Opportunities and challenges in particle physics for the next decade

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Particle Physics preparing for the update of its European Strategy

LIP 32nd Anniversary

LIP – Lisbon, May 9, 2018

Happy Anniversary, LIP!

initially founded as the national centre to support research at CERN and now an active and lively Research Centre in Portugal

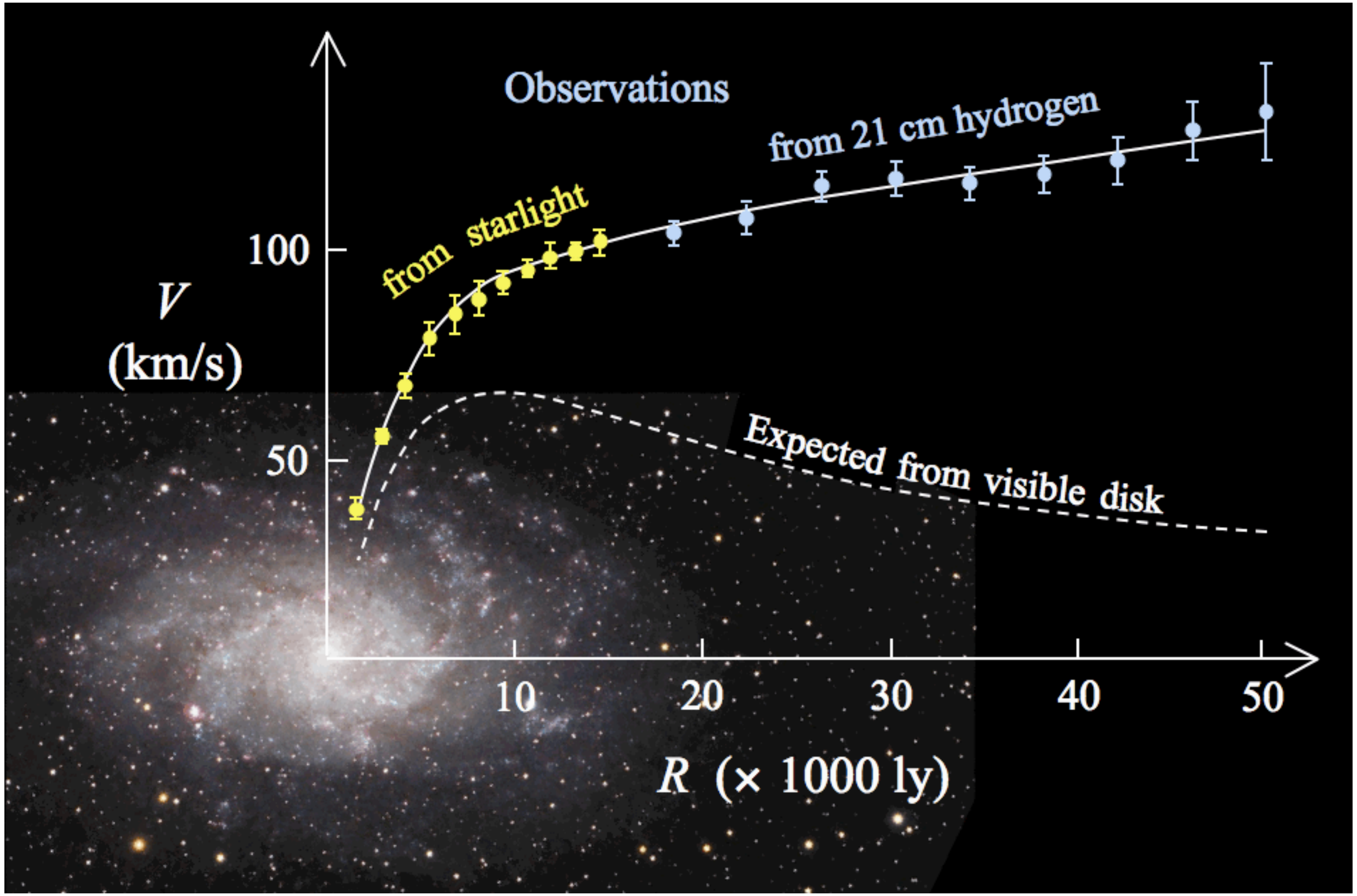
Much of the initial success is owed to the visionary *José Maria Mariano Rebelo Pires Gago* a politician turned scientist on the European Landscape

There must be more than the Standard Model…

e.g. Dark Matter

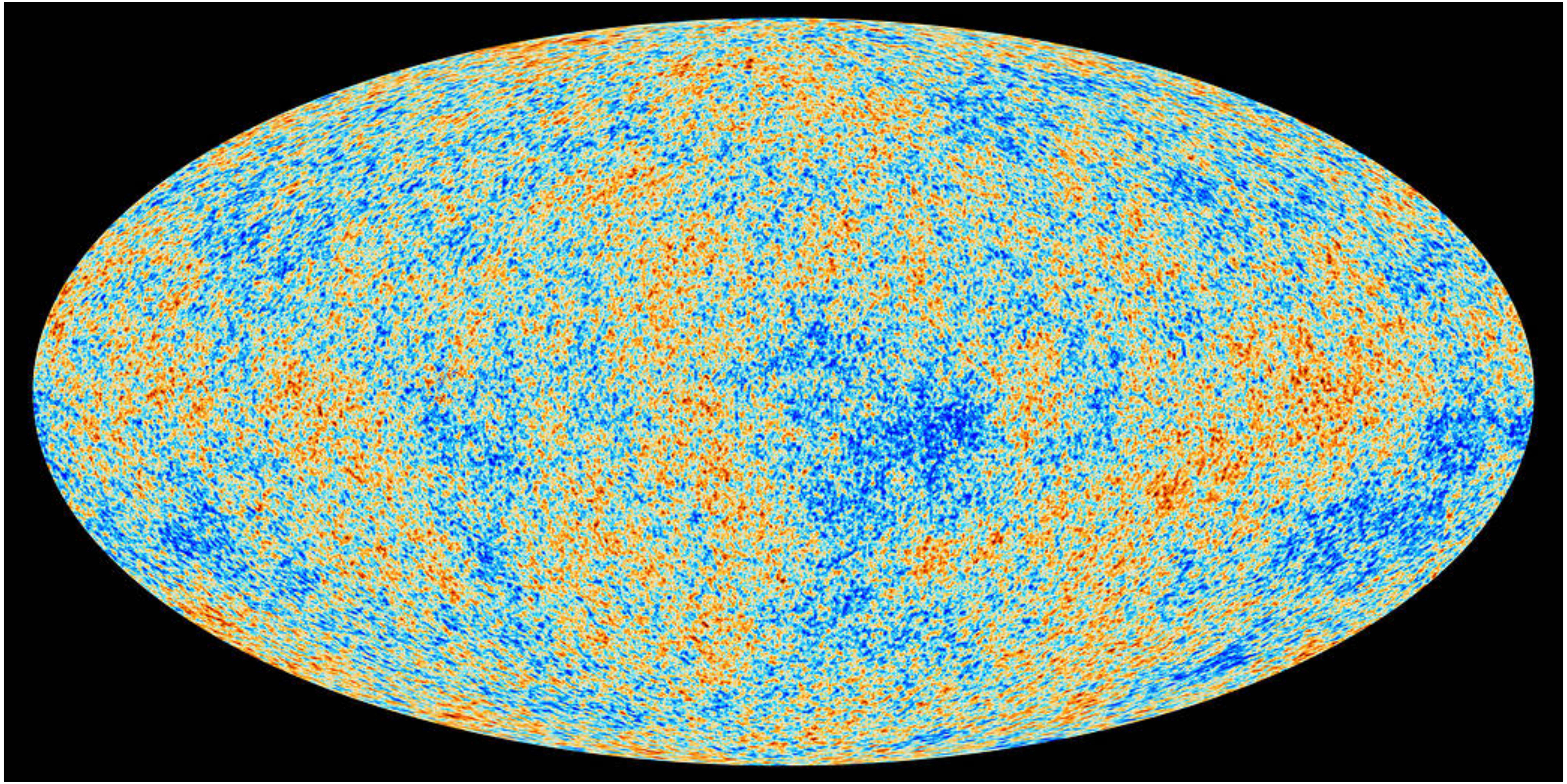
Rotational Curves of Galaxies

- Outer rim of galaxies is seen to rotate faster than expected from Newtonian mechanics
    - there is more mass than is seen interacting



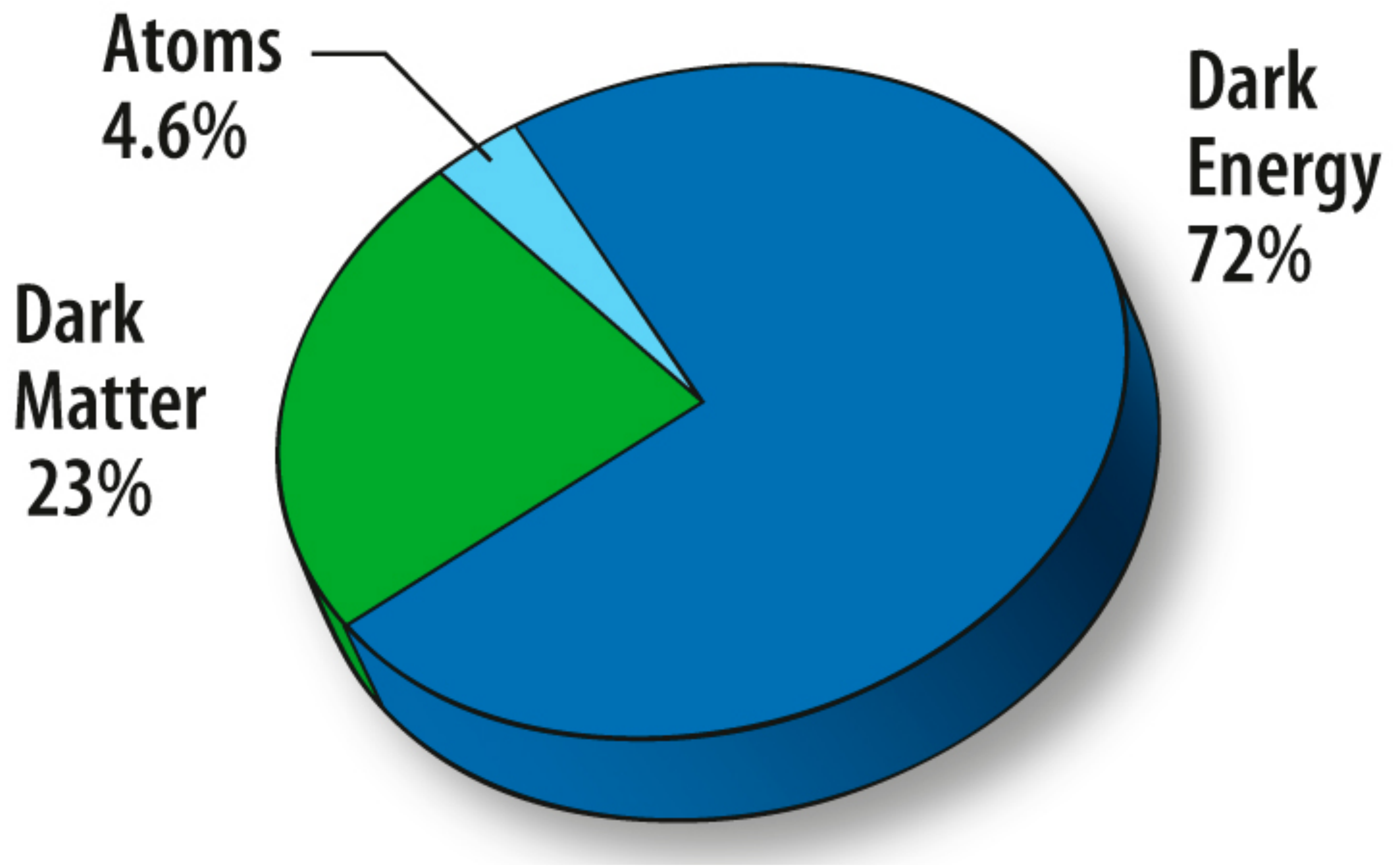
Dark Matter

Planck – Map of the Fluctuations of the Cosmic Microwave Radiation



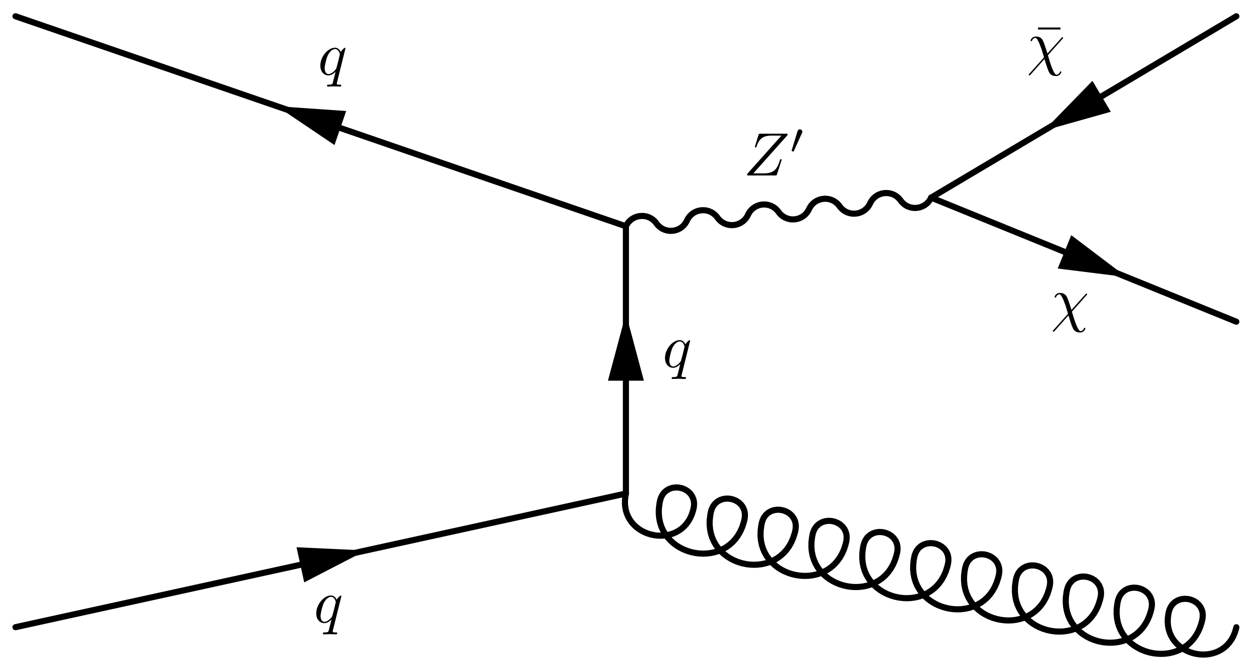
Energy Density of the Universe

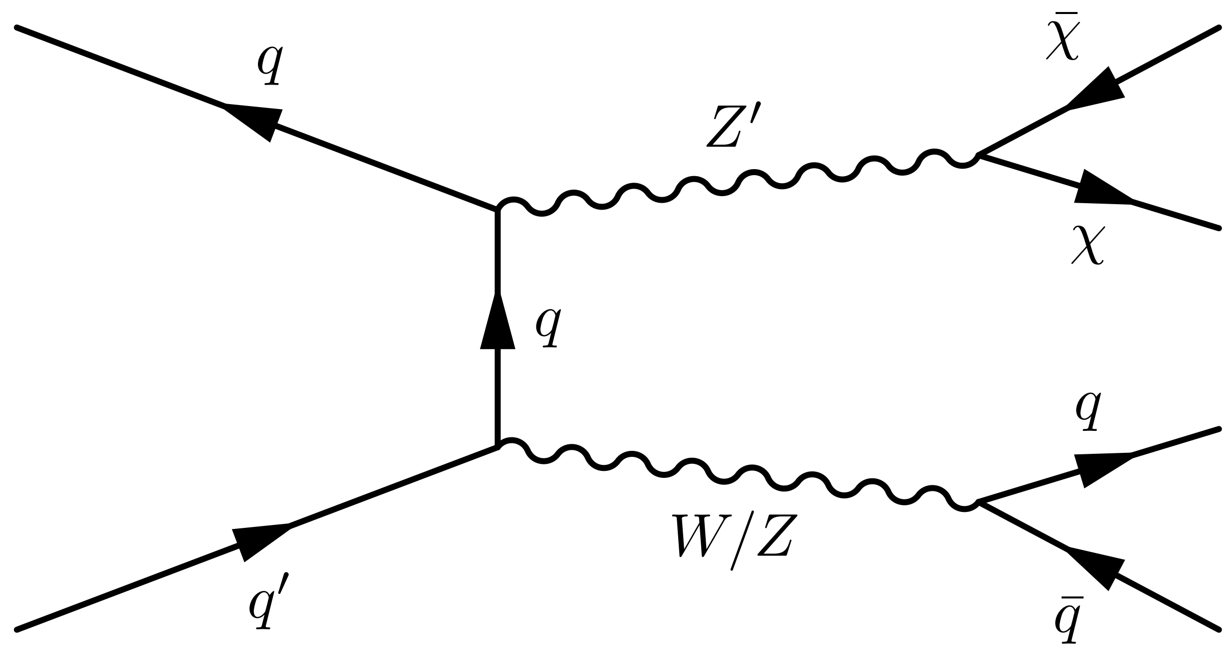
- Known matter makes up ~5% of the Universe
    - Dark matter constitutes 23%
- The expansion of the Universe is accelerating
    - Dark energy

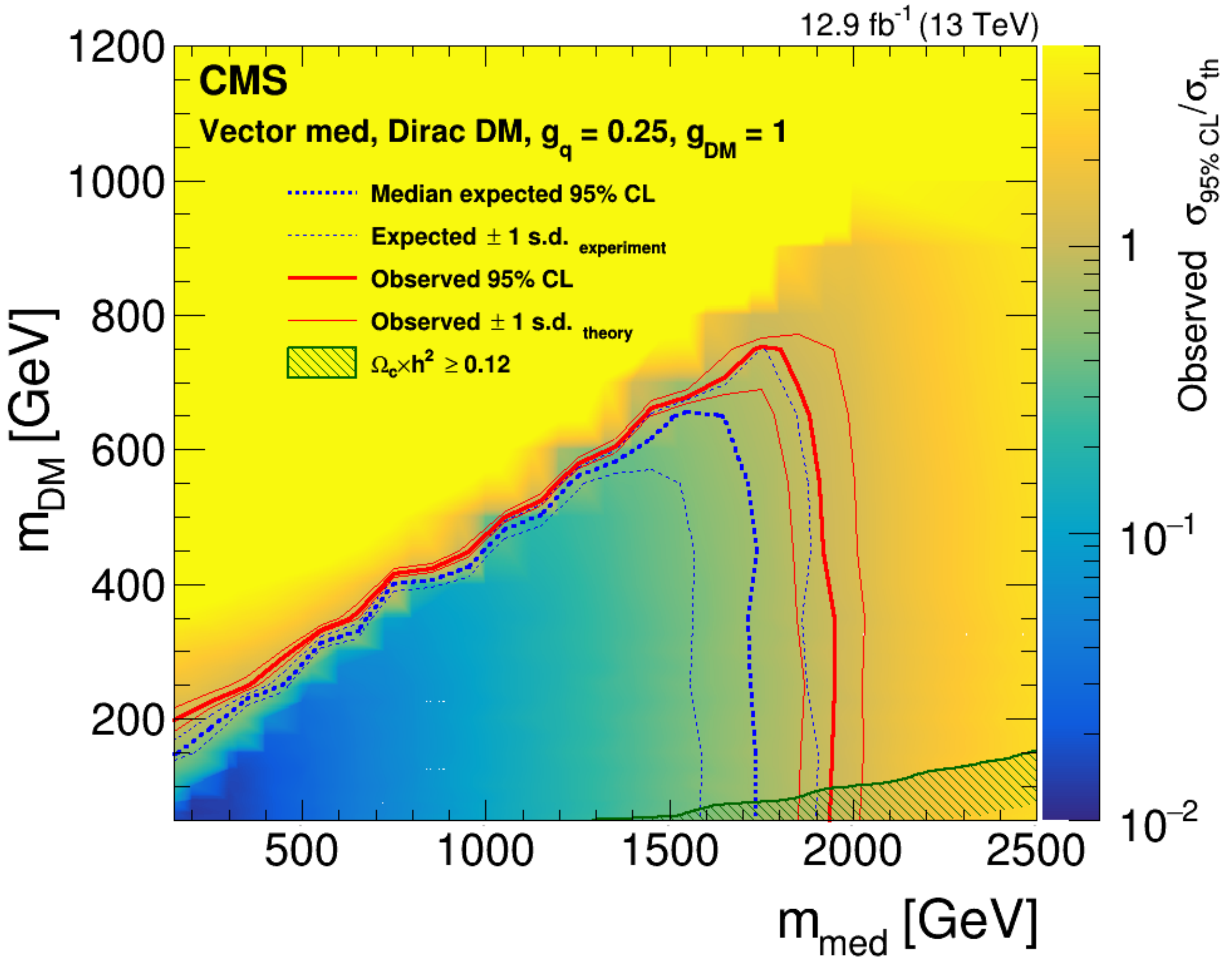


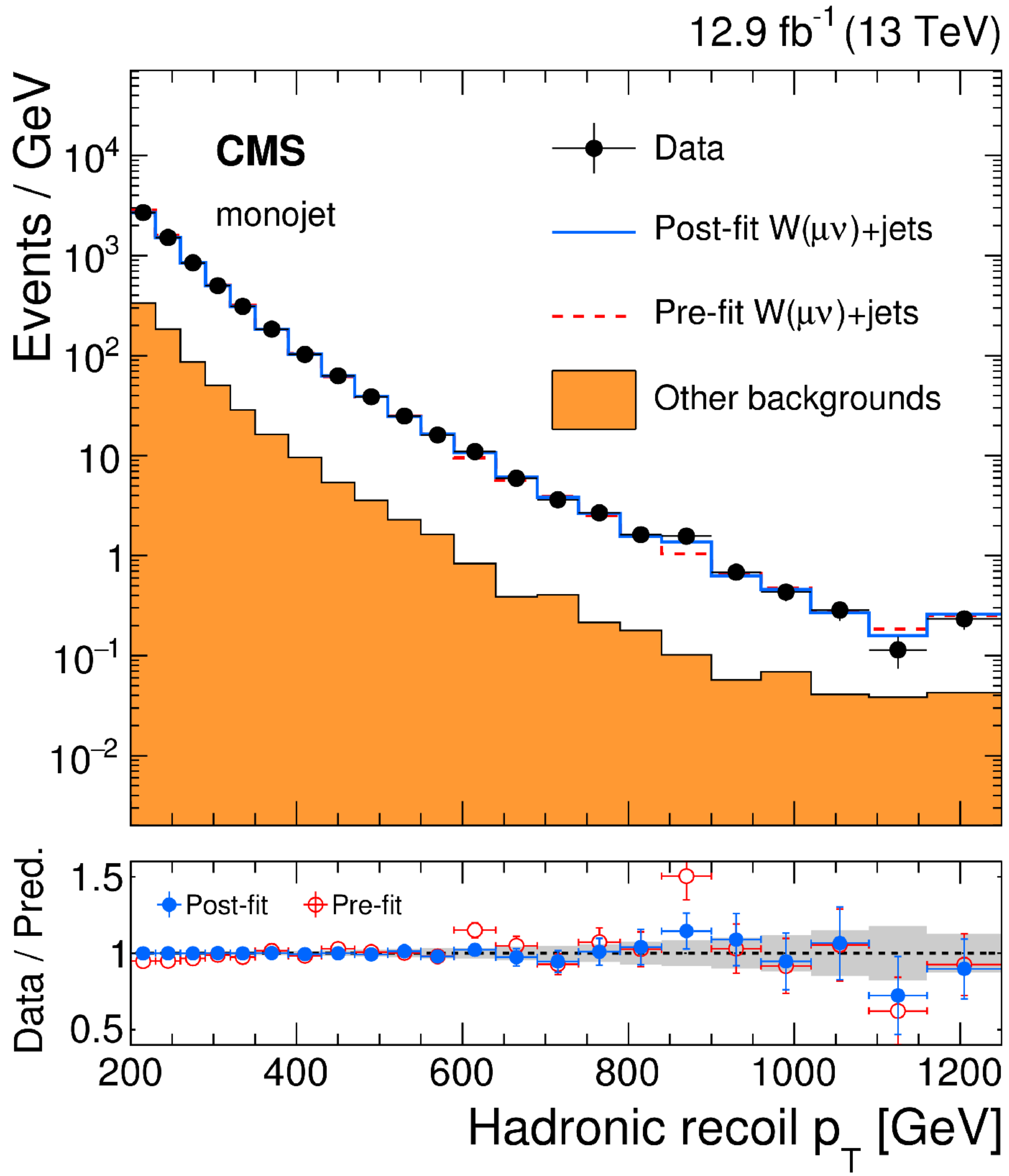

will the LHC tell…?
LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Example of Dark Matter Search at the LHC









…and many more open questions

Topics and Experimental Methods

- Dark sector
  - WIMP miracle???
- Significance of electroweak scale ~250 GeV
  - Exploration of the highest energies
- Preponderance of particles over anti-particles
  - Flavour physics

look everywhere

direct searches

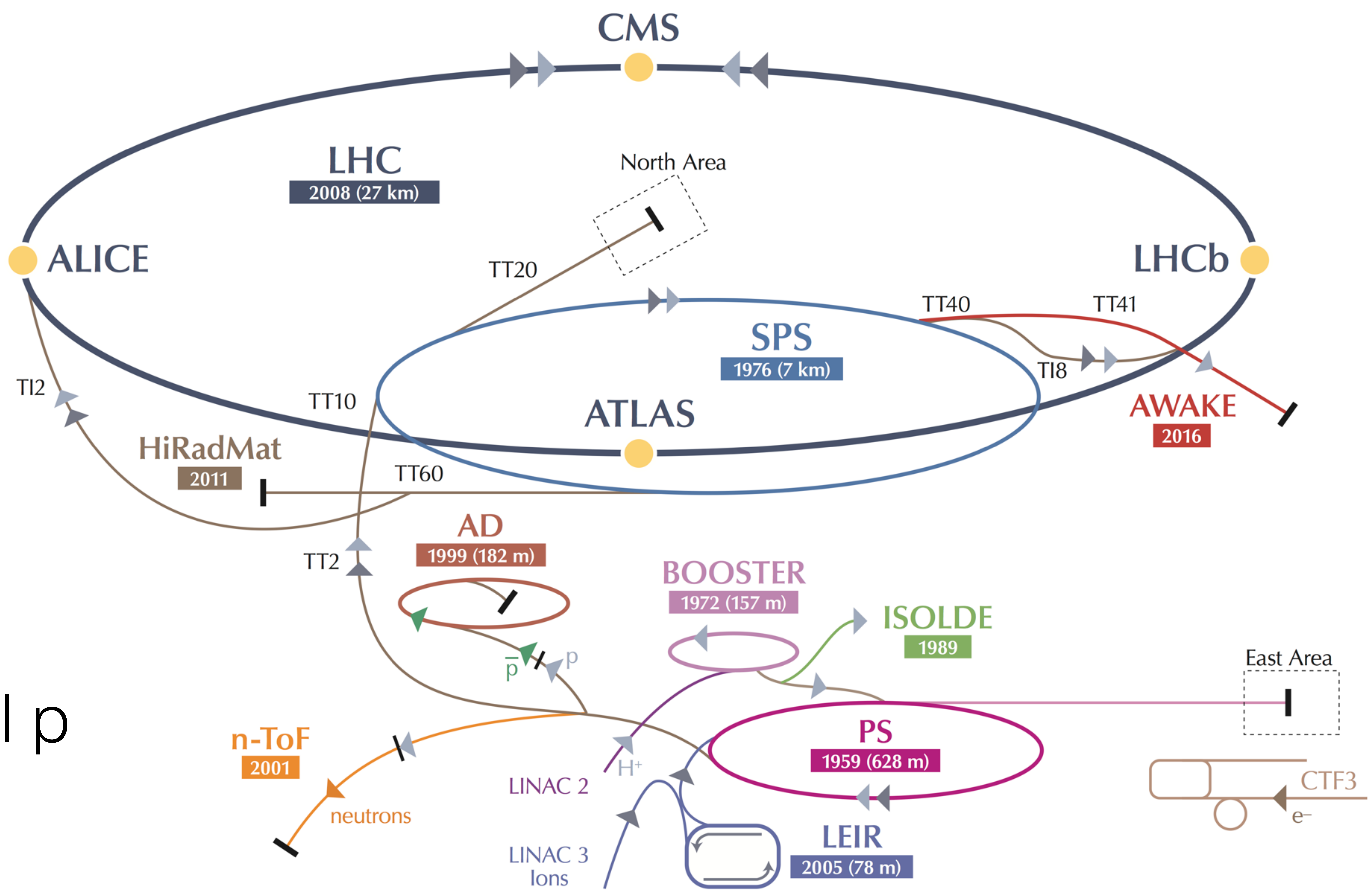
indirect searches

CERN Physics Programme in a broader context

LHC and its injector chain

- LHC
  - ongoing Run 2 @ 13 TeV
- Injectors supporting
  - Fixed target programme
  - ISOLDE (isotopes)
  - n-ToF
  - AD-programme

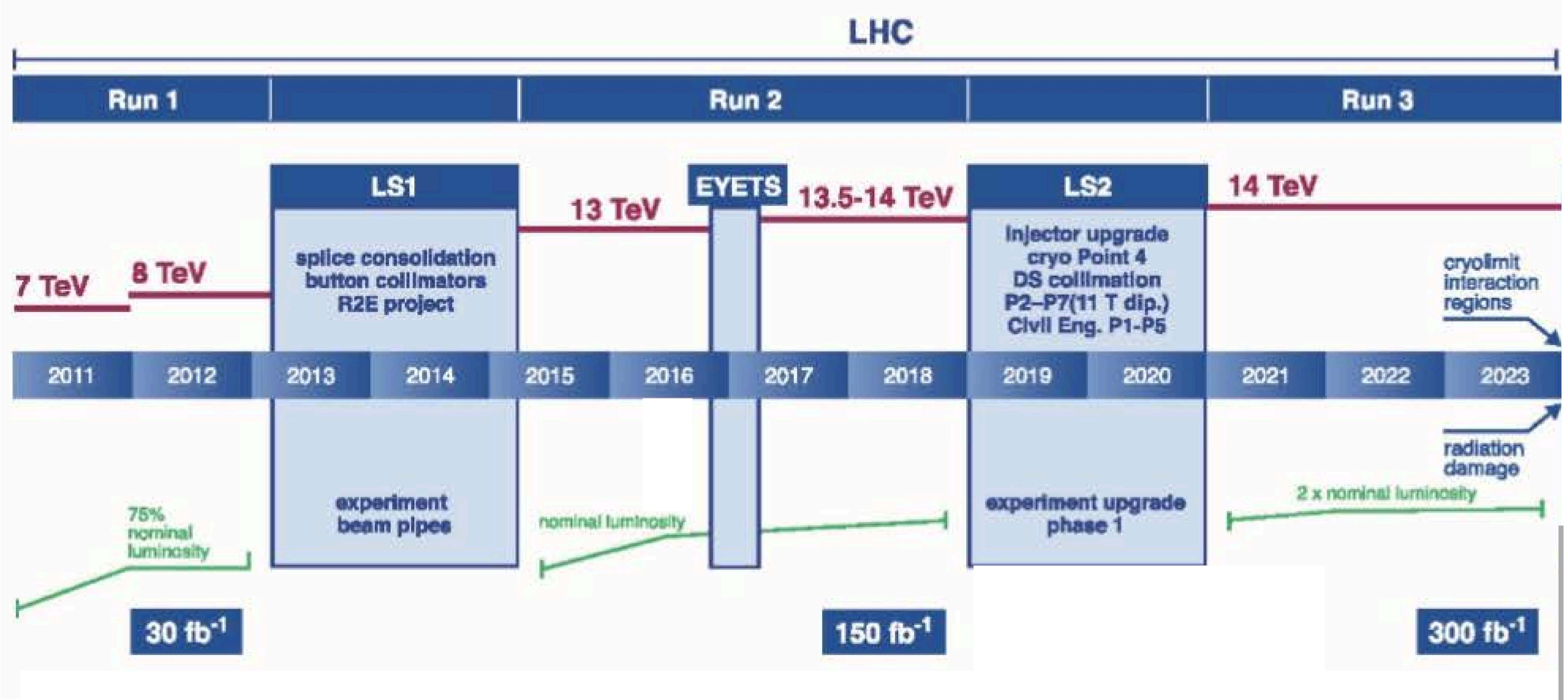
75% of all p



Goals of LHC

- Identify the Physics beyond the Standard Model
  - Explore an energy regime that has not been chartered before
    - have entered 13 TeV regime in *production* mode
    - 14 TeV *after* LS2 and possibly 15 TeV albeit with lower luminosity
  - Look for small deviations (small couplings) from the Standard Model
    - Precision measurements of (rare) processes

LHC schedule



HL-LHC
High
Luminosity
Phase of LHC

Substantial upgrades for ALICE and LHCb; preparatory upgrades for ATLAS and CMS including civil construction

end of original LHC

LHC Configuration 2018

- More bunches
    - also good for LHCb
- Levelled pile-up ~60; bunch luminosity similar to 2018
- Introduction of β*-anti-levelling down to 25 cm

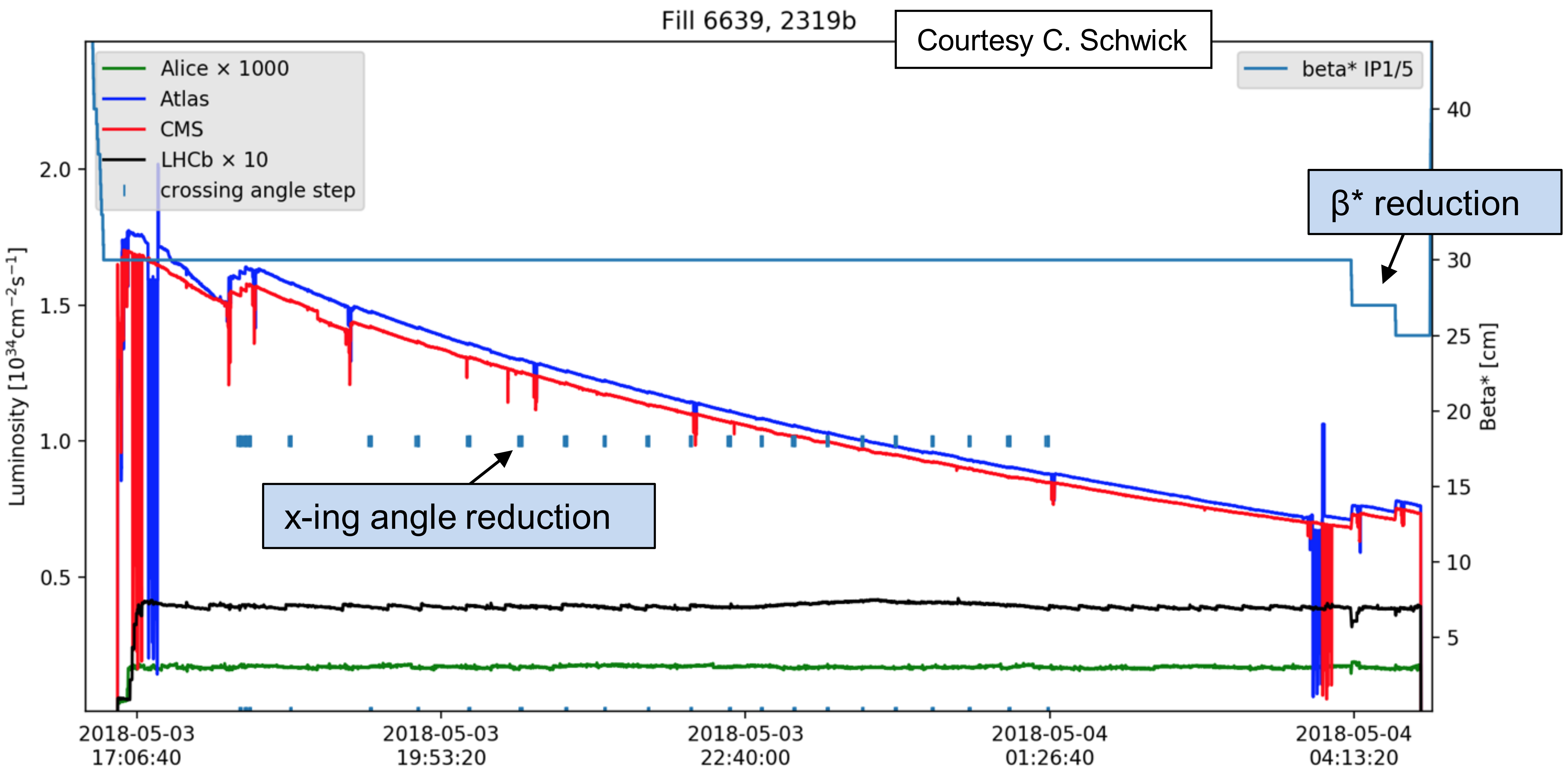
dynamically increase particle density in region of beam overlap

