# Status and prospects of the LHC

*and future circular colliders at CERN*

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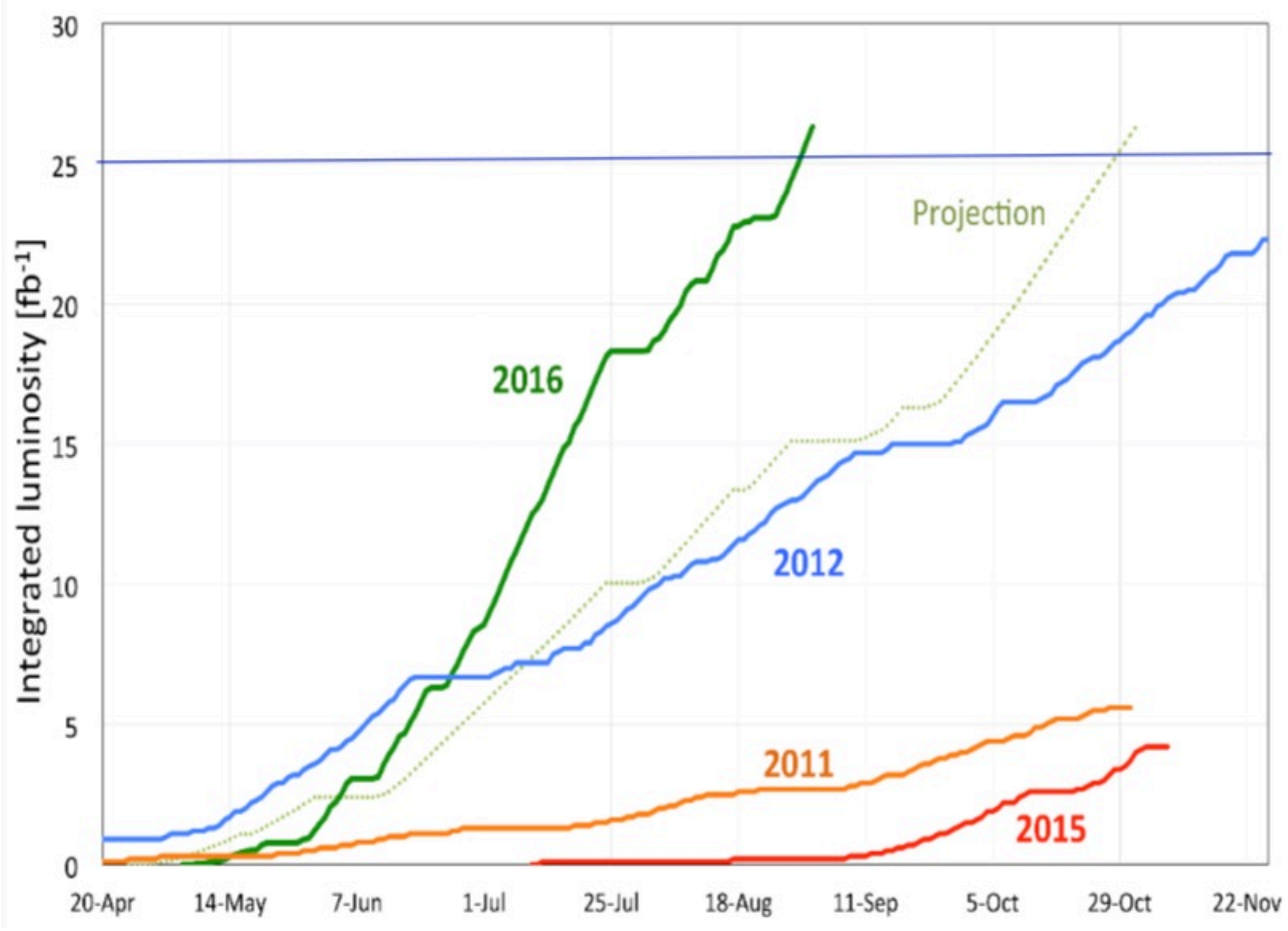
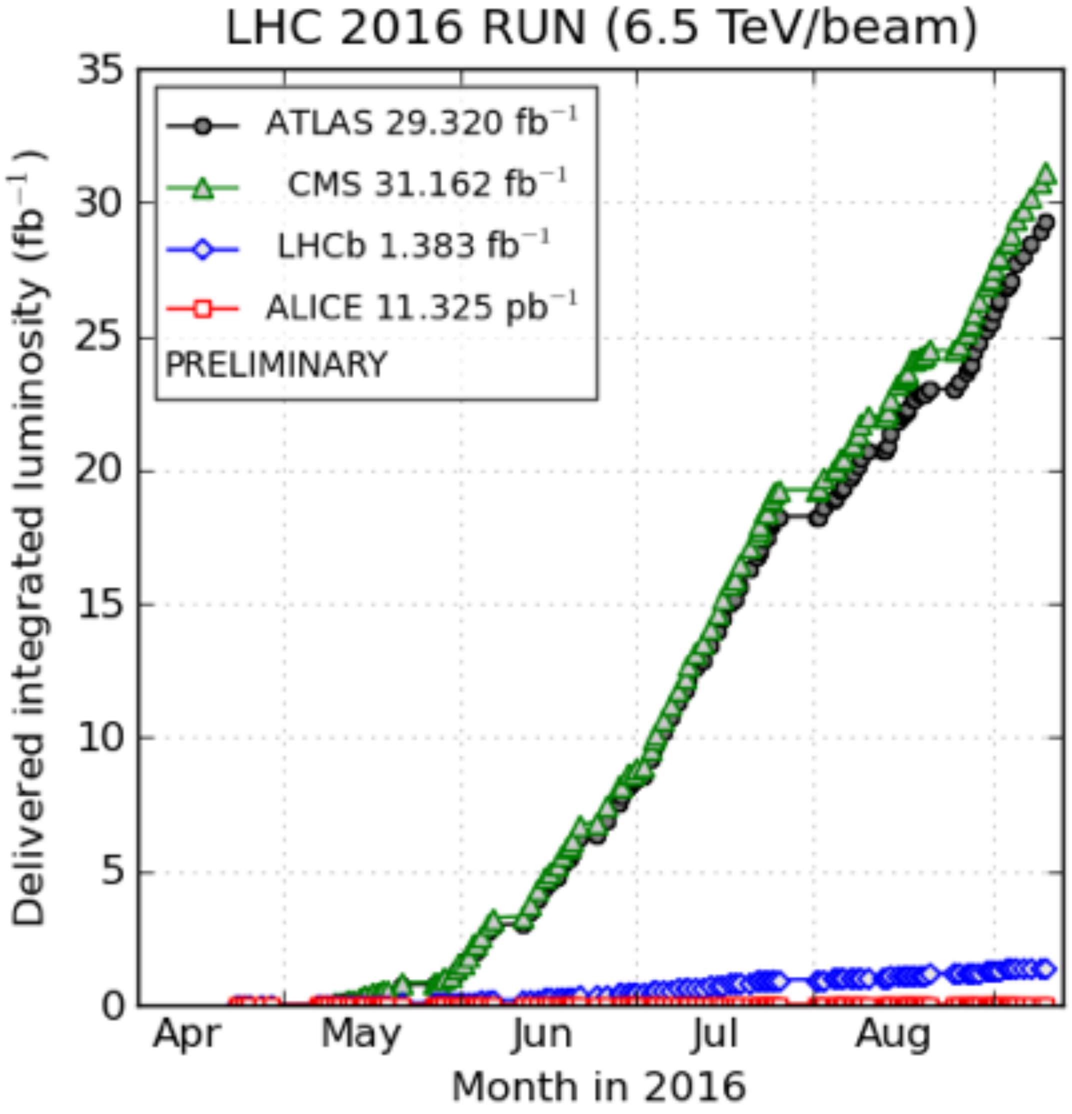
Theoretical Physics Department
CERN

# Status of LHC running





( 2016-09-15 10:37 including fill 5288; scripts by C. Barschel )

mid-August 2016: comparison with luminosity evolution in previous years

today ~30fb$^{-1}$: already met the 2016 goal, with still few more weeks to go

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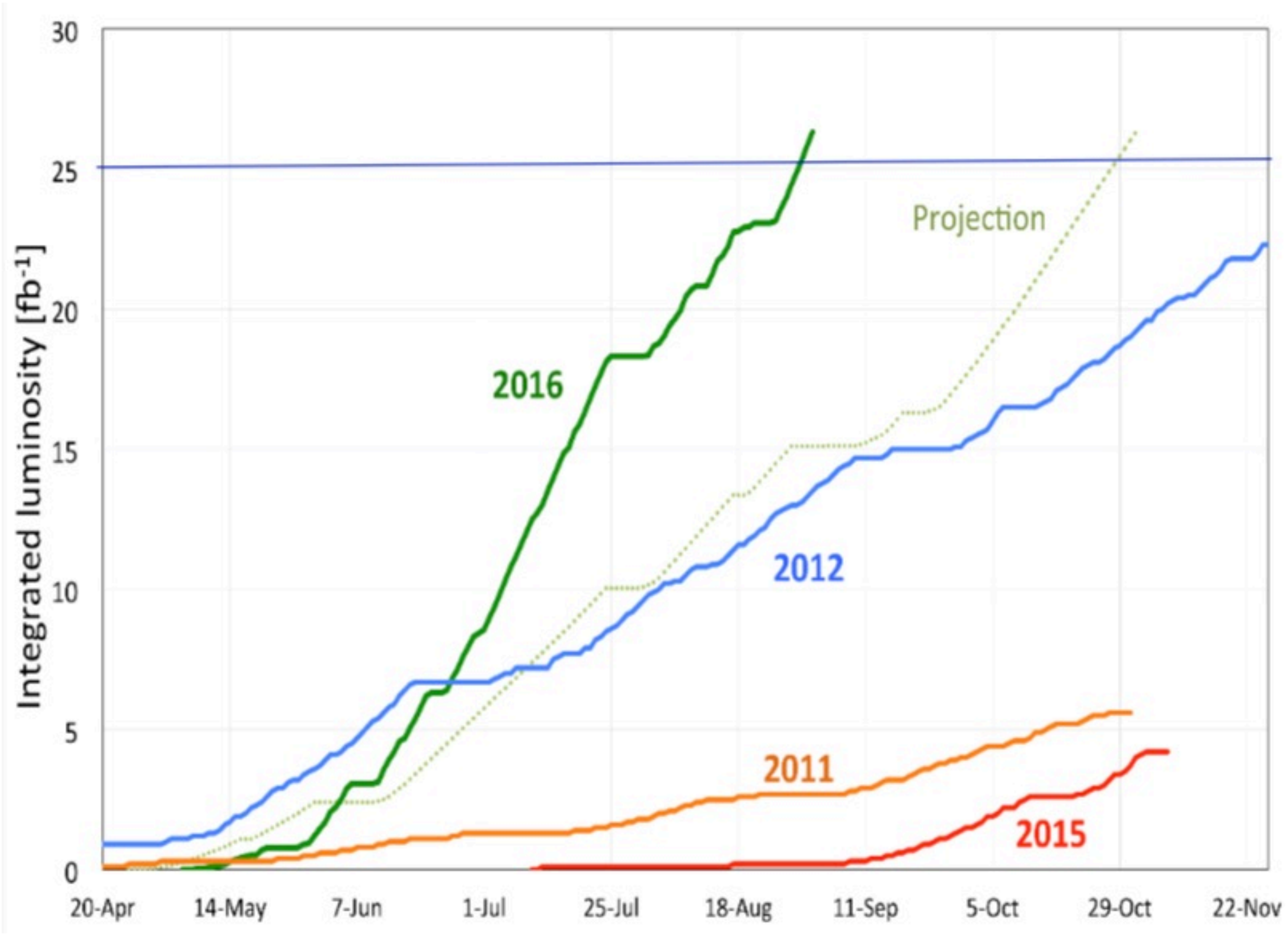

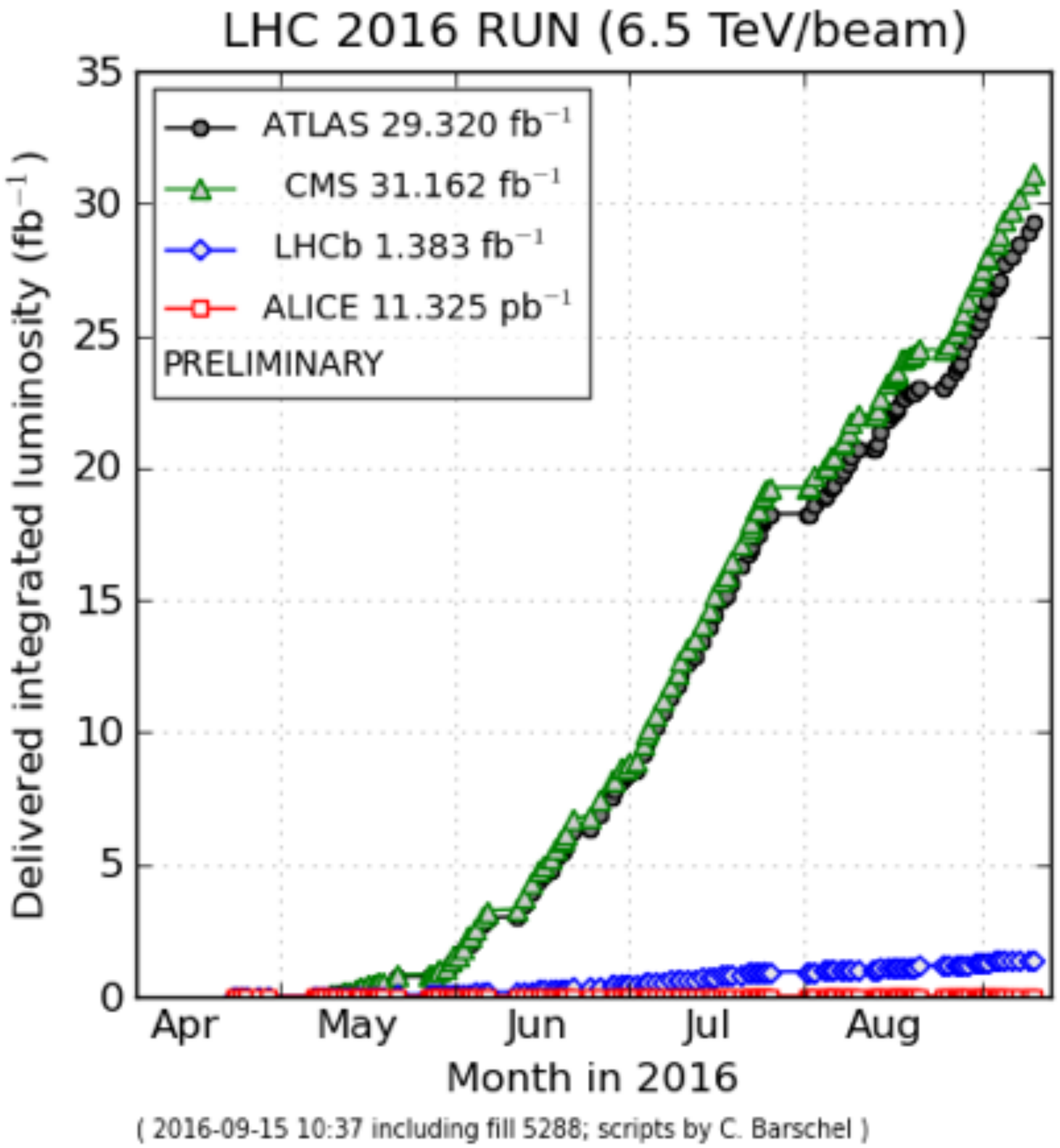

mid-August 2016: comparison with luminosity evolution in previous years

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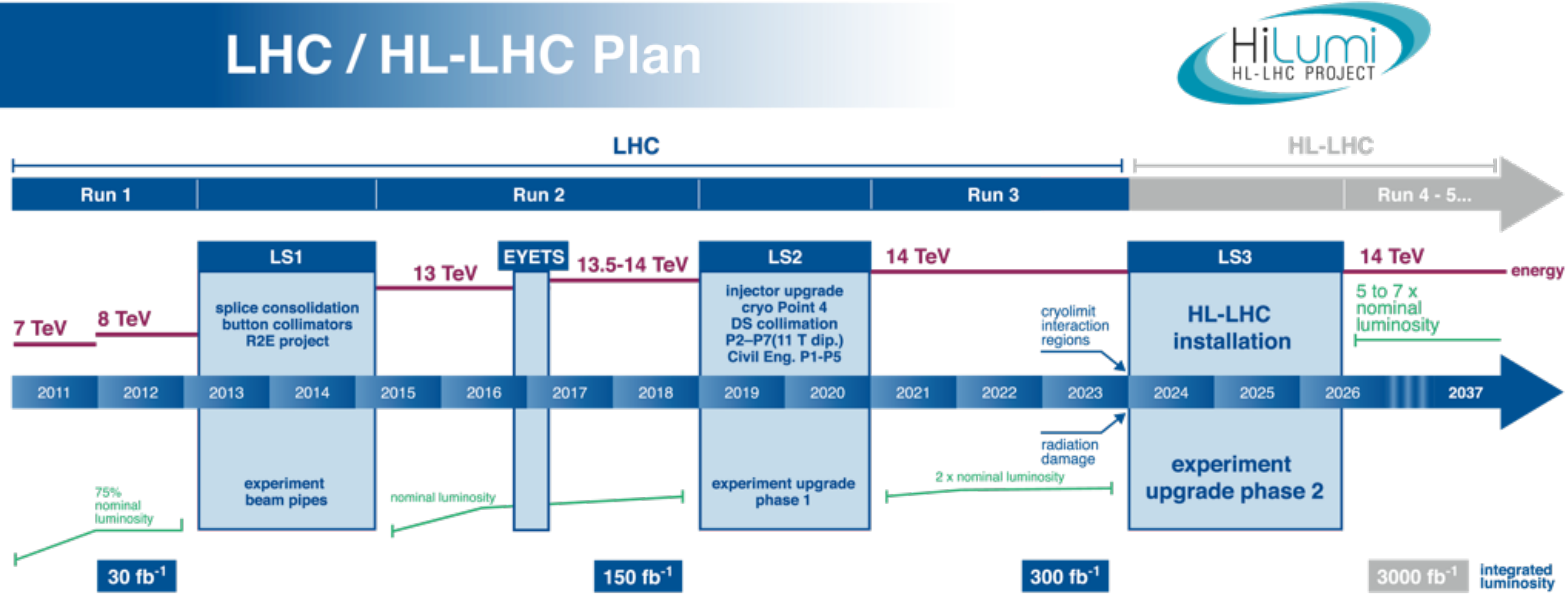
**Message: the LHC works extremely well, better than expected**

# Long-term LHC plan



The 30fb$^{-1}$ so far are just 1% of the final statistics

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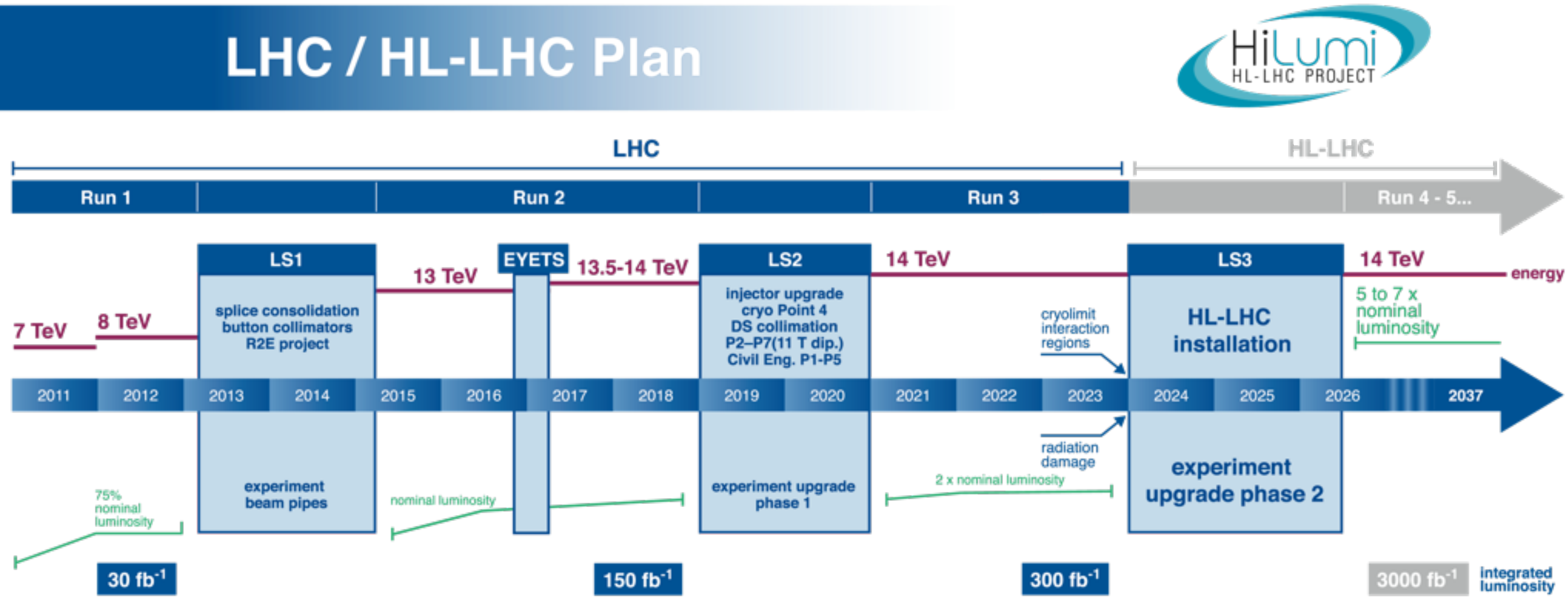

