



# Physics at LHC (with ATLAS)

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Georgian Teachers' Programme

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## Vakhtang (Vato) Kartvelishvili

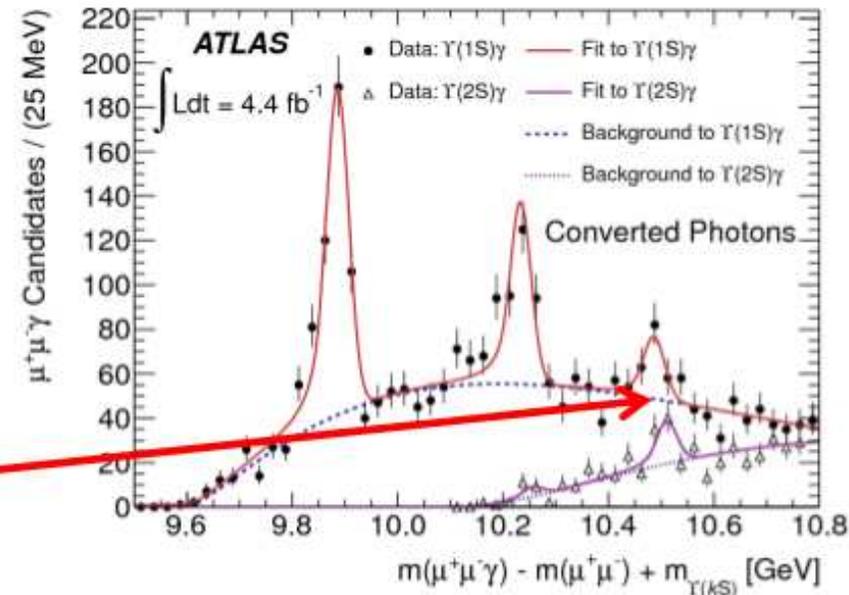


- Graduated from Ivane Javakhishvili Tbilisi State University in 1976
- PhD at IHEP (Protvino) in 1979, worked for HEPI TSU for many years
- Since 2001: permanent position (Readership) at Lancaster University, UK
- Created and lead Quarkonium physics subgroup in ATLAS since 2006
- Lead a number of published measurements on  $J/\psi$ , Upsilon production in ATLAS

One of them resulted in the  
**DISCOVERY OF THE FIRST NEW  
PARTICLE AT LHC:**

[Phys. Rev. Lett. 108 \(2012\) 152001](#)

$\chi_{b(3P)}$



- Now finalizing several measurements with Run I data, preparing for Run II



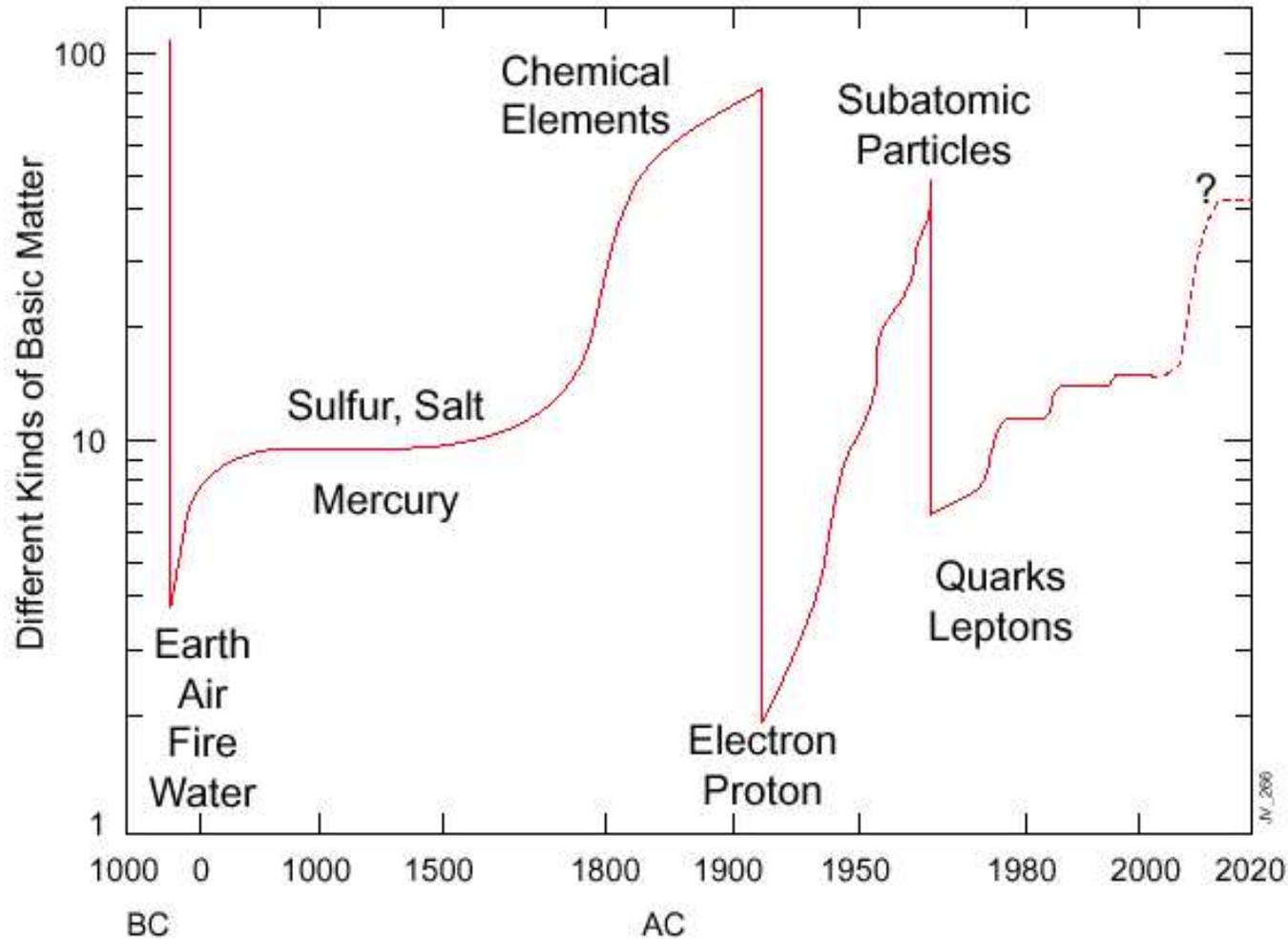
## Outline



- ◆ The Standard Model (SM)
- ◆ Proton-proton collisions in terms of quarks and gluons
- ◆ Luminosity and Triggers
- ◆ Lepton pair production:  $J/\psi$ ,  $\Upsilon$ ,  $Z$ , ...
- ◆ Some measurements:  $J/\psi$  – prompt, non-prompt
- ◆ The first new particle discovered at LHC:  $\chi_b(3P)$
- ◆ Other SM measurements:  $t\bar{t}$ ,  $W^\pm$ ,  $Z$ , ...
- ◆ Observation of the Higgs Boson
- ◆ Searches for Supersymmetry, Exotics
- ◆ Summary and outlook



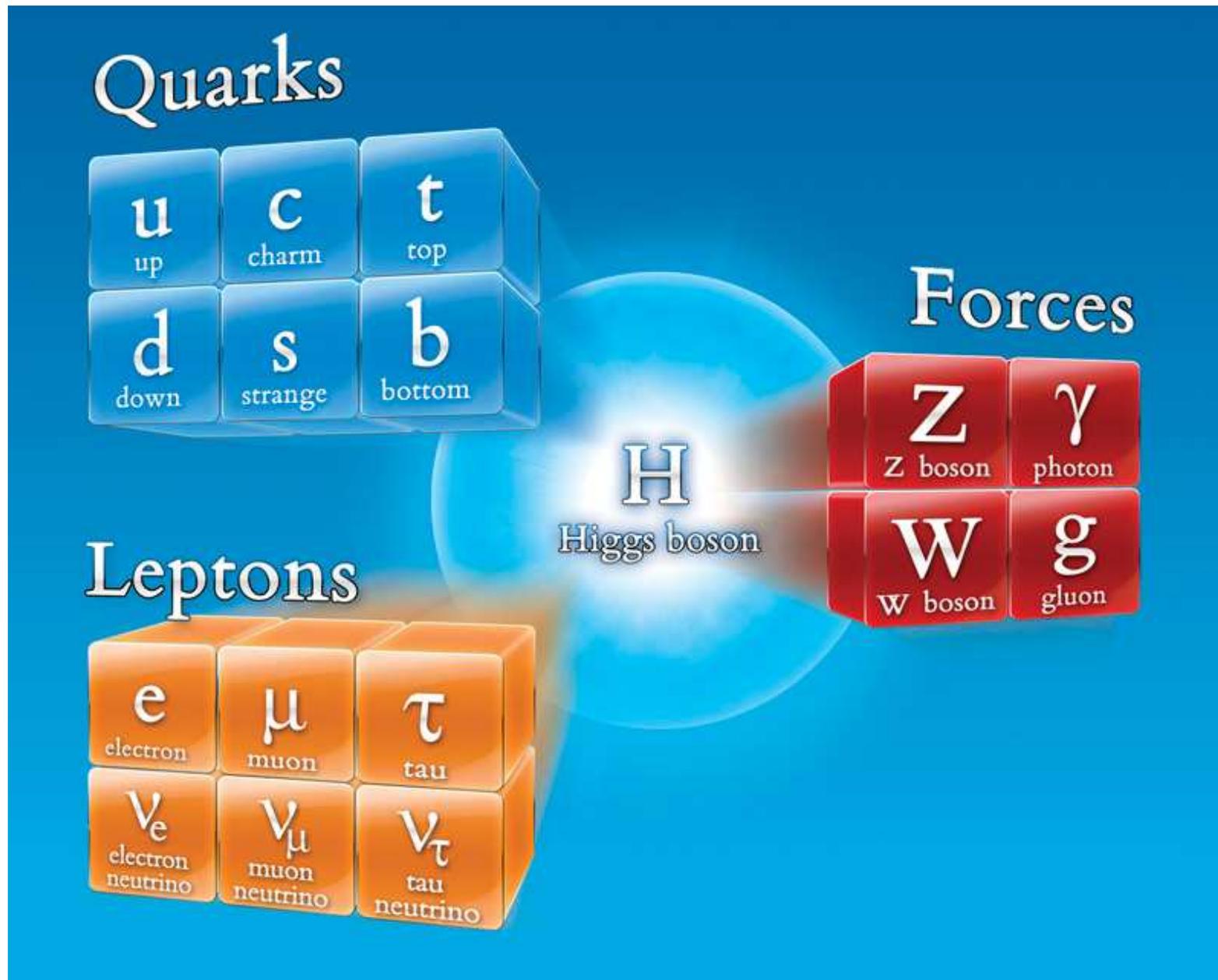
# Constituents of Matter



From [http://teachers.web.cern.ch/teachers/archiv/HST2002/webgroup/mcclean/Introduction to Particle Physics.ppt](http://teachers.web.cern.ch/teachers/archiv/HST2002/webgroup/mcclean/Introduction%20to%20Particle%20Physics.ppt)



# Fundamental constituents of the Standard Model





# Generations and masses

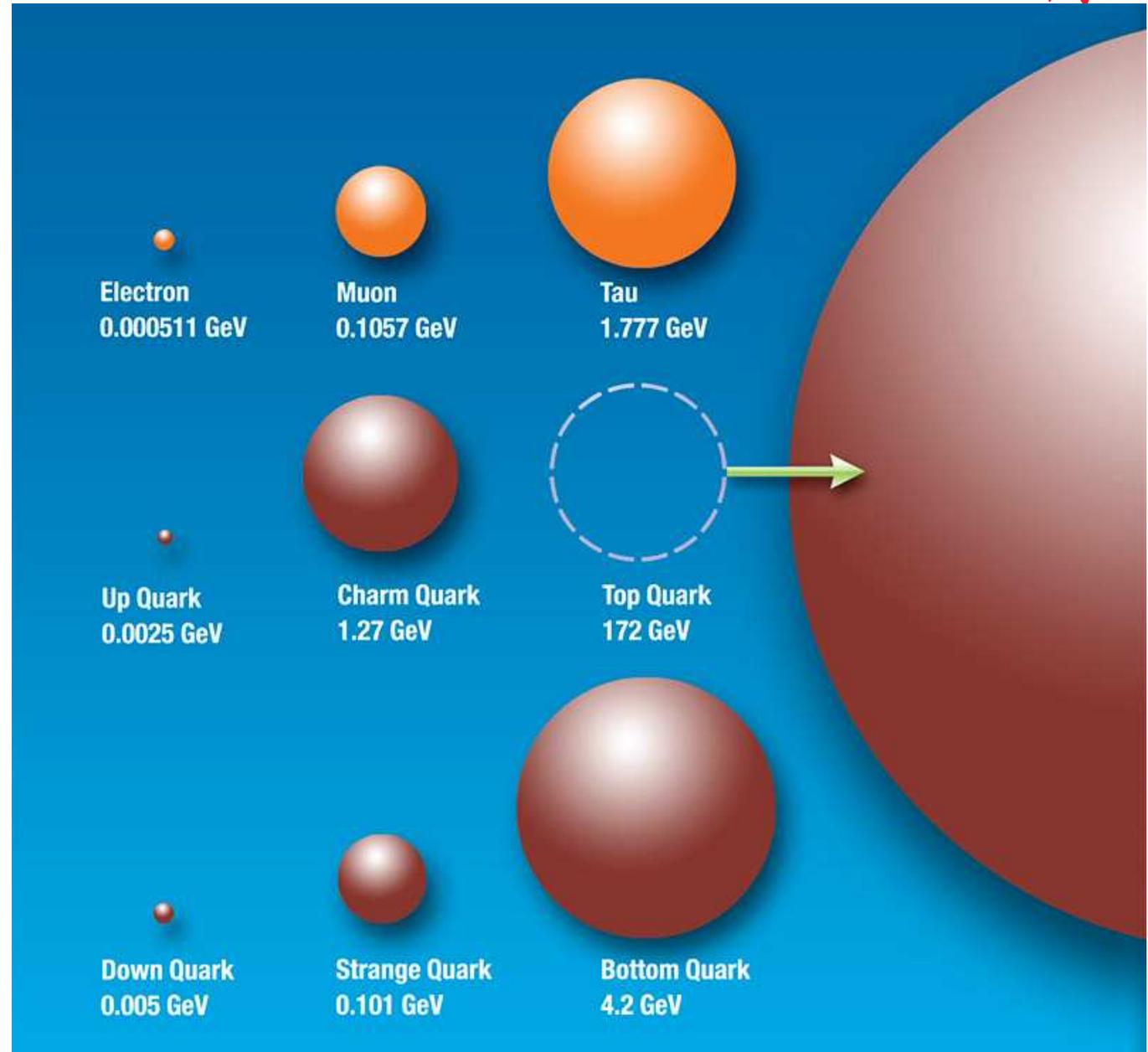


Three “generations”

Getting heavier and heavier

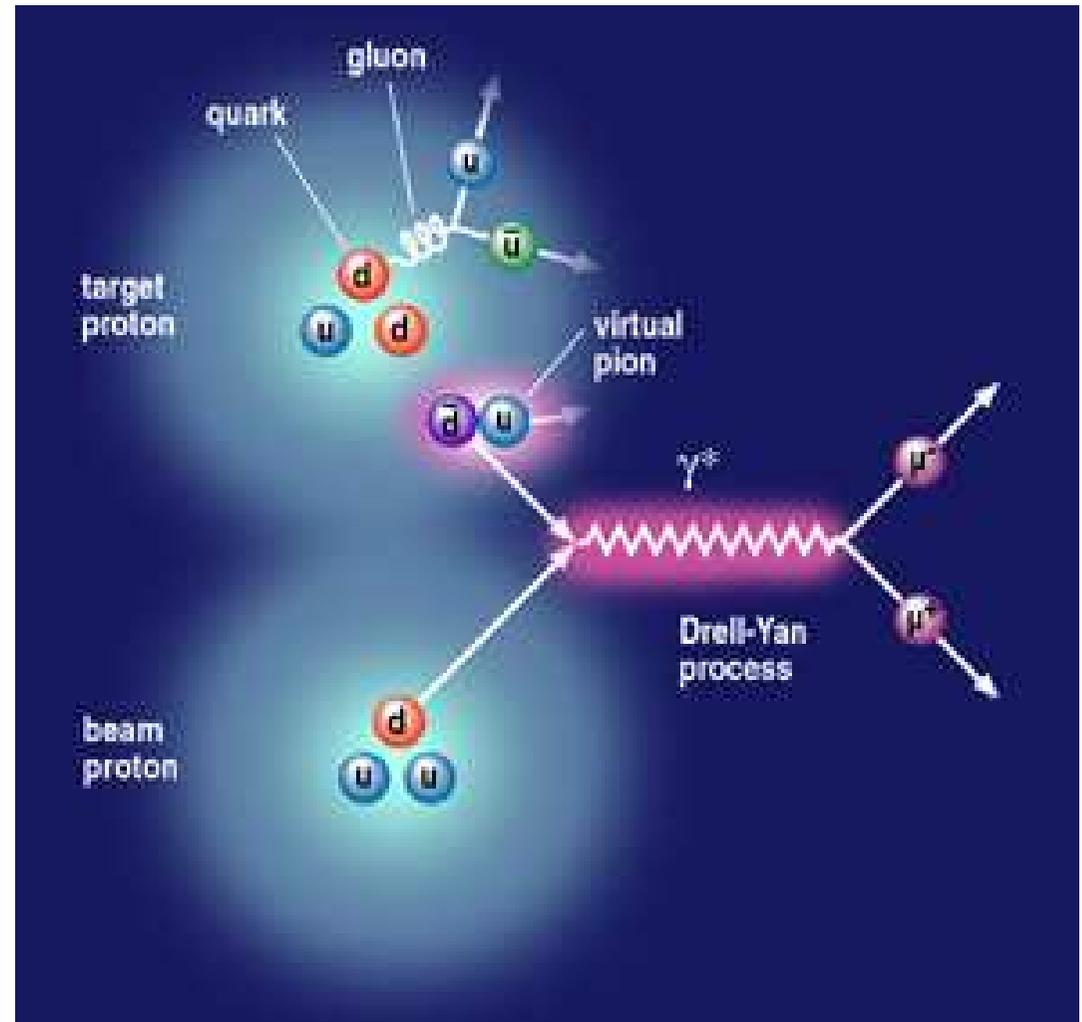
Top quark especially heavy

No clue why...





# Is LHC really a proton - proton collider?



High energy of constituents is needed to produce something new and interesting

A proton is a bunch of quarks and gluons, each carrying a fraction of energy  
8 TeV of  $pp$  collision energy barely enough to produce a 1 TeV object...



