

Diffraktív proton-proton ütközések: a CERN LHC CMS és TOTEM kíséreték új eredményei



Szanyi István

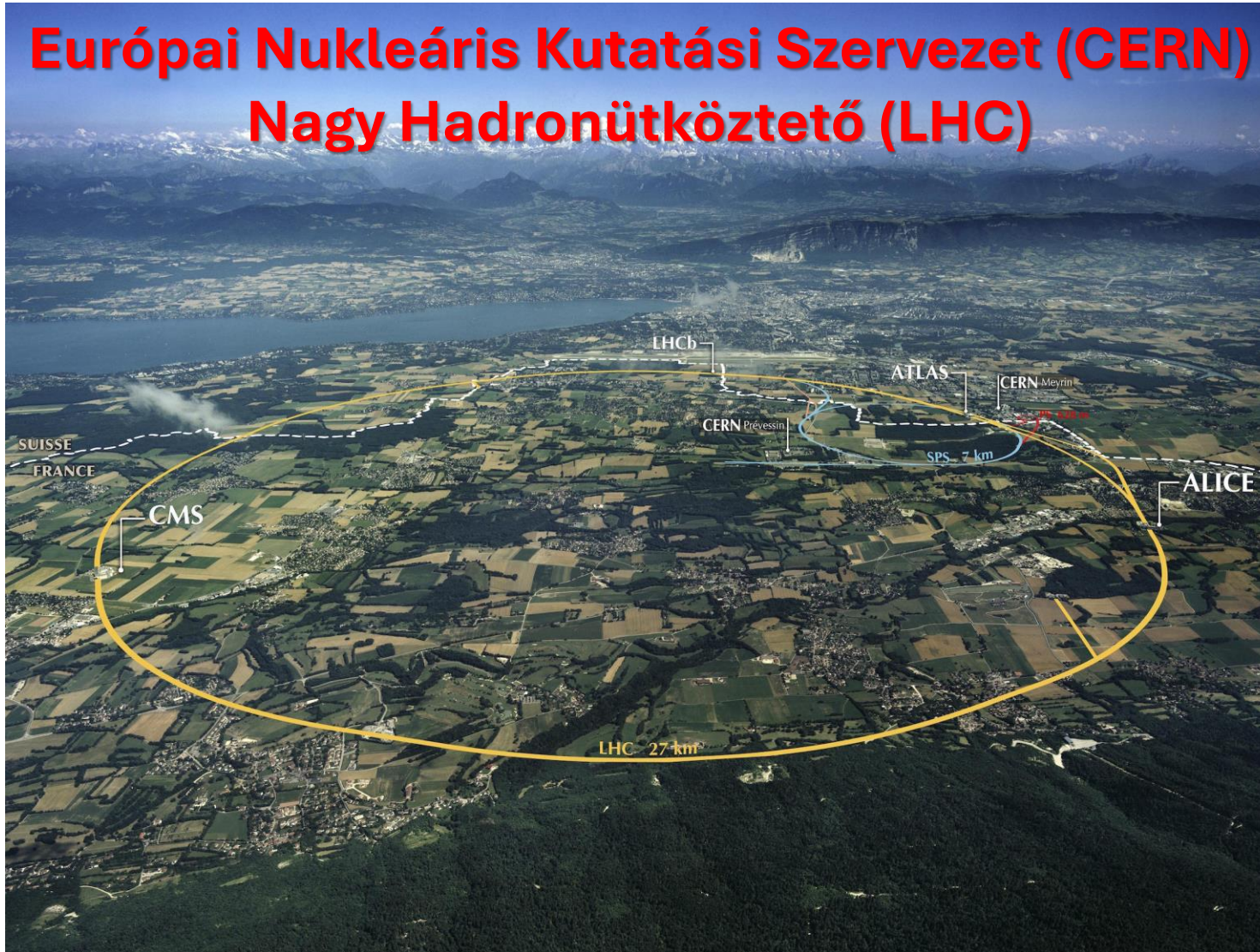
MATE Műszaki Intézet, KRC, Gyöngyös
HUN-REN Wigner Fizikai Kutatóközpont, Budapest
Kansasi Egyetem, Lawrence, USA

10. Femtoszkópia Nap

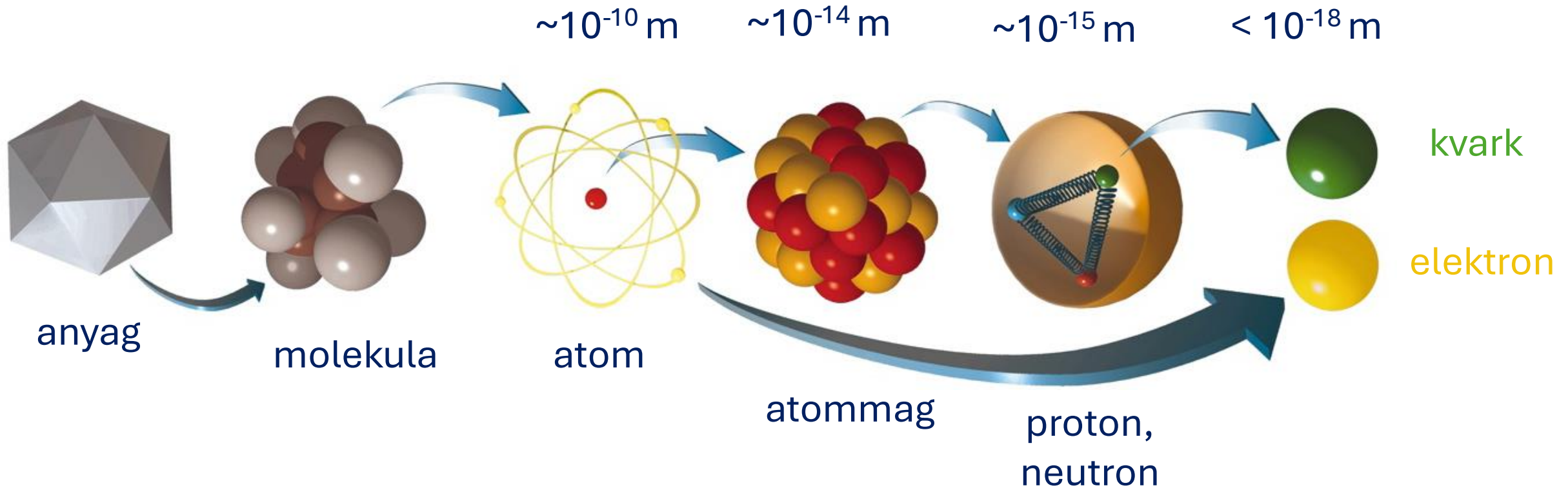
Gyöngyös, 2024. október 29-30.

A világ legnagyobb részecskegyorsítója: az LHC

Európai Nukleáris Kutatási Szervezet (CERN) Nagy Hadronütköztető (LHC)



Hogyan is jutunk el a részecskékig?



az **elektron** és a **kvarkok** az anyag tovább már nem bontható, elemi építőkövei közé tartoznak (az eddigi ismereteink szerint)

Részecskék és antirészecskék

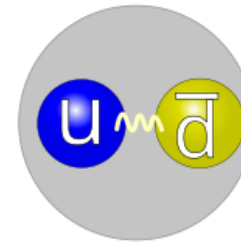
Az anyagi részecskék három családja (fermionok)

	I	II	III		
Kvarkok	u u-kvark	c c-kvark	t t-kvark	γ foton	H Higgs-bozon
	d d-kvark	s s-kvark	b b-kvark	g gluon	
	ν_e elektron-neutrínó	ν_μ műon-neutrínó	ν_τ tau-neutrínó	Z^0 Z-bozon	
Leptonok	e elektron	μ műon	τ tau	W^\pm W-bozon	

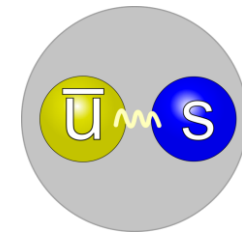
Bozonok (kölsönhatások)

az anyagi részecskéknek vannak **antirészecske** párjaik

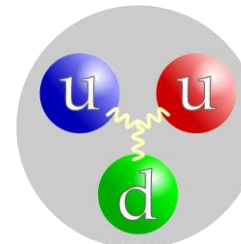
a **kvarkok** és **antikvarkok** az erős kölcsönhatás révén **összetett hadron részecskéket** alkotnak (színbezárás)



