Accelerators and Cosmic Ray Physics

Michael Albrow, Fermilab (emeritus)

Contents:

Just a few highlights
Some history
Proton-proton and p-nuclei collisions
Now at LHC
Very far from complete!

History of the interaction of High Energy Physics and Cosmic Ray communities

Why me?

1) Post-doc at CERN 50 years ago. **ISR = Intersecting Storage Rings** started 1971 (1st pp collider)
Equivalent Fixed Target energy 26 GeV → 2000 GeV « Into the realm of cosmic rays »
Small Angle Spectrometer – measured charged hadron spectra all $x_F = p_z/p_{beam}$
Feynman scaling & Hypothesis of Limiting Fragmentation
~ 1990 SPS [Cygnus X3]

2) Fermilab – CDF. AUGER's early days, Fermilab study and Technical Design Report (FT looking in)

3) ISVHECRI 2010 at Fermilab : Accelerator Data for Cosmic Ray Physics – unexplored phase space

4). Tevatron (**CDF**) > LHC (**CMS**) > LHC (**FHS** = Forward Hadron Spectrometer)? 2024??

Topics – too vast a field for one talk

The cosmic ray spectrum

Hadron production – generalities – focus on very forward region

Fixed target experiments : SPS – FNAL – CERN

Hadron and ion collider experiments : ISR – SppS – Tevatron – RHIC – LHC

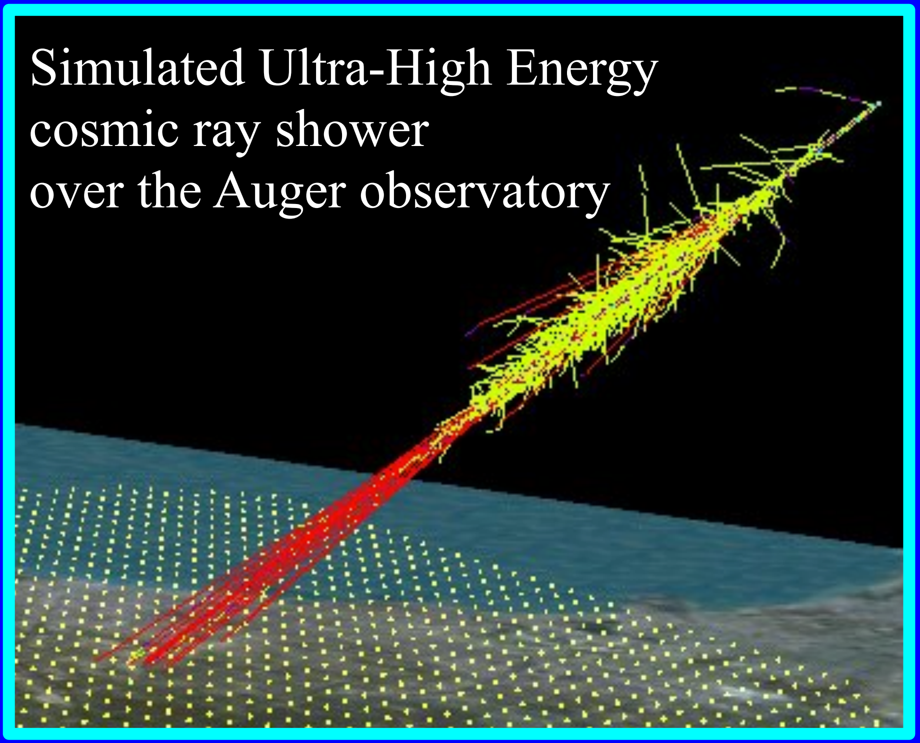
Future at LHC : AFTER (A Fixed Target Experiment at LHC) – FHS? –

Far future? : FCC = Future CERN Collider (pp & Pb+Pb & p-O and O-O …)?

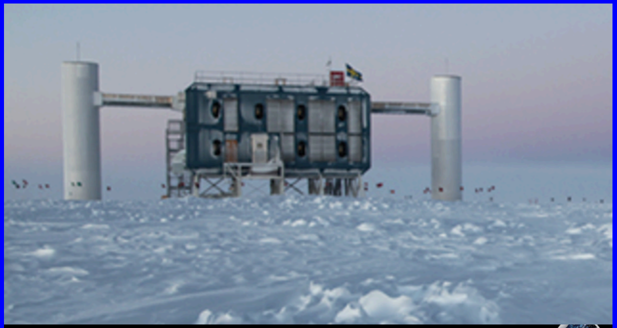
Conclusions

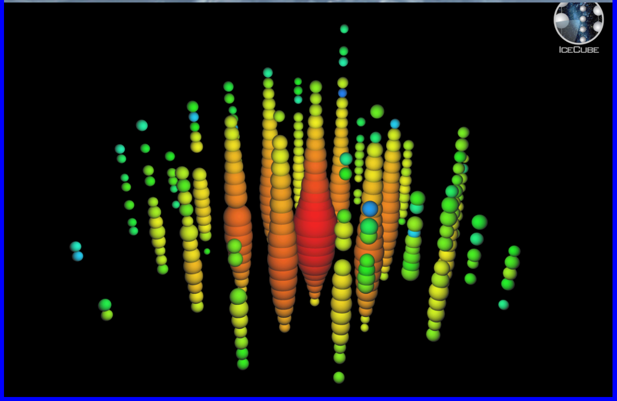
Studying the cosmos with ultra-high energy particles

A particle shower in Antarctic ice, 1 km^3 **ICECUBE** started by a 1100 TeV neutrino



Water Cherenkov tanks ~ 1 km spacing
+ Giant eyes looking at light flashes on dark nights





Simulating showers and ν rely on particle production cross sections that are not well known

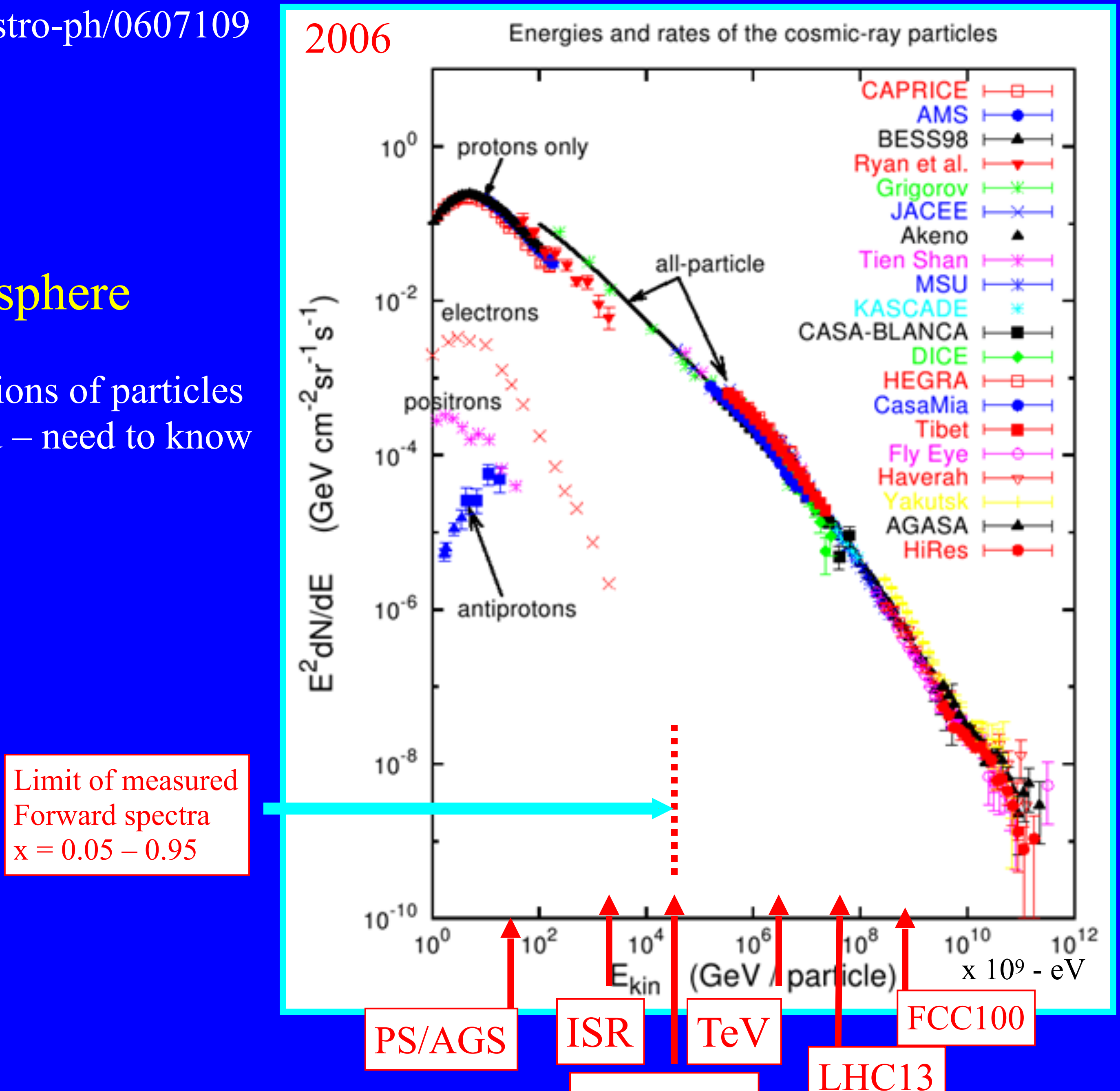
From **A.Hillas**, astro-ph/0607109

Showers in atmosphere

Light emitted

Numbers and distributions of particles

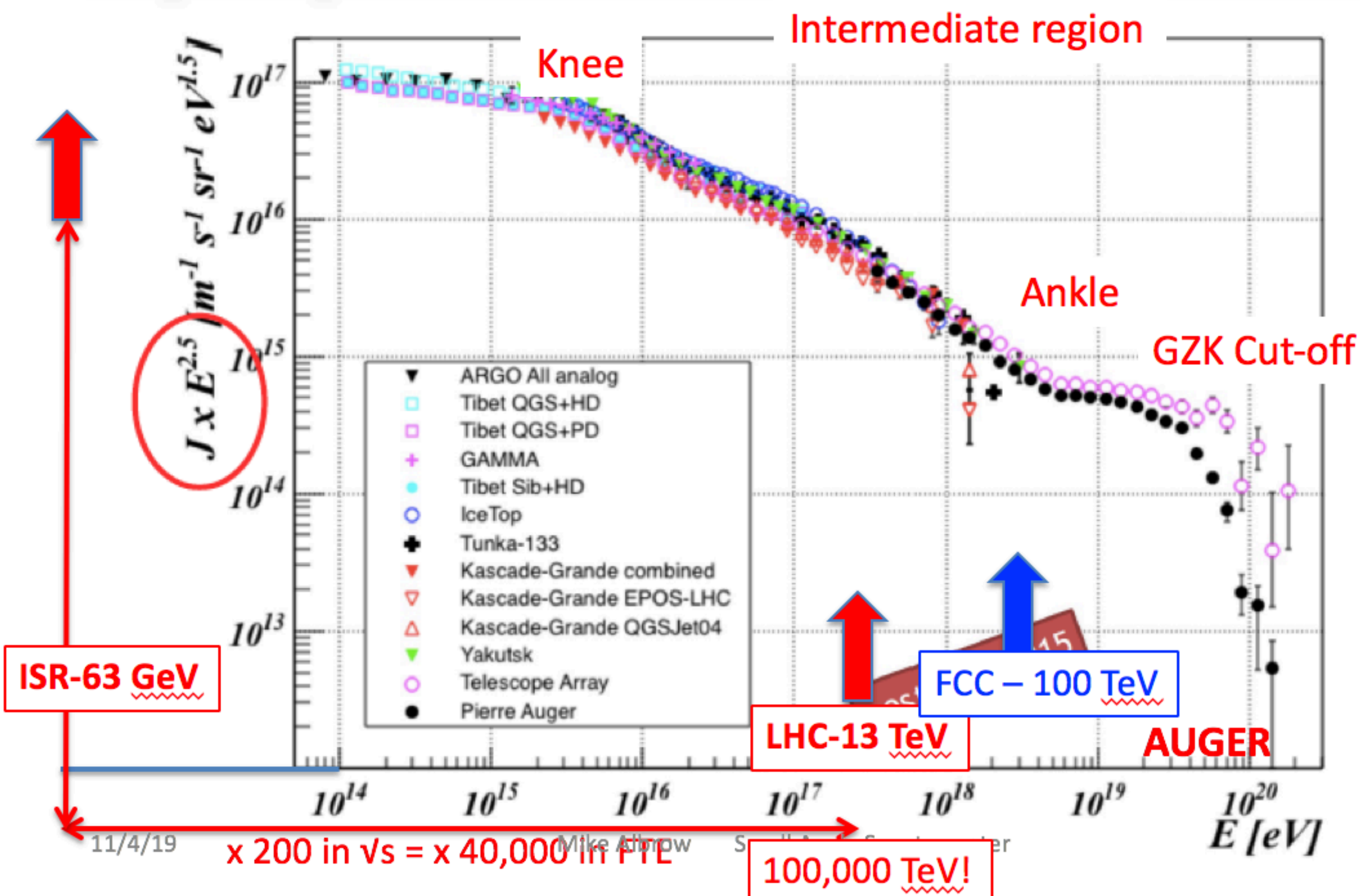
Neutrinos not included – need to know



COSMIC RAY SHOWERS: ASTROPHYSICS CONNECTION

Spectrum of high energy Cosmic Rays $\phi(E) \times E^{2.5}$

All particle spectrum



1940s – 1950s

Post-war support in USA for research accelerators

1946: Rad Lab at Berkeley (now LBL) 184-inch cyclotron
1947: Charged pions discovered in cosmic rays (next slide)

Associated Universities Army Camp Upton → Brookhaven National Lab.
UNESCO originated CERN 1952. 600 MeV in 1957 (synchrocyclotron)

Strong focusing principle invented →

AGS at Brookhaven (30 GeV), PS at CERN (28 GeV)
Cf. NIMROD in UK 7 GeV

1950 – From C.F. Powell's Nobel lecture (discovery of the pion)

Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary cosmic radiation. As a result of investigations extending over more than 30 years, we now know the nature of the incoming particles, and some, at least, of the most important physical processes which occur as a result of their passage through the atmosphere. … concluding:

with their fixed and eternal atoms. At the present time a number of widely divergent hypotheses, none of which is generally accepted, have been advanced to account for the origin of the cosmic radiation. It will indeed be of great interest if the contemporary studies of the primary radiation lead us - as the Thomsons suggested, and as present tendencies seem to indicate - to the study of some of the most fundamental problems in the evolution of the cosmos.

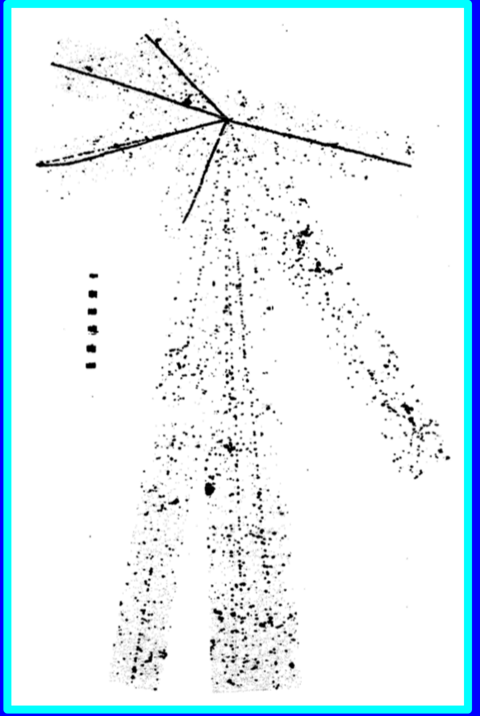
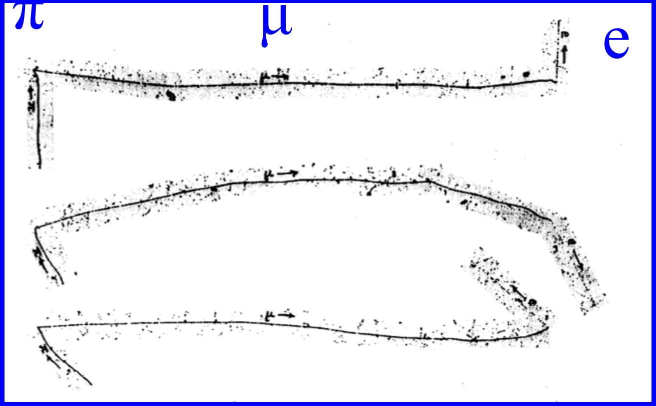
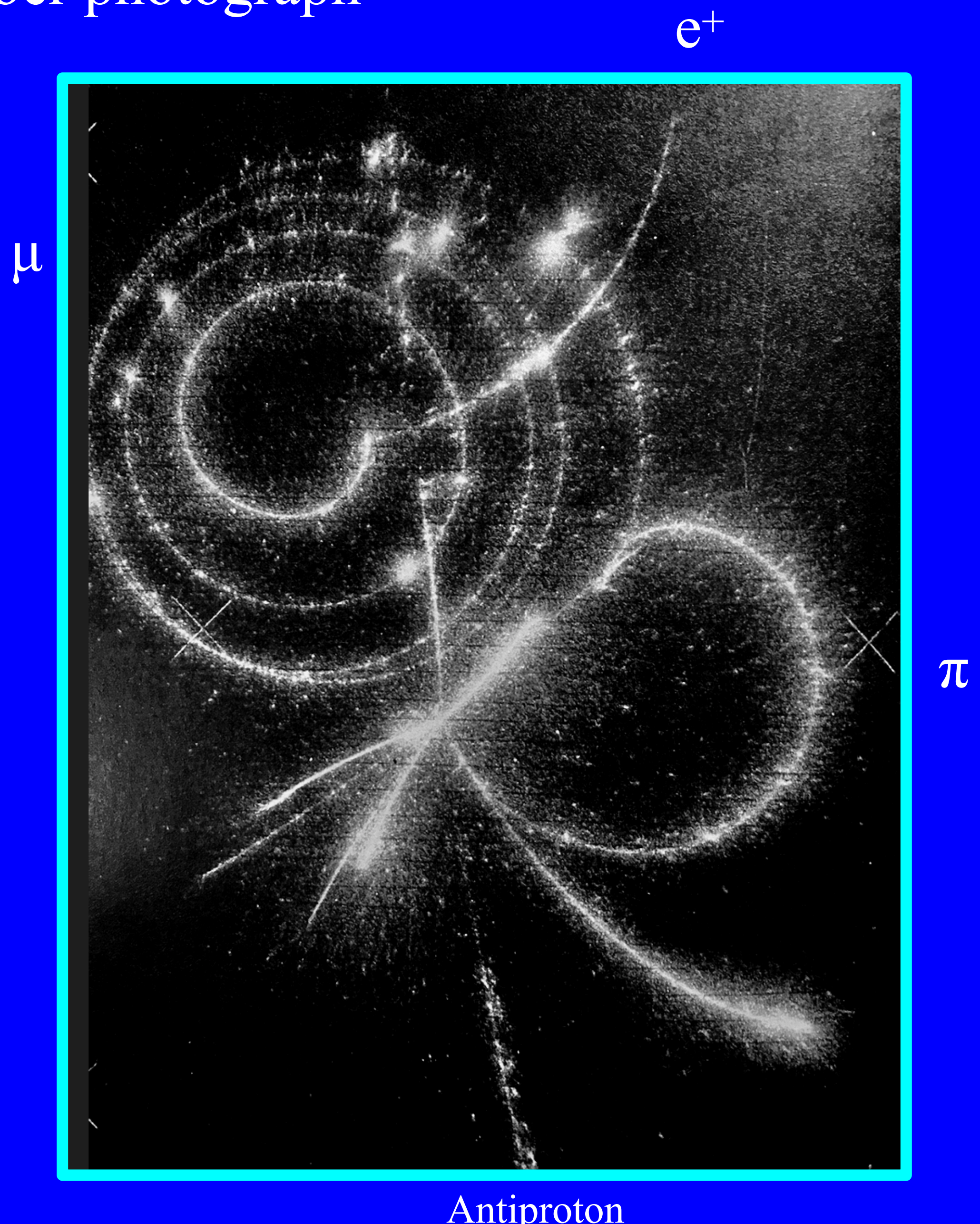


Fig. 4. A disintegration caused by a fast neutron of the cosmic radiation. The «thin tracks» of the fast-moving shower particles can be distinguished. Most of these are due to π-particles. A γ-ray, produced by the decay of a neutral π-meson, gives rise to a pair of electrons near the «star».



