LHC bize (başka) ne veriyor?

Bugra Bilin (ULB/IIHE)

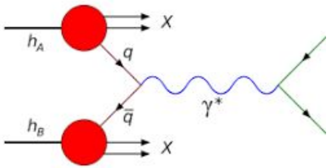
pp çarpışmalarından ne elde ettik?

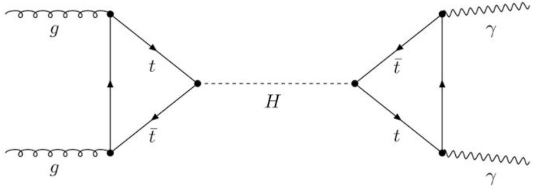
Farklı konular

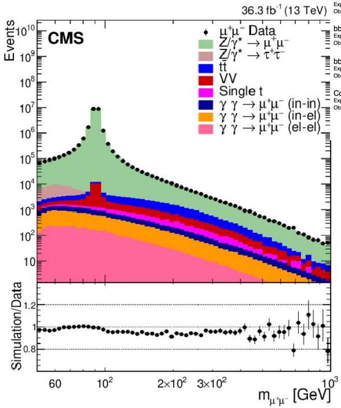
Ağır iyonlarla ulaşılan fizik

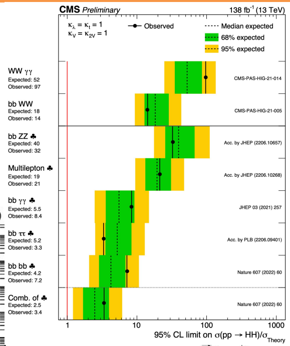
LHC bir foton/lepton çarpıştıcısı olarak çalışır mı

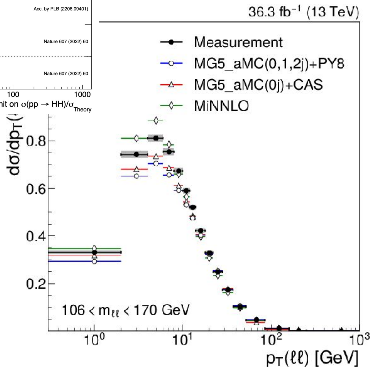
…











Önceki Ders Özeti: Datadan fizik sonucuna

pp $\longrightarrow$ detektör $\longrightarrow$ DAQ $\longrightarrow$ reconstruction $\longrightarrow$ Analiz $\longrightarrow$ Fizik Sonucu

Selection
Background
Detector corrections
Systematics
Statistical inference
ML

$$\boxed{\frac{d\sigma}{dX}, \quad m_W, \quad \mu_H, \quad Z, \quad \sigma_{95}}$$

1. Detector-level distribution $\neq$ physics result
2. $d = Rt + b \quad \Rightarrow \quad$ Unfolding is an inverse problem
3. Measurement $=$ value $+$ uncertainty $+$ correlations
4. Systematics belong inside the analysis
5. $L(\mu, \theta)$ connects data to physics parameters
6. ML should improve physics sensitivity