Optics	2017 ATS
Beam type	**BCMS** (25ns)
Bunch intensity	1.15 - **1.3** x 10^{11} p/bunch
#bunches per train	144
Total number of bunches	2556
Initial/baseline β*	30 cm
Final β* (by leveling) (*)	**27/25 cm**
½ xing angles(**)	**160**/200/**160**/-250
CMS bump	**-1.8 mm**

* Use of β* levelling *initially at end of fills* to make it operational, requiring closing of TCTs in IR1 and IR5 by an additional σ wrt to 2017
** same ATLAS Xing angle polarity as in 2017, *continuous* crossing angle anti-leveling

Exploiting the fills – maintain high luminosity for extended periods

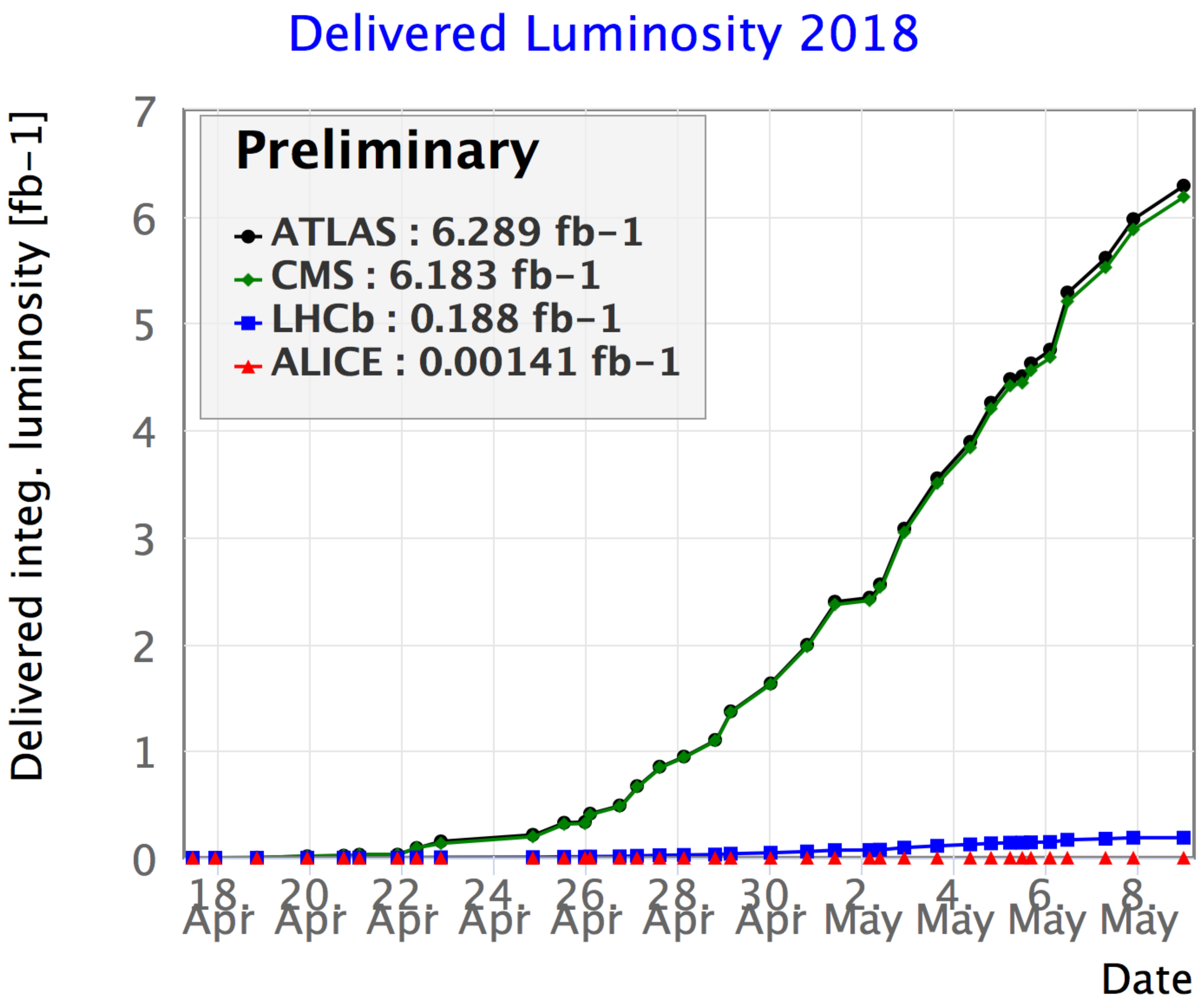
- Continuous crossing angle reduction (anti-levelling)
  - 160 μrad → 130 μrad during fill (as the bunch charge decreases the in- and outgoing bunches interfere less)
- β*-anti-levelling
  - 30 cm → 27 cm → 25 cm (nominal LHC value: 55 cm)



both schemes are seen to work

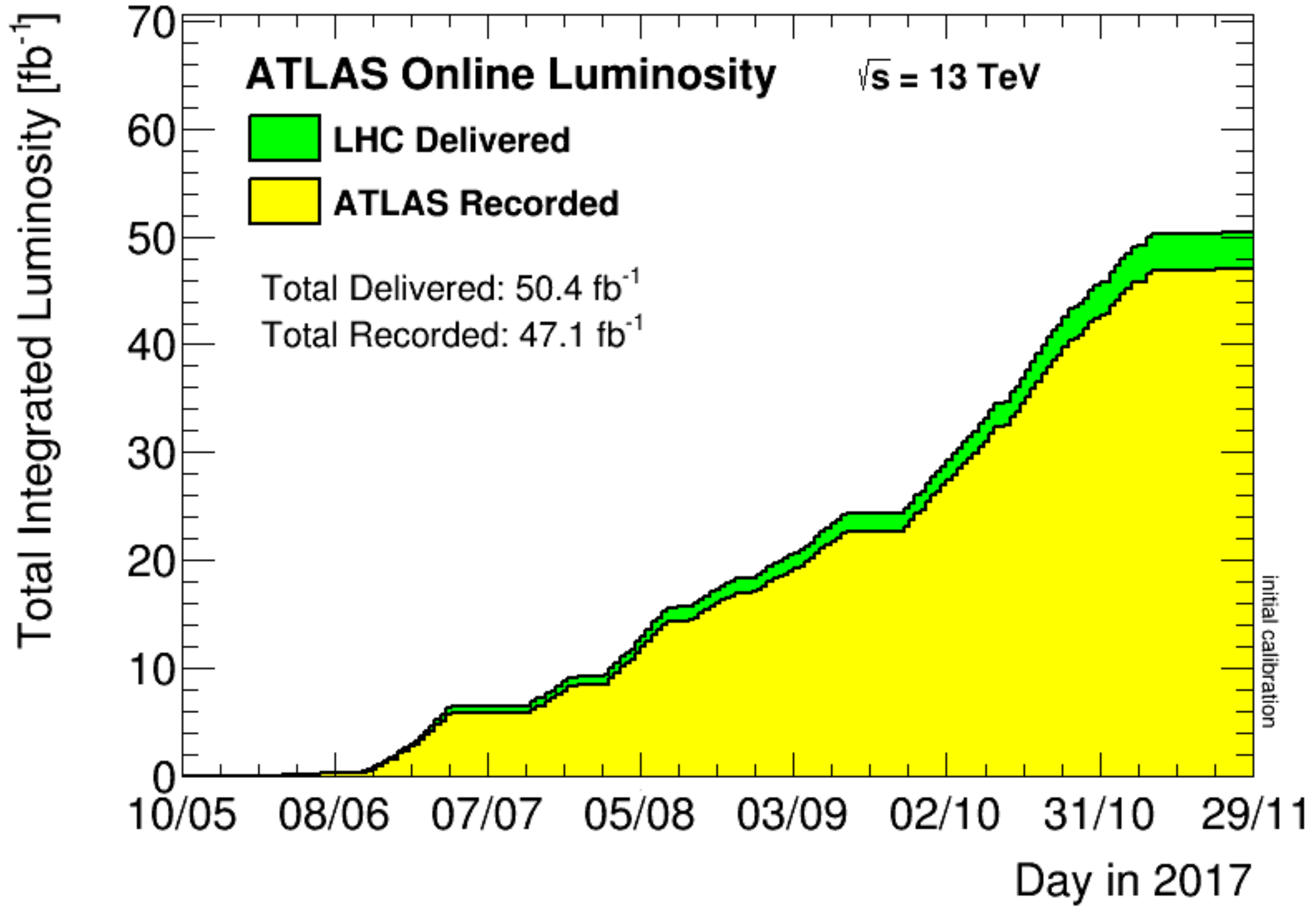
Great start in 2018

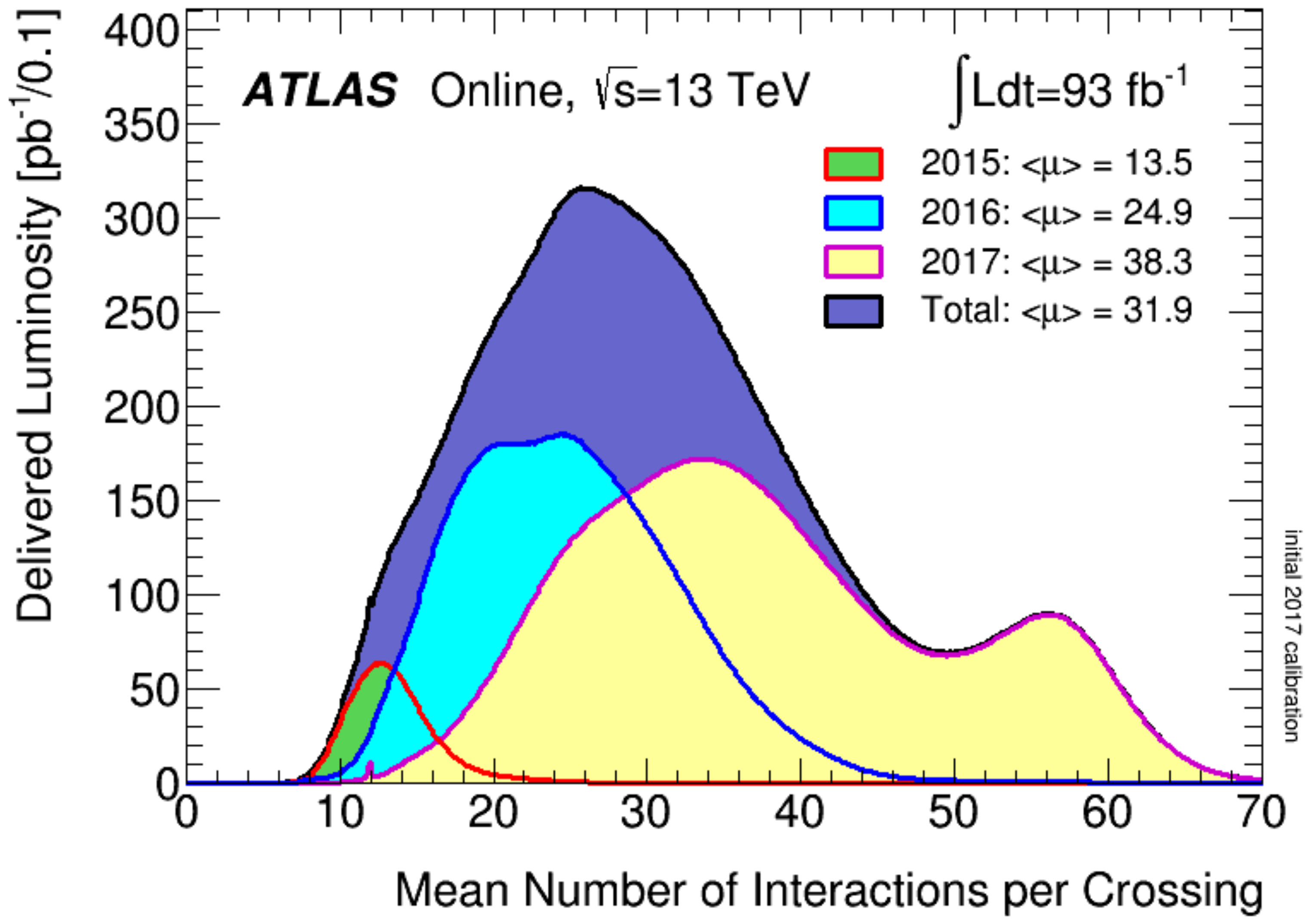
- Luminosity goal for 2018
  60 fb^{-1}
- a month of PbPb running towards the end of the year
- special runs
  - Total cross section at lower energy etc.

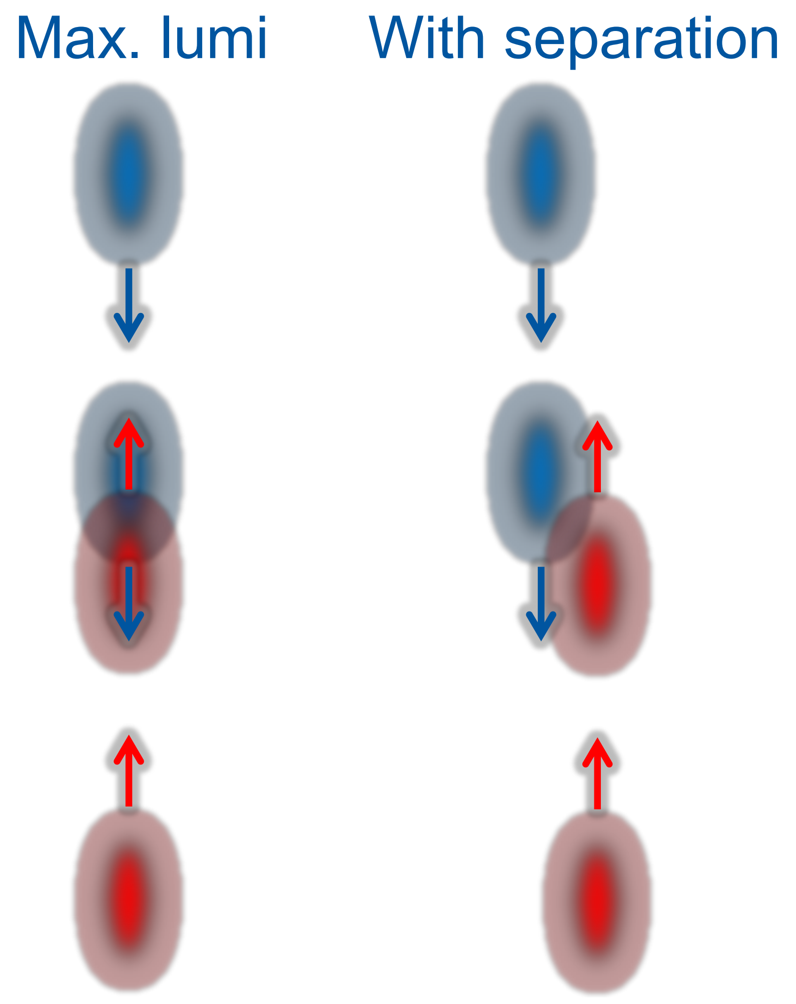


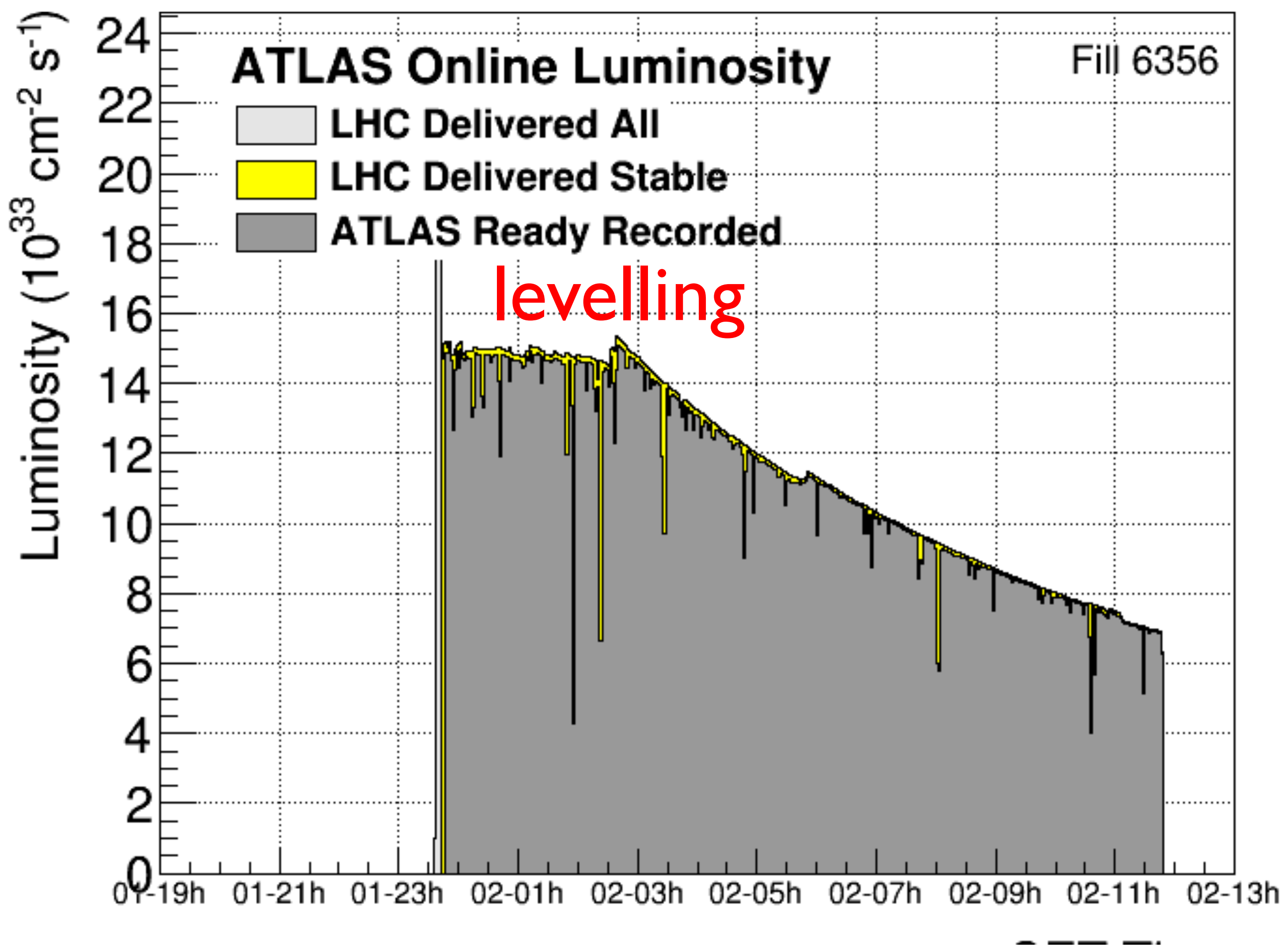
Event Pile-Up and Luminosity Levelling at LHC (2017)

- Peak L ~ 2×10^{34} cm^{-2}s^{-1}
- ATLAS and CMS prefer L ≤ 1.5×10^{34} cm^{-2}s^{-1} and longer fills (slow beam burn-off)
- Initially separate the beams transversely and slowly increase overlap









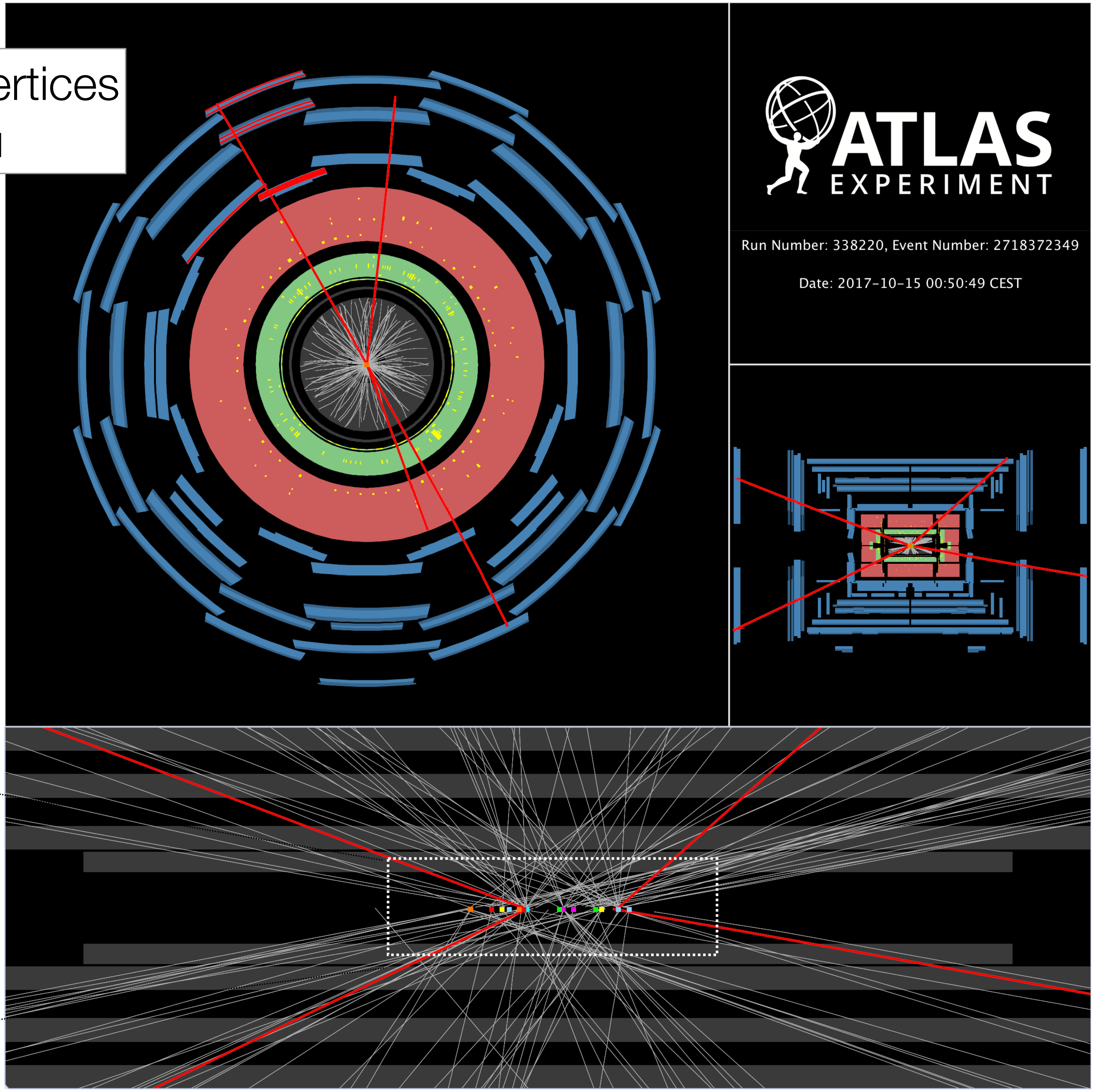
Levelling leads to cleaner events and only small degradation of integrated luminosity.

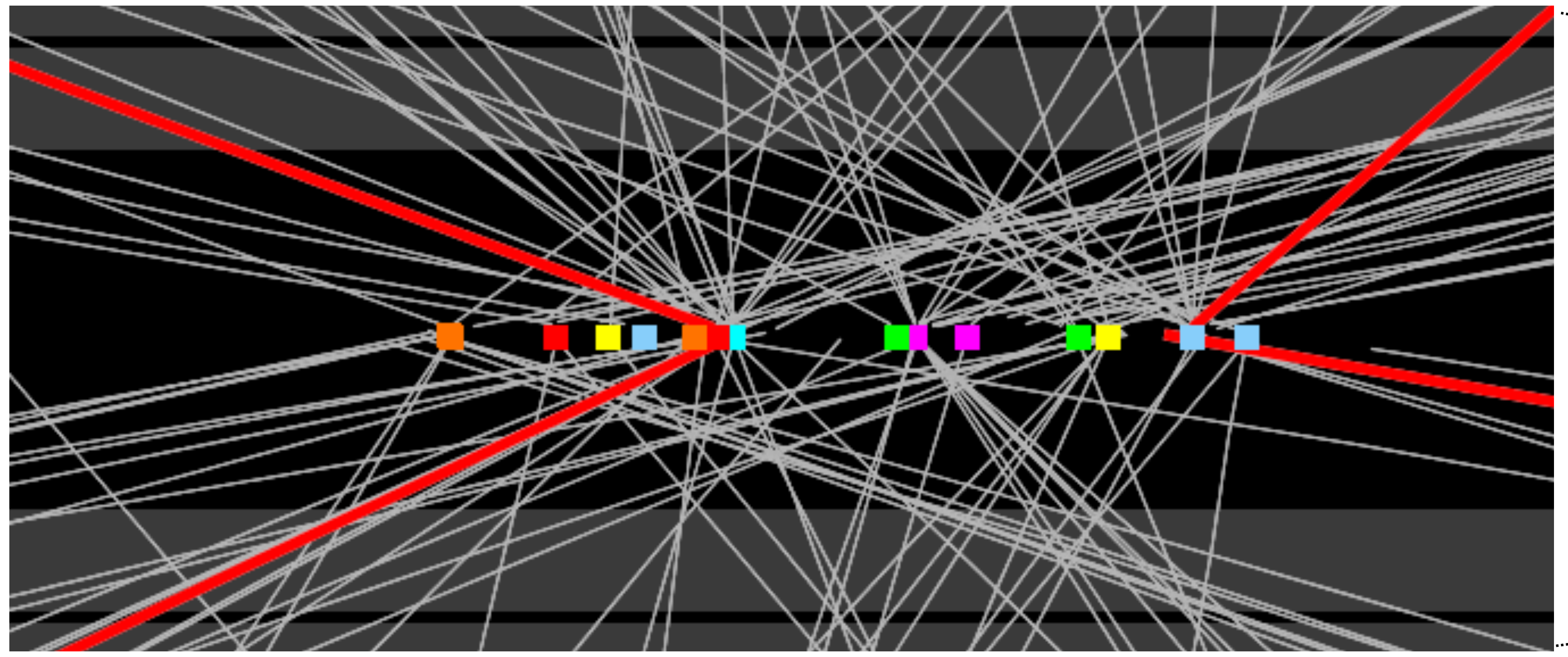
Pile-up affects physics

- For low pile-up:
  - 1 hard interaction and many minimum-bias interactions
- for high pile-up
  - possibly more than 1 hard interaction + min-bias

2 independent hard-scale events

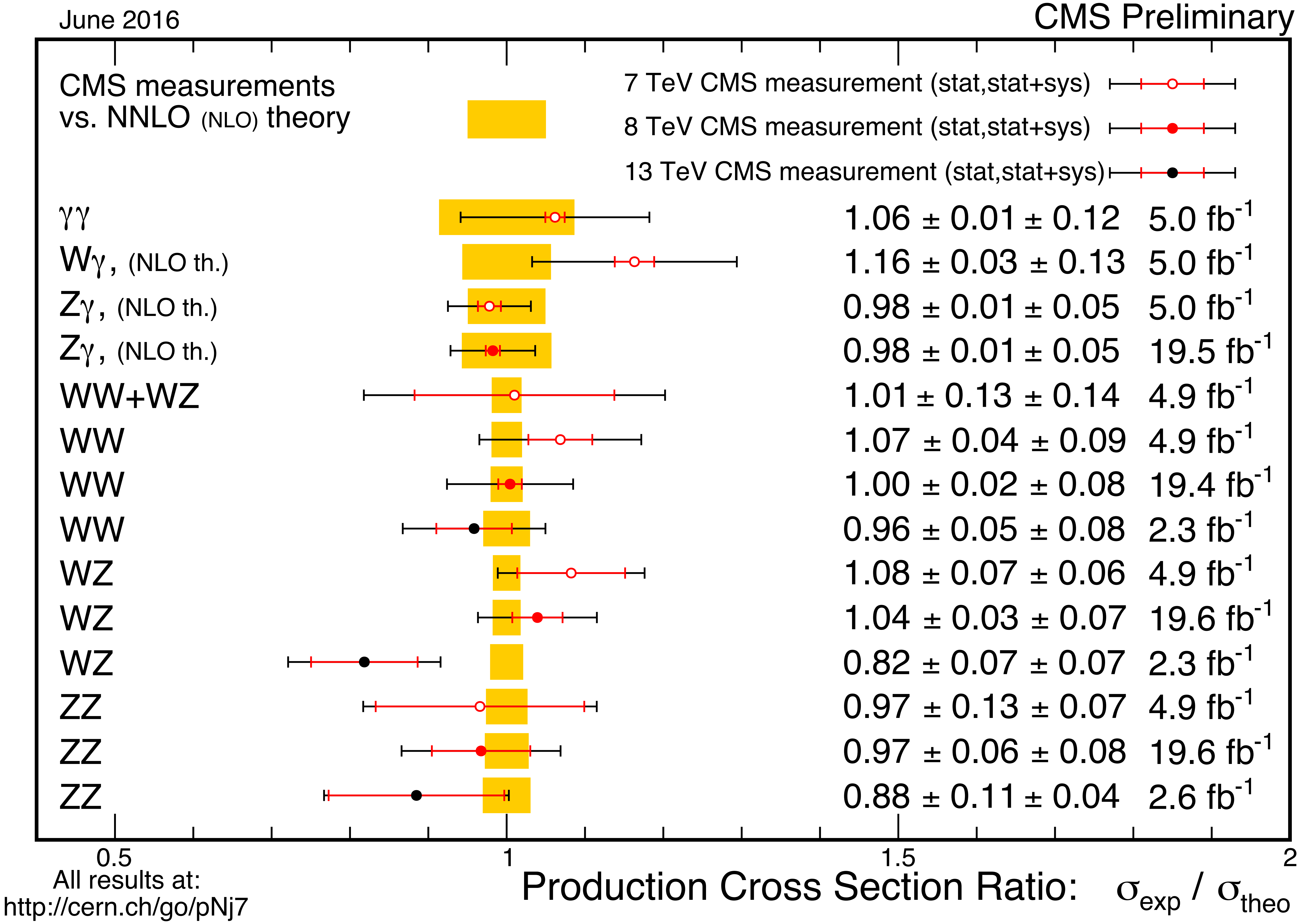
2 separate vertices
$Z \to \mu\mu$





Vector boson and theoretical understanding

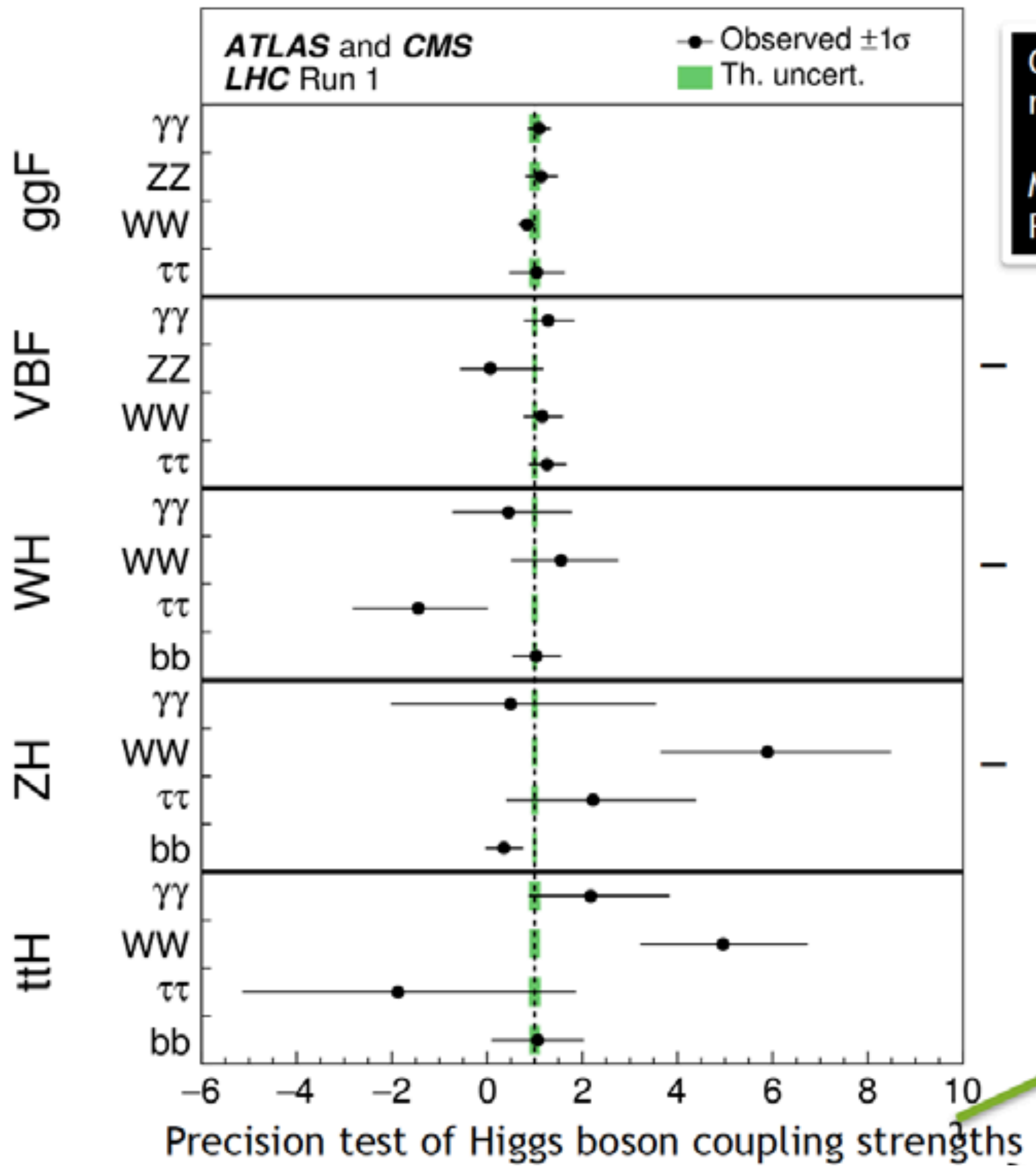
- Rate of interaction, i.e. the cross section for pp-collisions varies dramatically
  - high mass cross sections are of very low rate
  - requires very high selectivity (trigger, event selection)



Higgs Boson at 7 and 8 TeV (Run 1)

ATLAS and CMS have combined their Run 1 data to extract precise measurement of Higgs coupling

Higgs (125 GeV) compatible with SM



CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Mass: Phys. Rev. Lett. 114, 191803
Rates and couplings: arXiv:1606.02266

- Mass has been measured to 0.2% precision m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