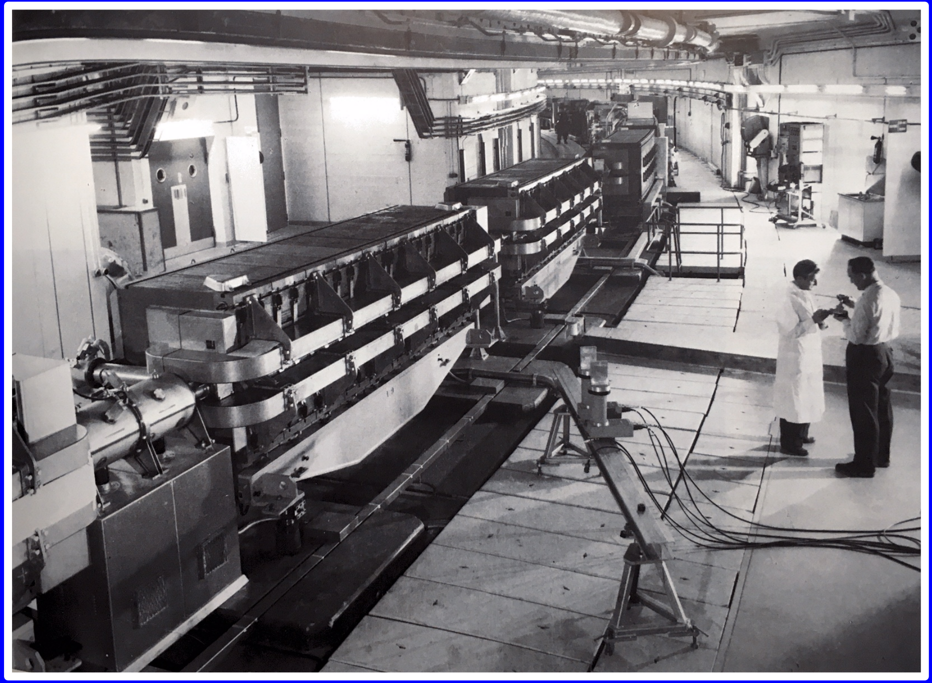
Examples of π - μ – e decays in photographic emulsion

Streamer chamber photograph



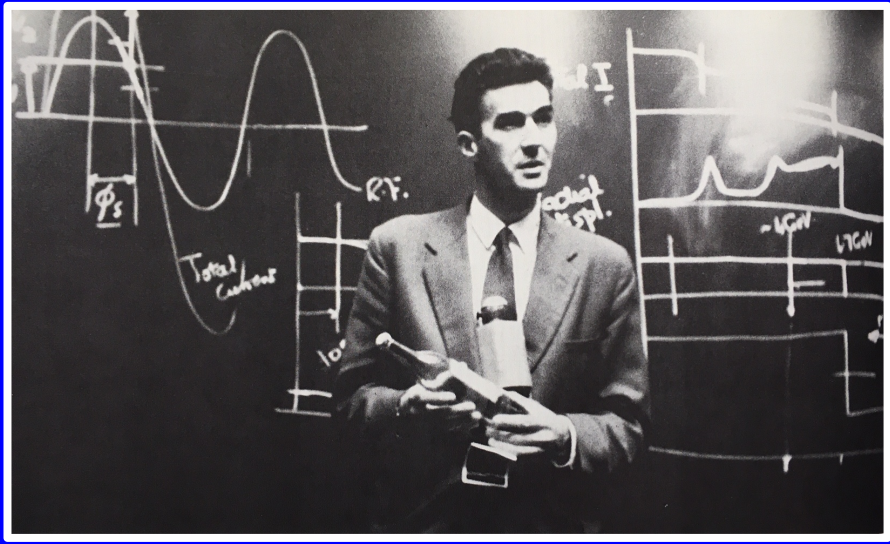
1959 Where were we then? Accelerators first steps to the cosmos

CERN's PS = Proton Synchrotron achieves 24 GeV proton beam on November 24th beating Dubna's record of 10 GeV.



Detectors: two scintillation counters!

John Adams announcing world record in Auditorium
Bottle has polaroid of scope trace to send to Dubna



Soon - July 1960 Brookhaven AGS → 33 BeV (GeV)

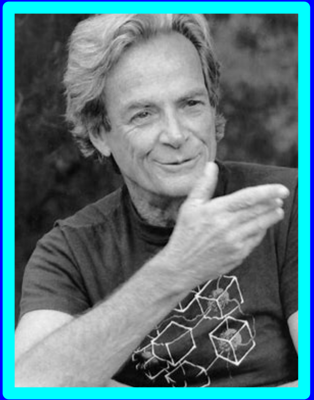
1969 Where were we then, 10 years later?

Highest energy accelerators:
CERN's Proton Synchrotron PS
Brookhaven's Alternating Gradient Synchrotron AGS
And in 1967 U70 at Serpukhov, Protvino, Russia

Proton beams on targets > beams of π-mesons, K-mesons, etc.
Proliferation of strongly interacting particles (hadrons)

GM:1929-2019

Gell-Mann gets Nobel Prize for symmetries, quarks
Bjorken had just derived scaling relations
Electron hard scattering at SLAC(Stanford) finds scaling
Feynman proposes pointlike parton model → scaling
Feynman scaling : hadron spectra functions p_T & $x_F = p_z/p_{beam}$



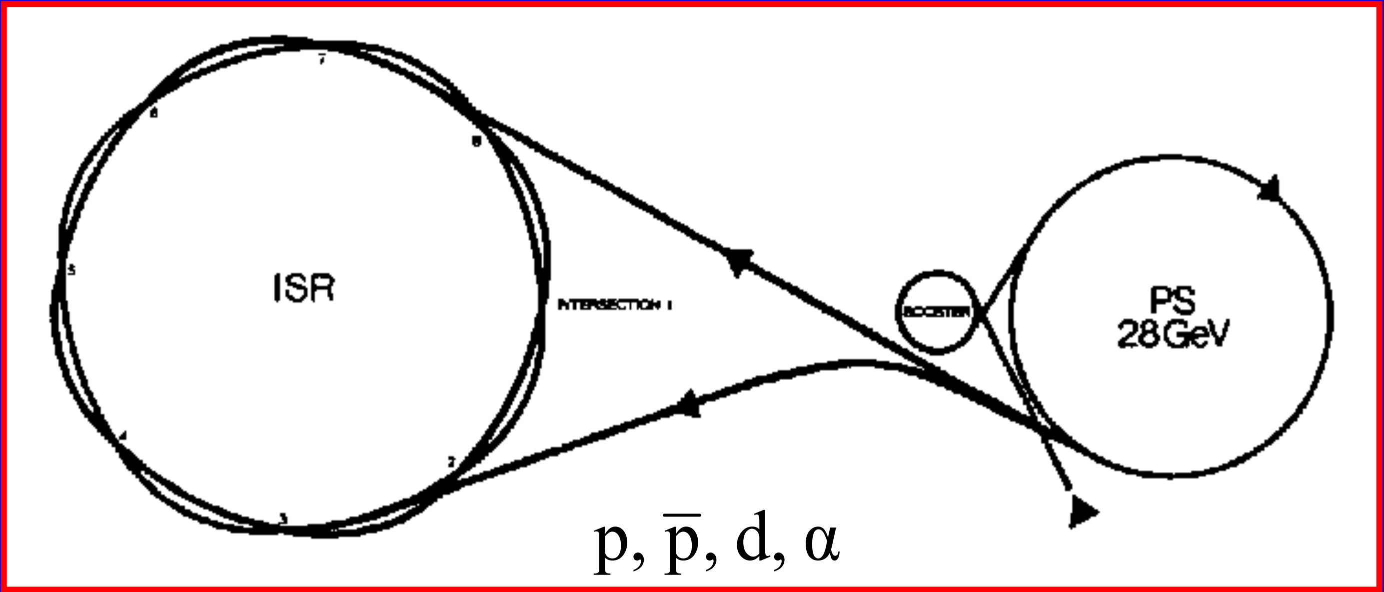
F: 1918-1988

Later: Partons known as quarks and the gluons that bind them
Theory of strong force **Quantum ChromoDynamics QCD**

ISR

Intersecting Storage Rings at CERN

1971, first colliding proton beams - 1982



Eventually 60 amp proton beams!!

p(31.4 GeV/c) p(31.4 GeV/c) p(28 GeV/c) p

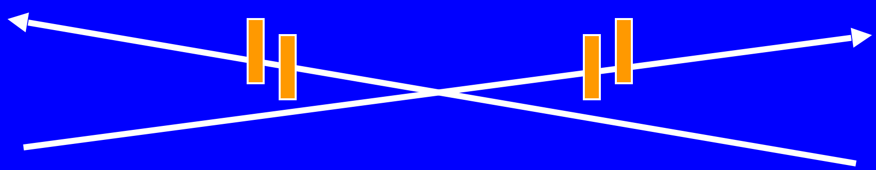
Centre of Mass Energy = 63 GeV **Centre of Mass Energy = 7.4 GeV**

Equivalent to beam of 2110 GeV + fixed p target

"Into the realm of cosmic rays!"

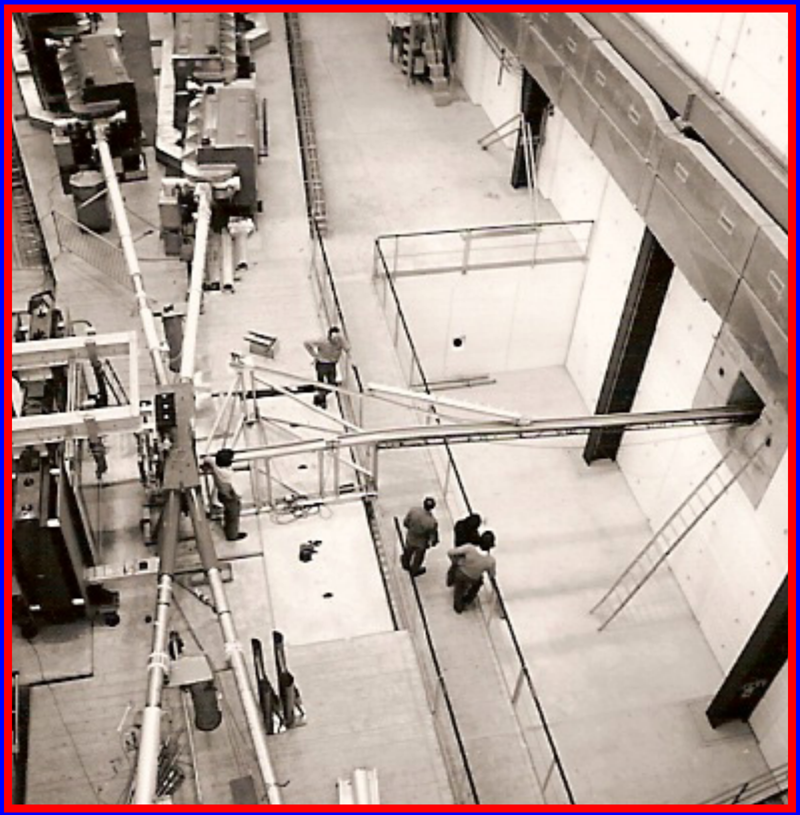
Free quarks? W-boson? What surprises to come?

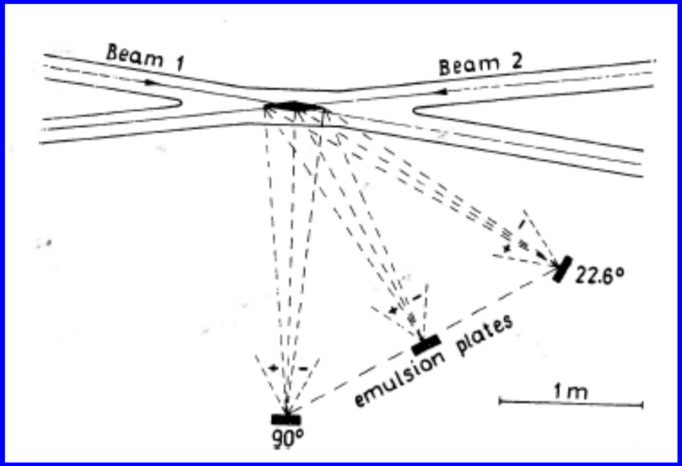
First collisions ... no detectors installed! ... put in 4 scintillation counters!
Saw 'scope traces due to collisions (timing!)



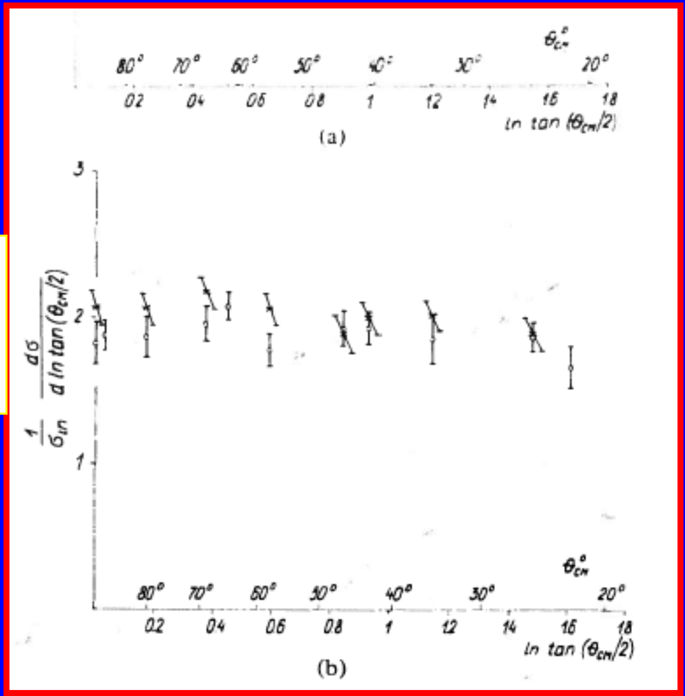
Experiment R101, First at ISR (1971) Emulsions on a toy train set!

ISR





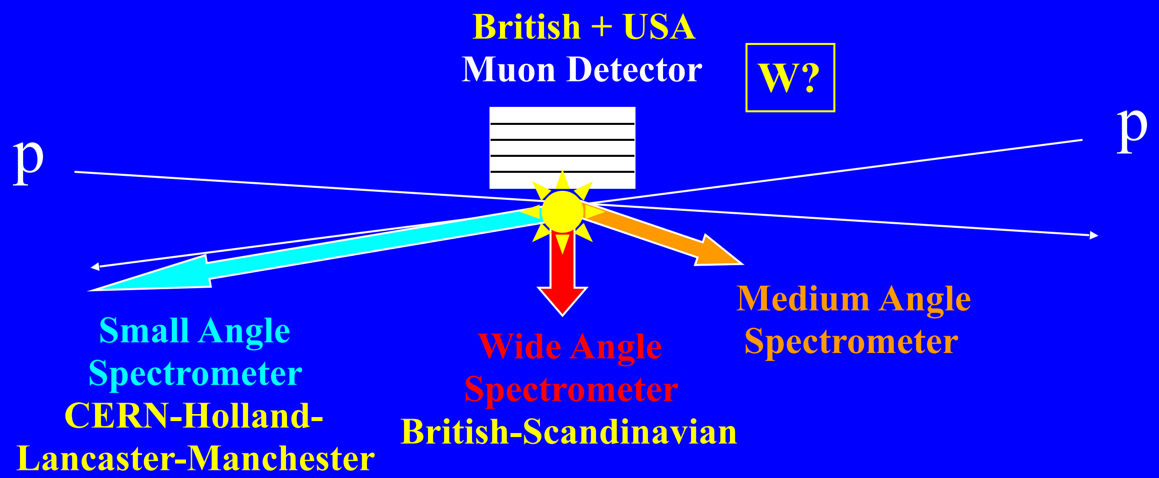
$$\frac{1}{\sigma_{inel}} \frac{d\sigma}{d\eta}$$



η = - log tan (θ/2)

2009 - 38 years later
First paper on LHC physics:
Also angular distribution of charged particles

Intersection I-2: ISR



Single particle inclusive spectrometers:

Muon Detector: Looking for W(~3-4 GeV!) ... missed J/ψ (several did!)
Wide Angle Spectrometer: co-discovered high p_T (quark & gluon scattering)
Small Angle Spectrometer:
Feynman scaling of forward production tested &
discovered high mass diffraction - Masses ~ 12 GeV > N* (2 GeV)

Why is accelerator data important for VHECR?

If energy of a showering cosmic ray is totally contained in the atmosphere, it is a homogeneous calorimeter. But ν's disappear!
E.g. in Auger: total fluorescence light ***f(Σ- path lengths charged particles)***
…$\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^- \rightarrow$ many e's in shower (Cherenkov)
Number muons *(from π,K,c,b –decay)* measured at some depth.
Lateral (and some longitudinal) profiles measured.

E(primary) and A(=1, >1)(primary) inferred

Many simulation models KASKADE, HPDM, VENUS, SIBYLL, QGSJET …
What we think we expect about VHE interactions,
far extrapolation over accelerator data.

