Elements of the CERN programme 2016 – 2020

Eckhard Elsen

European Strategy

- *LHC and its upgrade*
- *Future energy frontier machines*
- *e^+e^- colliders*
- *ν–physics*
- *…*
- *Theory*

Energy Frontier

- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

  Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

2015 LHC Luminosity (p-p)

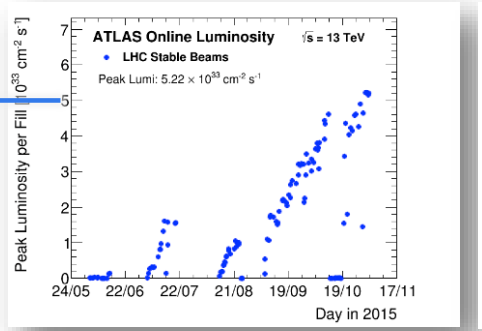
ATLAS

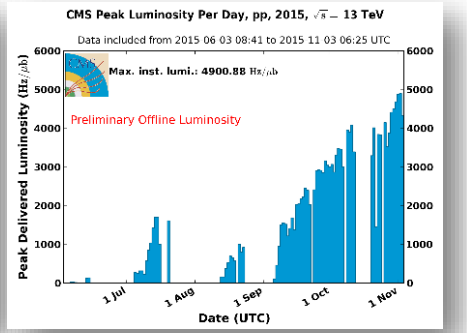
CMS

Peak

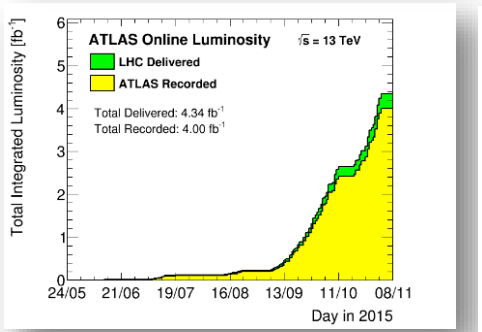
5 x 10^{33} cm^{-1} s^{-1}

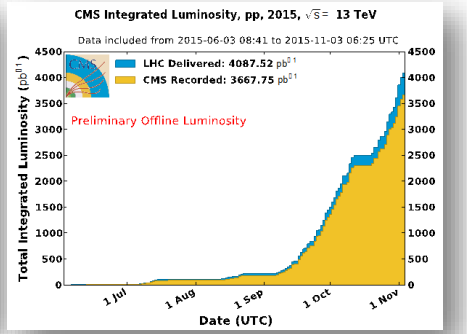
Design 10^{34} cm^{-1} s^{-1}





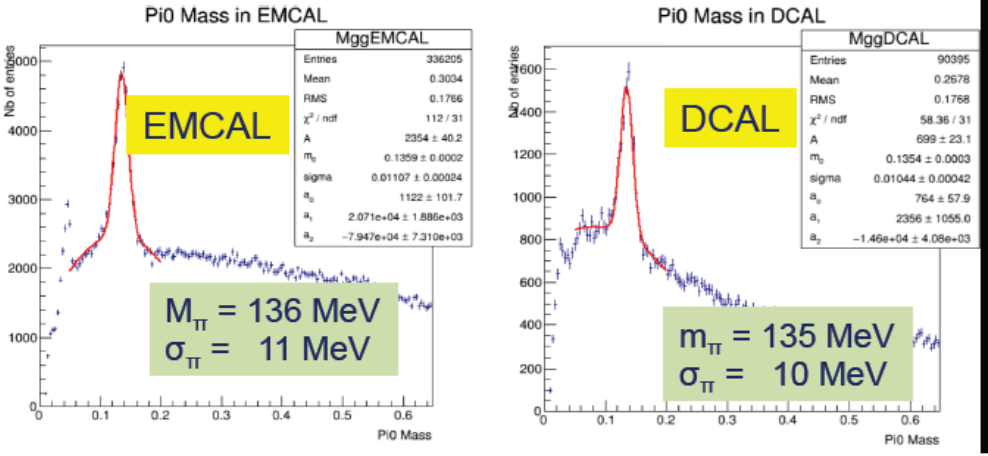
Integrated

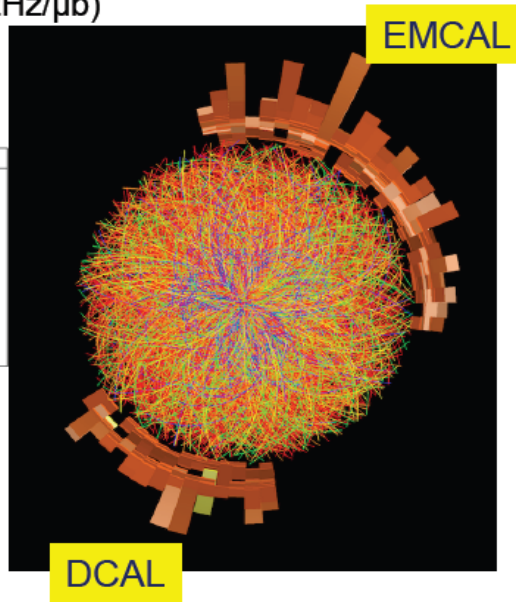




Detector performance - I

- **Good detector stability and running efficiency**
- TPC gas mixture changed from $NeCO_2$ (90:10) to $ArCO_2$ (90:10)
  → TPC **stable response at high fluxes** (up to 800 kHz, 14 Hz/μb)
- New detectors (EMCAL/DCAL, AD, CPV) and new triggers (TRD sub-L0, CALO L0 and L1γ,jet) are **in production**
  → Calorimeter system (EMCAL, DCAL, PHOS) calibrated
- Muon Chambers tested up to Run III rates (2.5 MHz, 42Hz/μb)



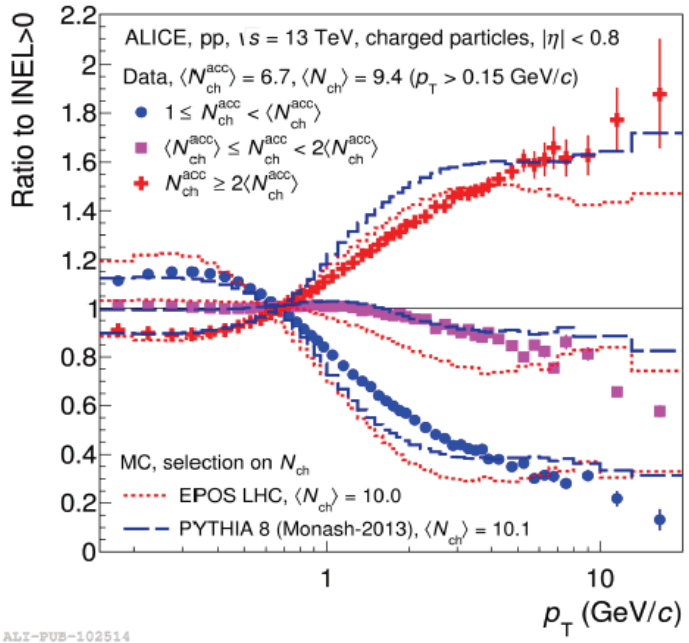


Charged particle spectrum

"Day 1" measurement: pseudorapidity distribution shown at the last LHCC meeting (22.09.2015)

New: spectrum of charged particles measured in $0.15 < p_T < 20$ GeV/c and compared to calculations

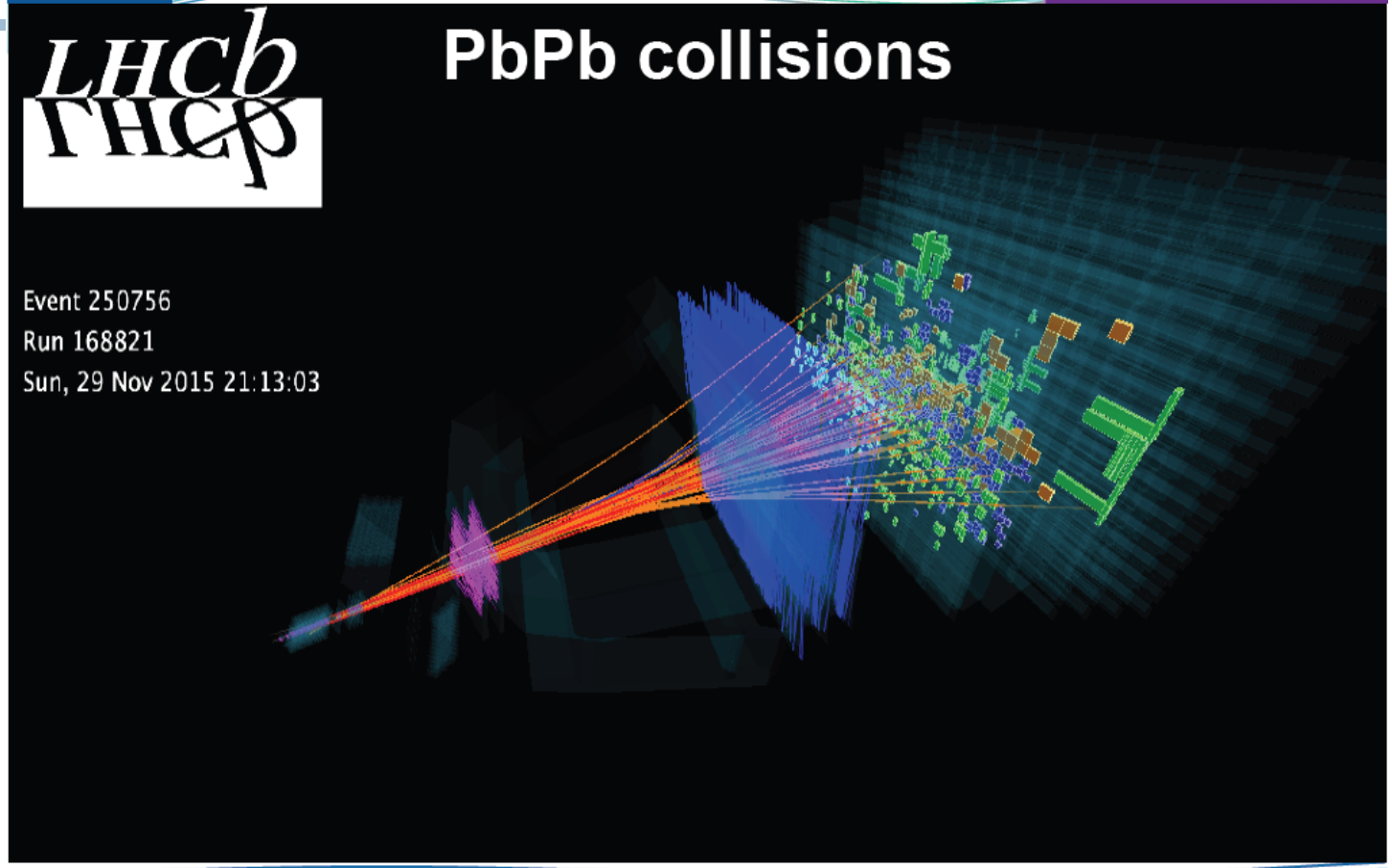
- Ratio to data similar for PYTHIA 8 and EPOS LHC; PYTHIA 6 overestimates at high-p_T
- spectrum significantly harder than at 7 TeV
- Ratio of spectra in different multiplicity intervals understood in terms of low-p_T jets contributing to the multiplicity