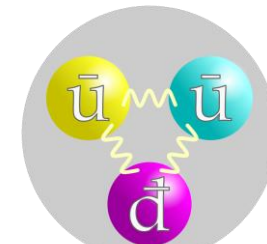
pozitív pion (π^+)



negatív kaon (K^-)



proton (p)

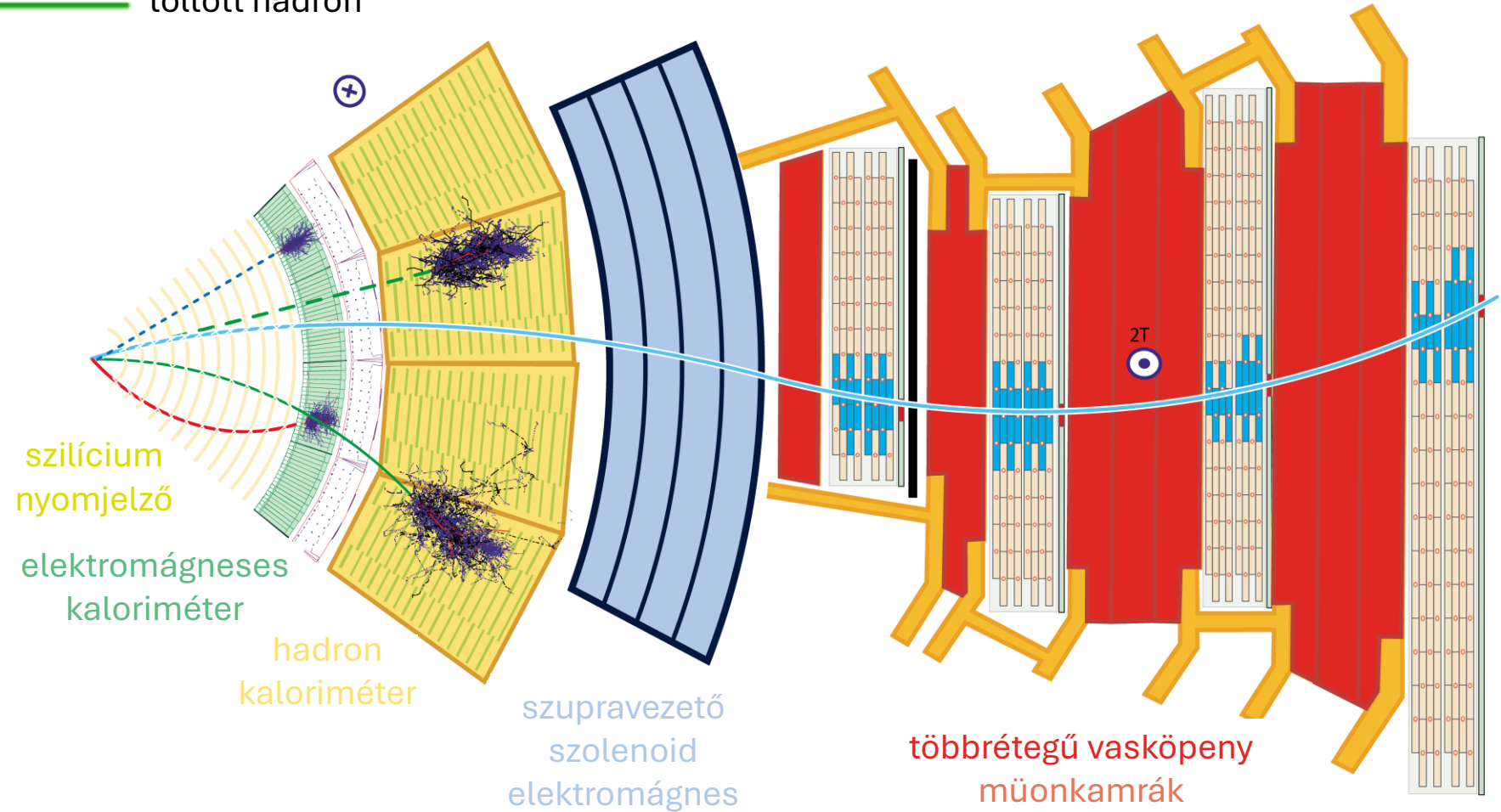
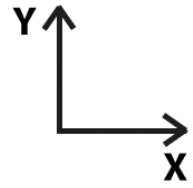
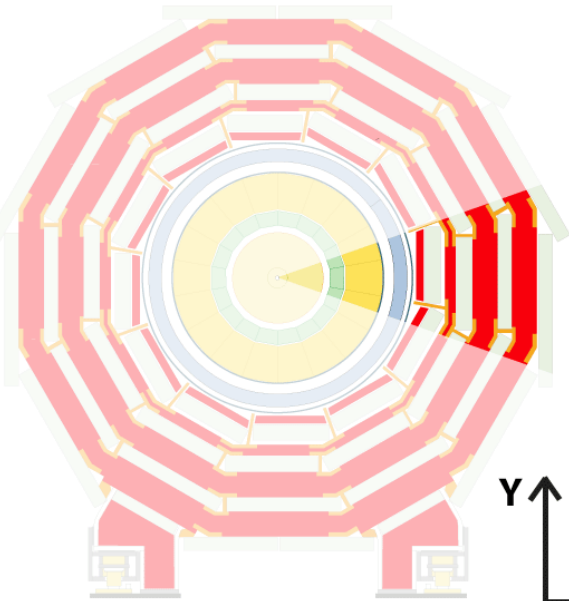


antiproton (\bar{p})

Részecskék a Compact Muon Solenoid (CMS) detektorban

- müon
- elektron
- töltött hadron
- - - semleges hadron
- · - · - foton

a CMS detektor keresztmetszete



CMS DETECTOR

Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 1\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

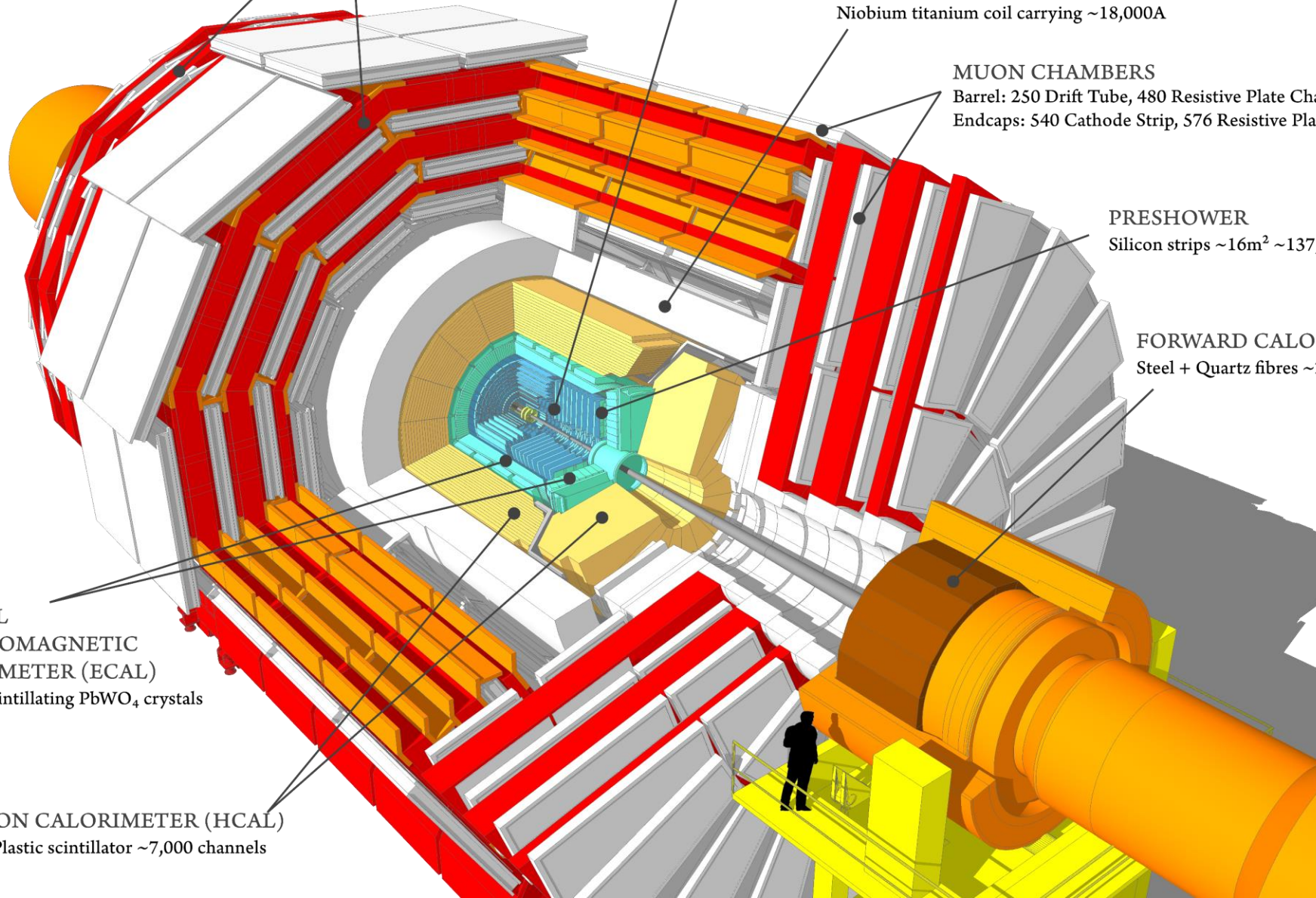
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