Ne ölçüyoruz, ne arıyoruz

ÖLÇÜM

σ, dσ/dX, oranlar

kütleler, bağlaşım sabitleri

SM parametreleri

ARAMA

rezonans / bump

MET, LLP, sıra dışı topolojiler

yüksek-enerji tail'lerinde sapma

Precision measurement ↔️ indirect BSM search

LHC fizik alanı

QCD
jets • PDFs • α_s

EW
W/Z/γ • diboson • VBS

TOP
$t\bar{t}$ • single-top • m_t

HIGGS
production • decays • couplings

BSM
SUSY • resonances • DM • LLP

HI
QGP • nPDF • collectivity

Ölçümler, yeni fizik arayışları

Direct

$pp \to X \to ab$

resonance / excess

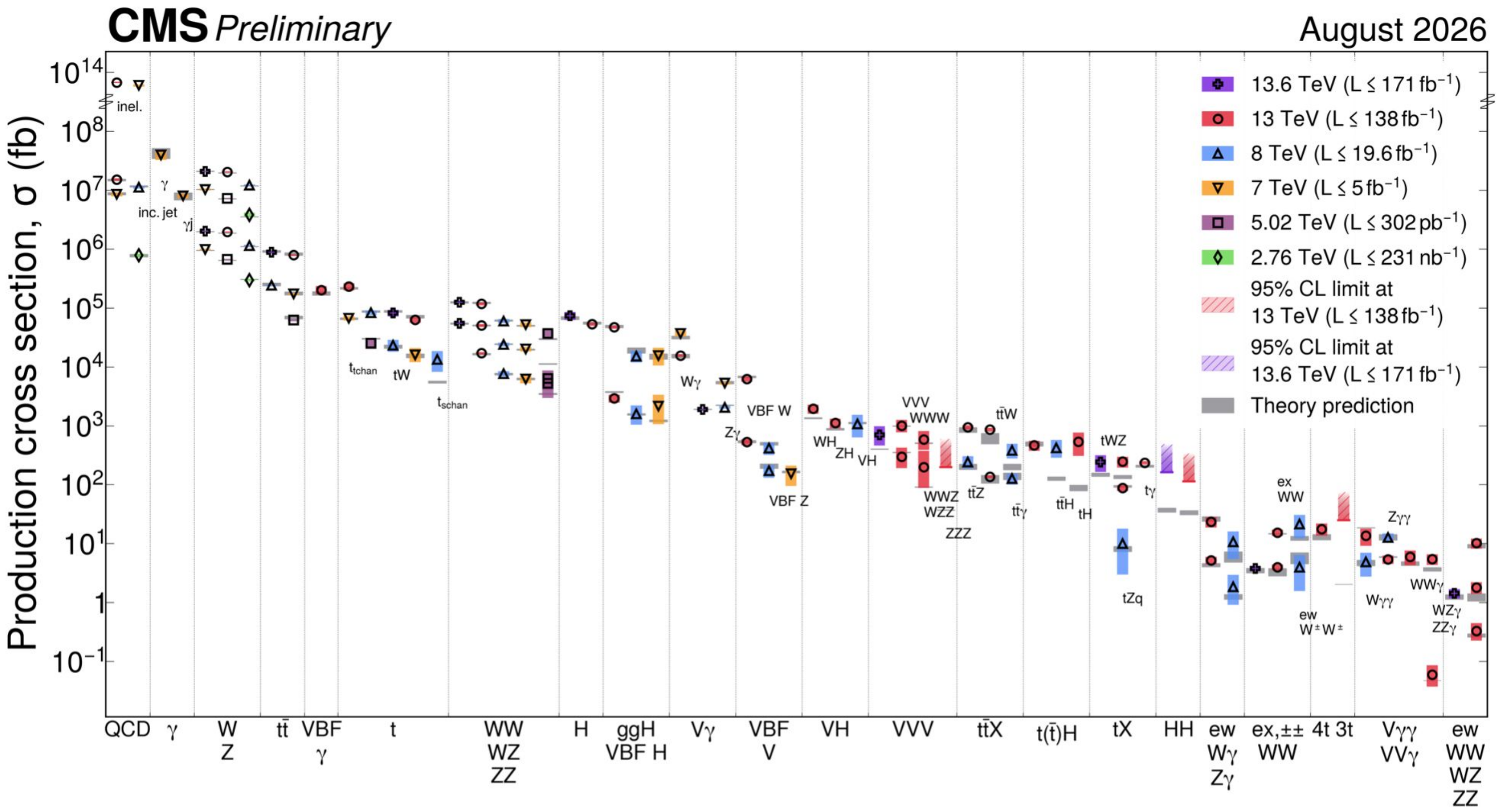
Indirect

$L = L_{SM} + c_i O_i / \Lambda^2 + \ldots$

precision tails / EFT

Yeni fizik illa invariant-mass peak'i olmak zorunda değil.

Şimdiye kadar ne ölçtük



Neleri aradık, neleri bulduk (bulamadık)

Aradık

- SUSY
- Z′ / W′
- leptoquarks / VLQ
- dark matter mediators
- LLP

NO CONFIRMED BSM PARTICLE — YET

No discovery ≠ no new physics

Nereye bakıyoruz?

- daha fazla luminosity
- rare / unusual signatures
- farklı initial states

Ağır iyon çarpışmaları: Motivasyon

Neden ağır iyon?

