OVERVIEW OF LHC RUN-I RESULTS: ATLAS, CMS, LHCB

Caterina Doglioni – University of Geneva / ATLAS Collaboration
for the ATLAS, CMS and LHCb Collaborations

01/07/2014 – SPS Annual Meeting, Fribourg

OUTLINE

LHC Run-I data taking has come to a close

This talk:

selected highlights from ATLAS, CMS and LHCb

1) The **LHC** and the **LHC experiments**

2) What we have **rediscovered** and **measured**

3) What we have **discovered** and **measured**

4) What we **haven't discovered** (yet)

5) **Prospects** for measurements and discoveries at Run-II

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1. THE LHC AND ITS EXPERIMENTS

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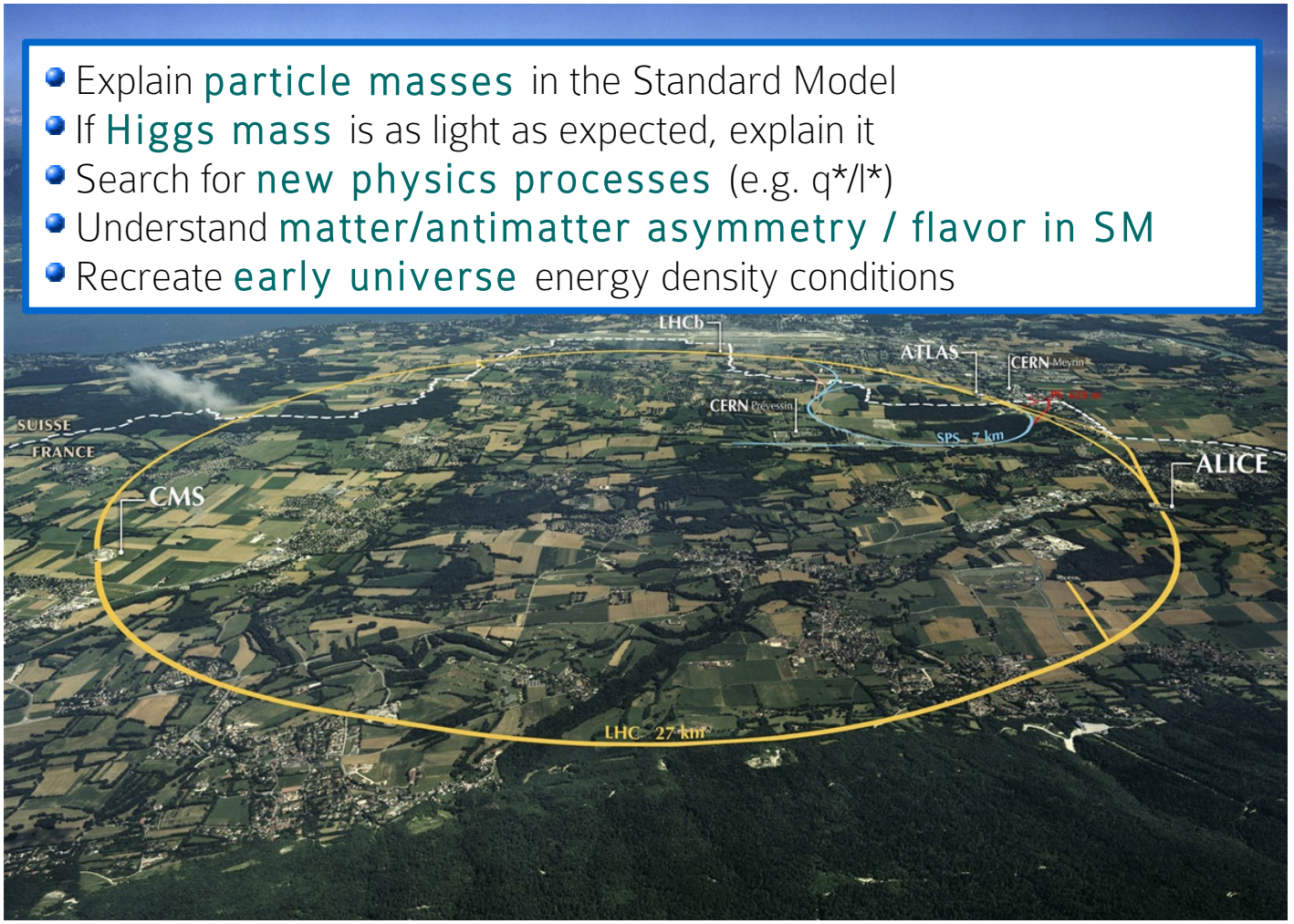
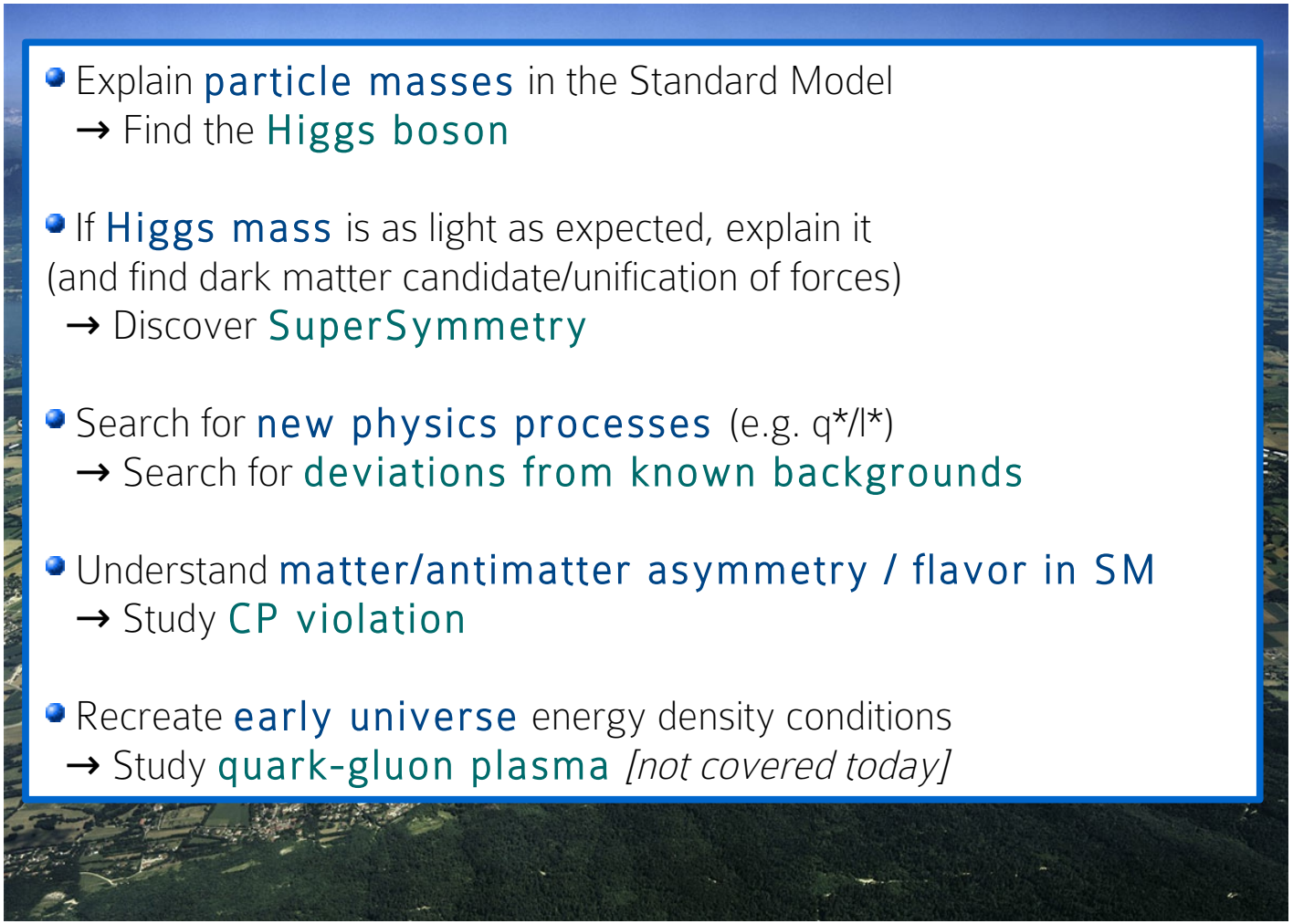
PHYSICS GOALS AT THE LHC

- Explain **particle masses** in the Standard Model
- If **Higgs mass** is as light as expected, explain it
- Search for **new physics processes** (e.g. q*/l*)
- Understand **matter/antimatter asymmetry / flavor in SM**
- Recreate **early universe** energy density conditions



PHYSICS GOALS AT THE LHC



- Explain **particle masses** in the Standard Model
  → Find the **Higgs boson**

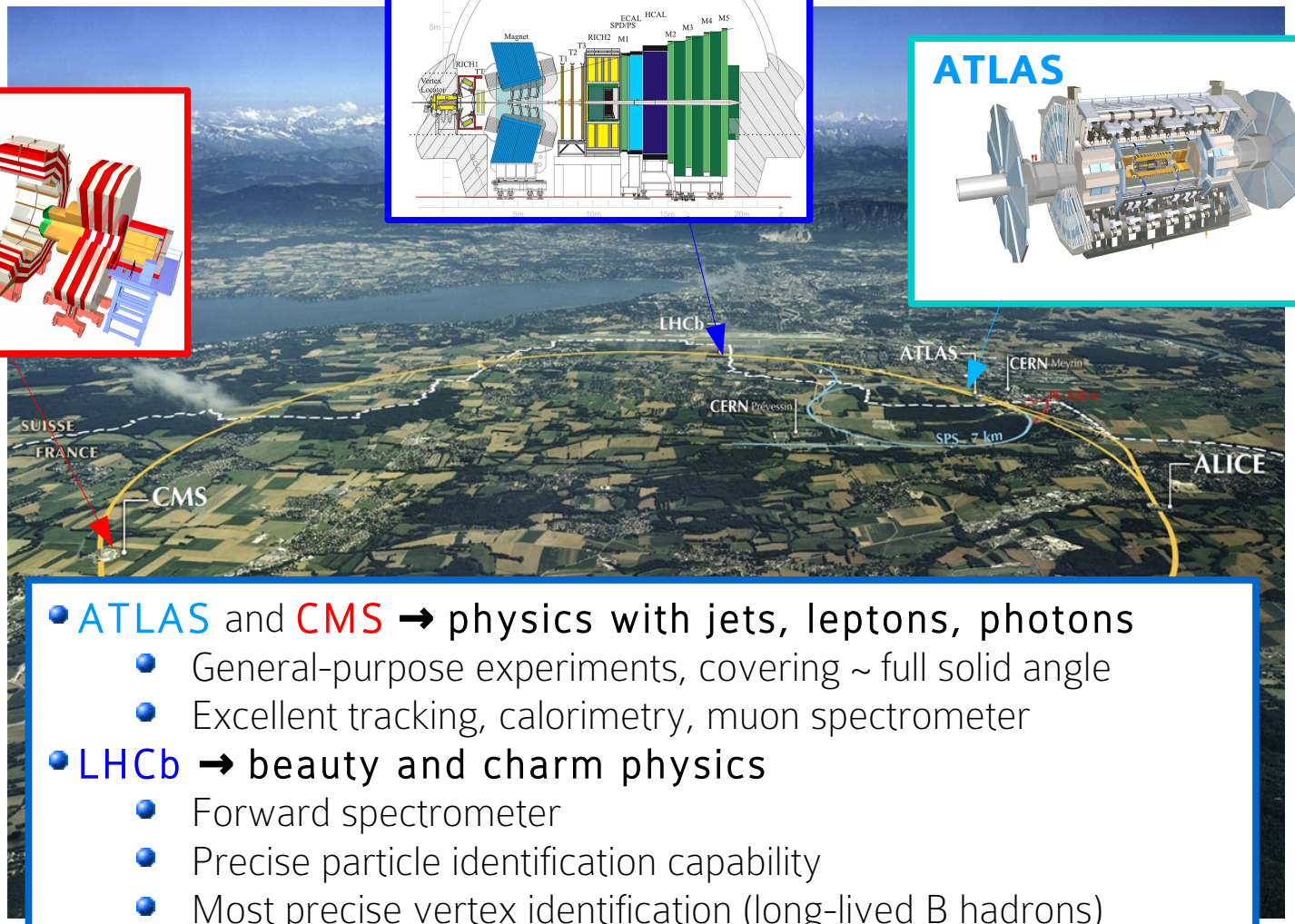
- If **Higgs mass** is as light as expected, explain it
(and find dark matter candidate/unification of forces)
  → Discover **SuperSymmetry**

- Search for **new physics processes** (e.g. q*/l*)
  → Search for **deviations from known backgrounds**

- Understand **matter/antimatter asymmetry / flavor in SM**
  → Study **CP violation**

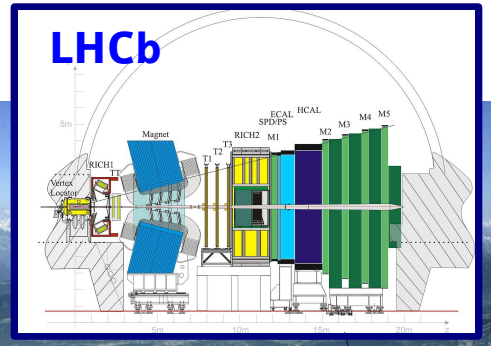
- Recreate **early universe** energy density conditions
  → Study **quark-gluon plasma** *[not covered today]*

