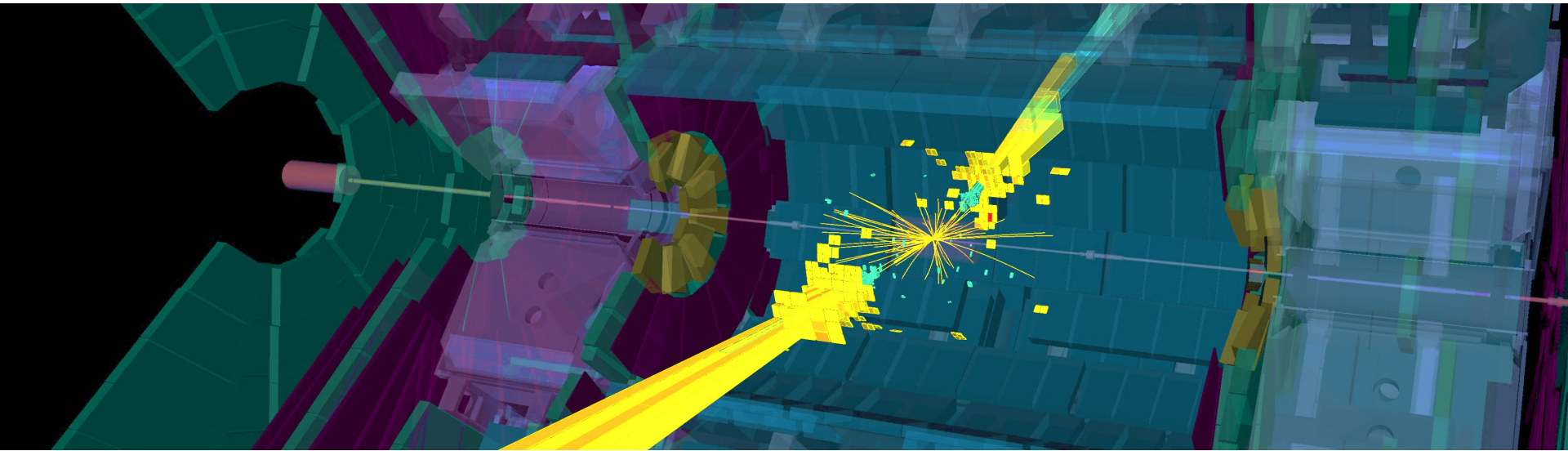


Daybreak at the LHC — what we learned from the 13 TeV data so far



Andreas Hoecker (CERN)

Israeli Physical Society Meeting, Technion, December 17th, 2017

The ATLAS Lol was presented to the LHCC on 5th Nov 1992

ATLAS

Letter of Intent for a General-Purpose pp Experiment at the LHC

Introduction and overview

- general concept
- magnet systems
- integration and radiation
- costs

Detector subsystems, R&D and expected performance

- calorimetry
- inner detector
- muon detector
- trigger and DAQ

Physics performance

ATLAS Collaboration

Alberta, Alma Ata, NIKHEF Amsterdam, LAPP Annecy, Athens, NTU Athens, UA Barcelona, Bern, Birmingham, Bratislava, Cambridge, CERN, Clermont-Ferrand, NBI Copenhagen, Cosenza, INP Cracow, IPNT Cracow, Debrecen, Dortmund, JINR Dubna, Edinburgh, Florence, Frascati, Freiburg, Geneva, Glasgow, ISN Grenoble, Technion Haifa, Hamburg, Heidelberg, SEFT Helsinki, Innsbruck, Jena, Kobe, Kosice, Lancaster, Lisbon, Liverpool, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPM Marseille, Melbourne, Milano, Montreal, ITEP Moscow, Lebedev Moscow, MEPhI Moscow, MSU Moscow, Munich, MPI Munich, Nijmegen, LAL Orsay, Oslo, Oxford, Paris VI and VII, Pavia, Pisa, Prague, IHEP Protvino, COPPE Rio de Janeiro, Rome I and II, Rutherford Appleton Laboratory, DAPNIA Saclay, CST Saratov, Sheffield, Siegen, LITMO St. Petersburg, NPI St. Petersburg, Stockholm, MSI Stockholm, Ansto Sydney, Tel-Aviv, Tokyo, Uppsala, Valencia, UBC Vancouver, Victoria, Vienna, Warsaw, Weizmann Rehovot, Wuppertal

(88 Institutions with about 850 authors on Lol)

Spokespersons: F. Dydak and P. Jenni

Experimental particle physics has come a long way...



Event shows tracks produced in the 1200 litre Gargamelle bubble chamber that provided the first confirmation of a neutral current interaction (image: CERN)

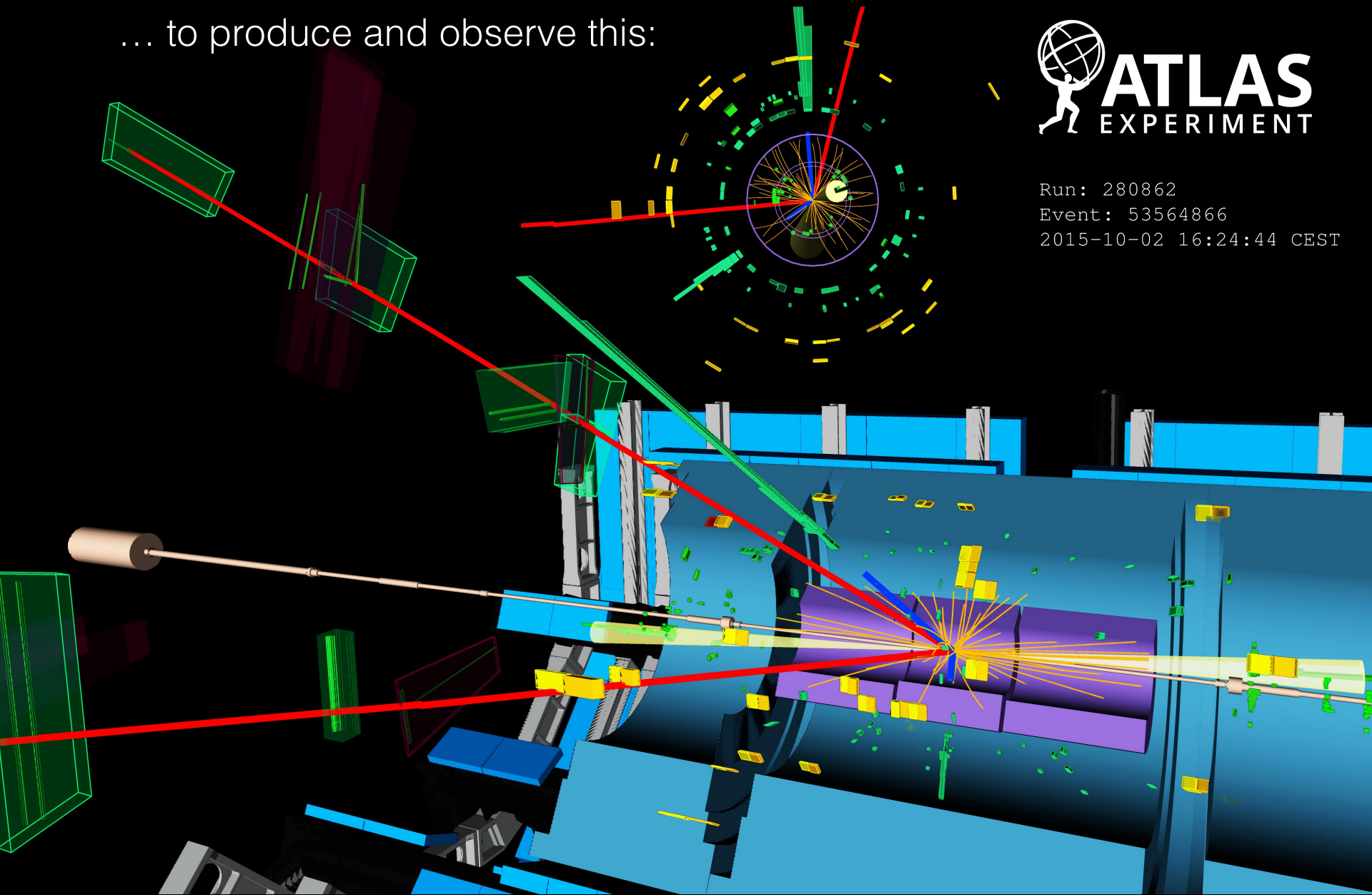
... to produce and observe this:



Run: 280862

Event: 53564866

2015-10-02 16:24:44 CEST



Display of VBF $H \rightarrow ee\mu\mu + 2\text{jets}$ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the dielectron (dimuon) invariant mass is 91 (29) GeV, the pseudorapidity difference between the two jets is 6.4 and the dijet invariant mass is 2 TeV.

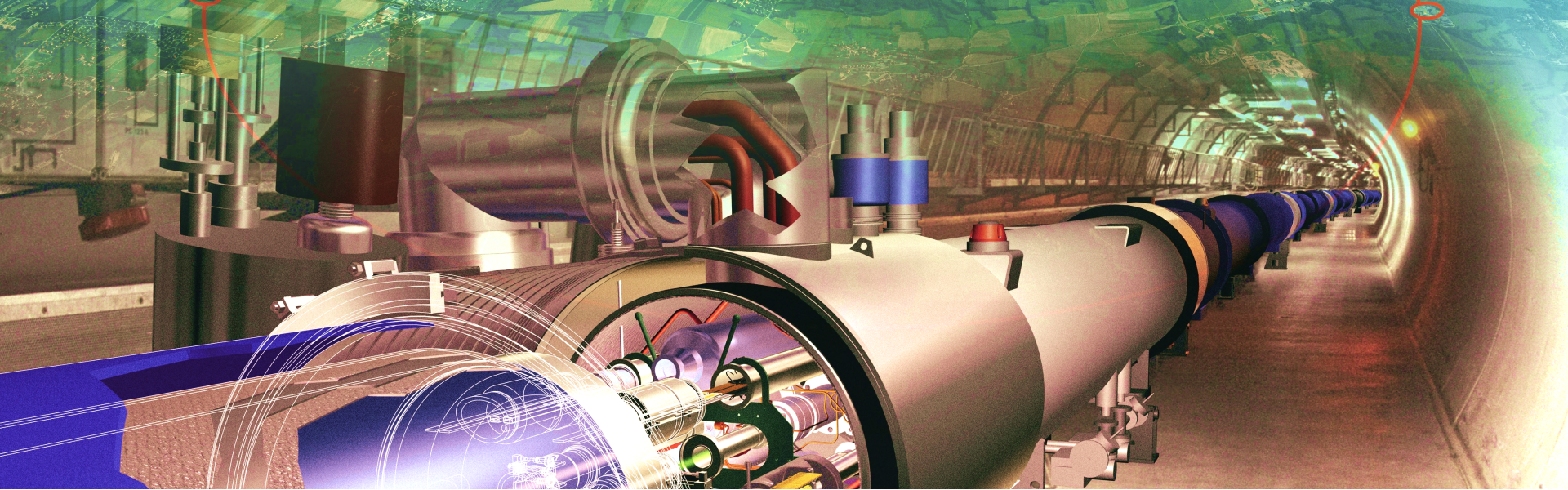
... and this:

Run: 329716
Event: 857582452
2017-07-14 10:48:51 CEST



ATLAS
EXPERIMENT

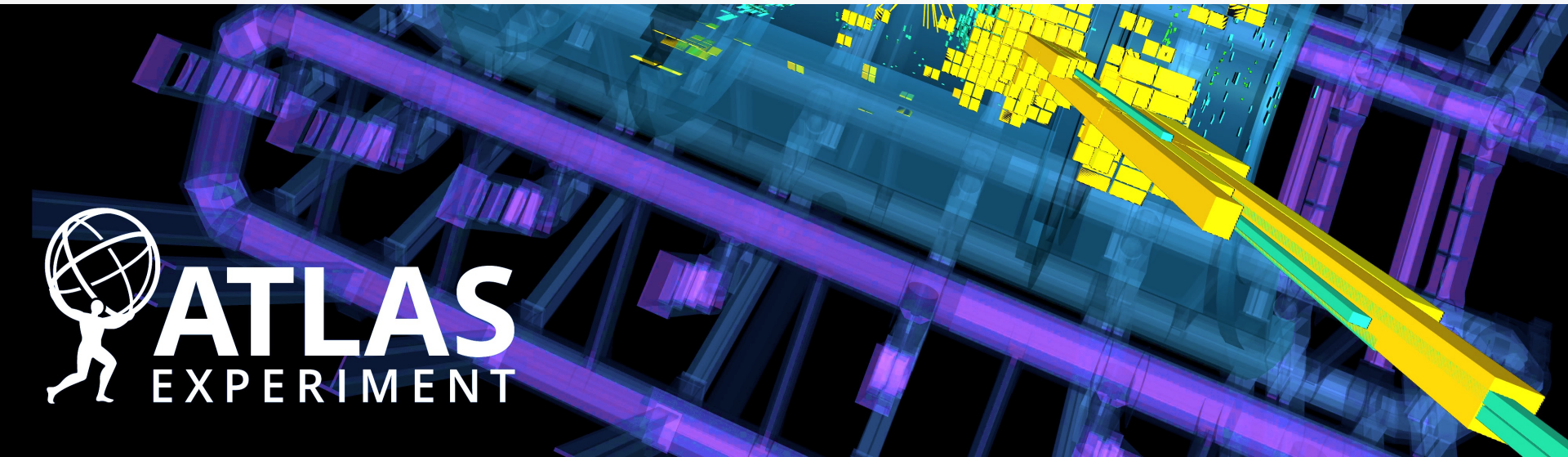
Display of *huge* di-jet event with $m_{jj}=9.3$ TeV, produced in pp collisions at $\sqrt{s} = 13$ TeV in 2017. The two high- p_T jets both have $p_T=2.9$ TeV, one is at $\eta=-1.2$ and the other at $\eta=0.9$.



Producing the Higgs Boson and Searching for New Physics
at the TeV Scale Requires a Huge Machine



ATLAS
EXPERIMENT



Superconducting proton/ion accelerator and collider installed in a 27 km circumference underground tunnel (4 m tunnel cross-section diameter)

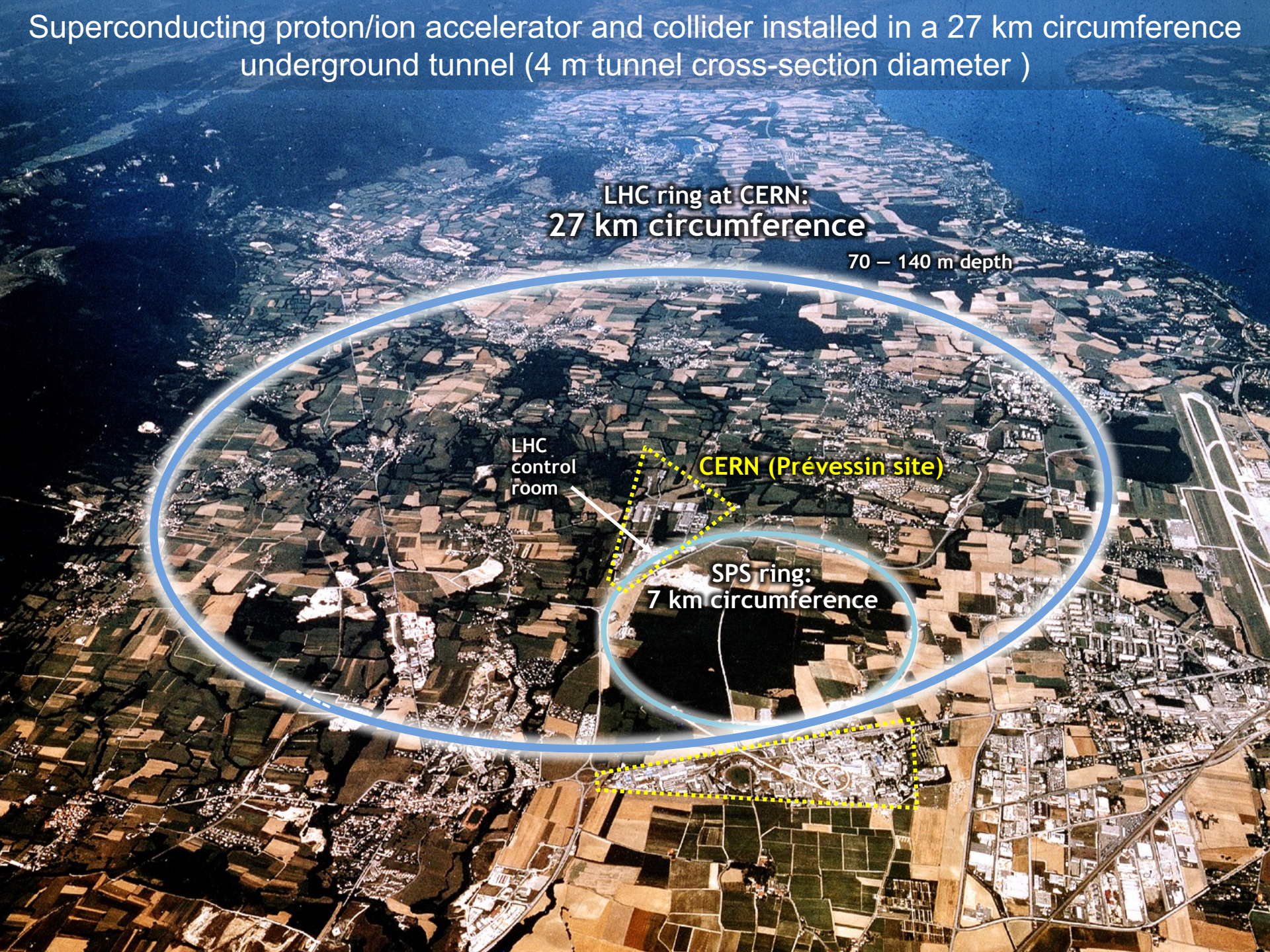
LHC ring at CERN:
27 km circumference

70 – 140 m depth

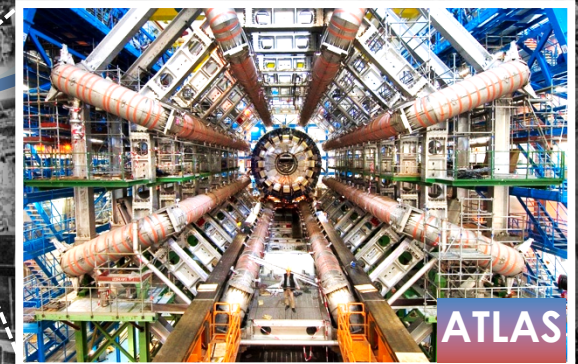
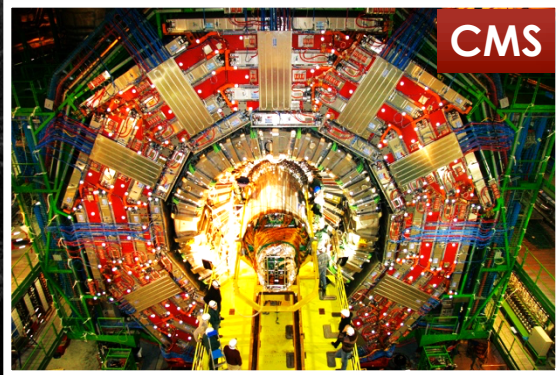
LHC
control
room

CERN (Prévessin site)

SPS ring:
7 km circumference



ATLAS & CMS: giant, ultra sophisticated general purpose particle detectors



Luminosity — single most important quantity

- Luminosity drives our ability to detect low cross-section processes

$$N_{\text{events}}^{\text{obs}} = \text{cross section} \times \text{efficiency} \times \int L \cdot dt$$

“Cross section” given by Nature

“Efficiency” of detection optimised by experimentalist

Integrated luminosity delivered by LHC

- Luminosity is a function of the LHC beam parameters

$$L = \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{4\pi \sigma_x \sigma_y} \cdot R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

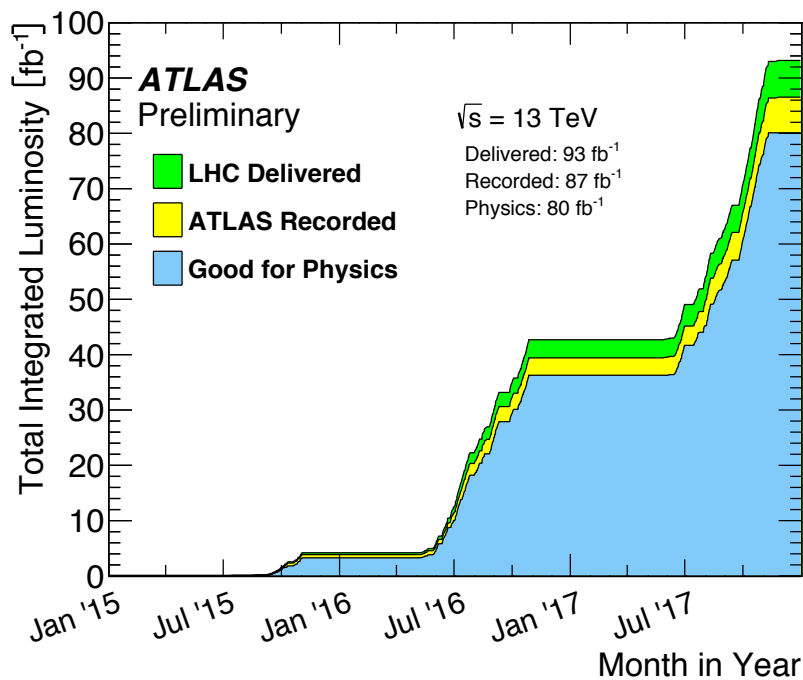
Reduction factor

Crossing angle (0.3 mrad) and
“hourglass effect” ($\sigma_z \sim 4\text{--}6\text{ cm}$)

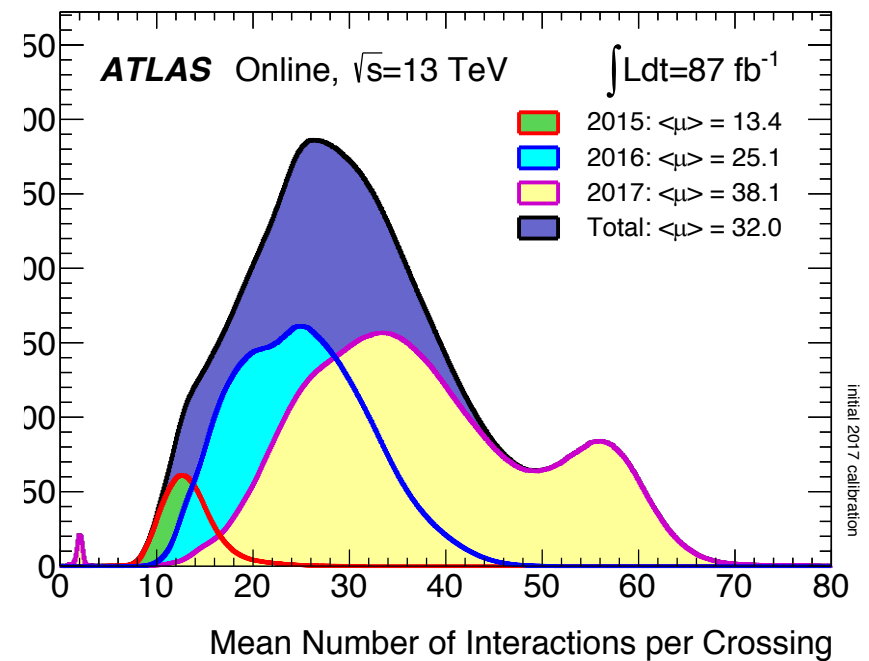


Luminosity — single most important quantity

Integrated delivered luminosity since 2011



High-luminosity comes with a challenge



Total of 93 fb⁻¹ delivered at $\sqrt{s} = 13$ TeV during LHC Run-2, 80 fb⁻¹ good for physics in ATLAS

The Higgs boson

Run-1 magnus opum

The SM predicts all its properties, except for its mass

Full references for mechanism:

F. Englert and R. Brout, PRL 13 (1964) 321.

P.W. Higgs, PRL 13 (1964) 508.

