希格斯和它的小伙伴们W／Z的发现

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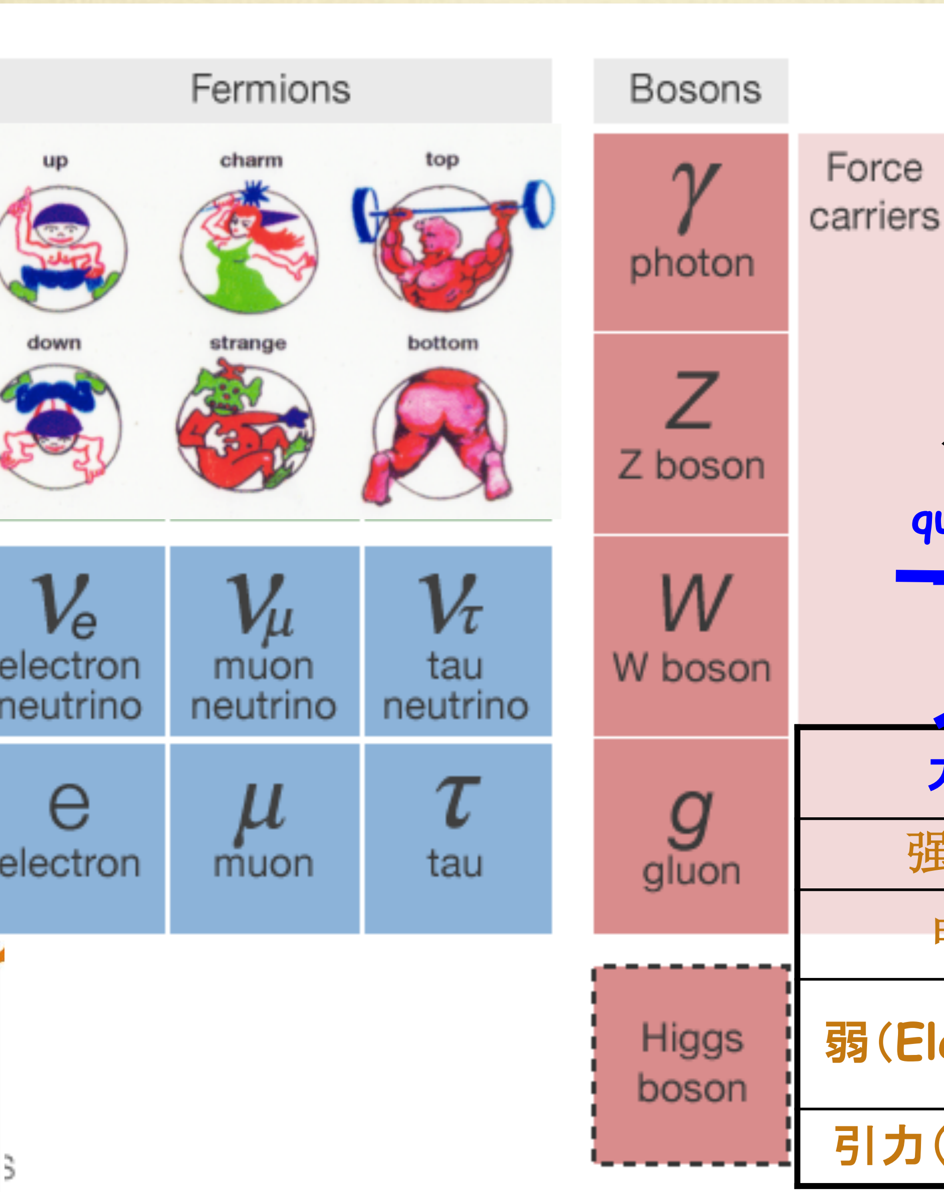
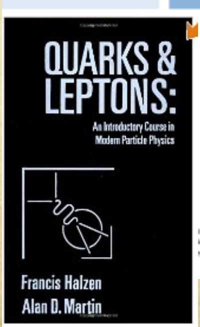
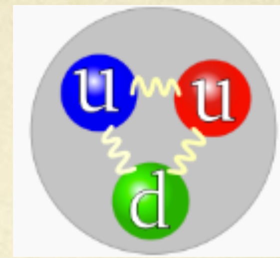
什么是标准模型(Standard Model)？



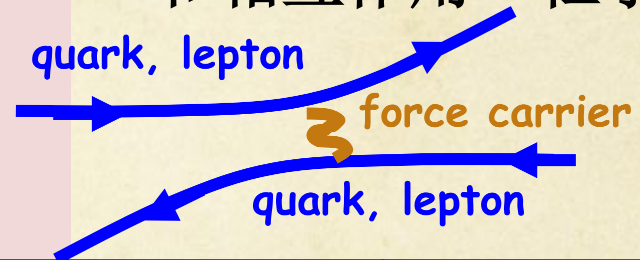


- ✓ 描述物质世界构成

e.g. 质子：up-up-down



- ✓ 和相互作用－粒子载体



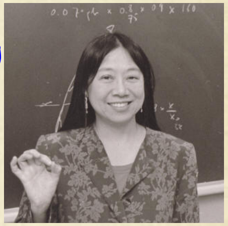
力(Force)	载体(Carrier)
强(Strong)	胶子Gluons (g)
电磁(EM)	光子
弱(Electro-Weak)	玻色子bosons W/Z
引力(Gravitation)	?

在标准模型下粒子发现进展：

Year	Particle	Lab
1974	c quark	BNL & SLAC
1975	τ lepton	SLAC
1977	b quark	FermiLab
1979	gluon	DESY
1983	W,Z	CERN
1994	t quark	FermiLab
2012	Higgs	CERN

Force Carriers

Sau Lan Wu

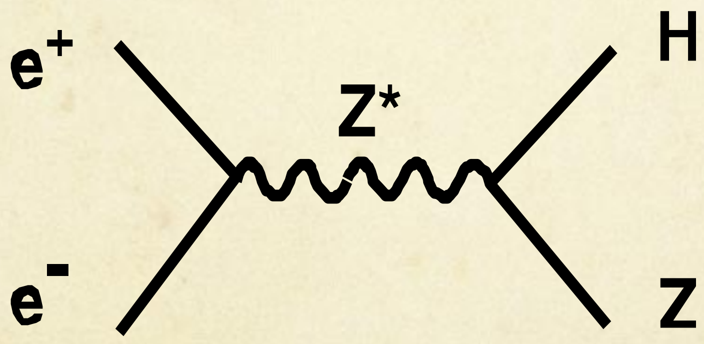


- The Standard Model is very successful BUT:

希格斯粒子：最后一个待发现的粒子
<2012

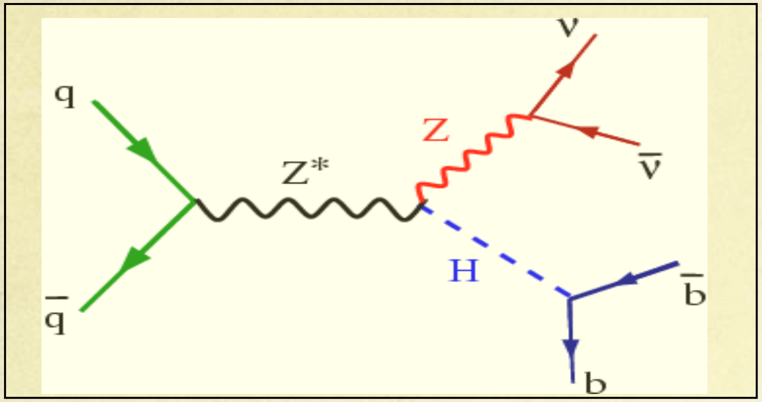
寻找希格斯粒子(The hunt for the Higgs)

- 希格斯机制虽然预言了希格斯粒子，但没有预言它的质量。
- 实验物理学家通过不同途径寻找 nuclei, π, K, B, Y, etc… 得到质量的下限 7, 8 GeV
- 大型正负电子对撞机(LEP)的一个重要目的就是寻找希格斯粒子 (e^+e^- collisions 1989-2000) 最高能量209 GeV



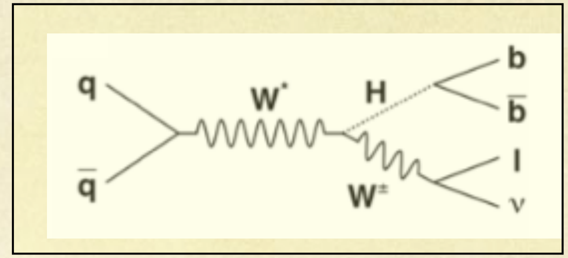
在Tevatron上寻找希格斯粒子

$ZH \Rightarrow \nu\,\nu\,bb$



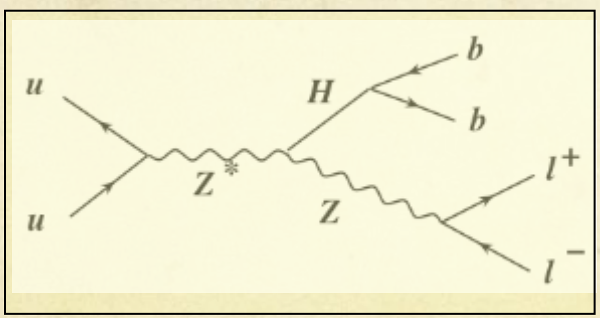
2 b jets ~ 1/2 M_H each 0 leptons
Missing E_T ~ 100 GeV

$WH \Rightarrow l\nu bb$

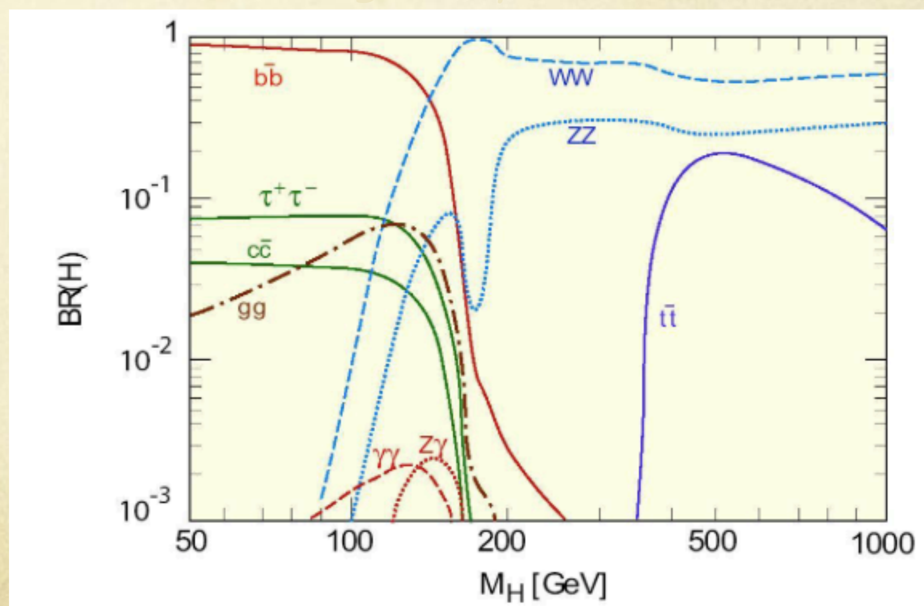


2 b jets ~ 1/2 M_H each
1 lepton ~ 50 GeV each
Missing E_T ~ 50 GeV

$ZH \Rightarrow l^+l^-\,bb$

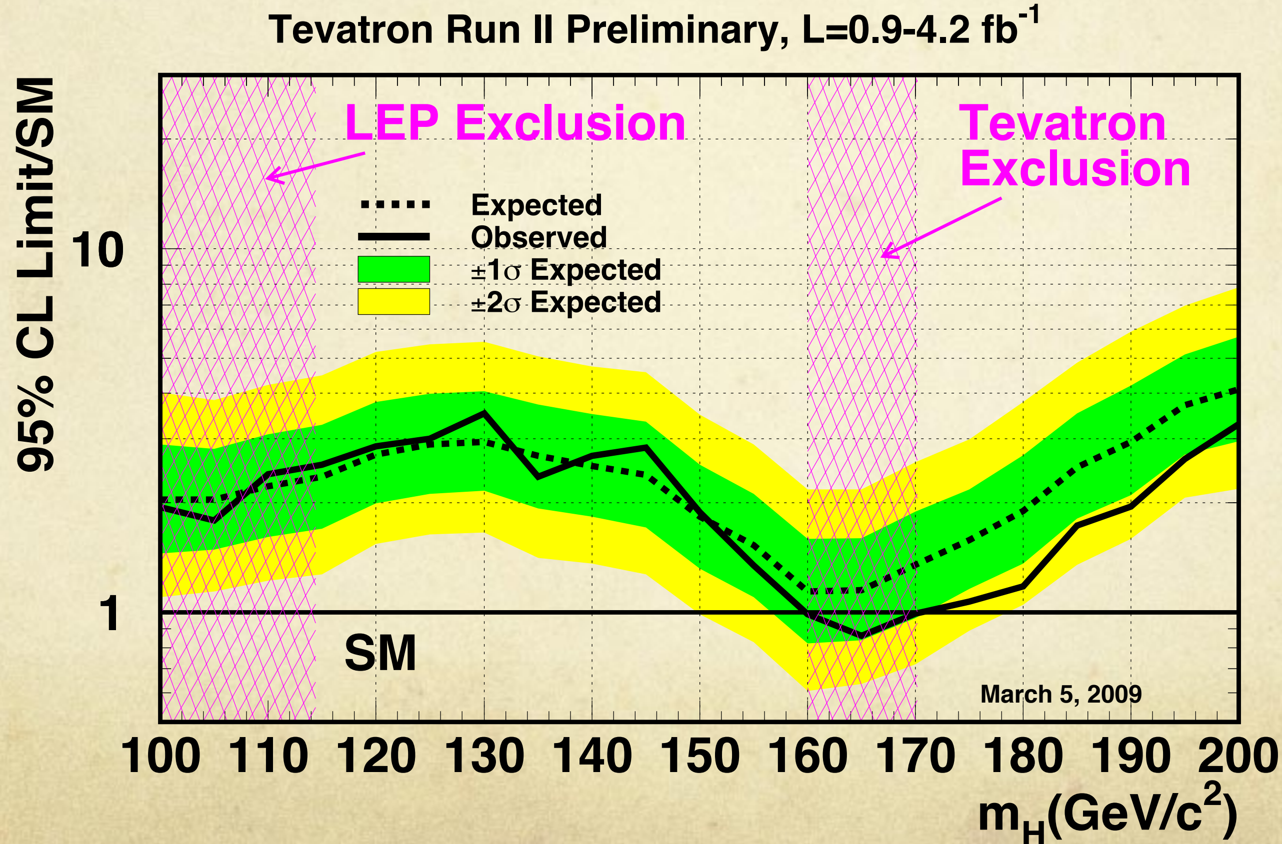


2 b jets ~ 1/2 M_H each
2 leptons ~ 50 GeV each
Z mass constraint
Cleanest signal



寻找希格斯粒子的坎坷路：LEP and Tevatron 排除的结果

- *2000年: 质量排除的范围* *<114.3 GeV* *from LEP.* LEP 看到10 个黄金事例~115GeV
- *2009年冬: Tevatron的第一个排除的范围 LEP (at 95%CL):* *160<m_H<170 GeV*



September 2008: LHC on hold

- *First protons around full ring on September 10, 2008*
- *But on Sept 19, an electrical fault triggered a major setback*

cause: faulty electrical connection between two of the accelerator's magnets; this resulted in mechanical damage and release of tons of liquid helium

- ***Actually: no beam for over a year; low energy beams circulated in Nov 2009 for the first time since the accident***

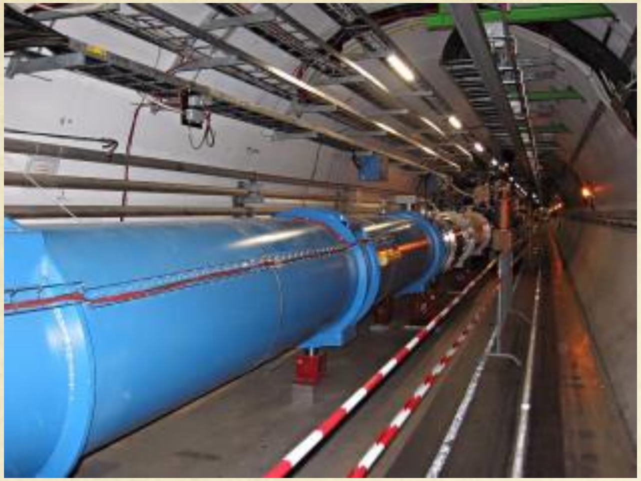
一个世纪之“赌”

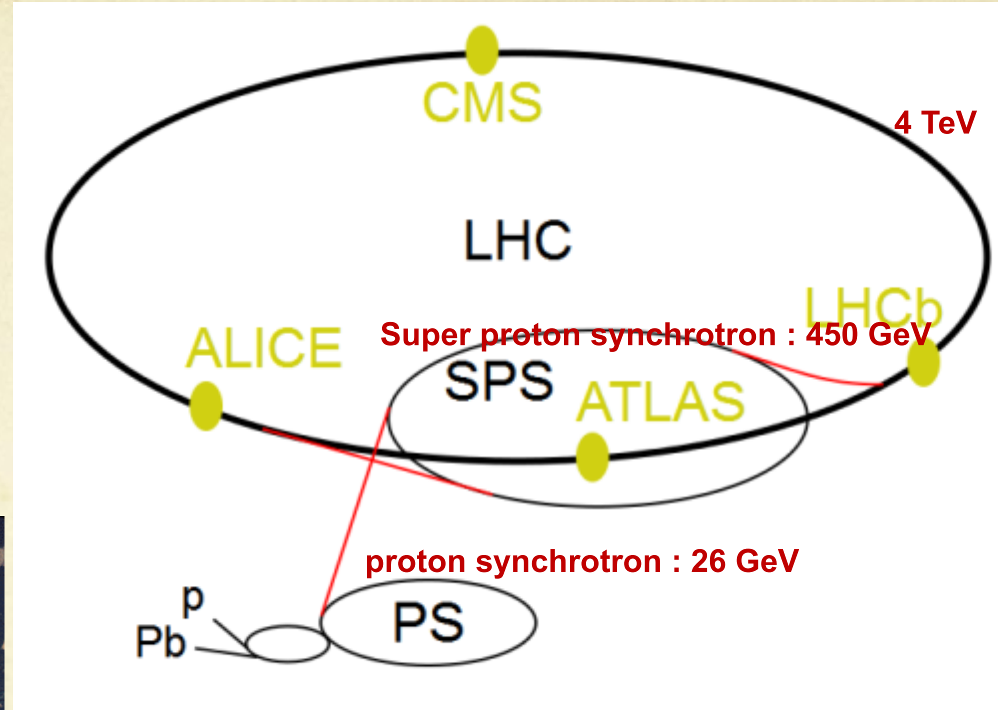
霍金愿意出 100$ 打赌希格斯粒子不存在。。。
这不是给我们找希格斯粒子的添“堵”嘛？！

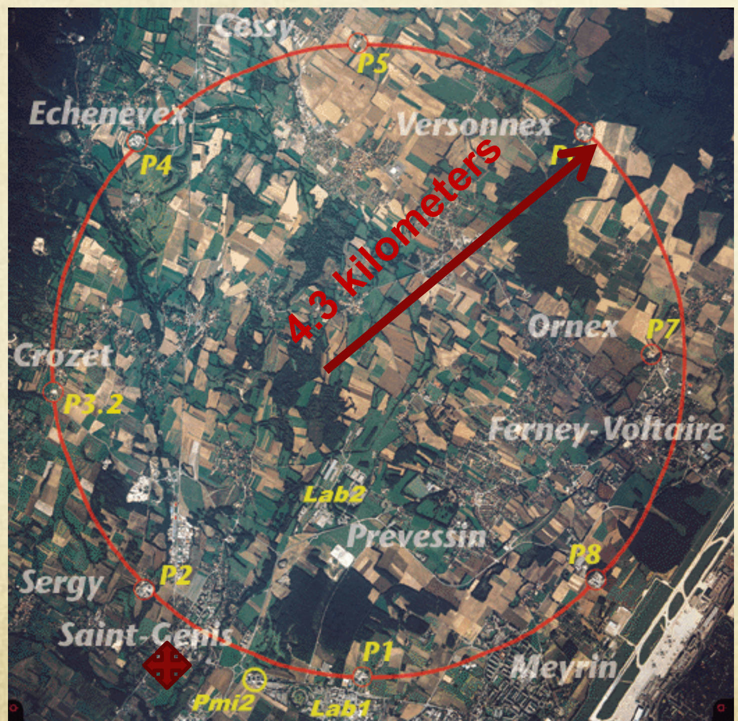
欧州核子研究中心(CERN)

位于日内瓦的近郊。
WWW的诞生之地
诺贝尔奖的摇篮

大型强子对撞机(Large Hadron Collider， 简称LHC)







- ❑ 地下100米的圆环, 半径4.3 公里。
- ❑四个实验 ： ATLAS，CMS, ALICE，LHCb
- ❑ 质心能量： 2012，8 TeV； 2011, 7 TeV

LHC简史 (*short LHC history*)

1983 *LEP* - S. Myers and W. Schnell propose twin-ring *pp* collider in LEP tunnel with 9-T dipoles

1991 CERN Council: LHC approval in principle

1992 EoI, LoI of experiments

1993 SSC termination

1994 CERN Council: LHC approval

1995-98 cooperation w.Japan,India,Russia,Canada,&US

2000 LEP completion

2006 last s.c. dipole delivered

2008 first beam

2010 first collisions at 3.5 TeV beam energy

2012 collision at 4 TeV, Higgs particle found!!!!