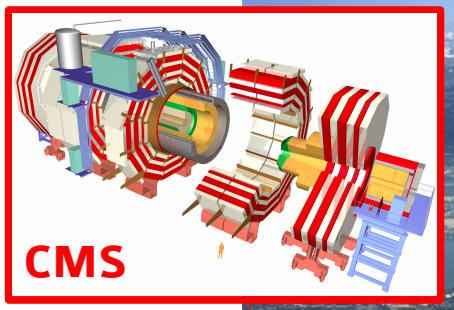
PHYSICS GOALS → LHC EXPERIMENTS

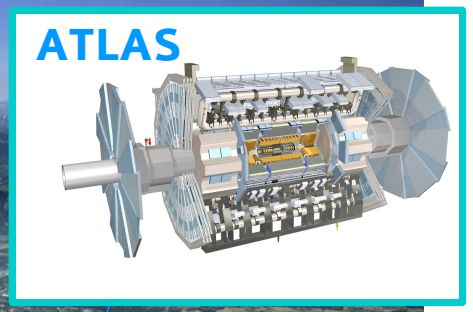


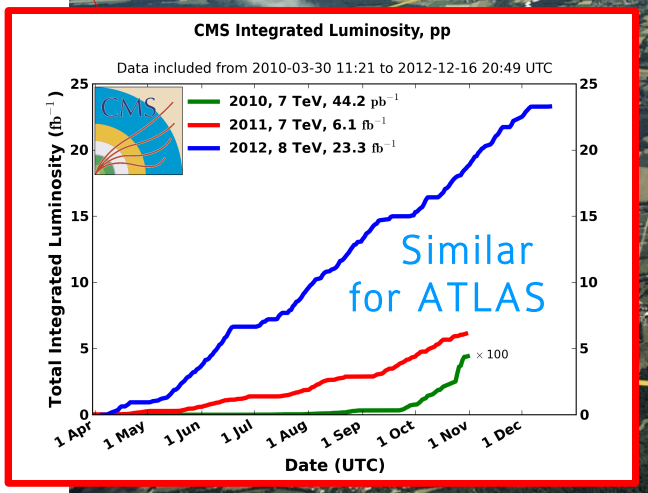
- ATLAS and CMS → physics with jets, leptons, photons
  - General-purpose experiments, covering ~ full solid angle
  - Excellent tracking, calorimetry, muon spectrometer
- LHCb → beauty and charm physics
  - Forward spectrometer
  - Precise particle identification capability
  - Most precise vertex identification (long-lived B hadrons)

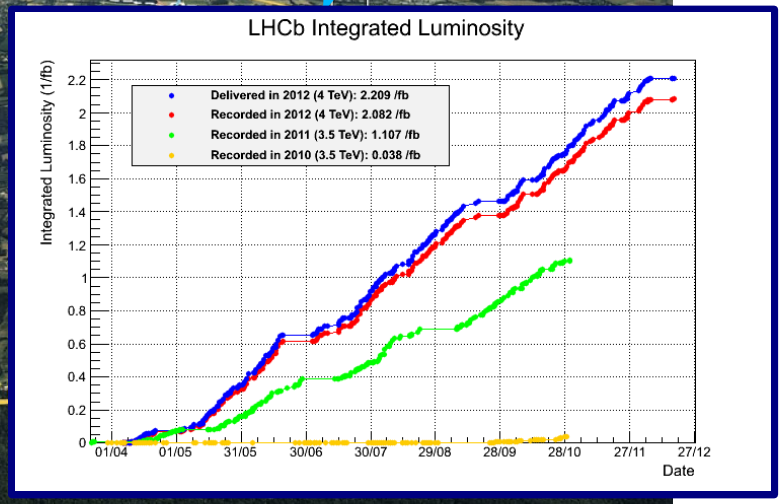
2010: THE START OF THE LHC ERA







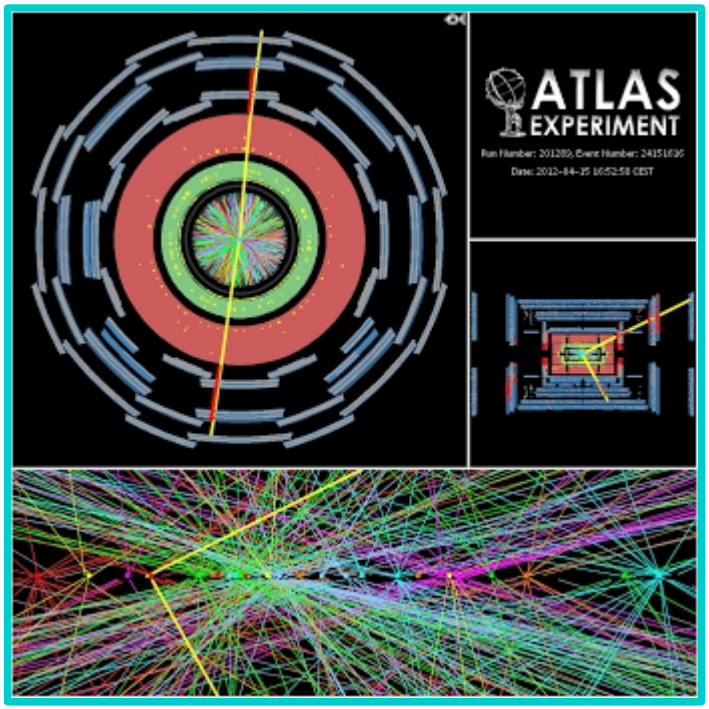




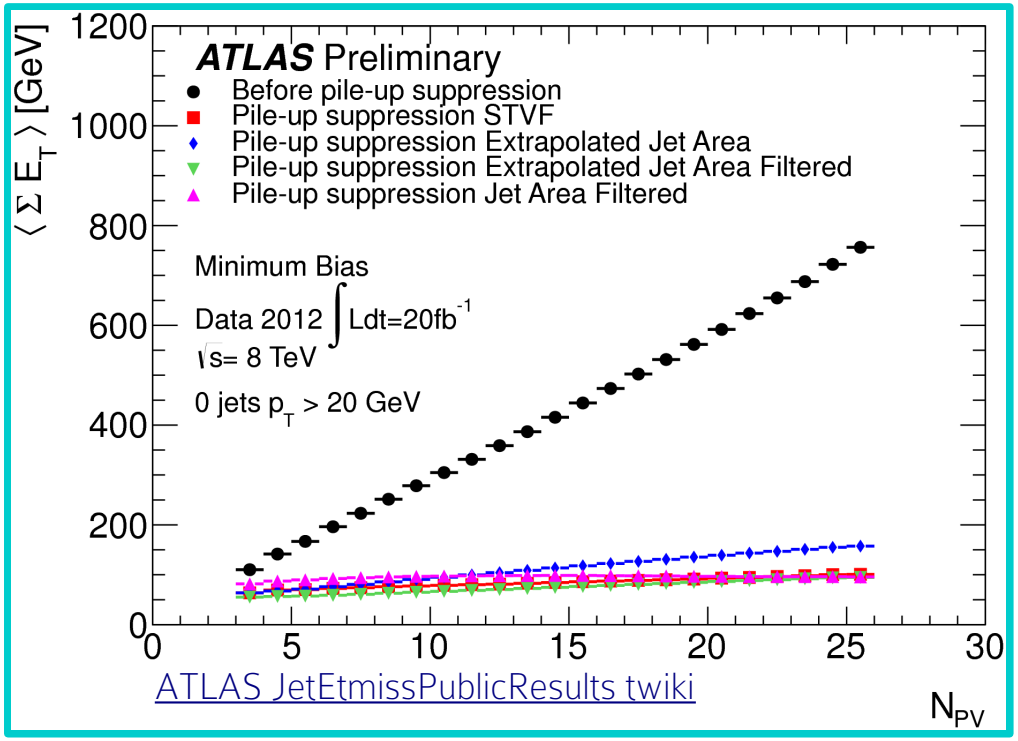
First LHC collisions for physics: March 2010

MORE DATA AT A PRICE: PILE-UP

- Pile-up: additional interactions within the same bunch crossing:
  - Both ATLAS and CMS performed well under high pile-up conditions
  - LHCb *luminosity-levelling* keeps pile-up under control for precision measurements



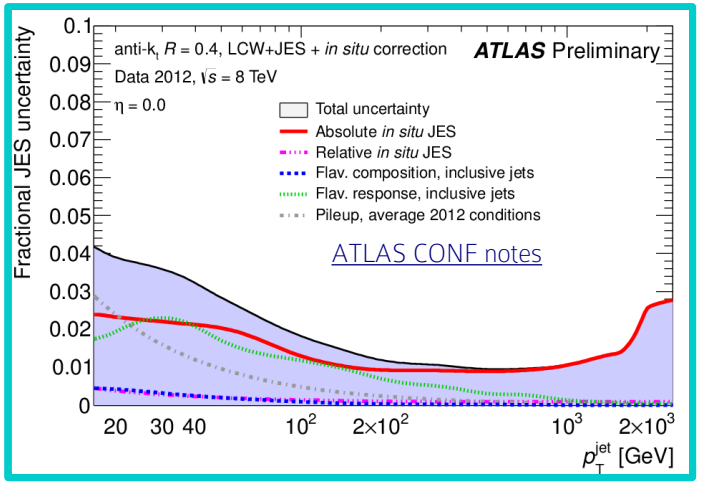
Z event with 25 reconstructed vertices

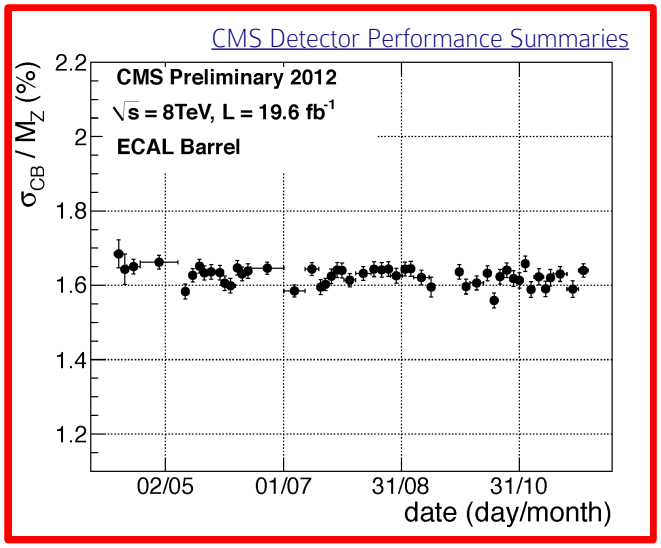


Pile-up suppression techniques in action on missing transverse momentum

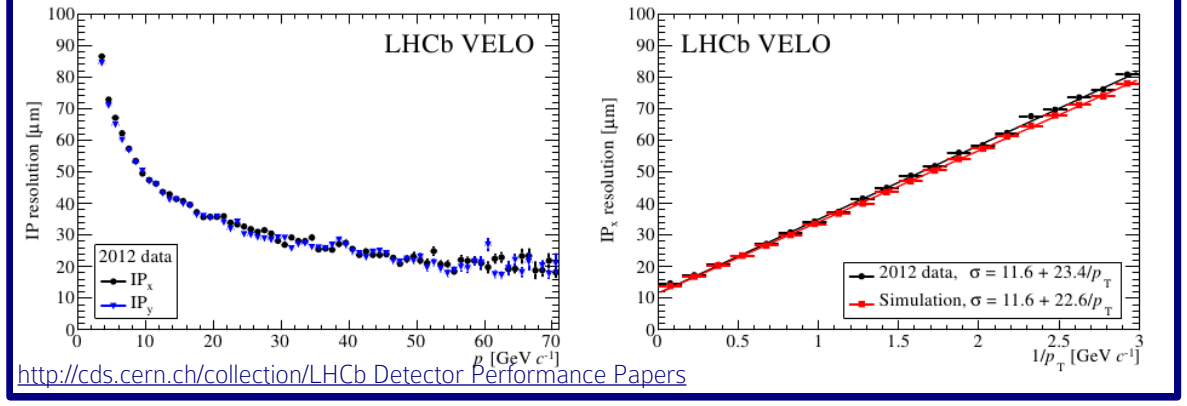
PERFORMANCE OF THE EXPERIMENTS

Excellent overall performance of experiments, close to or surpassing design specifications!





Talk by C. Elsasser



Scientific output: approaching 1000 peer-reviewed publication across the four experiments
→ can only cover a tiny fraction of the results in this talk!