Coupling strengths

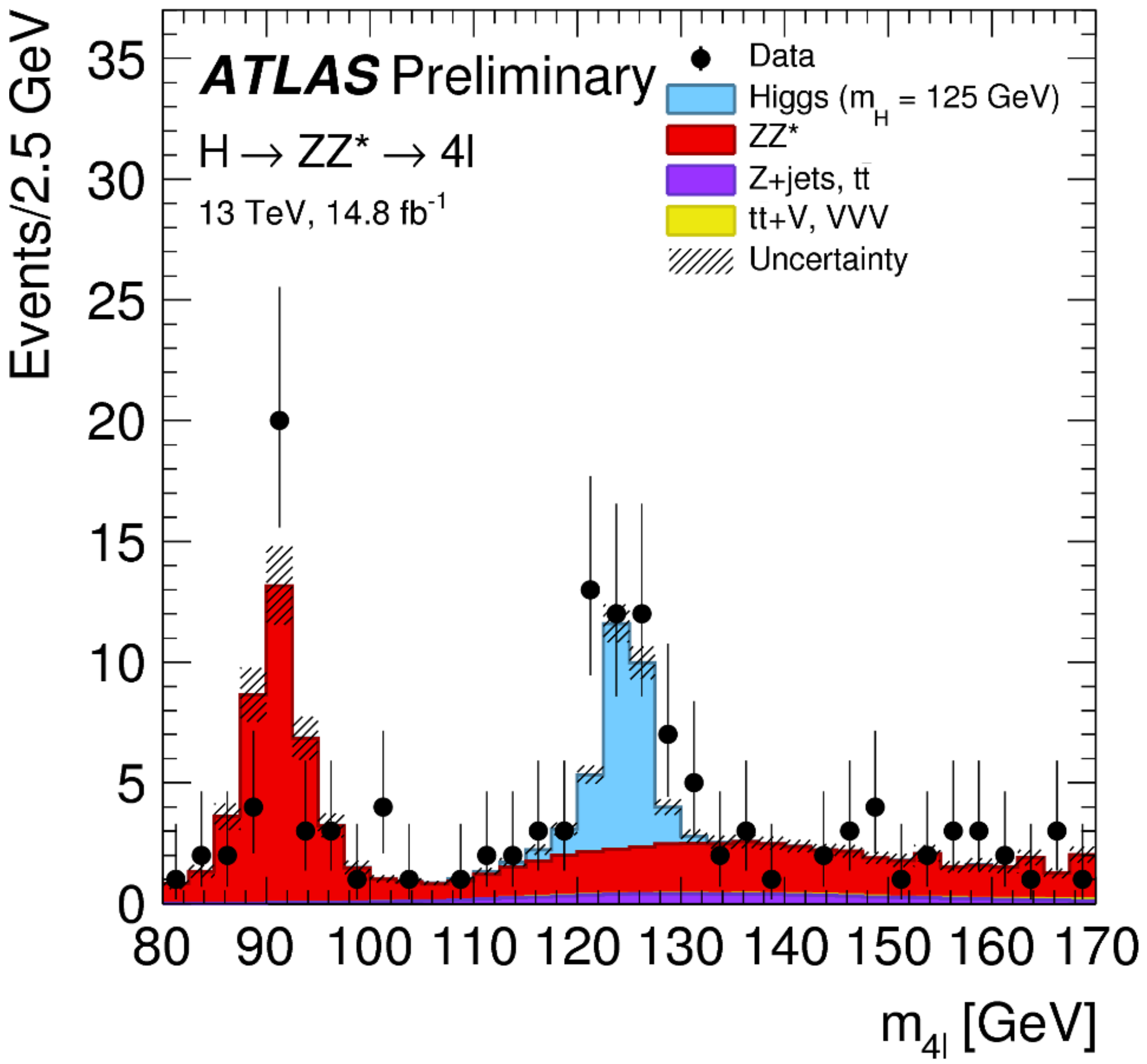
$$\mu = \frac{\sigma}{\sigma_{SM}}$$

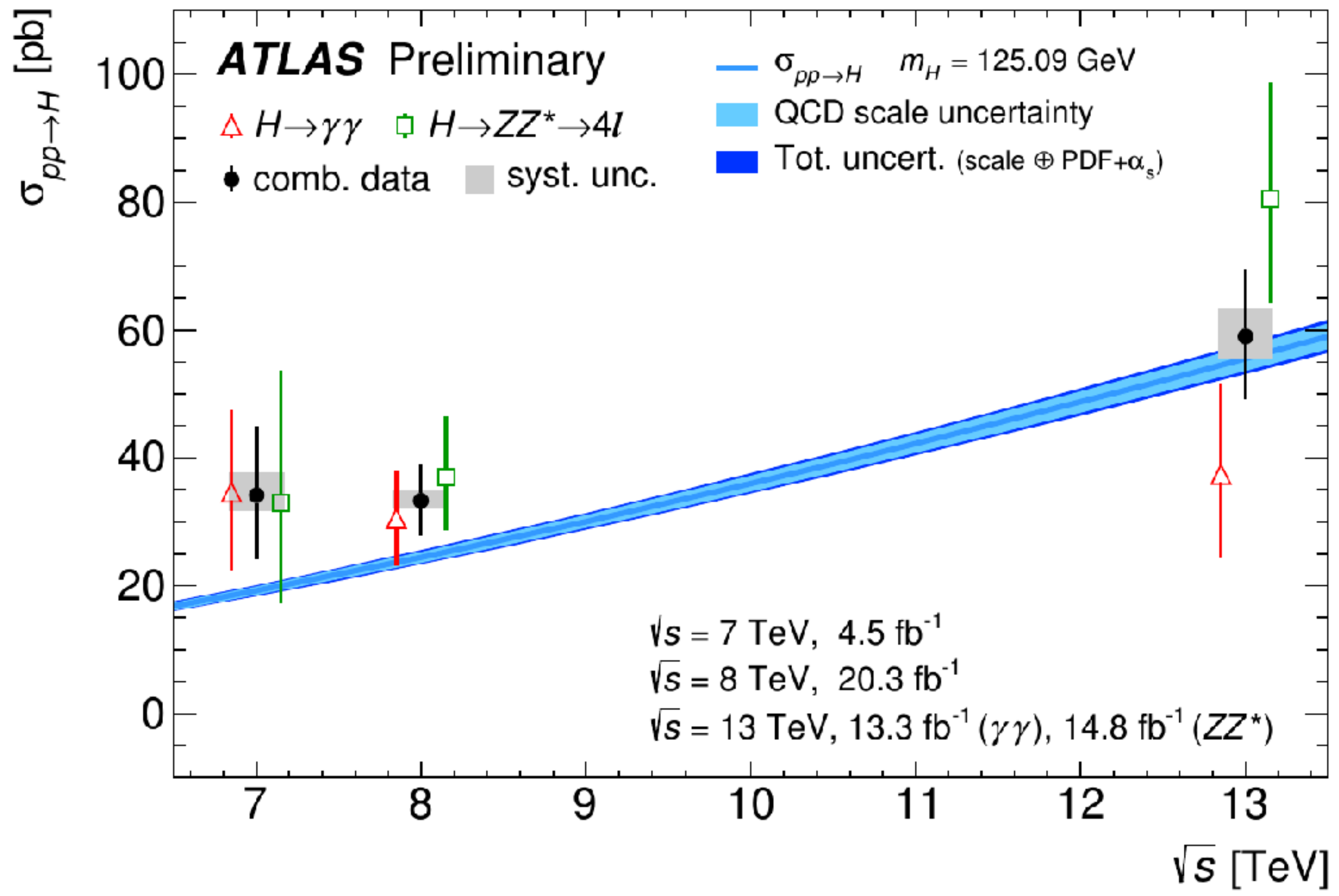
Higgs Production at 13 TeV (Run 2)

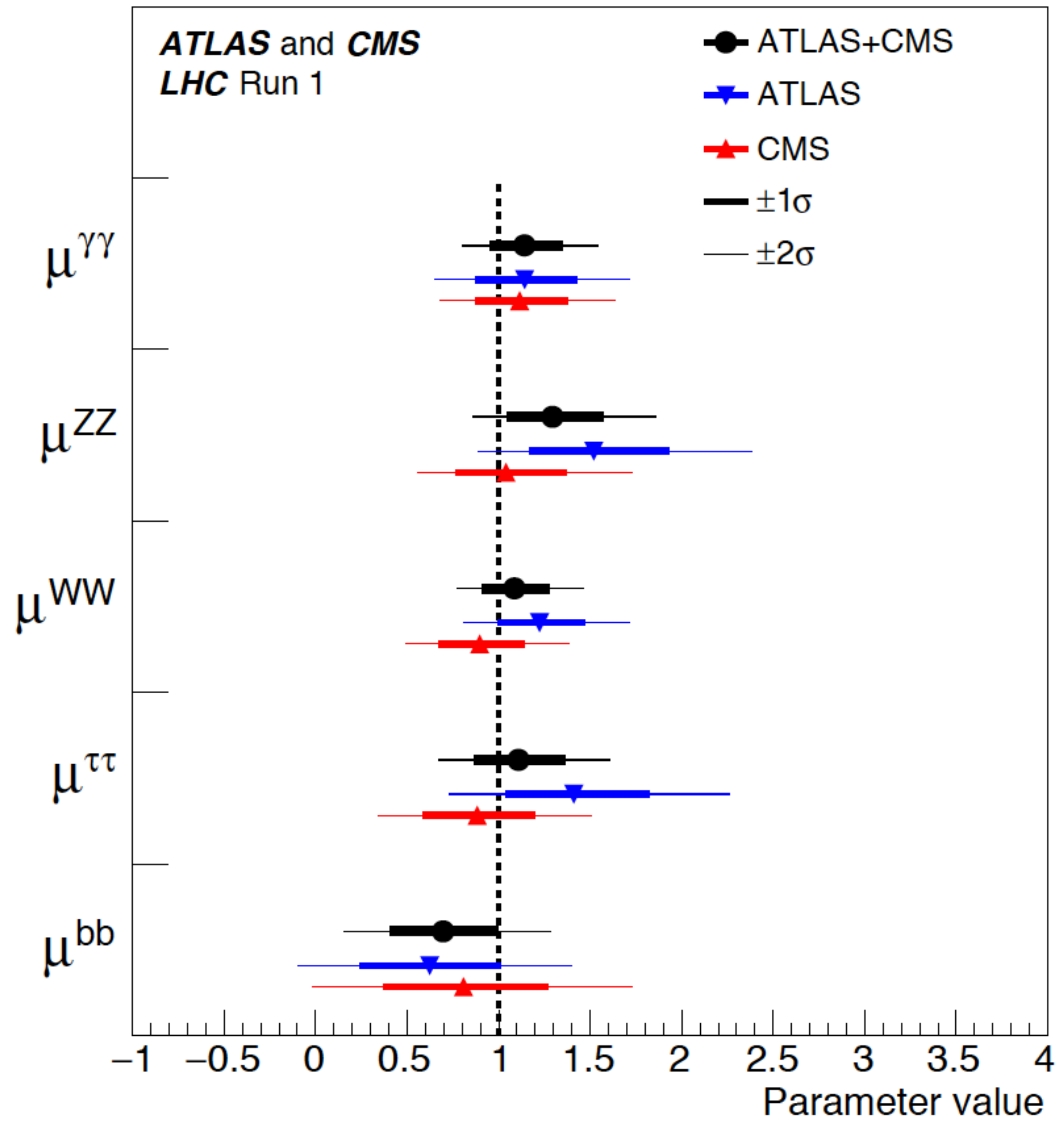
- Overall significance of Higgs production: ~10 σ
- σ(pp→H+X)=

$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb

$55.5^{+2.4}_{-3.4}$ pb SM



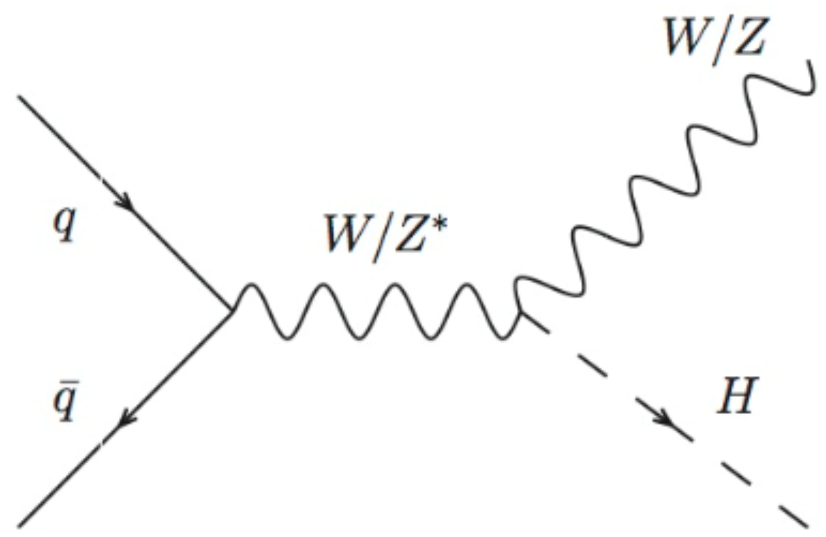


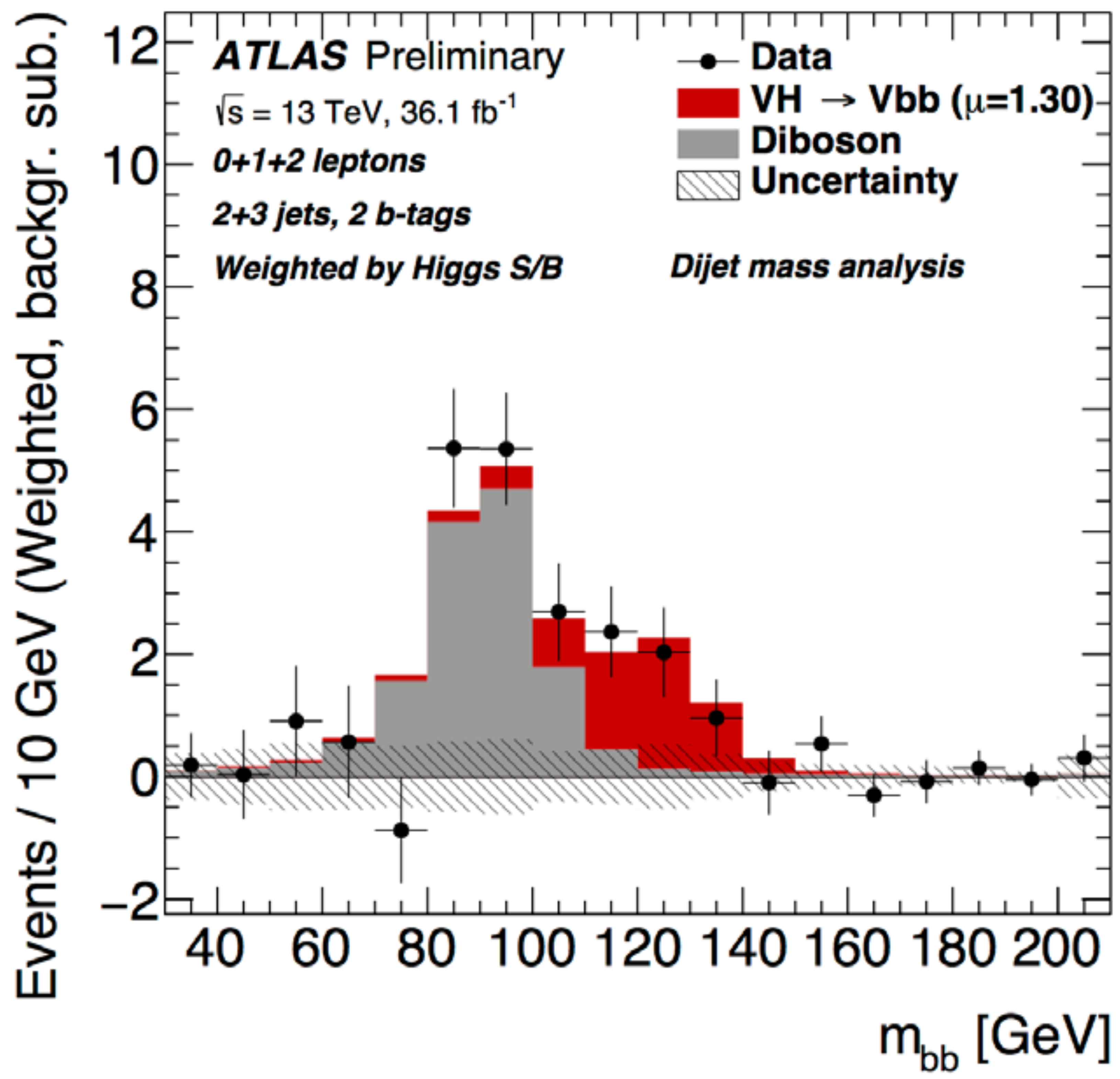


H→bb, i.e. the dominant decay remained an experimental challenge in Run 1

H → bb observed at LHC

- Higgs boson couples to mass
  - preferential decay to heaviest quark (b-quark, BR=58%)
  - overwhelming background from light quarks
- Use associate production with W or Z

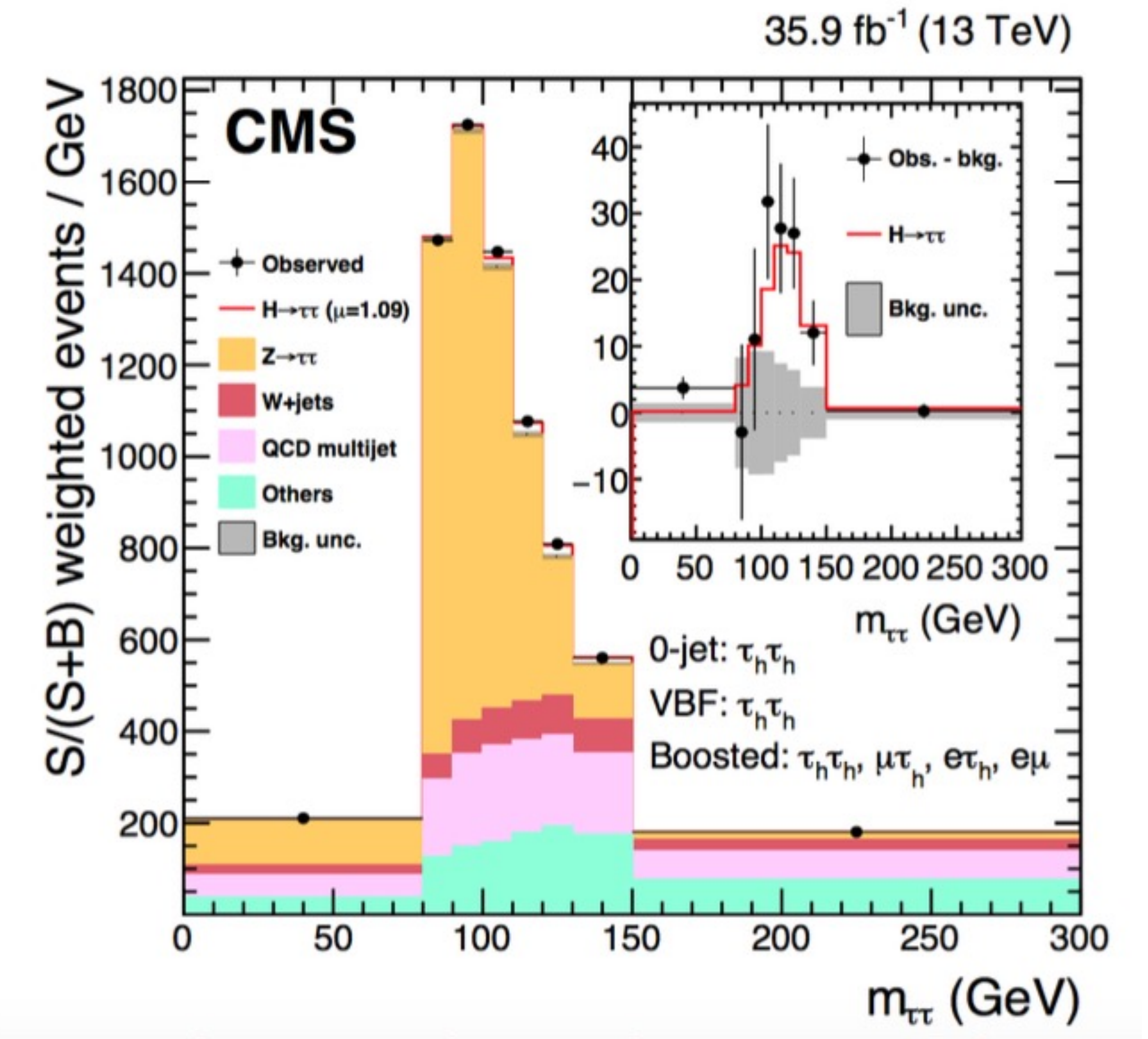


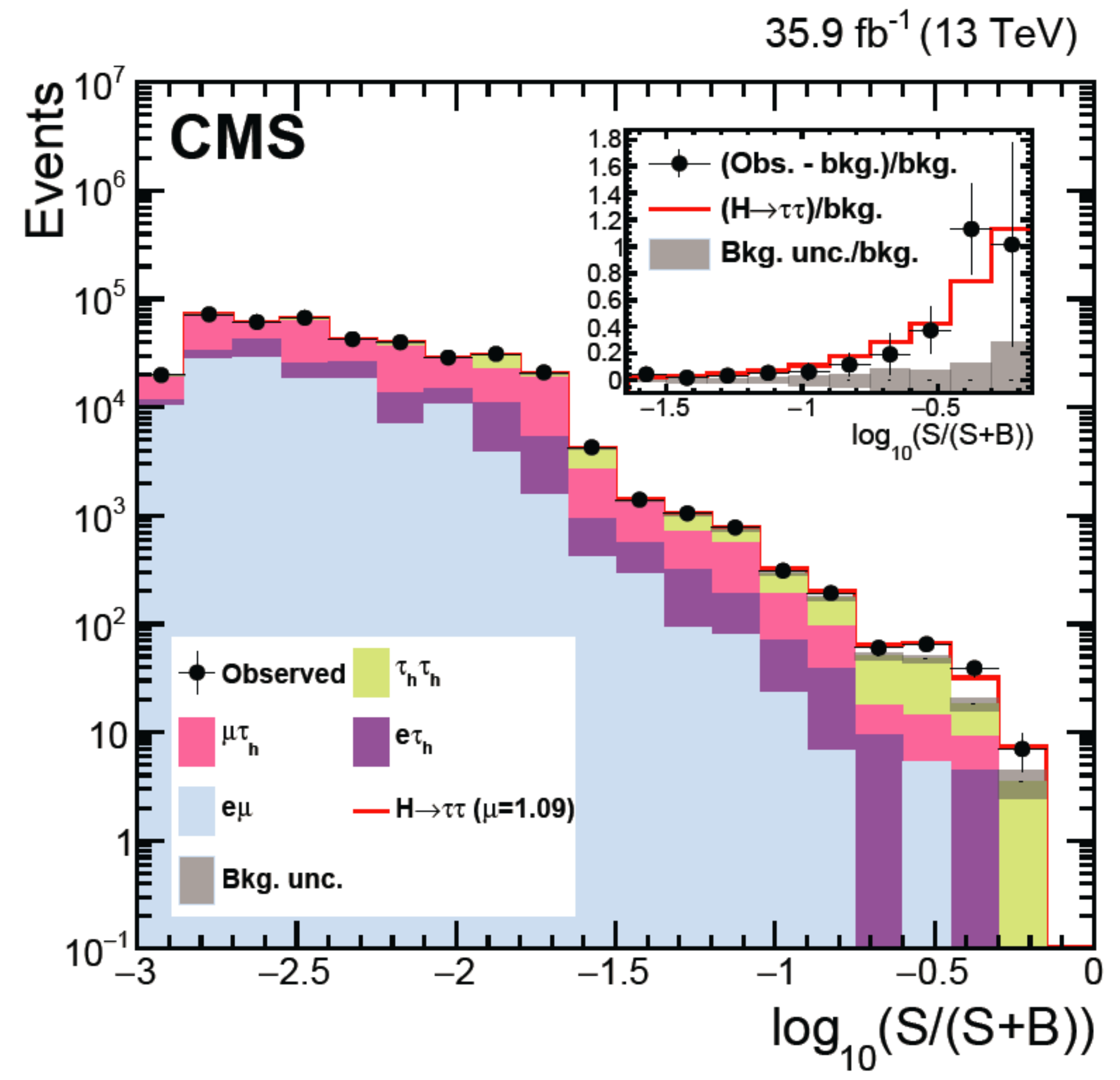


3.6 σ

H → ττ at LHC

- Higgs boson couples to mass
  - among fermions the decay to τ-leptons is preferred (τ-quark, BR=6.3%)
  - τ-detection challenging
    - $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$- modes used

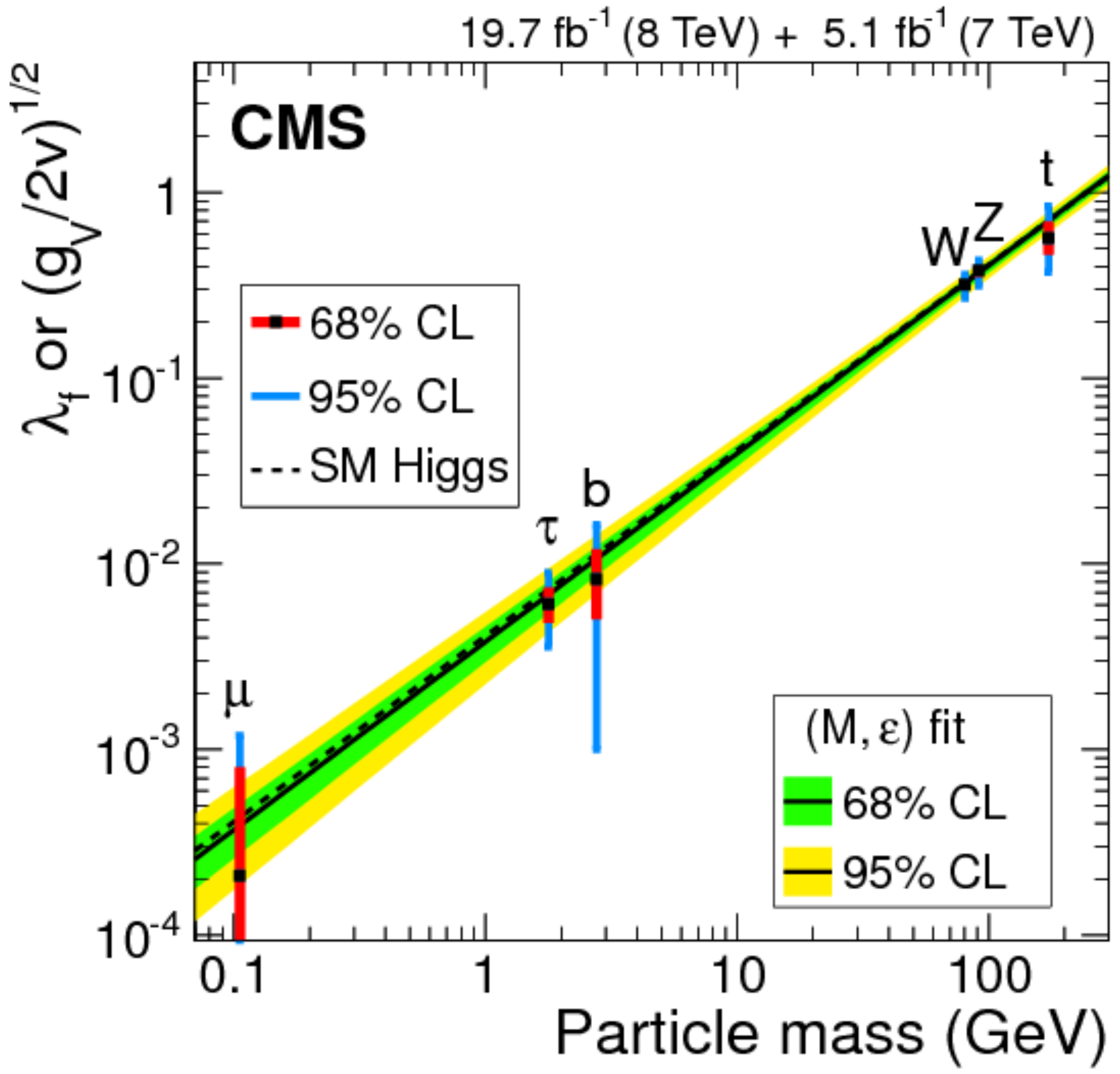


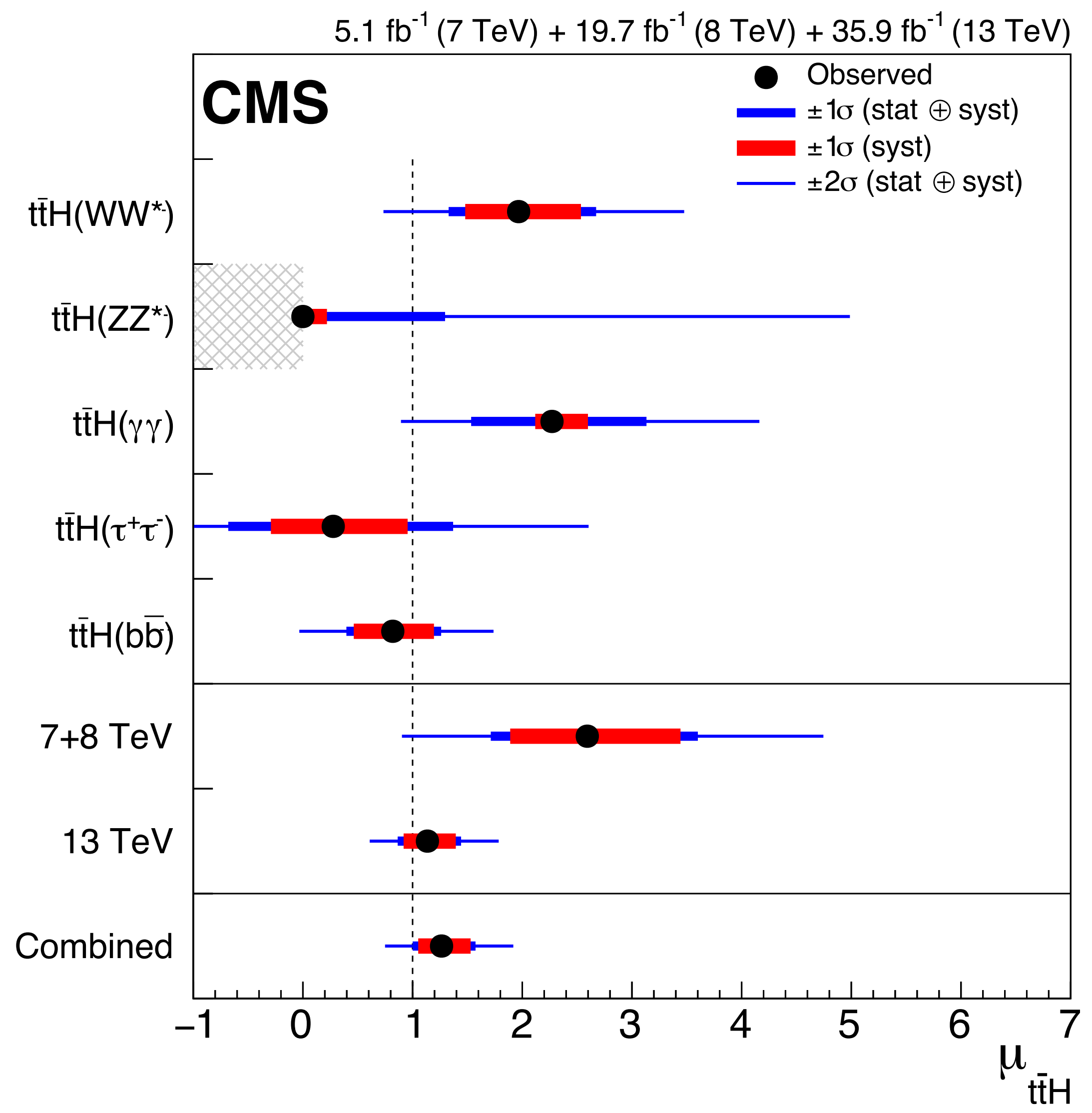


4.9 σ from 13 TeV data

Observation of ttH coupling

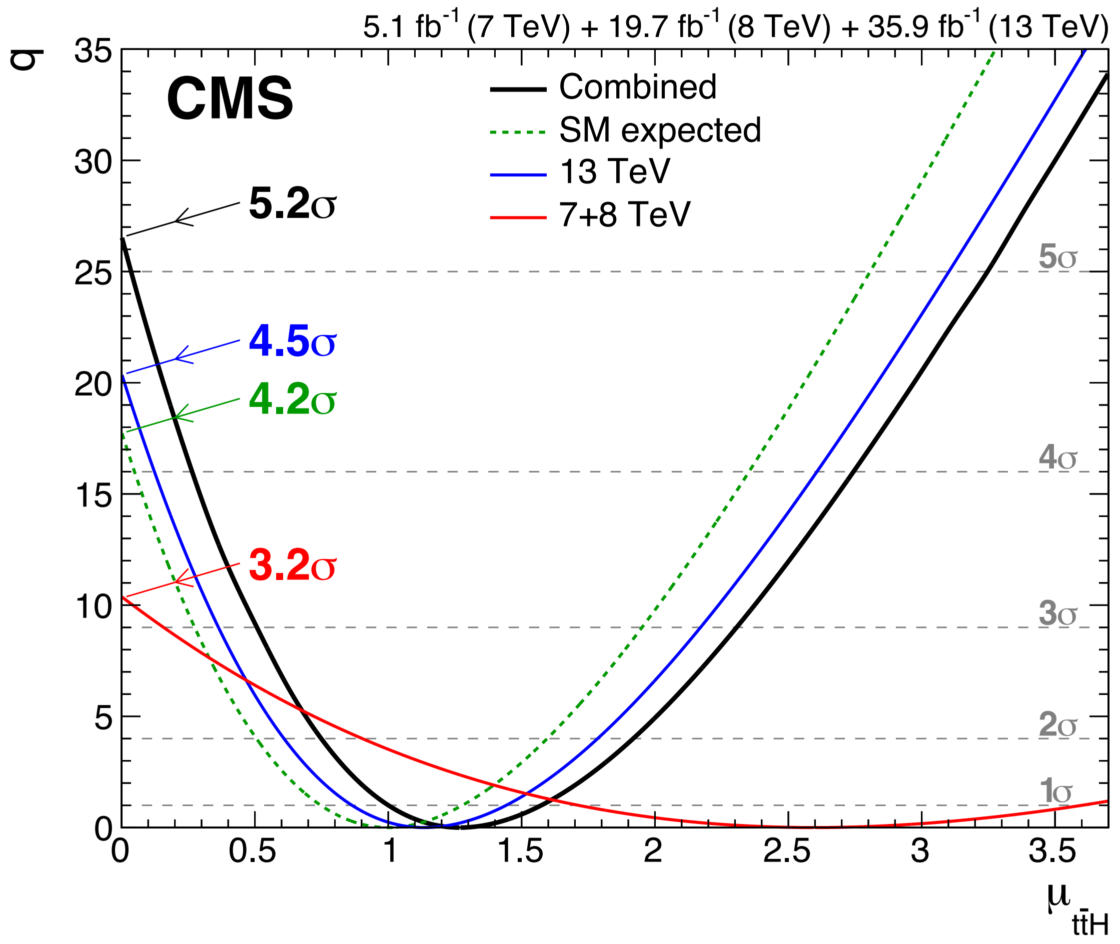
- Higgs boson couples to mass
    - decay to virtual top-quarks is prevalent (explains the γγ-rate)
- Direct observation is challenging and requires combination of various top decay channels
- CMS combined 7 TeV, 8 TeV and 2016-part of 13 TeV