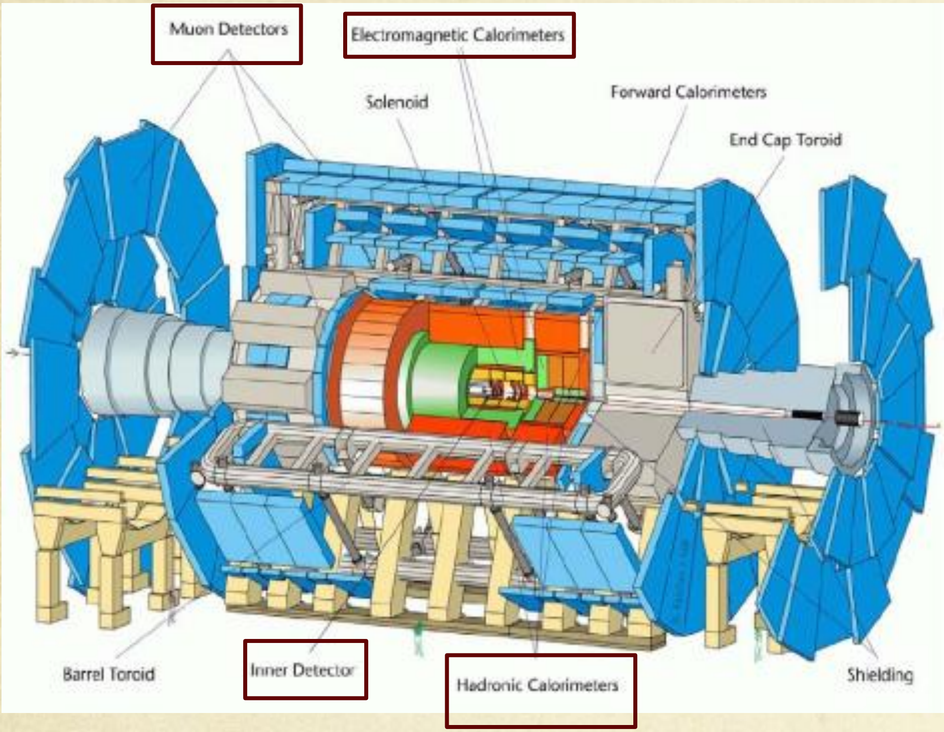
>30 years!

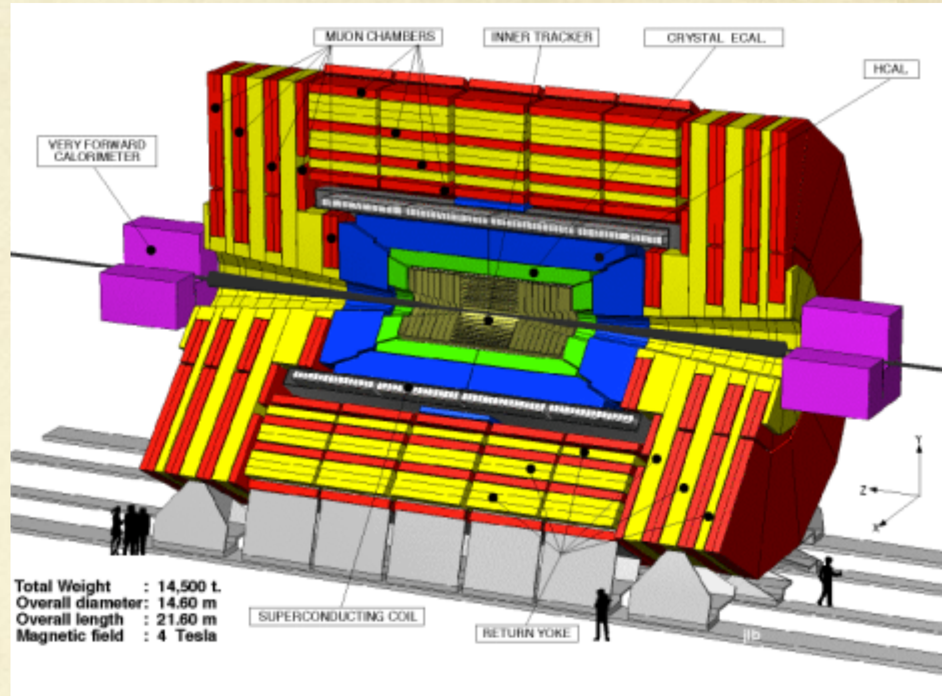
未来史：now is the time to plan for ~2040

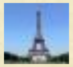
ATLAS and CMS 探测器

A Toroidal LHC ApparatuS

Compact Moun Soleniod





- 长: 44米，截面半径12.5米，~7000 吨.
  (One Eiffel tower  ,~100 jet 747).

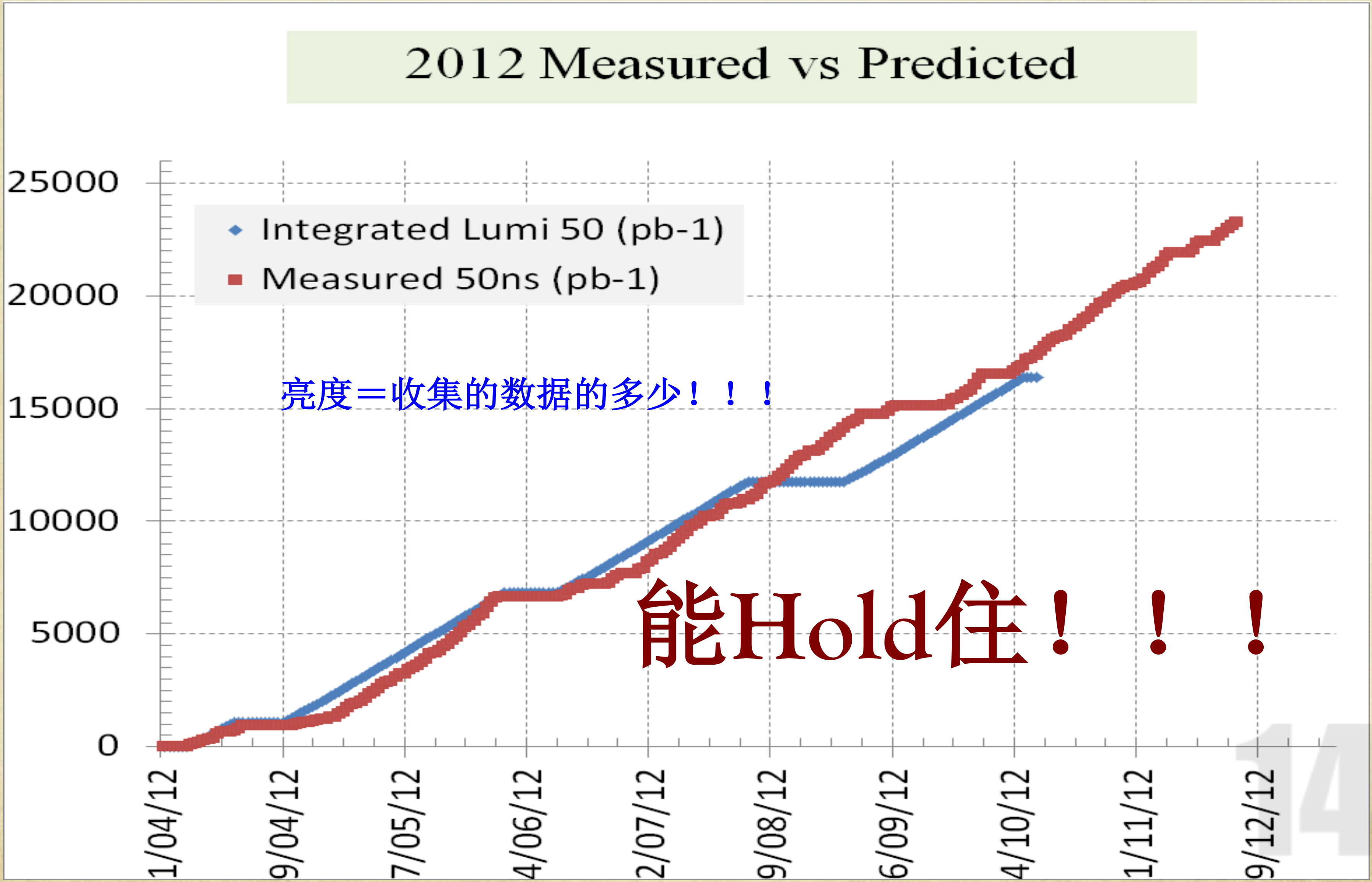
Total Weight	:	14,500 t.
Overall diameter	:	14.60 m
Overall length	:	21.60 m
Magnetic field	:	4 Tesla

探测器就象一个照相机，将我们感兴趣的碰撞事例照下来，通过**Grid**传到世界各地，科学工作者可以进行远程分析。最后将结果收集起来。

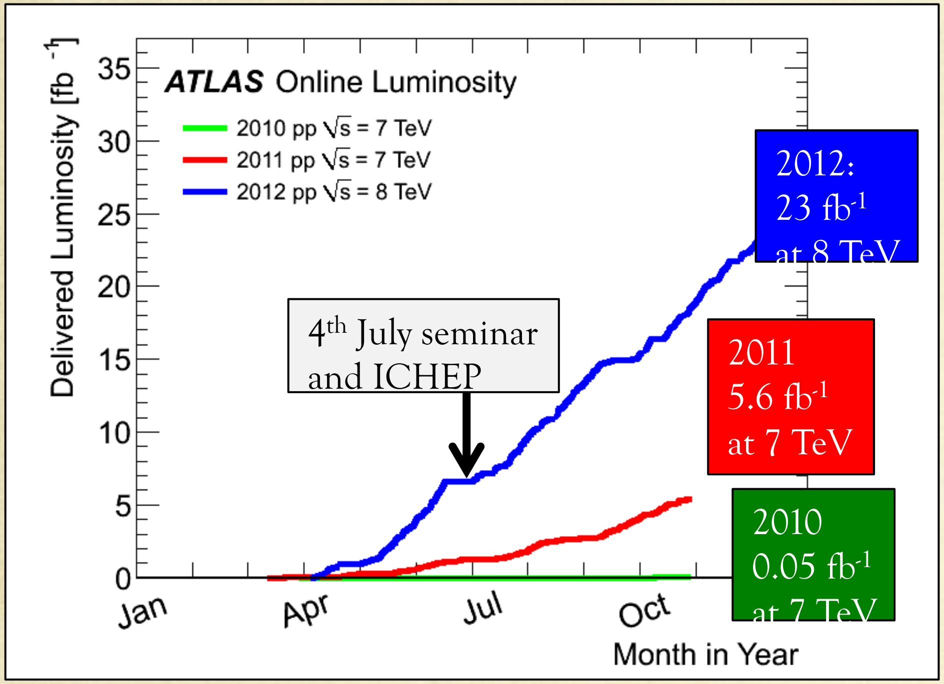
ATLAS 合作组

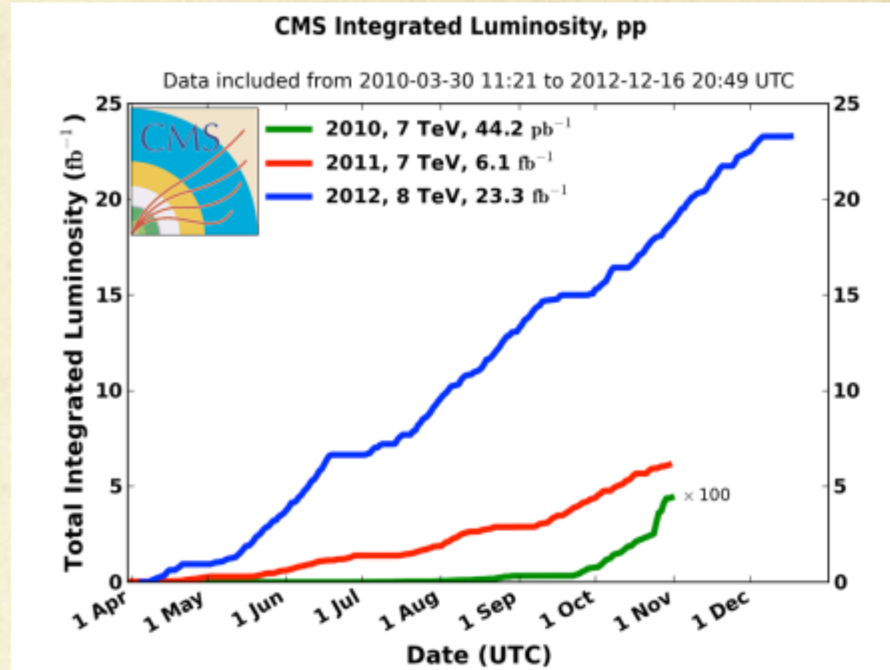
3000 scientists
including 1000 graduate students
38 countries
174 universities and research labs

亮度：运行vs预言


2012 Measured vs Predicted
Integrated Lumi 50 (pb-1)
Measured 50ns (pb-1)
亮度＝收集的数据的多少！！！
能Hold住！！！
25000
20000
15000
10000
5000
0
1/04/12
9/04/12
7/05/12
4/06/12
2/07/12
9/08/12
6/09/12
4/10/12
1/11/12
9/12/12

ATLAS/CMS的数据采集

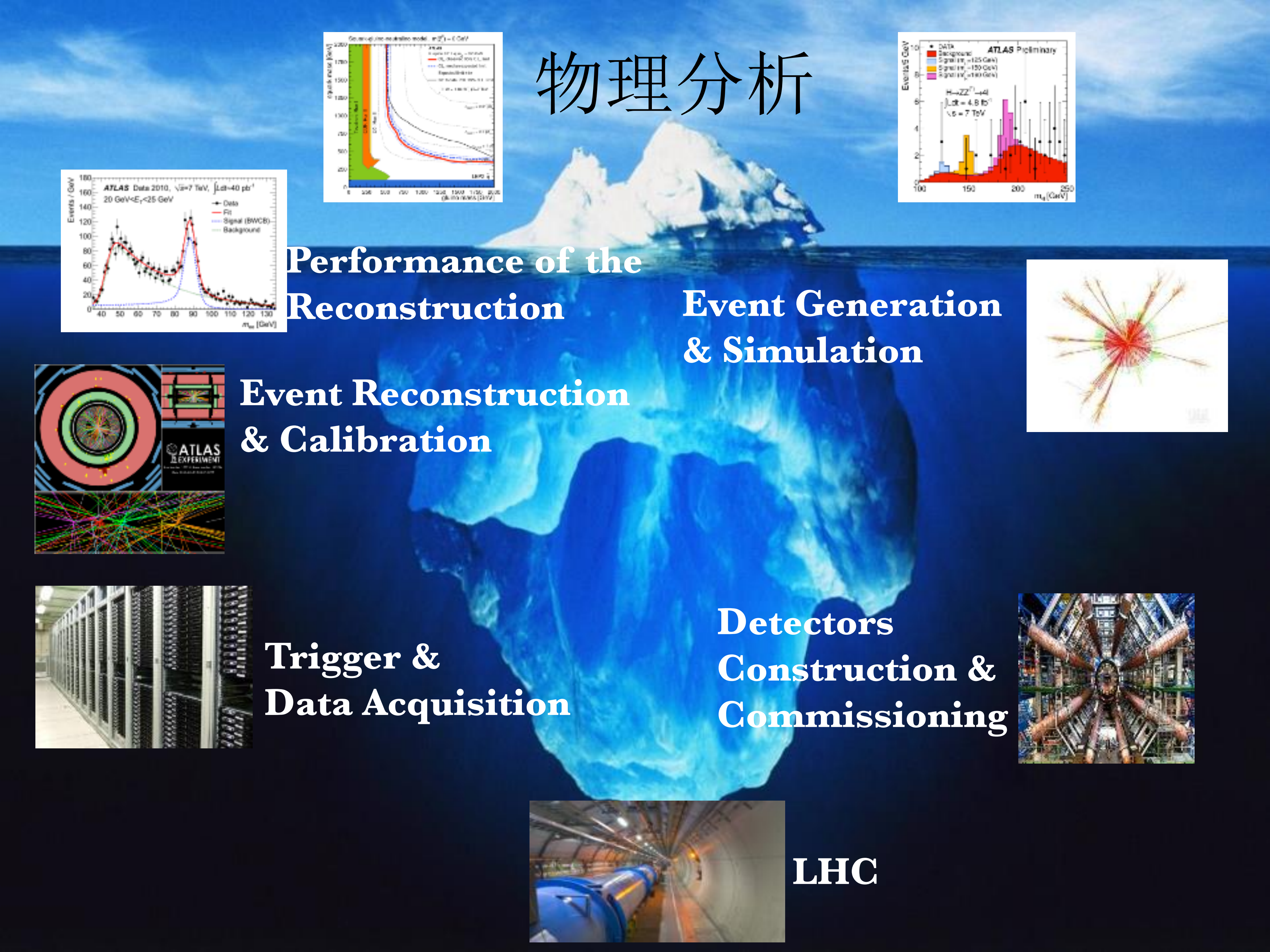




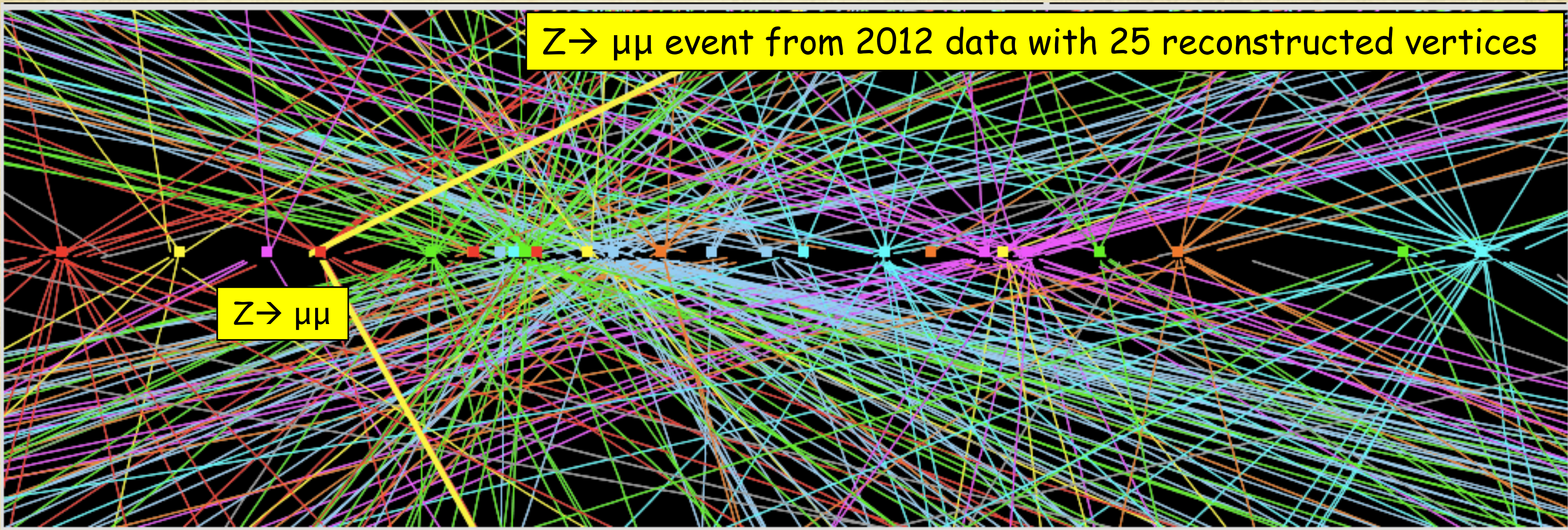
ＬＨＣ是史上最强的粒子产生工厂

目前(ATLAS)上有：

- > 2,000,000,000 W
- > 700,000,000 Z
- > 8,000,000 top pair
- > 600,000 Higgs


物理分析
Performance of the Reconstruction
Event Generation & Simulation
Event Reconstruction & Calibration
Trigger & Data Acquisition
Detectors Construction & Commissioning
LHC

难点 ：Pile-up



简直就是:

荆棘丛生难下足！！！

利用各种技术将它们CUT掉

如何处理数据：网格计算 (Grid Computing)

The Worldwide LHC Computing Grid combines the computing resources of more than 100,000 processors from over 170 computing centers in 36 countries, producing a massive distributed computing infrastructure that provides more than 8000 physicists around the world with near real-time access to LHC data, and the power to process it.

