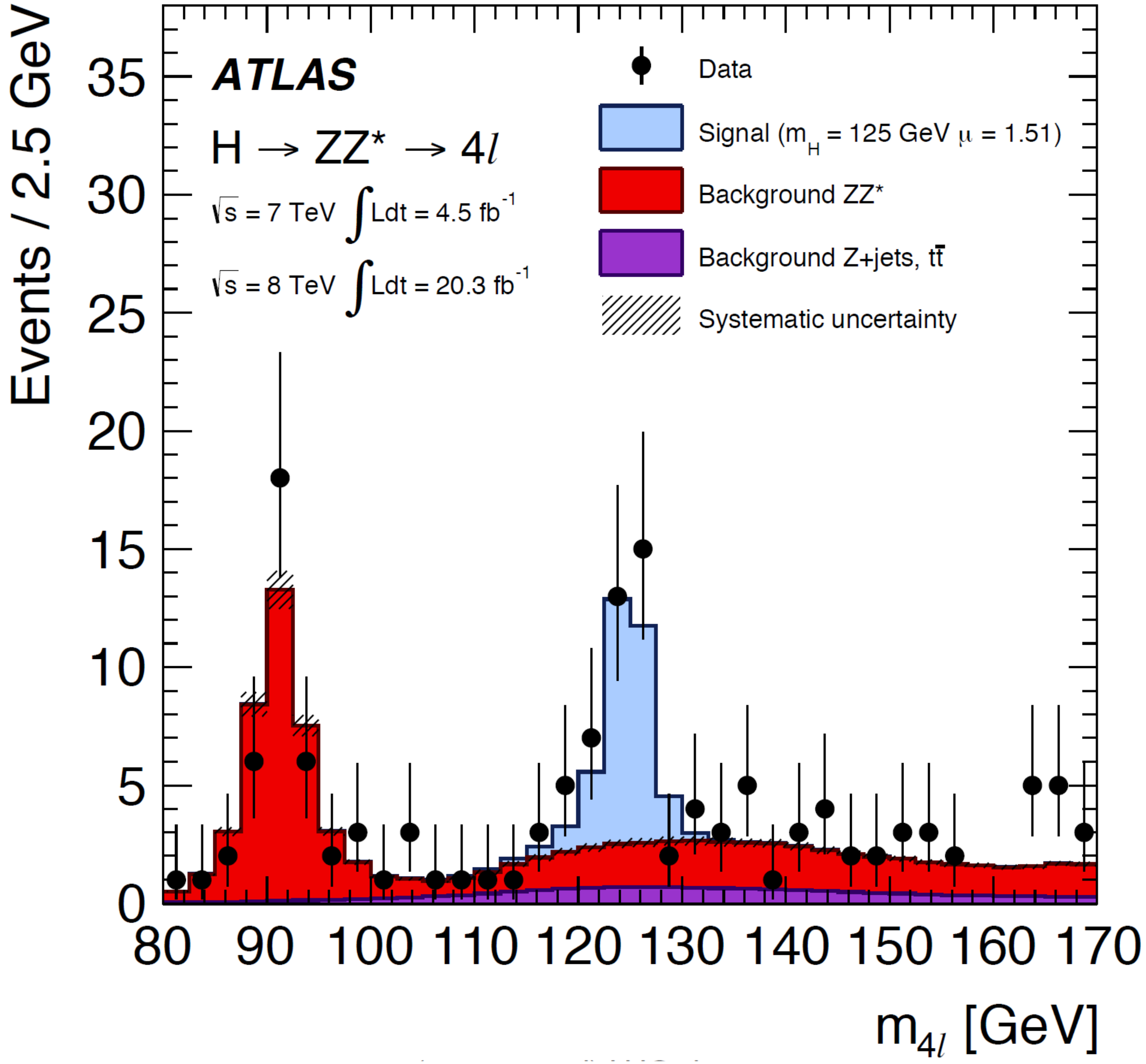
is there an excess?

statistically estimate background from "control regions"



$$Z \sim \frac{S}{\sqrt{B}}$$

Значительно ли превышение?



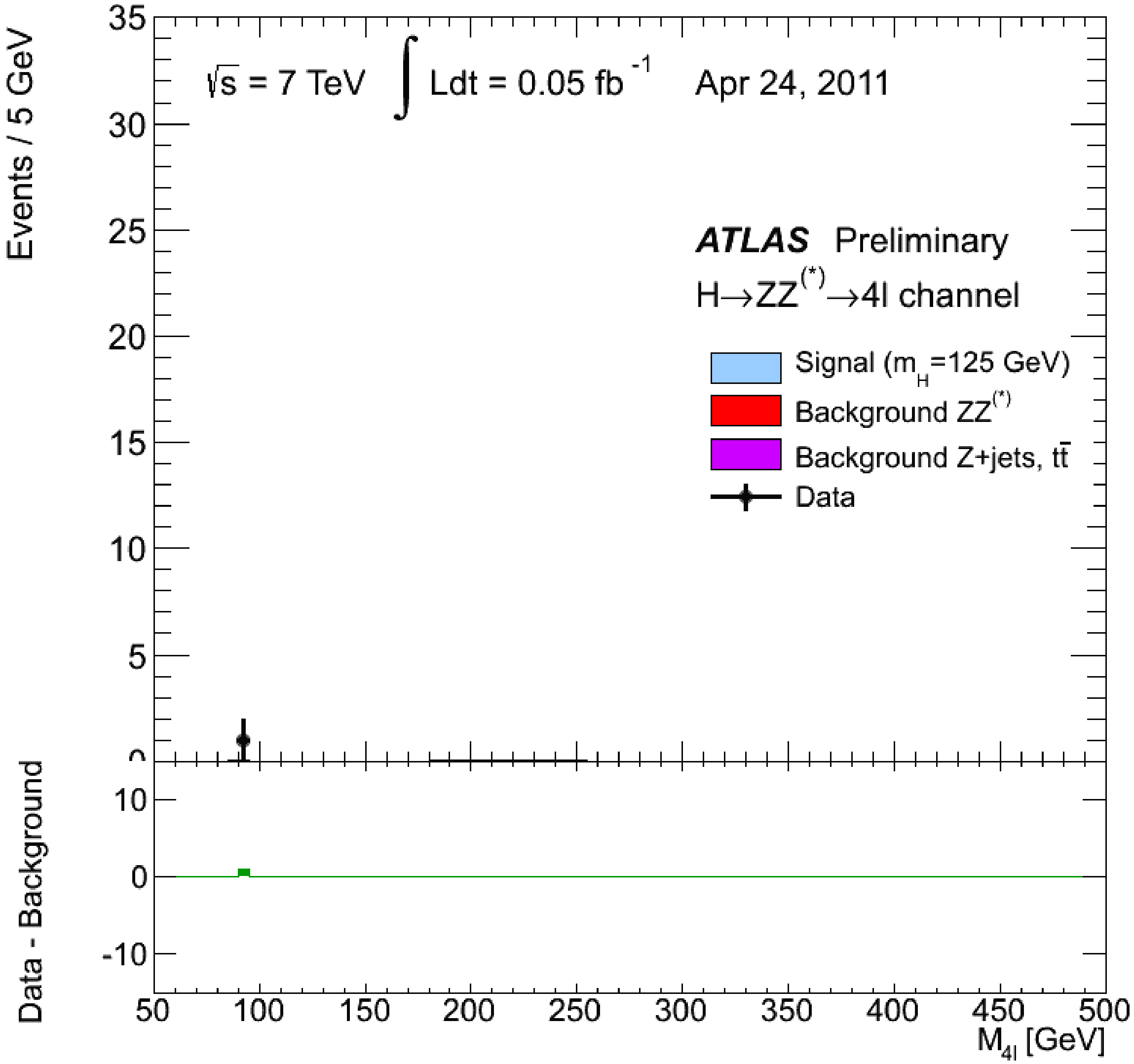
$$Z \sim \frac{S}{\sqrt{B}}$$

$3\,\sigma$ is an evidence

$5\,\sigma$ is a discovery

Пять стандартных отклонений
- 5σ -
(1-in-3.5 миллионов шанс произойти случайно) требуется для утверждения об открытии новой частицы.

Увеличение значимости со временем

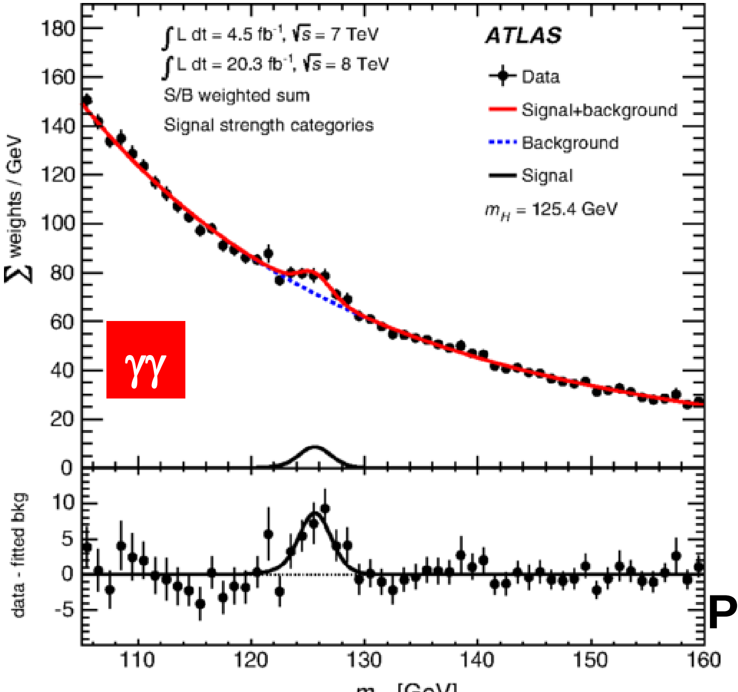


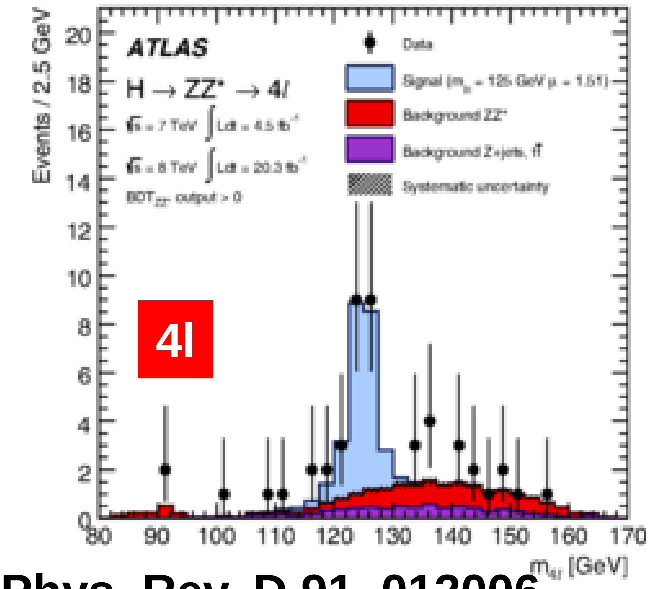
Higgs Boson Decays (m_H=125GeV)

Mode	Sensitivity	Mass res.	S/B (incl)	rate	comments
$ZZ^* \to 4l$	🟩	🟩	🟩	🟥	very pure; m_H; SpinCP
$\gamma\gamma$	🟩	🟩	🟨	🟩	m_H; via loop
$WW \to l\nu l\nu$	🟩	🟥	🟨	🟩	high rate
$\tau\tau$	🟨	🟥	🟥	🟩	mainly VBF (sensitivity)
bb	🟨	🟥	🟥	🟩	mainly VH (trigger,QCD)
$ZZ^* \to llqq/ll\nu\nu$	🟨	🟨	🟨	🟨	high-mass (mainly)
$WW \to l\nu qq$	🟨	🟨	🟨	🟩	high-mass (mainly)
$\mu\mu$	🟥	🟩	🟥	🟥	rare
$Z\gamma$	🟥	🟩	🟥	🟥	

Mode	BR
bb	57.7%
WW	21.5%
gg	8.6%
$\tau\tau$	6.3%
cc	2.9%
ZZ	2.6%
$\gamma\gamma$	0.23%
$Z\gamma$	0.15%
$\mu\mu$	0.022%