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2. WHAT WE KNEW WE WOULD FIND

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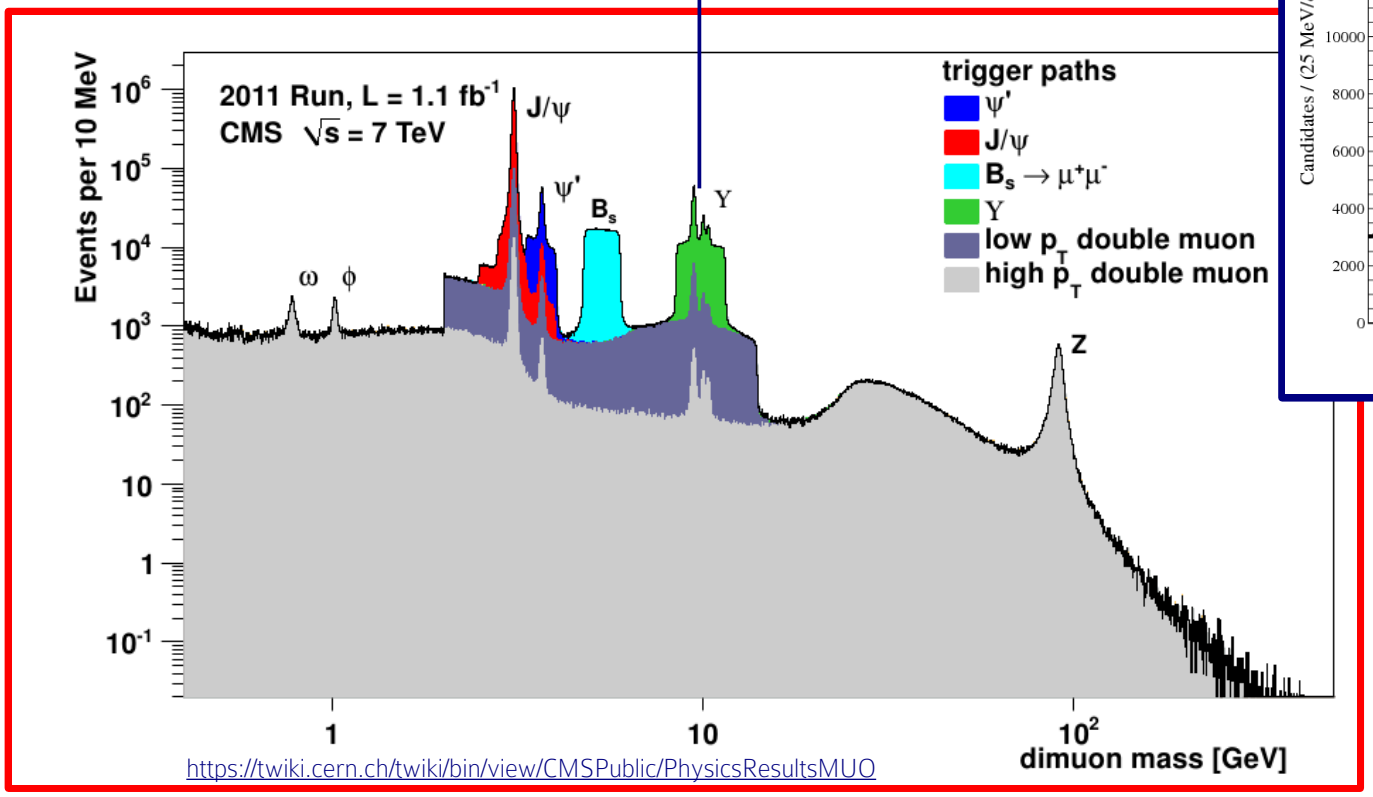
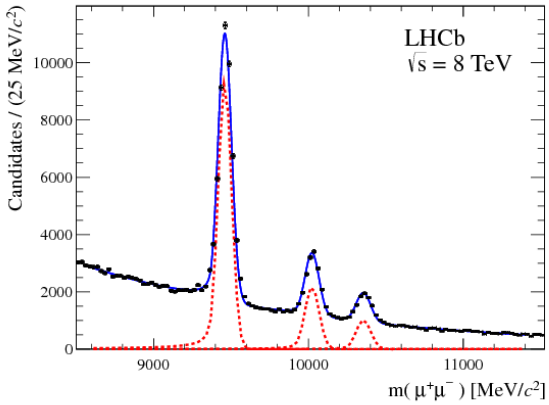
THE REDISCOVERY OF THE STANDARD MODEL



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO

http://arxiv.org/abs/arXiv:1304.6977



- Increase precision on existing measurements/verify open issues
- Use known processes as standard candles:
  - Validation of theory calculations and experiments at a new energy regime
  - Stepping stone towards discoveries (understand backgrounds)

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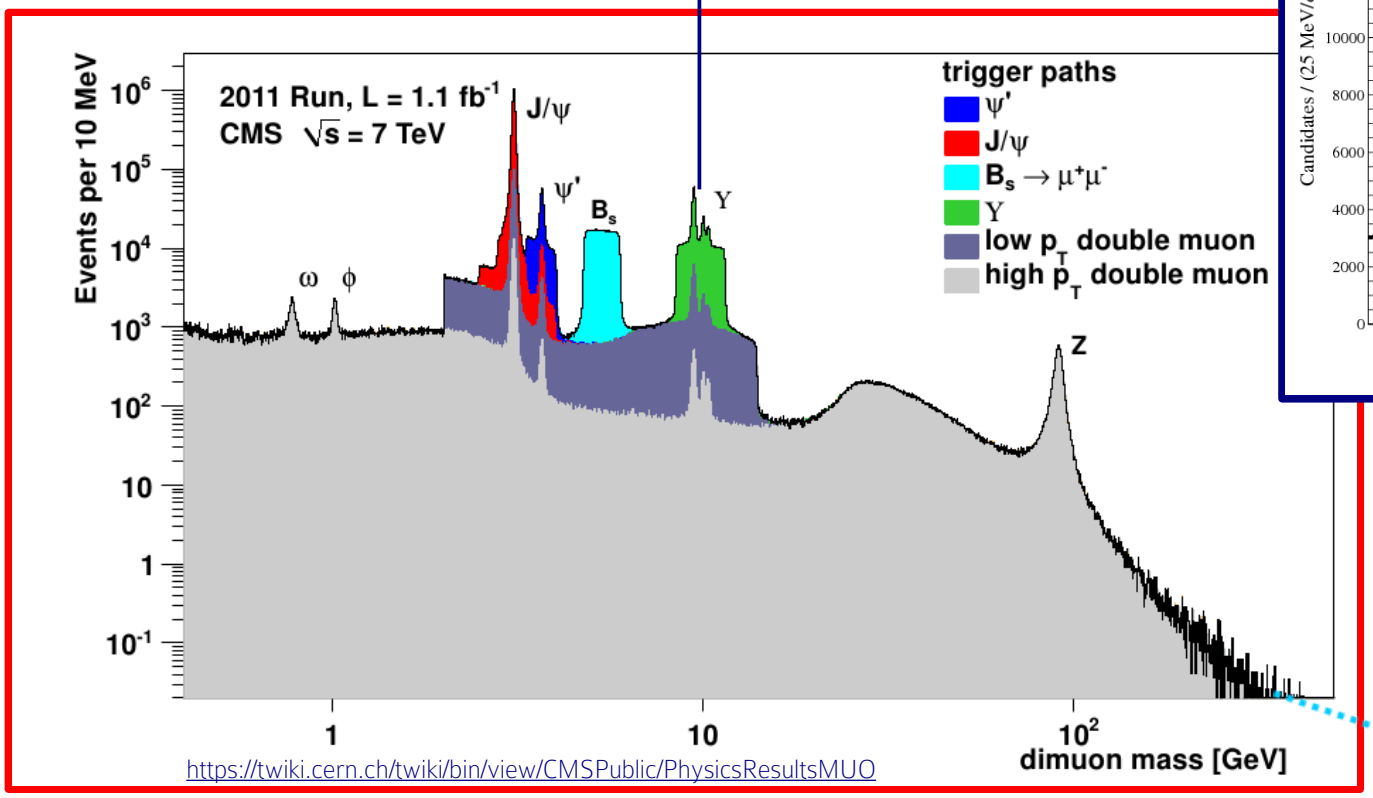

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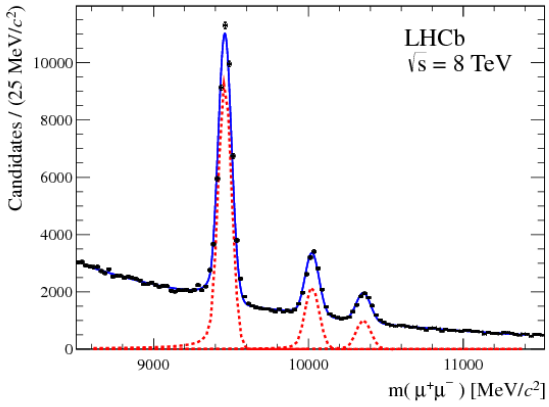
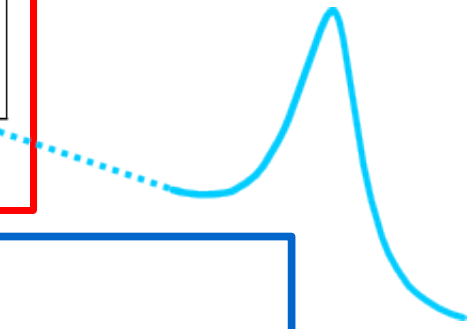


New, heavy Z'?



- Increase **precision** on existing measurements/verify **open issues**
- Use known processes as **standard candles:**
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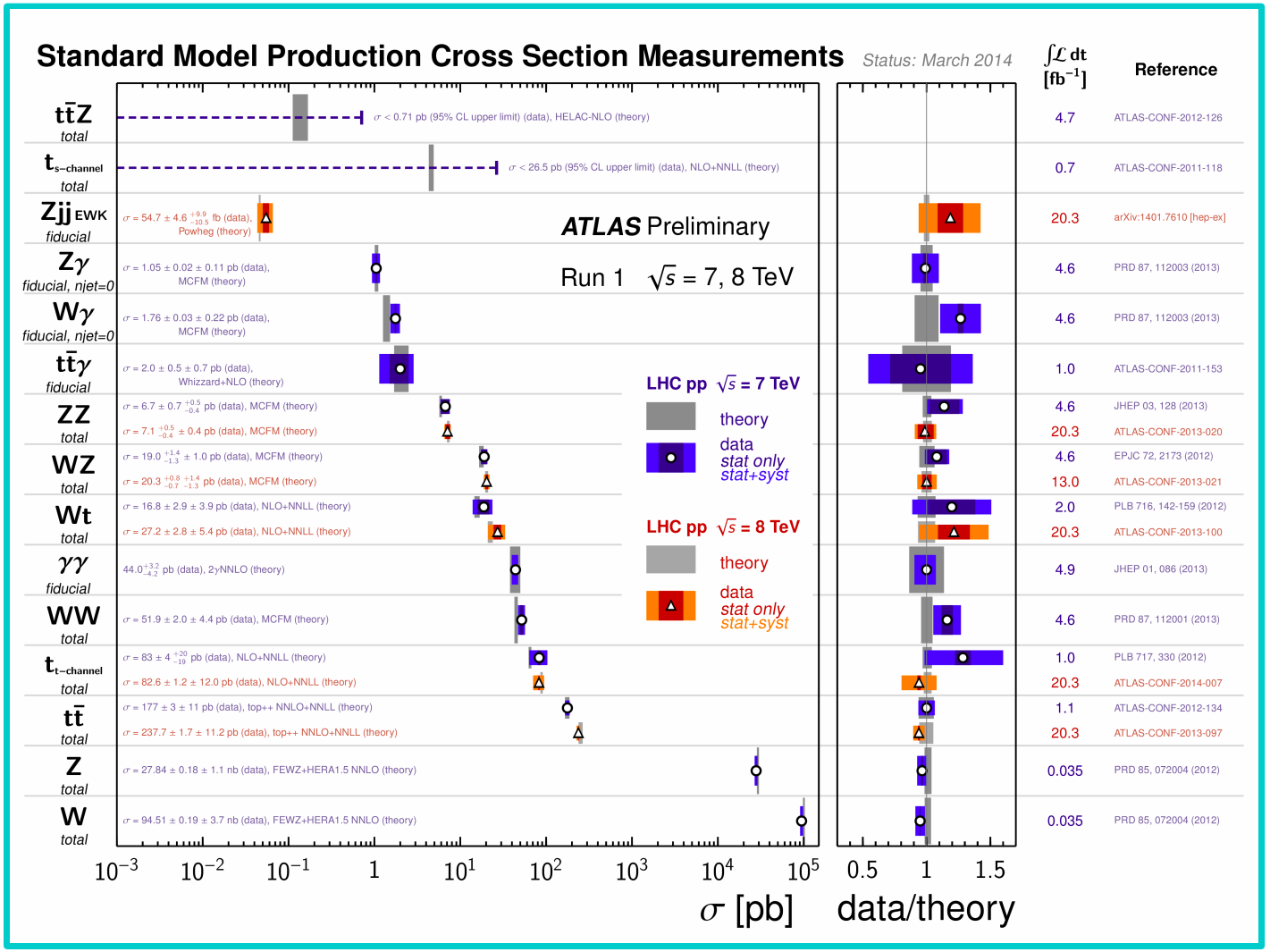
  - Stepping stone **towards discoveries** (understand backgrounds)

