The first decade of experiments at the LHC – what have we learnt?

Eckhard Elsen

CERN Director Research and Computing (2016-2020)

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

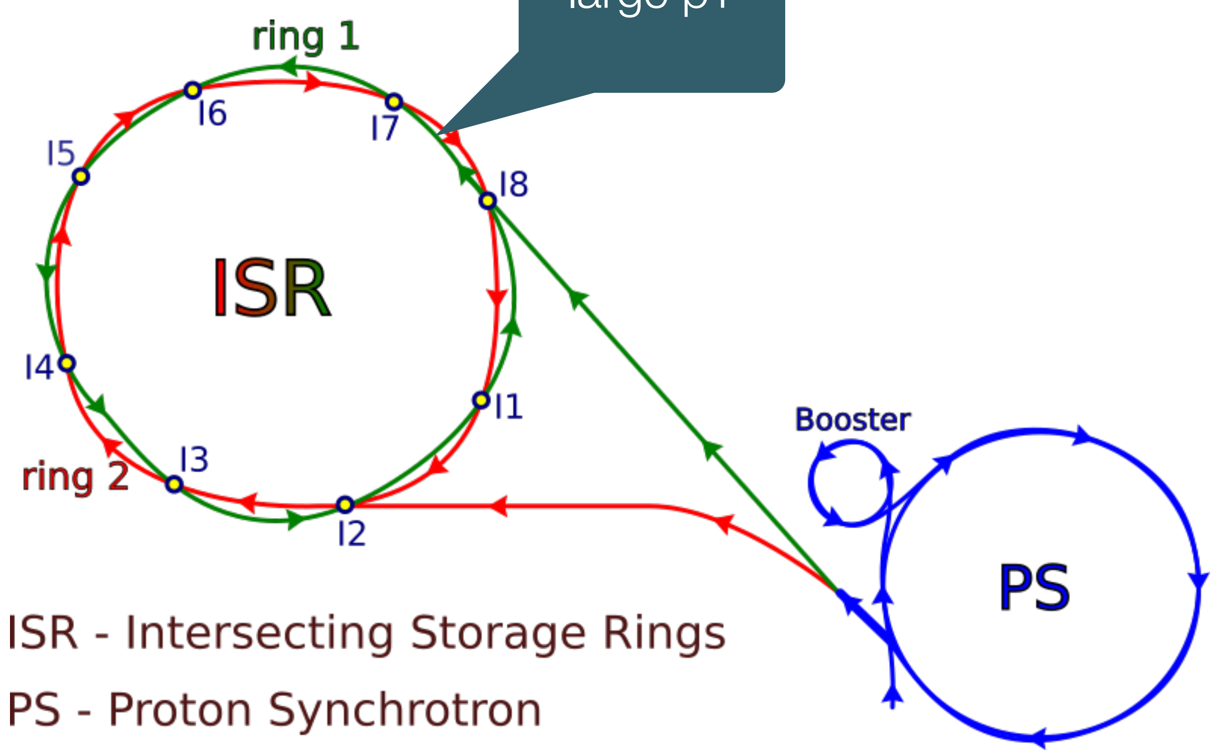
14th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale", 23.-24.11.2021


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

Hadron Colliders before the LHC

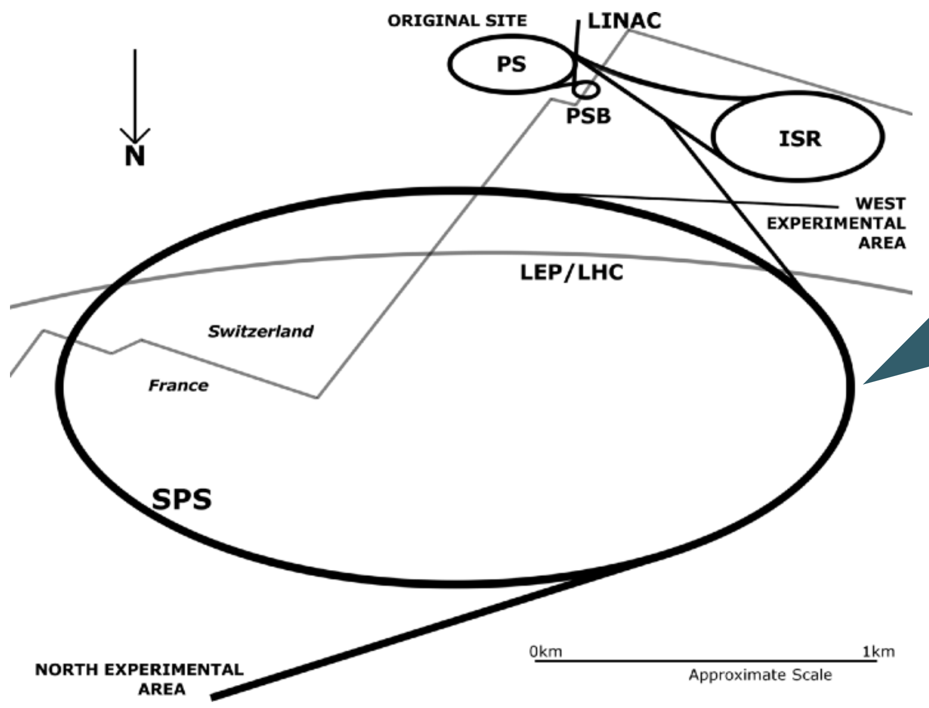
pp

pp-collider; large pT



ISR

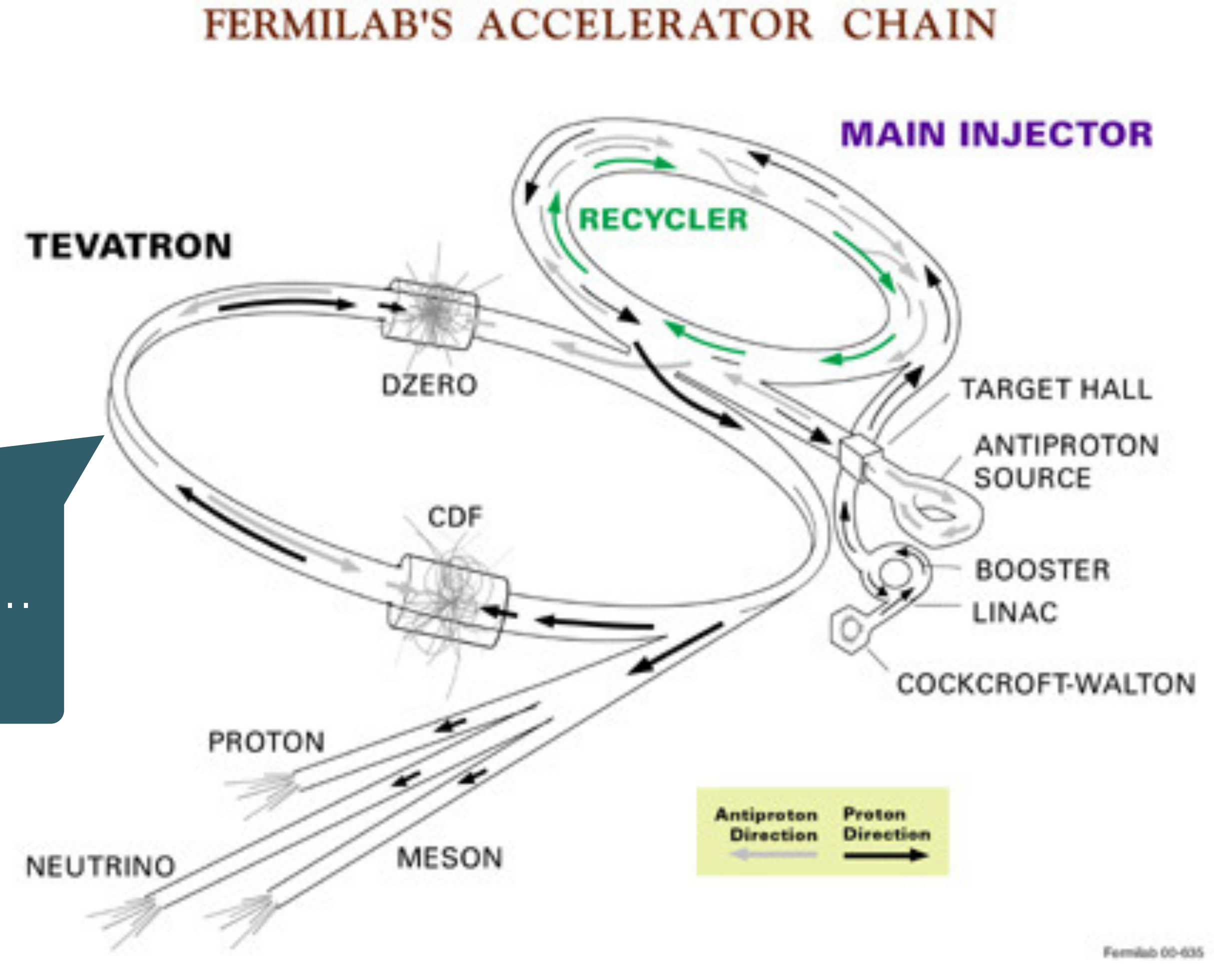
$p\bar{p}$



Stochastic cooling; W and Z

SppS

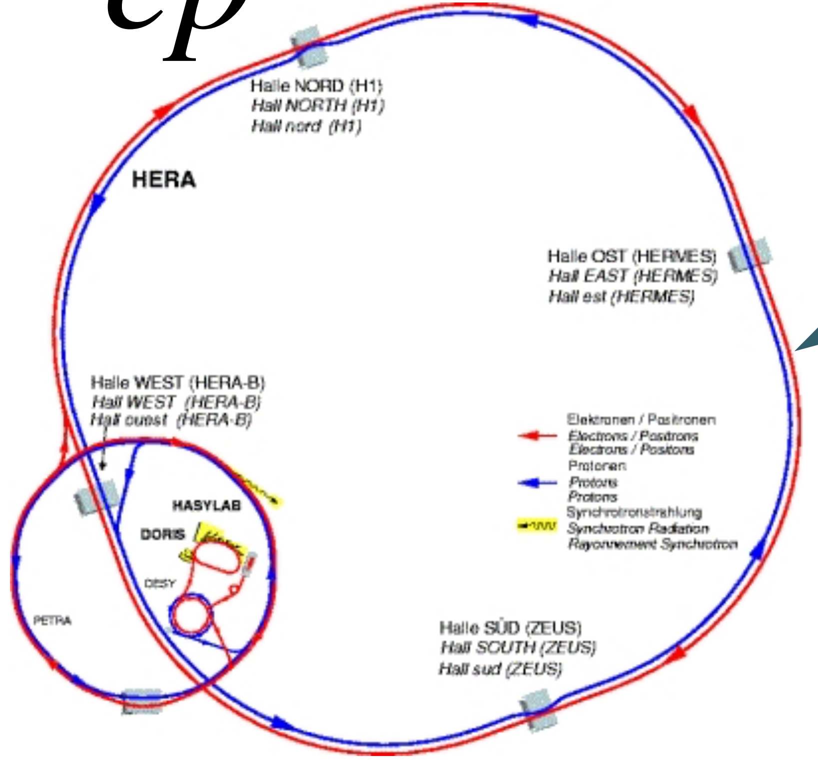
$p\bar{p}$



Top, flavour, … and $\sqrt{s}$

Tevatron

ep

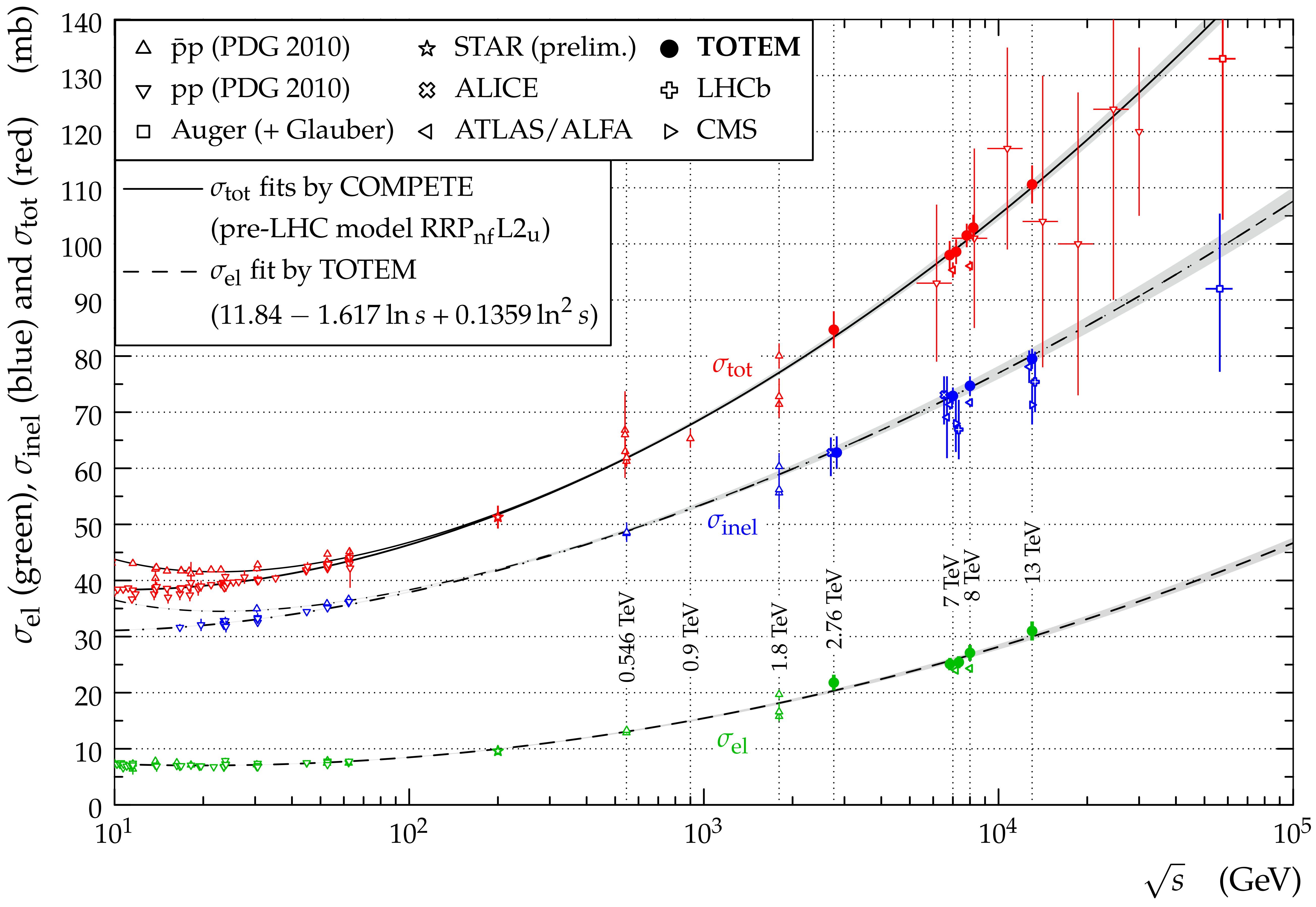


Structure functions, hard diffraction and electroweak …; ep-collider

HERA

Steadily building up knowledge and advancing collider technolgy

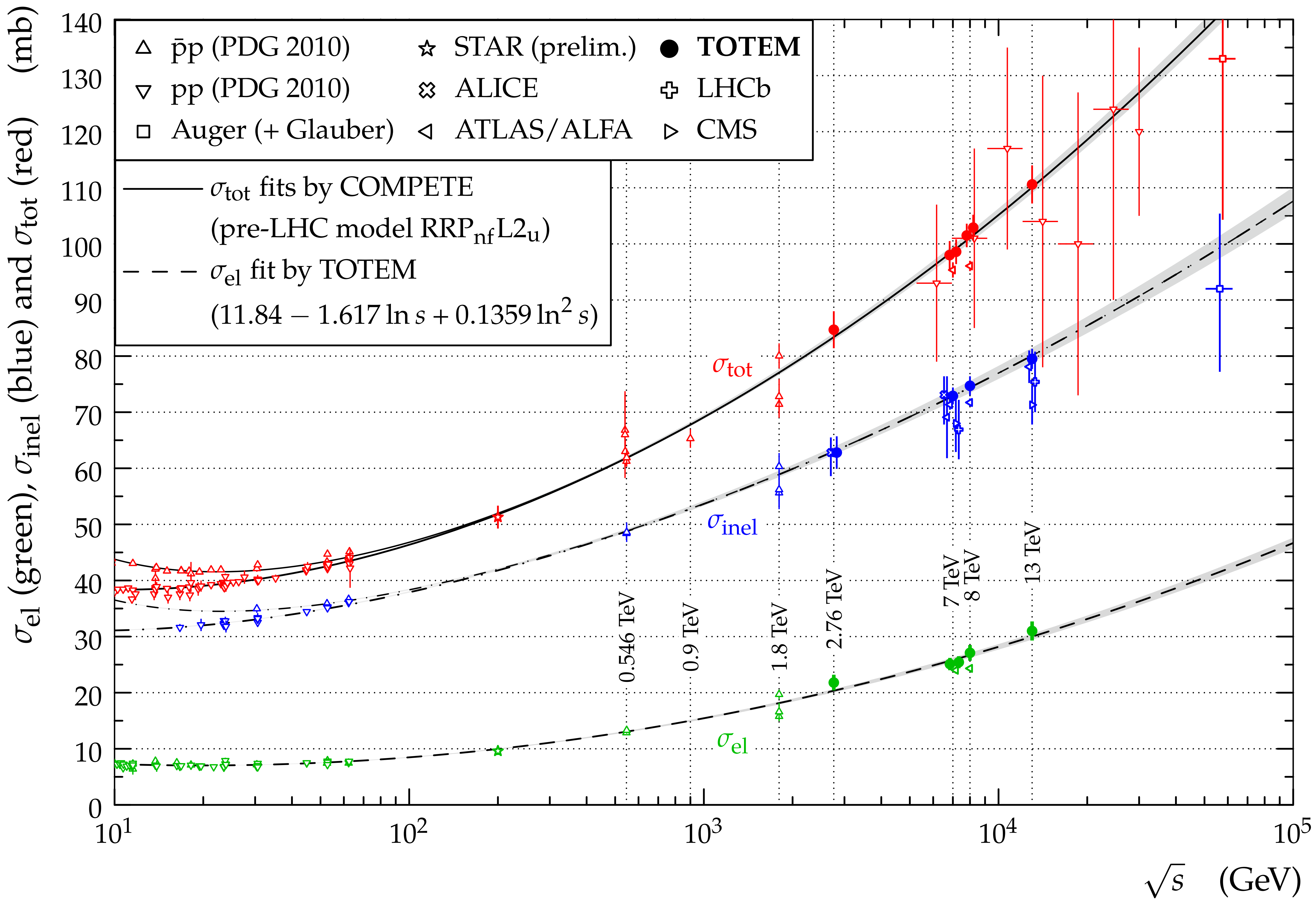
Total Cross Section $pp \to X$



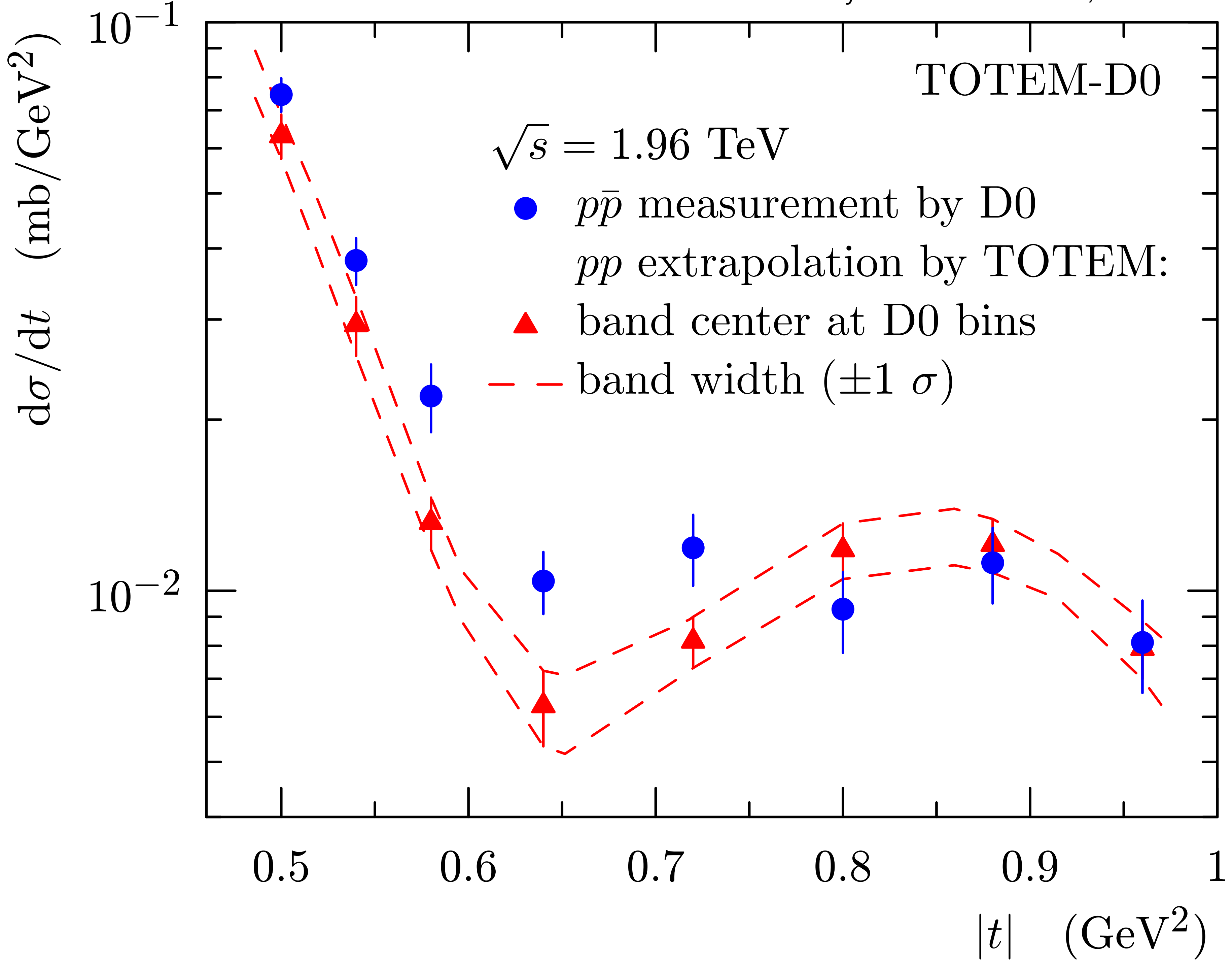
- The total cross section at $\sqrt{s}$=13 TeV exceeds **100 mbarn**
- Hadrons „like“ to interact via the strong interaction; the detailed mechanisms are not yet fully understood ab initio: what used to be Pomeron and Regge-trajectories are today explained as multi-gluon exchange.
- The rise of σ_{tot} has been a matter of considerable debate