5.2 σ

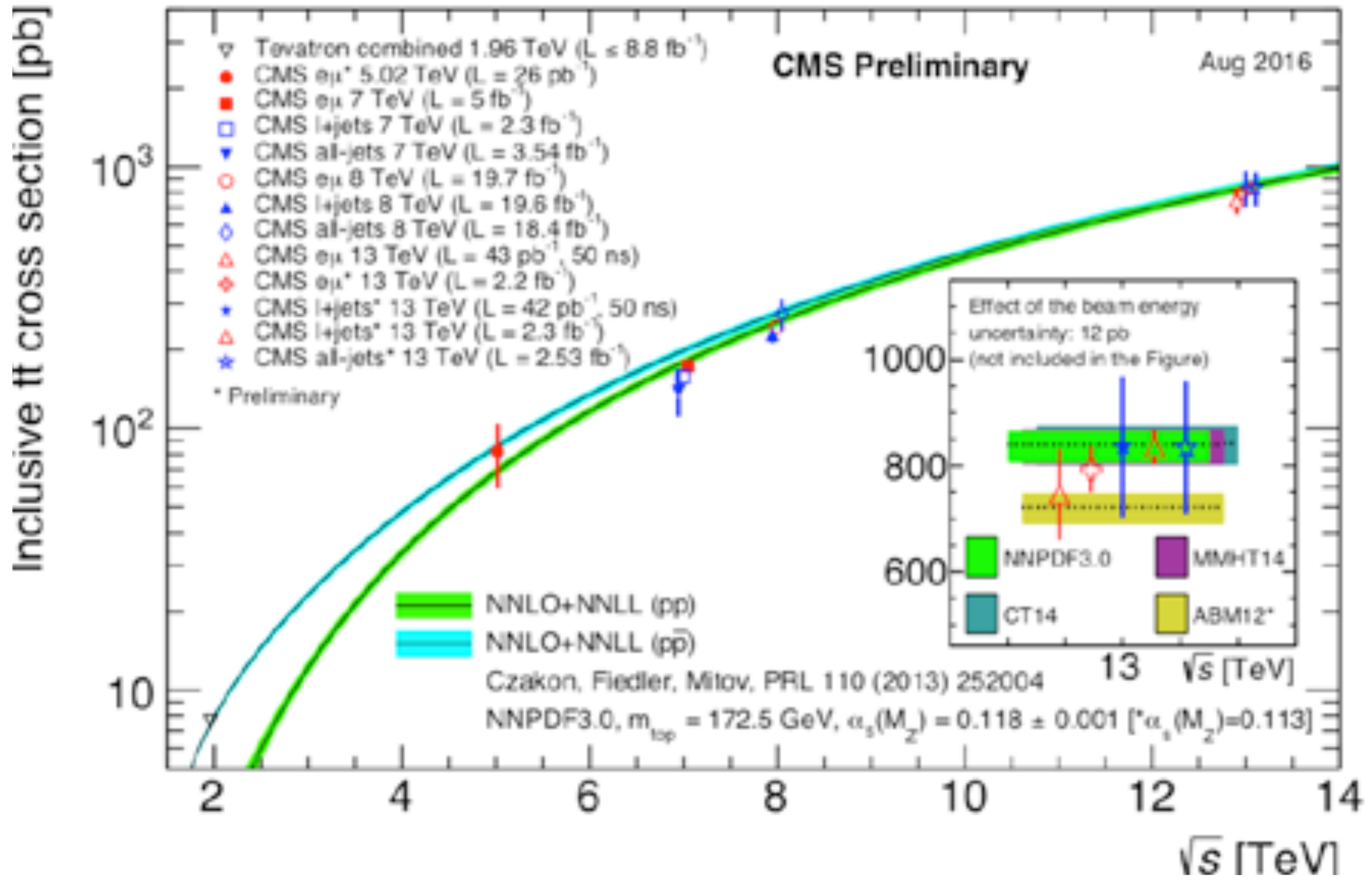
more at LHCP conference

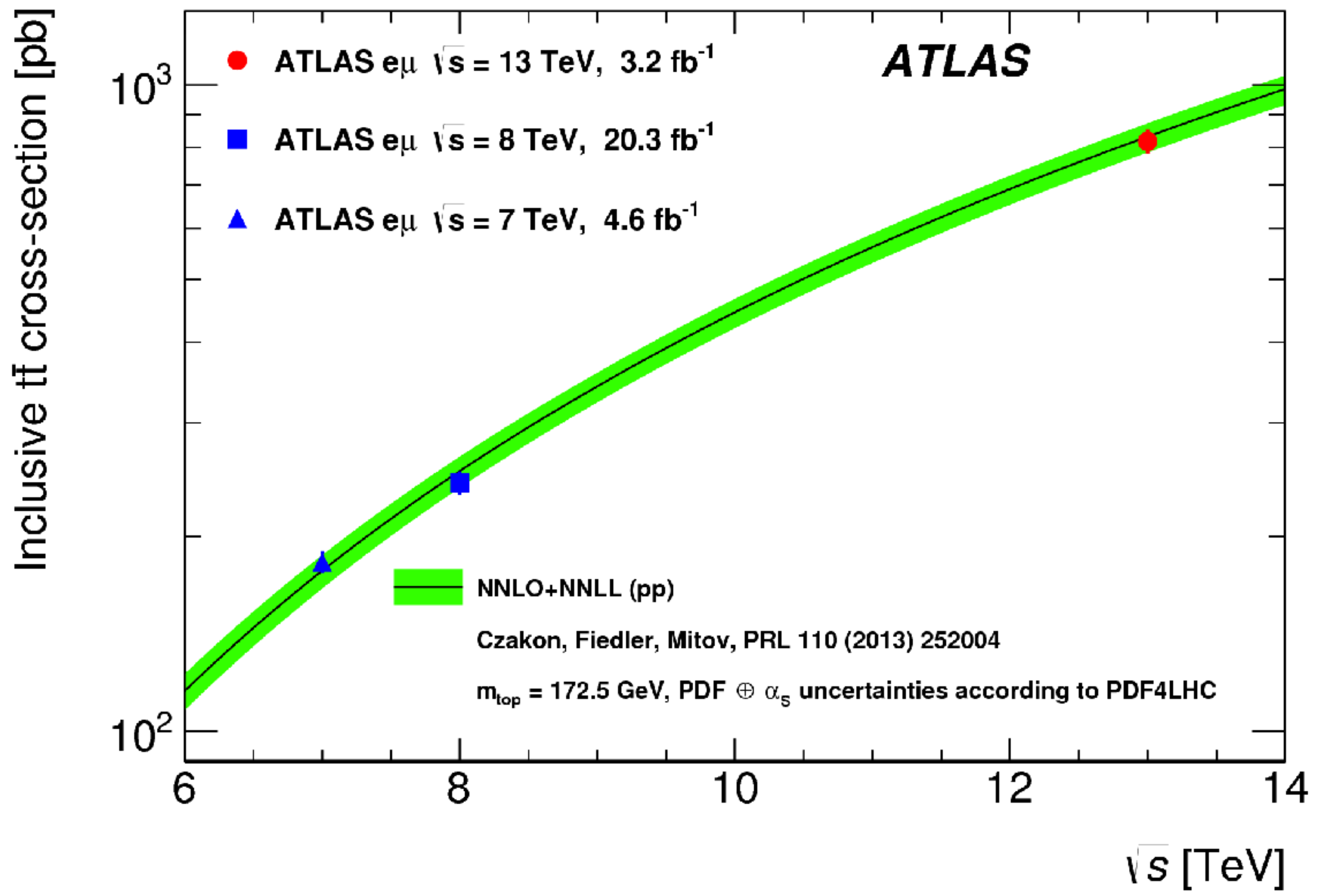


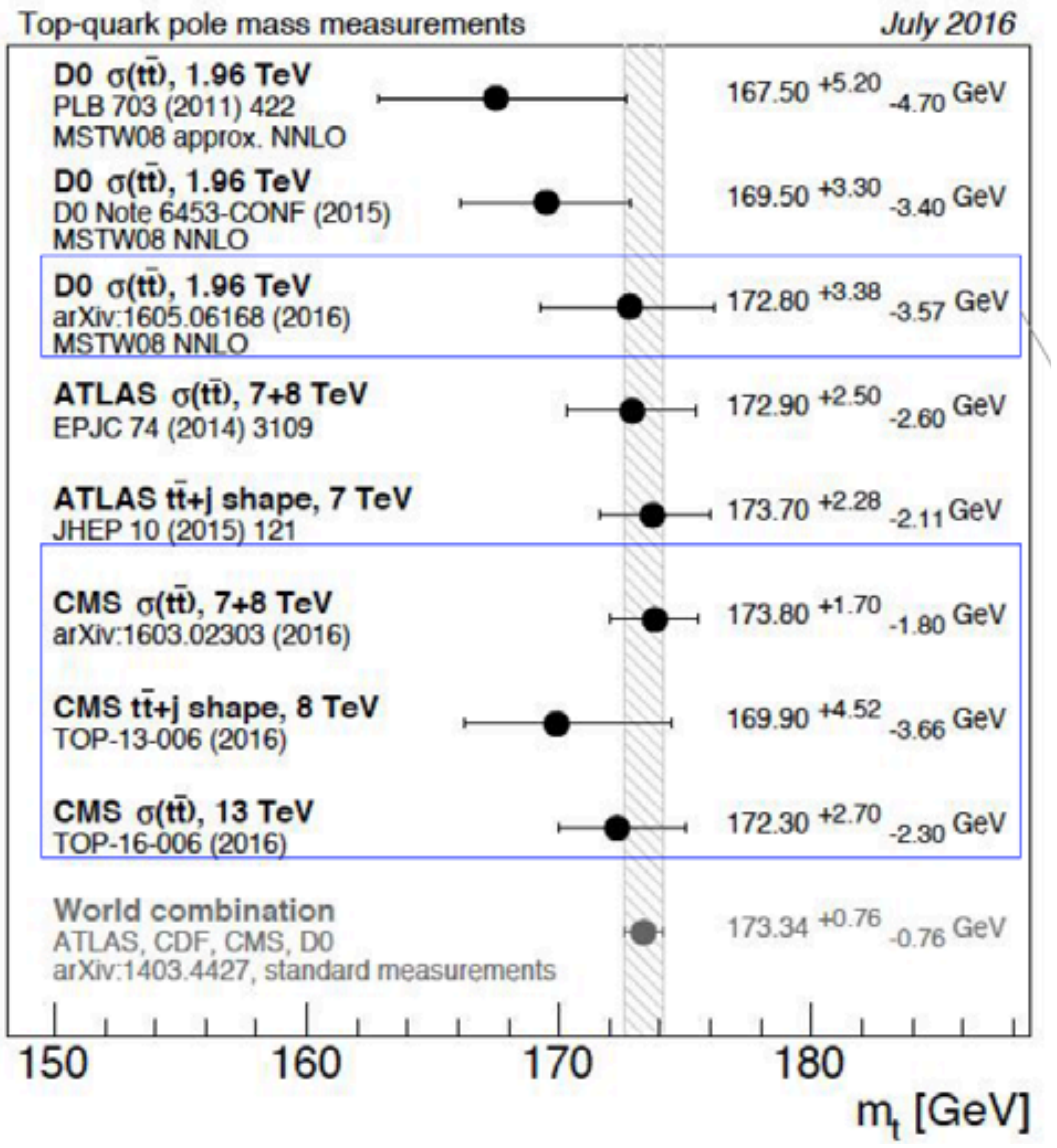
Top Production

Top cross section and mass measurement are key ingredients in predictions for Physics beyond SM

NNLO + NNLL calculations give excellent description of σ

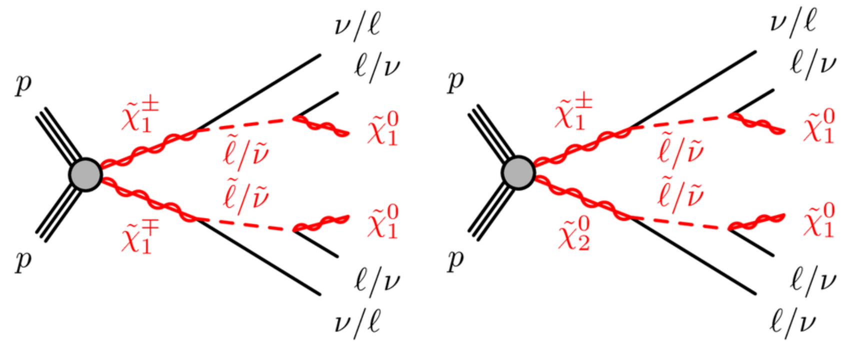


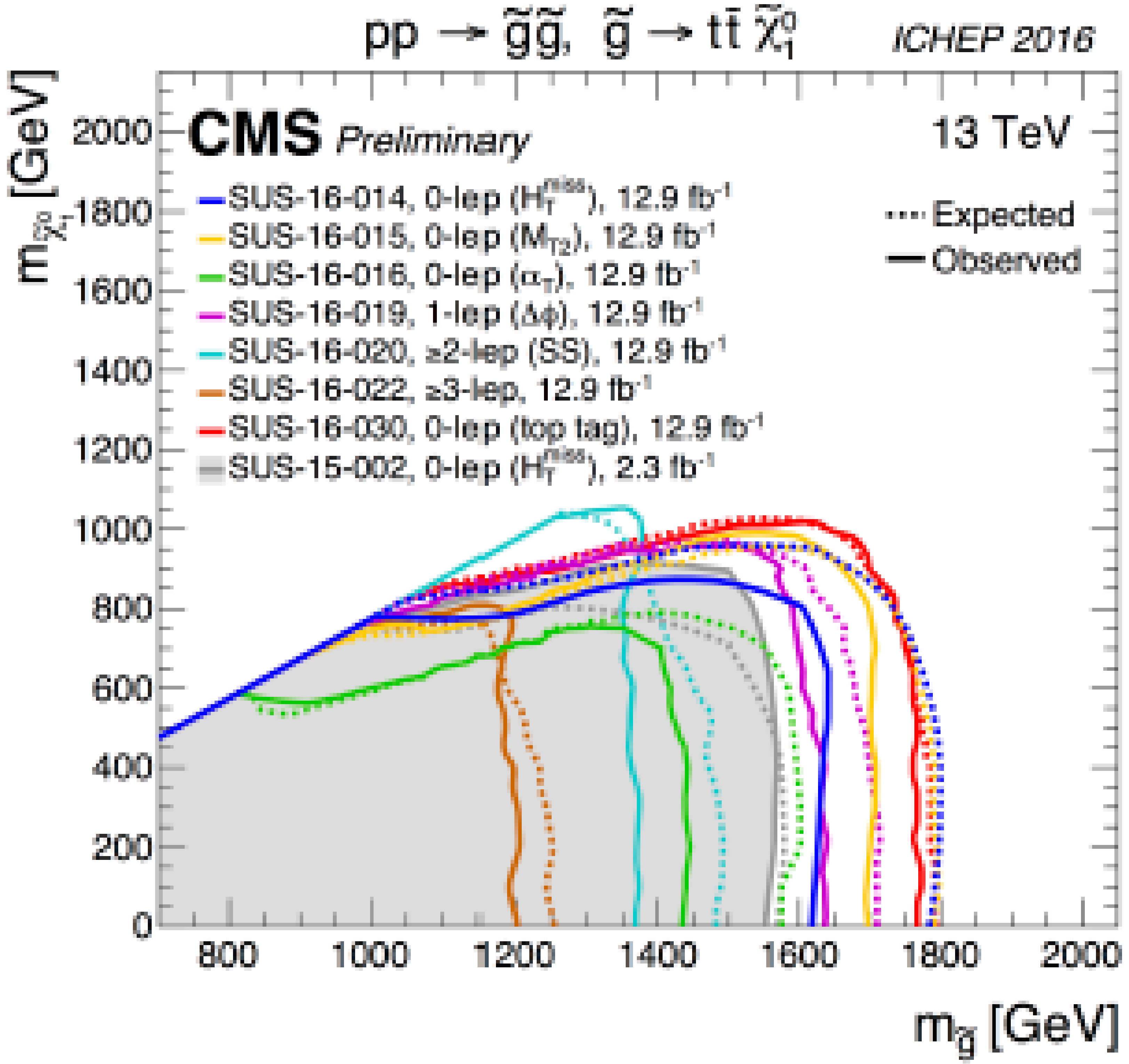


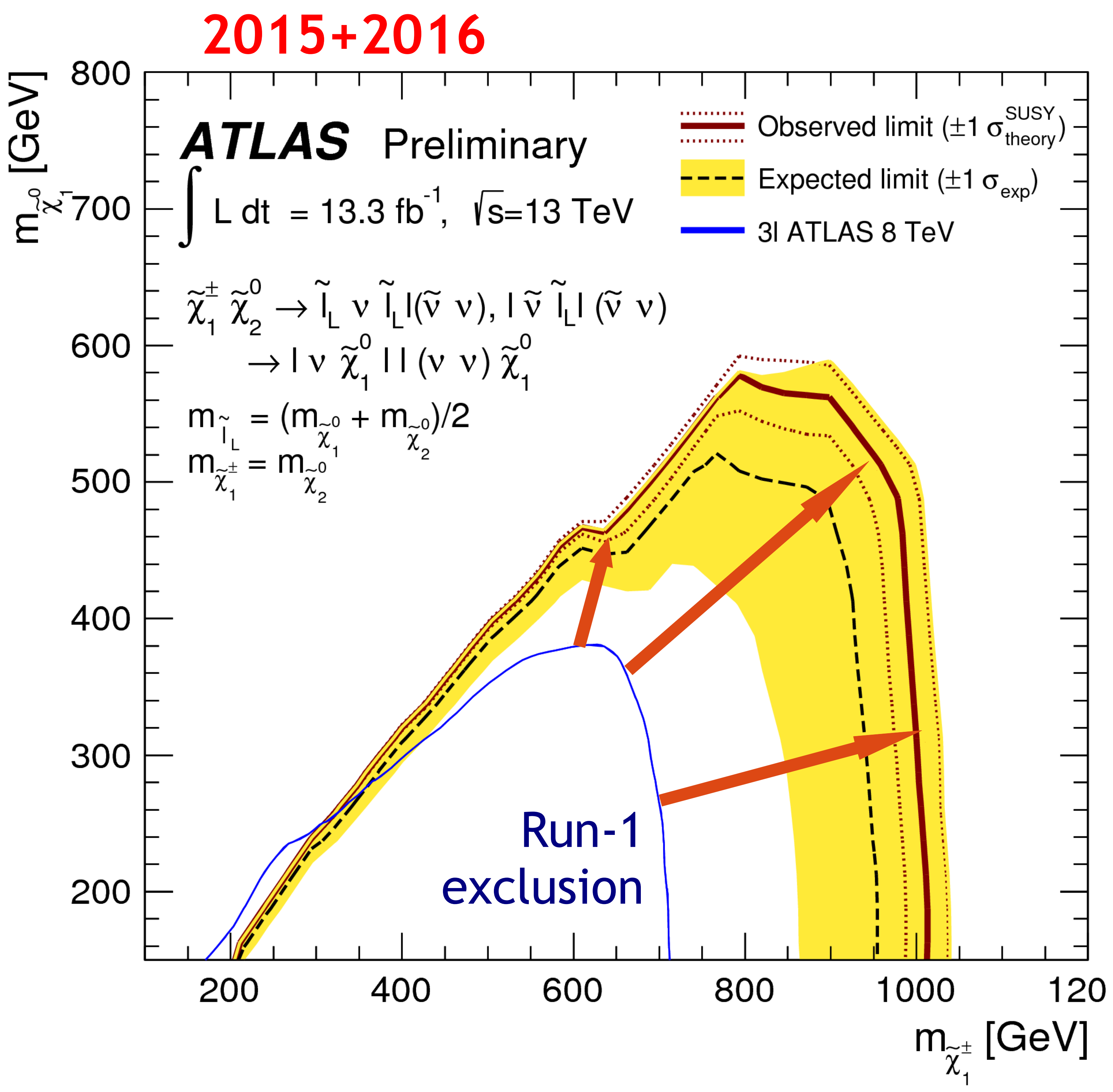


Search for Supersymmetry

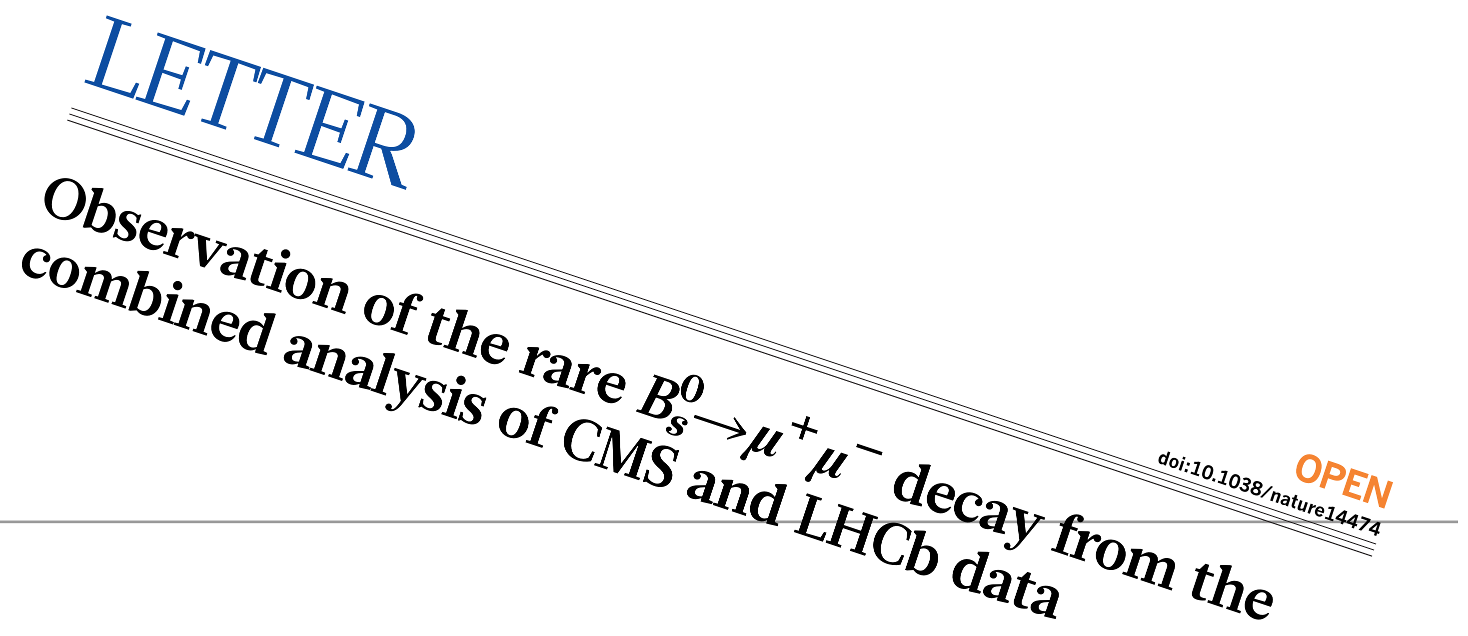
- Limits extended into the TeV mass range for specific channels
    - huge step from Run 1 analyses



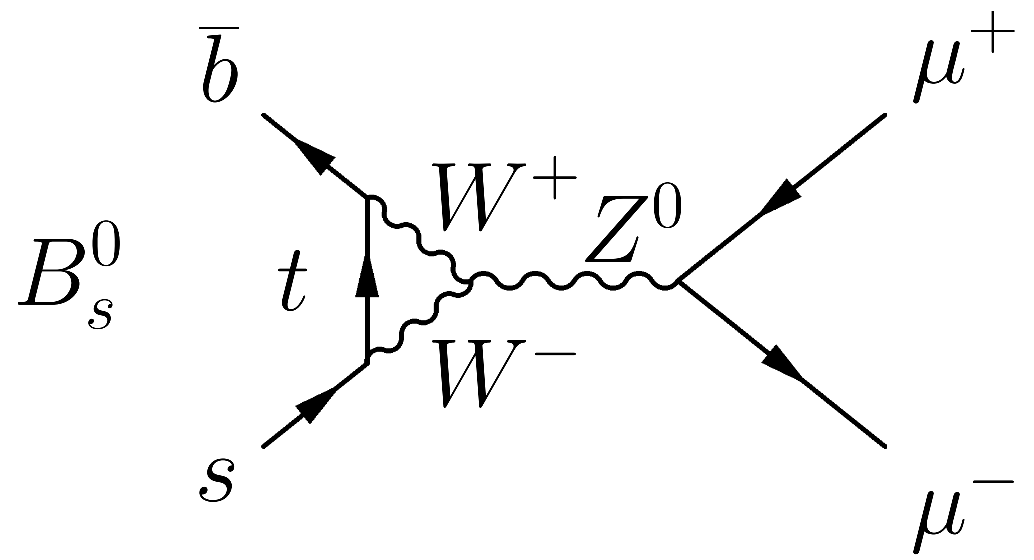


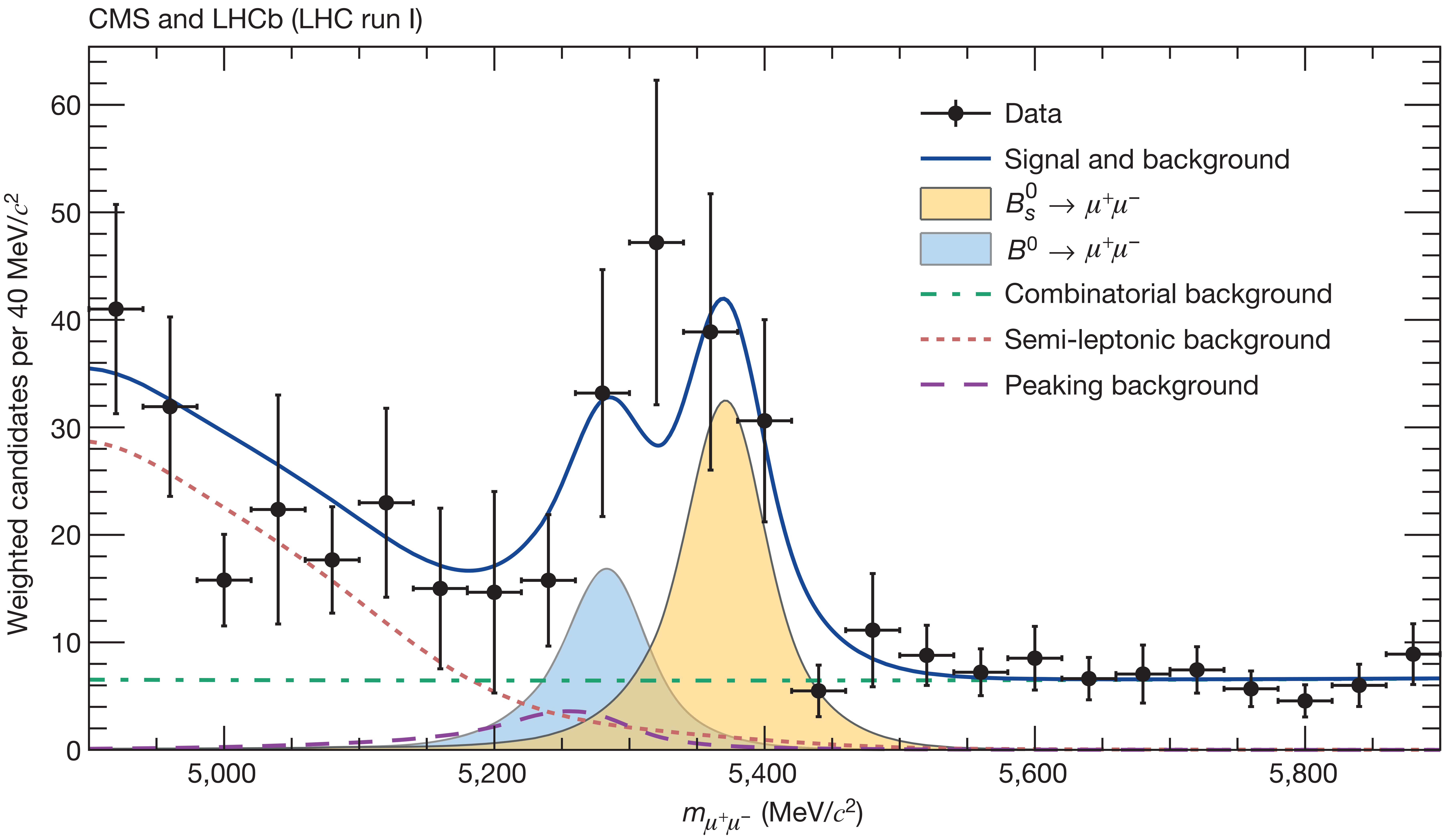


$B^0 \rightarrow \mu\mu$



Extremely rare decay in Standard Model



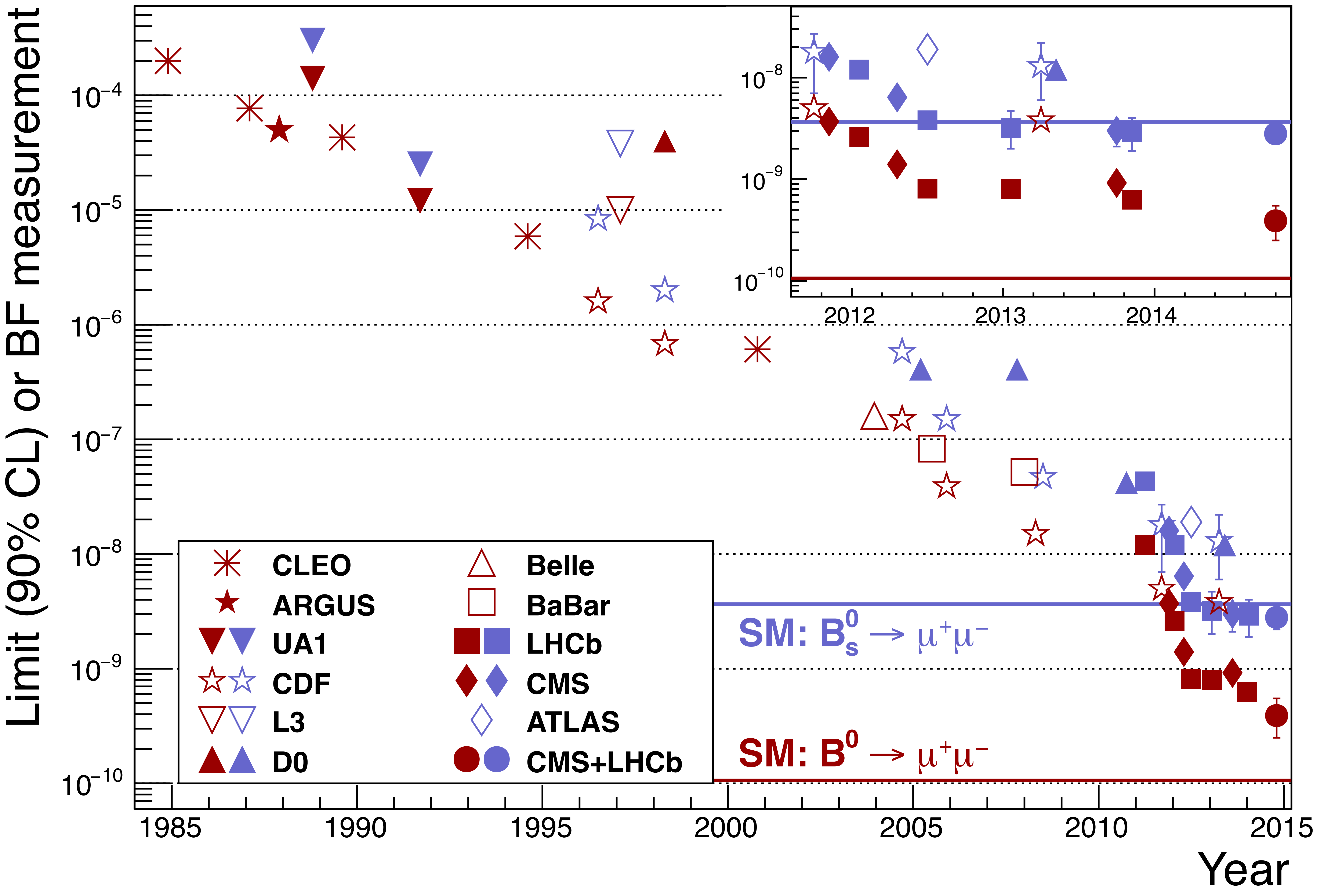


From limit to measurement for $B^0 \rightarrow \mu\mu$

The rare decay was known to be particularly sensitive for new physics.

25 years of experimental research to reach SM sensitivity.

Compatible with SM – new physics not hiding here?

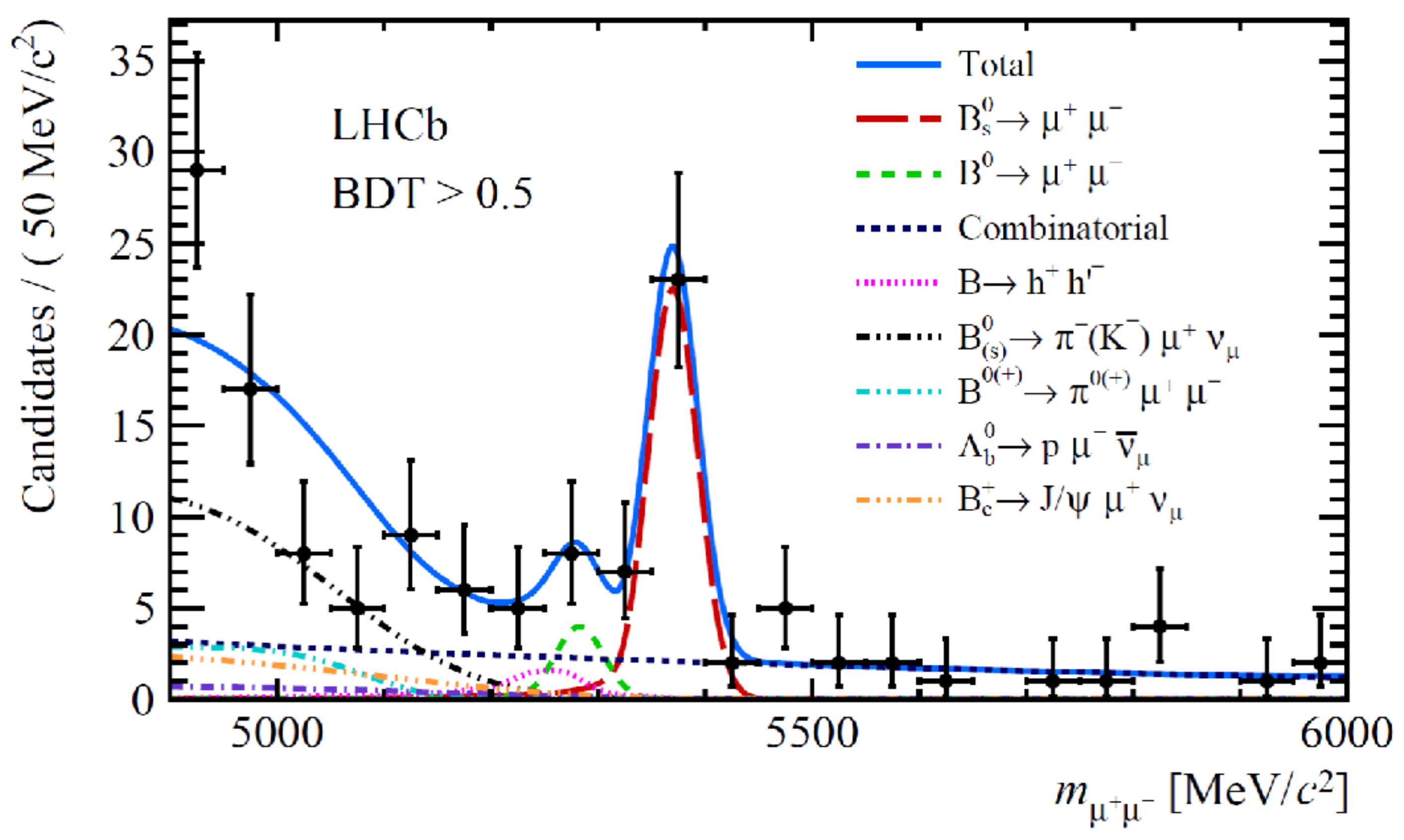


Measurement of BR($B_s \rightarrow \mu\mu$) and search for $B_d \rightarrow \mu\mu$

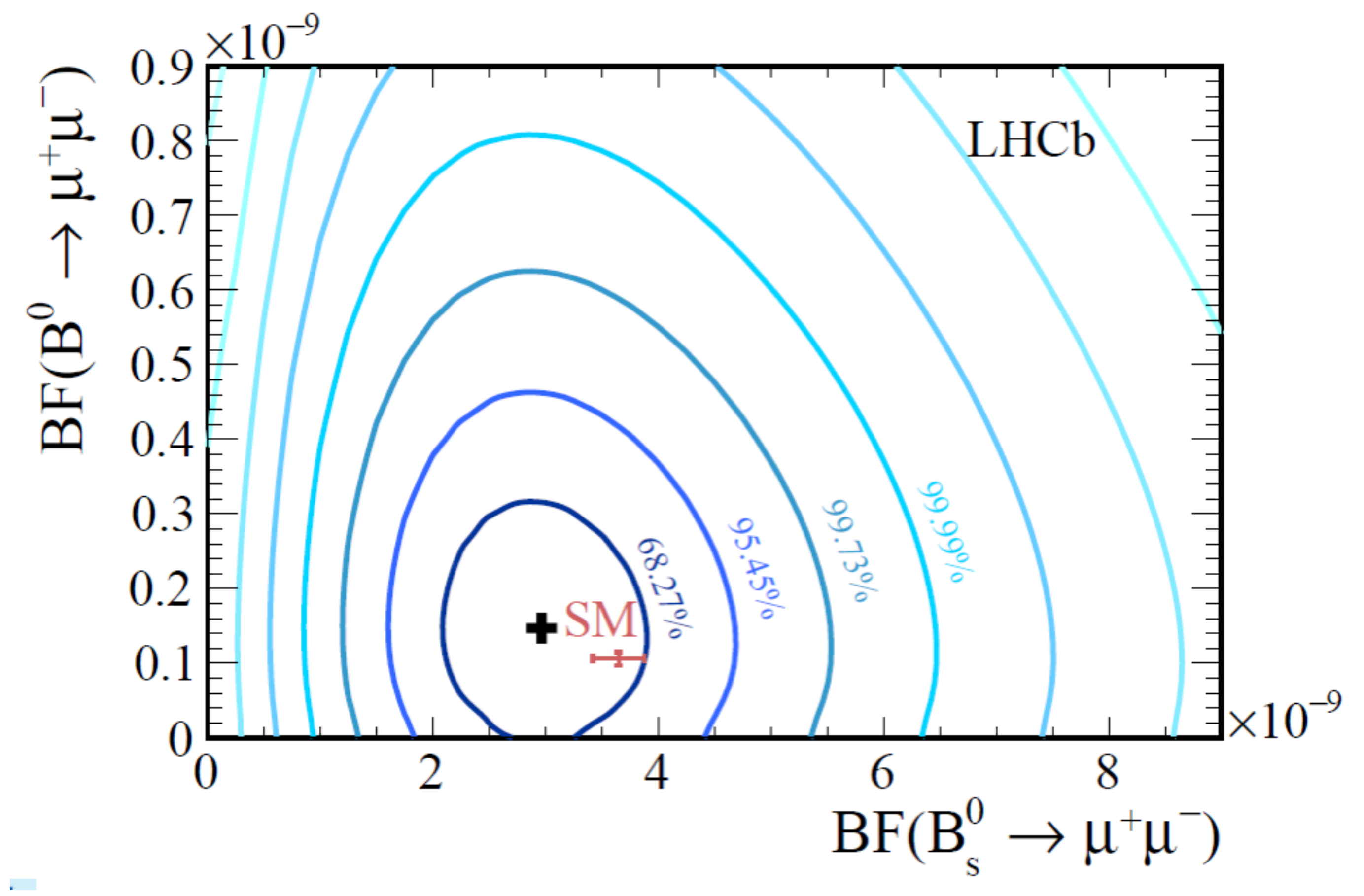
Result from LHCb alone

- Re-analyse Run 1 data with improved selection (background halved) and add 1.4 fb^{-1} of Run 2 data
- First single-experiment observation of $B_s \rightarrow \mu\mu$ mode; measurement of BR has same precision as previous Run 1 LHCb-CMS combined analysis [NATURE 522 (2015) 68].