- ~170 computing Centers
- ~36 countries
- ~250K cores
- ~100 million gigabytes of disk (10 million DVDs)

Needles in a haystack

In ATLAS, up to July 4, 2012:

million billion collisions

billion events analyzed

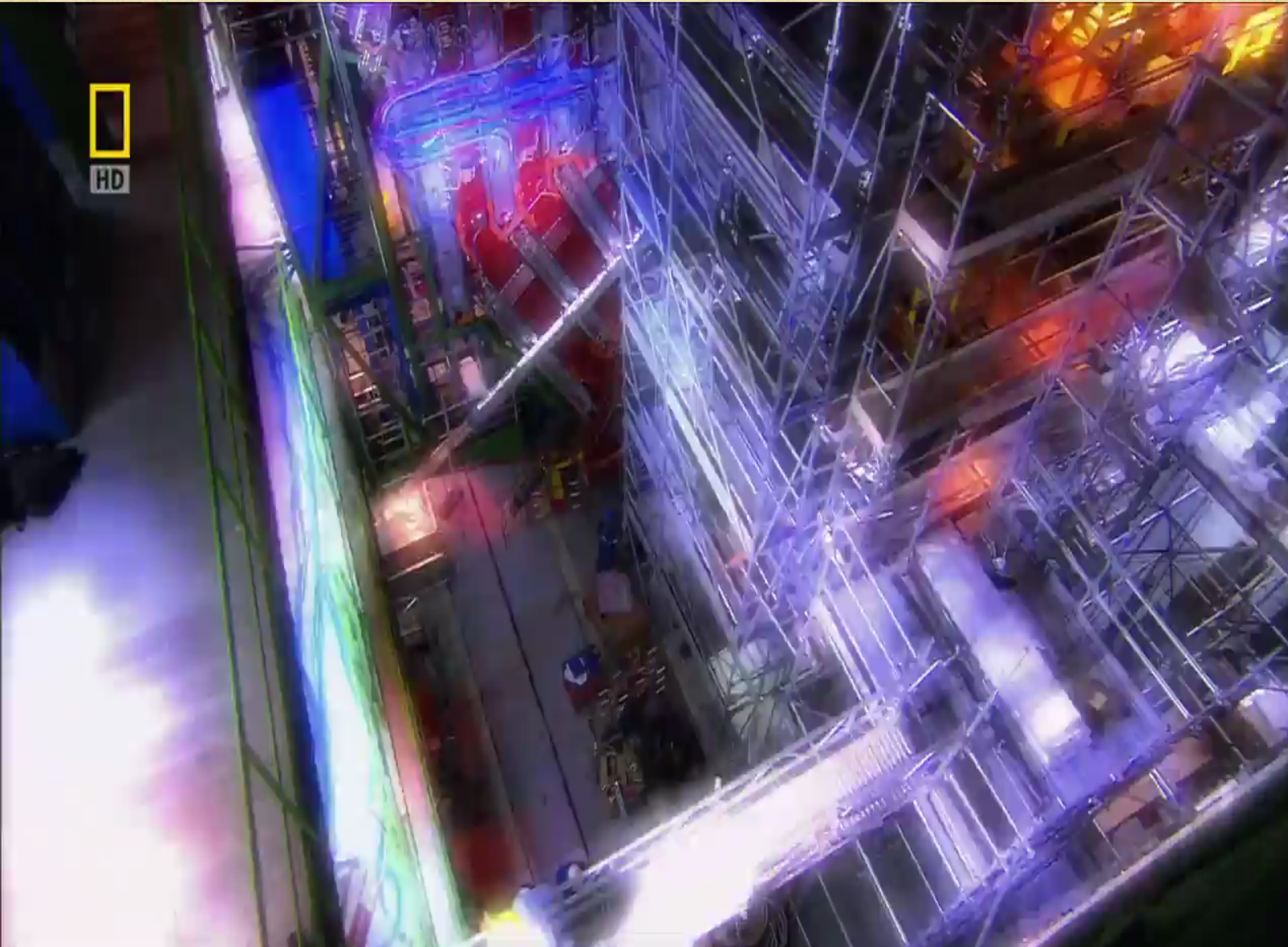
240,000 Higgs particles produced

~350 diphoton Higgs events detected

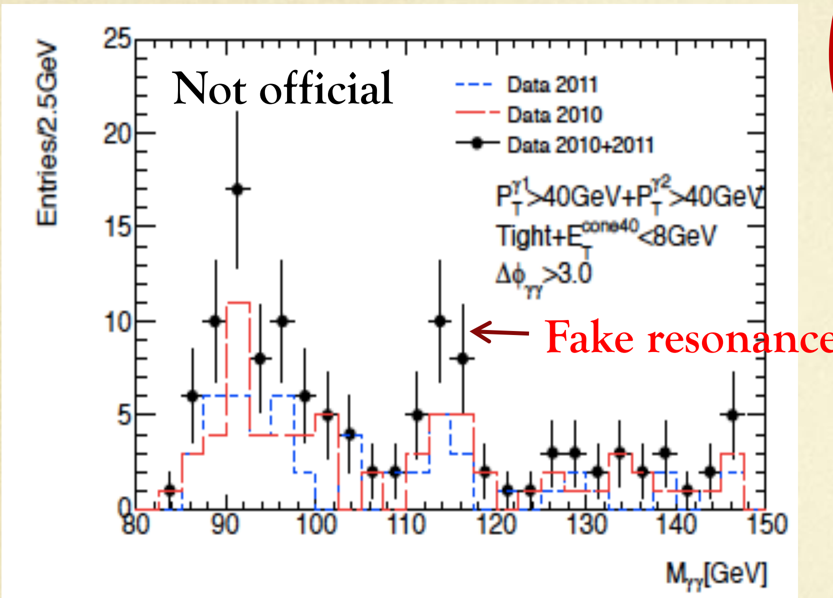
~8 four-lepton Higgs events detected

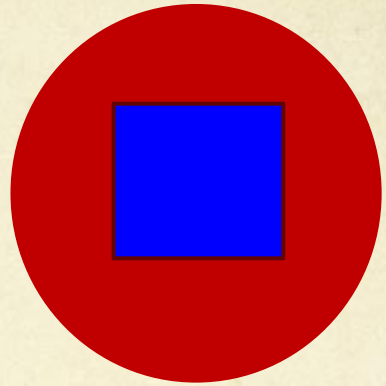
真正的联合国，地球村！！！！

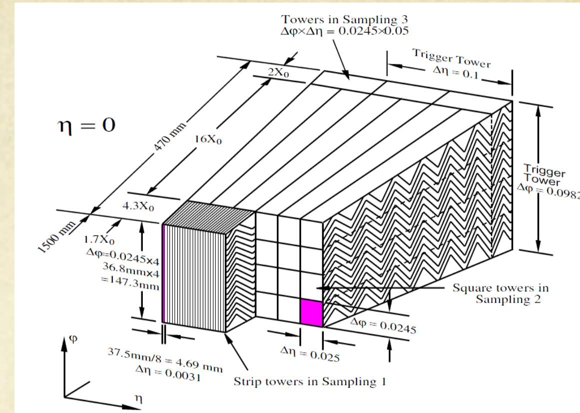
Lessons learned in managing, securing and linking up on this global scale have driven innovation in computing grids all over the world. Grids are being used in the fight against disease, climate change, air pollution, etc.

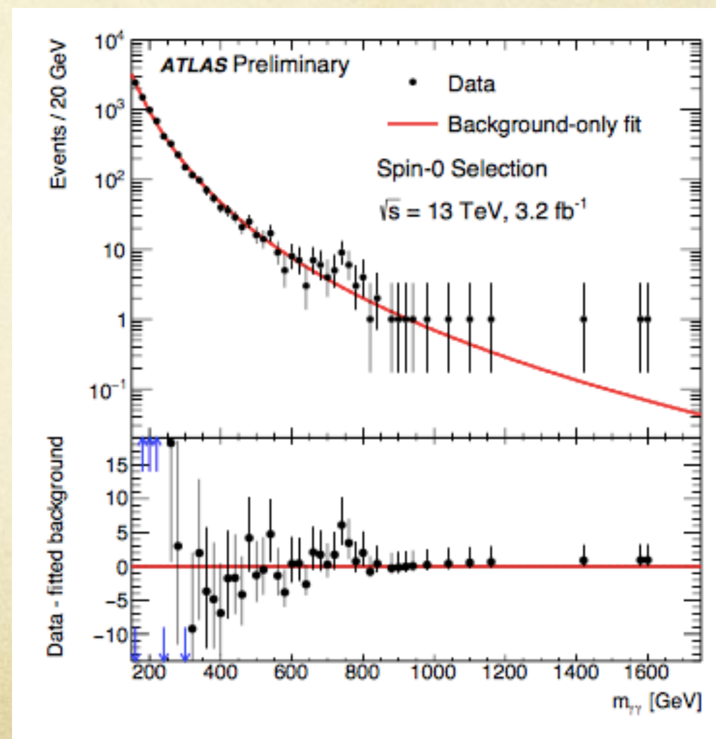

HD

2011复活节的小插曲





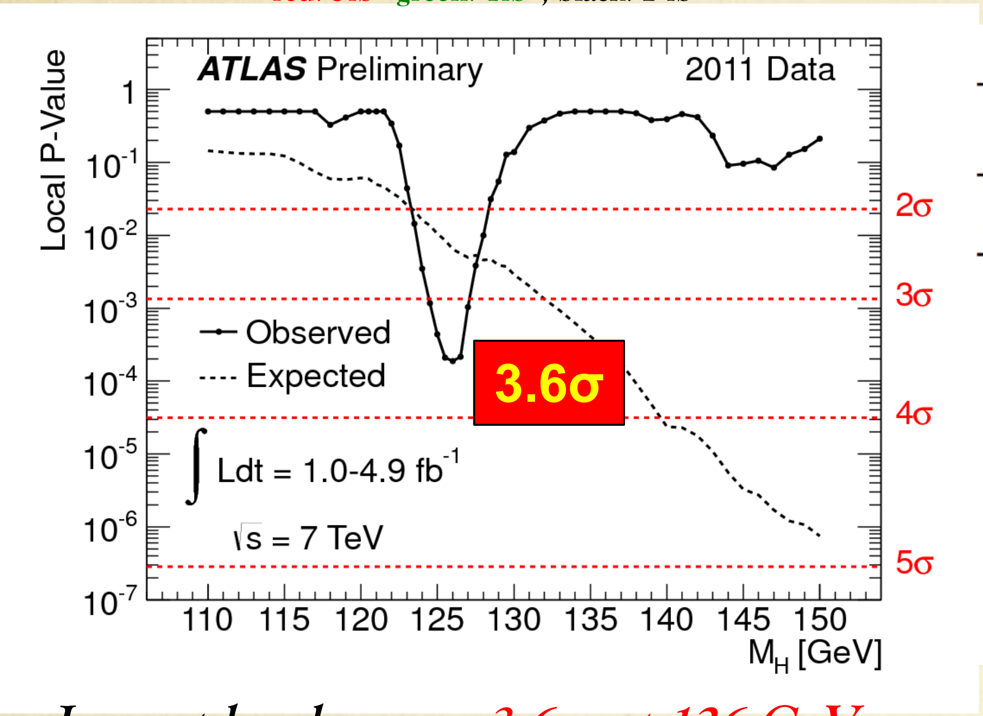




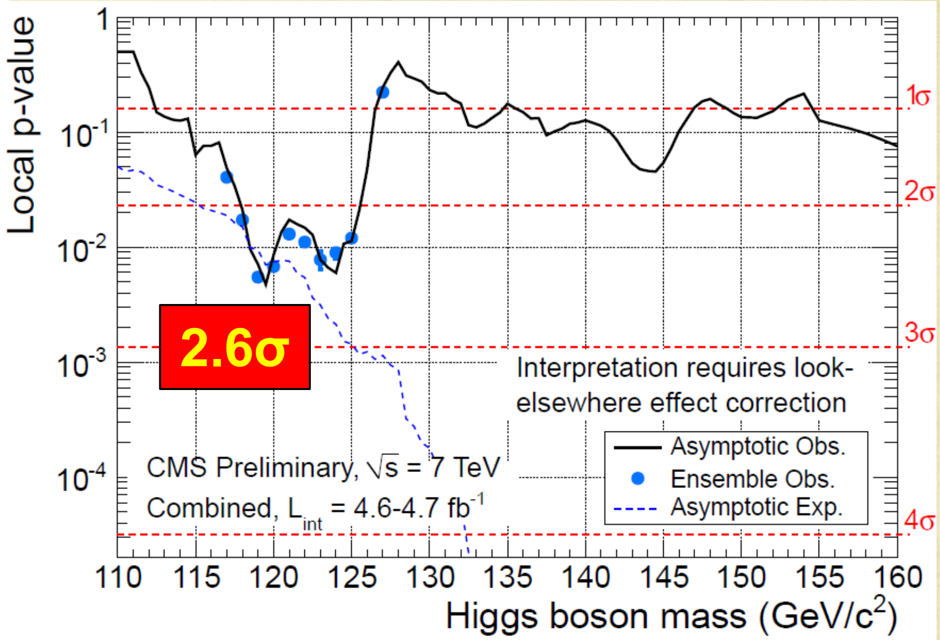
- 该特点是当光子的隔离变松(isolation)，峰值反而变高。从喷注 (jet)而来的伪光子
有这一特点。
- 去年750 GeV的峰也有这一特点。

LHC CERN Council (Dec 2011) Higgs combined

ATLAS $H \rightarrow \gamma\gamma$, $\tau\tau$, WW(lvlv, lvqq), ZZ(4l, llvv, llqq, llbb)
red: 5fb^{-1} green: 1fb^{-1}, black: 2 fb^{-1}



CMS $H \rightarrow \gamma\gamma$, bb, $\tau\tau$, WW(lvlv), ZZ(4l, ll$\tau\tau$, llvv, llqq)



Largest local excess: 3.6σ at 126 GeV

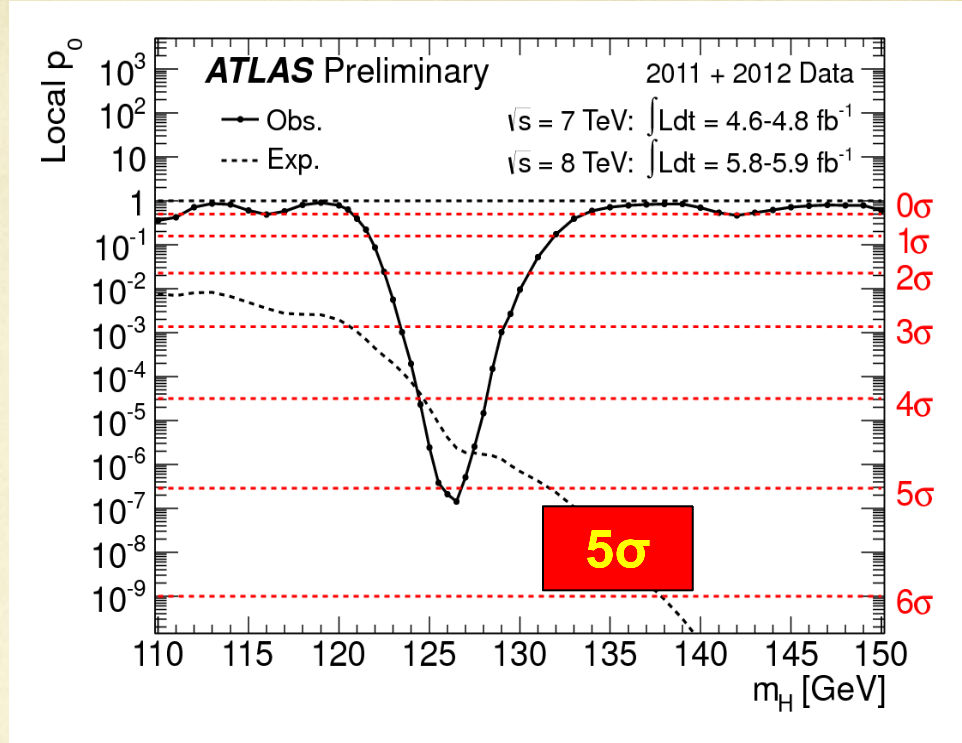
Largest local excess: 2.6σ at ~120 GeV

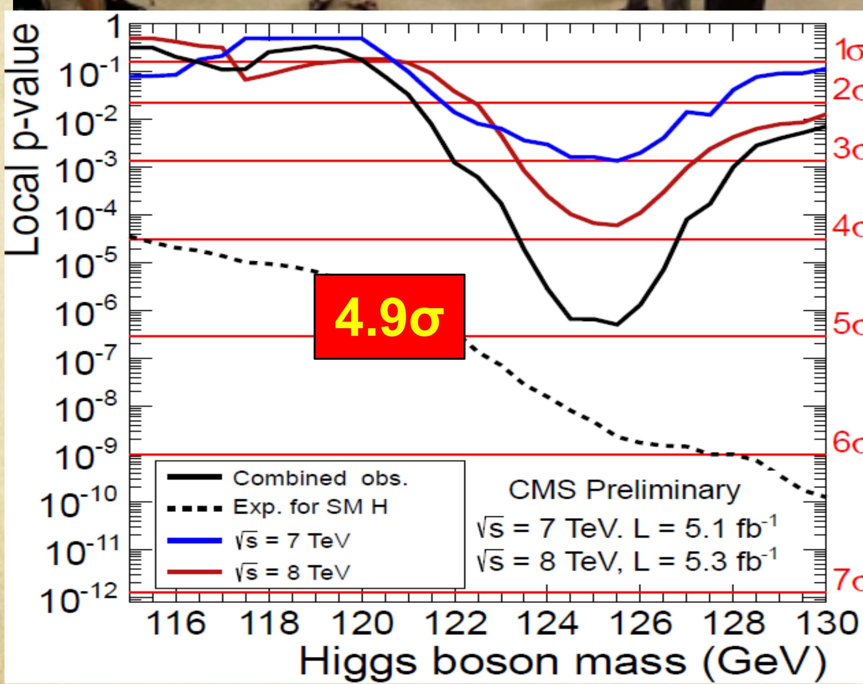
"Tantalizing hints"

Guido Tonelli

Fabiola Gianotti

The discovery on July 4th, 2012





A milestone discovery announced in July, 2012.

- *Both ATLAS and CMS observed a new particle with ~5σ evidence .*
- *Will the signal be confirmed in the additional 2012 data? SM Higgs?*
- *Properties, future?*

We found Higgs

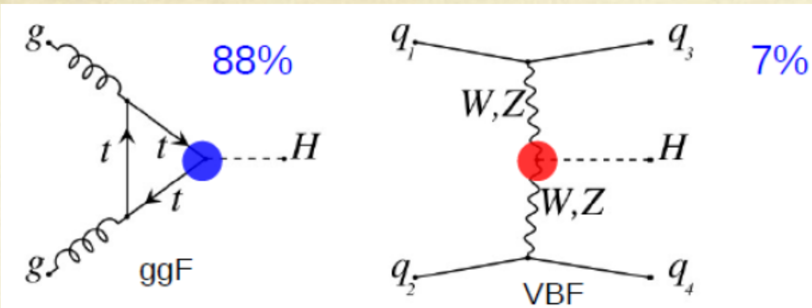
Right after the seminar on July 4th, Sau Lan Wu walked towards Peter Higgs and said :

We have worked for many years looking for you.

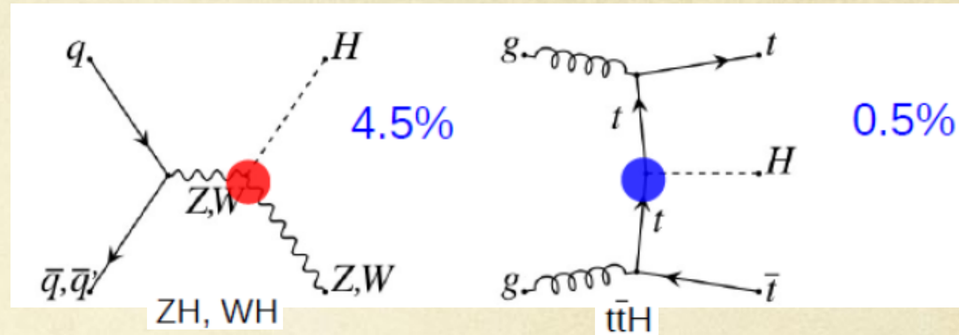
You found me.

Is the New Boson the SM Higgs?