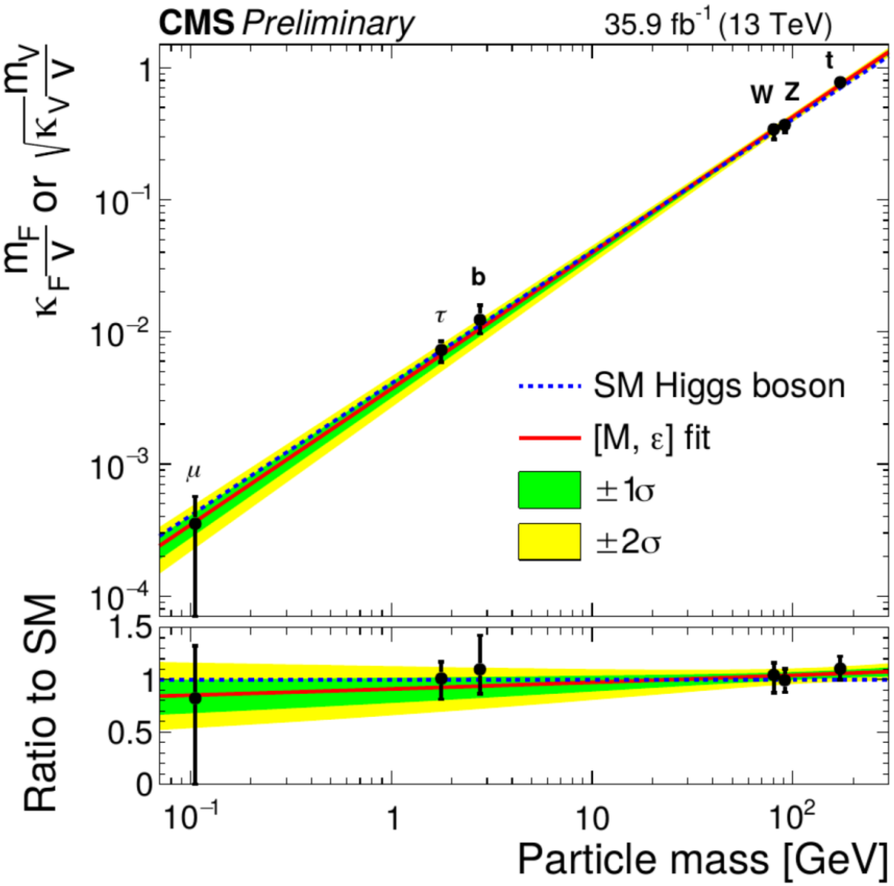
Phys. Rev. D 90, 112015



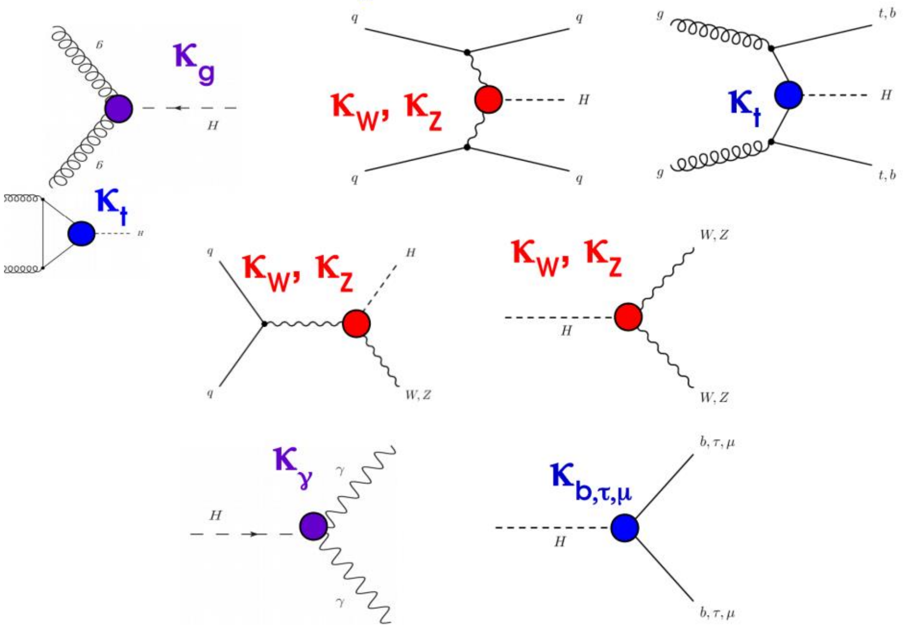


Phys. Rev. D 91, 012006

Распады бозона Хиггса



Coupling modifiers κ_x for **all Hxx vertices**

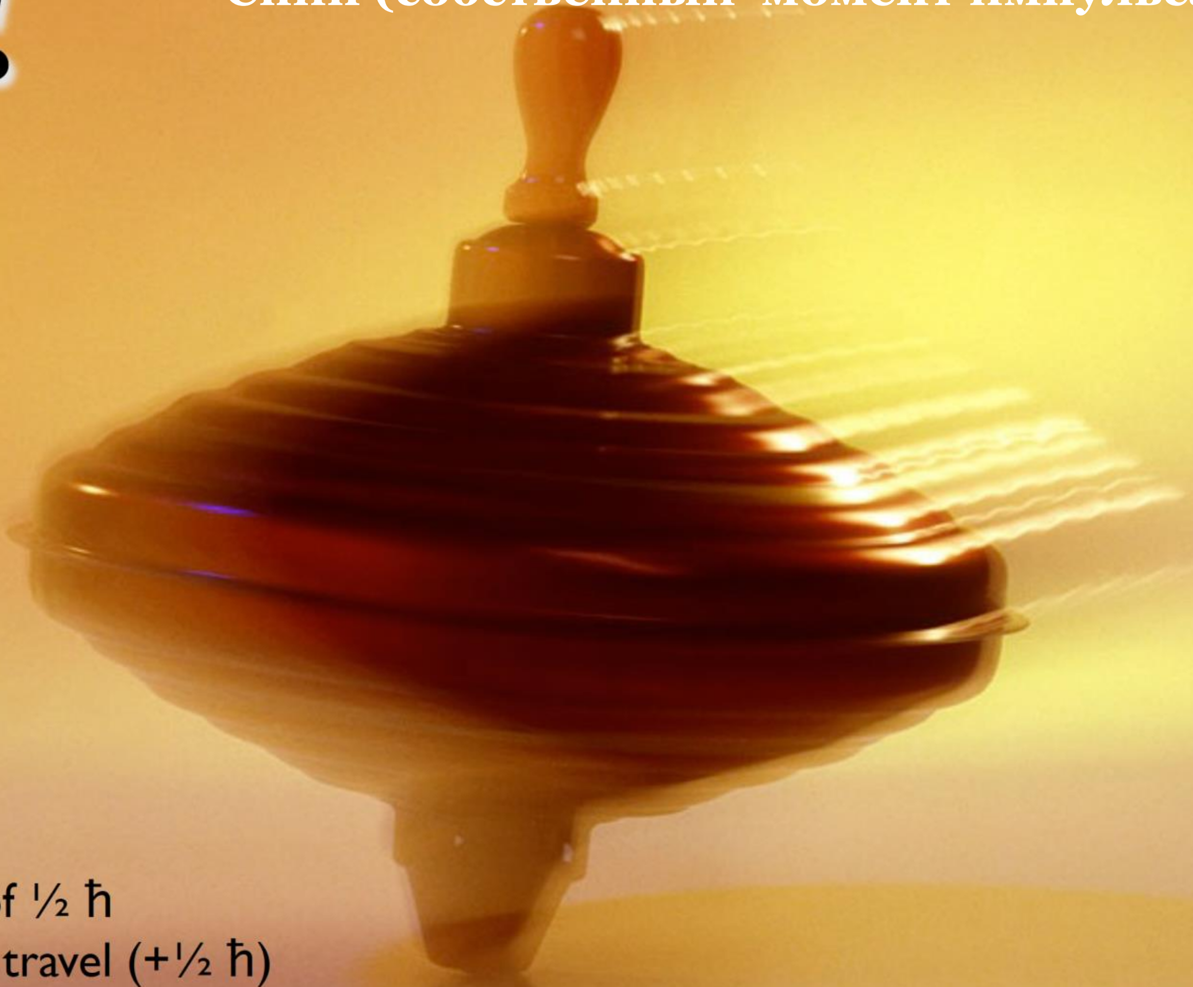


"LO-inspired" scaling for **i→H→f**

$$\sigma(i \to H)\cdot B(H \to f) \;=\; \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}\left[\sigma_{SM}(i \to H)\cdot B_{SM}(H \to f)\right]$$

Spin!

Спин (собственный момент импульса)



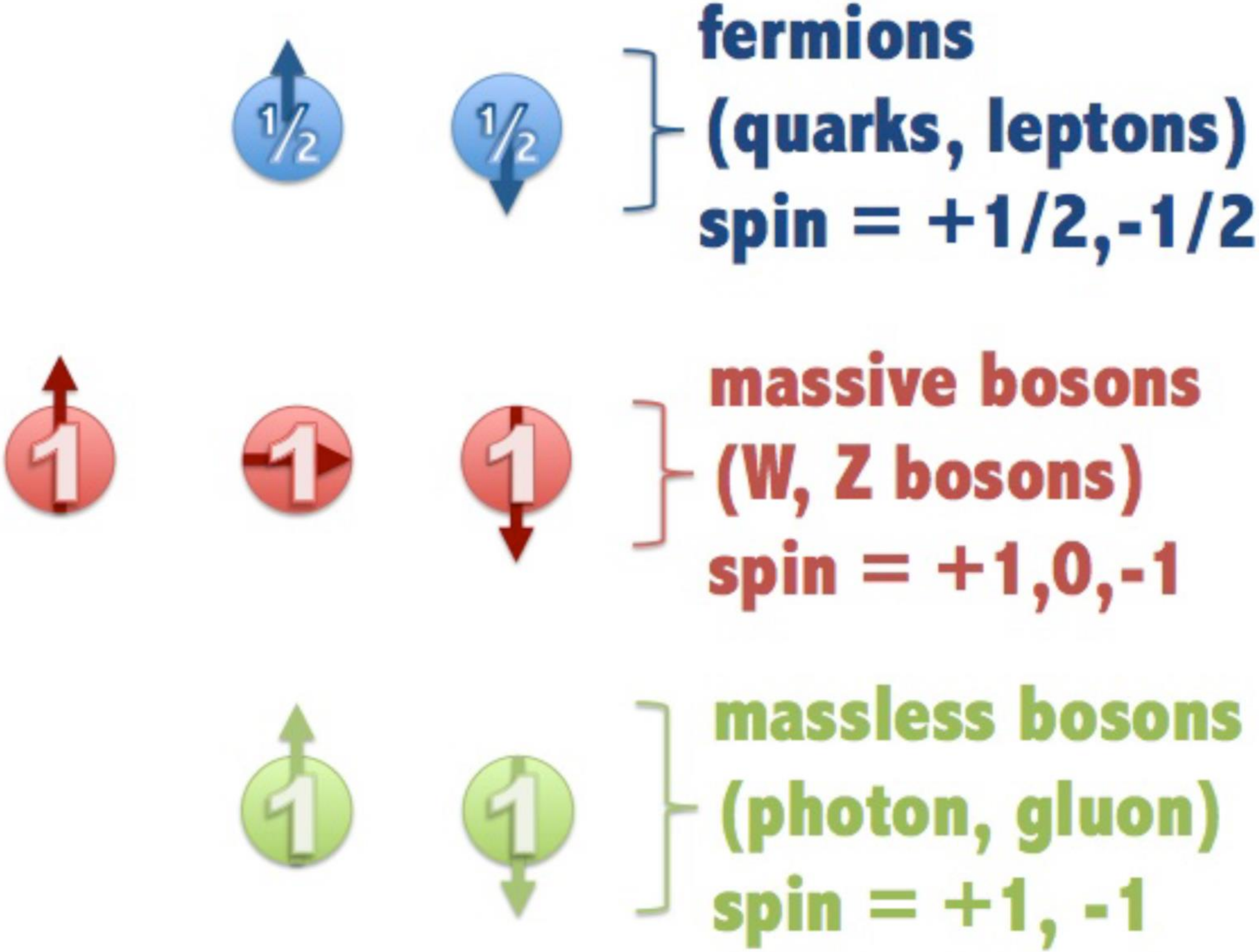
What’s a particle spin?

“An *amount of rotation* that is somehow quantized”

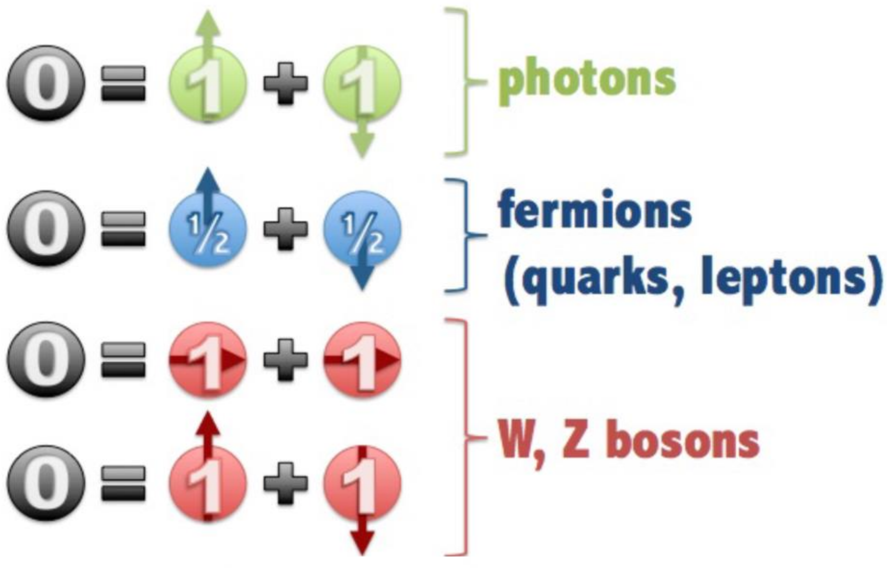
An electron has always an angular momentum of ½ ħ either in its direction of travel (+½ ħ) or opposite to it (-½ ħ)

$\hbar = 1.0545 \times 10^{-34}\ m^2\ kg / s$

Спин частиц СМ



Спин и распад частицы

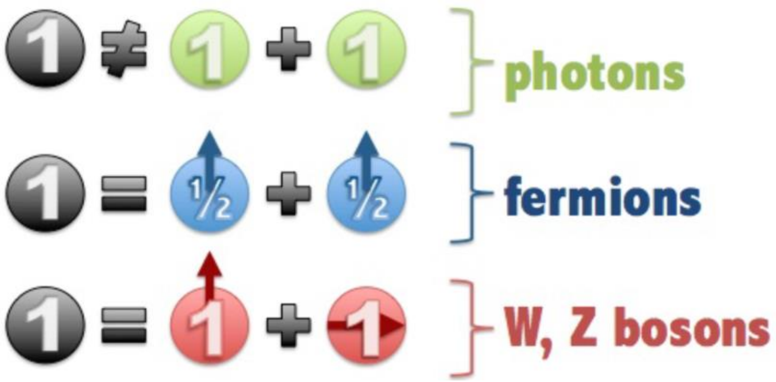


$0 = 1 + 1$ photons

$0 = \frac{1}{2} + \frac{1}{2}$ fermions (quarks, leptons)

