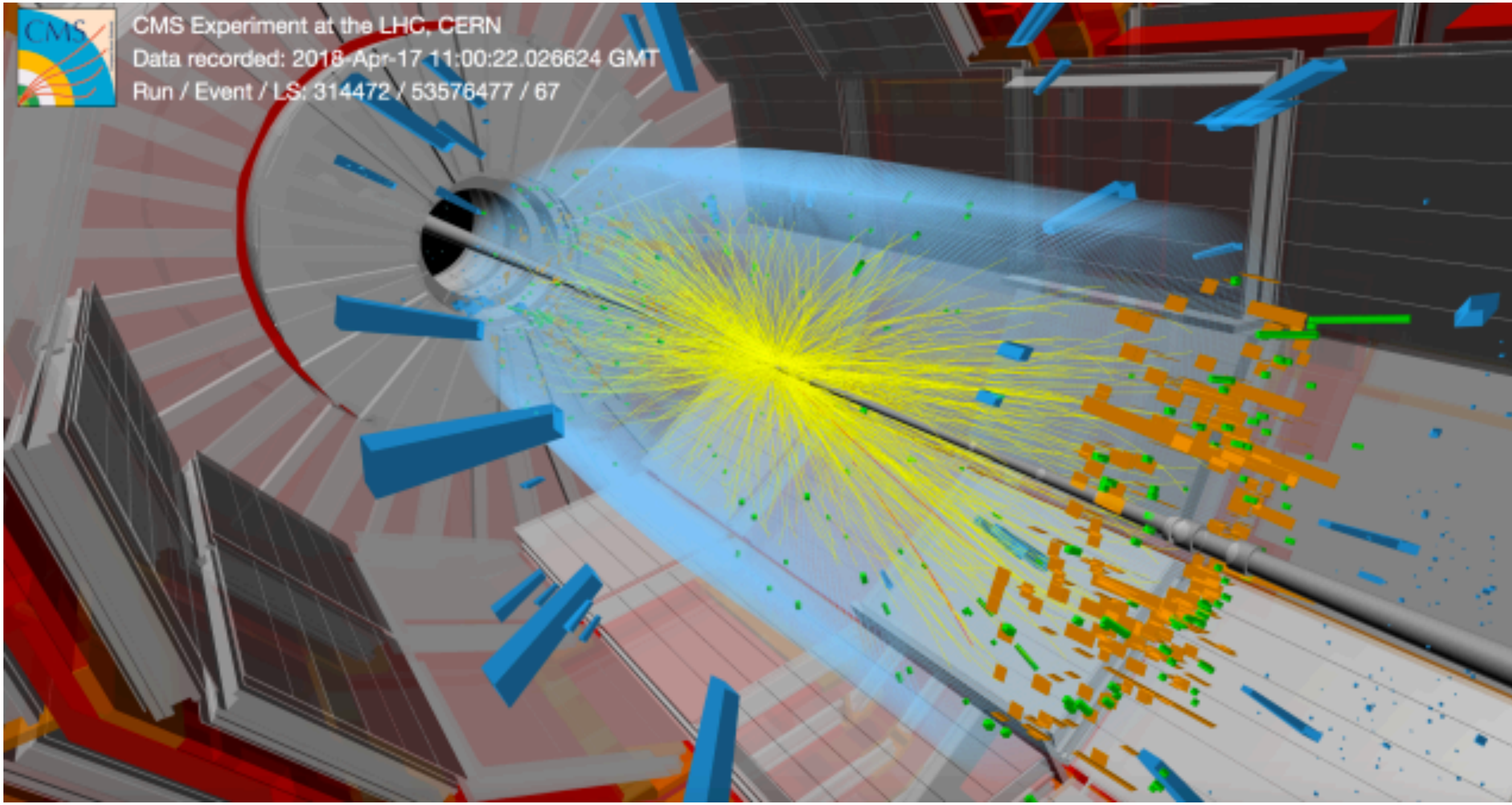

The Large Hadron Collider in the Middle of its Lifetime

Dr. Thomas Kress, III. Physikalisches Institut B (Prof. A.Stahl), RWTH Aachen

8th Georgian-German School & Workshop in Basic Science (GGSWBS'18)

Tbilisi, 2018

Aug. 21st

Georgian German Science Bridge
Connecting people & knowledge
7th Georgian-German School and Workshop in Basic Science
GGSWBS'16

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

CMS Germany

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Outline of this Presentation

- The Standard Model of particle physics
- The CERN Lab, the LHC accelerator and one of the four detectors
- From LHC Run 1 to Run 2
  - discovery of "a/the" Higgs boson in Run 1
  - benefits in Run 2
- A few selected new ATLAS and CMS results
  - focus on Higgs physics
  - skipped ALICE's Heavy Ions and LHCb results
- The LHC beyond 2018 – Run 3 + Run 4
- Conclusions
- (Activities of the local RWTH Aachen University CMS/HEP groups)

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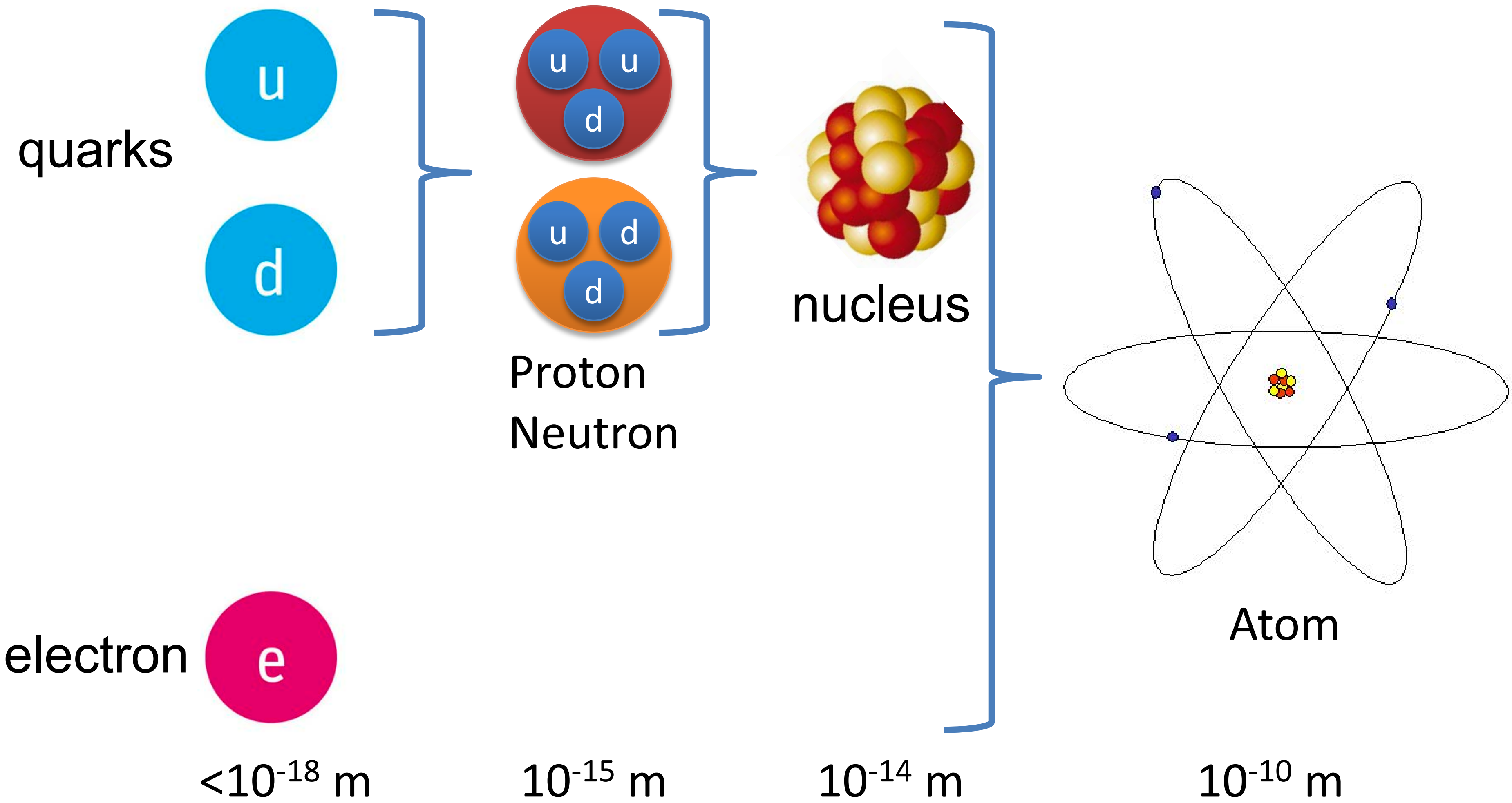
The smallest particles