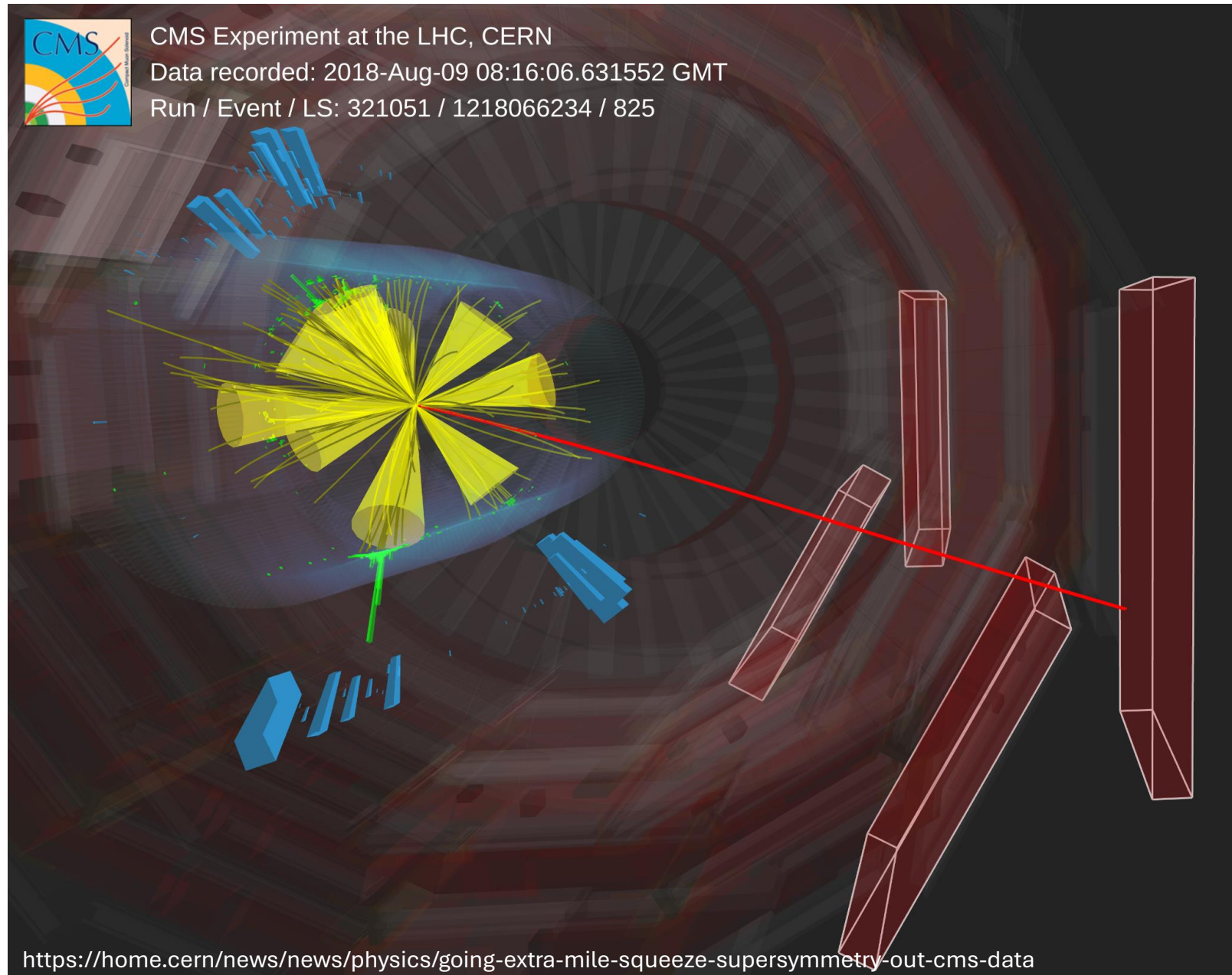


Részecskefizikai esemény mérése a CMS detektorban

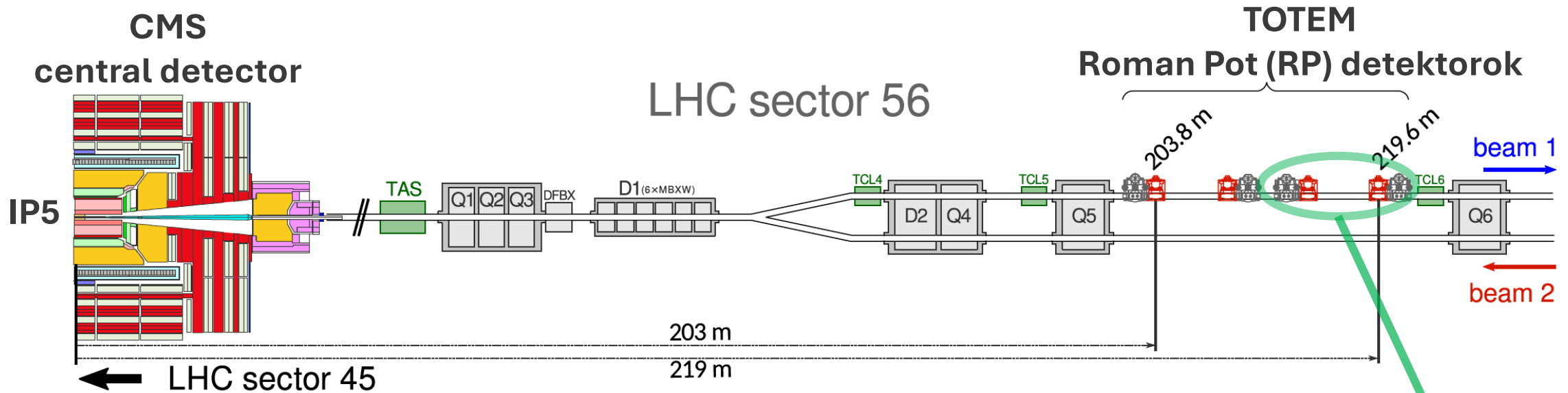


másodpercenkénti 40 millió „lefényképezett” eseményből (~TB/s)
1000 érdekes esemény (~MB/s) kerül csak mentésre (trigger)