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,{}^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$

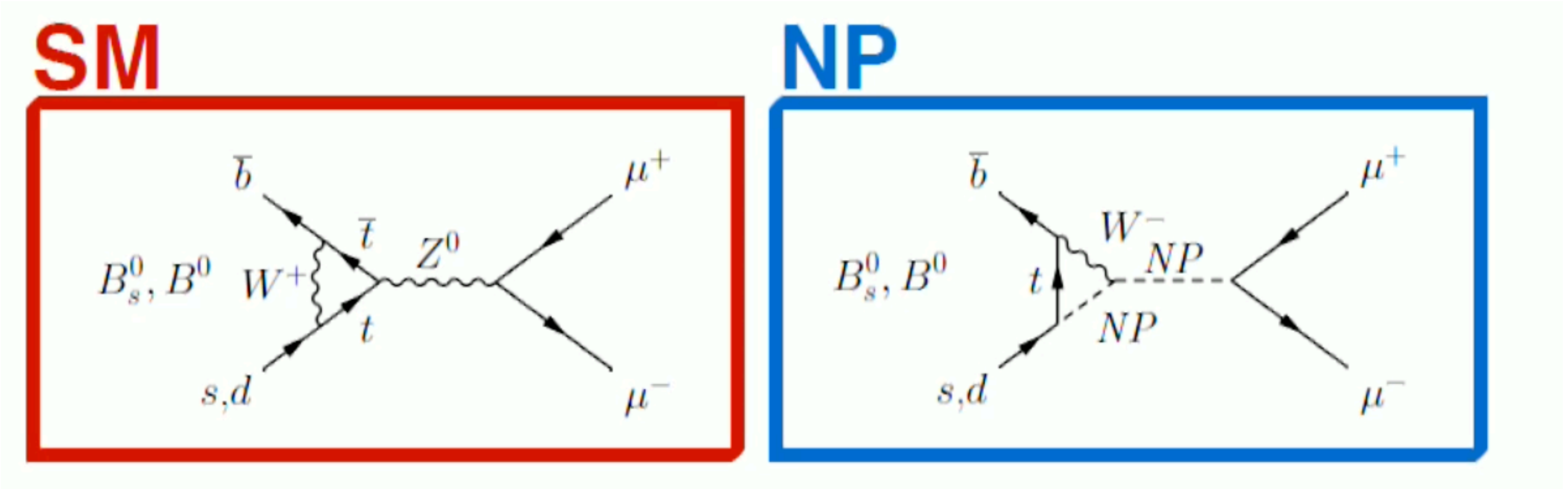


$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \quad @\ 95\,\%\ \text{C.L.}$$

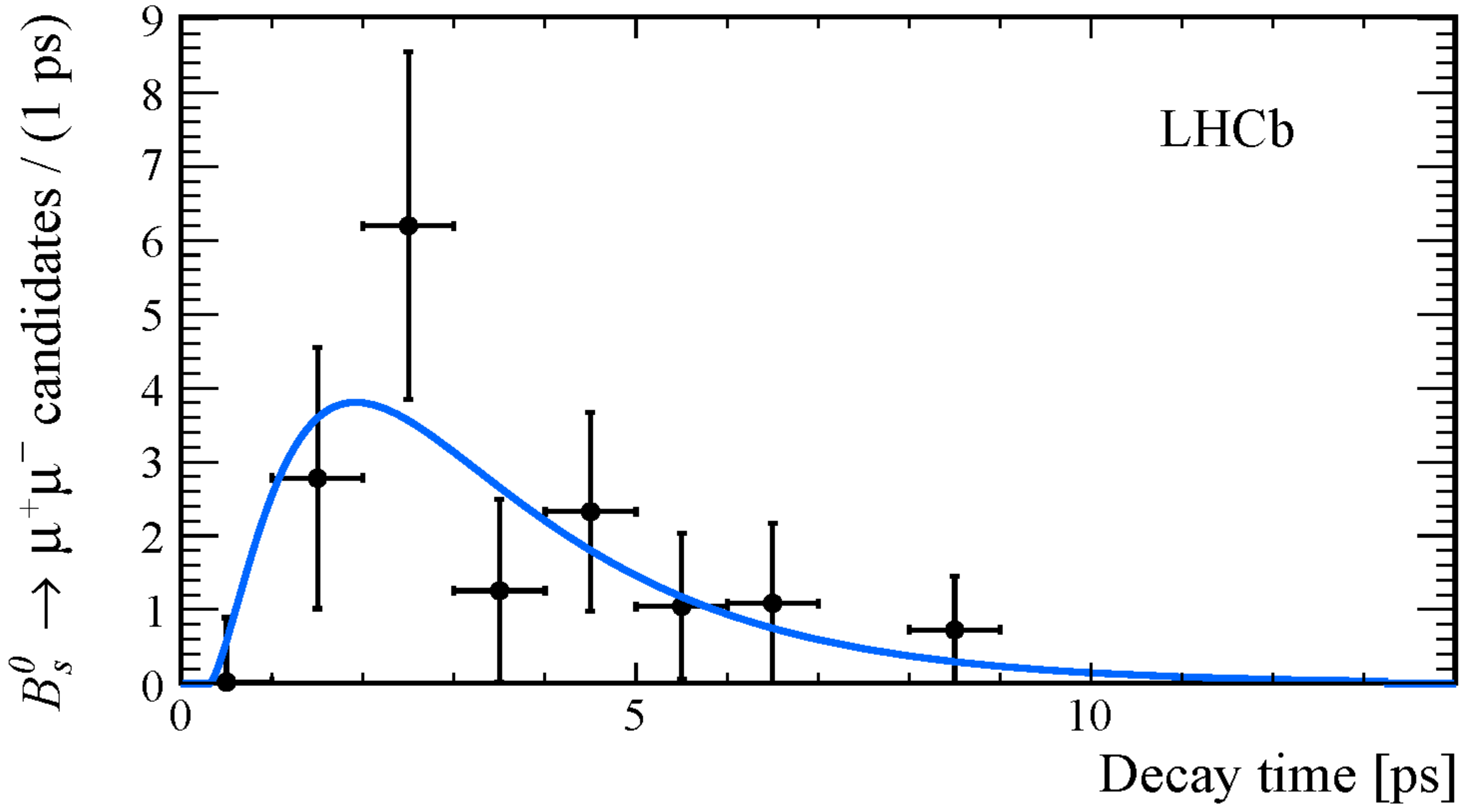


First measurement of effective lifetime of $B_s \to \mu\mu$

- Start to measure new observables for ultra-rare decay: effective lifetime
- e.g. first measurement of the effective lifetime, which with more data will become a powerful probe of New Physics models



[LHCb-PAPER-2017-001]



$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44\,(\text{stat}) \pm 0.05\,(\text{syst})\text{ ps}$$

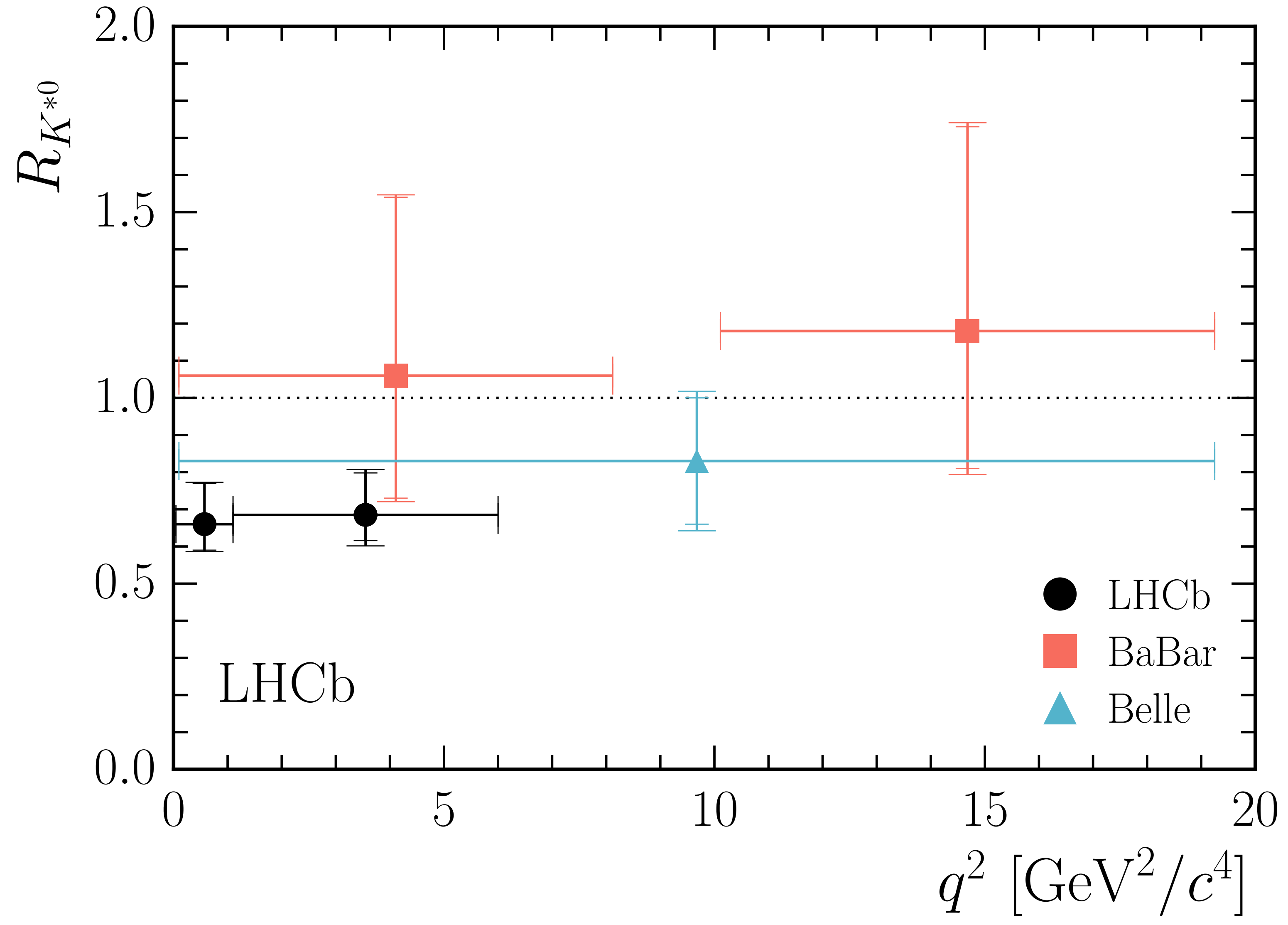
Measurement of R_{K^*}

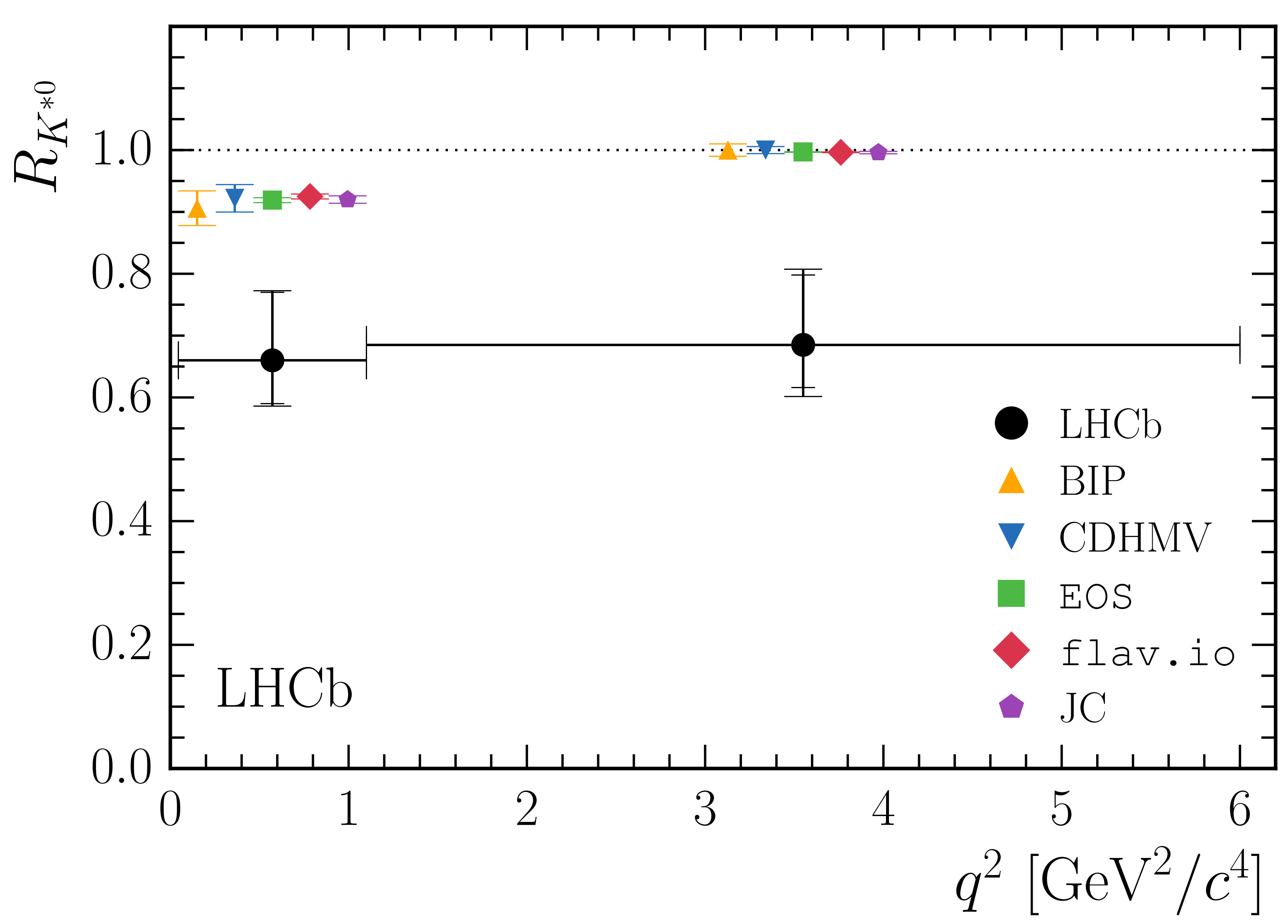
Expect μμ and ee-branchings to be the same – apart from well understood mass contributions

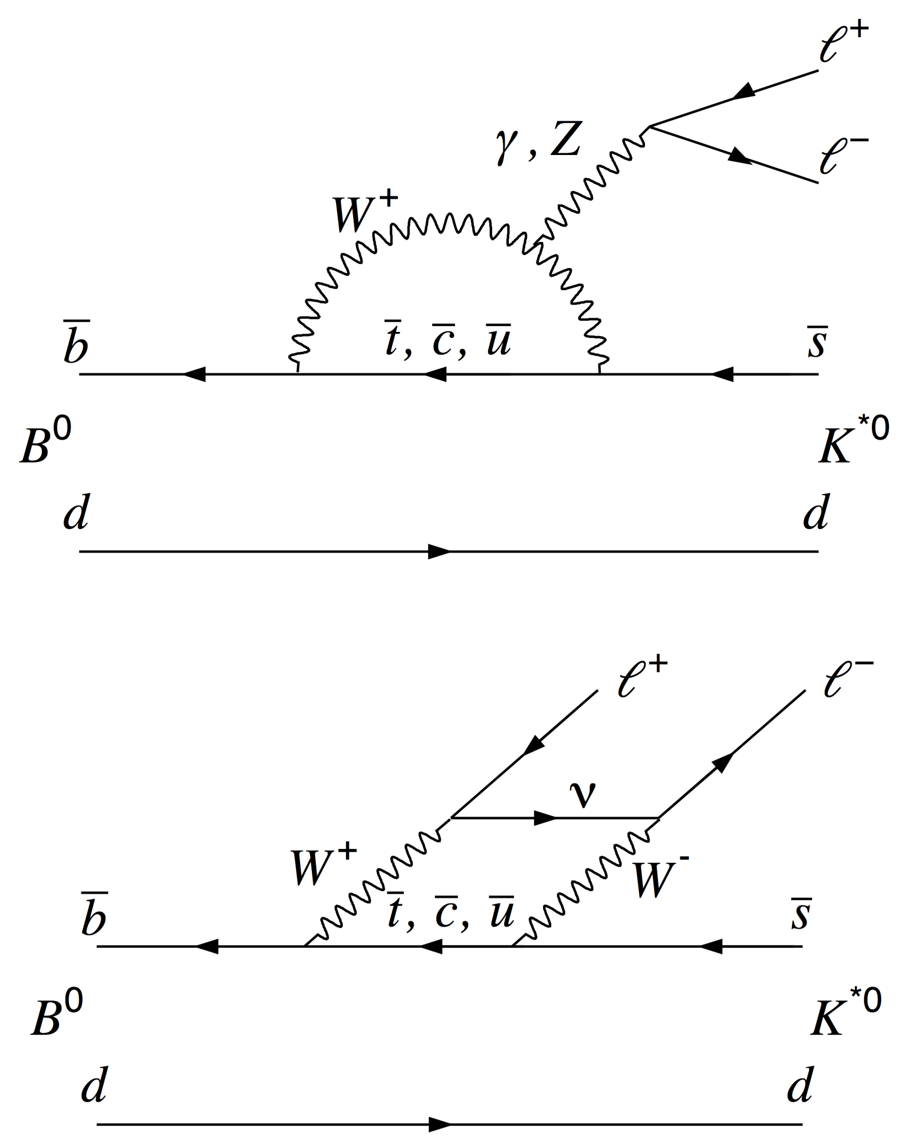
LHCb-Paper-2017-013

So far a ~2.5 σ effect

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$



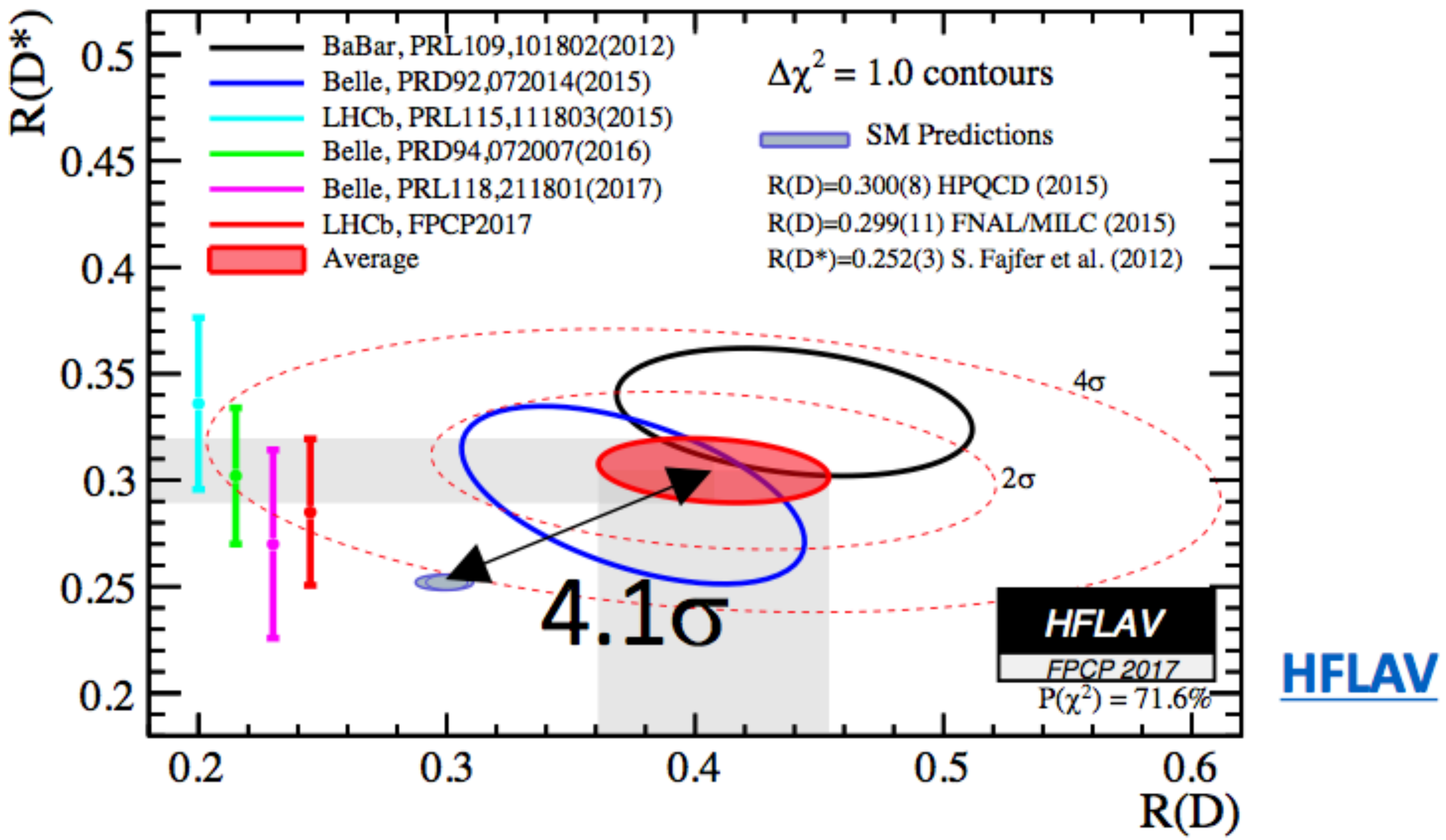




Other B-Anomalies

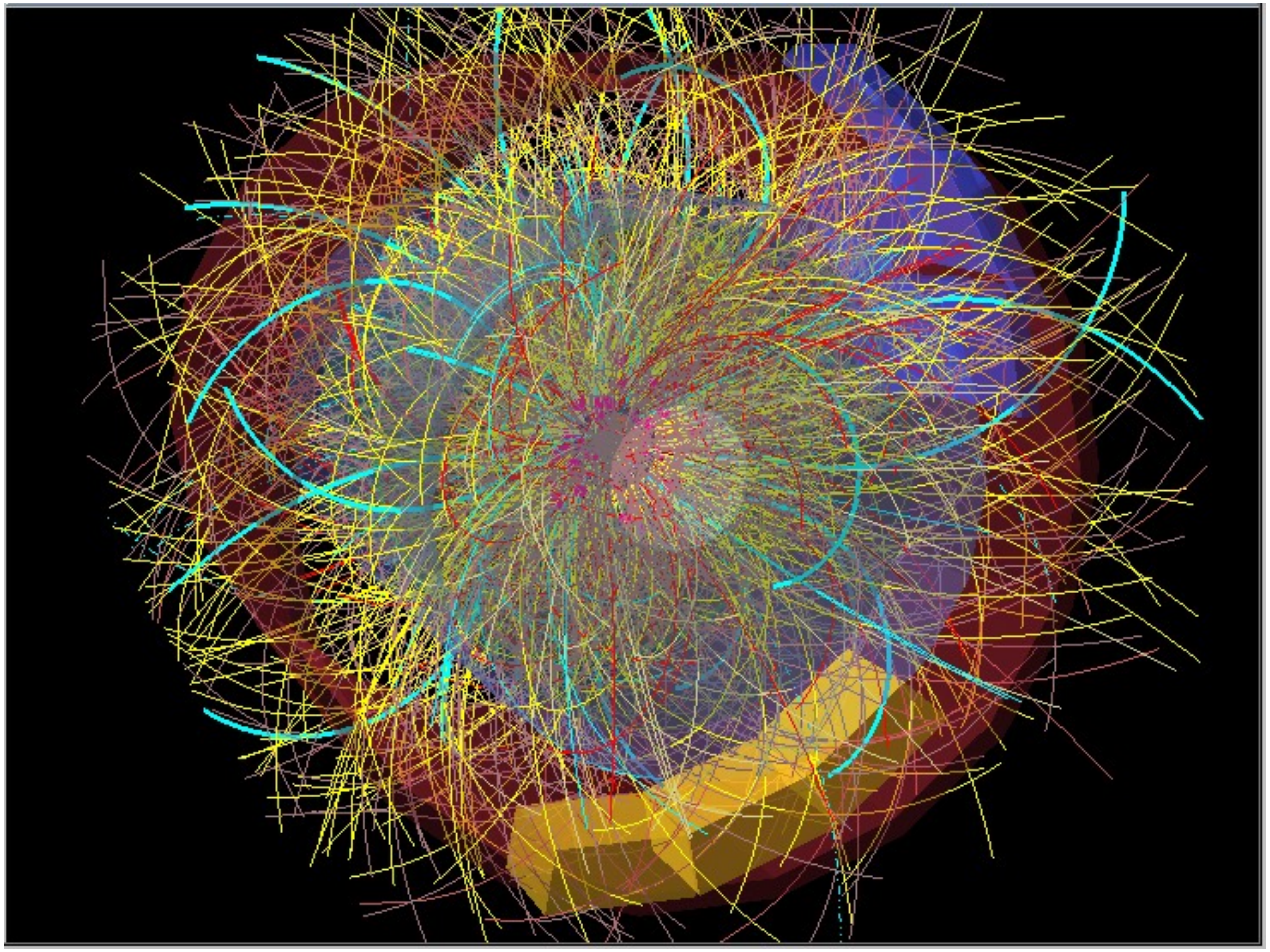
- Eagerly awaiting significant result of single experiment to shed light on the question of lepton flavour universality

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}\ell\bar{\nu})}$$



Experimental updates on some anomalies still this year

Heavy Ion Physics



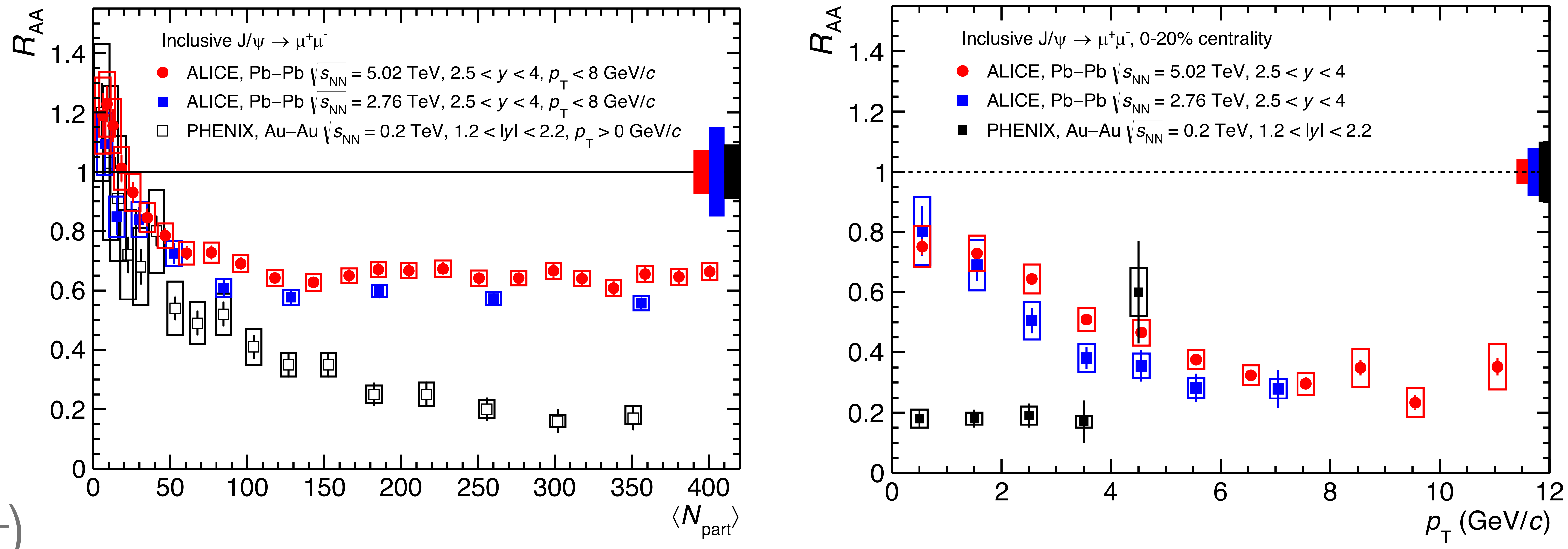
Pb-Pb: J/ψ suppression at 5 TeV

- nuclear modification factor R_{AA}:

$$R_{AA} = \frac{N(J/\psi)_{AA}}{\langle N_{bin}\rangle N(J/\psi)_{pp}}$$

- very different behaviour between LHC and RHIC (vs both centrality and p_T)

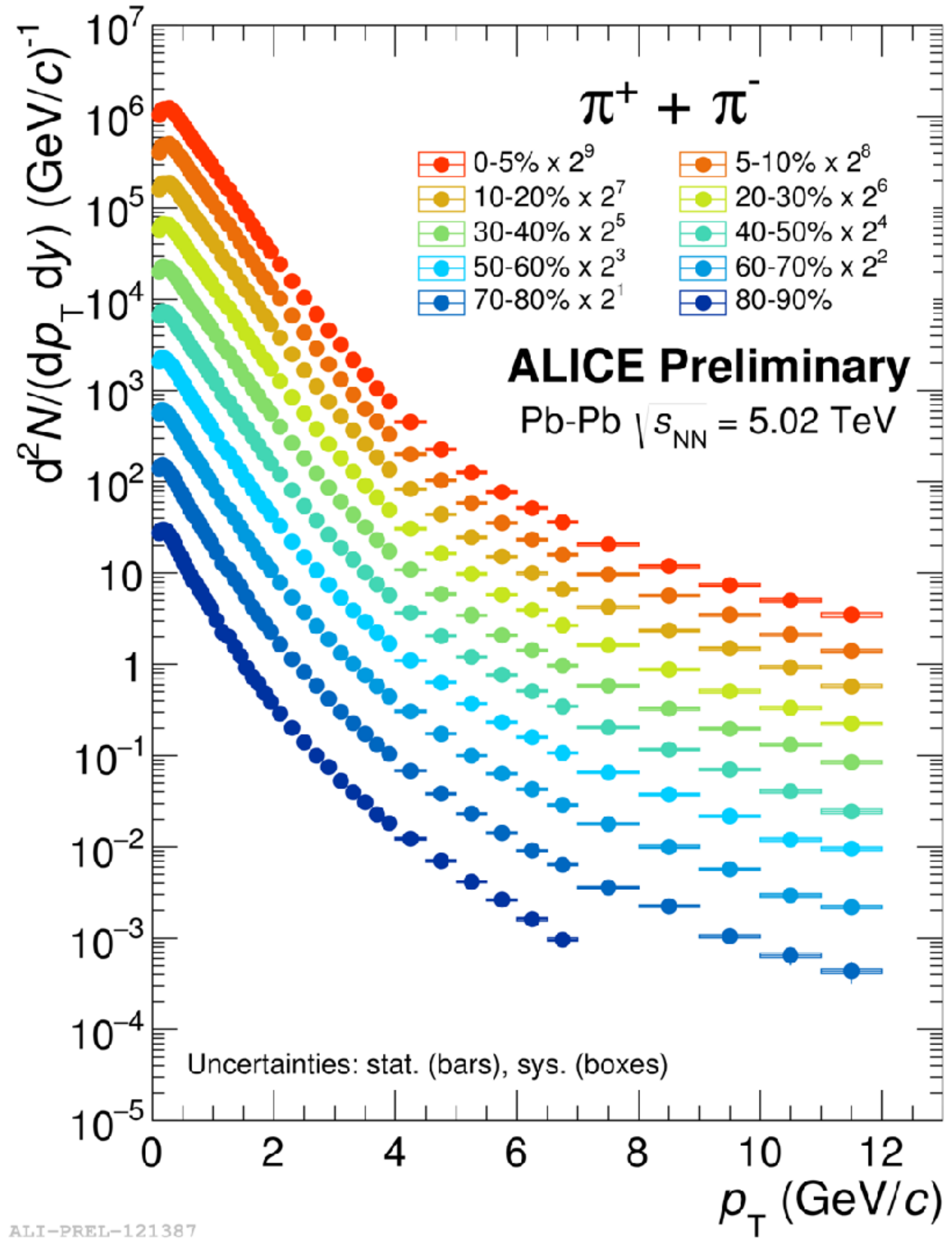
- most straightforward explanation: c-cbar recombination at LHC

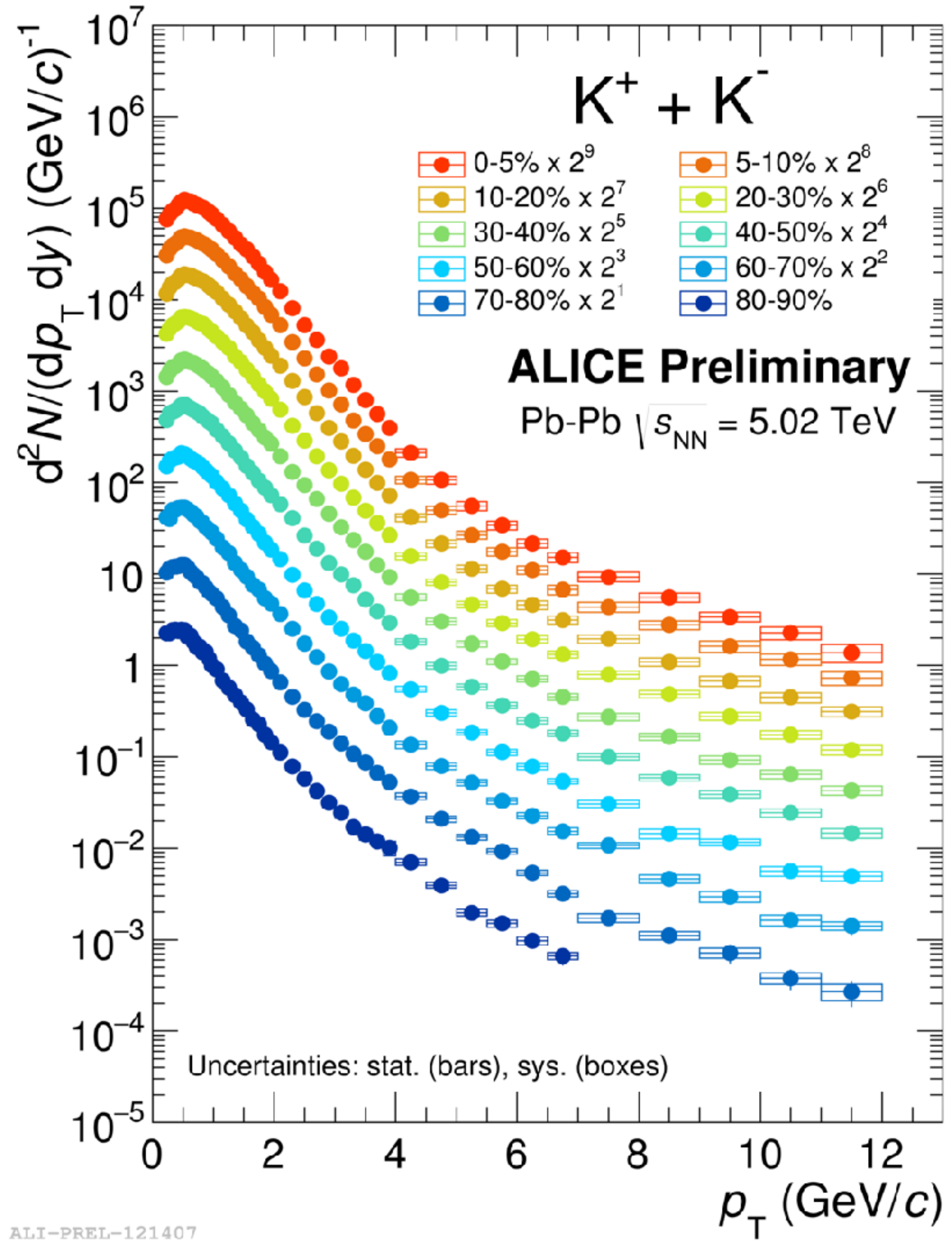


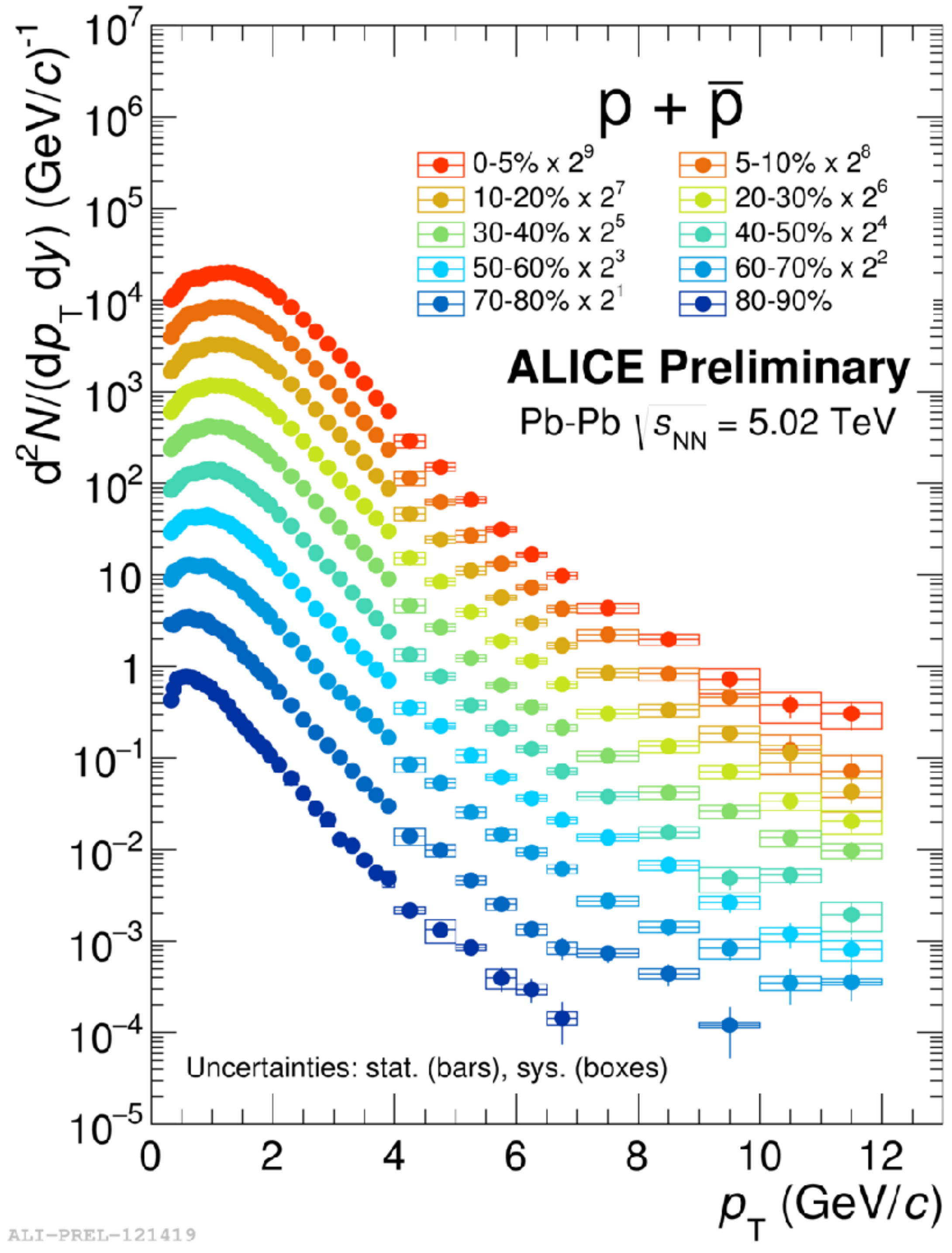
New and precise 5 TeV data support even further increase