G. Guralnik, C. Hagen, and T.W.B. Kibble, PRL 13 (1964) 585.

It should be noted that Landau and Ginzburg had proposed a field giving the photon a mass in a superconductor, the mathematics of which is identical to the "Higgs mechanism" and predates it by several years.

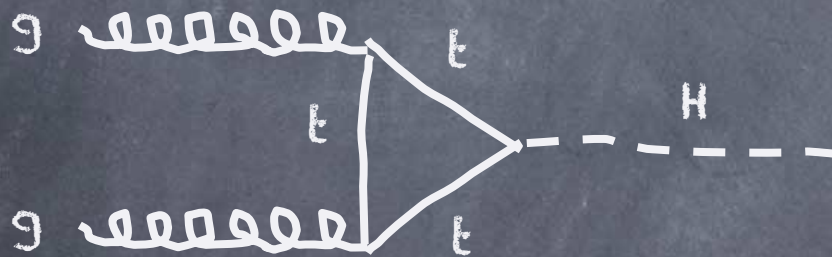


<http://www.shardcore.org/shardpress>

Higgs boson production at the LHC

At the LHC, the Higgs boson is dominantly produced via gluon fusion for $\sigma_{H,\text{total}} = 56 \text{ pb}$ at $\sqrt{s} = 13 \text{ TeV}$ for $m_H = 125 \text{ GeV}$

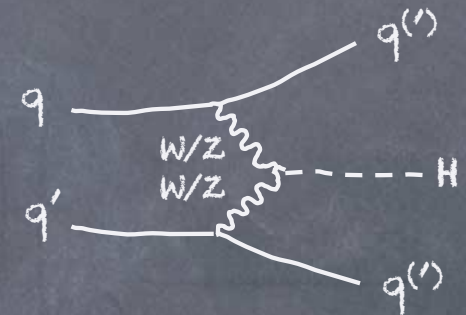
Cross section steeply falling with Higgs mass



$\sigma_{H,\text{ggF}} \sim 49 \text{ pb}$ at 13 TeV

Total production of almost 6 million SM Higgs bosons of 125 GeV by today in each ATLAS and CMS

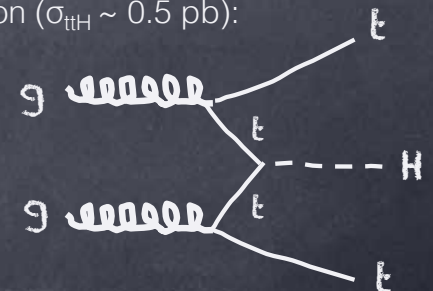
Weak boson fusion ($\sigma_{W/Z+H} \sim 3.8 \text{ pb}$):



Higgs-strahlung ($\sigma_{W/Z+H} \sim 1.4/0.9 \text{ pb}$):



“ttH” production ($\sigma_{\text{ttH}} \sim 0.5 \text{ pb}$):

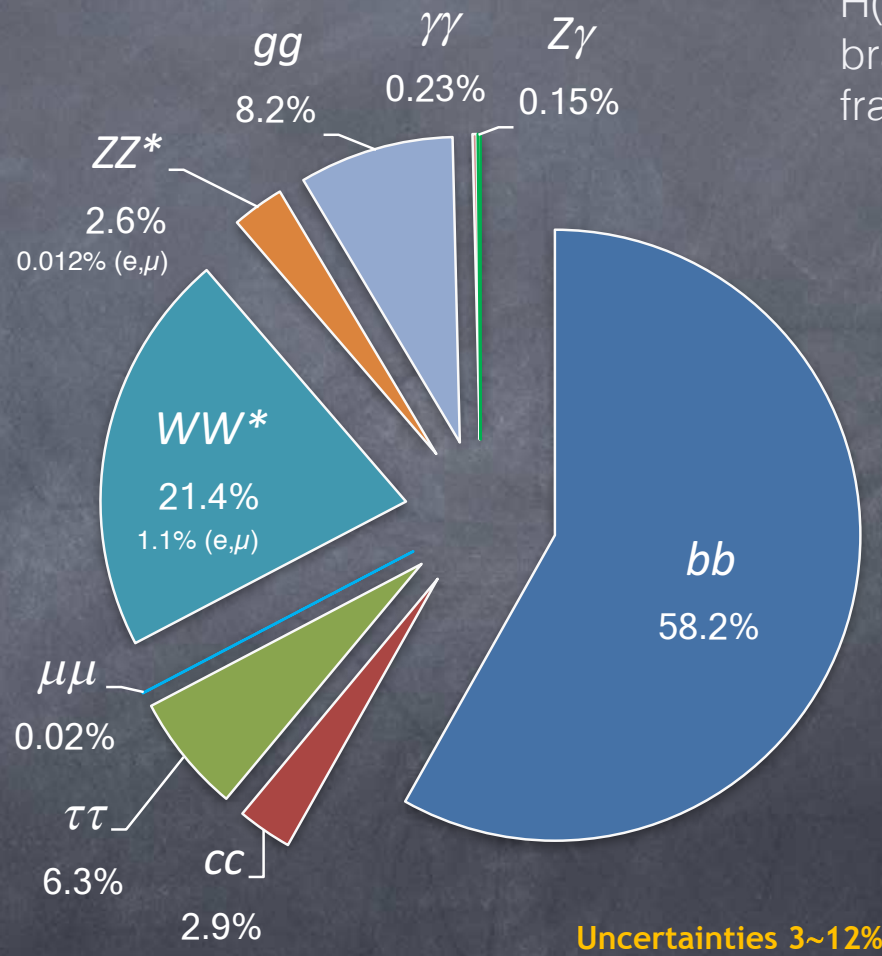


Higgs boson production at the LHC

Because of the coupling to the mass of the decay particles:

... the Higgs will decay with preference to the heaviest particles allowed

... the Higgs does not couple directly to photons and gluons, but only via “loops” involving preferentially heavy particles (e.g., top, W)



Combined ATLAS & CMS Higgs analysis and flurry of Higgs property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]

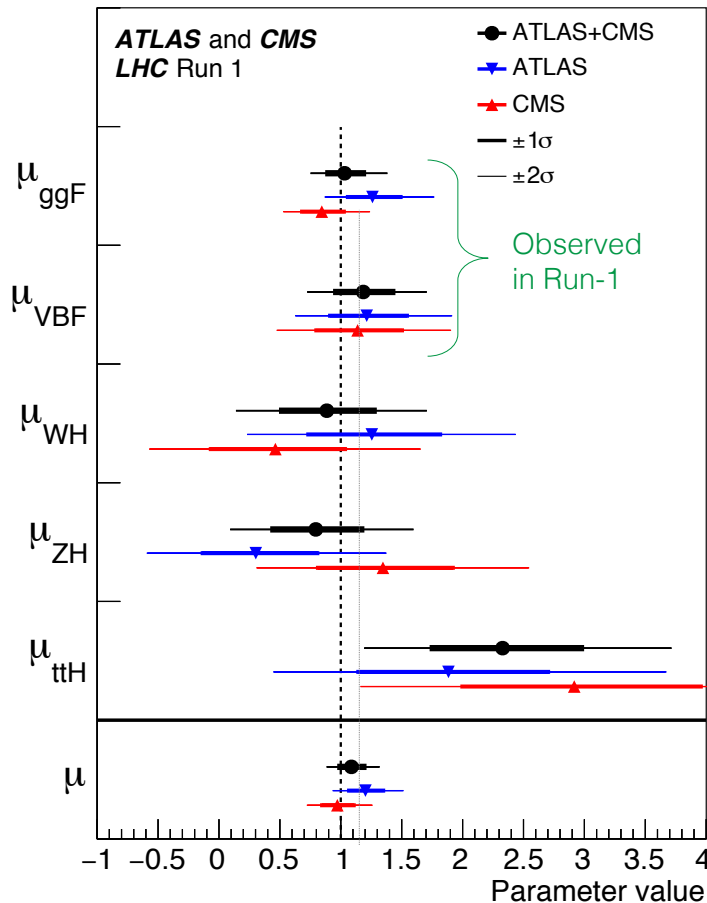
Agreement among experiments

Overall signal strength: $\mu = 1.09 \pm 0.11$

Precise mass combination (0.2%):

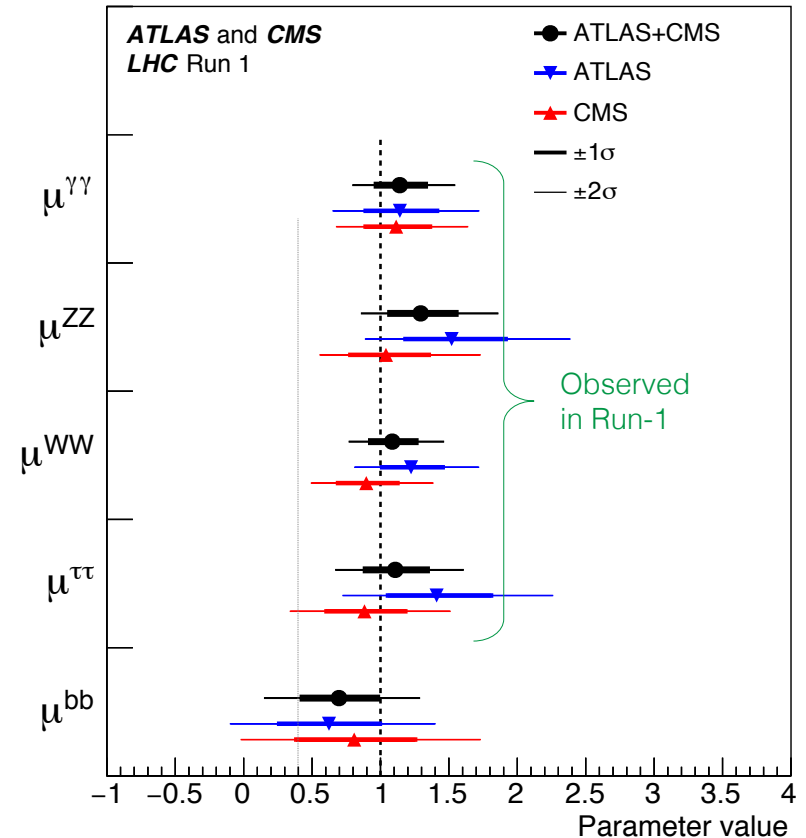
$$m_H = 125.09 \pm 0.21_{\text{stat}} \pm 0.11_{\text{syst}} \text{ GeV}$$

Higgs production processes



Note that the least model-dependent observables at the LHC are **ratios of couplings**

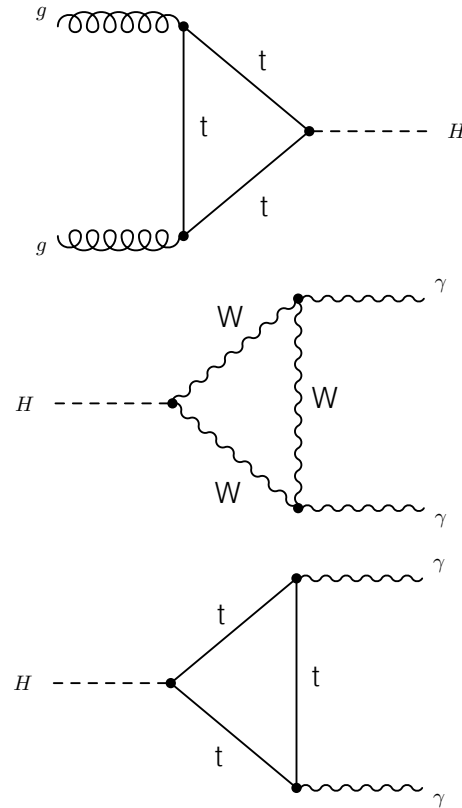
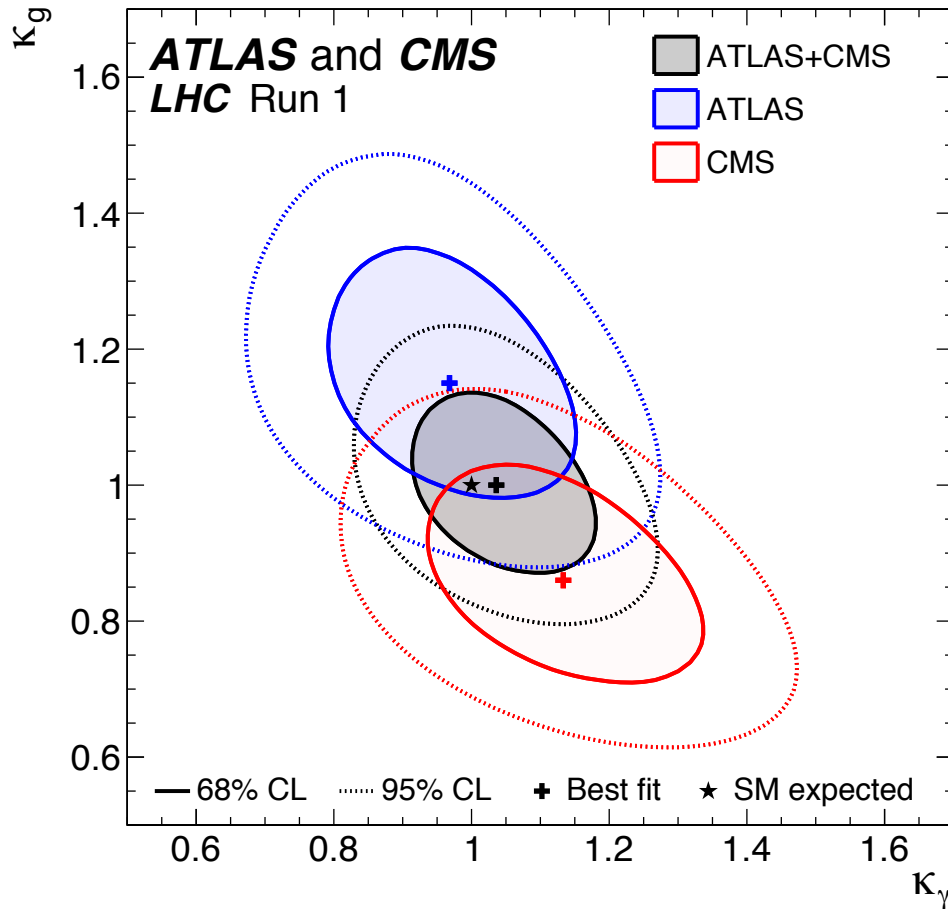
Higgs decay processes



Combined ATLAS & CMS Higgs analysis and flurry of Higgs property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]



Couplings to massless particles mediated by loops involving heavy particles

Powerful test for new physics (eg, excludes SM-like heavy 4th fermion generation)

The Higgs boson as a *portal* to beyond the SM physics

Higgs is narrow: 4.1 MeV

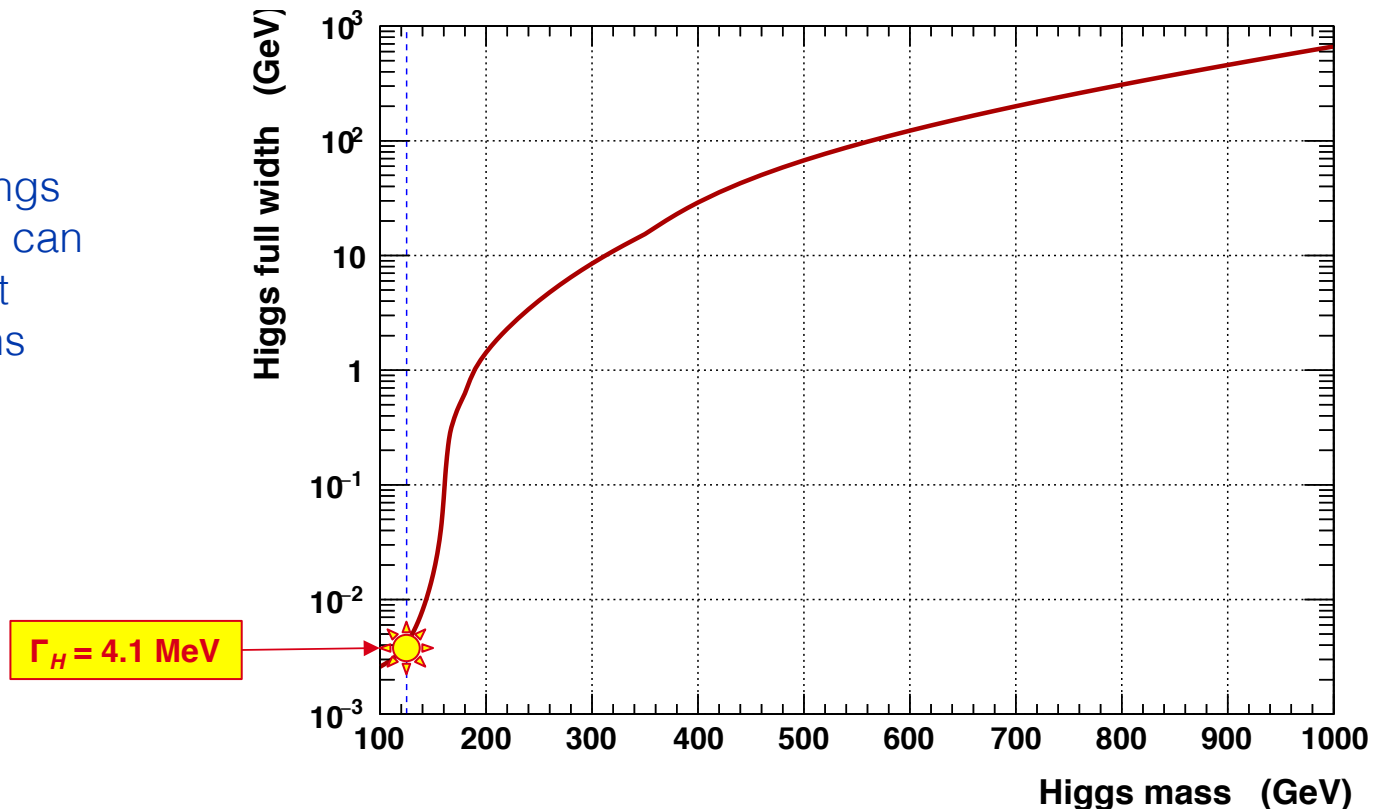
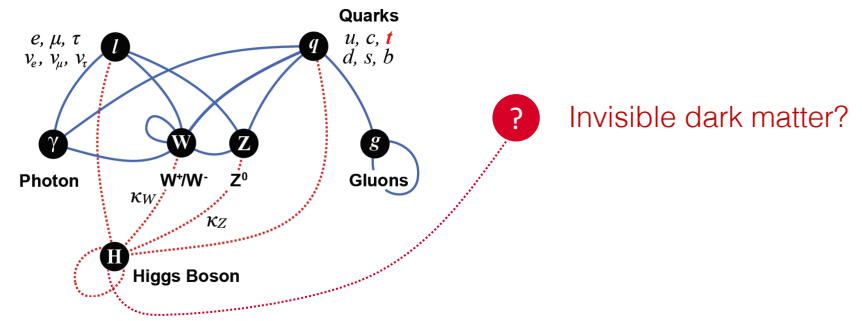
For comparison:

$$\Gamma_W = 2.1 \text{ GeV}$$

$$\Gamma_Z = 2.5 \text{ GeV}$$

$$\Gamma_{\text{top}} = 1.3 \text{ GeV}$$

Even small couplings
to new light states can
measurably distort
branching fractions



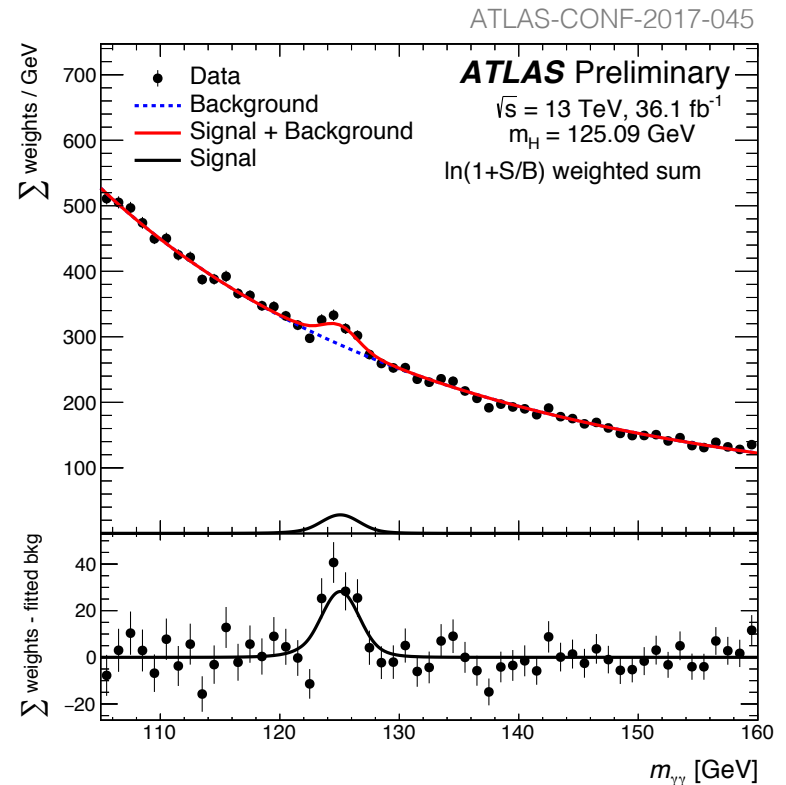
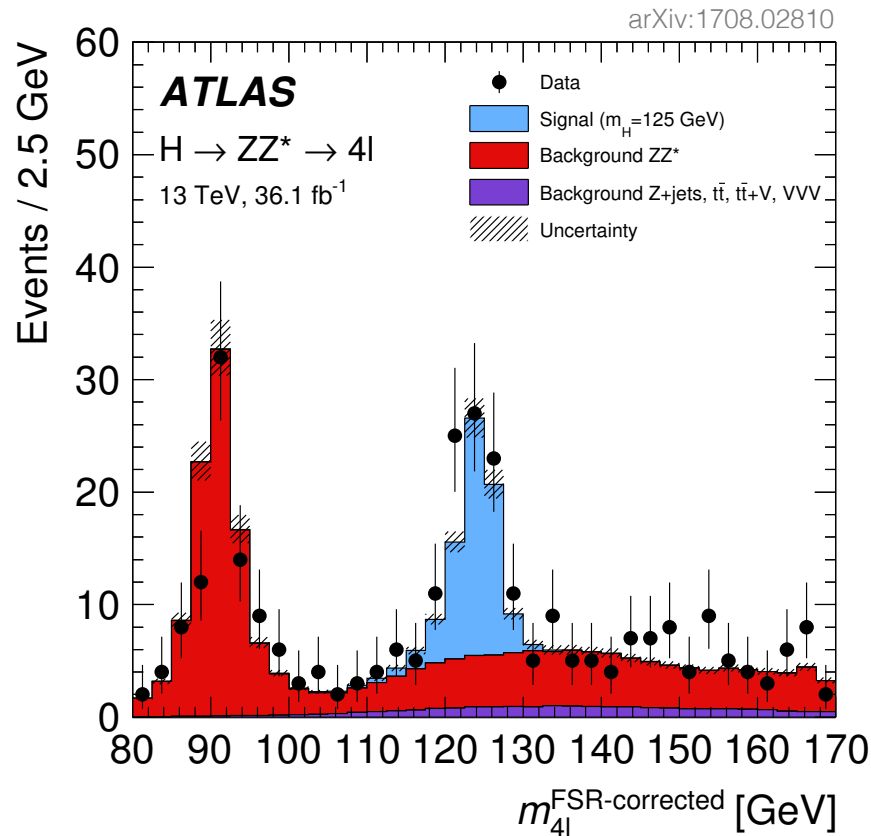
Higgs in the bosonic channels