- QCD at extreme T / density
- deconfined quarks & gluons
- collective behaviour
- parton energy loss
- nuclear structure

Pb + Pb

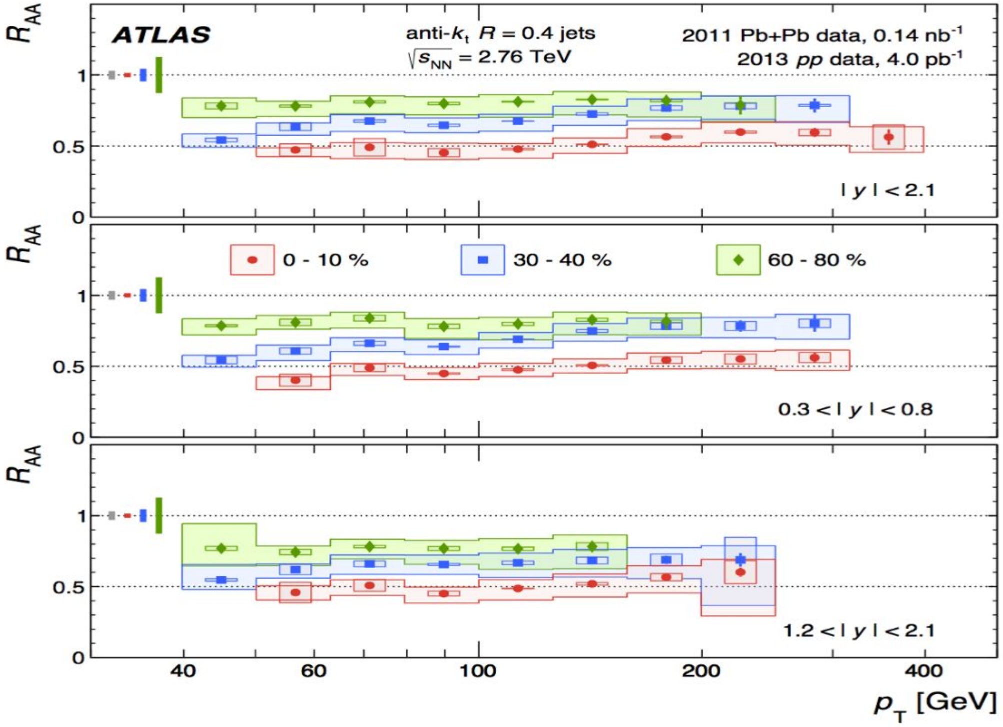
↓

QGP

↓ hadrons

pp: hard scattering
PbPb: hard scattering + üretilen medium

Ağır iyon çarpışmaları: QGP



QGP observables

flow: v_2, v_3

jet quenching: RAA < 1

γ/Z+jet, heavy flavour, quarkonia

Central collisions: jet yield ≈ 1/2 of pp-scaled expectation

ATLAS/CERN

Ağır iyon çarpışmaları: ZDC ile ne ekliyoruz

Central detector

What was produced?

participants → tracks / jets / energy

ZDC

What happened to the nuclei?