Total Cross Section and
Observation of the exchange of a colorless C-odd gluonic compound

„Odderon-Discovery“



Phys. Rev. Lett. 127, 062003

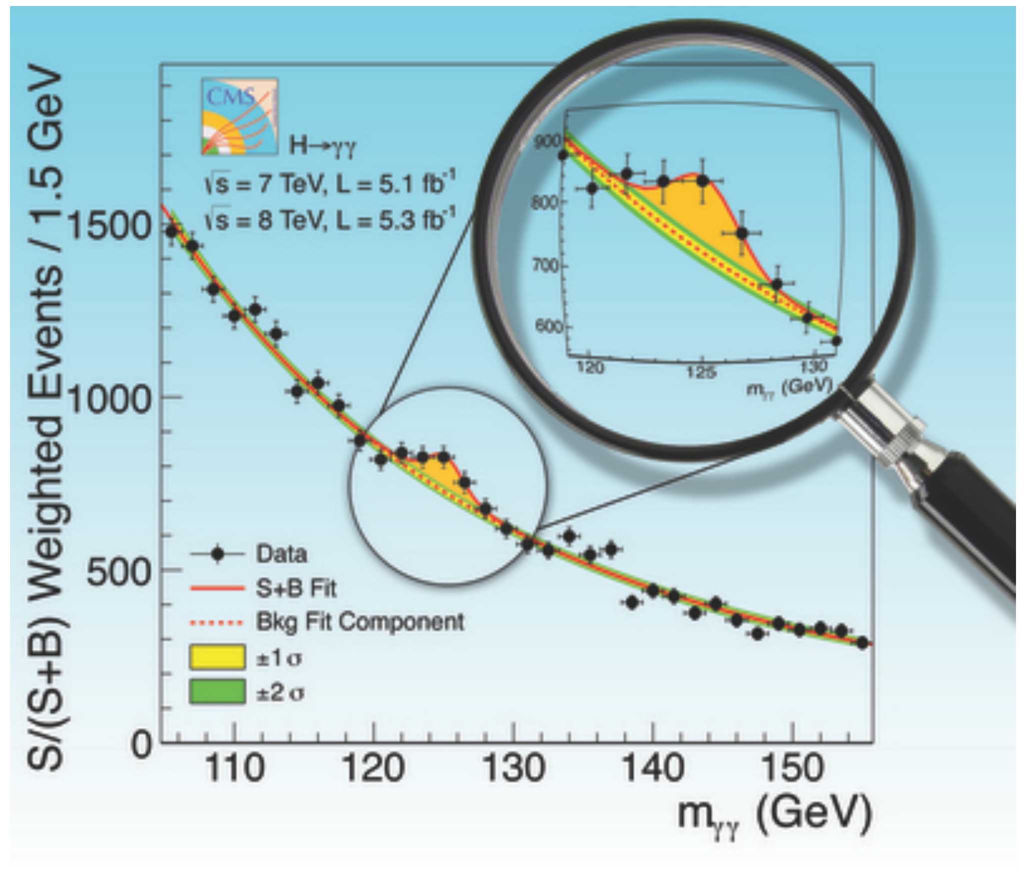


Comparison of the pp and $p\bar{p}$ cross sections extrapolated to $\sqrt{s} = 1.96$ TeV

Physics expectations for the LHC at the start and now

- Explore the electroweak scale to discover new physics
  - SUSY ?
  - Provide an explanation for Dark Matter
- Discover the Higgs particle
  - ***done***
  - much more fertile ground than expected

?

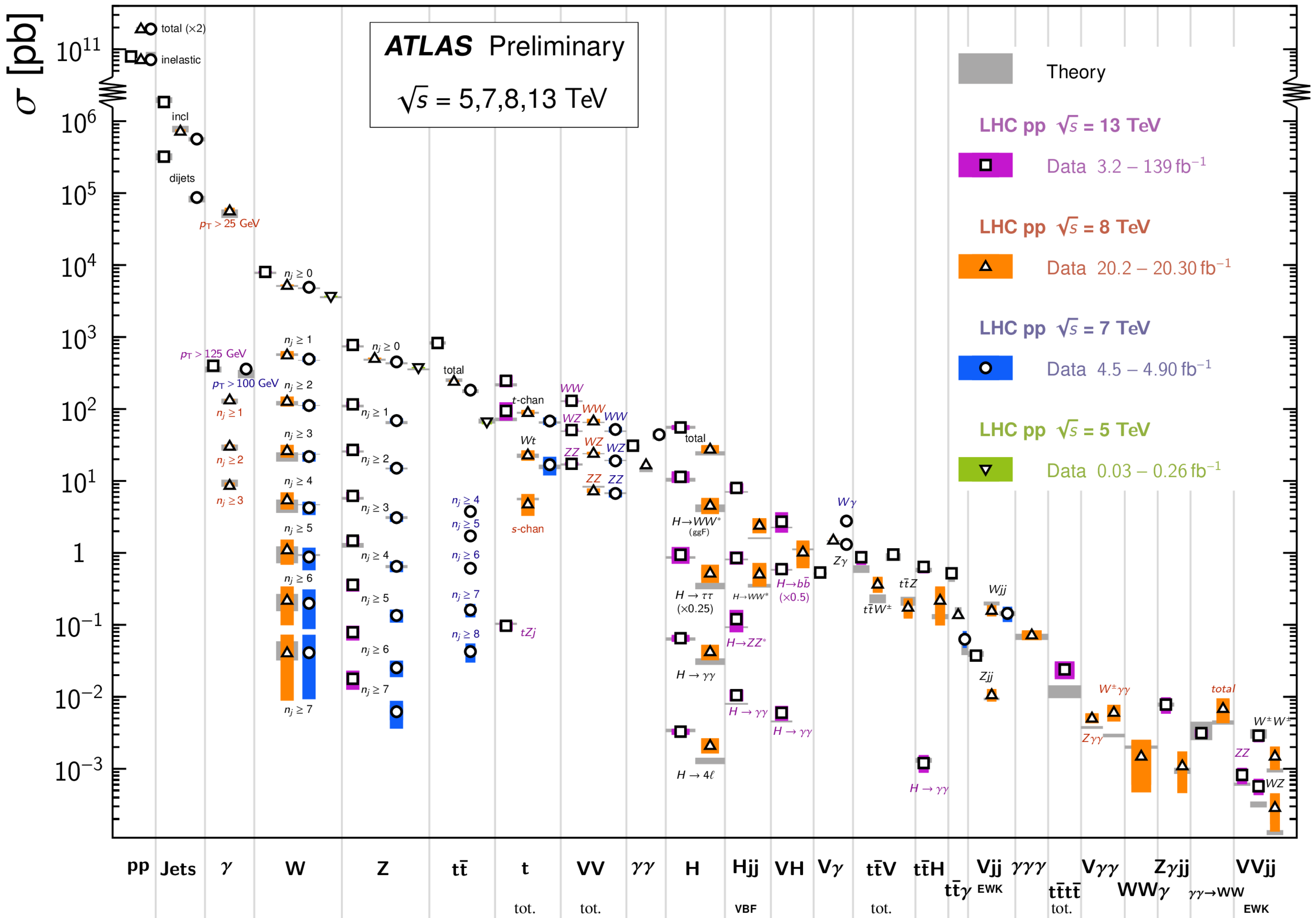


The advantage and dilemma of the LHC (from a 2021 perspective)

- pp-collisions offer tremendous interaction rates; protons can be accelerated to high energies
  - We have learnt from Run 1 and 2 that New Physics is not strongly coupled to quarks and gluons in the energy regime we can explore up to a few TeV
  - Hence we have to resort to electroweak processes to search for New Physics or allow for very weakly interacting particles in strong interactions.
    - the strong interaction is largely a background
    - LHC will serve predominantly as a factory of weakly interacting particles – very much like an e^+e^-- or $\mu^+\mu^-$-collider

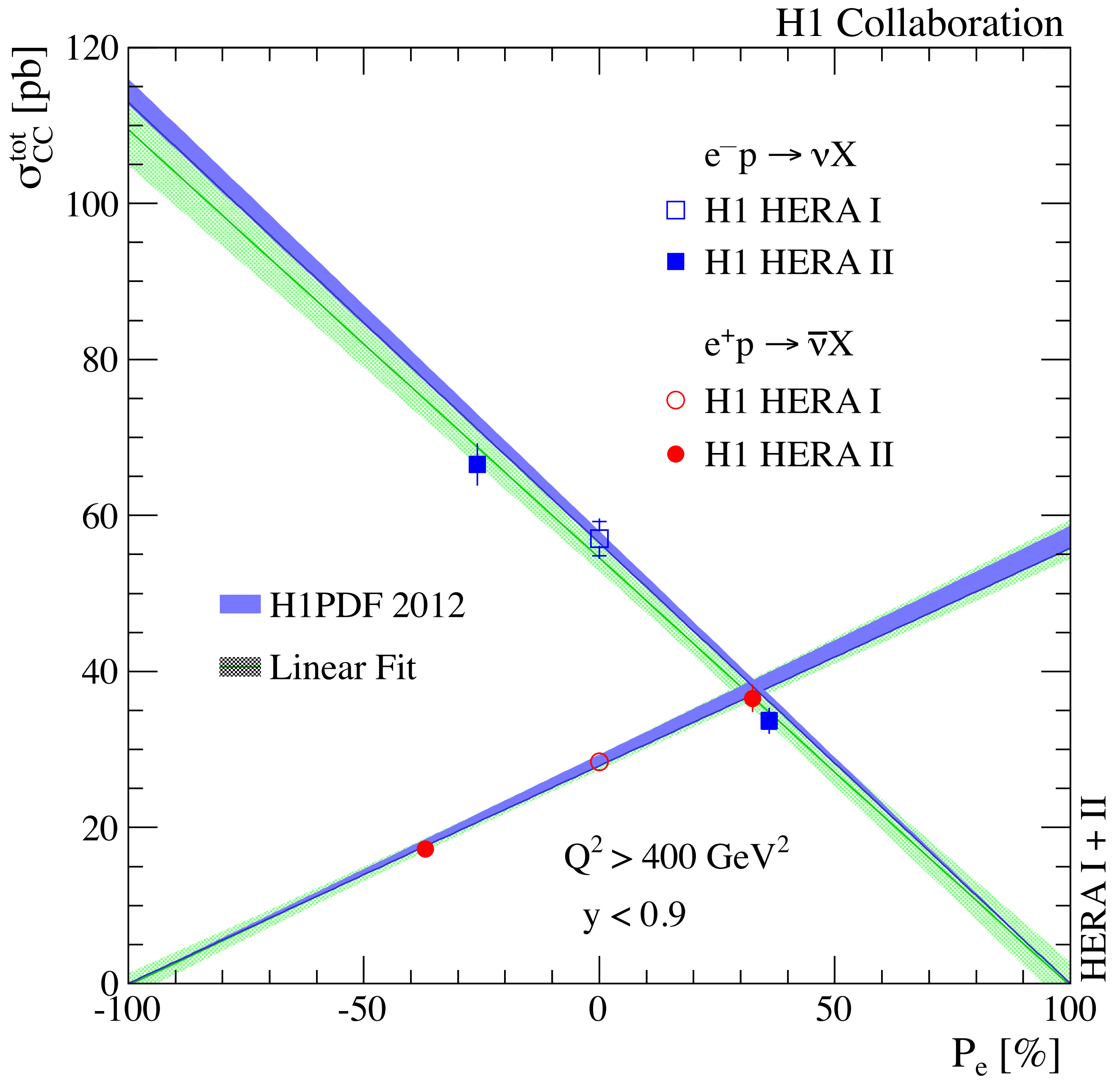
Standard Model Production Cross Section Measurements

Status: March 2021



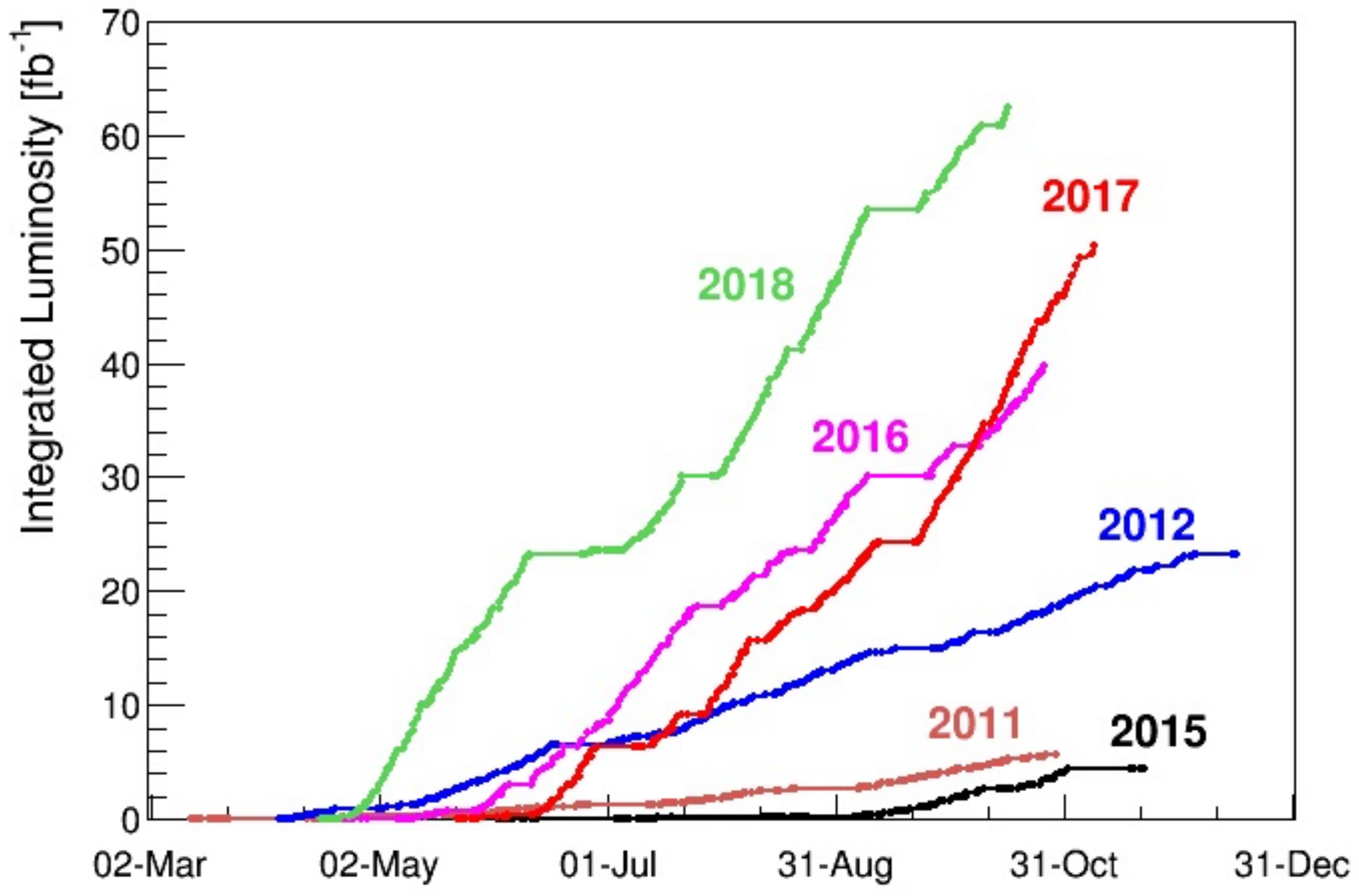
Luminosities

- Effective cross sections range from ~nb to ~fb and smaller
- Searches thus require the highest sustainable luminosities at the LHC and the experiments to deal with the huge backgrounds
- Protons are „burnt off“ in less interesting collisions
- It is not possible to prevent interactions in a way that was possible e.g. with polarised electron beams at HERA.



Luminosities

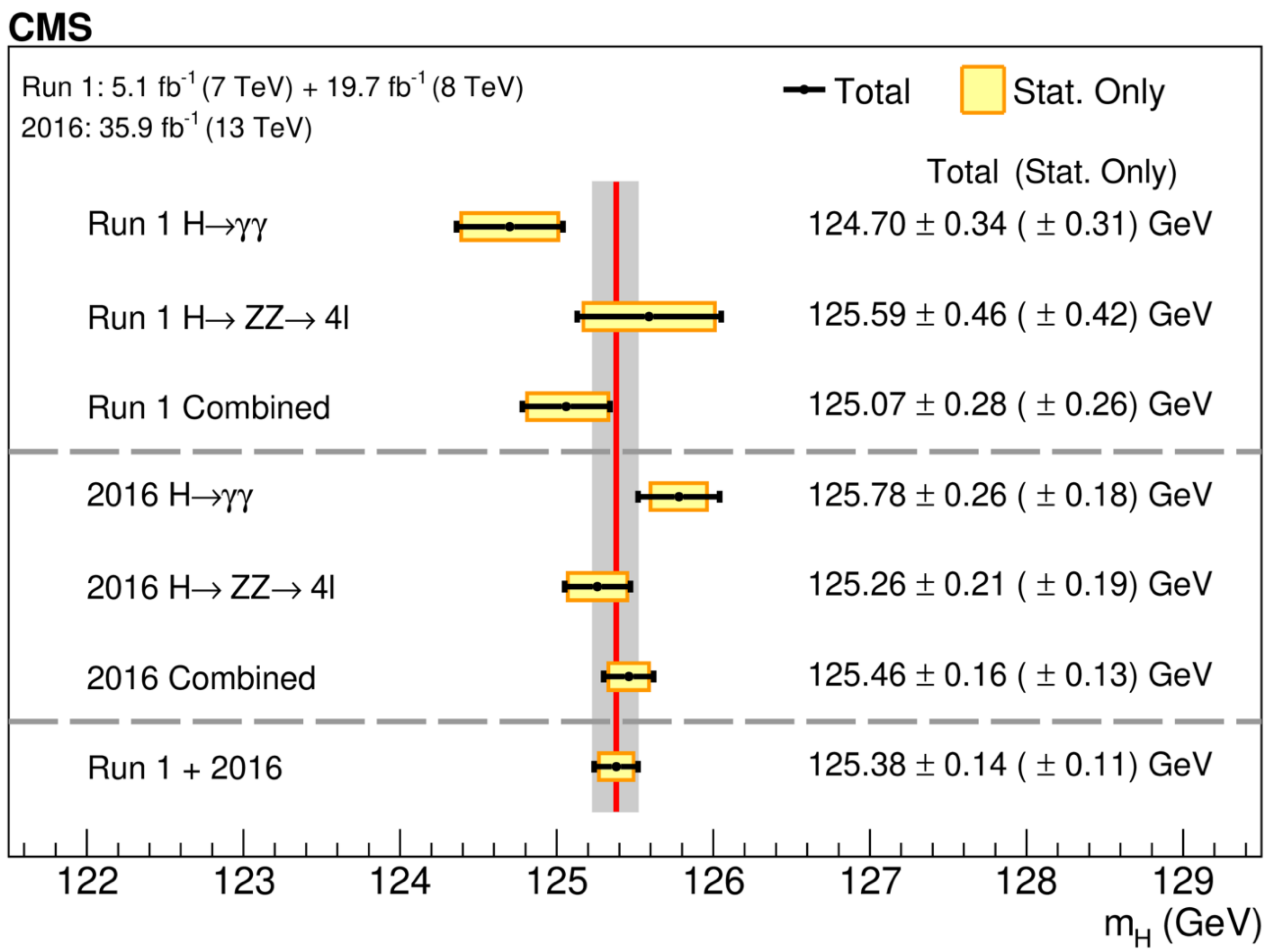
- Effective cross sections range from ~nb to ~fb and smaller
- Searches thus require the highest sustainable luminosities at the LHC and the experiments to deal with the huge backgrounds
- The rates of "interesting events" are dominated by the smallest cross section. The current sensitivity is at the level of ~fb.
- HL-LHC will attain 3-4 ab^{-1} at ≥13.6 TeV; a factor ~20 of what is available today