Reobservation at 13 TeV and improved property measurements

ATLAS-CONF-2017-047

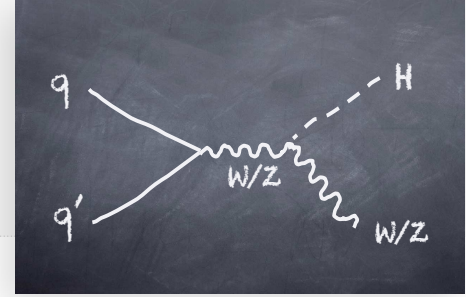
Combination of $\gamma\gamma$ and ZZ^* channels gives $\mu = 1.09 \pm 0.09_{\text{stat}} \pm 0.06_{\text{exp}} \pm 0.06_{\text{theo}}$

Combined measurement of Higgs mass: $124.98 \pm 0.28 \text{ GeV}$ (in agreement with Run-1 ATLAS & CMS)



Higgs in the fermionic channels

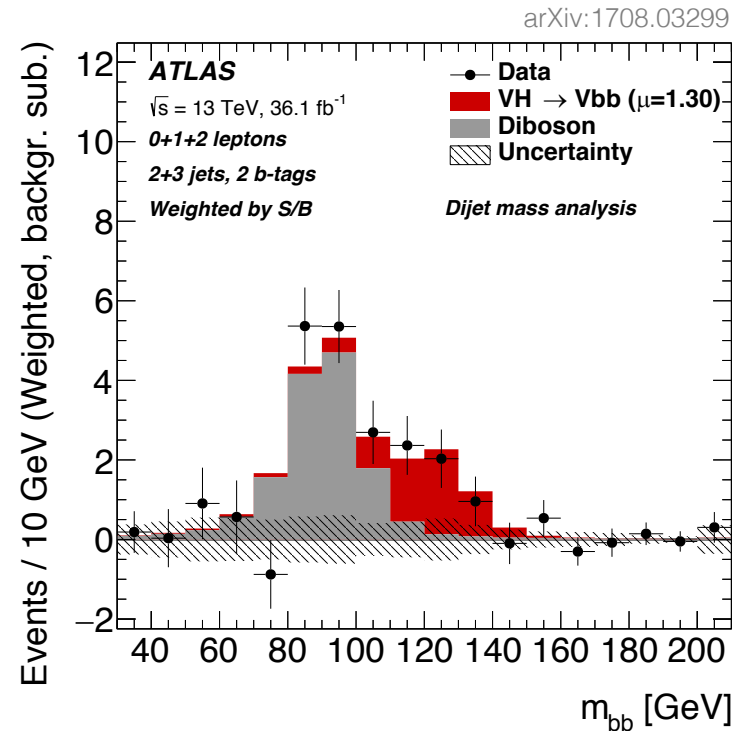
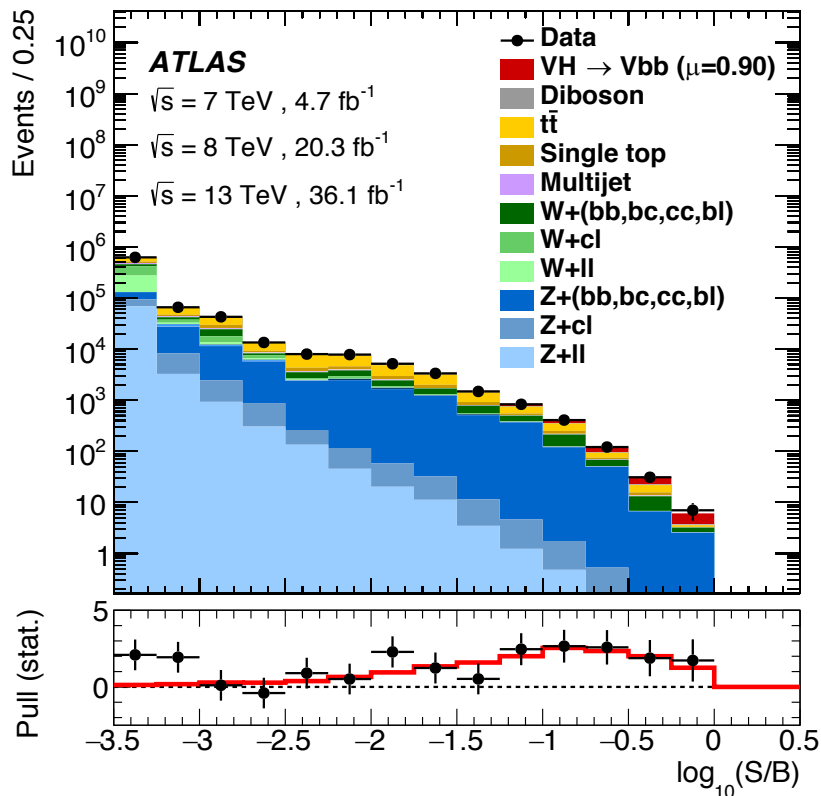
$H \rightarrow bb$ (BR: 58%), best channel: $W/Z+H \rightarrow 0$ (+MET), 1, 2 leptons + H



Extremely complex and challenging analysis yielding $H \rightarrow bb$ evidence at 3.6σ (4.0σ expected)

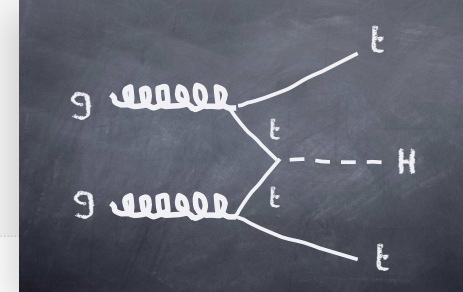
Powerful validation channel: $W/Z+Z(\rightarrow bb)$ observed at 5.8σ (5.3σ expected)

Analysis benefits from improved b-tagging due to new innermost Pixel layer (IBL)



$$\mu(VH(bb)) = 0.90^{+0.28}_{-0.26}$$

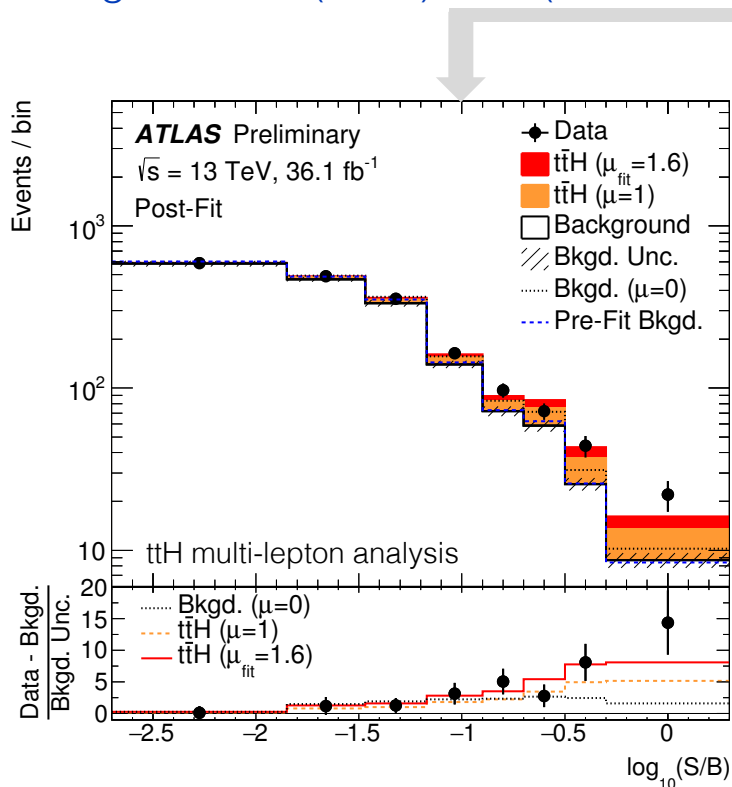
tt+H production directly probes Higgs–top coupling



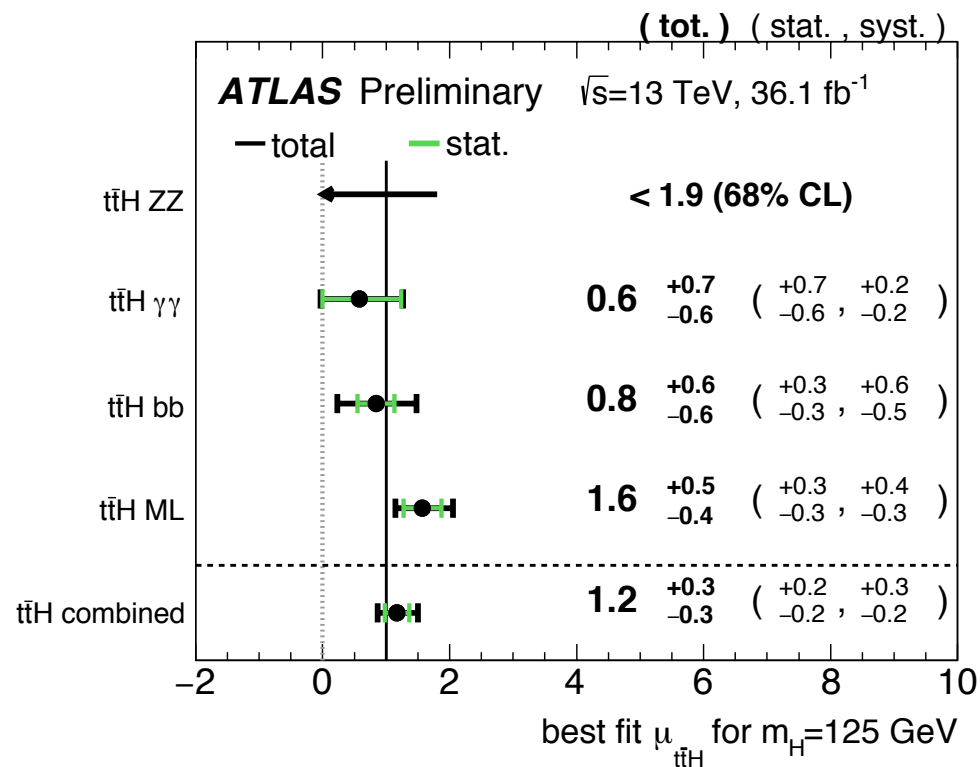
ATLAS-CONF-2017-076
ATLAS-CONF-2017-077

Combine large variety of final state depending on top and Higgs decays

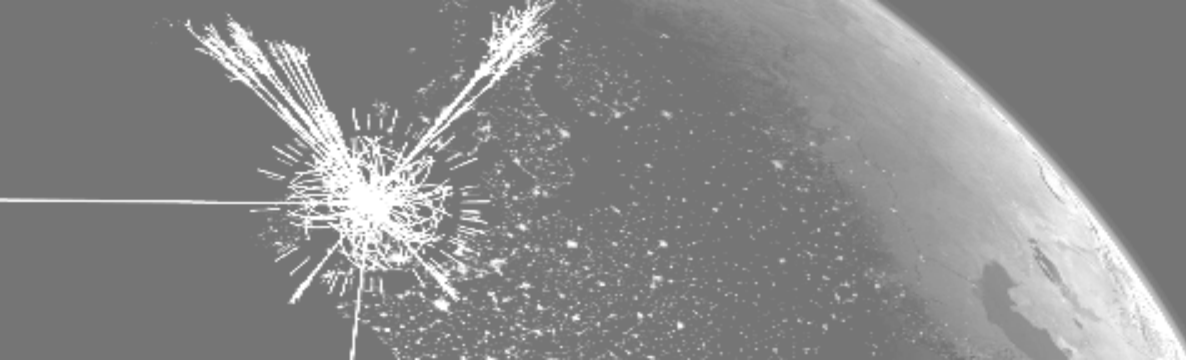
Distinguish: $tt+H(\rightarrow bb)$, $tt+H(\rightarrow WW^*, \tau\tau)$, $tt+H(\rightarrow \gamma\gamma)$, $tt+H(\rightarrow ZZ^*)$



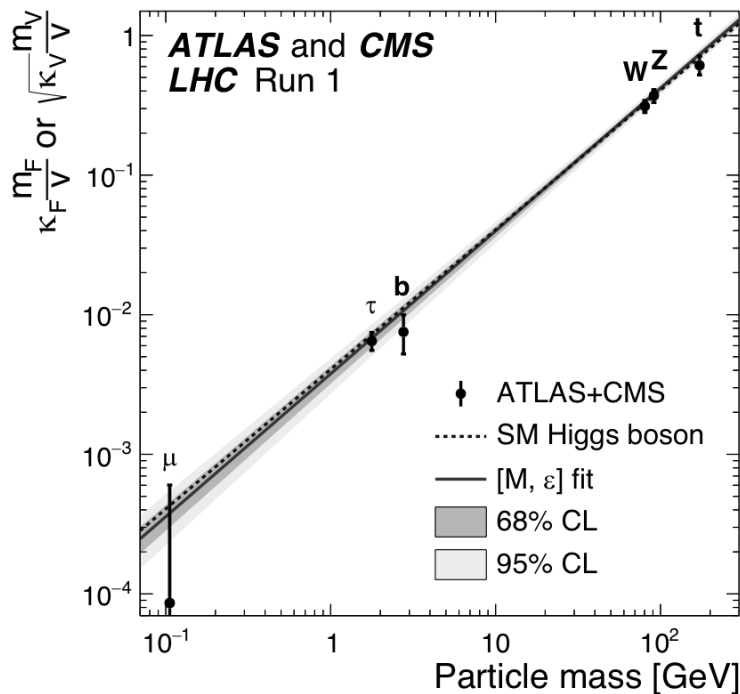
Heavy use of data-driven constraints
and multivariate classification



Run-2 combination yields **4.2 σ evidence**
(3.8 σ expected)



The Brout-Englert-Higgs mechanism is real !



The (mysterious) scalar sector of the SM is directly connected with profound questions of the SM: naturalness, vacuum stability and energy, flavour

The Higgs discovery allows us to directly study this sector, requiring a broad experimental programme that will extend over decades

The Standard Model

BEH mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

Symmetric phase – early universe

Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

Top quark 

The Standard Model

BEH mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

At a phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11}
s after big bang, causal domain of few cm)
the Higgs field displaces the ground state
breaking gauge symmetry

It fills all space time (but without orientation
as it has no spin)

Particles interact with Higgs field and
effectively reduce their velocity. Acquired
mass proportional to interaction strength

→ Action of the Higgs field
creates “vacuum viscosity”

Higgs quantum liquid in broken phase

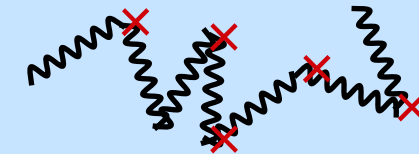
Gravity



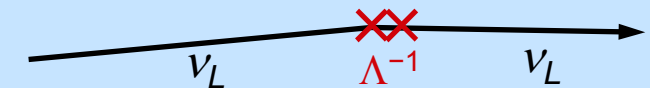
Photon



Weak boson



Neutrinos



Electrons

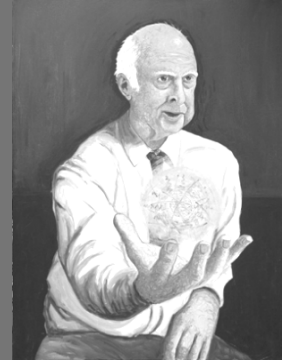
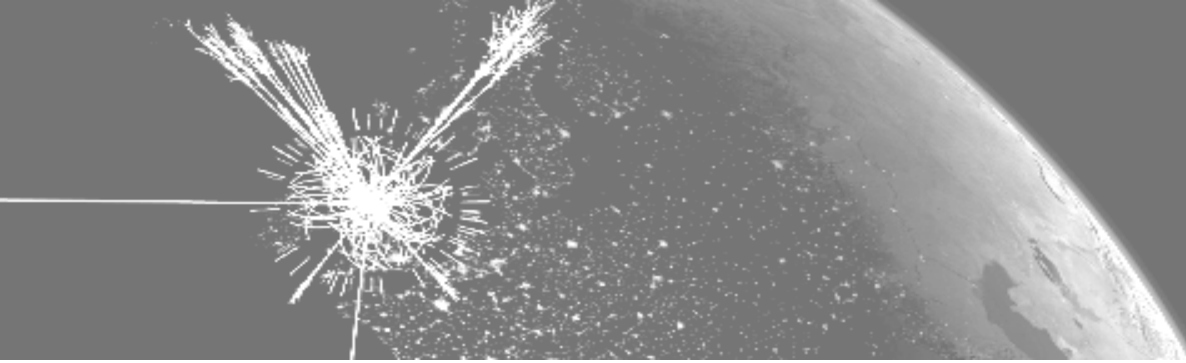


Top quark

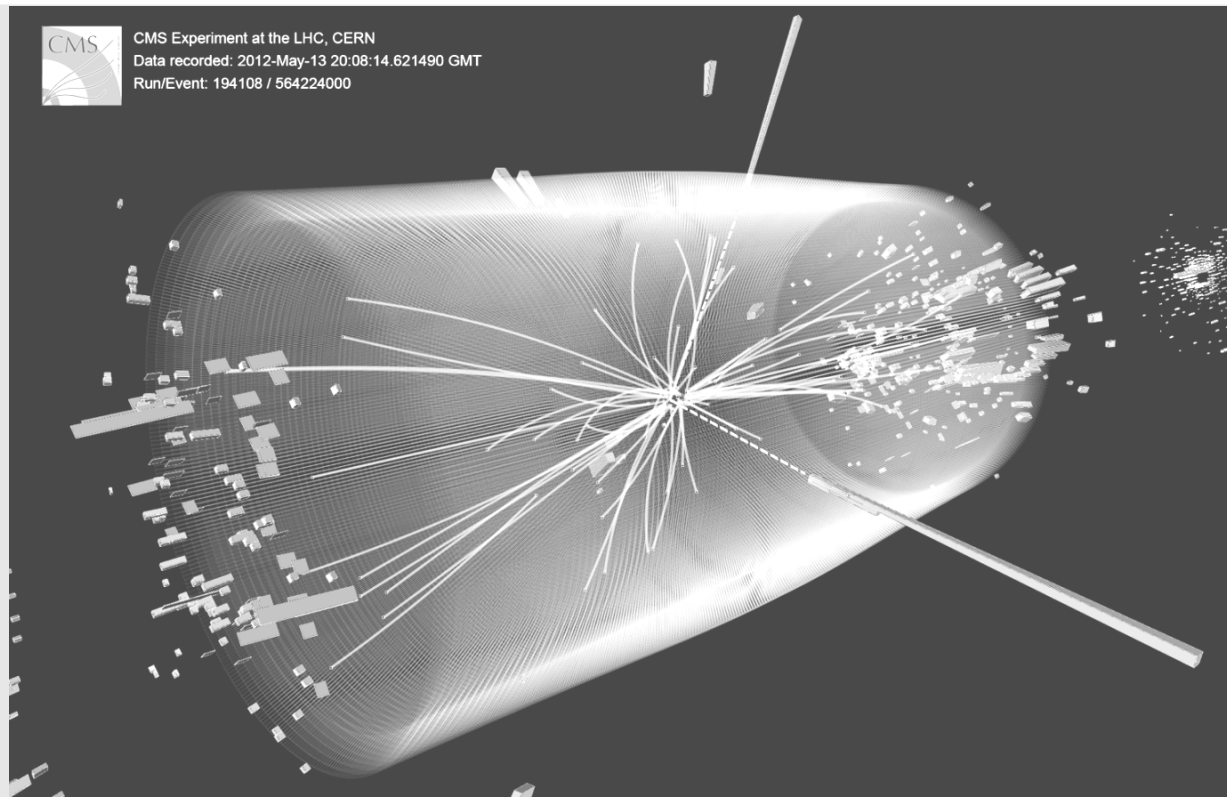


Interaction with Higgs
field alters chirality of
massive Dirac fermion

H. Murayama



The Higgs boson does more



The electroweak sector needs the Higgs boson

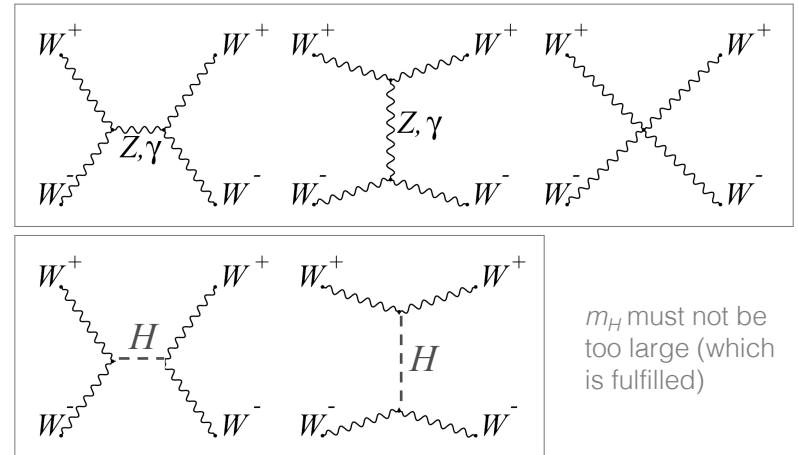
Higgs boson acts as “moderator” to unitarise high-energy longitudinal vector boson scattering

Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

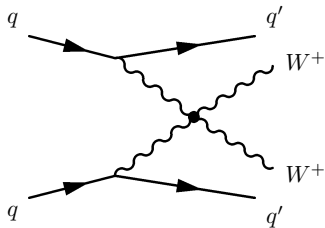
$$A_{Z,\gamma}(W^+W^- \rightarrow W^+W^-) \propto \frac{1}{v^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

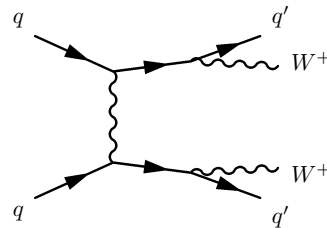
$$A_H(W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$



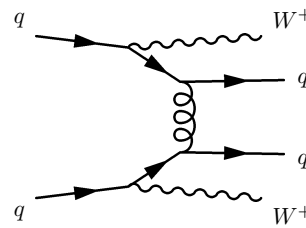
Same-sign WW selection greatly reduces strong production.
Removes s-channel Higgs process:



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

The electroweak sector needs the Higgs boson

Higgs boson acts as “moderator” to unitarise high-energy longitudinal vector boson scattering

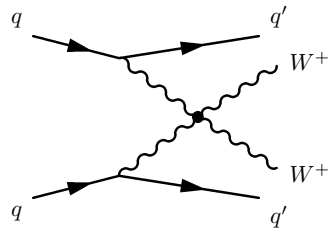
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