Jetek (hadronzárporok) a CMS detektorban

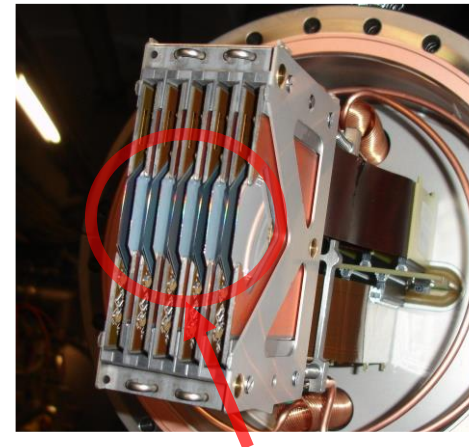


TOTEM: nagyon kis szögben szóródott, ép protonok mérése

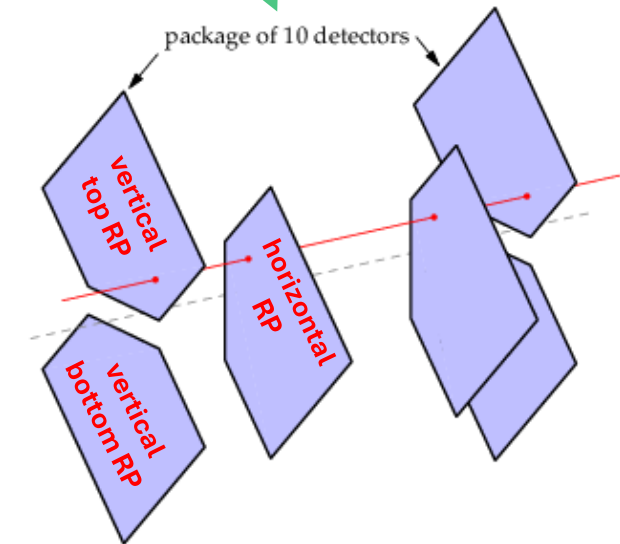


TOTEM RP detektorok 200-220 m távolságra vannak a IP5-től (az 5-ös ütközési ponttól)
CMS mindkét oldalán

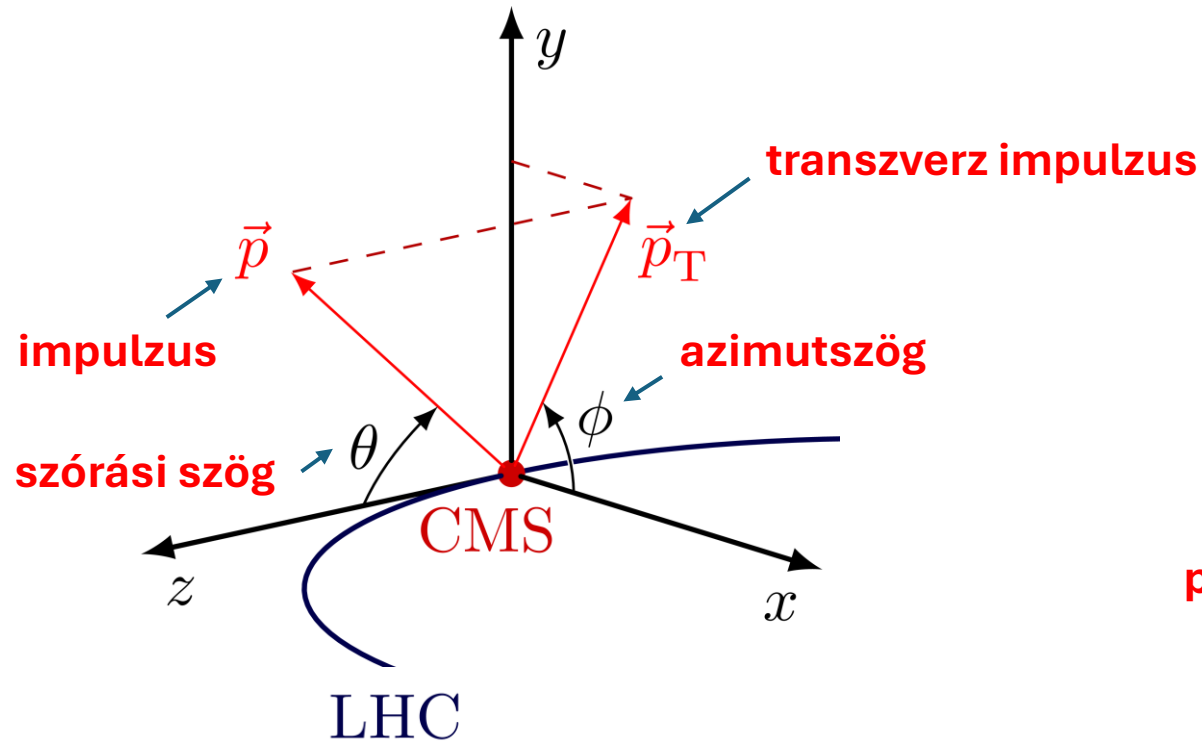
az RP-k (10 szilícium detektor lemez) a nyalábot horizontális vagy vertikális irányból közelítik meg



szilícium nyomjelző detektorlemezek



Kinematikai változók, koordináták

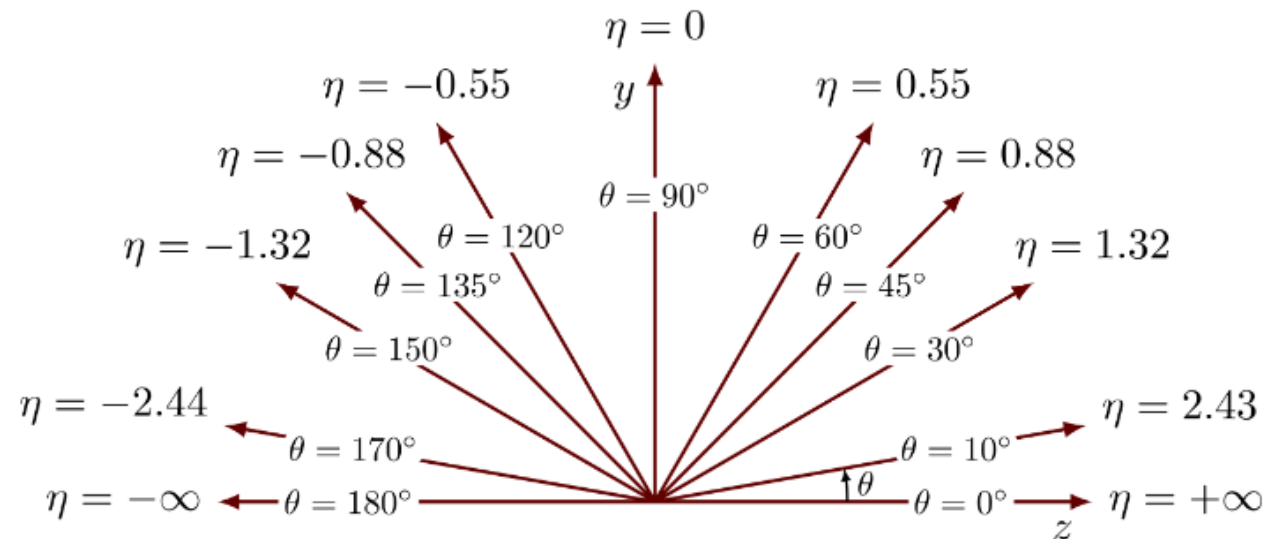


\sqrt{s} : tömegközépponti energia

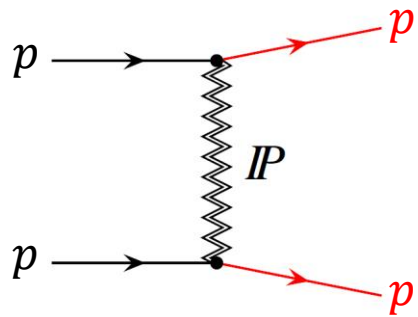
t : átadott négyesimpulzus-négyzet

ξ : a részecske impulzusvesztési hányada

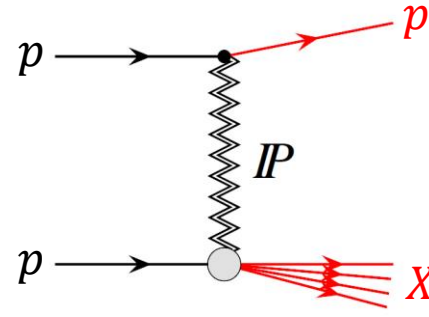
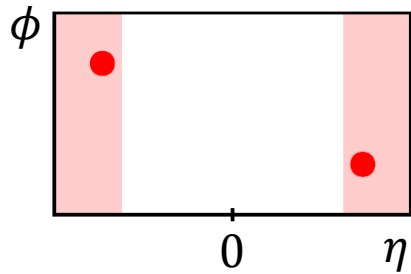
pszeudorapiditás: $\eta = -\ln \tan \theta/2$