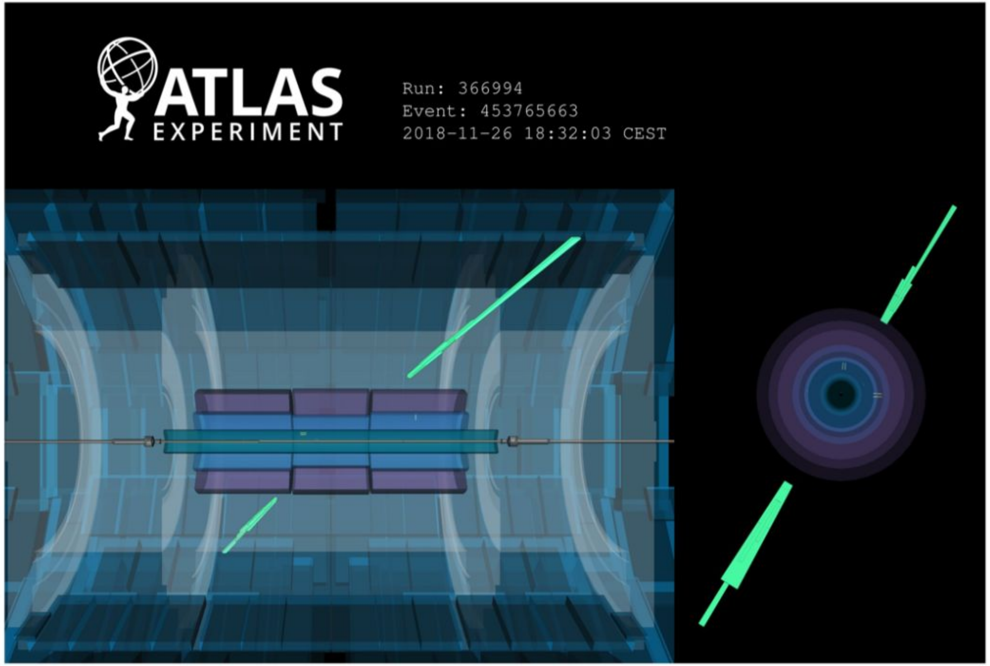
spectator / breakup neutrons → ZDC

IP

———→ **beam**

ZDC: very forward neutral particles; UPC / centrality / neutron classes

Ağır iyon çarpışmaları: UPC



ATLAS light-by-light event

Ultra-peripheral

$b > R_1 + R_2$

$Pb \rightarrow Pb + \gamma$

$\gamma\gamma \rightarrow X$ / $\gamma Pb \rightarrow X$

photon flux ∝ Z^2

ZDC: 0n0n • 0nXn • XnXn

LHC as a photon collider

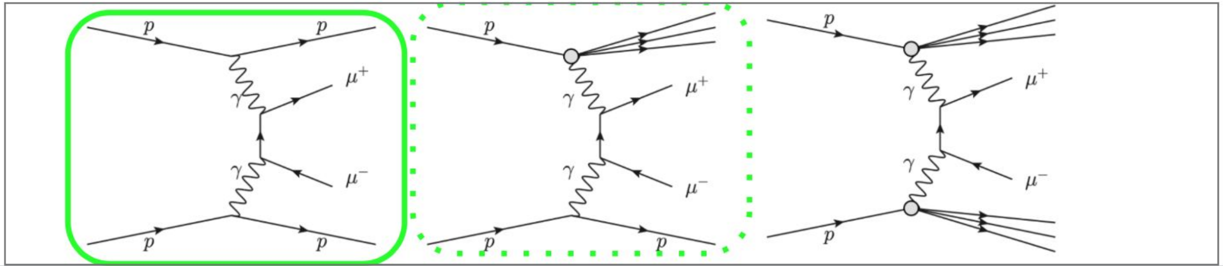
$p \rightarrow p + \gamma$ $p \rightarrow p + \gamma$

$\gamma + \gamma$

$\downarrow$

$\ell\ell$ • WW • $\gamma\gamma$ • ALP?

Without proton tagging: exclusivity inferred from low activity / acoplanarity / gaps