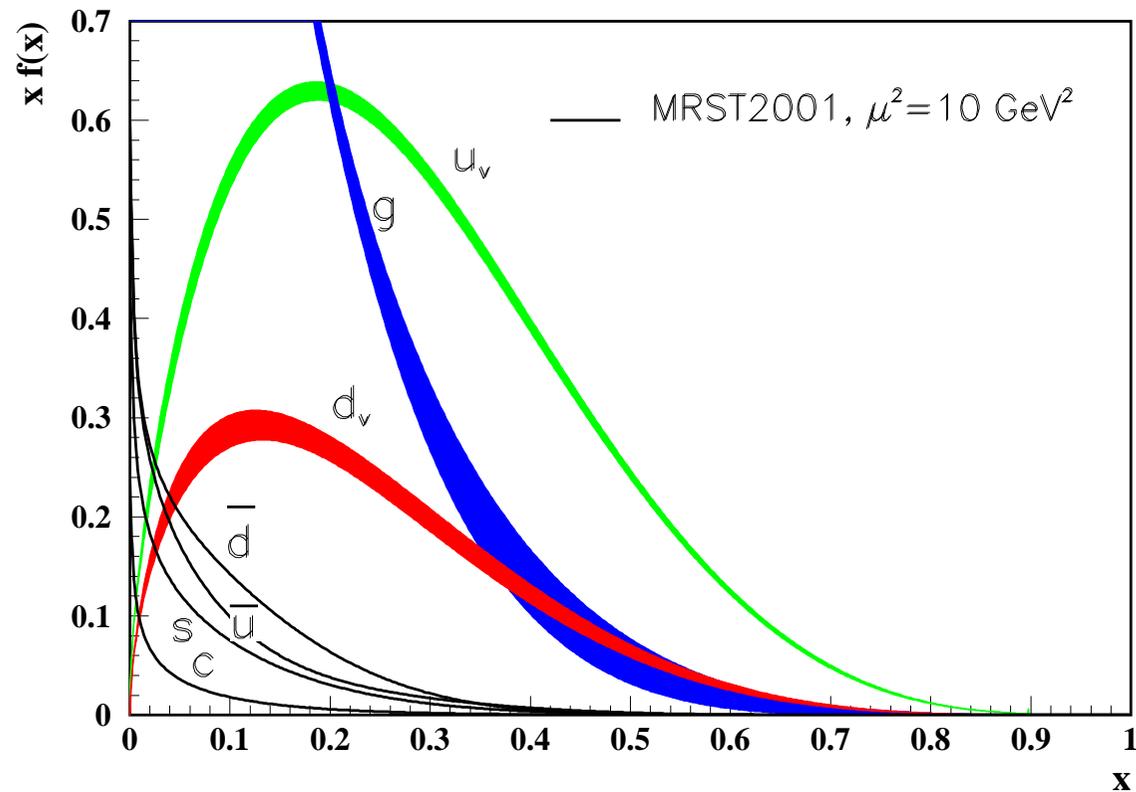
# Quark and gluon distributions in a proton



Only 30% of proton energy is carried by the three constituent  $uud$  quarks

Most of proton energy is carried by gluons

The “sea” of quark-antiquark pairs is also important



$$M^2 = x_1 \times x_2 \times (8 \text{ TeV})^2$$

$$d\sigma \sim f_1(x_1) \times f_2(x_2) \times \hat{\sigma}(M^2)$$



## Cross sections and units



- ◆ The intensity of various collisions is measured in terms of the cross section for particular reactions
- ◆ Cross section is the effective area which needs to be crossed by a test particle to get scattered
- ◆ Since early days of nuclear physics, measured in barns

$$1 \text{ barn} = 10^{-28} \text{ m}^2 = 100 \text{ fm}^2$$

is about the size of lead or uranium nucleus

- ◆ Total cross section of proton-proton collisions is about 100 millibarn at 7 TeV
- ◆ Interesting processes like Higgs production have much smaller probabilities, and hence much smaller cross sections, measured in picobarns ( $10^{-12}$  barn) or femtobarns ( $10^{-15}$  barn) or even attobarns ( $10^{-18}$  barn)
- ◆ The smaller the cross section of a process, the fewer events you get
- ◆ Integrated luminosity of  $100 \text{ pb}^{-1}$  means that if the cross section is 1 pb, you will see 100 events



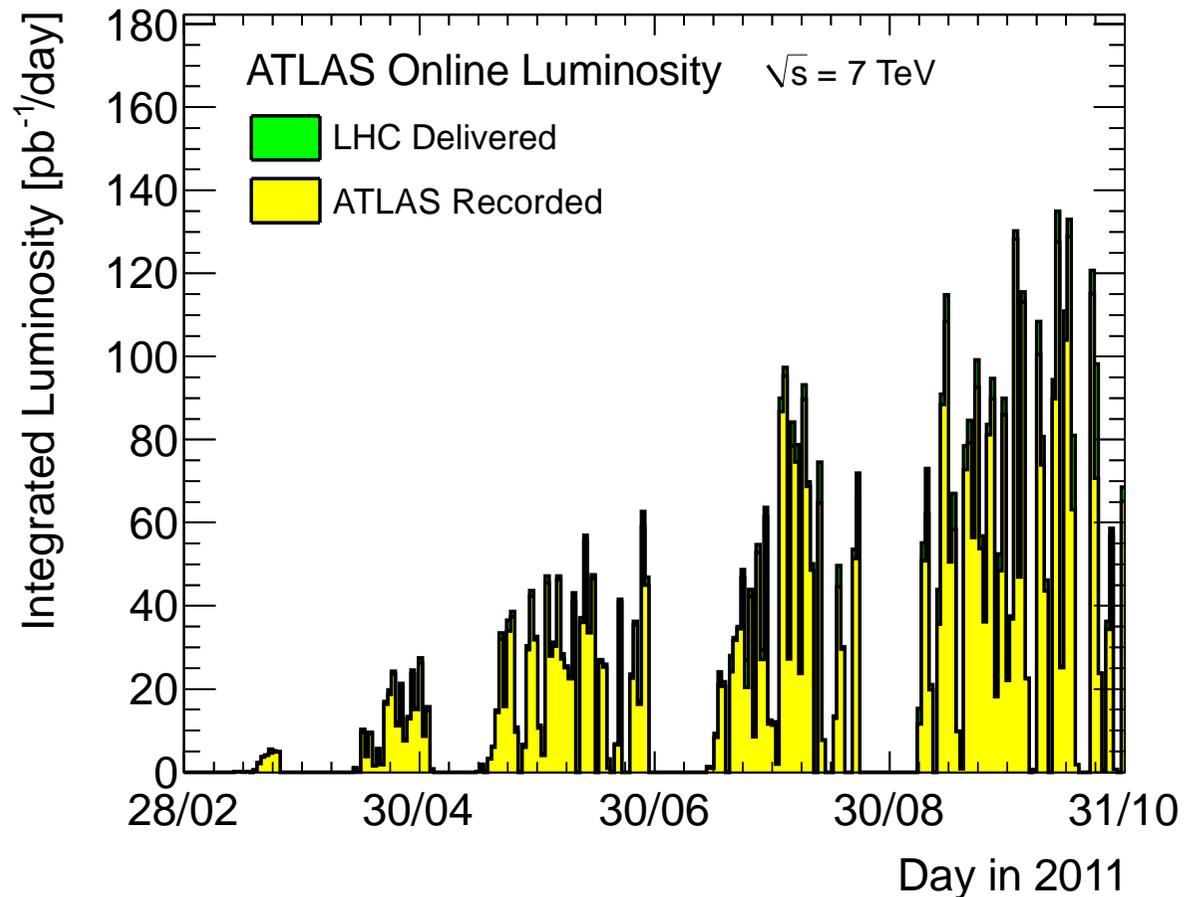
# Luminosity



In early days of LHC:  
100's of collisions / sec

Now:  
many millions / sec

No time for viewing  
events one-by one...



Full computing power of CERN only allows to reconstruct “just” a few hundred events per second

Very careful selection (“triggering”) of potentially interesting events is required!

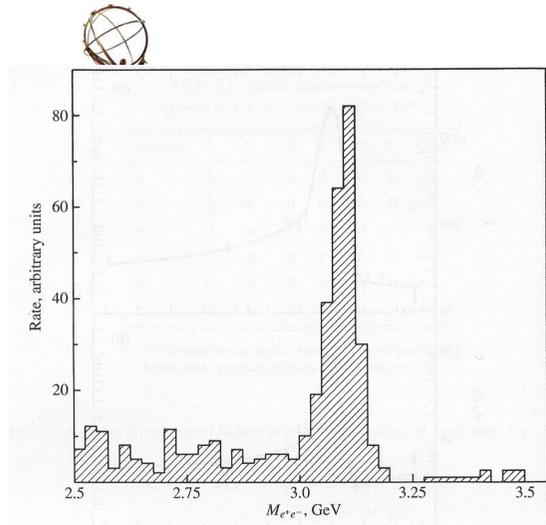
# 1974: discovery of $J/\psi$

⇐ **Discovery 1:** Ting's group

$$pN \rightarrow e^+e^- X$$

at  $P_{\text{lab}} = 30 \text{ GeV}/c$

[Aubert et al., PRL, 6/11/1974]



Found a peak in  $e^+e^-$  inv.mass at 3.1 GeV, called it  $J$ .

**Discovery 2:** Richter's group ⇒

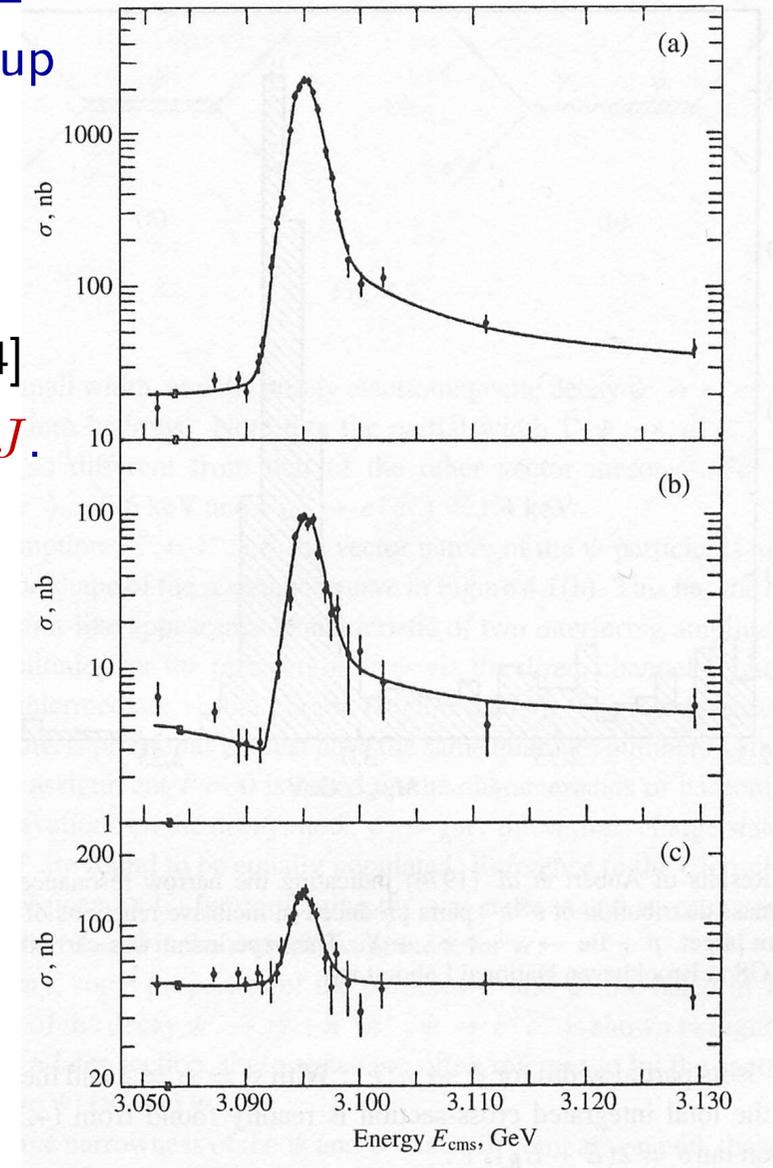
(a)  $e^+e^- \rightarrow \text{hadrons}$

(b)  $e^+e^- \rightarrow \mu^+\mu^-$

(c)  $e^+e^- \rightarrow e^+e^-$

[Augustin et al., PRL, 7/11/1974]

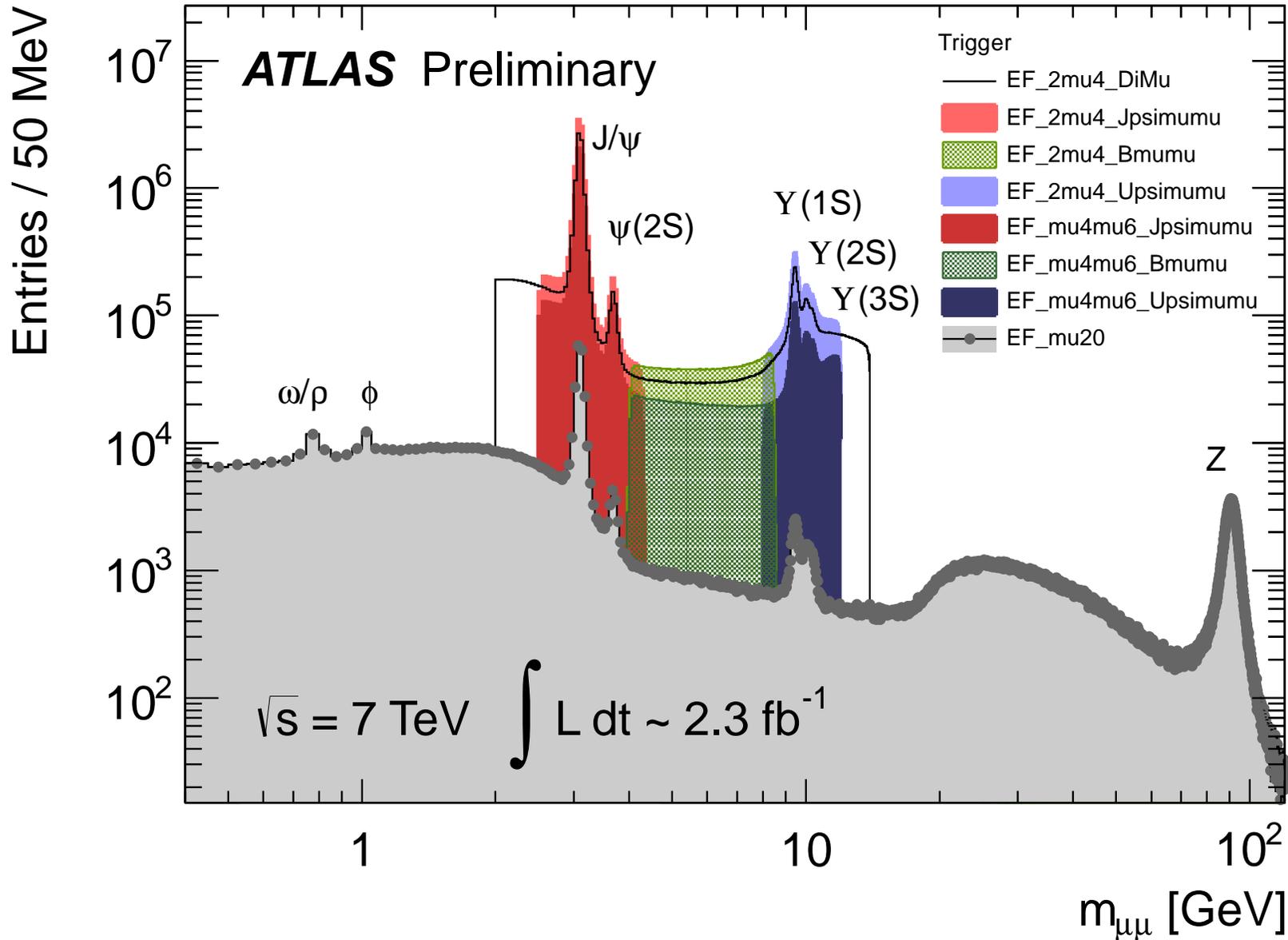
Found a peak in all these three cross-sections, at the c.m.s. energy 3.1 GeV; called it  $\psi$ .