→ Study the correlation between p_T and particle multiplicity (hard-scattering contribution)

arXiv:1509.08734

PbPb collisions

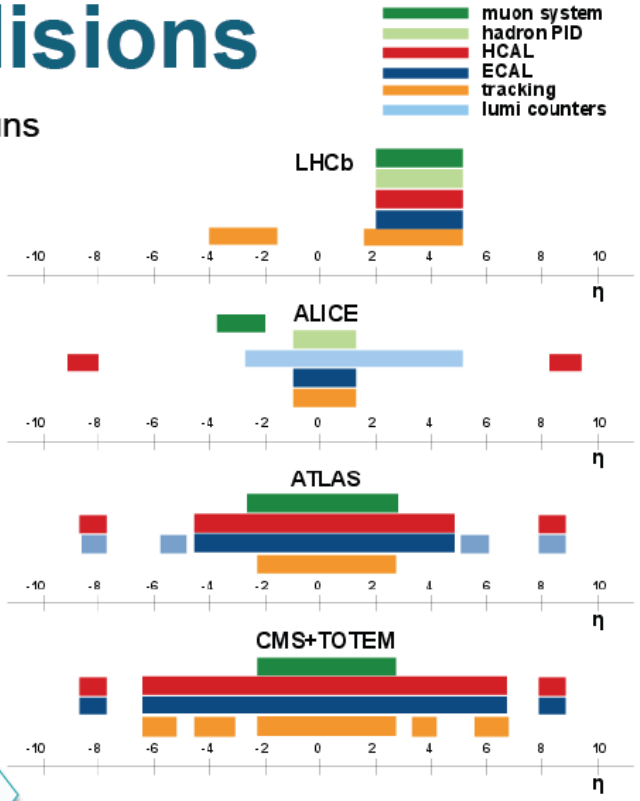


PbPb collisions

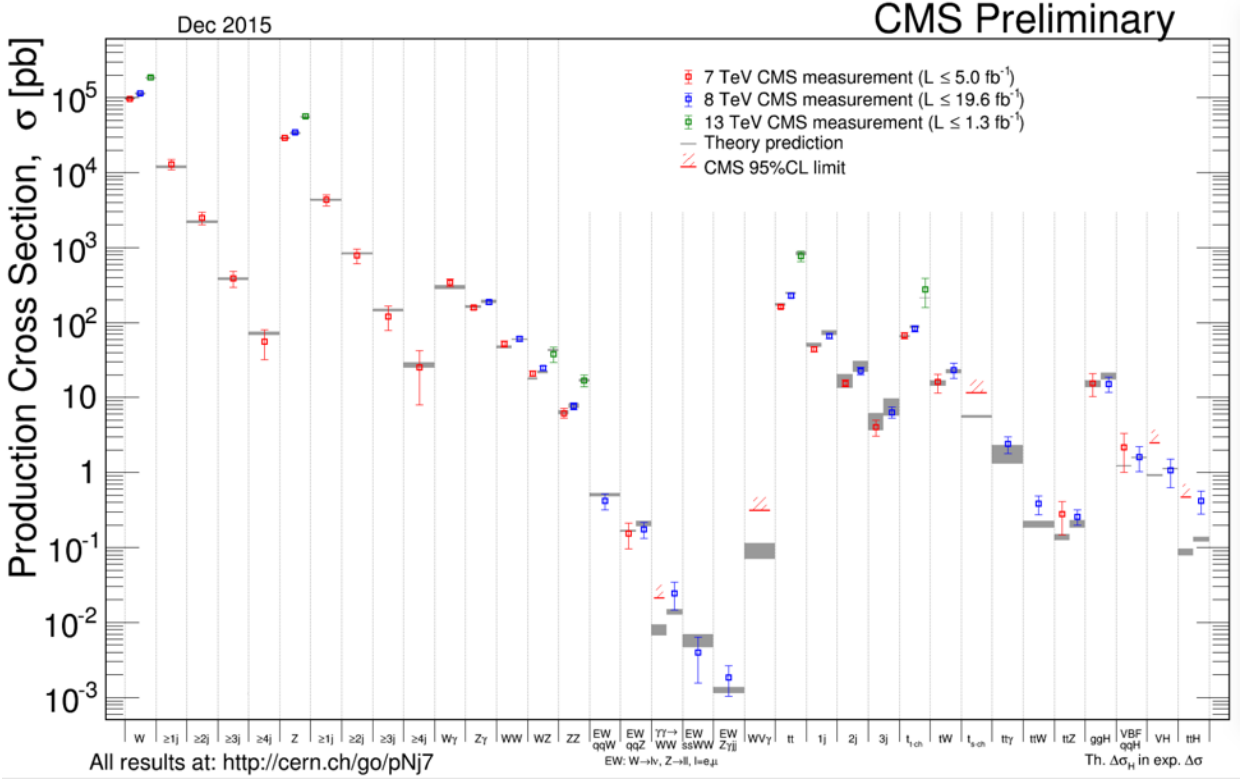
- LHCb is participating in Pb-Pb collision runs
- Unique fully instrumented experiment in the forward region
- Physics motivations:
  - Probe colour screening and quark gluon plasma (QGP) temperature through sequential melting of quarkonium states
  - Structure of nucleons, hadronisation, central exclusive production, …
  - Focus on peripheral collisions in Pb-Pb, with a centrality up to 50%

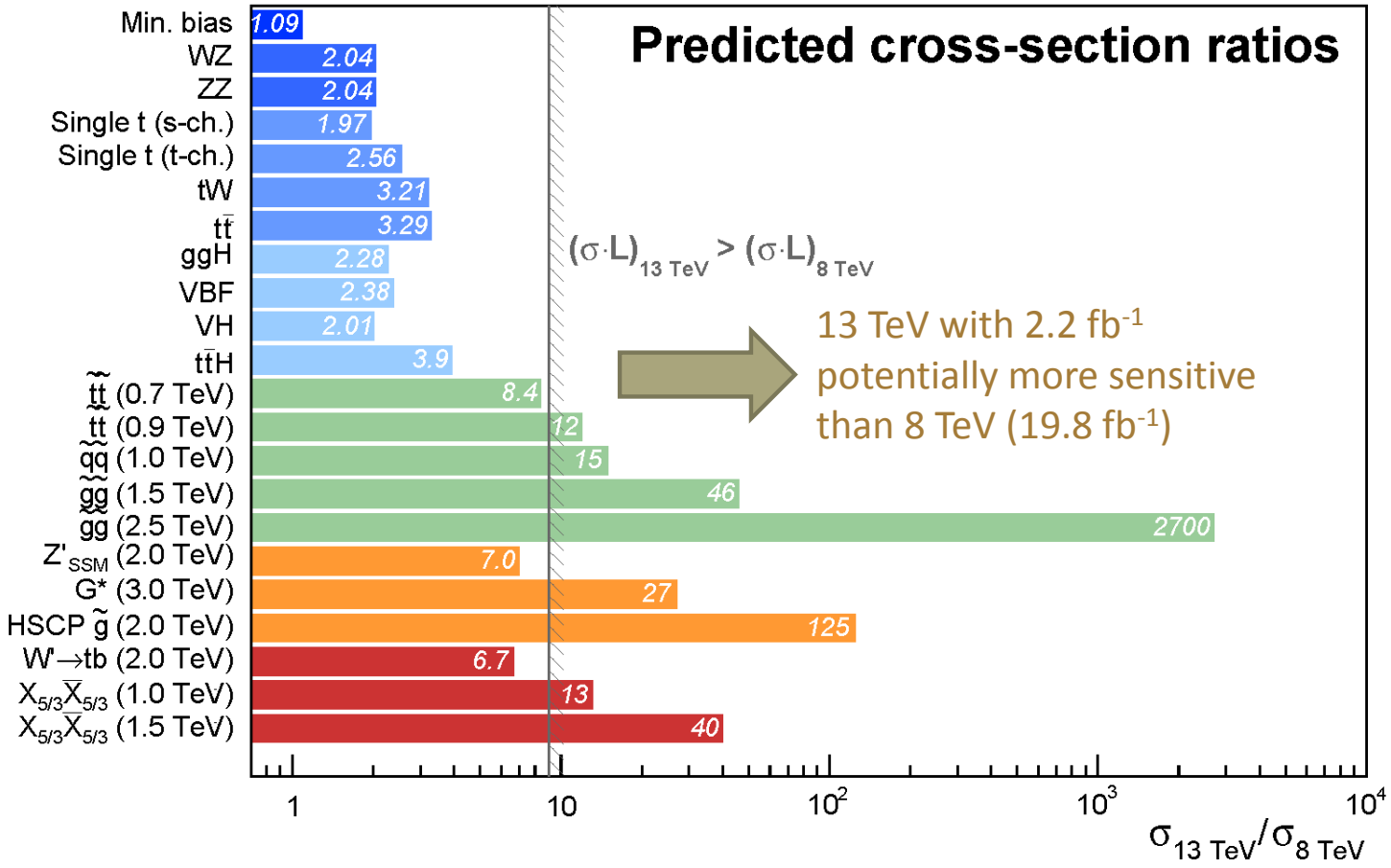
	Date	Data sample
PbPb	25 Nov.-….	
PbAr	27 Nov.-…	