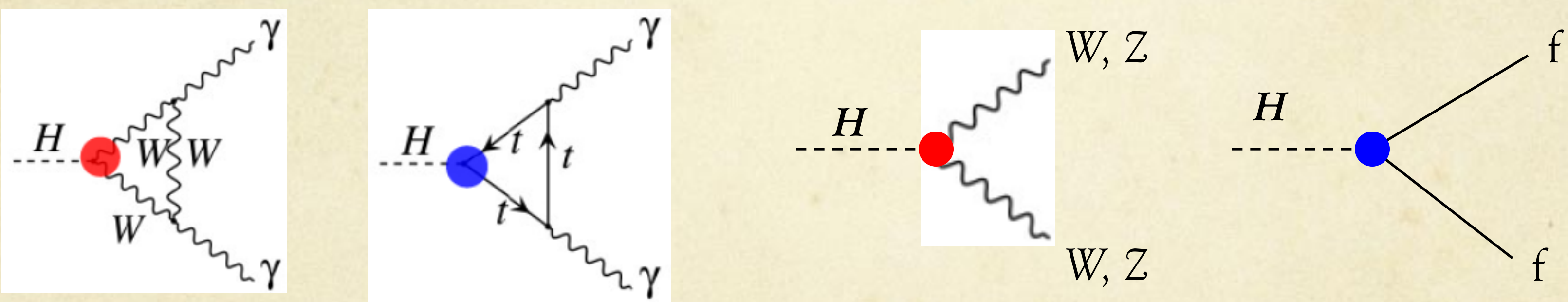
- Signal strength
- Higgs production (m_H = 125 GeV)



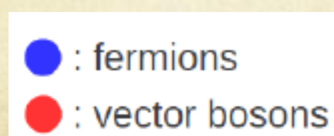
Vector Boson Fusion



- Higgs decays



- Couplings



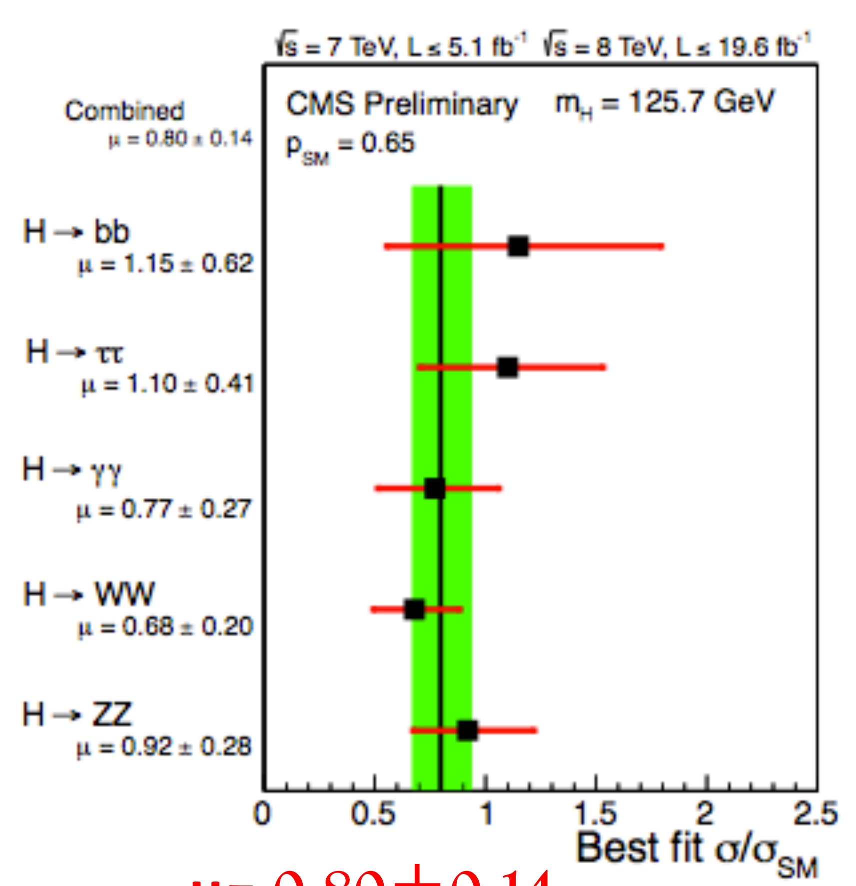
g_F (Yukawa coupling) $=\sqrt{2} \times m_F/\nu$

g_V (Gauge coupling) $= 2m_V^2/\nu$

(ν is the vacuum expectation value)

- Spin-Parity

Signal strength



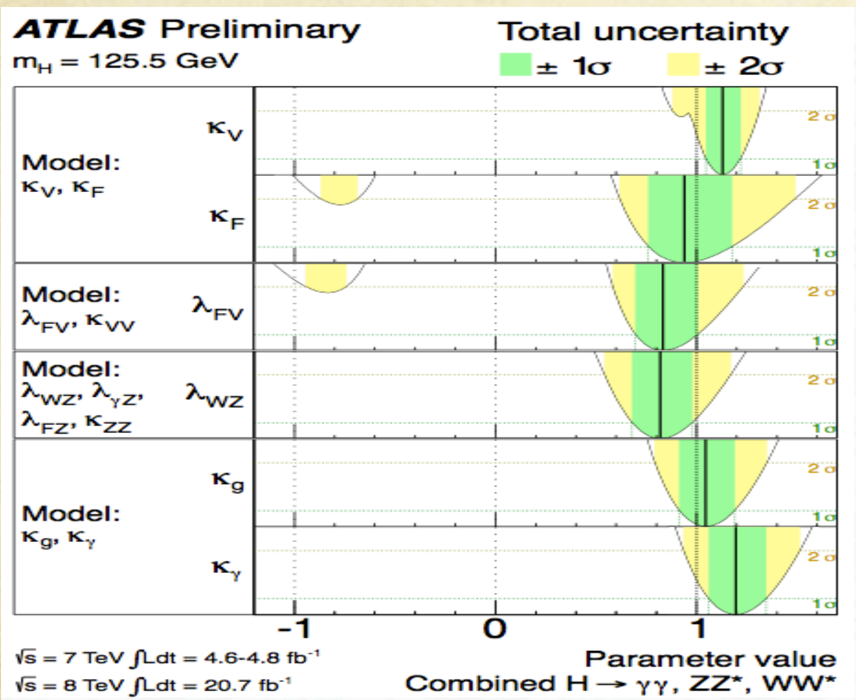
$\mu = 0.80 \pm 0.14$

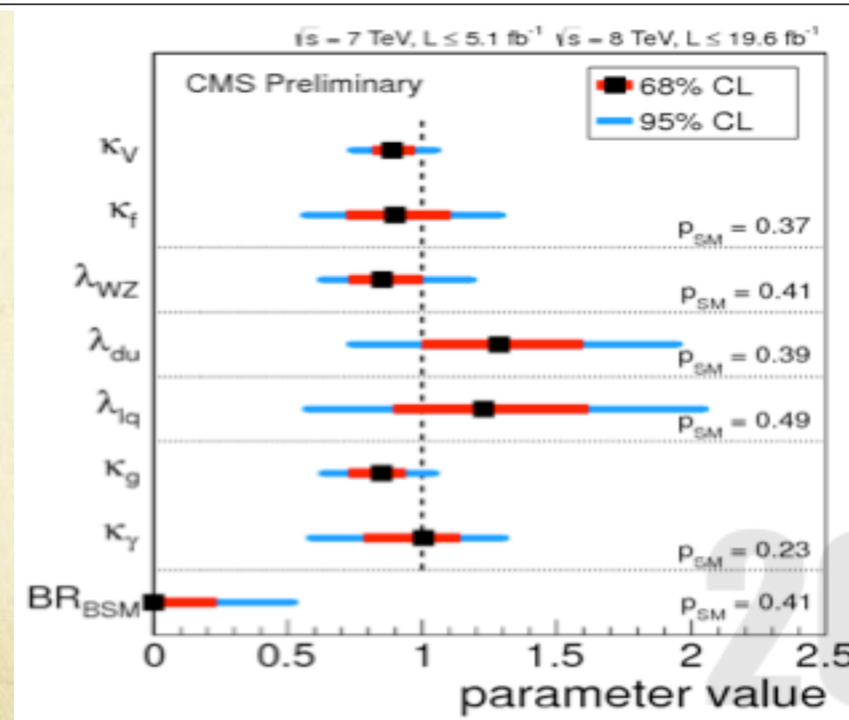
- **Consistent with SM prediction within 2σ.**
- **Systematic and theoretical uncertainties become more and more important.**

Coupling Measurements

Coupling strengths κ_i & ratio: $\kappa_F = g_F/g_{F,SM}$, $\kappa_V = g_V/g_{V,SM}$, $\lambda_{ij} = \kappa_i / \kappa_j$

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$

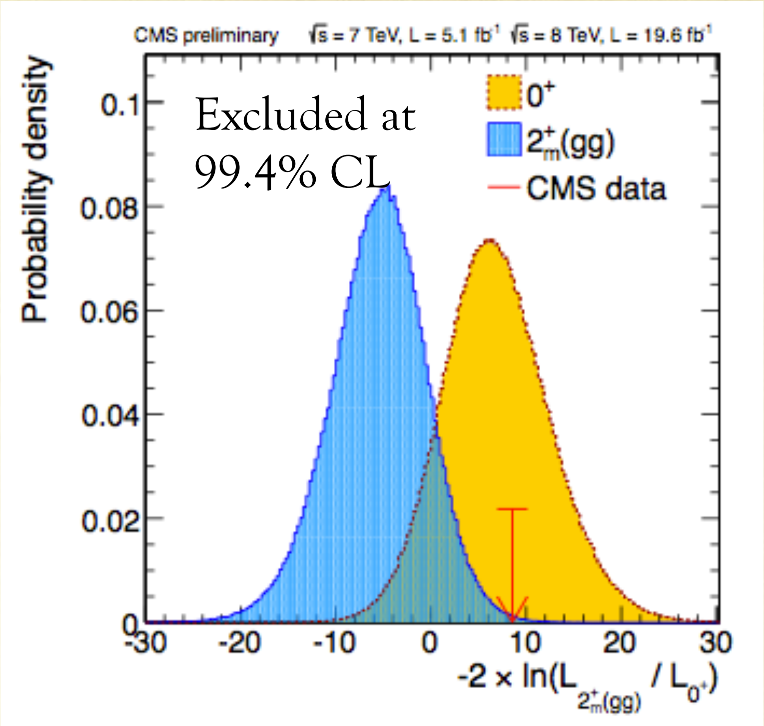


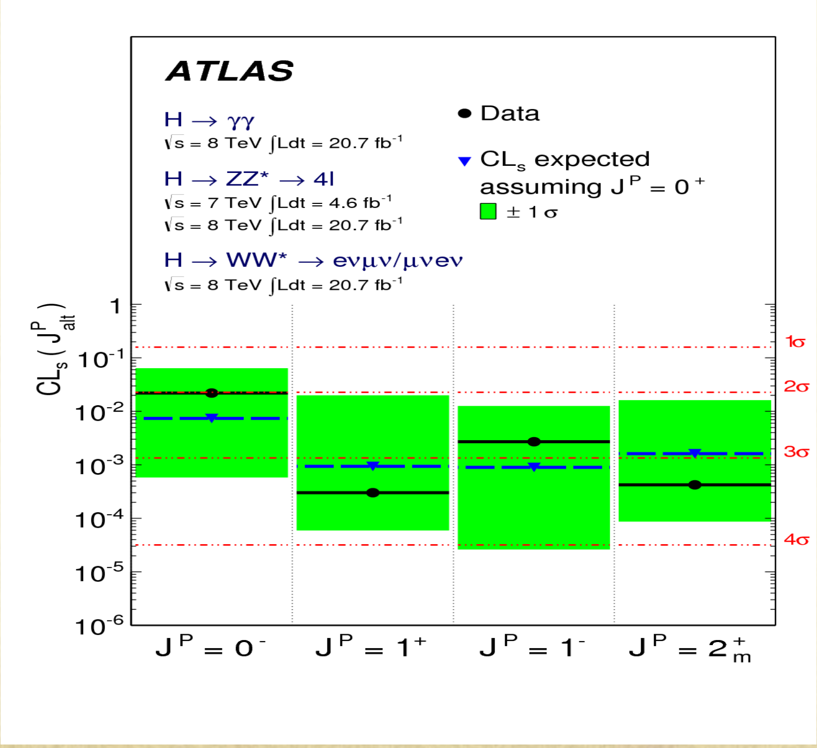


Agree with SM within 2σ.

Summary results for Spin study

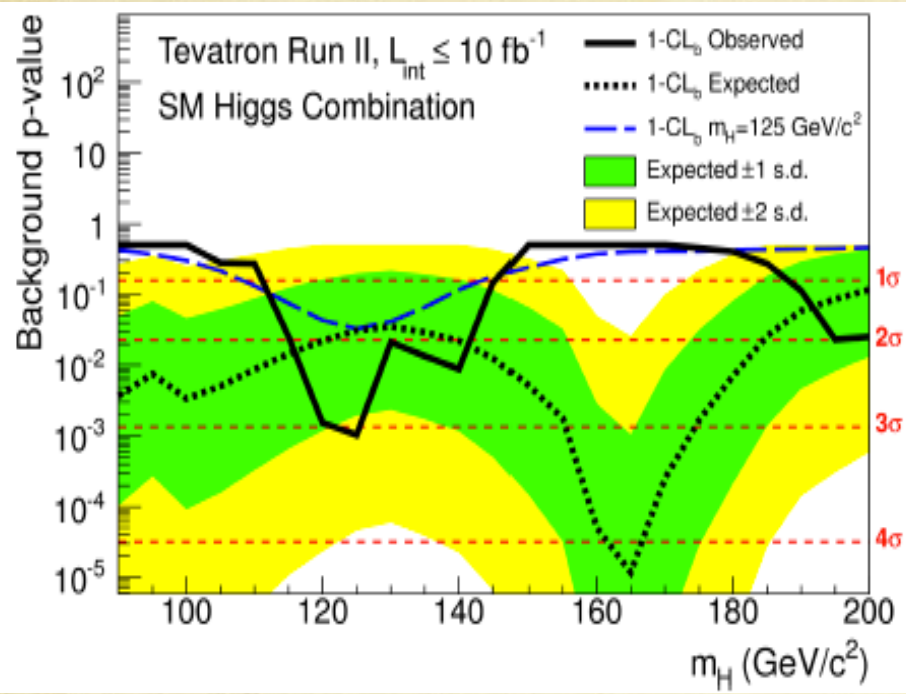
- 0^- hypothesis excluded at 97.8% CL in favor of 0^+ by H→ ZZ*→ 4l analysis
- 1^+ and 1^- excluded at 99.7% CL, respectively by WW and ZZ analysis
- 2^+ excluded at 95.2% to 99.96% CL

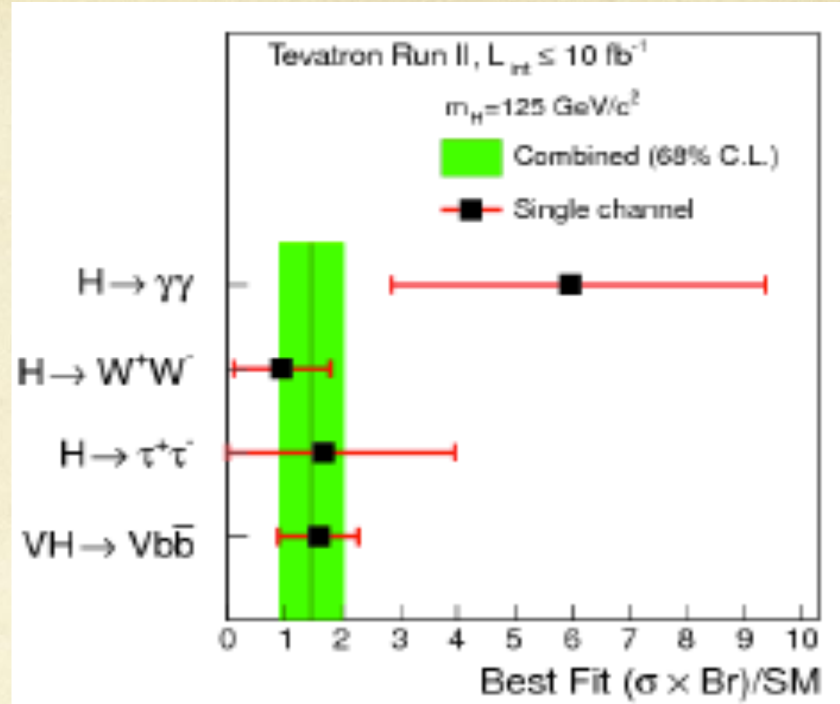


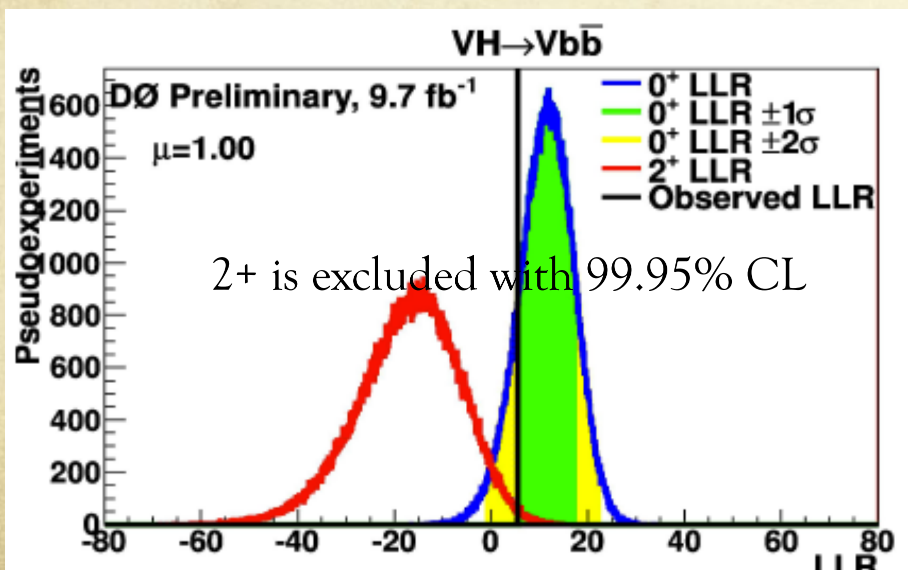


– Spin 1 is strongly disfavored with the observation of H→γγ.
– Data favor the SM Higgs 0^+

Tevatron result



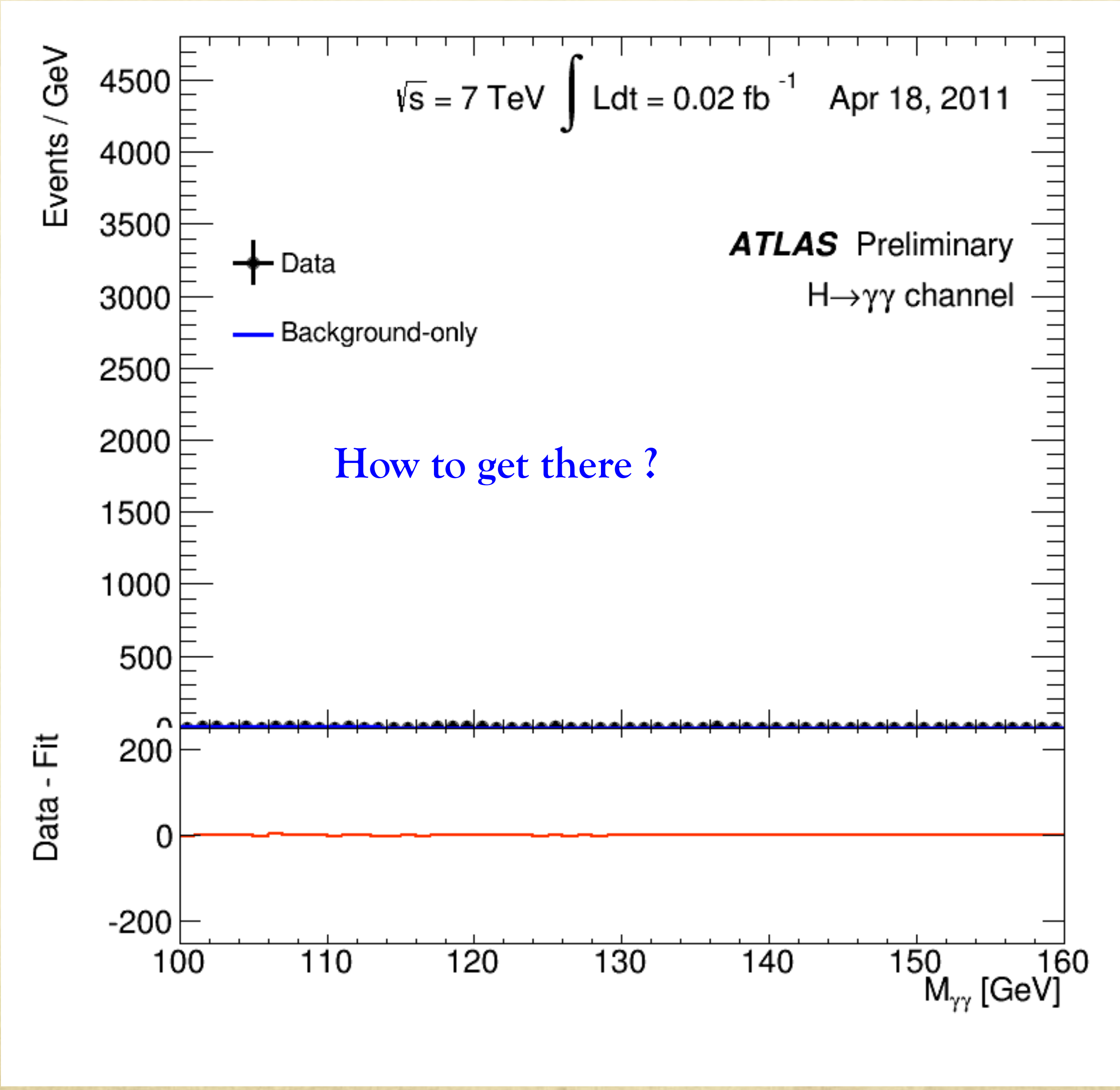




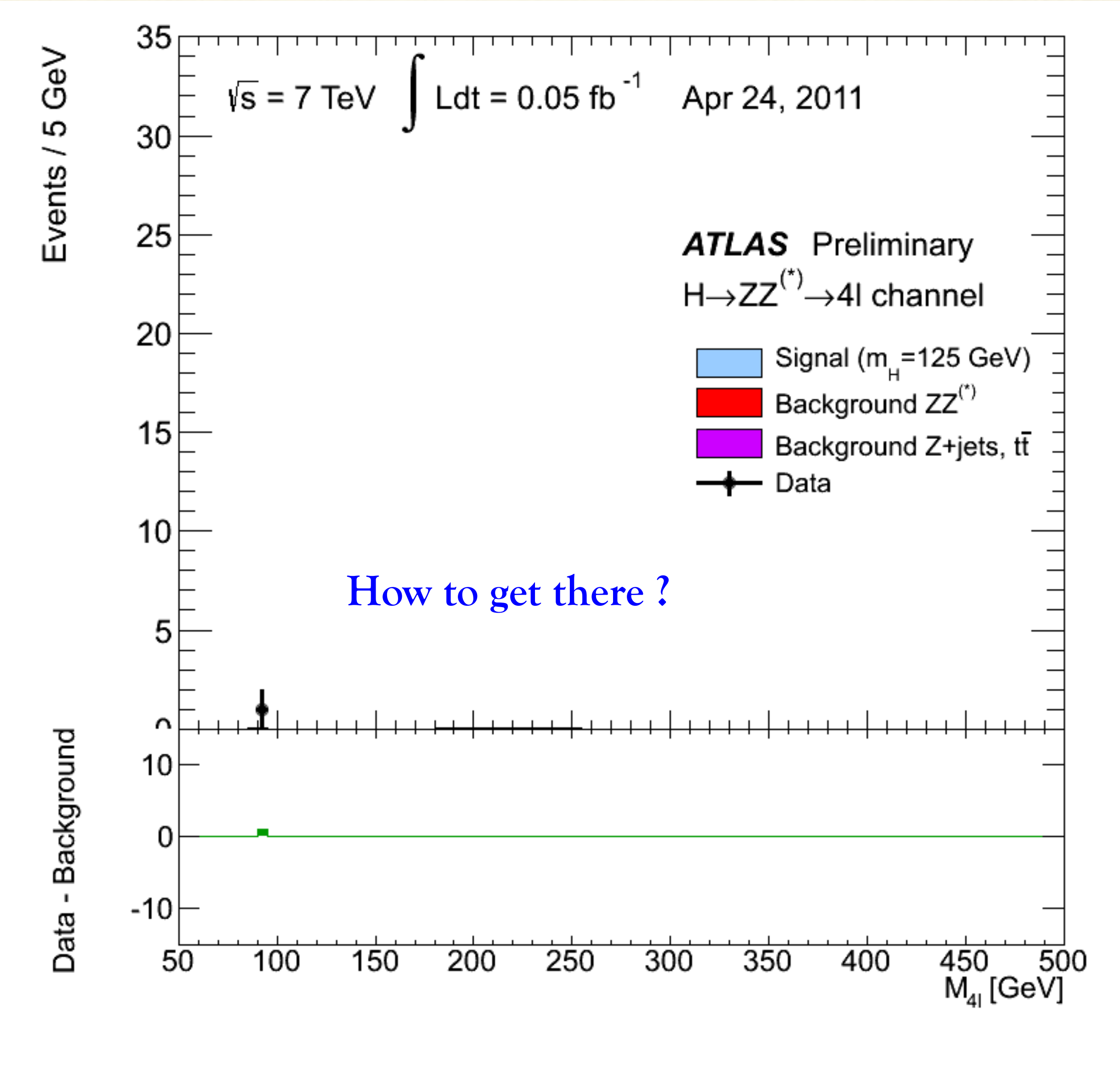
- Tevatron observes 3σHiggs as well.
- The main contribution is from VH(bb).
- Spin 2 Higgs is excluded with 99.95% CL.