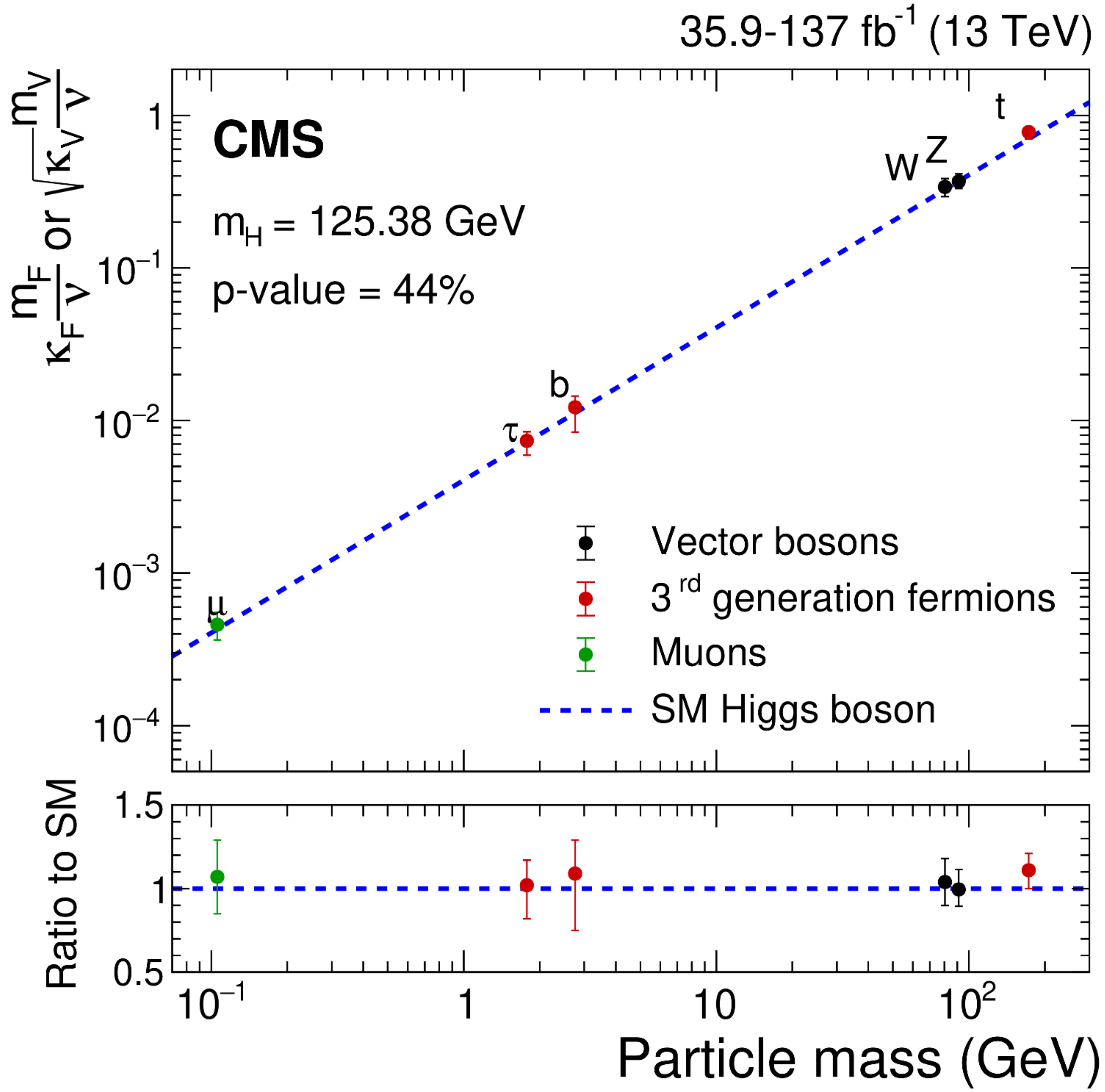


LHC past and present and HL-LHC Plan

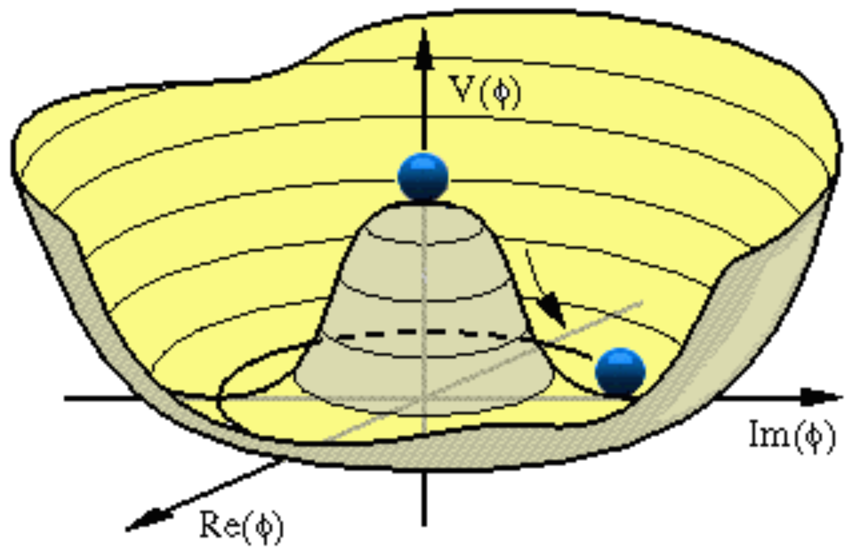
Selected physics results

Higgs Particle – the only fundamental scalar in the SM

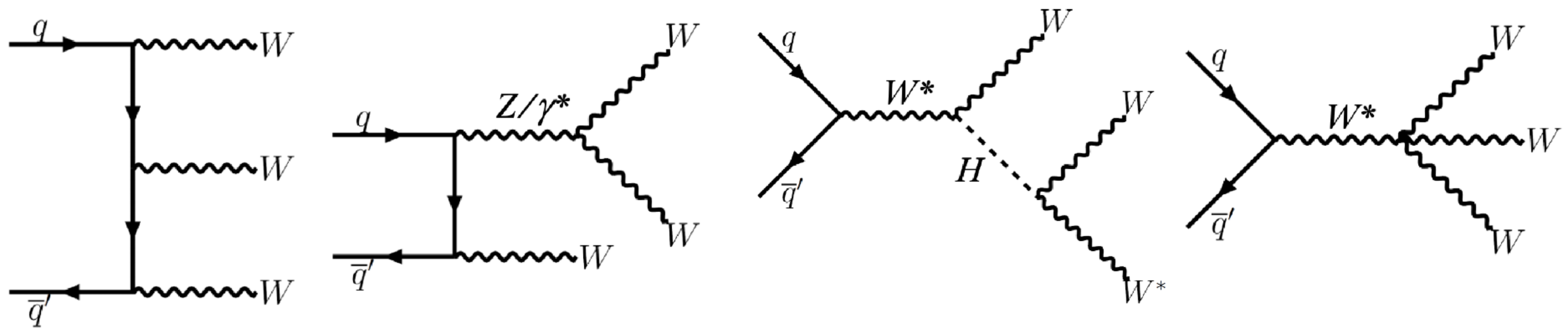




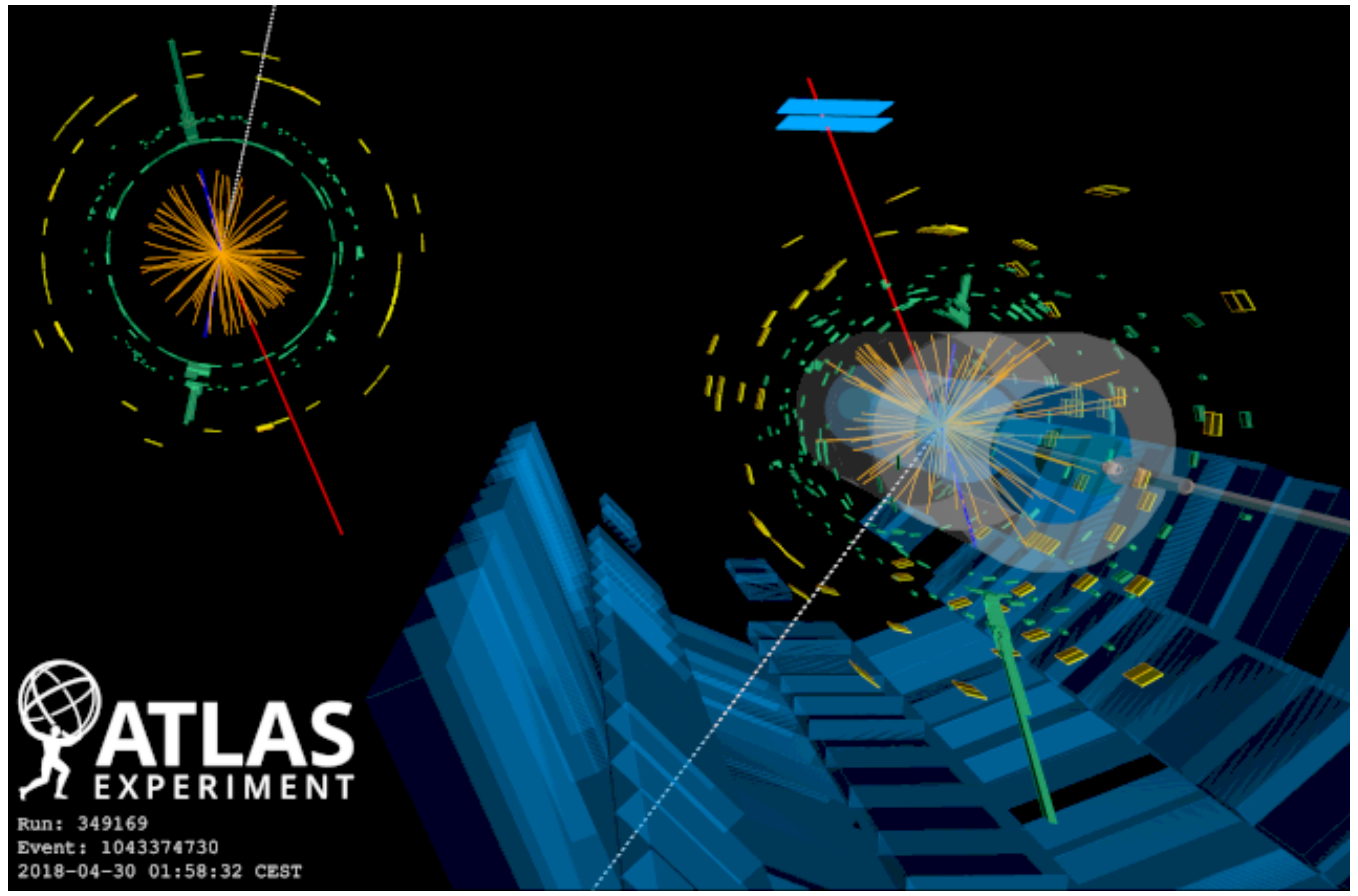
Need to examine Higgs potential



Production of WWW – announced at EPS 2021



a purely electroweak process



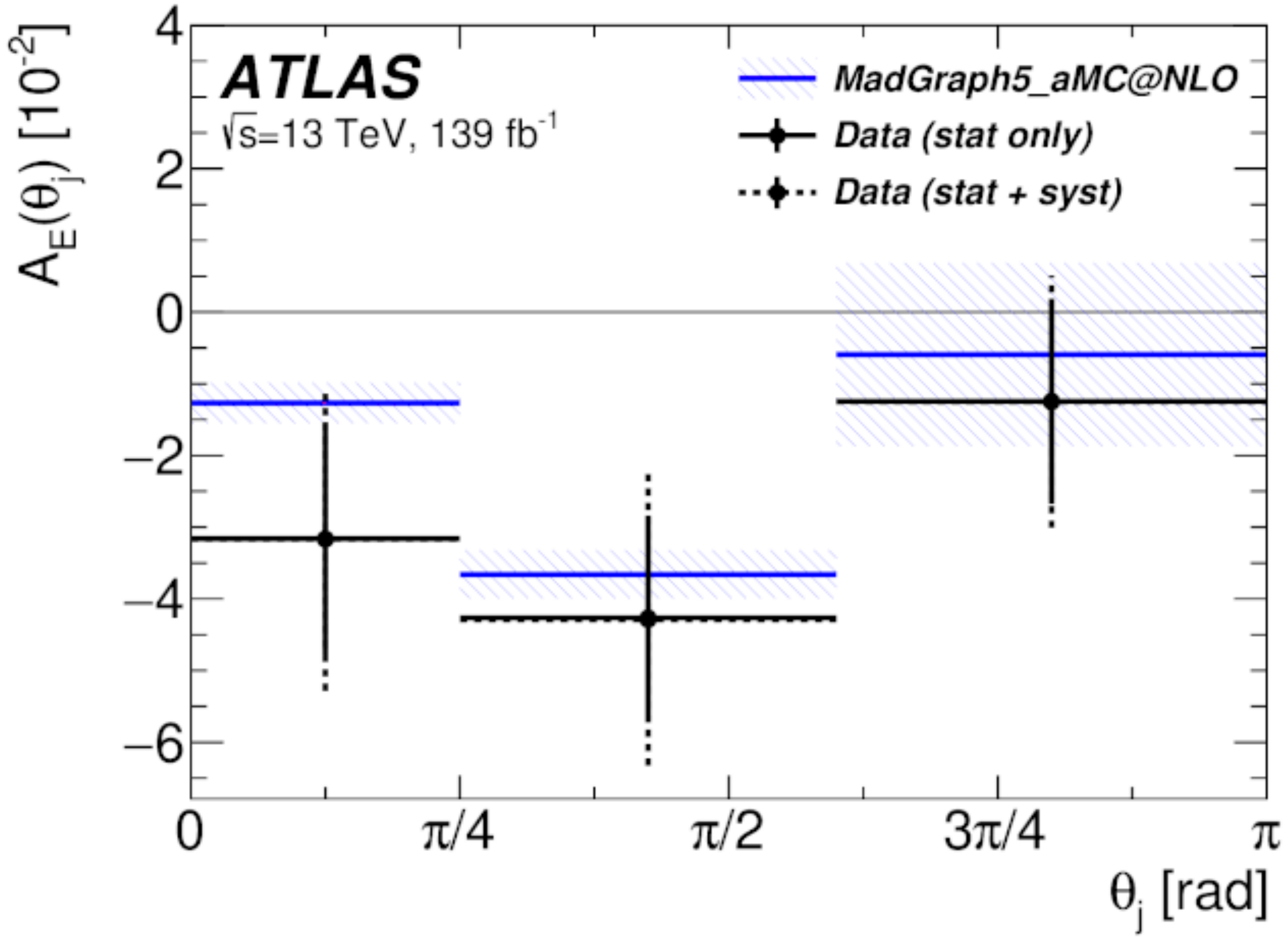
WWW-production has also been observed in the CMS experiment

Top Pair Production in association with a jet

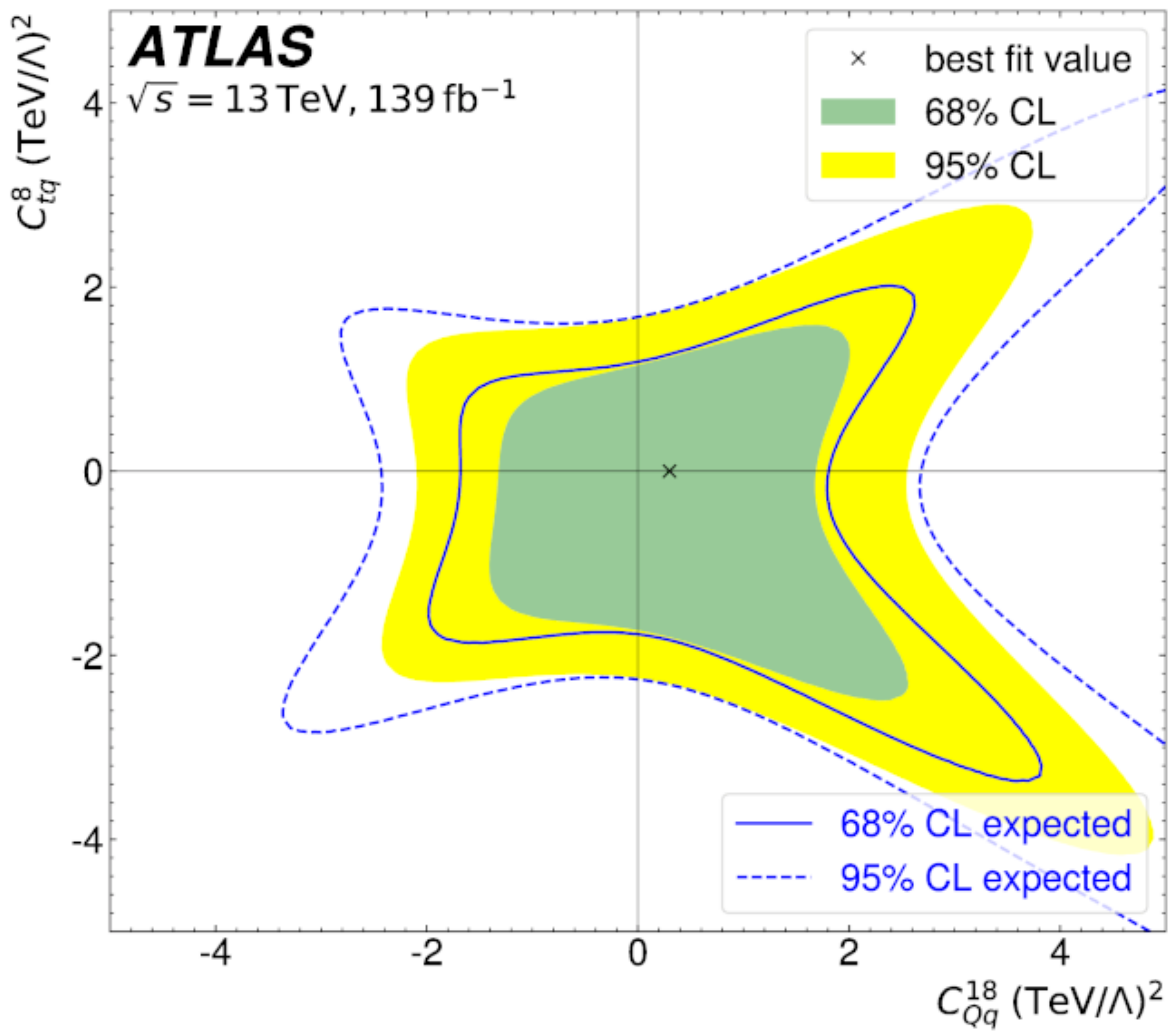
- Define an energy asymmetry

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$

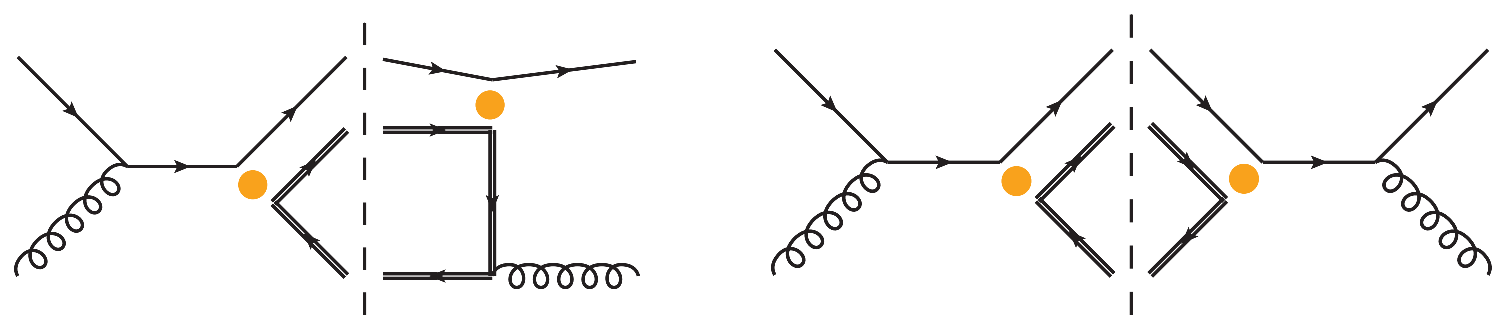
- and measure



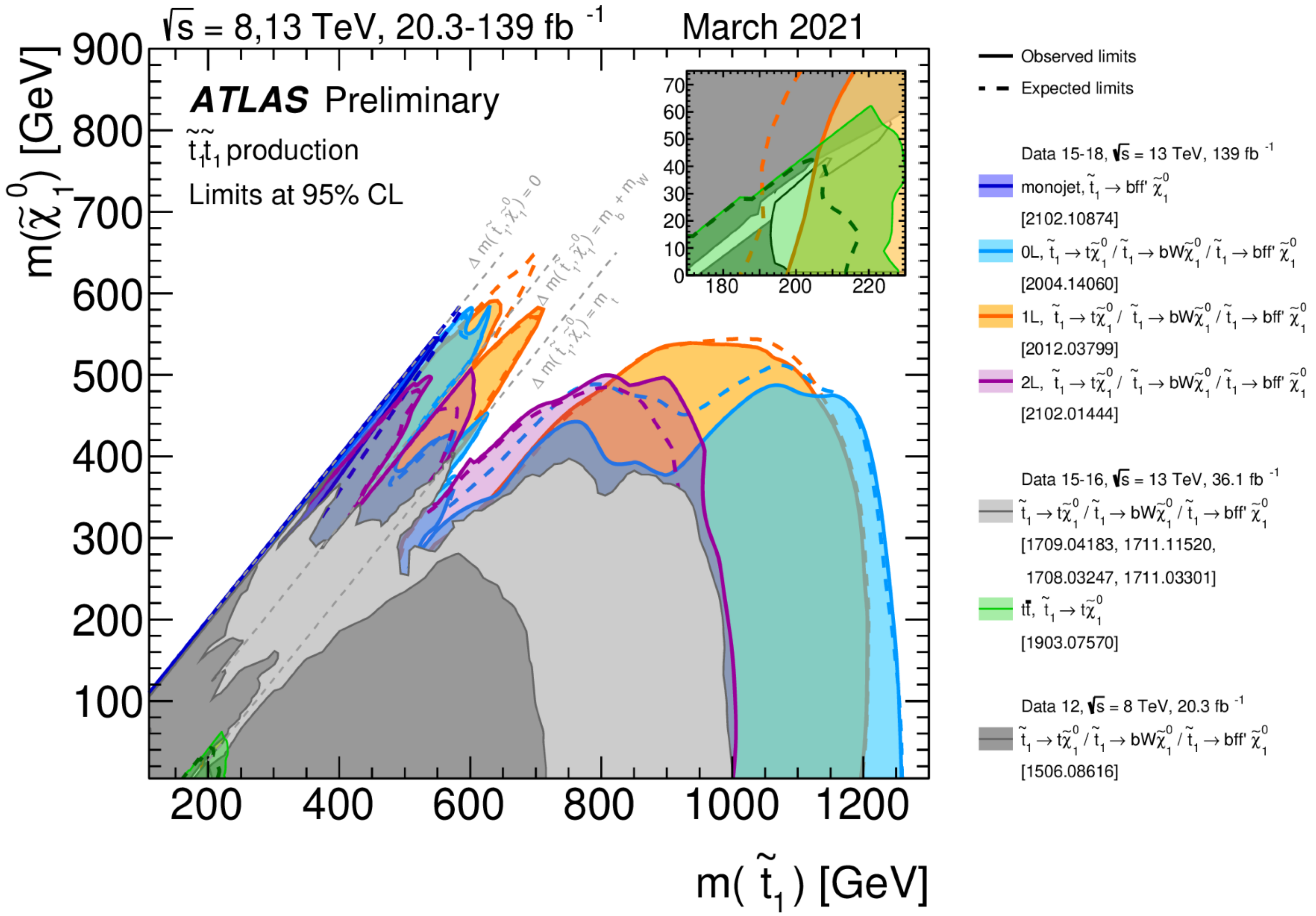
Interpret in terms of effective field theories SMEFT