Identified particle production in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

- Precision tracking and particle identification over a wide range in p_T



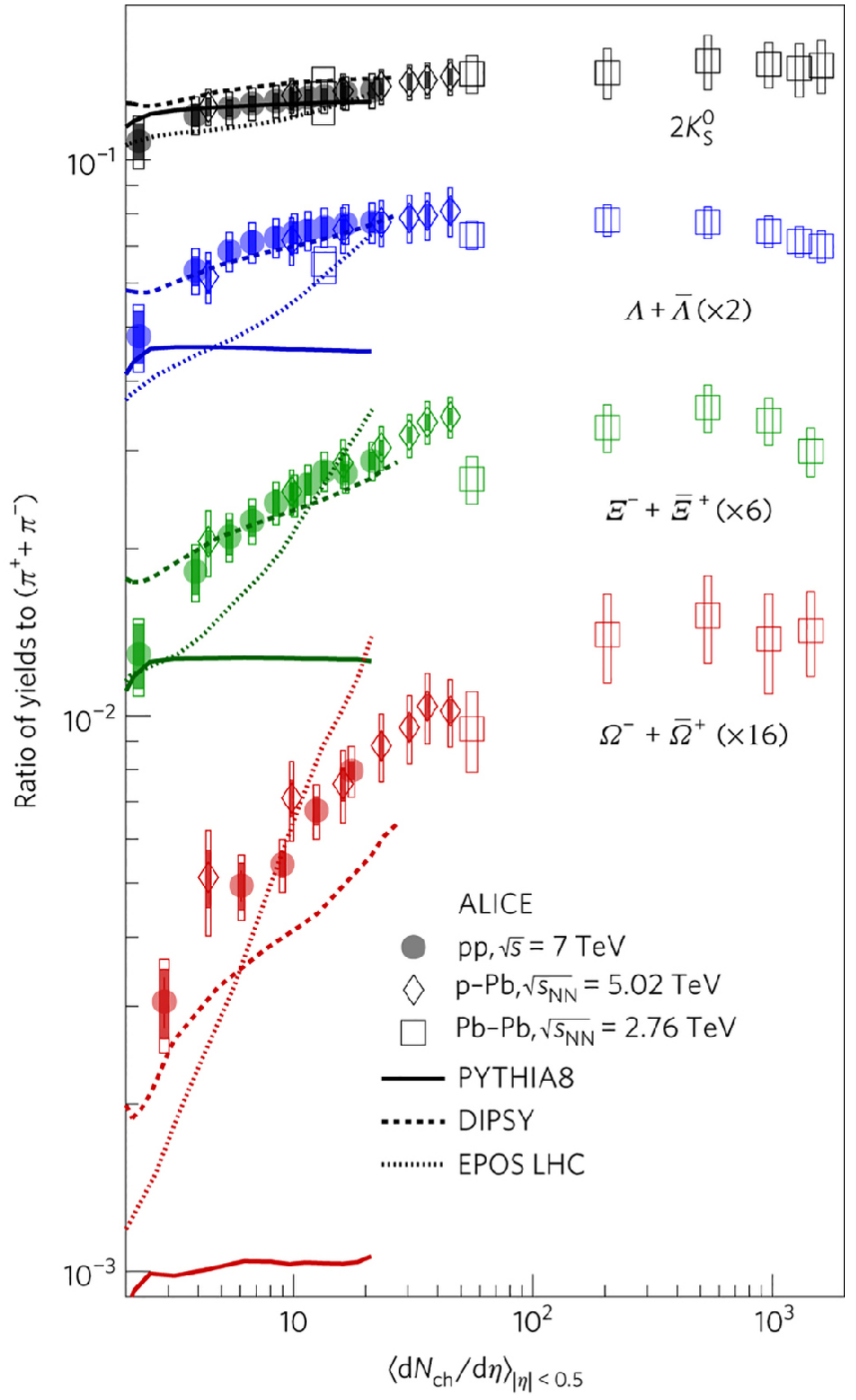


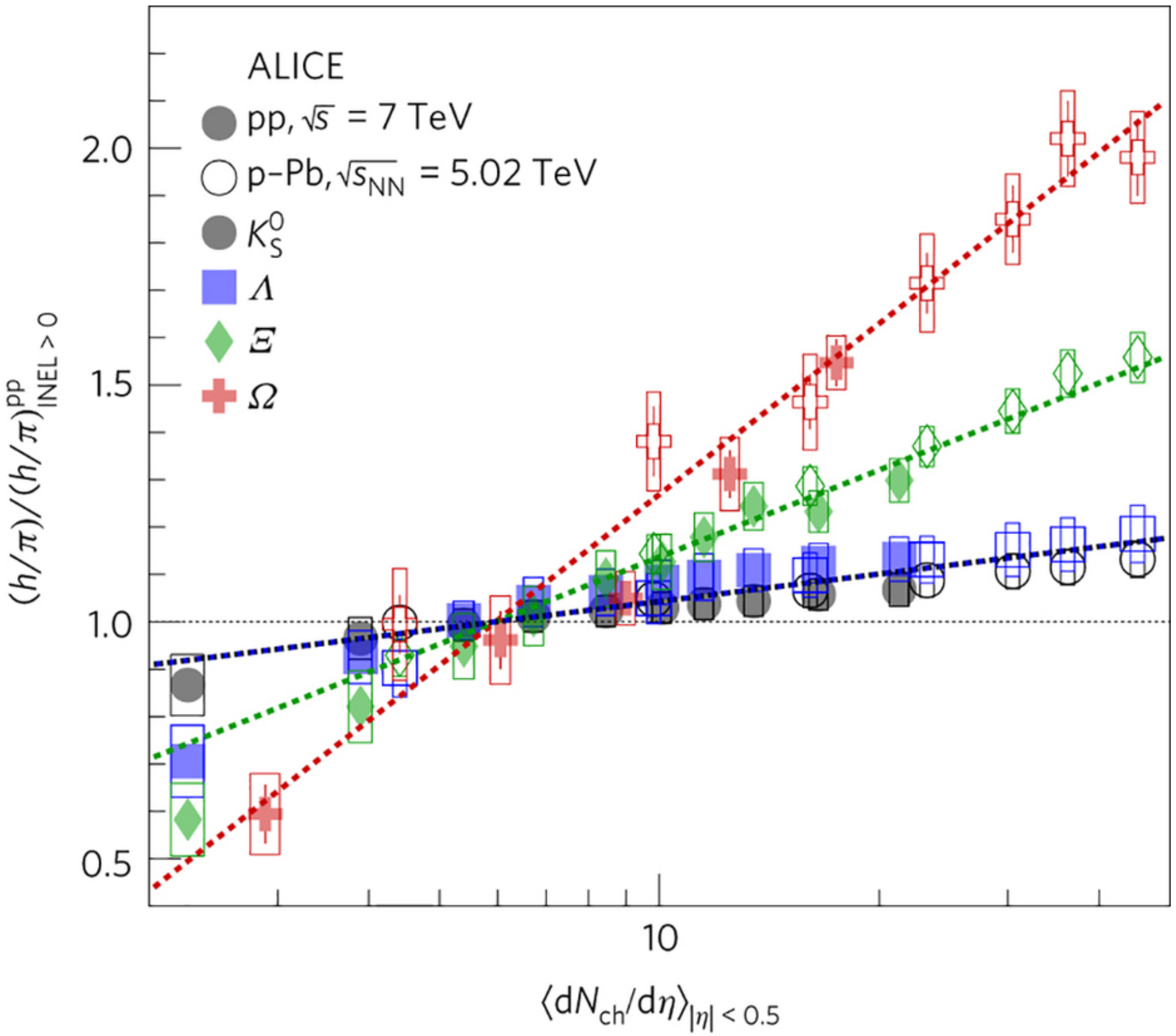


Strangeness production in high-energy pp

Strangeness increases in high-multiplicity pp-collisions

Evidence for Quark-Gluon plasma in pp collisions

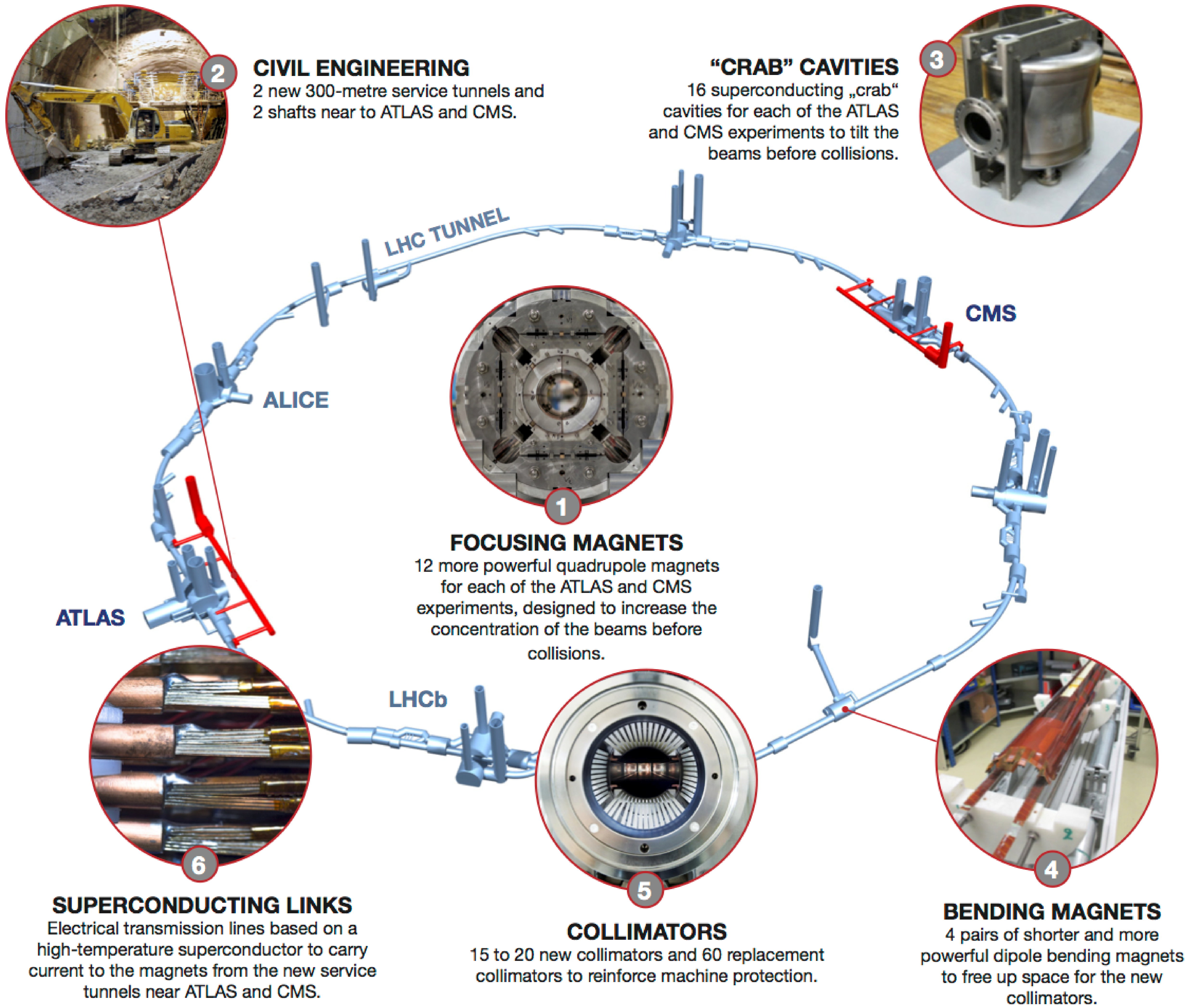




High Luminosity LHC

High-Luminosity LHC (HL-LHC)

- 5×10^{34} cm^{-2}s^{-1} levelled; i.e. factor 5 over design
  - to yield 3 ab^{-1} by ~2035
- requires
  - focussing β^*=15 cm
  - crab crossing



Nb_3Sn Magnet Development

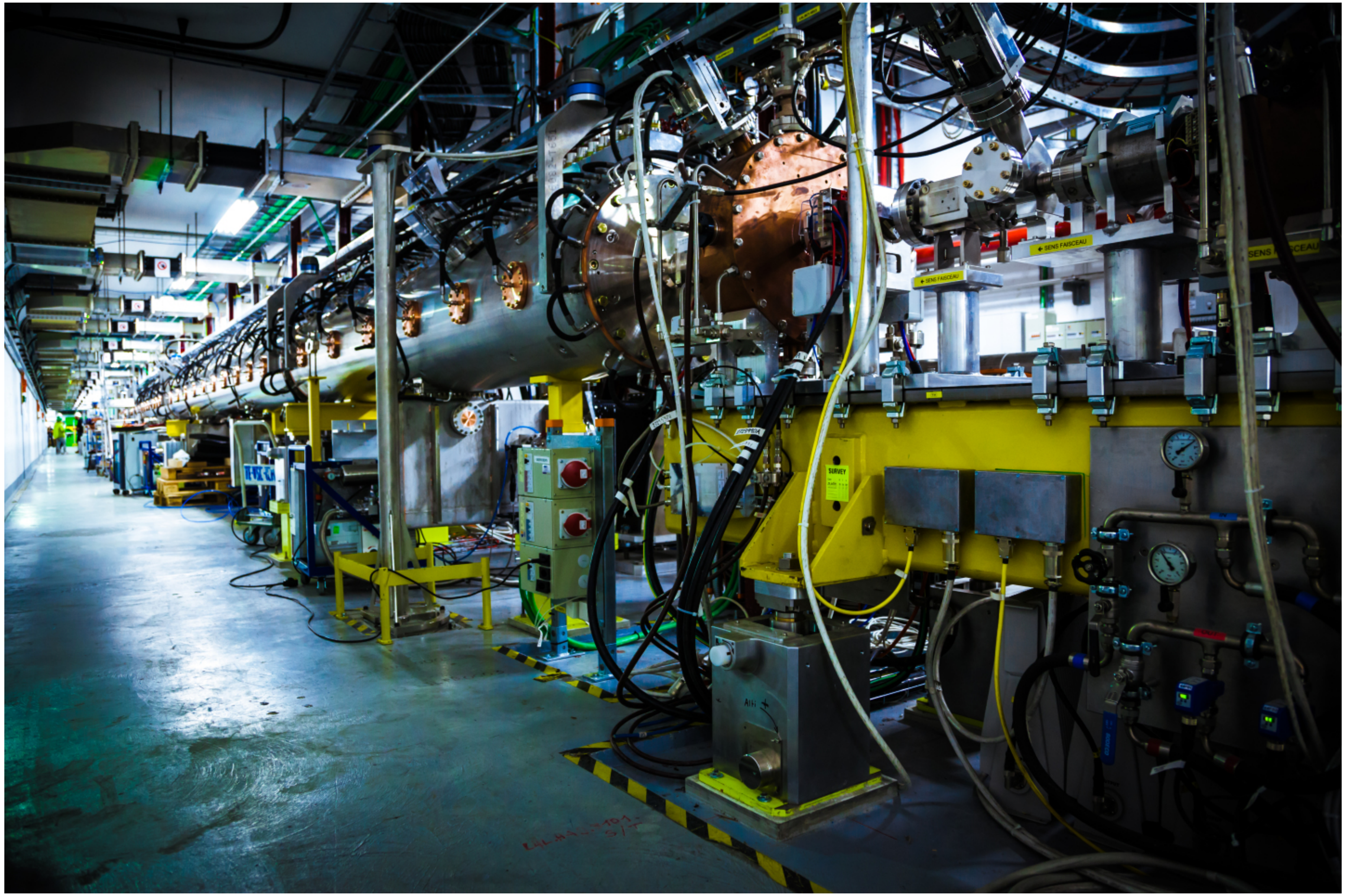
- 1.2 km of accelerator have to be redone
  - inner triplet Nb_3Sn quadrupole, 4.2 m long
  - short and stronger dipole, Nb_3Sn, 11 T

both magnets will be tested in 2018

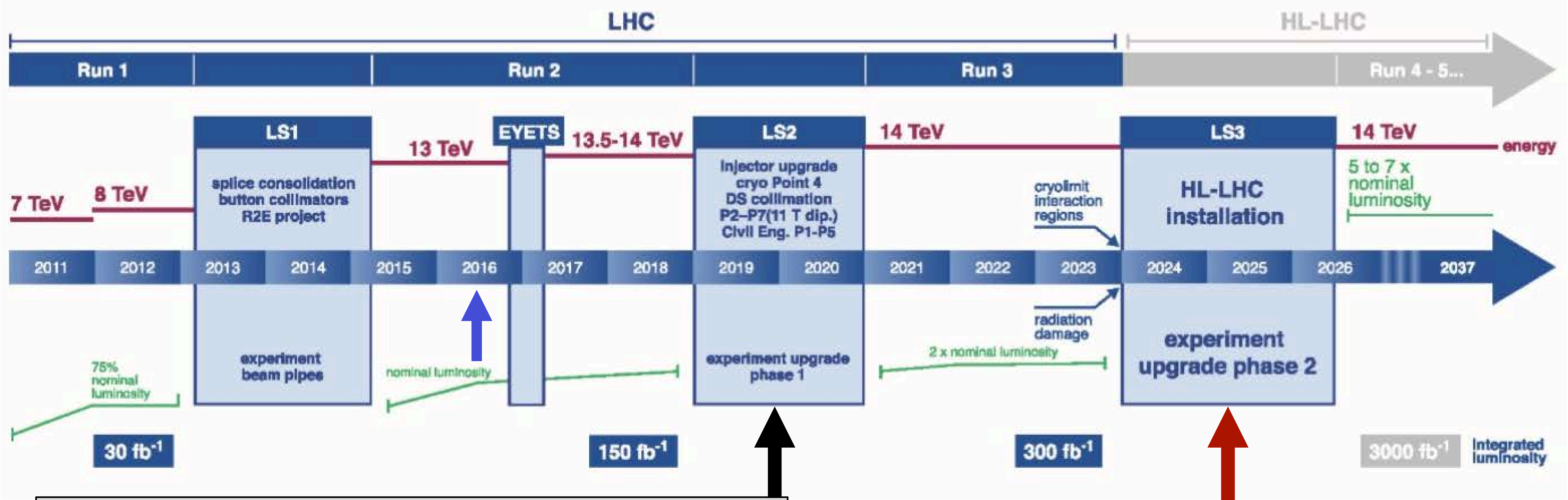
Nb_3Sn inner triplet quadrupole:
full-size prototype at FNAL

Linac 4 taken into operation

- Commissioning started 2014
- protons have been accelerated to 160 MeV
- using π-mode structures PIMS for high energy acceleration
- Connection to booster in LS2



HL-LHC schedule



LS2 (2019-2020):

- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

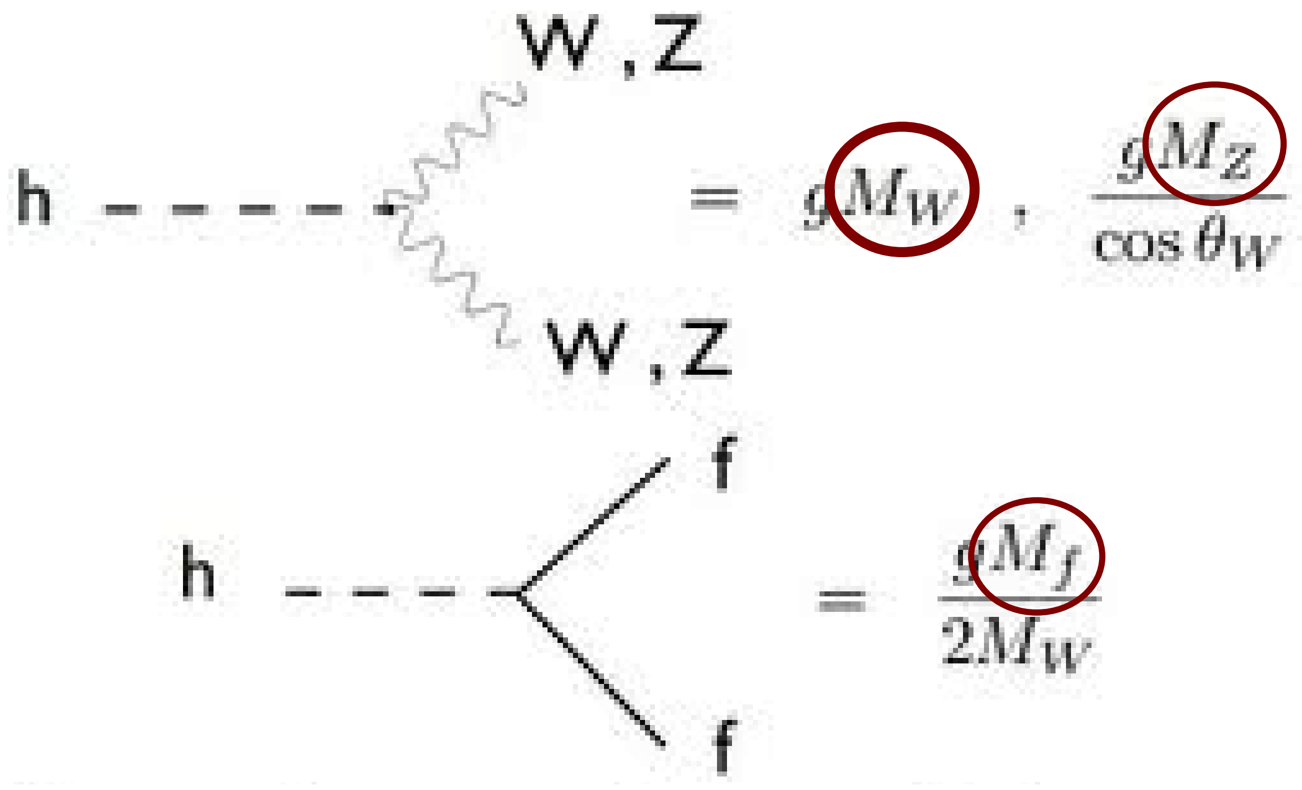
LS3 (2024-2026):

- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)

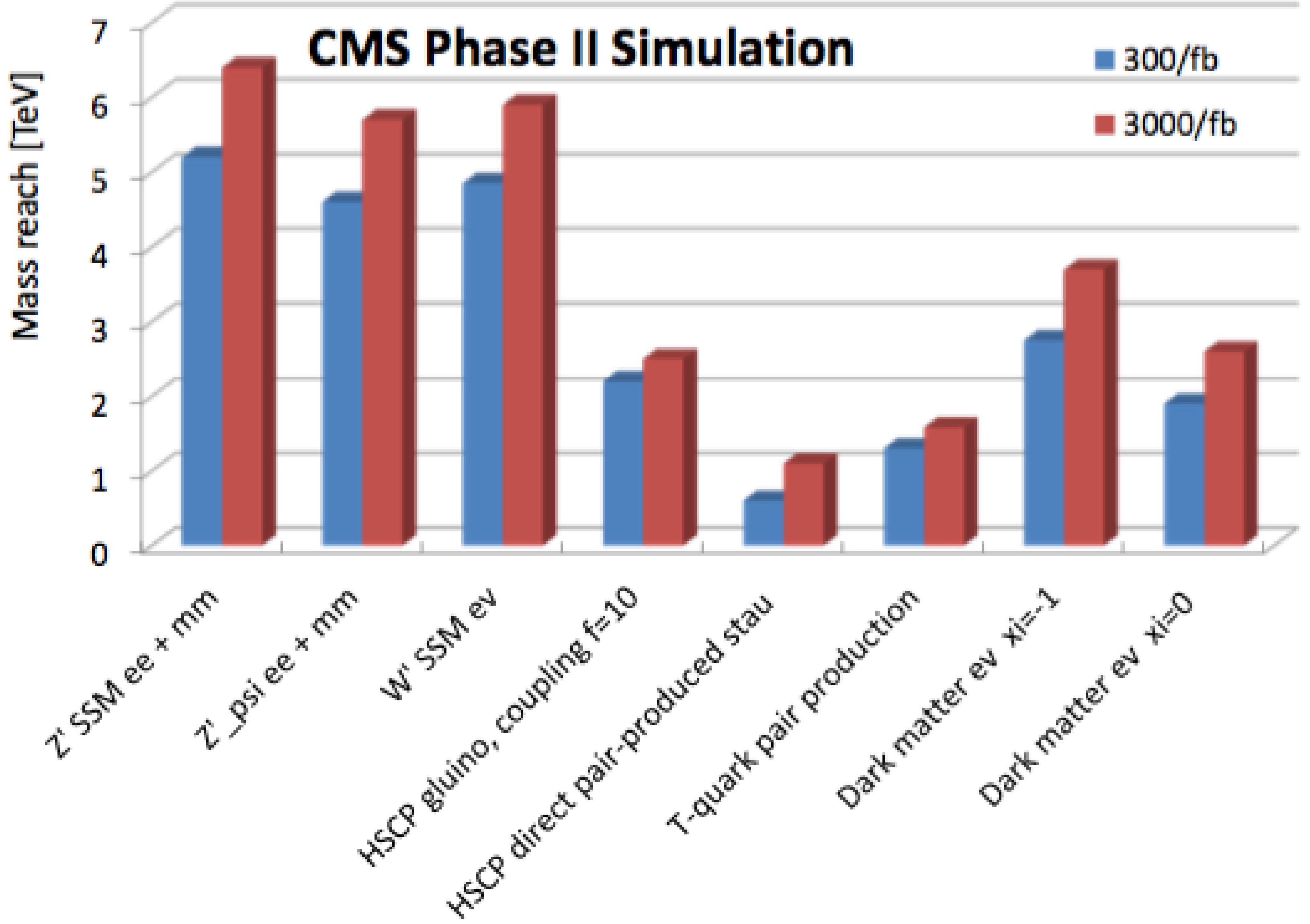
Just a few physics example for HL-LHC

- measurement of Higgs couplings
  - deviations may be at the few %-level
  - access to second generation couplings H→μμ



use Higgs as a portal to new physics

- 20-30% larger discovery potential (8 TeV)
  - precision measurements

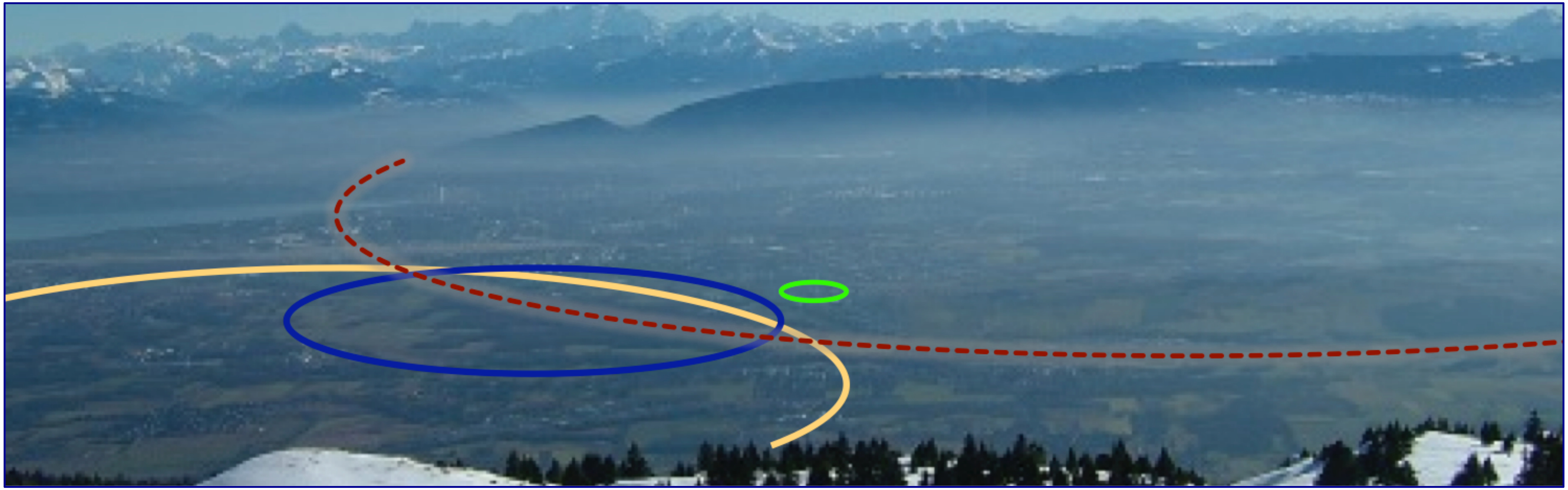


Highest energy hadron colliders

From European Strategy of Particle Physics

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



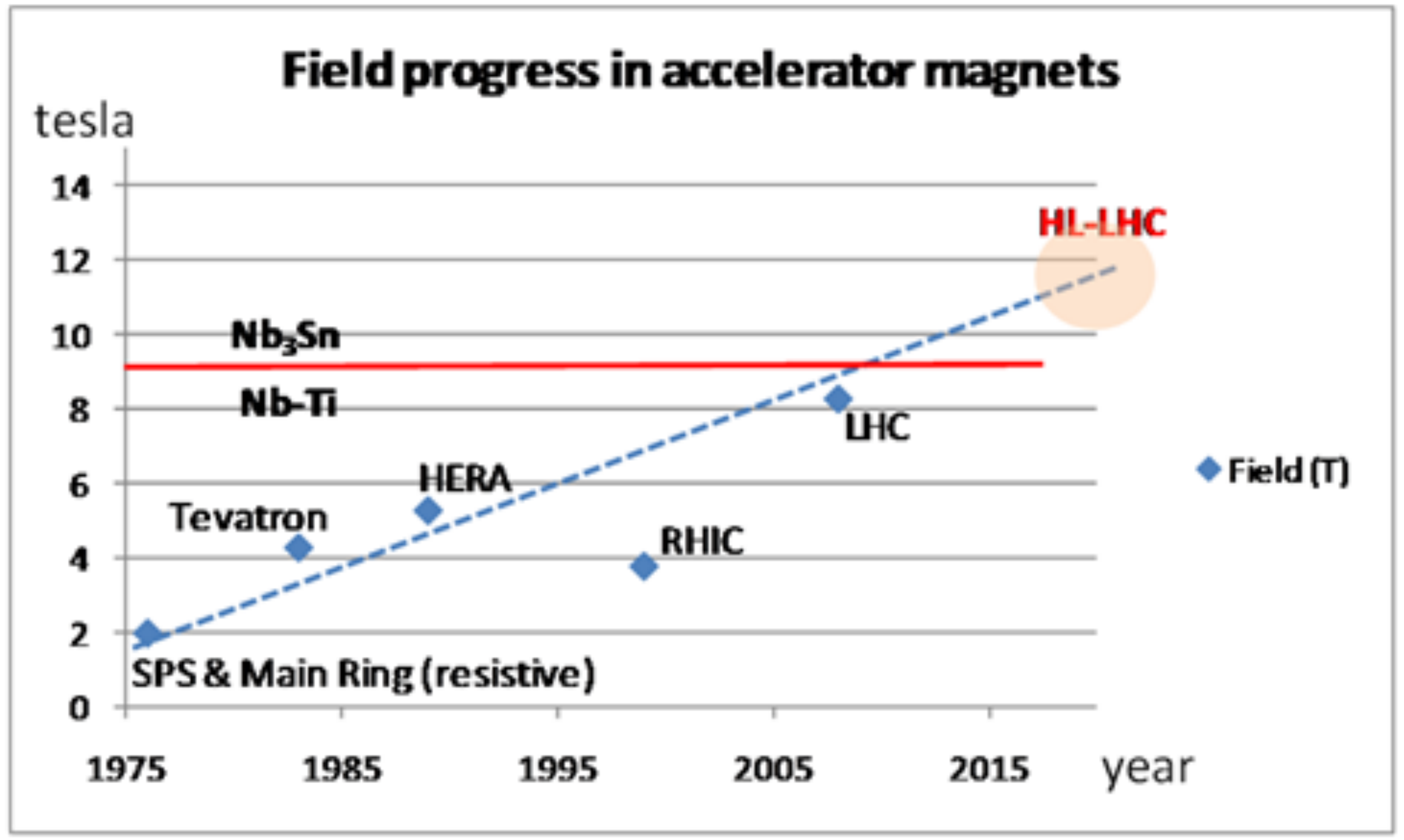
- Study for A 100 km ring providing collisions at 100 TeV cm
    - employs injector chain of CERN