$0 = 1 + 1$

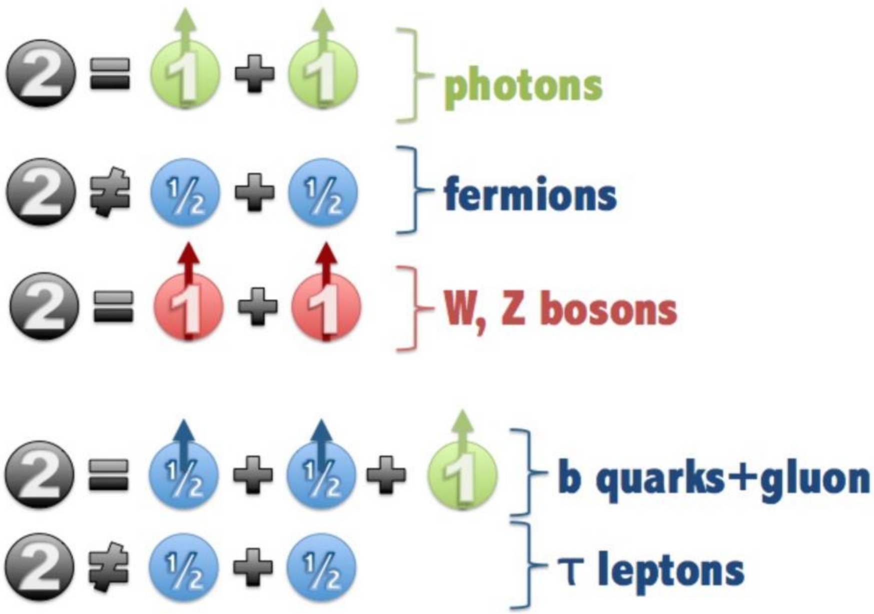
$0 = 1 + 1$ W, Z bosons



$1 \neq 1 + 1$ photons

$1 = \frac{1}{2} + \frac{1}{2}$ fermions

$1 = 1 + 1$ W, Z bosons



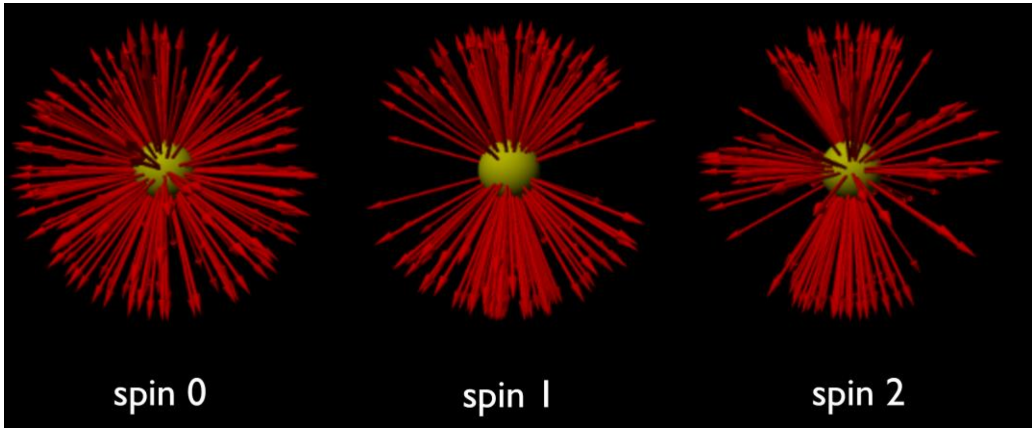
$2 = 1 + 1$ photons

$2 \neq \frac{1}{2} + \frac{1}{2}$ fermions

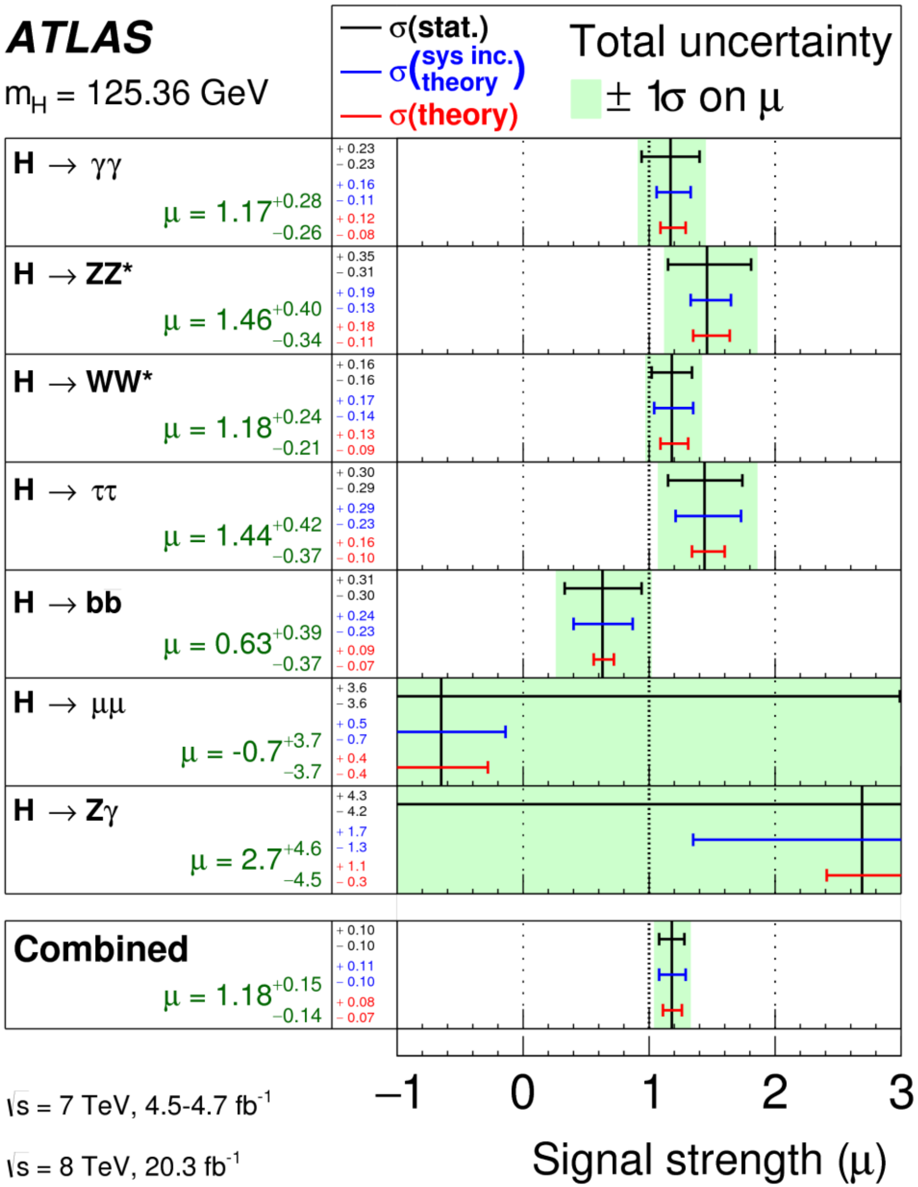
$2 = 1 + 1$ W, Z bosons

$2 = \frac{1}{2} + \frac{1}{2} + 1$ b quarks+gluon

$2 \neq \frac{1}{2} + \frac{1}{2}$ τ leptons

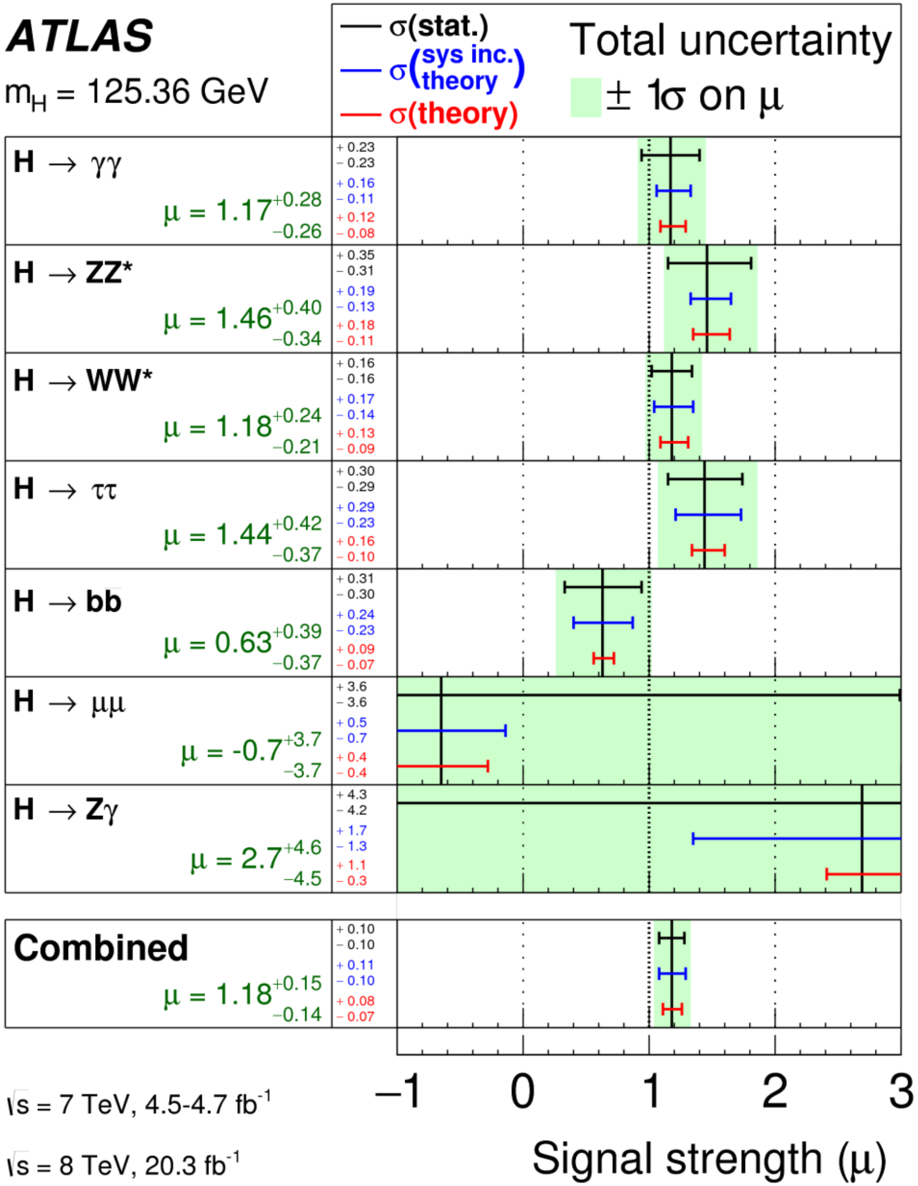


Распады бозона Хиггса



Spin	γγ	ZZ	ττ
0	☺	☺	☺
1	☹	☺	☺
2	☺	☺	☹

Распады бозона Хиггса



Spin	γγ	ZZ	ττ
0	☺	☺	☺
1	☹	☺	☺
2	☺	☺	☹

Хиггс частица со спин=0,
как предсказано СМ

Физика вне Стандартной Модели ?

С открытием бозона Хиггса мы нашли все частицы СМ, но на много вопросов нет ответа:

- Почему Хиггс легок?
- Что такое темная материя?
- Почему существует 3 поколения?

  …

Как найти ответ на наши вопросы?

1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: DESY g gluon
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1956: Savannah River Plant ν_e electron neutrino	1982: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W *W* boson
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			2012: CERN H Higgs boson

Физика вне Стандартной Модели ?

С открытием бозона Хиггса мы нашли все частицы СМ (кроме аксиона), но на много вопросов нет ответа:

- Почему Хиггс легок?
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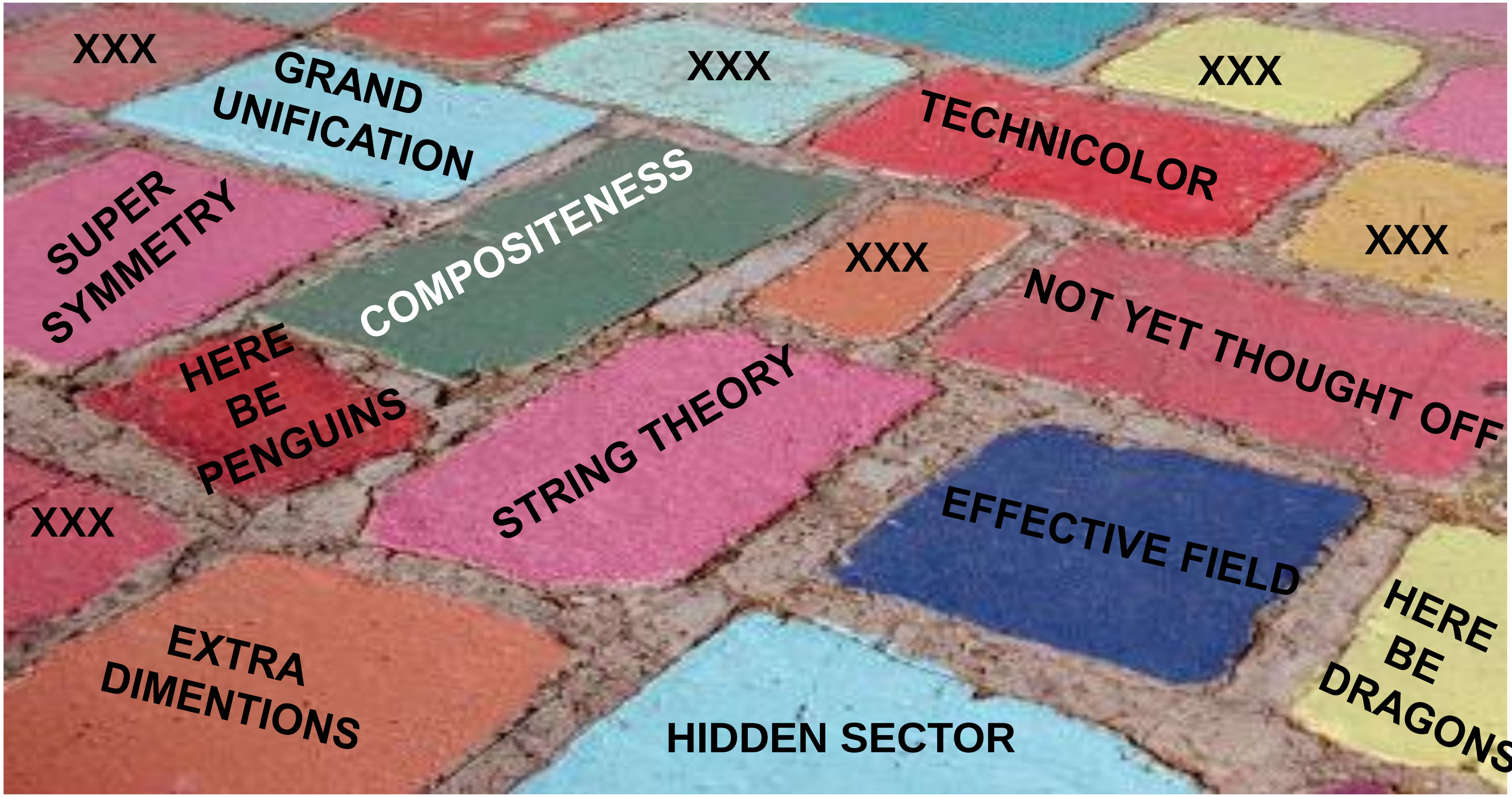
  …

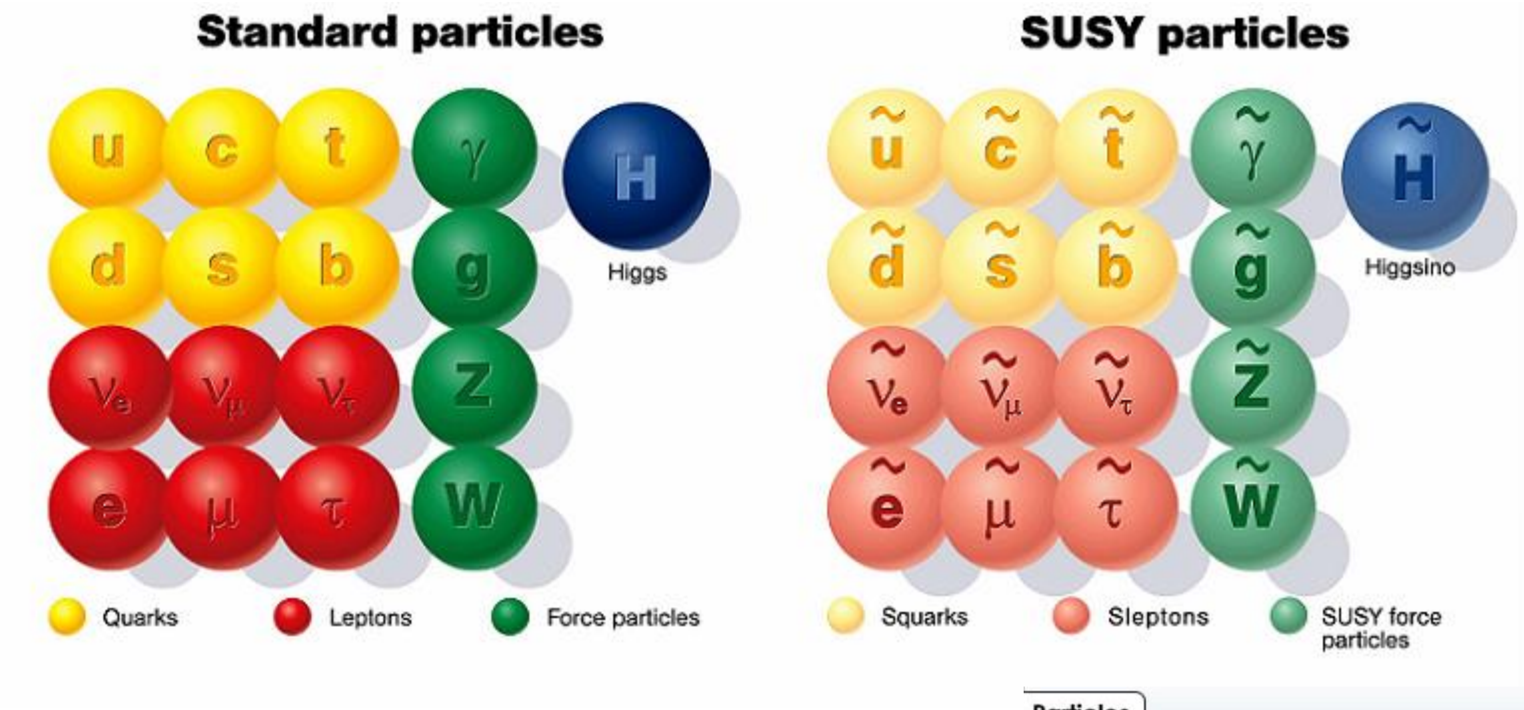
Как найти ответ на наши вопросы?