**Now we know:**  $J/\psi$  is a bound state of charm-anticharm,  $c\bar{c}$ .

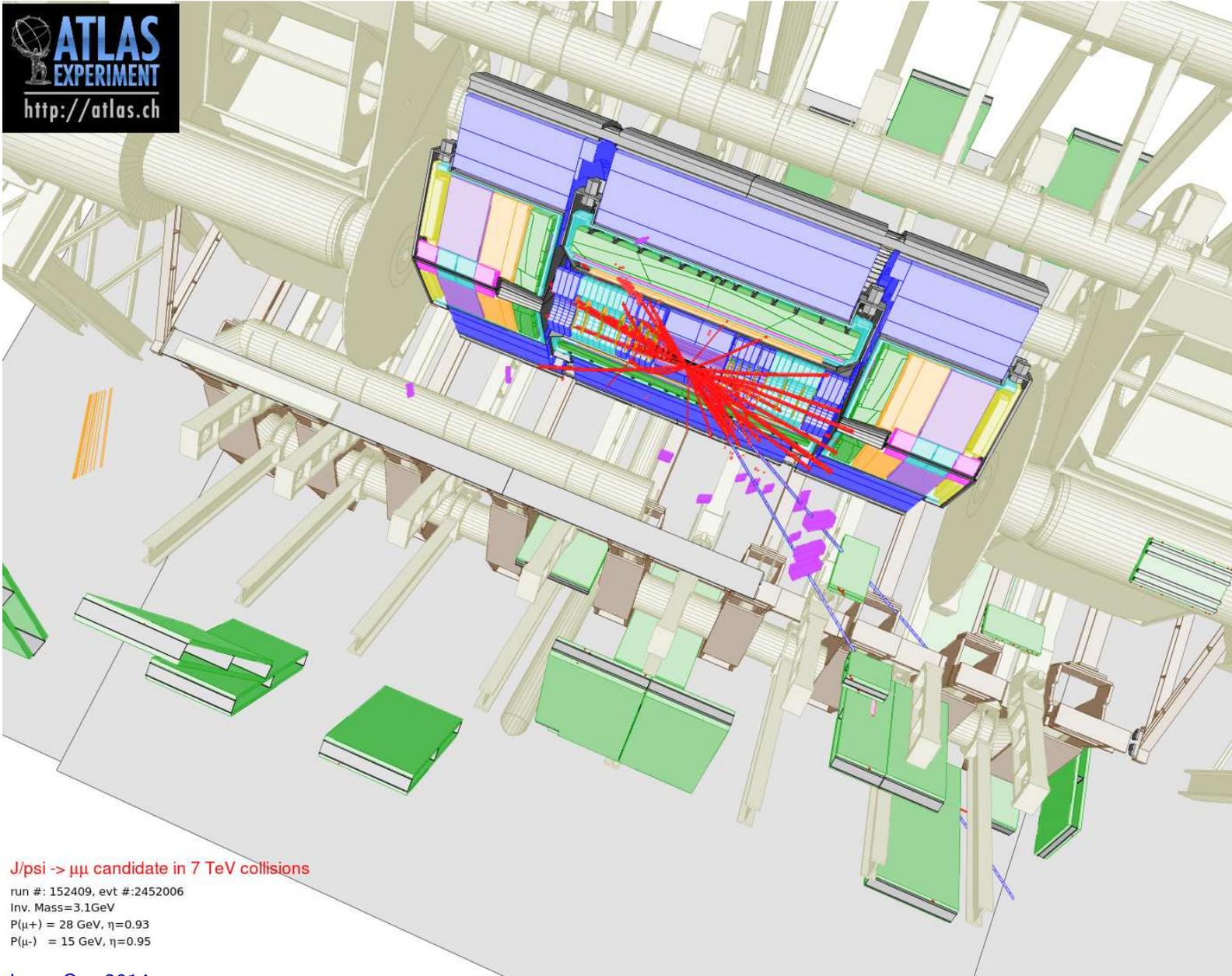


# History of 20th century Particle Physics in one plot





$$pp \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) + X$$

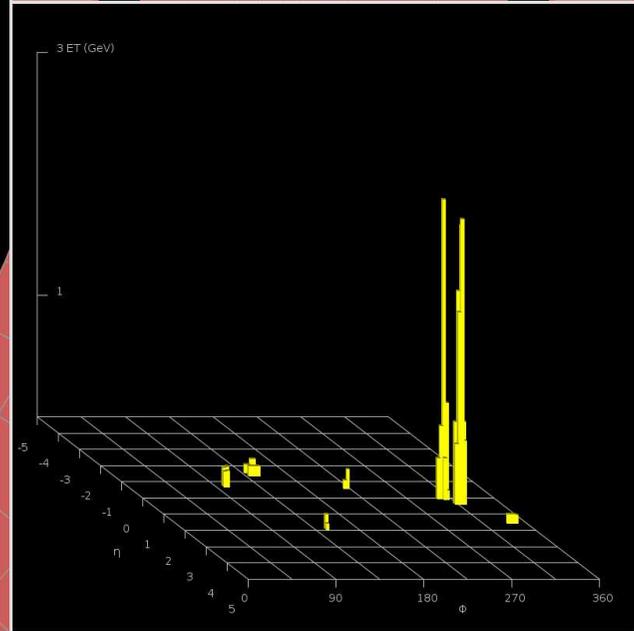
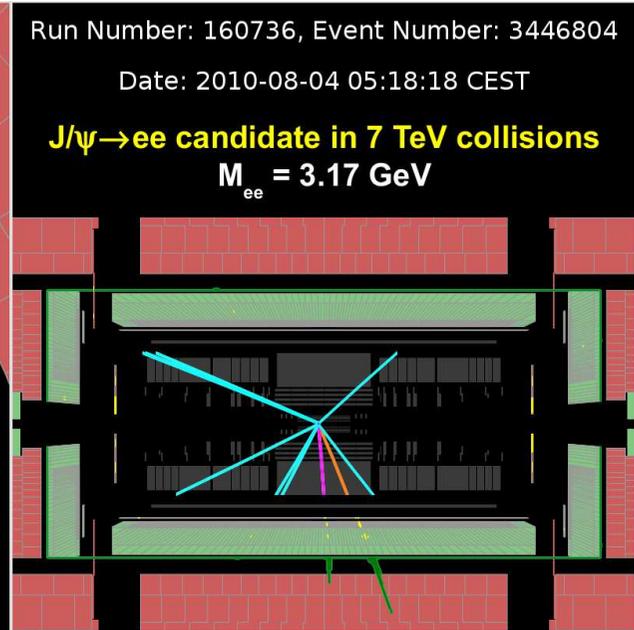
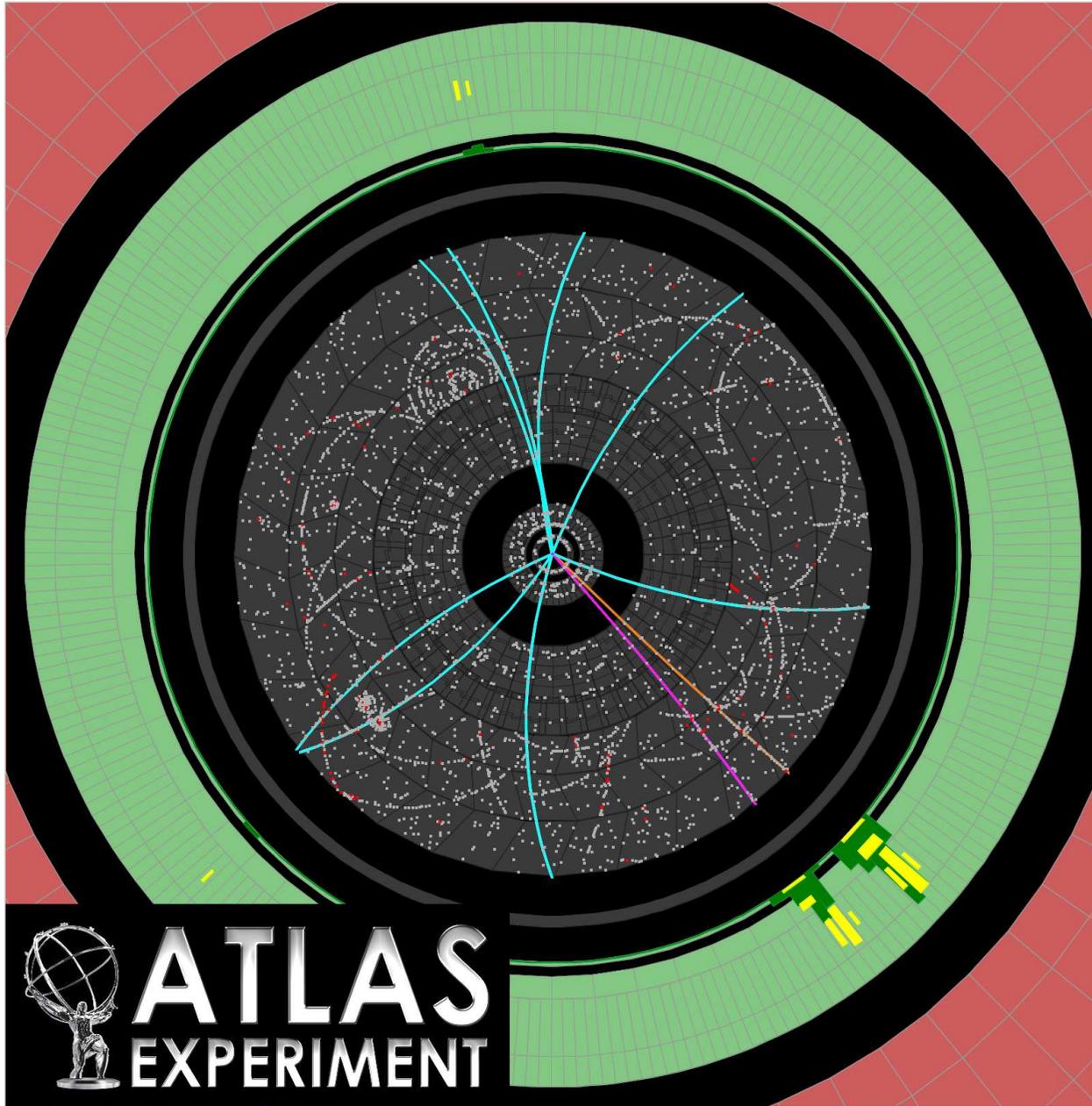


J/psi ->  $\mu\mu$  candidate in 7 TeV collisions

run #: 152409, evt #: 2452006  
Inv. Mass=3.1GeV  
P( $\mu^+$ ) = 28 GeV,  $\eta=0.93$   
P( $\mu^-$ ) = 15 GeV,  $\eta=0.95$