PS → ISR → SppS/Tevatron → LHC
New physics came in at each step!

But most inelastic collisions have many outgoing particles!

What to do? 10 particles → 40 variables, with just 4 E-p constraints.

No 36-dimensional graph paper! Hard to measure all!

The ISR dilemma!

A solution: Just measure 1 and ignore the rest.

$$p + p \rightarrow \pi^{+} + \text{"anything"}(X)$$

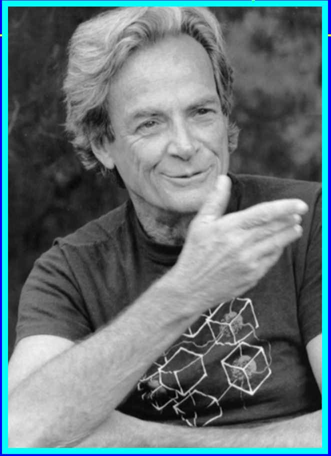
Single particle inclusive:

$$\sigma = \sigma_{inv}(s, p_T, x_F) \underset{s\to\infty}{\longrightarrow} f(p_T, x_F)$$

$$\text{Feynman } x_F = \frac{p_z}{p_{beam}}$$

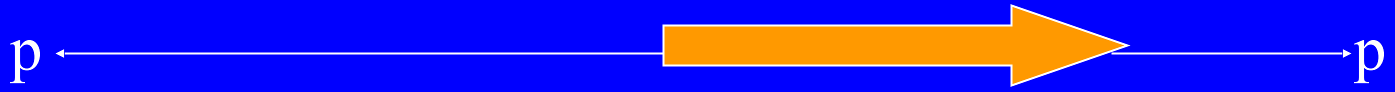
$$\text{Longitudinal Rapidity } y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

Feynman scaling hypothesis (pre-parton model)



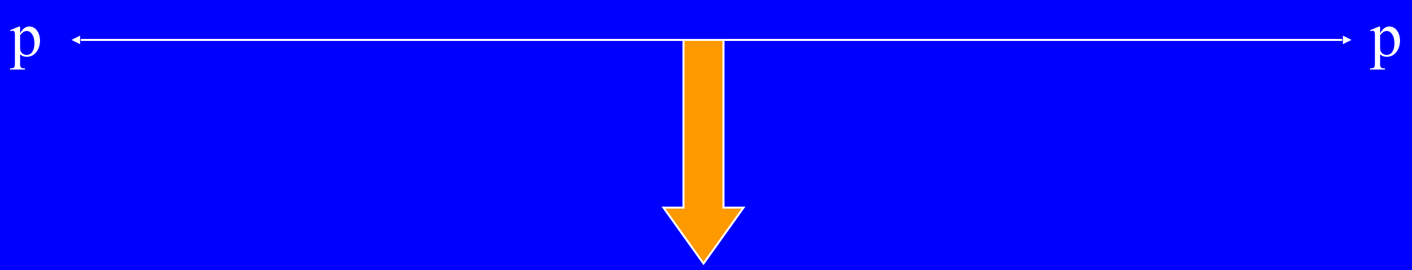
Primary focus shifted – ISR a ‘transitional machine’:

< 1971



Low transverse momenta
large distance (~ 1 fermi : fm = 10^{-13} cm)
Strong interaction difficult to calculate - models

> 1976

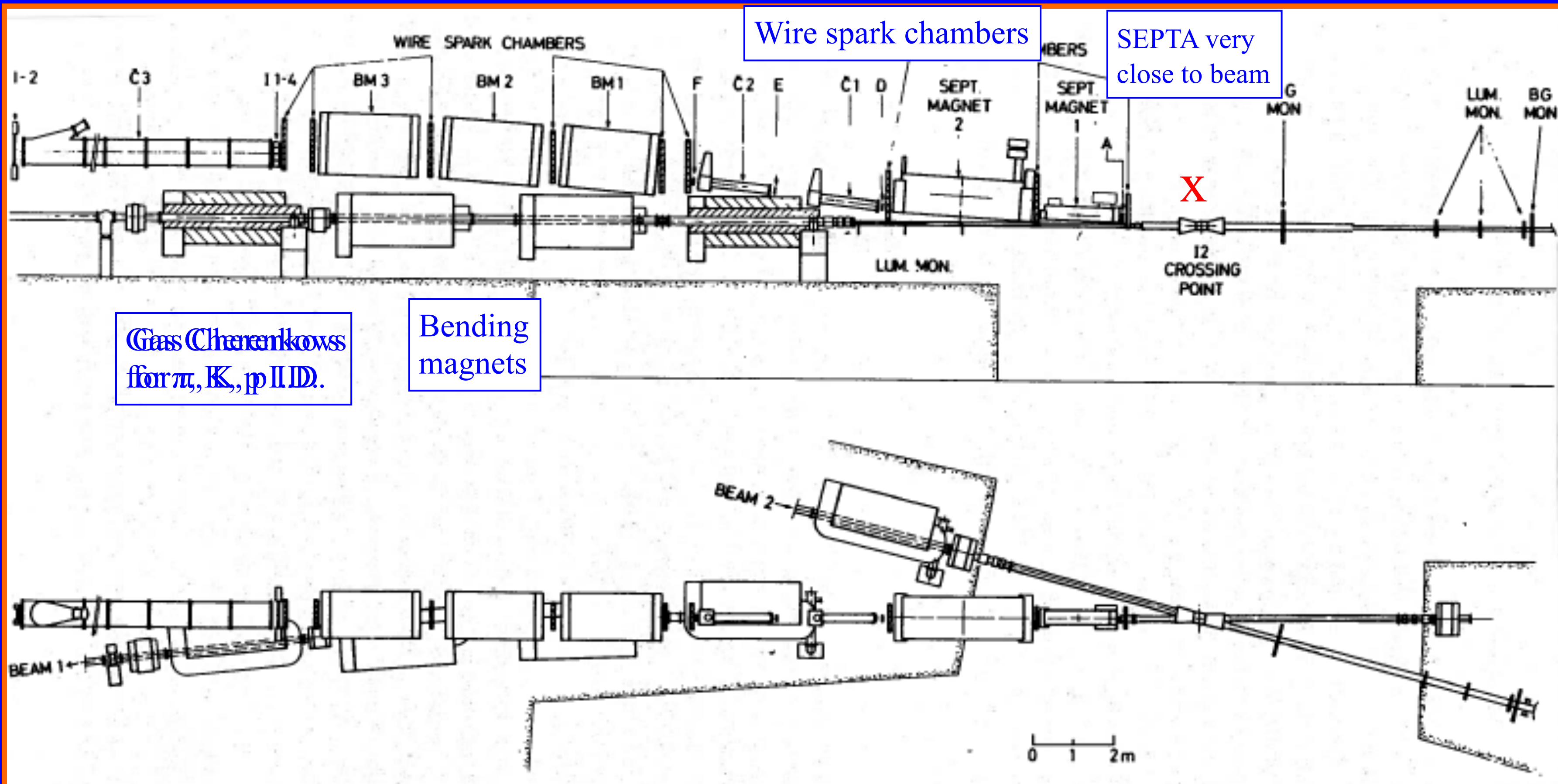


High transverse momenta
small distances (<< fm)
QCD calculations work (‘perturbative’)

Small Angle Spectrometer (CERN-Holland-Lancaster-Manchester)

ISR

$\pi^+, \pi^-, K^+, K^-, p, \bar{p}$ spectra, low p_T, $x_F = 0.1 - 1.0$, $\sqrt{s} = 23 - 63$ GeV



All elements moveable to cover range of angles

ISR: CHLM

Feynman-x distributions

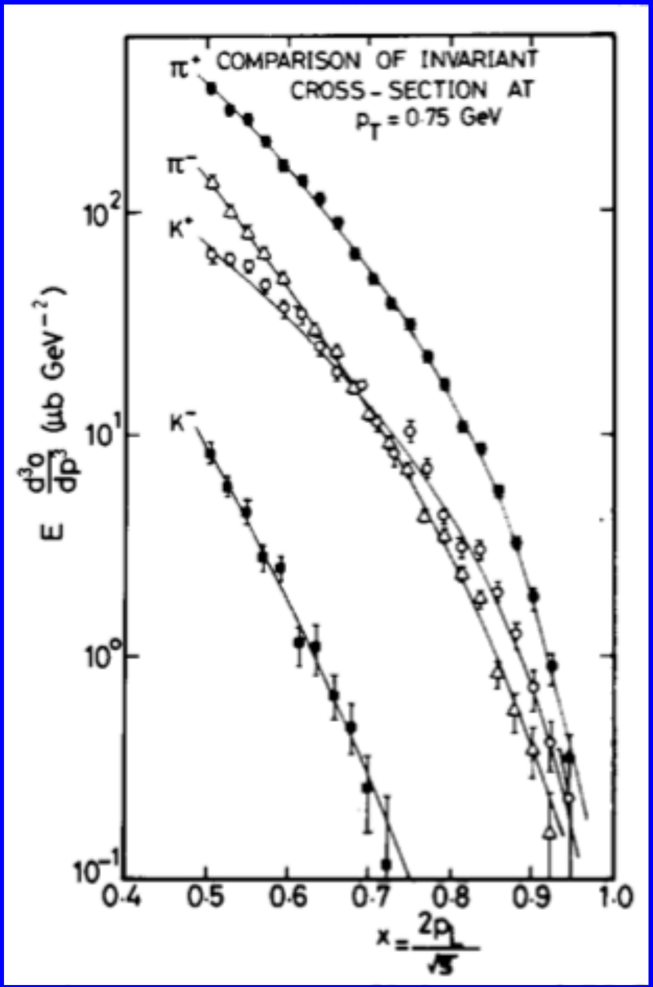
Fixed small $p_T = 0.75$ GeV/c scale

Leading proton, scaling peak $x_F > 0.9$, ISR

Discovery of high mass diffraction

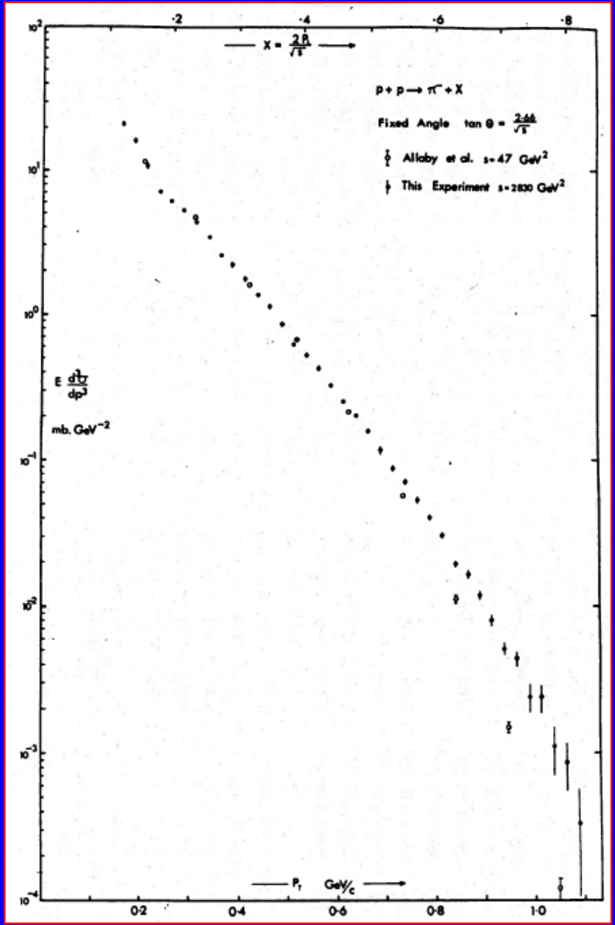
High-x peak 'scales" → high masses

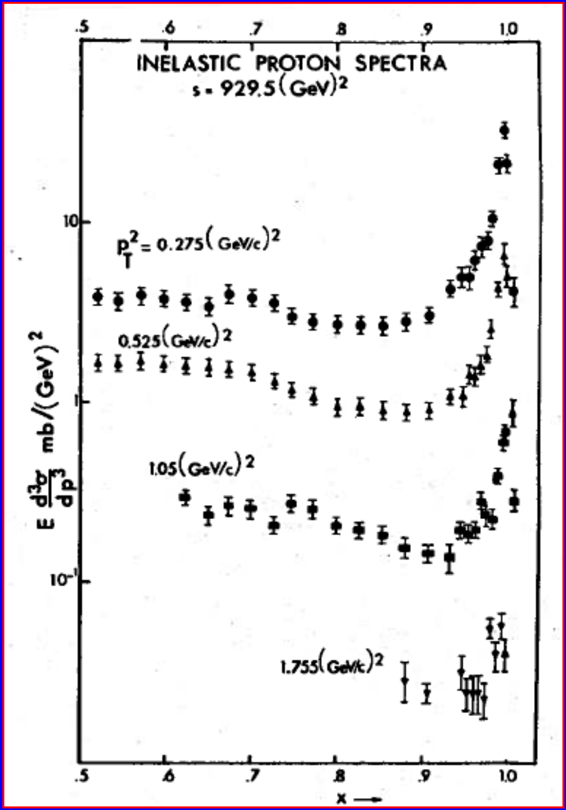
π^+ scale K^+ rise



Fixed small angle

$x_F = 0.1$ $x_F = 0.8$





Feynman $x_F = p_z/p_{BEAM}$

$$\frac{M^2}{s} <\sim 0.05 \Rightarrow M <\sim 0.22\sqrt{s}$$

$M \sim 1.5$ GeV @ PS $\Rightarrow M \sim 14$ GeV @ ISR

Do the CR models fit this data well?

R608 Forward multiparticle spectrometer, exclusive diffraction studies.

ISR

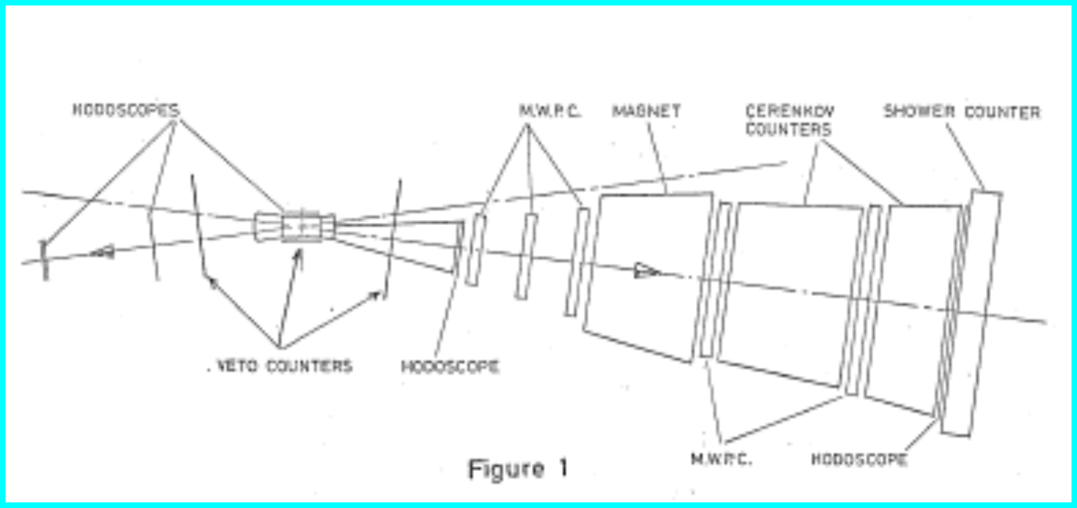


Figure 1

pp and $p\bar{p}$ collisions; $\sqrt{s}$ = 53 GeV

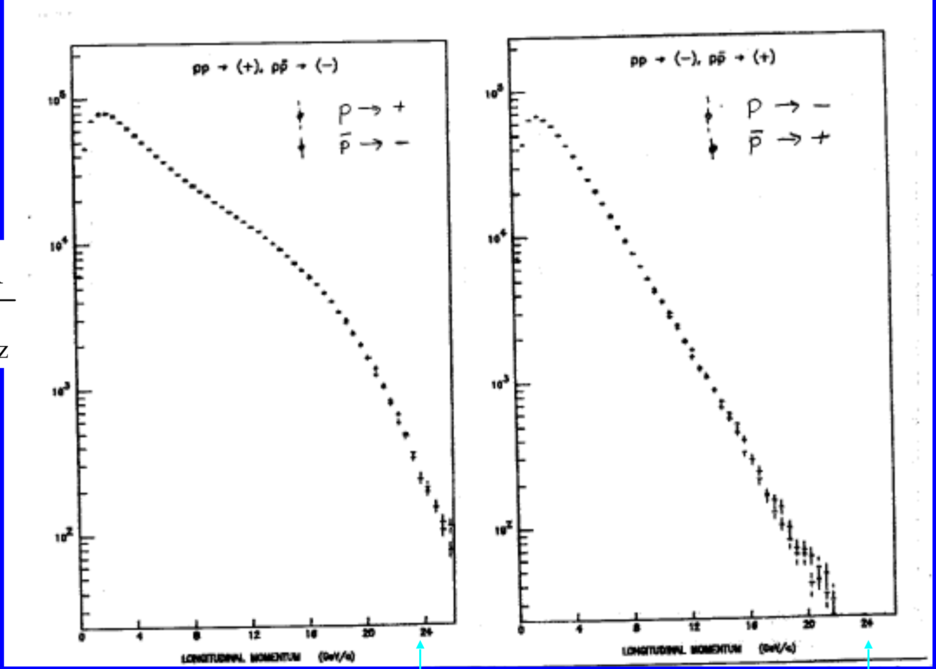
$p \to h^+ \quad p \to h^-$

$\bar{p} \to h^- \quad \bar{p} \to h^+$

Particle momenta and identities (Cherenkov)

Similarly p_T distributions to 2 GeV/c

$\frac{dn}{dp_z}$



p_z=24 GeV/c

p_z=24 GeV/c

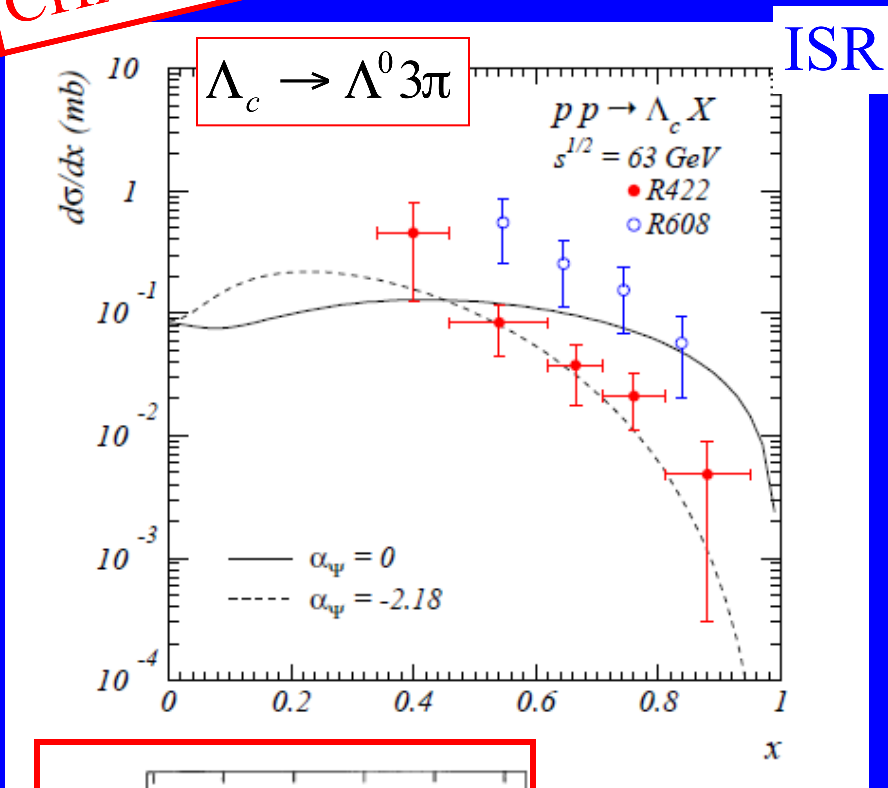
Baryon fragmentation does not care about identity of opposite side baryon.
L-R Factorization & C-conjugation.