"STAIRWAYS TO HEAVEN": SM CROSS SECTIONS



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

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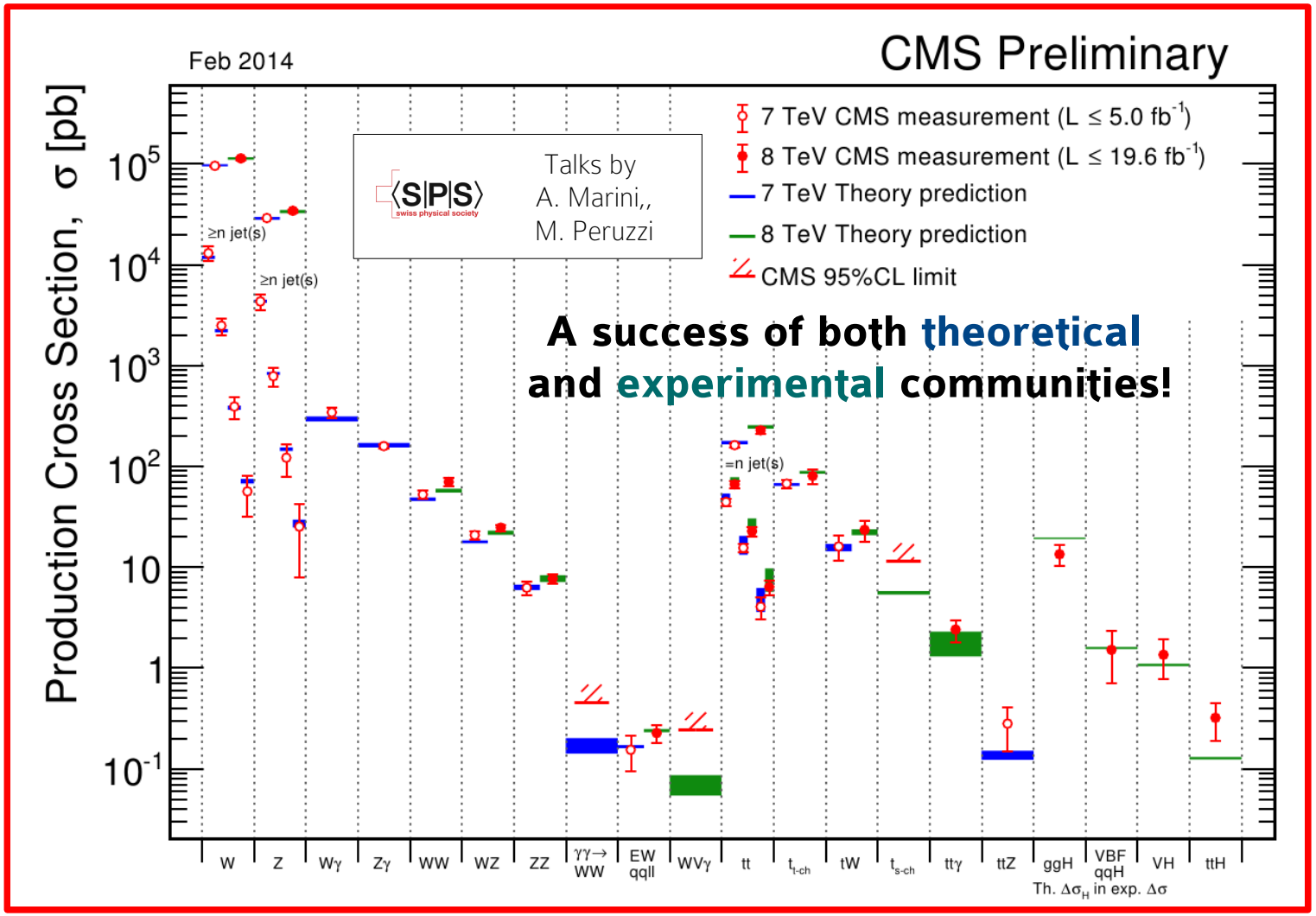
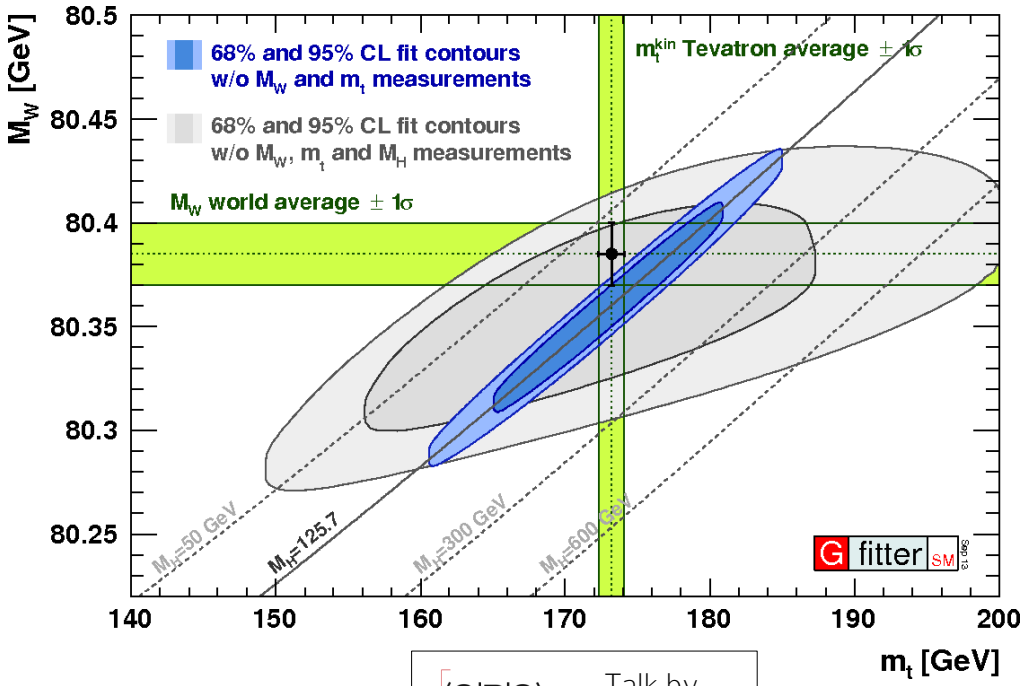


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

TOP QUARK PHYSICS

- LHC: top factory → surpass Tevatron statistics
- Top quark crucial to understand consistency of SM parameters (link between H, W and top mass)
  - Implications on New Physics constraints



LHC/Tevatron NOTE

ATLAS-CONF-2014-008
CDF Note 11071
CMS PAS TOP-13-014
D0 Note 6416

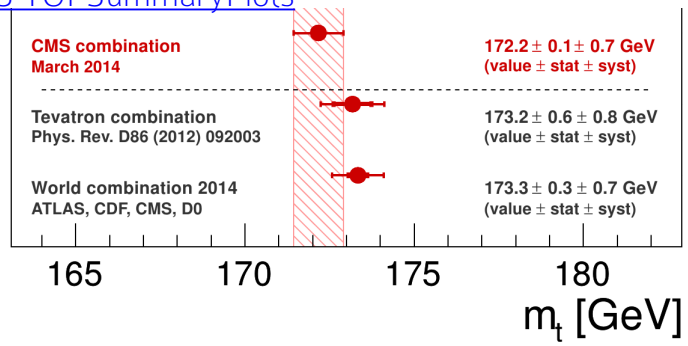
March 17, 2014

http://arxiv.org/abs/1403.4427

First combination of Tevatron and LHC measurements of the top-quark mass

M_{top} = 173.3±0.3(stat)±0.7(syst) GeV

CMS TOPSummaryPlots



M_{top} = 172.2±0.1(stat)±0.7(syst) GeV

http://arxiv.org/abs/1405.1756

FERMILAB-PUB-14-123-E

Precision measurement of the top-quark mass in lepton+jets final states

M_{top} = 175.0±0.6(stat)±0.5(syst) GeV

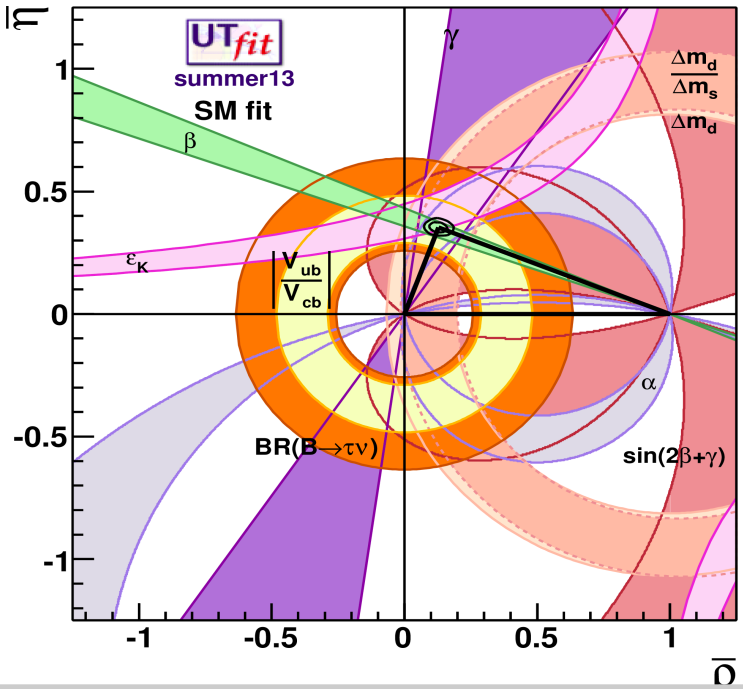
Talk by G. Barone

CP VIOLATION AND MORE

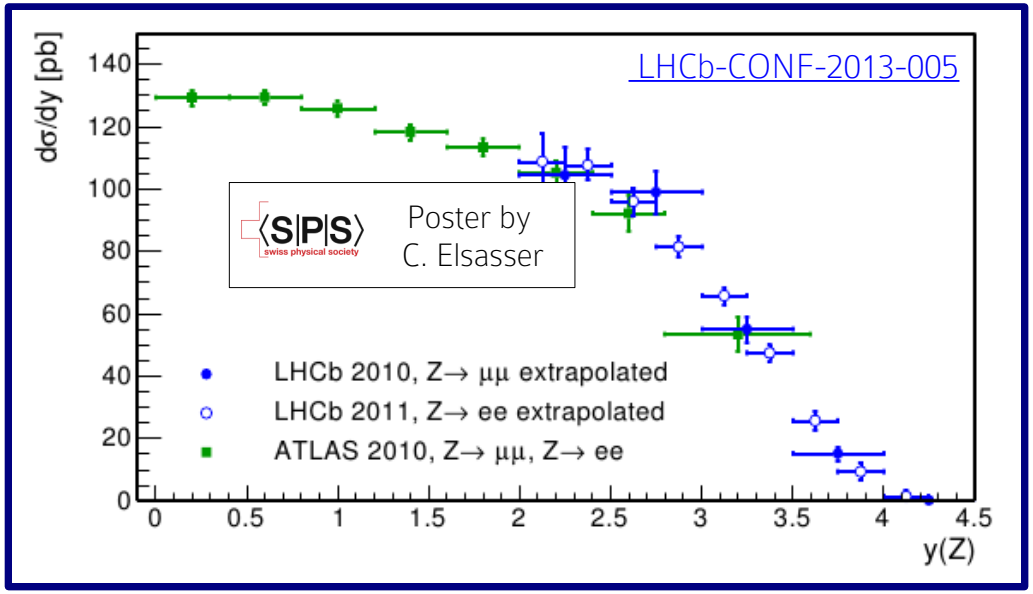
Talks by
J. Prisciandaro
M. Dorigo

- LHCb probes CP violation in Charm and Beauty:
  - CP violation predictions from SM will be modified by New Physics
  - → Precision measurements of angles of unitarity triangle
- LHCb covers different phase space wrt all other LHC experiments (forward coverage) → results input to theory e.g. for EW bosons

Summer 2013 http://www.utfit.org/UTfit/



Z boson rapidity for LHCb and ATLAS/CMS expt.