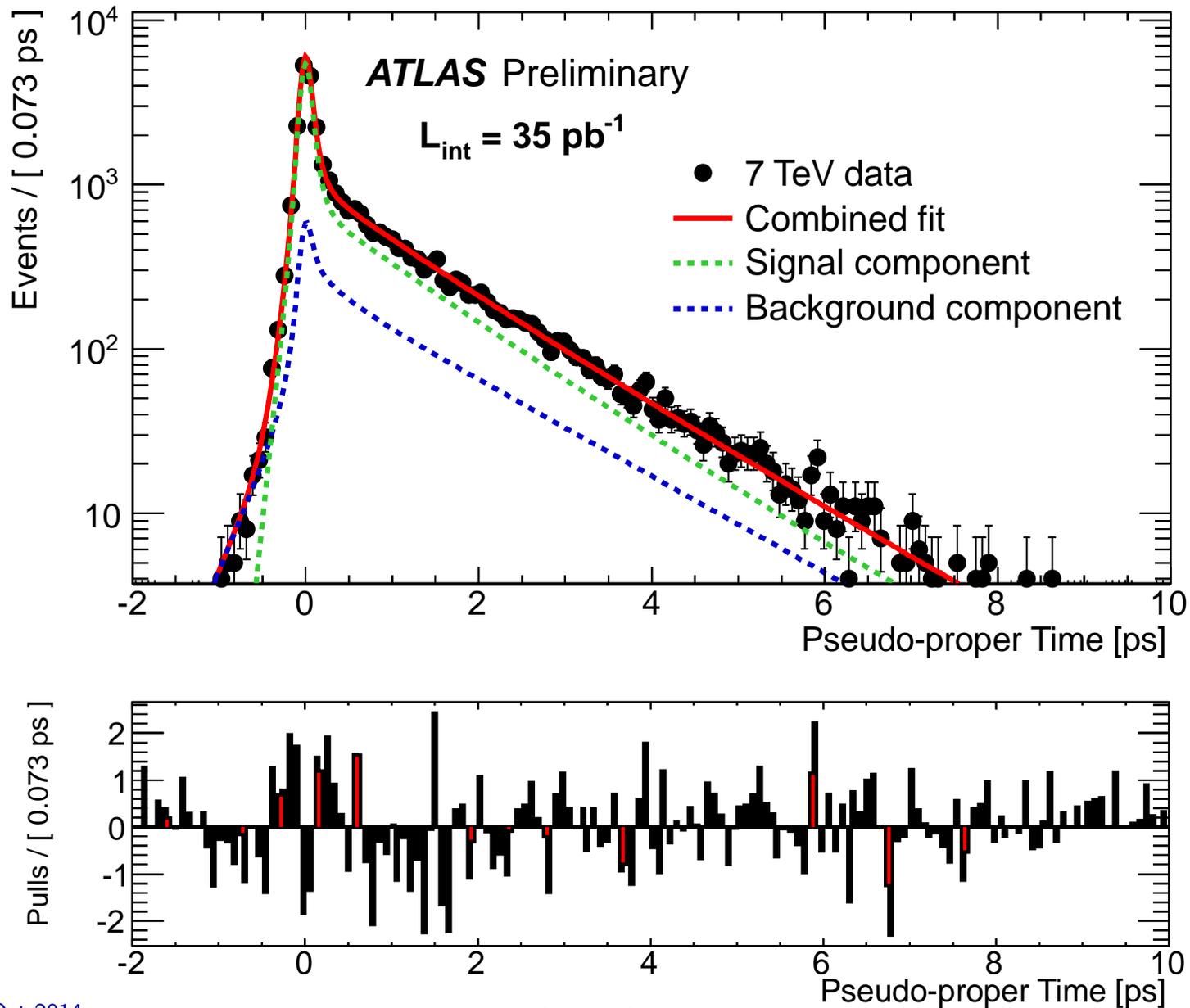


$$pp \rightarrow J/\psi(\rightarrow e^+e^-) + X$$



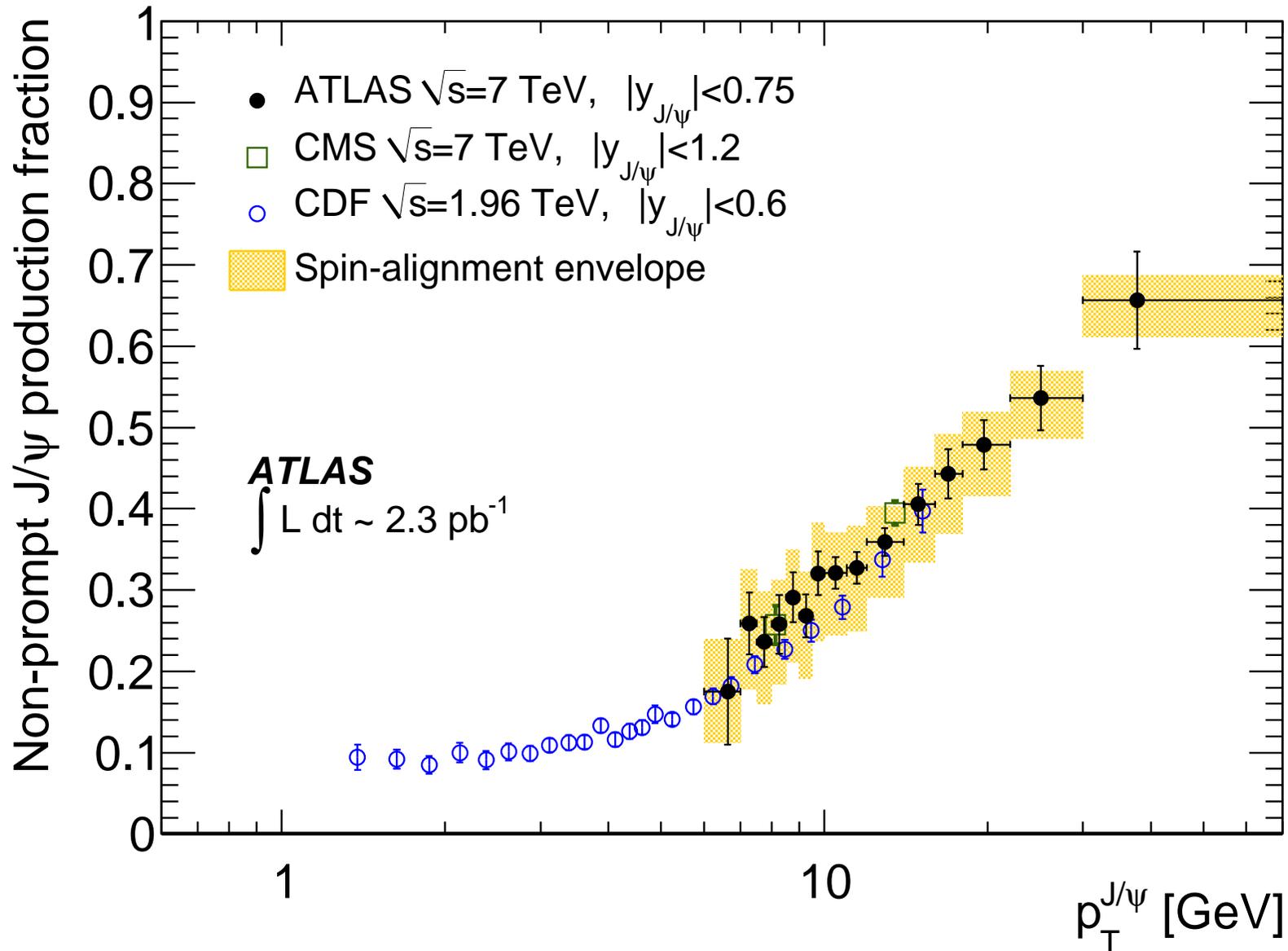


# Proper Decay Time of the $J/\psi$ vertex



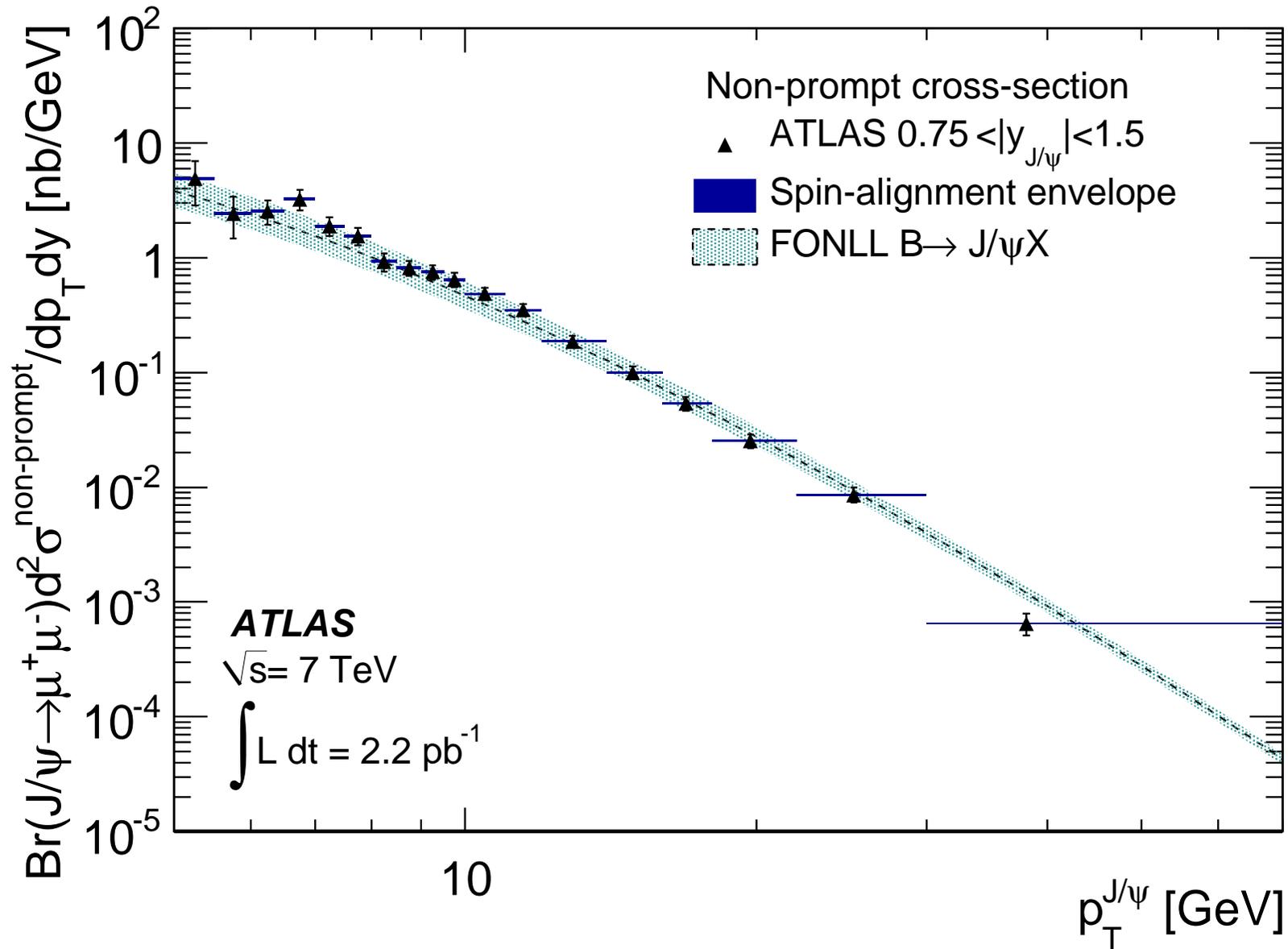


# Fraction of non-promptly produced $J/\psi$



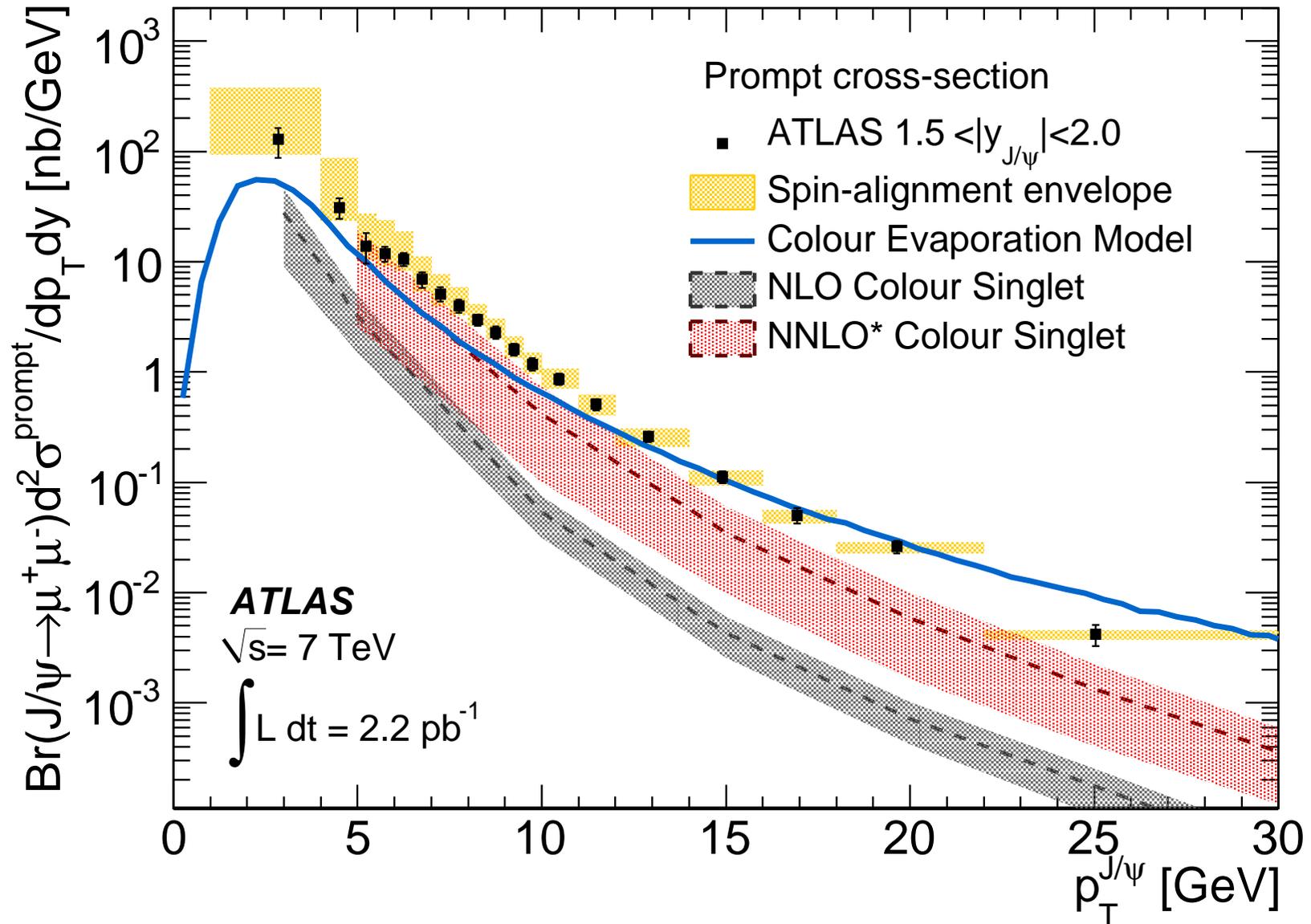


# $p_T$ dependence of non-prompt $J/\psi$



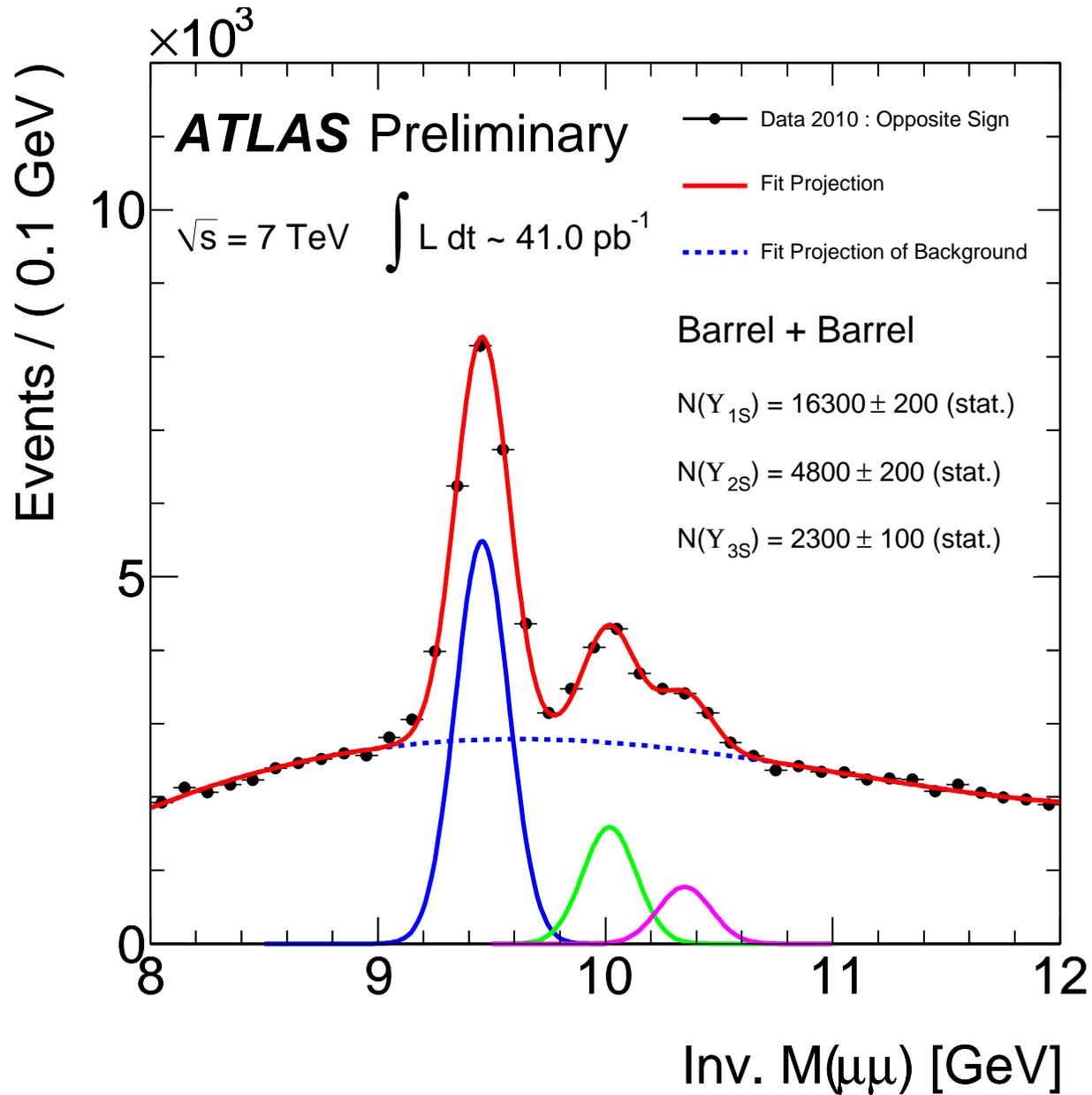


# $p_T$ dependence of prompt $J/\psi$





# $b\bar{b}$ bound states: $\Upsilon$ system





# Spectroscopy of $b\bar{b}$ mesons



Spectroscopy similar to hydrogen atom

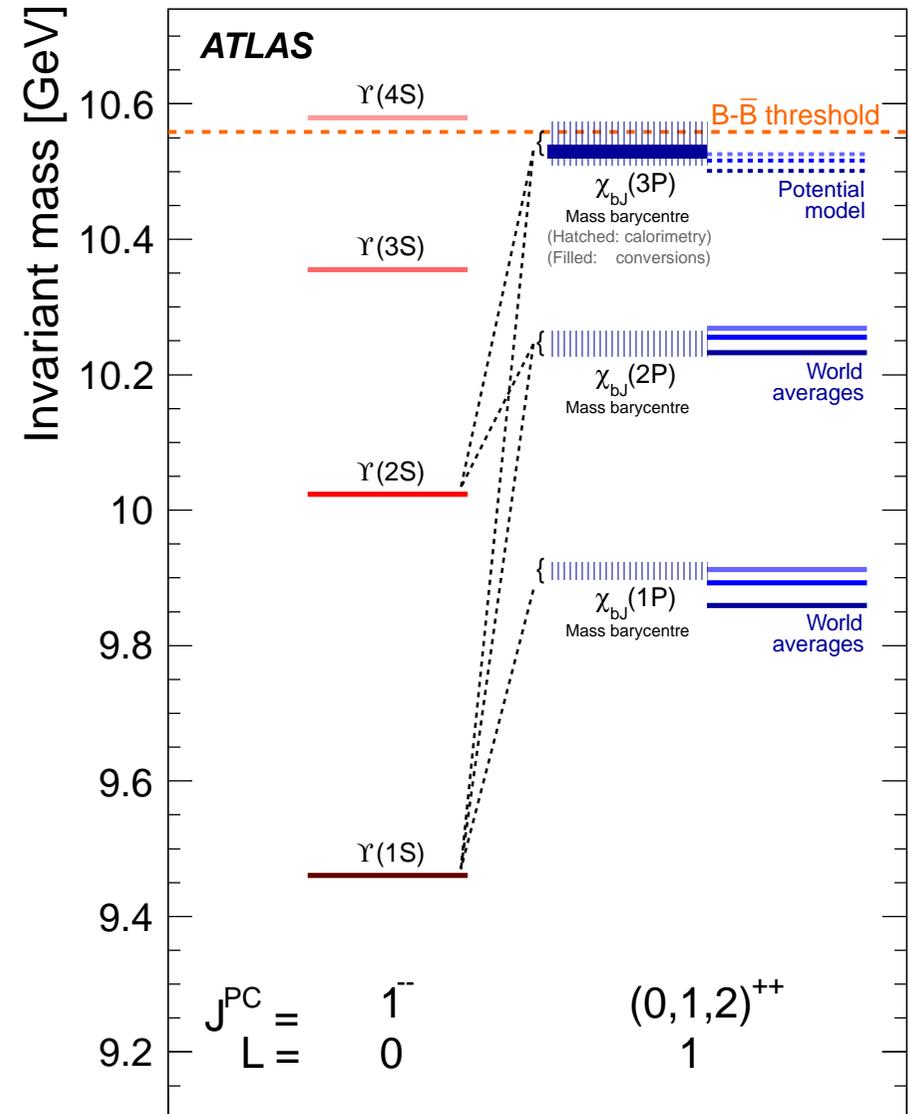
$\Upsilon(1S)$ : ground state

$\Upsilon(2S, 3S)$ : radial excitations

Three families of  $\chi_b$ :  
orbital excitations,  $L = 1$

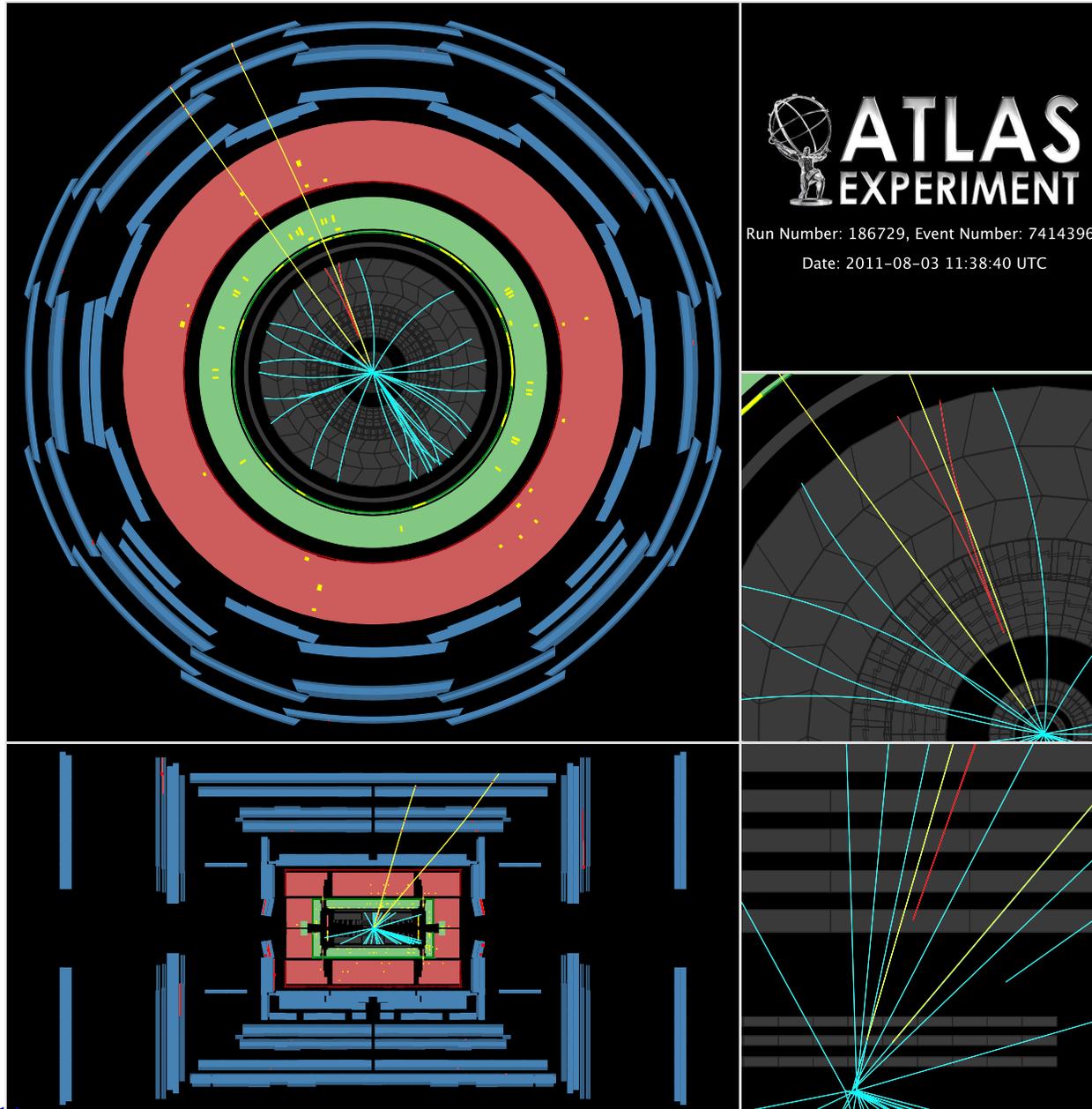
Until 22 December 2011, only  
 $\chi_b(1P)$  and  $\chi_b(2P)$  were observed

Observed bottomonium radiative decays in ATLAS,  $L = 4.4 \text{ fb}^{-1}$



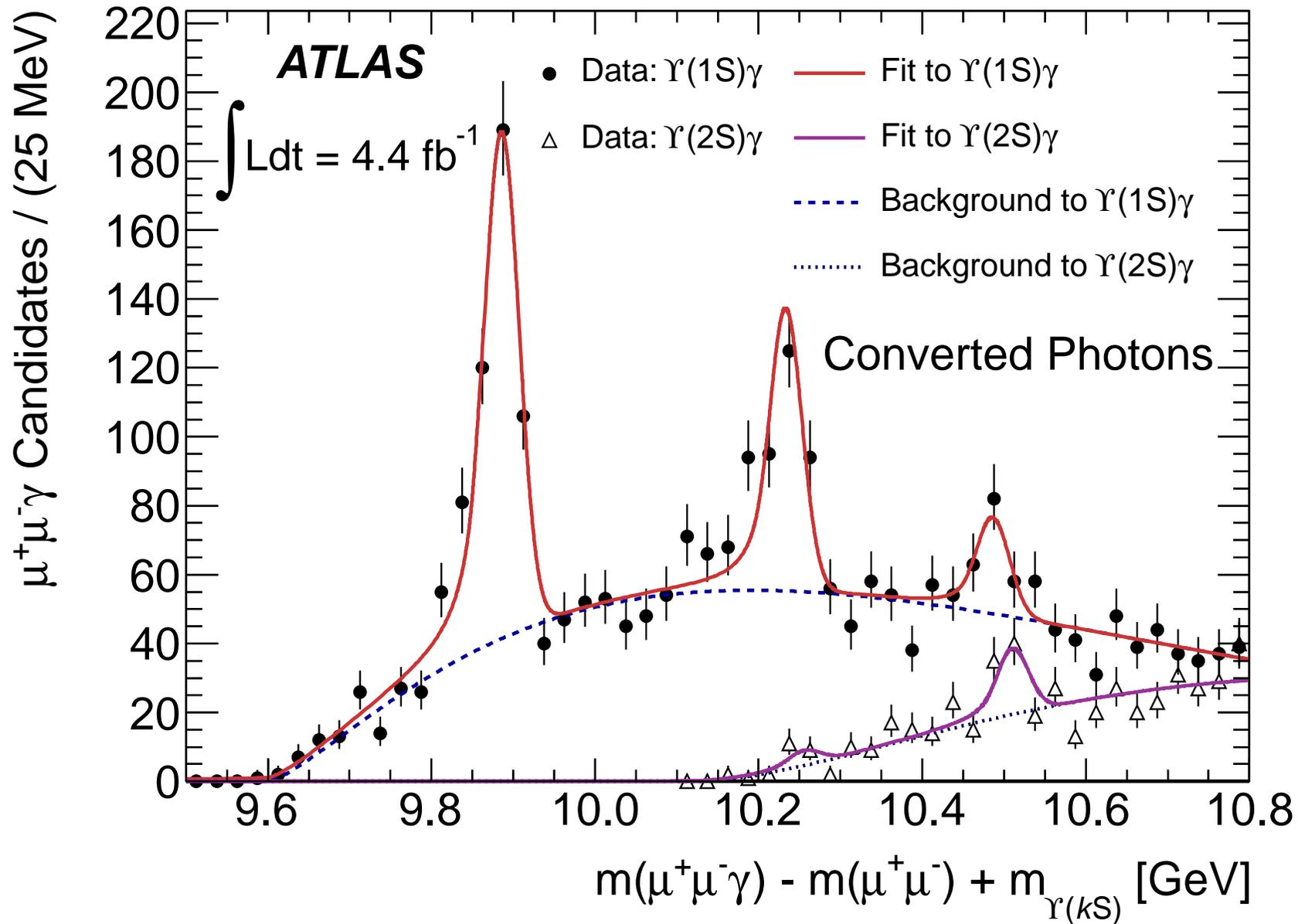


# Event with $\chi_b(3P)$ candidate



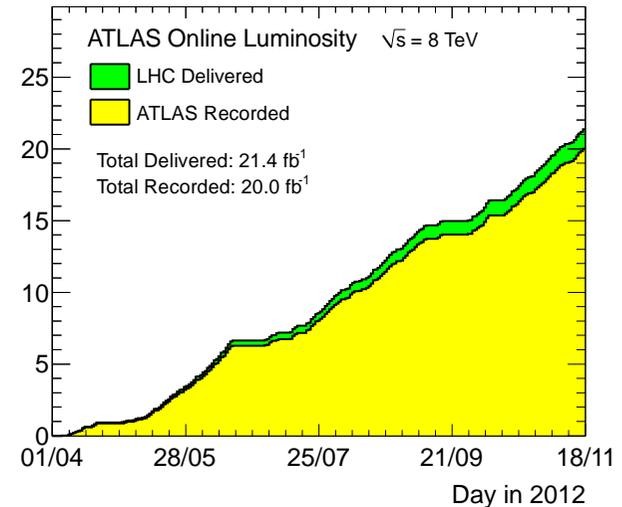
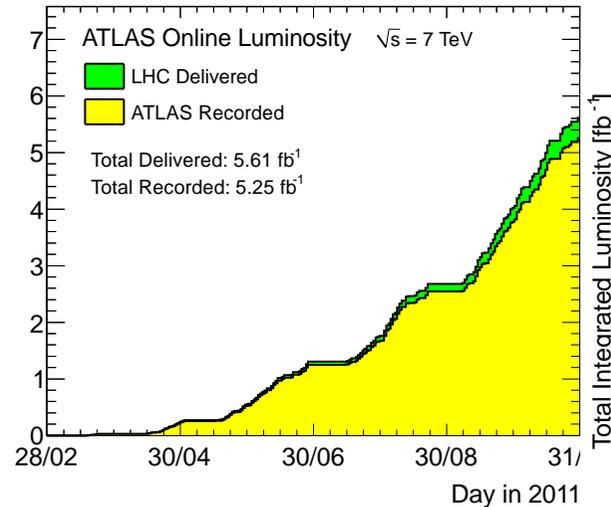
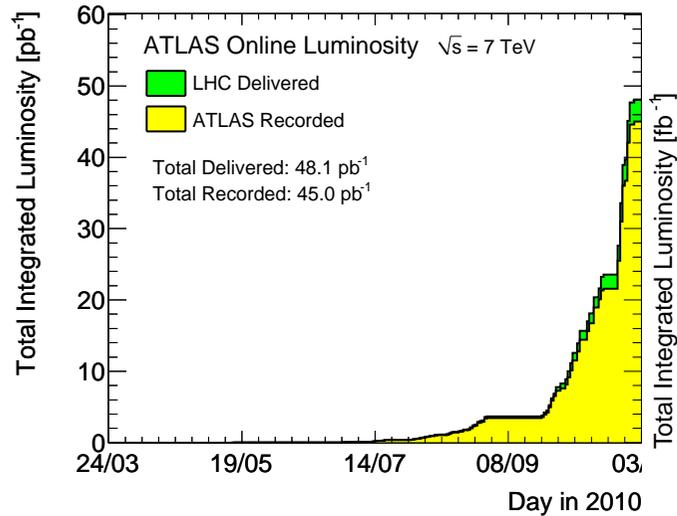


# All three $\chi_b$ peaks as seen by ATLAS





# Integrated luminosity in 2010, 2011, 2012



Look at the scales on  $y$ -axes:  $1 \text{ fb}^{-1} = 1000 \text{ pb}^{-1}$

Dramatic progress in luminosity over the years, meaning that one can now access less and less frequent processes...