Data taking ongoing



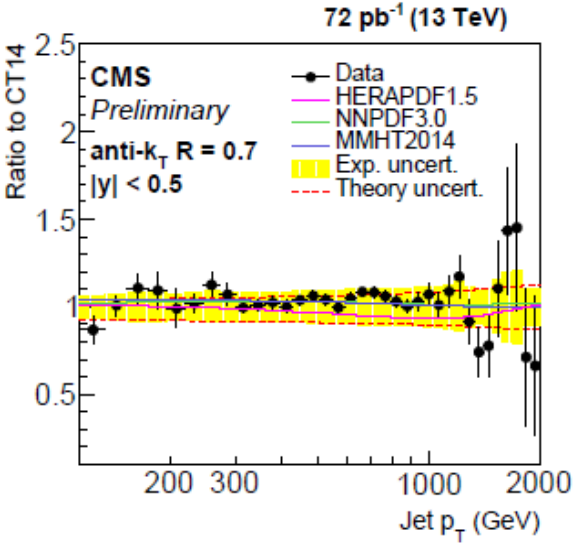
- SM cross sections, incl. 13 TeV data

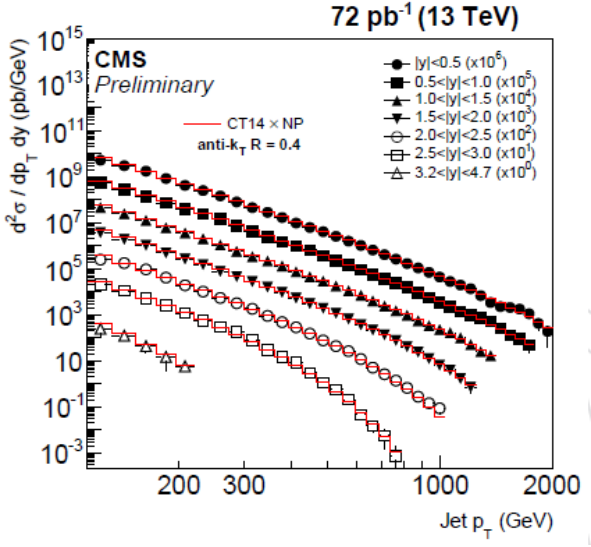



Predicted cross-section ratios
Min. bias
WZ
ZZ
Single t (s-ch.)
Single t (t-ch.)
tW
$t\bar{t}$
ggH
VBF
VH
$t\bar{t}H$
$\tilde{t}\tilde{t}$ (0.7 TeV)
$\tilde{t}\tilde{t}$ (0.9 TeV)
$\tilde{q}\tilde{q}$ (1.0 TeV)
$\tilde{g}\tilde{g}$ (1.5 TeV)
gg (2.5 TeV)
Z'_{SSM} (2.0 TeV)
G* (3.0 TeV)
HSCP $\tilde{g}$ (2.0 TeV)
W'→tb (2.0 TeV)
$X_{5/3}\bar{X}_{5/3}$ (1.0 TeV)
$X_{5/3}\bar{X}_{5/3}$ (1.5 TeV)
1.09
2.04
2.04
1.97
2.56
3.21
3.29
2.28
2.38
2.01
3.9
8.4
12
15
46
2700
7.0
27
125
6.7
13
40
$(\sigma \cdot L)_{13\ TeV} > (\sigma \cdot L)_{8\ TeV}$
13 TeV with 2.2 fb^{-1}
potentially more sensitive
than 8 TeV (19.8 fb^{-1})
1
10
10^2
10^3
10^4
$\sigma_{13\ TeV}/\sigma_{8\ TeV}$