LHC as a photon collider: Tagging protons with PPS

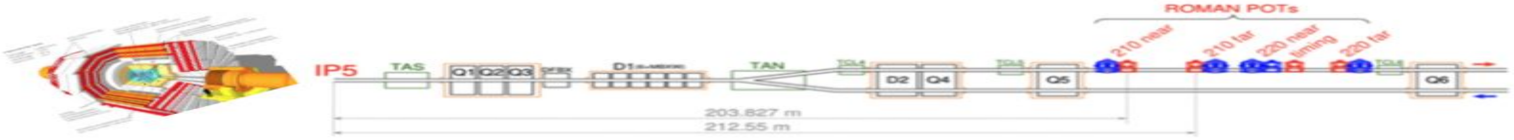


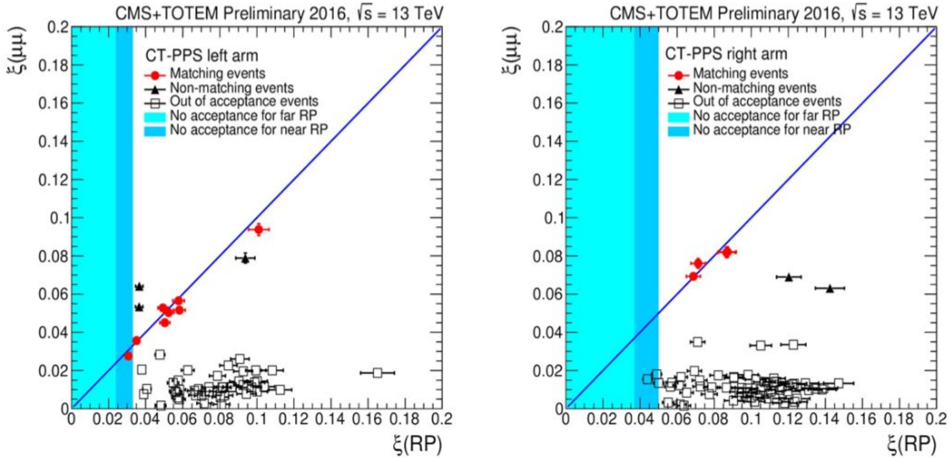
Figure 3: A schematic layout (not to scale) of the beam line between the CMS interaction point (IP5) and the location of the Roman Pots (RPs) in sector 56. Dipole magnets (D1, D2) of single (MBXW) and twin-aperture, quadrupoles (Q1-Q6), collimators (TCL4-TCL6), absorbers (TAS, TAN), and quadrupole feedboxes (DFBX) are shown. The 210-far and 220-far units are indicated along with the timing stations (not used here). The 210-near and 220-near are also shown. The RPs shown in red are those reserved for PPS; those in blue are part of the TOTEM experiment.

$$p + p \rightarrow p + X + p$$

$$\xi = \Delta p / p$$

PPS: ~200 m downstream, beam optics turns momentum loss into measurable displacement

LHC as a photon collider: What physics can we probe with tagging protons



CMS-TOTEM: matching events lie near ξcentral = ξPPS

Kinematic closure

$$M_x^2 \simeq \xi_1 \xi_2 s$$

$$y_x \simeq ½ \ln(\xi_1/\xi_2)$$

central system ↔️ tagged proton

Physics

γγ→ℓℓ / WW / ZZ / γγ

aQGC / EFT

ALPs / resonances

exclusive $t\bar{t}$

Ağır iyon çarpışmaları: p O

COSMIC RAY

p_cosmic + O/N

↓ hadronic shower
π, K, p, n → μ, e, γ, ν

↔️

LHC

p + O

controlled laboratory interaction

2025: first pO collisions at the LHC • $\sqrt{s_{NN}}$ = 9.62 TeV

Use pO data to constrain hadronic interaction models → Xmax, muon content, composition

Ağır iyon çarpışmaları: p O

pO: LHC as a cosmic-ray laboratory

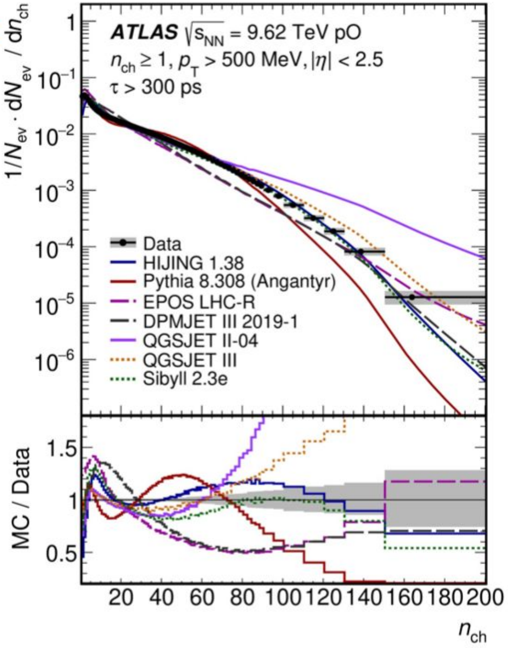
proton beam ≈ cosmic ray • oxyg
atmosphere

ATLAS, √sNN = 9.62 TeV

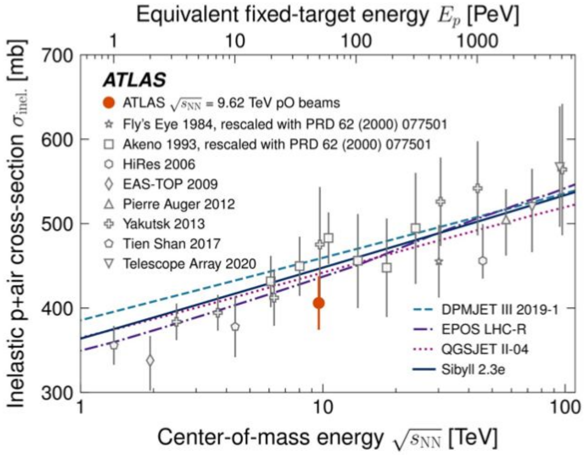
246 million selected events
σfid(pO) = 396 ± 6(exp) ± 9(lumi) mb
σinel(p+air) = 406 ± 6 ± 9 ± 28(th) mb