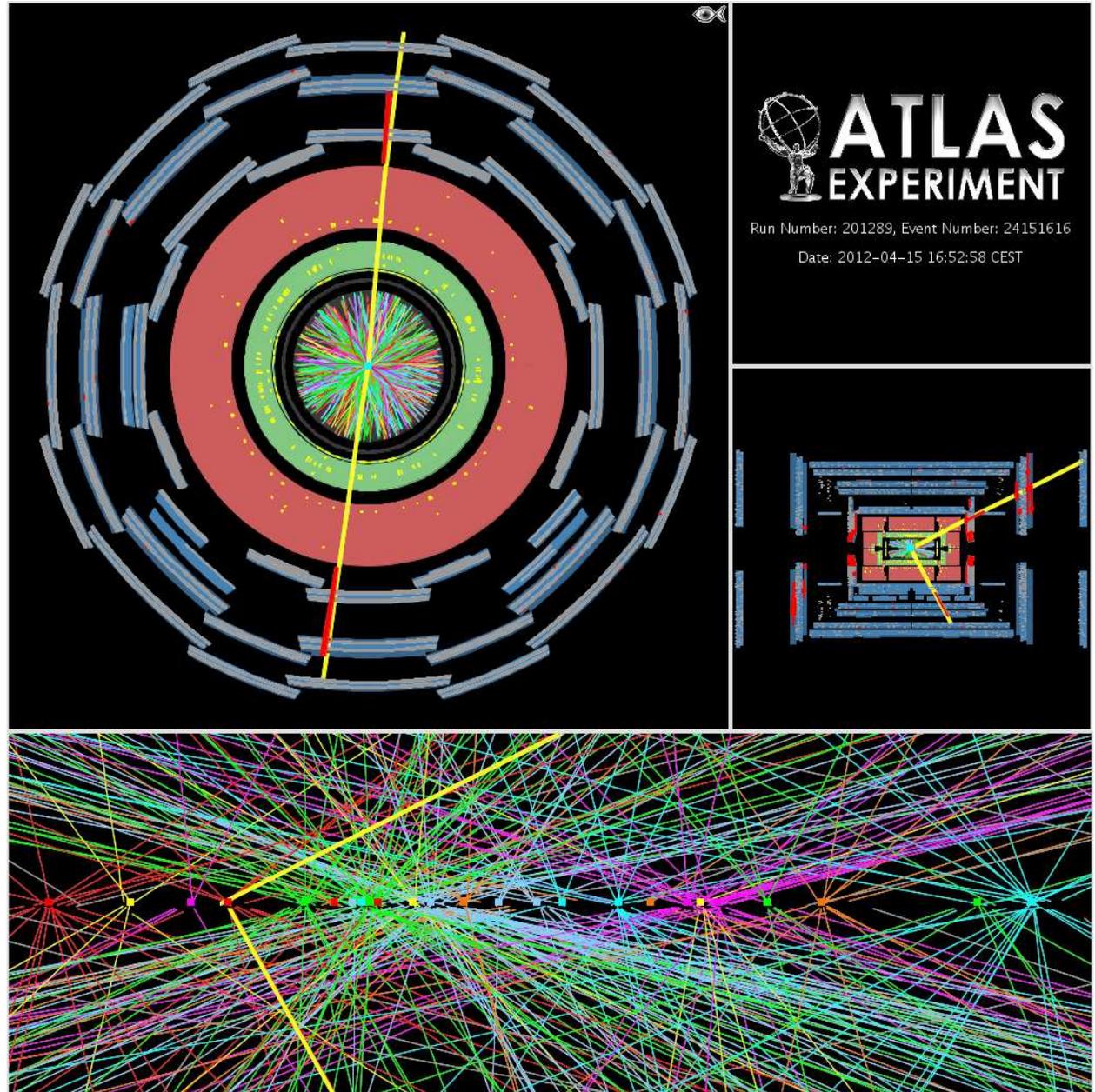
...but need tighter and tighter trigger selections!



# $Z \rightarrow \mu^+ \mu^-$ candidate at high luminosity



There are 20+ collisions  
in one bunch crossing,  
with a  $Z \rightarrow \mu^+ \mu^-$  candidate  
produced in one of them.





# $W^+W^-$ pair production

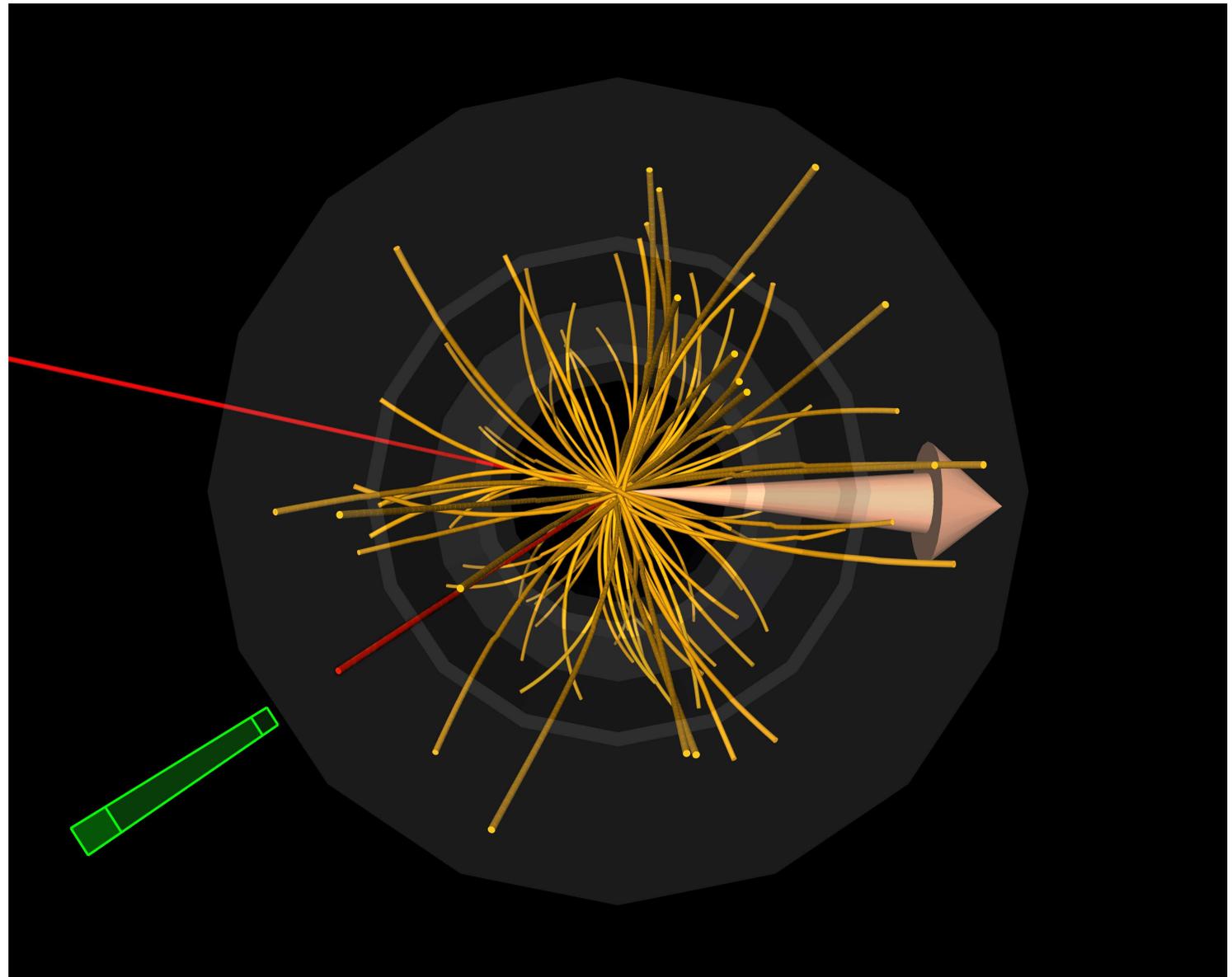


$$W^+ \rightarrow \mu^+ \nu_\mu$$

$$W^- \rightarrow e^- \bar{\nu}_e$$

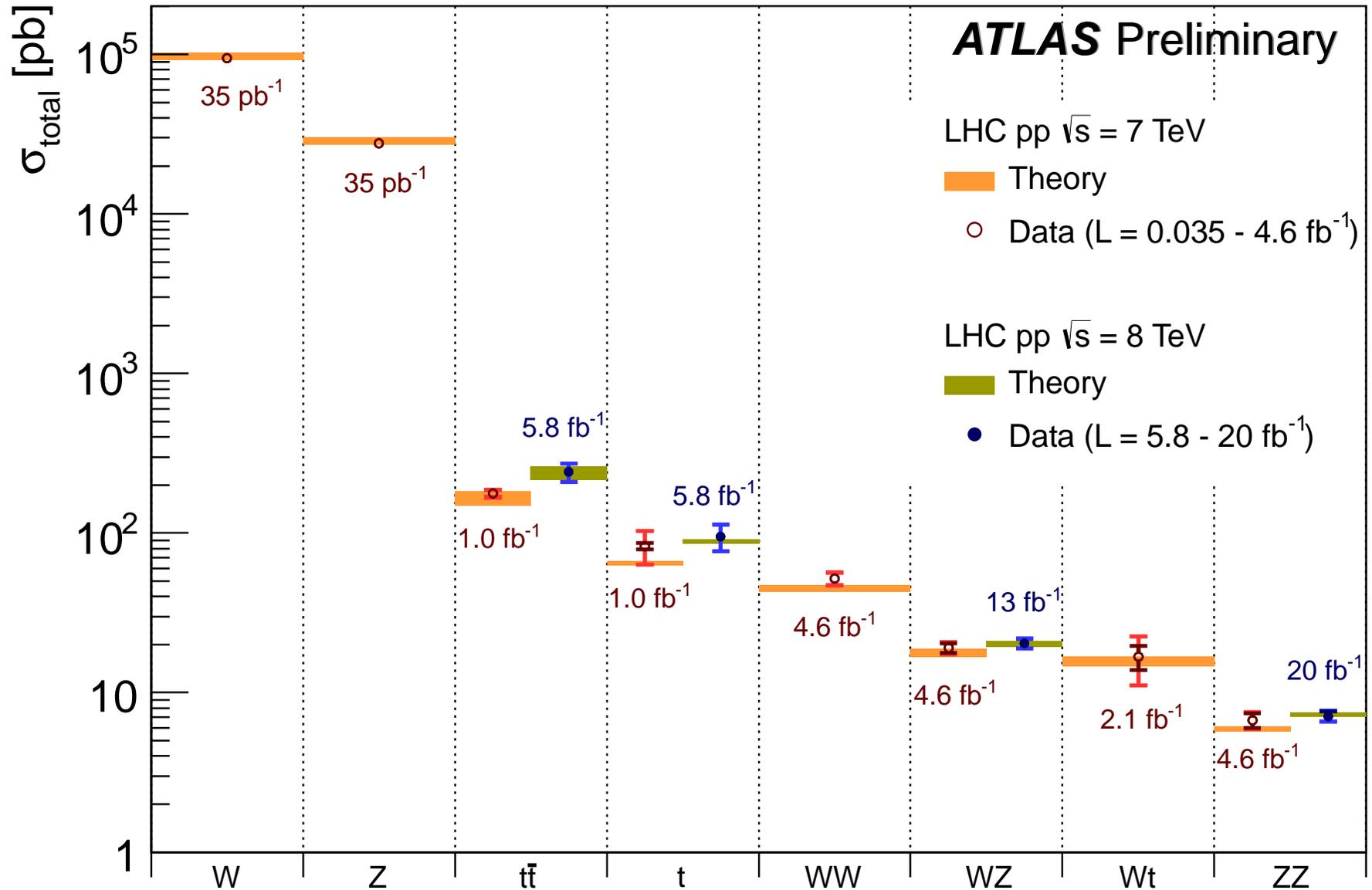
Neutrinos escape  
detection

$\Rightarrow$  missing  $P_T$





# Standard Model cross sections vs theory





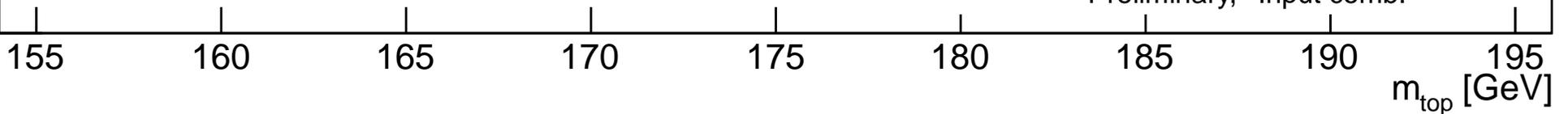
# Top quark mass measurement



**ATLAS Preliminary**  $m_{\text{top}}$  summary - Oct. 2013,  $L_{\text{int}} = 35 \text{ pb}^{-1} - 4.7 \text{ fb}^{-1}$

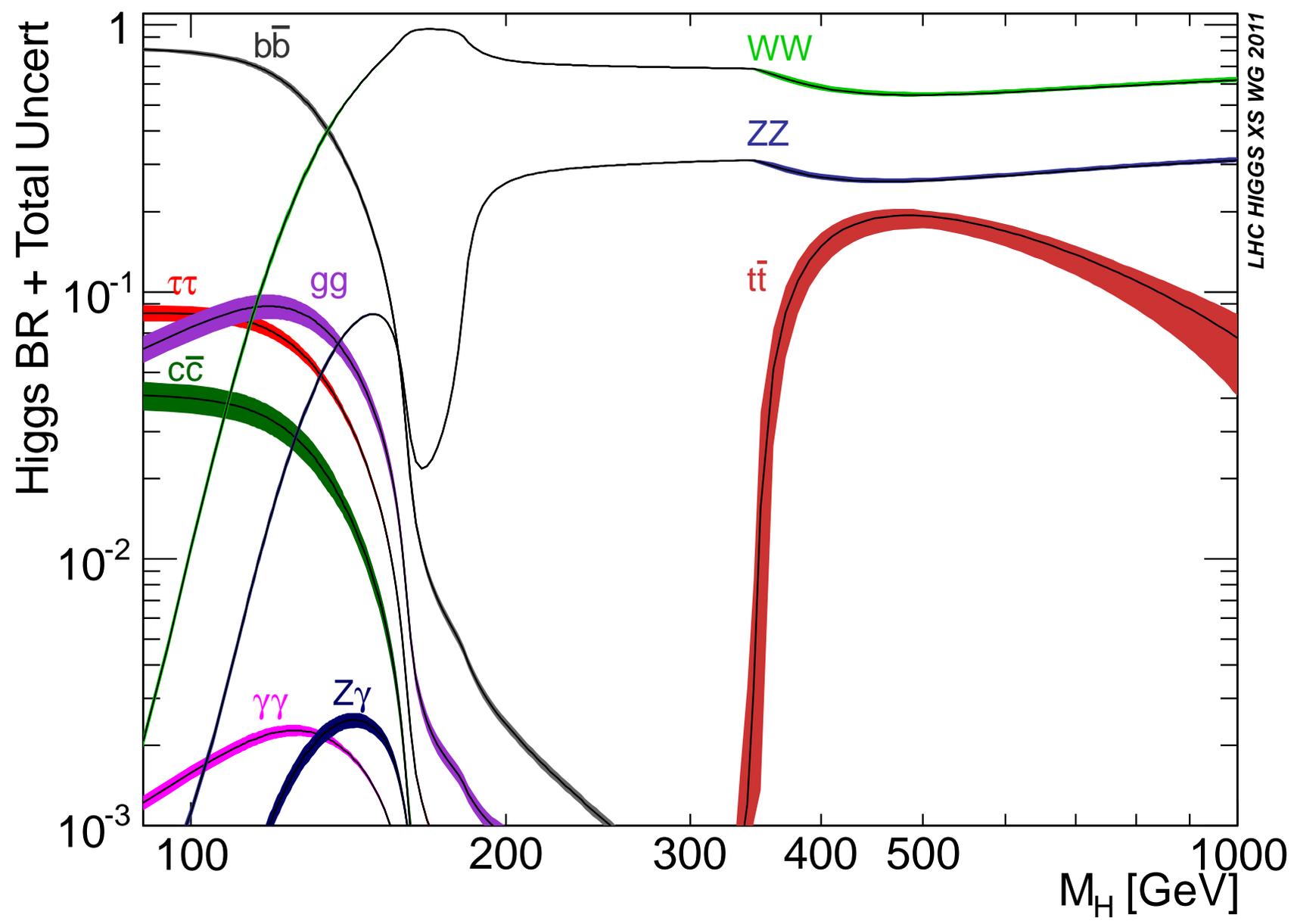
2010, lepton+jets* CONF-2011-033, $L_{\text{int}} = 35 \text{ pb}^{-1}$		$169.3 \pm 4.0$	$\pm 4.9$
2011, lepton+jets Eur. Phys. J. C72 (2012) 2046, $L_{\text{int}} = 1.04 \text{ fb}^{-1}$		$174.5 \pm 0.6 \pm 0.4$	$\pm 2.3$
2011, all jets* CONF-2012-030, $L_{\text{int}} = 2.05 \text{ fb}^{-1}$		$174.9 \pm 2.1$	$\pm 3.8$
2011, dilepton* CONF-2012-082, $L_{\text{int}} = 4.7 \text{ fb}^{-1}$		$175.2 \pm 1.6$	$\pm 3.1$ $\pm 2.8$
2011, lepton+jets* <sup>Ⓢ</sup> CONF-2013-046, $L_{\text{int}} = 4.7 \text{ fb}^{-1}$		$172.31 \pm 0.23 \pm 0.27 \pm 0.67 \pm 1.35$	
2011, dilepton* <sup>Ⓢ</sup> CONF-2013-077, $L_{\text{int}} = 4.7 \text{ fb}^{-1}$		$173.09 \pm 0.64$	$\pm 1.50$
<i>ATLAS Comb. Sept. 2013 (CONF-2013-102)</i> $172.65 \pm 0.31_{\text{stat.}} \pm 1.40_{\text{JSF} \oplus \text{bJSF} \oplus \text{syst.}}$			

stat. uncertainty  
 stat.  $\oplus$  JSF  $\oplus$  bJSF uncertainty  
 total uncertainty  
 \*Preliminary, <sup>Ⓢ</sup>Input comb.