CHARM!

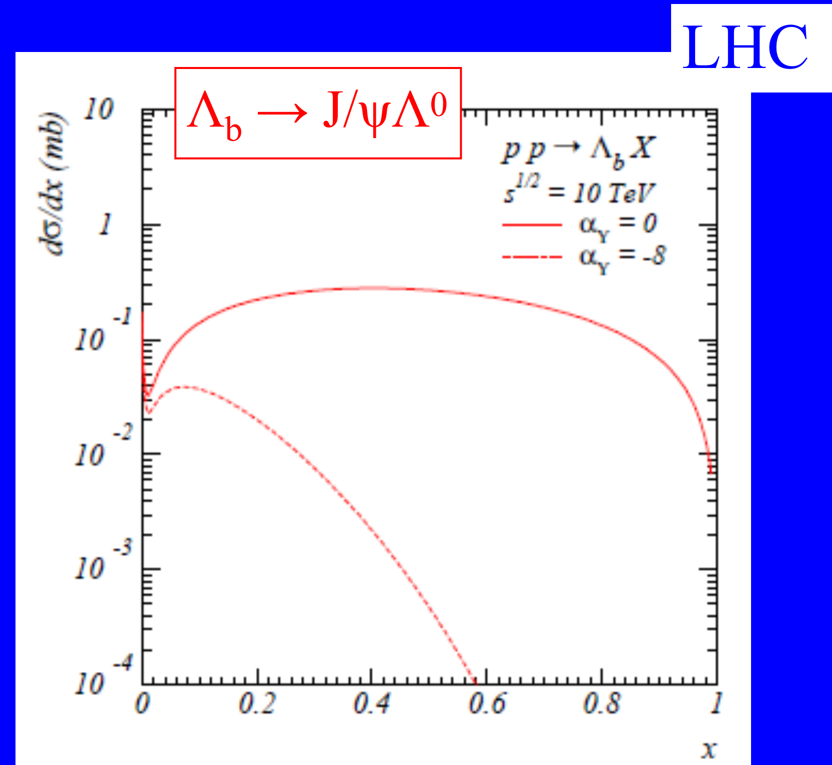
From Bednyakov, Lykasov and Lyubushkin arXiv:1005.0559

Lines: Regge exchange J/ψ, α(0) = 0, -2.18. in Quark Gluon String Model

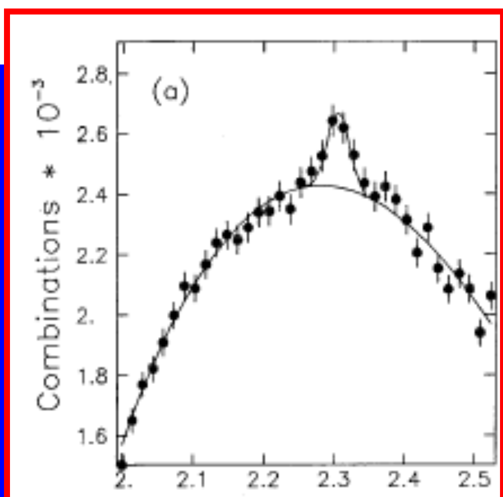
ISR



LHC



Predictions!



$\Lambda_c^+(2286) \rightarrow \Lambda^0\pi^+\pi^+\pi^-$ (2.6%)

R608 (ISR) P.Chauvat et al

PL B199 (1987) 304

Leading charm, beauty?

→ muons! neutrinos!

FT

SPS & FNAL Fixed Target Experiments

SPS = Super Proton Synchrotron – to 900 GeV protons at CERN
FNAL = Fermi National Accelerator Laboratory IL, USA

NA22 European Hybrid Spectrometer Bubble chamber + tracker FT

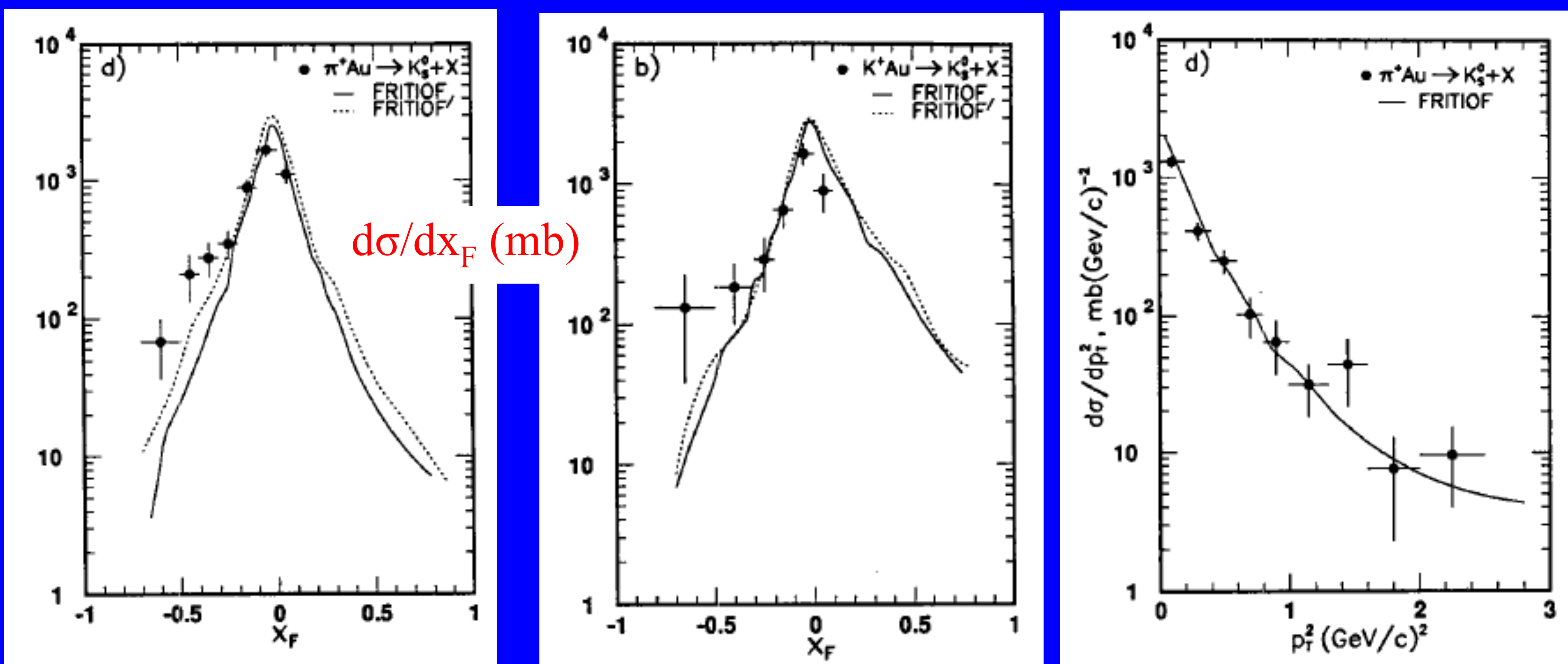
250 GeV/c K^+ π^+ beams on H, Al & Au nuclei (foils in BC)

$-1 < x_F < 0.1$, cf FRITIOF (quark/parton model)

Z.Phys.C55:373-382,1992

$$\begin{Bmatrix} K^+ \\ \pi^+ \end{Bmatrix} + \begin{Bmatrix} p \\ Al \\ Au \end{Bmatrix} \Rightarrow \begin{Bmatrix} K_S^0 \\ \Lambda^0 \\ \overline{\Lambda}^0 \end{Bmatrix} + X$$

$\sigma \sim A^{0.9}$
Λ in target+central region
Strangeness prodn. preferentially in central collisions
FRITIOF' "reasonable" agreement?



NA27 LEBC+EHS: Little European Bubble Chamber + European Hybrid Spectrometer (Charm mainly)

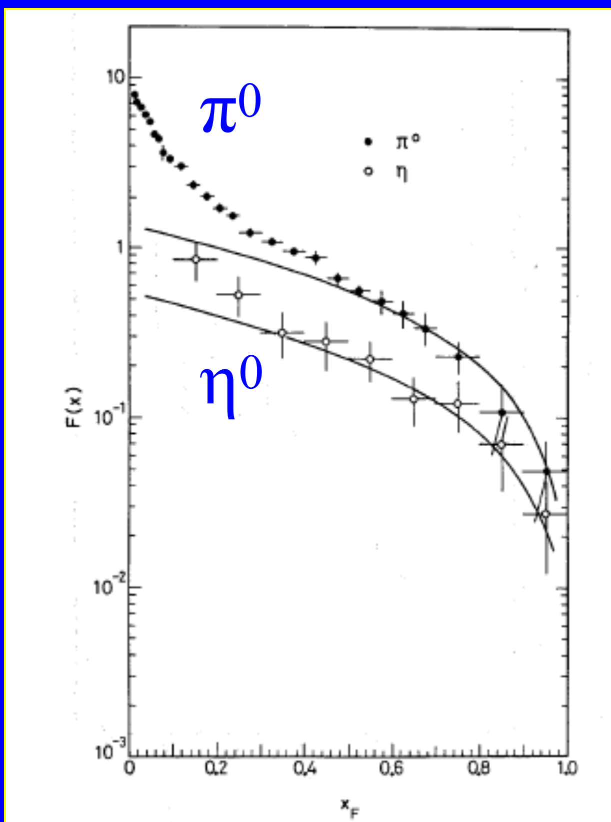
CERN-SPS FT

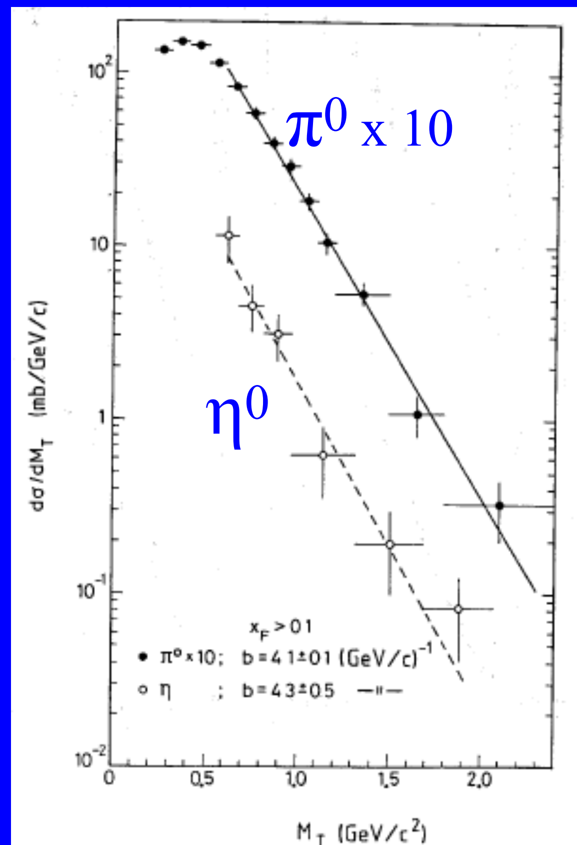
$\pi^- + p \rightarrow \pi^0, \eta^0 + X$ at 360 GeV/c

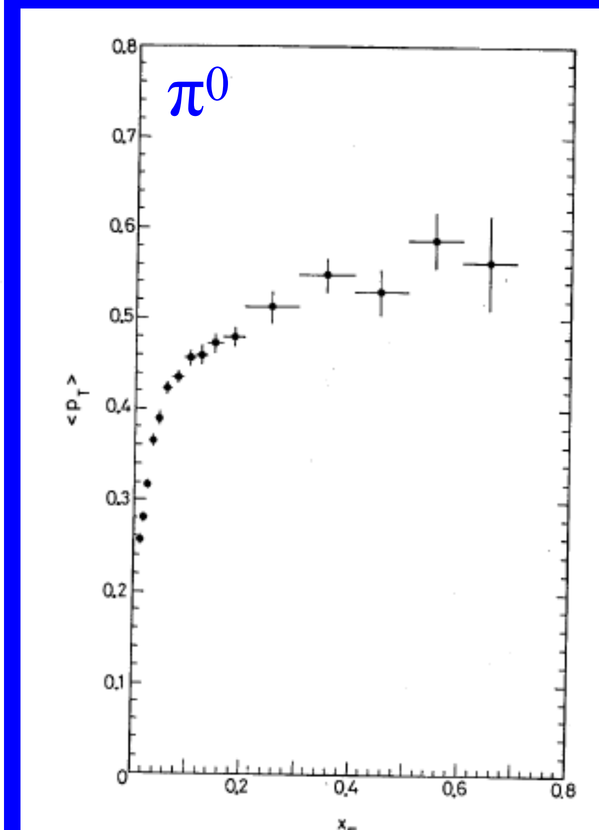
Studied also vs. n(charged) etc.

$\pi^0 / \eta^0 = 2.9 +/- 0.5$

π^0 and η^0 same slope in transverse mass: $M_T = \sqrt{m^2 + p_T^2}$





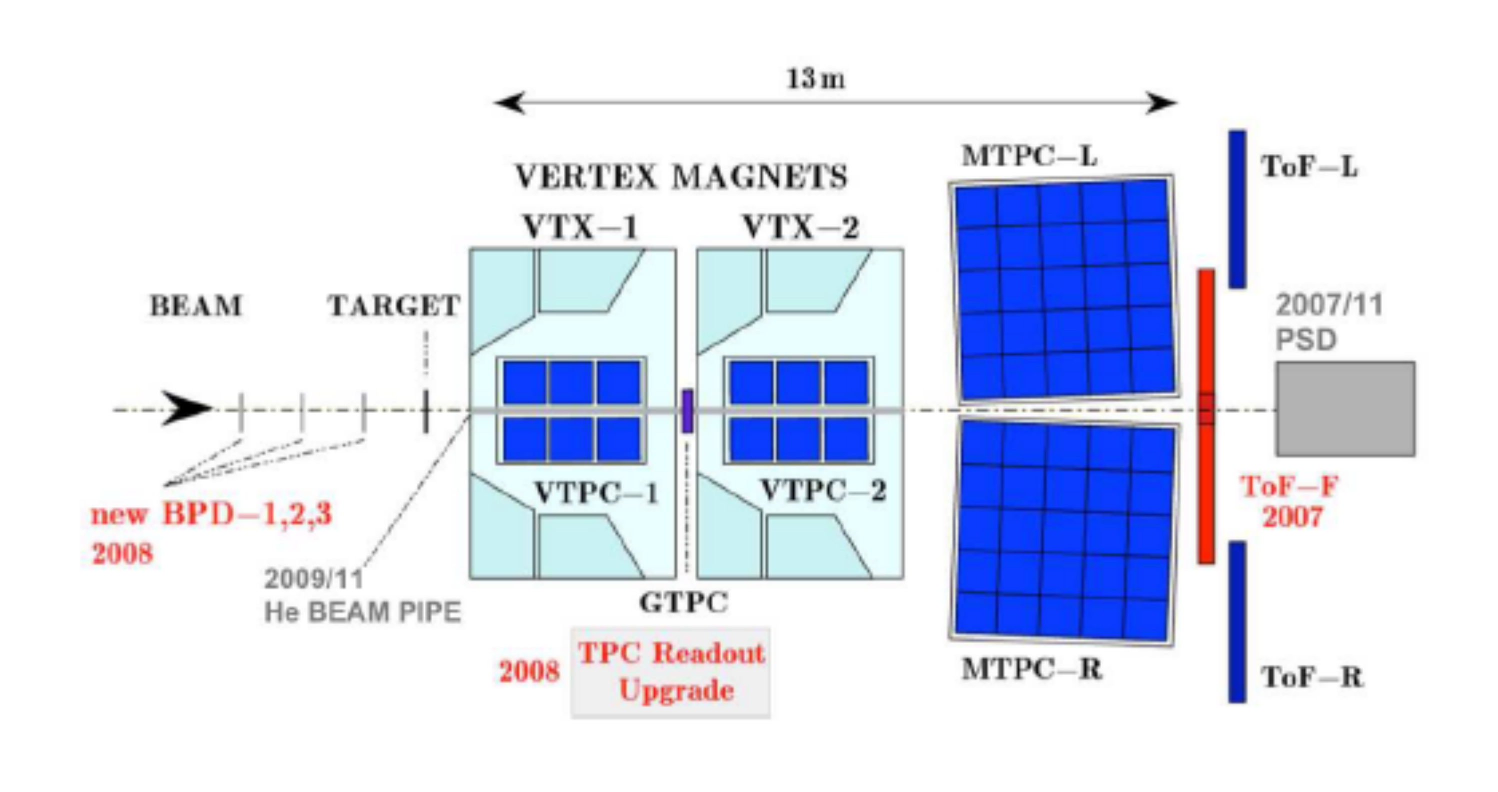


NA61 / SHINE CERN SPS
arXiv:1006.0767

FT

30 GeV/c p + C → π, K, p

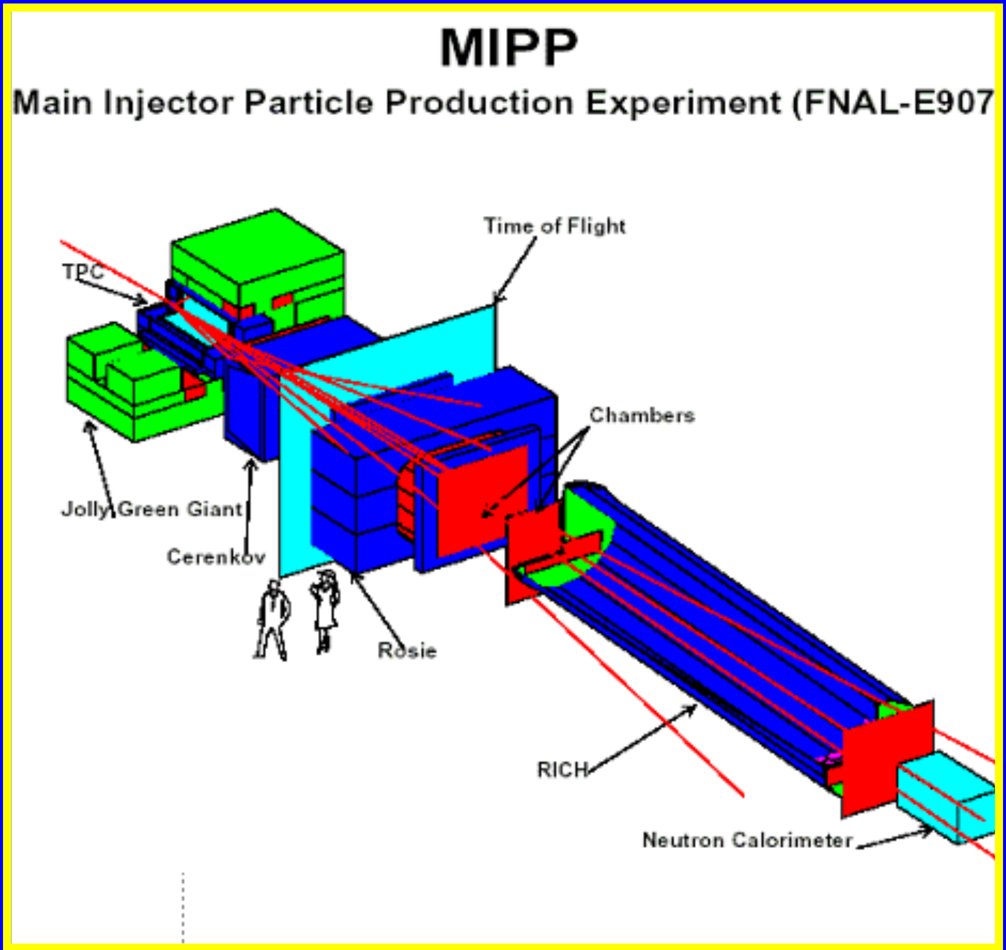
Hadron production measurements for cosmic ray and neutrino experiments e.g. T2K