The smallest particles

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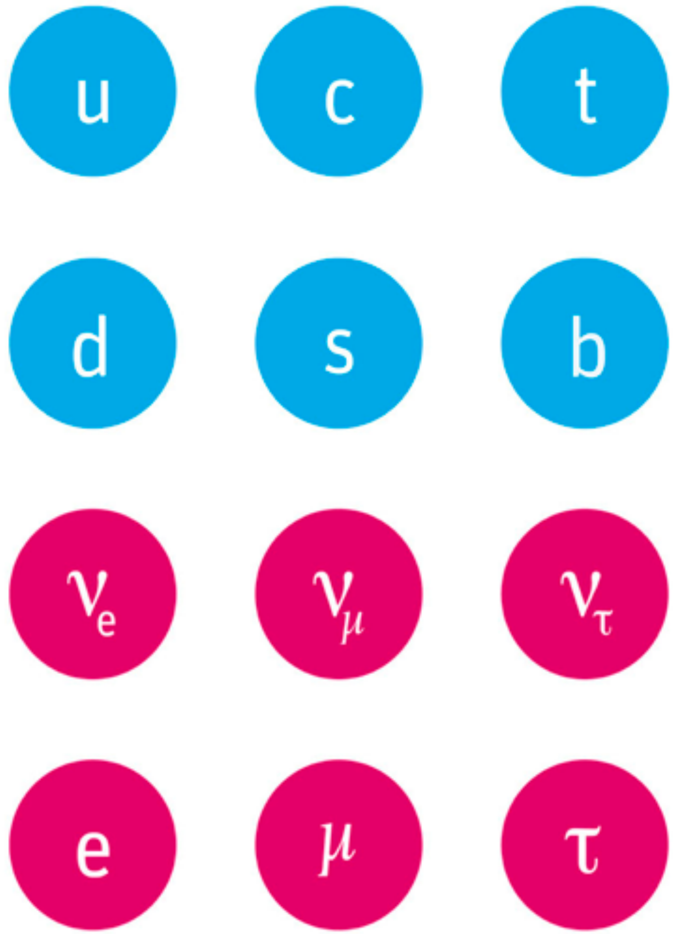
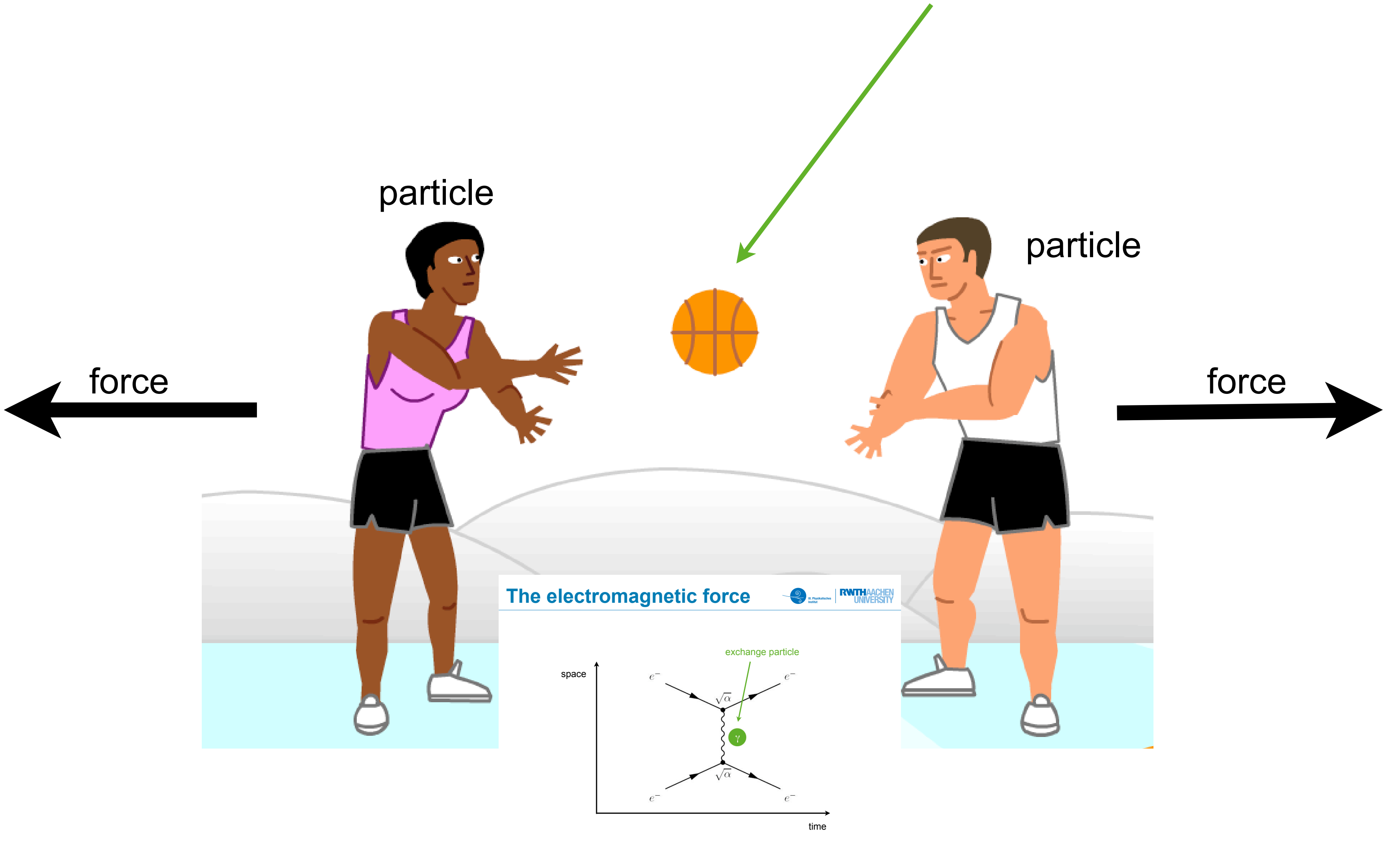
- quarks
- leptons



Actually we have three ”generations”