Мир вне СМ глазами теоретиков

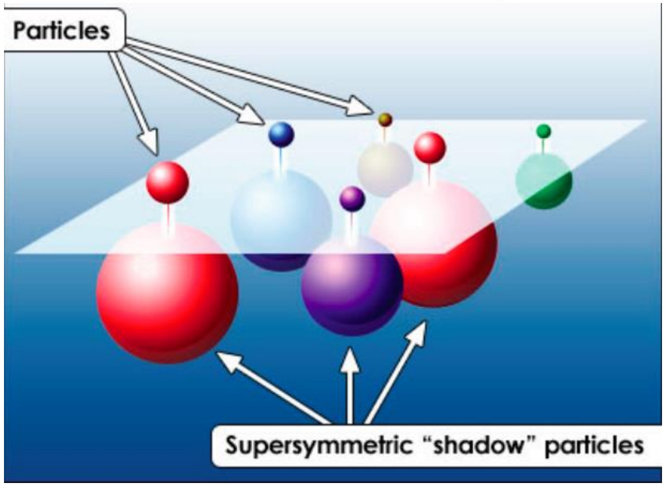


Balboa Park, San Diego, USA, from https://beautifulbalboapark.wordpress.com

Суперсимметрия (SUSY)



Симметрия между фермионами и бозонами.
У каждой частицы СМ со спином S
появляется партнер со спином S-1/2.
Так как мы не еще видели супер-частиц
Эта симметрия должна быть нарушена.



Много новых частиц и
новых параметров (120!). ☹

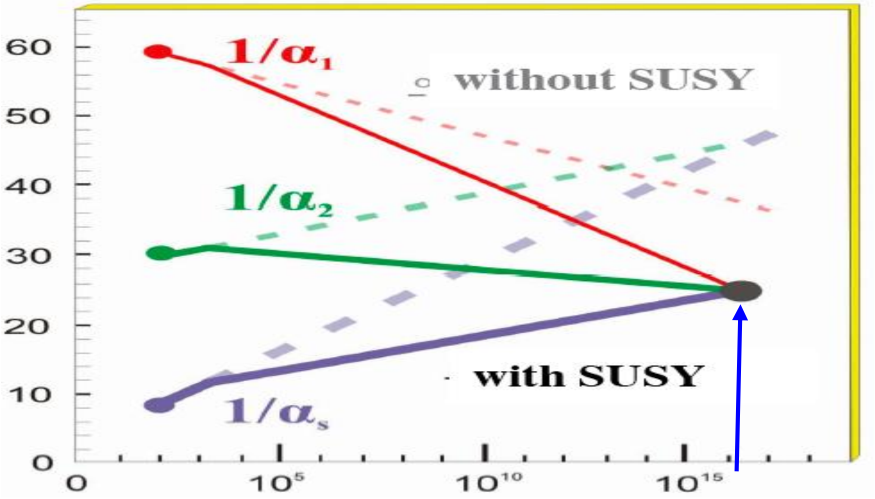
Зачем нужна Суперсимметрия?

- Объединение электро-магнитной, слабой и сильной констант взаимодействия при одной энергии
- Новая стабильная, нейтральная частица ⇒ идеальный кандидат для темной материи
- Простейшее обобщение СМ:

Минимальная

Суперсимметричная

Стандарная Модель (MSSM)



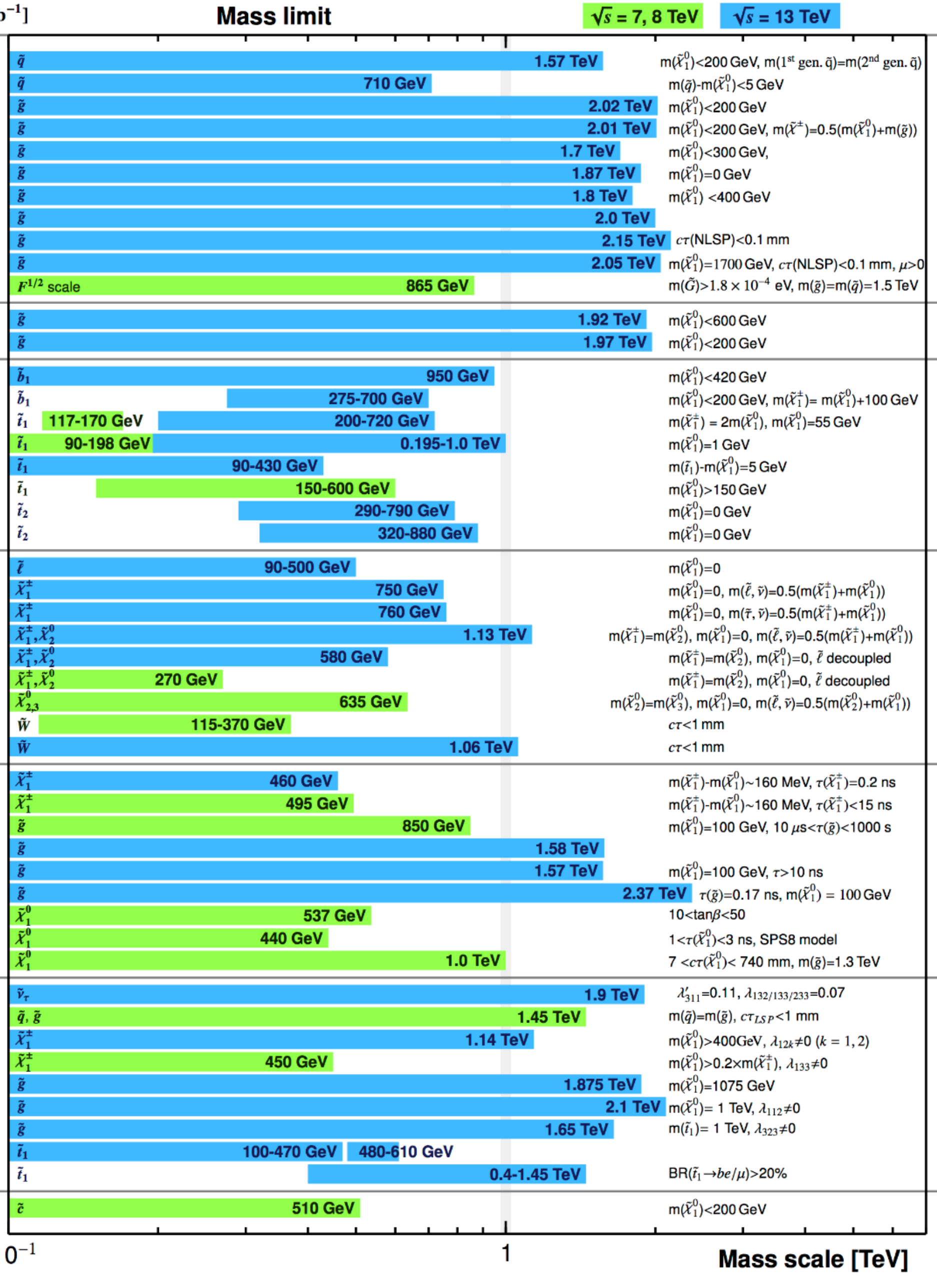
Энергия(ГэВ)

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

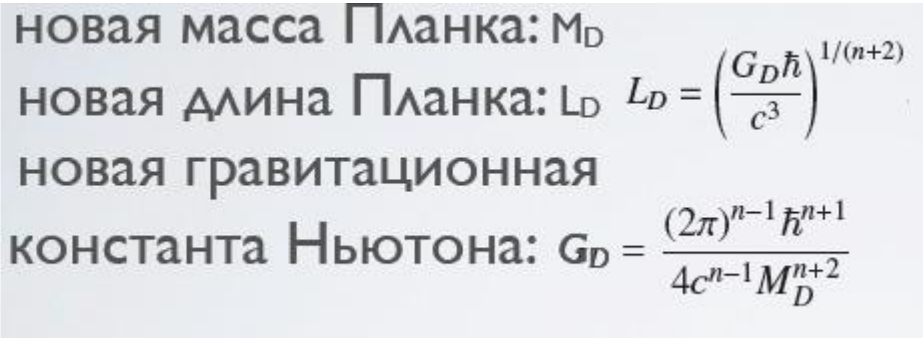
$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e,μ,τ,γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{q}$ 1.57 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1712.02332
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	36.1	🟦 $\tilde{q}$ 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.02 TeV	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.01 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	Yes	14.7	🟦 $\tilde{g}$ 1.7 TeV	m($\tilde{\chi}^0_1$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	36.1	🟦 $\tilde{g}$ 1.87 TeV	m($\tilde{\chi}^0_1$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	🟦 $\tilde{g}$ 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	🟦 $\tilde{g}$ 2.05 TeV	m($\tilde{\chi}^0_1$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.92 TeV	m($\tilde{\chi}^0_1$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.97 TeV	m($\tilde{\chi}^0_1$)<200 GeV	1711.01901
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	36.1	🟦 $\tilde{b}_1$ 950 GeV	m($\tilde{\chi}^0_1$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	1 b	Yes	36.1	🟦 $\tilde{b}_1$ 275-700 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm_1$)= m($\tilde{\chi}^0_1$)+100 GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}^\pm_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 0.195-1.0 TeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	36.1	🟦 $\tilde{t}_1$ 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	🟦 $\tilde{t}_2$ 290-790 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	🟦 $\tilde{t}_2$ 320-880 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\ell}$ 90-500 GeV	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}^\pm_1$ 750 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	🟦 $\tilde{\chi}^\pm_1$ 760 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 1.13 TeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	36.1	🟦 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 580 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 270 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_{\mathrm{R}}\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^0_{2,3}$ 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	1 $e,\mu+\gamma$	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	2 γ	-	Yes	36.1	🟦 $\tilde{W}$ 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	🟦 $\tilde{\chi}^\pm_1$ 460 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}^\pm_1$ 495 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	displ. vtx	-	Yes	32.8	🟦 $\tilde{g}$ 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}^0_1$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}^0_1$ 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}^0_1$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q}$, $\tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}^\pm_1$ 1.14 TeV	m($\tilde{\chi}^0_1$)>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$ 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	36.1	🟦 $\tilde{g}$ 1.875 TeV	m($\tilde{\chi}^0_1$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 2.1 TeV	m($\tilde{\chi}^0_1$)= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	1704.08493
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	🟦 $\tilde{t}_1$ 100-470 GeV 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	🟦 $\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

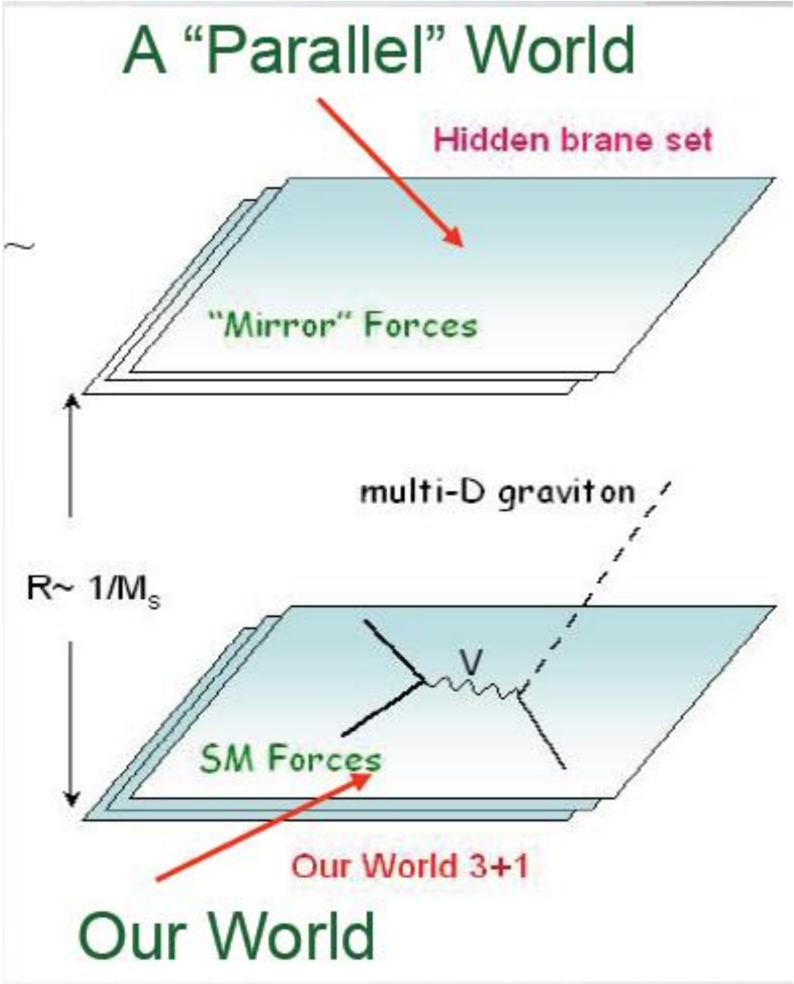
Дополнительные измерения

- Суперсимметрия не отвечает на все вопросы
  - Почему слабое взаимодействие в 10^{32} раз сильнее гравитационного
- Если существуют >1 новых измерения размером<мм, гравитационные эффекты могут быть в пределах энергий БАК
  - Гравитонные резонансы (G)
  - Производство **мини черных дыр (QBH)**
  - …
- 