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**Message: the LHC physics programme has barely started!**

# LHC programme

## Key pillars

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- discovery of the Higgs boson

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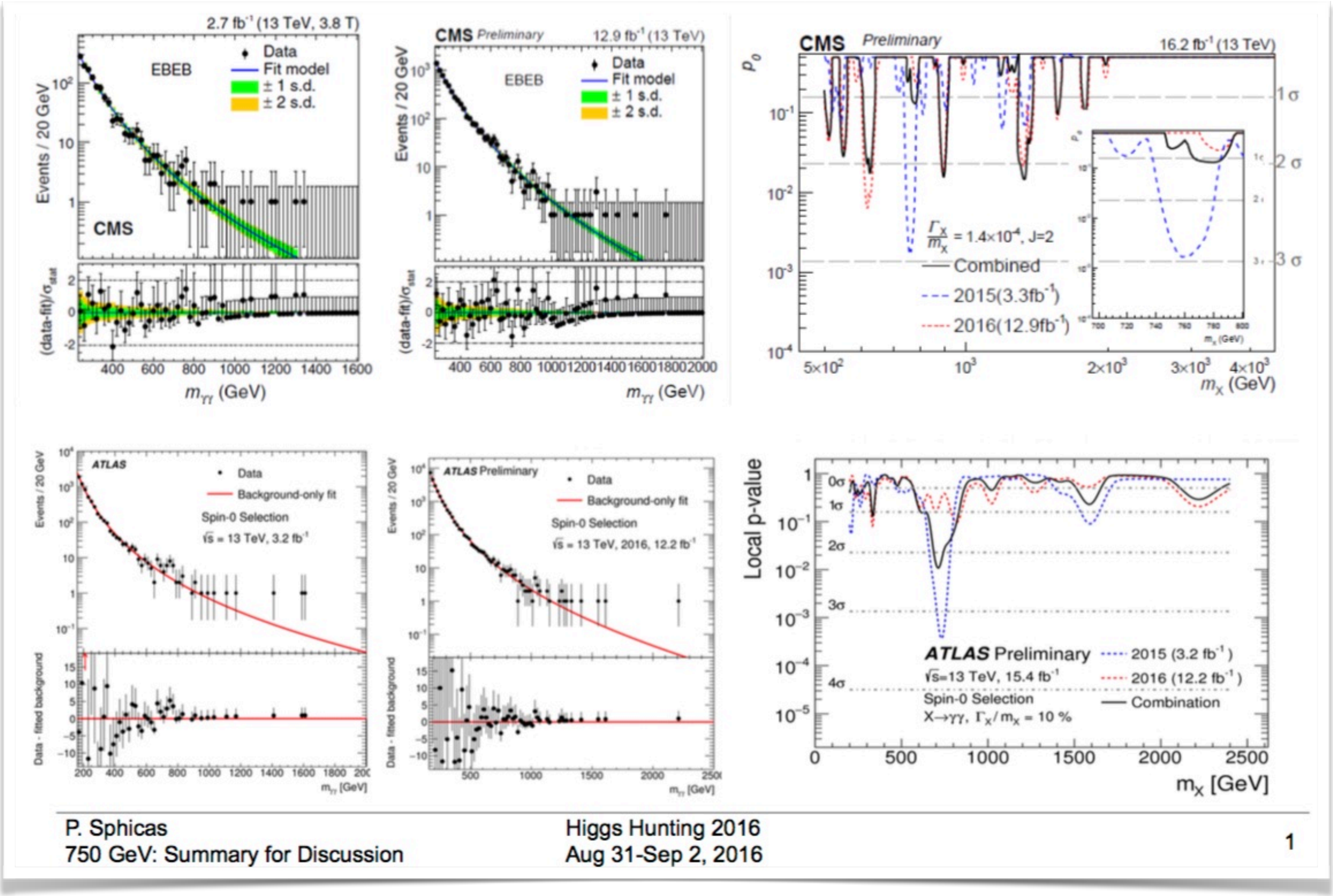
# Mid-July 2016 update on the 750 GeV γγ excess



P. Sphicas
750 GeV: Summary for Discussion

Higgs Hunting 2016
Aug 31-Sep 2, 2016

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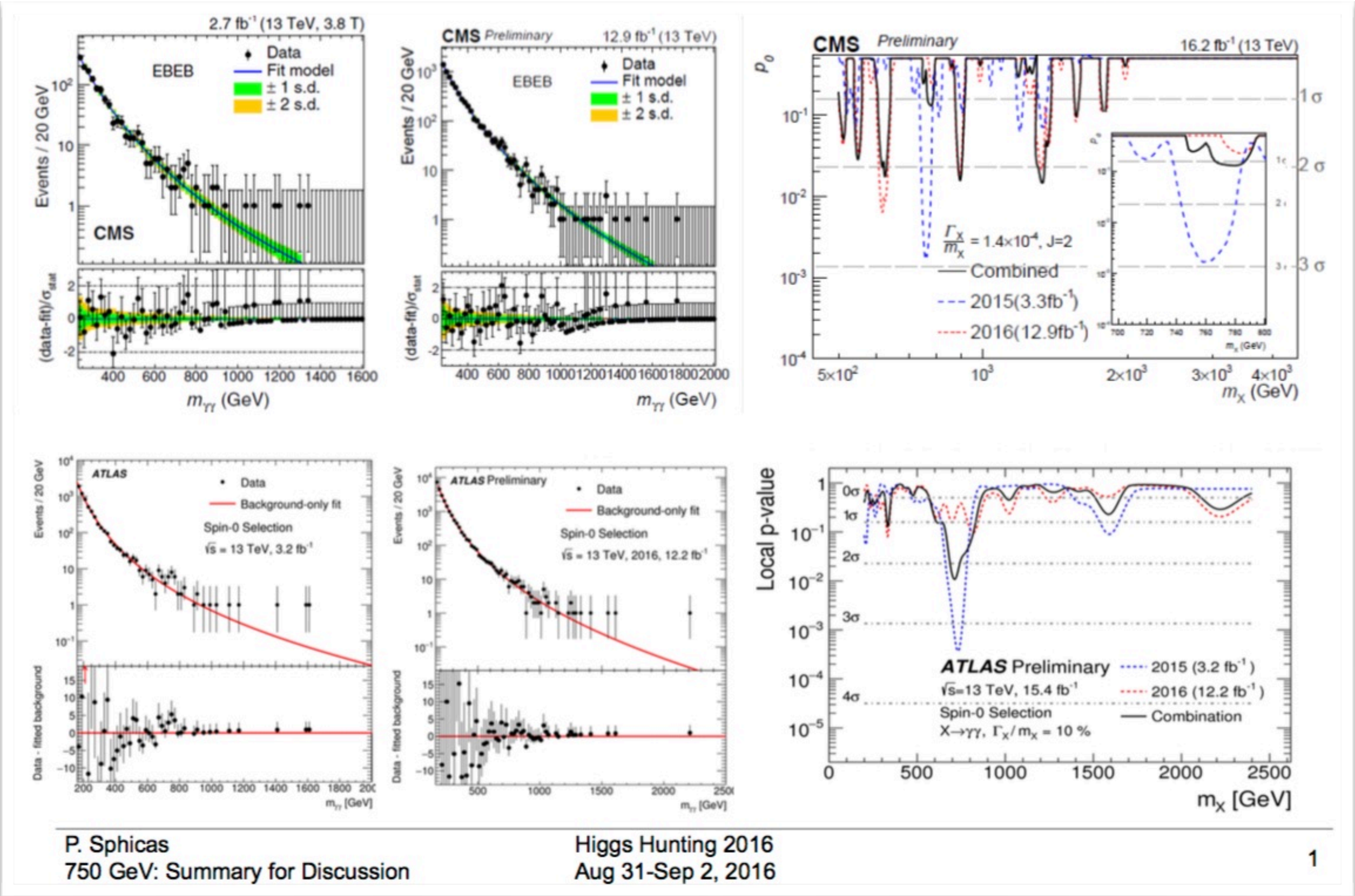

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1

**=> the resonant signal is not confirmed. But …**

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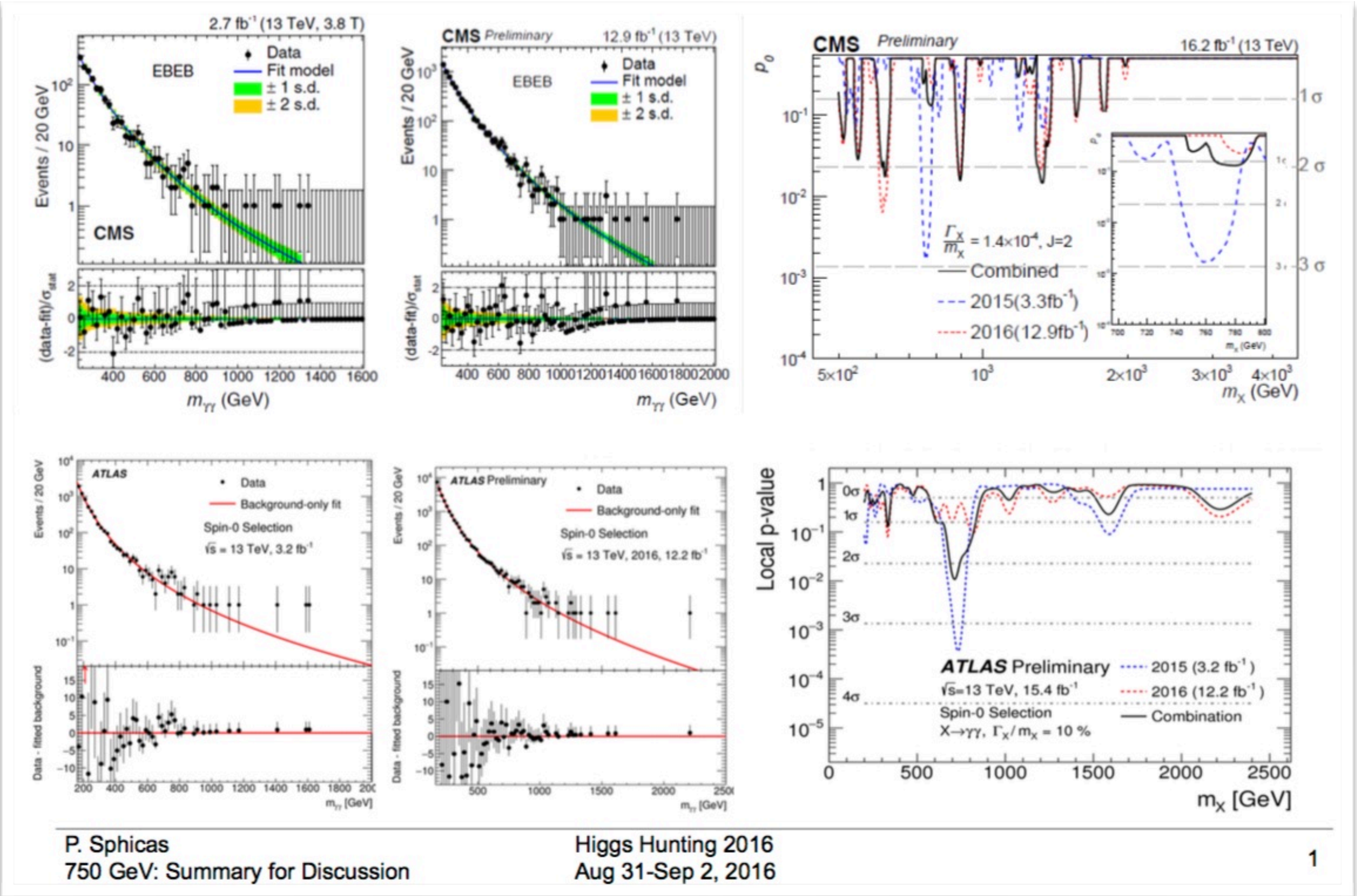

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1

**=> the resonant signal is not confirmed. But …**

**… message: little we know about the TeV scale!!**

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  - *theoretically justified BSM*: origin of EWSB, solutions to the hierarchy problem
  - *possible surprises …*
- BSM probes:
  - direct search of new particles
  - indirect sensitivity through the measurement of Higgs properties, gauge boson couplings, the flavour sector (hvy flavour decays), etc.etc.
- Sensitivity to new physics from **precision** (small departures from SM behaviour, e.g. in the Higgs couplings), from large **statistics** (rare or forbidden decays), from **reach** in energy (explore large-$Q^2$, with s- and t-channel phenomena). *Precision, large statistics and energy reach are the key ingredients of the LHC programme*

# LHC programme

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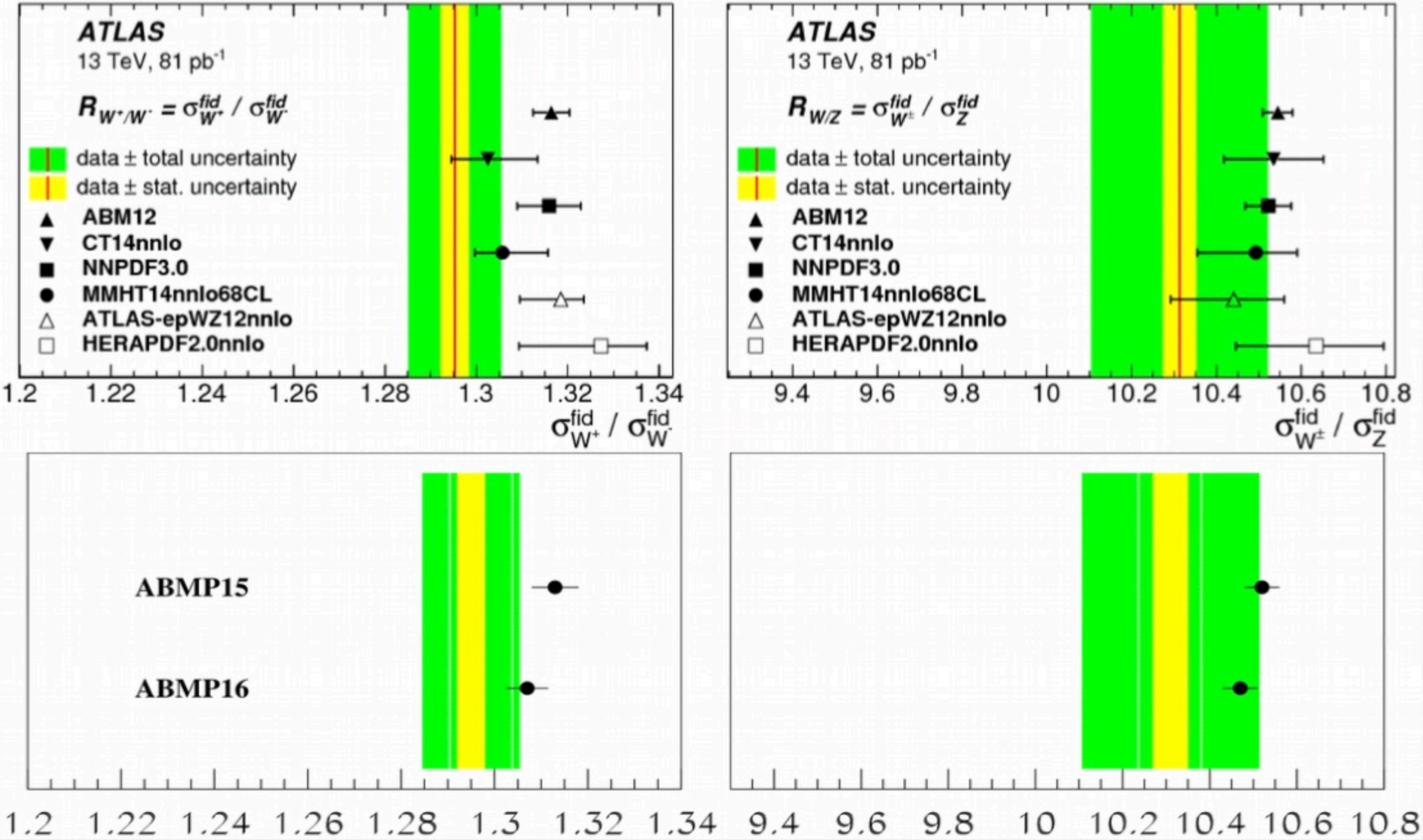
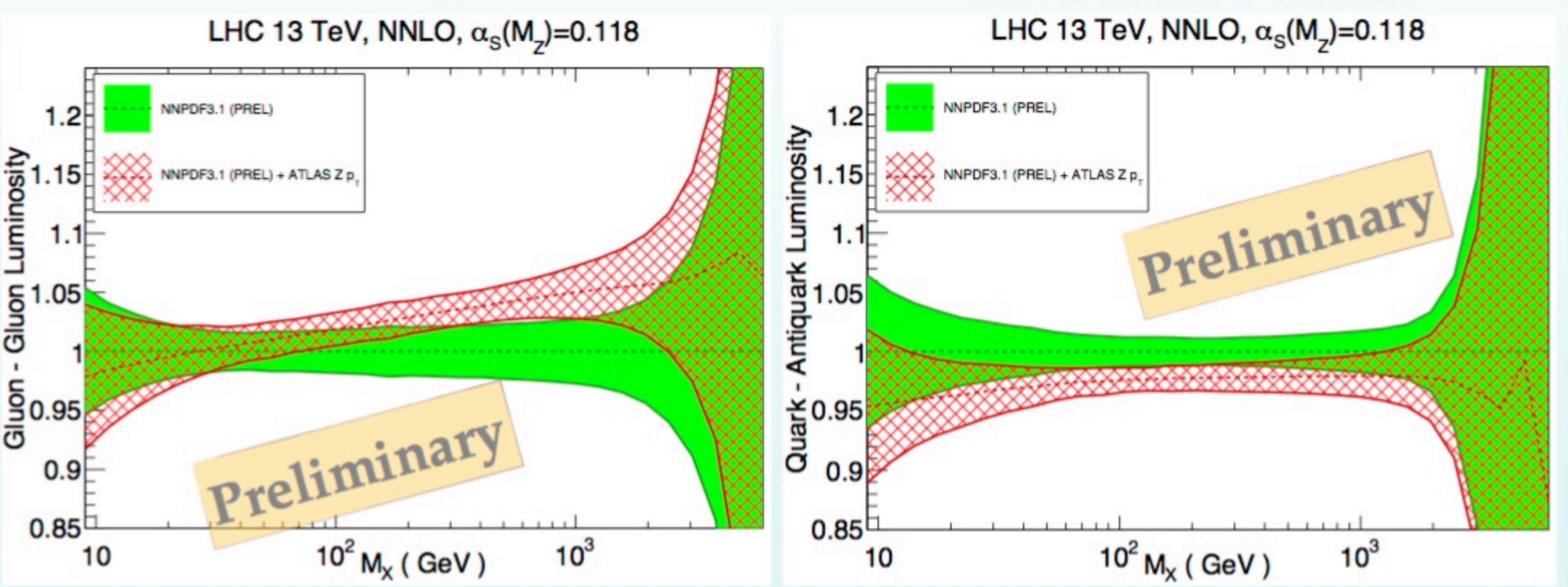
# ATLAS W&Z at 13 TeV

ATLAS, hep-ex/1603.09222



# Impact of Z $p_T$ spectrum on PDF fits

**Preliminary NNPDF3.1 NNLO fits** suggest a **sizeable impact** of the **LHC Z $p_T$ data** on the PDFs



Including the LHC Z $p_T$ data could be a **game-changer** in global NNLO PDF fits ……