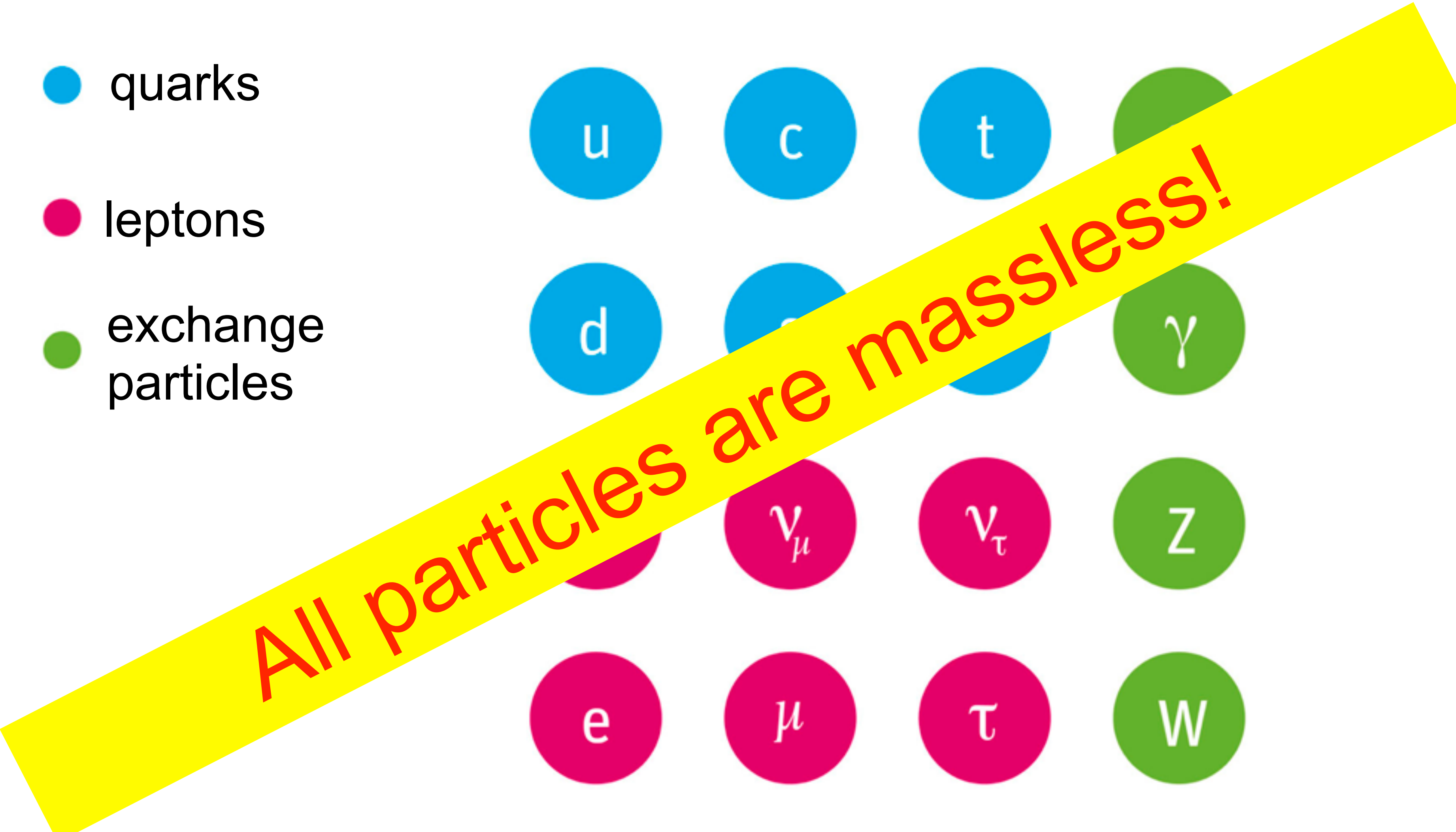
The forces

Forces between particles by **particle exchange**



The big problem

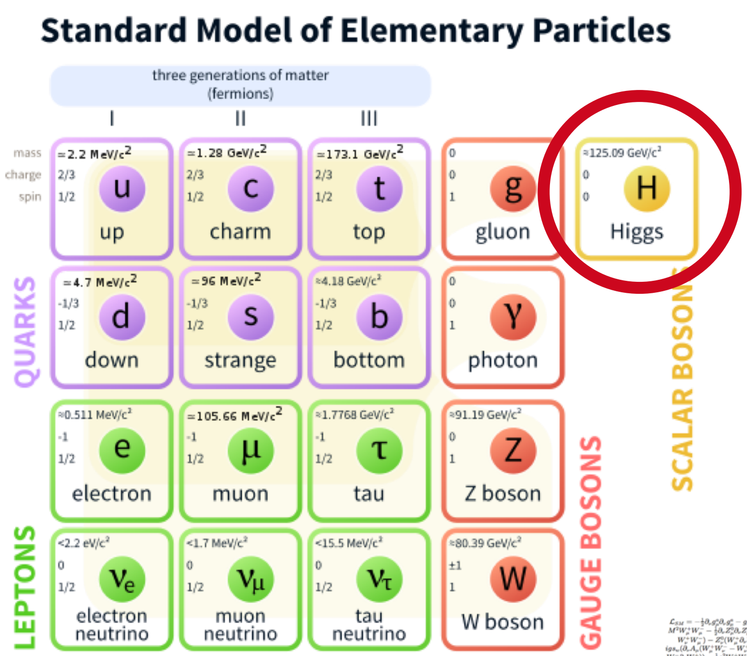
- quarks
- leptons
- exchange particles



Picture is incomplete – we need a mechanism to create mass

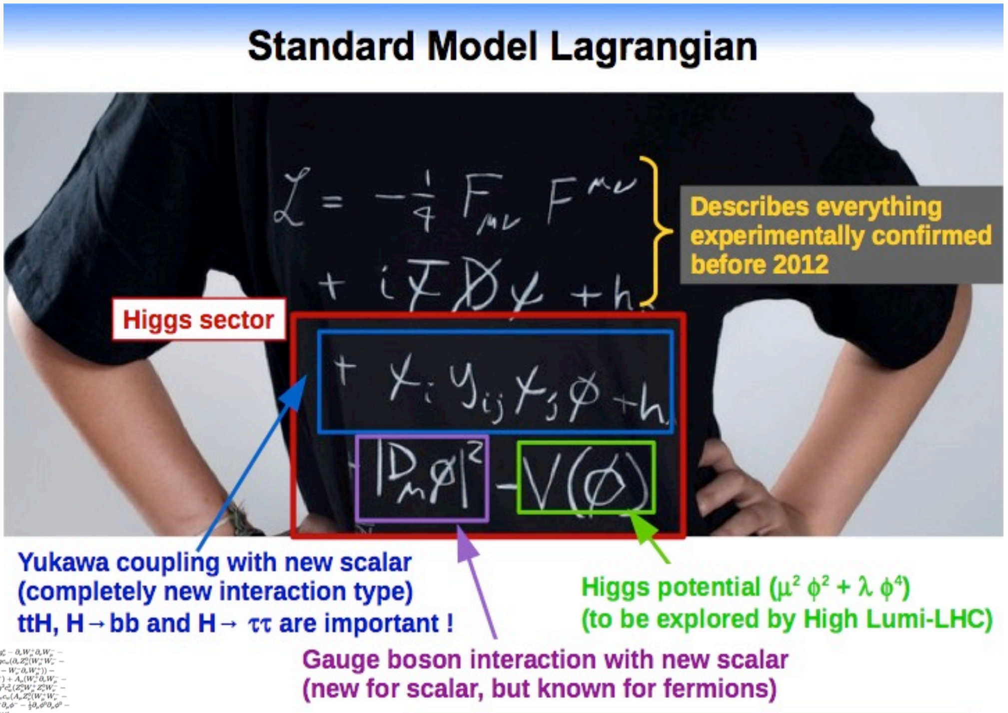
The Standard Model (SM) of Particle Physics

A HEP experimentalist´s view:



Source: PBS Nova, Fermilab.

A HEP theoretician´s view:



Higgs measurements at LHC test new part of SM

G Salam LHCP2018

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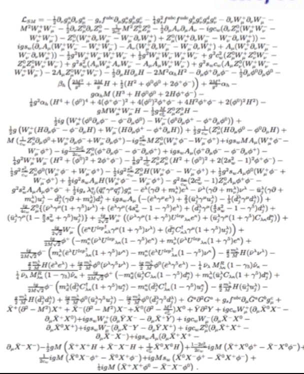


for a T-Shirt in XXL

The Large Hadron Collider at CERN

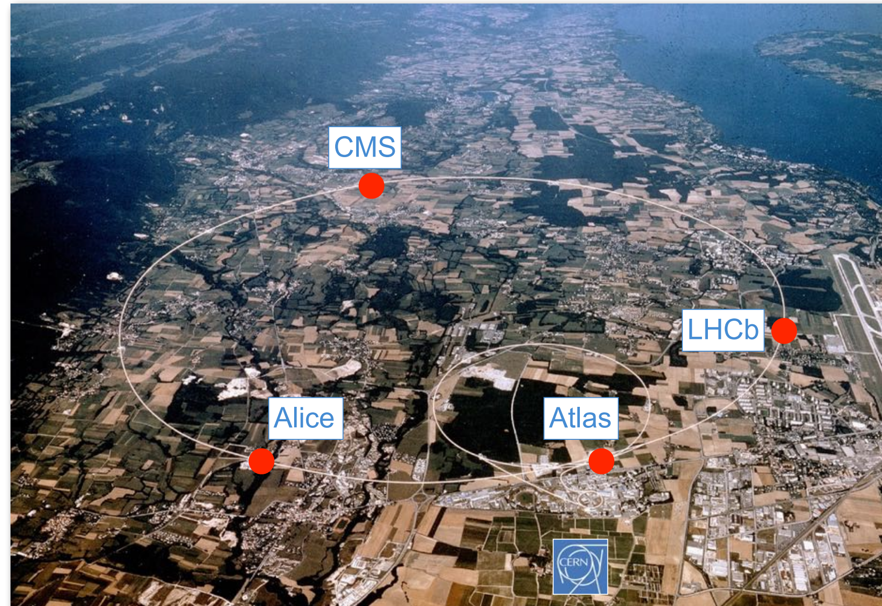
CERN budget: ~1 billion €/year
International science lab since 1954