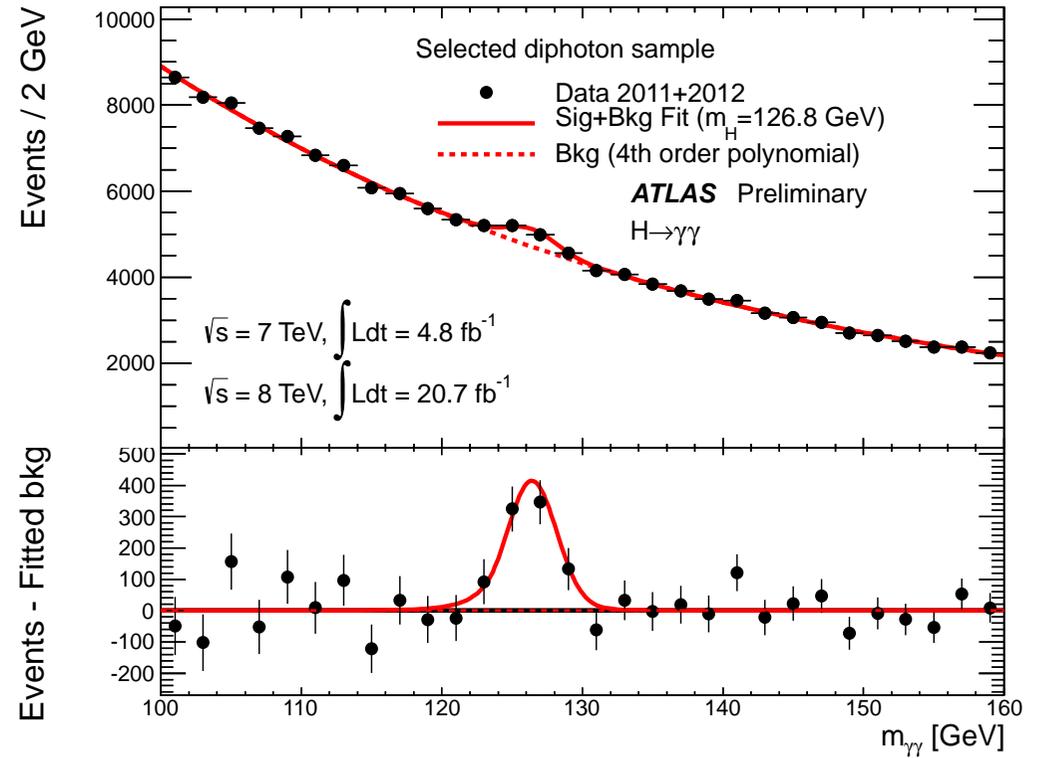
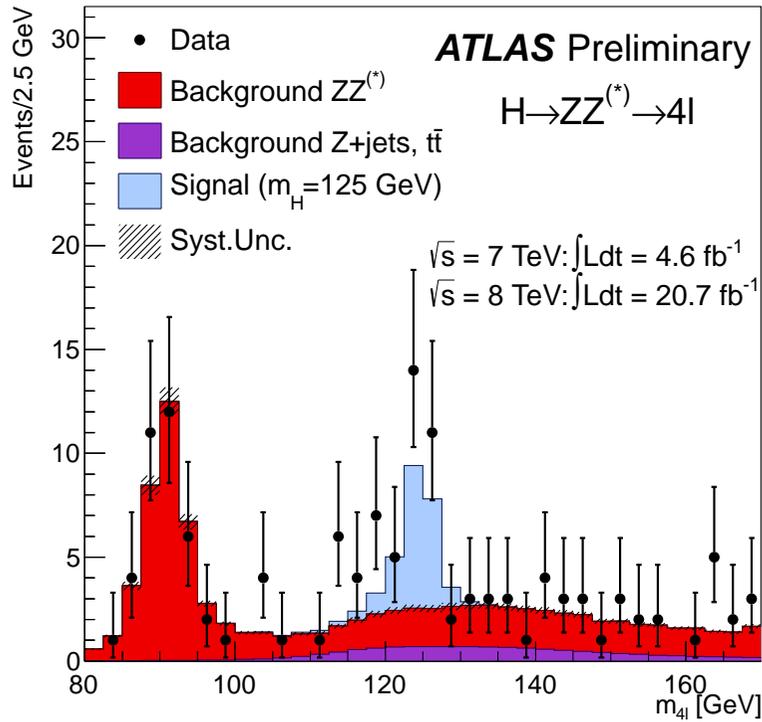


# Decay modes of the Standard Model Higgs Boson



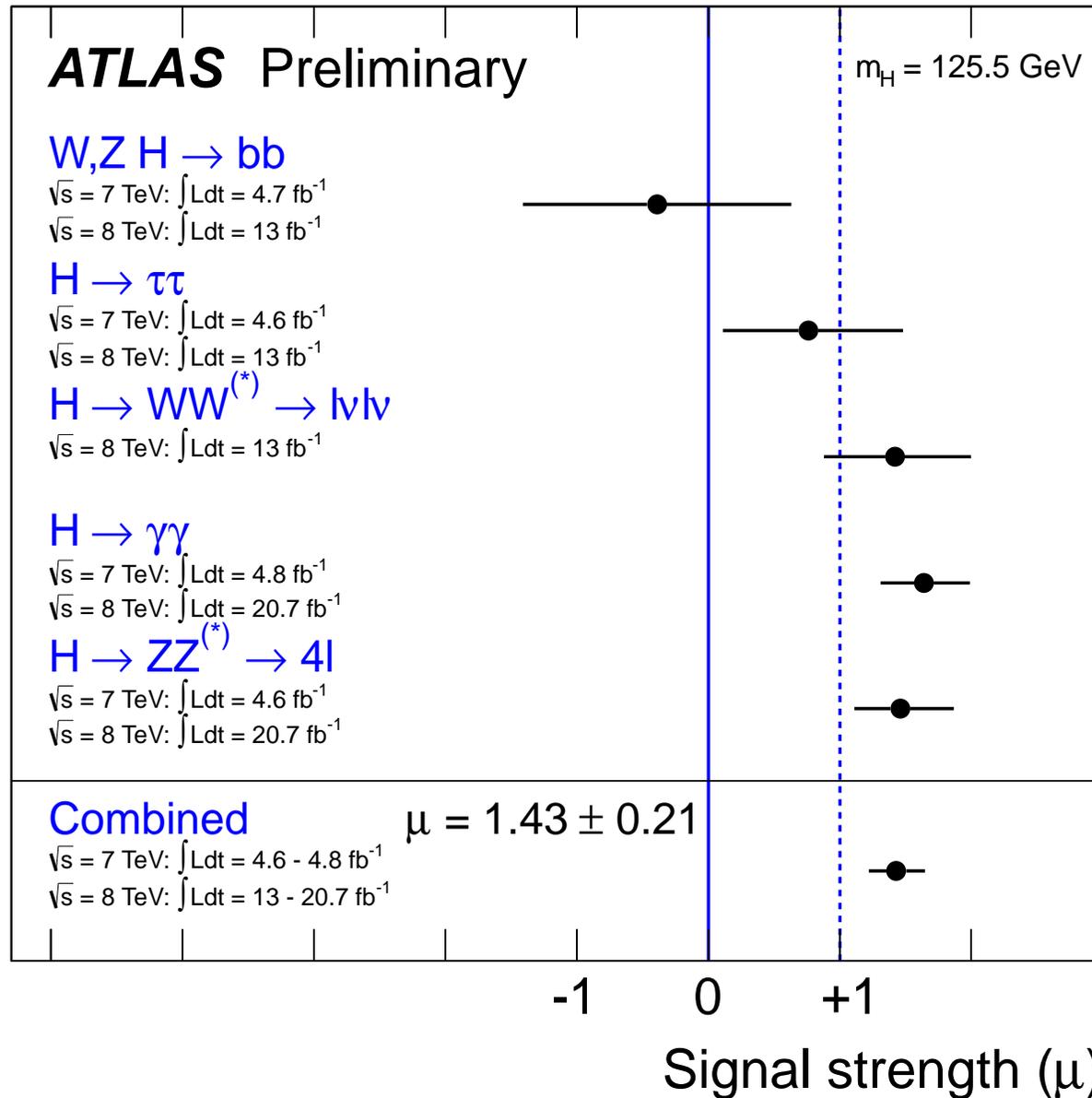


# Higgs(-like object) observation



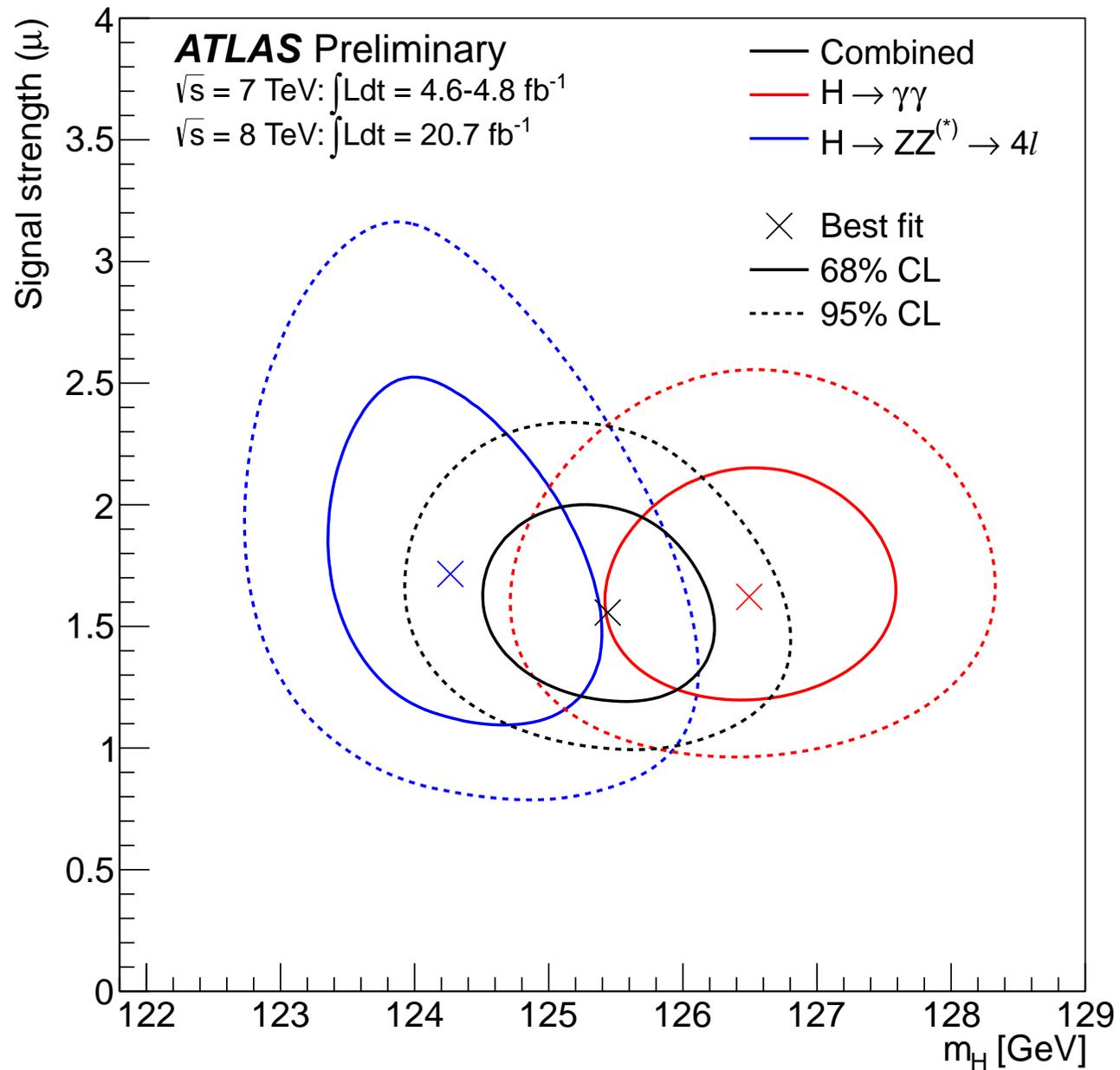


# Higgs(-like object): signal strength



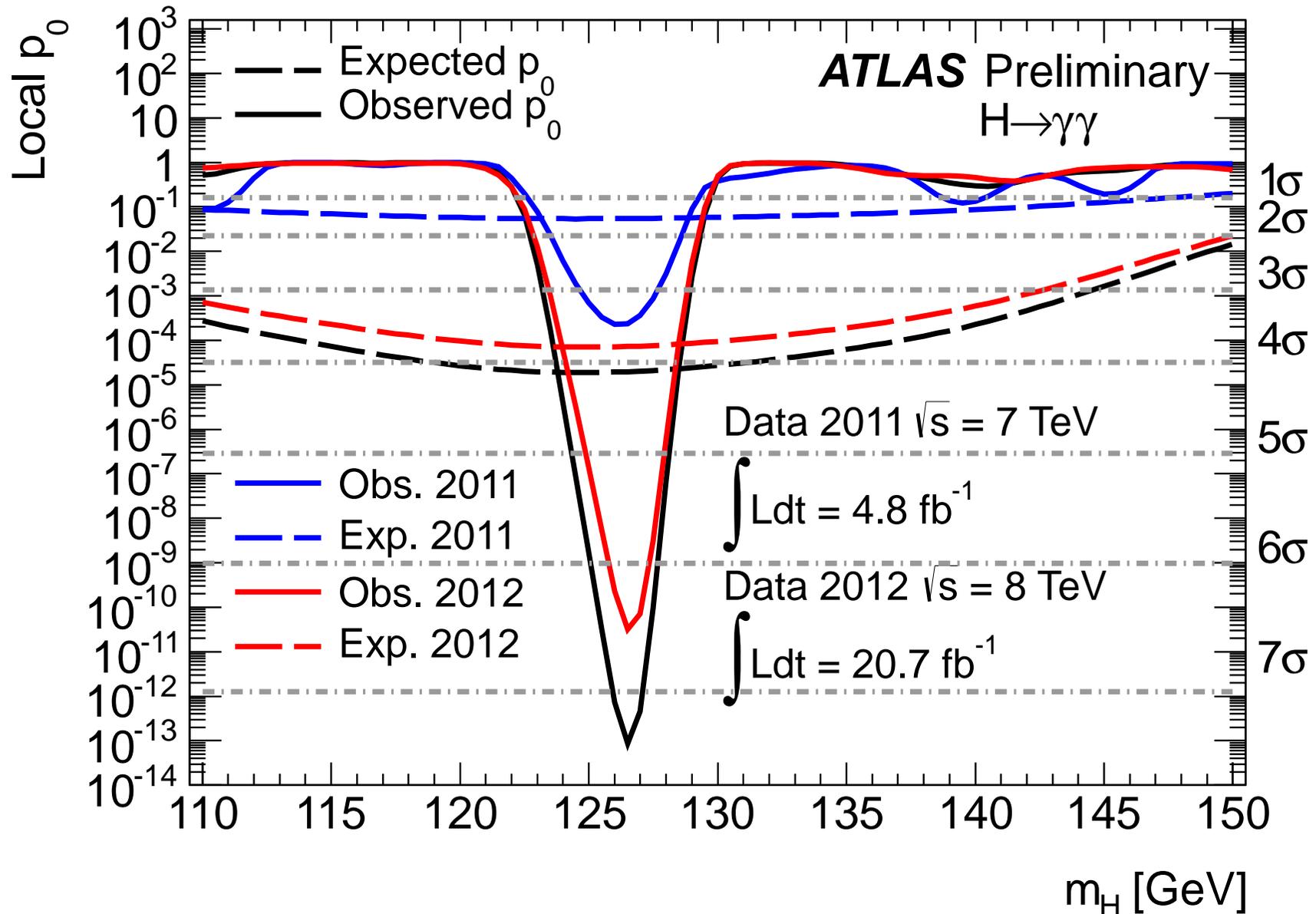


# Higgs(-like object): mass contours





# SM Higgs(-like) object: summary





## Questions to the Standard Model



The (gauge) symmetry group of the Standard Model is  $SU(2) \times U(1) \times SU(3)$

Hence three types of interactions, and the variety of gauge bosons, the interaction carriers:  $\gamma, W^\pm, Z^0, g$

- ◆ Why are these three types so different – and the fourth, gravity, even more so?
- ◆ Why three generations?
- ◆ Why fractional electric charges of quarks?
- ◆ Why are the fermion masses so different?
- ◆ What determines the mixing of various generations?

These and many more questions cannot be answered within SM.

**We need a bigger theory...**



## Cosmology: source of inspiration



- ◆ Universe is made up of  $\sim 10^{11}$  galaxies; each galaxy contains  $10^{10} - 10^{12}$  stars
- ◆ Cosmology: science about the history of the Universe
- ◆ Assumption: laws of physics have not changed along the way
- ◆ Method 1: observe the Universe evolution NOW and try to extrapolate backward
- ◆ Method 2: assume some starting point (the Big Bang) and extrapolate forward
- ◆ The overall established picture in modern cosmology is arguably as stable and solid as the Standard Model in Particle Physics, but it also has its unanswered questions
- ◆ The hope (from both camps) is that the answers may be shared!