Why cosmic-ray physicists care

Air-shower interpretation depends on hadronic models. pO data directly test multiplicity, pT and η predictions used by EPOS, QGSJET, Sibyll, DPMJET, …



charged-particle multiplicity



p+air cross section vs cosmic-ray data

Phase-II: Ne değişiyor

HL-LHC = luminosity frontier

Today → HL-LHC

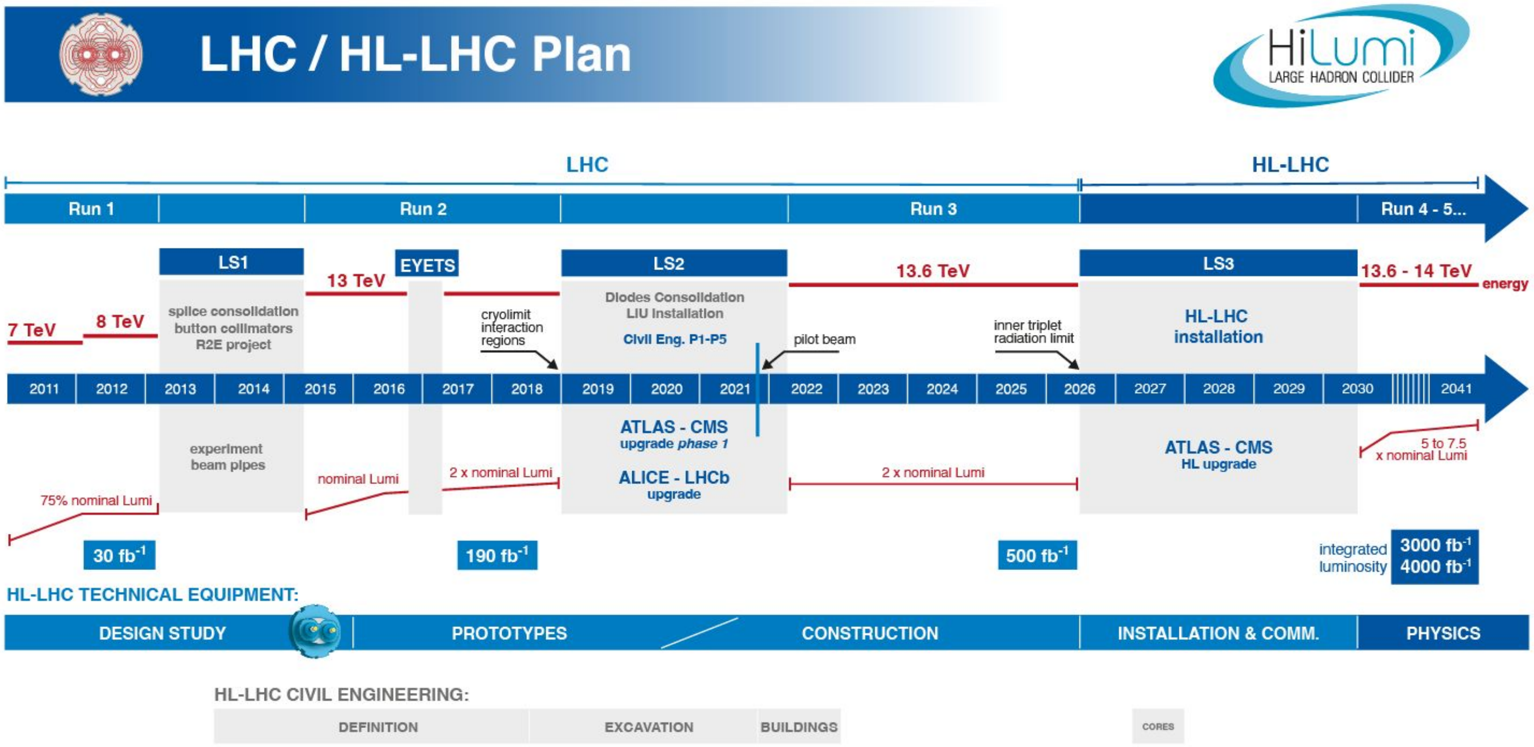
- $\sqrt{s}$: 13.6 → 14 TeV
- L_int → ~3000 fb^{-1}
- pileup O(200)

Phase-II

- new tracker / forward reach
- precision timing
- calorimeter & muon upgrades
- trigger / DAQ

Energy barely changes; statistics and detector capability change dramatically.