CP VIOLATION AND MORE

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J. Prisciandaro
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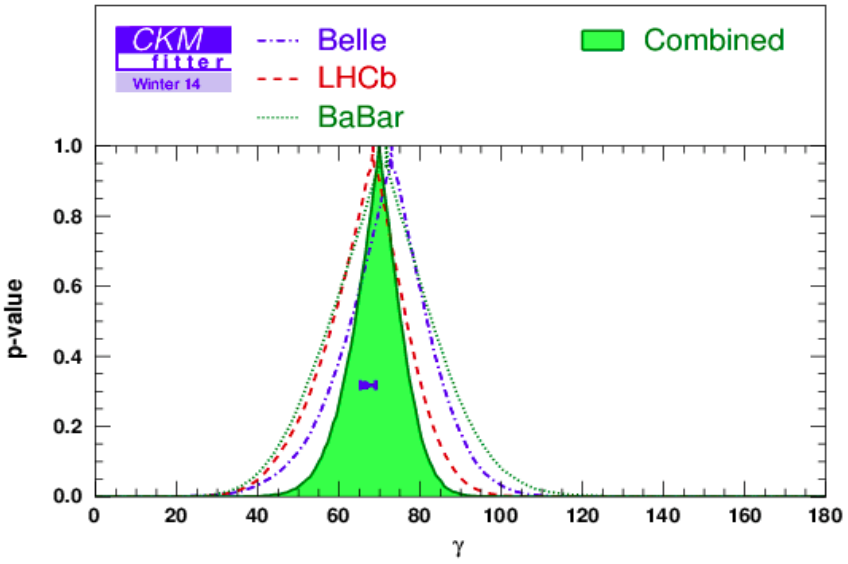
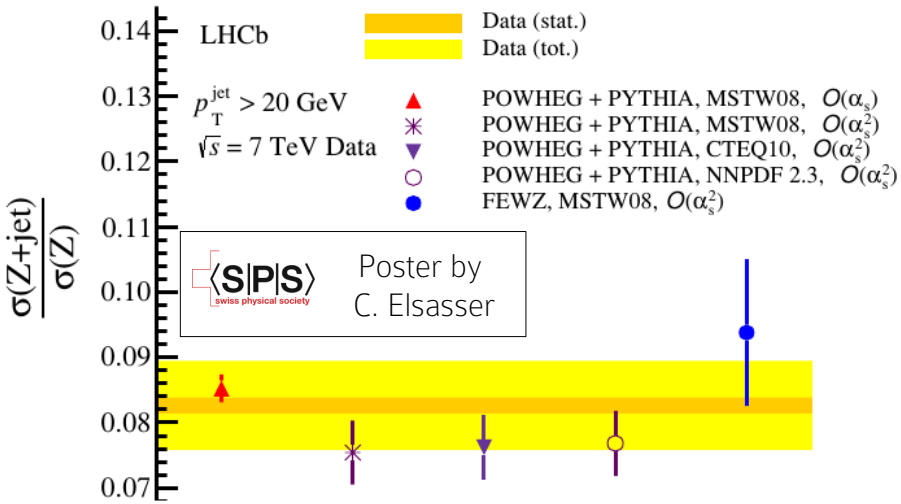
  - CP violation predictions from SM will be modified by New Physics
  - → Precision measurements of angles of unitarity triangle
- LHCb covers different phase space wrt all other LHC experiments (forward coverage) → results input to theory e.g. for EW bosons

Constraints on the angle **γ:10% precision**
(Moriond 2014) http://ckmfitter.in2p3.fr/





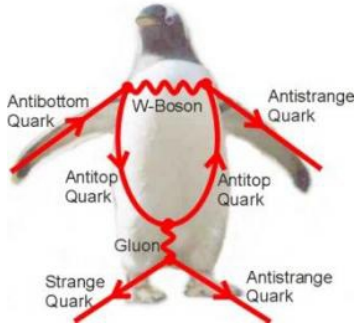
http://arxiv.org/abs/1310.8197

Forward Z+jets cross-section measurement

SM AND FLAVOR CONSTRAINTS

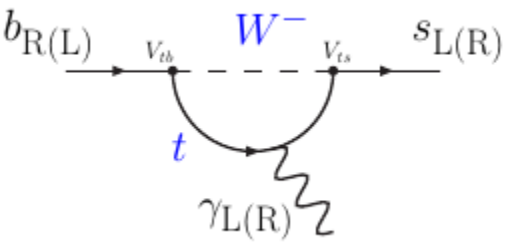
Talk by G. Veneziano

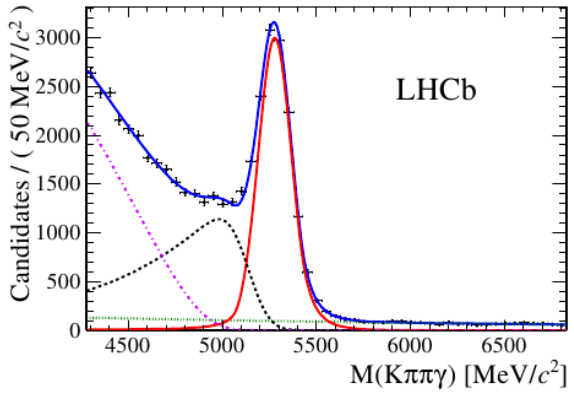
- Precisely measuring consistency of branching fraction / properties of known processes with SM:
  - Tree-level (small loop contamination) → verify SM
  - Penguins (affected by loop contributions) → discrepancies would signal New Physics

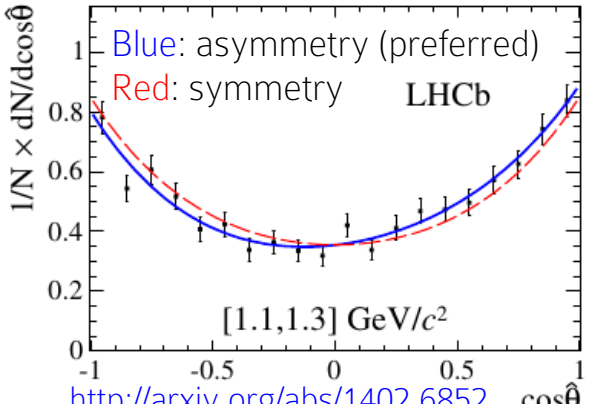


$B^+ \rightarrow K^{**}\,\gamma$, $K^{**} \rightarrow \pi\pi$

Rates agree with SM, does γ polarization? **No direct observation**
Infer γ polarization from asymmetry of γ direction in Kππ rest frame:
Polarized photons → asymmetry → consistency with SM







http://arxiv.org/abs/1402.6852

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3. WHAT WE HAVE FOUND

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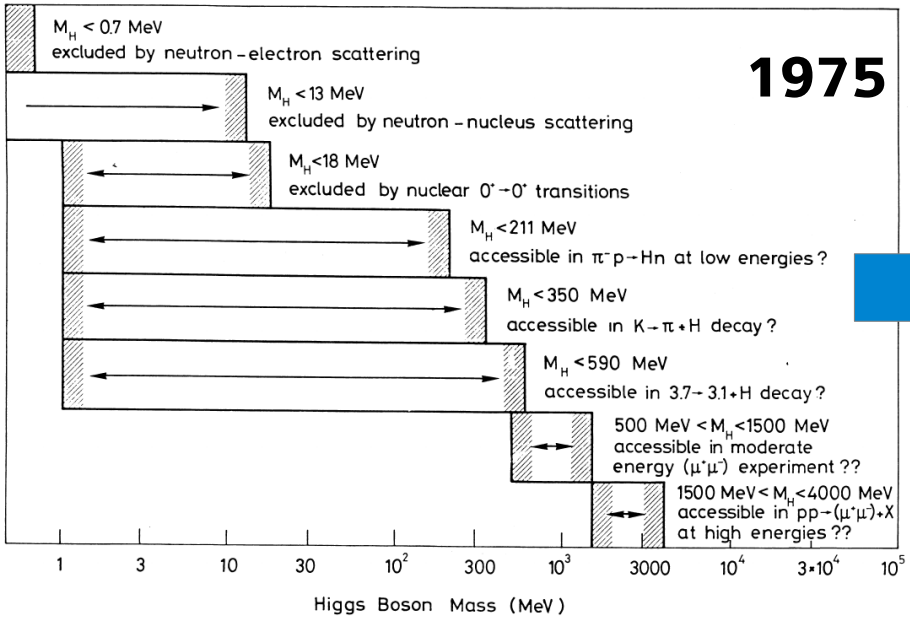
THE ELUSIVE HIGGS BOSON

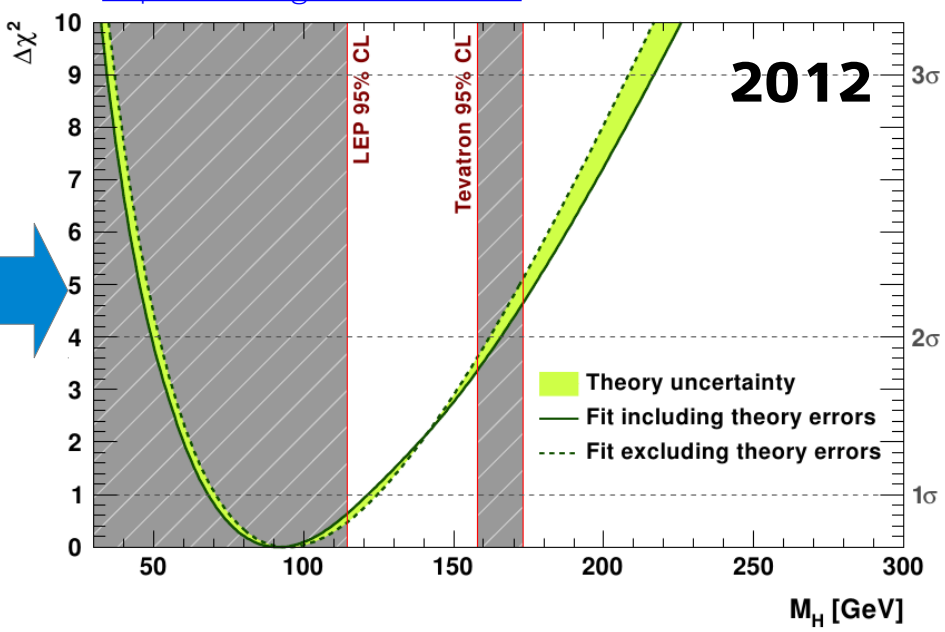
Presence of Higgs boson: **naturally introduce mass** for particles of SM..
(...but predicted Higgs boson mass poses a problem for **naturalness of SM**)

https://cds.cern.ch/record/874049



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

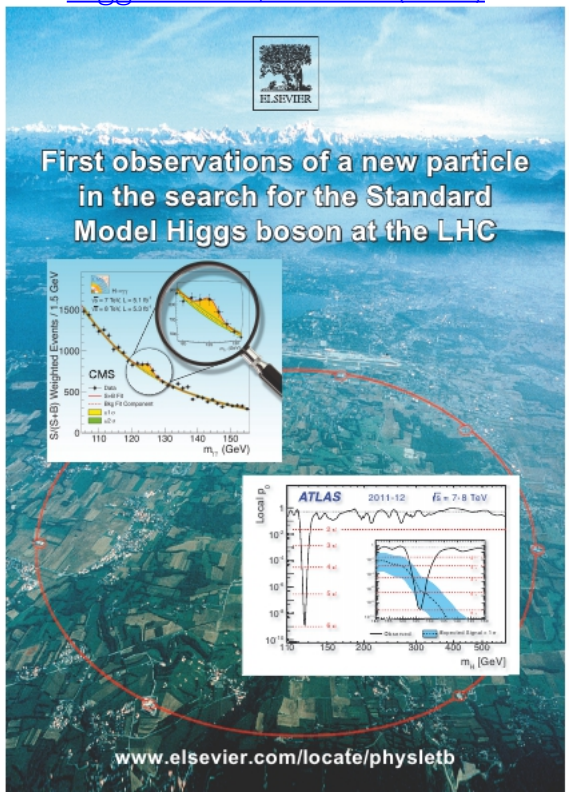
http://arxiv.org/abs/1107.0975

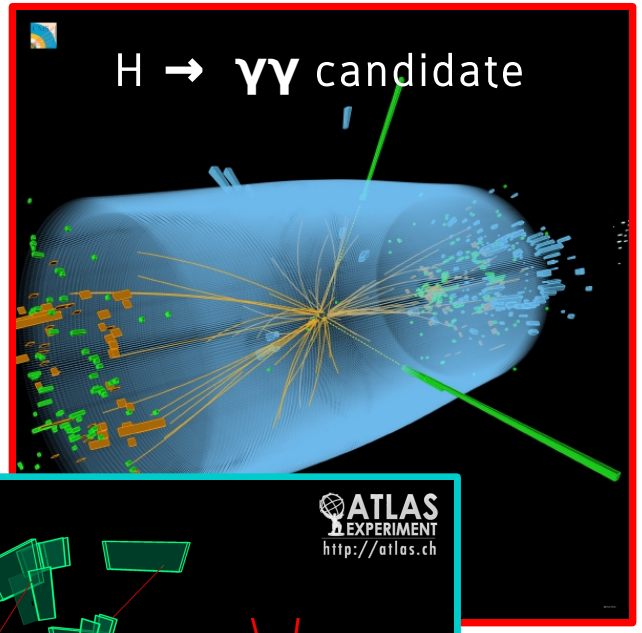


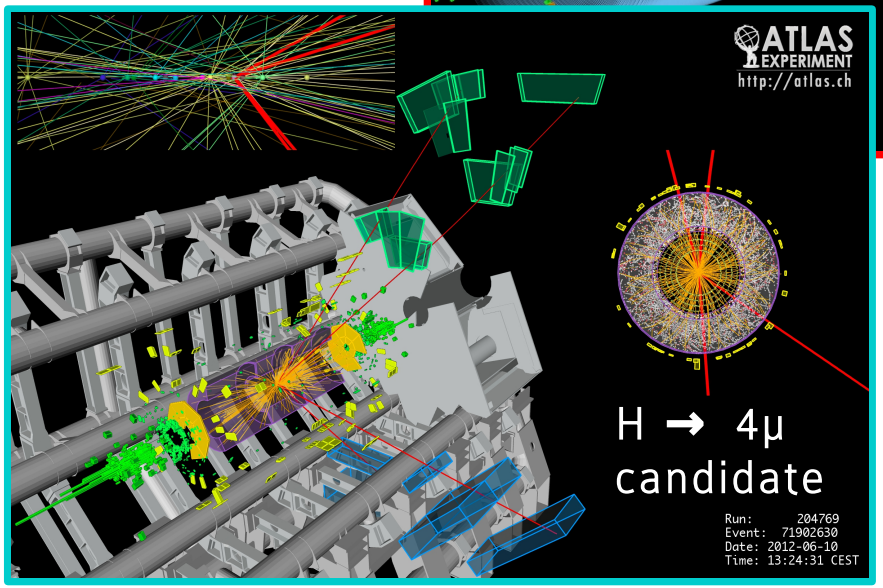
Given the strong performance of the LHC and its experiments, with already over 1 fb^{-1} integrated luminosity accumulated at the date of this paper, the present analysis might be among the last global electroweak fits working with Higgs limits only. In case of a Higgs discovery, the