# Glashow's serpent



As usual, "natural" system of units:

◆  $\hbar = 1, c = 1, k_B = 1$

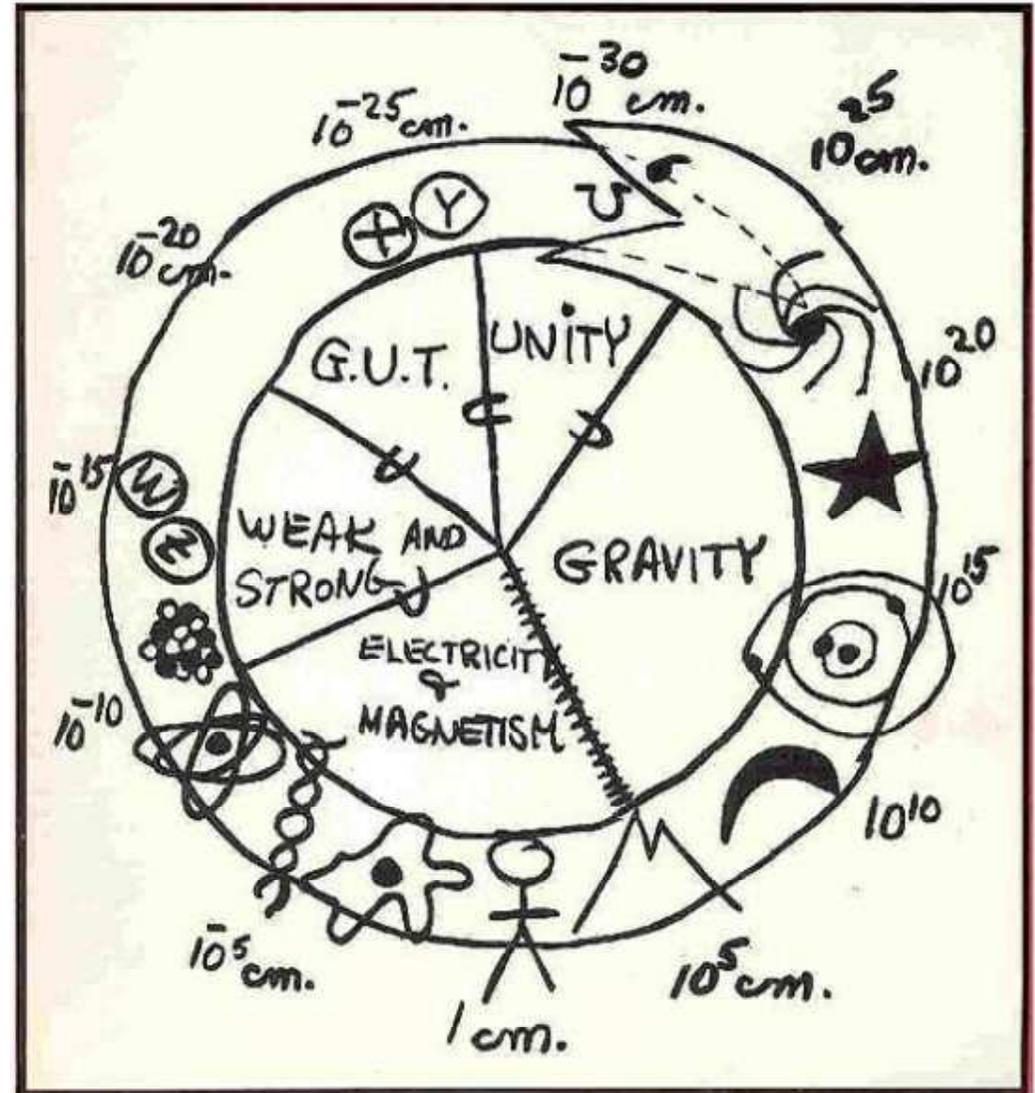
◆ distance  $\sim$  time

◆ Energy  $\sim$  1/distance

◆ Temperature  $\sim$  Energy

◆ Hence, Planck's mass

$$M_p = \sqrt{\frac{\hbar c}{G_N}} = 10^{19} \text{ GeV}$$







# Expanding Universe



Experimental fact: Universe is expanding

Light from distant galaxies is red-shifted (Doppler effect)

The larger the distance, the more the shift (can be measured precisely)

The light wave expands with space, hence the shift towards lower frequency

Hubble constant: 70 km/s per Megaparsec

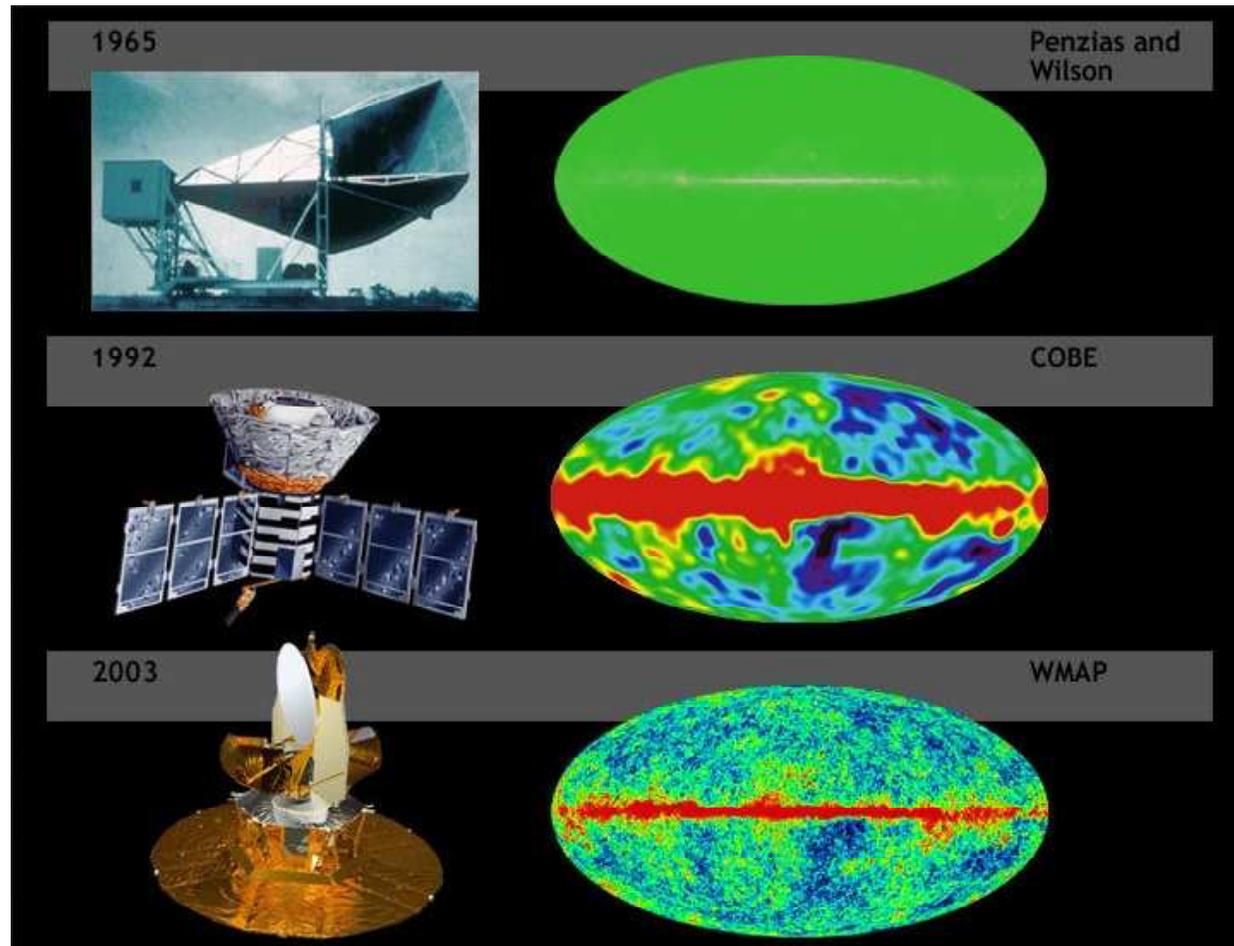
Once, the Universe was 3000 times smaller – and 3000 times hotter than today

Cosmic Microwave Background 2.7 K today: photons wandering in space since then

Almost isotropic (same in all directions) – but NOT EXACTLY!



# CMB anisotropy

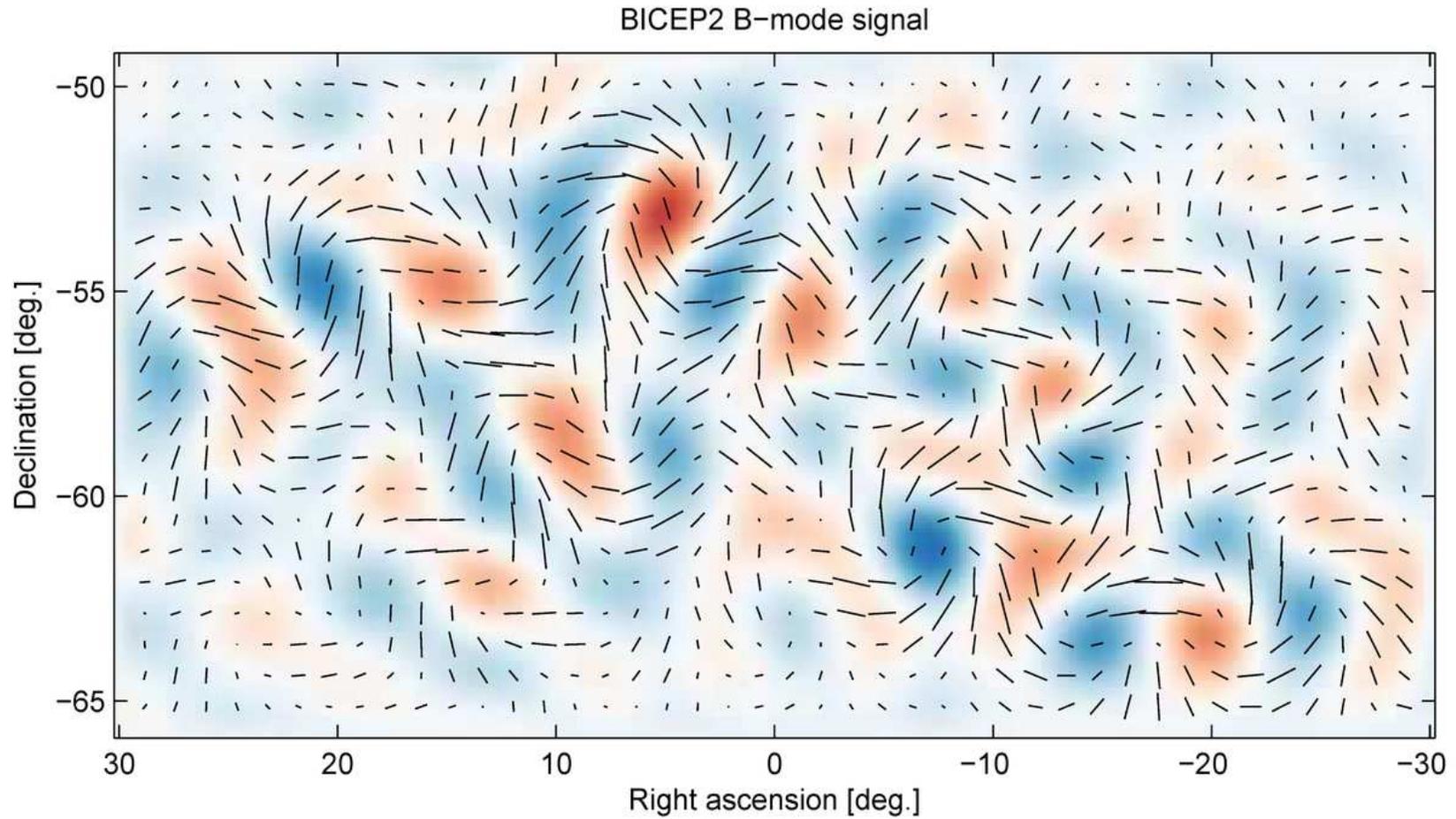


Ripples from times 300 000 years ago, at the level of  $10^{-3}$

These small non-uniformities may be signals from the seeds of galaxy formation



# Polarisation fluctuations



Possible signs of gravitational waves from the Big Bang?



# Bariogenesis



Once the Universe was a billion times smaller and hotter than today

Light chemical elements were formed:  $He^4$ ,  $D$ ,  $He^3$ ,  $Li$ , ...

Relative abundance of these elements can be predicted by theory

Depends on density of matter and number of types of particles

Does not seem to be enough to stop expansion, or even to form the galaxies like ours:



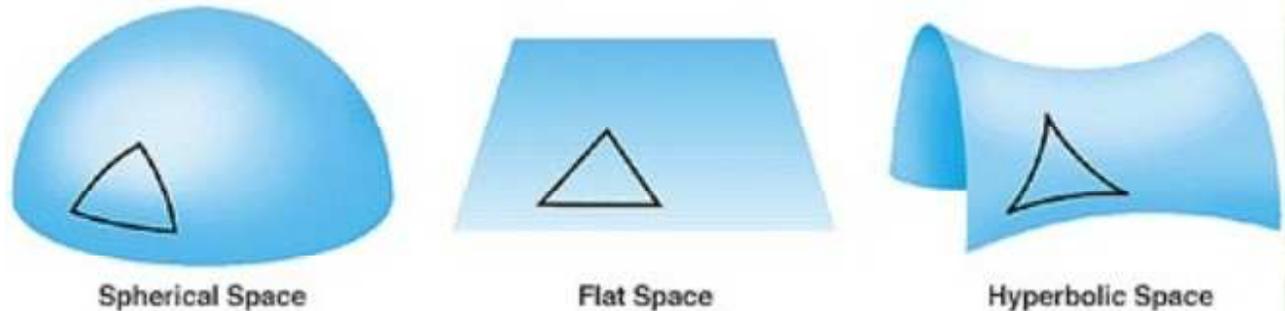


# Cosmological inflation

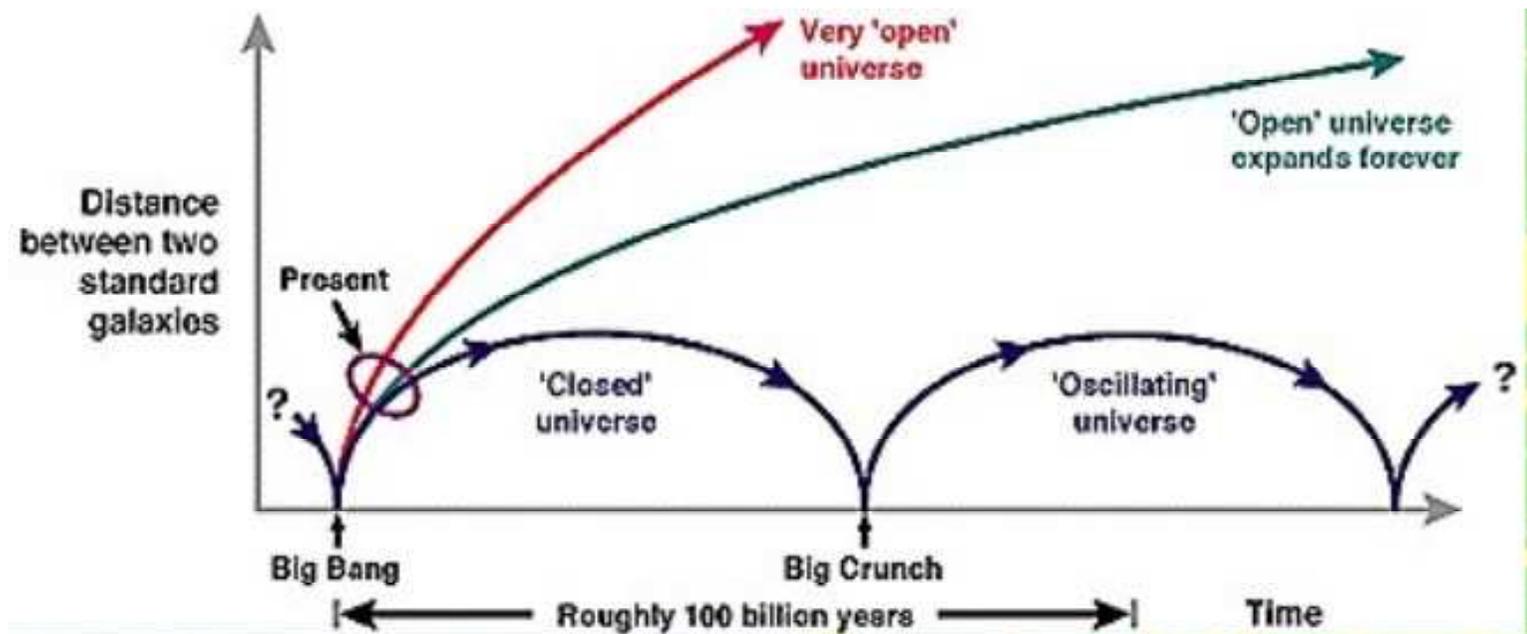


Basic idea: very early, about maybe  $10^{-35}$  s after the Big Bang, the expansion was exponentially fast

Can explain why the universe looks almost flat now



Fate of the Universe depends on this:





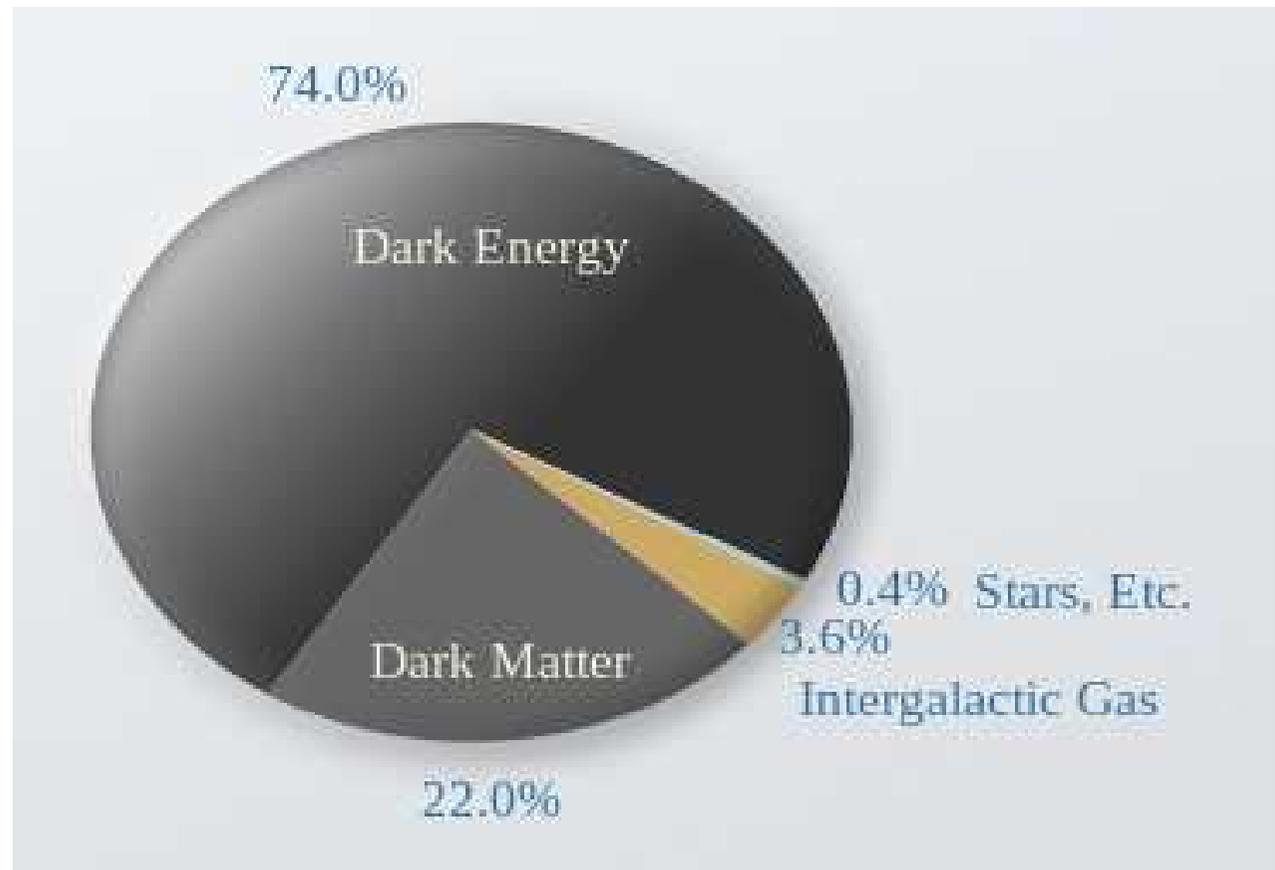
# Energy density budget of the Universe



There is some critical value of the energy density which keeps the balance between expansion and contraction of the universe.