Fermilab: MIPP = Main Injector Particle Production

FT

Primary 120 GeV/c Proton beam and Secondary beams of $\pi^{\pm}$ $K^{\pm}$ $p^{\pm}$ 5, 20, 35, 60,85 GeV/c to measure particle production cross sections of various nuclei span H, Be, C,Al, Bi, U thin targets and exact NuMI target.



TPC-dE/dx,
ToF,
differential Cherenkov
and RICH technologies.

$S\bar{p}pS$ Collider
Proton-antiproton

Van der Meer invented stochastic cooling of antiprotons
Made possible proton-antiproton collisions in SPS → 540 GeV
(900 GeV for very brief periods)

→ Discovery of W and Z bosons, carriers of weak force

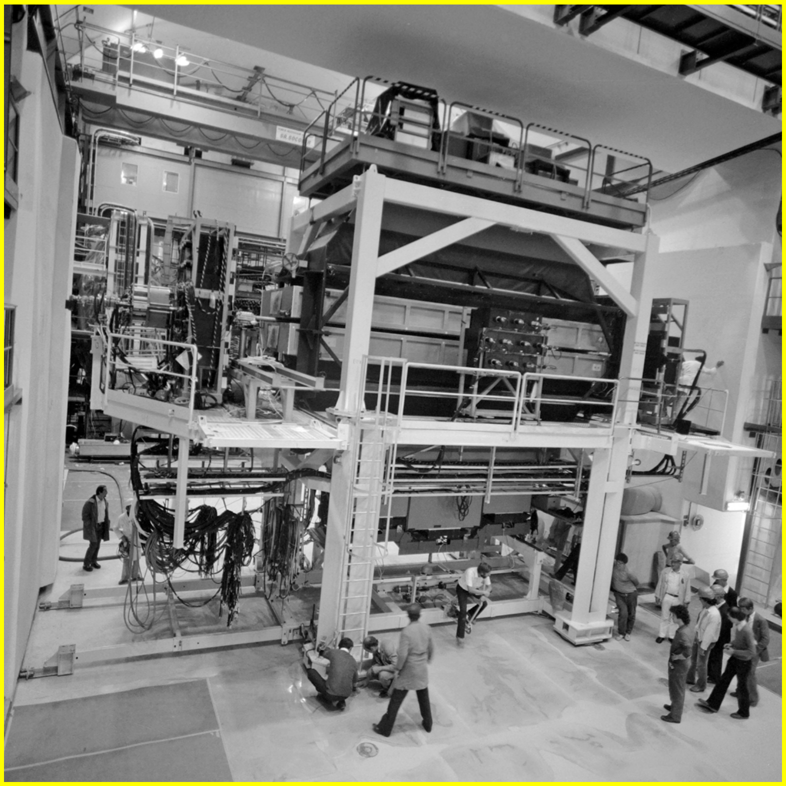
UA5: A general study of proton-antiproton physics at $\sqrt{s}$=546 GeV

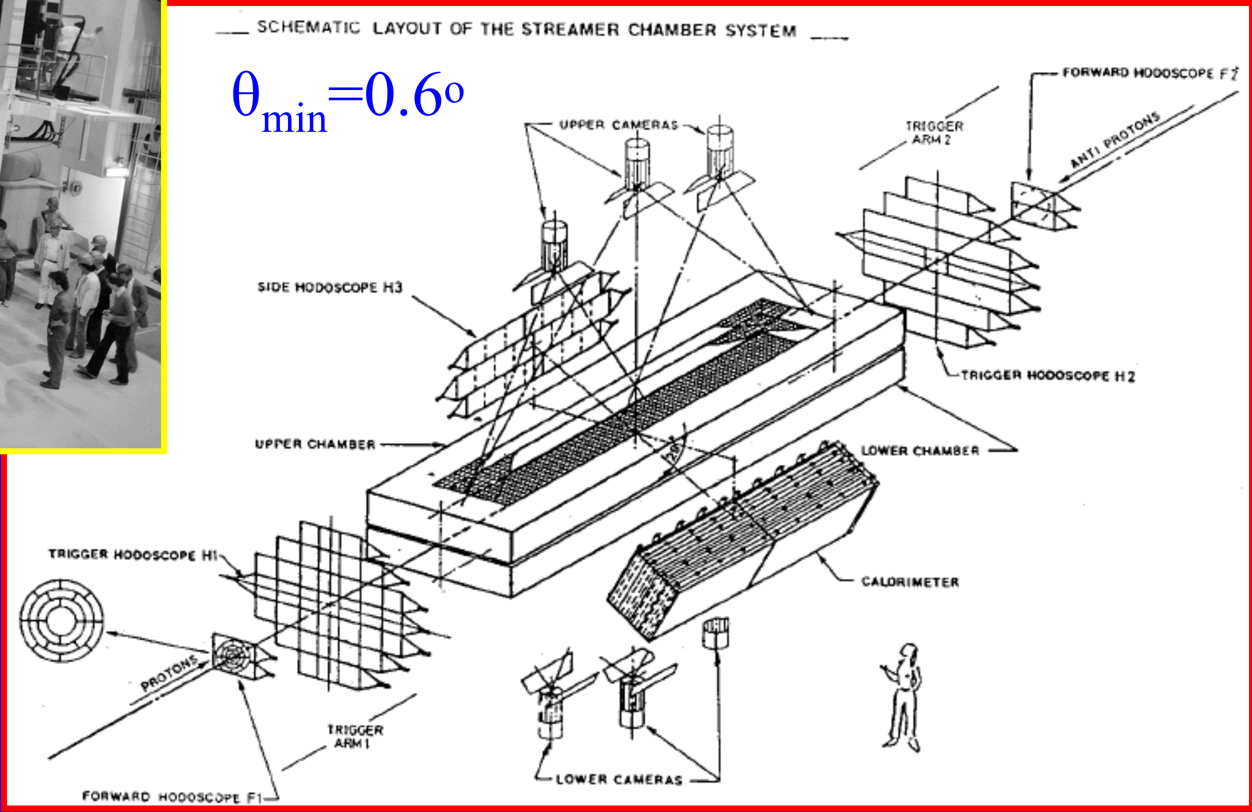
Physics Reports 154 (1987) p.247

SppS

$\sqrt{s}$ = 200 – 900 GeV

Ramping up & down





θ_{min}=0.6°

6m long streamer chamber triggered with hodoscopes & Pb-glass for γ-showers

Streamer Chamber CERN UA5, Proton Antiproton Collider

SppS

Stereo pair:

500 kiloVolts for 10 nanoseconds

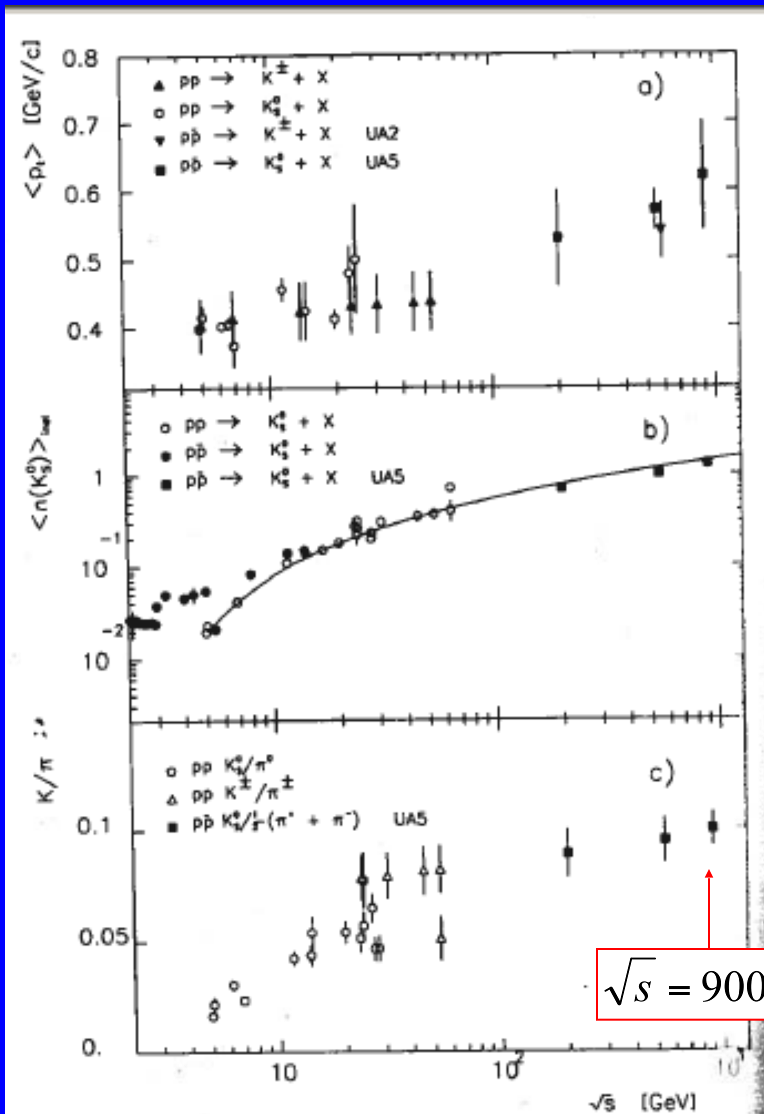
proton

antiproton

UA5: General properties of 6000 collisions photographed

First look at the « collider » regime – before UA1 & W,Z

SppS



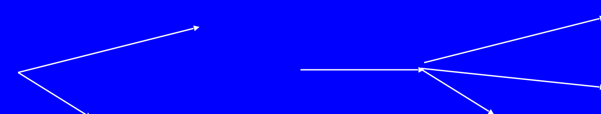
$\sqrt{s}$ = 900 GeV

$$\langle p_T \rangle, \langle n_K \rangle, \frac{K}{\pi}$$

all rising with sqrt{s} → 900 GeV

Data at $\sqrt{s}$ = **200, 546, 900 GeV**

Compared with DPM, FRITIOF, PYTHIA



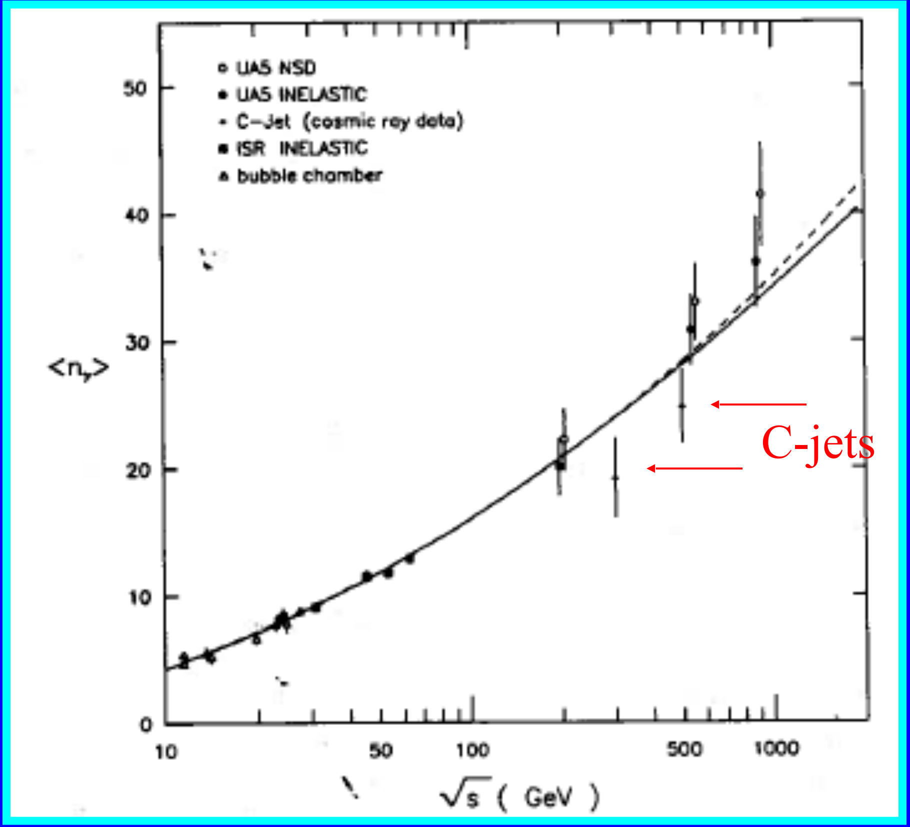
$K^0 \rightarrow \pi^+\pi^-$ $\qquad$ $K^+ \longrightarrow \pi^+\pi^+\pi^-$

UA5: Photon measurements.

Not direct, mostly $\pi^0 \to \gamma\gamma$ but more. If from $\eta \to \gamma\gamma$, $\eta / \pi^0 \sim 20\%$
(FNAL FT & ISR (forward) found even higher, $\eta / \pi^0 \sim 45\%$

Photon conversions in vacuum pipe and Pb-glass plate in streamer chamber

C-jet cosmic ray data:
N.Arata et al., Nucl.Phys.B211 (1983) 189



Find n(γ) tracks n(π+-),
& no sign of "Centauros"

- Claims of extreme neutral or charged particle content

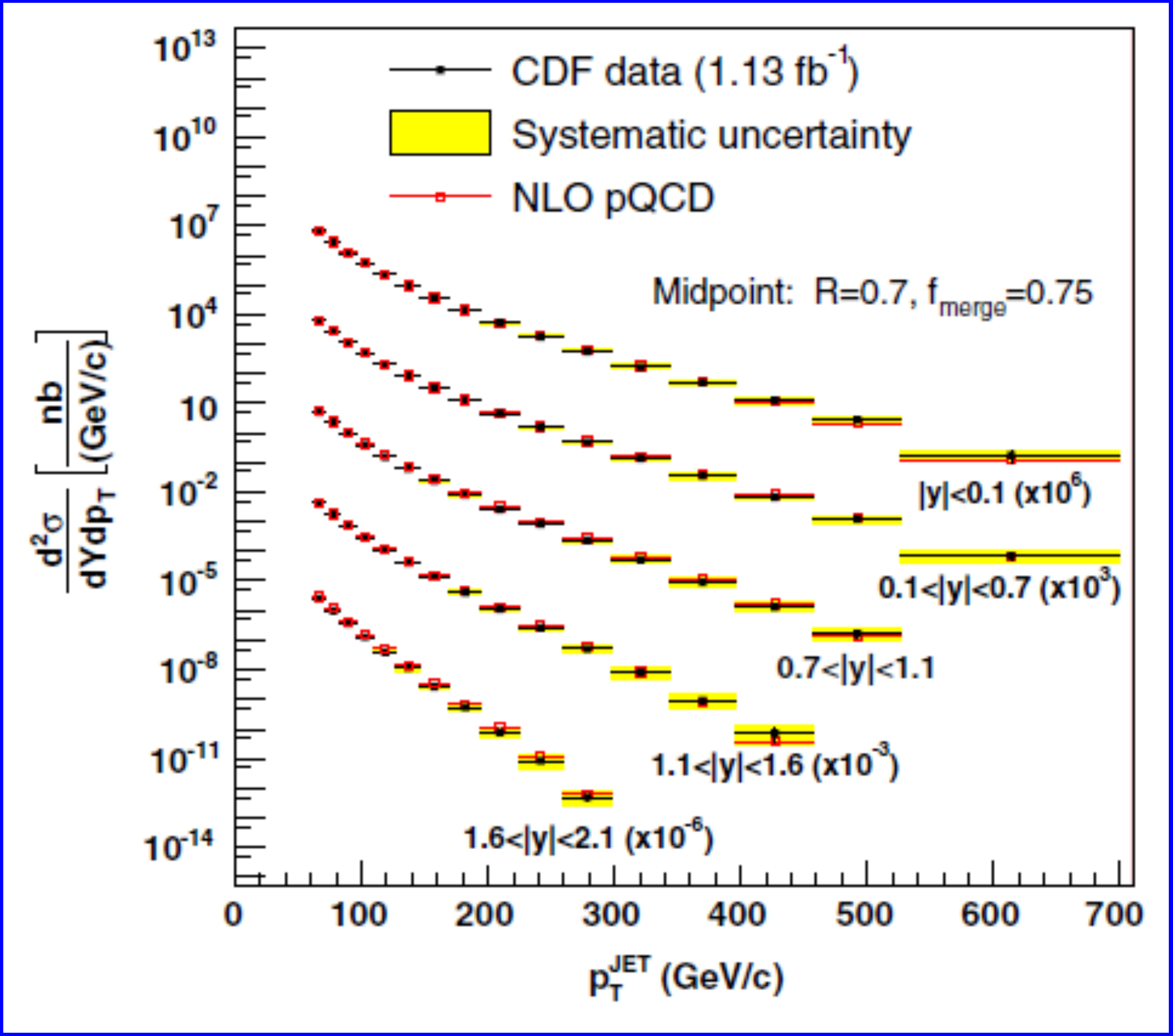
Tevatron proton-antiproton Collider at Fermilab. $\sqrt{s}$ = 1800, 1960 GeV (+300, 630)