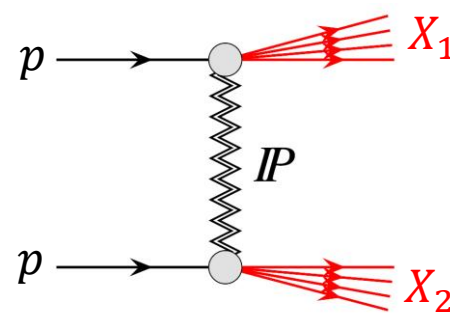
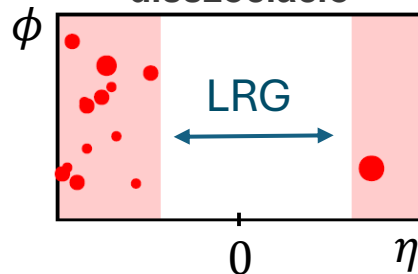
Diffraktív események proton-proton ütközésekben



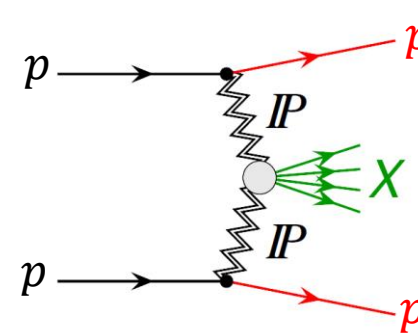
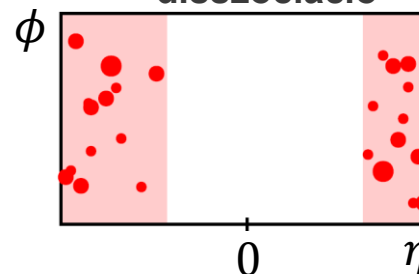
rugalmas



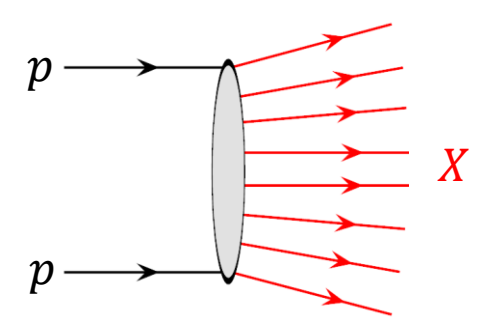
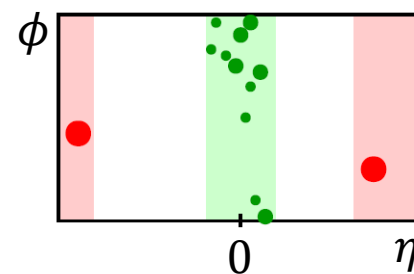
egyszeres diffraktív disszociáció



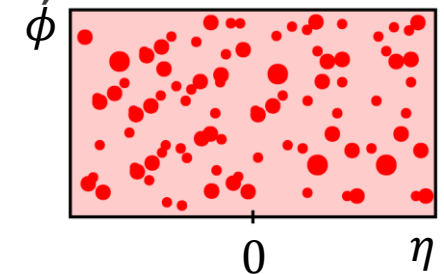
dupla diffraktív disszociáció



dupla pomeron csere
(centrális exkluzív keletkezés)



nem diffraktív

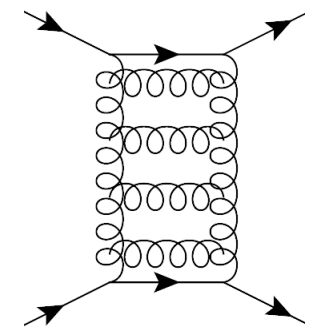


domináns **pomeroncsere** → **nagy rapiditásrés (LRG)**,
részecskék nélküli terület

“soft” pomeron a **Regge elméletben**: a vákuum kvantumszámaival rendelkező részecskék egész családja; energiával növekvő hadronikus keresztmetszeteket ad

“hard” (BFKL) pomeron a **pQCD-ben**: két kölcsönható gluon színtelen állapota

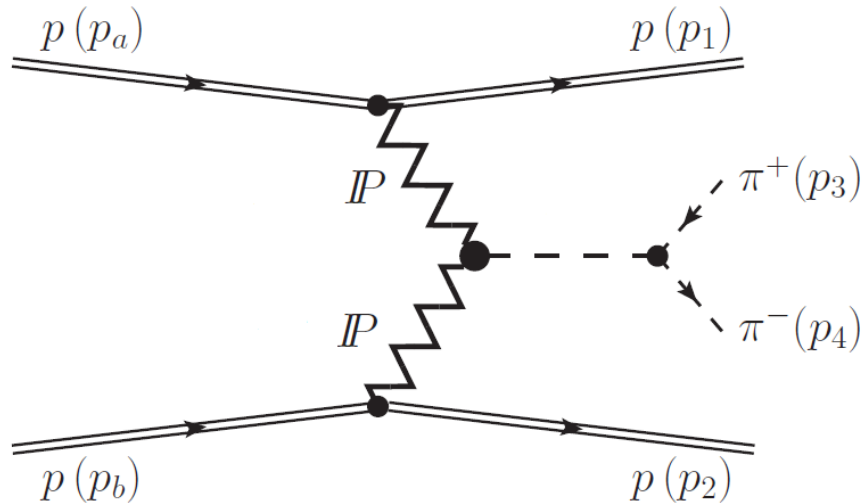
a pomeronfizika elméleti és kísérleti oldalról is népszerű és érdekes kutatási téma



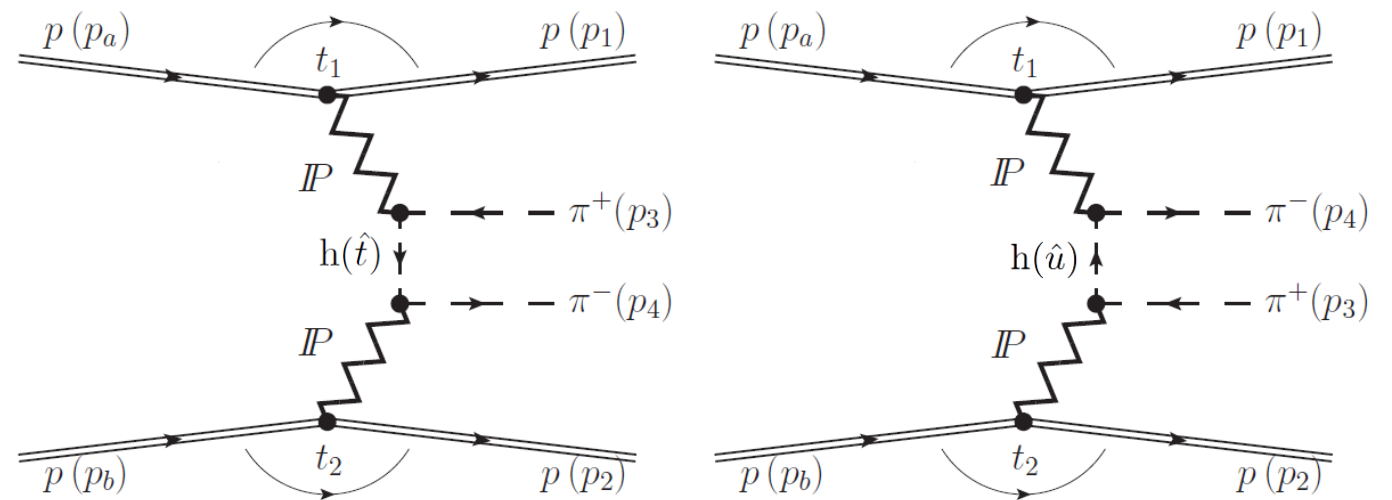
BFKL pomeron

Central exclusive production (CEP) of charged pion pairs

resonant component (Born-level)



nonresonant continuum component (Born-level)