новая масса Планка: M_D

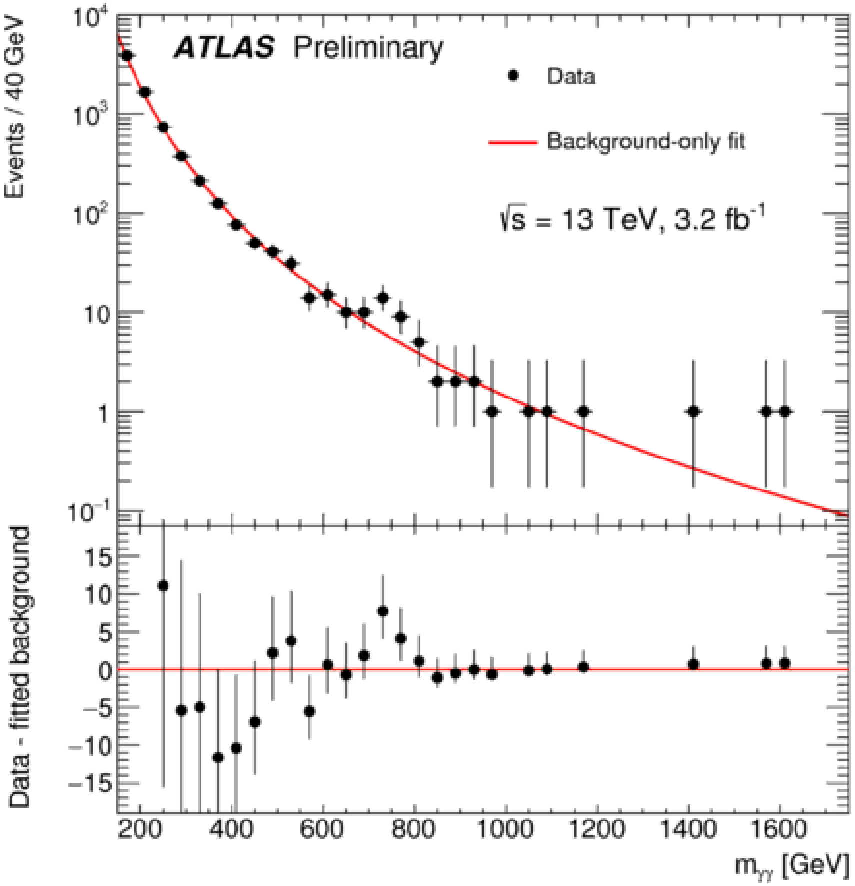
новая длина Планка: L_D $L_D = \left(\frac{G_D \hbar}{c^3}\right)^{1/(n+2)}$

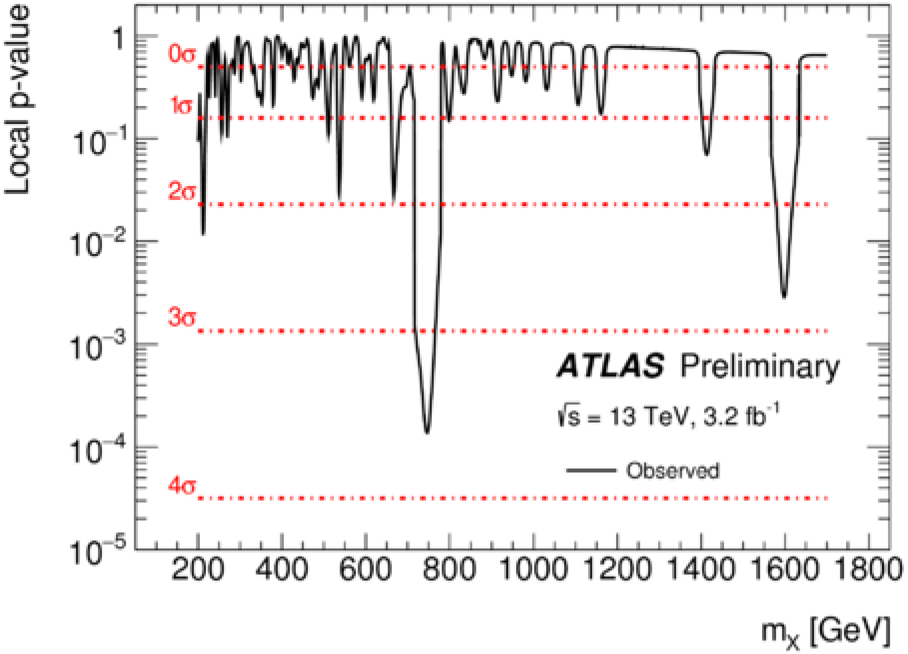
новая гравитационная константа Ньютона: $G_D = \frac{(2\pi)^{n-1}\hbar^{n+1}}{4c^{n-1}M_D^{n+2}}$



Каналы поиска:
qq, qγ, γγ, ql, ll,
multi-jet etc.

Ди-бозоны $\gamma\gamma$ (2015)

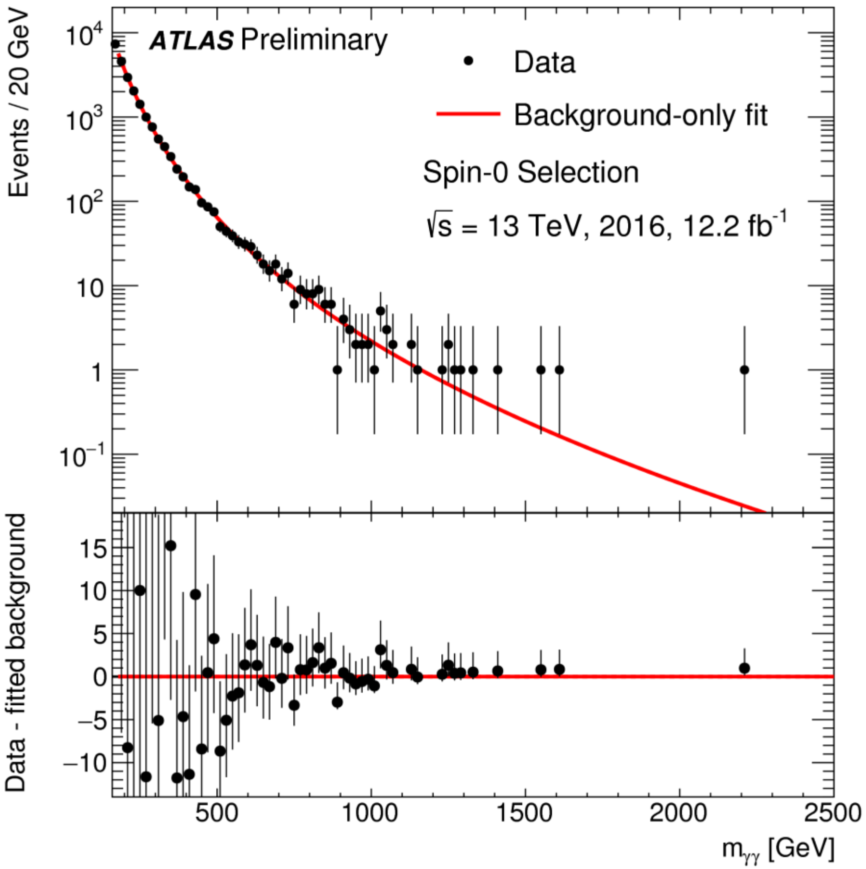


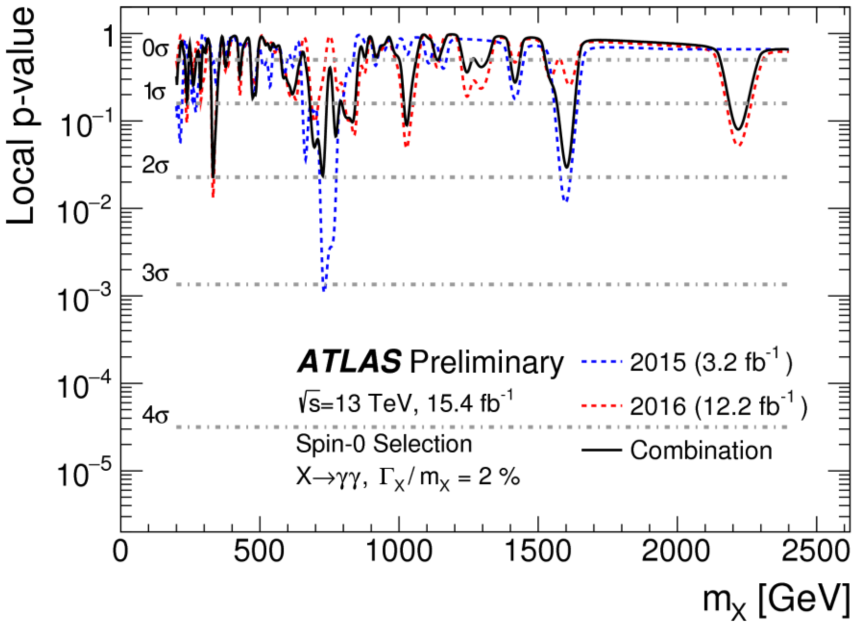


		Local σ	Global σ
ATLAS @ 750 GeV	NWA	3.6	2.0
	LWA (6%)	3.9	2.3
CMS @ 760 GeV	NWA	2.6	1.2
	LWA (6%)	~2	n/a

Интерестный новый
избыток событий
в обоих экспериментах.

Ди-бозоны $\gamma\gamma$ (2015)

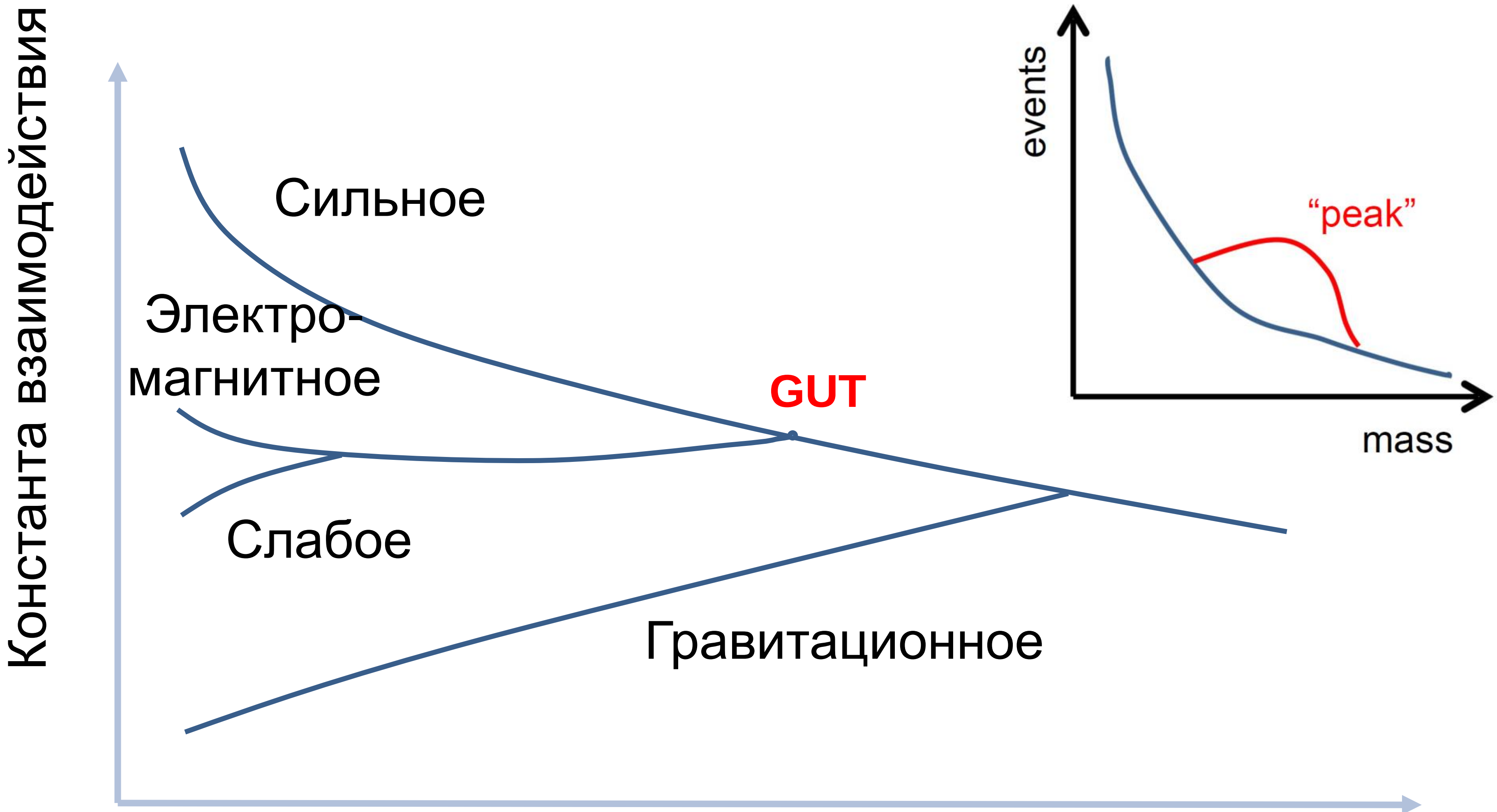




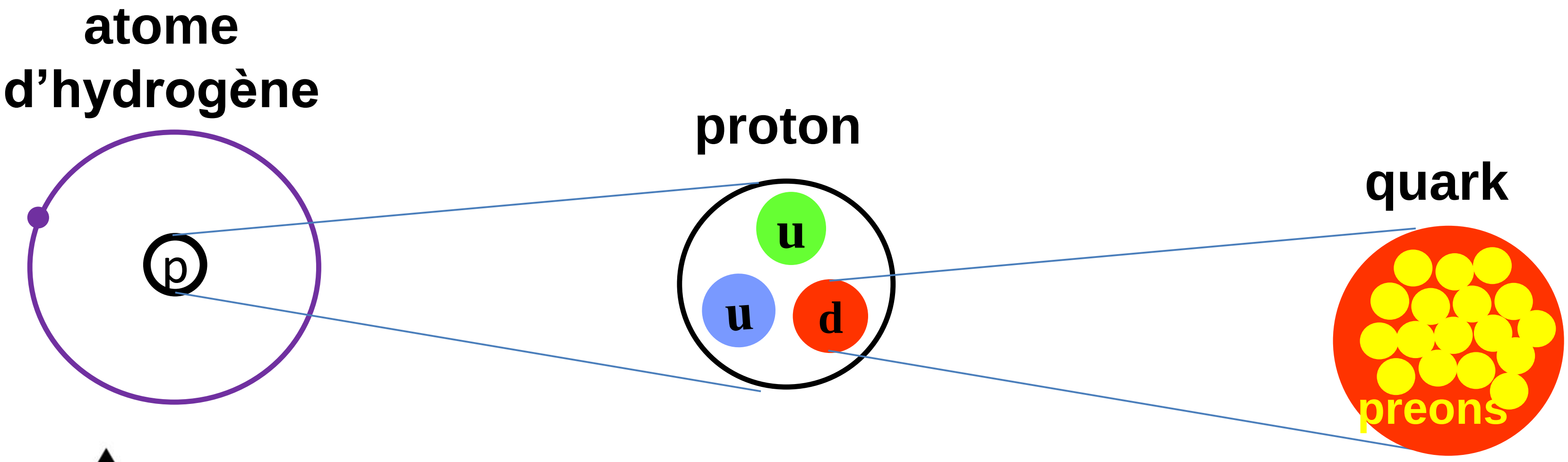
Новые данные не подвердили присутствие сигнала.