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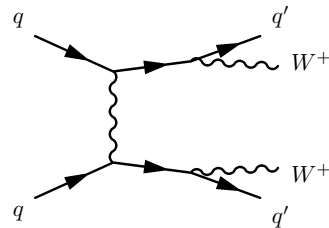
Higgs boson restores unitarity of total amplitude:

$$A_H(W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$

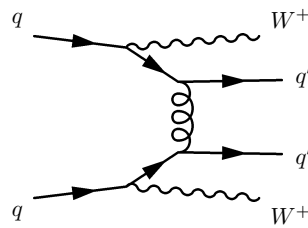
Same-sign WW selection greatly reduces strong production.
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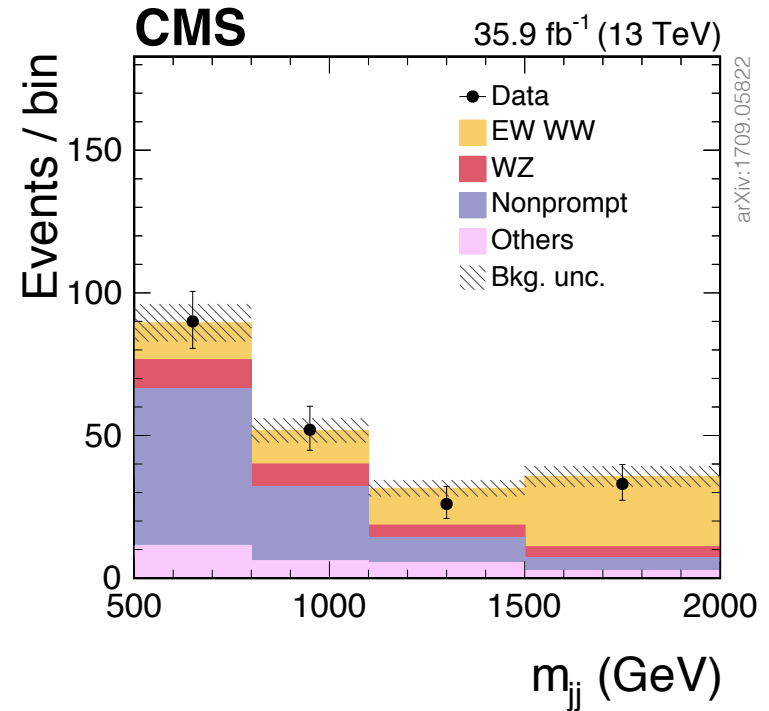
EW VBS production



Non-VBS production



Strong production



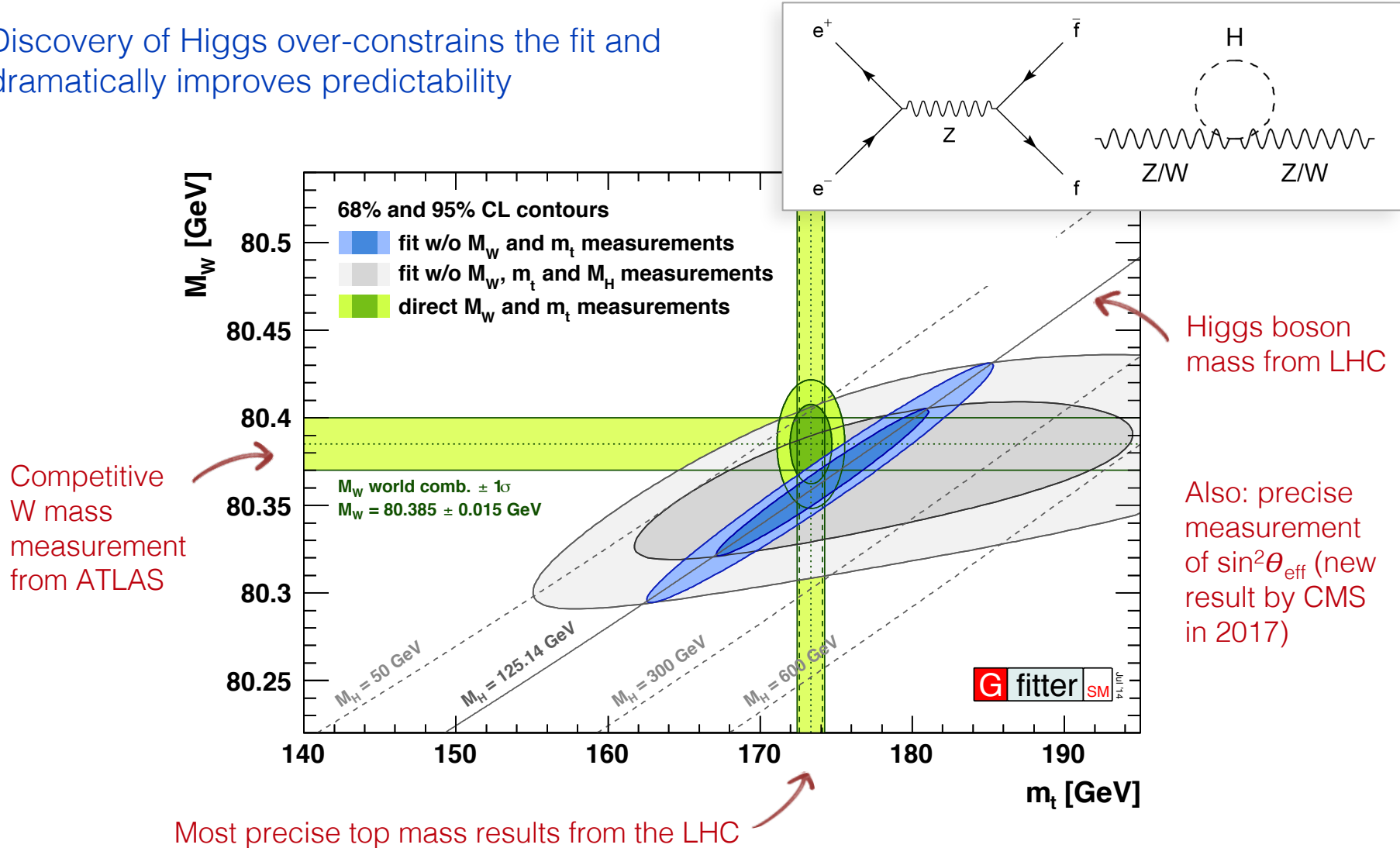
Look for VBS scattering in high dijet invariant mass distributions

CMS observes EW production at 5.7σ

The electroweak sector needs the Higgs boson

Global electroweak fit was masterpiece of LEP/SLD (e^+e^-) era

Discovery of Higgs over-constrains the fit and dramatically improves predictability



Ultimate precision is possible at the LHC

ATLAS measured the W boson mass to 0.02% and the top quark mass to 0.3% precision

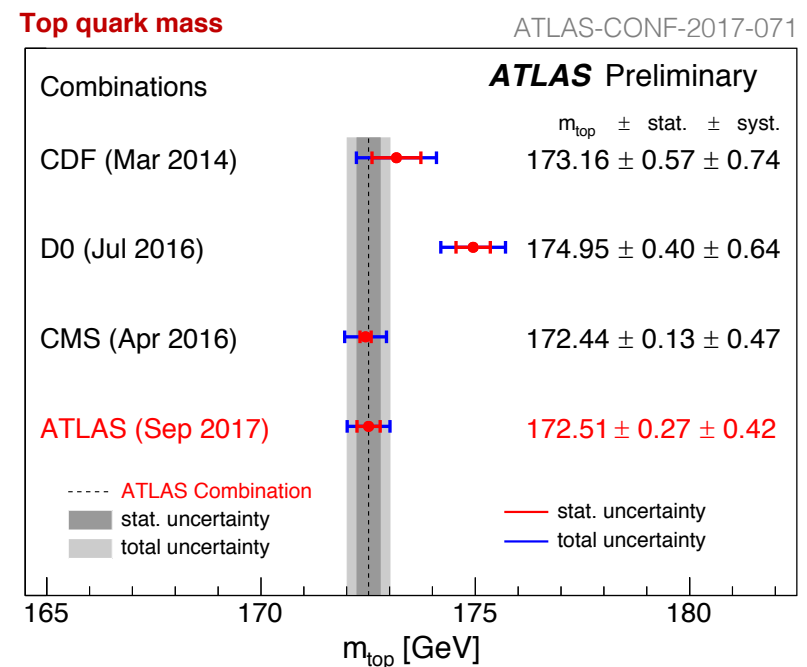
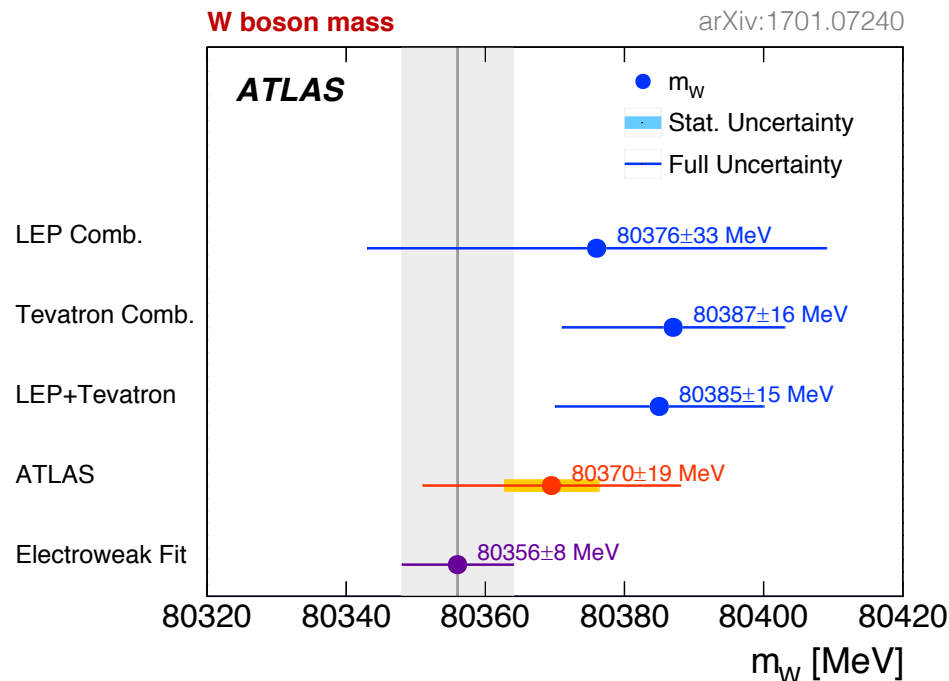
Measurement uses $W \rightarrow e\nu, \mu\nu$ events

Excellent agreement of results among e / μ channels, W^+ / W^- and $p_{T,\ell} / m_T$

Combined result:

$$\begin{aligned} m_W (\text{ATLAS}) &= 80370 \pm 7_{\text{stat}} \pm 11_{\text{exp syst}} \pm 14_{\text{mod syst}} \text{ MeV} \\ &= 80370 \pm 19 \text{ MeV} \end{aligned}$$

arXiv:1701.07240



Searches for new physics

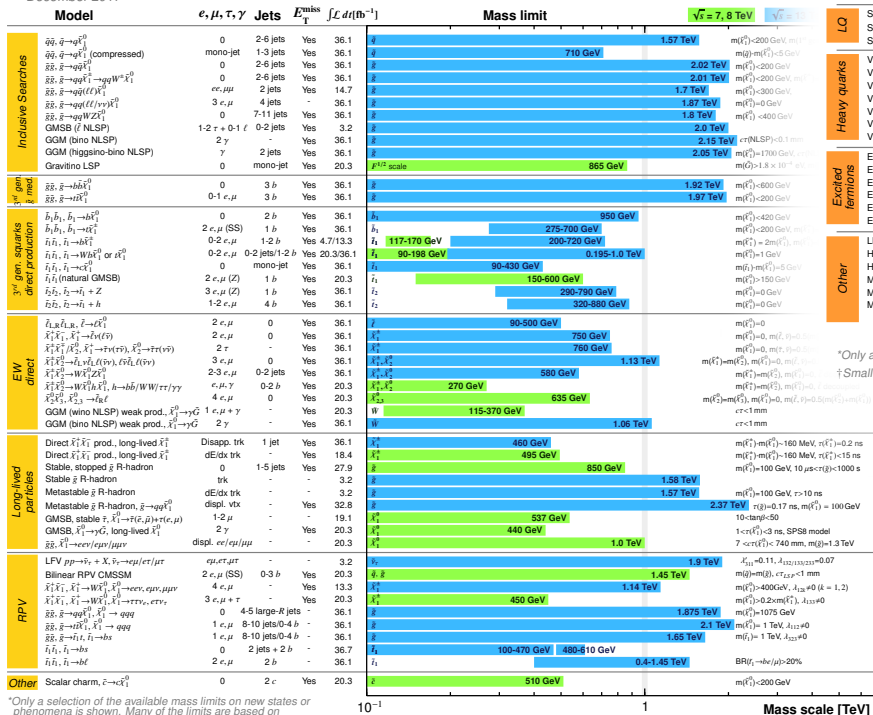
Cover all areas: high mass, electroweak production, long-lived particles, forbidden decays, ...

Theory-agnostic, signature based searches, as well as highly targeted model-dependent ones

Most high-profile searches on 2015+2016 data released

ATLAS SUSY Searches* - 95% CL Lower Limits

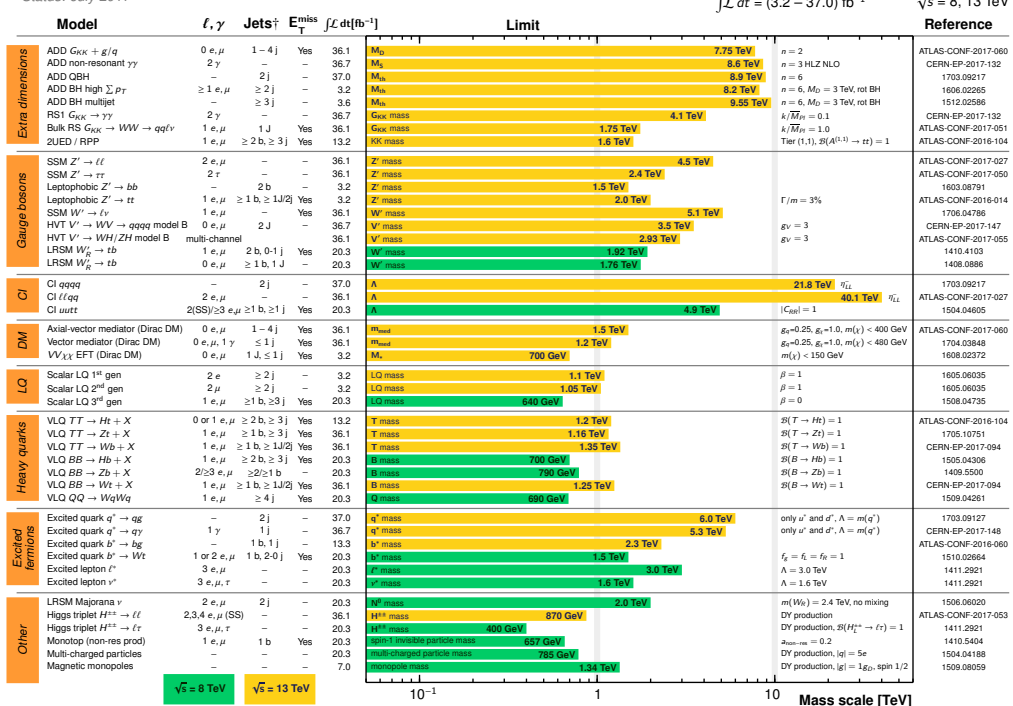
December 2017



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

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017



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

† Small-radius (large-radius) jets are denoted by the letter j (J).

No significant anomaly seen so far



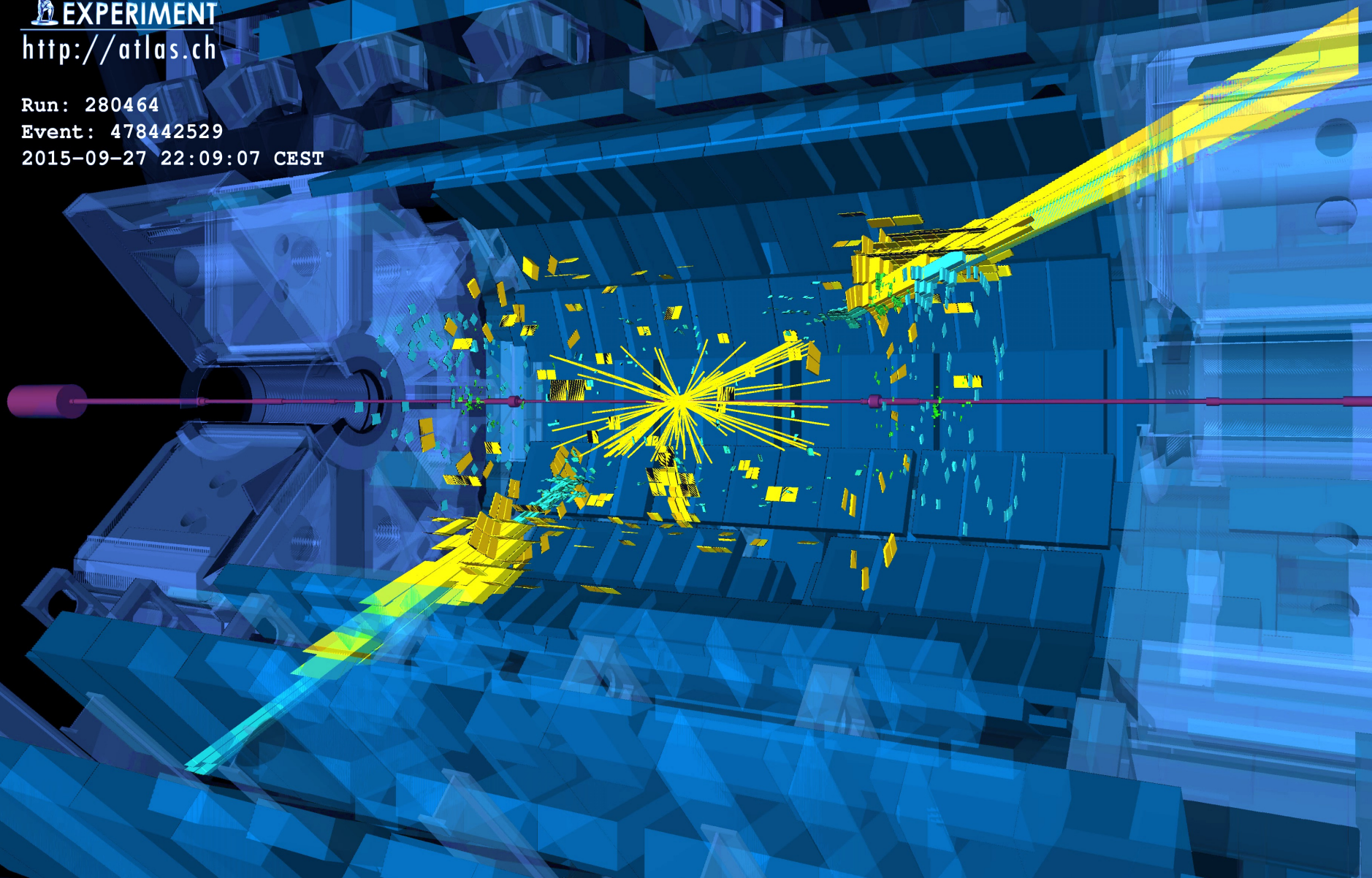
<http://atlas.ch>

Run: 280464

Event: 478442529

2015-09-27 22:09:07 CEST

New physics in events with jets ?

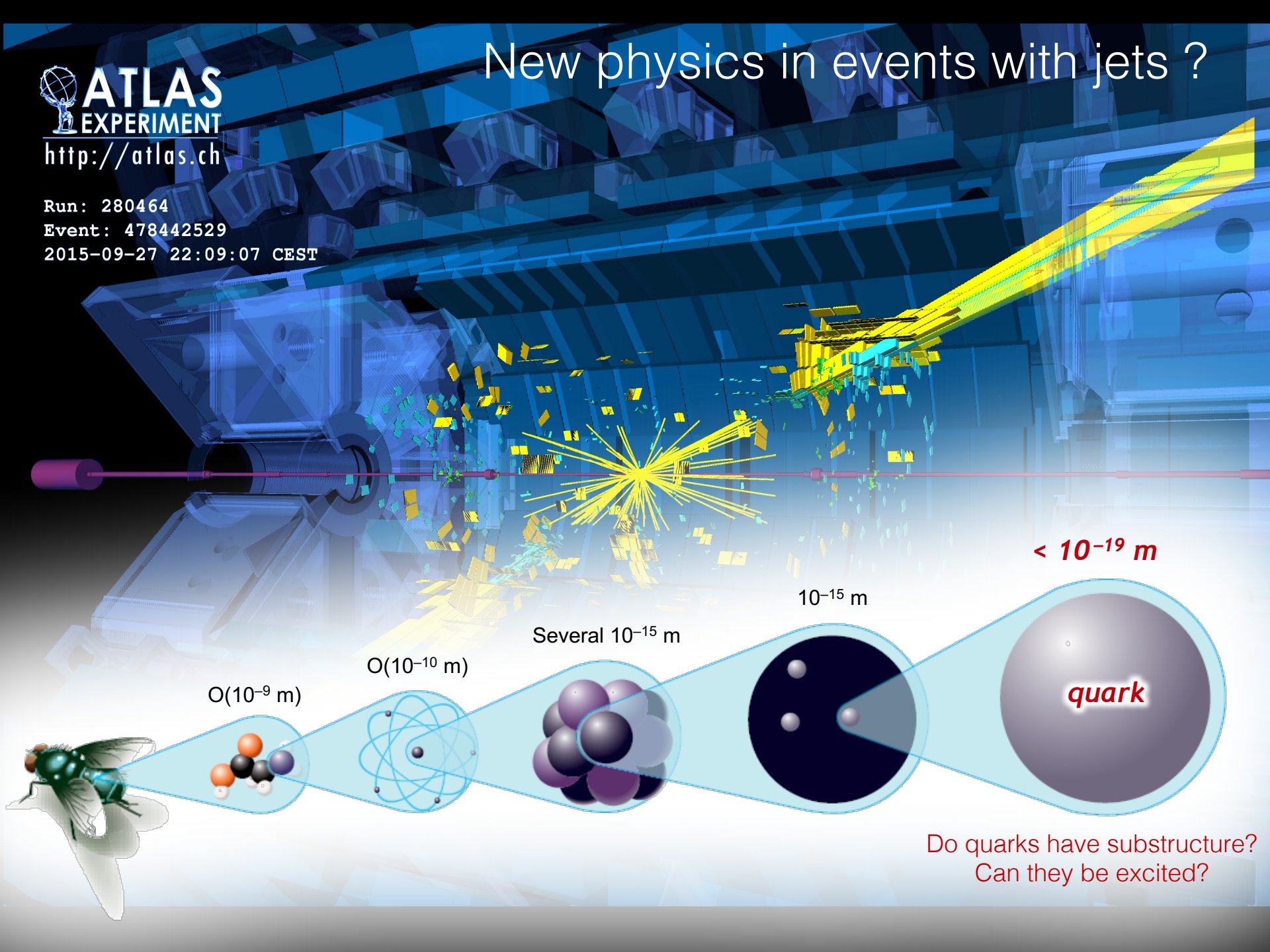


Run: 280464

Event: 478442529

2015-09-27 22:09:07 CEST

New physics in events with jets ?