CERN

European
centre of particle physics

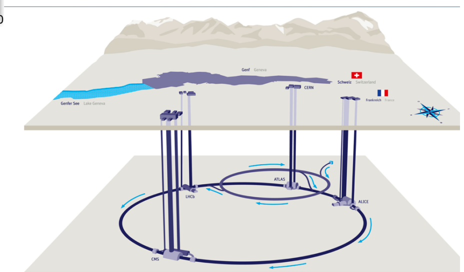
Oliver Pooth 30

Large Hadron Collider LHC



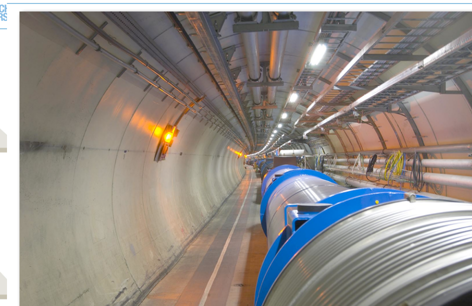
Oliver Pooth 31

LHC



Oliver Pooth

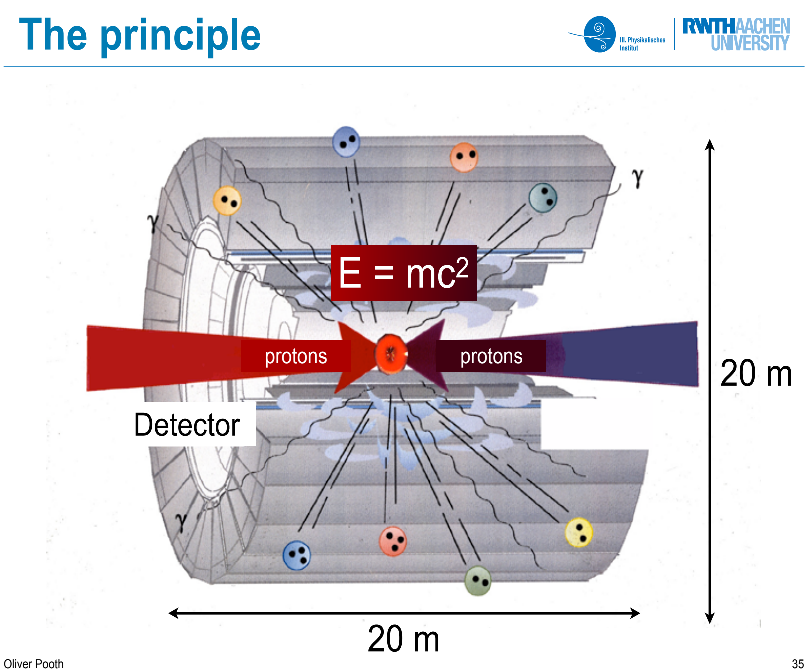
LHC tunnel

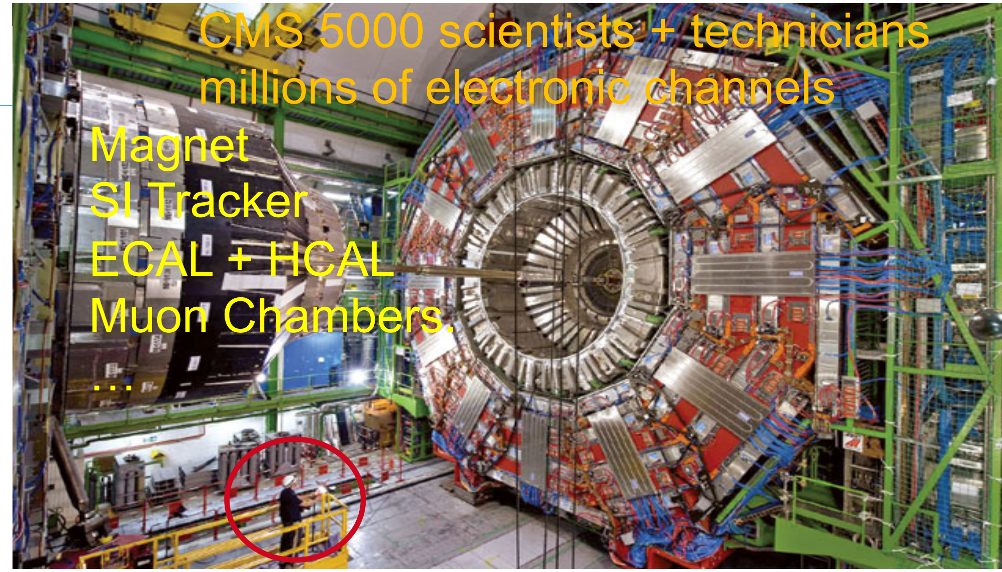


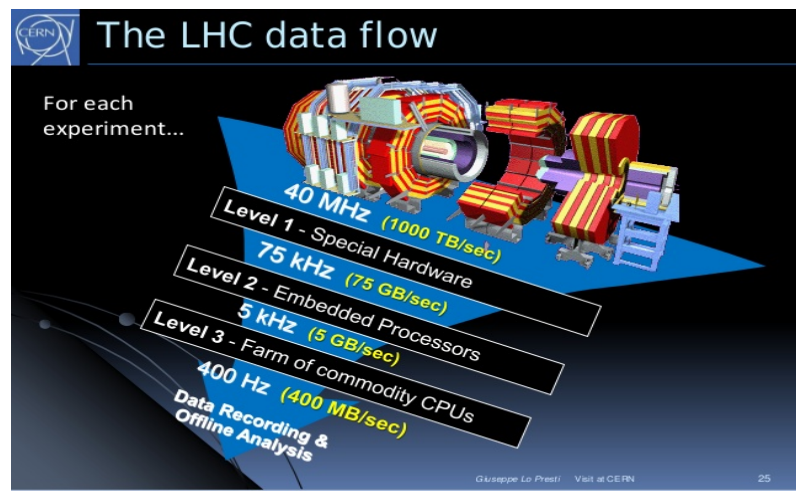
Oliver Pooth 33

LHC: 27 km ring, -100 m
Accelerates and collides bunches of protons
Four huge experiments/detectors

The CMS Detector







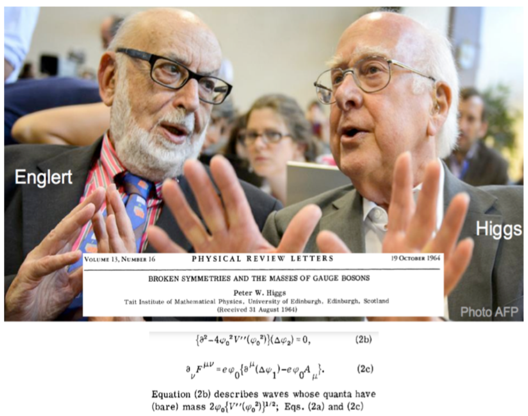
Records huge number of "events" with specific pattern of objects (#,E,angle,..)
Performing statistical ensemble analysis

LHC Achievements in Run 1 (2010 – 2012) at E_{cm} = 7 & 8 TeV

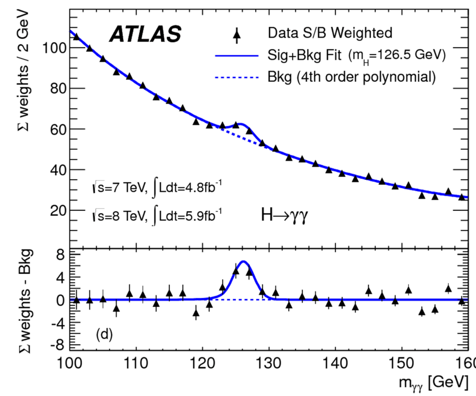
Analysis: construct sensitive observables, study shape and/or compare measured data with predictions with vs. w/o new effects/particles

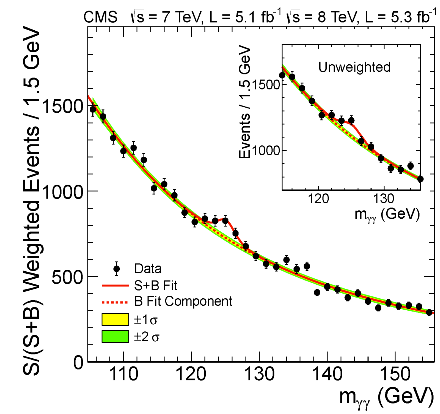
Numerous important physics publications

A Higgs boson (m=125 GeV) as the cornerstone of the Standard Model established by ATLAS+CMS in several (bosonic) channels

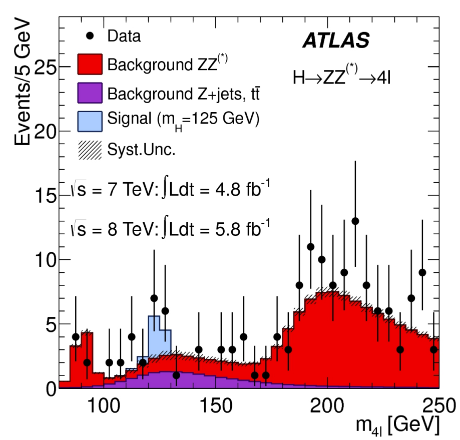


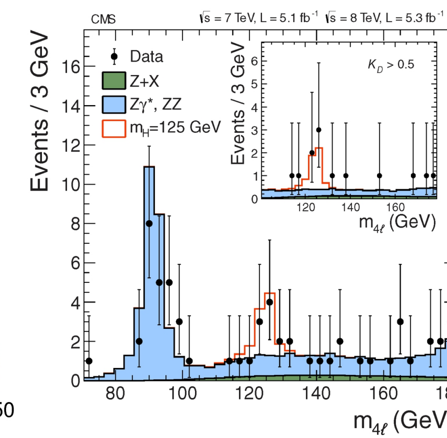
1964 predicted
2011/12 established
2013 Noble Prize





(not with full 2012 data sample)





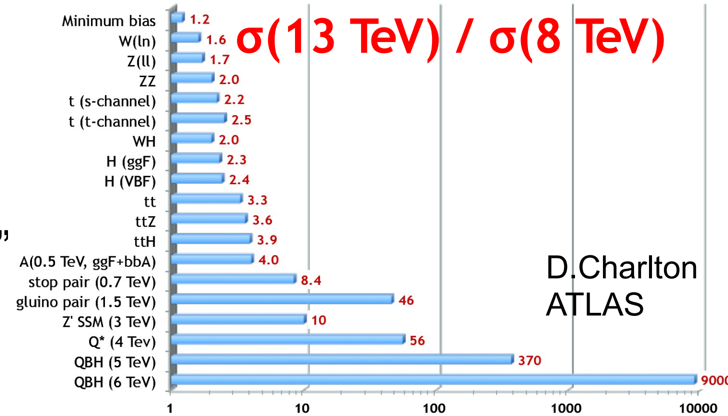
Higgs explains masses of $W^{+/-}$, Z^0
(also masses of the fermions (for neutrinos more complex))

In Run 1 no observation of physics beyond the SM

From Run 1 at 7/8 TeV to Run 2 (2015-2018) at 13 TeV

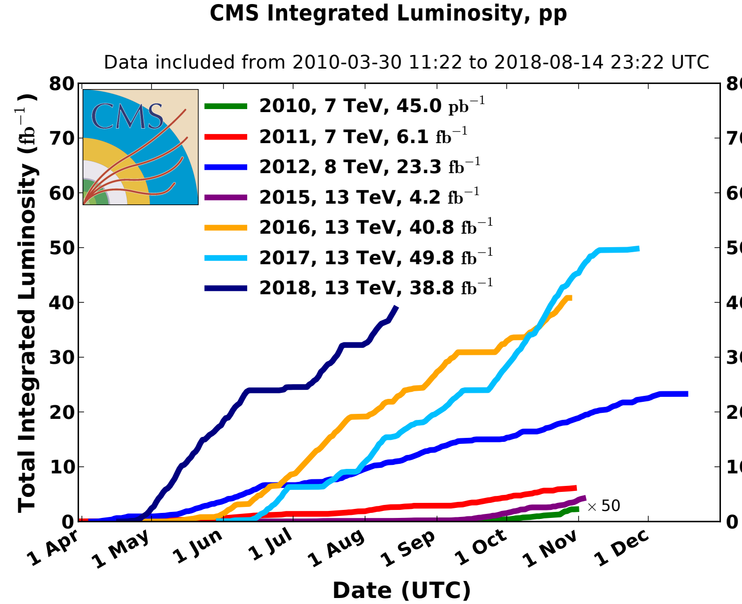
Major changes:

(Much) Higher potential for SM & searches
(in most cases) “higher E_{cm} beats more lumi”



Improvements in theory calculations
and Monte Carlo model generators

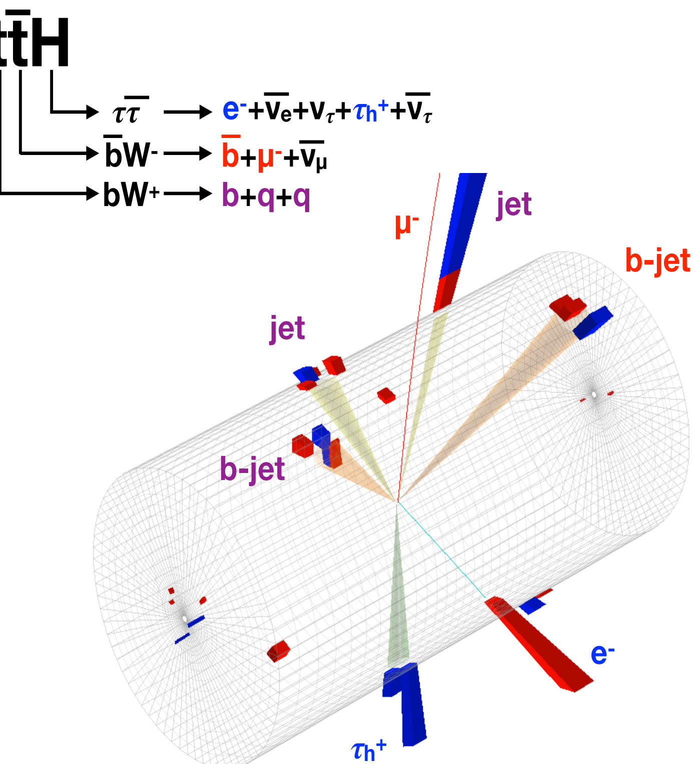
A few detector upgrades, trigger ~1kHz
Computing becomes more flexible



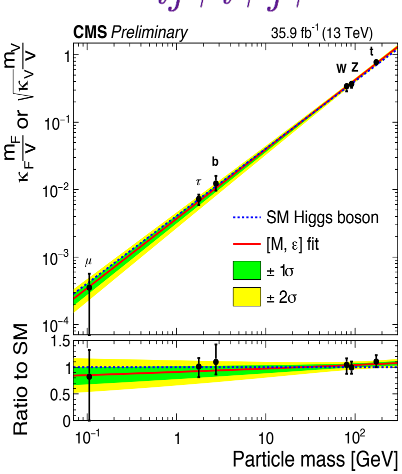
Much more data is available for analyses
- LHC peak luminosity ~2 x design
  (use lumi levelling to get less pile-up)
- plus (CMS) “parking” of b physics data
- 2018 expect ~65 fb^{-1} for whole year

Selected New Results from Run 2 – Higgs Physics

S.Rahatlou, CMS



$Y_{ij}\psi_i\psi_j\phi$



HIGGS
FROM DISCOVERY TO PRECISION

Higgs to fermion coupling first established in H->$\bar{\tau}\tau$

First observation of a Higgs to (direct) quark coupling ($t\bar{t}$) (in production) by ATLAS/CMS

H->$b\bar{b}$ now > 5 standard dev.
(huge cross section but high backgrounds)

Higgs spin consistent with 0

As expected small total width
(measured by ZZ on-/off-shell interference)

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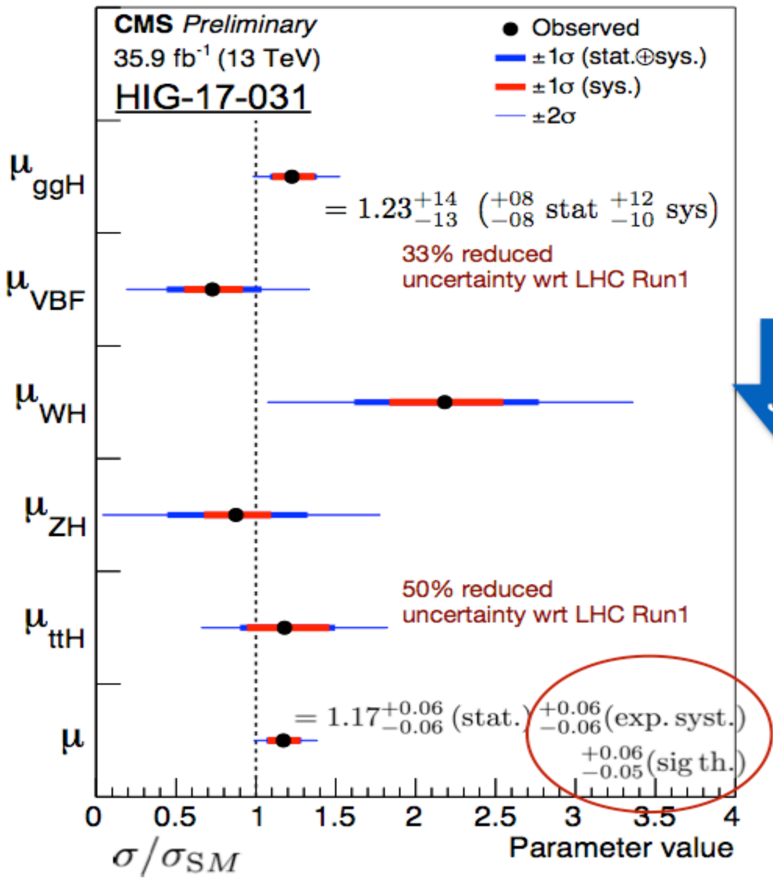
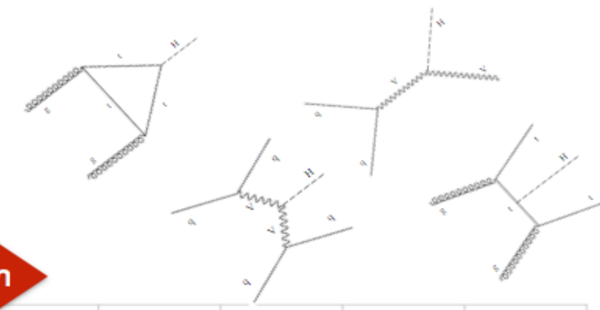
HIGGS PROPERTIES





Production

Decay

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●	●	●
H→bb	●		●	●
H→ττ	●	●		●
H→μμ	●	●		
H→inv	●	●	●	

Total of 250 even categories

$$BF(H \rightarrow \mathrm{inv.}) < 22\% \,@\, 95\%\,\mathrm{C.L.}$$

- Nearing theory-limited territory with just 2016 data

Shahram Rahatlou, Roma Sapienza & INFN

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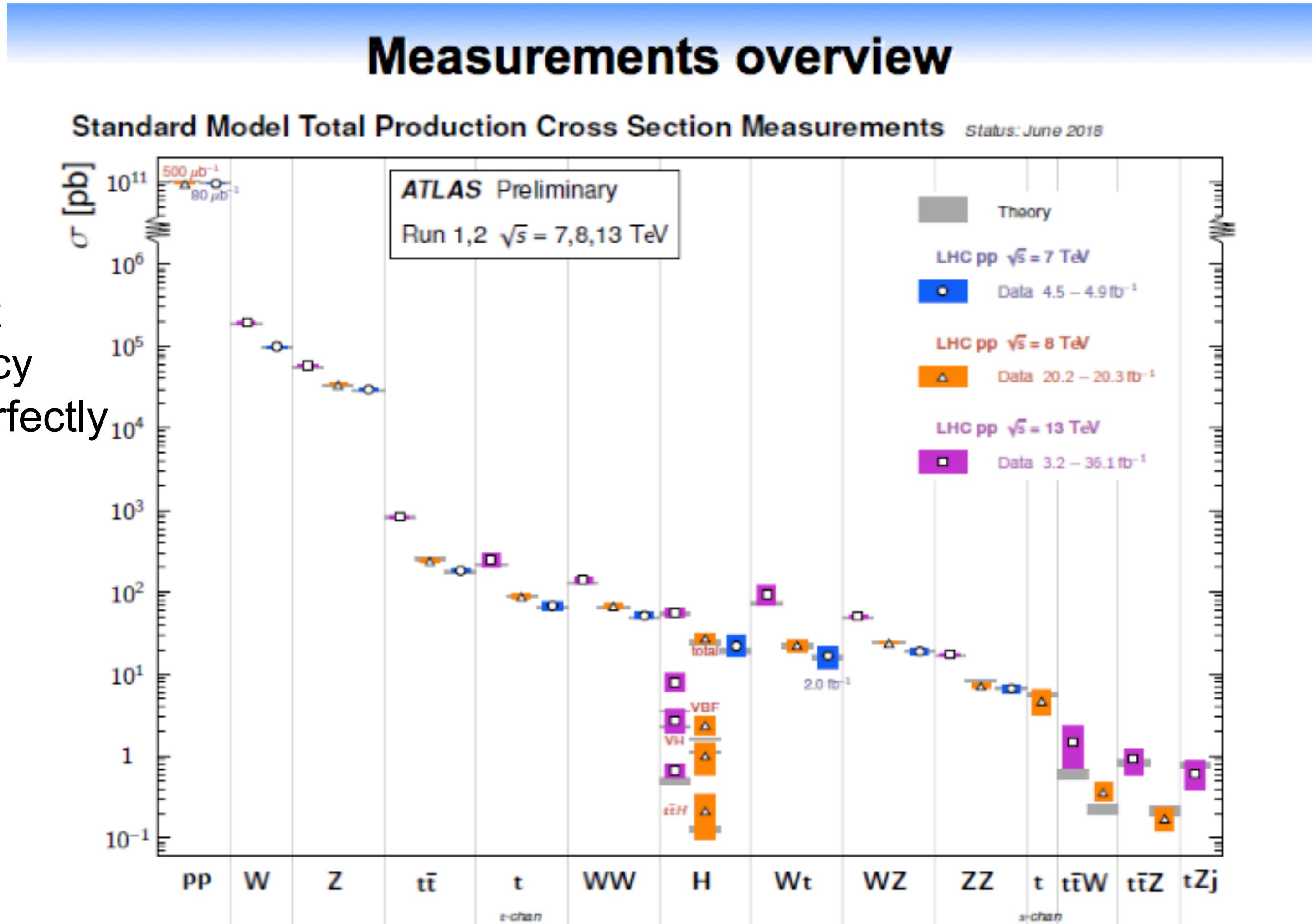
Selected New Results from Run 2 – SM Measurements