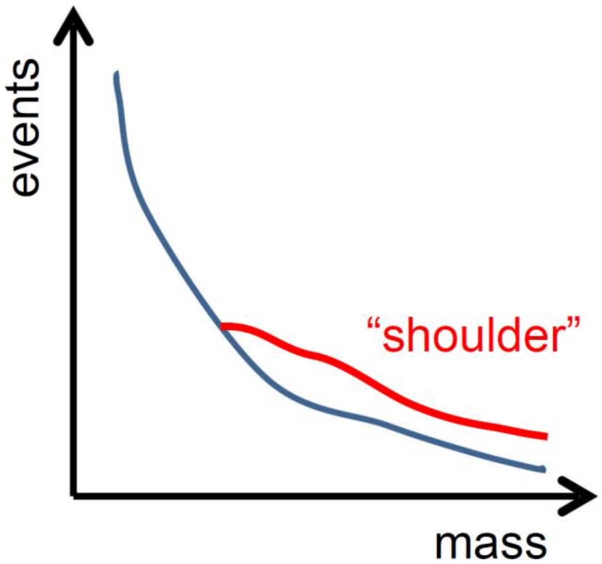
Теории великого объединения (GUT)

Предсказание: появление новых бозонов взаимодействия (Z’, W’)



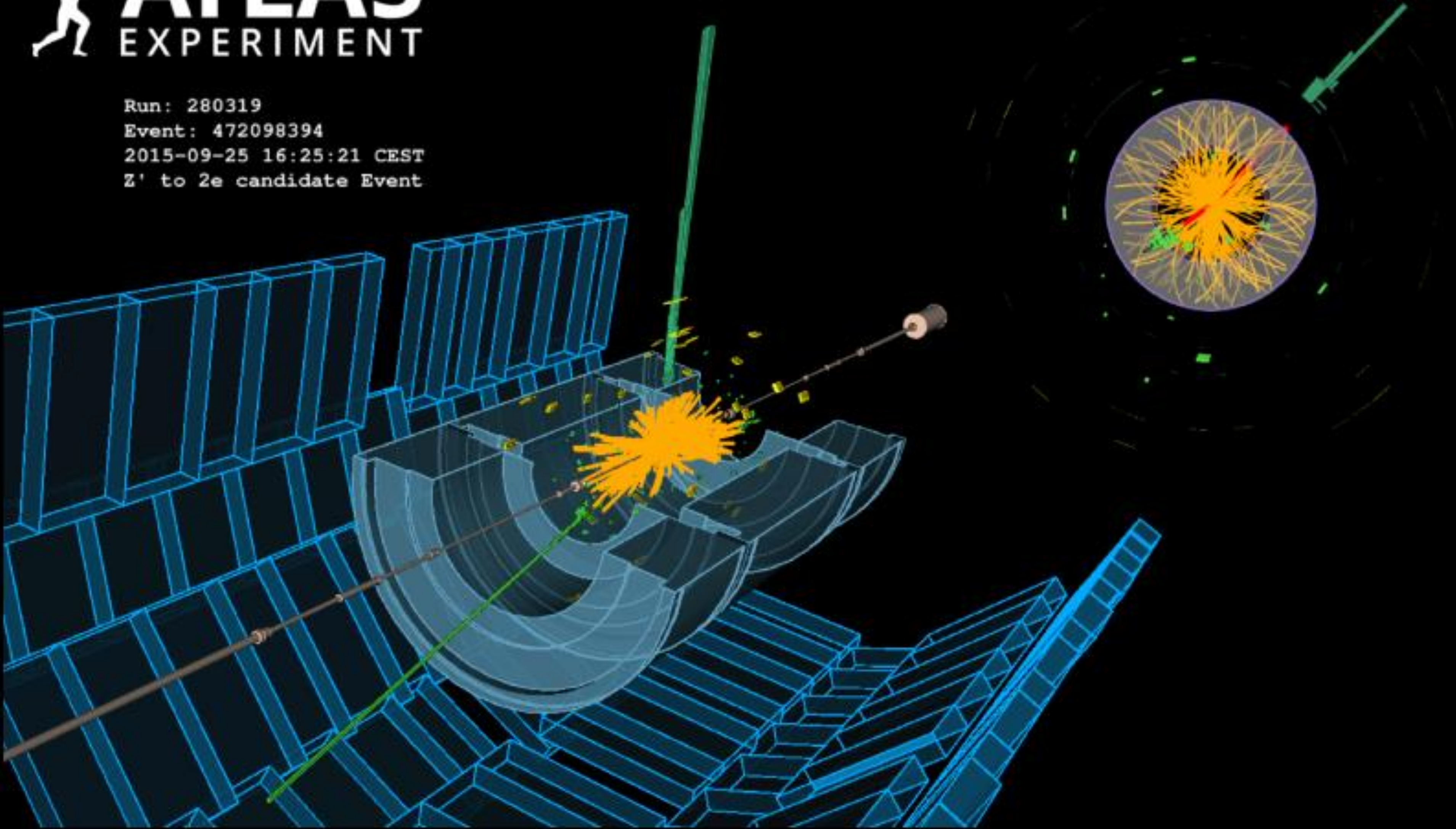
Подструктура





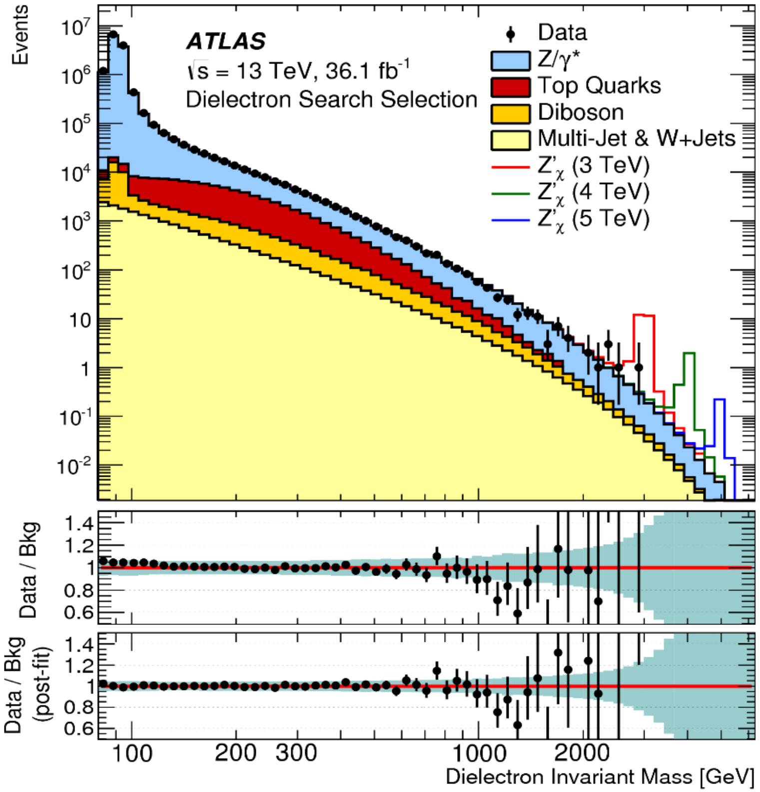
Di-Electron Event

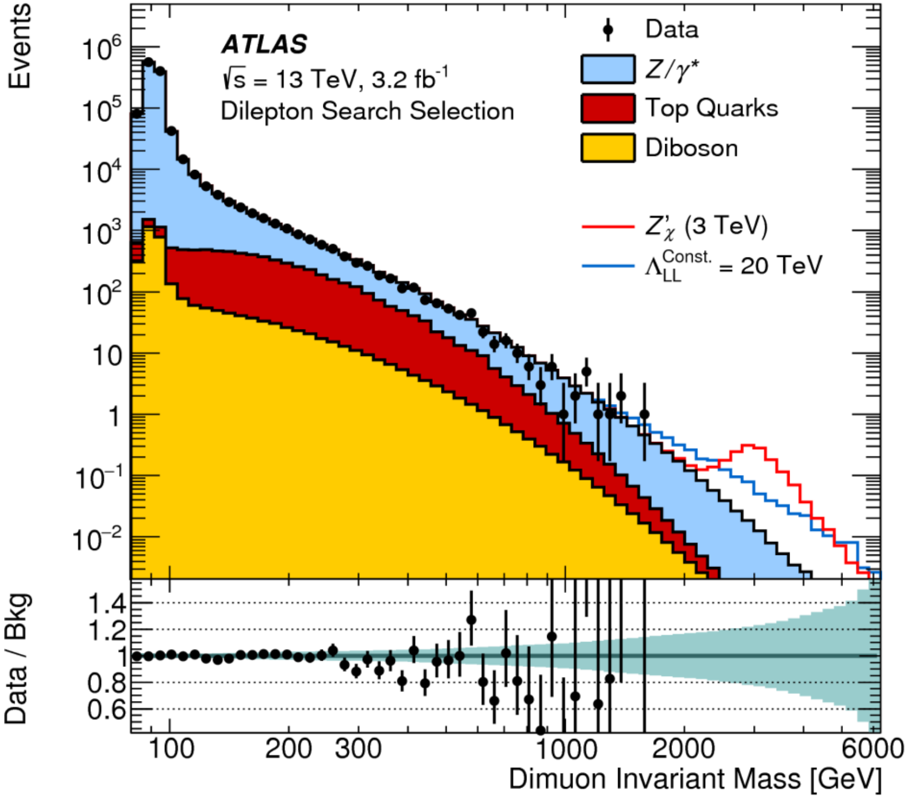
High Mass Dielectron
ET_1 = 370 GeV ET_2 = 246 GeV
m_{ee} = 1.8 TeV



```
Run: 280319
Event: 472098394
2015-09-25 16:25:21 CEST
Z' to 2e candidate Event
```

Спектр дилептонов





- Спектр соответствует предсказаниям СМ.
- Многие теоритические модели предсказывают сигналы с одинаковыми конечными состояниями.

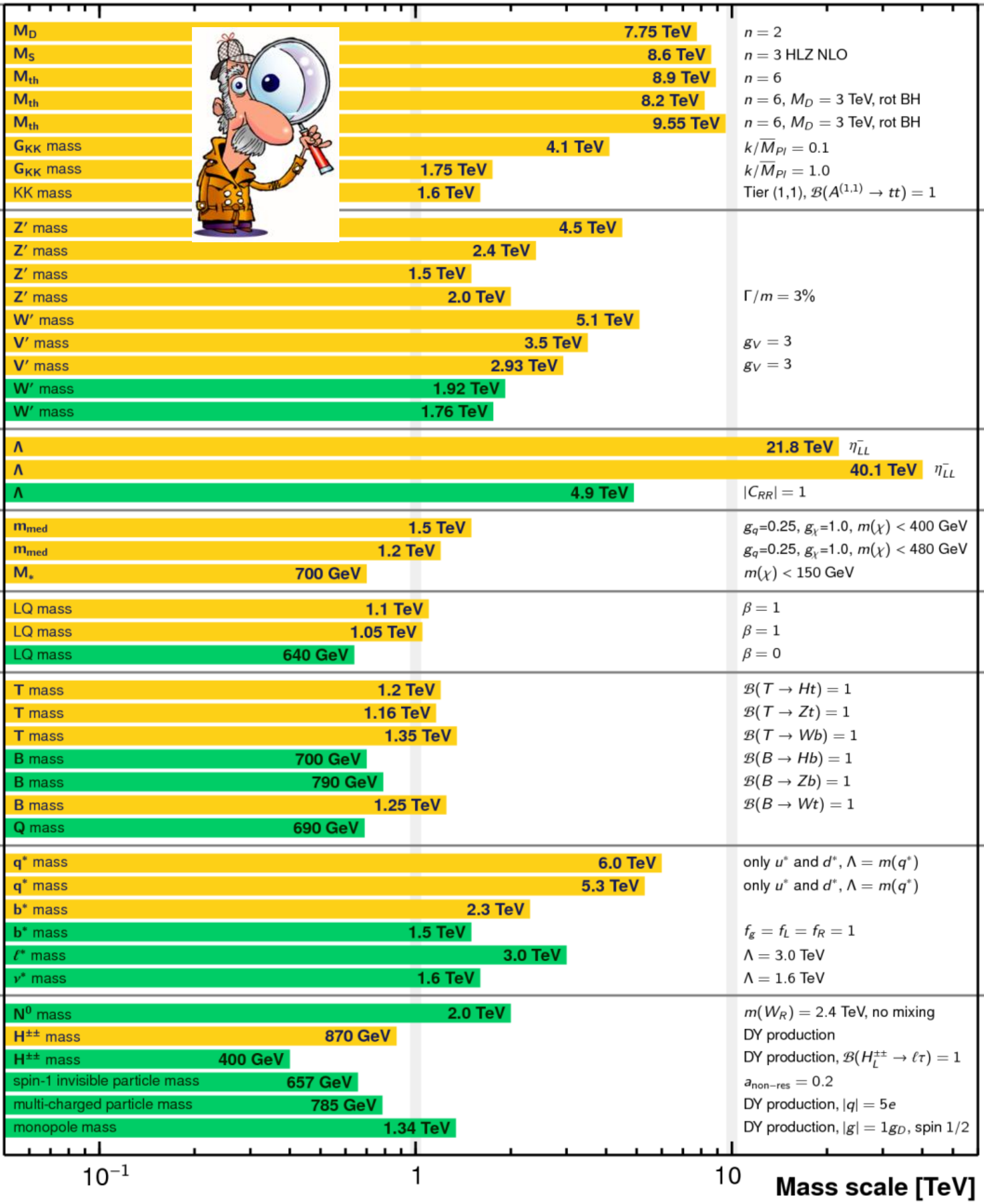
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