$< 10^{-19} \text{ m}$

10^{-15} m

Several 10^{-15} m

$O(10^{-10} \text{ m})$

$O(10^{-9} \text{ m})$

quark

Do quarks have substructure?
Can they be excited?

Searches in high- p_T multijet final states at 13 TeV

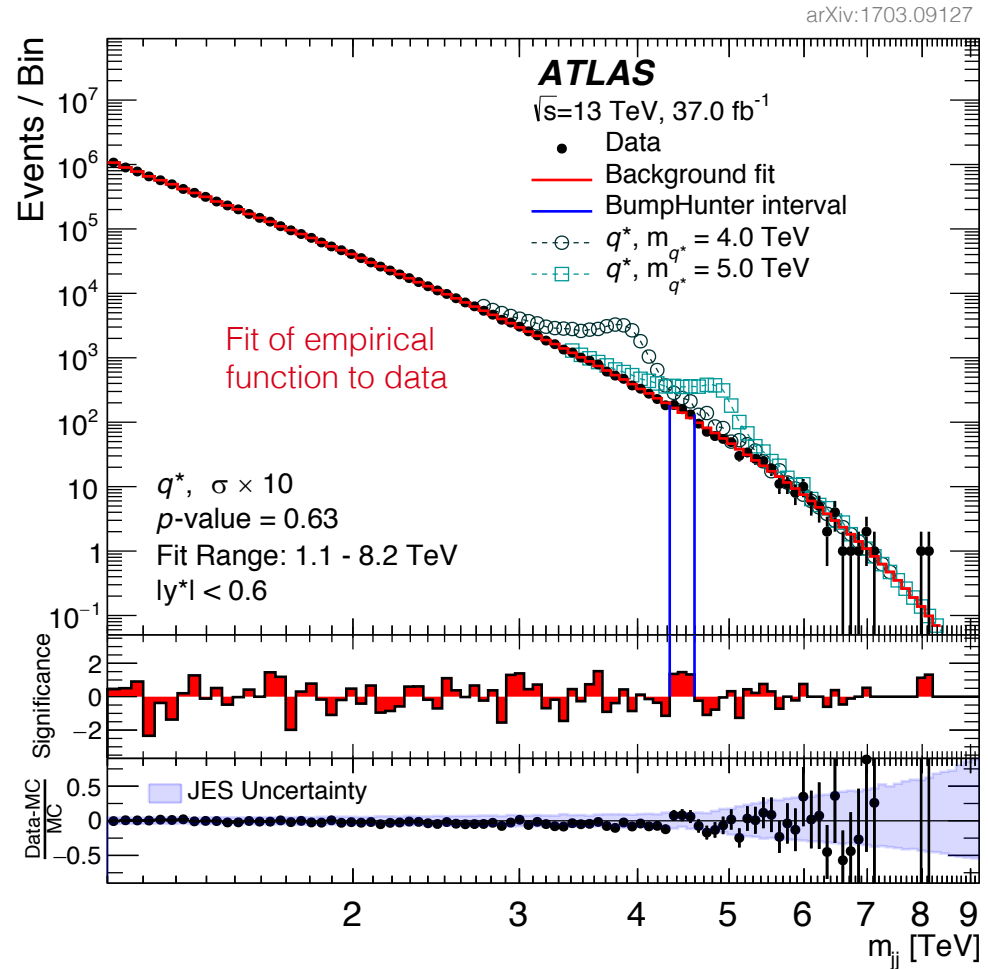
Processes with large cross-sections, sensitivity to highest new physics scales

Basic but very powerful searches

- Dijet resonance and angular distribution (incl. lower mass via ISR)
- High- p_T multijets produced, eg, by strong gravity

No anomaly seen in these or similar searches

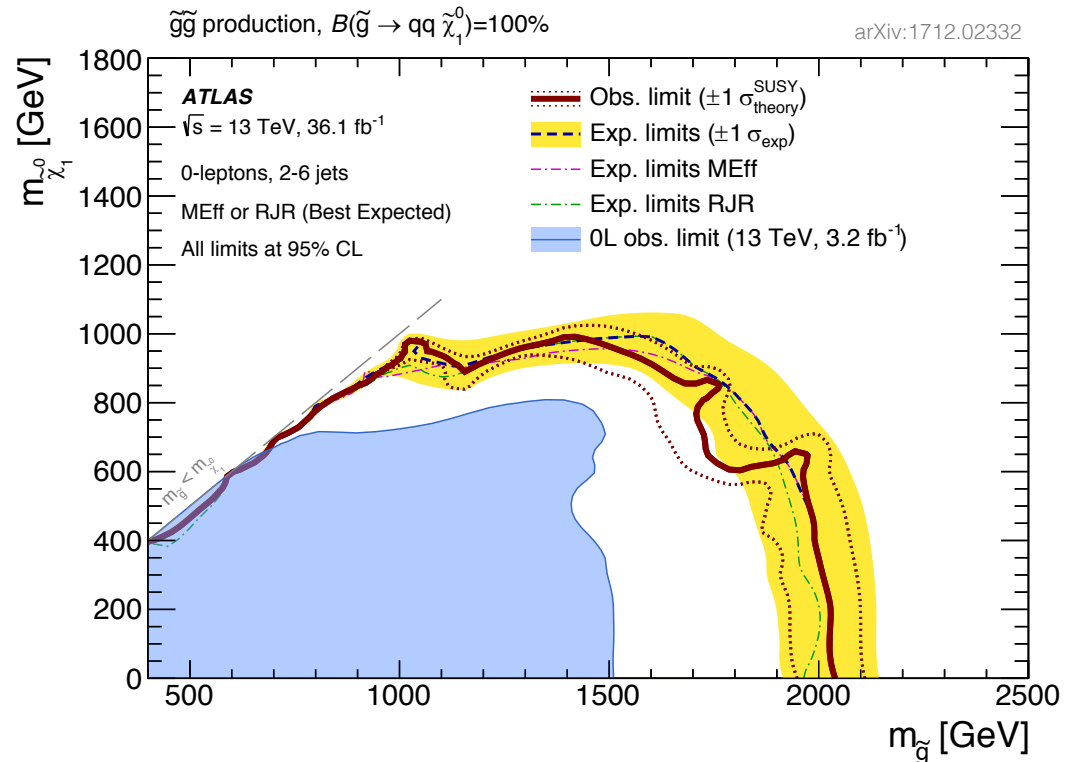
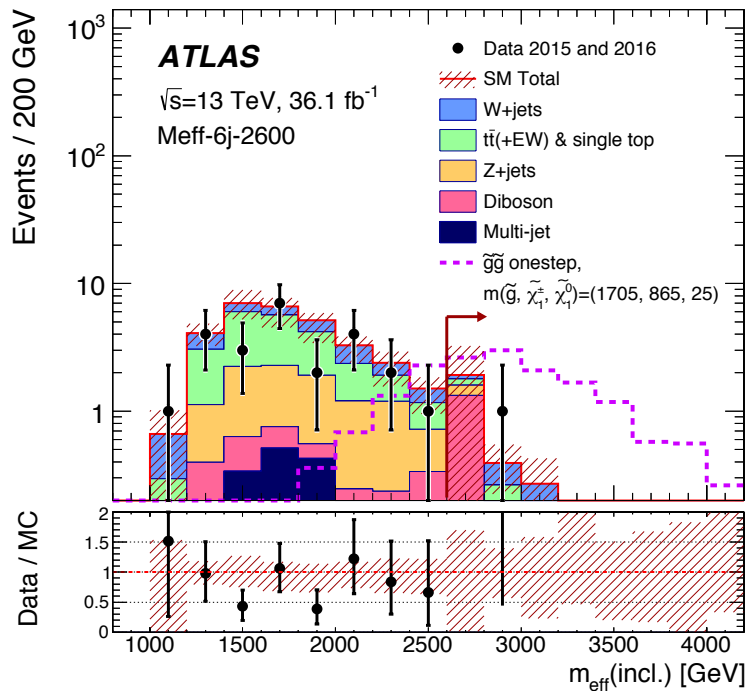
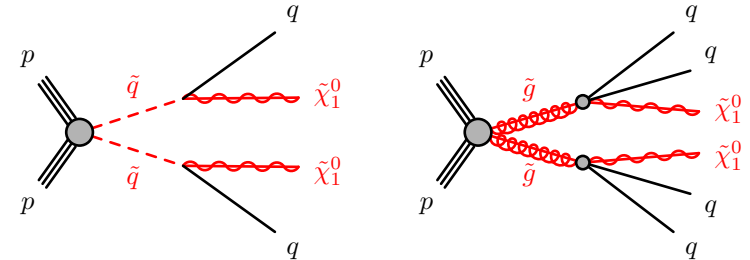
**Limits on excited quarks
(for example) at 6.0 TeV**



Supersymmetry

Offers elegant solution to: **naturalness problem, unification, dark matter**

Very diverse signatures. Highest cross-section events produce gluino / squark pairs with decays to jets and missing transverse momentum

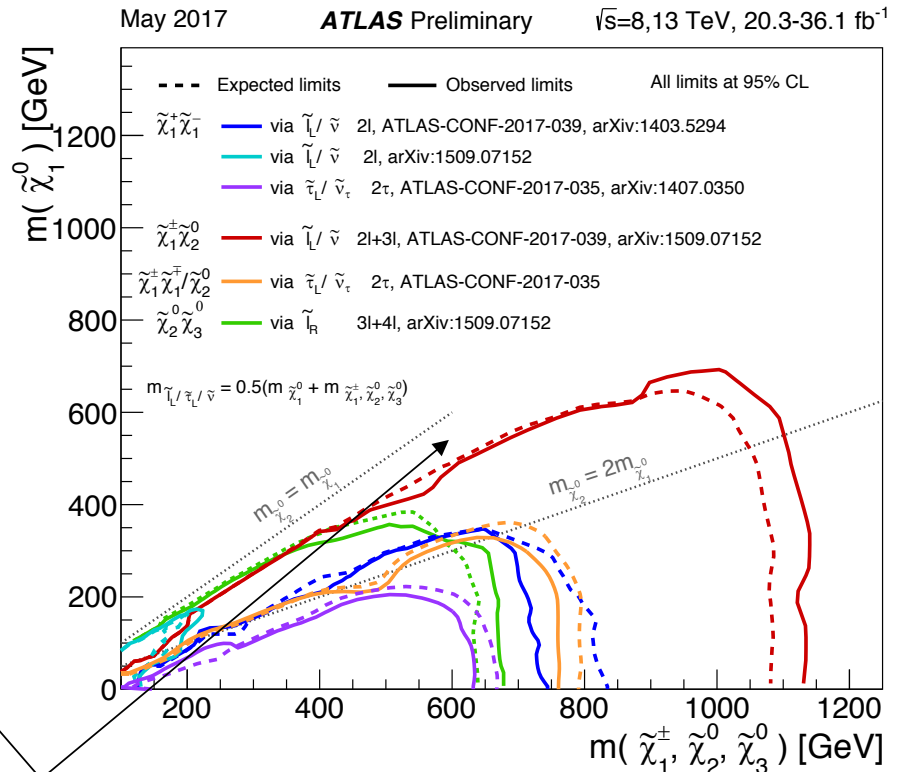
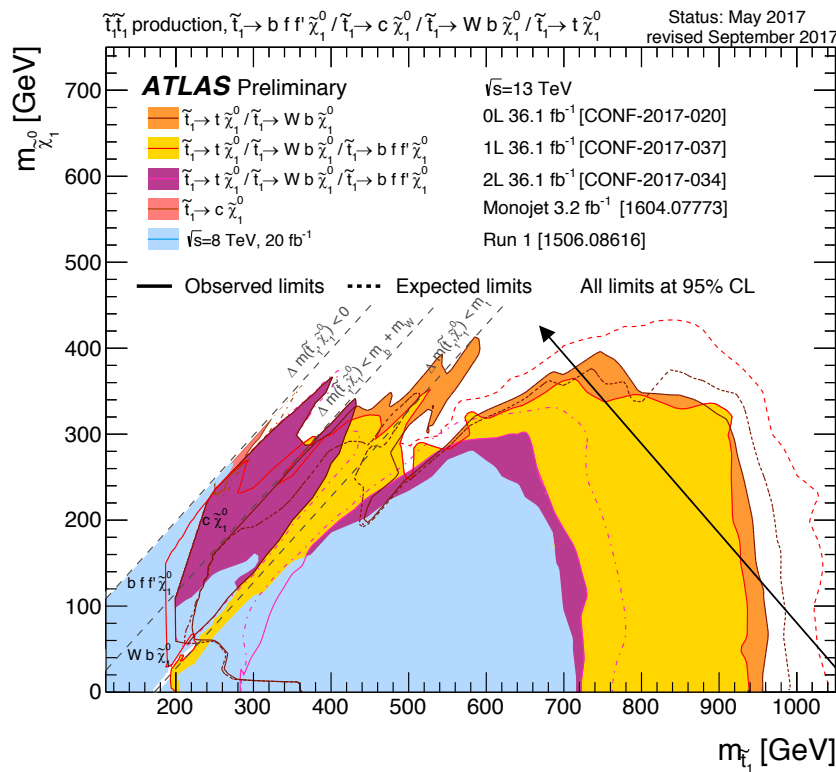
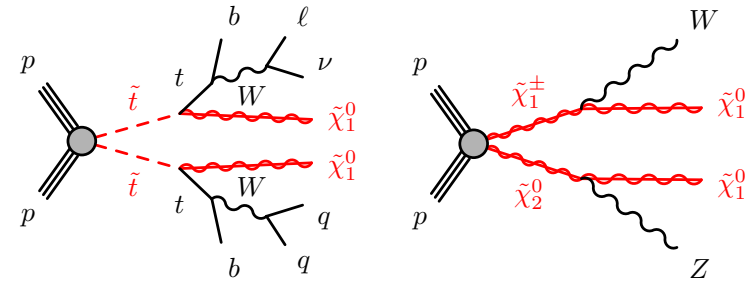


Naturalness driven SUSY searches

Searches for direct production of stop/sbottom & charginos/neutralinos

SUSY stop and sbottom, or “Electroweak-inos”

may be the lightest SUSY particles. Low-cross section searches requiring dedicated optimisation. Long-term search effort



“Compressed” regions

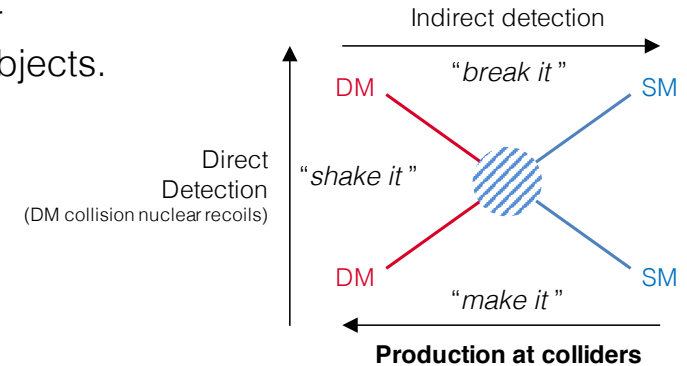
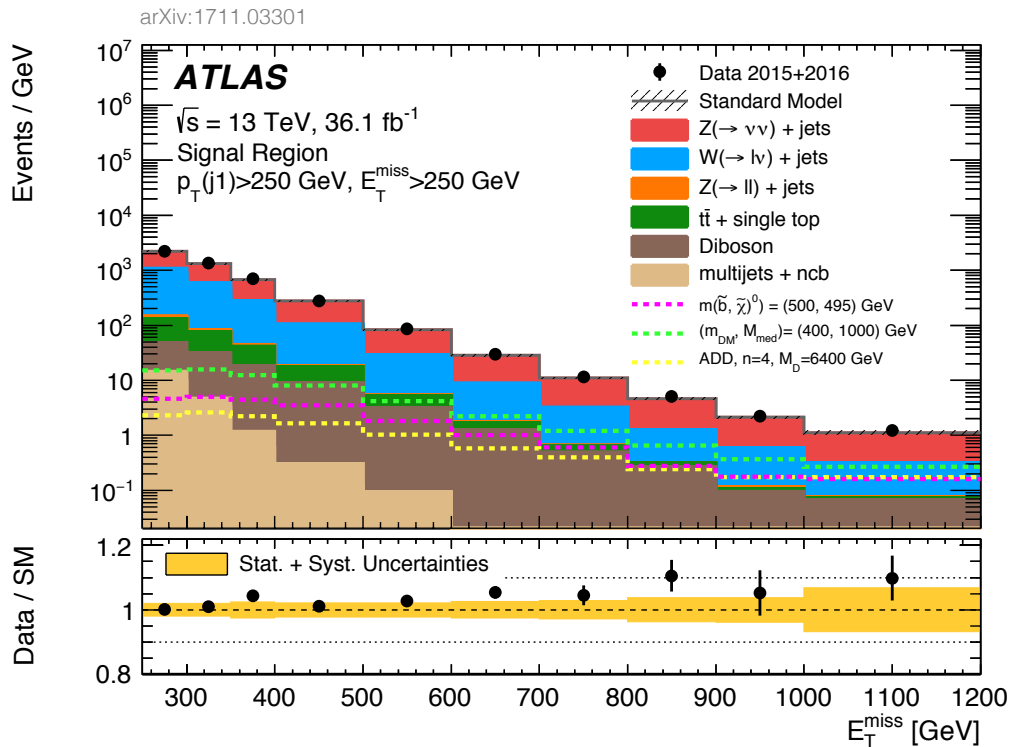
Searches for dark matter production at the LHC

Canonical signature is 'X+MET' with large variety of 'X'

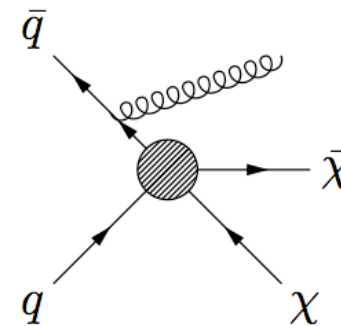
May not be able to prove at LHC that a signal is dark matter

Direct dark matter production at the LHC requires boost for triggering. Depending on coupling it can be made by different objects.

Experimentally challenging to control Z/W+jets background. Theory input needed.



Energetic gluon/photon radiation in the initial state



Can also directly search for mediator in, eg, dijet events

Many other 13 TeV results available:

- jets + MET
- γ + MET
- V + MET
- H + MET
- $t\bar{t}$ + MET

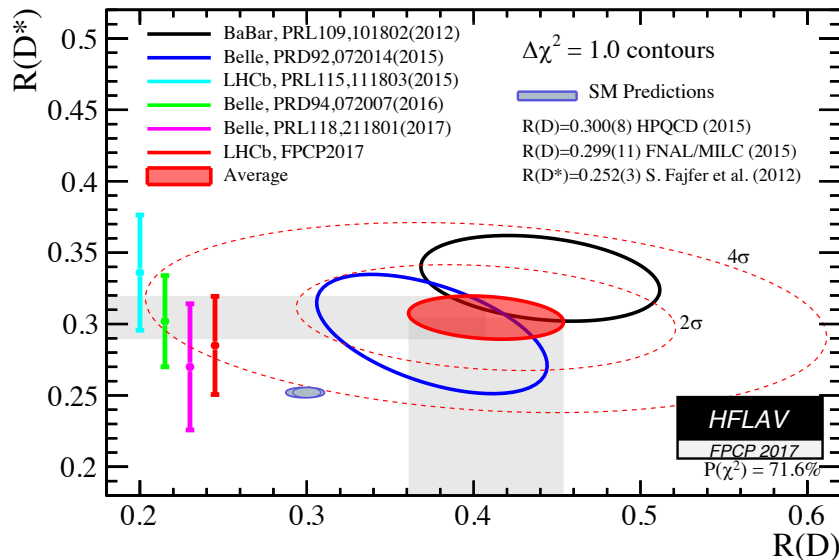
No anomaly seen so far

Anomalies in charged lepton transitions?