Phase-II: Ne değişiyor



Phase-II: Ölçülecek ne kaldı

Rare Higgs

$H \to \mu\mu$

$H \to Z\gamma$

rare / exotic decays

Higgs self-coupling

$pp \to HH$

λHHH

EWSB

$VV \to VV$

longitudinal VBS

Unusual signatures

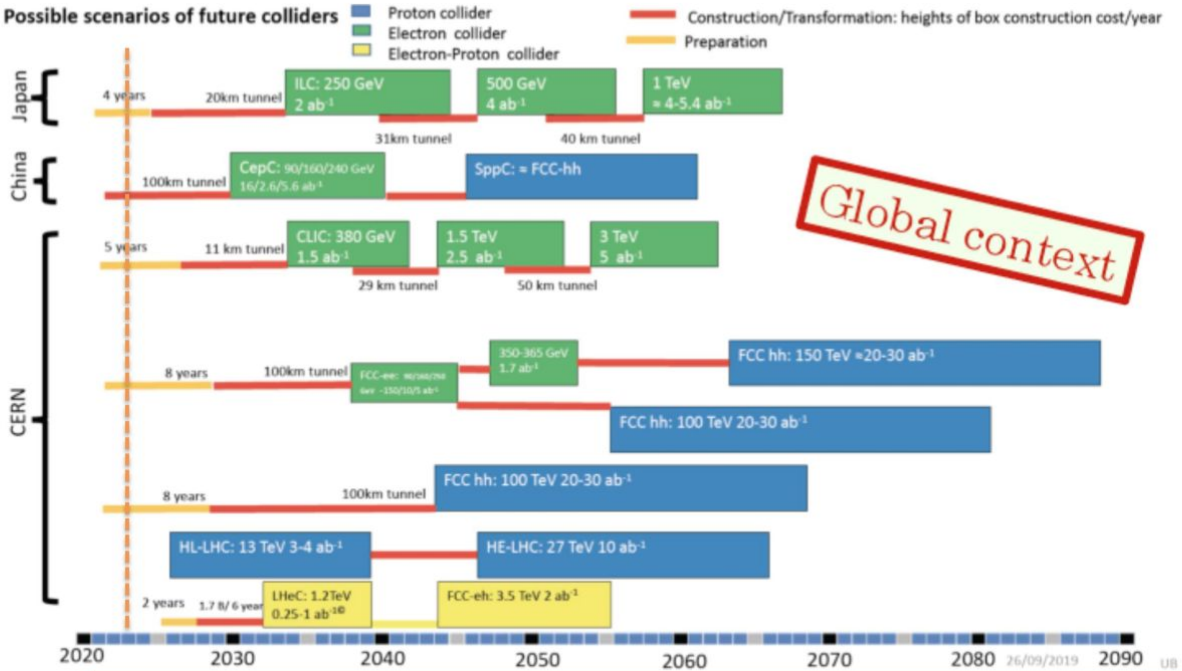
LLP

compressed spectra

invisible / dark sectors

exclusive photon-induced

Sonrası: FCC? Başka bir çarpıştırıcı?



→ Beyond 2038 is a multi-parameter problem.
  → We "might" have a Run-6
  → FCC? LHeC? HE-LHC? Muon collider?
    → All depends on the results (to-be) obtained from current LHC

All depends on what we will observe:

Lots of cutting-edge physics results to obtain from current and upcoming datasets

Exciting upgrade program for Phase-II, possibilities for further upgrades before Run6…

ECFA ECR Debate paper: https://arxiv.org/abs/2002.02837

Özet

pp	PbPb / OO	UPC	pp + PPS	pO
parton collider	**QCD matter lab**	**photon collider**	**tagged photon collider**	**cosmic-ray lab**
Higgs • top • EW • BSM	QGP • flow • quenching	$\gamma\gamma$ • γA	exclusive • EFT • BSM	air showers • hadronic models

ONE MACHINE — MANY COLLIDERS

The LHC is much more than a proton–proton collider.