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

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

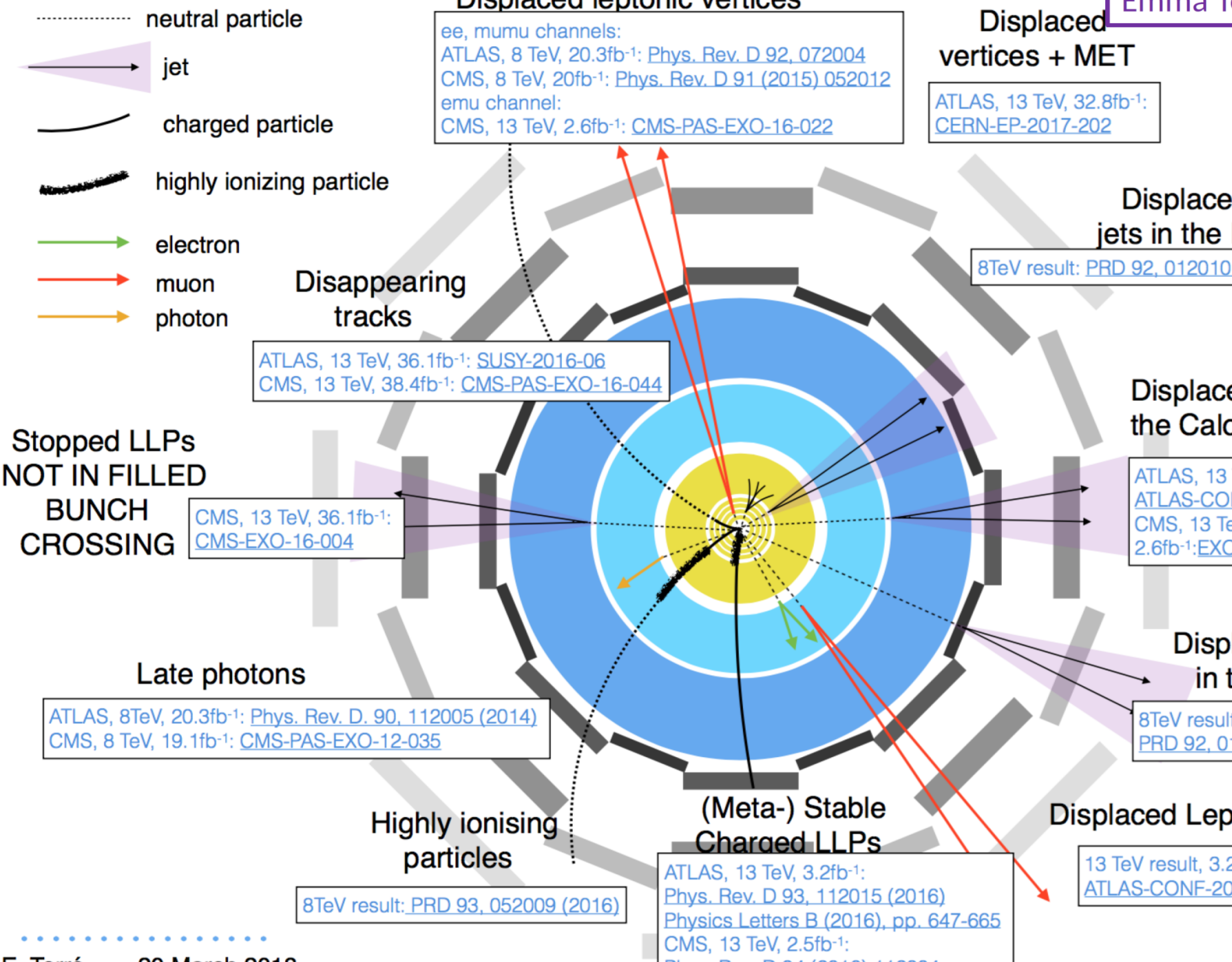


	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	🟨 G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	3.2	🟨 Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	36.1	🟨 W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	🟨 V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV	η_{LL}^{-}	1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.1 TeV	η_{LL}^{-}	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\|C_{RR}\| = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu$, $1\ \gamma$	≤ 1 j	Yes	36.1	🟨 m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or $1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	🟨 T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	🟨 B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or $2\ e, \mu$	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\mathrm{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\|q\| = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\|g\| = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 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).



Displaced leptonic vertices

ee, mumu channels:
ATLAS, 8 TeV, 20.3fb^{-1}: Phys. Rev. D 92, 072004
CMS, 8 TeV, 20fb^{-1}: Phys. Rev. D 91 (2015) 052012
emu channel:
CMS, 13 TeV, 2.6fb^{-1}: CMS-PAS-EXO-16-022

Displaced vertices + MET

ATLAS, 13 TeV, 32.8fb^{-1}:
CERN-EP-2017-202

Displaced jets in the ID

8TeV result: PRD 92, 012010 (2015)

Disappearing tracks

ATLAS, 13 TeV, 36.1fb^{-1}: SUSY-2016-06
CMS, 13 TeV, 38.4fb^{-1}: CMS-PAS-EXO-16-044

Displaced jets in the Calorimeter

ATLAS, 13 TeV, 3.2fb^{-1}:
ATLAS-CONF-2016-103
CMS, 13 TeV,
2.6fb^{-1}:EXO-16-003

Stopped LLPs NOT IN FILLED BUNCH CROSSING

CMS, 13 TeV, 36.1fb^{-1}:
CMS-EXO-16-004

Displaced jets in the MS

8TeV result:
PRD 92, 012010 (2015)

Late photons

ATLAS, 8TeV, 20.3fb^{-1}: Phys. Rev. D. 90, 112005 (2014)
CMS, 8 TeV, 19.1fb^{-1}: CMS-PAS-EXO-12-035

Highly ionising particles

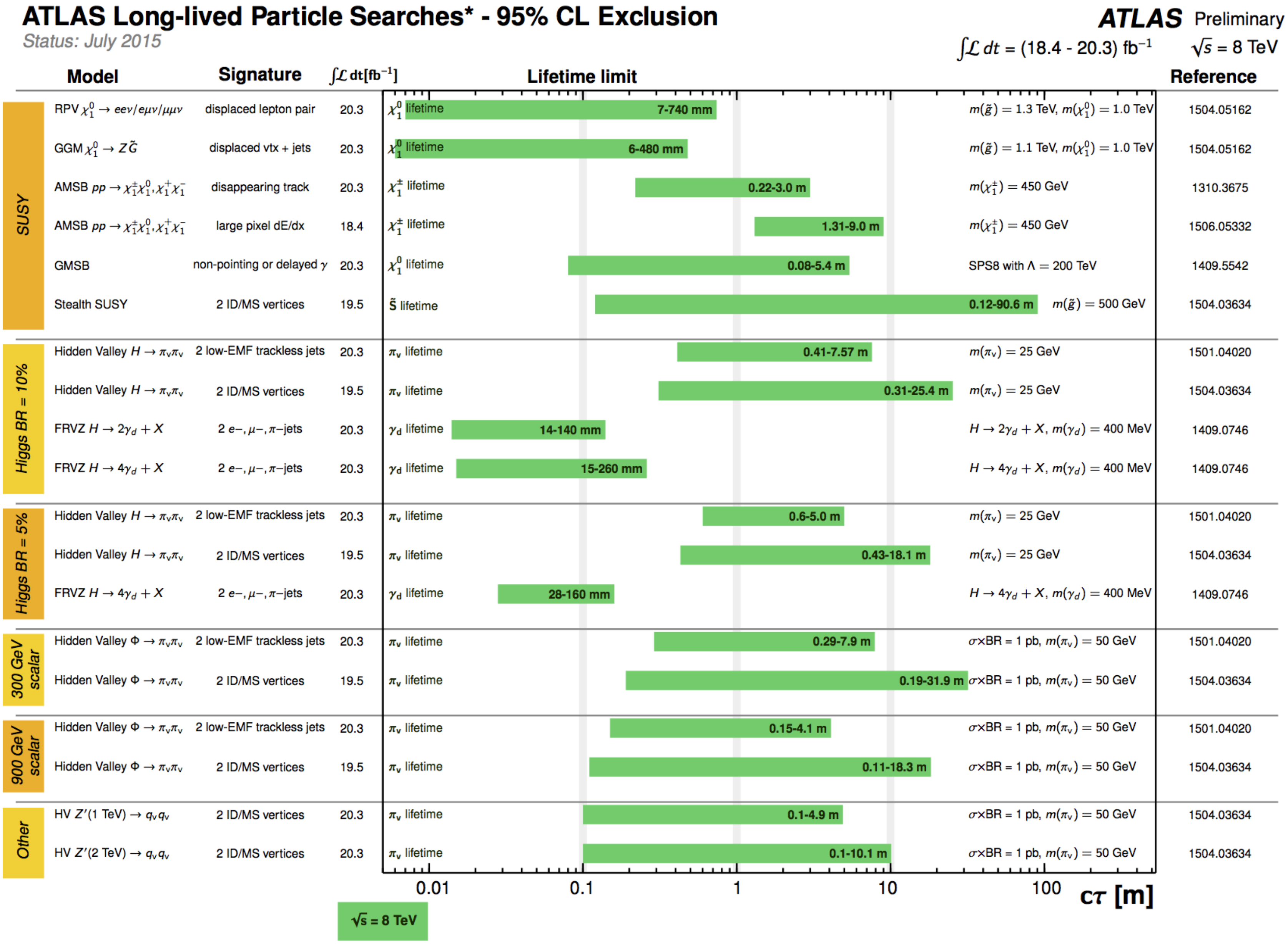
8TeV result: PRD 93, 052009 (2016)

(Meta-) Stable Charged LLPs

ATLAS, 13 TeV, 3.2fb^{-1}:
Phys. Rev. D 93, 112015 (2016)
Physics Letters B (2016), pp. 647-665
CMS, 13 TeV, 2.5fb^{-1}:
Phys. Rev. D 94 (2016) 112004

Displaced Lepton-jets

13 TeV result, 3.2fb^{-1}:
ATLAS-CONF-2016-042



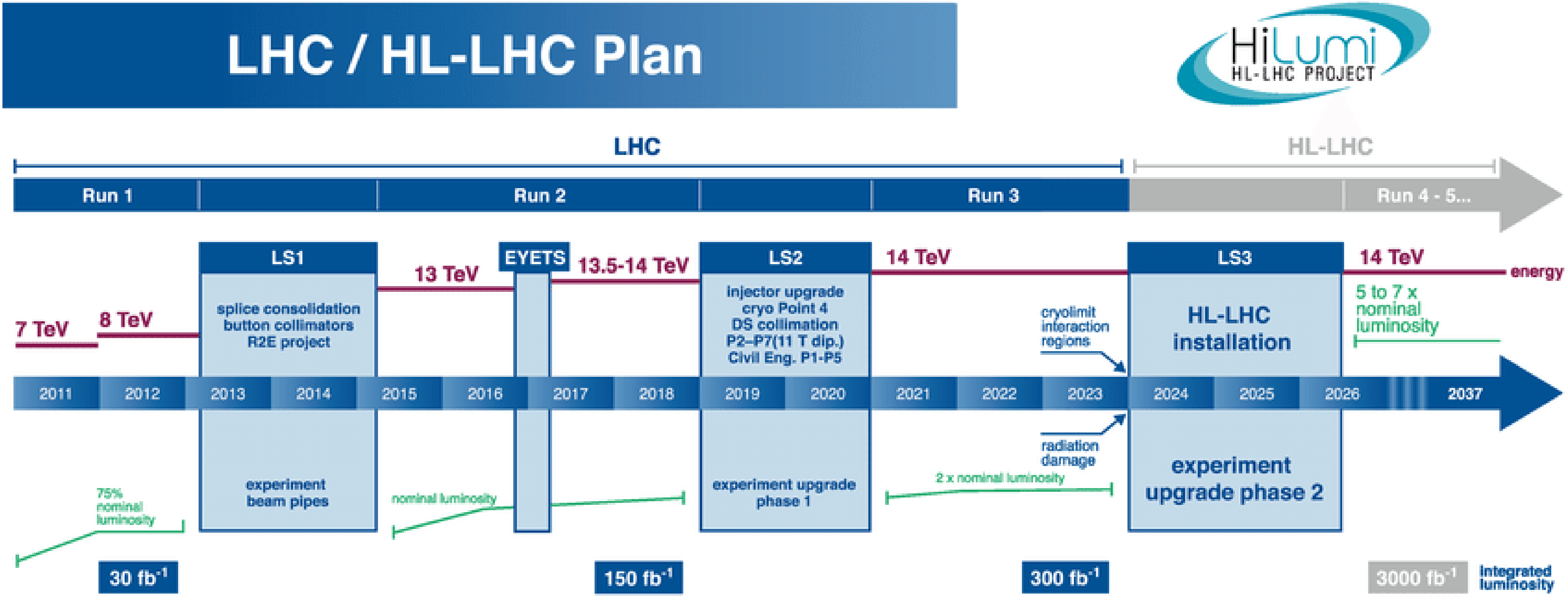
ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2015

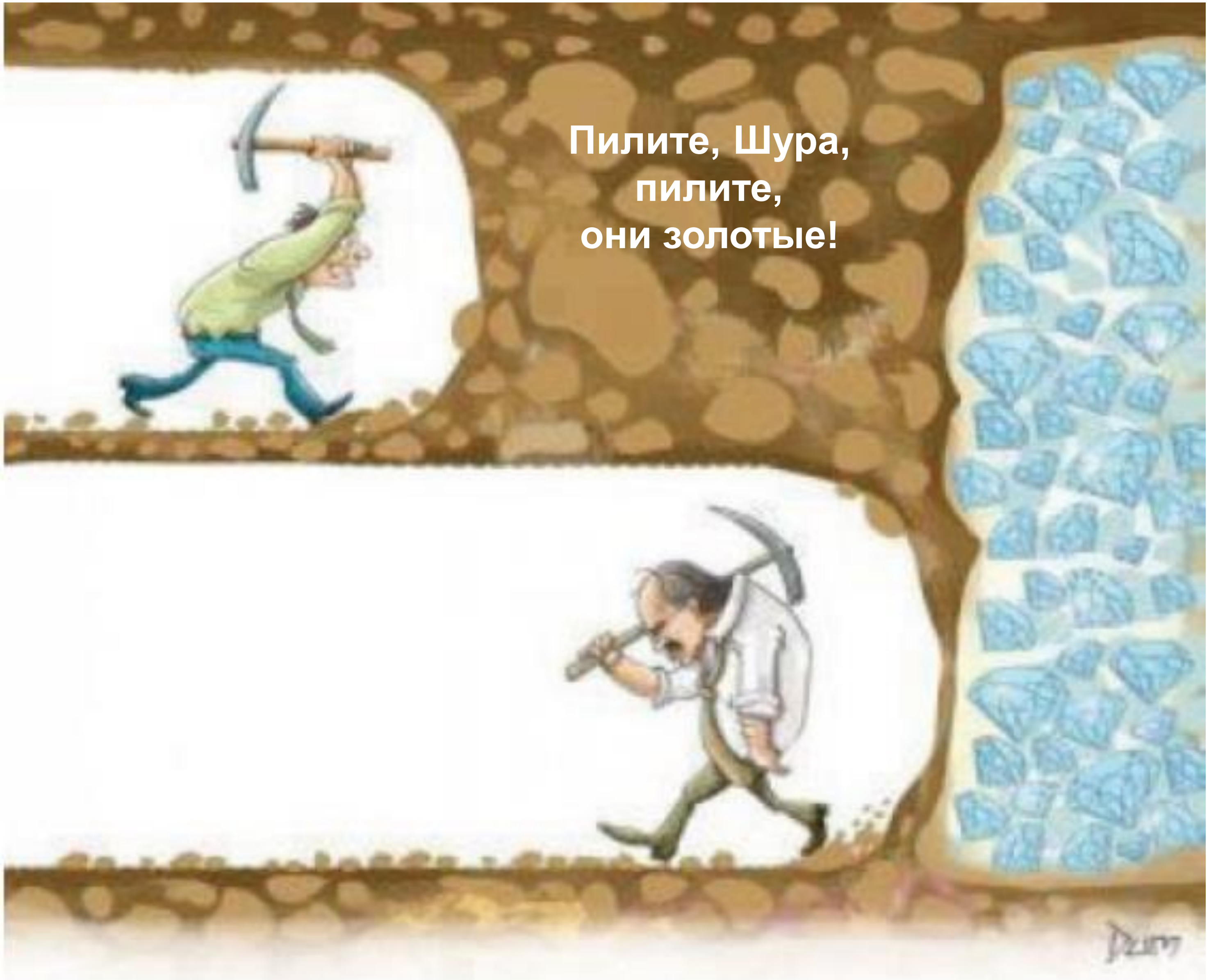
	Model	Signature	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Lifetime limit		Reference
SUSY	RPV $\chi_1^0 \to eev/e\mu v/\mu\mu v$	displaced lepton pair	20.3	χ_1^0 lifetime 7-740 mm	$m(\tilde{g}) = 1.3$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime 6-480 mm	$m(\tilde{g}) = 1.1$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^\pm$ lifetime 0.22-3.0 m	$m(\chi_1^\pm) = 450$ GeV	1310.3675
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	18.4	$\chi_1^\pm$ lifetime 1.31-9.0 m	$m(\chi_1^\pm) = 450$ GeV	1506.05332
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime 0.08-5.4 m	SPS8 with $\Lambda = 200$ TeV	1409.5542
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime 0.12-90.6 m	$m(\tilde{g}) = 500$ GeV	1504.03634
Higgs BR = 10%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.41-7.57 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.31-25.4 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 14-140 mm	$H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 15-260 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
Higgs BR = 5%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.6-5.0 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.43-18.1 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 28-160 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
300 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.29-7.9 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.19-31.9 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
900 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.15-4.1 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.11-18.3 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
Other	HV $Z'(1\text{ TeV}) \to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime 0.1-4.9 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
	HV $Z'(2\text{ TeV}) \to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime 0.1-10.1 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634

*Only a selection of the available lifetime limits on new states is shown.