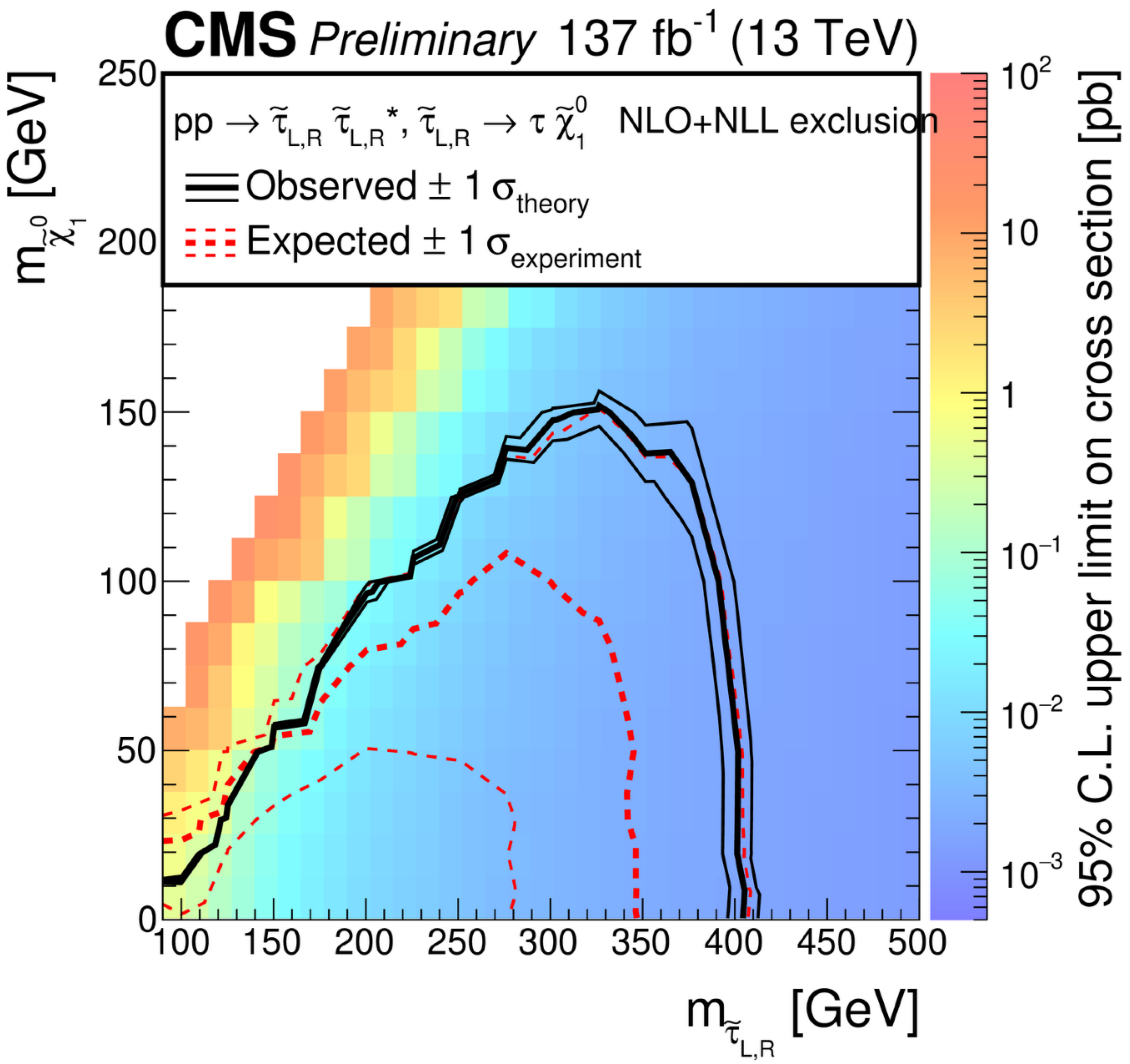


Example contributions to asymmetry

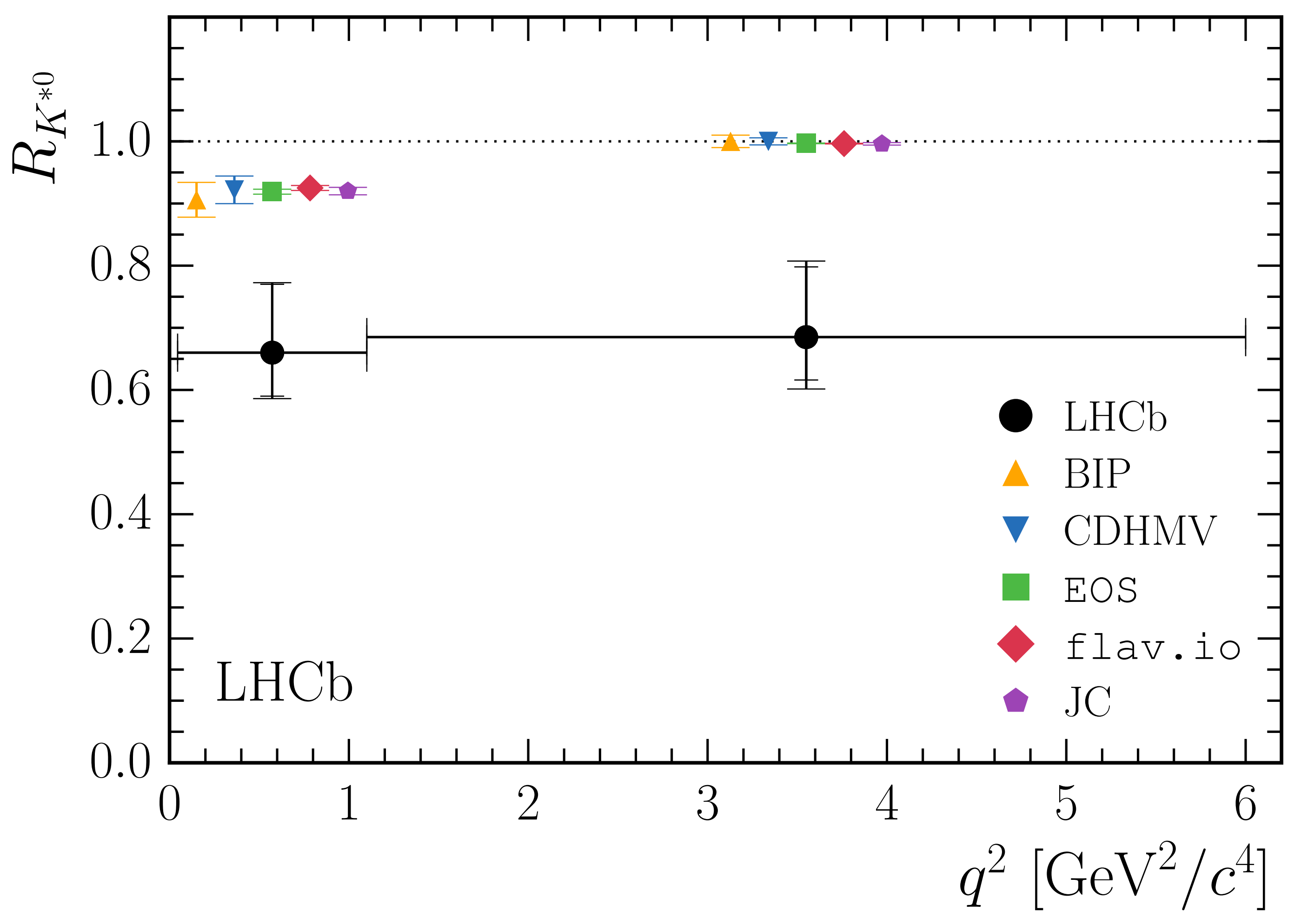


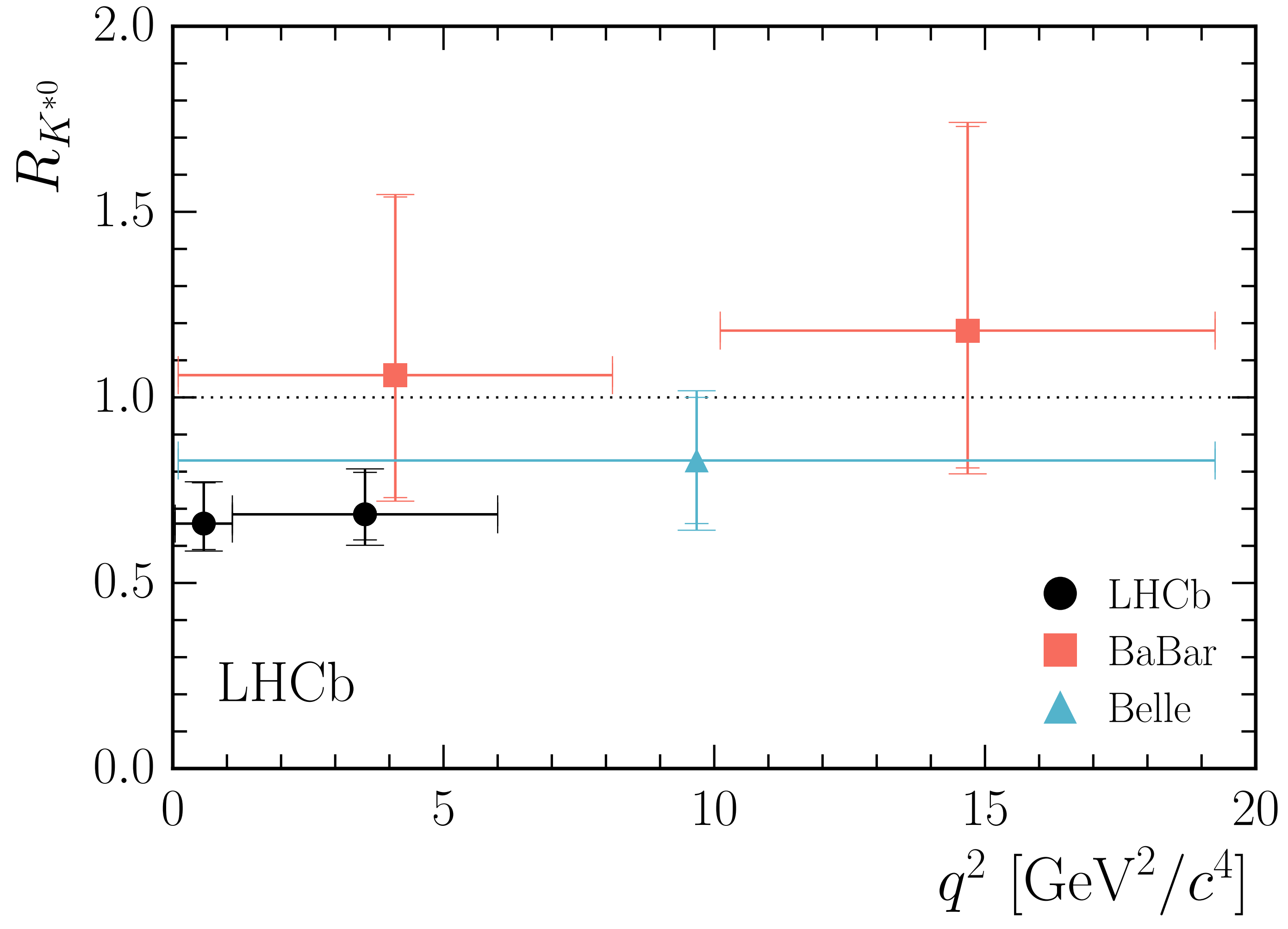
Limits on SUSY quark and lepton production

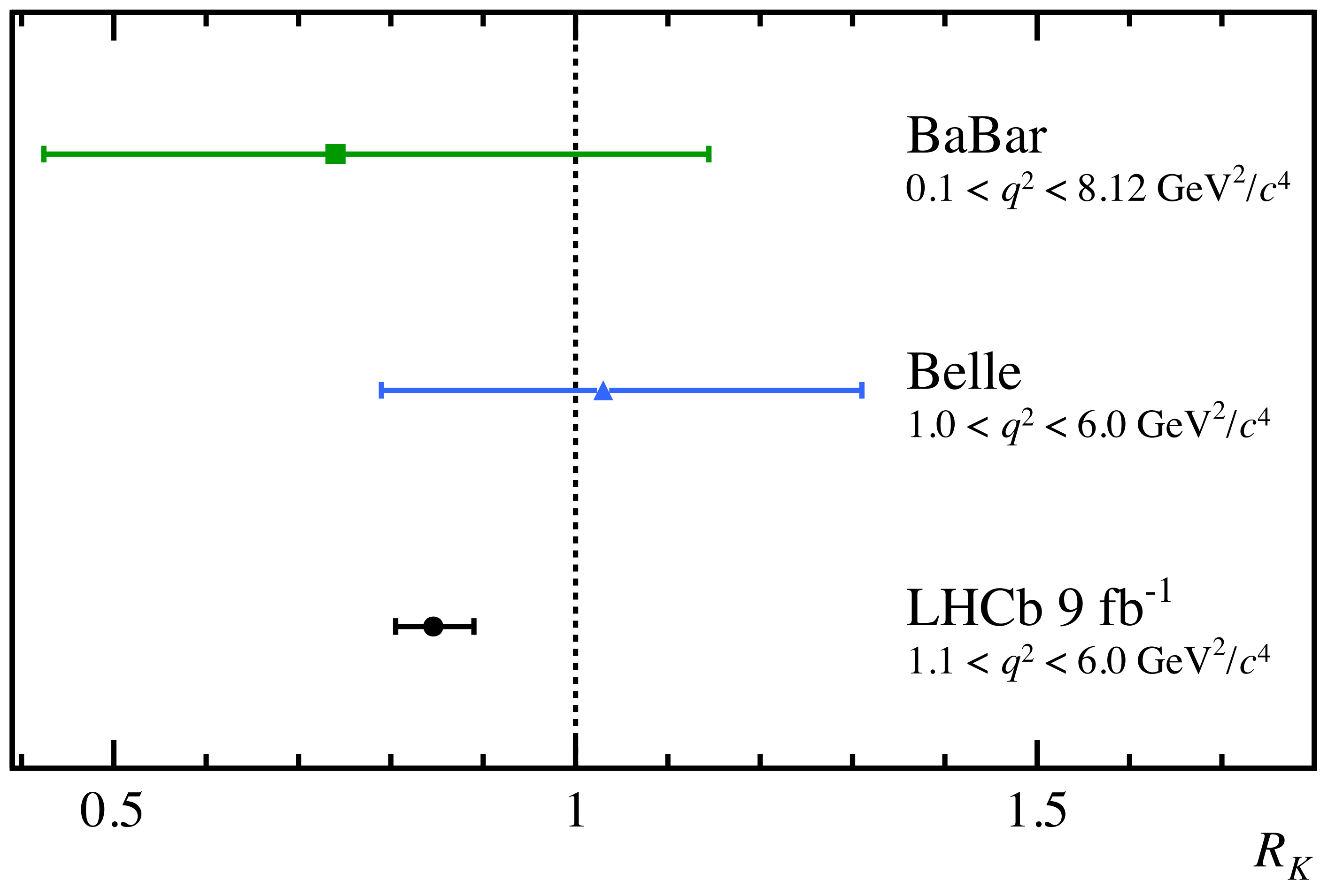




Test of Lepton Universality







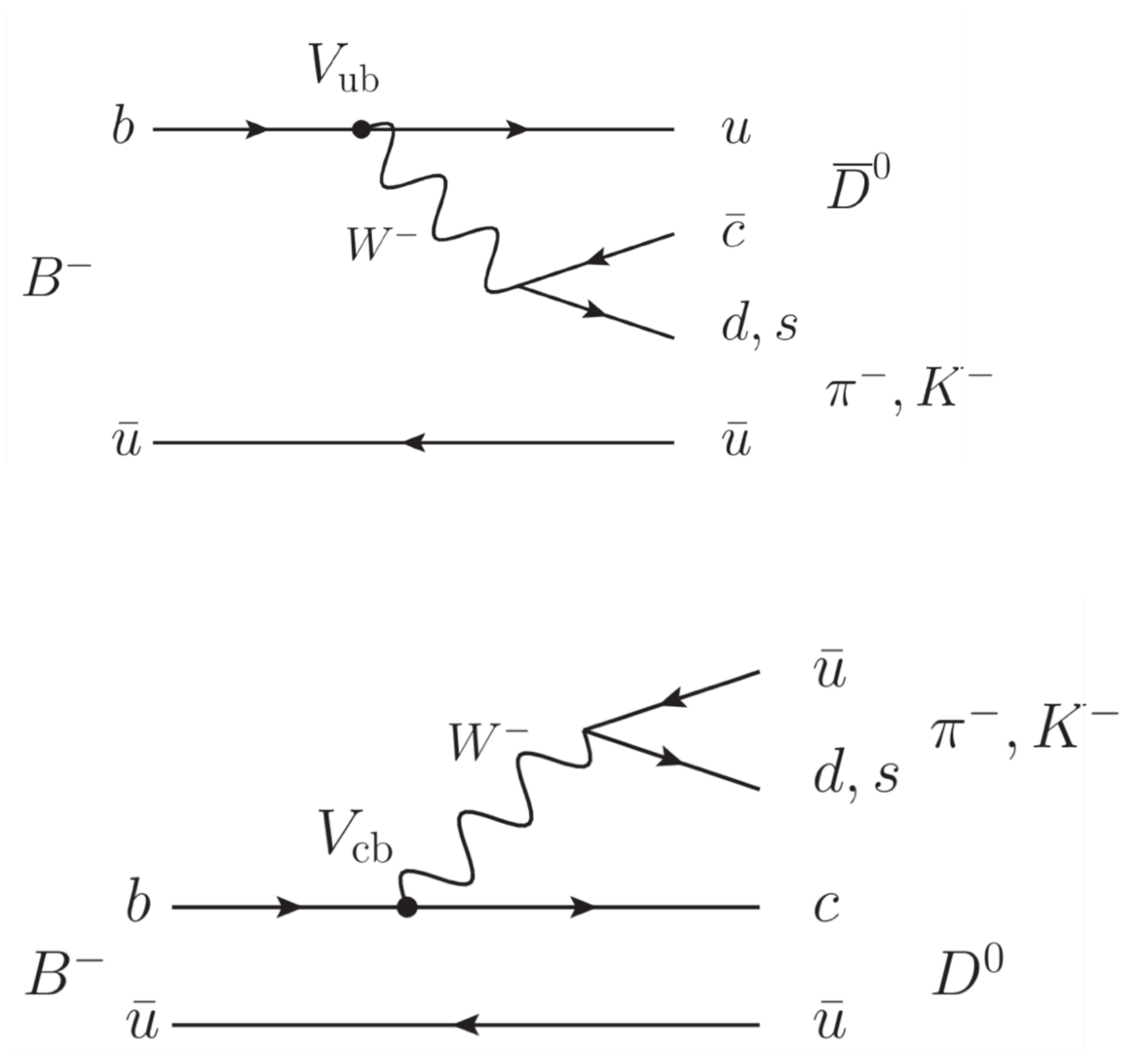
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