$\Omega = 1$  corresponds to a flat universe – close to what we see today

Latest measurements show that there are different components to this density:





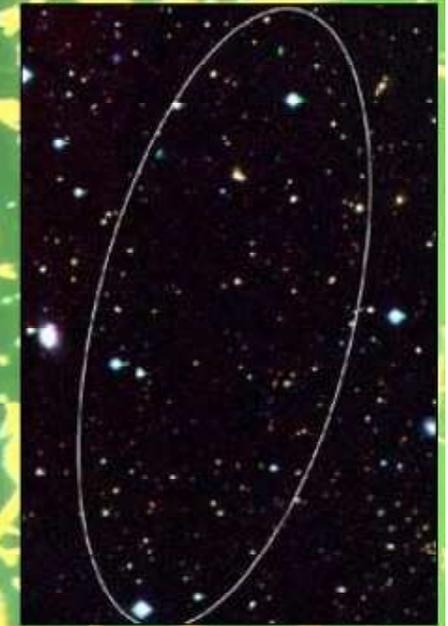
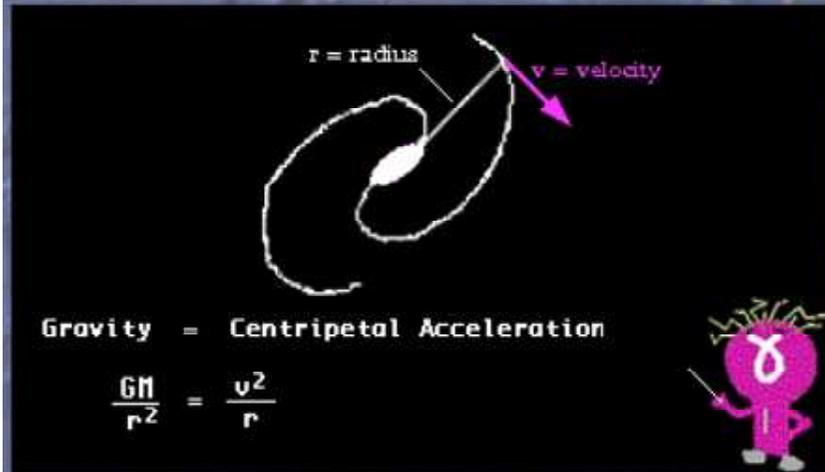
# Evidence for Dark Matter – I



Galaxies rotate more rapidly than allowed by centripetal force due to visible matter

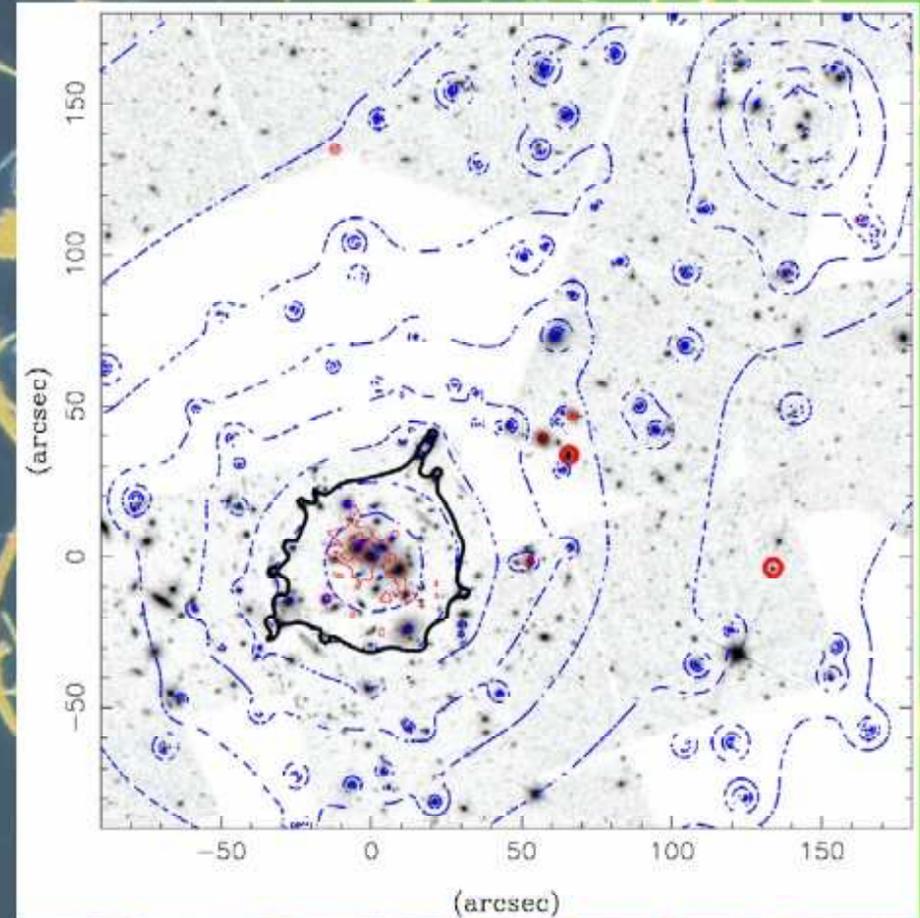
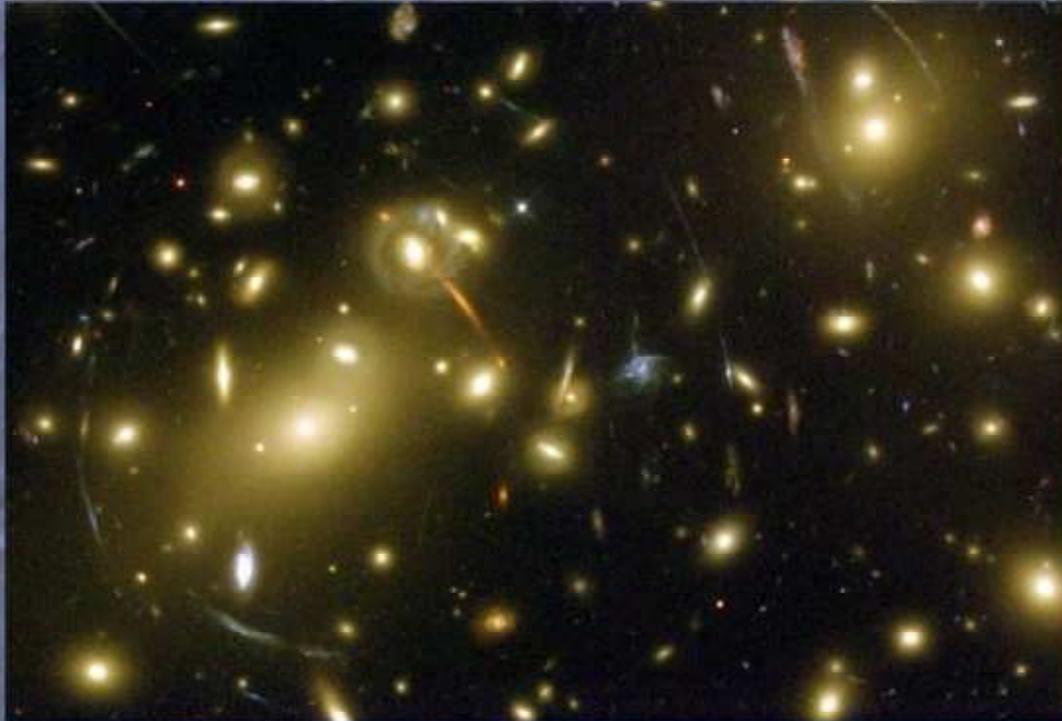
X-ray emitting gas held in place by extra dark matter

Even a 'dark galaxy' without stars



Light bent by gravitational field of dark matter

Contours of mass density

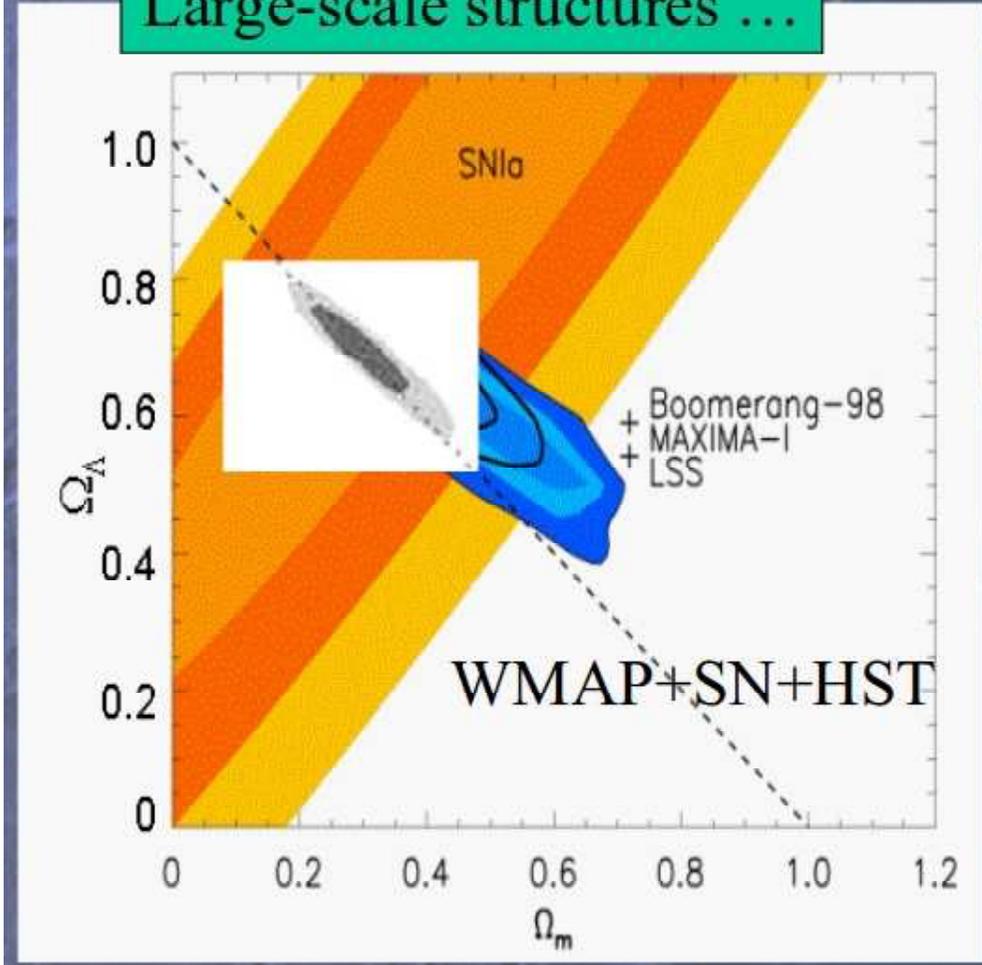




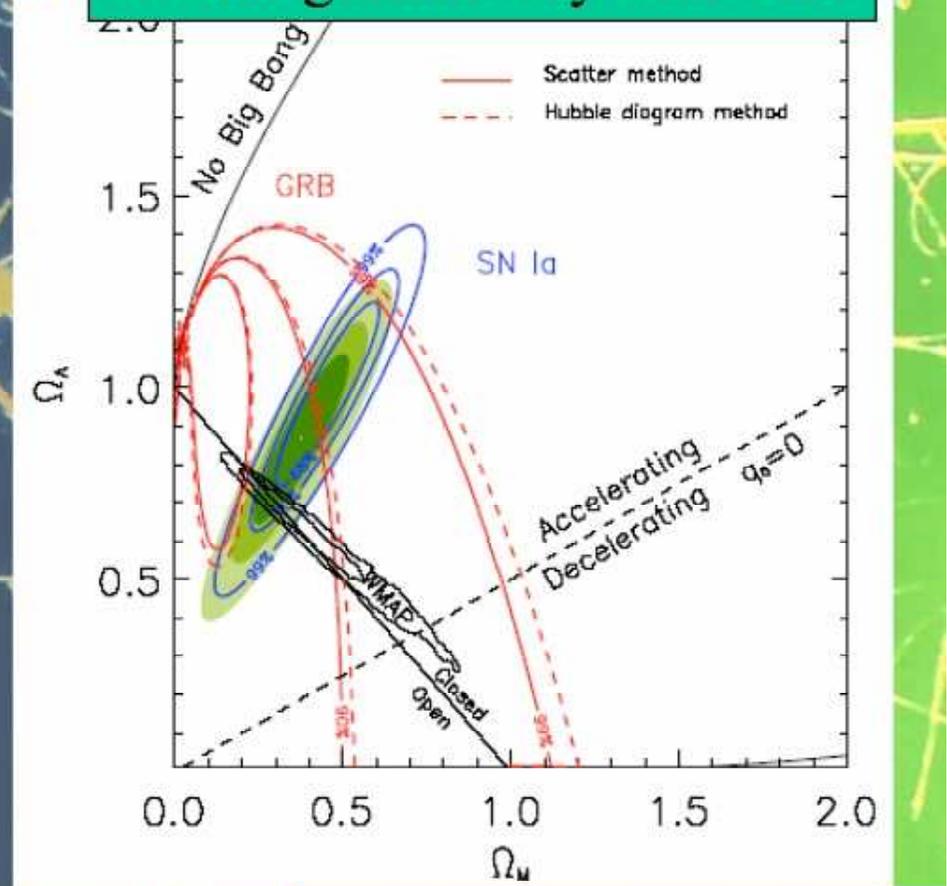
# Experimental data on components of $\Omega$



WMAP, Supernovae,  
Large-scale structures ...



... and gamma-ray bursters?



Barbiellini //, Ghirlanda et al



## Unresolved questions in Cosmology



- Why is the Universe so big and old?  
~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?  
almost flat: density nearly critical
- Where did the matter come from?  
1 proton for every 1,000,000,000 photons
- How did structures form?  
ripples + invisible dark matter?
- What is the dark matter?
- What is the dark energy?

The hope is that Particle Physics can help answer at least some of these!



## Beyond the Standard Model



- ◆ Is there a bigger symmetry group, which will become visible at higher energies?  
⇒ Grand Unification
- ◆ Or maybe the Poincaré-Lorentz invariance group can be extended to include anticommutation relations?  
⇒ Supersymmetry
- ◆ Or maybe our space-time has more than  $3+1$  dimensions, some of which are “compactified” ?  
⇒ Large extra dimensions

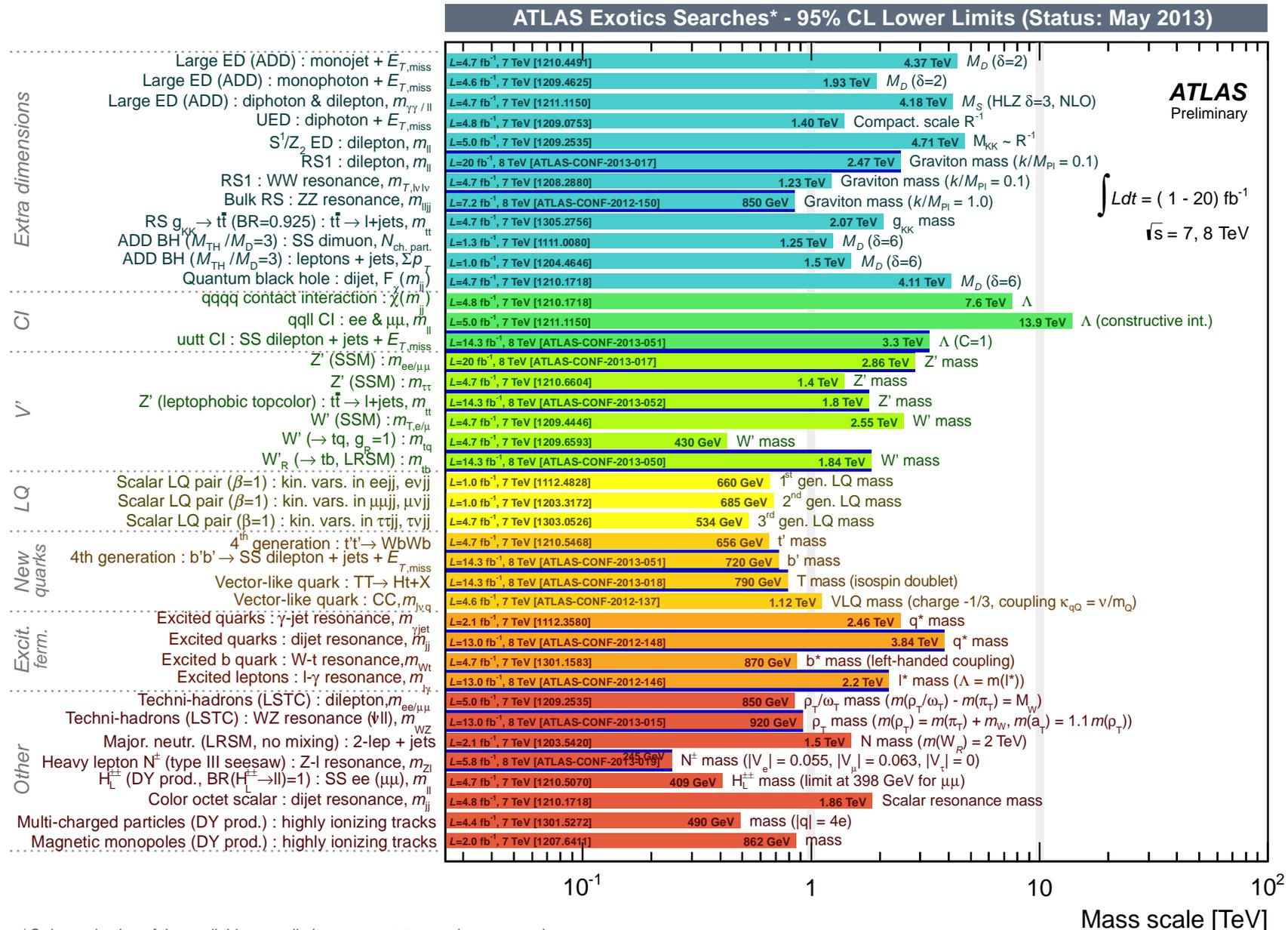
These, and many other, theories exist — and predict some observable effects.

Physicists are searching for them, in a hope to answer some of the questions...





# Exotics searches: lower limits



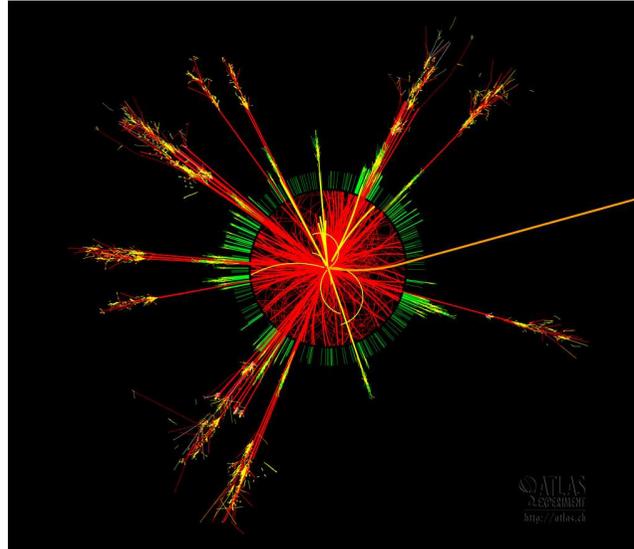
\*Only a selection of the available mass limits on new states or phenomena shown



## Summary and outlook



- ◆ Huge amount of work has been done by LHC experiments
- ◆ An object was observed which looks very much like a Higgs boson!
- ◆ Future studies will determine if this is indeed the Standard Model Higgs
- ◆ The Standard Model is standing strong – no SUSY, no sign of any exotics either. . .
- ◆ Some data still to be analysed, and much more data is still to come
- ◆ Hoping for many fascinating discoveries in the near future!





## Info on Higgs-like object observation in ATLAS



Web-page with the official Press release:

<http://www.atlas.ch/news/2012/latest-results-from-higgs-search.html>

Official press release in Georgian:

<http://www.atlas.ch/news/2012/HiggsStatementATLAS-Georgian.pdf>

Other ATLAS Higgs resources:

<http://www.atlas.ch/HiggsResources/>