THE HIGGS DISCOVERY

Higgs booklet, Elsevier (2012)



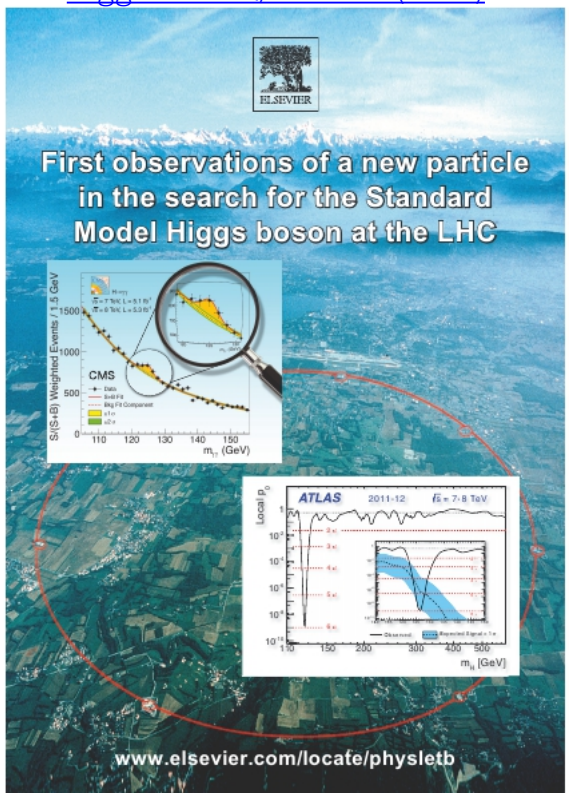


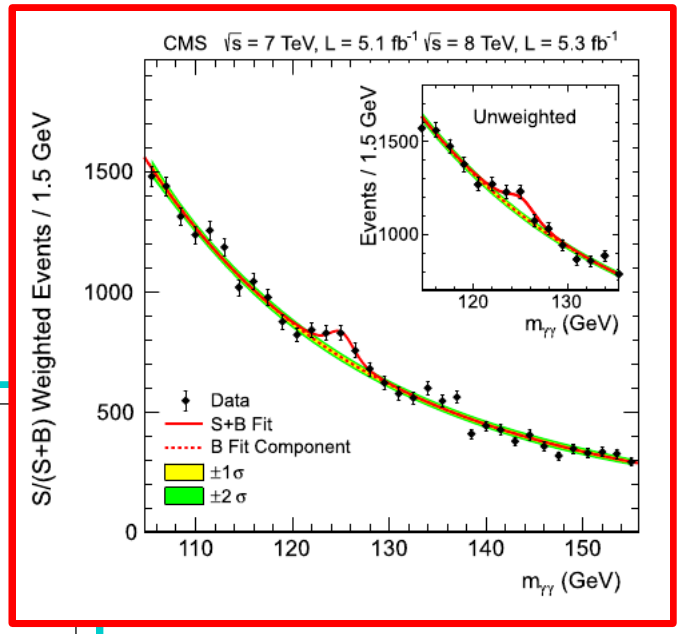


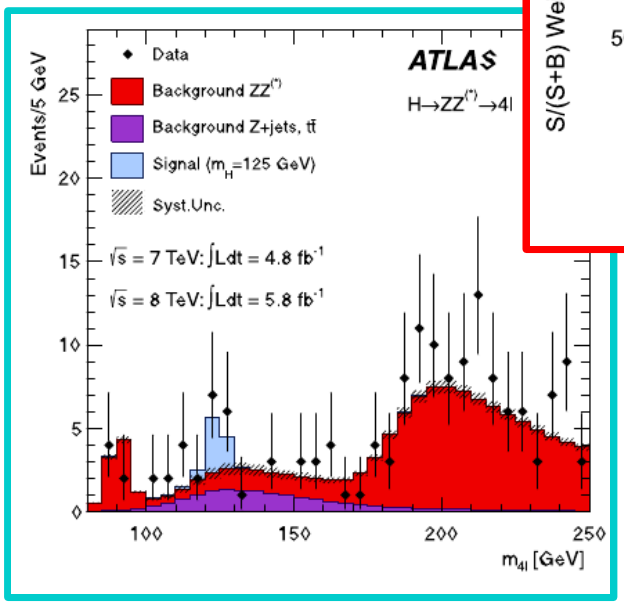
Profit from **golden channels** ("high" yields, well-understood backgrounds) for a **discovery** announced by both ATLAS and CMS in July 2012 (2011+2012 datasets)

THE HIGGS DISCOVERY

Higgs booklet, Elsevier (2012)







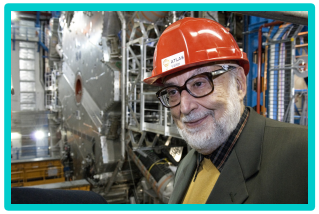
SPS swiss physical society — Talk by E. Benhar

Profit from **golden channels** ("high" yields, well-understood backgrounds) for a **5-σ discovery** announced by both ATLAS and CMS in July 2012 (2011+2012 datasets)

...SINCE THE HIGGS DISCOVERY...

The Nobel Prize in Physics 2013

Peter W. Higgs
Prize share: 1/2

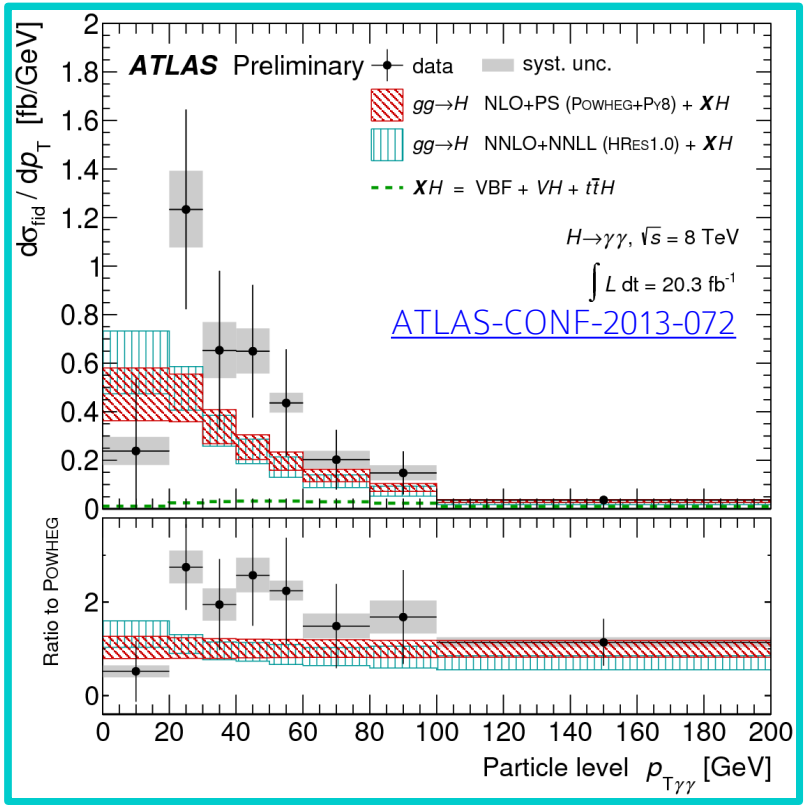


François Englert
Prize share: 1/2

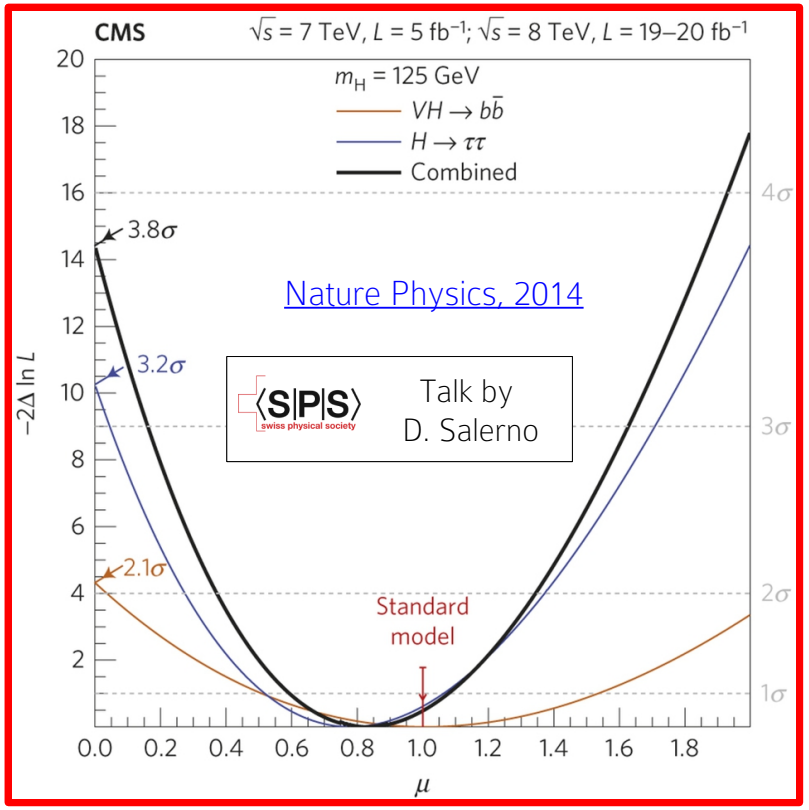
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental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

FROM DISCOVERY TO MEASUREMENT: HIGGS PROPERTIES

- Discovery in **more decay channels** → Verification of *Higgs* **nature of new boson**
- More **statistics** in golden channels → Measurement of **properties and kinematics**



Higgs pT spectrum in **γγ** final state

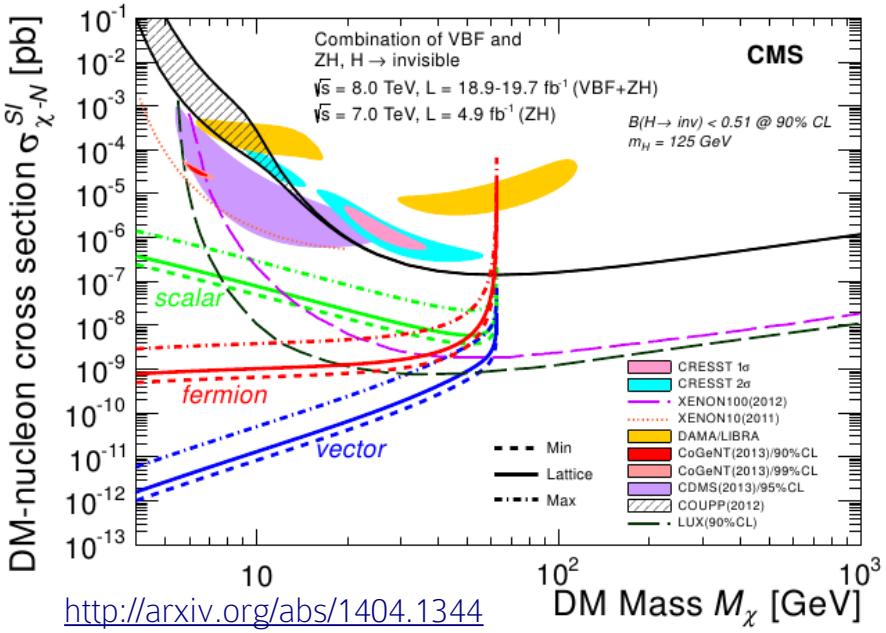


Higgs decays in fermions (bb and **ττ**)

FROM DISCOVERY TO MEASUREMENT: HIGGS AS A PORTAL TO NEW PHYSICS

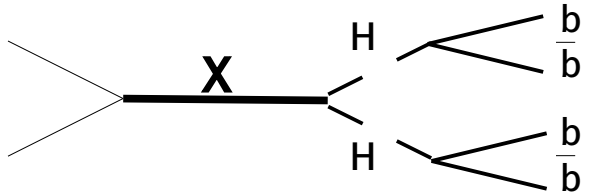
Talk by C. Galloni

Invisible decays of the Higgs boson: Higgs as SM/Dark Matter mediator?