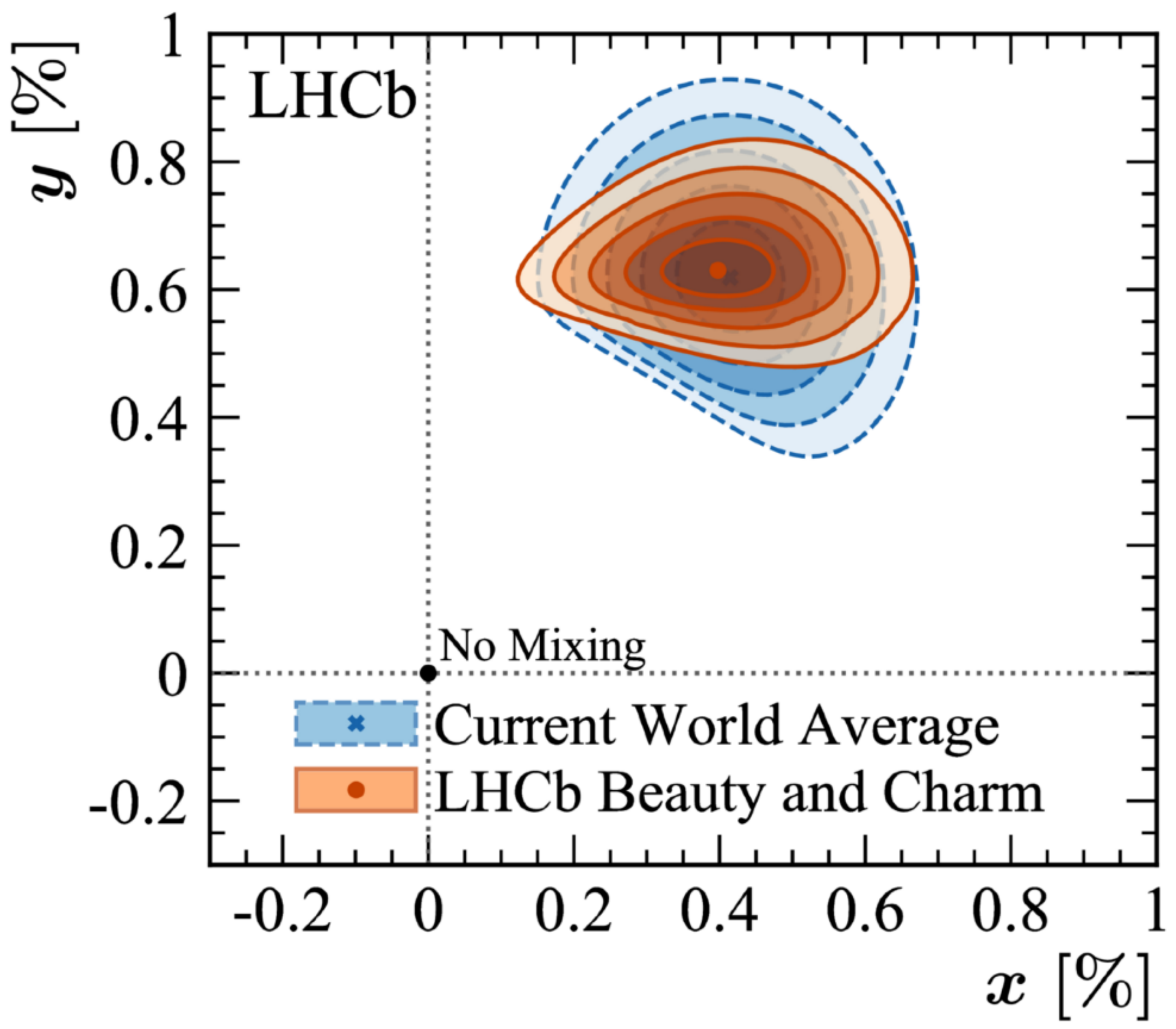
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

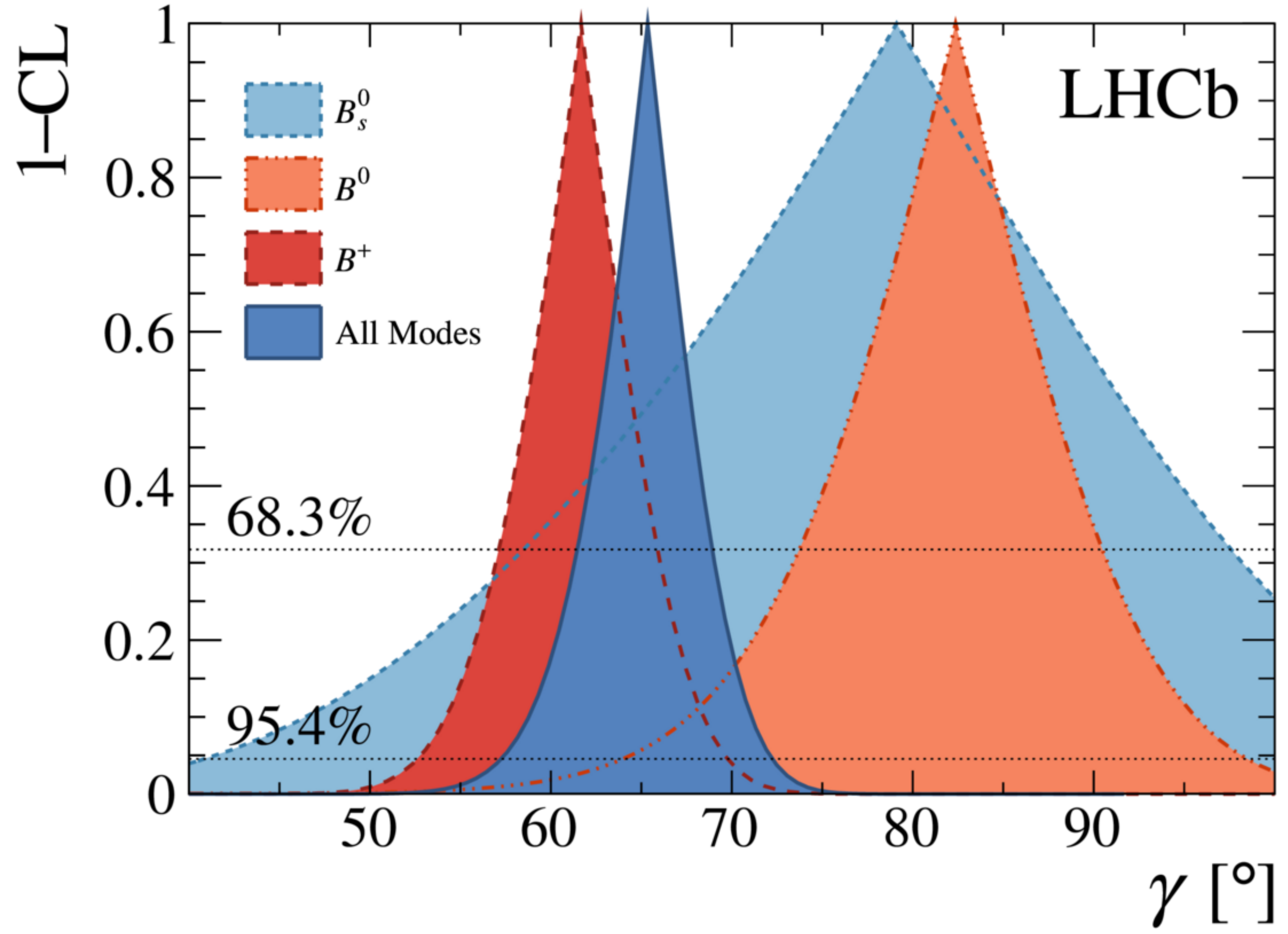
Other channels have also been measured.
More statistics needed.

→ talk of Emi Kou

Simultaneous fit of CKM angle γ and charm mixing parameters





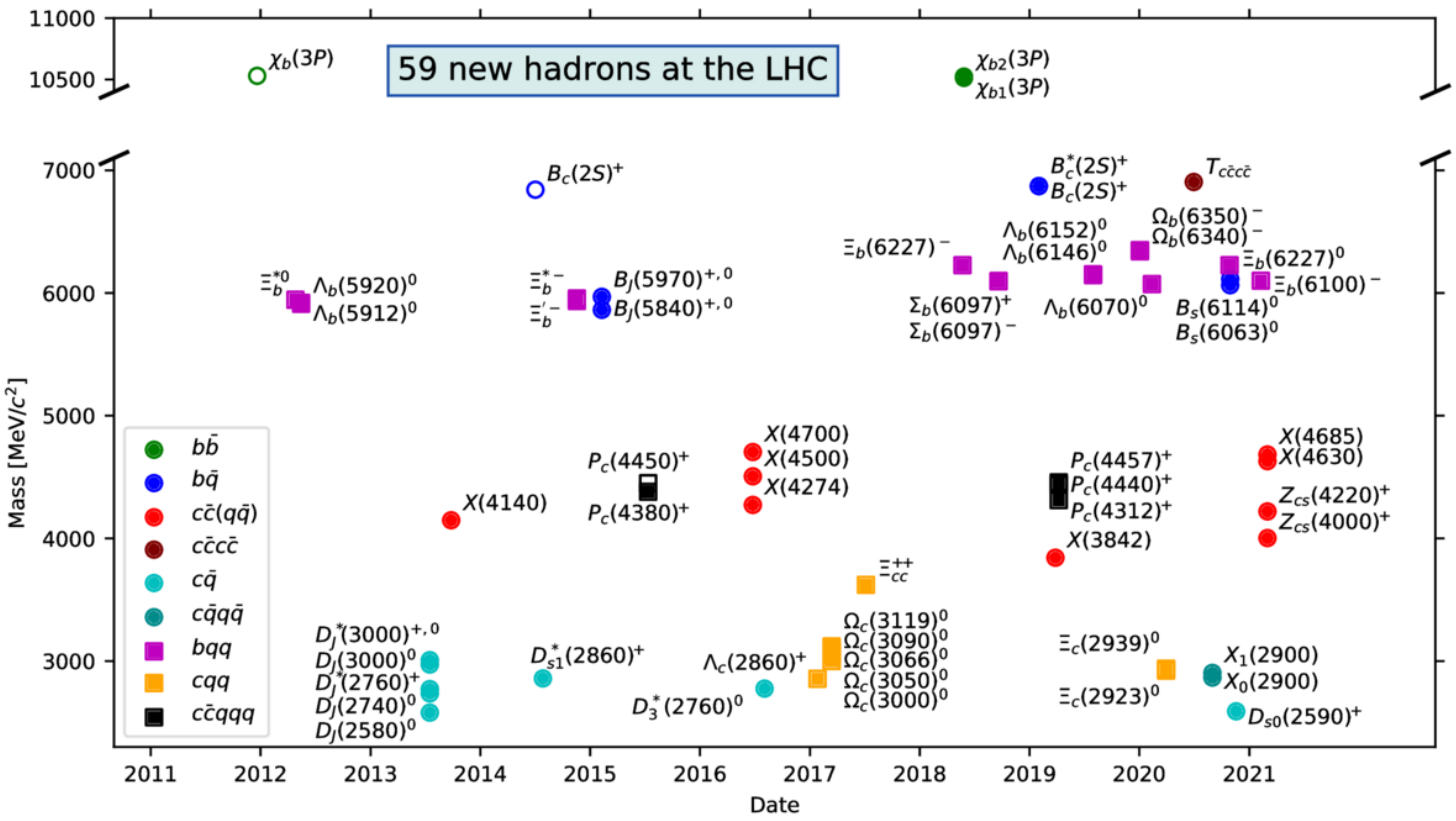


with $x \equiv (m_1 - m_2)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/\Gamma$ the mixing parameters of the charm mass eigenstates

$$\gamma = 65.4^\circ {}^{+3.8^\circ}_{-2.7^\circ}$$

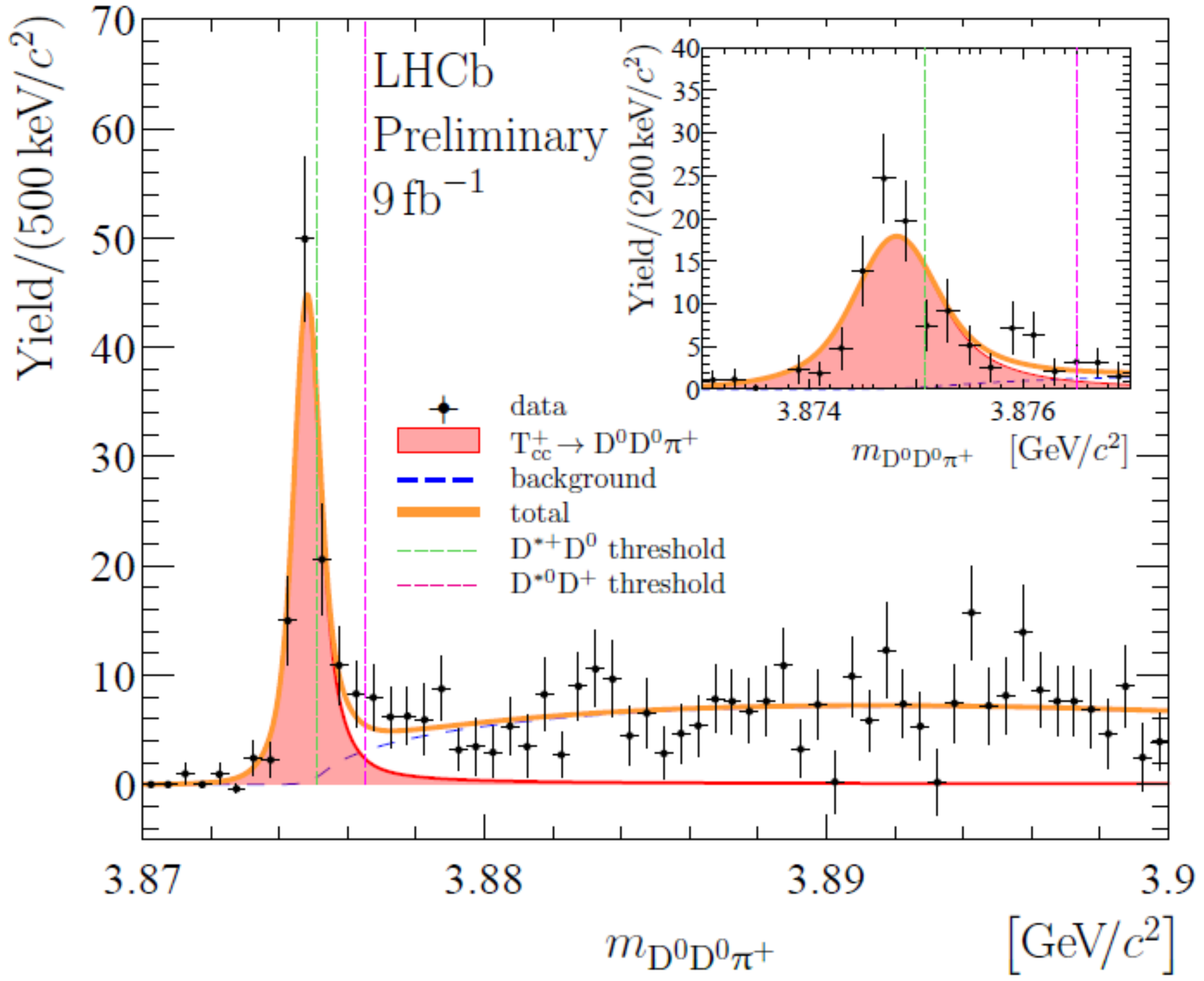
LHCb

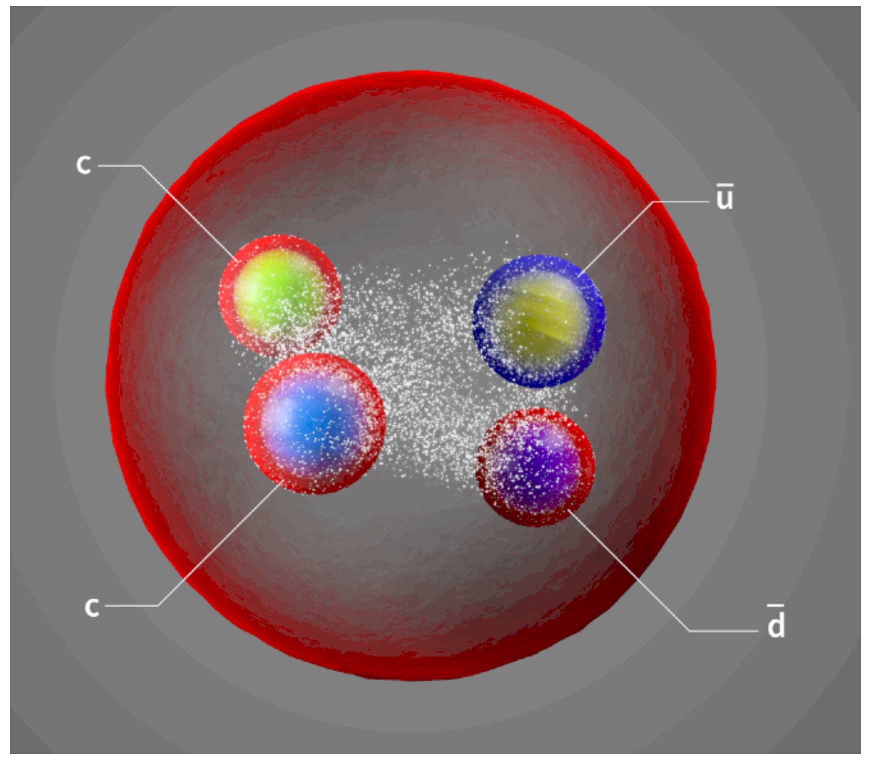
LHC produces (new) hadrons



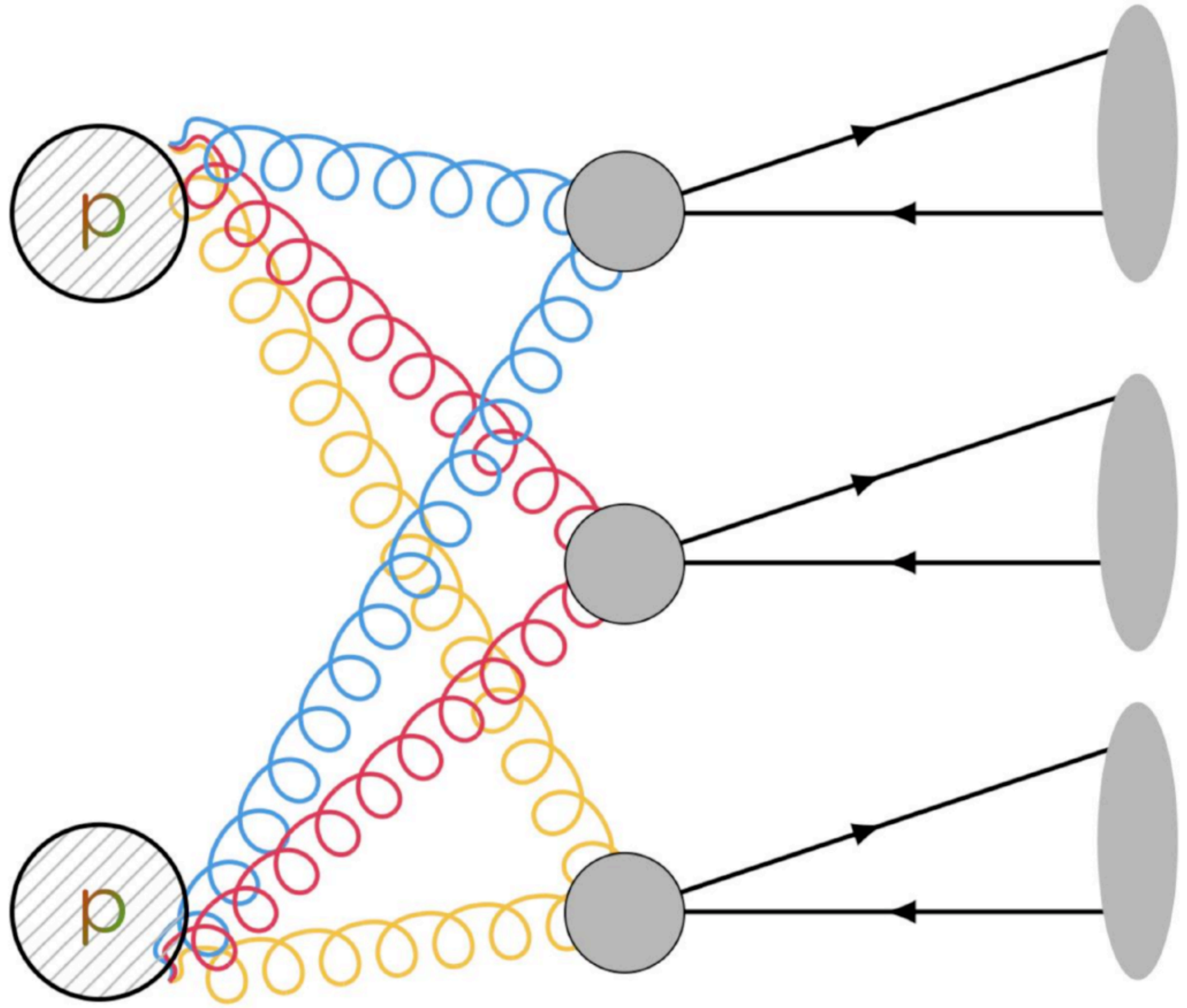
Observation of a charmed Tetra-quark – announced at EPS 2021

- Ordinary matter is colourless
  - baryons, containing 3 constituent quarks
  - Mesons contain a quark-antiquark system
- LHCb observes a Tetra-quark state T_{cc}^{+} containing $cc\bar{u}\bar{d}$, i.e. an open charm system.