No significant discrepancy
SM works perfectly



Tancredi, ATLAS

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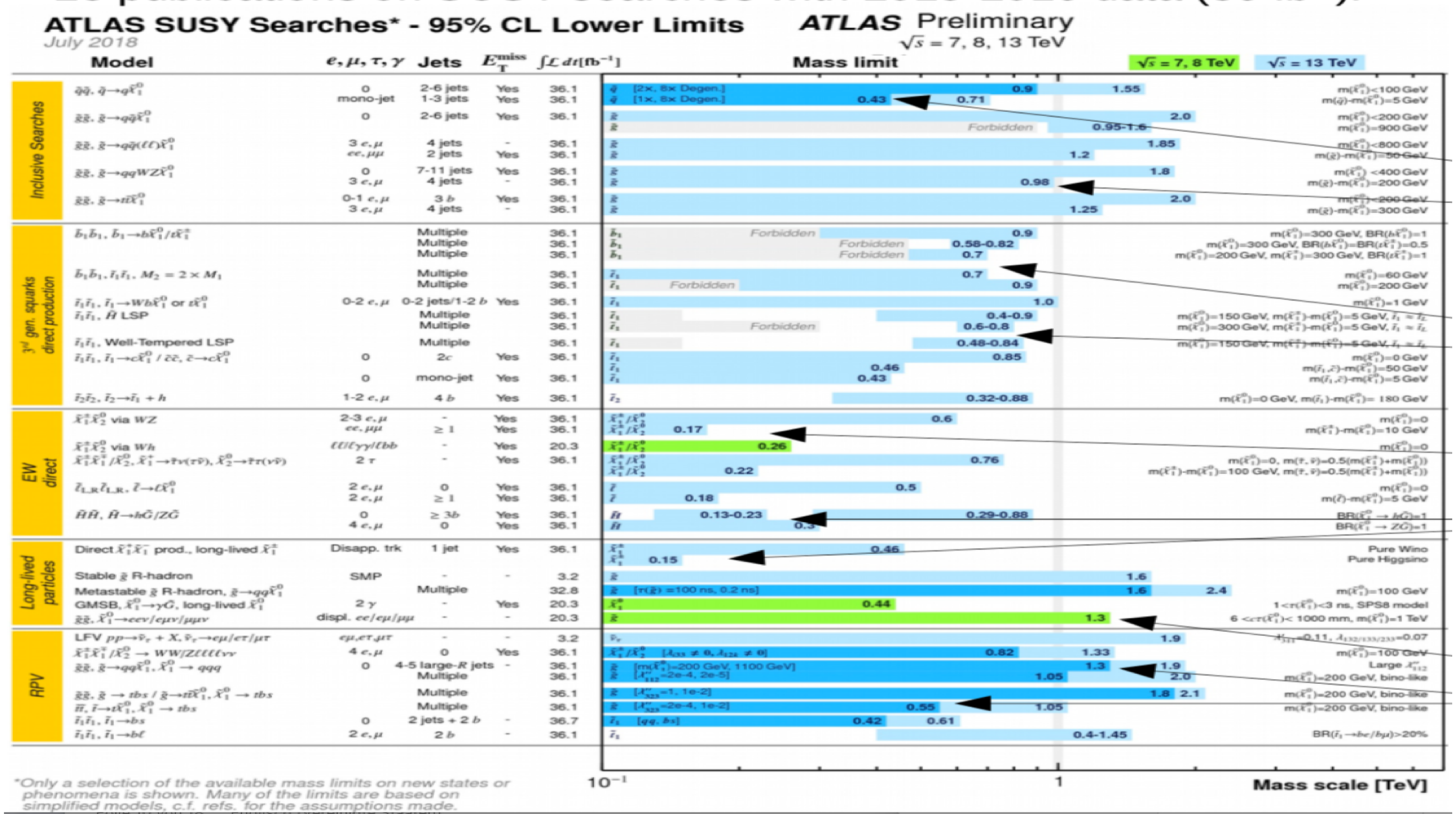
Selected New Results from Run 2 – SUSY (Supersymmetry)

Many were hoping to establish SUSY – unfortunately no sign so far

-> set limits!

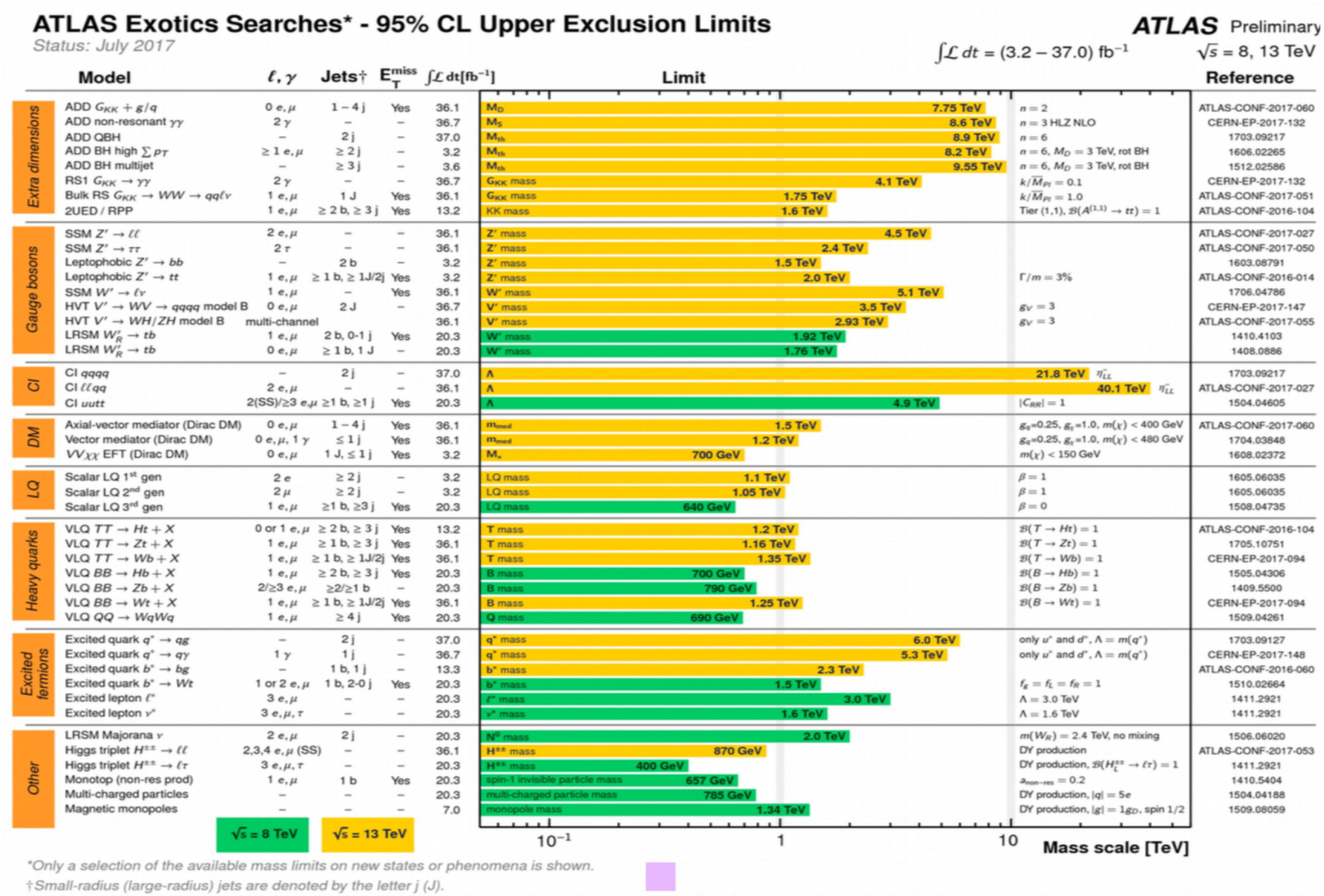
28 publications on SUSY searches with 2015-2016 data (36 fb^{-1}).