LHCb and the B-factories measure ratios of semileptonic B decays. Robust SM predictions due to lepton flavour universality

$$R_{D^{(*)}} = \frac{\text{BR}(B^0 \rightarrow D^{(*)}\tau\nu)}{\text{BR}(B^0 \rightarrow D^{(*)}\ell\nu)}$$

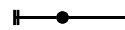
$$R_K = \frac{\text{BR}(B^+ \rightarrow K^+\mu\mu)}{\text{BR}(B^+ \rightarrow K^+ee)}$$



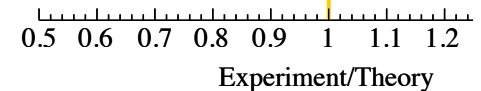
$$R_K (1.0 < q^2 < 6.0 \text{ GeV}^2)$$



$$R_{K^*} (0.045 < q^2 < 1.1 \text{ GeV}^2)$$



$$R_{K^*} (1.1 < q^2 < 6.0 \text{ GeV}^2)$$



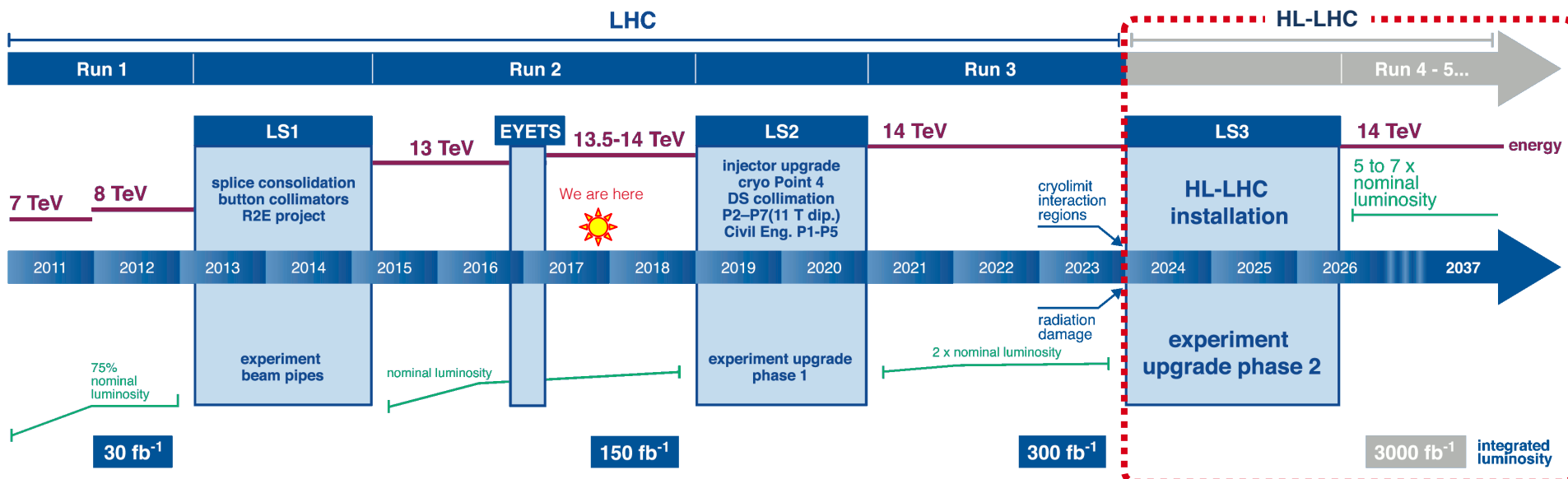
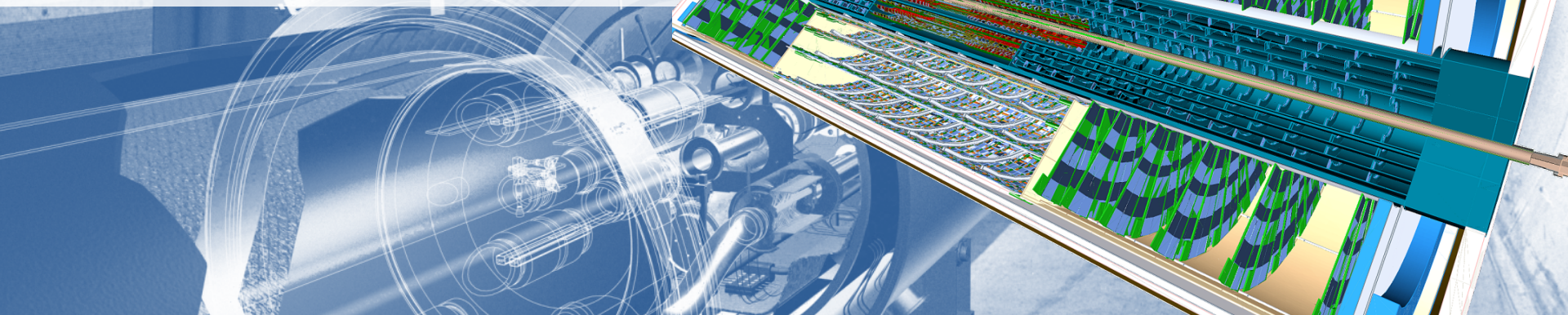
Some deviation seen in both tree (left) and loop(right) decays, but **more data needed before any conclusions can be drawn**



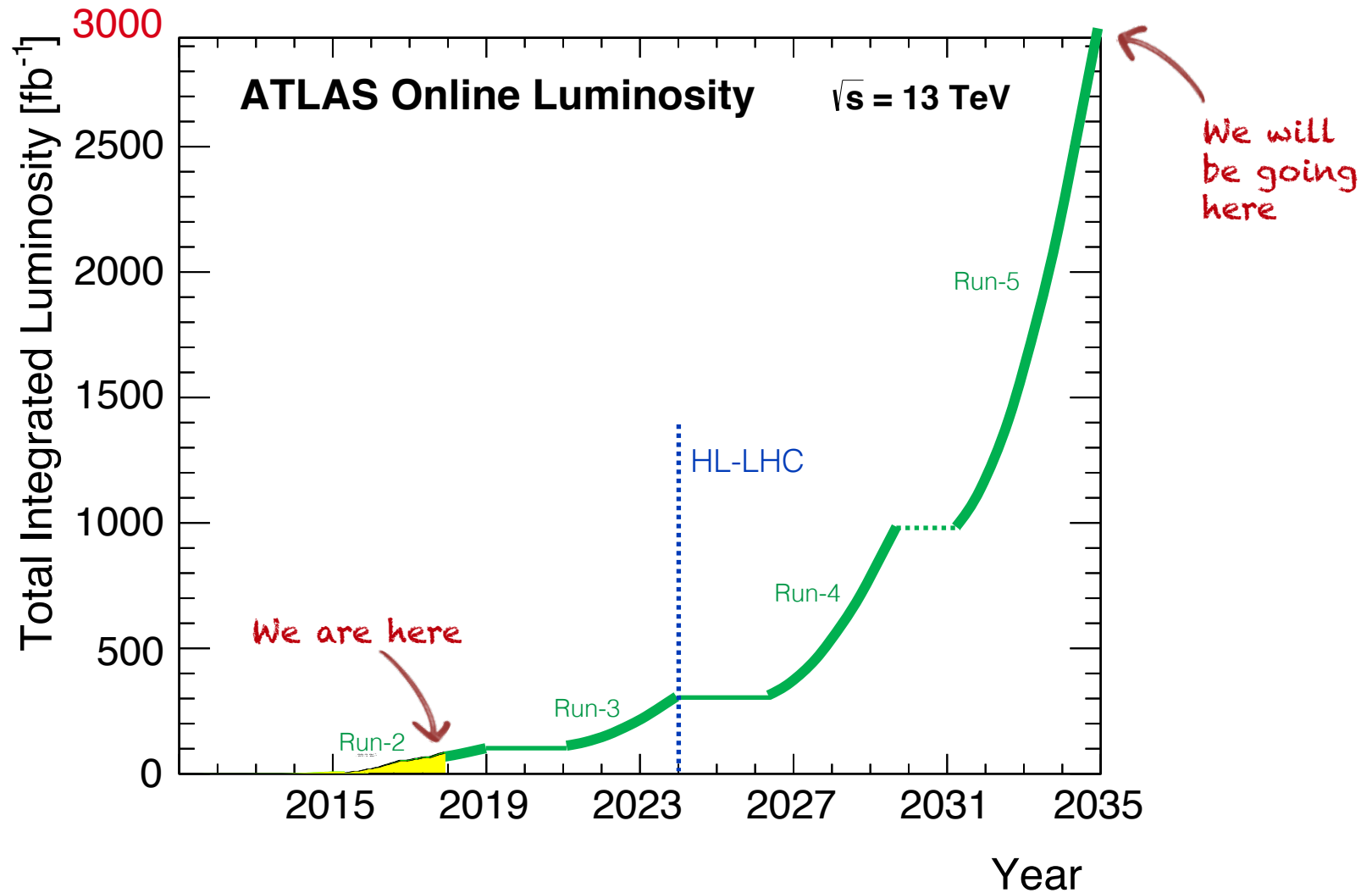
The next steps

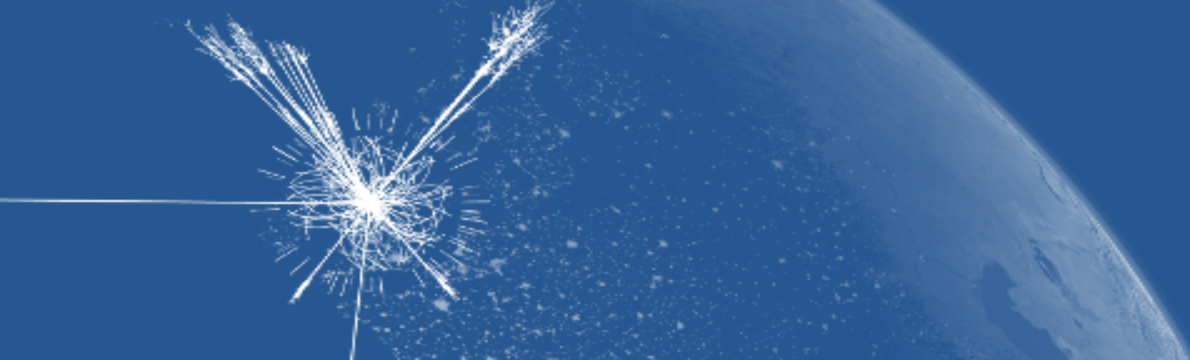
Design image of the ATLAS Phase-2 tracker (ITk)

Phase-2: The High-Luminosity LHC



Expected integrated luminosity of LHC & HL-LHC

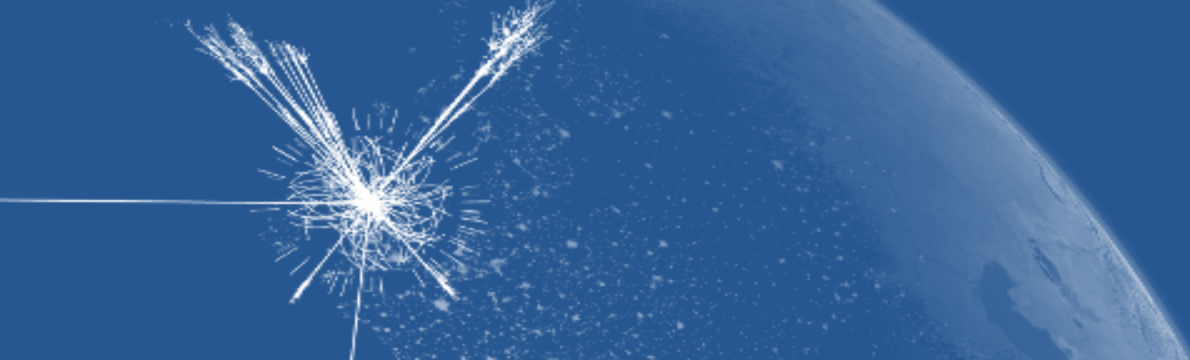


A composite image showing a blue-tinted view of Earth's horizon from space. Overlaid on the left side are several bright, white, star-like particle tracks, resembling those from a bubble chamber or a particle detector, with multiple lines radiating from a central point.

Challenges and opportunities

Particle physics has entered an era of uncertainty: we have a beautiful theory, and many indications that it is incomplete.

Contrary to Fermi, who knew the TeV scale, we do not know the next new physics scale. Naturalness suggests $O(\text{TeV})$, but we do not know how much Nature cares about naturalness.

A visualization of a particle collision, showing a central bright point with numerous tracks radiating outwards, set against a dark blue background with a curved horizon line.

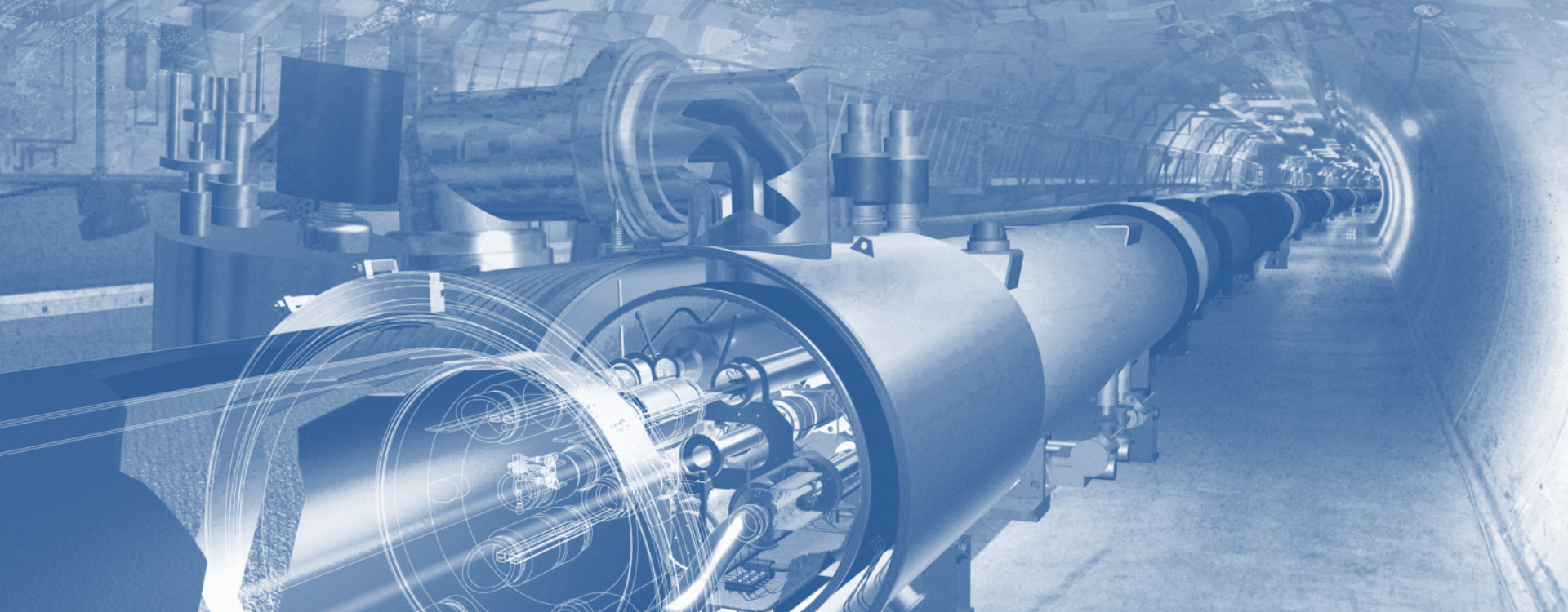
Challenges and opportunities

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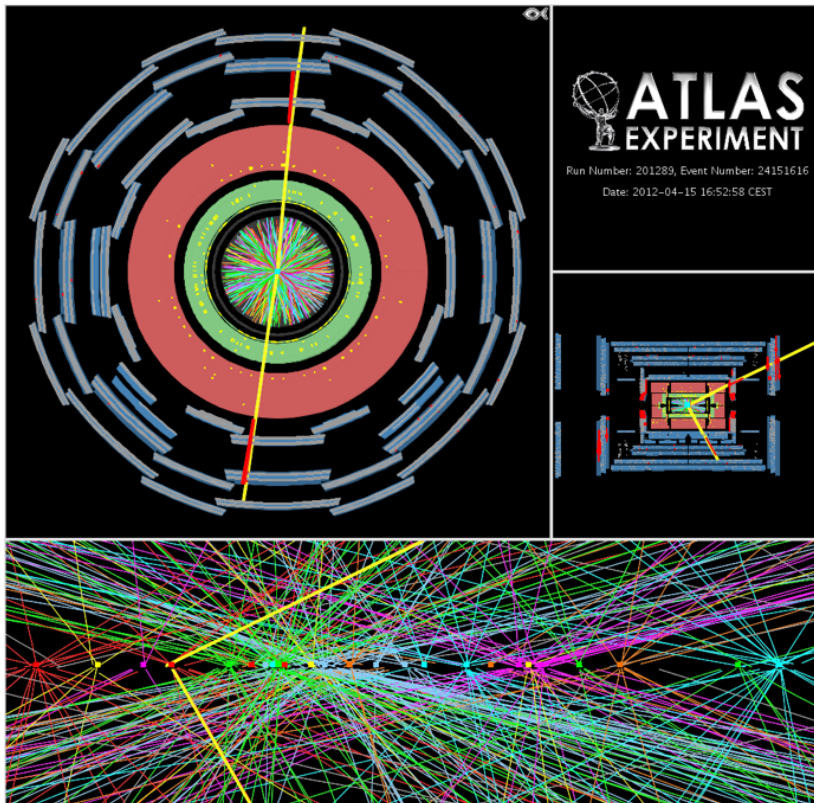
We live in **data-driven times**, experiment must guide us to the next stage. That means we need a very **broad and diverse research programme**.

- We need **flagship collider programmes at the energy frontier**: the **strength and diversity of the LHC and HL-LHC** are unequalled today: ATLAS alone released > 700 papers on collision data
- We need to develop high-field magnets and compact high-gradient accelerators for the **long-term future**
- We need to continue and further extend the **intensity and precision programme**: rare B & kaon physics, $g-2$, lepton flavour violation, $n/p/e/\mu$ EDM, neutrino physics with all that belongs to it, proton decay
- We need to search for dark matter particles/WIMPs using direct DM experiments, indirect searches in space, fixed target searches, axion searches
- **Altogether, this is a fantastic toolset to find answers to the many open questions in our field**



Extra slides

High luminosity comes at price of pileup interactions



Pileup interactions

- Average of 21 (peak: 40) interactions per crossing in 2012. Similar in 2016.
LHC design value:

$$\mu = \frac{\sigma_{\text{inel}} \cdot L}{f_{\text{rev}} \cdot n_{\text{bunch}}} \approx \frac{80 \text{ mb} \cdot 10 \text{ nb}^{-1} \text{s}^{-1}}{11245 \text{ s}^{-1} \cdot 2808} = 25$$

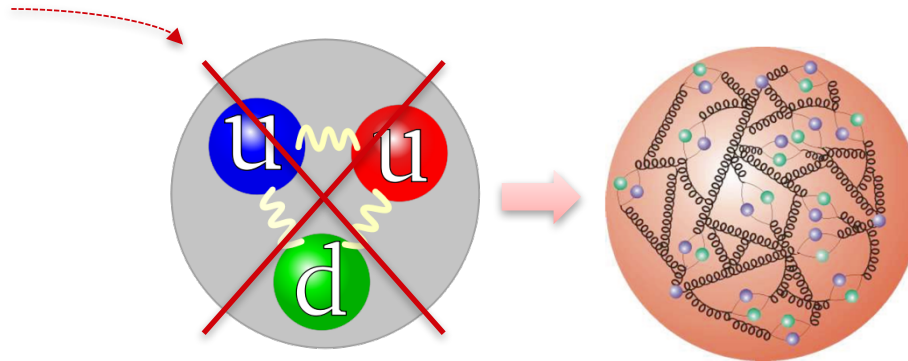
- Most analyses quite insensitive to pileup at this rate, several mitigation methods used
- However: higher trigger thresholds
→ low- p_T physics suffers

Proton-Proton Collisions

- For proton-proton collisions, cross section is **convolution of Parton Density Functions (PDF) with parton scattering Matrix Element**

Parton distribution functions

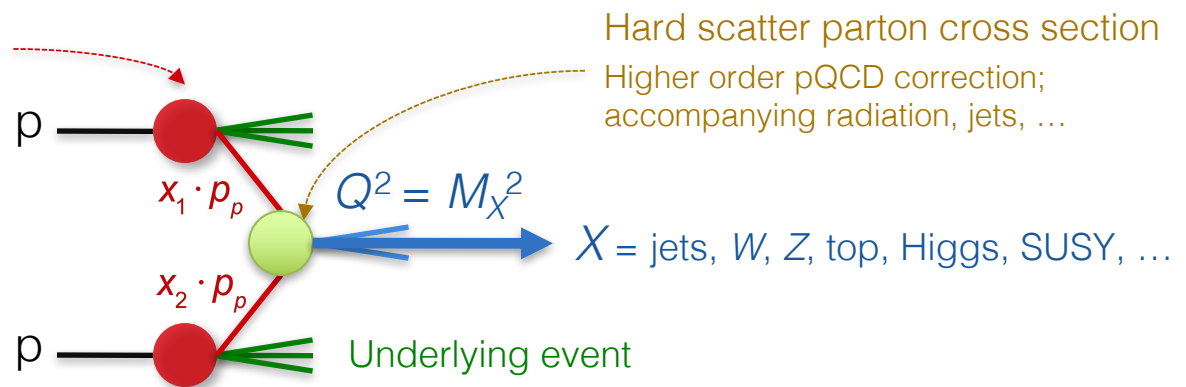
Representing structure of proton,
extracted using experimental
data and QCD properties



Proton–Proton Collisions

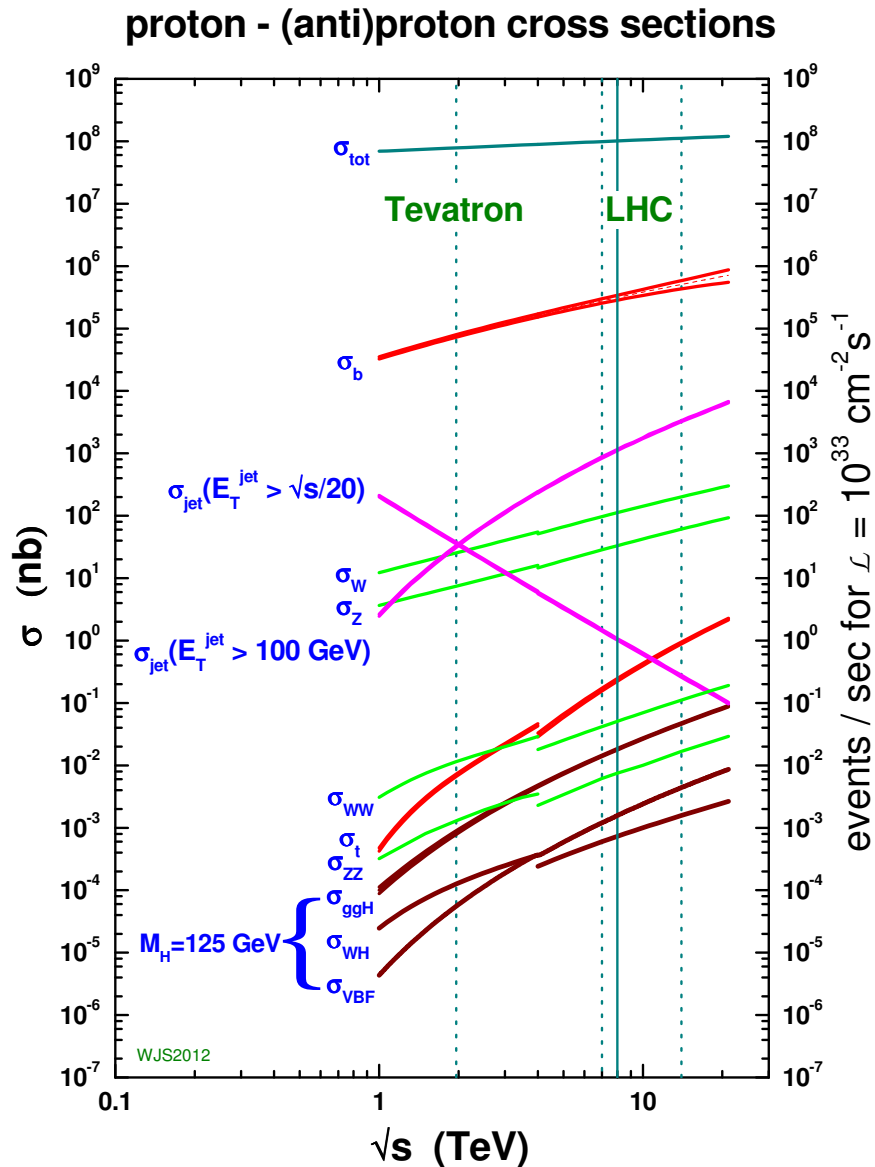
- For proton–proton collisions, cross section is **convolution of Parton Density Functions (PDF) with parton scattering Matrix Element**

Parton distribution functions
Representing structure of proton,
extracted using experimental
data and QCD properties



- CM energy-squared of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- The PDFs rise dramatically towards low x :
 - Higher cross section at higher proton–proton collision energy
 - More luminosity also achieves higher achievable energy
 - Low- x regime (eg, Higgs production) dominated by gluon–gluon collisions: “gluon collider”

Proton-Proton Collisions



- Cross-section fully dominated by inelastic strong interaction
“minimum bias” events
- Detectors cannot record 40 MHz event rate* (each event $\sim 2 \text{ MB}$ size $\rightarrow 80 \text{ TB}$ / second)
- Online custom hardware and software “triggers” reduce rate to filter out events with a million & more times smaller cross-sections than minimum bias events

*The LHCb phase-1 upgrade is preparing for exactly that!