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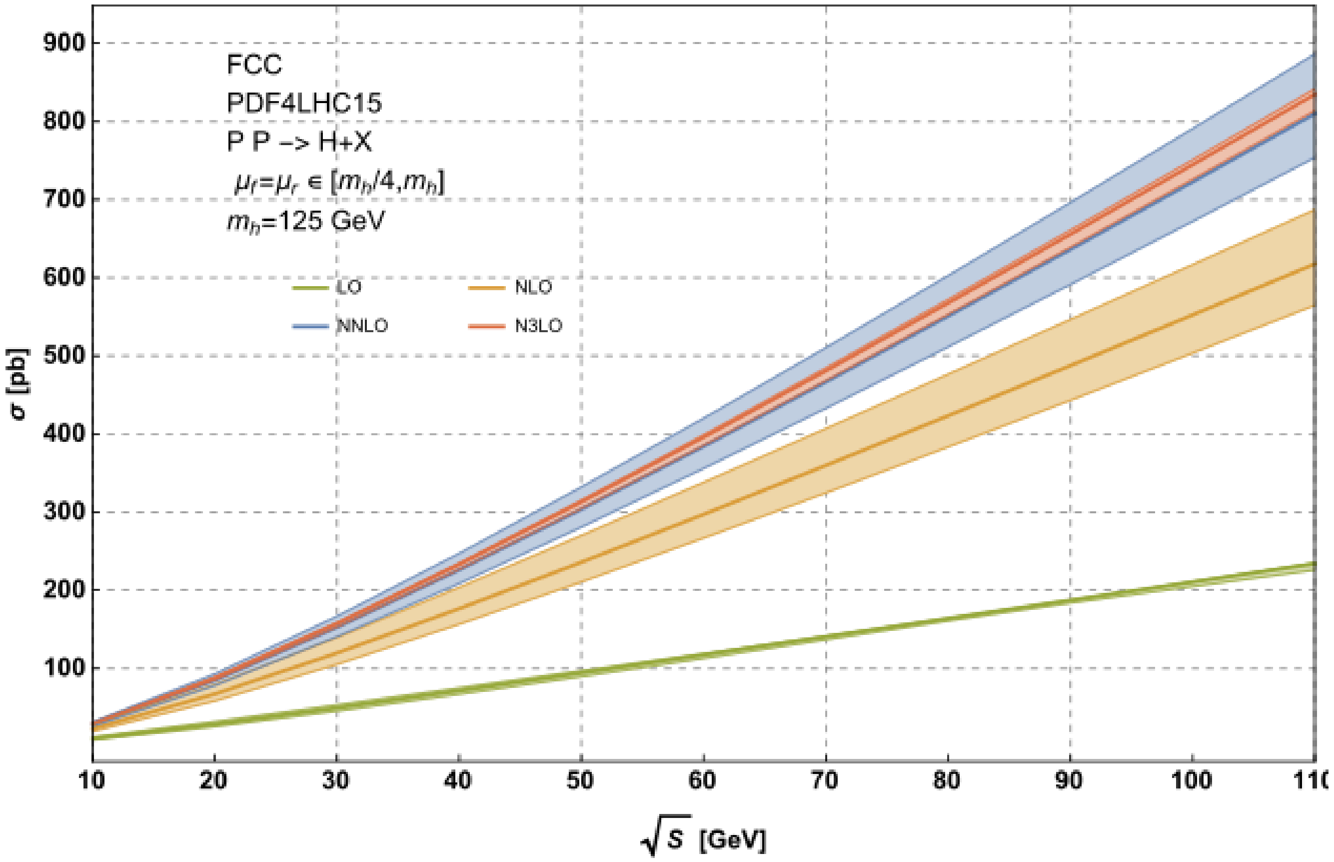
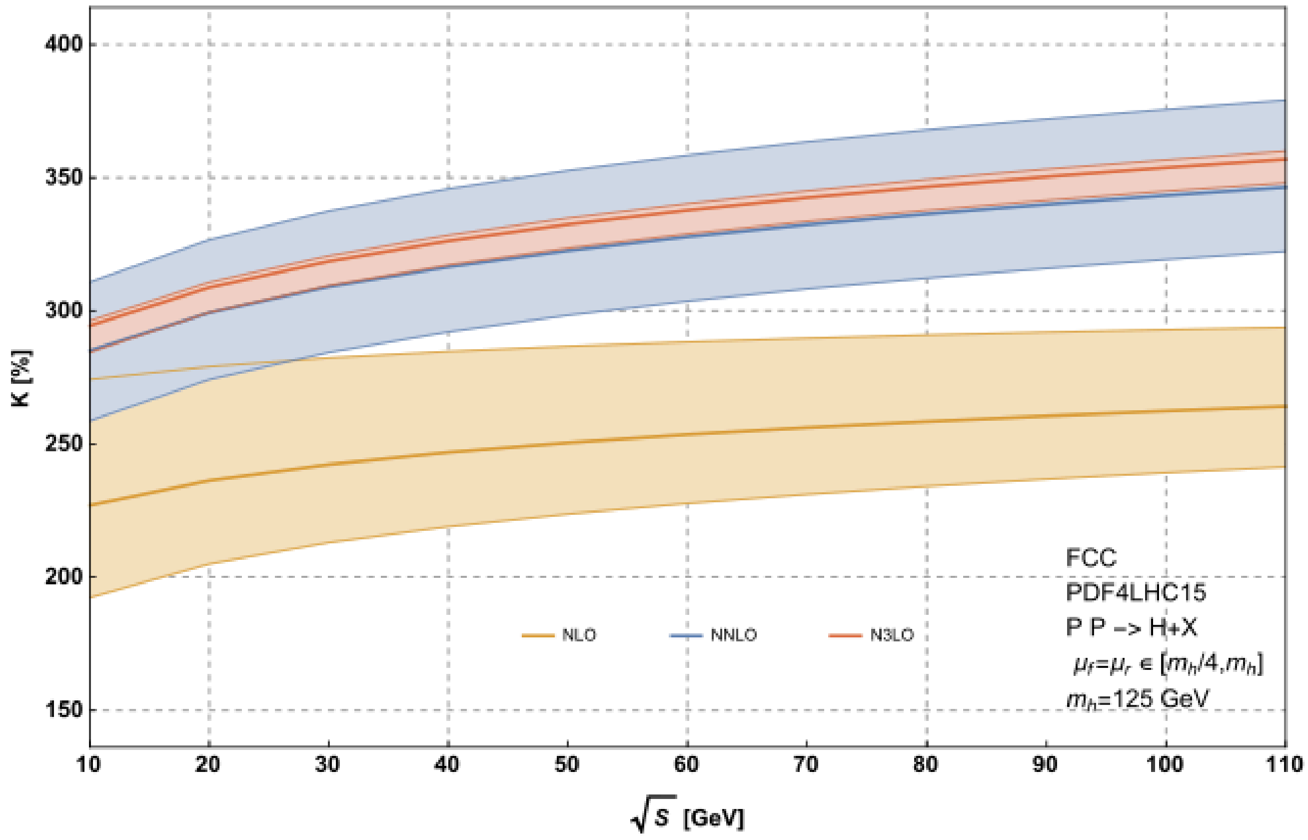
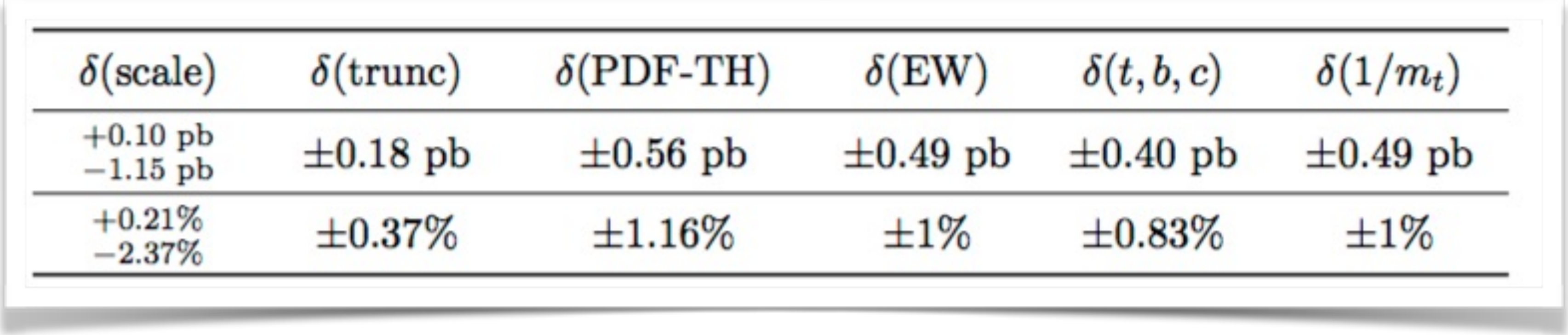
    - new generation of theoretical calculations ($N^nLO$)

# TH progress, an example

Anastasiou, Duhr, Dulat, Herzog, Mistlberger, arXiv:1503.06056
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger, arXiv:1602.00695

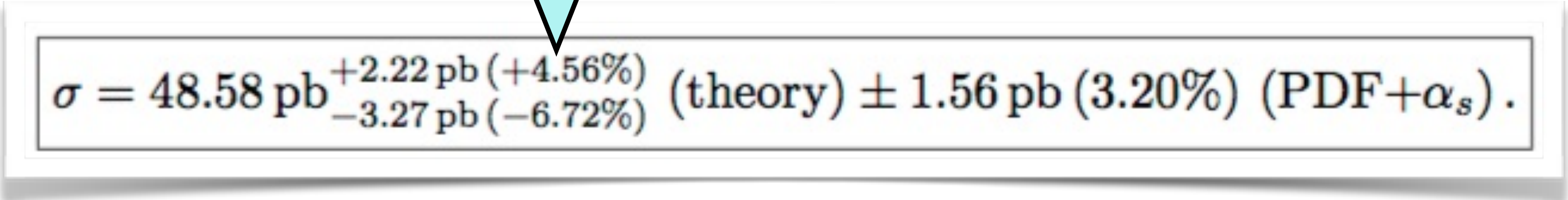






| $\delta(\text{scale})$ | $\delta(\text{trunc})$ | $\delta(\text{PDF-TH})$ | $\delta(\text{EW})$ | $\delta(t,b,c)$ | $\delta(1/m_t)$ |
|---|---|---|---|---|---|
| $^{+0.10\text{ pb}}_{-1.15\text{ pb}}$ | ±0.18 pb | ±0.56 pb | ±0.49 pb | ±0.40 pb | ±0.49 pb |
| $^{+0.21\%}_{-2.37\%}$ | ±0.37% | ±1.16% | ±1% | ±0.83% | ±1% |

linear sum of all but PDF and $\alpha_s$



$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.$$

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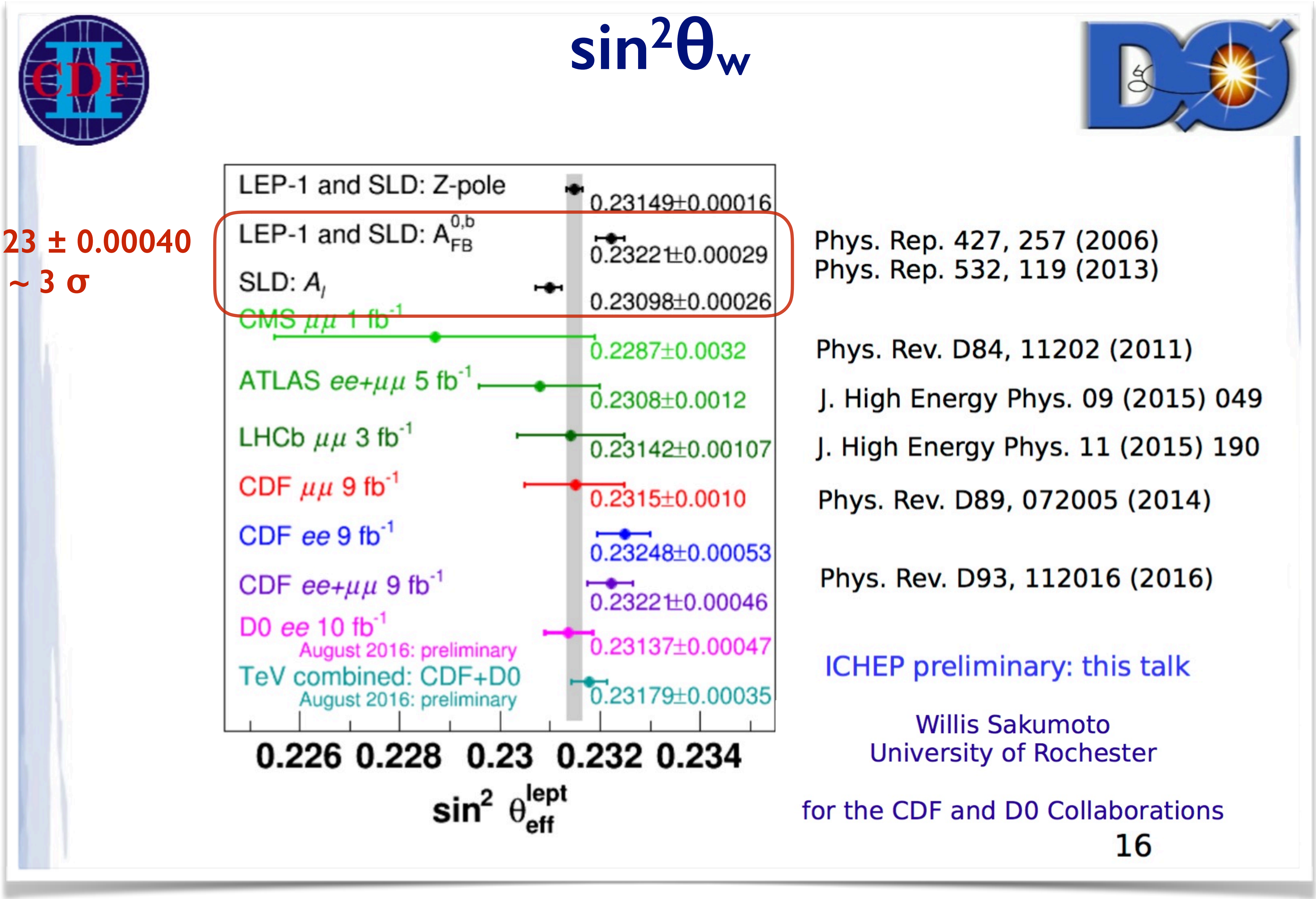

# $\sin^2\theta_W$

$\Delta$ = 0.00123 ± 0.00040
=> ~ 3 $\sigma$

LEP-1 and SLD: Z-pole 0.23149±0.00016

LEP-1 and SLD: $A_{FB}^{0,b}$ 0.23221±0.00029

SLD: $A_l$ 0.23098±0.00026

Phys. Rep. 427, 257 (2006)
Phys. Rep. 532, 119 (2013)

CMS $\mu\mu$ 1 $fb^{-1}$ 0.2287±0.0032 Phys. Rev. D84, 11202 (2011)

ATLAS $ee+\mu\mu$ 5 $fb^{-1}$ 0.2308±0.0012 J. High Energy Phys. 09 (2015) 049

LHCb $\mu\mu$ 3 $fb^{-1}$ 0.23142±0.00107 J. High Energy Phys. 11 (2015) 190

CDF $\mu\mu$ 9 $fb^{-1}$ 0.2315±0.0010 Phys. Rev. D89, 072005 (2014)

CDF $ee$ 9 $fb^{-1}$ 0.23248±0.00053

CDF $ee+\mu\mu$ 9 $fb^{-1}$ 0.23221±0.00046 Phys. Rev. D93, 112016 (2016)

D0 $ee$ 10 $fb^{-1}$ August 2016: preliminary 0.23137±0.00047

TeV combined: CDF+D0 August 2016: preliminary 0.23179±0.00035

ICHEP preliminary: this talk

Willis Sakumoto
University of Rochester

for the CDF and D0 Collaborations

LHC requires higher statistics w.r.t. Tevatron, to overcome symmetry of initial state (pp), which dilutes the charge asymmetry

Hard work, long term, but no conclusive showstopper to eventually reach/improve LEP/SLD precision and clarify the $A^b_{FB}$ vs $A_l$ mismatch

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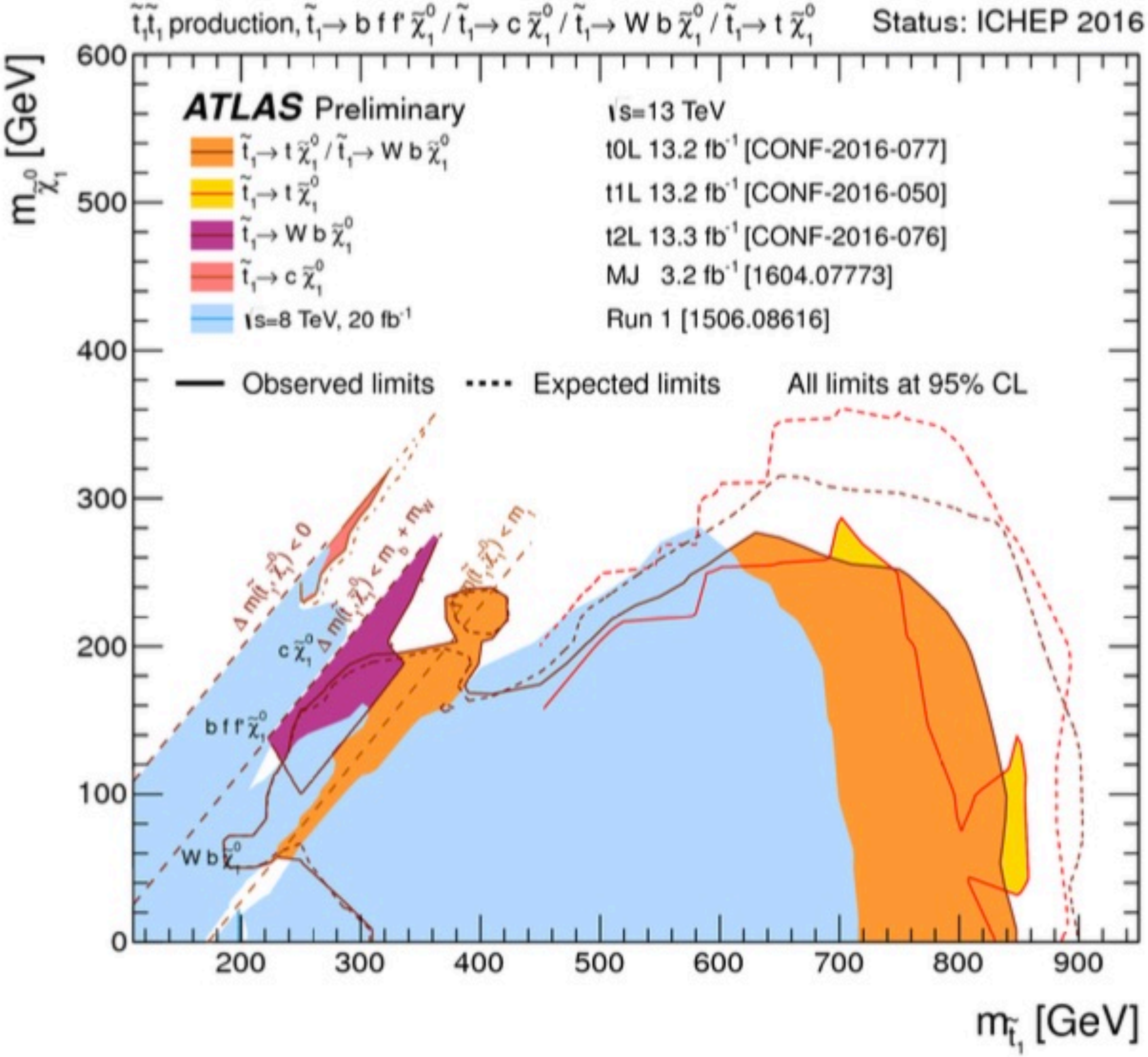
  - continued improvement in the knowledge of the fundamental parameters of the SM: $m_{top}$, $m_W$, $\sin^2\theta_W$, CKM, $\alpha_S$, …
- **constant development of new&ingenious analysis approaches** (e.g. machine learning, …), **full and novel exploitation of detector and trigger capabilities** (e.g. use of jet-substructure, data scouting, etc)