H→ γγ (Moriond EW 2013)

ATLAS

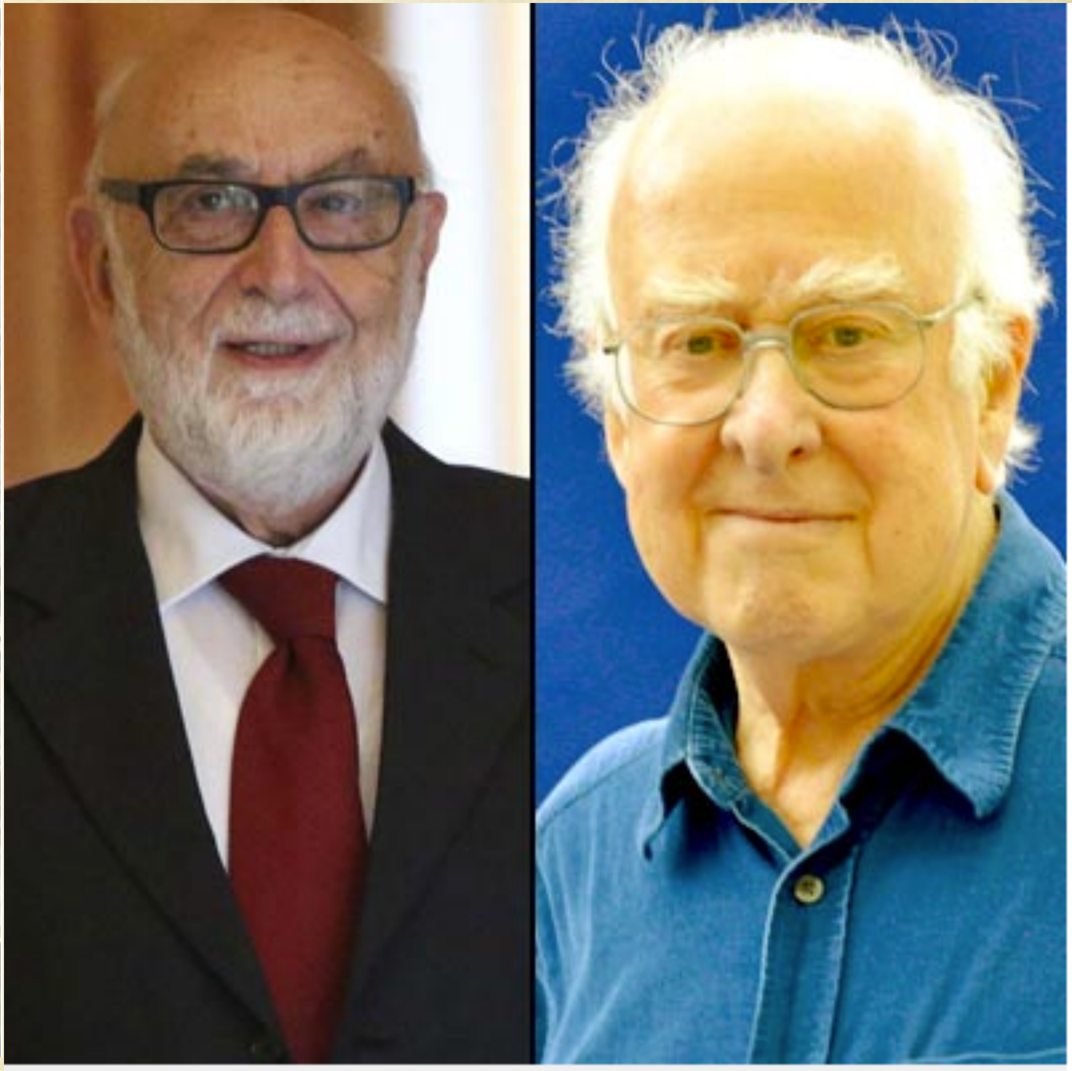


H→4 leptons (Moriond EW 2013)



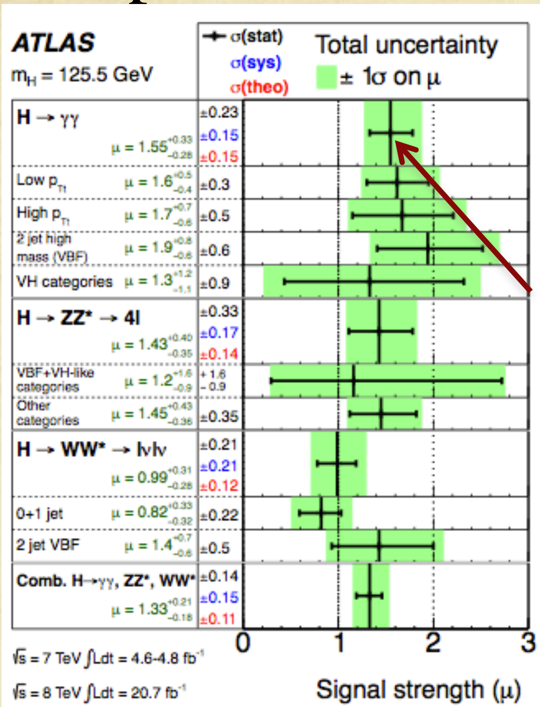
ATLAS

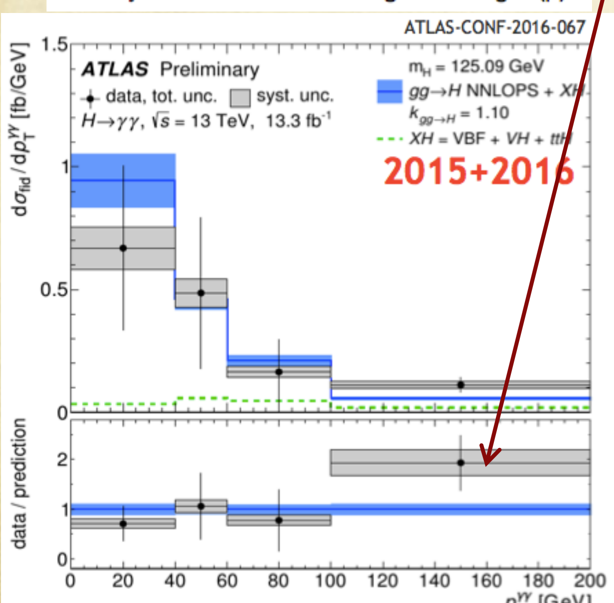
Breakthrough is awarded



The Nobel prize in 2013: François Englert and Peter Higgs

Topics after Higgs discovery (BSM di-Higgs search)

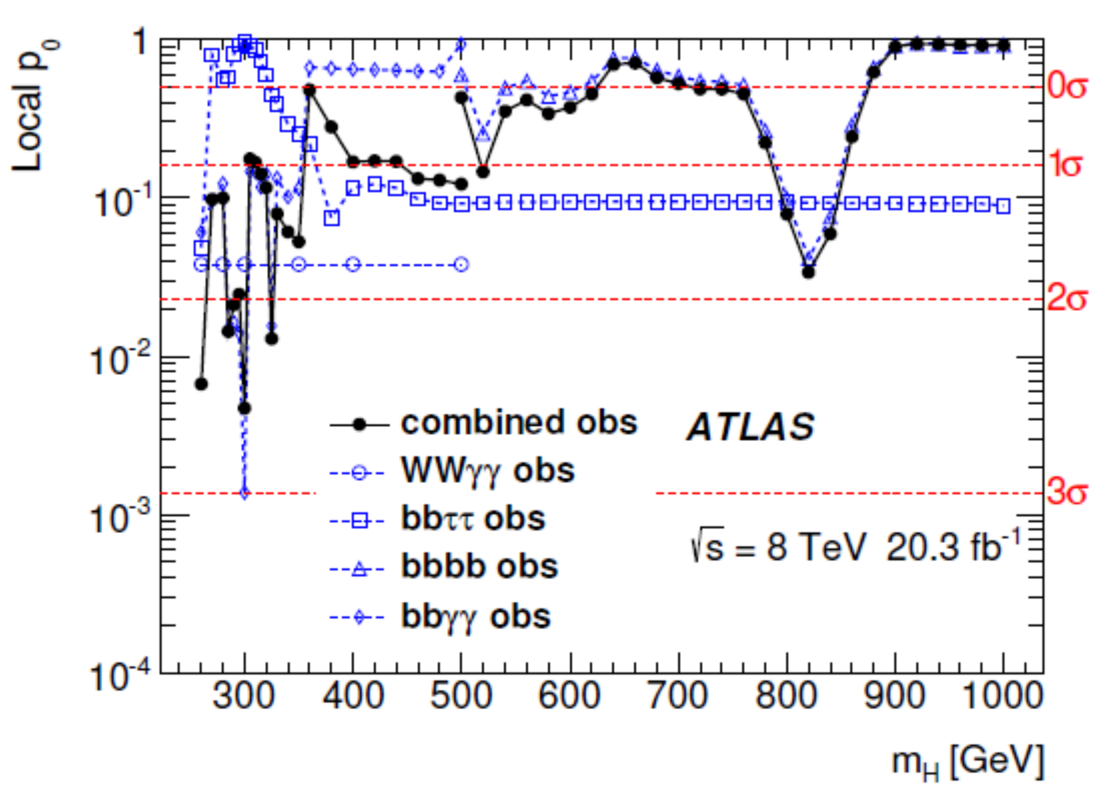


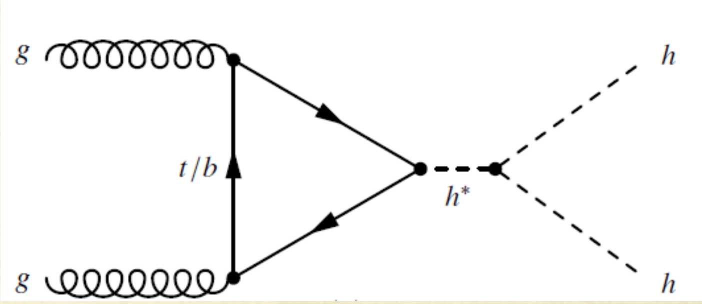


a bit excess *One Higgs* → *"Multi-Higgs"*

- The measurements of the signal strength are consistent with SM prediction within 2σ.
- Some channels (e.g. Di-photon) still show some deviation.
- It is possible that some Beyond Standard Model (BSM) Higgs mixed inside?

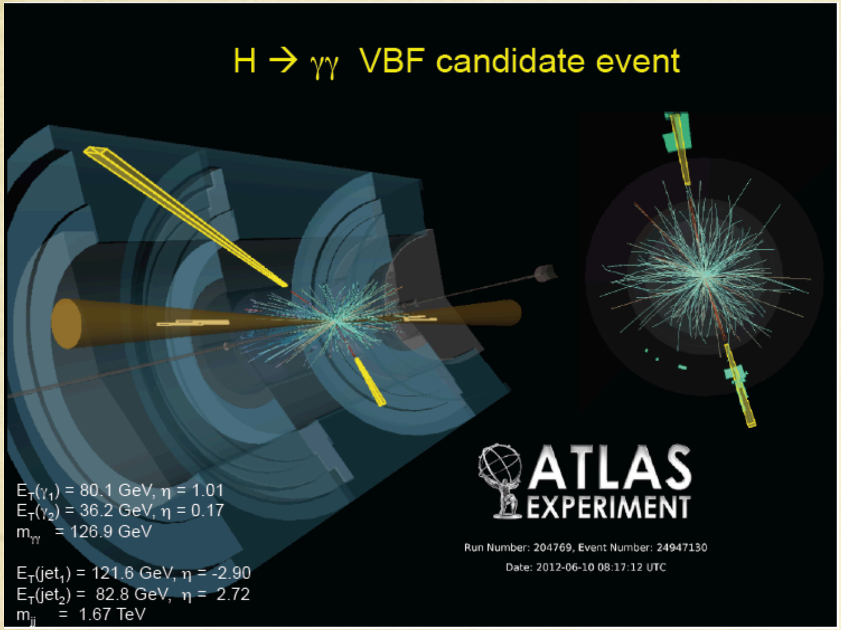
Combination of H->hh->γγbb, γγWW, tautaubb,4b

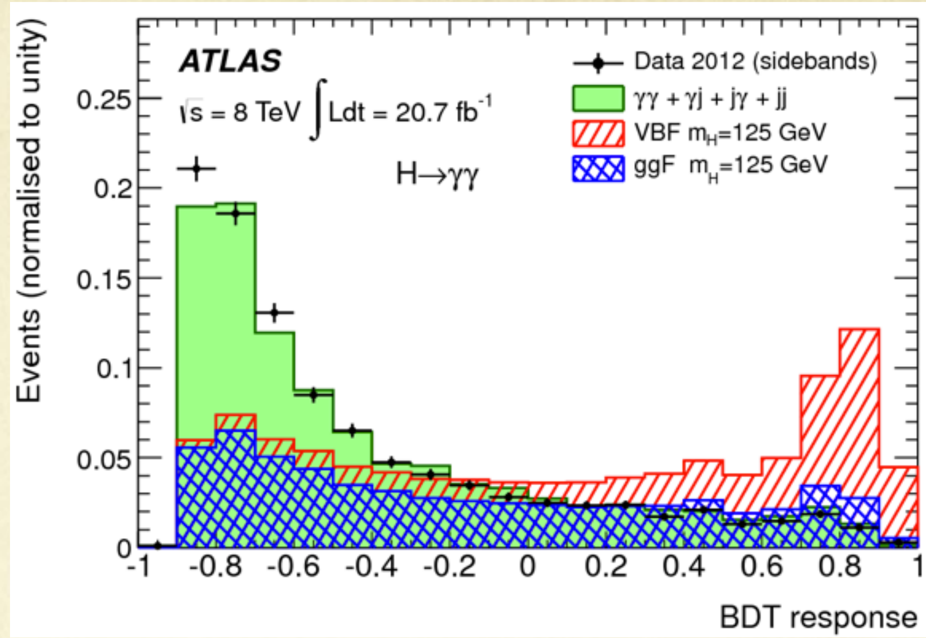




- Due to the downward fluctuation of tatutaubb, the overall significance is 2.5σ.
- No excess with Run2 data.

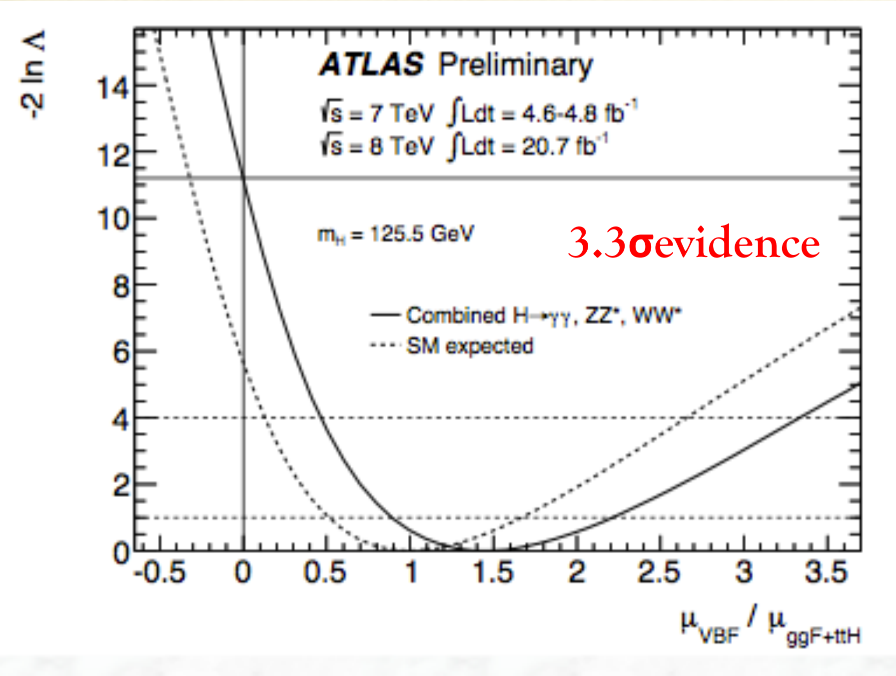
其它希格斯产生模式 VBF

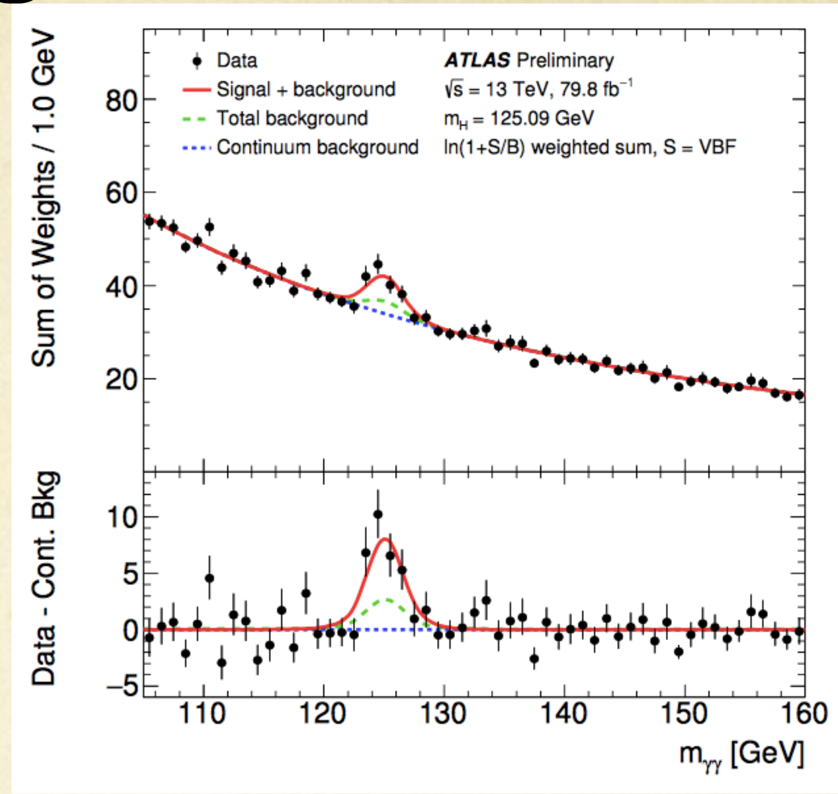




- VBF process has the event signature with 2 forward jets and no much jet activity in the central region.
- MVA (BDT) can maximize the discriminating power of the signal from the background.
  - Improvement is above 10-20% w.r.t cut based one.