Tancredi, ATLAS

Selected New Results from Run 2 – Exotic Searches

Many were hoping to find (other) physics beyond the SM – not (yet)



Tancredi, ATLAS

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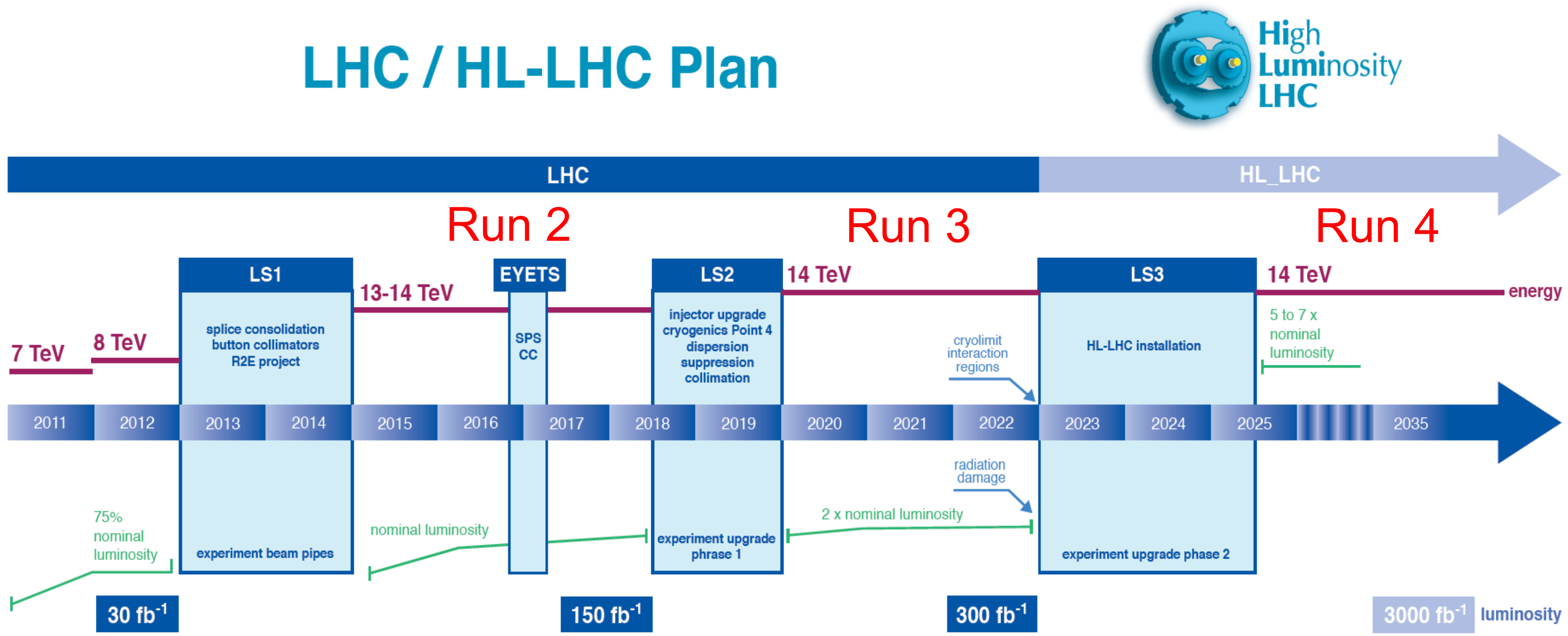
LHC & HL-LHC Schedule and Challenges

Physics potential for the next two decades – huge increase of data set



Run 3: ”moderate” increase of luminosity, a few “upgrades phase 1” detector and trigger upgrades, probably increasing E_{cm} a bit (13->14 TeV)

Run 4: trigger, electronics, computing, detector (radiation esp. in endcap regions), major “upgrade phase 2” replacements necessary – huge challenges ahead!

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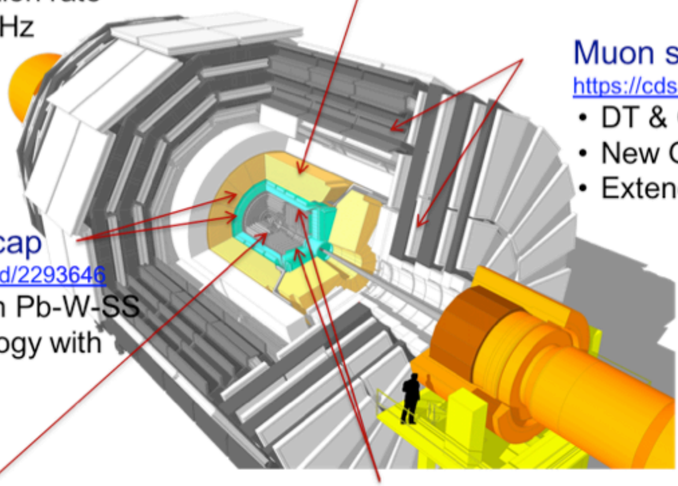
CMS Phase II Upgrade

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2296612
- ≃ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Shahram Rahatlou, Roma Sapienza & INFN 34

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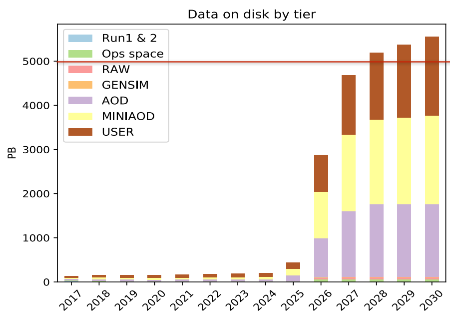
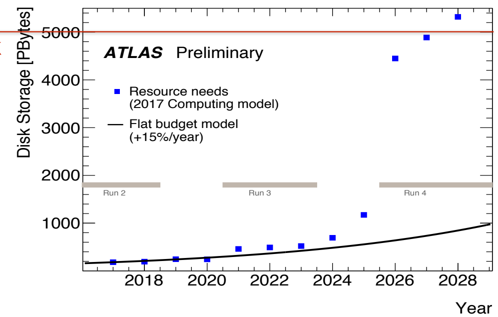
LHC & HL-LHC Schedule and Challenges - Computing

HL-LHC Current Data Predictions

- These plots were created at the request of our funding agencies and represent what the needs would be extrapolating from current practice.



5 Exabytes of Data on Disk

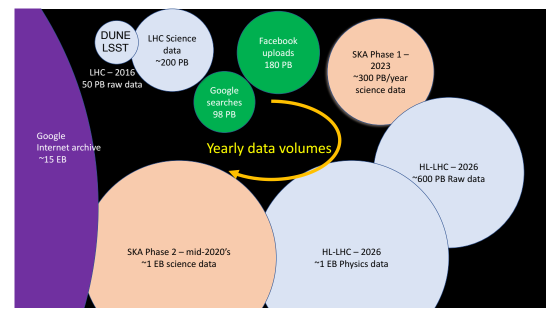


Fermilab

7 9-Jul-2018 Liz Sexton-Kennedy I Future of Software and Computing for HEP

For Run 4 (for ALICE Run 3): with a ”flat budget” and current technology extrapolation and harvesting of “opportunistic resources” still a factor ~5 for CPU and storage missing

- We do this today with a world wide computing grid. It will need to grow.
- Reliable and performant networking is key to our federated data model.
- Usage of this infrastructure will have to expand to support other HEP domains as well.



Fermilab

11 9-Jul-2018 Liz Sexton-Kennedy I Future of Software and Computing for HEP

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Conclusions:

LHC Run 2: excellent performance of accelerator, detectors, computing, analyses

- Resonance at 125 GeV seems to be THE SM Higgs, lots of quantitative H results
- So far in CMS and ATLAS no evidence of signals for SUSY or other "new" physics
  - most of us think there must be more ... SM is great but has fundamental "deficiencies"
  - No more low-hanging fruits – have to explore niches in parameter space, other ideas, ...
- (LHCb with a lot of new interesting results on CP, spectroscopy/particle compo-sitions; first indications of flavor anomalies (to be confirmed with full Run2 data))
- (As usual ALICE Heavy Ions data taking will start end of the year)

Collaborations are already working intensively on detector, computing, ... upgrades for Run 3/4

Challenging ~15 years of LHC physics with a huge data set are still ahead of us!

- In the next few years, do we find/establish „New Physics" (at LHC)?
- If nature is different than our expectations, perhaps this is even more exciting?!

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CMS Projects at RWTH Aachen University, Germany

HEP theory and three large experimental CMS groups

Almost 100 persons!