Discovered **top quark** – heaviest known fundamental particle

Tevatron, CDF & D0, Central region only

TeV

Perturbative QCD + phenomenology (eg PYTHIA tuned) amazingly good



σ(ttbar) agrees with QCD prediction at 15% level, etc etc

Phys.Rev.D 78, 052006 (2008)

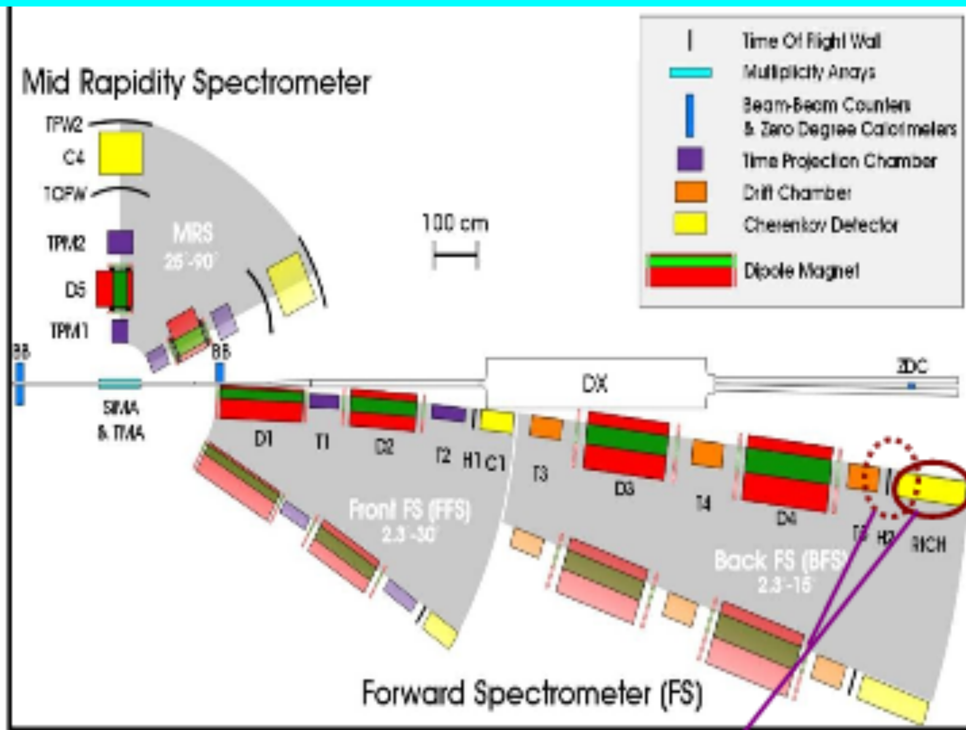
RHIC
Relativistic Heavy Ion Collider

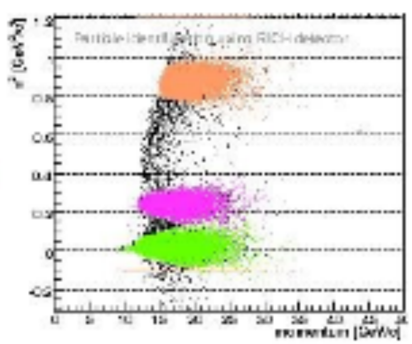
Brookhaven on Long Island

p + p at $\sqrt{s}$ = 200 GeV & A + A collisions

RHIC: Brahms forward spectrometer

RHIC

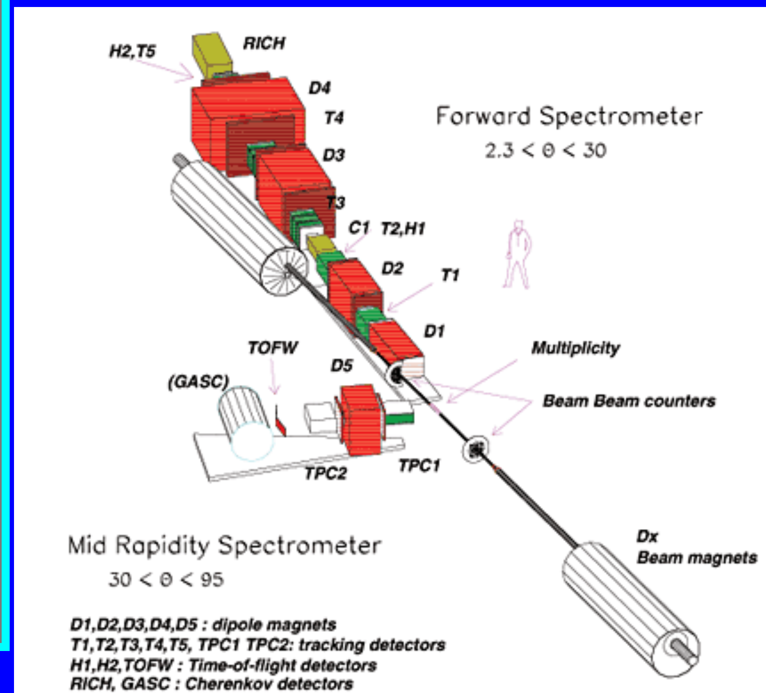




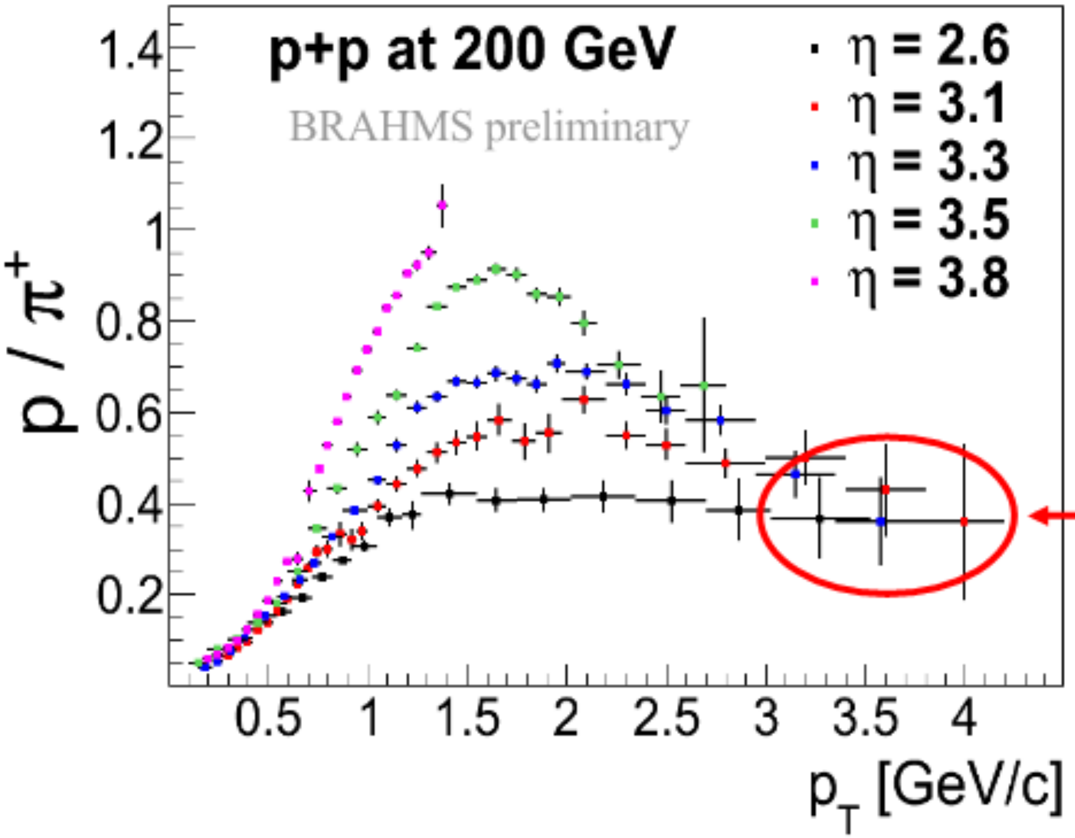
RICH detector situated in forward arm allows to identify high momentum particles ($e^-, \mu^{-/+}, \pi^{-/+}, K^{-/+}$, pbar/p);

ToF H2 placed before RICH measures hadrons with lower velocity.

3



RHIC

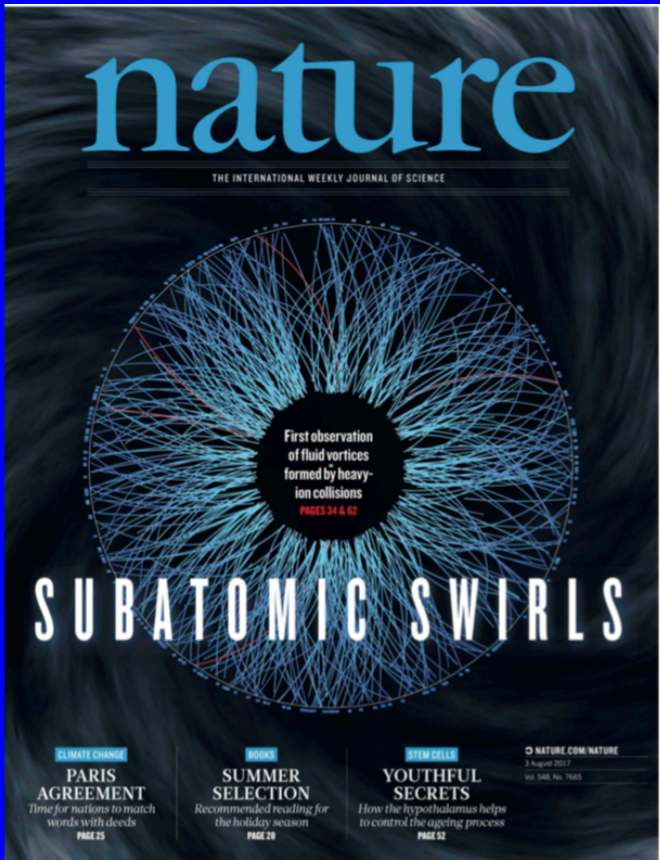


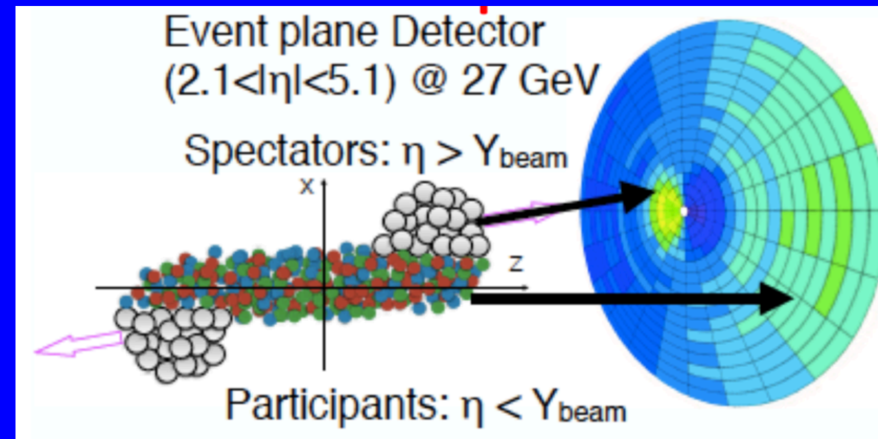
Strong rapidity dependence at intermediate p_T

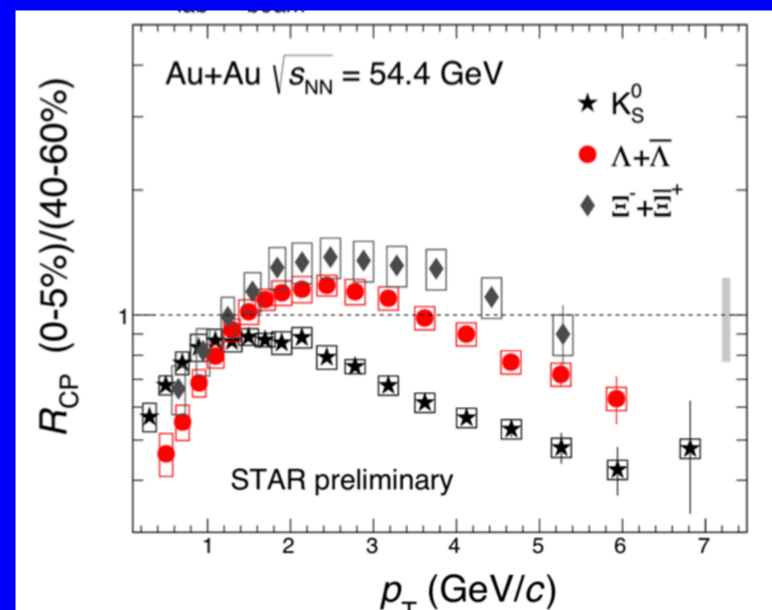
At hight p_T ratios seem to converge to common value of ~0.4 → consistent with pQCD predictions

P.Staszel

STAR Experiment at RHIC (Relativistic Heavy Ion Collider at BNL)







Ratio of Central:Peripheral R_{CP}

LHC
Large Hadron Collider
At CERN, Geneva

Next run p-O and O-O (= N-N) collisions at LHC
Planned for next Run 3 – want also in Run 4 2025 +

Large Hadron Collider: LHC

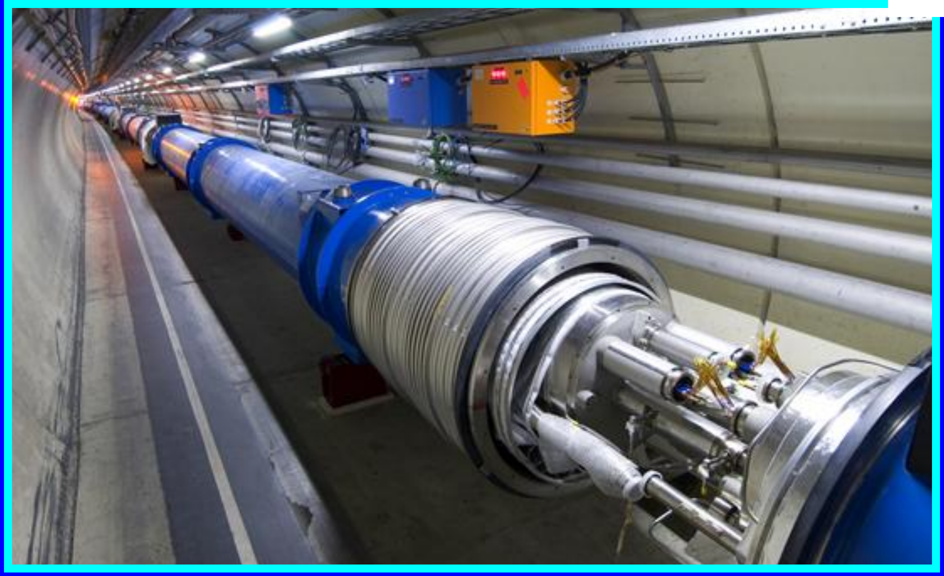
LHC

7 TeV = 7000 GeV ⟶ ⟵ **7 TeV = 7000 GeV**

Now 6.5 + 6.5 TeV

$\equiv 10^8 \text{ GeV} = 10^{17} \text{ eV}$

cf. cosmic cut off $\approx 10^{20}$ eV



ALICE
ATLAS
CMS
LHCb
LHCf

} Beautiful detectors, but central region.