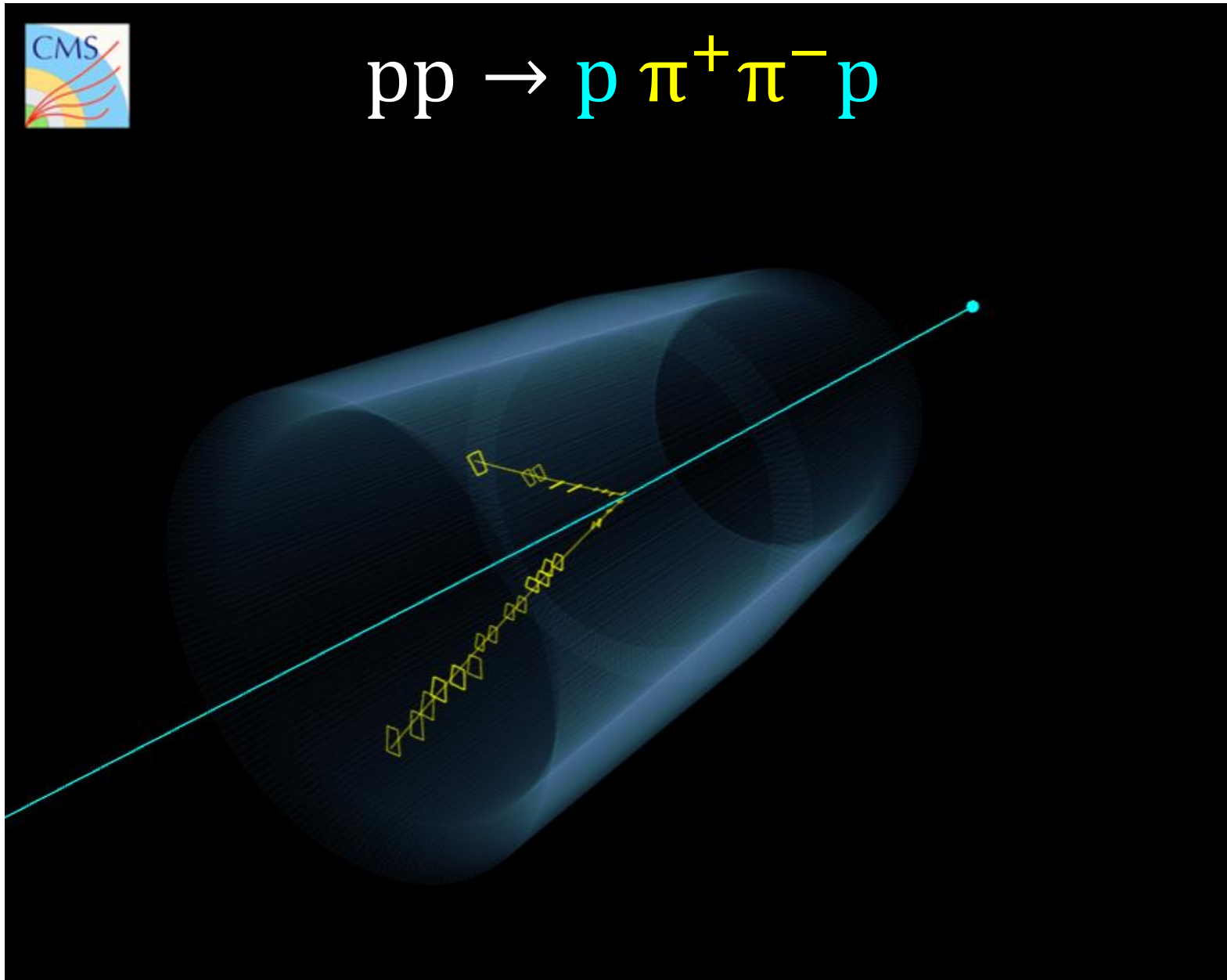


**nonresonant continuum production of charged pion pairs
is studied by CMS and TOTEM experiments**

in pp collisions at $\sqrt{s} = 13$ TeV

in the resonance-free region: $m_{\pi^+\pi^-} < 0.7$ GeV, $m_{\pi^+\pi^-} > 1.8$ GeV

Töltött pionpárok és ép protonok rekonstrukciója



Results, $d^3\sigma/dp_{1,T} dp_{2,T} d\phi$

studied variables:

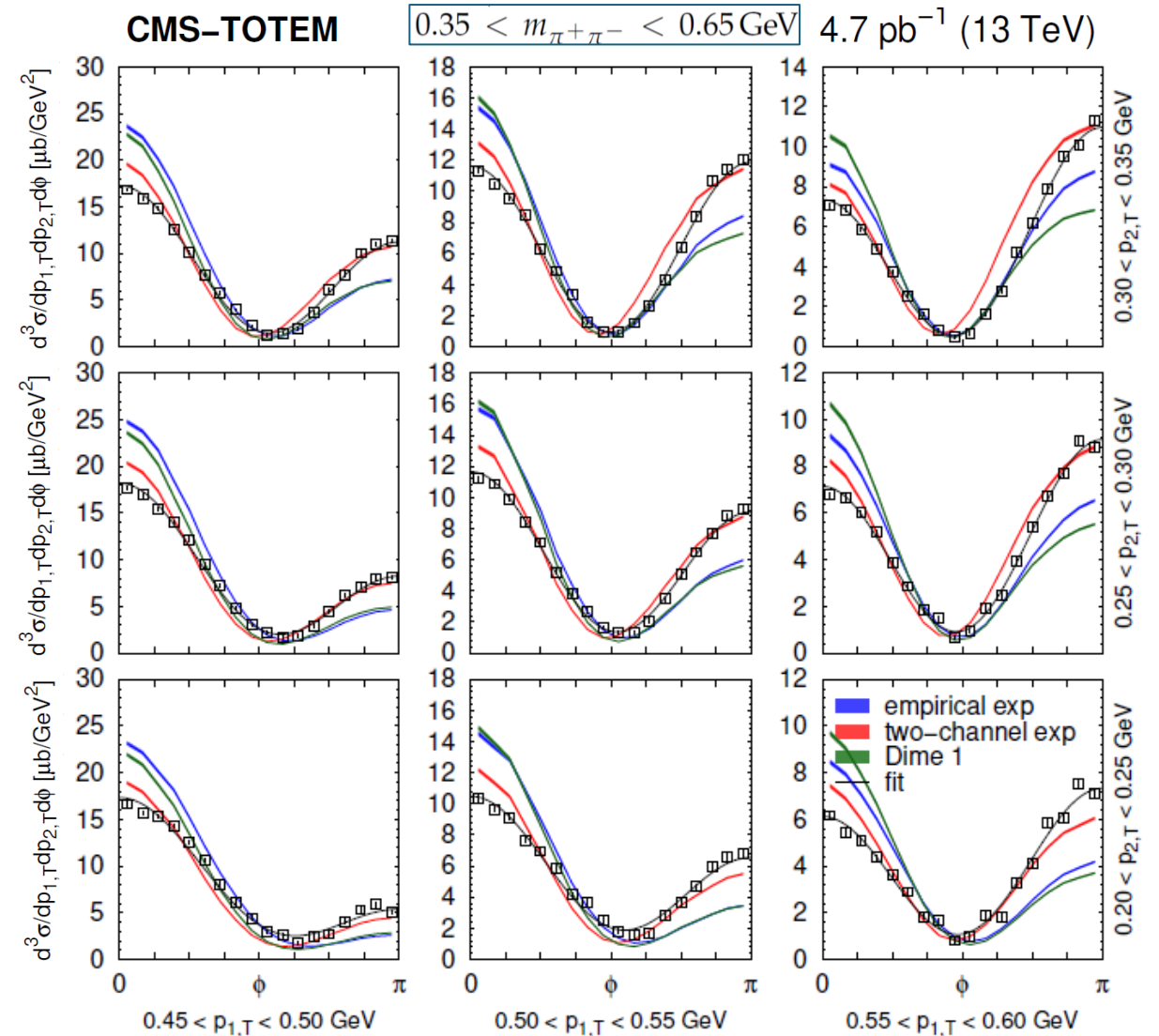
$p_{1,T}$ and $p_{2,T}$, the transverse momenta of final state protons;
 ϕ , the azimuthal angle between the scattered protons;
 m , the invariant mass of the pion pair;
 $\max(t, u)$ squared four momentum of the virtual meson