Inclusive Jets

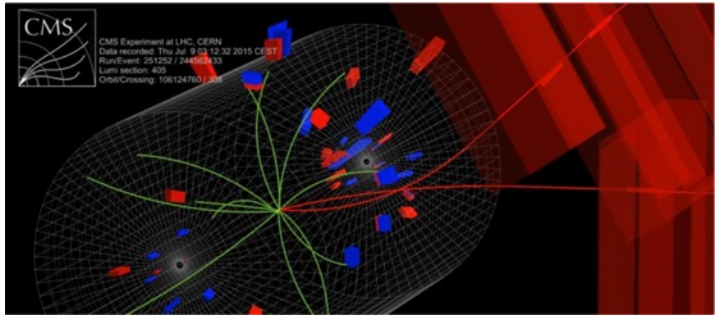
CMS



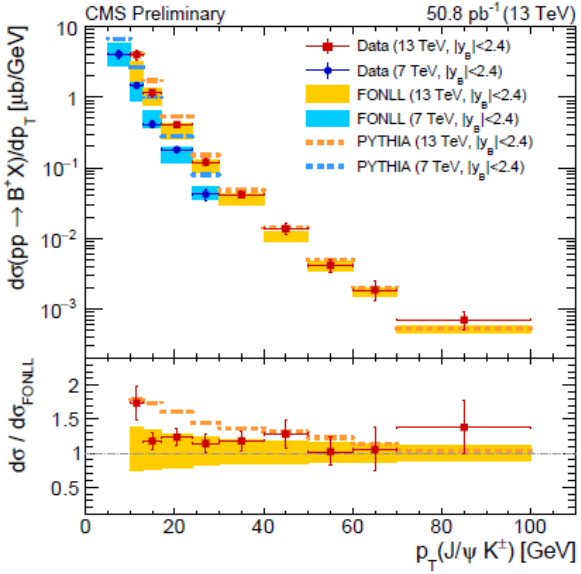


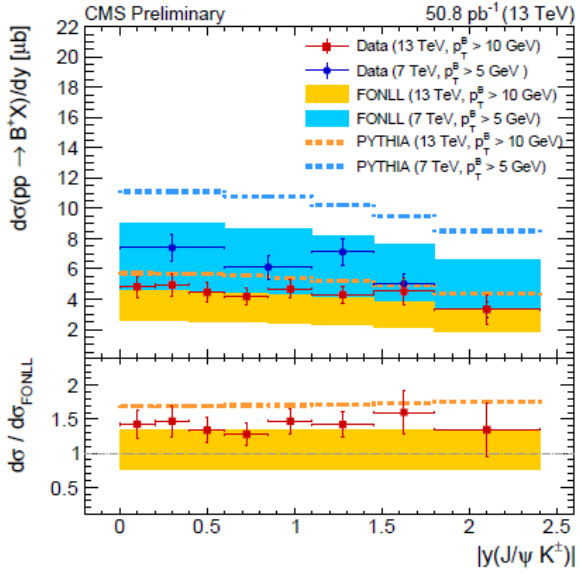
B-Mesons

- 8 TeV Data
- FONLL predictions



CMS



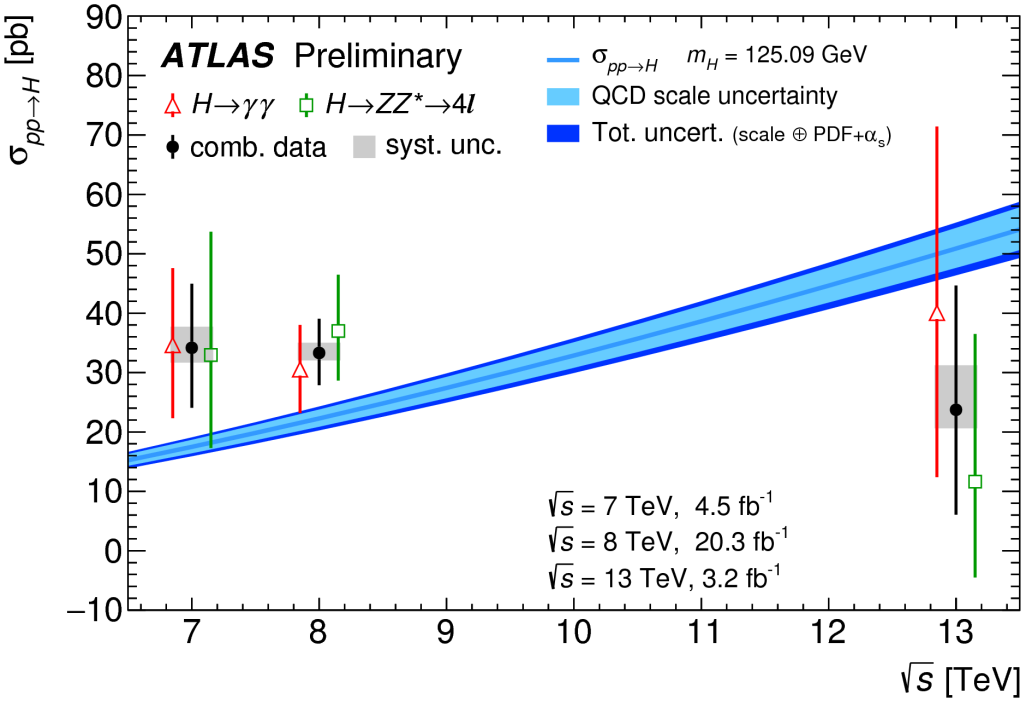


Measurement of the Higgs Cross Section

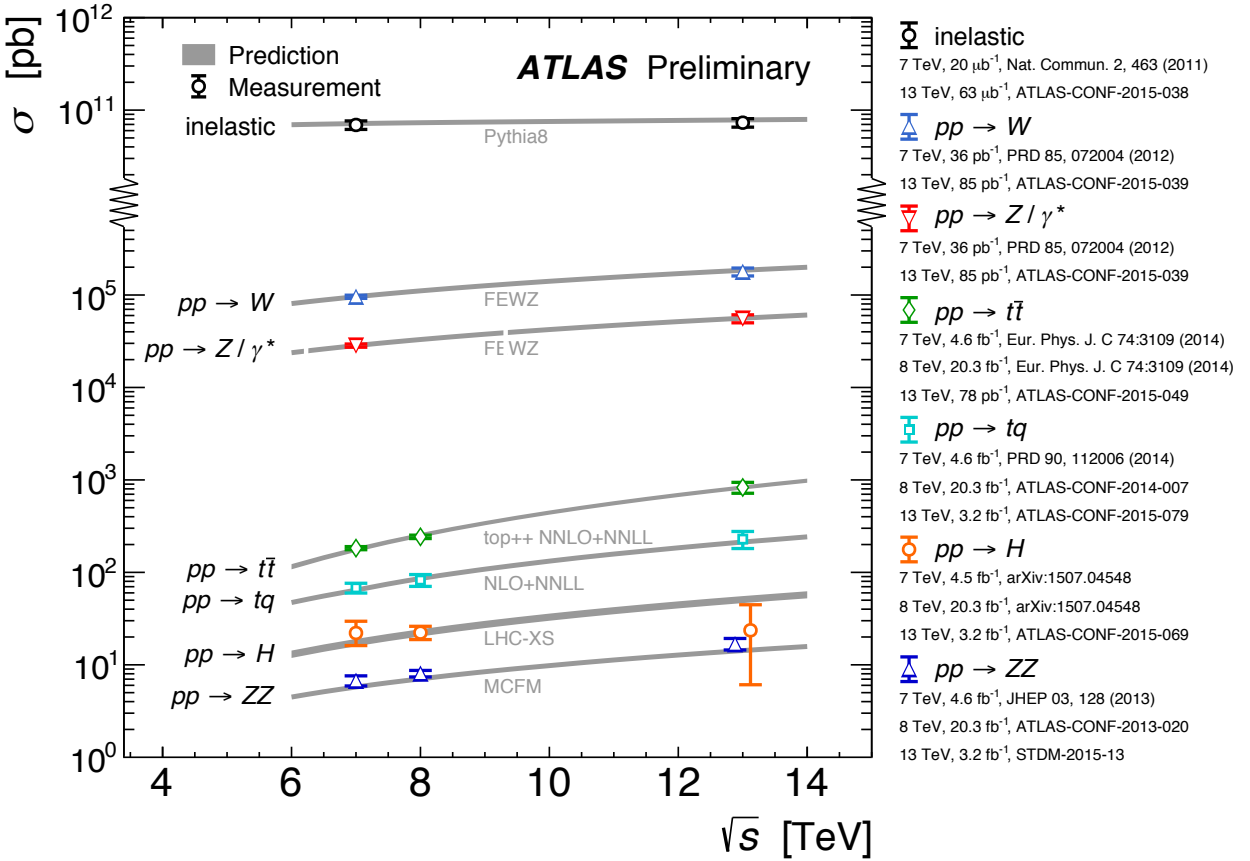
ATLAS

ATLAS-CONF-2015-069

- Combined significance from γγ and 4l
  - expected 3.4σ
  - observed 1.4σ



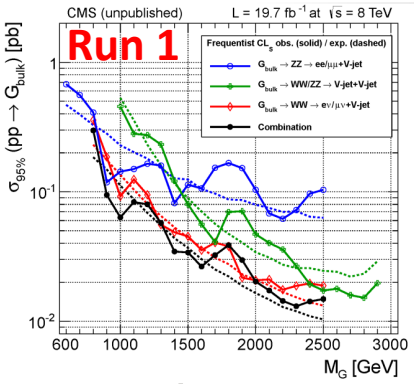
Cross Sections

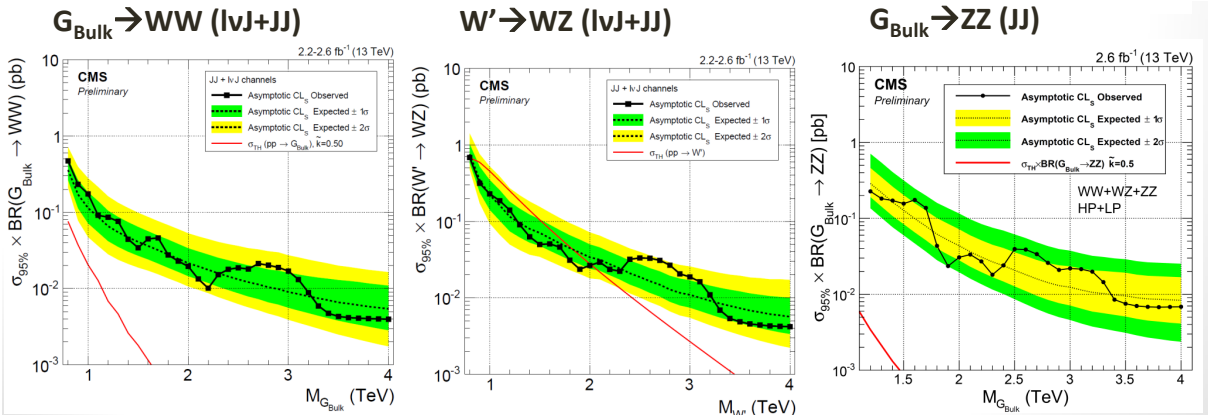


Search for Diboson resonances

CMS

- Run 1: CMS ~2σ excess near 1.8-2.0 TeV
  - Repeat search at 13 TeV using most sensitive channels: lvJ, JJ
  - Analysis categorised in dijet mass for optimal sensitivity to WW, WZ, ZZ signals
- 13 TeV: no excess observed in the region of interest near 2 TeV
- More data needed to fully exclude Run 1 excess





Search for Dilepton resonances

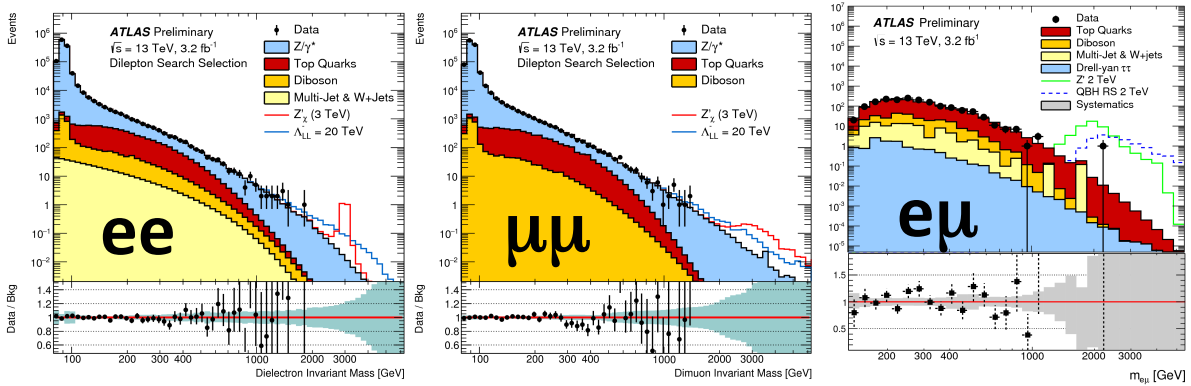
ATLAS

Search for Z' in dilepton (LFC) and (LFV) *(in eμ decays)*

ATLAS-CONF-2015-070

ATLAS-CONF-2015-072

- Main background DY is taken from MC
- Top and diboson extrapolated at very high masses using a functional form
- Background from MC except for MJ in dielectron uses Matrix method (based on electron ID)



Highest di-electron mass event at 1.8 TeV

Highest di-muon mass event at 1.4 TeV

Highest eμ mass event at 2.1 TeV

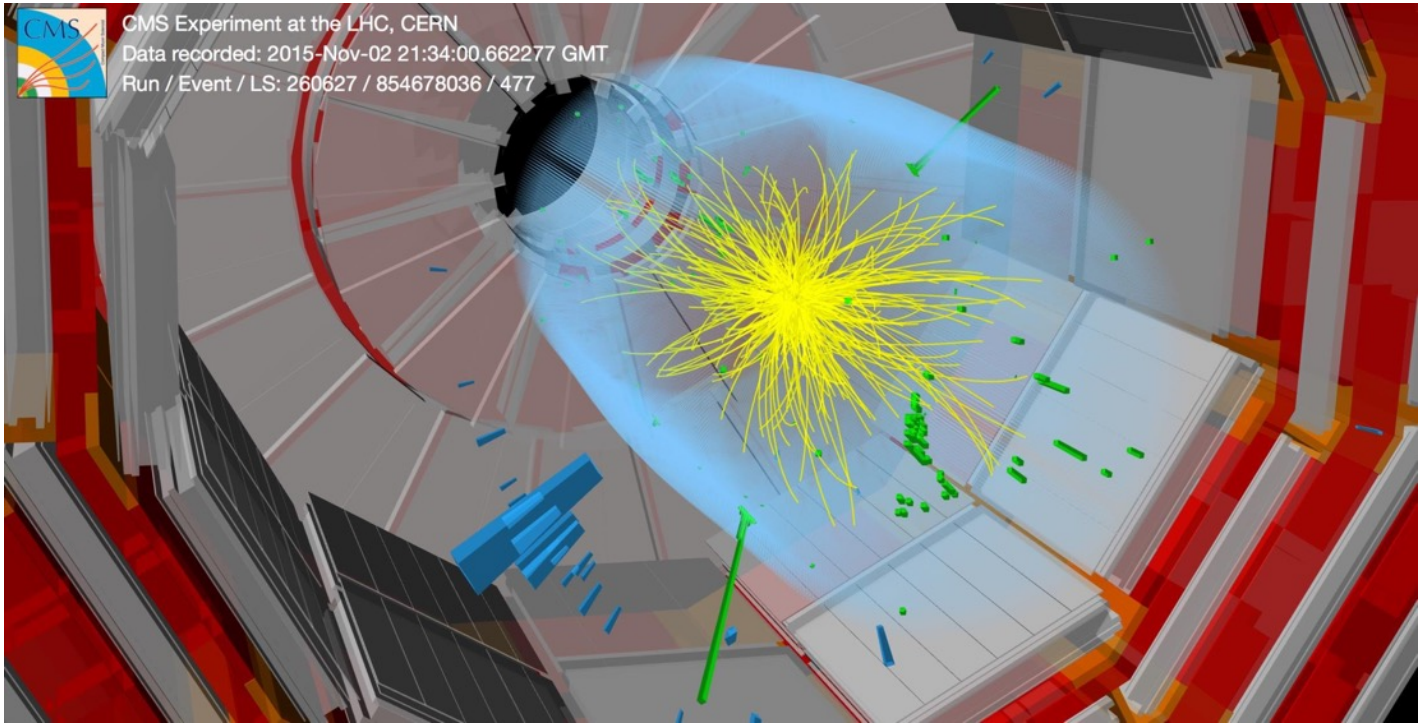
No Excess found !