Theoretical predictions based on *perturbation theory*

Progress in theoretical calculations — **NNLO revolution**

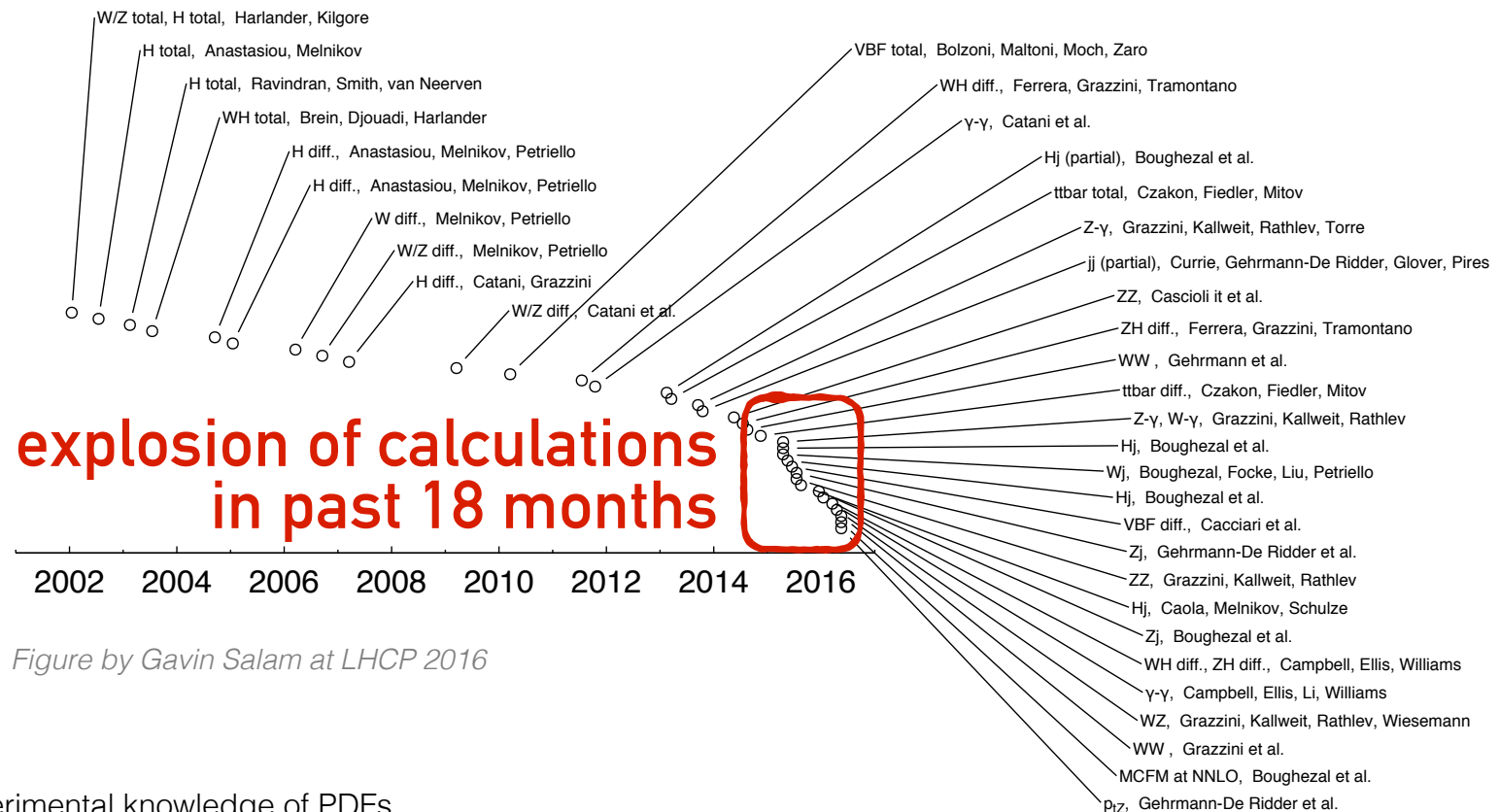
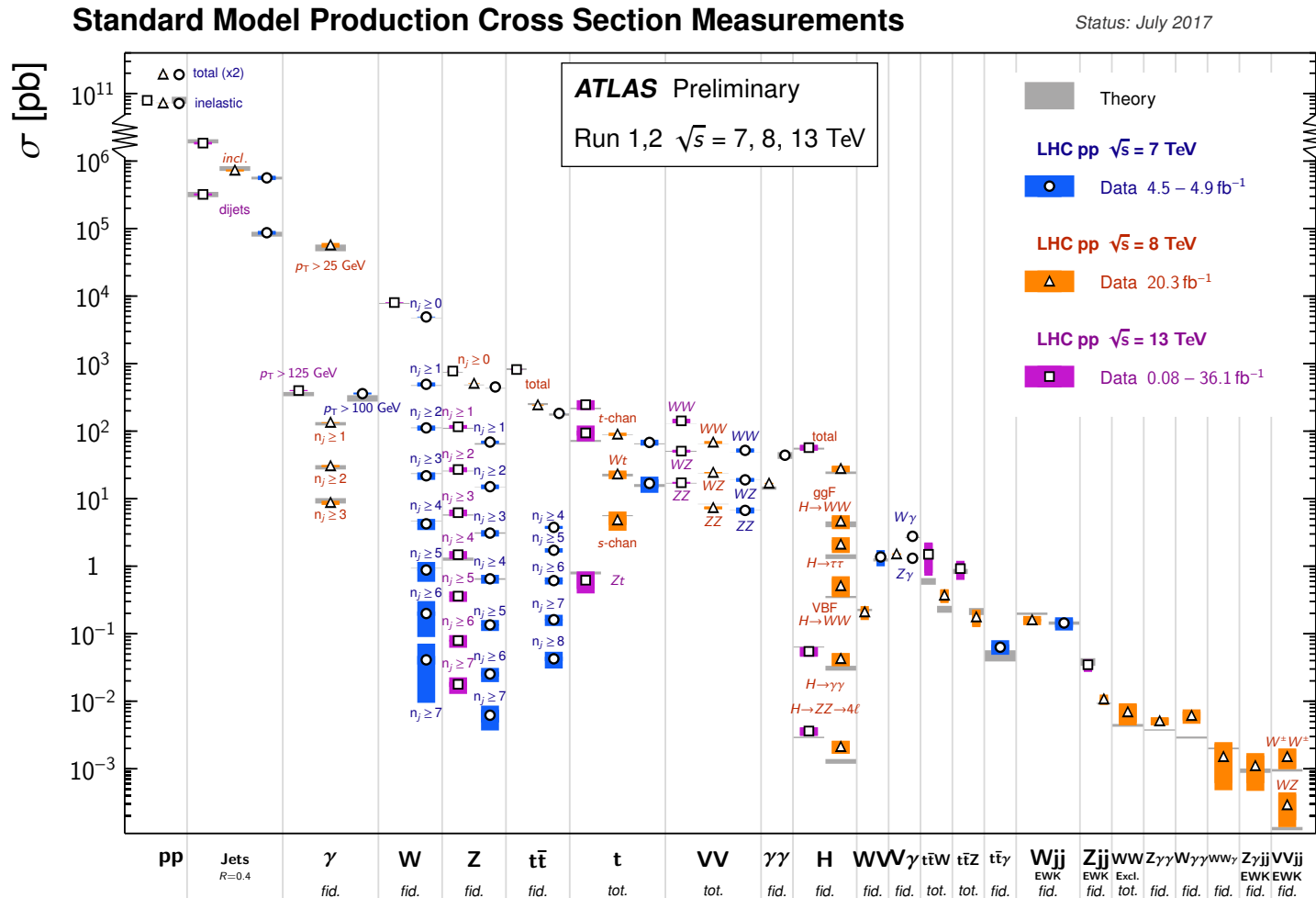


Figure by Gavin Salam at LHCP 2016

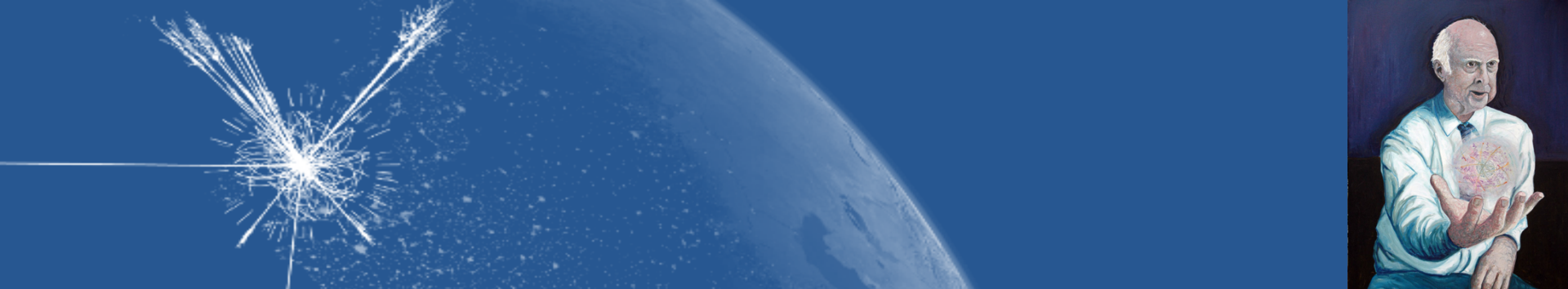
Also experimental knowledge of PDFs
limits precision in many LHC analyses !

Across widely different processes



Harvest of cross-section measurements from LHC experiments (> 500 papers / exp) confirmed the predictive power of the Standard Model

Run-1 is not over yet:
high-quality, extremely
well understood data
sample for precision
measurements



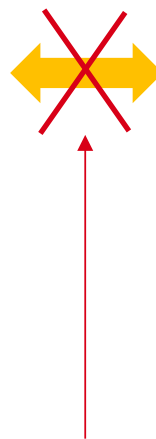
Two beautiful, extremely precise theories

The Standard Model of EW and strong interactions

Predicting, e.g., the anomalous magnetic moment of the electron to a relative precision of better than 10^{-9} in agreement with experiment

General relativity — theory of gravitation

Tested up to an accuracy of order 10^{-5} (Cassini probe [B Bertotti et al., Nature 425, 2003])



Unfortunately, the SM and general relativity don't work in regimes where both are important (ie, at very small scales)

A background image showing particle tracks in a detector, with a bright central point and several tracks extending outwards, set against a dark blue background.

Many open questions remain...

Scalar sector

- Single doublet or more
- Elementary or composite
- Form of potential
- Origin of Yukawa couplings

Dark matter

- Composition: WIMP, axions, sterile neutrinos, hidden sector particles, gravitational effect only
- Single or multiple sources

Expansion of Universe

- Primordial expansion via inflation; which fields, role of quantum gravity?
- Accelerated expansion today: cosmological constant problem

Strong CP problem

Quarks and leptons

- Origin of families, mass, mixing, CPV
- Matter–antimatter asymmetry
- Baryon and lepton number conservation (proton decay)

Neutrinos

- Origin and values of neutrino masses
- Nature: Majorana or Dirac
- CP violation
- Sterile neutrinos

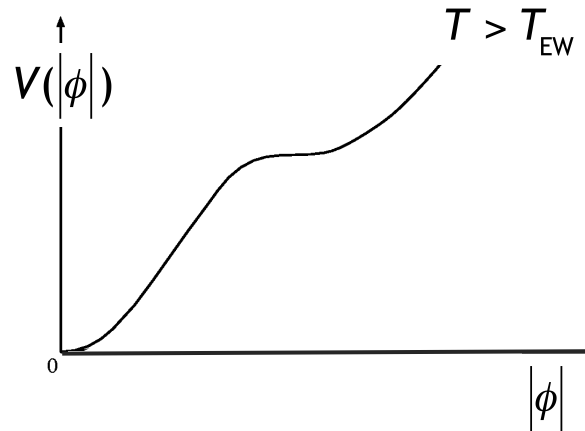
High-scale physics

- Hierarchy problem and new physics at TeV scale
- Grand unification of forces
- Unification with gravity
- Quantum gravity, string theory

BEH Potential

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)

Elementary fermions and
gauge bosons are massless

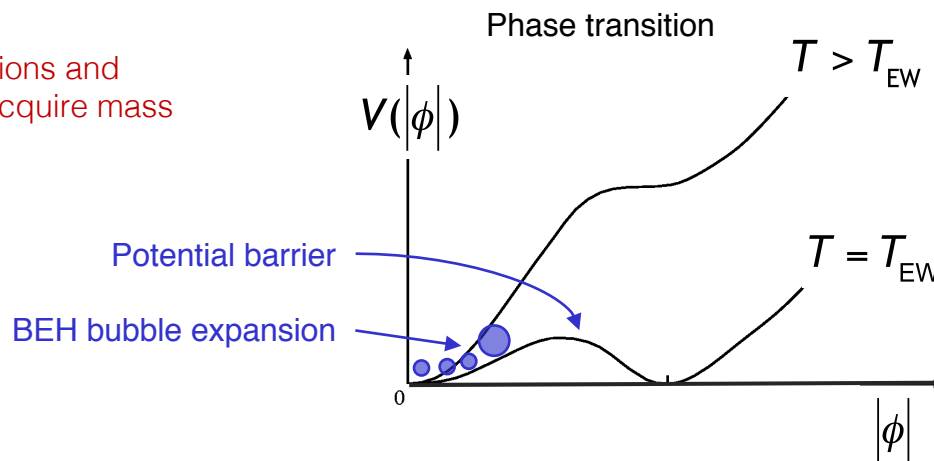


$V(T)$ dependence mainly governed
by top loop, adding a cubic ϕ^3 term

BEH Potential

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$

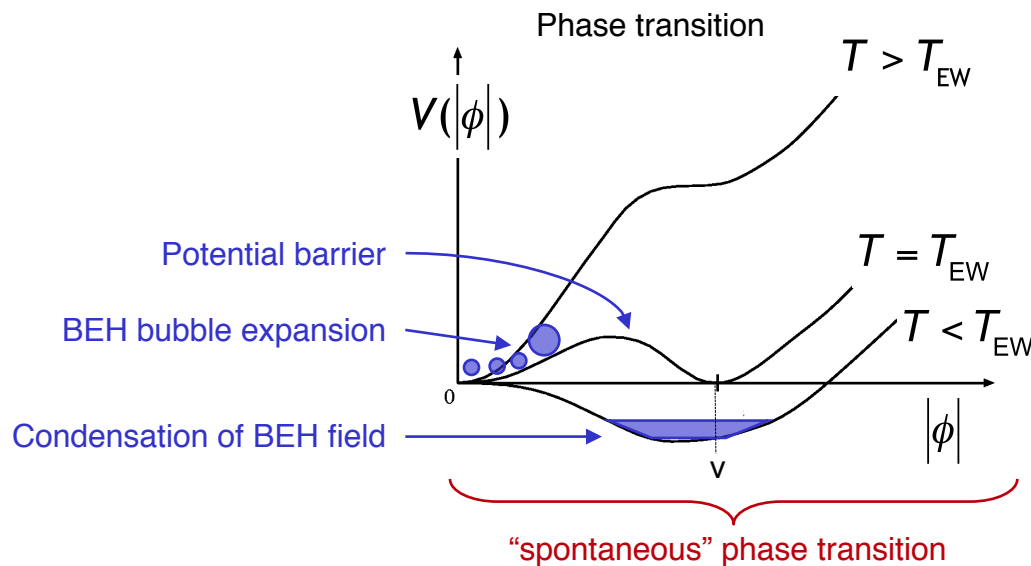
Elementary fermions and
gauge bosons acquire mass



Picture describes a 1st order
phase transition that would
require light Higgs, or new
physics $\rightarrow$ currently disfavoured

BEH Potential

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
 A phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$



The condensed field fills all space and time but without orientation as it has no spin. (One might view it as a Lorentz-invariant ether creating a vacuum viscosity)

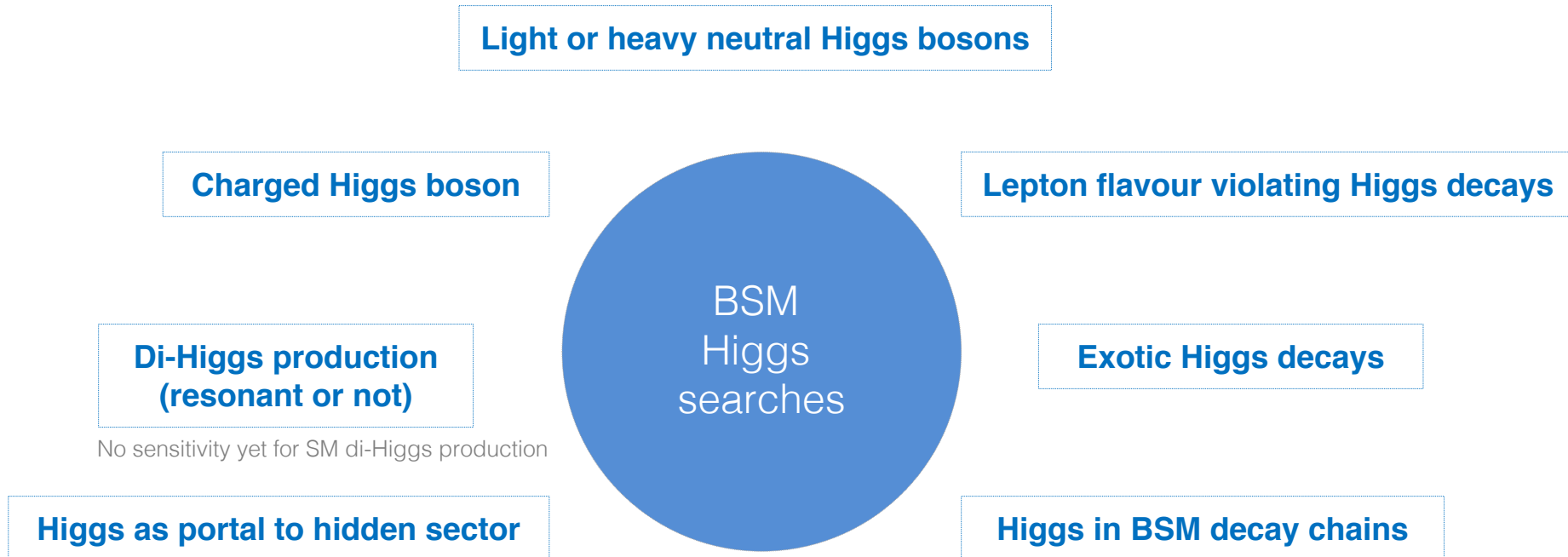
$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Is it just the simplest toy model?

Higgs sector may be non-minimal and/or Higgs boson may couple to new physics

Diverse search programme at the LHC:

So far: no deviation from SM found in any of these searches

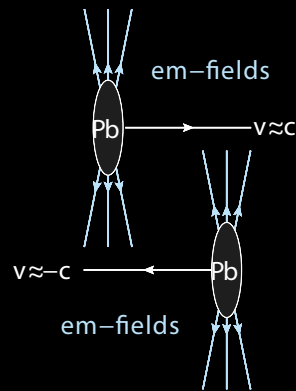


$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

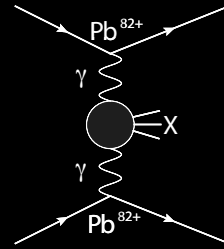
Evidence for $\gamma\gamma \rightarrow \gamma\gamma$
light-by-light scattering
(LBLS) seen by ATLAS in
5.02 TeV ultraperipheral
Pb+Pb collisions

13 events observed for
 2.6 ± 0.7 expected
background (4.4σ)

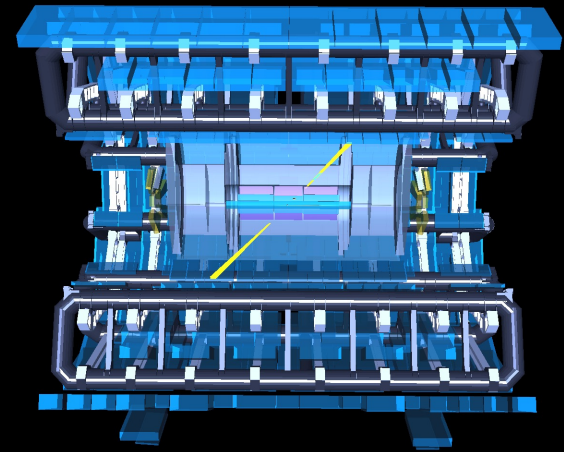
[arXiv:1702.01625]



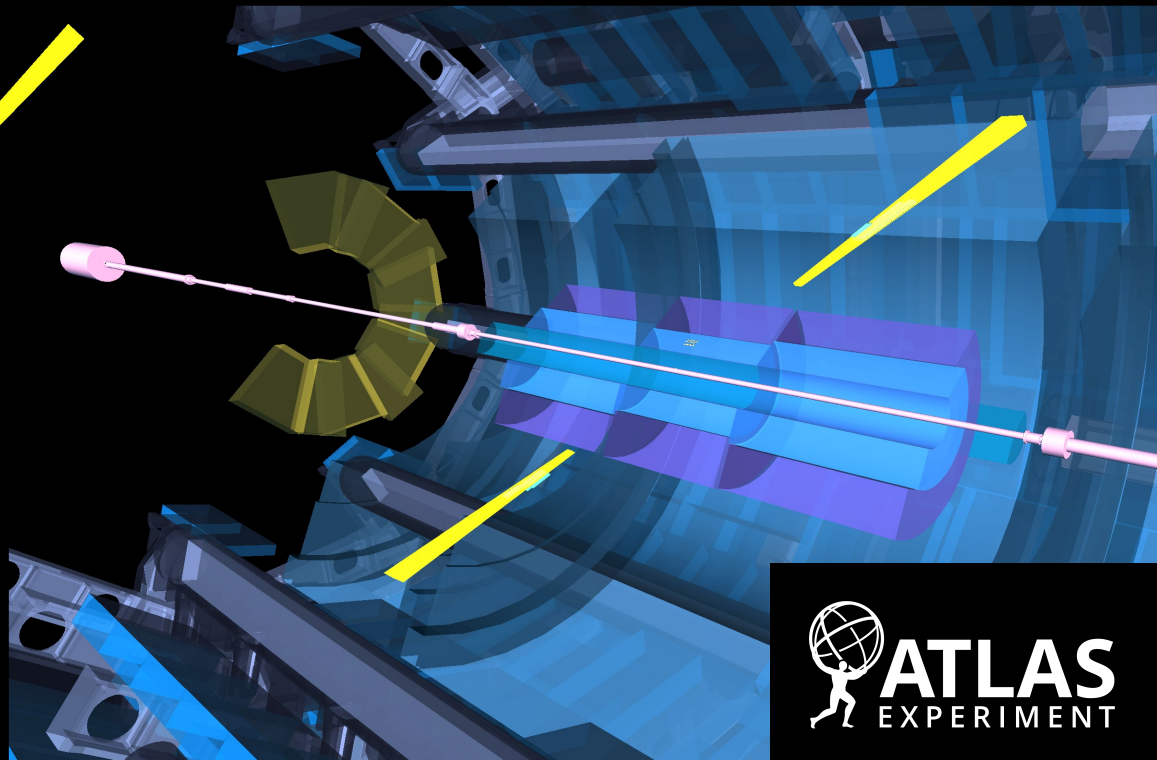
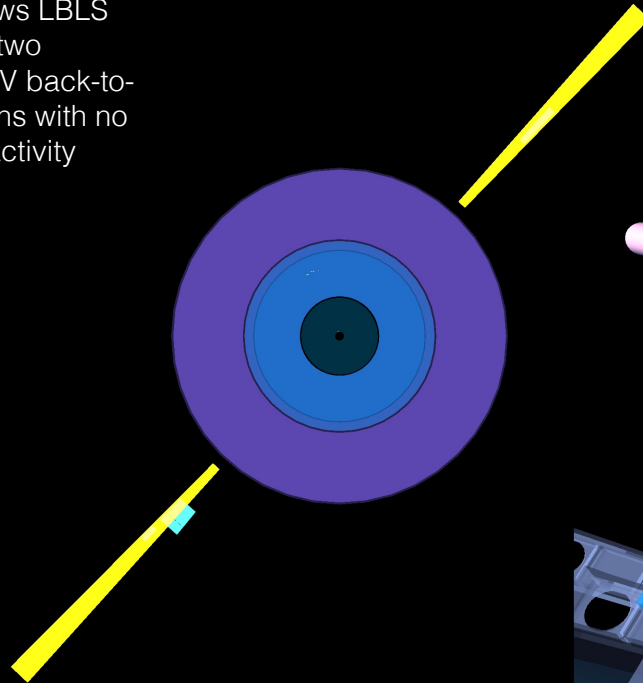
=