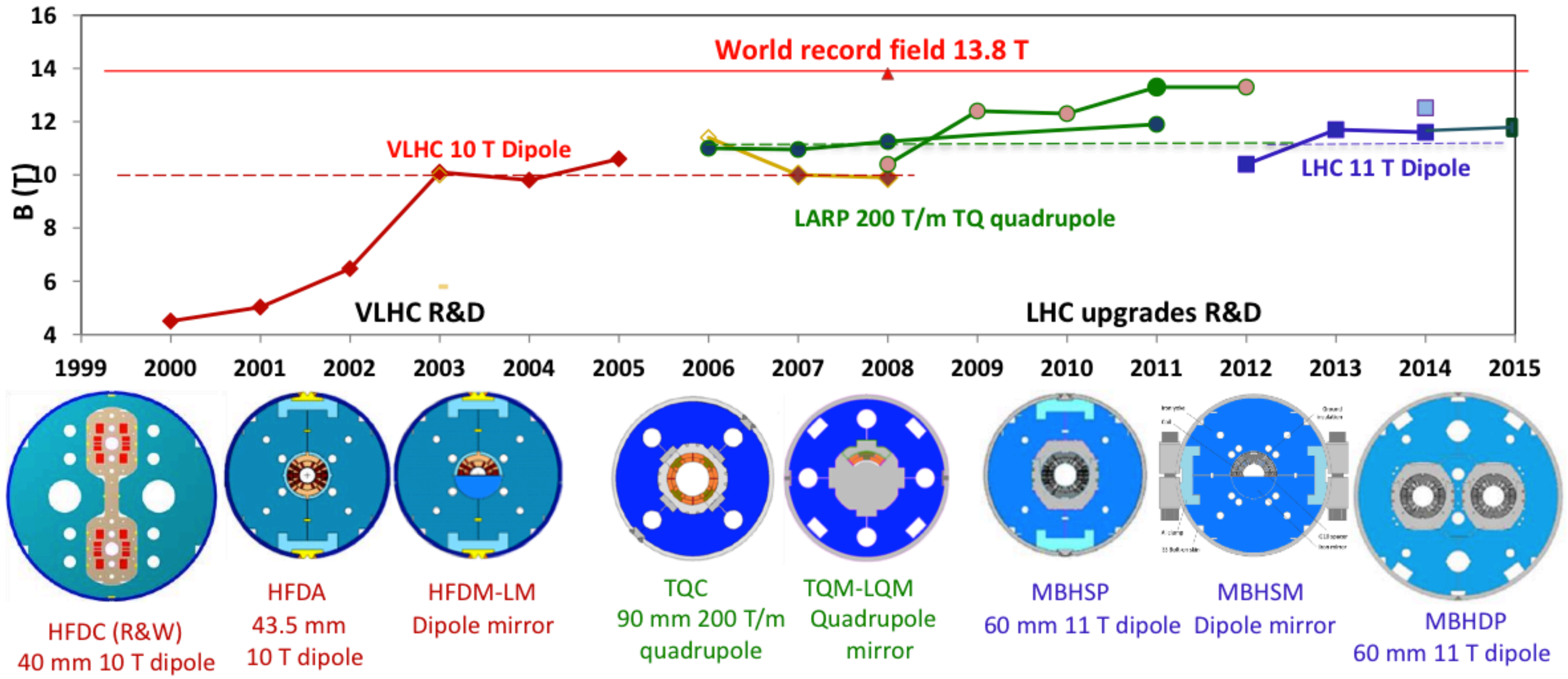
High-field magnets

- Key to high energies
  - FCC and
  - HE-LHC = use of high field magnets in existing LHC ring
- Technology
  - Nb_3Sn allows ~16 T magnets that need to be developed (size, cost, industry…)
    - HL-LHC magnets provide a ~1.2 km test of the technology (11 T magnets)
  - an insert of HTS may increase field to 20 T (requires much research)

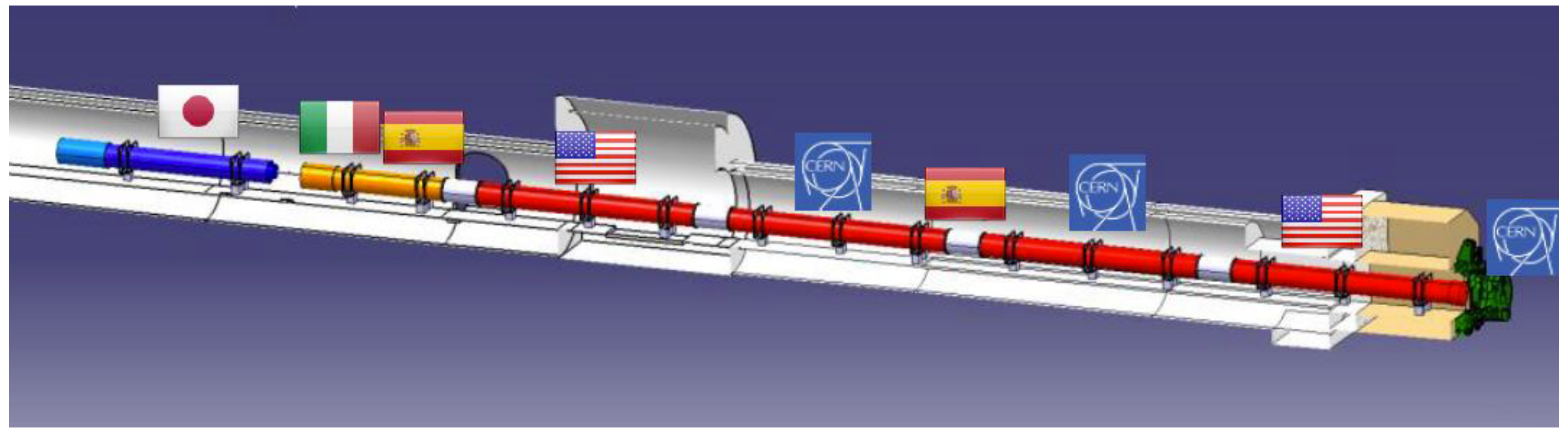
International Collaboration on Magnet Development

- Nb_3Sn magnets: international R&D programme
  - several European countries and US LARP programme and its successor



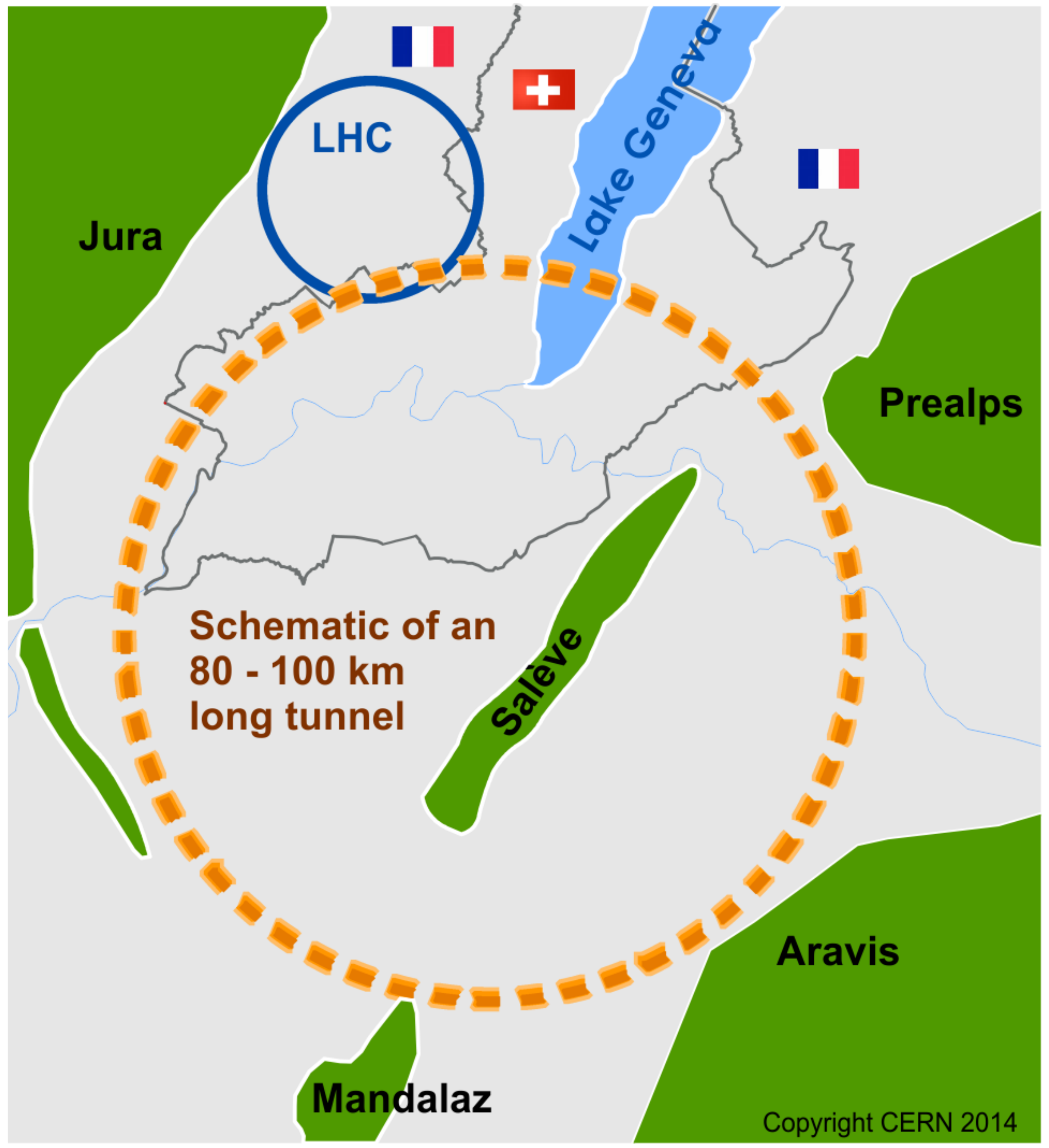


1.2KM of LHC modified



FCC Conceptual Design Report by end 2018

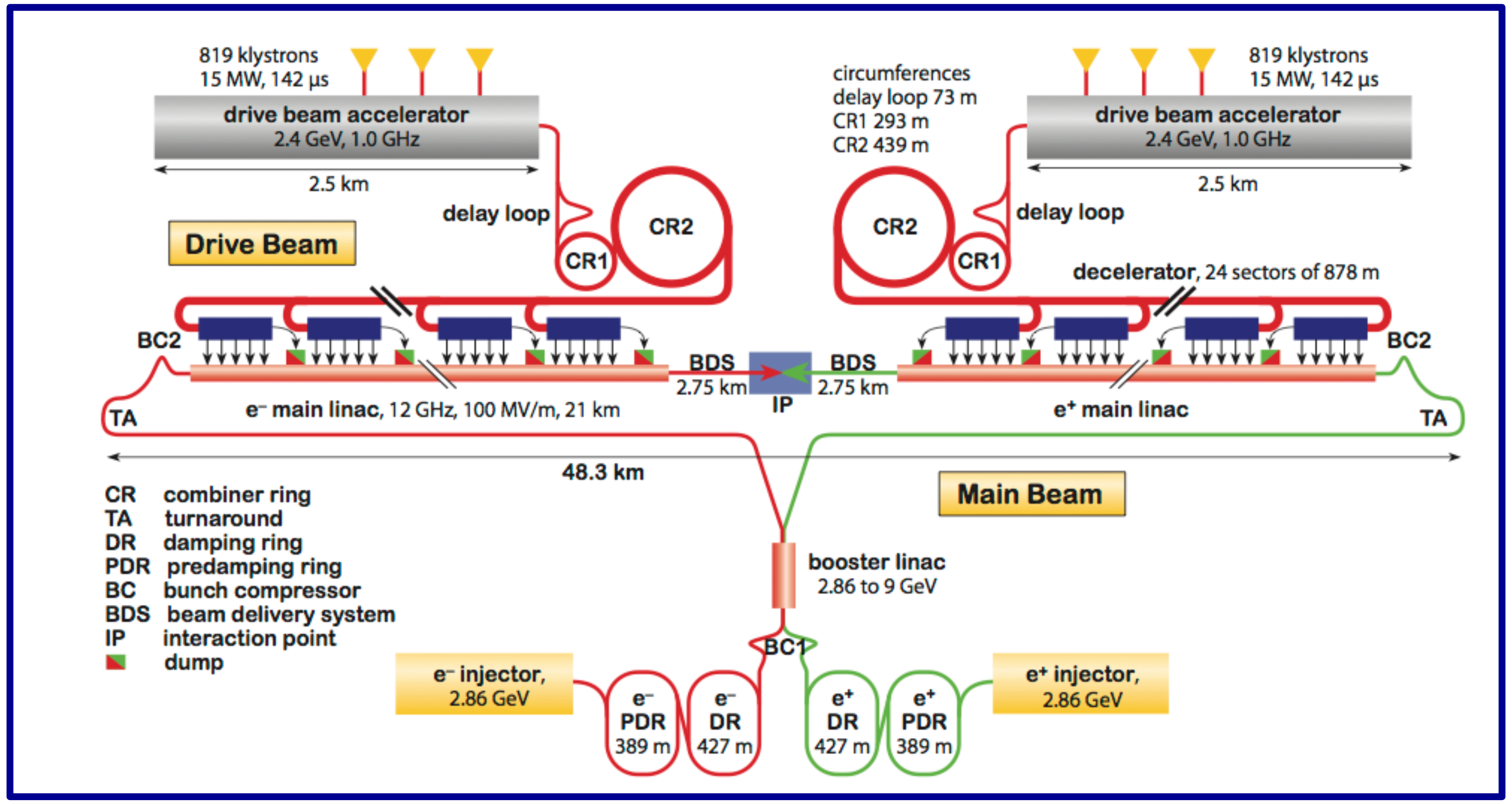
- **pp-Collider (FCC-hh) – sets the boundary conditions**
  - **100 km ring, $\sqrt{s}$=100 TeV, L~2x10^{35}**
  - **HE-LHC is included (~28 TeV)**
- e^+e^--Collider as a possible first step
  - $\sqrt{s}$= 90 - 350 GeV,
    L~1.3x10^{34} at high E
- eh-Collider as an option
  - $\sqrt{s}$=3.5 TeV, L~10^{34}



Highest energy with lepton colliders

Compact Linear Collider CLIC

- e^+e^- collider 1-3 TeV
- currently only option for the TeV region
- 380 GeV study has been completed both for 2-beam and klystrons approach; now explore 250 GeV
- decisive input to next update of European Strategy for Particle Physics



- CDR 2013
- CTF3 has provided key results
  - experimental programme ended 2016
- ready for a demonstrator

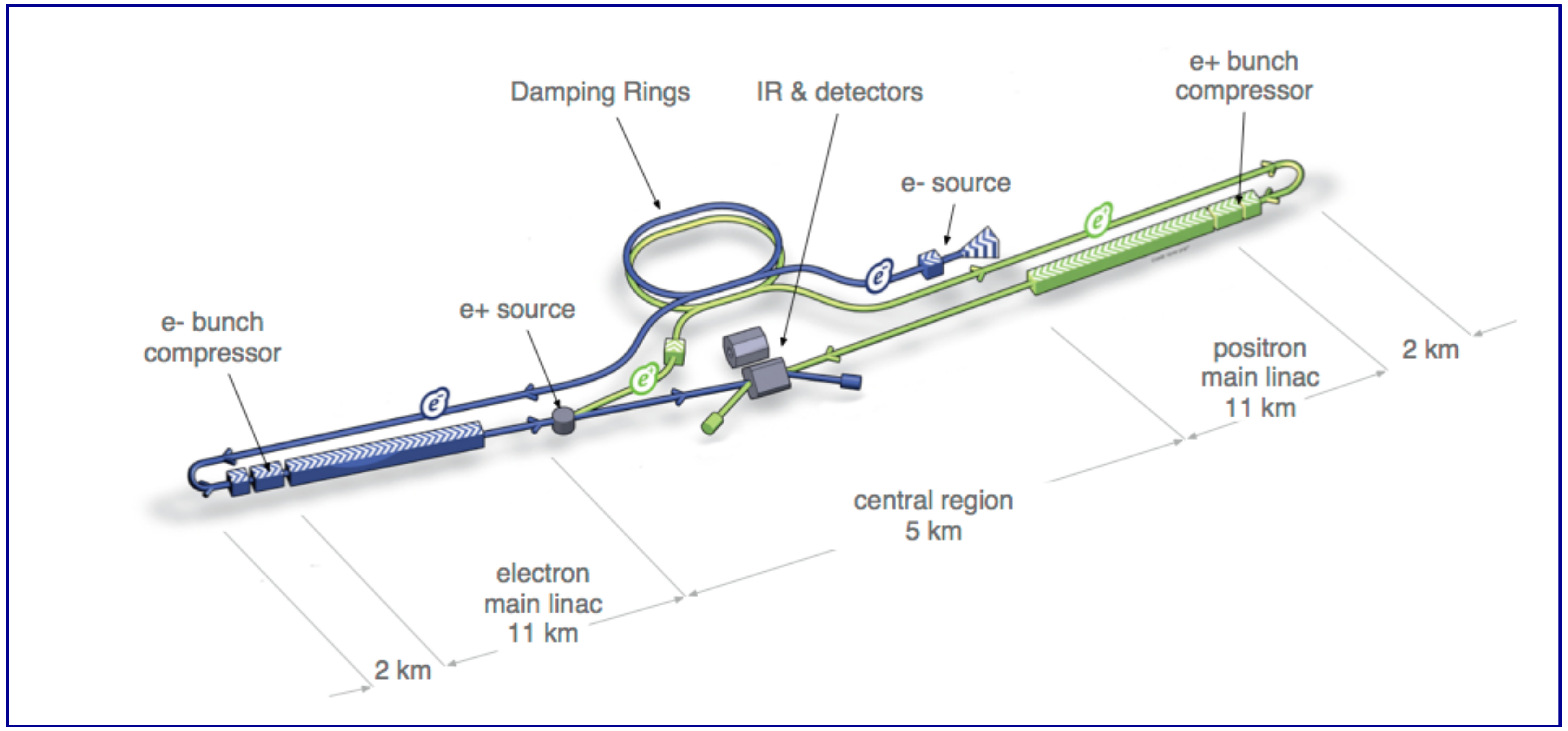
e^+e^- collider

- 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 $\sqrt{s}$ = 0.5 TeV (upgradeable to 1 TeV)
  - staged version for $\sqrt{s}$ = 0.25 TeV being seriously discussed
- precision Higgs (and Top) programme and beyond
- Ministry MEXT continues to evaluate the implications of hosting ILC in Japan w.r.t. cost, manpower (skills)



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

Japanese Government has to make a statement before end 2018

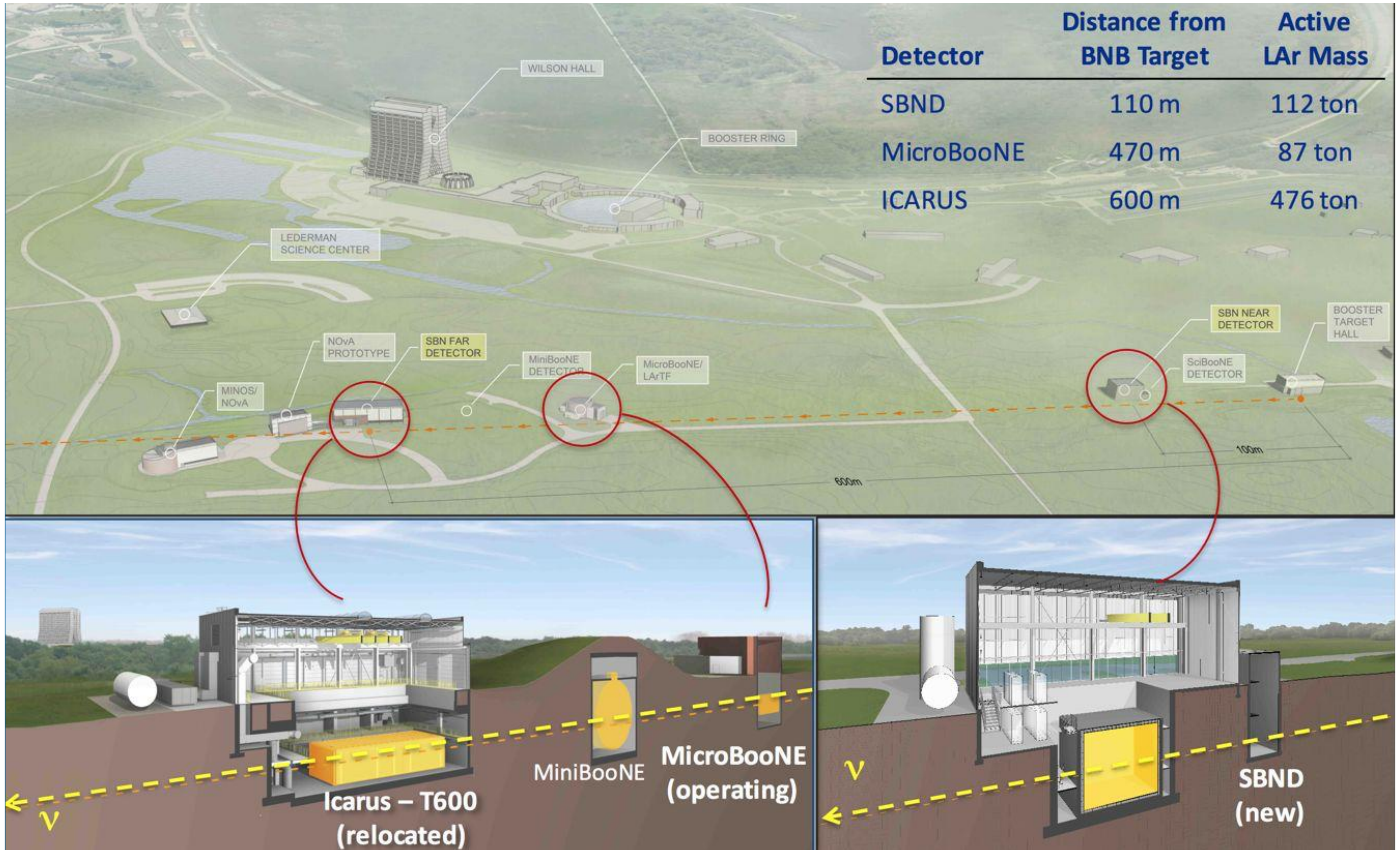
ν-physics

From European Strategy of Particle Physics

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

Short baseline programme at Fermilab

- To resolve experimental inconsistencies in the measured ν-spectrum
  - SBND (near detector)
  - MicroBooNE (operating)
  - MiniBooNE
  - refurbished ICARUS waiting for installation at FNAL

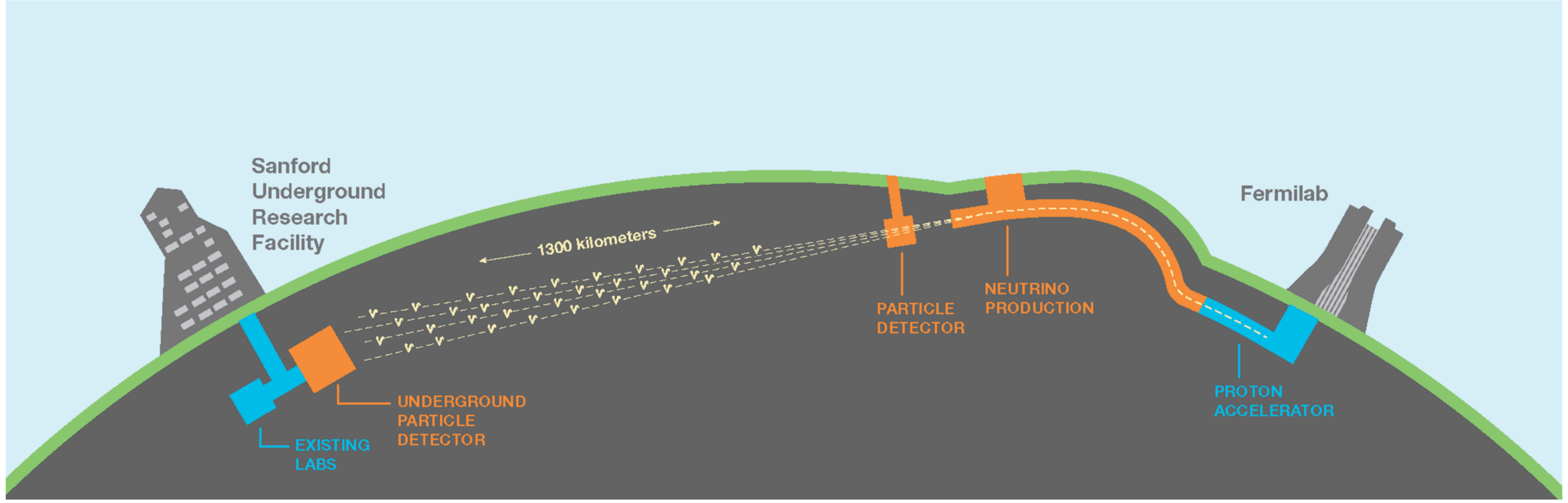


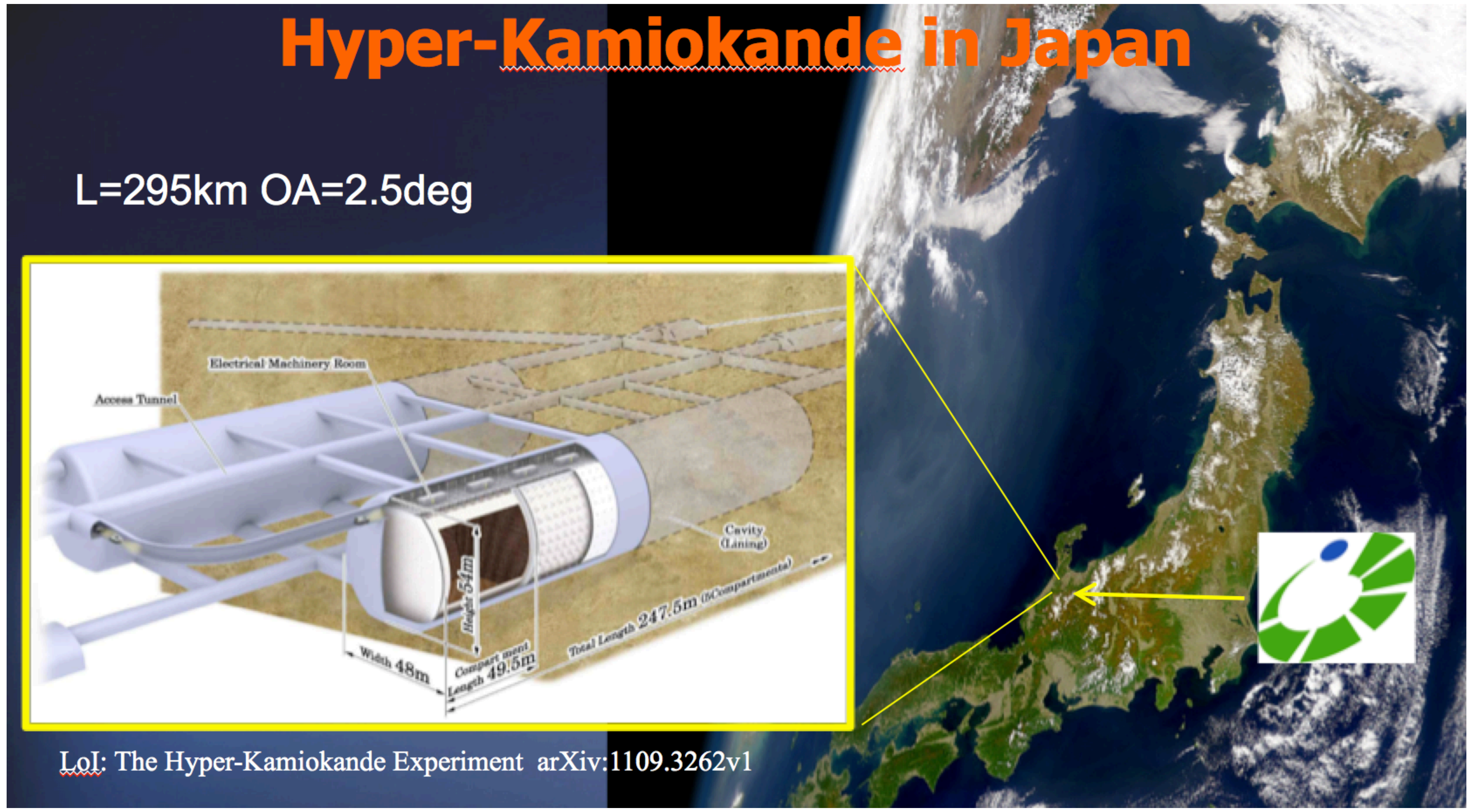
Long baseline neutrino programmes

- Fermilab is planning a long baseline neutrino facility (LBNF), a wide band neutrino beam to the DUNE experiment (LArTPC) in South Dakota

- Tokyo is considering Hyper-K (water Cherenkov detector) at Kamioka

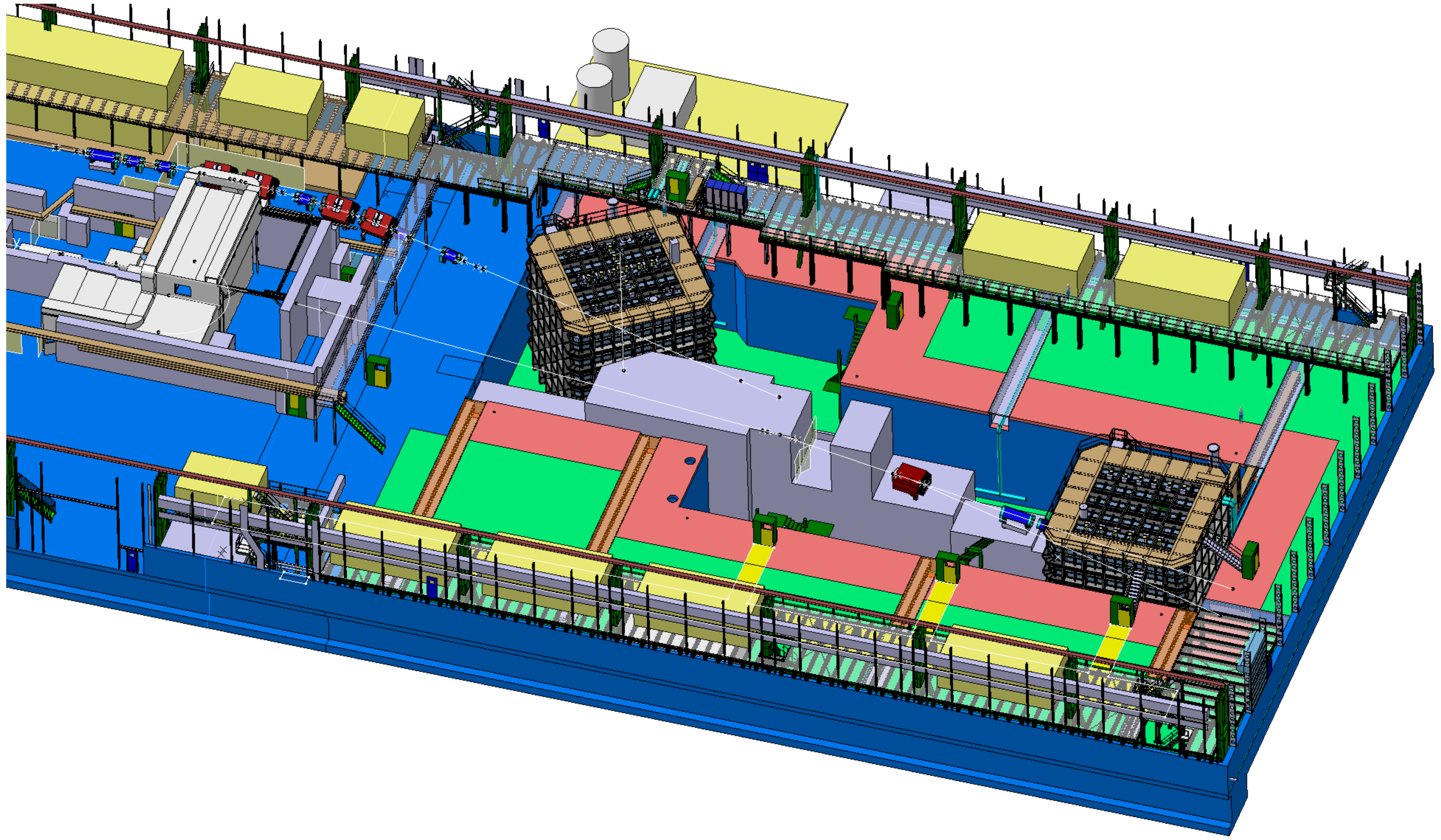
- Goals: neutrino-oscillation parameters, mass hierarchy and CP-violation

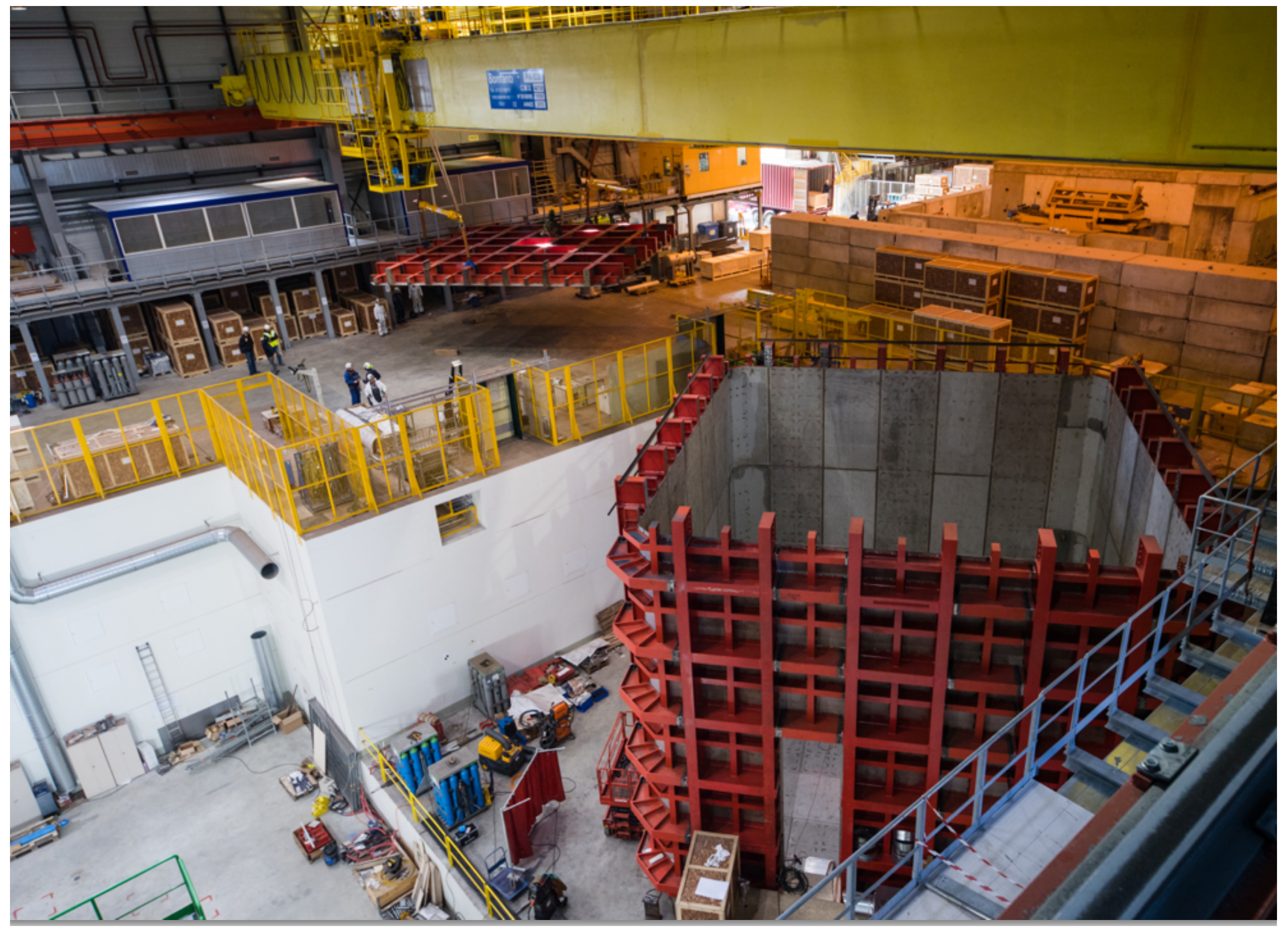




Neutrino Platform at CERN

To develop experimental techniques, e.g. protoDUNE
– single phase LArTPC
– double phase LArTPC