95% CL Limit on SSM Z' at 3.4 TeV (2.9 TeV from Run-1)

95% CL Limit on SSM LFV Z' at 3.0 TeV (2.5 TeV from Run-1)

Search for Diphoton resonances CMS

$m_{\gamma\gamma}$=745 GeV



Search for Diphoton resonances

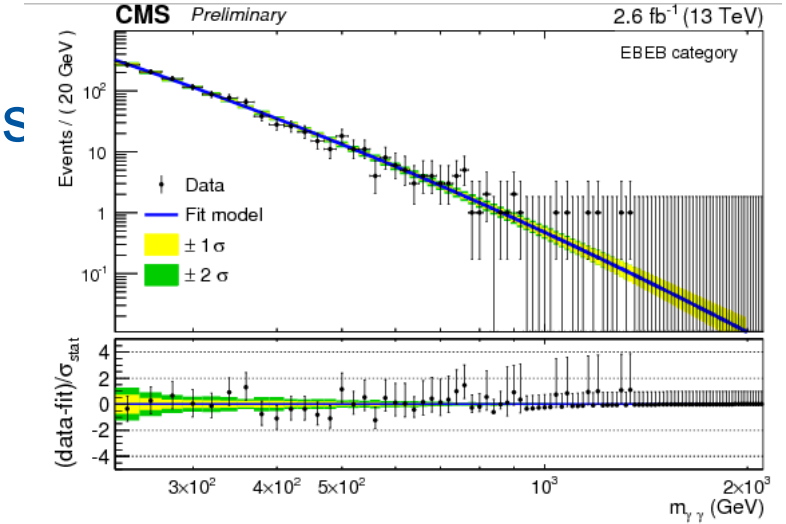
Search in two categories

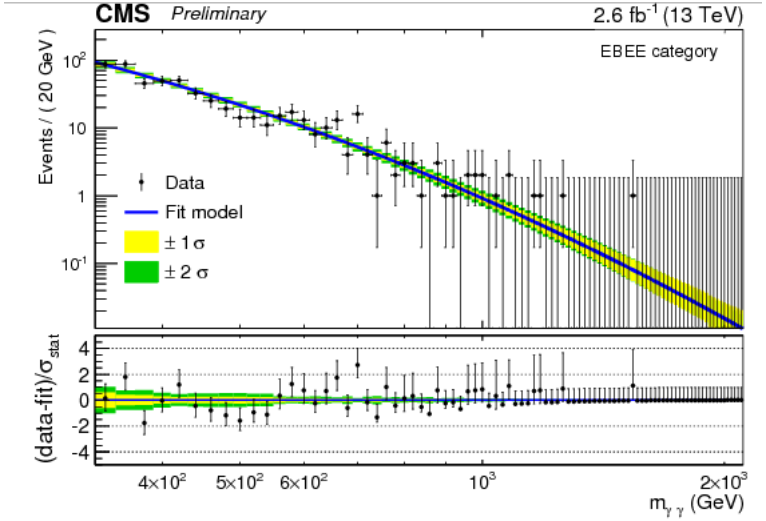
- barrel endcap (EBEE)
- barrel barrel (EBEB)

pT(γ) > 75 GeV, I_{ch} < 5 GeV (in 0.3 cone around photon direction)

Efficiency, scale and resolution calibrated on Z → ee and high-mass DY events

Search for RS graviton with three assumptions on coupling:
κ = 0.01 (narrow), 0.1, 0.2 (wide)



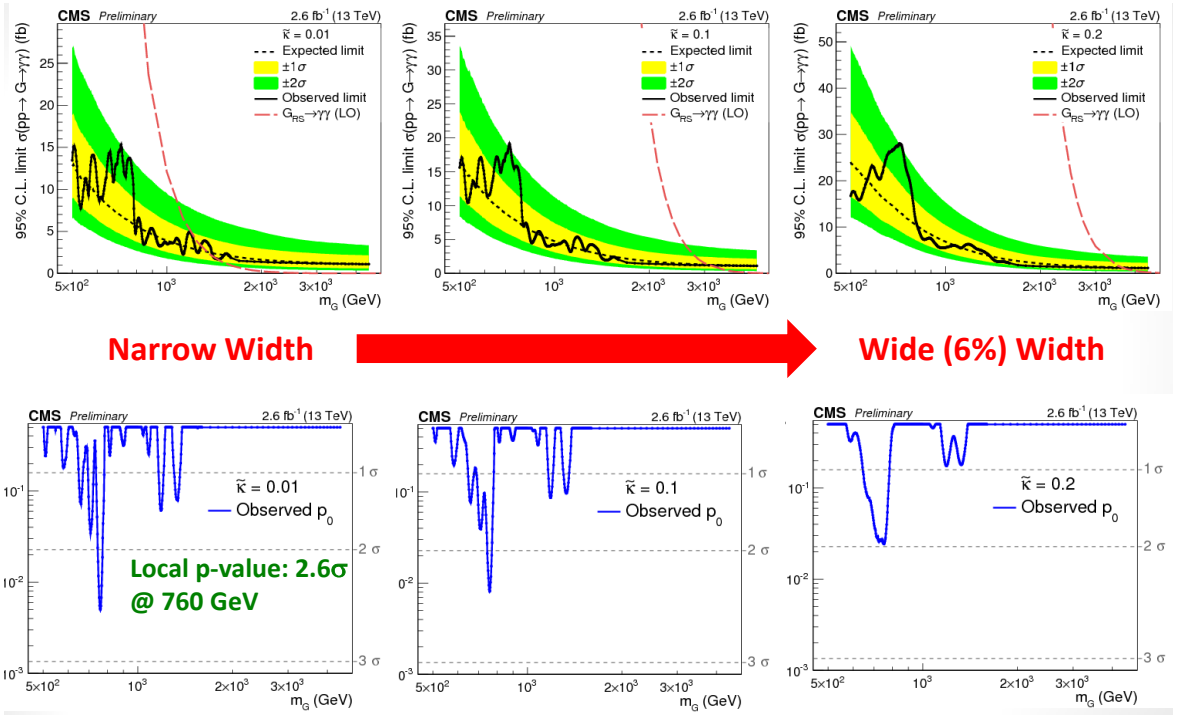


Combined limits and p-values

CMS

Including Look-elsewhere-effect in the range (0.5 - 4.5 TeV; narrow width)

global p-value σ< 1.2



Search for 2 Photon resonance

ATLAS

Inclusive search for two photon resonance
(optimized for a scalar resonance)

- Selection of two photons with pT/m thresholds of 0.3 and 0.4 and pT dependent calorimeter and track isolation criteria
- Typical prompt photon purity 90%

Background from a functional

Similar to the dijet search but chosen using the Fisher F-test and the spurious signal method measured in events from Sherpa, Diphox and Jetphox:

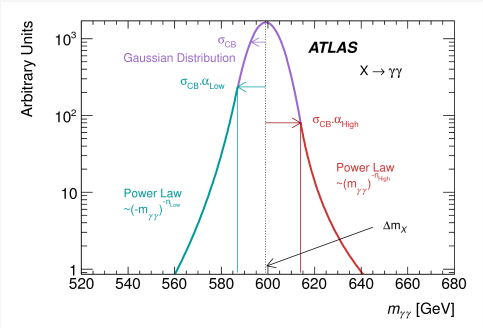
$$f_{bkg}(x;b,\{a_k\}) = (1-x^{1/3})^b\, x^{\sum_{j=0}^{k} a_j \log(x)^j}$$

$$x \equiv \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

Here a simple form with k=0 is used

Signal Model

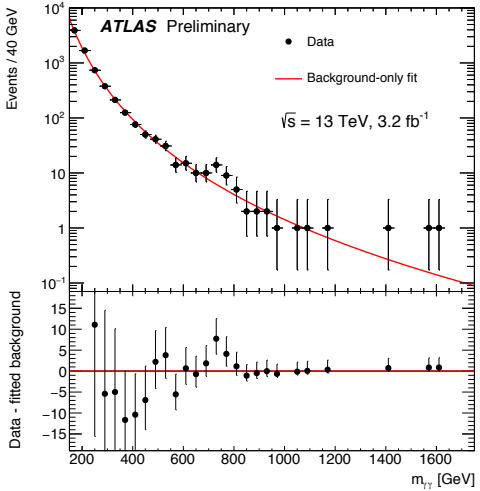
- **NWA**: Use Double Sided Crystal Ball function
- **LW**: Use DSCB fitted from simulated samples with different widths with up to 25% of the resonance mass



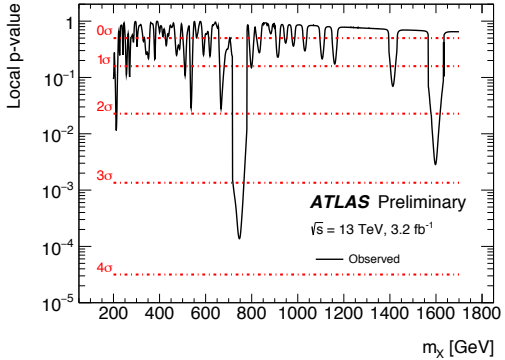
Search for 2 Photon resonance

ATLAS

Results: Events with mass in excess of 200 GeV are included in **unbinned fit**



- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_0 of 750 GeV
- Taking a LEE in a mass range (fixed before unblinding) **of 200 GeV to 2.0 TeV** the global significance of the excess is **2.0σ**



In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.5σ

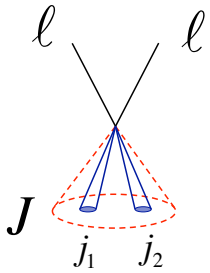
The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV
(Approx. 6% of the best fit mass of approximately 750 GeV)

- As expected the local significance increases to **3.9σ**
- Taking into account a LEE in mass and width of up to **10%** of the mass hypothesis of **2.3σ** (Note: upper range in resolution fixed after unblinding)

Searches for a **Resonance** in **Diboson VV** Final States

ATLAS

ZV (with Z to **dilepton**)

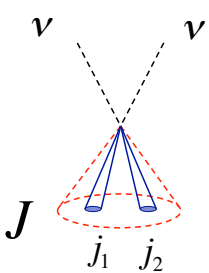


Backgrounds

Z-jets is the main background, estimated using MC and normalised to mJ sidebands

Diboson and top from MC

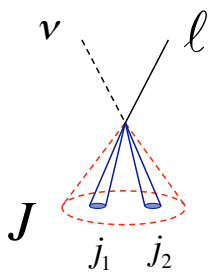
ZV (with Z to **vv**)



Backgrounds

Z-jets, W-jets and top are main backgrounds, these are estimated using CRs with 1 or 2 muons and one b-tag for the Top CR.