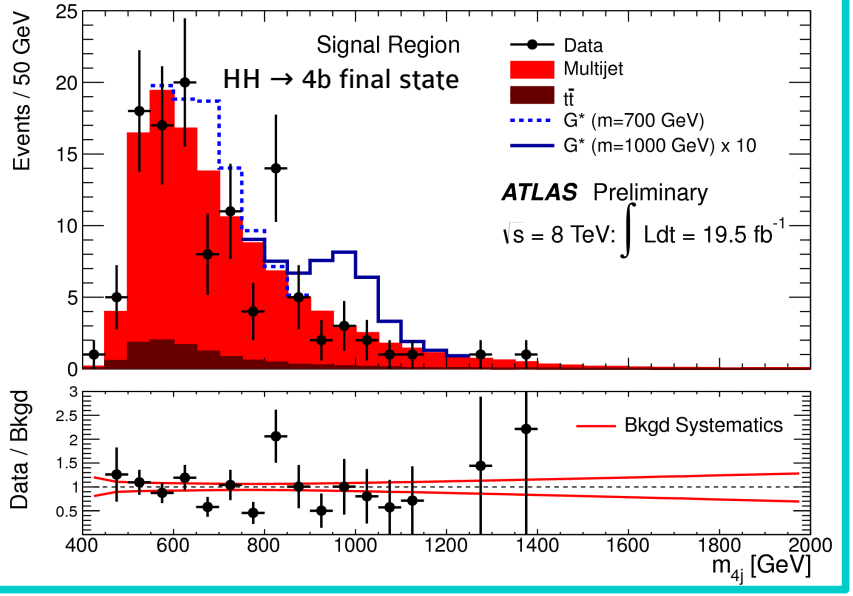


http://arxiv.org/abs/1404.1344

New resonances decaying in di-Higgs



ATLAS-CONF-2014-005



A NEW PARTICLE STATE: $Z^-(4430)$

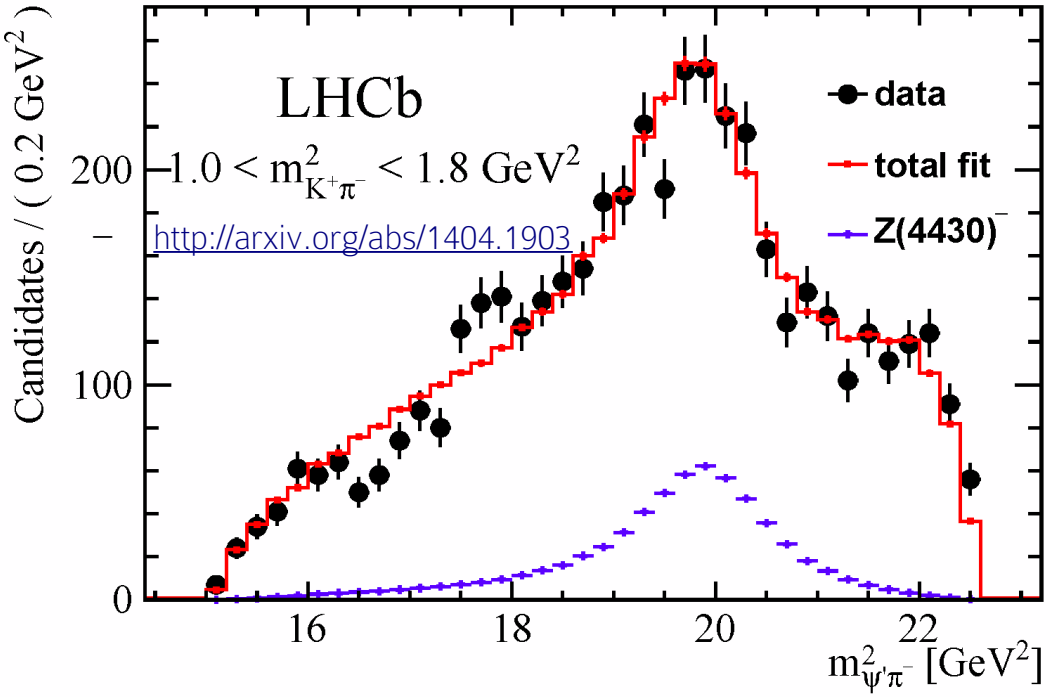
- Long-standing history of B-factories on search for **a tetraquark state**
  - $Z^-(4430)$ does not fit the quark model (charged meson),
  - Minimal quark content: $c\bar{c}d\bar{u}$
- LHCb significance for new resonance: **13.9 σ** (Belle: **5.2 σ**)

New resonant state from analysis of **ψπ** mass distribution

$B^0 \rightarrow \psi K \pi^-$, $\psi \rightarrow \mu\mu$

New resonance is charged → cannot be a $c\bar{c}$ bound state

Analysis of spin/parity confirm quantum numbers of 1^+



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4. WHAT WE HAVE NOT FOUND (YET)

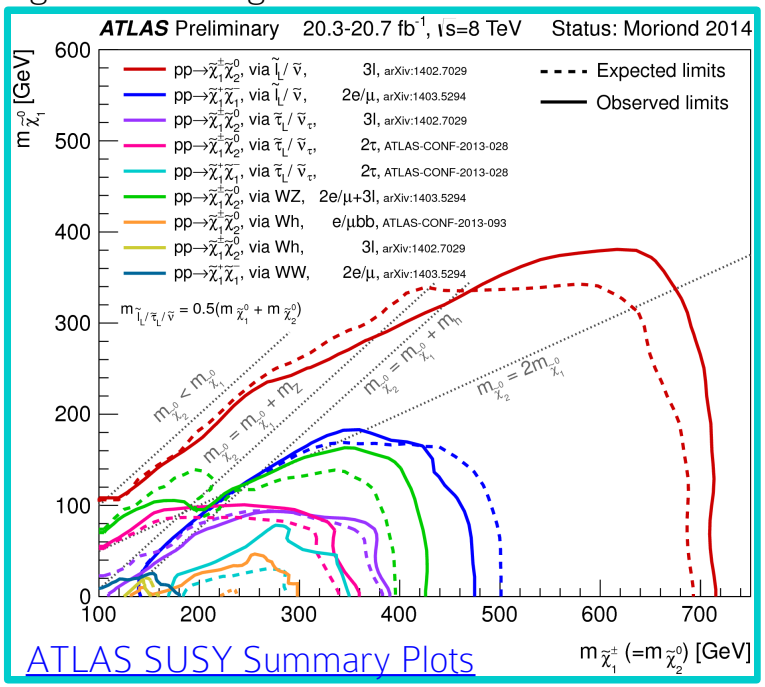
01/07/2014 – SPS Annual Meeting, Fribourg

SUPERSYMMETRY SEARCHES

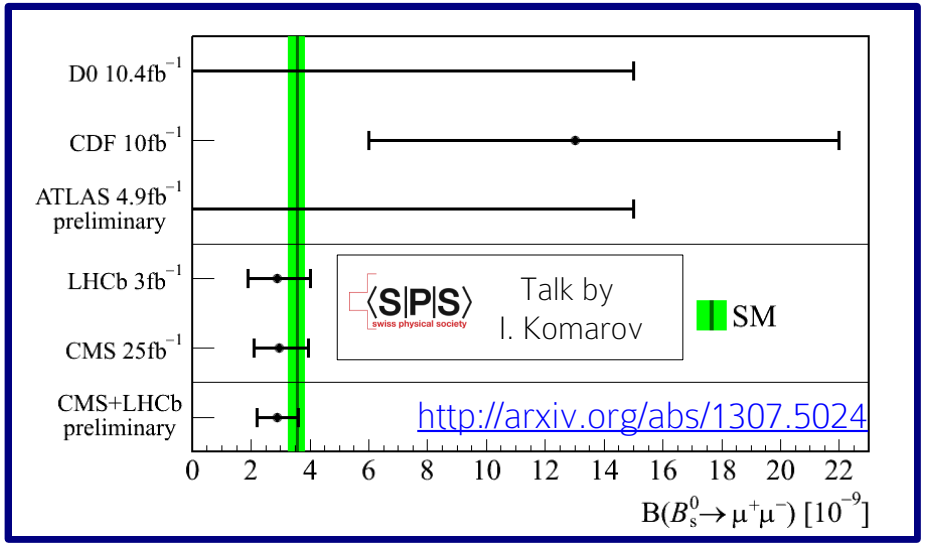
- **Supersymmetry** (or similar mechanism) seems necessary to hold **natural SM** together in presence of **light Higgs boson**
  - Particles partners of SM cure fine-tuning in large corrections to Higgs mass
  - (Caveat: naturalness might just be an aesthetic principle…)

Talks by
Q. Python
M. Masciovecchio

Direct searches for SUSY particles: look for strongly/electroweak produced SUSY particles, with signatures of large transverse momentum: ATLAS, CMS



Indirect searches: use **loops** to probe energy scales unreachable in direct LHC production: ATLAS, CMS, LHCb



Well-known (small) BR from SM in $B_s \to \mu\mu$: no enhancements from new particles observed

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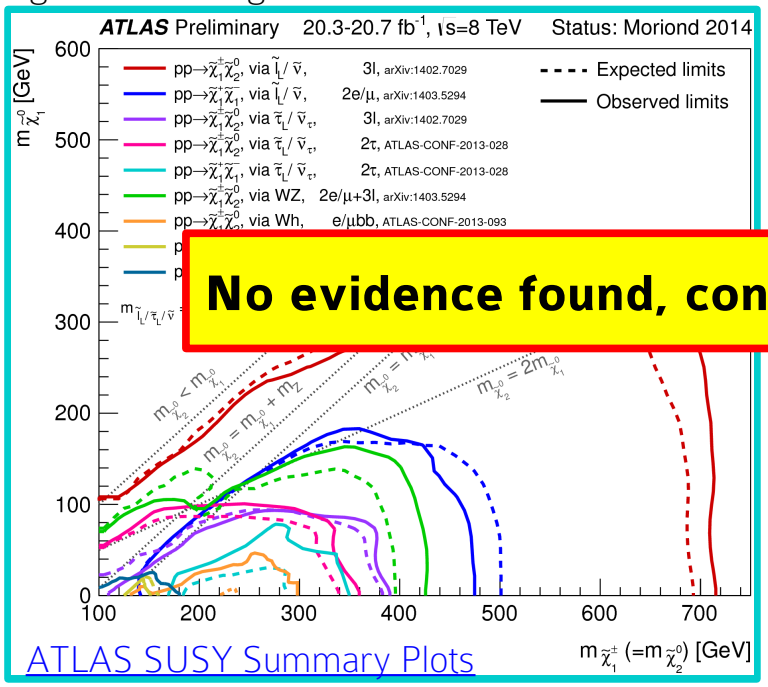
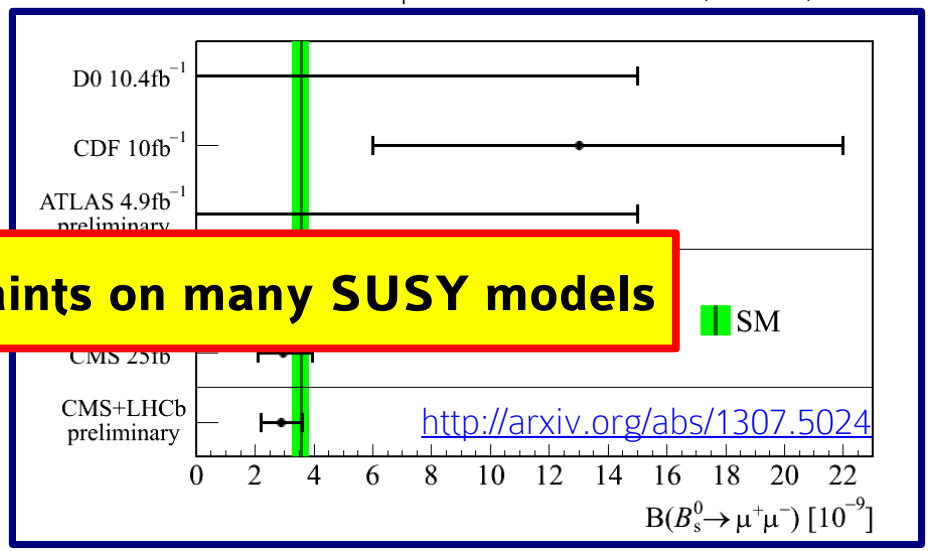


ATLAS SUSY Summary Plots

Indirect searches: use **loops** to probe energy scales unreachable in direct LHC production: ATLAS, CMS, LHCb



No evidence found, constraints on many SUSY models

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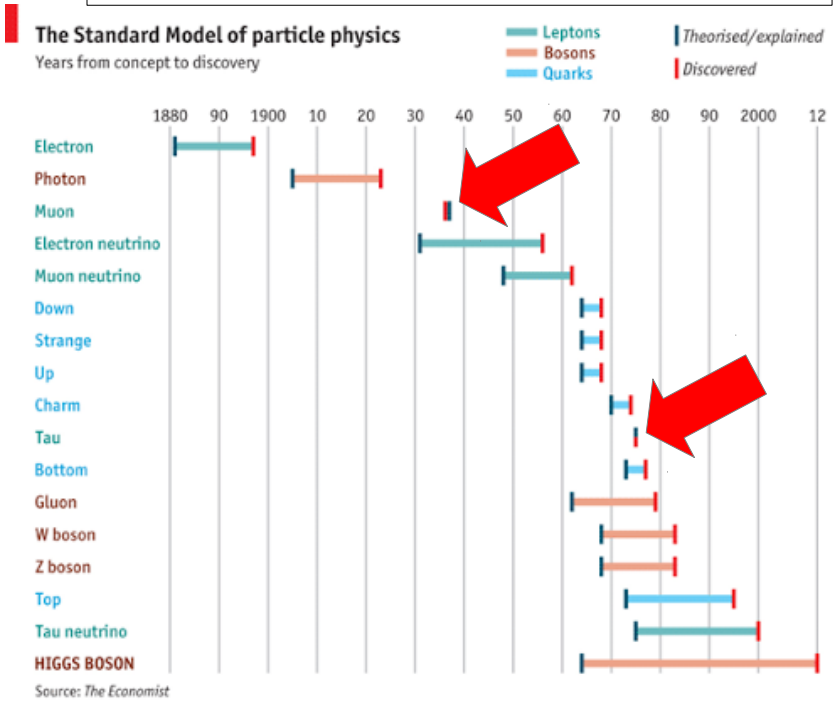
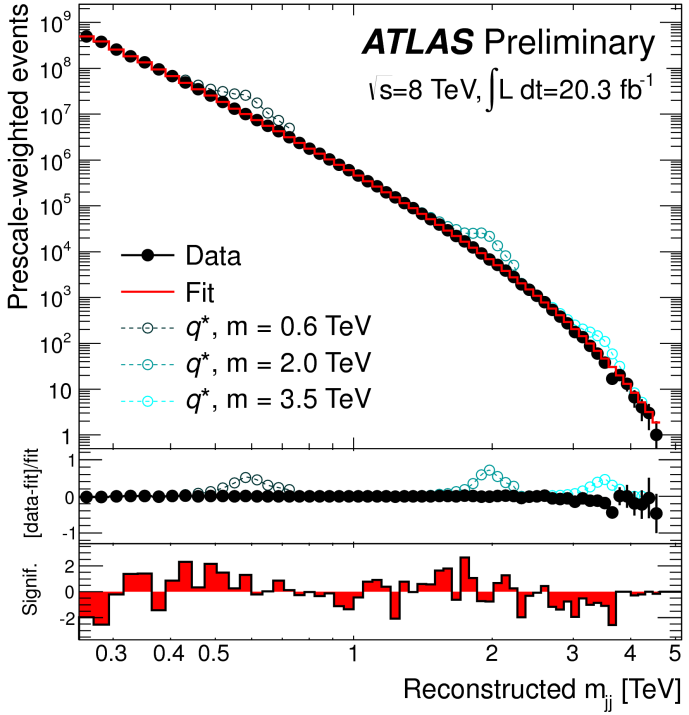
SEARCHES FOR OTHER EXOTIC PARTICLES

- Strong theoretical motivations important for searches…
- …but **do not forget the unexpected**: new physics might appear before M_{pl} !