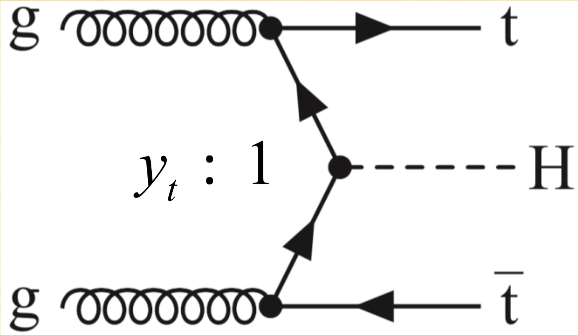
VBF Higgs





- First 3σ VBF Higgs evidence has been seen with ATLAS detector with RUN1 data.
- The most important contribution to the 125.5 GeV VBF Higgs is from $H \rightarrow \gamma\gamma$
- With the combination between ATLAS and CMS with RUN1 data, one observed 5.4σ.
- With Run2 data, combining channels $H \rightarrow \gamma\gamma, WW, ZZ, \tau\tau$ with ATLAS detector, we observed 6.5σ/5.3σ(observed/expected)

Observation of ttH Production



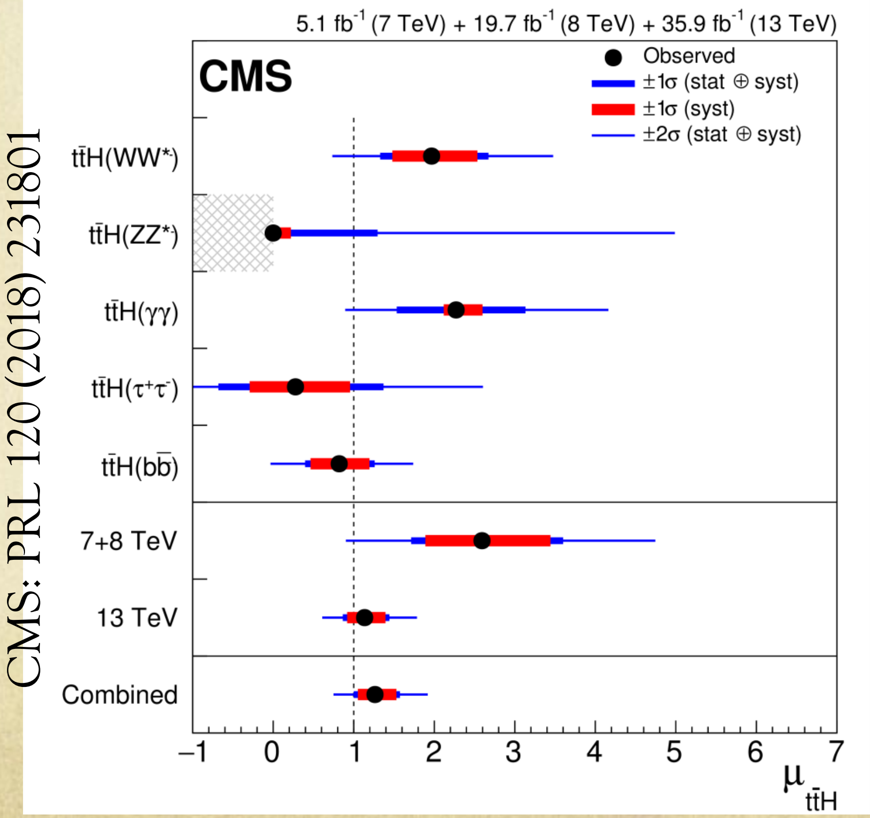
CMS: $\mu = 1.26^{+0.31}_{-0.26}$ $(8+13 \text{ TeV data})$

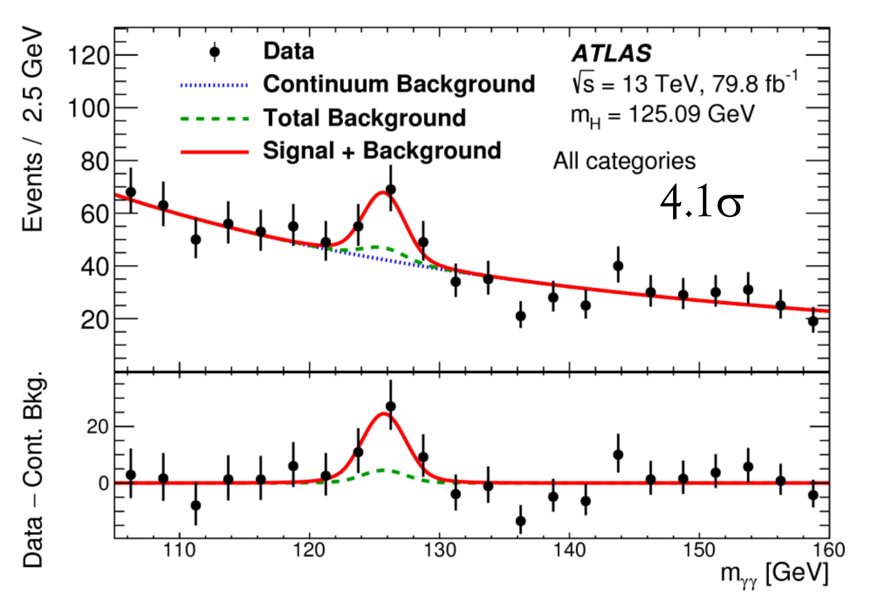
$5.2\sigma(4.2\sigma)$ observed (expected)

ATLAS: $\mu = 1.32^{+0.28}_{-0.26}$ $(13 \text{ TeV data only})$

$5.8\sigma(4.9\sigma)$ observed (expected)

CMS: PRL 120 (2018) 231801





ATLAS: 1806.00425

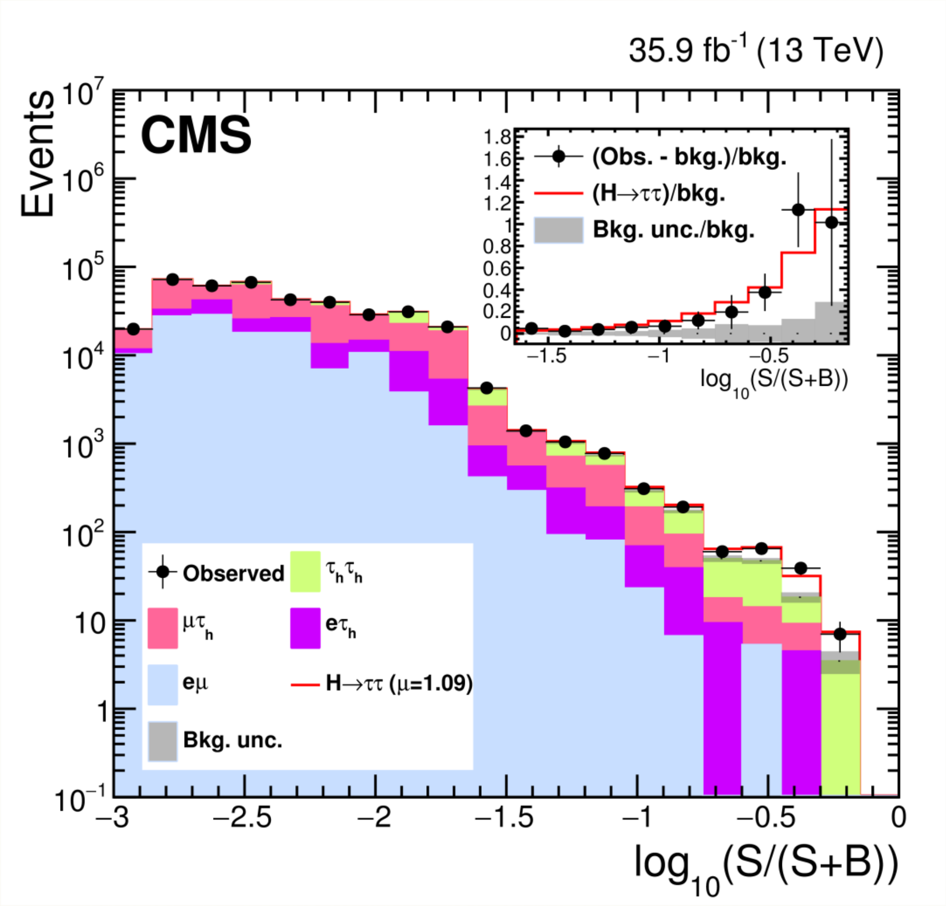
H→ττ decay

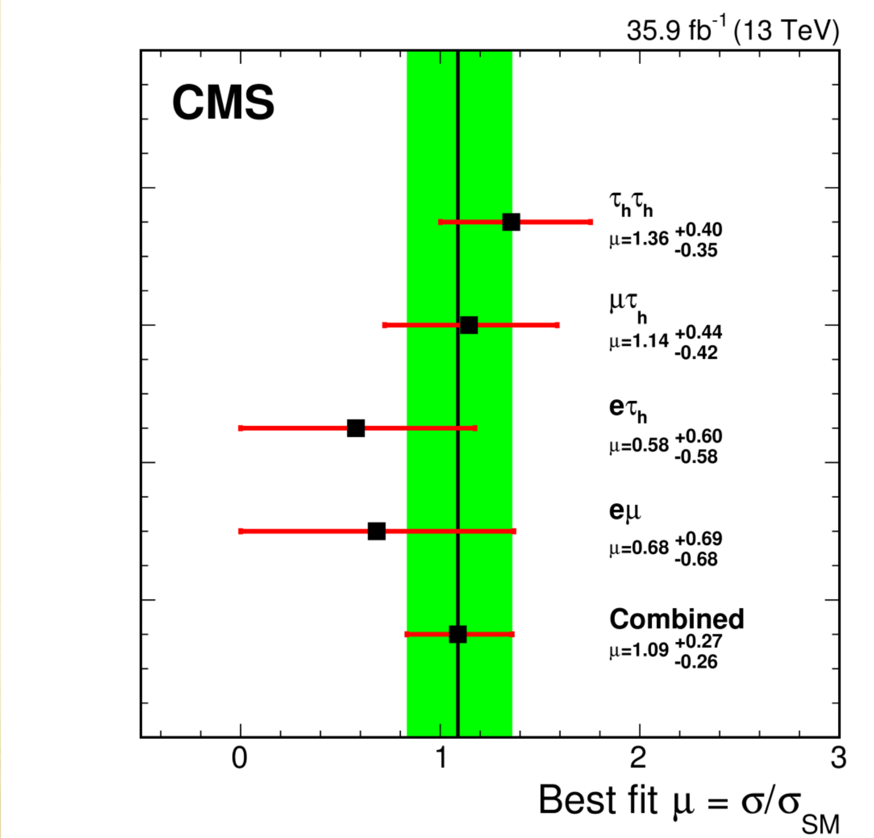
Run 1 + Run 2

Observation from both experiments:

ATLAS: $6.4\sigma\,(5.4\sigma)$ observed (expected)

CMS: 5.9 observed

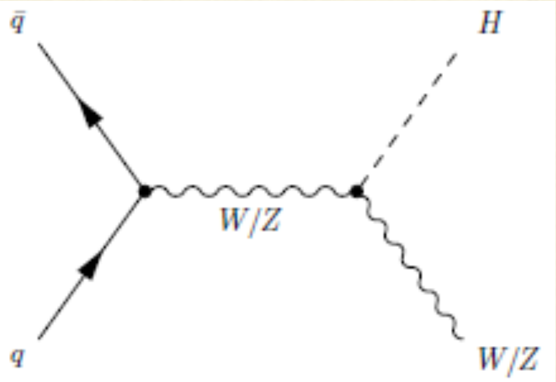




ATLAS: ATLAS-CONF-2018-021; CMS: PLB 779 (2018) 283

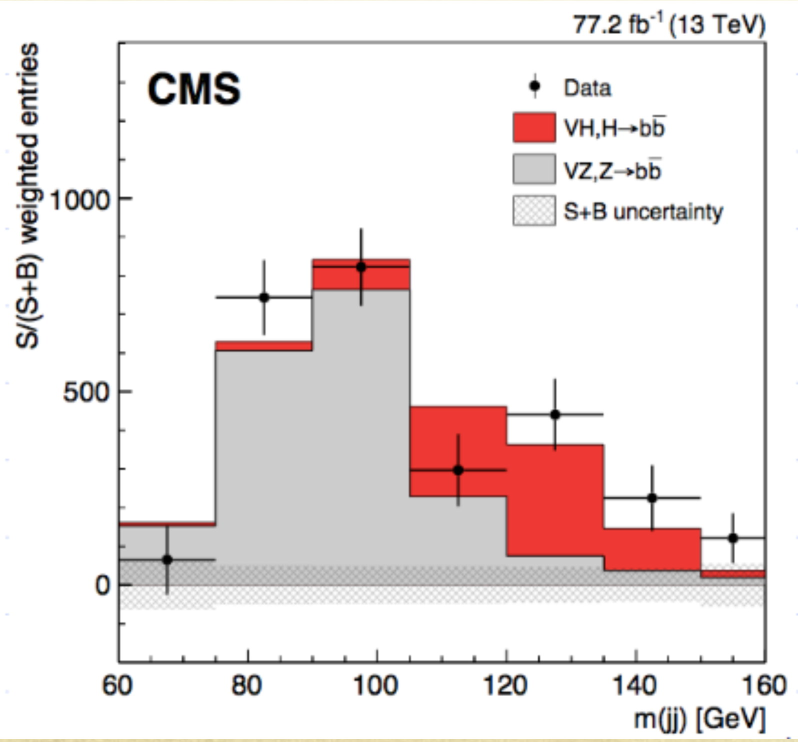
VH Production with *H→bb* decay

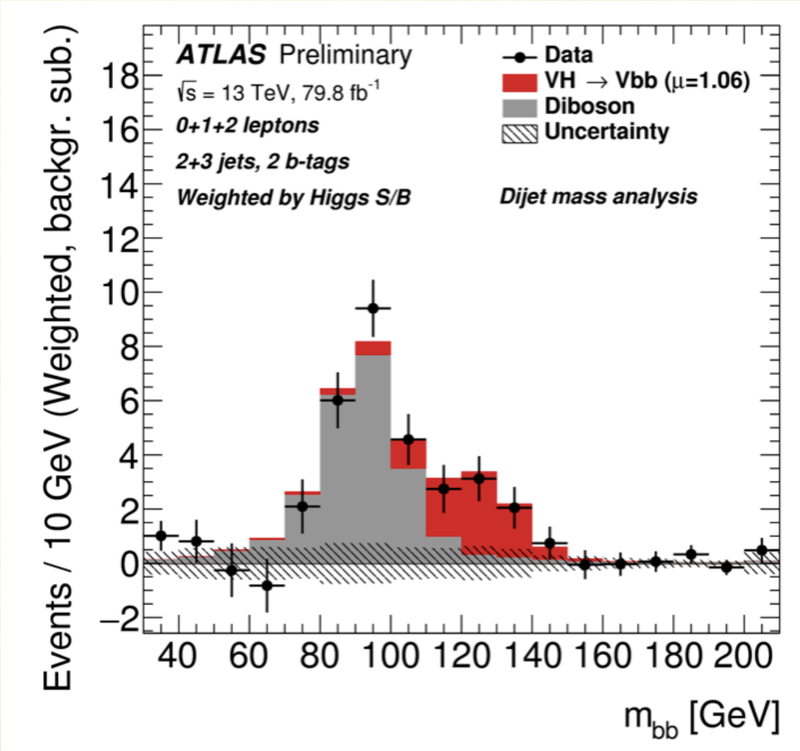
Run 1 + Run 2



ATLAS: 5.4σ/5.5σ (observed/expected)
CMS: 5.6σ/5.5σ (observed/expected)

VZ/VH with $Z/H \to bb$

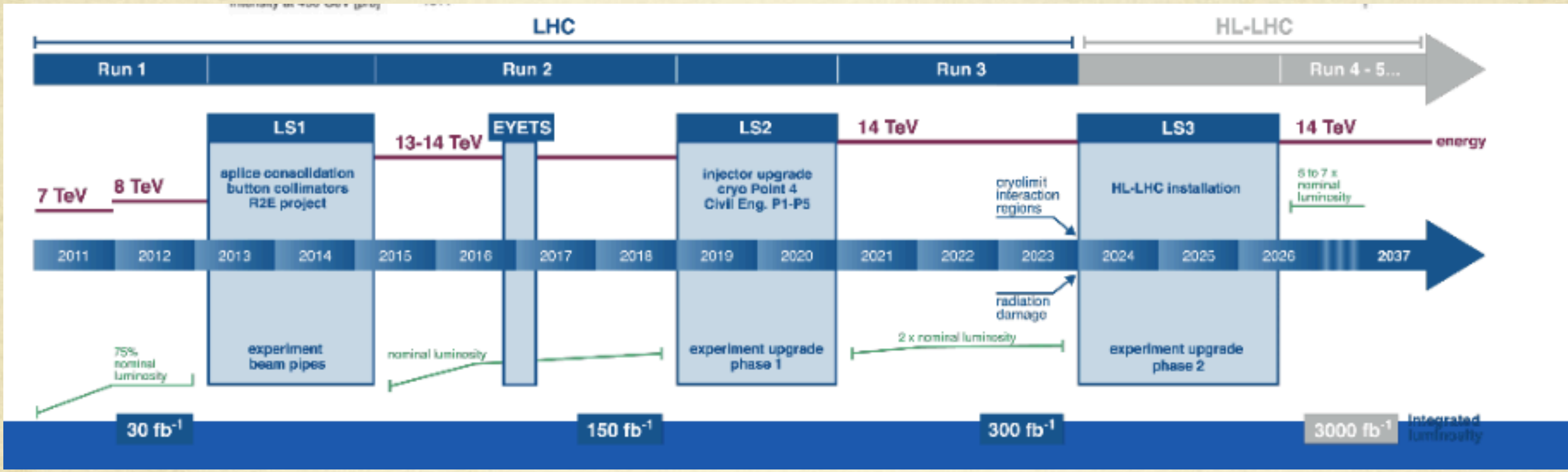




ATLAS: ATLAS-2018-036 CMS: PLB 780 (2018) 501
CMS: PRL 121(2018) 211801

Forward looking

Forward looking of LHC

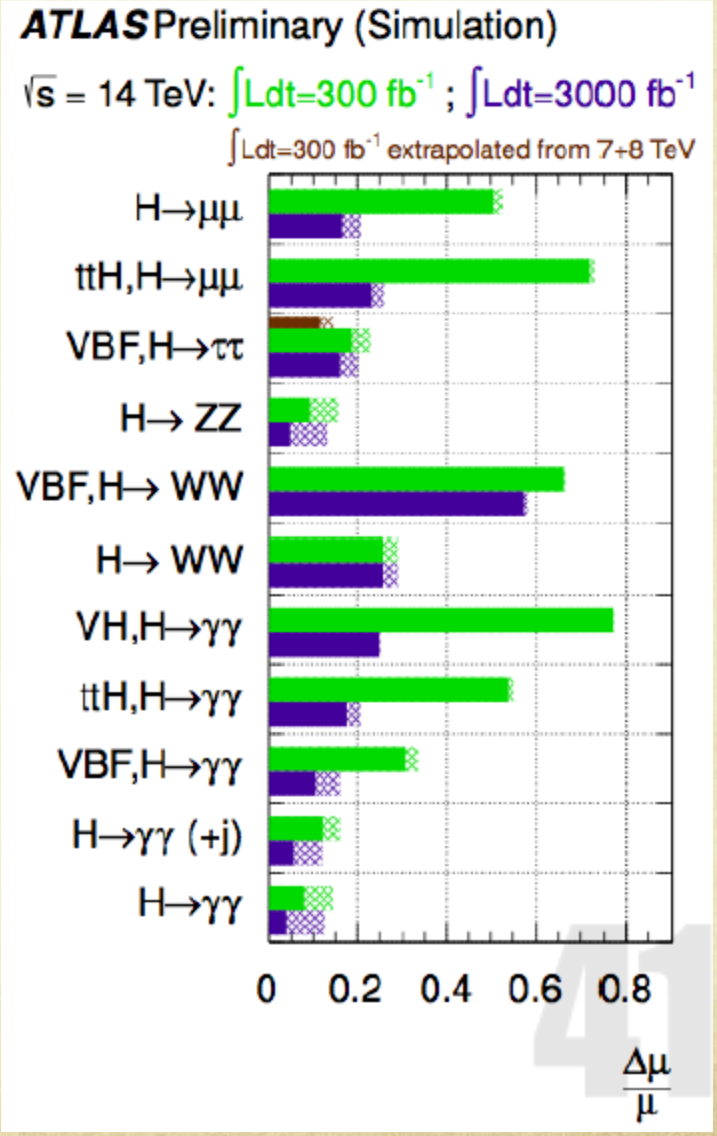


30 fb^{-1} (done)

- ✓ A lot of things can be done with Run2 considering the lum. will be 300 fb^{-1} around 2023
- ✓ More precise measurement of Higgs.
- ✓ VBF Higgs, VH, ttH, BSM Higgs.
- ✓ Explore wide phase space in SUSY, Dark matter, exotic, CP violation etc..

Exciting Physics in the future

- LHC :14 TeV; 400 fb^{-1}, 3000 fb^{-1}
- Precision Higgs physics
  - Establish fermion decay signals
  - Precision coupling measurements
  - Observe rare decay modes, including Higgs self interactions
- Study of vector boson scattering – key processes to connect EWSB
- Continue to search for BSM Higgs – if there are more scalar particles?
- Dark Matter signature ?
- Suppersymmetry (still highly motivated)
  - Weakly produced new physics
  - Significantly increase chargino-neutralino mass sensitivity from ~350 GeV to ~ 1TeV
- Explore unknown at 14 TeV!

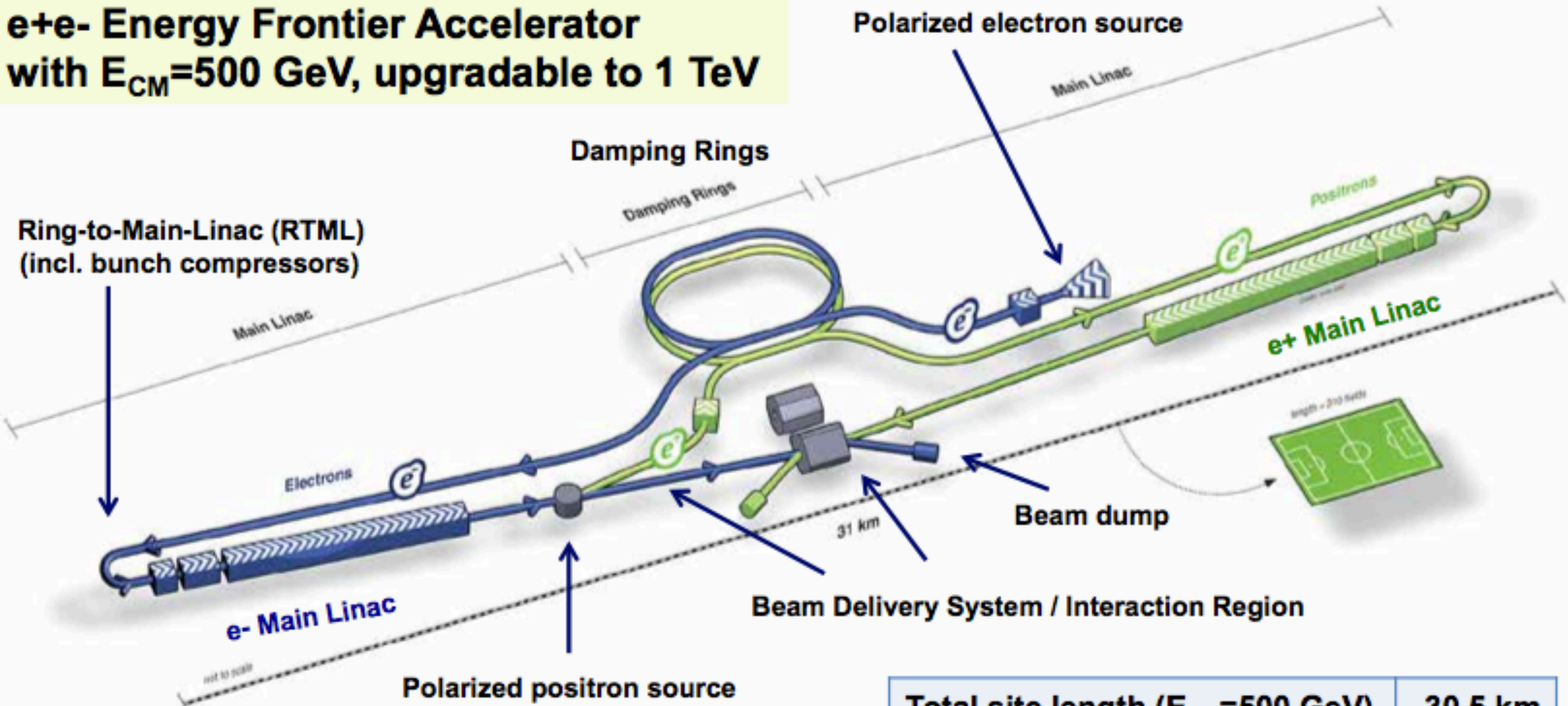


Higgs factories (希格斯工厂)

- Precise measurement of the Higgs property, coupling, etc.
  - For e+e- collider, background is cleaner.
  - Low theoretical uncertainties.
- Can be upgraded to new hadron collider.
  - New physics at TEV level.
    - Susy, dark matter, etc.