WV (with W to **lv**)



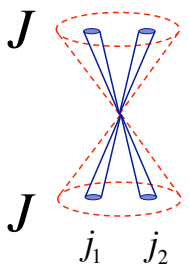
Backgrounds

Z, W and top shapes from MC

Diboson fully from MC

Multijet shape from loose lepton ID

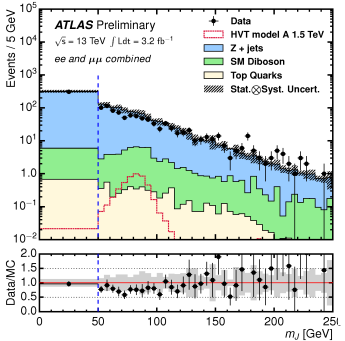
VV to **JJ**

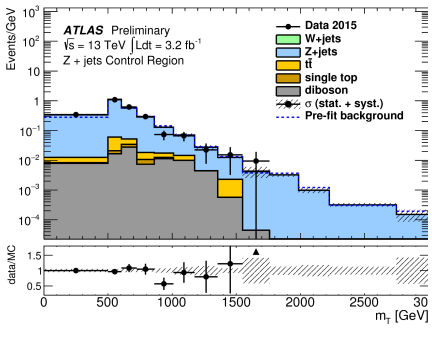


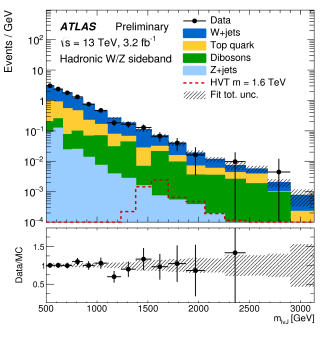
Modest excess Run-1 observed at Run 1 to be checked

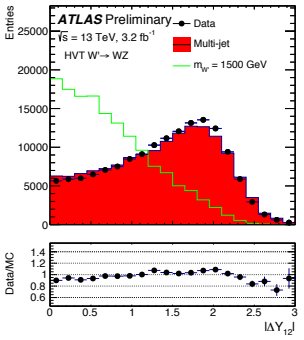
Background

Estimated using a functional form









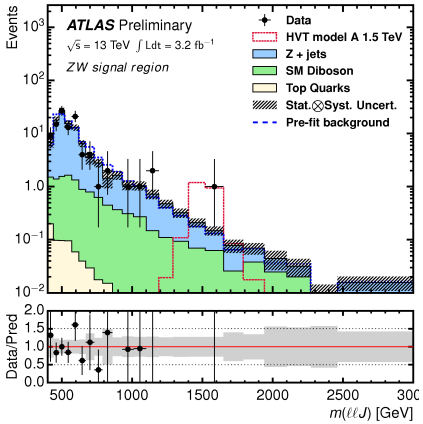
Searches in **Resonant Diboson VV** Final States

ATLAS-CONF-2015-075
ATLAS-CONF-2015-068
ATLAS-CONF-2015-071

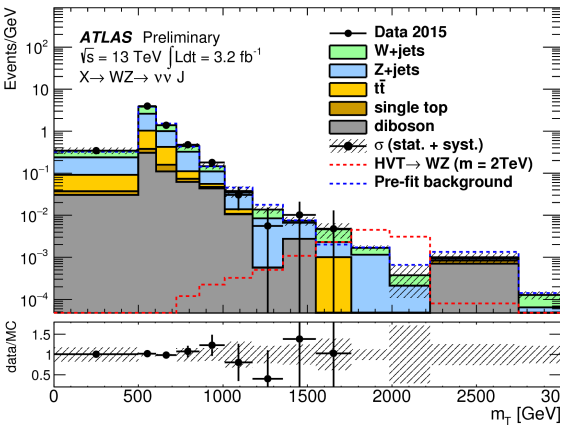
ATLAS

Signal regions (WZ) distributions in m_{VV}

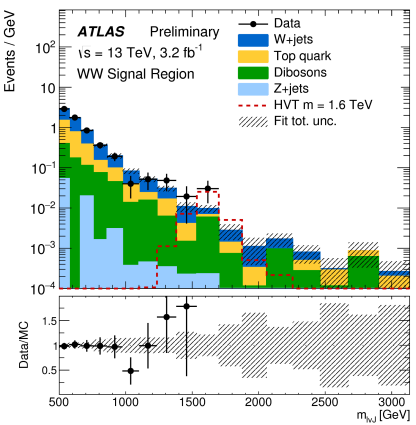
ZV (with Z to **dilepton**)



ZV (with Z to **vv**)



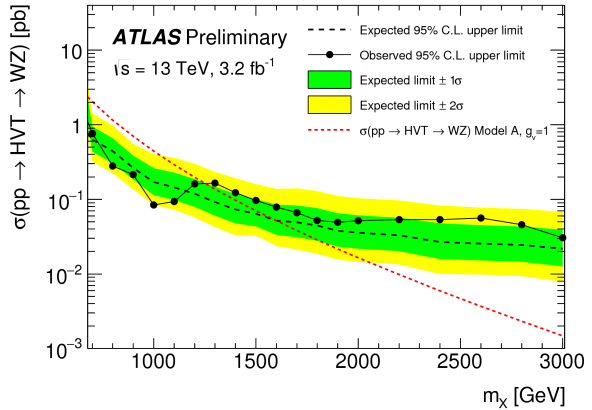
WV (with W to **lv**)



Results

All analyses have similar sensitivities ranging between **1.4 TeV** and **1.6 TeV** for HVT additional vector bosons

- No significant excess observed, limits are set in these scenarios
- Interpretations also in Higgs and Graviton hypotheses