triple differential cross sections:

in ranges of $p_{1,T}$ and $p_{2,T}$, distributions of ϕ , m , and $\max(t, u)$

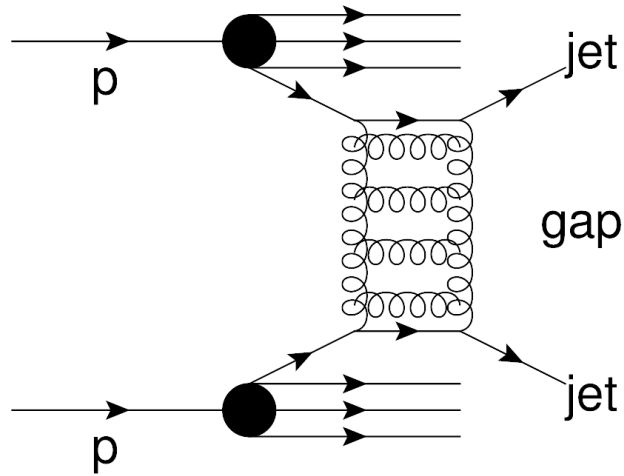
a parabolic minimum in the distribution of ϕ is observed for the first time

the minimum can be interpreted as an effect due to rescattering (absorption) corrections



models after tuning give better descriptions but still need for further theoretical developments

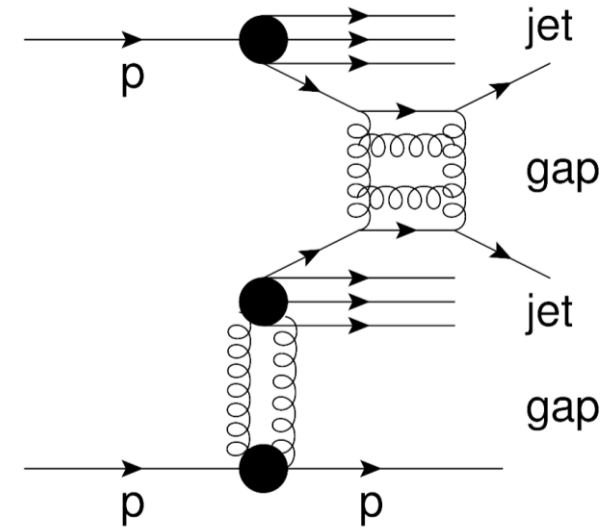
Dijet events with hard color-singlet exchange



jet-gap-jet event
by hard color-singlet exchange

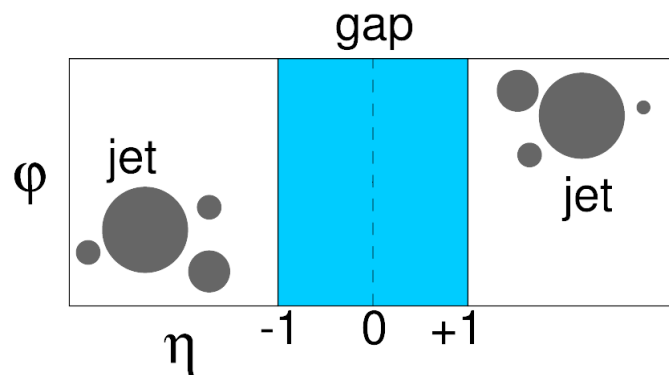
devoid of particle activity between the final-state jets due to **BFKL pomeron exchange**

tool to study BFKL dynamics



jet-gap-jet with intact proton event
by hard color-singlet exchange

[Phys. Rev. D 104 \(2021\) 032009](#)

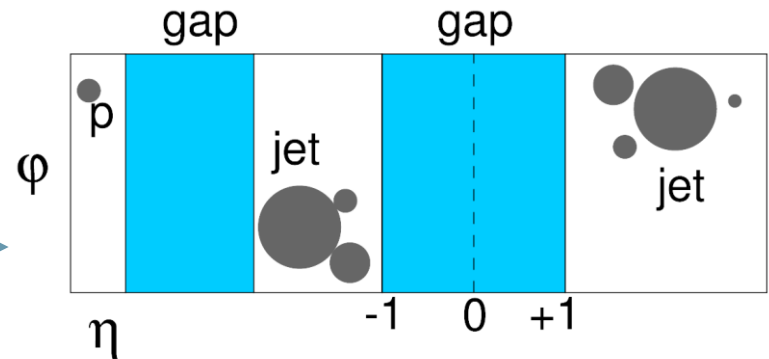


jet-gap-jet event signature in the φ - η plane

measured by CMS

measured by CMS+TOTEM

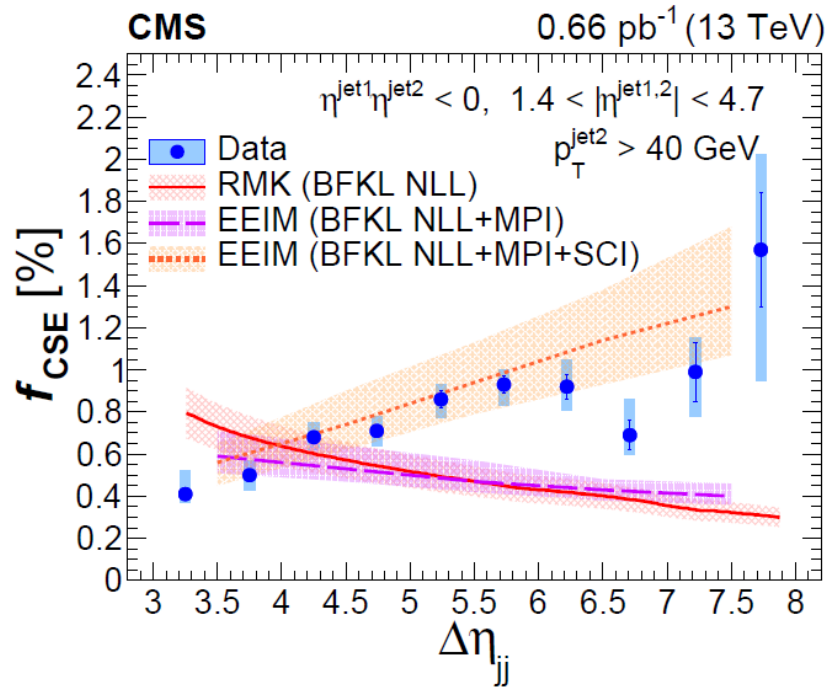
$\sqrt{s} = 13 \text{ TeV}$



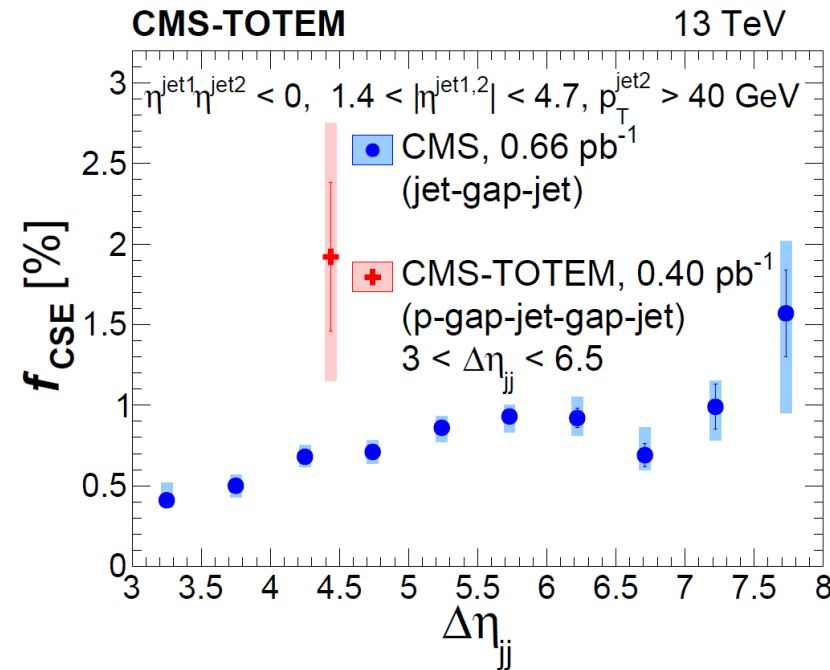
jet-gap-jet + intact proton event signature in the φ - η plane