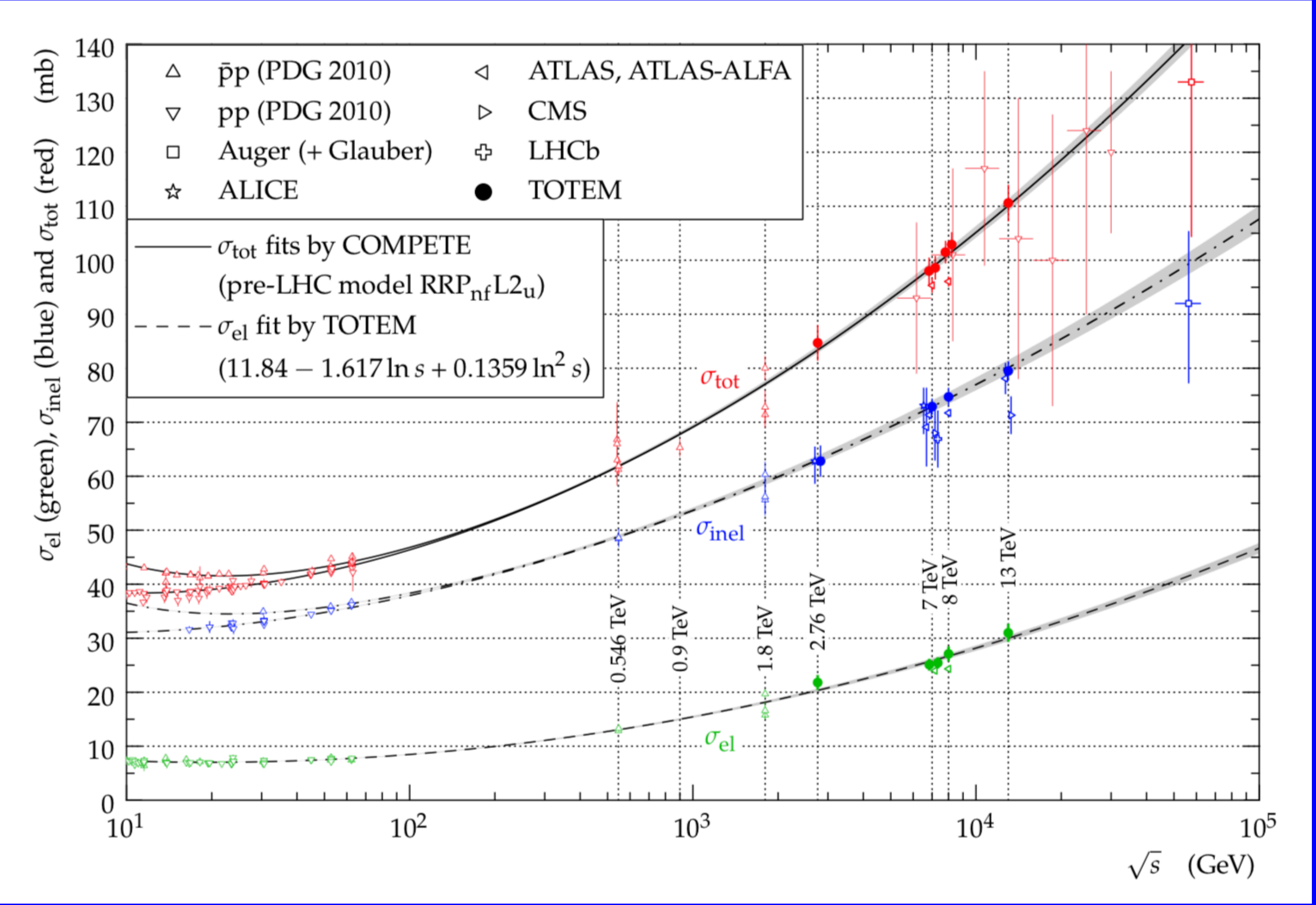
Comments on more forward →

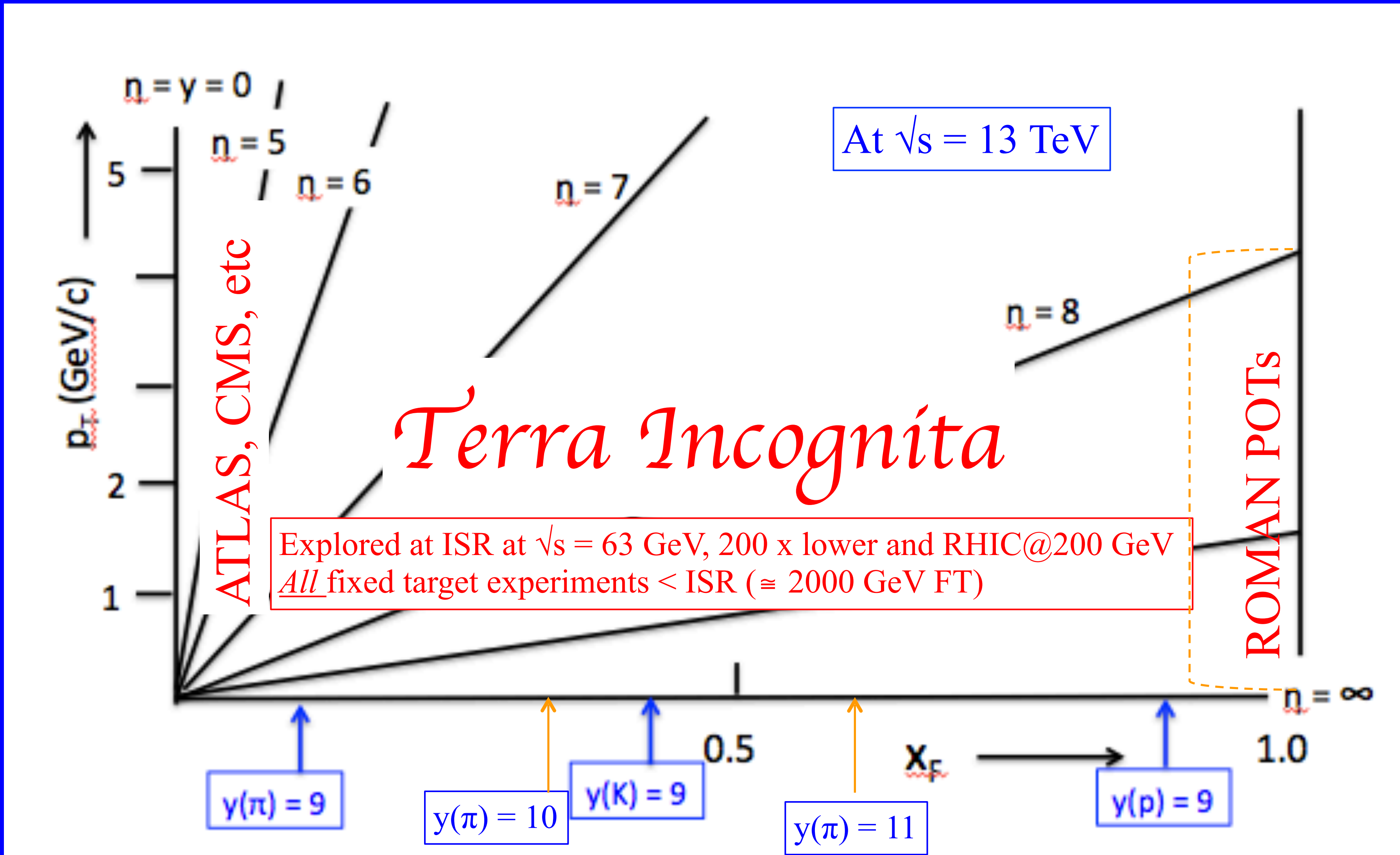
LHCf --- Zero-degree calorimeter for neutral particles

TOTEM --- Small far detectors for scattered protons

First measurement of elastic, inelastic and total cross-section at $\sqrt{s} = 13$ TeV by TOTEM and overview of cross-section data at LHC energies

arXiv:1712.06153v2 [hep-ex]



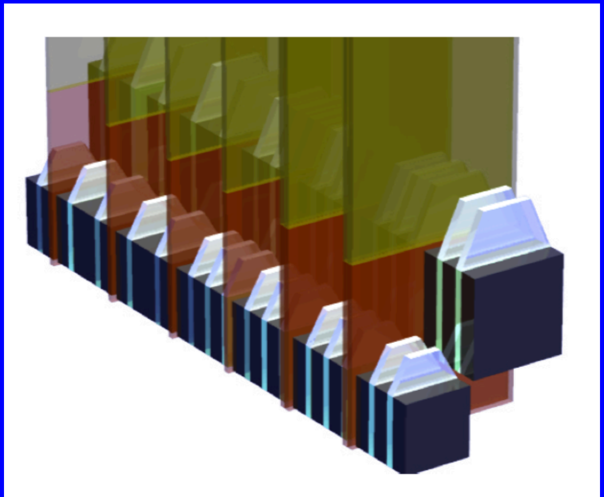


$y_{BEAM} = \ln(\sqrt{s}/m_p) = 9.54$

ZDC & LHCf measure neutrals ($n + K^0_L$, $\pi^0 \rightarrow \gamma\gamma$) at $\theta \sim 0^o$.

LHCf is a small 0º calorimeter measuring photon-like and n-like showers
Only 1.6 λ_I and 4 cm in size, $\sigma(E)/E \sim 40\%$ for neutrons.

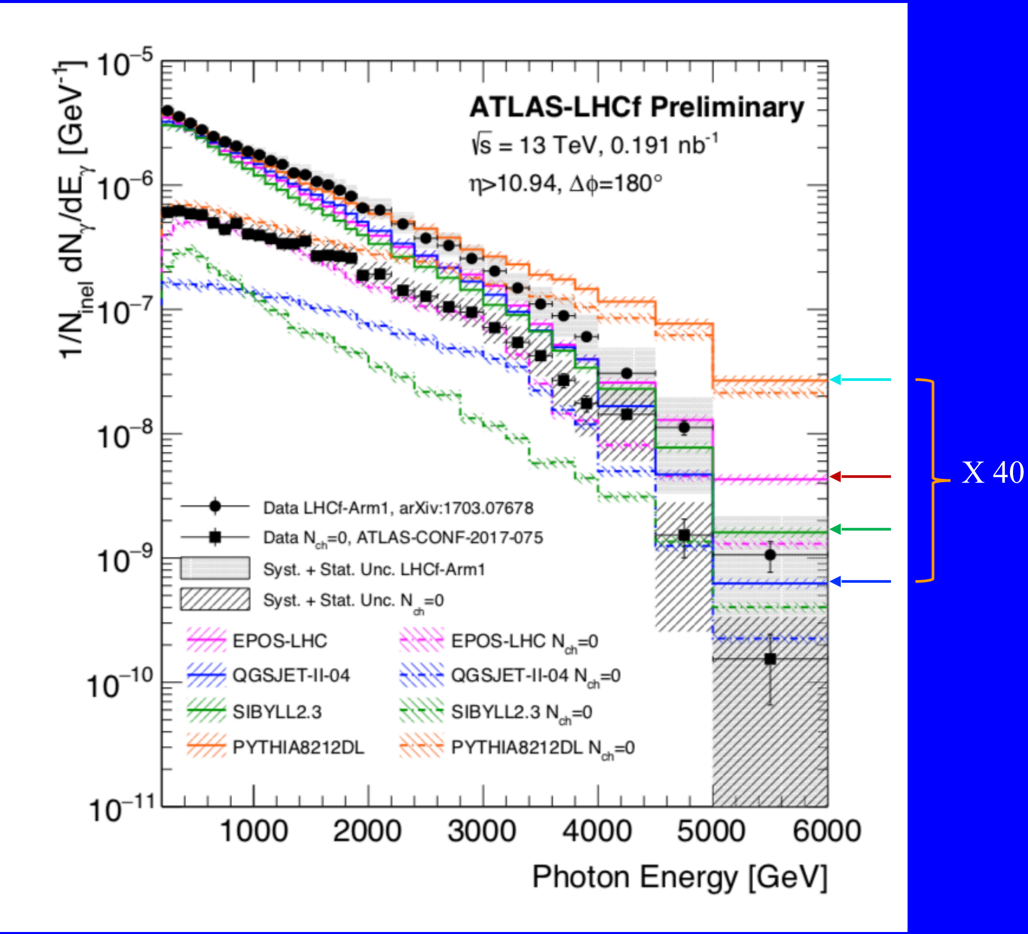
Low-PU, High β^* runs



Arm 1: 2cm x 2cm & 4cm x 4cm
Arm 2: 2.5 x 2.5 & 3.2 x 3.2 cm

Common data with ATLAS for some Low-PU runs: diffractive events

ZDC in CMS
7 λ_I and 8cm x 10 cm
Expect $\sigma(E)/E \sim 15\%$ at 3 TeV



Photon energy (mostly from π^0)

DPMJET prediction

Very uncertain! Illustration only

Spectra generated by /DPMJET-MARS
With 10^6 pp events, √s = 13 TeV
(N.Mokhov and O.Fornieri)

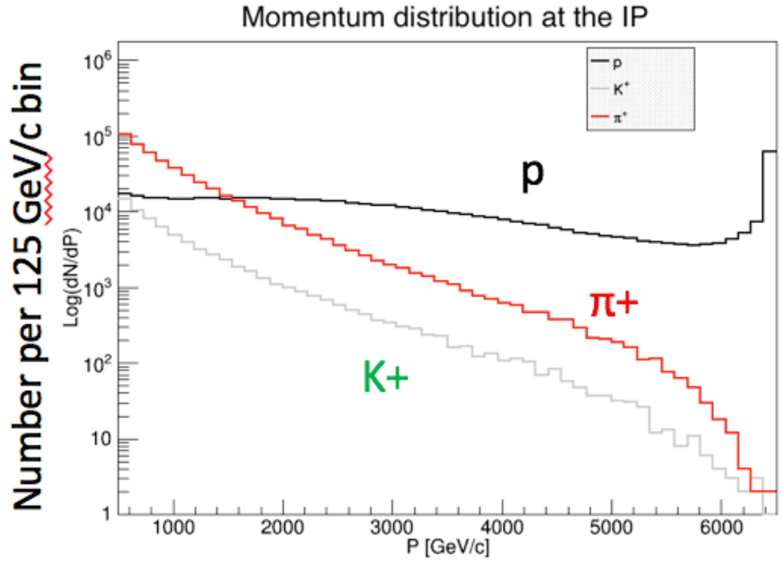
In 1 second, with 2808 bunches,
Have 30×10^6 bunch crossings and
$30 \times 10^6 \times \mu$(= interactions/X) events.

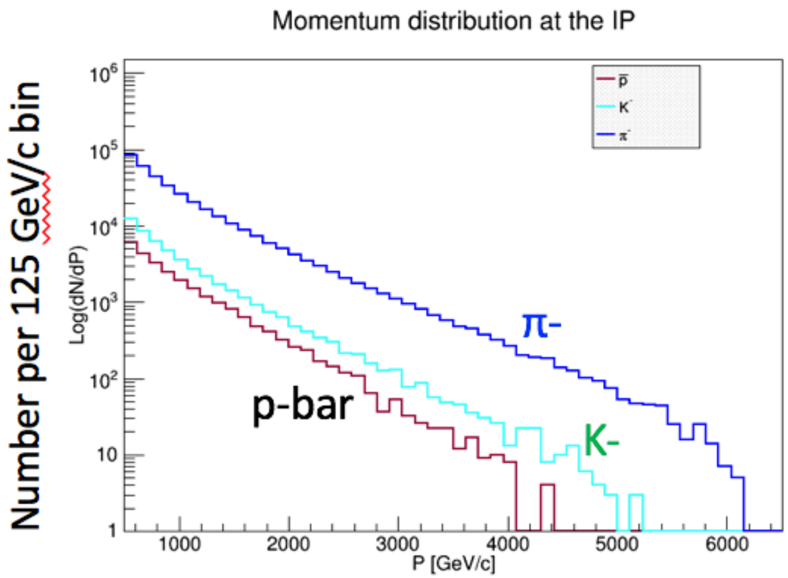
Notes:
At 0.5 TeV (~ central)
$\pi^+ = \pi^-$ & $K^+ \cong K^-$ & K/π ~ 10%

p's > π^+ above 1.5 TeV and flattish;
High x_F peak from diffraction

K^-(s-ubar) steeper than K^+ (u-sbar)
π^- (d-ubar) steeper than π^+ (u-dbar)

Antiprotons < K^- but only by a factor ~ 0.5
Anti-deuterons/tritons/He^3 to measure too





~ 100 x Acc/bin/sec if μ ~ 3

Neutrons not = protons, K^0 not = $K^{+/-}$

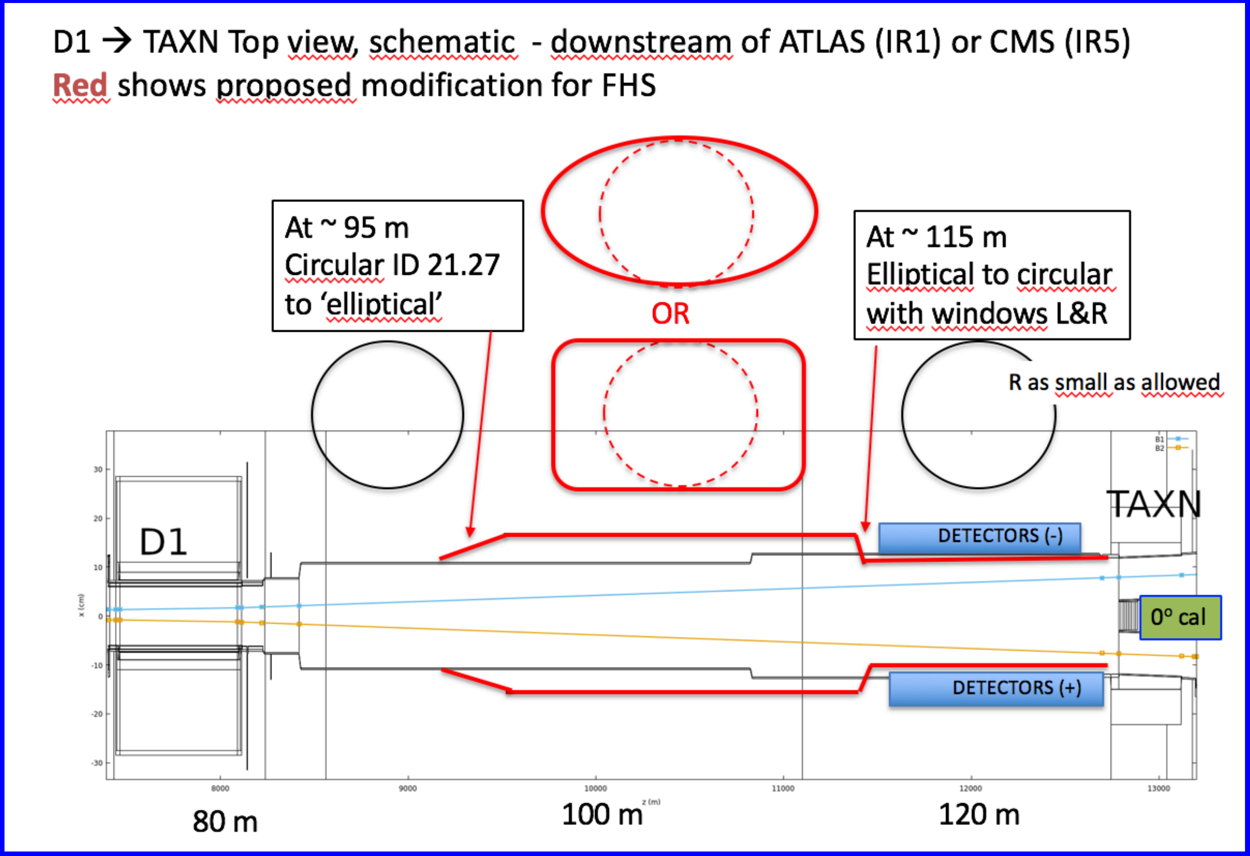
FORWARD HADRON SPECTROMETER FHS for LHC – to come?

Precise measurements of multi-TeV identified charged particle spectra

In principle: e, μ, **π**, **K**, D^0(K+π-), **p,pbar**, Λ/Λbar, d,dbar, t, tbar …

When? First weeks of Run 4 2025? pp but want p-O and O-O also for CR

CERN Workshop April 16+17 2020 – Collaboration to form – contact me!