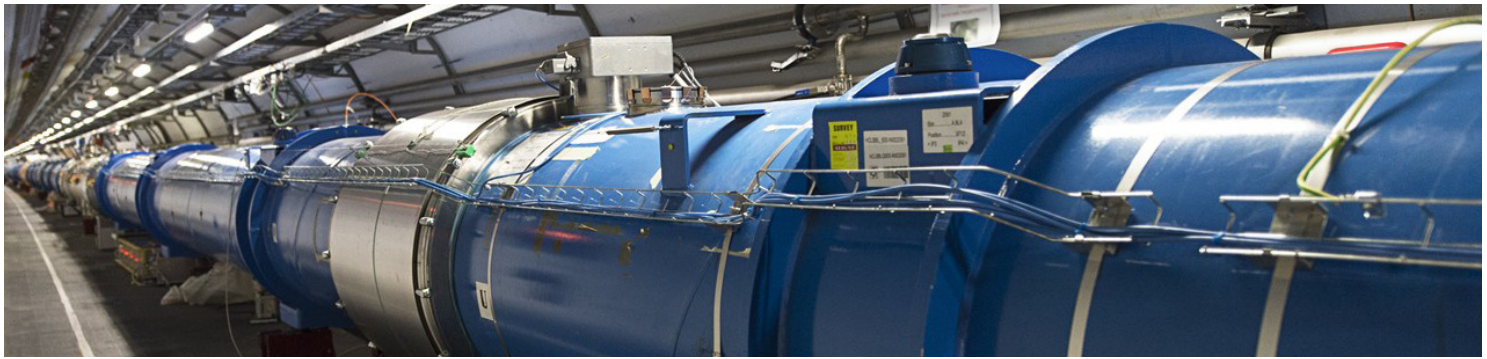


Run 2

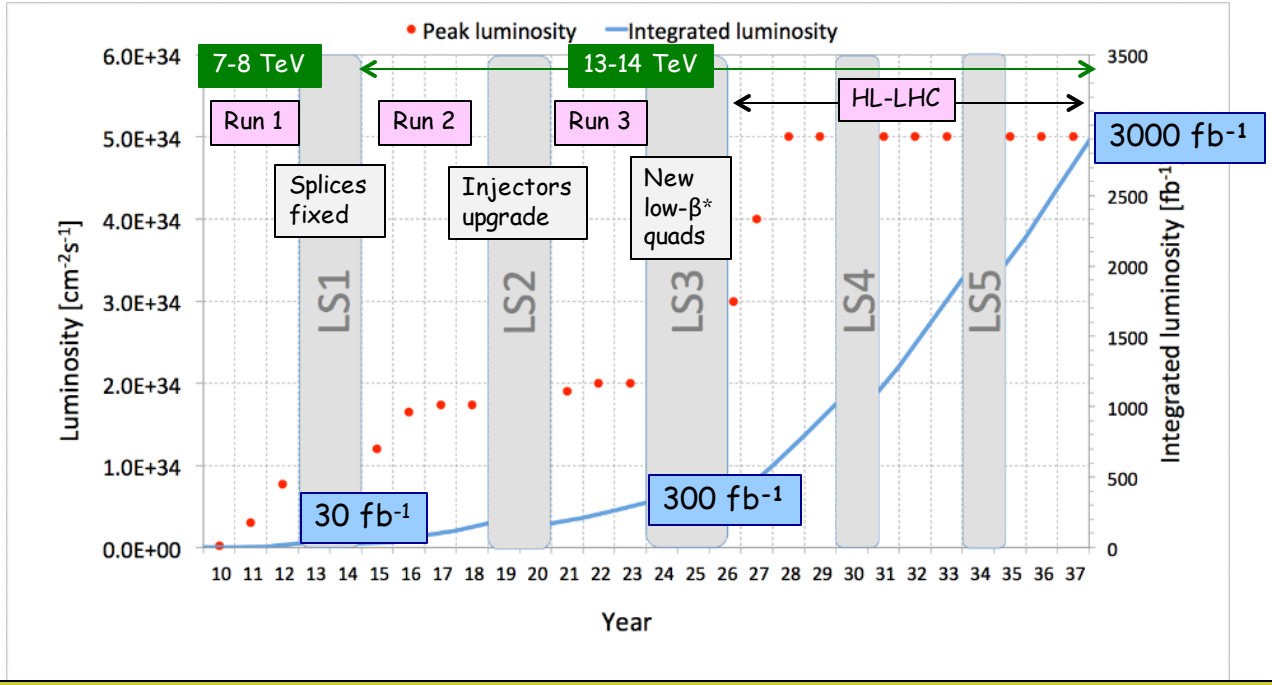
- Many new results from run 2 have become available
  - see seminar by M Kado and J Olsen this week for wealth of ATLAS and CMS results
  - Intriguing **fluctuations** are seen – new data will come soon

High Lumi LHC HL-LHC

- FP7 Design Study just completed
  - first 11 Tesla magnet
- Now underway as a project at CERN



The present and near/medium-term future: LHC and HL-LHC



F.Gianotti
EPS 2015

LHC is highest-E, highest-L operational collider → full exploitation ($\sqrt{s}$ ~ 14 TeV, 3000/fb) is mandatory:

- If new physics discovered in Run 2-3:
  → first detailed exploration of new physics with well understood machine and experiments
- If no new physics in Run 2-3:
  → extend direct discovery potential by ~ 20-30% (up to m ~ 8 TeV)

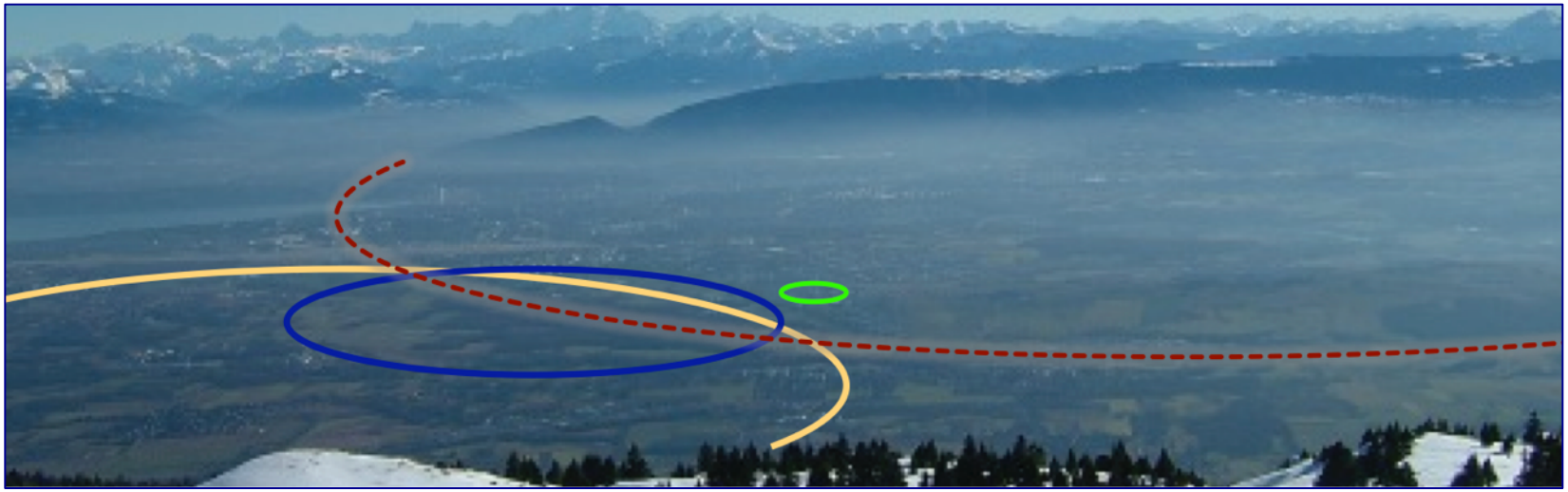
In either case: measure H couplings to few percent (including 2nd generation: Hμμ)

Energy Frontier

- To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

  CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron- positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

Future Circular Collider FCC



- European Design Study
- ~100 TeV pp in a ~100 km ring

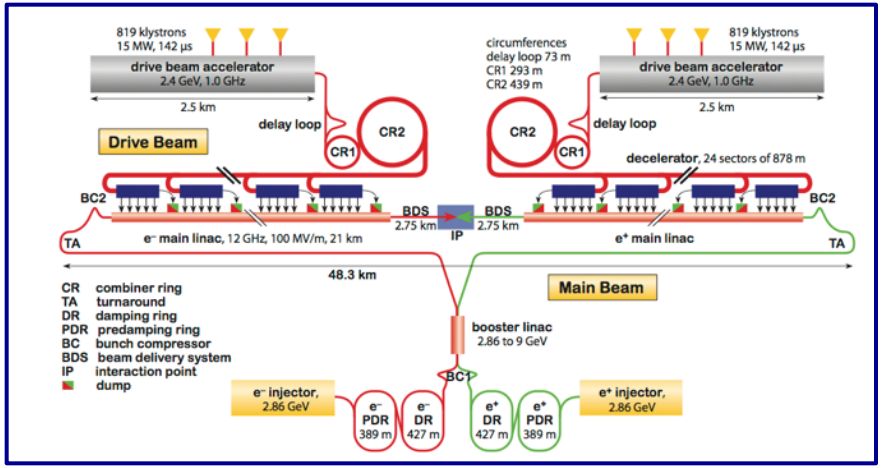
Physics discussion in M Mangano's talk

High field magnets

- Key to high energies (both HE-LHC and FCC)
  - Nb_3Sn may lead to ~16 T magnets
    - HL-LHC magnet provide a ~1.2 km test of the technology
  - an insert of HTS may increase the field to 20 T

Compact Linear Collider CLIC

- e^+e^- collider 1-3 TeV
- currently only option for the TeV region



- CDR 2013
- CTF3 has provided key results (end 2016)
- ready for a demonstrator

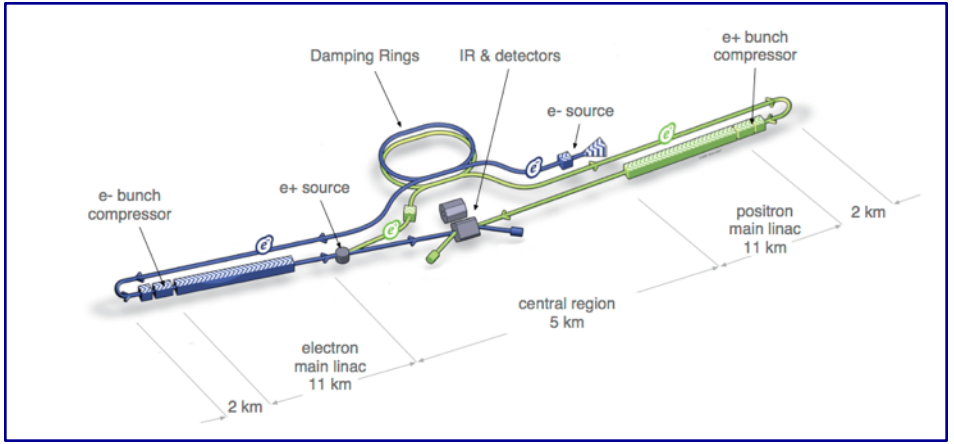
e^+e^- collider

- There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.

  Europe looks forward to a proposal from Japan to discuss a possible participation.

International Linear Collider ILC

- e^+e^- collider 0.5 TeV (upgradeable to 1 TeV)
- precision Higgs programme and beyond