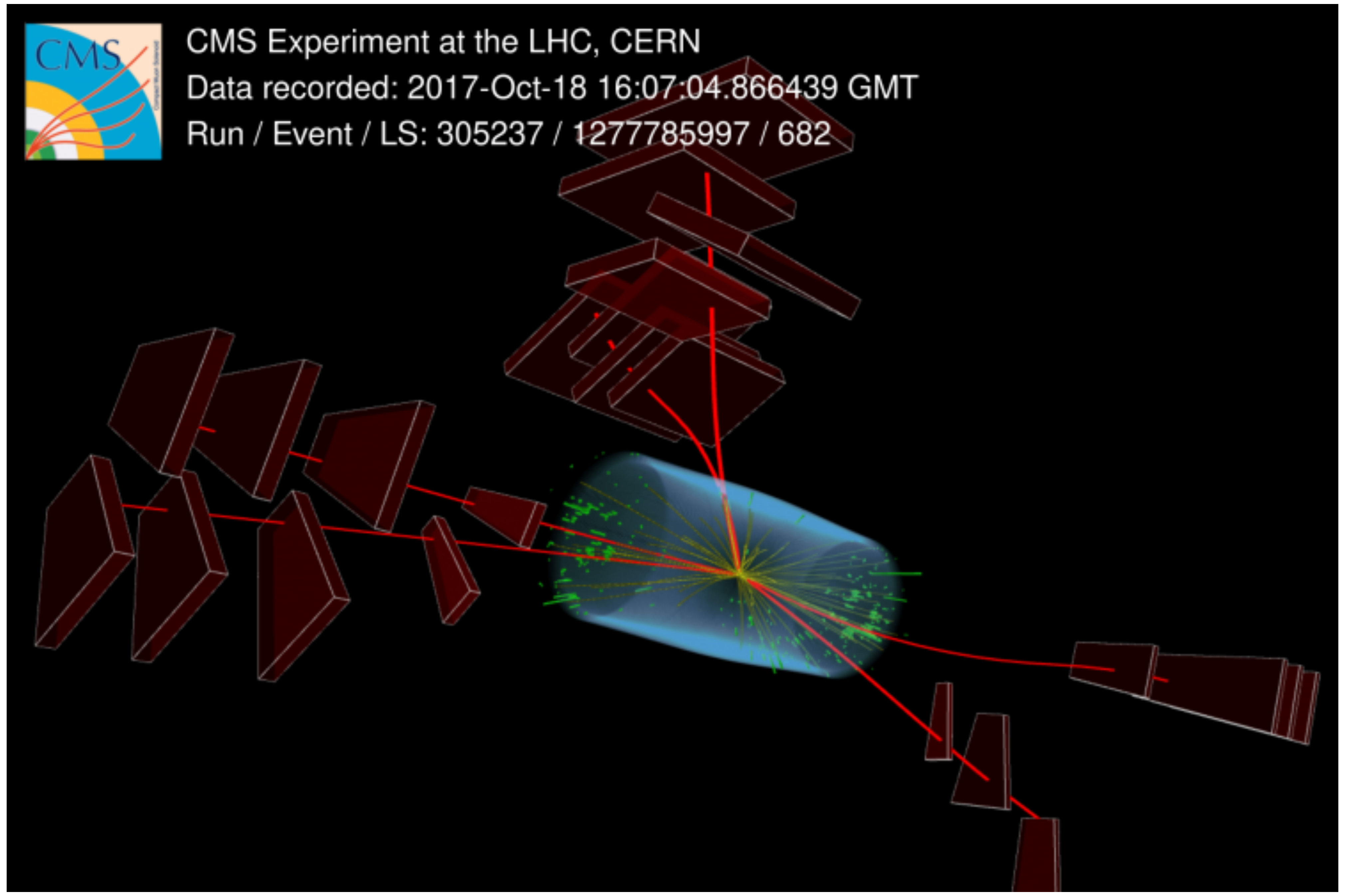
Triple J/Ψ-Production observed in CMS



J/Ψ

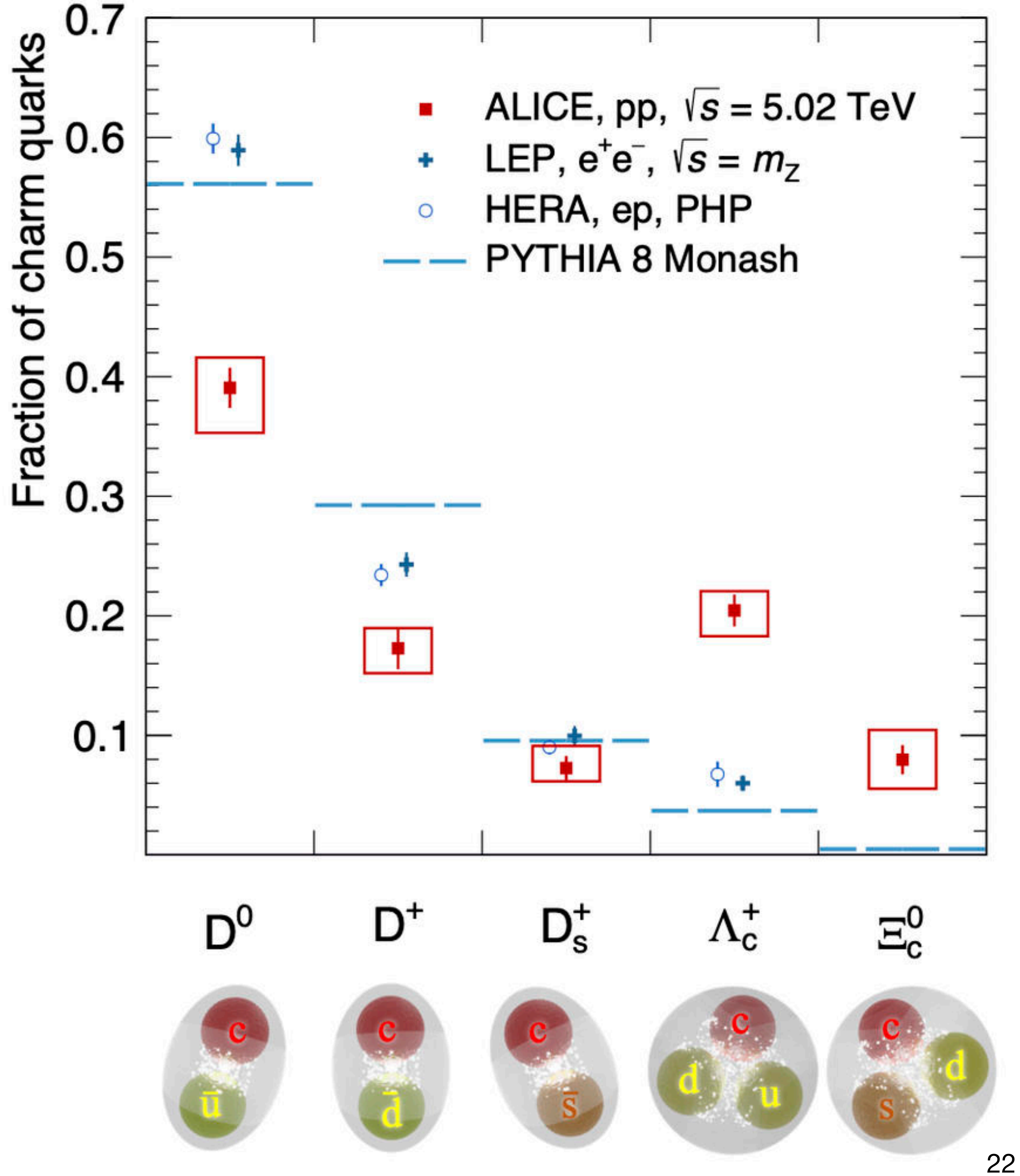
J/Ψ

J/Ψ



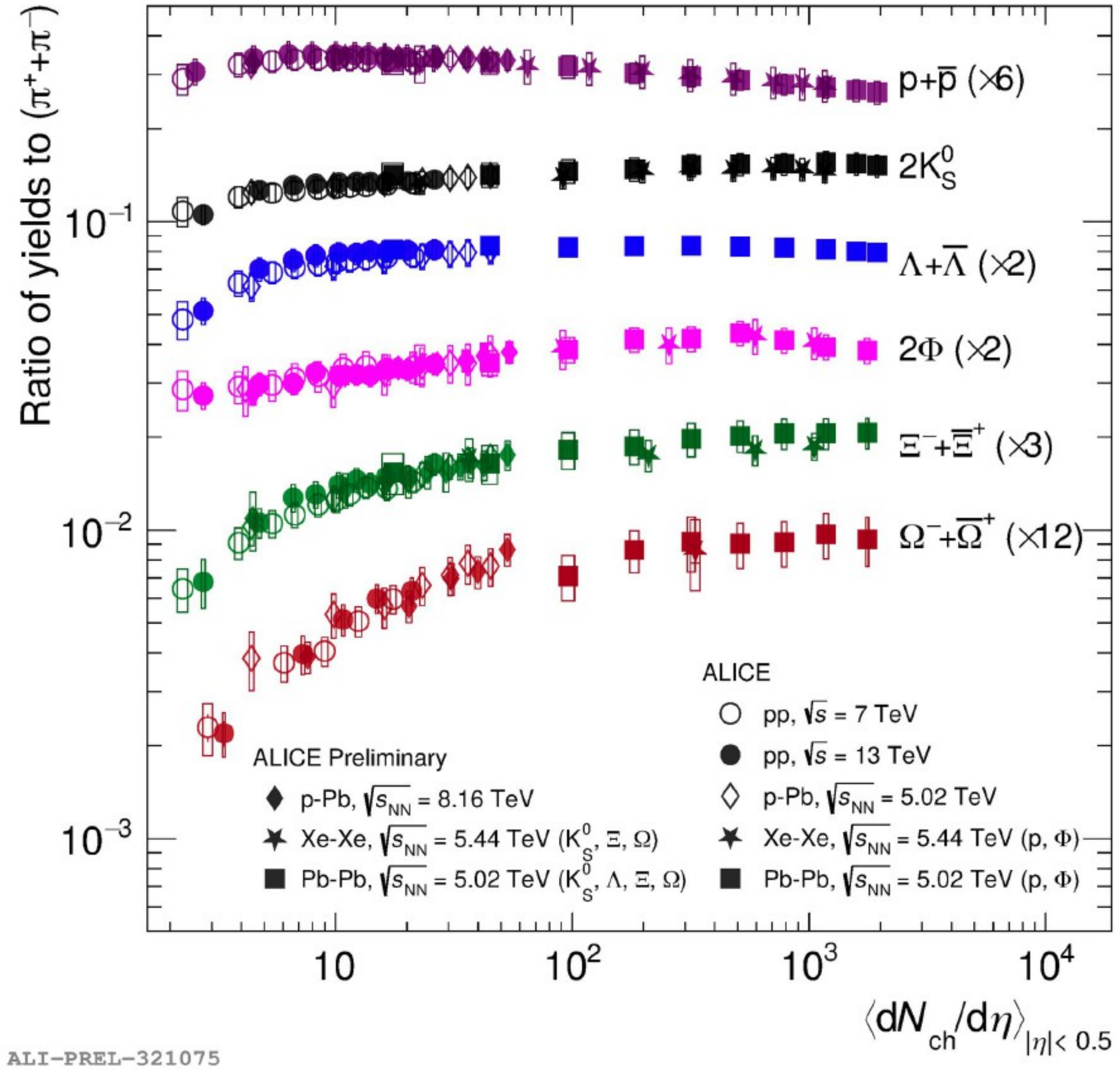
Charm production in pp-collisions

- Production of charm-quarks has been measured by the ALICE experiment
  - Λ_c^+ are much more copiously produced than in e^+e^- or in ep-collisions



Strangeness production - to explore QGP

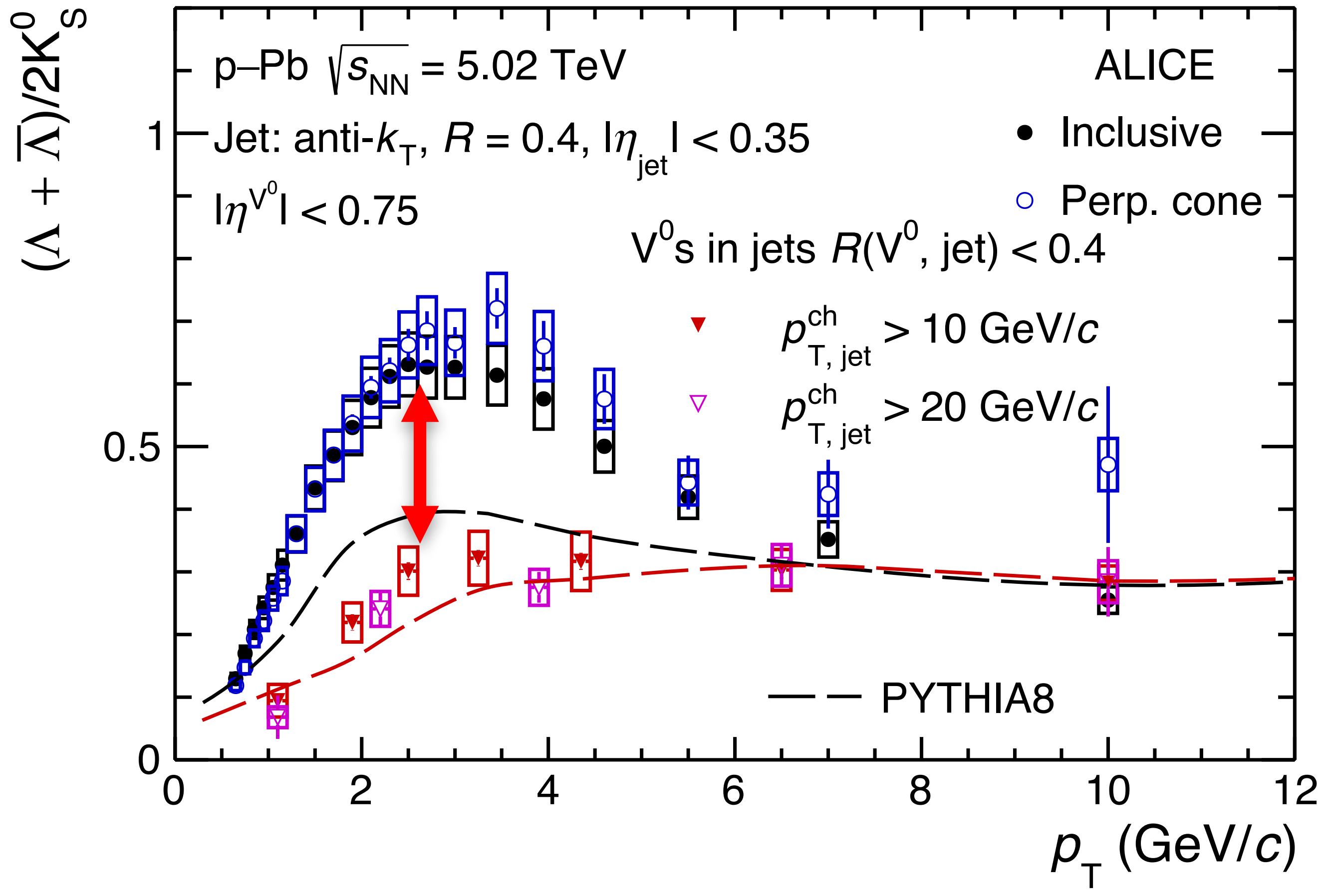
ALICE Collaboration, Nature Phys 13, 535–539 (2017)
ALICE Collaboration, Eur. Phys. J. C80, 167 (2020)



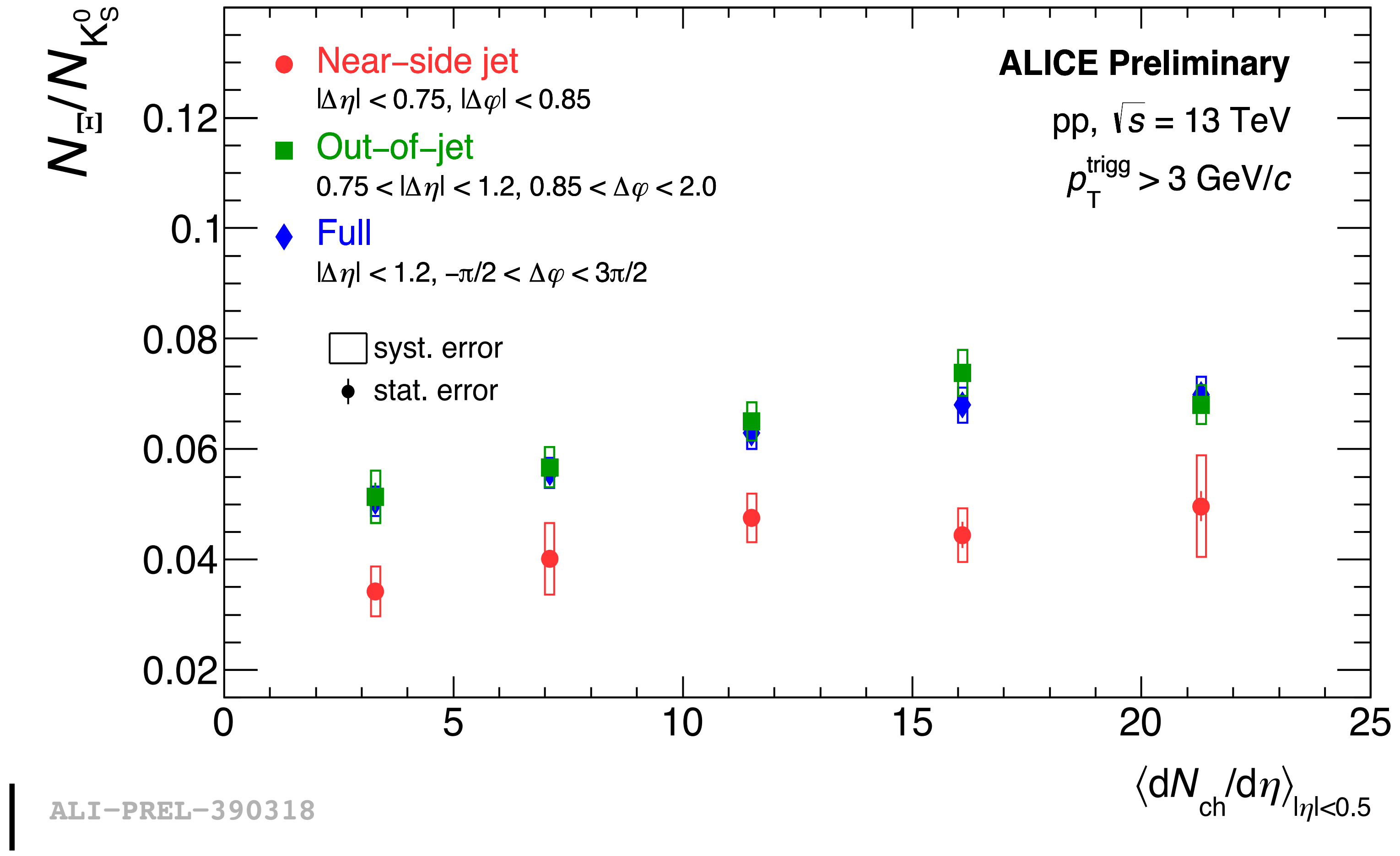
ALI-PREL-321075

p–Pb

arXiv:2105.04890



pp



ALI-PREL-390318

- Larger enhancement for strange baryons
- Enhancement predominantly in perpendicular cone

Preparing for HL-LHC

Detector Resolution

- We have learnt from LEP and SLD, from BaBar and Belle/Belle II that full reconstruction of the complex final states is only possible with ultimate resolution
  - momentum and energy reconstruction
  - flavour tagging
  - particle identification

Experiments at the LHC / HL-LHC in perspective

- Experiments must - at least - provide the resolution of the best proposed detectors at e^+e^- factories and still reject the pile-up of other events
  - e.g. **Timing** has be added as an important tool to reject (slightly) out-of-time interactions (pile-up). This is a tremendous challenge and added complexity but a necessary tool to provide sensitivity to new physics.
    - ps-timing will also be key to make LHCb during Run 5 feasible

Flavour physics

- LHCb profits from the large cross section for b-quark production in pp-collisions but has to throttle the rate due to detector limitations (LHC is separating the beams laterally at the IP).
    - LHCb has published a wealth of results on b-physics and observed CP-violation in the charm system
    - For rare decays the detector rate capability needs to be improved; hence the LS2 upgrade, a rebuild of the detector, and plans for a further upgrade in LS4
    - so far the physics is limited by the performance (granularity) of the detector

Heavy Ion Physics

- The purpose of ALICE is primarily to study the strong interaction
  - comparison of PbPb to pp and pPb collisions and other ions
  - large cross sections and hence use only a small fraction of possible pp-luminosity
- Lessons, in particular from Run 1 and 2:
  - strangeness, charm and beauty production originate from different phases of the quark gluon plasma and hence prove particularly interesting
  - Need for higher rate capability