Poster by C. D., Talks by A. Katre, M. Duenser, B. Munster



A workhorse search: diiet mass resonances



Plan for LHC searches that are **signature-based** and **model-independent,** include **non-mainstream physics objects** (e.g. monopoles, long-lived particles…)

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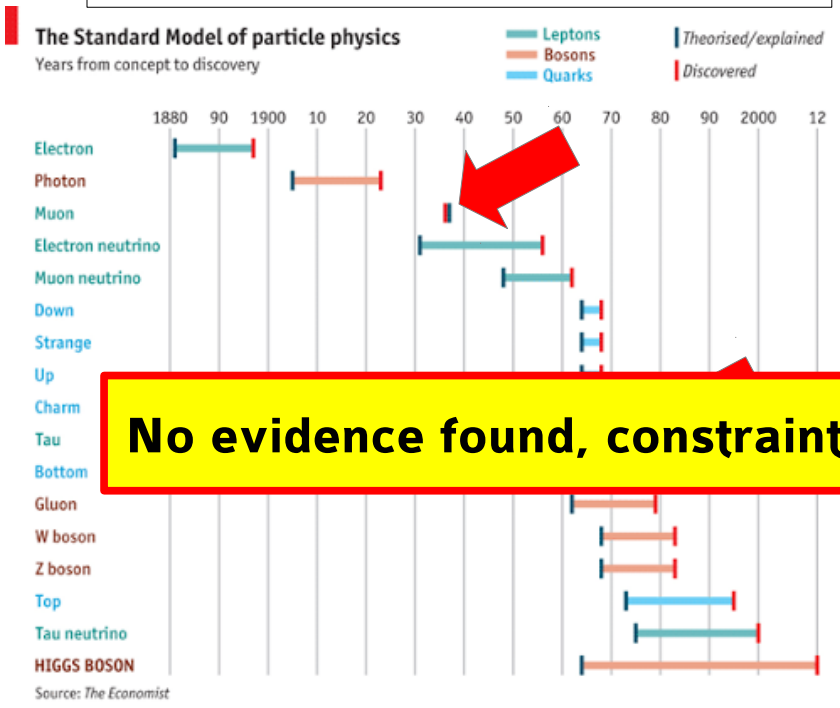

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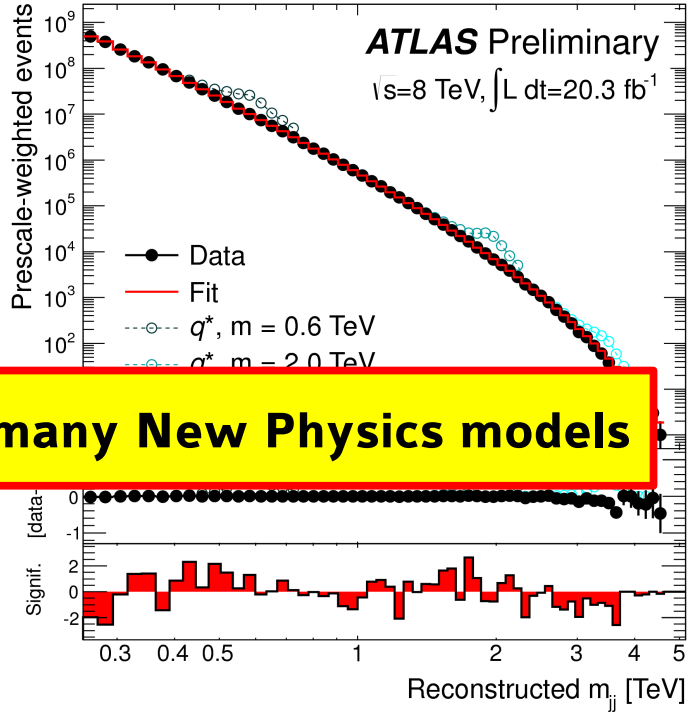

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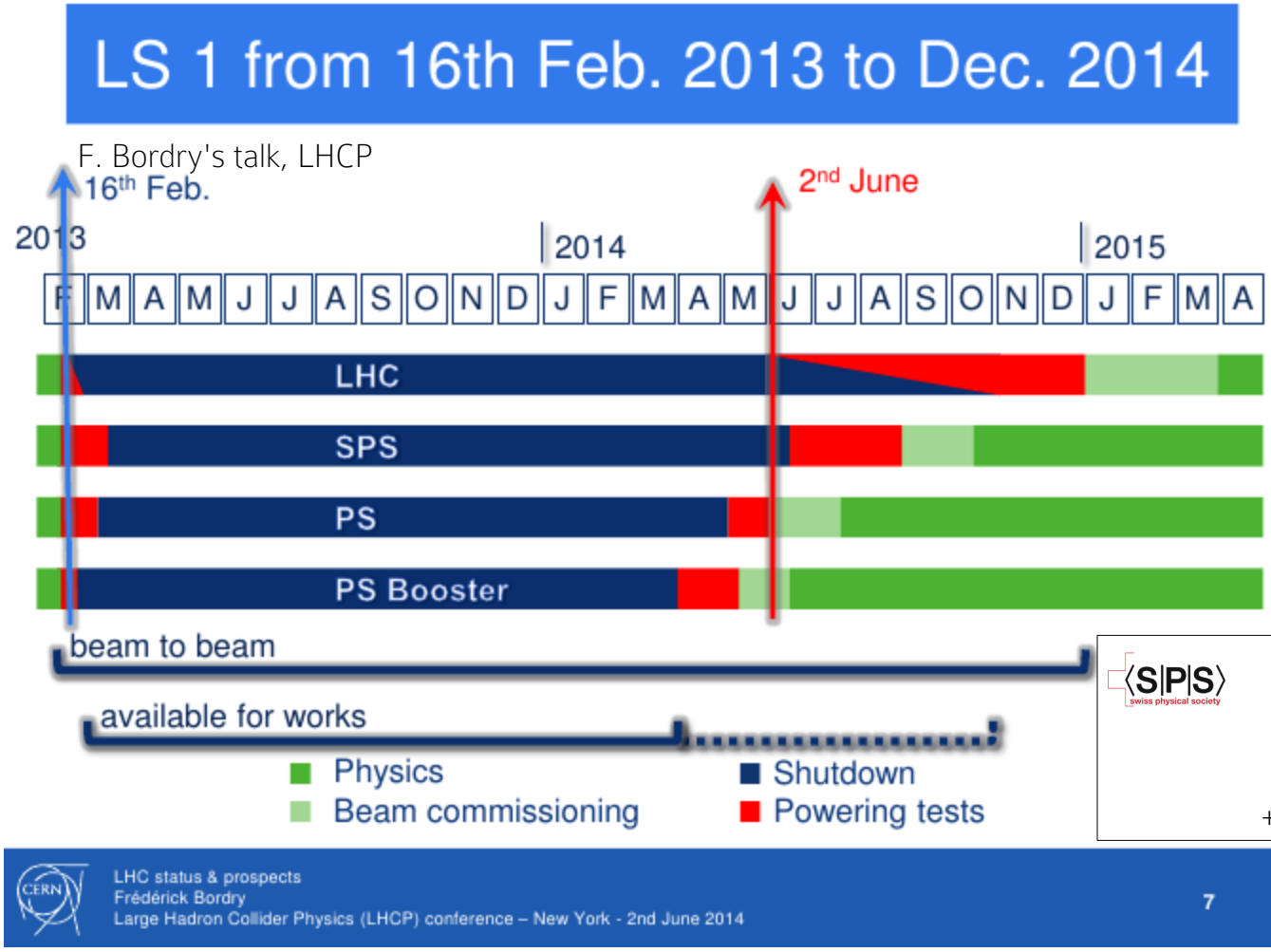
5. WHAT WE MIGHT FIND (SOON)

01/07/2014 – SPS Annual Meeting, Fribourg

LONG SHUTDOWN → LHC RESTART SCHEDULE

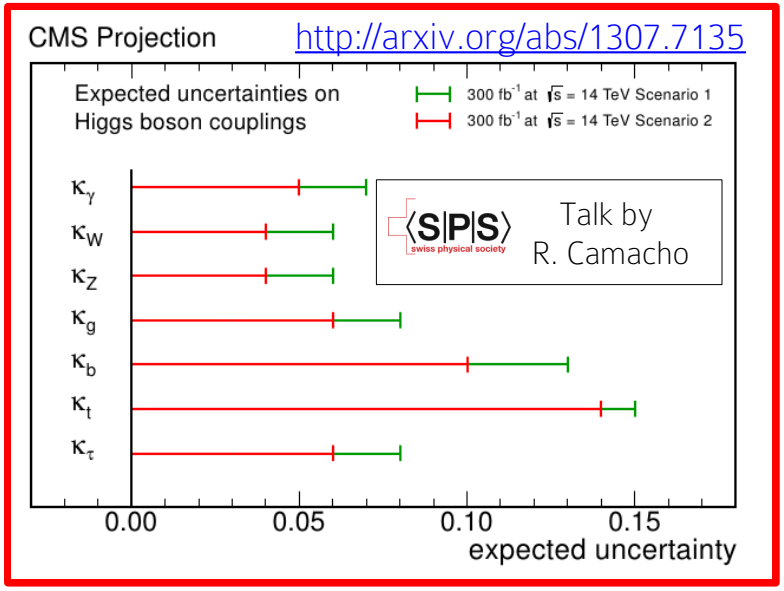


Talks by
M-E Stramaglia
J. Bilbao, P. Eller,
M. Tobin, S.Stucci
+ V. Tavolaro, Z. Xu

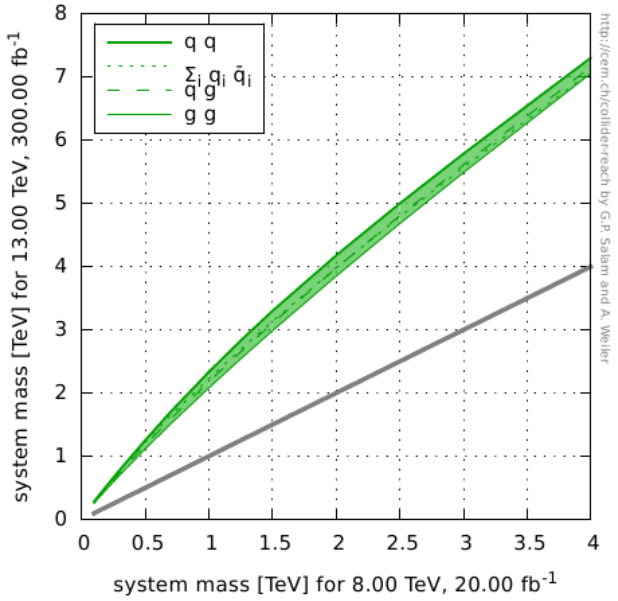
HIGGS AND NEW PHYSICS PROSPECTS @ RUN-II

- Two advantages from LHC for physics prospects at Run-II
  - Increased **center of mass energy** (13 TeV)
    → higher reach for new **massive** particles
  - More data: **300 fb^{-1} integrated luminosity** expected by end of 2018
    → more sensitive to **rare** / statistically-limited processes

10x existing dataset, 2.5x Higgs cross section
→ improved precision on BR and couplings



Comparison of (new physics) mass reaches with full 8 and 13/14 fb^{-1} datasets



LHC RESULTS FOR RUN-I: CONCLUSIONS

A wealth of physics results brought to the HEP community by LHC **Run-I** data taking (only a few from ATLAS, CMS and LHCb shown today)

1) The **LHC** and the **LHC experiments** performed extremely well

2) **Rediscovery** and **measurements** of many SM processes

3) Historical **discovery** of the **Higgs boson**

4) Still looking to **answer open questions** (no New Physics yet)

Much more to come, soon:
soon ready to analyse **a larger dataset** at a **higher center of mass energy** with **upgraded detectors**