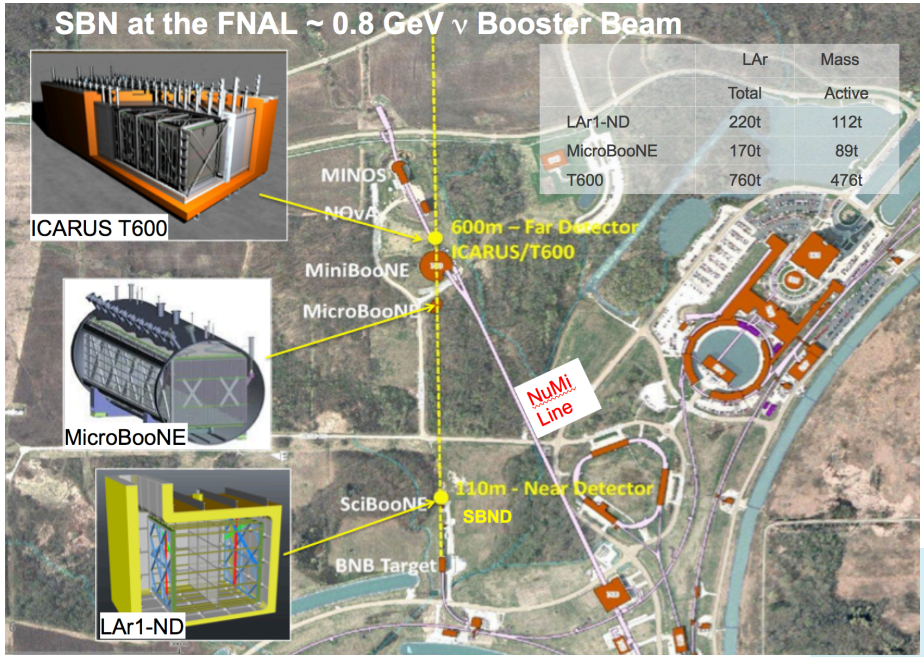


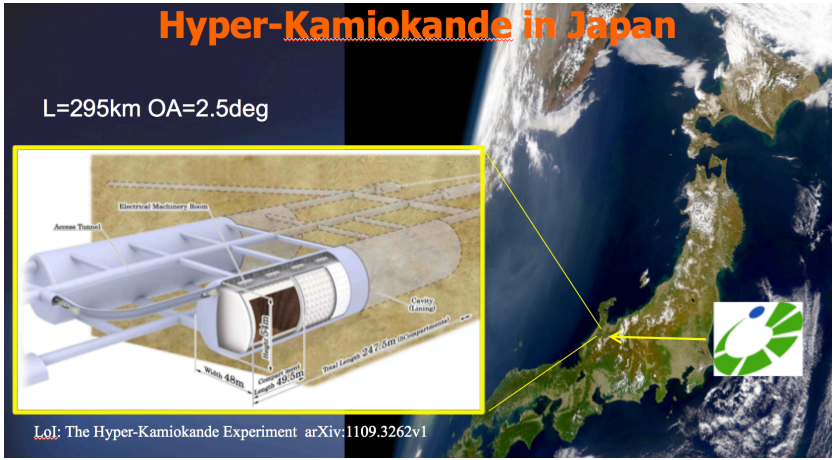
- Project is mature (TDR 2012)
- hosting evaluated by Japanese government
- international project (without host laboratory)

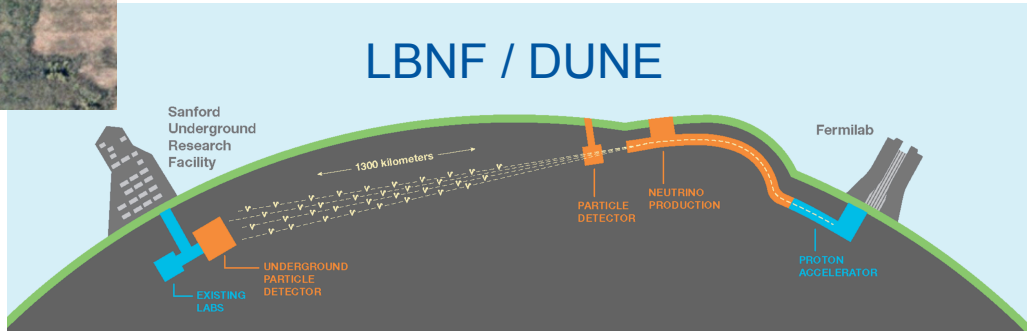
ν-physics

- Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments.

  Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

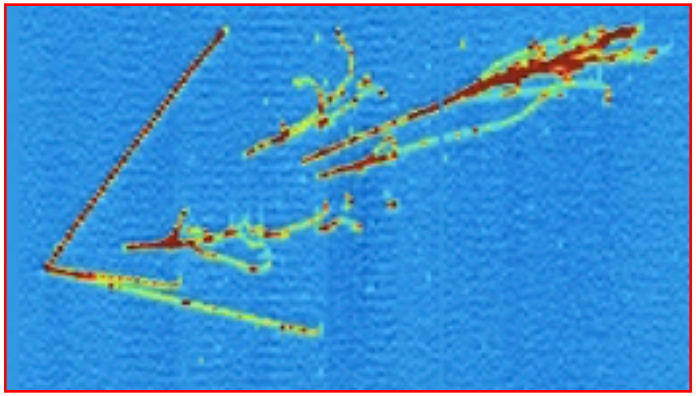

SBN at the FNAL ~ 0.8 GeV ν Booster Beam
LAr Mass
Total Active
LAr1-ND 220t 112t
MicroBooNE 170t 89t
T600 760t 476t
ICARUS T600
MINOS
NOvA
600m – Far Detector
ICARUS/T600
MiniBooNE
MicroBooNE
NuMi Line
MicroBooNE
110m - Near Detector
SBND
SciBooNE
BNB Target
LAr1-ND

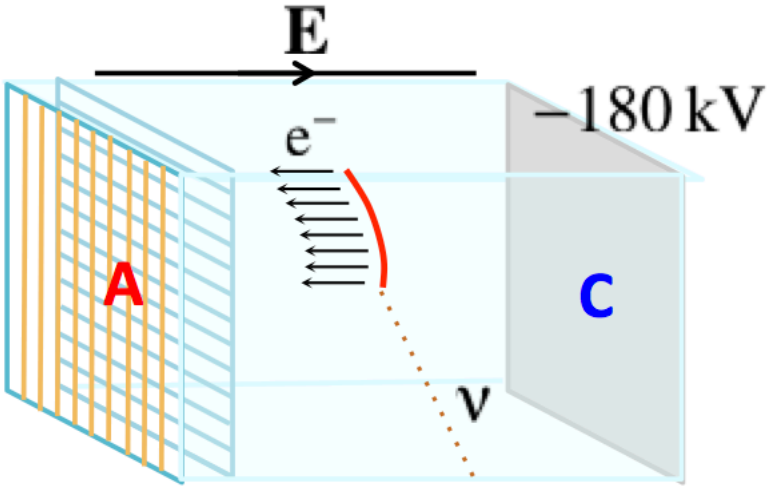

Hyper-Kamiokande in Japan
L=295km OA=2.5deg
LoI: The Hyper-Kamiokande Experiment arXiv:1109.3262v1


LBNF / DUNE
Sanford Underground Research Facility
1300 kilometers
Fermilab
PARTICLE DETECTOR
NEUTRINO PRODUCTION
PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS

LAr Technology

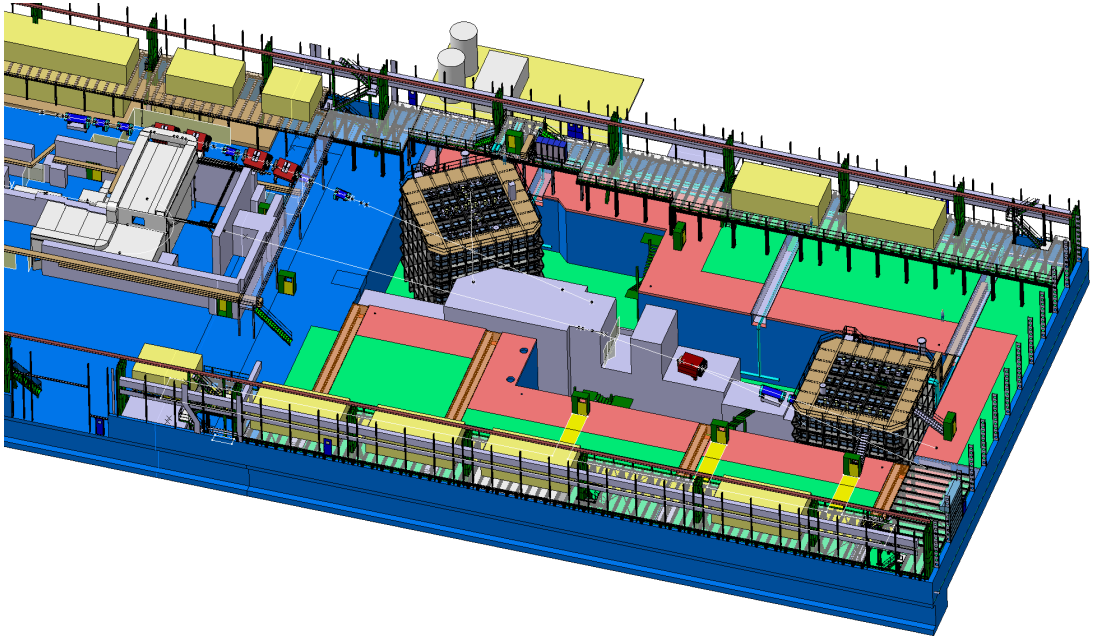
- LarTPC large scale active detectors
  - few mm precision
  - good energy resolution





Membrane cryostats
GTT license

Neutrino Platform at CERN



Theory

- Theory is a strong driver of particle physics and provides essential input to experiments, witness the major role played by theory in the recent discovery of the Higgs boson, from the foundations of the Standard Model to detailed calculations guiding the experimental searches.

  Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.

Theory providing input/guidance?

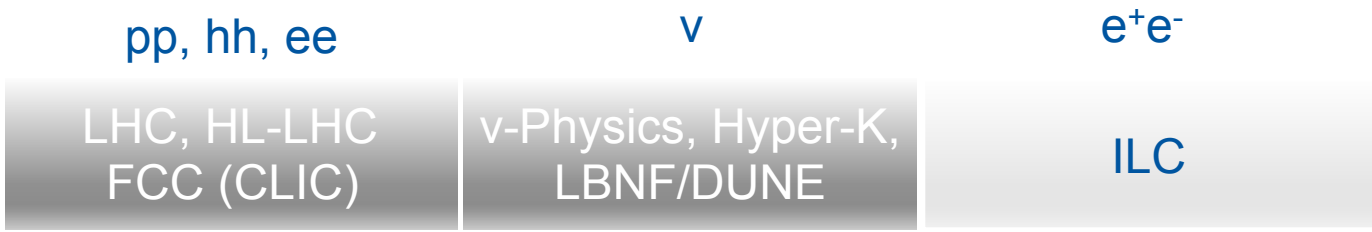
- Phenomenology is key for precision tests at the LHC and future facilities
- SUSY?, …
- fundamentally new ideas?

Disclaimer – there is much more

- ISOLDE, HIE-ISOLDE
  - TSR
- nToF
- Discussions on physics with injectors
  - e.g. SHiP
- NA61, NA62
- AWAKE

Conclusion

- HEP community executing the Global Strategy 2013
  - 2/3 down the road



  - …preparing for the future
- CERN is a key player in this endeavour

www.cern.ch