# Example: stop searches



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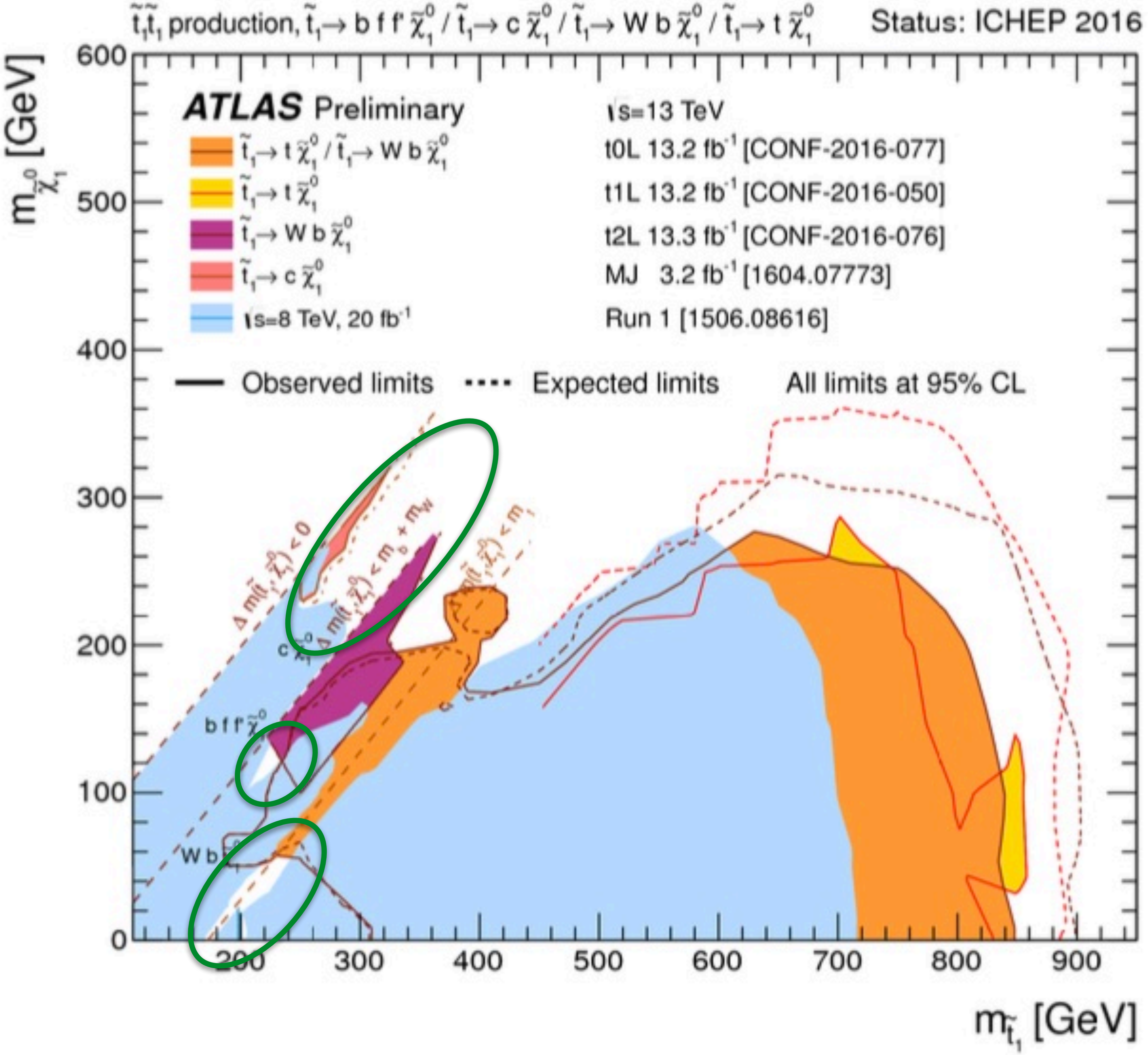
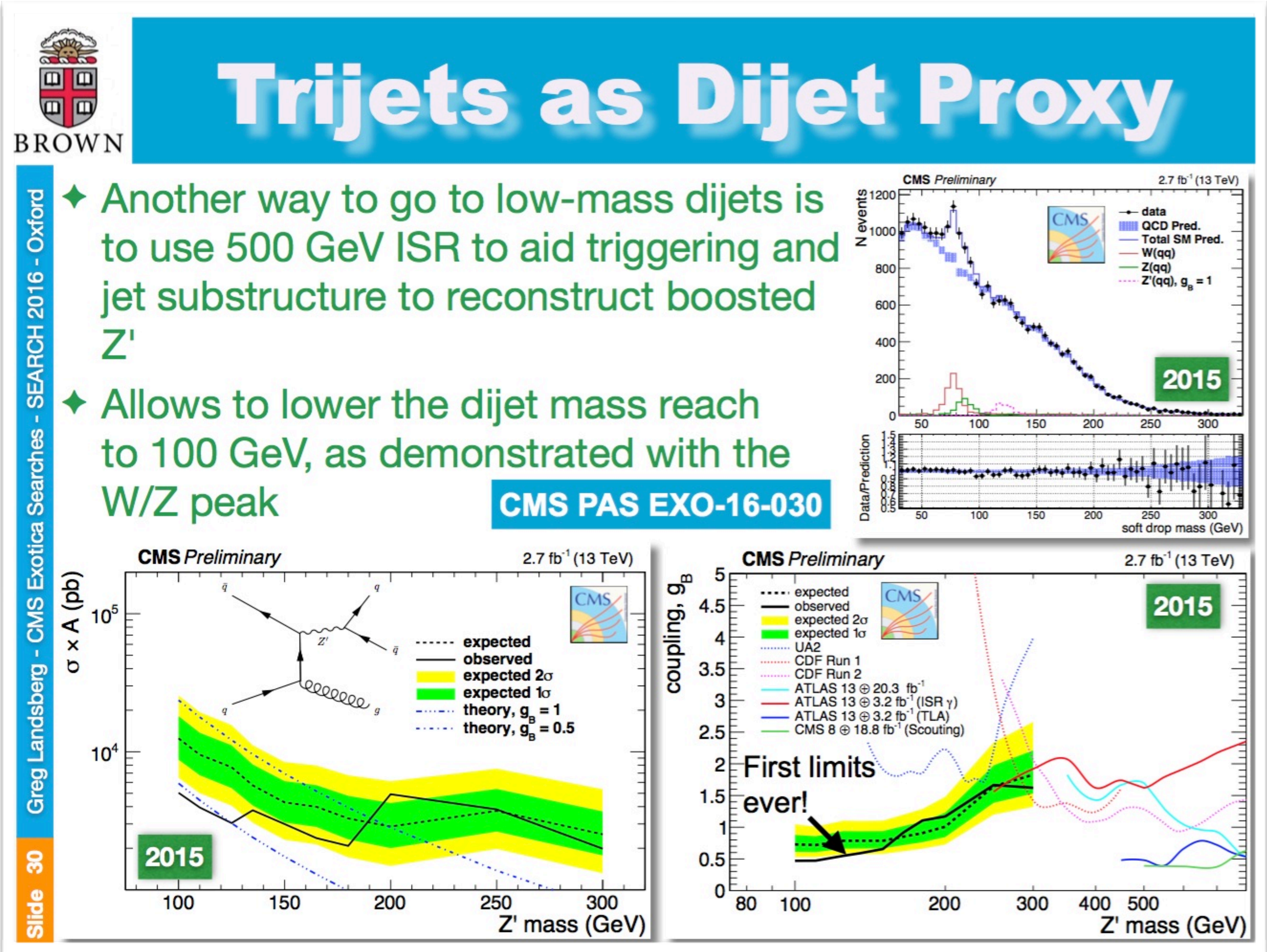


The challenge: gain sensitivity to all small gaps of parameter space, achieve a complete a conclusive coverage of the accessible phase space.

Probing each corner of this phase space is almost like a small-experiment in itself!!

# Example: search for low-mass dijet resonances



BROWN

## Trijets as Dijet Proxy

- Another way to go to low-mass dijets is to use 500 GeV ISR to aid triggering and jet substructure to reconstruct boosted Z'
- Allows to lower the dijet mass reach to 100 GeV, as demonstrated with the W/Z peak

**CMS PAS EXO-16-030**

First limits ever!

2015

Greg Landsberg - CMS Exotica Searches - SEARCH 2016 - Oxford

Slide 30

# LHC programme

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# *Anomalies left over from run 1, some examples*

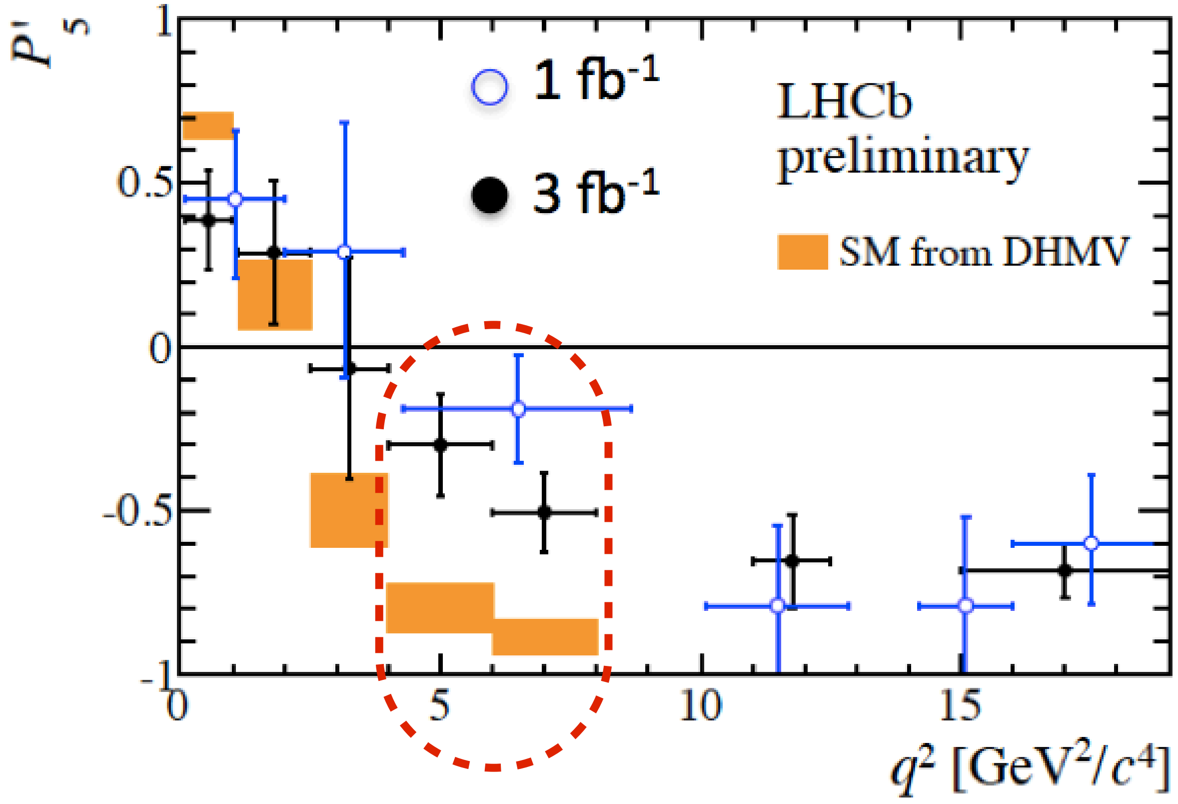
$$\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\,\%$$

CMS-PAS-HIG-14-005

**stat** **syst**

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

LHCb, arXiv:1406.6482



- B → K$*$μ+μ− anomaly

LHCb, arXiv:1308.1707 and
3fb$^{-1}$ update LHCb−CONF−2015−002

*For possible interpretation within a single BSM model*
*see e.g. Crivellin, D'Ambrosio, Heeck, arXiv:1501.00993 (2HDM w. gauged $L_\mu$–$L_\tau$)*

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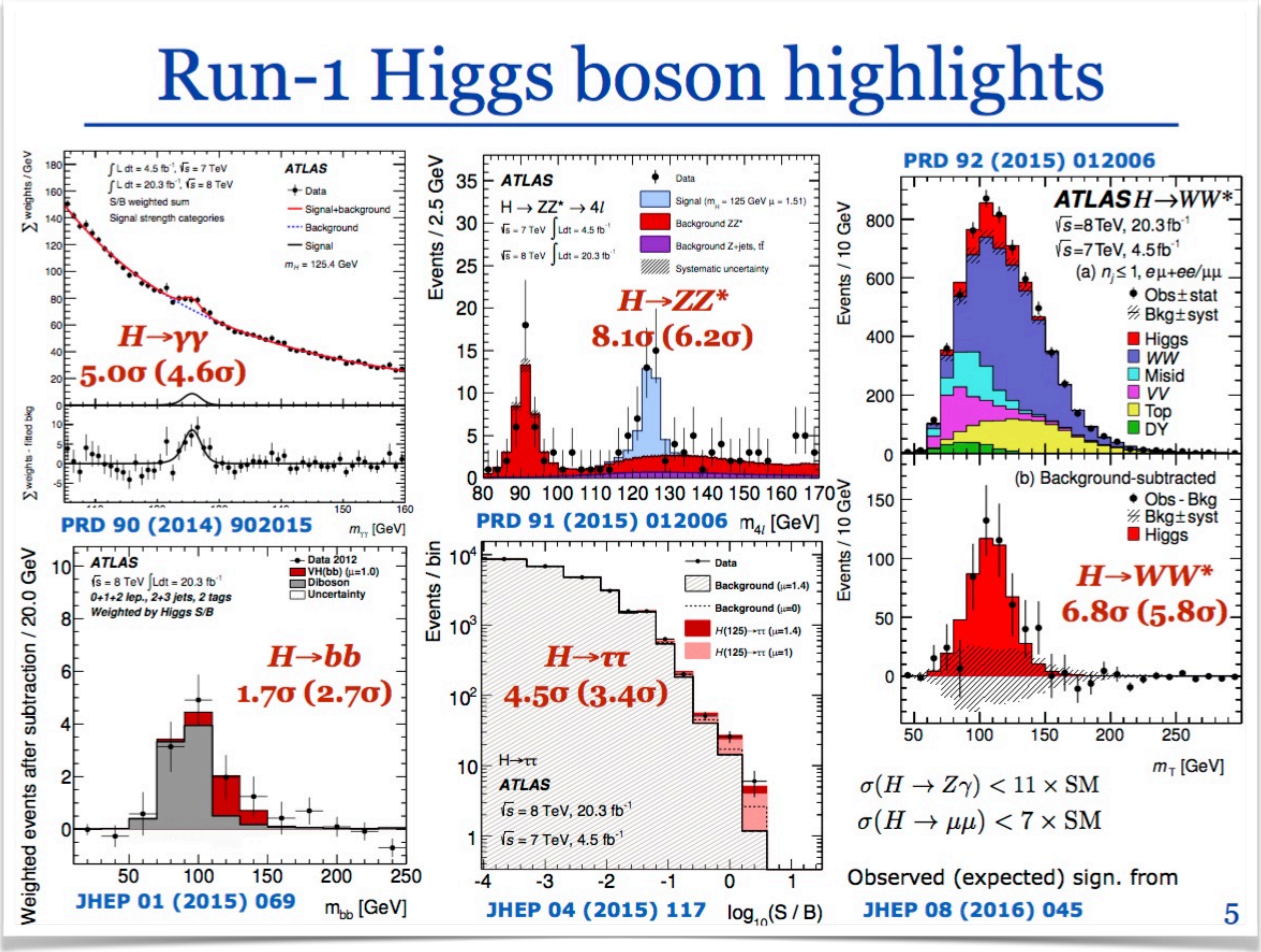
  - nuclear PDF determinations with the pA programme
  - heavy ion collisions, QGP

# Progress in Higgs physics



# Run-1 Higgs boson highlights

*H→γγ*
5.0σ (4.6σ)
PRD 90 (2014) 902015

*H→ZZ**
8.1σ (6.2σ)
PRD 91 (2015) 012006

PRD 92 (2015) 012006
*H→WW**
6.8σ (5.8σ)

*H→bb*
1.7σ (2.7σ)
JHEP 01 (2015) 069

*H→ττ*
4.5σ (3.4σ)
JHEP 04 (2015) 117

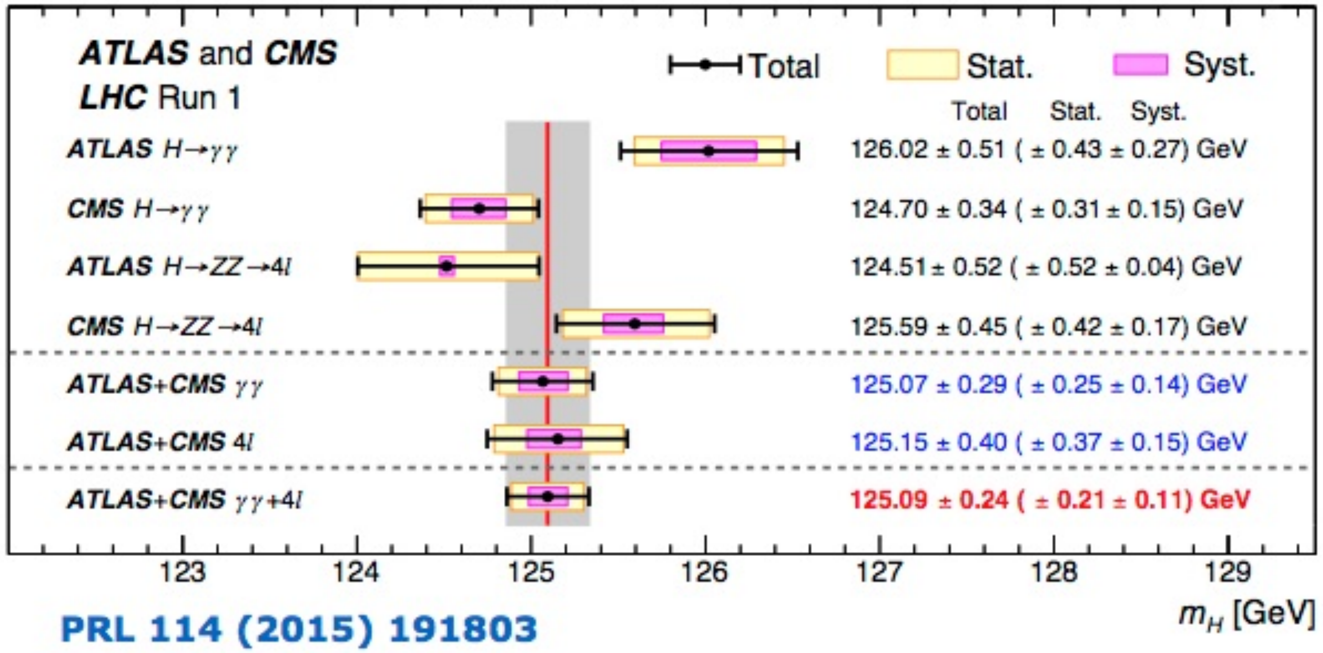
$\sigma(H \to Z\gamma) < 11 \times \mathrm{SM}$

$\sigma(H \to \mu\mu) < 7 \times \mathrm{SM}$

Observed (expected) sign. from
JHEP 08 (2016) 045

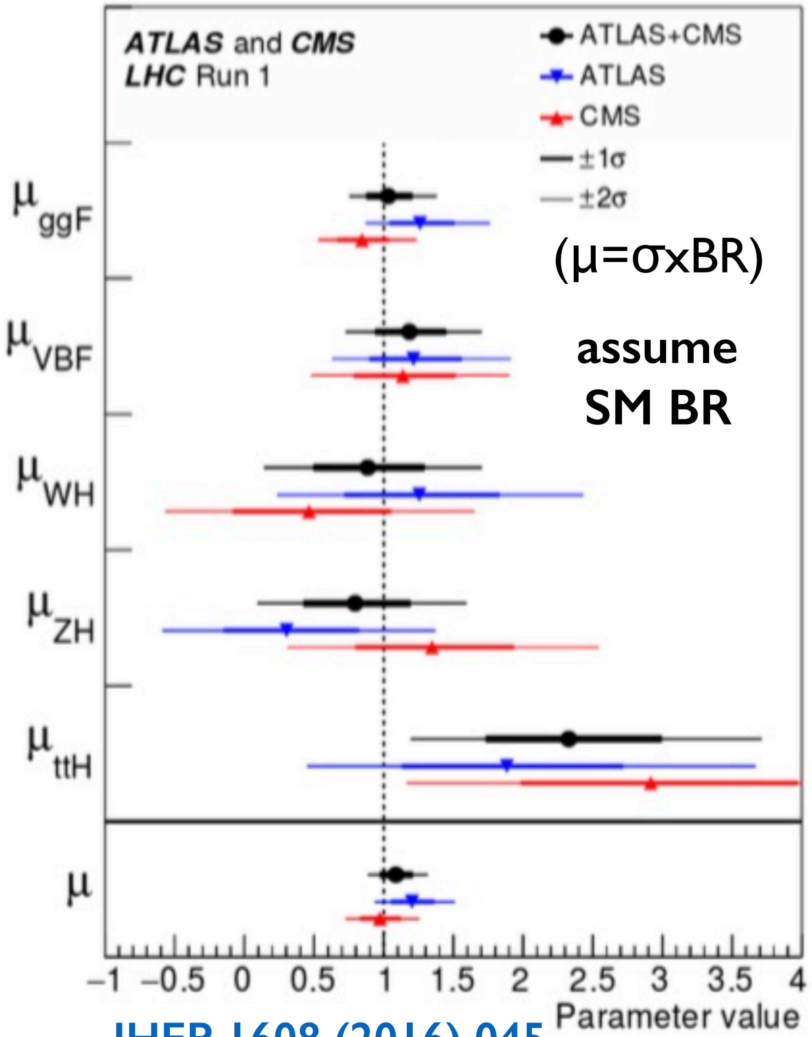
D.Gillberg (ATLAS) at “Higgs Hunting” 2016