Tracking – TRD (π/K/p) – Targets+minitracking – calorimeter - muons

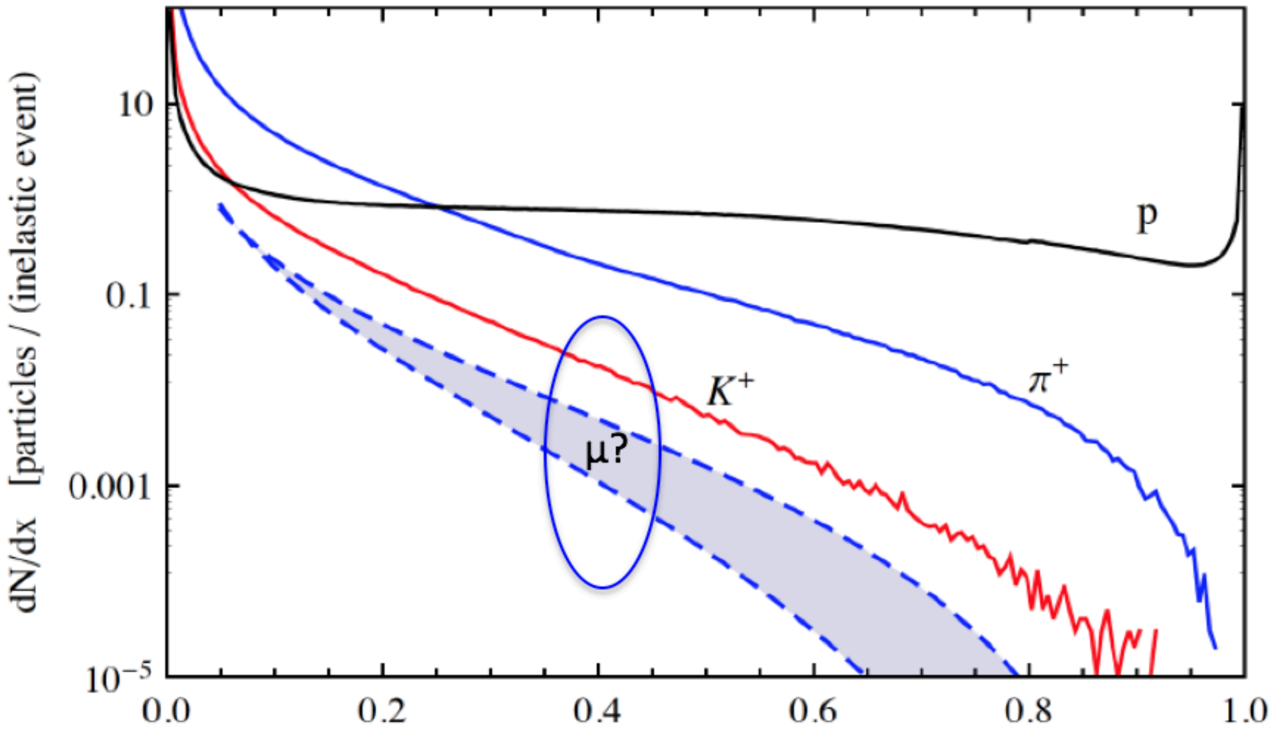
Charm and beauty hadrons only measured at LHC in central region.

Some models, e.g. Stan Brodsky "intrinsic heavy flavor" have enhanced forward Q production

-- Massive Quarks in sea carry high momentum for same rapidity (At $p_T = 0$ $x_F = m.e^y / \sqrt{s}$)

c, b → μ gives excess prompt muons at large xF.

In $\Delta x = 0.1$ at $x = 0.4$ about 10^{-3} per inelastic event. At PU = 1 have 30 million X/sec : ~ 10^4 μ/s !



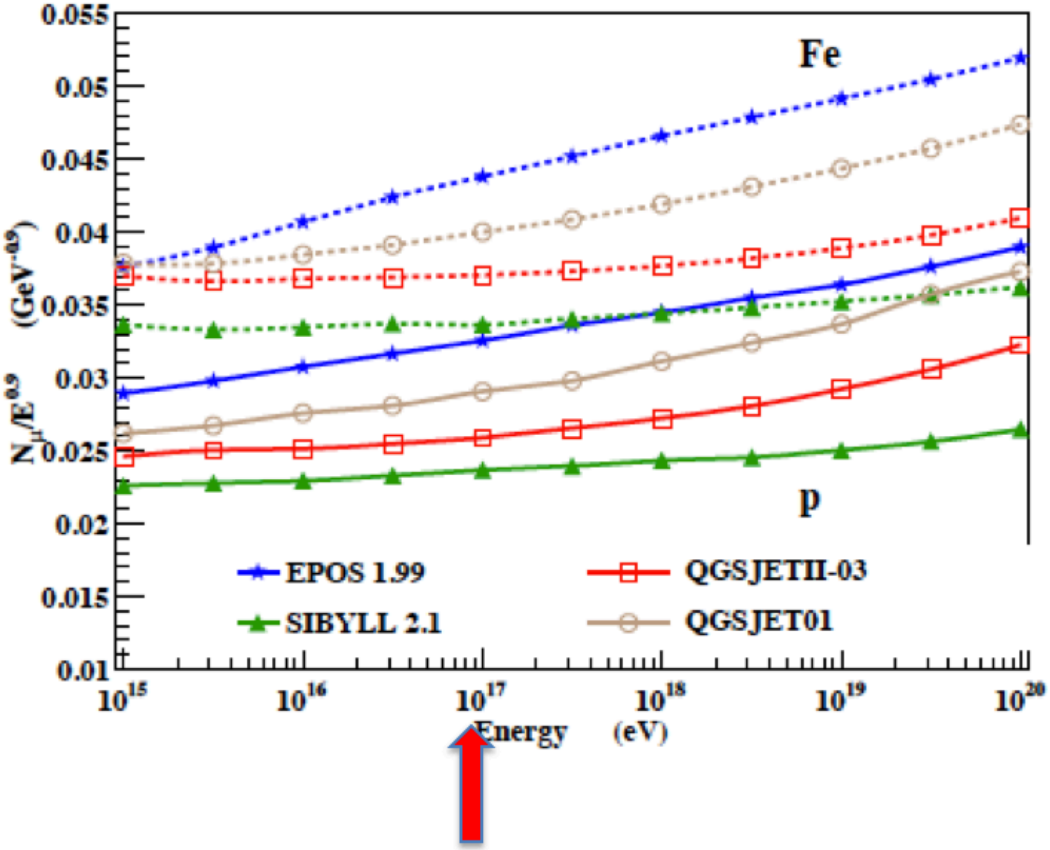
Muons from charm decay
(from exotic model)

May reconstruct D^0 → Kπ
Also measure very forward μ

Example of spread in Cosmic ray shower simulations
muons on ground / $E^{0.9}$ (to flatten curves) vs E.
p- Air (solid) and Fe- air (dashed)

Muon production

From FPWG_YELLOW_REPORT : CERN/LHCC 2013-021



These are on air not pp.

LHC has run p-Pb and Pb-p
And p-O and O-O are planned.
Requested by
heavy ion groups (ALICE et al).

Big spread even assuming no surprises, e.g. high forward heavy flavor production (Brodsky)

Equivalent FT energy of √s = 13 TeV
$E_{\cong} = s/2m_p$

Production of antinuclei at LHC.

Possible signals of dark matter annihilation in galactic center in γ-rays

Central region: |y|< 0.5 at $\sqrt{s} = 7$ TeV pp.

Physics Reports 618 (2016) 1–37

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

T. Aramaki [a,b], S. Boggs [c], S. Bufalino [d], L. Dal [e], P. von Doetinchem [f,*],

ALICE has central LHC data

Need to measure forward too

PHYSICAL REVIEW C **97**, 024615 (2018)

Production of deuterons, tritons, ^{3}He nuclei, and their antinuclei in *pp* collisions at $\sqrt{s} = 0.9$, 2.76, and 7 TeV

A Very Forward Hadron Spectrometer for the LHC and Cosmic Ray Physics

arXiv:1811.02047v1

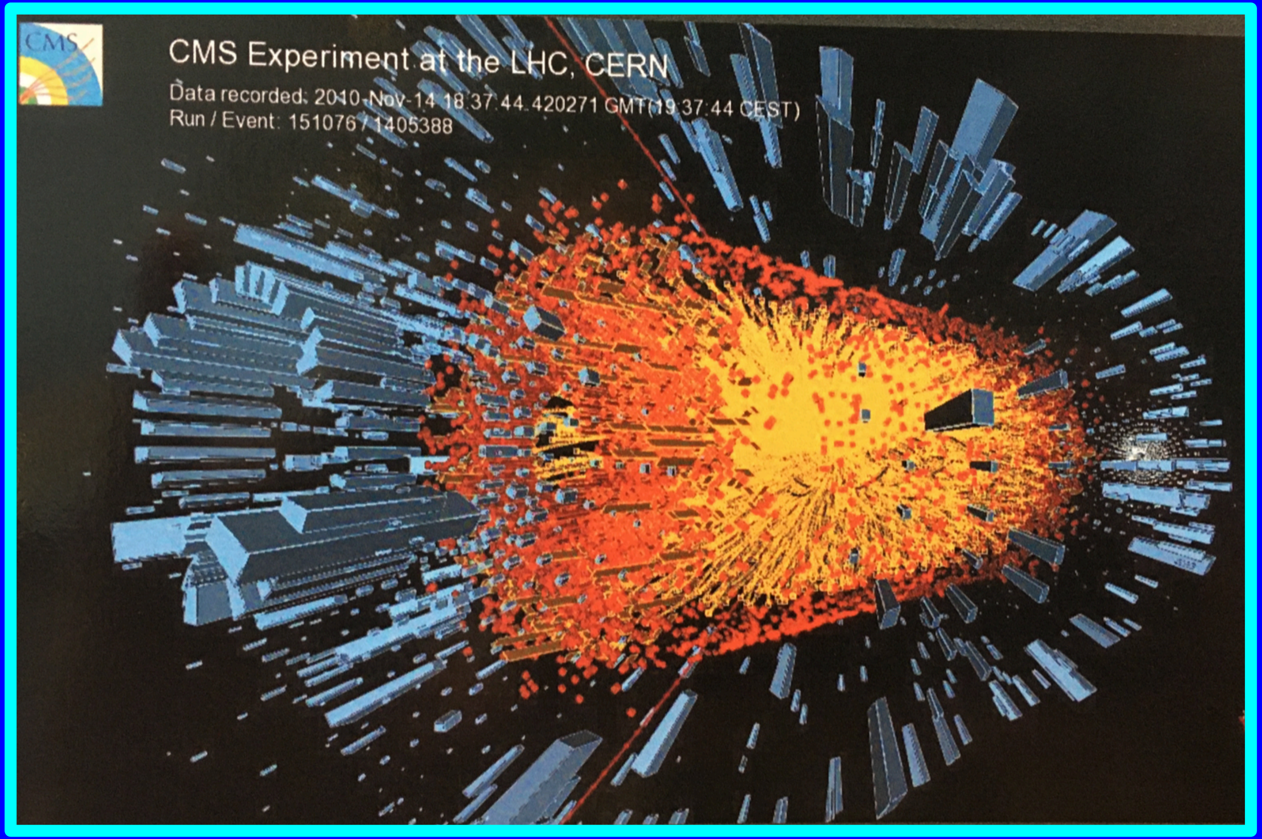
Michael Albrow[*†]
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA.
ORCID 0000-0001-7329-4925
E-mail: albrow@fnal.gov

Charged hadron production in hadron-hadron collisions with longitudinal momentum fraction Feynman-x, x_F, between 0.1 and 0.9 has not been measured above $\sqrt{s}$ = 63 GeV at the CERN Intersecting Storage Rings. I discuss a way to measure this at the Large Hadron Collider at $\sqrt{s}$ = 13 TeV, which is 40,000 times higher in equivalent fixed target energy, and important for understanding cosmic ray showers.

2nd World Summit: Exploring the Dark Side of the Universe
25-29 June, 2018
University of Antilles, Pointe-Ãă-Pitre, Guadeloupe, France

Brief note – please comtact me albrow@fnal.gov

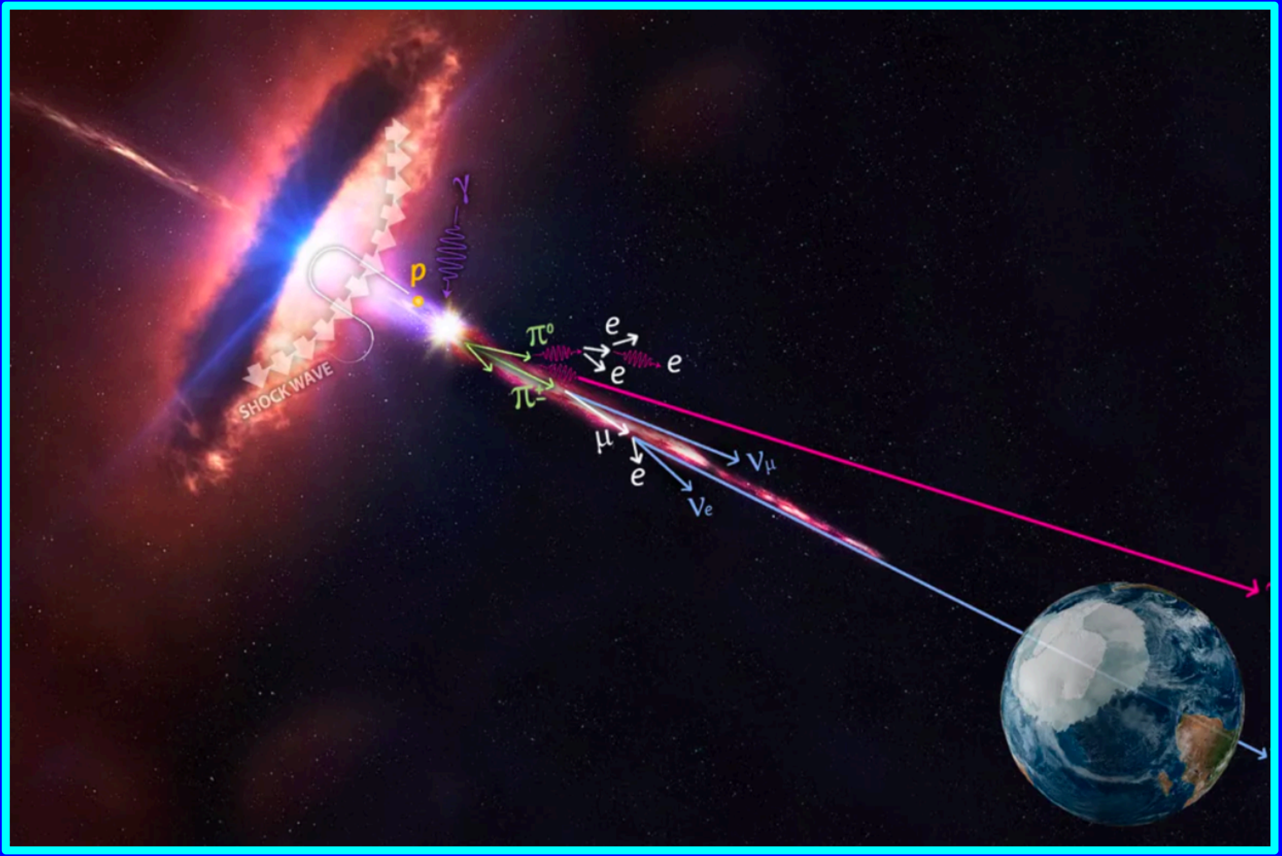
At CERN's Large Hadron Collider (LHC) –
Lead-Lead (Pb+Pb) nuclei colliding!
ALICE is dedicated experiment, but here is a collison in CMS



We need proton-oxygen pO and oxygen-oxygen OO too!
Planned for next run – but want in Run 4 too!

Neutrinos ν_e ν_μ ν_τ from violent cosmic events

Sources: $\boldsymbol{\pi} - \boldsymbol{\mu} - \tau - \mathbf{c} - \mathbf{b} - \mathbf{W} - \mathbf{Z}$ **- ? -?**



Produced in p-p, p-A, A-A collisions at ultra-high energies and cascading down through LHC region

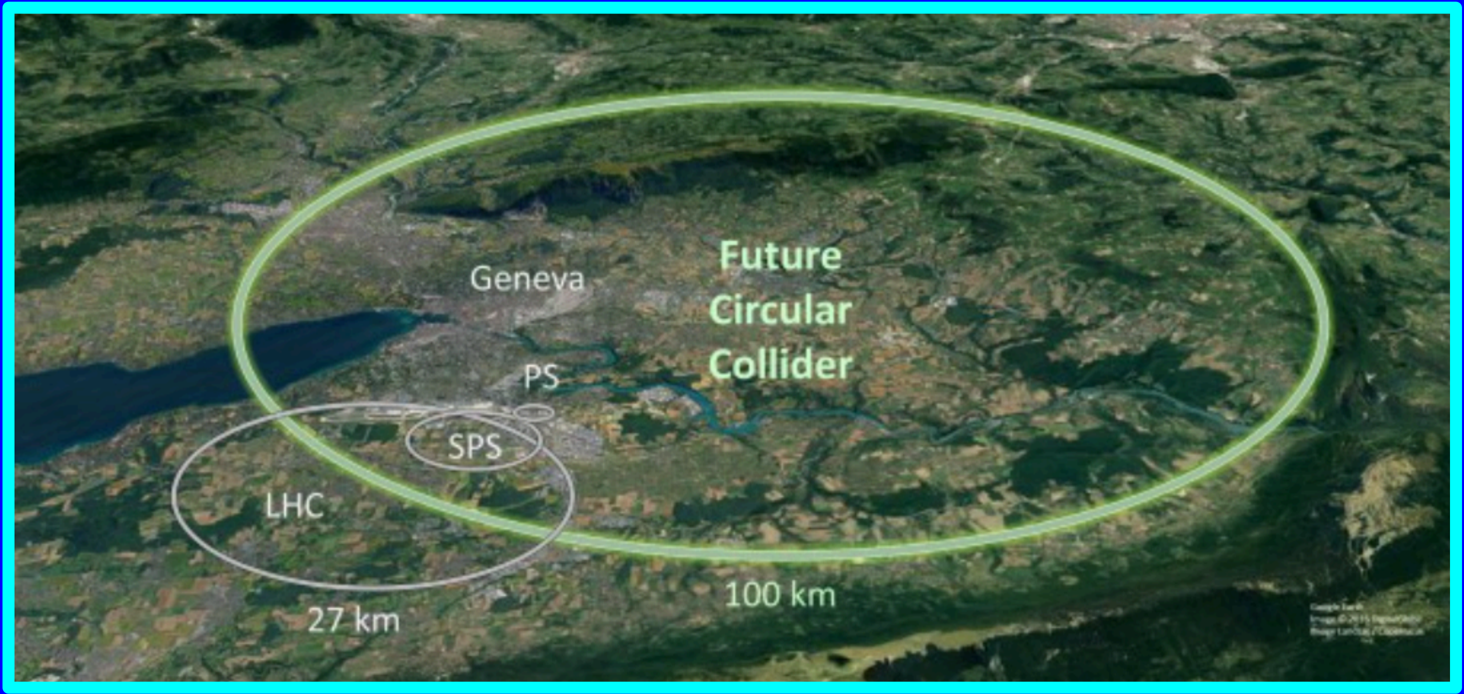
CERN's Future? Future Circular Collider

(Name will have to change when it exists!)

$e^+ e^-$ collisions - > Higgs boson with high precision (as LEP did for Z-boson)

100 TeV total energy pp collisions 7x LHC

+ Heavy ion collisions – as in cosmic ray showers



Conclusion:

Cosmic ray physics and 'multimessenger astronomy' need data from accelerator experiments to do best science.

Vast amounts of accelerator – experiment data but either

(a) At much lower energies, or
(b) In the central region (large angles), or
(c) n (not precise), π^0 at 0^o or quasi-elastic or elastic protons

We can do better – mutually beneficient!

Thank you