Field strength of up to 10^{25} V/m reached



Picture shows LBLS
candidate: two
 $E_T = 4.9$ GeV back-to-
back photons with no
additional activity

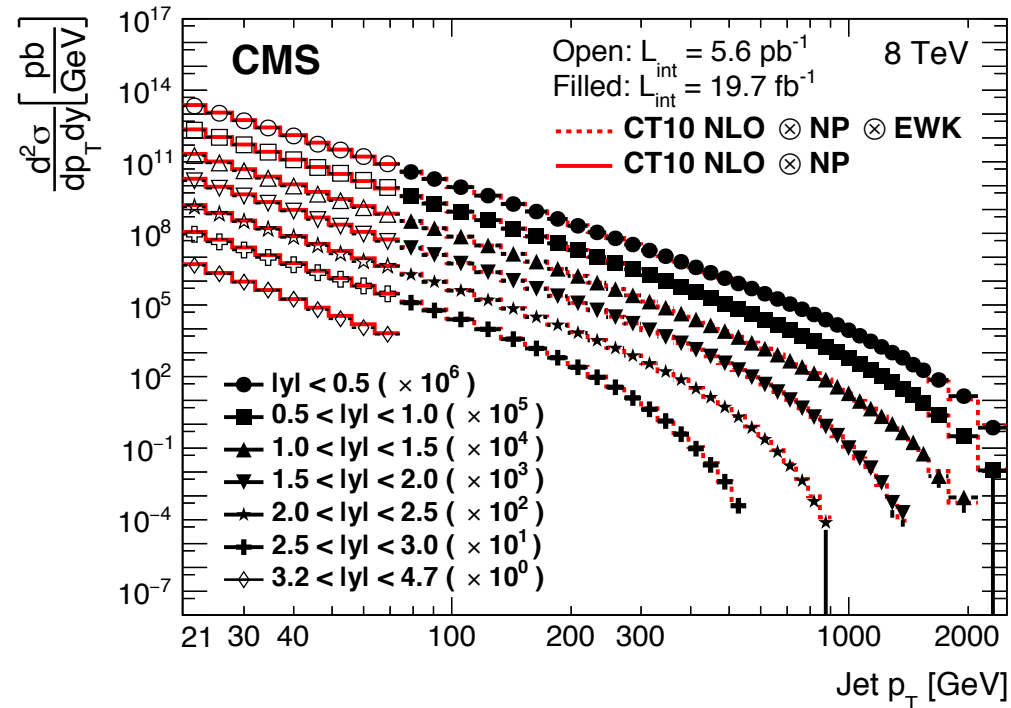
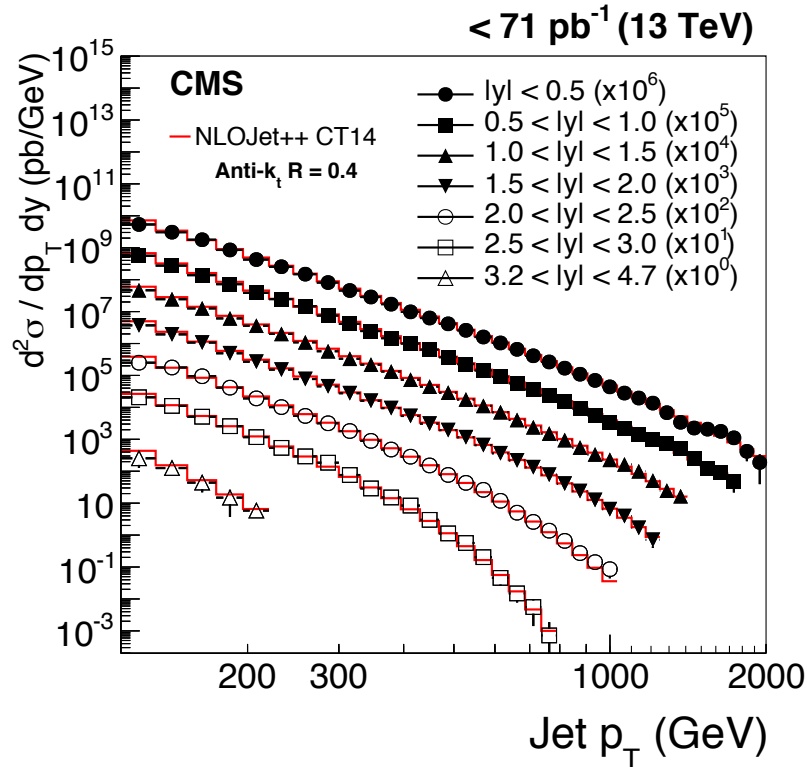


Measurement of jet cross section at 13 TeV

Primary test of QCD at highest collision energy

CMS 1605.04436, 1609.05331

Double differential cross section measured by CMS

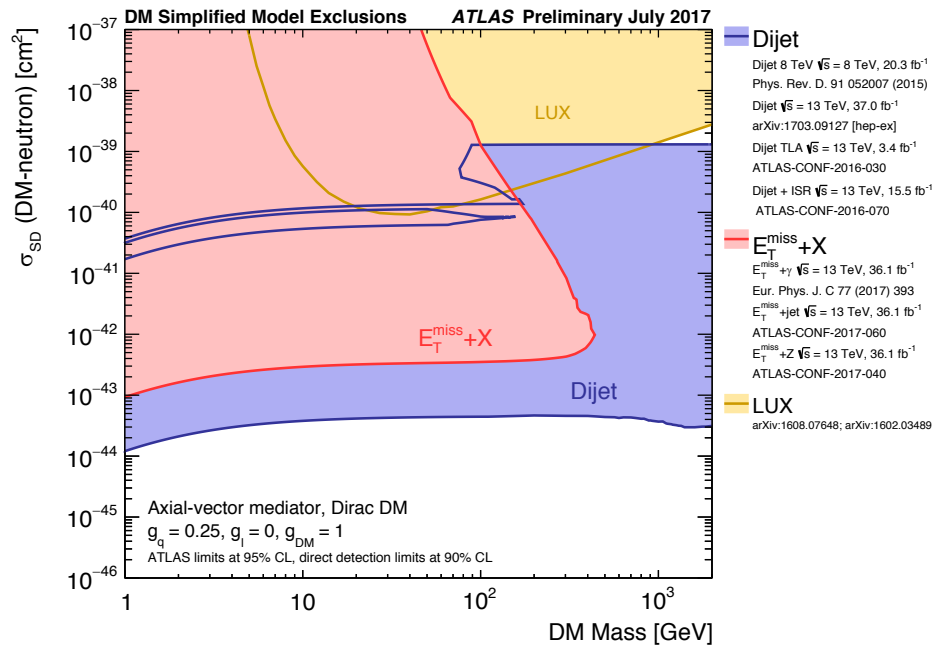


Comparison with 8 TeV plot (right) shows effect of increased parton luminosities at high jet p_T

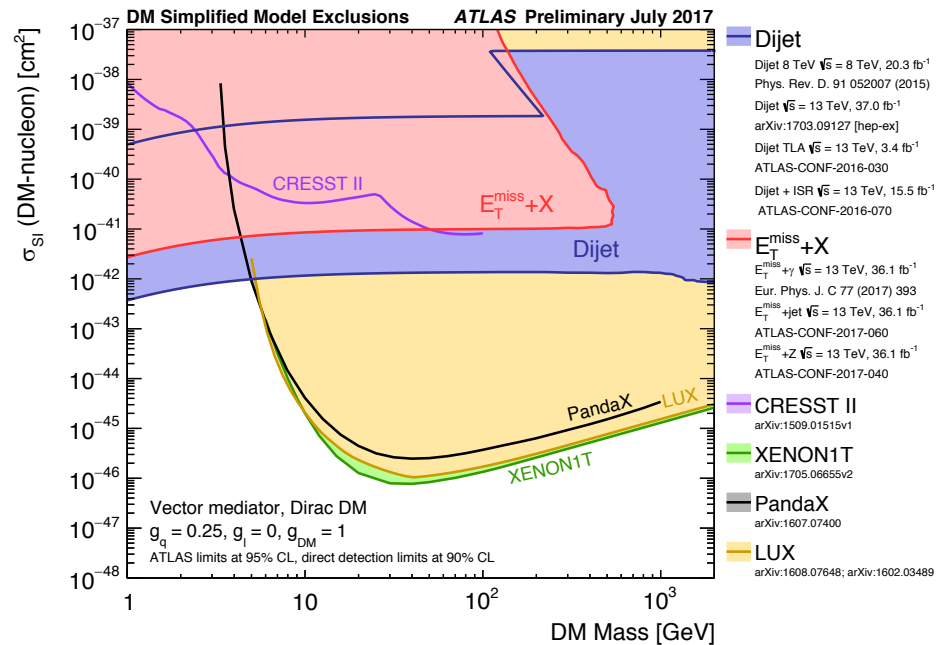
Searches for dark matter production at the LHC

Canonical signature is 'X+MET' with large variety of 'X'

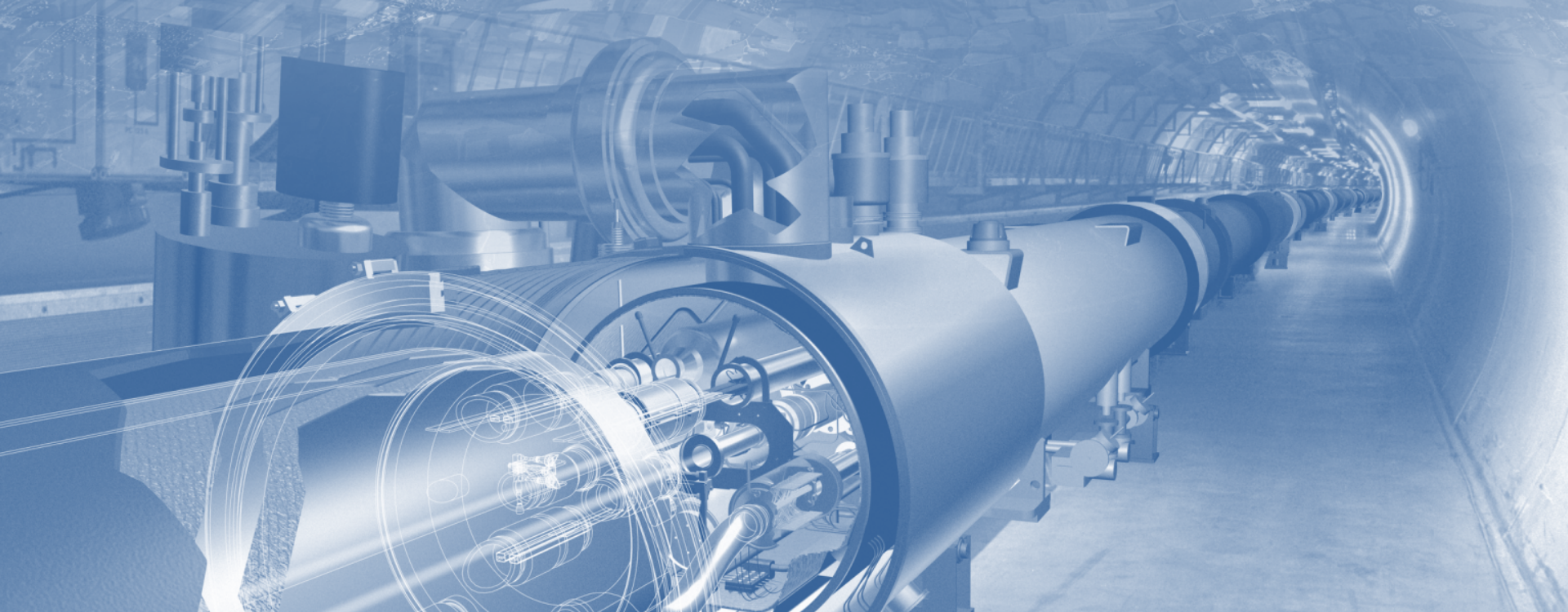
Comparison of ATLAS monojet and dijet resonance searches with direct dark matter searches



Spin-dependent DM-nucleon cross section versus DM mass



Spin-independent DM-nucleon cross section versus DM mass



Beyond the HL-LHC

Only a very brief enumeration of projects

Future hadron collider projects in a nutshell

The next discovery machine

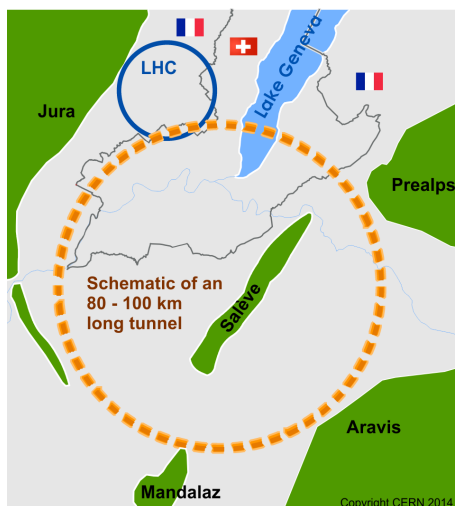
HL-LHC: $E_{\text{CM}} = 14 \text{ TeV}$, 3 ab^{-1} , 2026~2035... (formally approved as *project* by CERN council last week)

Future Circular Collider FCC-hh (CERN):

- $E_{\text{CM}} \sim 100 \text{ TeV}$ in 100 km ring, $L \sim 2 \times 10^{35} \text{ s}^{-1}\text{cm}^{-2}$
- $\sim 16 \text{ T}$ magnets, possibly HE-LHC ($E_{\text{CM}} \sim 28 \text{ TeV}$) as intermediate stage
- Huge detectors needed for muon p_T measurement
- Possible start of physics ~ 2035

SppC (China):

- $E_{\text{CM}} \sim 71 \text{ TeV}$ in 55 km ring, $L \sim 1 \times 10^{35} \text{ s}^{-1}\text{cm}^{-2}$
- Requires very high gradient dipole magnets $\sim 20 \text{ T}$
- Possible start of physics ~ 2042



Parameter	FCC-hh		SppC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main + 2		2	2 main + 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/lp [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	~ 25	12	1	5
events/bunch crossing	170	~ 850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
E-loss/turn	5 MeV		2 MeV	7 keV	7 keV
synchrotron radiation/beam	3 MW		5.8 MW	5.4 kW	9.5 kW

Future e⁻e⁺ collider projects in a nutshell

Measure EW & EWSB sector to highest precision

International Linear Collider ILC (host candidate: Japan)

- 20 years of R&D, mature technology, ~32 MV/m accelerating gradient ~ xFEL at DESY (45 MV/m for 1 TeV)
- $E_{\text{CM}} \sim 500\text{--}1000$ GeV in 31–45 km total length, $L \sim 1.8 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$, only one interaction region
- nm beam size, possible start of physics ~ 2030

Compact Linear Collider CLIC (CERN)

- High-gradient 2-beam scheme*: 100 MV/m gradient
- $E_{\text{CM}} \sim 380\text{--}3000$ GeV, 11–50 km total length, $L \sim \text{a few} \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$, only one interaction region
- 0.5 ns bunch distance, nm beam size, large beamstrahlung, physics ~ 2035

*A low energy, high current, “drive” beam is decelerated in power extraction structures and the RF power is transferred to the cavities that accelerate the main beam

Future Circular Collider FCC-ee (CERN):

- $E_{\text{CM}} \sim 90\text{--}350$ GeV in 2 rings (90k bunches), $L \sim 70\text{--}1.3 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- Synchrotron power (E^4/R up to 7.5 GeV/turn): 100 MW (LEP-2: 22 MW)

Circular EP collider CEPC (China):

- $E_{\text{CM}} \sim 240$ GeV, $L \sim 2 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- Single ring, 50 bunches
- Possible start of physics ~ 2028

parameter	FCC-ee			CepC	LEP2
energy/beam [GeV]	45	120	175	120	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP $\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	70	5	1.3	2.0	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

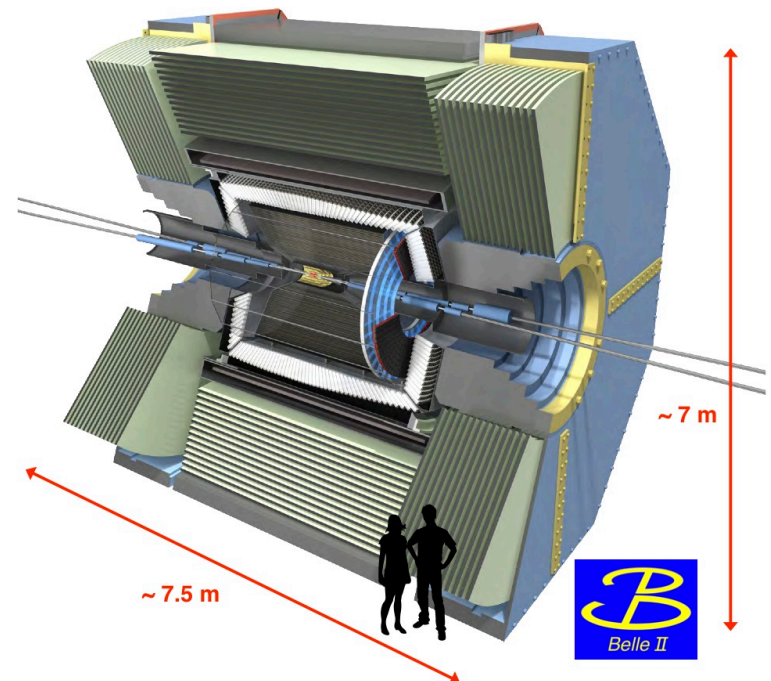
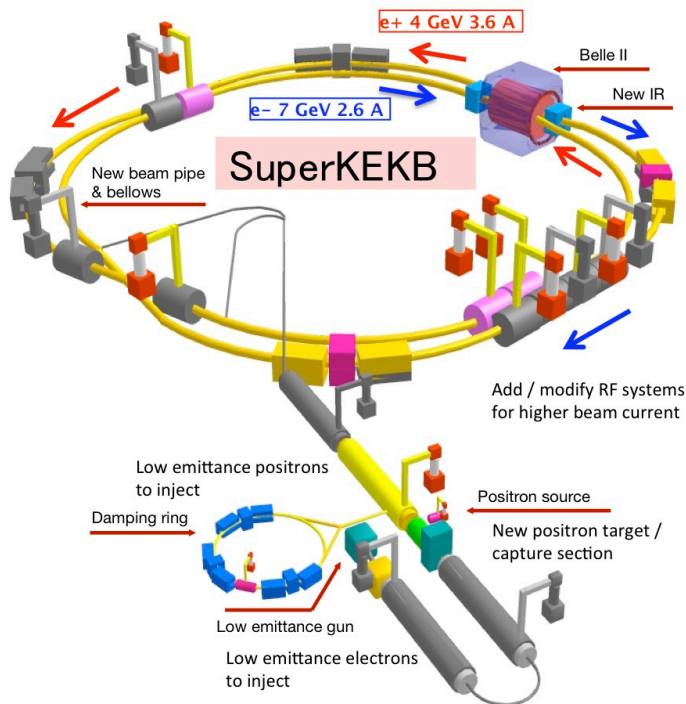
More Standard Model and Flavour physics

Complementary to SuperKEKB / Belle II programme !

Expect ~40 times luminosity of 1st generation asymmetric B-factories: up to 50 ab^{-1}

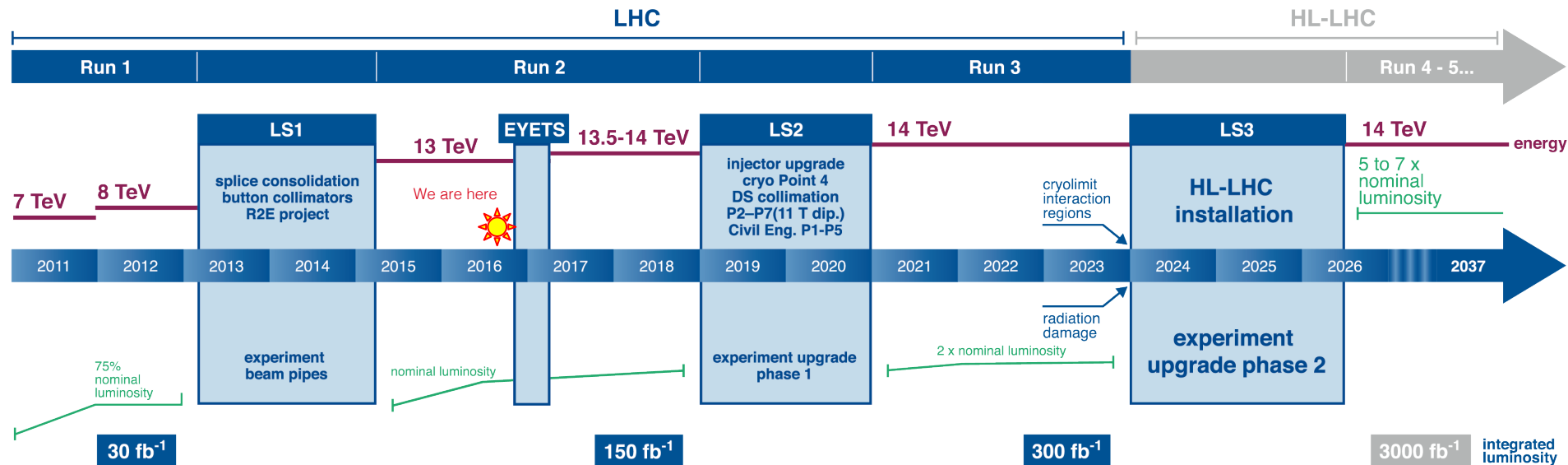
Among the physics highlights:

- Rare decays: $B \rightarrow \tau \nu$ ($< 5\%$), $R_{D^{*}}$, detailed $b \rightarrow s$ studies (incl. $B \rightarrow K^{(*)} \nu \nu$ penguin+box to ~20%)
- Lepton flavour violation, universality tests
- CP violation in bottom and charm systems



How can these LHC luminosity improvements be achieved ?

Parameter	LHC Run-1	LHC Run-2 & 3	HL-LHC
Beam energy [TeV]	0.45–4	6.5–7	7
Peak inst. luminosity [$\text{cm}^{-2} \text{s}^{-1}$]	$0.8 \cdot 10^{34}$	$(0.7\text{--}2) \cdot 10^{34}$	$5 \cdot 10^{34}$ (levelled)
Bunch distance [ns]	50	25	25
Max. number of bunches	1380	2028~2748	2748
β^* [cm]	60	40	15
ε_n [μm]	2.3	2.5–3.5 (2.3 with BCMS)	2.5
Max. num. protons per bunch	$1.7 \cdot 10^{11}$	$1.2 \cdot 10^{11}$	$2.2 \cdot 10^{11}$
Average pileup $\langle\mu\rangle$	21	21~50	140



Particle physics at the dawn of the LHC Run-2

No new physics in direct searches or study of quantum fluctuations

QED tested to parts per million accuracy (slight anomaly in muon $g-2$)

Asymptotic freedom in strong interactions verified at % level

Electroweak unification tested to high precision

Quark sector: CKM picture for quark mixing & CP violation confirmed

Lepton sector: massive neutrinos, unknown nature, masses, CP violation, sterile ν 's ? No flavour violation in charged lepton sector. Lepton universality tested to per-mil level

No compelling sign of new physics found at high mass scales, or anywhere else, eg: no electric dipole moments (EDM), no dark matter particles (gravitational hints only), no axions, no proton decay