# Higgs boson properties from run 1



PRL 114 (2015) 191803

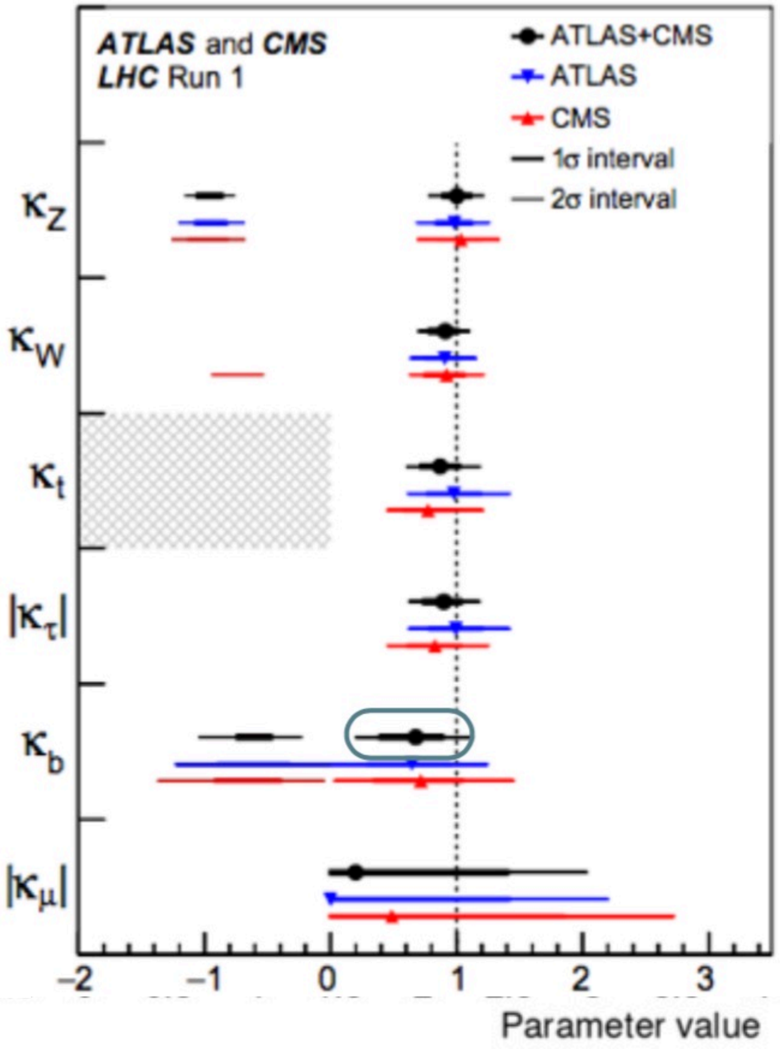
δm/m = 0.2%



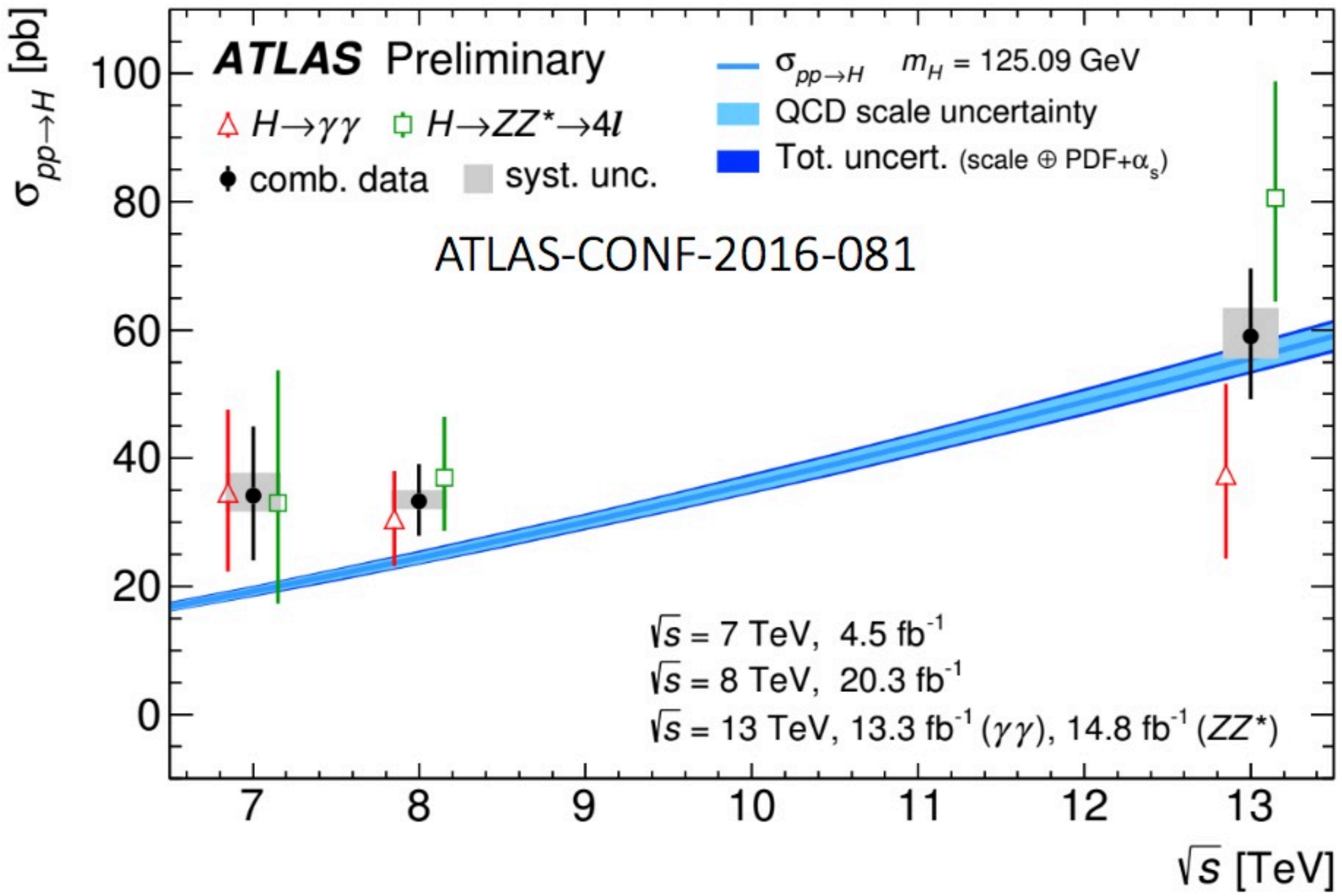
(μ=σxBR)

assume SM BR

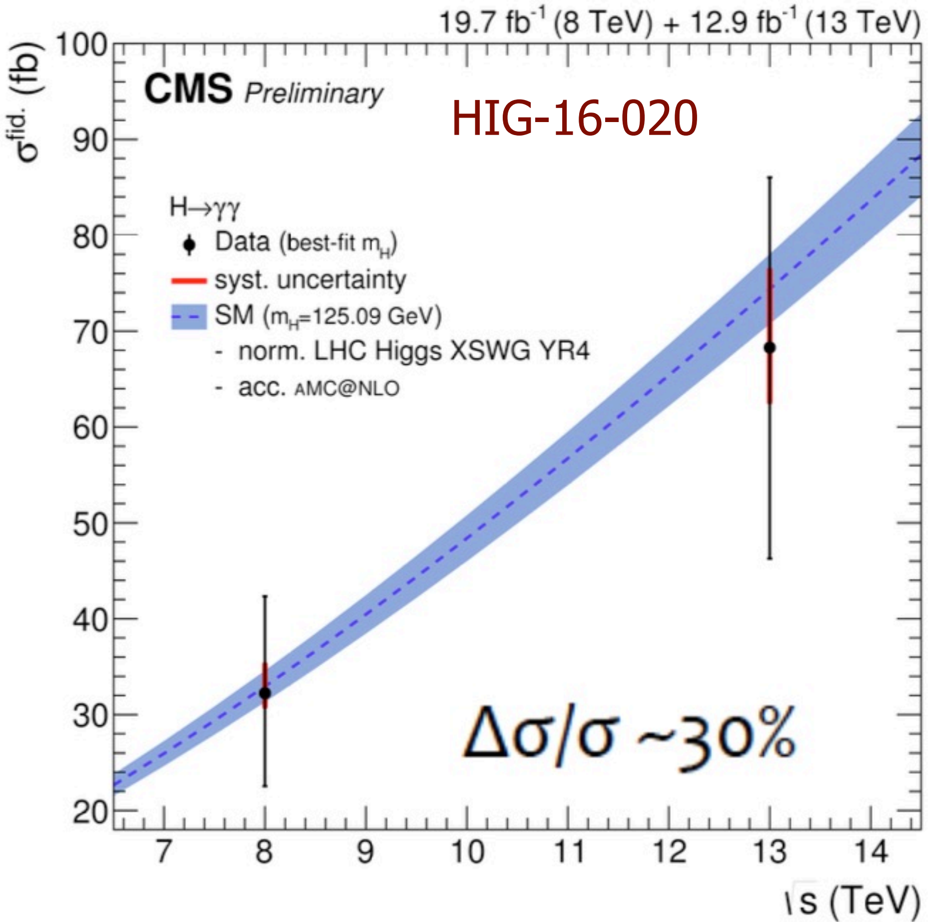
JHEP 1608 (2016) 045



# First run 2 Higgs results

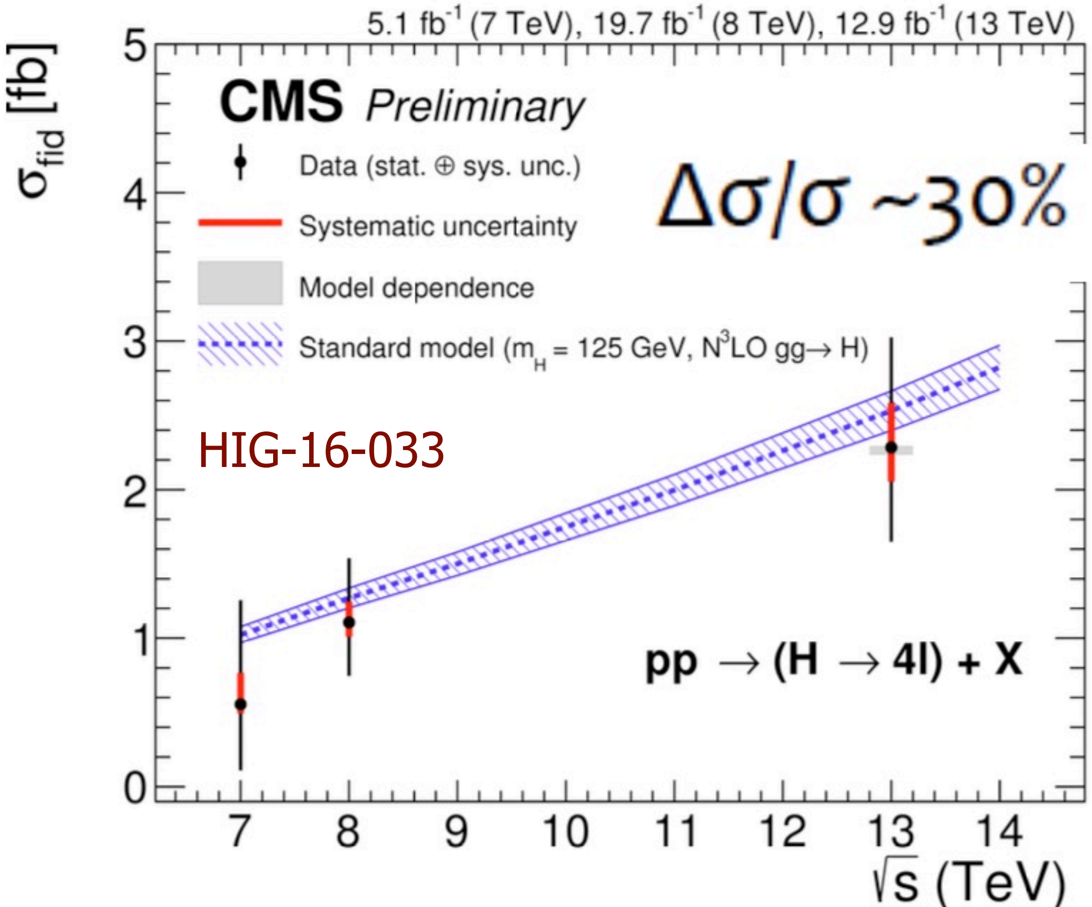


ATLAS-CONF-2016-081



HIG-16-020

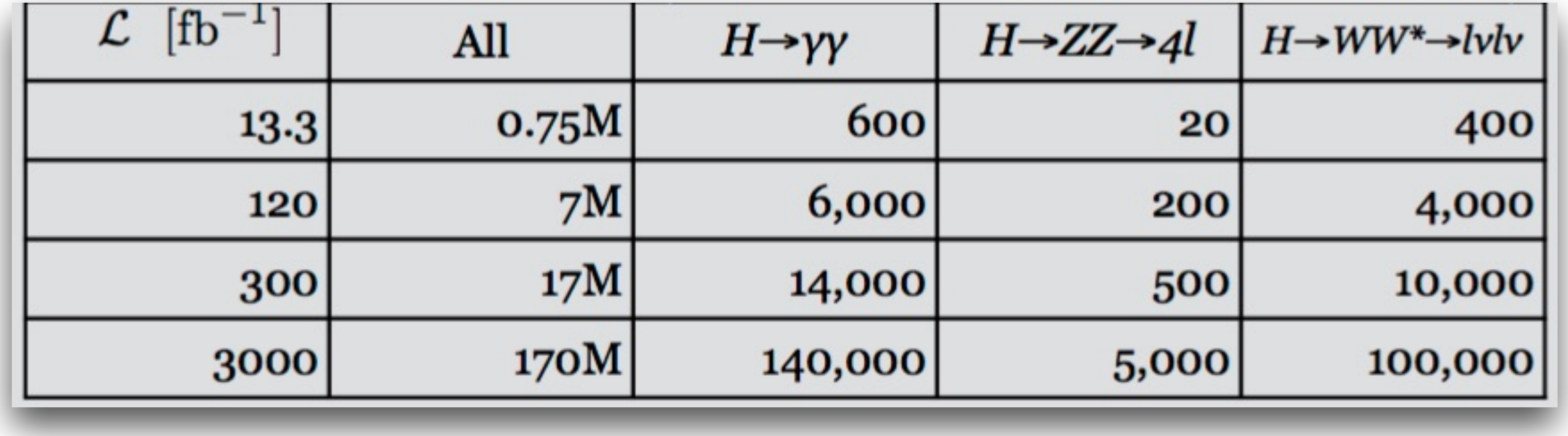
Δσ/σ ~30%



Δσ/σ ~30%

HIG-16-033

# Future evolution of Higgs statistics



| | $\mathcal{L}$ [fb$^{-1}$] | All | $H\to\gamma\gamma$ | $H\to ZZ\to 4l$ | $H\to WW^*\to lvlv$ |
|---|---|---|---|---|---|
| July '16 | 13.3 | 0.75M | 600 | 20 | 400 |
| End '18 | 120 | 7M | 6,000 | 200 | 4,000 |
| End '23 | 300 | 17M | 14,000 | 500 | 10,000 |
| ~ 2035 | 3000 | 170M | 140,000 | 5,000 | 100,000 |

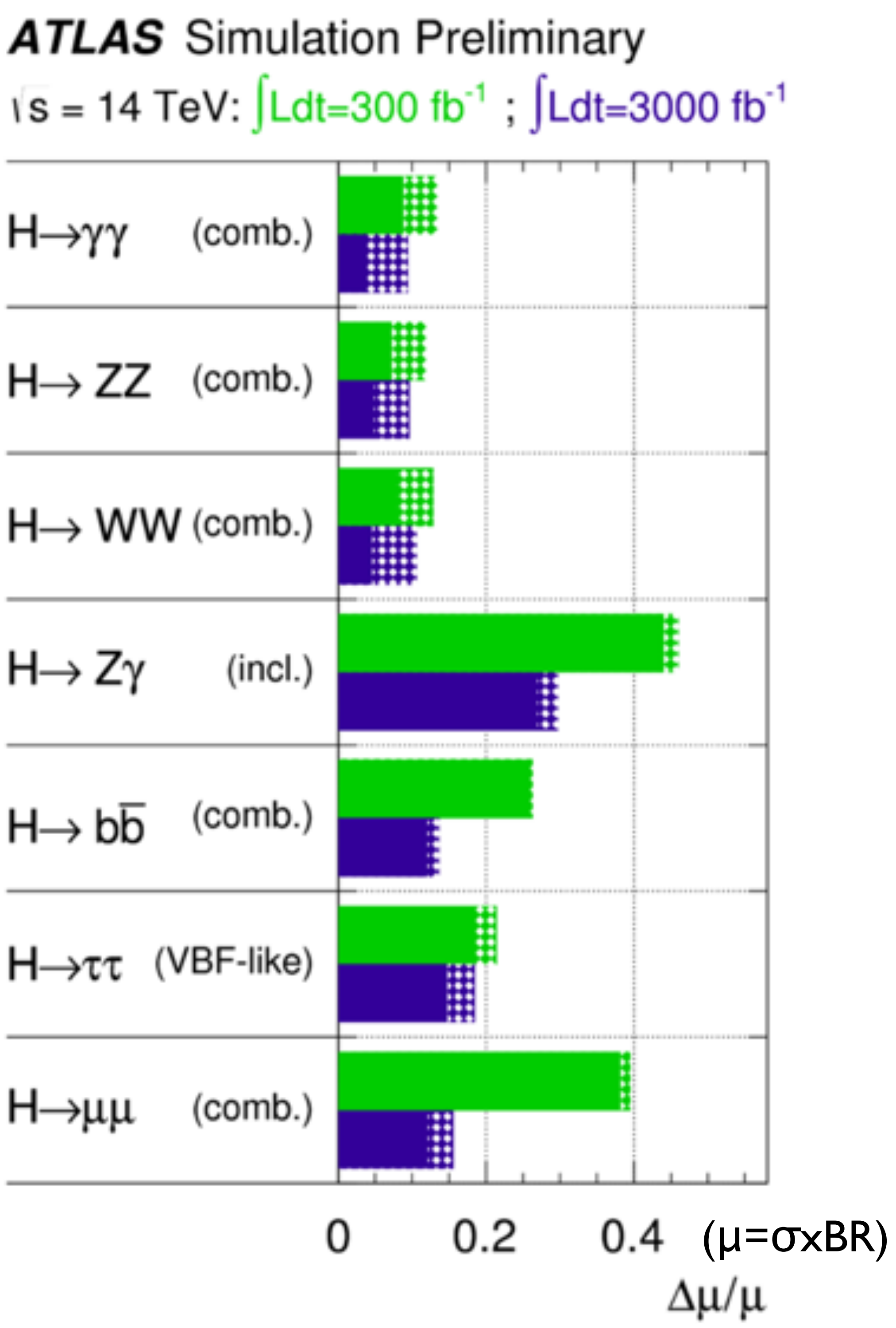
*include estimates of analysis cuts and efficiencies*

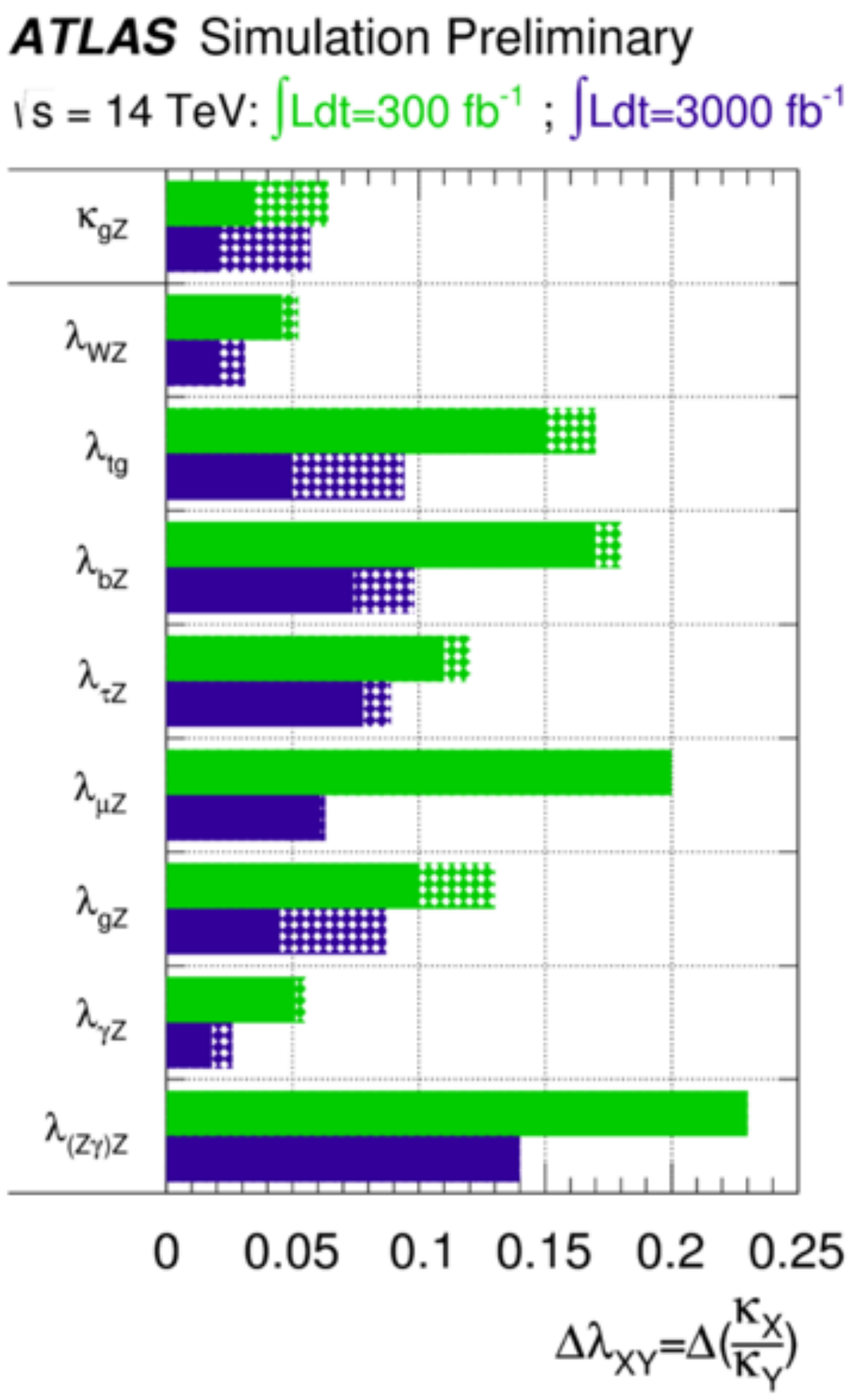
Current projections of future results are mostly extrapolations of today's analyses. Focus so far has been on exploring impact of higher luminosity and aging of detectors, to plan relevant upgrades and maintain or improve detector performance over the full LHC lifetime.

There is still plenty of room to design new analyses, exploiting in new ways the future huge statistics. Current projections should thus be seen as being likely rather conservative….