CMS color-singlet exchange (CSE) dijet event fractions

the fraction of color-singlet exchange dijet events, f_{CSE} , is measured in bins of different variables eg. $\Delta\eta_{jj} = |\eta^{\text{jet1}} - \eta^{\text{jet2}}|$

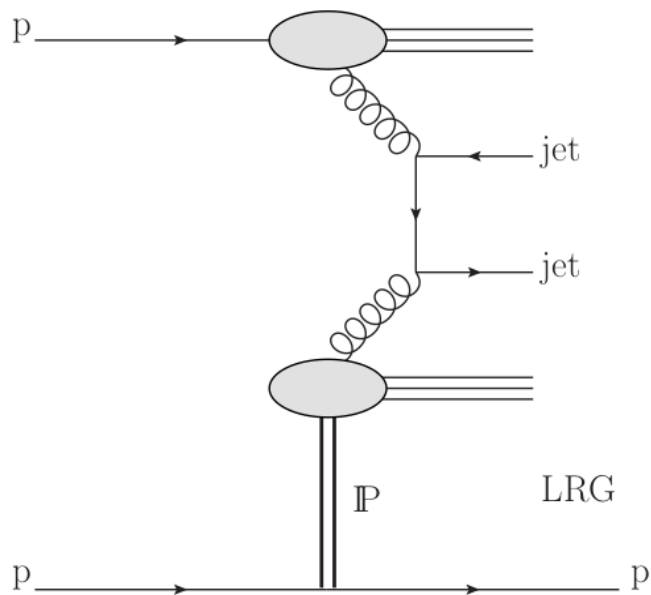


there are theoretical (BFKL) calculations with different details that quite well agree with measurement



limited sample size, a measurement as a function of kinematic variables is not possible: the f_{CSE} is extracted using the entire sample of events

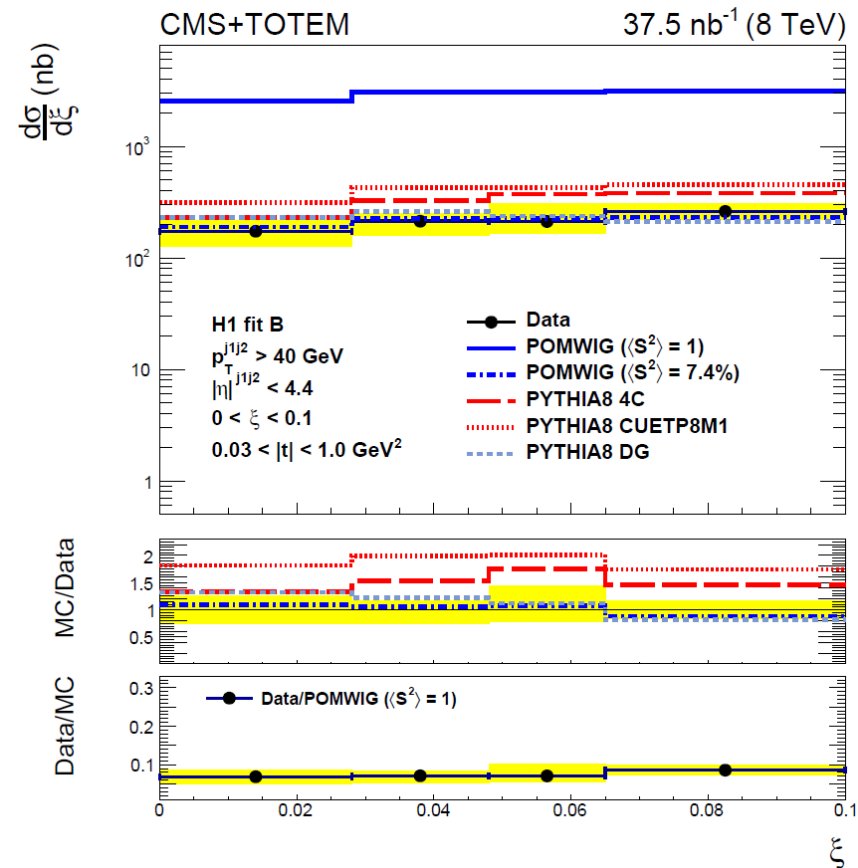
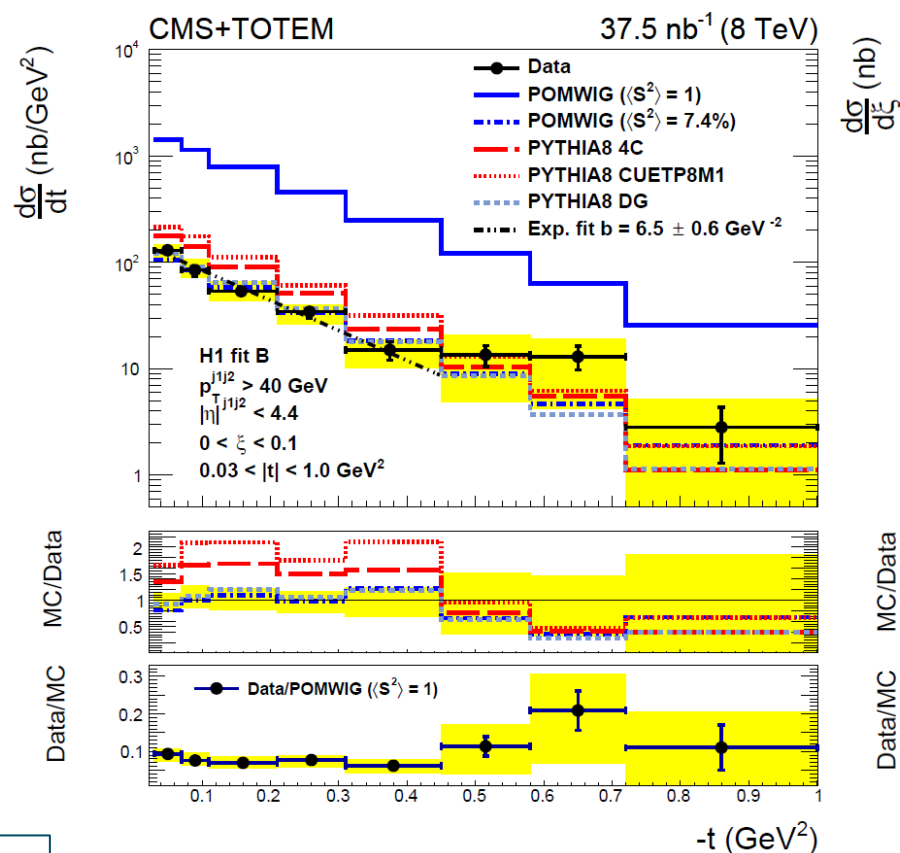
Single-diffractive (SD) dijet production



Schematic diagram of single-diffractive dijet production

high- p_T jets are measured in CMS,
the scattered proton is measured
in the TOTEM detectors

[Eur. Phys. J. C 80 \(2020\) 1164](#)



POMWIG (with $\langle S^2 \rangle = 7.4\%$) and PYTHIA8 DG MC predictions show good agreement with the data

the t distribution up to about 0.4 GeV^2 is well described by an exponential function

Summary

- various diffractive processes measured jointly by CMS and TOTEM in pp collisions
- first time observation of a parabolic minimum in the distribution of the azimuthal angle difference of the final state protons in central exclusive production;
- various physical parameters related to pomeron physics extracted/tuned
- good agreement between BFKL and jet-gap-jet measurements
- first measurement of hard diffraction with a measured intact proton at LHC

Thank you for your attention!