Программа БАК

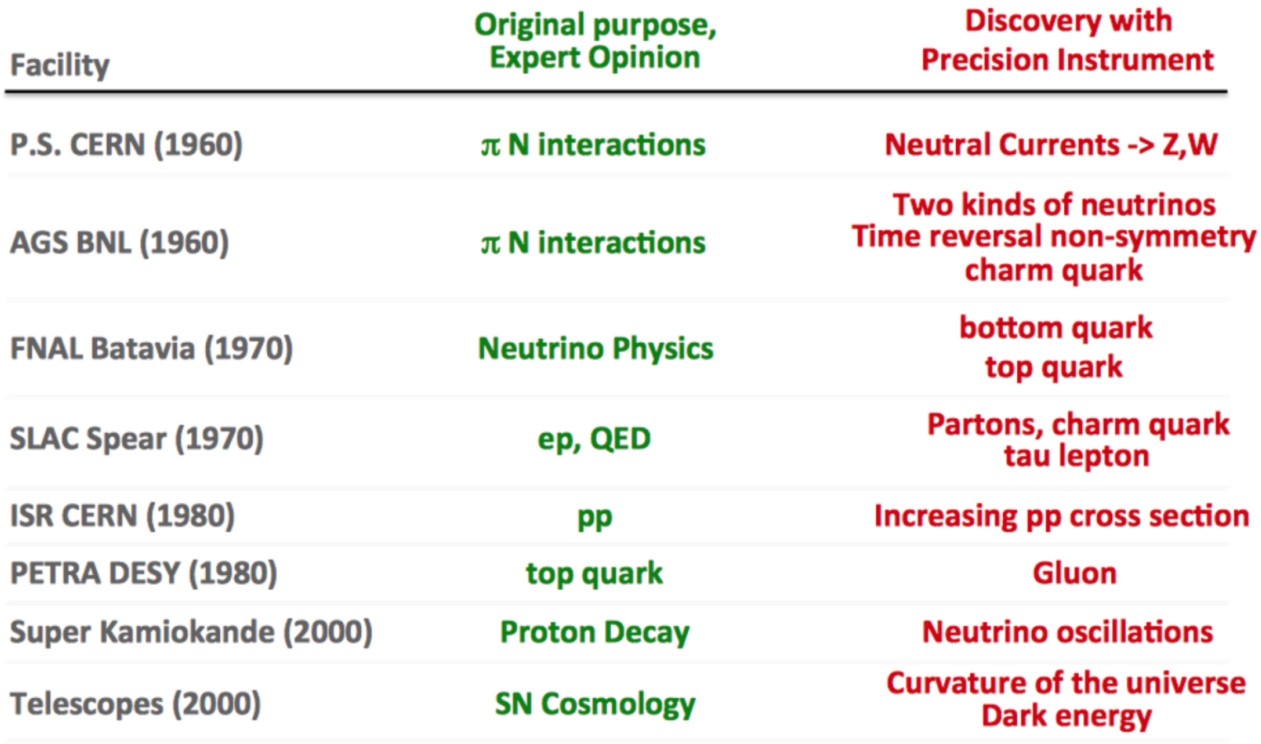


Заключение



Пилите, Шура,
пилите,
они золотые!

Discoveries in particle physics

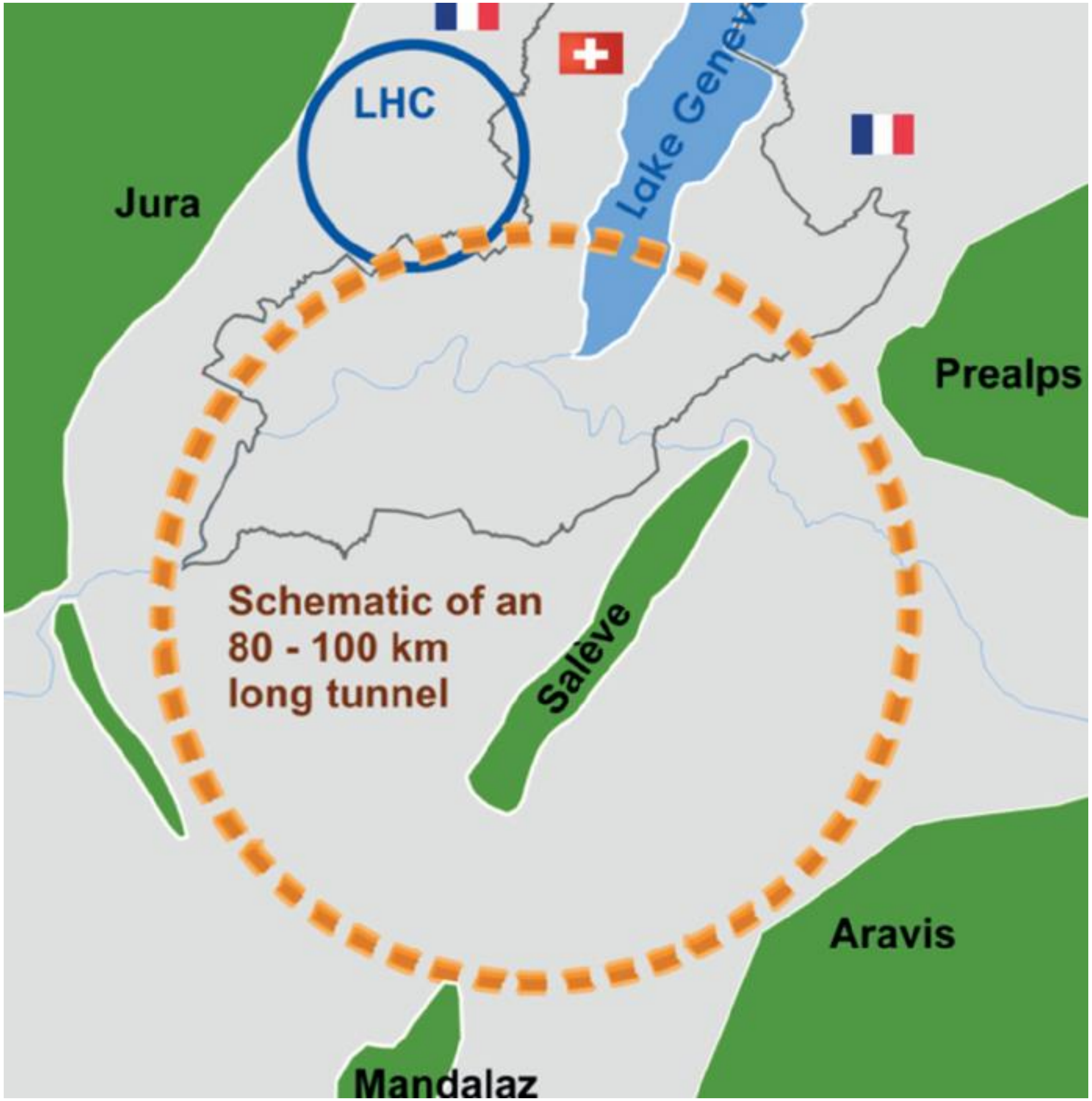


Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

Often when we embark on an experiment with a goal in mind, we find something new.

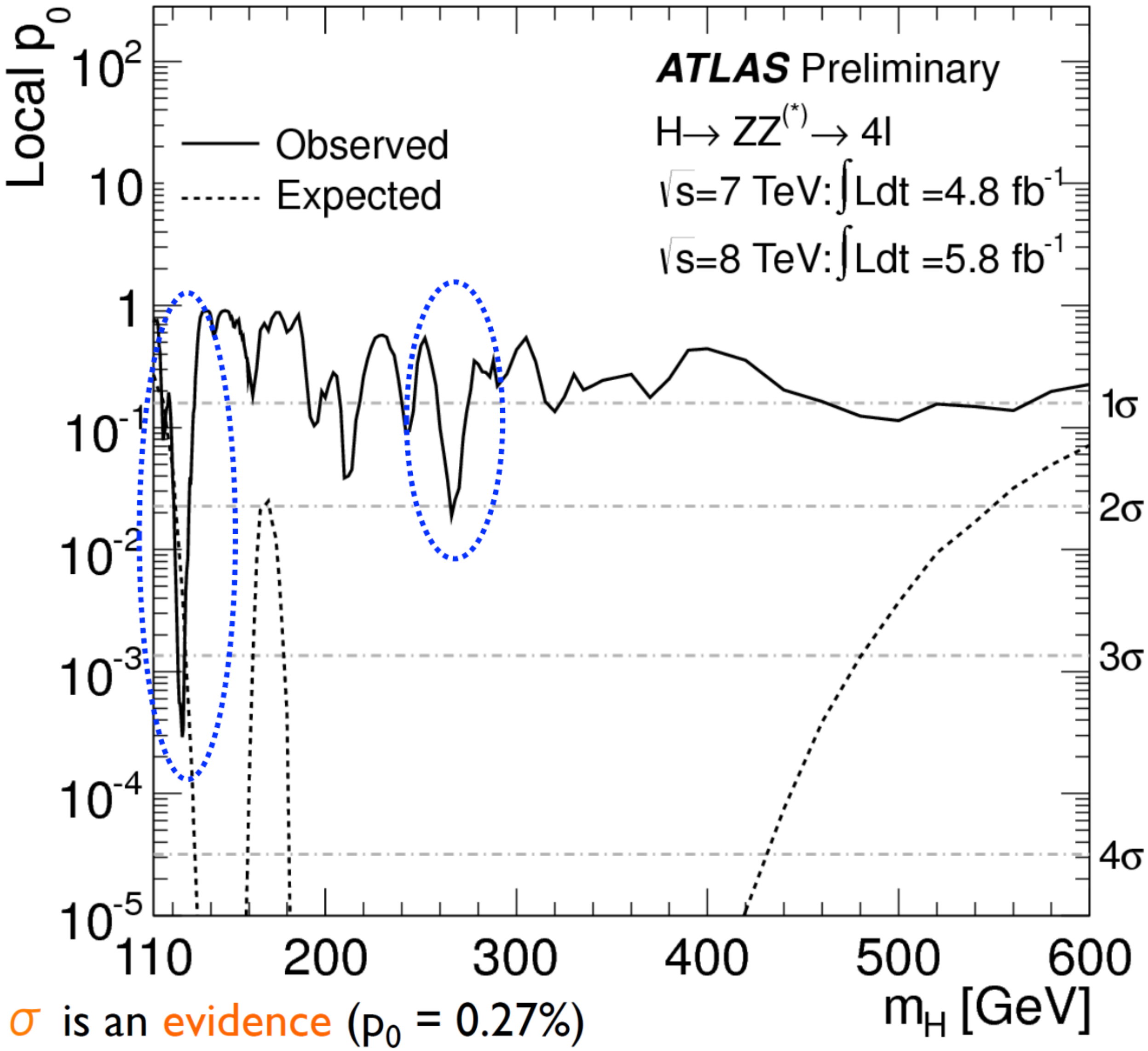
(From an original slide by S.C.C. Ting.)

Будуюшие ускорители



Дополнительные прозрачки

Значительно ли превышение?



P-значение (**англ.** ***P-value***)
величина,
используемая
при тестировании
статистических
гипотез.
это вероятность
ошибки
при отклонении от
нулевой гипотезы.

$$p_0 = 1 - \mathrm{Erf}\left(\frac{Z}{\sqrt{2}}\right)$$

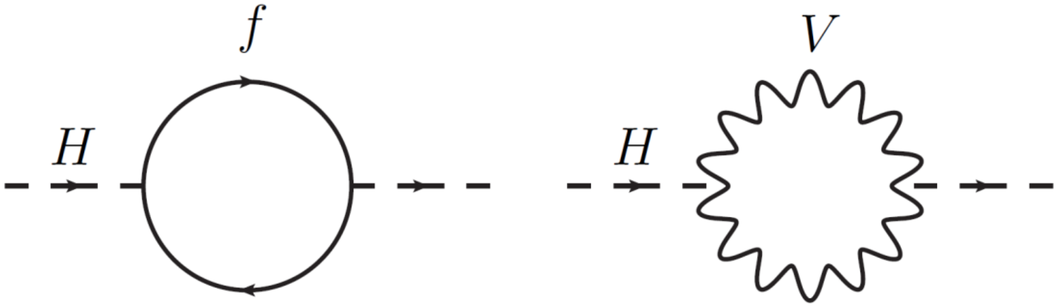
$$\mathrm{erf}\,(z) \equiv \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2}\, d\,t.$$

$3\,\sigma$ is an evidence (p_0 = 0.27%)

$5\,\sigma$ is a discovery ($p_0 = 5.7.10^{-7}$)

Hierarchy problem of SM

- SM is an effective theory valid up to a cut off scale Λ_{SM}
- Radiativ



$$\Delta m_H^2 = -\frac{|y_f|^2}{16\pi^2}\left[2\Lambda^2 + \mathcal{O}\left(m_f^2 \ln\left(\frac{\Lambda}{m_f}\right)\right)\right]$$