# Projected precision on H couplings

ATL-PHYS-PUB-2014-016



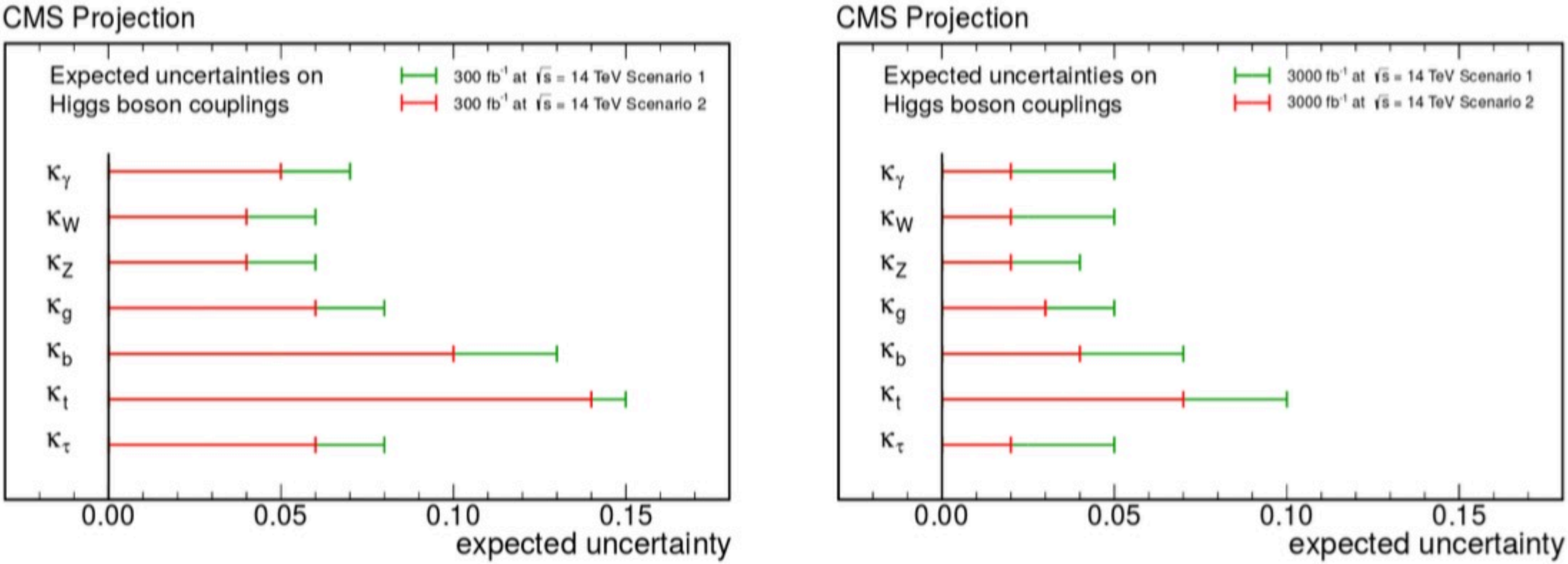


**solid areas: no TH systematics**

*shaded areas: with TH systematics*

# Projected precision on H couplings

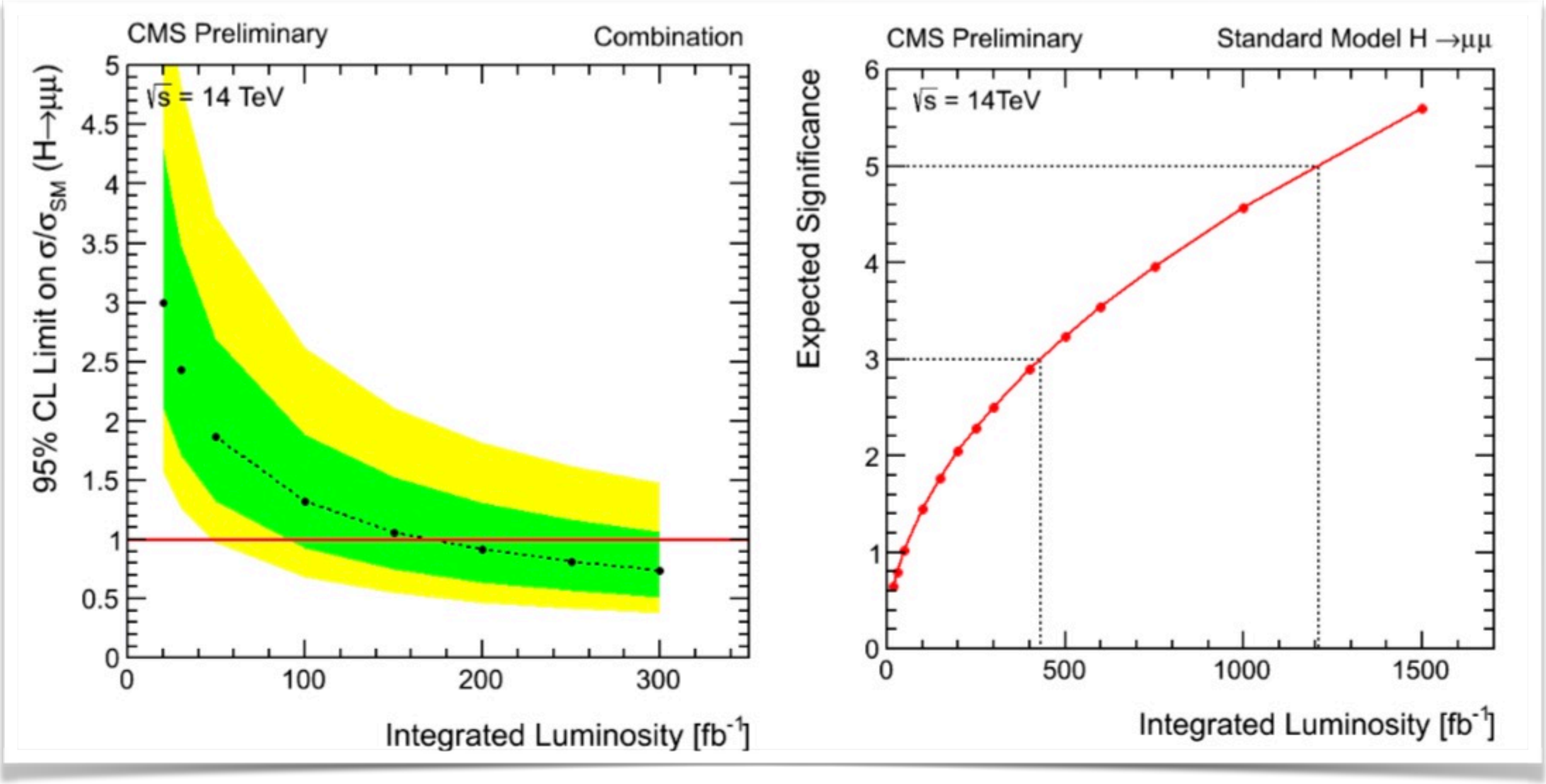
CMS-NOTE-2013-002



➔ Scenario1: systematics as in run 1

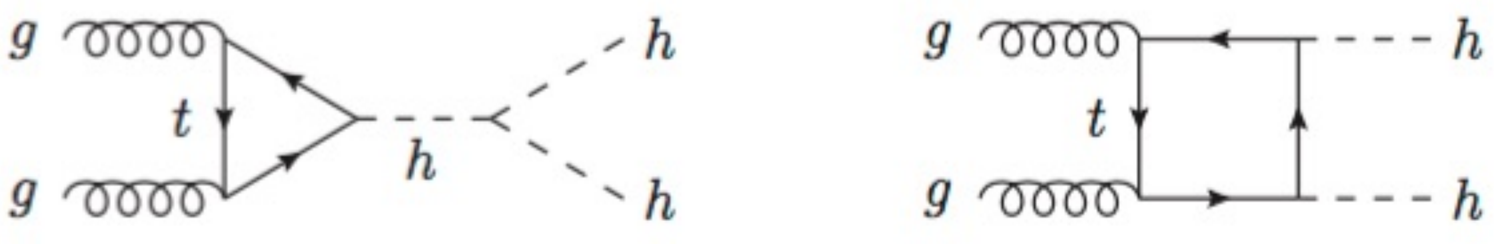
➔ Scenario2: TH syst scaled by1/2, exp'l syst scaled by $1/\sqrt{\int L}$

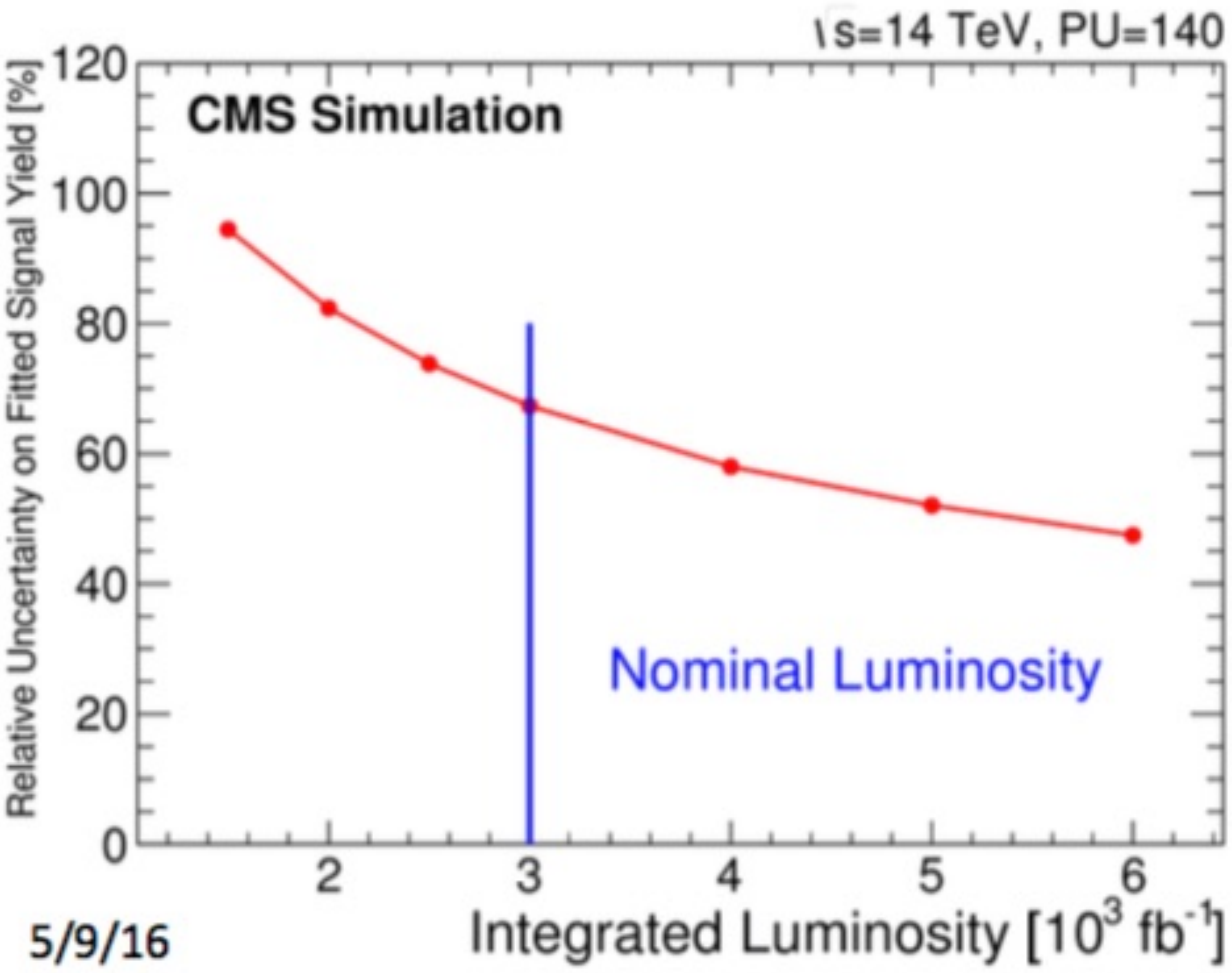
# Projections for H couplings to 2nd generation



Projections from CMS-HIG-13-007

# Higgs pair production, H self-coupling





5/9/16

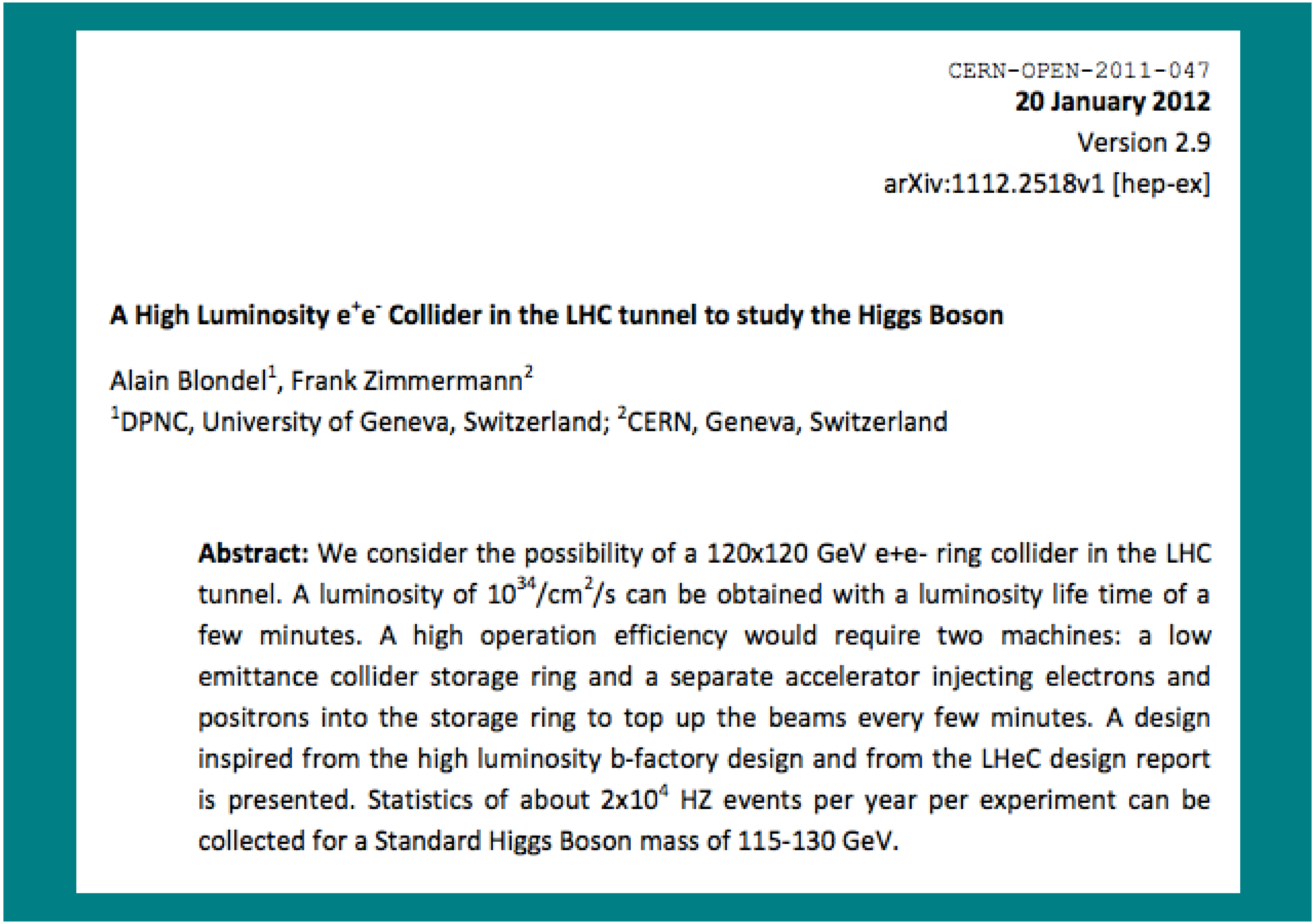
Only HH→bbγγ

More channels being studied

Possible reach for [3ab$^{-1}$ x 2expts] ~ 30% ?

# Setting the stage for the future

# **Dec 2011** *Latest LHC data corner the Higgs boson to within a small mass window in the 115-130 GeV range*



CERN-OPEN-2011-047
**20 January 2012**
Version 2.9
arXiv:1112.2518v1 [hep-ex]

## A High Luminosity $e^+e^-$ Collider in the LHC tunnel to study the Higgs Boson

Alain Blondel[1], Frank Zimmermann[2]
[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

**Abstract:** We consider the possibility of a 120x120 GeV e+e- ring collider in the LHC tunnel. A luminosity of $10^{34}$/cm$^2$/s can be obtained with a luminosity life time of a few minutes. A high operation efficiency would require two machines: a low emittance collider storage ring and a separate accelerator injecting electrons and positrons into the storage ring to top up the beams every few minutes. A design inspired from the high luminosity b-factory design and from the LHeC design report is presented. Statistics of about 2x$10^4$ HZ events per year per experiment can be collected for a Standard Higgs Boson mass of 115-130 GeV.

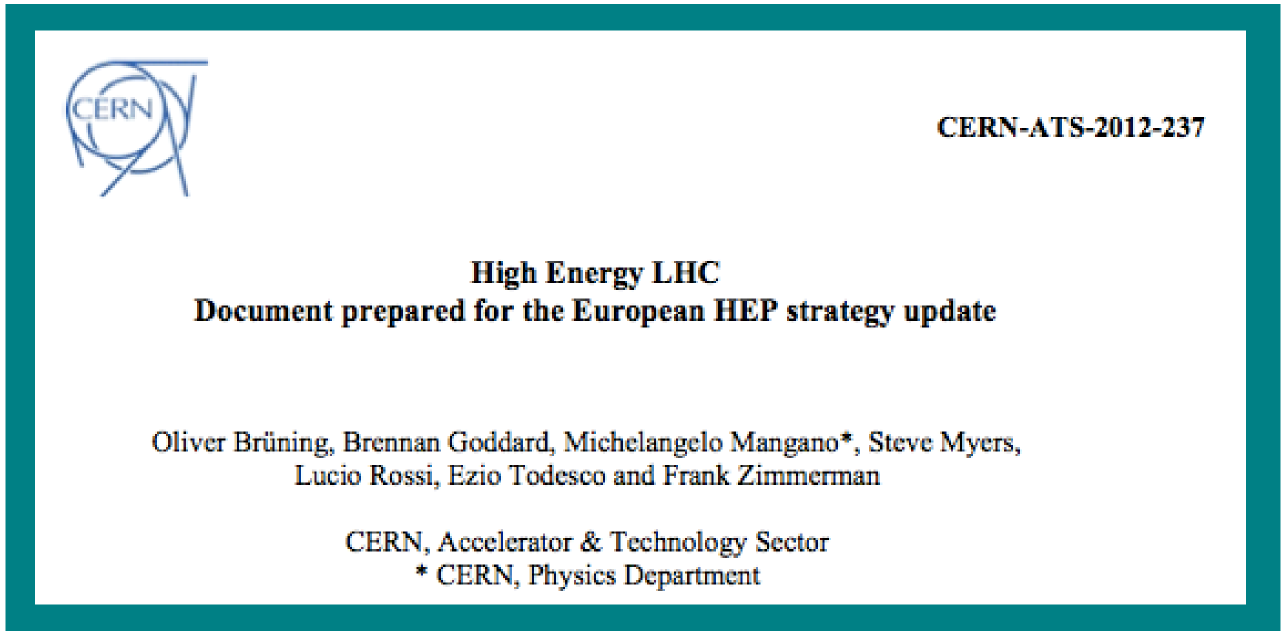
# Summer 2012.

*Higgs discovery => submissions to European Strategy Group Symposium*

From the upgrade of the accelerator infrastructure in the LHC tunnel .....

**LEP3 – Higgs factory in the LHC tunnel**

Prepared by Frank Zimmermann, CERN, 9 April 2012; revised on 3 August 2012



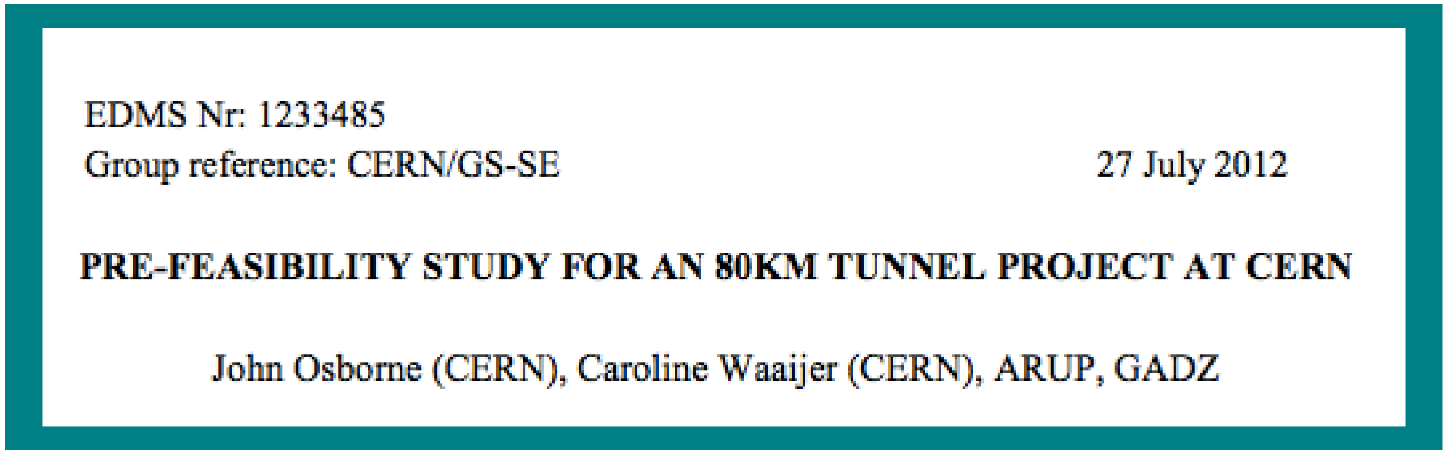
CERN-ATS-2012-237

**High Energy LHC**
**Document prepared for the European HEP strategy update**

Oliver Brüning, Brennan Goddard, Michelangelo Mangano*, Steve Myers,
Lucio Rossi, Ezio Todesco and Frank Zimmerman