Lessons learnt have been cast into a new Strategy for Particle Physics

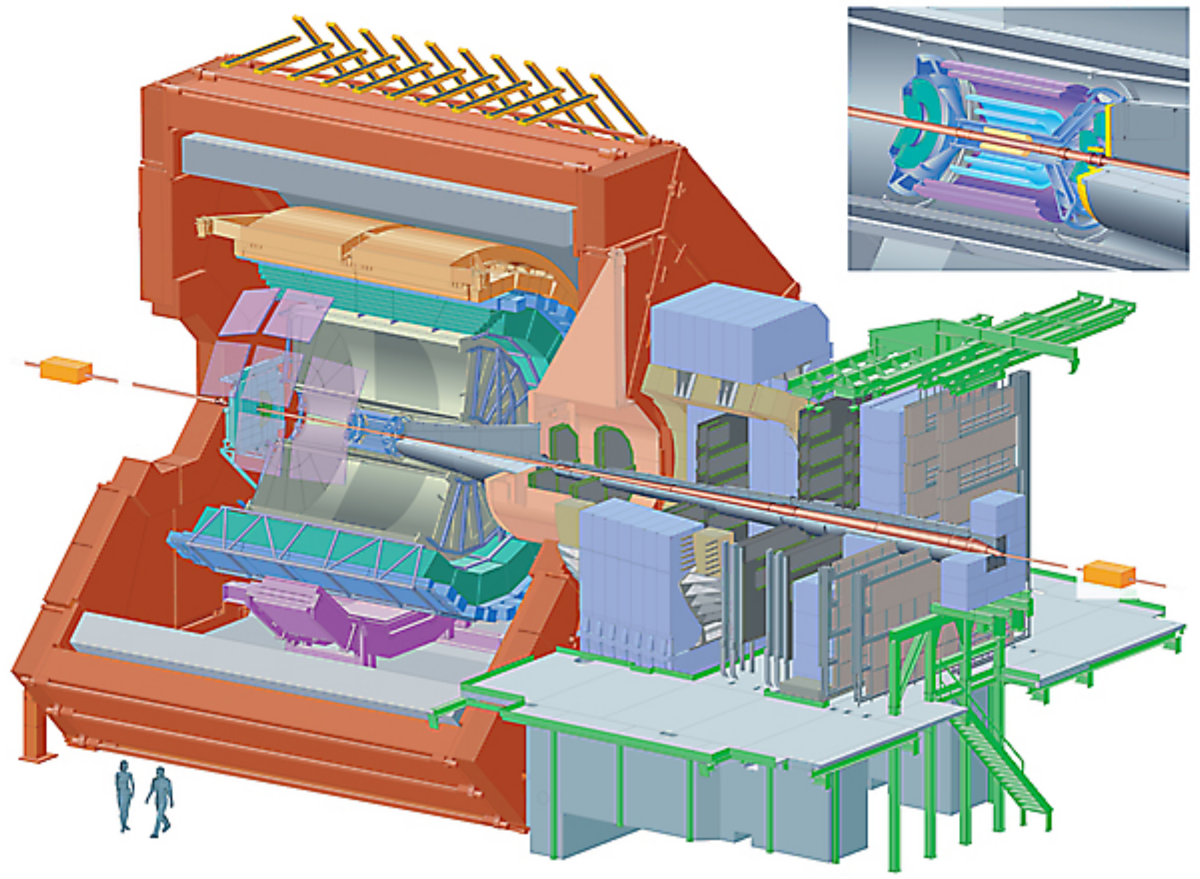
European Strategy for Particle Physics Update 2020…

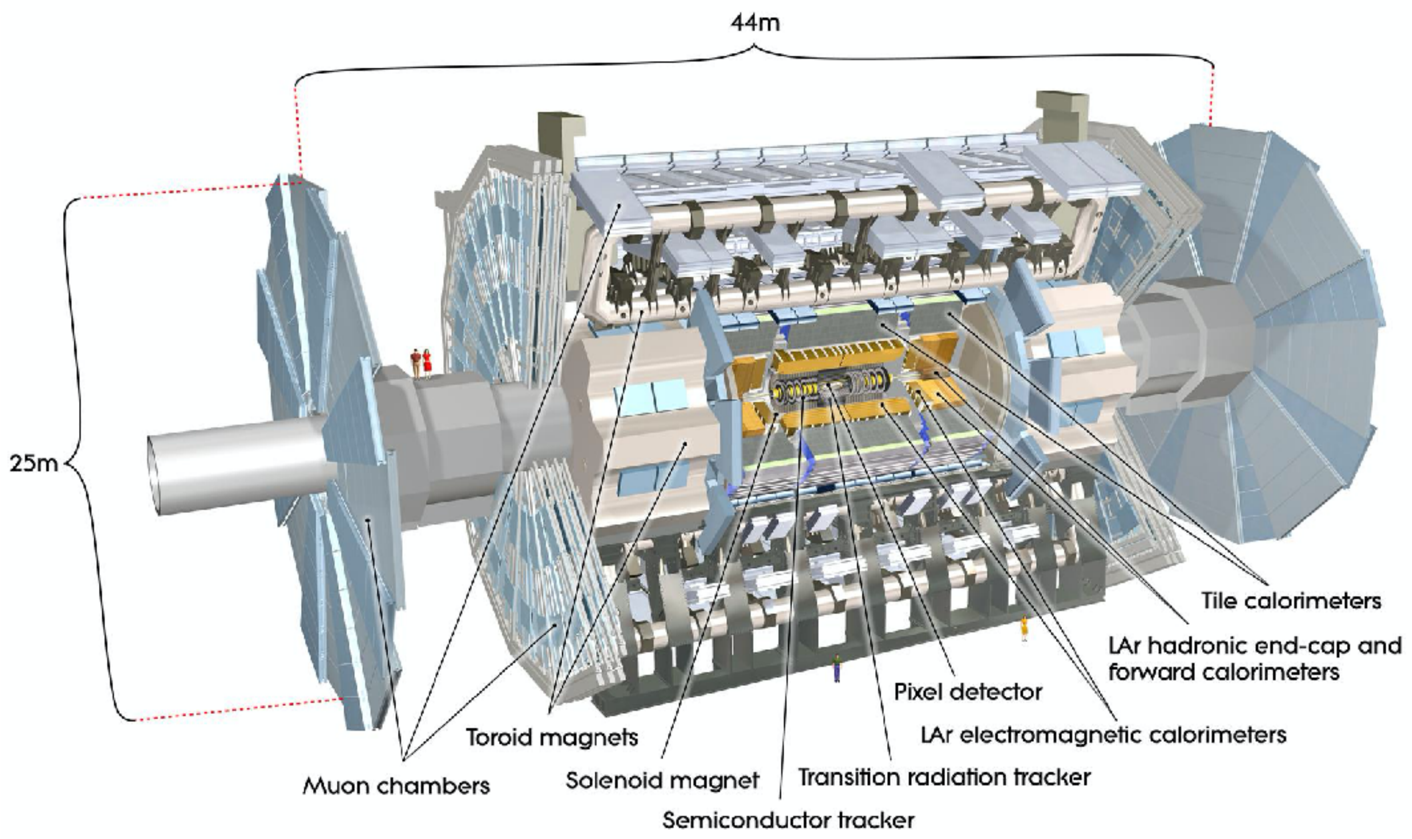
- The successful completion of the high-luminosity upgrade of the (LHC) machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques.
  - *New experimental ideas are welcome and key to progress*
- The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.
  - *ATLAS, CMS, LHCb and ALICE will continue to be upgraded and run till the end of the 2030s or early 2040s and beyond*

The LHC / HL-LHC will be our primary tool for research at the energy frontier for the next years to come

LHC detectors and their upgrades

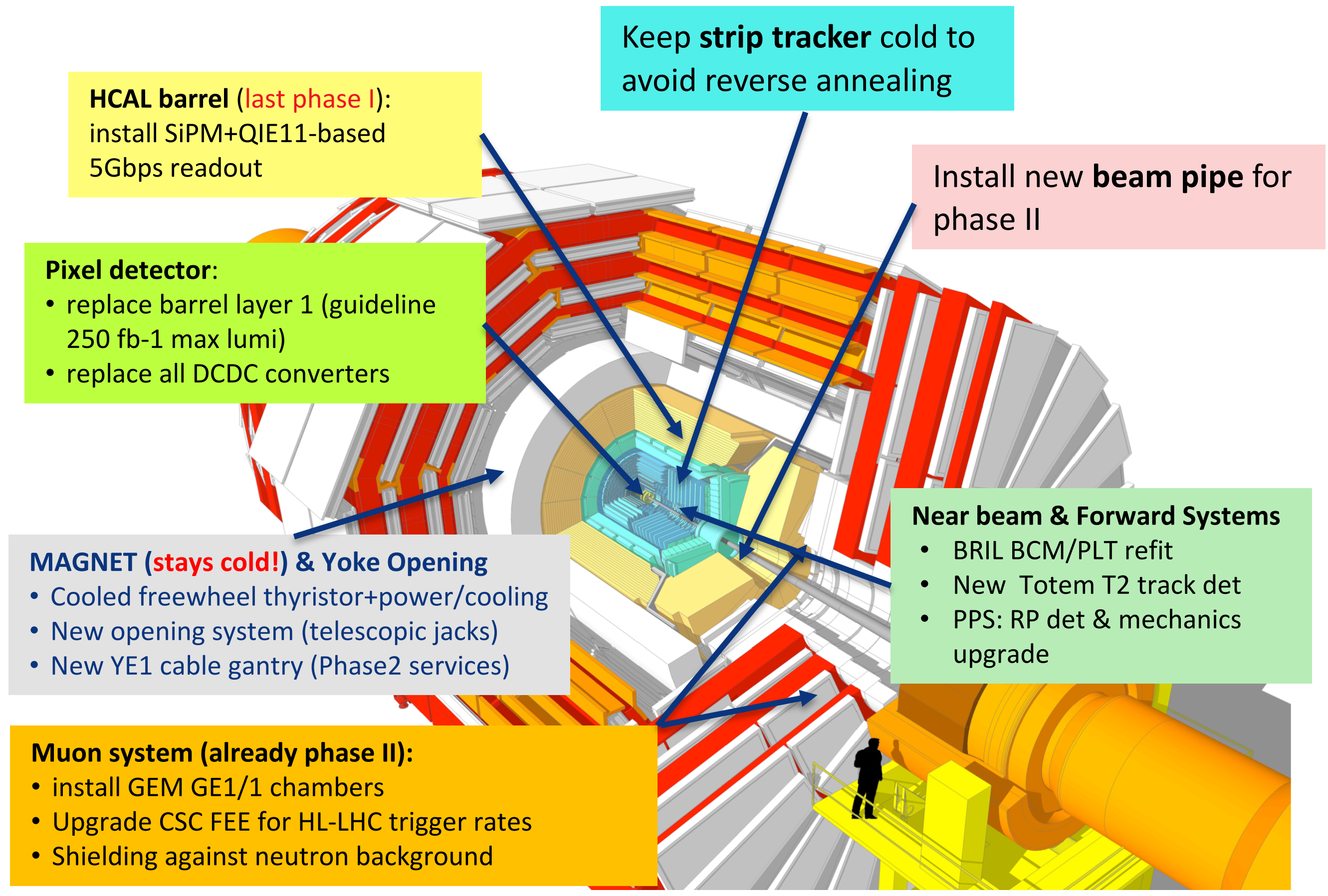
ALICE

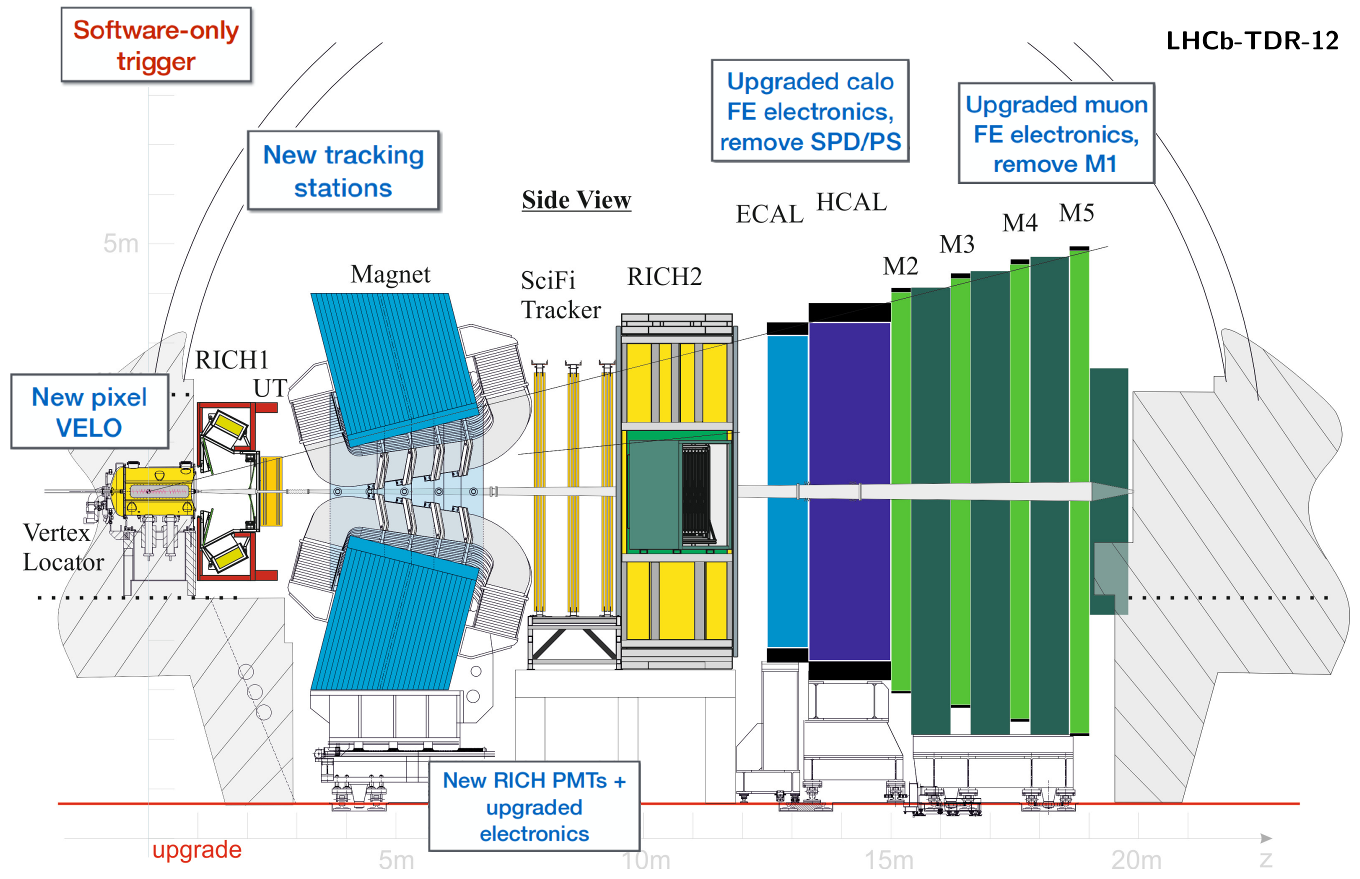




ATLAS

CMS





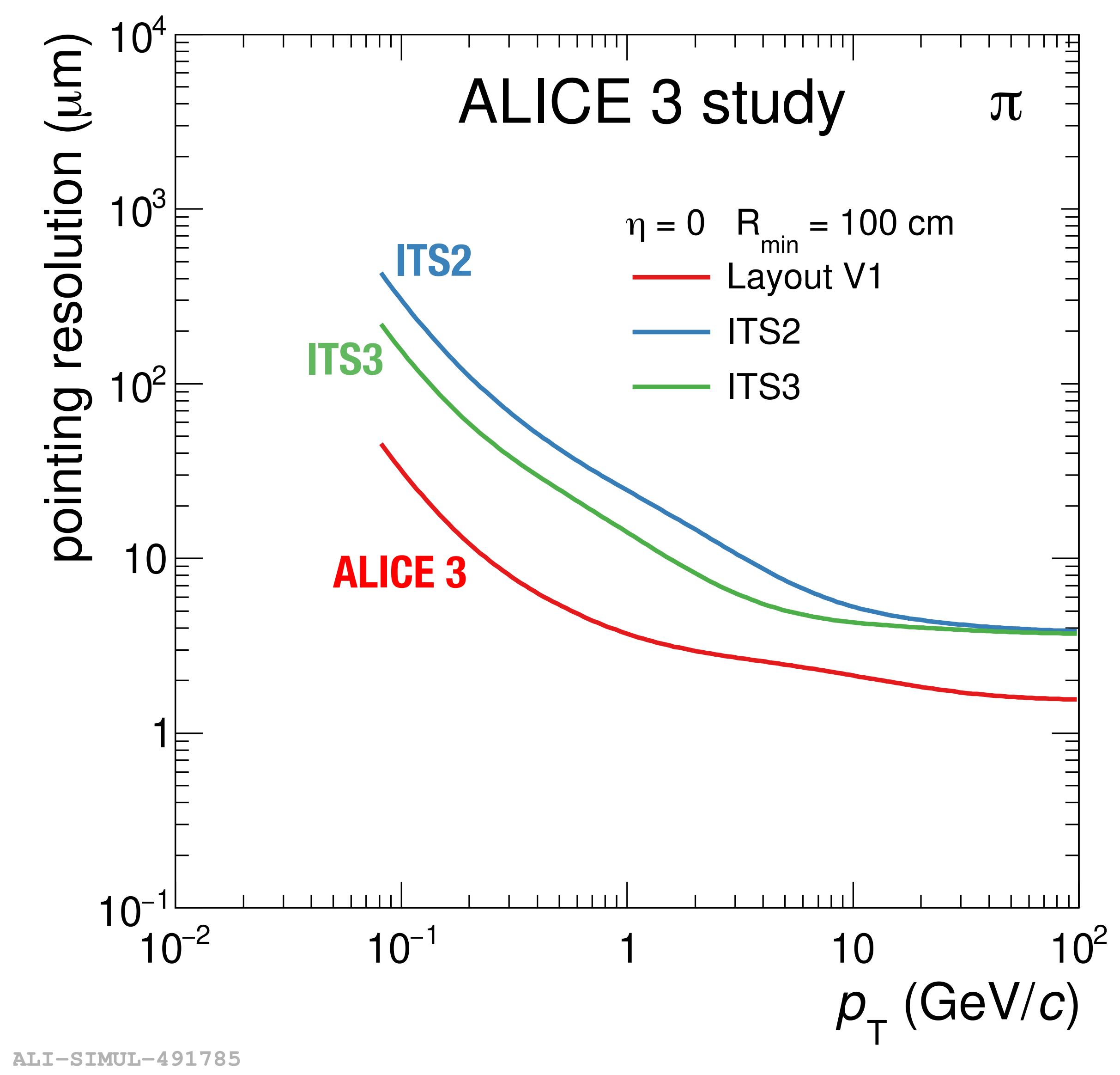
LHCb

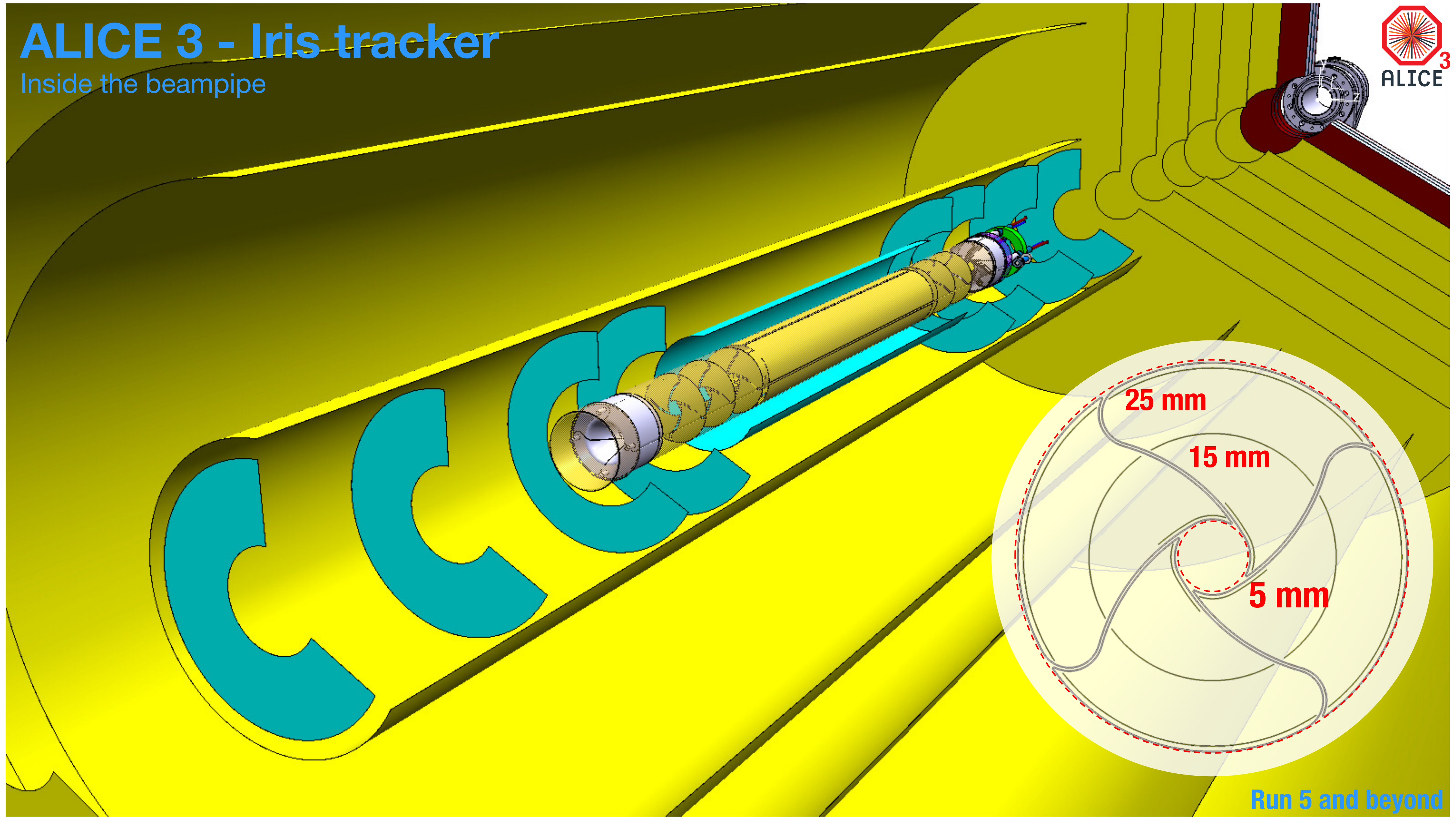
Why is this reasonable?