Japan: International Linear Collider

e+e- Energy Frontier Accelerator with E_{CM}=500 GeV, upgradable to 1 TeV



# of DRFS Klystrons: 7280

# of Cryomodules: 1680

# of SRF Cavities: 14560

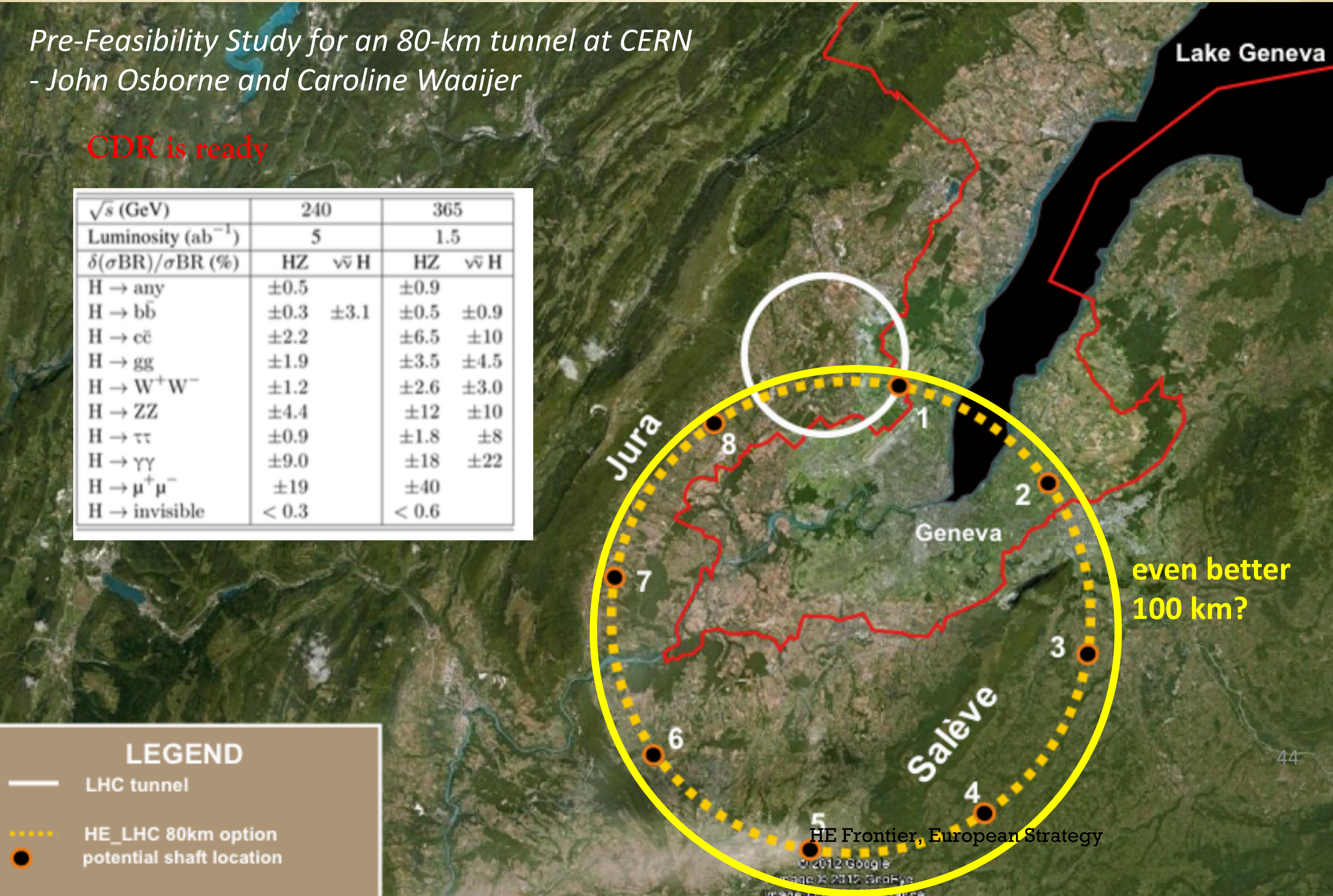
Total site length (E_{CM}=500 GeV)	30.5 km
SRF Main Linac	22.2 km
RTML (bunch compressors)	2.8 km
Positron source	1.1 km
BDS / IR	4.5 km
Damping Rings (circumference)	3.2 km

European Strategy

Pre-Feasibility Study for an 80-km tunnel at CERN
- John Osborne and Caroline Waaijer

CDR is ready

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to ZZ$	±4.4		±12	±10
$H \to \tau\tau$	±0.9		±1.8	±8
$H \to \gamma\gamma$	±9.0		±18	±22
$H \to \mu^+\mu^-$	±19		±40	
$H \to$ invisible	< 0.3		< 0.6	

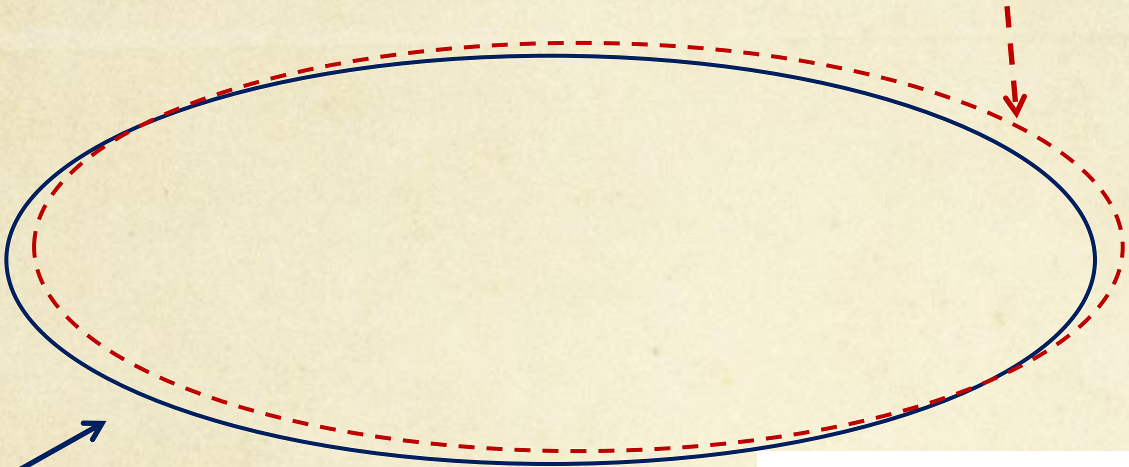


even better 100 km?

Chinese Strategy: Circular Electron-Position Collider) + Super pp Collider

pp collider

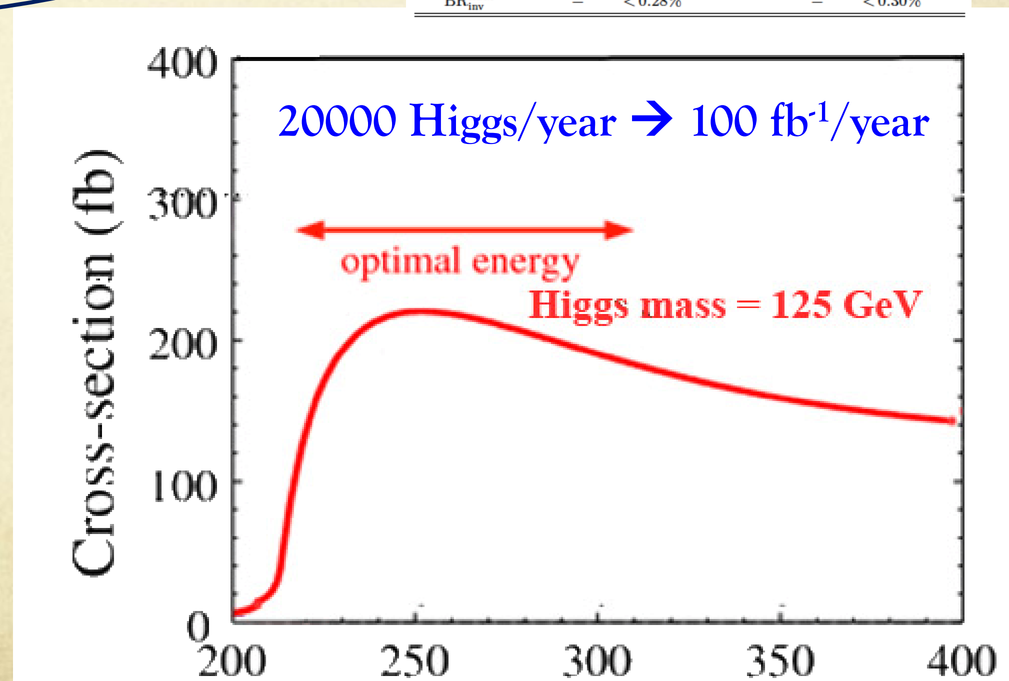
White paper & CDR are ready



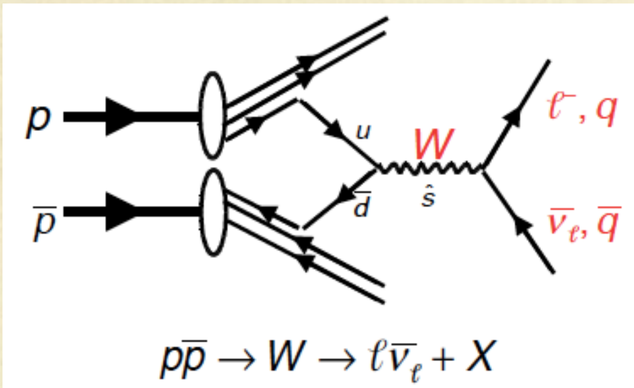
e^-e^+ Higgs Factory

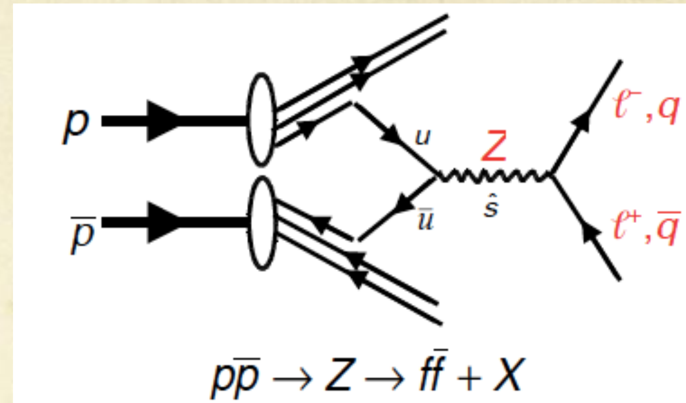
	Estimated Precision				
Property	CEPC-v1		CEPC-v4		
m_H	5.9 MeV		5.9 MeV		
Γ_H	2.7%		2.8%		
$\sigma(ZH)$	0.5%		0.5%		
$\sigma(\nu\bar{\nu}H)$	3.0%		3.2%		
Decay mode	$\sigma \times$ BR	BR	$\sigma \times$ BR	BR	
$H \to b\bar{b}$	0.26%	0.56%	0.27%	0.56%	
$H \to c\bar{c}$	3.1%	3.1%	3.3%	3.3%	
$H \to gg$	1.2%	1.3%	1.3%	1.4%	
$H \to WW^*$	0.9%	1.1%	1.0%	1.1%	
$H \to ZZ^*$	4.9%	5.0%	5.1%	5.1%	
$H \to \gamma\gamma$	6.2%	6.2%	6.8%	6.9%	
$H \to Z\gamma$	13%	13%	16%	16%	
$H \to \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%	
$H \to \mu^+\mu^-$	16%	16%	17%	17%	
BR_{inv}^{BSM}	–	$< 0.28\%$	–	$< 0.30\%$	

A Higgs factory +
A machine of discovery



W/Z 在超级质子反质子同步加速器产生



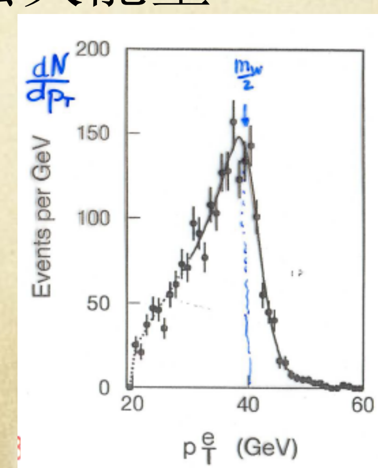


- **谢谢**理论粒子物理学家预言了W和Z的质量：
- 运行的质心能量是540 GeV
- W事例特征: 一个high pt lepton～45 GeV 和较大丢失能量（动量）

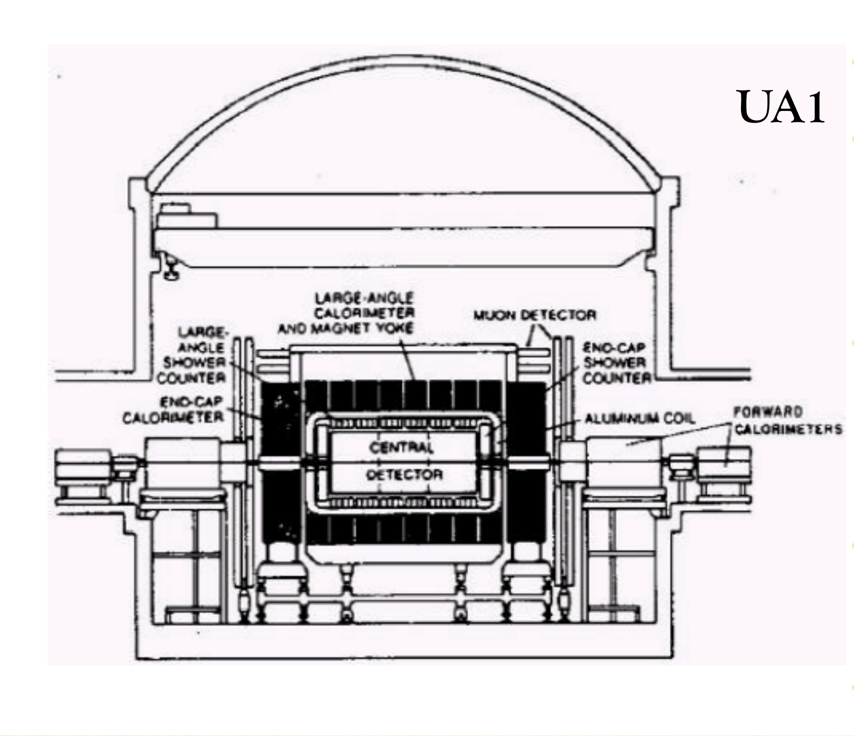
- $m_{W^\pm} \cong 83 \pm 3$ GeV
- $m_{Z^0} \cong 94 \pm 3$ GeV

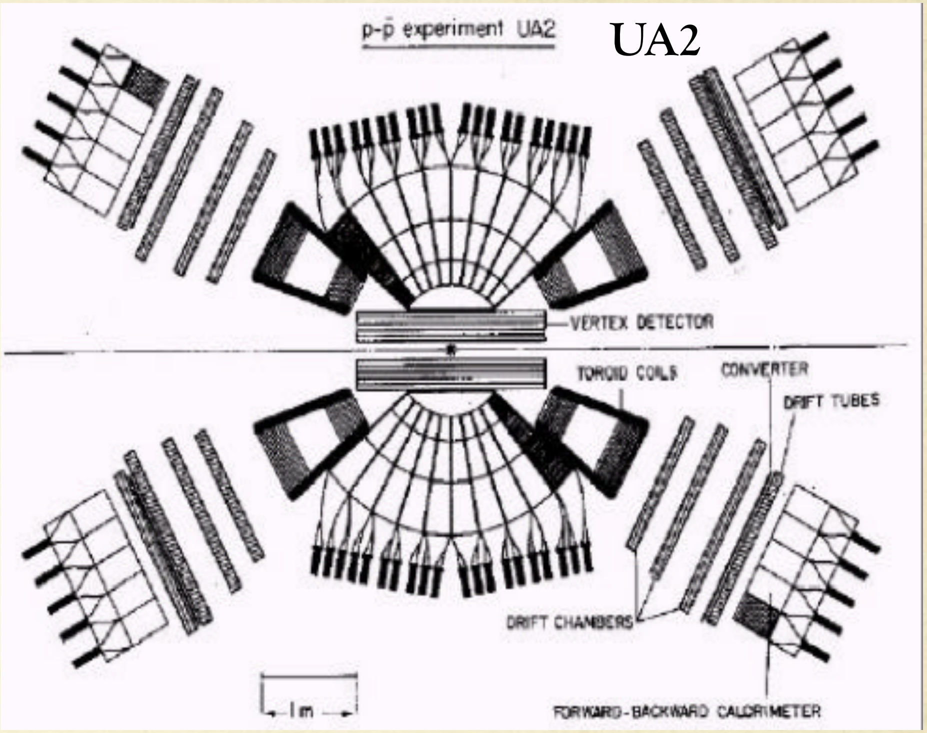
Jacobian Peak: $\frac{dN}{p_T} \sim \frac{2p_T}{M_W} \cdot \left(\frac{M_W^2}{4} - p_T^2\right)^{-1/2}$

- Z事例特征：两个不同电荷的高能量轻子
- 背景很干净。



UA1 和 UA2 探测器





- 密封性较好，gap比较少
- 有专门缪子(muon)和喷注探测器
- 径迹（track）电磁场

- 中心区间覆盖的好
- 径迹测量中没有电磁场
- 电磁量能器有很好电子能量测量和较强鉴别功能

W的发现时间表

- 机器第一次碰撞1981年12月
- 1982年十一月，UA1看到了
  第一个貌似W事例
（但自旋与碰撞的质子不一致）

- 机器运行到1982年12月7日，停机
- 1983年1月12日的罗马一个国际会议上：
  - Carlo Rubbia (UA1发言人) report 39 events with
    6 events :
    - No jets
    - Missing E_T = electron E_T.
  - UA2 report 4 W-like events （语气没有前者肯定）
- 1983年1月20日，Rubbia在CERN的主报告厅宣称了W发现，UA2在第二天做了类似的报告。
- UA2的文章在UA1一个月之后才发表。

Z的发现时间表

- 1982年8月，UA2看到了第一个貌似Z事例（92 GeV），但UA2同事拒绝发表
- 1983年4月12日，新的运行开始
- 5月4日早上5点，UA2看到第二个貌似Z事例，但这个事例的两个电子都射到了探测器的crack区。但UA2同事又决定暂不发表
- 5月4日早上3点，UA1观测到第一个貌似Z事例，当天9点半便宣布了发现
- 5月27日，Rubbia正式宣布发现了Z粒子
- 7月7日，UA2宣布观测到Z粒子。

The Nobel Prize in Physics 1984

Carlo Rubbia	Simon van der Meer

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

S. van der Meer

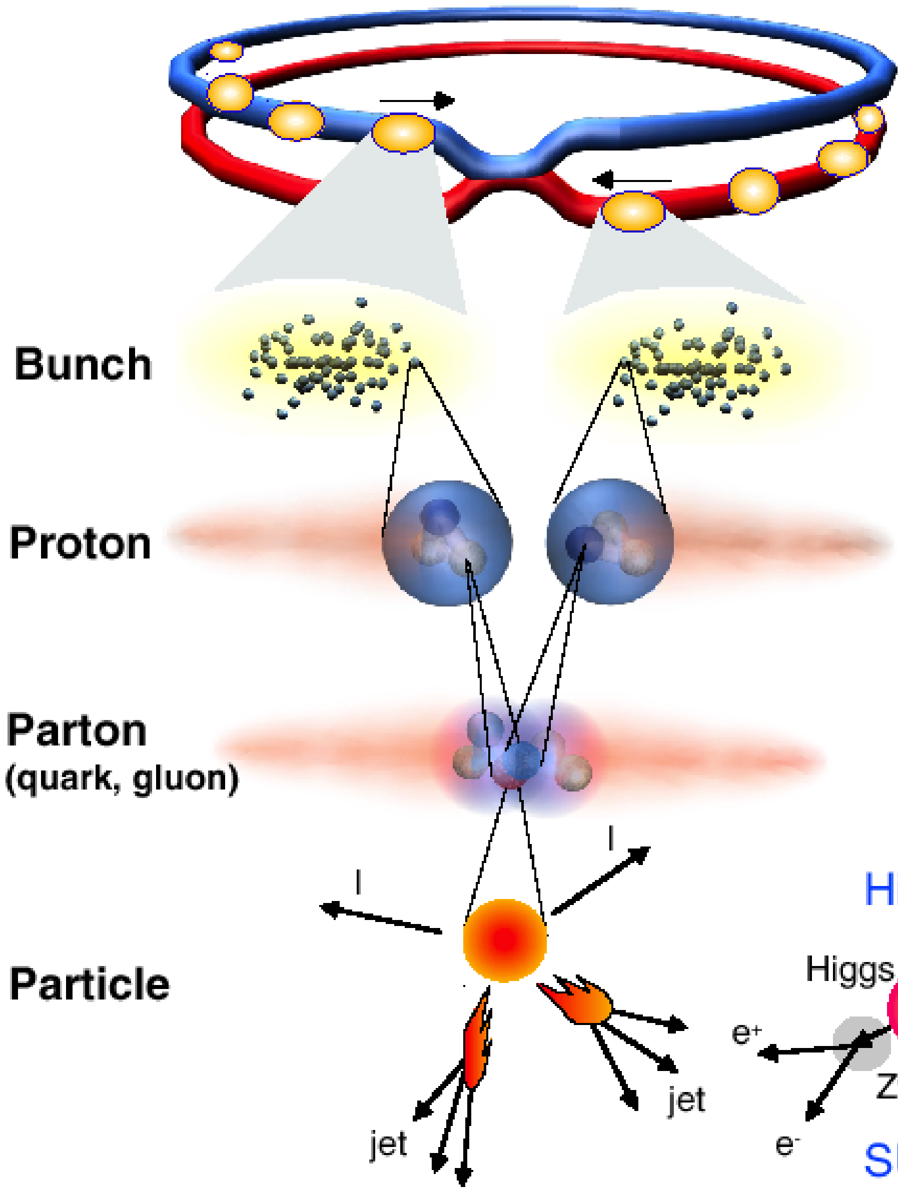
One of the achievements to allow high-intensity $p\ \bar{p}$ collisions, is stochastic cooling of the $\bar{p}$ beams before inserting them into SPS.