CERN, Accelerator & Technology Sector
* CERN, Physics Department

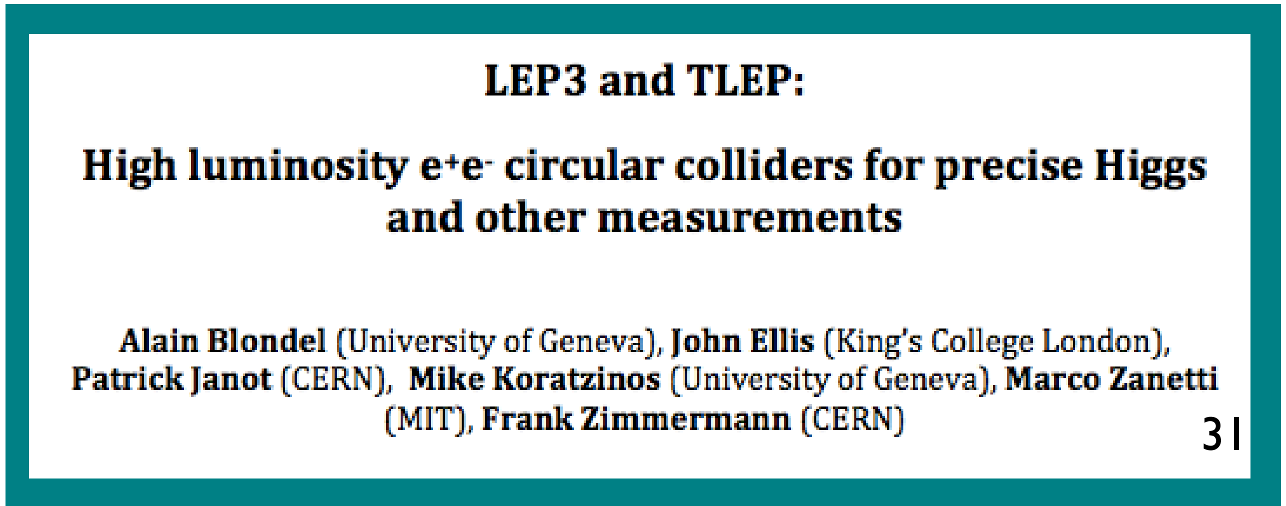
..... to the development of more ambitious goals



EDMS Nr: 1233485
Group reference: CERN/GS-SE 27 July 2012

**PRE-FEASIBILITY STUDY FOR AN 80KM TUNNEL PROJECT AT CERN**

John Osborne (CERN), Caroline Waaijer (CERN), ARUP, GADZ



**LEP3 and TLEP:**

**High luminosity $e^+e^-$ circular colliders for precise Higgs and other measurements**

**Alain Blondel** (University of Geneva), **John Ellis** (King's College London),
**Patrick Janot** (CERN), **Mike Koratzinos** (University of Geneva), **Marco Zanetti**
(MIT), **Frank Zimmermann** (CERN)

# *Fall 2012*
# *The idea caught up …*

Circular e+e- Higgs Factories

Convener: Dr. Daniel Schulte (CERN)

09:00 **LEP3 and TLEP** *25'*
Speaker: Dr. Frank Zimmermann (CERN)
Material: **Slides**

09:40 **SuperTristan** *15'*
Speaker: Dr. Katsunobu Oide (KEK)
Material: **Slides**

10:05 **Fermilab Site Filler** *15'*
Speaker: Dr. Tanaji Sen (Fermilab)
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11:00 **IHEP Higgs Factory** *15'*
Speaker: Dr. Qing QIN (IHEP)
Material: **Slides**

Accelerators for a Higgs Factory: Linear vs. Circular (HF2012)

chaired by Weiren Chou (Fermilab)

from Wednesday, November 14, 2012 at **08:00** to Friday, November 16, 2012 at **17:00** (US/Central)
at **Fermilab ( One West, Wilson Hall )**
Batavia, IL 60510 USA

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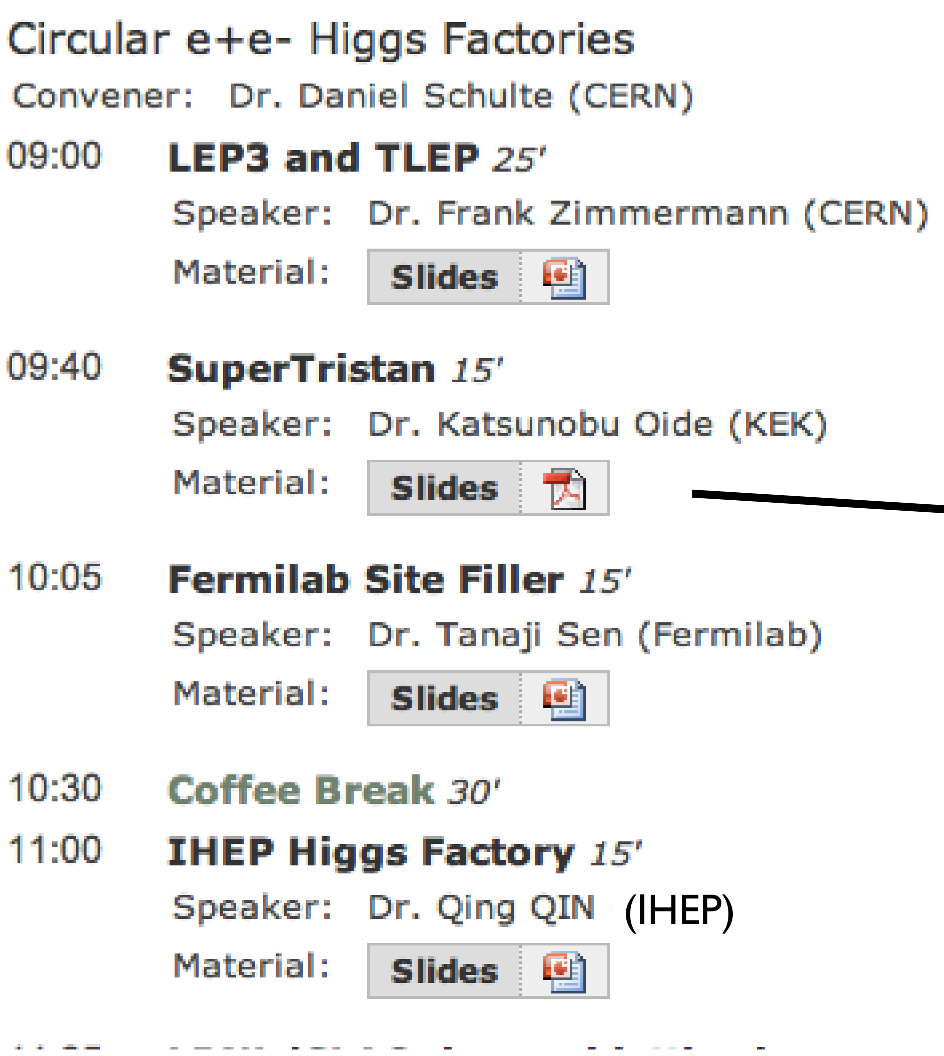

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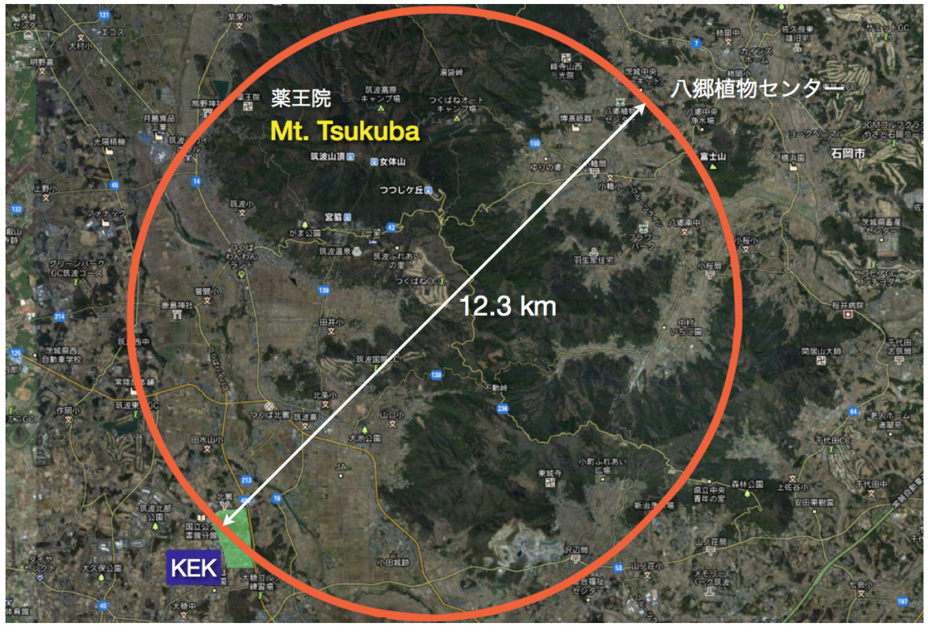

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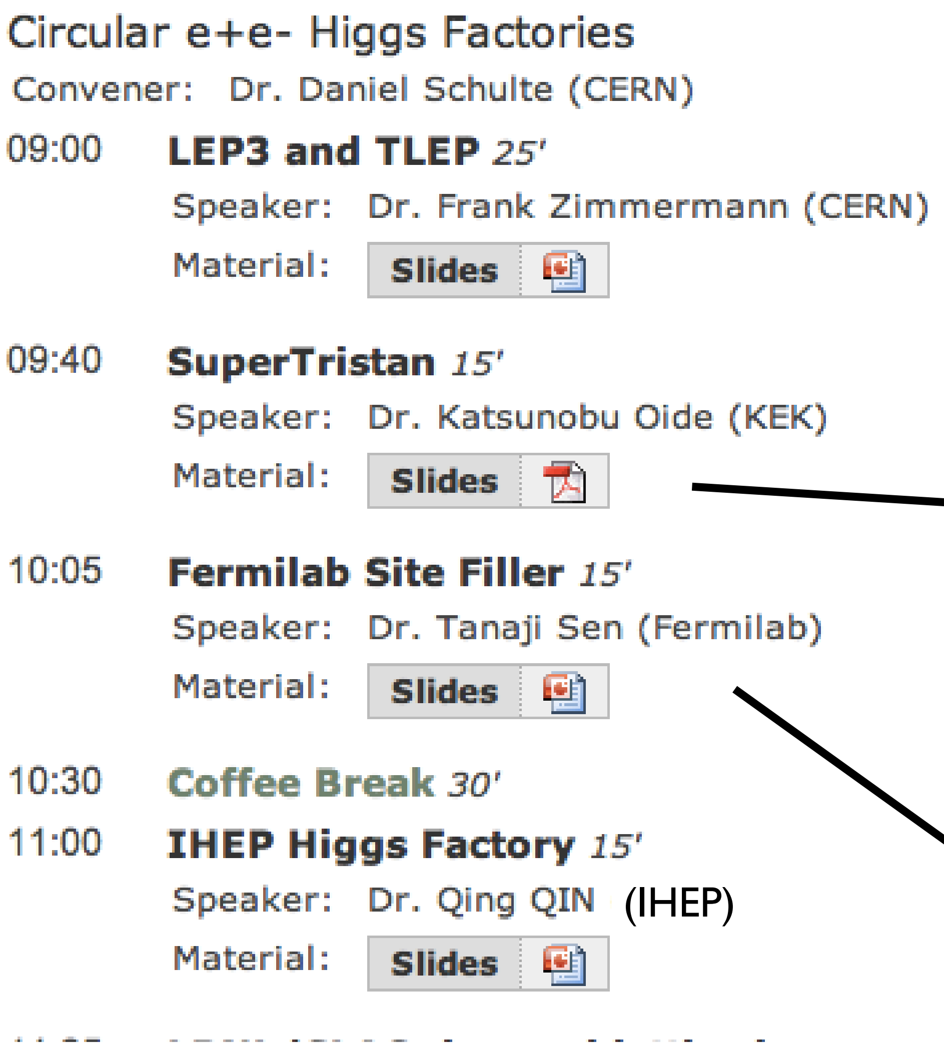

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Accelerators for a Higgs Factory: Linear vs. Circular (HF2012) (14-November 16, 2012)

indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=5775

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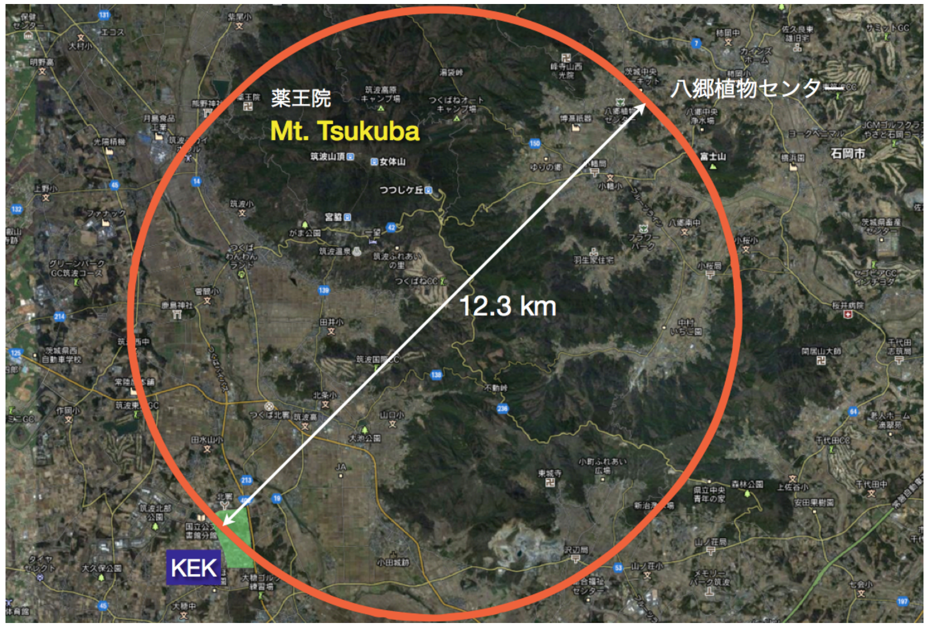

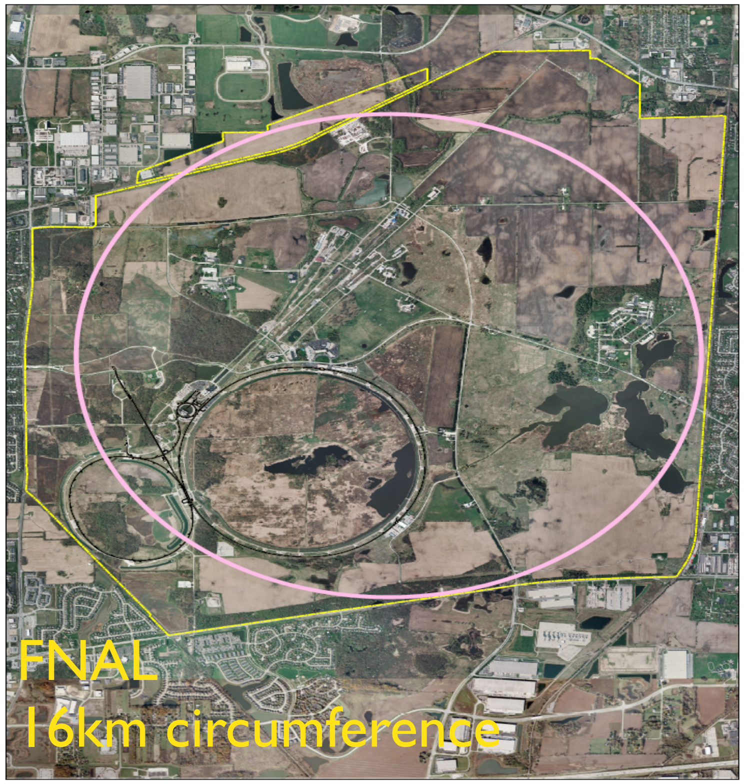

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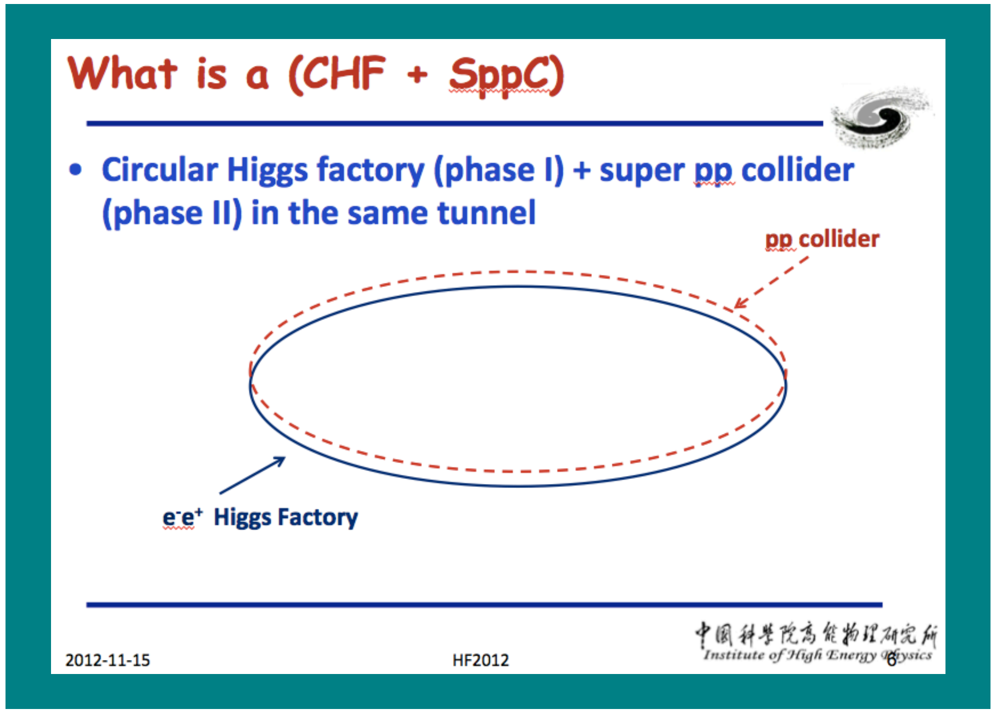
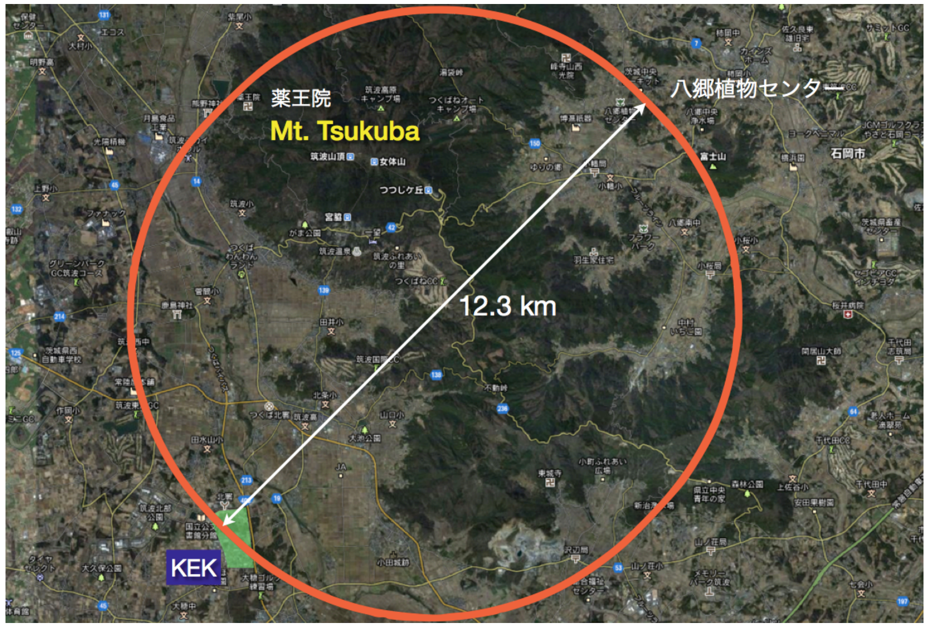


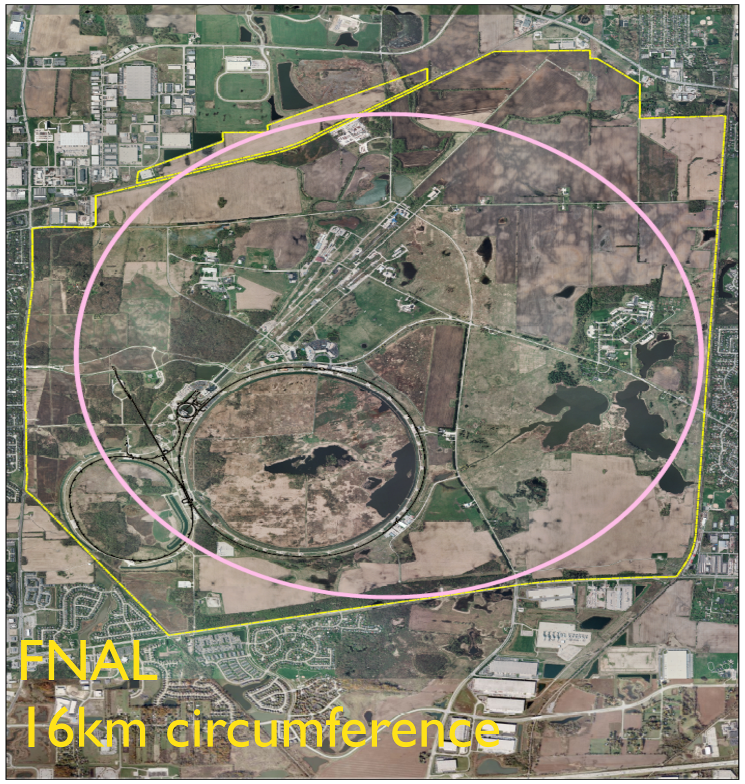
What is a (CHF + SppC)

- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel

2012-11-15 HF2012 6

中國科學院高能物理研究所
Institute of High Energy Physics

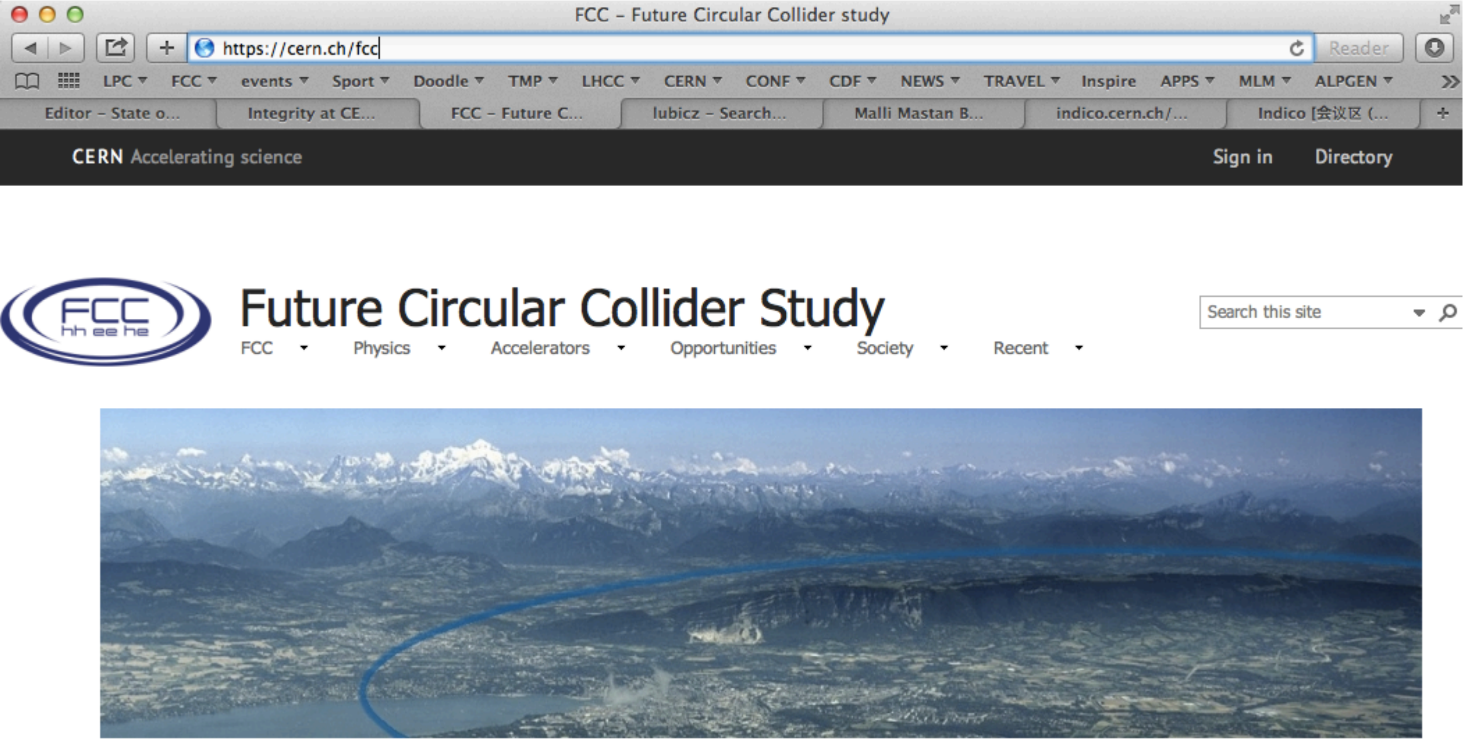




Final report:
http://www-bd.fnal.gov/icfabd/HF2012.pdf

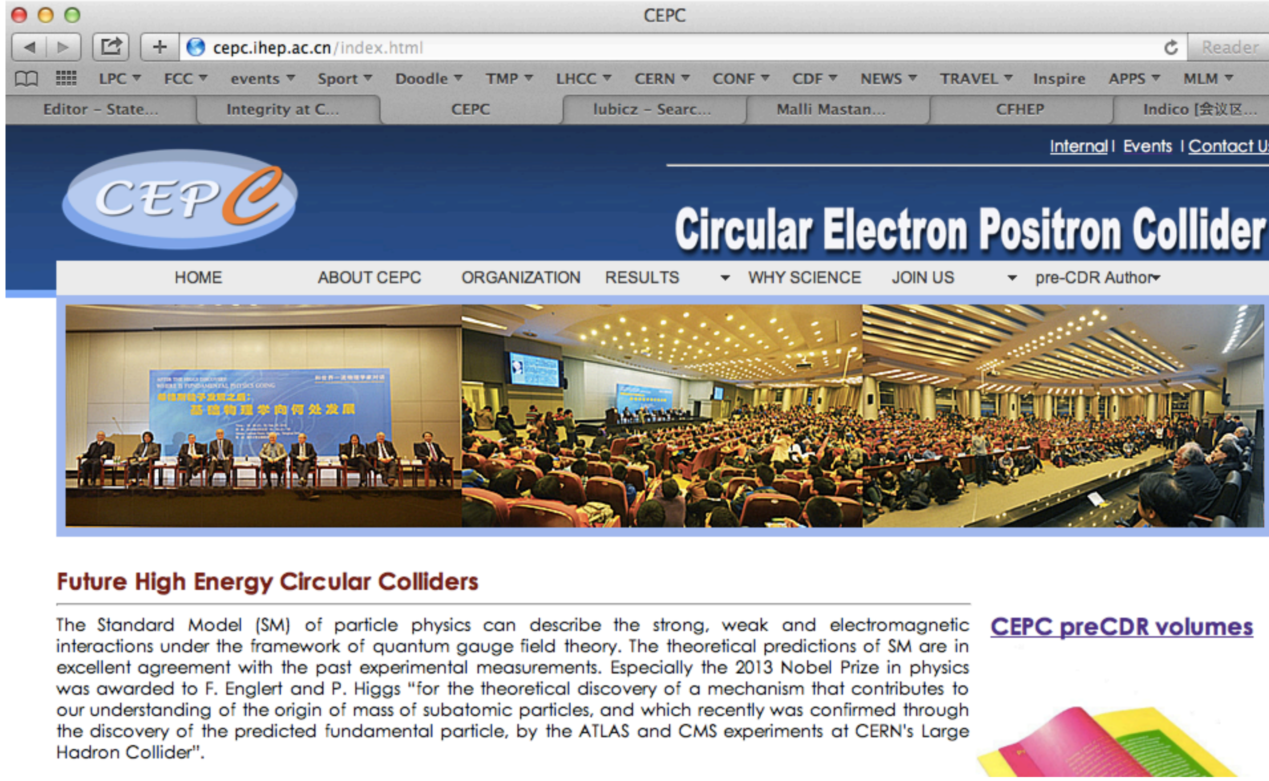
# *… and two efforts are formalized and develop into studies towards Conceptual Design Reports*

http://cern.ch/fcc



Future Circular Collider Study

http://cepc.ihep.ac.cn



**Future High Energy Circular Colliders**

The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. Especially the 2013 Nobel Prize in physics was awarded to F. Englert and P. 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".

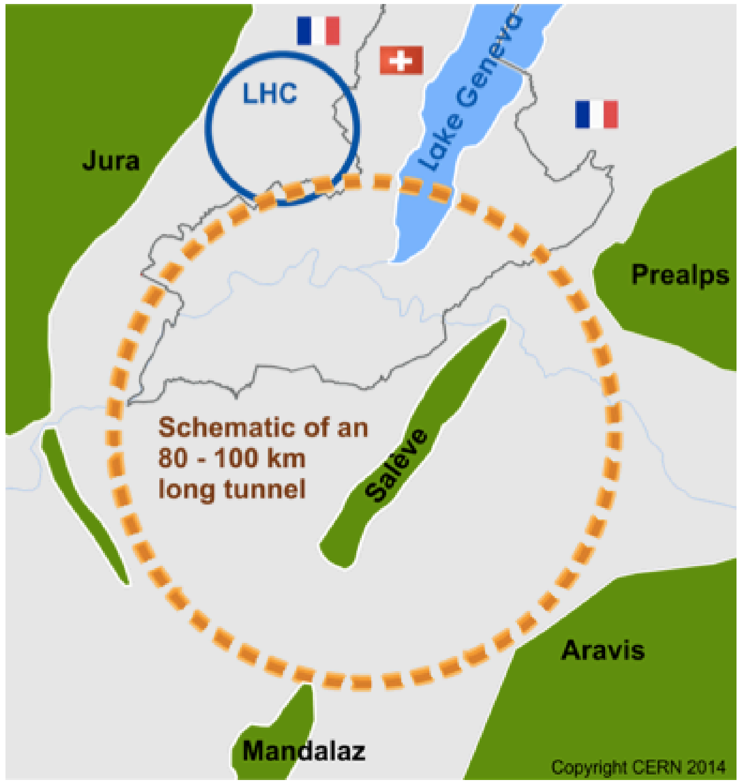
CEPC preCDR volumes

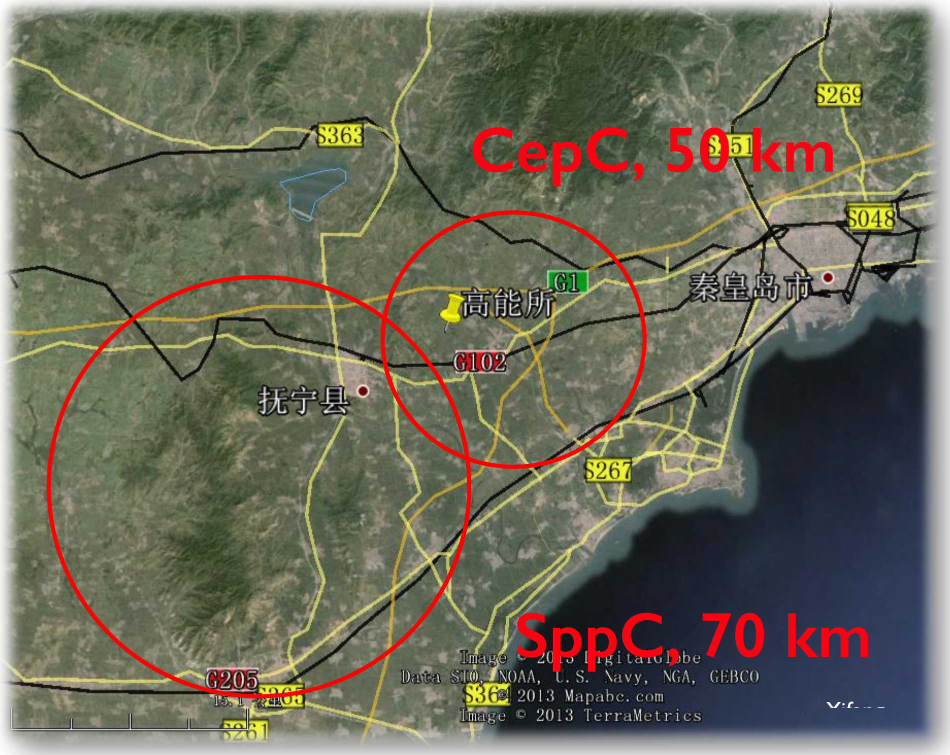
**Forming an international collaboration to study:**

- *pp*-collider (*FCC-hh*)
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- $e^+e^-$ collider (*FCC-ee*) as potential intermediate step
- *p-e* (*FCC-he*) option
- 80-100 km infrastructure in Geneva area





# *Key goals of a future circular collider complex*

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*Fulfilling these goals will also require dedicated attention to crucial ingredients, such as*

- *the progress of theoretical calculations for precision physics*
- *the experimental data needed to improve the knowledge of fundamental inputs such as SM parameters, PDFs and to assess/ reduce theoretical systematics*
  - *relevance of running* $e^+e^-$ *at Z pole and tt threshold*
  - *relevance of ep programme*

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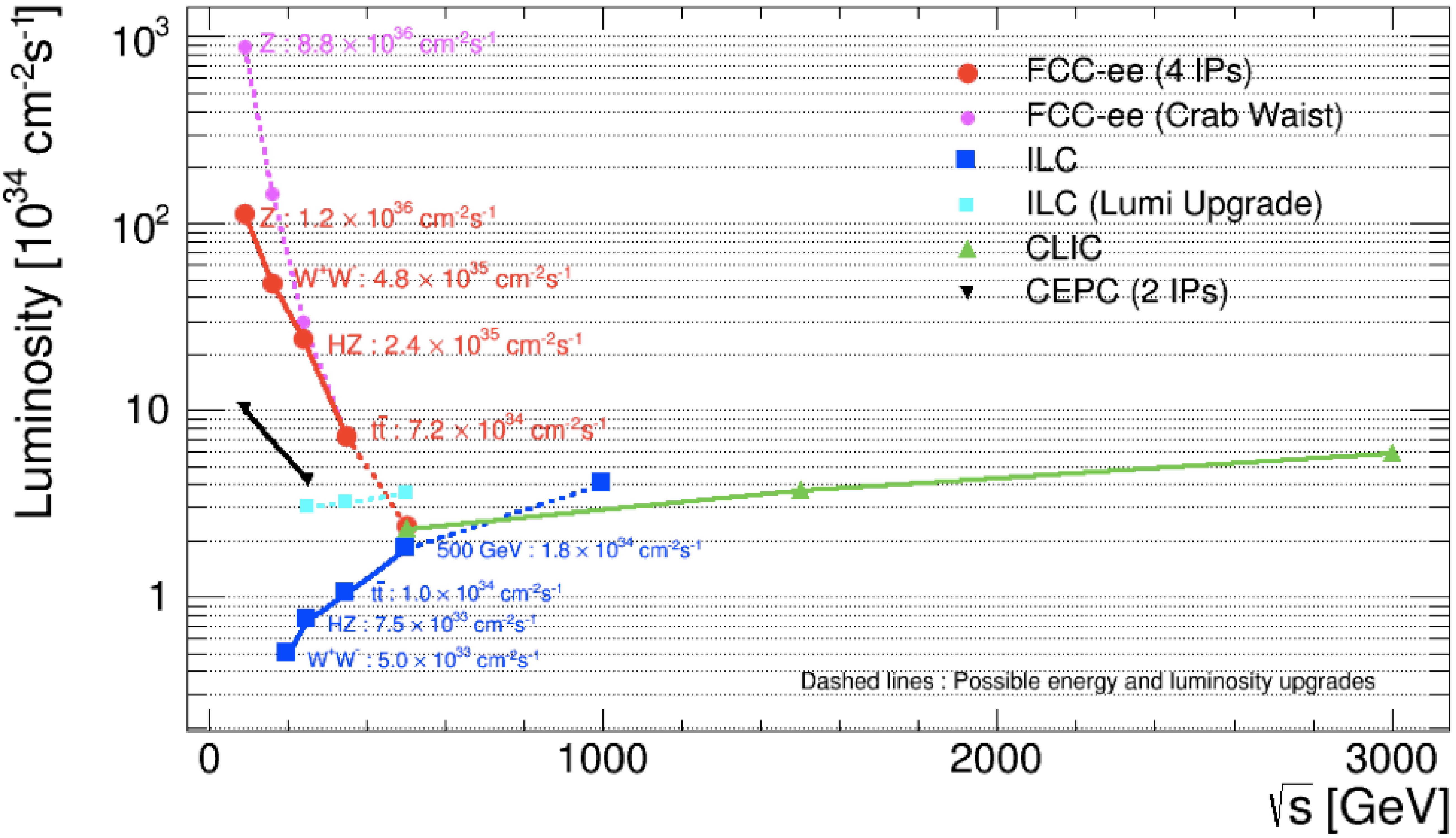
- Maximal exploitation of the facility, including
  - *physics with heavy ion collisions*
  - *physics with the injector complex*

# FCC-ee energy and lum goals



# FCC-hh parameters and lum goals

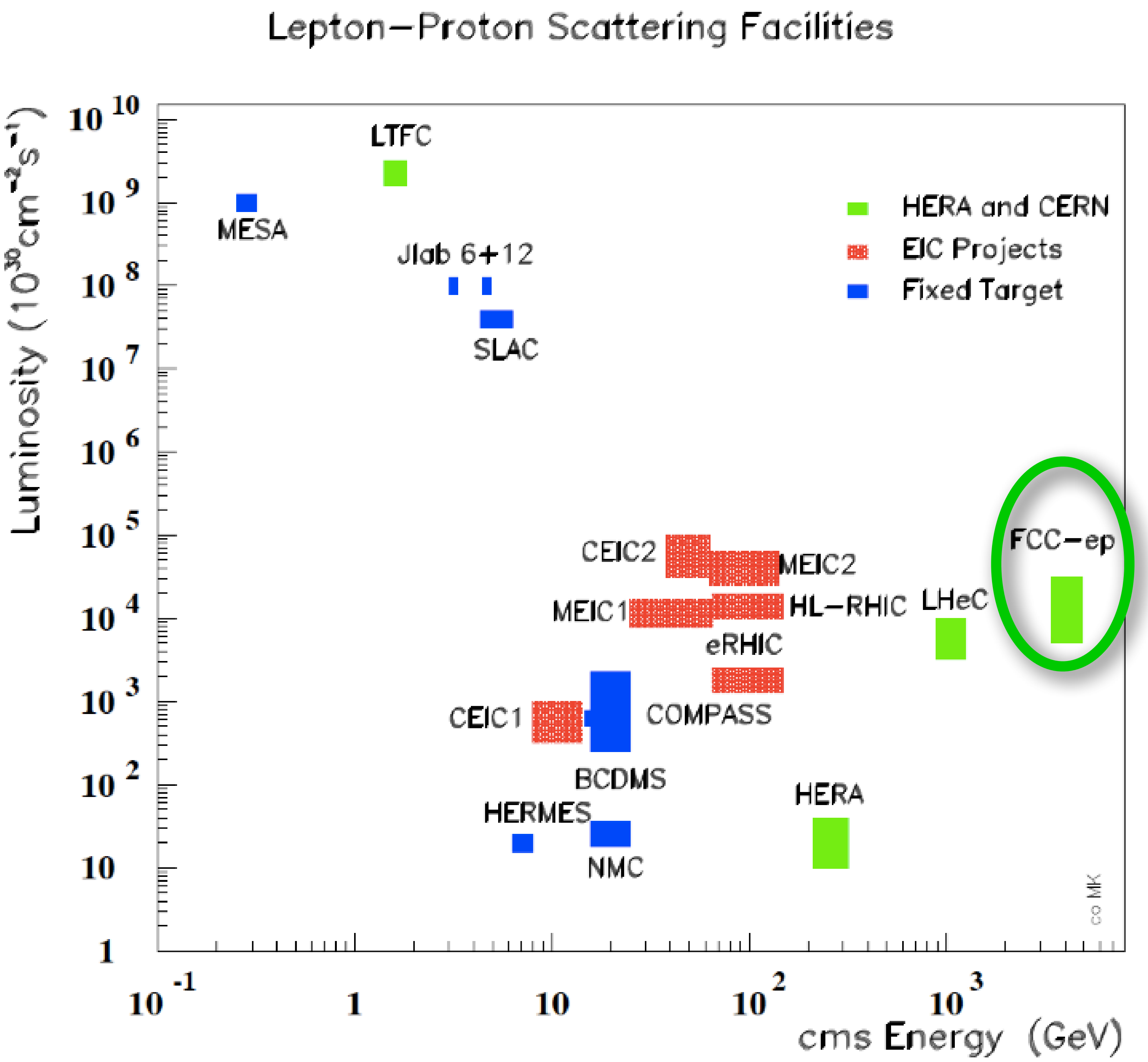
| Parameter | FCC-hh | LHC |
|---|---|---|
| Energy [TeV] | 100 c.m. | 14 c.m. |
| Dipole field [T] | 16 | 8.33 |
| # IP | 2 main, +2 | 4 |
| Luminosity/IP$_{main}$ [cm$^{-2}$s$^{-1}$] | 5 - 25 x $10^{34}$ | 1 x $10^{34}$ |
| Stored energy/beam [GJ] | 8.4 | 0.39 |
| Synchrotron rad. [W/m/aperture] | 28.4 | 0.17 |
| Bunch spacing [ns] | 25 (5) | 25 |

- **Phase 1 (baseline): 5 x $10^{34}$ cm$^{-2}$s$^{-1}$ (peak),**
  250 fb$^{-1}$/year (averaged)
  2500 fb$^{-1}$ within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x $10^{35}$ cm$^{-2}$s$^{-1}$ (peak),**
  1000 fb$^{-1}$/year (averaged)
  ➔ 15,000 fb$^{-1}$ within 15 years

- **Yielding total luminosity O(20,000) fb$^{-1}$ over ~25 years of operation**

# FCC-eh parameters and lum goals



175 GeV e- beam from FCC-ee and 50 TeV p beam from FCC-hh
Highest centre-of-mass energy ep collider, ~6 TeV
Luminosity ~$10^{34}cm^{-2}s^{-1}$

# Reference literature

- **FCC-ee**:
  - "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
  - "High-precision αs measurements from LHC to FCC-ee", arXiv:1512.05194
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: *"Physics at 100 TeV"*, Report, 5 chapters:
  - SM processes, arXiv:1607.01831
  - Higgs and EWSB studies, arXiv:1606.09408
  - BSM phenomena, arXiv:1606.00947
  - Heavy Ions at the FCC, arXiv:1605.01389
  - Physics opportunities with the FCC injectors, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider
- **CEPC/SPPC**: Physics and Detectors pre-CDR completed, see:
  - http://cepc.ihep.ac.cn/preCDR/volume.html

See also:

- Physics Briefing Book to the European Strategy Group (ESG 2013)
- Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 3: Energy Frontier, arXiv:1401.6081
- N. Arkani-Hamed, T. Han, M. Mangano, and L.-T. Wang, Physics Opportunities of a 100 TeV pp Collider, arXiv:1511.06495

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**~700 pages**

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- The BSM-search progamme relies on a complex and multidimensional programme of SM and QCD dynamics measurements, that will grow in parallel with the increase in luminosity and with the progress in the searches
- As a possible complement to the mature ILC and CLIC projects, plans are underway to define the possible continuation of this programme after the LHC, with the same goals of thoroughness, precision and breadth that inspired the LEP/LHC era