Experimental tools improve and systematic limitations are pushed out

Low mass detectors near beam - Example: Plans of ALICE 3

- 3 Inner layers closer to IP, (e.g. Iris tracker)
  - retractable innermost layer ~ 5 mm
  - X/X_0 ~0.1 % / layer





Will be used for flavour tagging

Timing - Example ATLAS HGTD

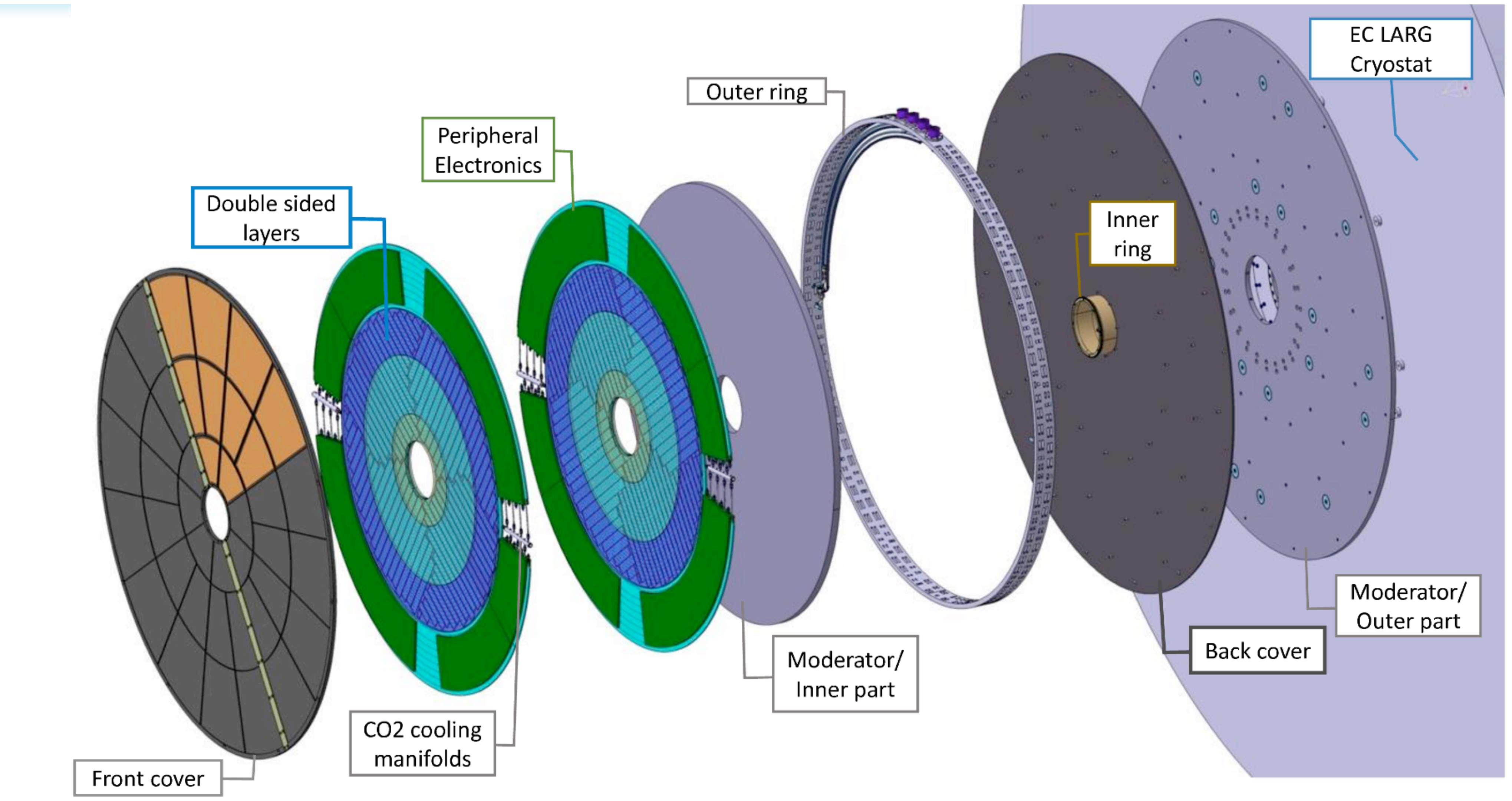
- 2 disks either side in gap between ATLAS barrel and end cap.

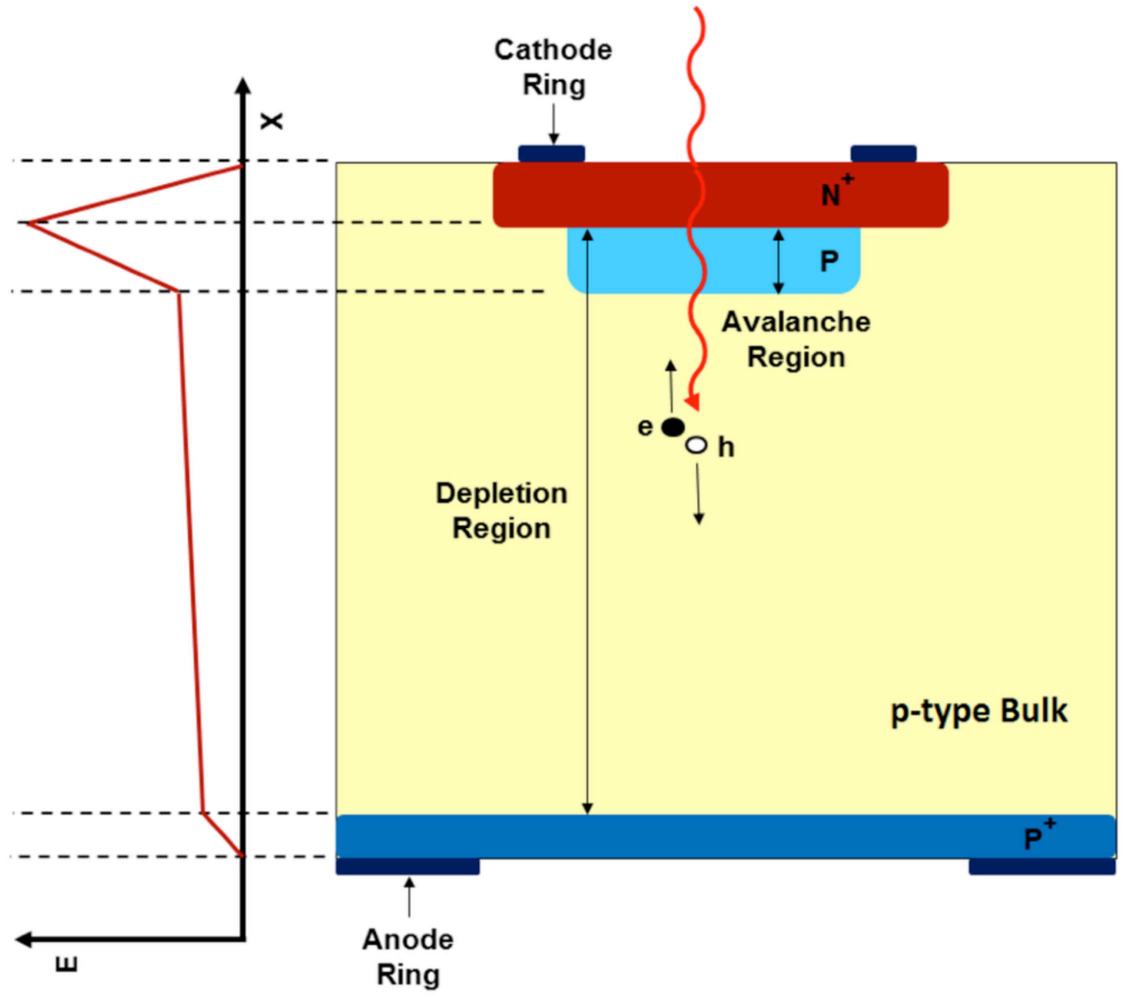
- Each instrumented double-sided layer supported by cryostat/support structure, moderator pieces for protection against back splash.

    - Acceptance at $2.4 < |\eta| < 4$

    - Low-Gain Avalanche Silicon Detectors (LGAD) sensors

    - Enable precision timing, retain signal efficiency after heavy irradiation



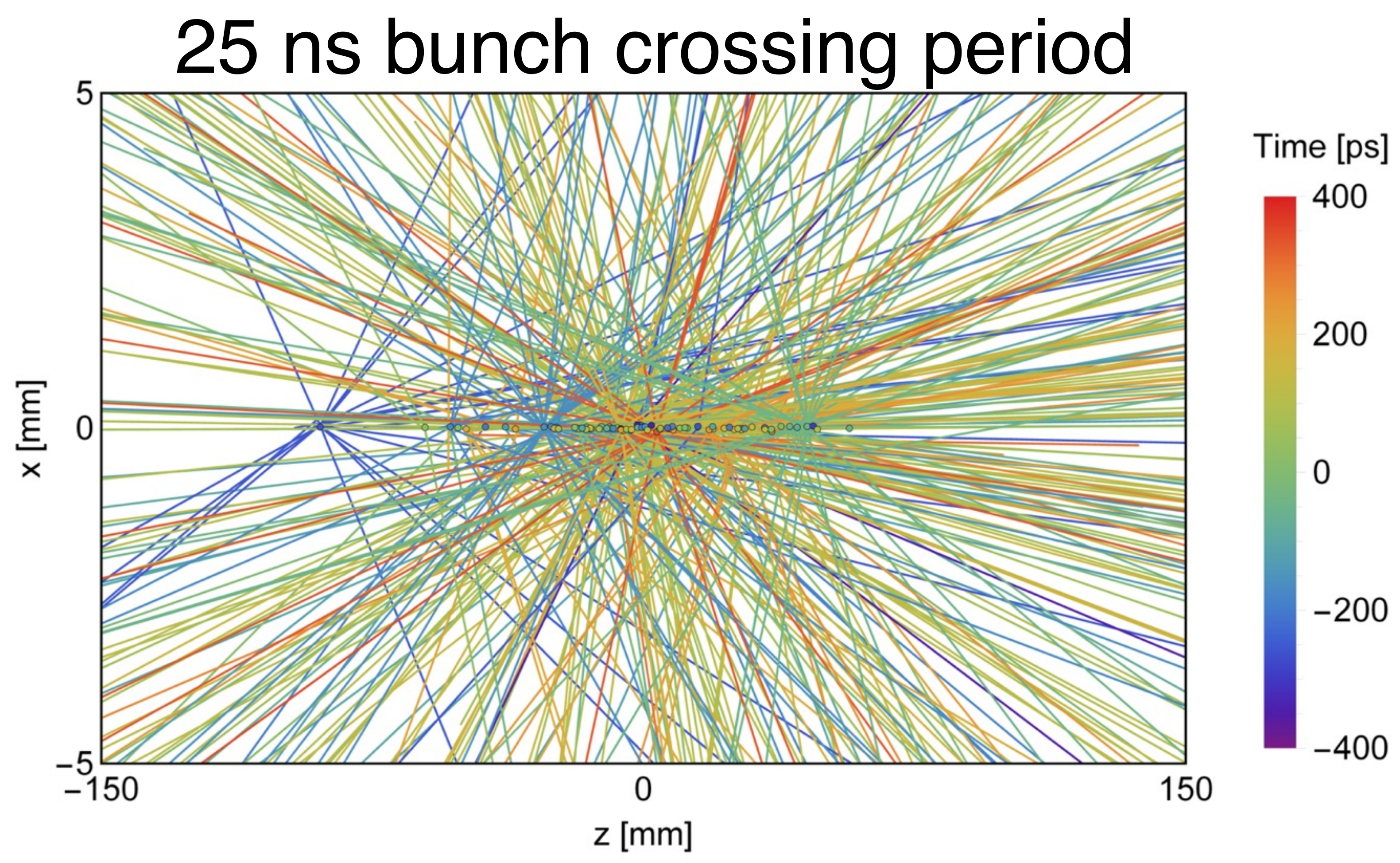


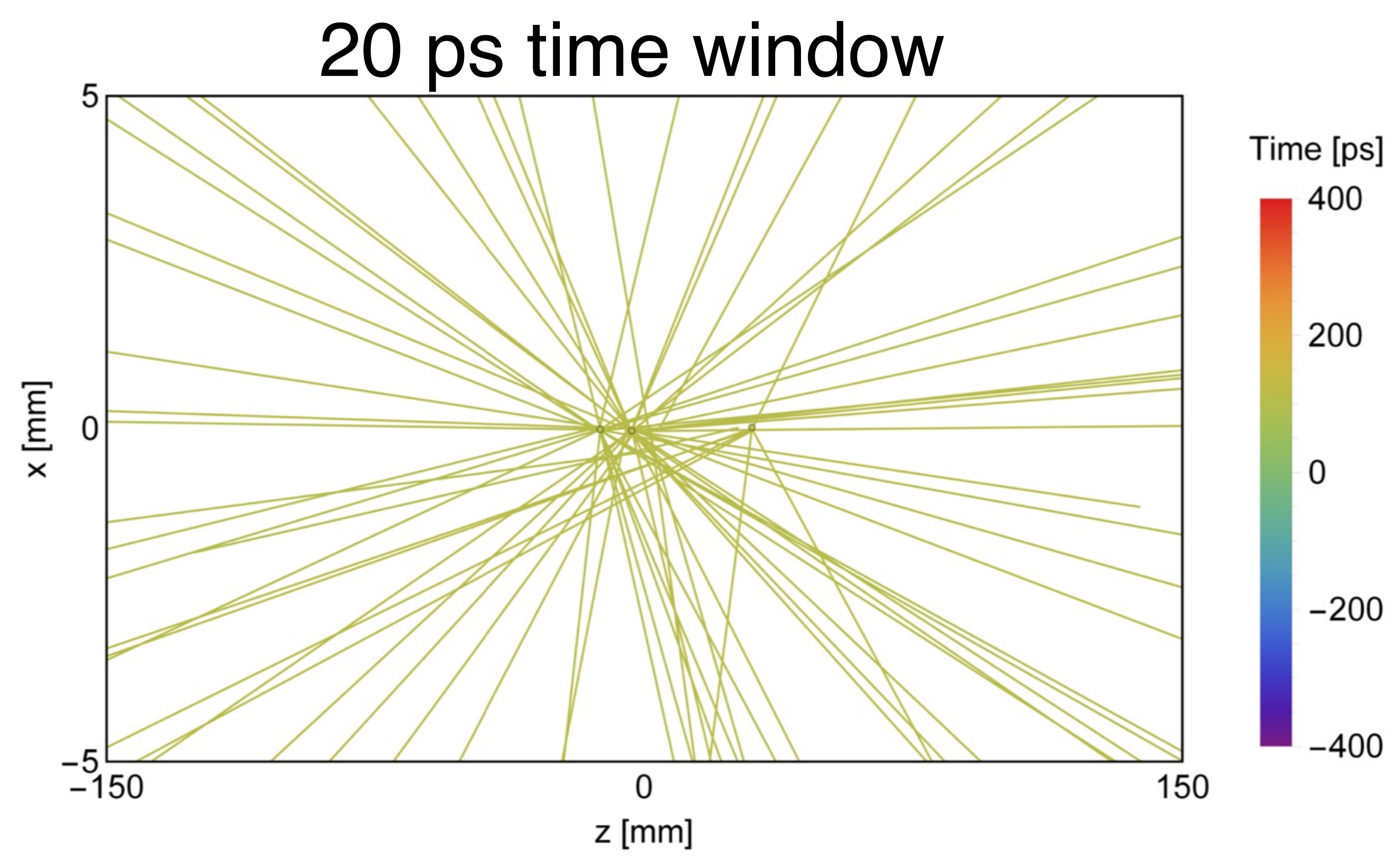
LGAD sensor: Silicon detector with internal low gain

pile-up protection

Integrated Fast Timing - Example LHCb for Run 5

- Fast Timing for
  - VELO
  - RICH
  - ECAL
  - TORCH

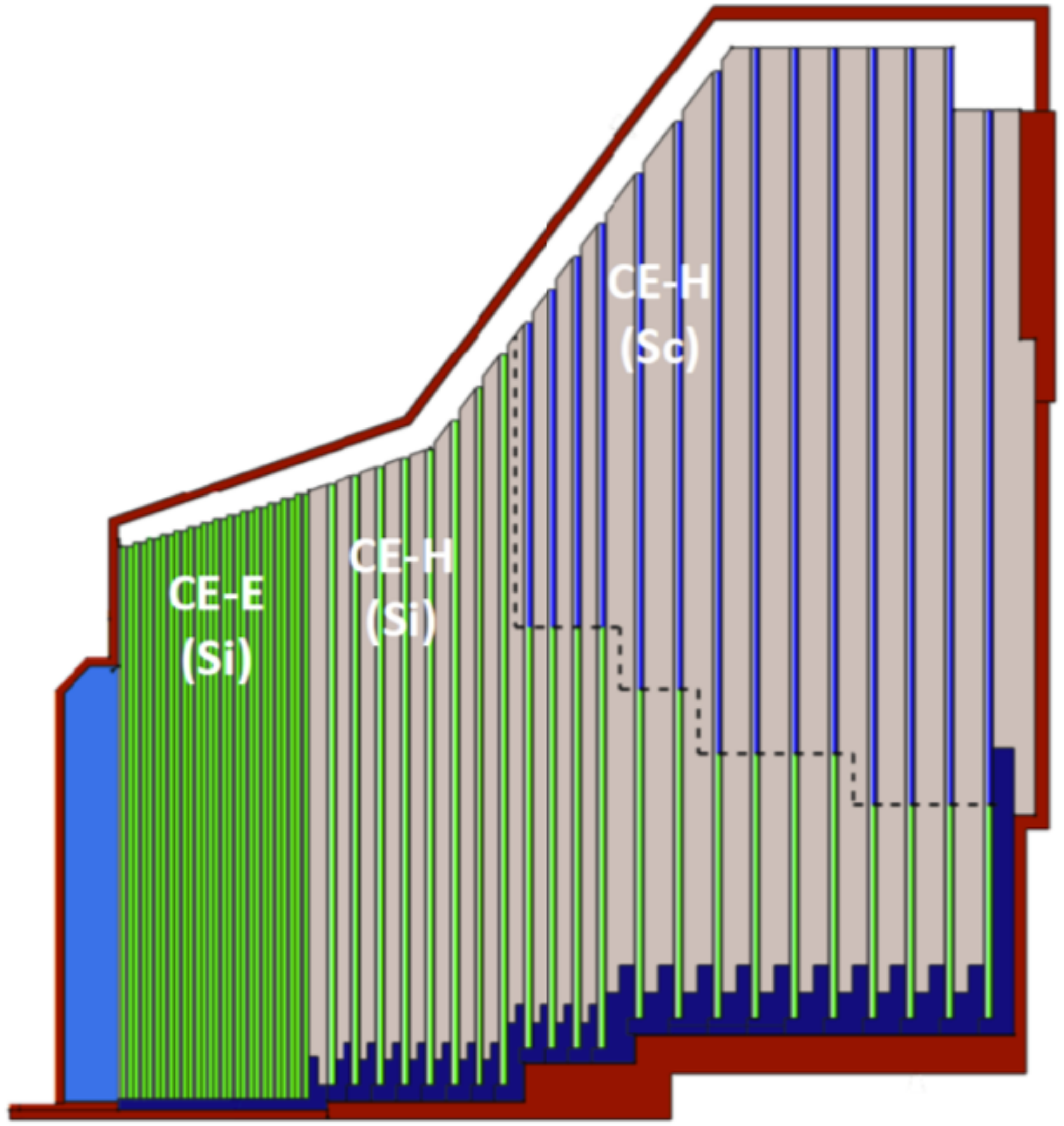




disentangling events

Precision Calorimetry - Example CMS

- Full replacement of existing CMS endcap ECAL and HCAL
- Integrated sampling calorimeter
- Absorber
  - EM section: Pb, CuW, Cu
  - Hadronic section: steel, Cu
- Active material
  - High radiation area: 8” hexagonal silicon sensors
  - Low radiation area: scintillator tiles with on-tile SiPM
- 5D imaging calorimeter
  - Extends tracking in forward regions
  - Highly granular spatial information
    - Si cell size: 0.5 cm^2 and 1.2 cm^2
    - Scintillator tile size: $(23\ mm)^2$ – $(55\ mm)^2$
  - Large dynamic range for energy measurements
  - Timing information to tens of picoseconds



Cut-away side view

Particle Flow Calorimetry

e.g. W-production in forward direction

Reconstruction and Simulation

- Some of the results from the LHC have been obtained earlier than expected from the integrated luminosity
  - This is largely owed to the advances in reconstruction and simulation
    - detailed simulation and parametrisation - understanding of pile-up
    - machine learning and much more
    - dedicated event streaming
      - optimising data formats

Upgrading / re-inventing the Software

- In addition to providing better resolution detectors also need the software to improve
  - Better algorithms yield:
    - better resolutions
    - lower backgrounds
    - and hence better signals

ML and better MC simulation

What does this mean for Particle Physics around 2040?

- We could be lucky and New Physics turns up directly
- LHC / HL-LHC will define the yardstick for physics reach of any other facility (e^+e^- and $\mu^+\mu^-$)
  - Today's predictions for HL-LHC physics reach are probably **too pessimistic** in view of new experimental ideas and reconstruction capability
  - Flavour physics becomes more important and better accessible; competition/ complementarity from Belle II and its possible upgrade is interesting
- LHC / HL-LHC will continue as the copious source of physics

Examples of new ideas

- FASER and SND
  - Neutrinos and non-interacting particles in the very forward direction
- SMOG at LHCb
  - pA collisions in front of the VELO detector
- Crystal channeling for rare charm decays
- MATHUSLA
  - a cosmic telescope and detector for long lived particles from the LHC

Summary

- LHC / HL-LHC will be the workhorse for Particle Physics for the next two decades
  - Direct observation of New Physics?
  - Its scope for precision is considerably better than originally expected and rivals the precision of lepton colliders

Fully exploit LHC

- But New Physics could hide elsewhere
  - Low mass Dark Matter searches
  - Neutrino Physics

Don't forget other experimental tools