Conclusion

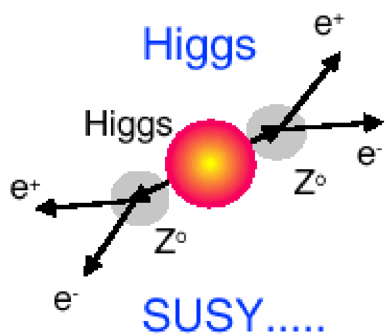
- The Higgs particle around 125 GeV was announced in 2012 at LHC experiments.
  - The additional 2012 data confirm the discovery.
- The new particle is consistent with the expectations from the Standard Model Higgs boson within current uncertainty.
  - Coupling strengths, production rates…
  - First observation of the VBF Higgs production has been seen with ATLAS detector.
  - Favor spin-0 particle.
- LHC has a successful run in Run1 (2011-2012) (with a lot experience).
  - Run 2 aims at 6.5/7 TeV /25 with a few hunderd fb^{-1} data.
  - HL-LHC will achieve ~3000 fb^{-1} data
  - There will be exciting time to study the Higgs boson with high precision and new physics at LHC experiments.
- Beyond LHC, Higgs factory is widely discussed:
  - ILC, TLEP, CEPC …
- What can we learn from the discovery of W and Z?

backup

Collisions at LHC



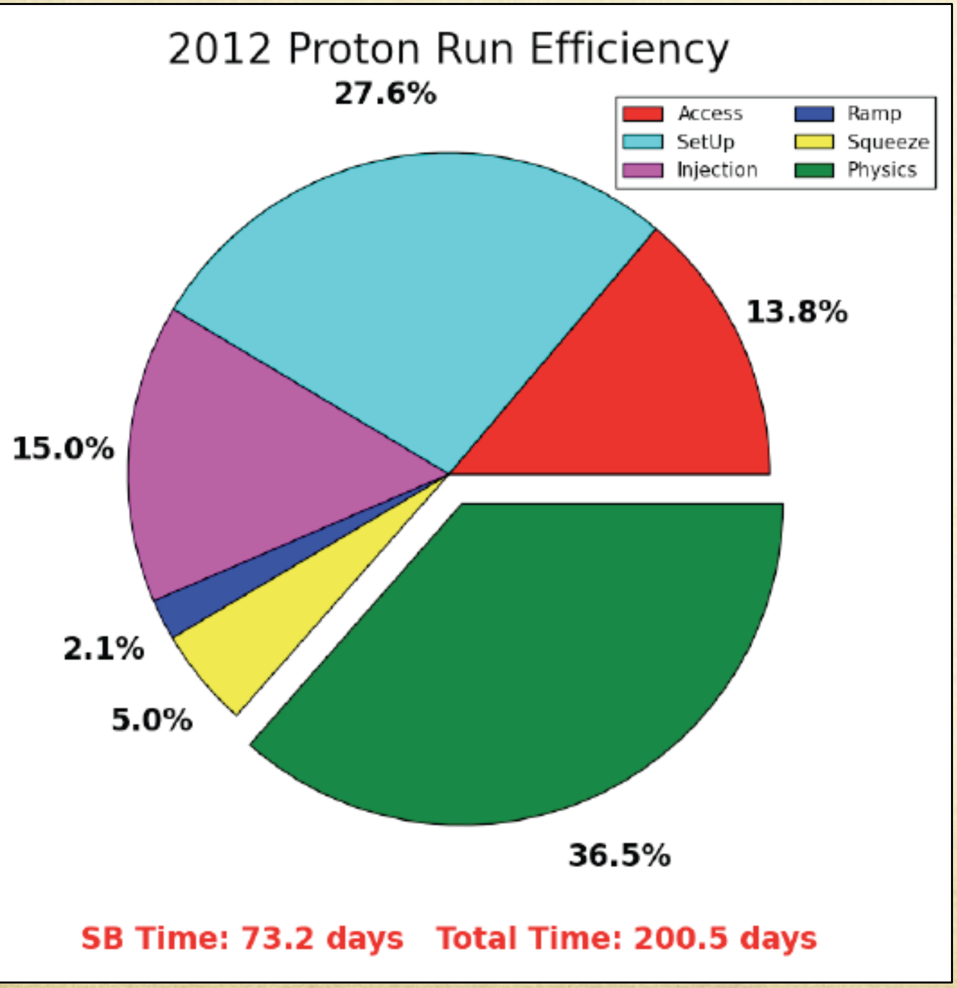
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

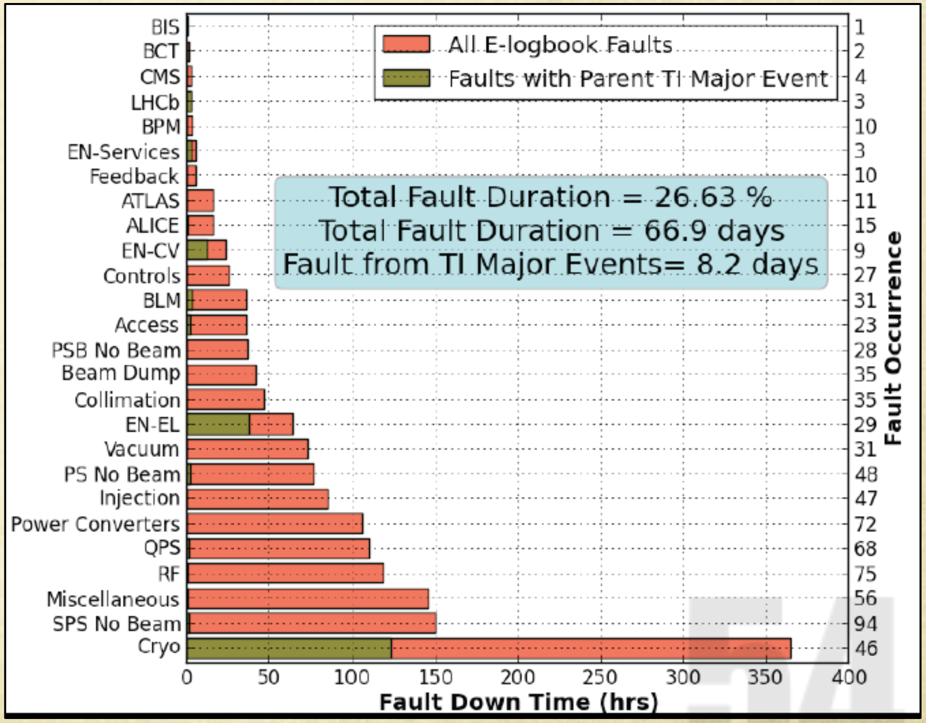


Selection of 1 in 10,000,000,000,000

availability

- "There are a lot of things that can go wrong – it's always a battle"
- Pretty good availability considering the complexity and principles of operation



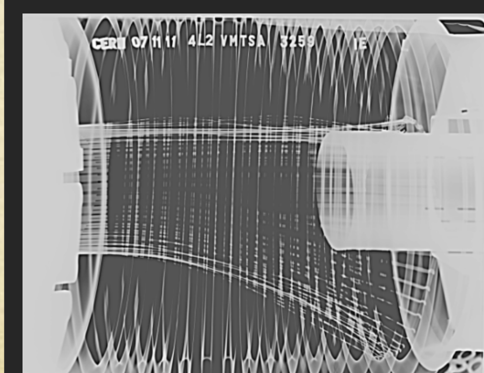


Cryogenics availability in 2012: 93.7%

some issues in 2011-12 operation

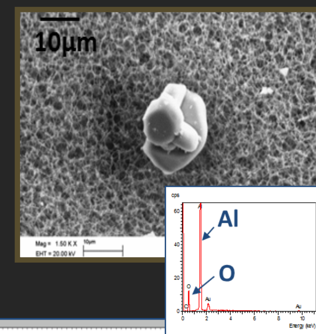
Beam induced heating

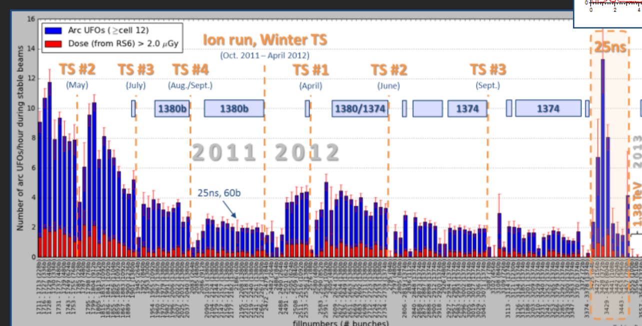
- Local non-conformities (design, installation)
  - injection protection devices
  - sync. Light mirrors
  - vacuum assemblies

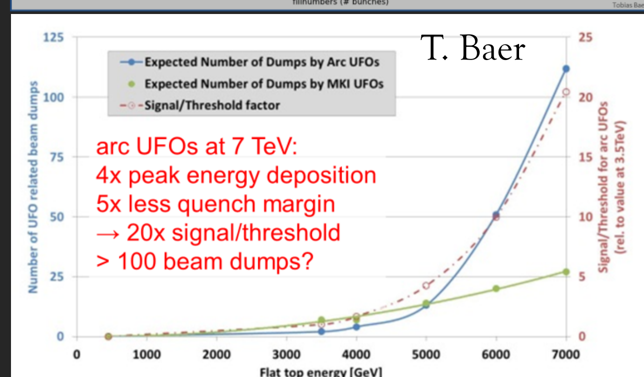


UFOs

- 20 dumps in 2012
- time scale 50-200 µs
- conditioning observed
- worry about 6.5 TeV and 25 ns spacing

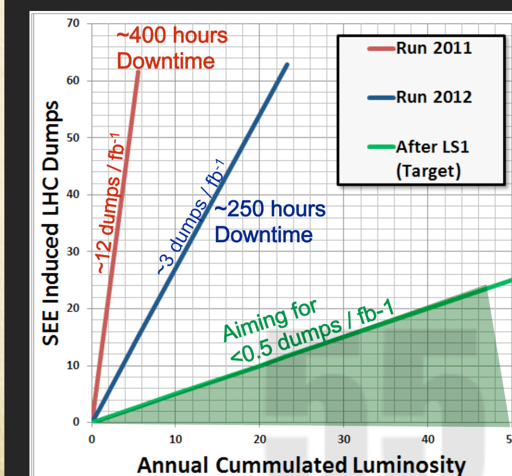






Radiation to electronics

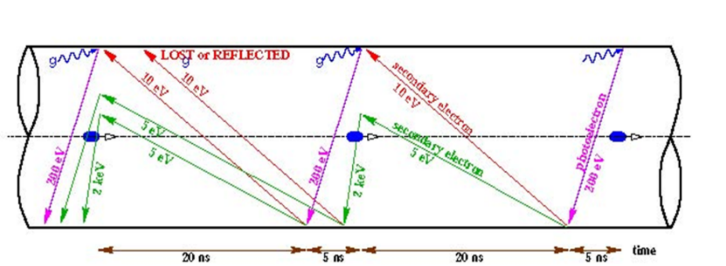
- concerted program of mitigation measures (shielding, relocation…)
- premature dump rate down from $12/fb^{-1}$ in 2011 to $3/fb^{-1}$ in 2012



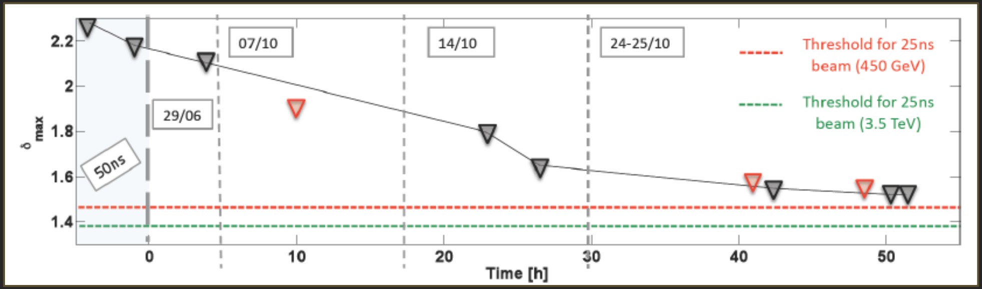
another issue in 2011-12 operation

Electron cloud

- beam induced multipactoring process, depending on secondary emission yield
- LHC strategy based on surface conditioning (scrubbing runs)
- worry about 25 ns (more conditioning needed) and 6.5 TeV (photoelectrons)



25-ns scrubbing in 2011 – decrease of SEY



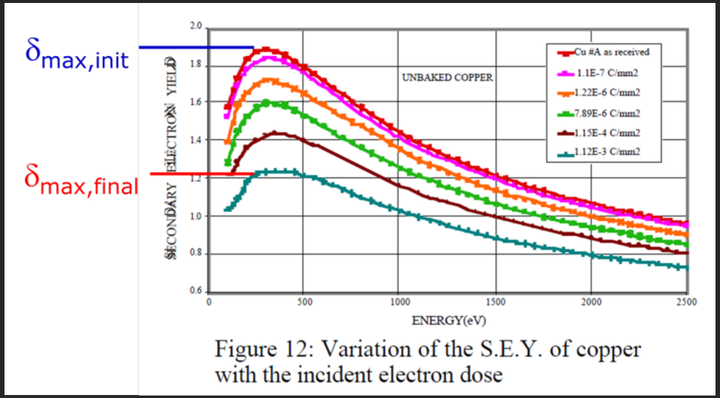
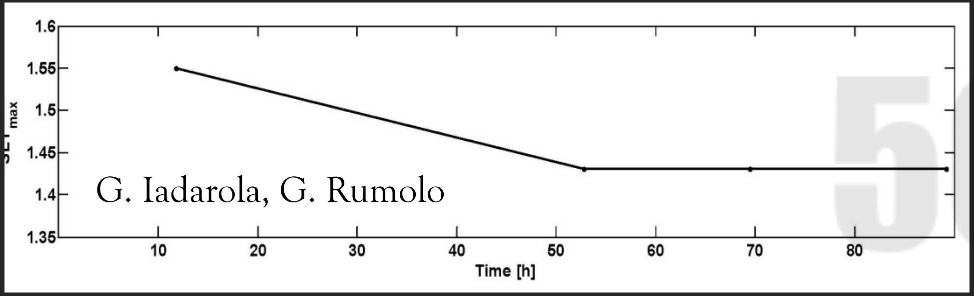


Figure 12: Variation of the S.E.Y. of copper with the incident electron dose

25-ns scrubbing in 2012 – conditioning stop?



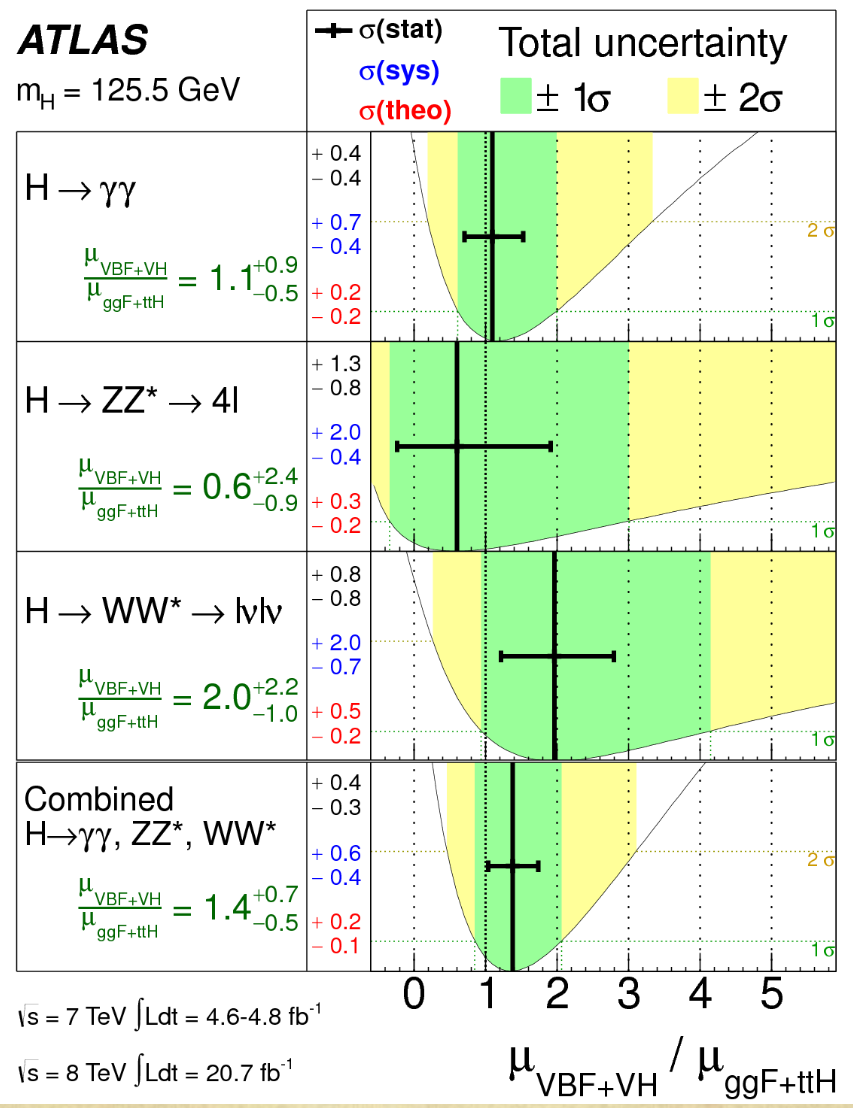
Bunch spacing

$$K_{tot} \propto \sqrt{\frac{1}{\tau_b}}$$

- 50 ns
  - Proven (injector) performance
  - Less long range encounters, can squeeze further
  - Some limited room for increasing bunch intensity (and perhaps reducing emittance blow-up)
  - Pile-up
- 25 ns
  - Lower bunch current/higher emittances from injectors
    - Considerably more total current for same performance
    - UFOs, SEEs, RF, vacuum
  - ~twice number of long range encounters
    - Can't squeeze as far (LRBB/bigger emittances/increased crossing angle)
  - Extended scrubbing required
  - Much lower pile-up

$$< N_{\mathrm{pileup}} >= \frac{\sigma_{\mathrm{inel}}}{(1\ \mathrm{b})} \times \frac{L}{(10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})} \times \frac{\tau_b}{(1\ \mathrm{ns})}$$

ggFusion and VBF



LS1 Consolidations

Pile up in proposed colliders

Facility	$\sqrt{s}$ [TeV]	σ_{inel} [mb]	L [10^{34} cm^{-2}s^{-1}]	τ_b [ns]	$< N_p >$	$< N_p > +2\sigma$
LHC (2012)	8	71.5	.75	50	27	38
LHC (nominal)	14	76	1	25	19	28
LHC (50 ns)	14	76	1	50	38	50
HL-LHC	14	76	5	25	95	114
HE-LHC	30	90	5	50	225	255
VHE-LHC	100	105	5	50	263	295
VLHC	100	105	2	19	40	53

Main beam parameters for 50km CEPC

Parameter	Unit	Value	Parameter	Unit	Value
Energy	GeV	120	Circumference	km	50
Number of IP		1	SR loss	(GeV/turn)	2.96
N_e/bunch	1E11	3.52	N_b/beam		50
Beam current	mA	16.9	SR power/beam	MW	50
Partition Je		2	Long. damp. time	ms	6.7
Dipole field	Tesla	0.065	Bending radius	km	6.2
Dipole length	m	9.978	Bending angle	mrad	1.609
Emittance (x/y)	nm	6.69/0.033	β_{IP} (x/y)	mm	200/1
Trans. size (x/y)	μm	36.6/0.18	Mom. compaction	1E-4	0.4
$\xi_{x,y}$ /IP		0.1/0.1	Bunch length	mm	3