- Theory HEP group: 10 seniors/post-docs, ~25 Ph.D./master/bachelor students
  - Top & Higgs physics, SUSY phenomenology
- Institute I B: 3 seniors/post-docs, ~10 Ph.D./master/bachelor students
  - Silicon tracker upgrade, SUSY analyses
- Institute III A: 10 seniors/post-docs, ~25 Ph.D./master/bachelor students
  - Muon chamber upgrade, exotica searches & single top analyses, improved analysis techniques, H->$c\bar{c}$
- Institute III B: 8 seniors/post-docs, ~10 Ph.D./master/bachelor students
  - Head: Prof. Achim Stahl
  - Silicon Tracker upgrade, Grid computing, tau, LVF & Higgs analyses

Plus: LHCb, AMS, Auger, IceCube, EnEx/RANGE, DChooz, T2K, JUNO, Borexino/SOX, EDM/Jedi, med. applications, detector R&D, Einstein telescope, cosmology theory

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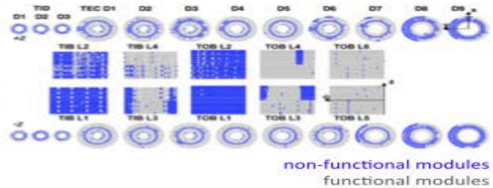
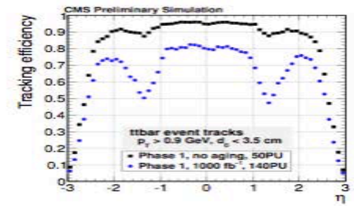
CMS Hardware Projects Aachen III B (Prof. Stahl, Dr. Pooth)

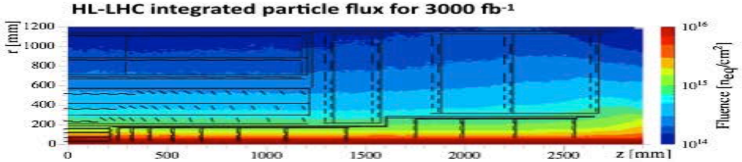
Need for a new CMS Phase-2 Tracker

The CMS Phase-1 Tracker would be suffering from radiation damage after 1000 fb^{-1} → degradation in track reconstruction efficiency





HL-LHC integrated particle flux for 3000 fb^{-1}



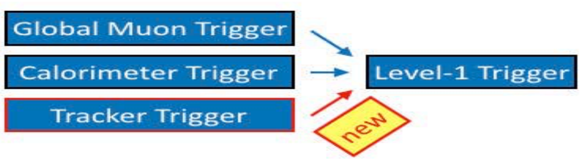
Challenges in Phase-2:

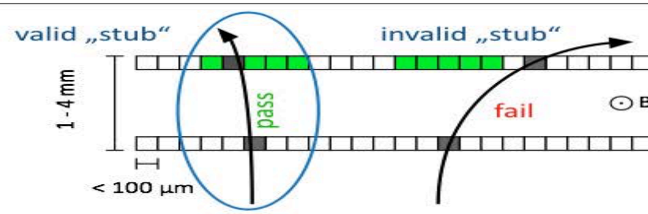
- $5 \times 10^{34}\, s^{-1}\, cm^{-2}$ → O(150) collisions per bunch crossing
- Withstand 3000 fb^{-1}
- Outer Tracker region: up to $1 \times 10^{15}\, n_{eq.} / cm^2$
- Inner Tracker region: up to $2 \times 10^{16}\, n_{eq.} / cm^2$

Requirements:

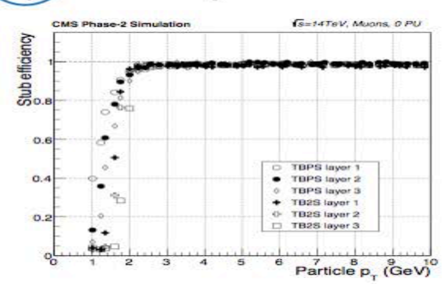
- Increased granularity (≤ 1% occ. in all Tracker regions)
- Less material in active volume to reduce material budget
- Contribute to Level-1 Trigger → Level-1 Trigger Upgrade: 750 kHz, 12.5 μs latency

Level-1 Trigger with Tracker Information





- Detector modules with on-board p_t discrimination
- Front-end ASICs correlate signals collected on two sensor planes and select pairs that form stubs compatible with particles above the chosen p_T threshold
- Stubs are used to form tracks
- Track Finder sends track parameters with 40 MHz to Level-1 trigger → max. 750 kHz to High Level Trigger



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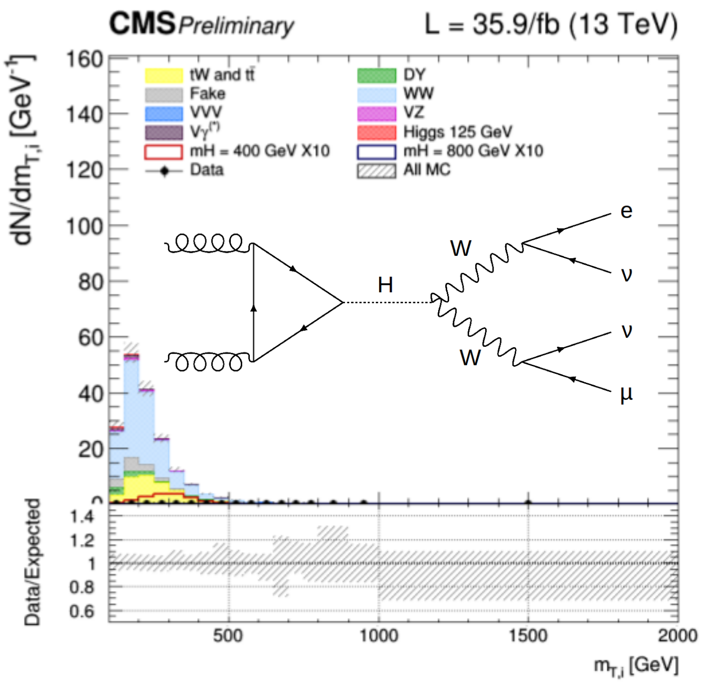
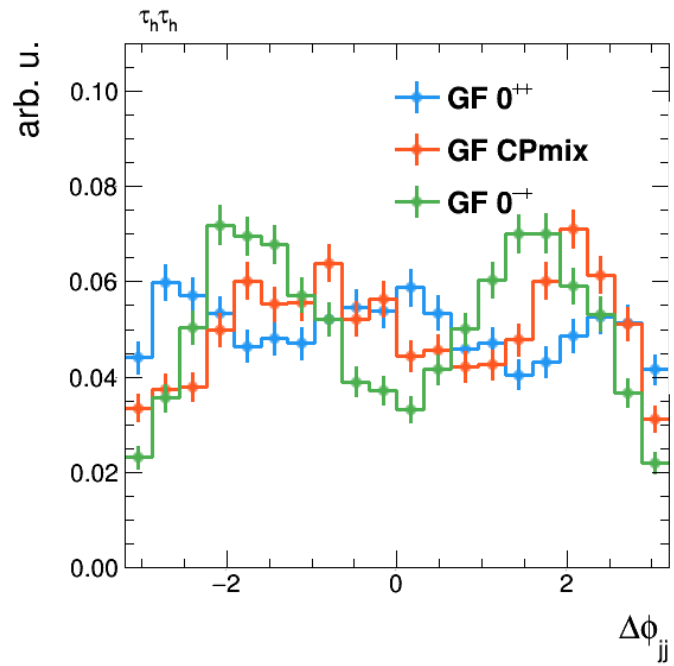
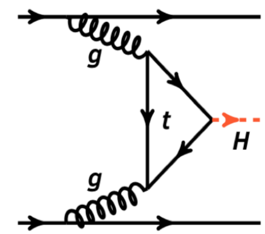
CMS Analyses Projects Aachen III B (Prof. Stahl, Drs. Mueller, Sert)

- Search for additional Higgs Bosons
  - H → tautau
  - H → WW
- Search for LFV Z boson decays

- Measurement of Higgs boson properties
  - CP in ggH Production
  - CP in H → tautau decay
- Measurement of Z boson properties
  - Tau Polarisation







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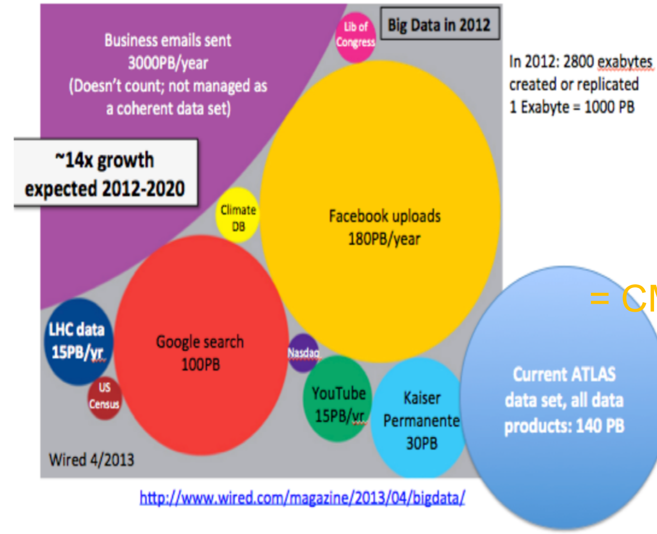
CMS Computing Projects Aachen III B (Drs. Kress, Nowack)

Distributed Grid computing – Tier 2+3

Started 2005, so far 2.5 M€ invest in computer hardware

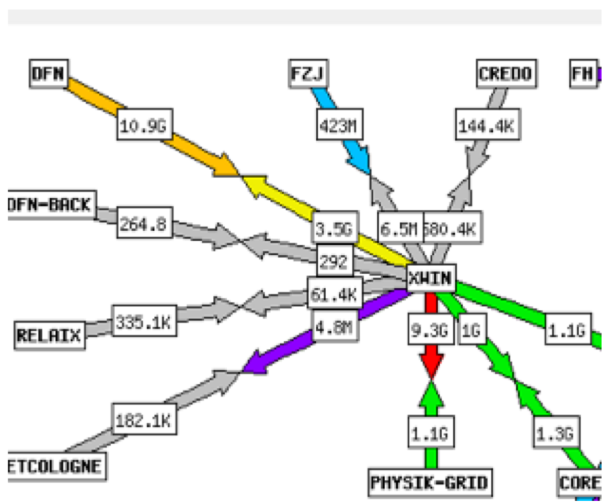


Presently 5500 CPU cores, 5 PB disks, in 12 racks

Supporting entire CMS collaboration

German & Aachen CMS users get extra resources

Started to work on virtualization/cloud techniques



Typical RWTH network WAN GRID data transfer rate (record so far: 30 Gbit/s)