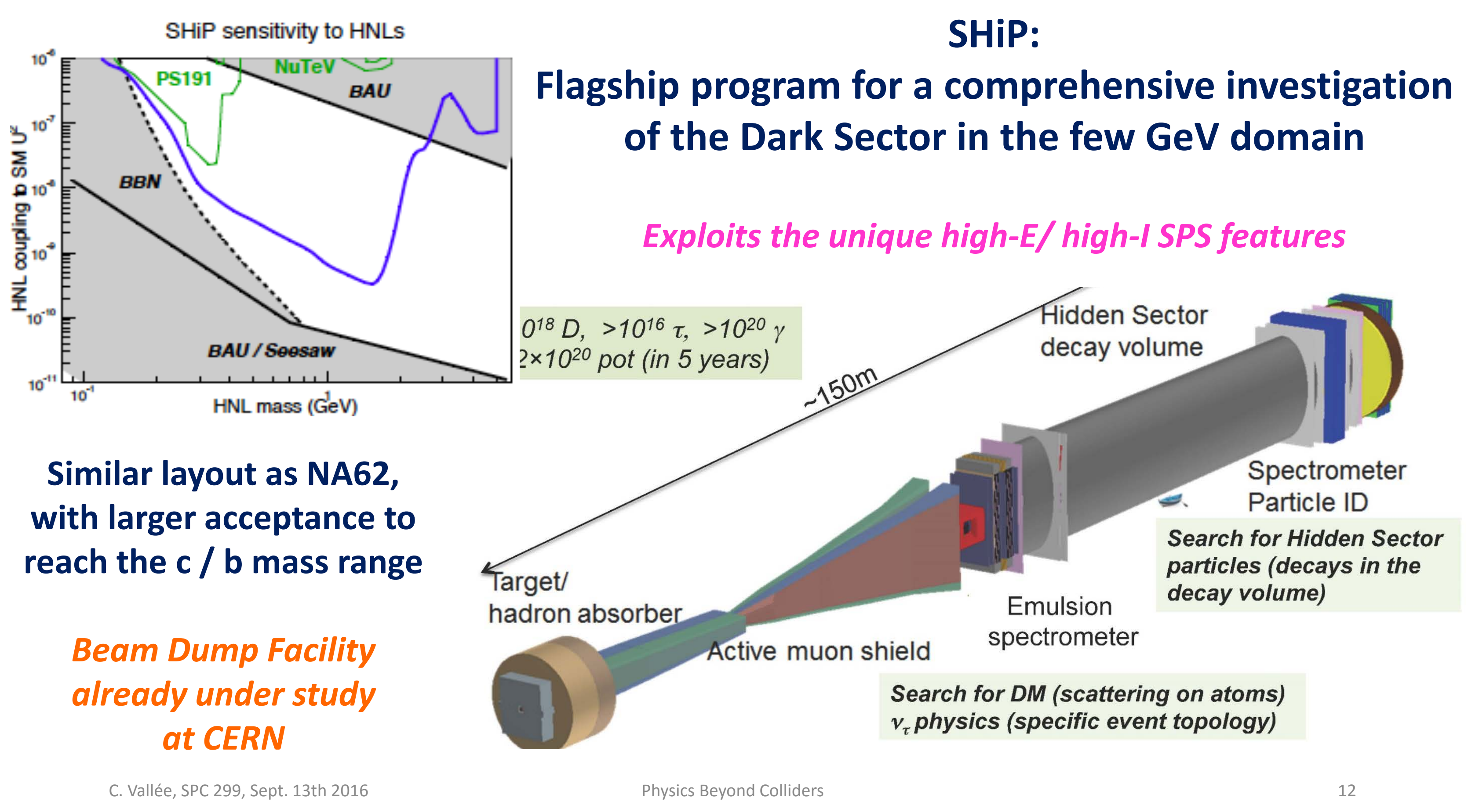


These prototype detectors will generate a data stream comparable to that of ALICE in Heavy Iron Running

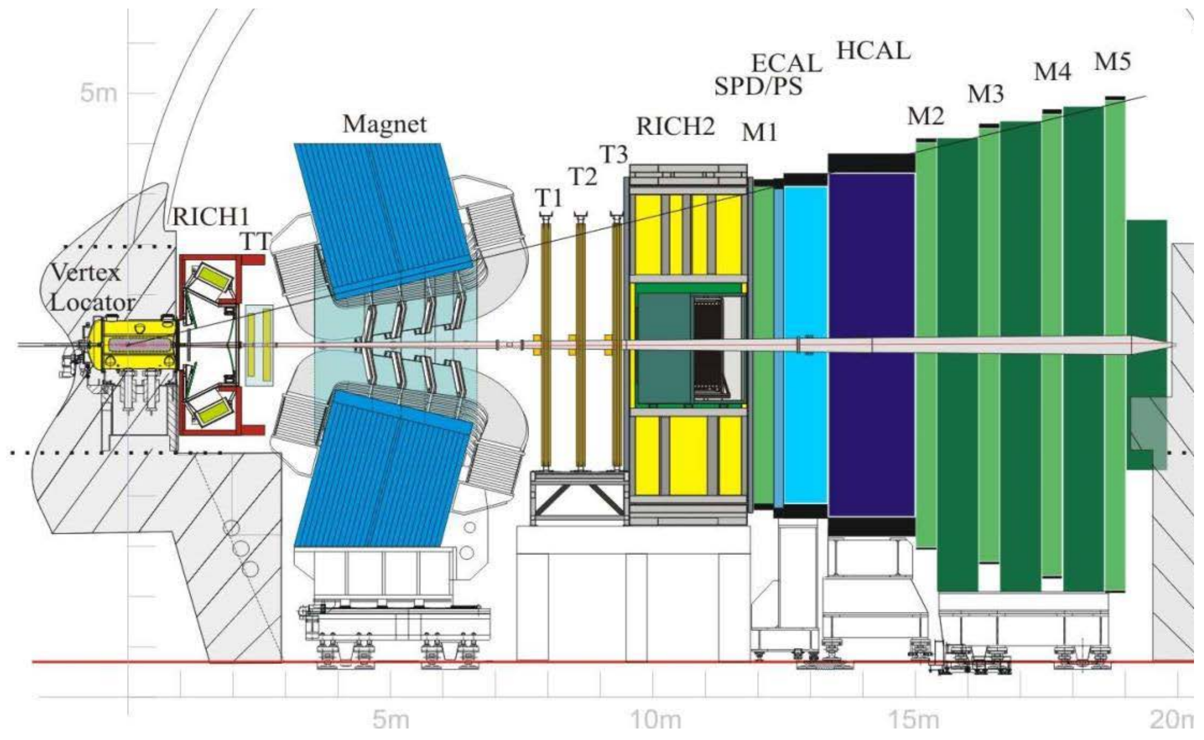
Towards 2020 Update of European Strategy for Particle Physics

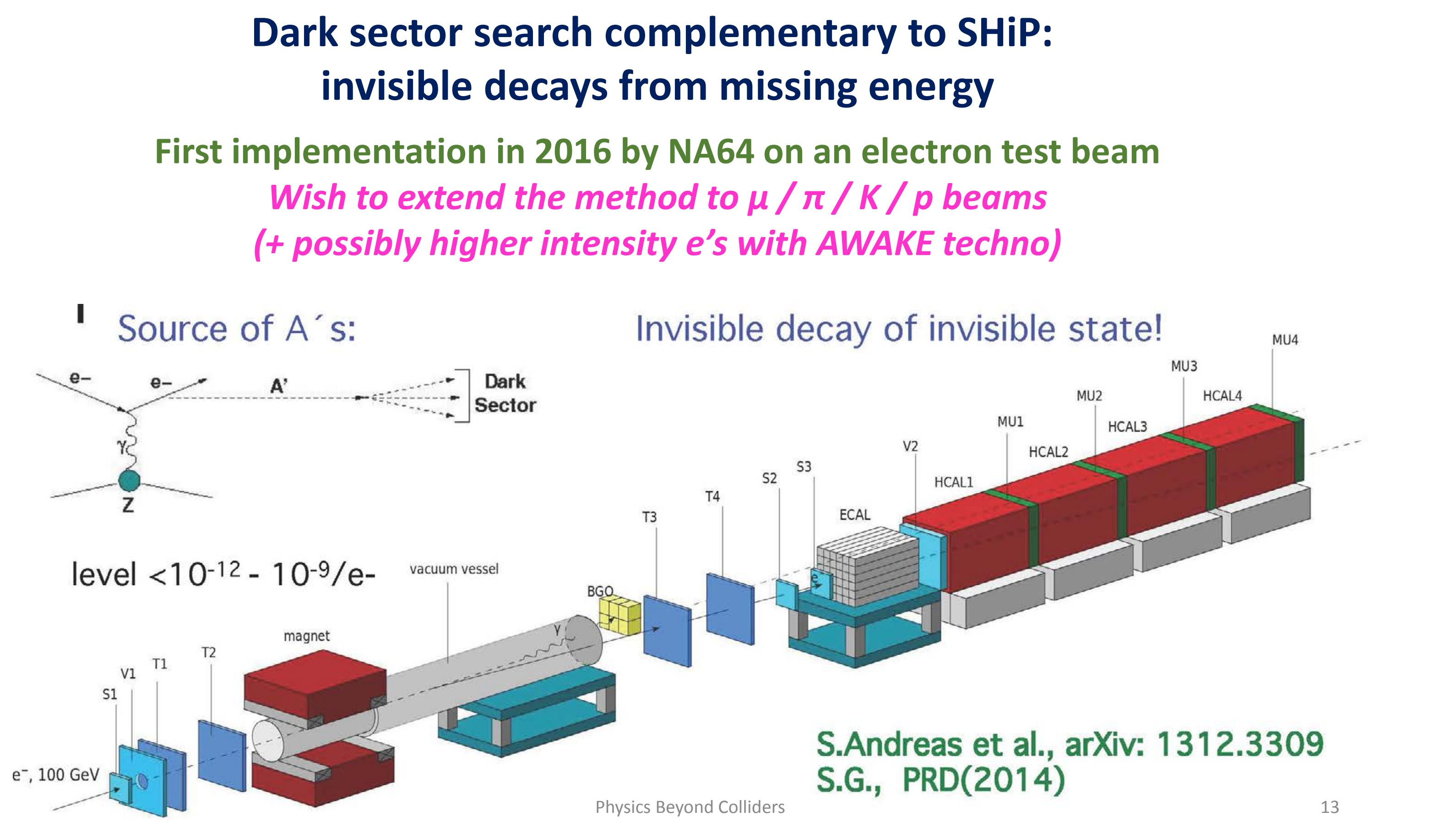
Physics Beyond Collider Study

- Meetings held in Sep 2016 and Nov 2017
  - Study of fixed target programme
    - NA61, NA62, NA64, COMPASS,…
  - even with LHC beams

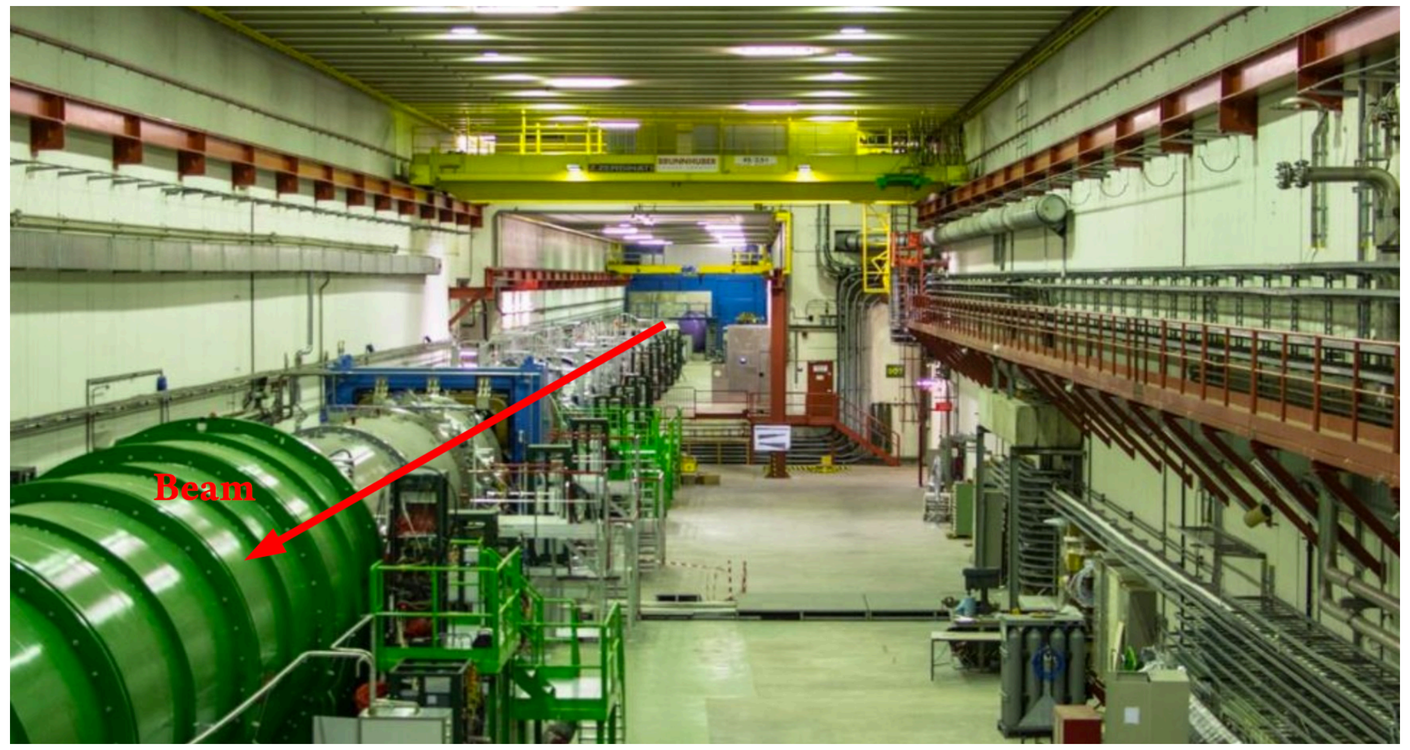


SMOG

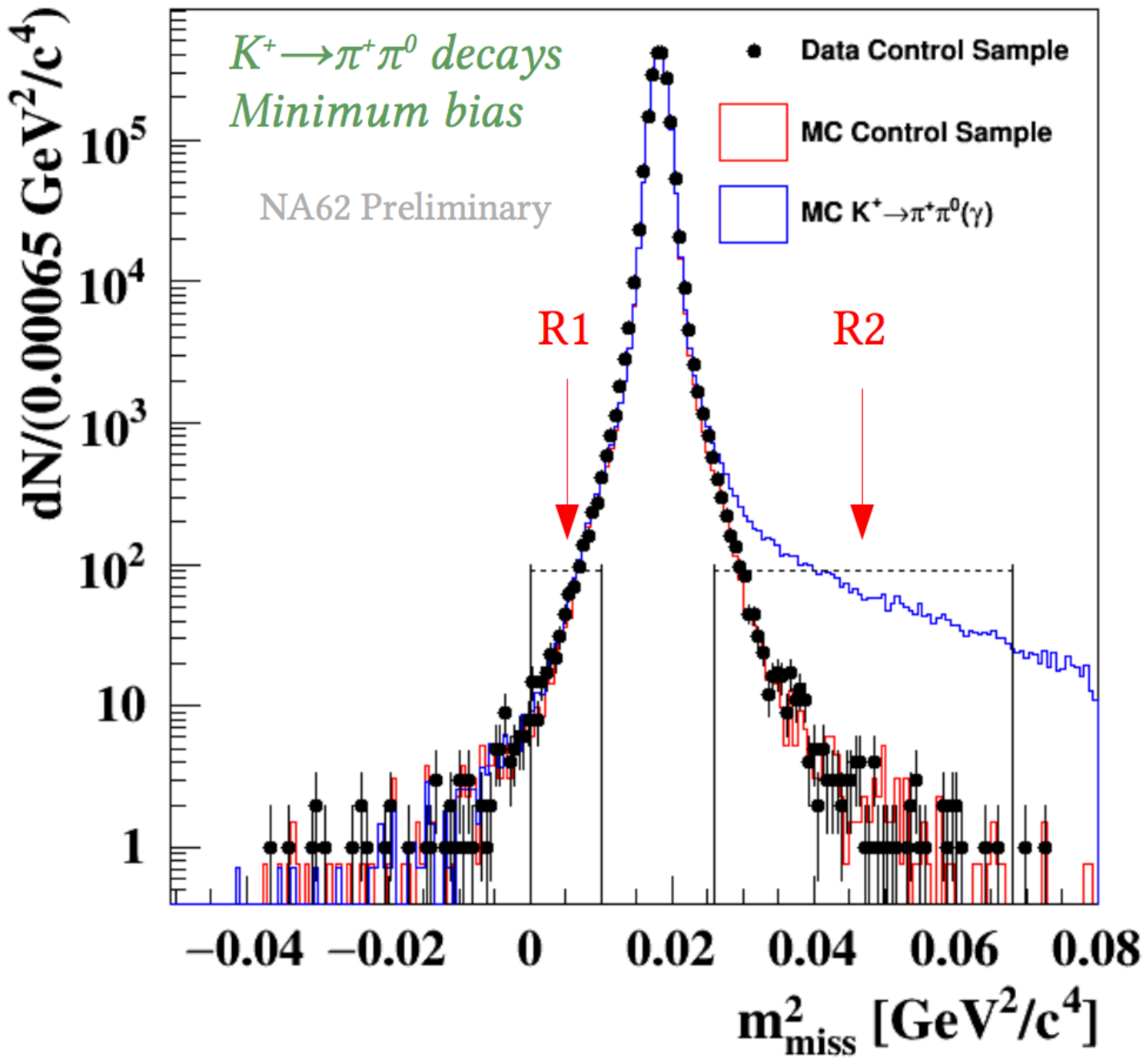




NA62: $K^+ \to \pi^+ \nu\bar{\nu}$ in-flight



Result from 2016 data



Process	Expected events in R1+R2
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

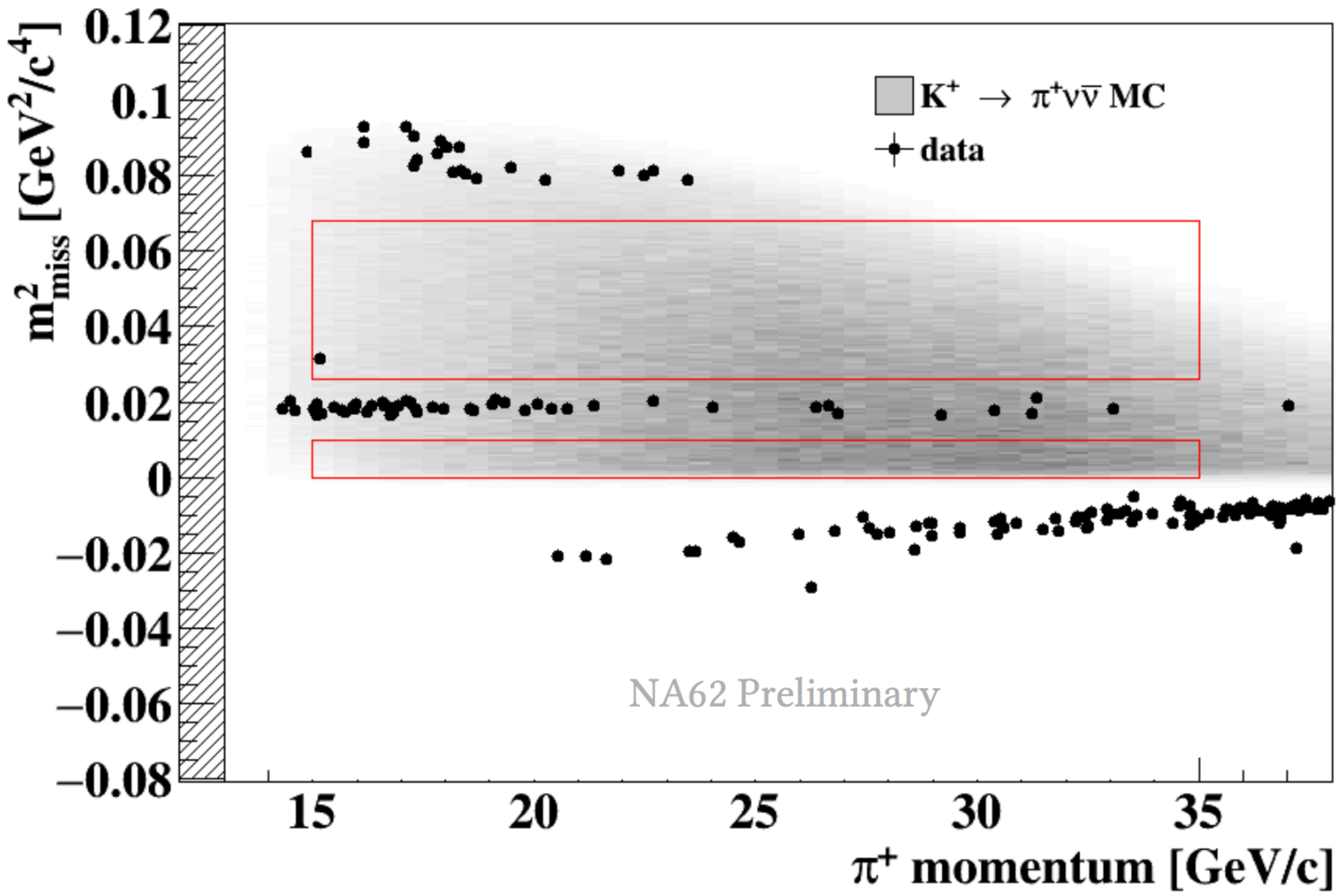
Single Event Sensitivity

$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

Results

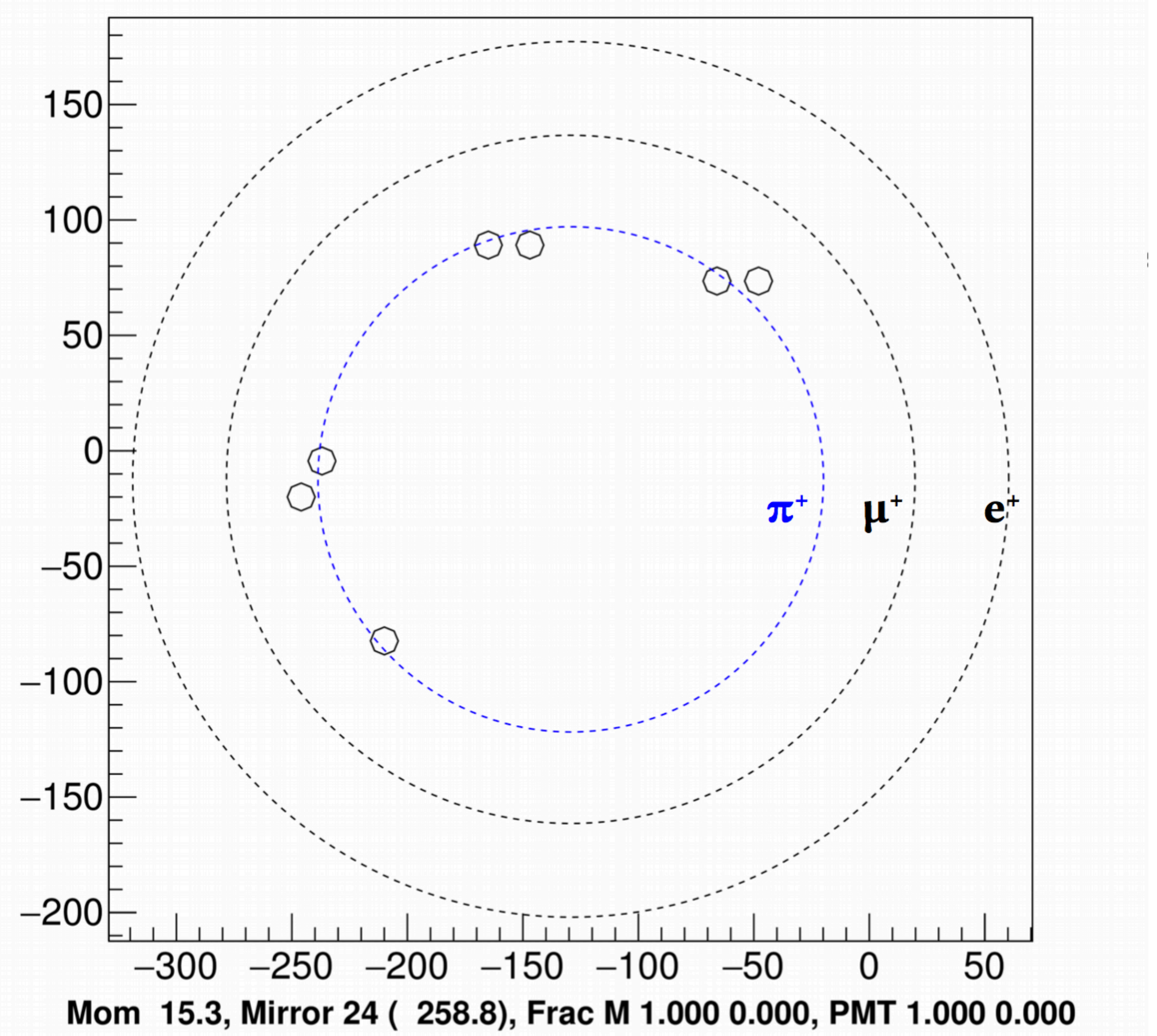
$K^+ \to \pi^+ \nu \bar{\nu}$

Recent result



One event observed

Results: RICH ring for the event



Results

$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 11 \times 10^{-10} \ @\ 90\%\ CL$$

$$\boxed{BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} \ @\ 95\%\ CL}$$

- One event observed in Region 2
- Full exploitation of the CLs method in progress
- The results are compatible with the Standard Model
- For comparison: $BR(K^+ \to \pi^+\nu\bar{\nu}) = 28^{+44}_{-23} \times 10^{-11}$ @ 68% CL

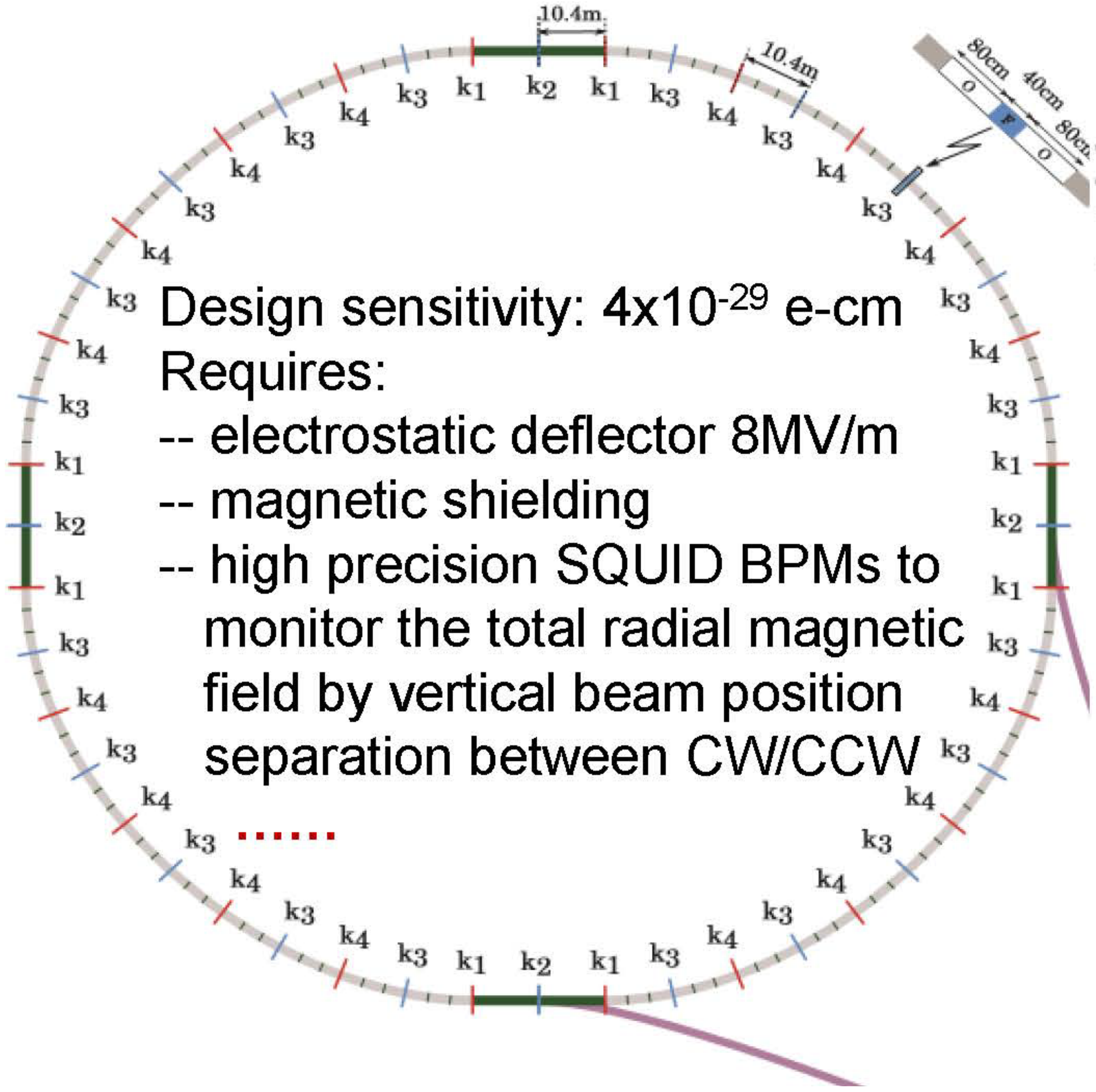
$$BR(K^+ \to \pi^+\nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$$

$$BR(K^+ \to \pi^+\nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$

- **In-flight technique works**
- **Expect ~20 SM events with data collected before LS2**
- **Input to European Strategy**
- **Solid extrapolation to ultimate sensitivity**

Physics Beyond Collider Study cont'd

Study of an all-electric storage ring



Design sensitivity: 4×10^{-29} e-cm

Requires:

-- electrostatic deflector 8MV/m

-- magnetic shielding

-- high precision SQUID BPMs to monitor the total radial magnetic field by vertical beam position separation between CW/CCW

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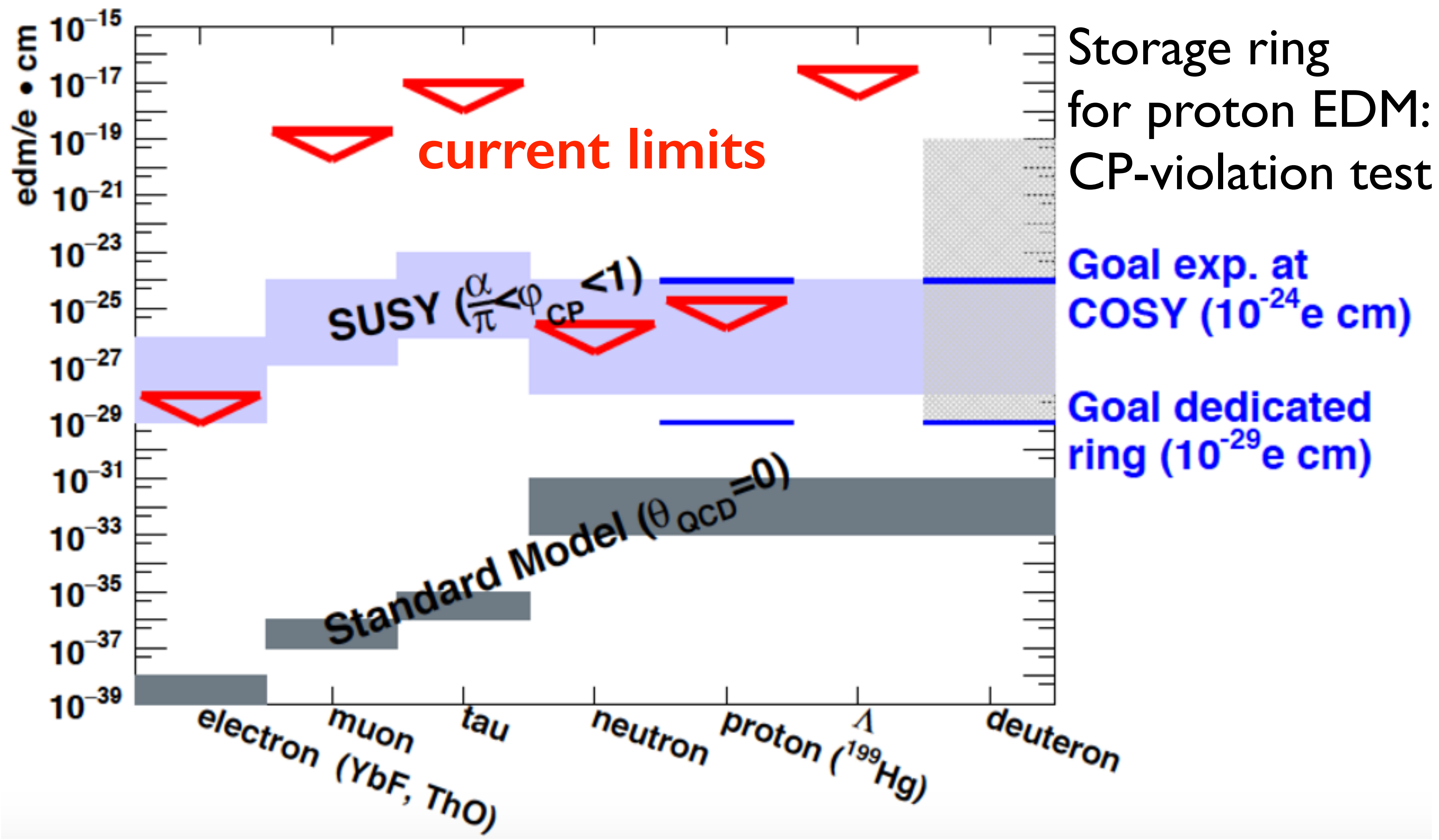
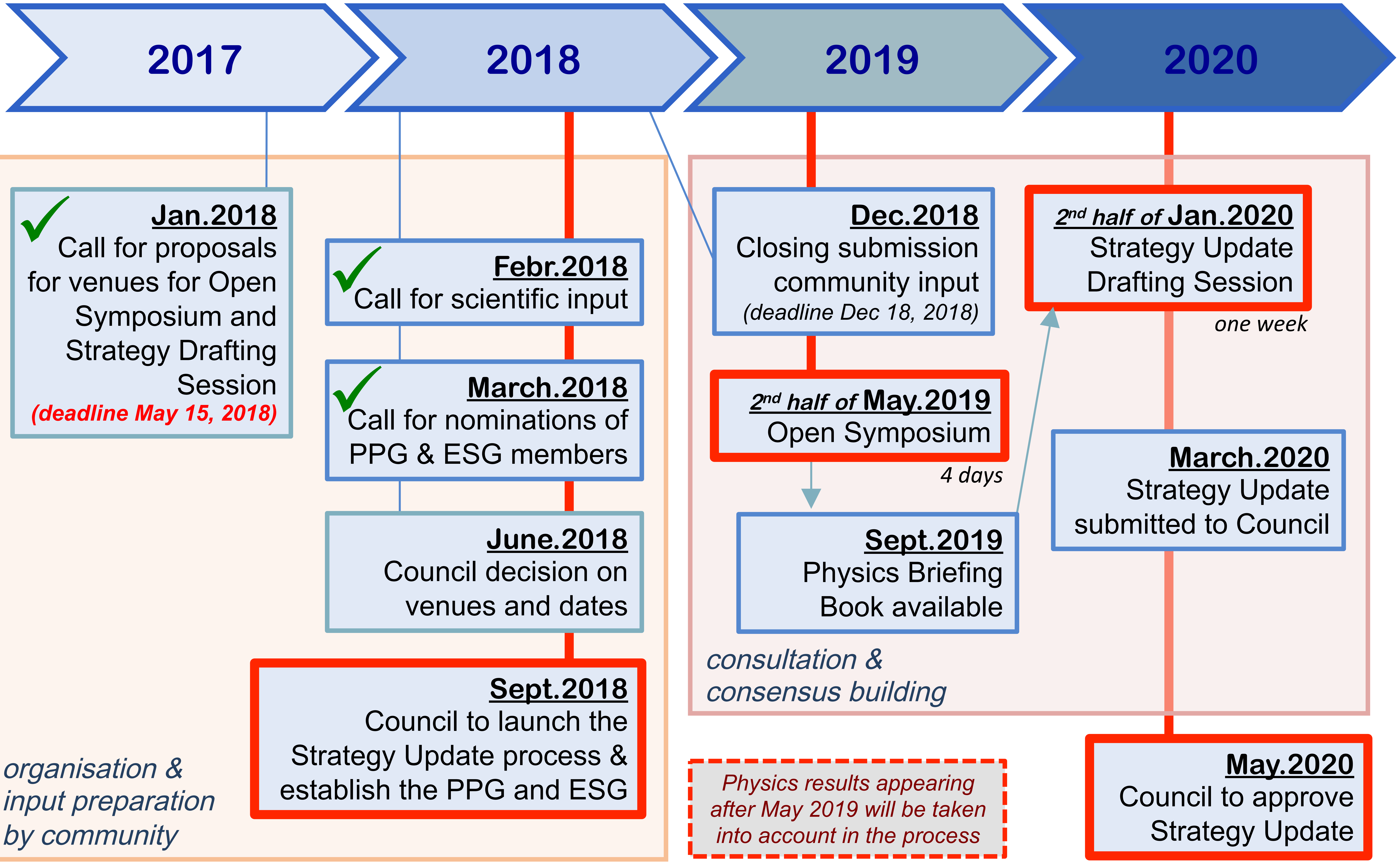


Sensitivity of 10^{-29} e-cm corresponds to 100 TeV for new physics scale

European Strategy Update

European Particle Physics Strategy *Update*



Summary

- Experimental Programme of LHC extremely rich; long range experimental programme guarantees physics return
    - by exploring the highest energies
    - by searching for violations of the SM in (highly sensitive) rare decays
- Preparing Update of the European Strategy for Particle Physics
  - LHC and HL-LHC
    - *ILC* (depending on Japanese input)
  - highest energies (CLIC, FCC, …)
  - Vibrant physics programme beyond colliders

2018 (end): reports on Physics
2019: community discussion
2020: Update publicly released