A Forward Multiparticle Spectrometer for LHC

Talk at EMMI Workshop on Forward Physics in ALICE 3 [20231019]
Michael Albrow, Fermilab

Measuring forward x_F ~ 0.1 – 0.4 charged hadrons
80– 125m downstream of IR in pp, pA, AA collisions

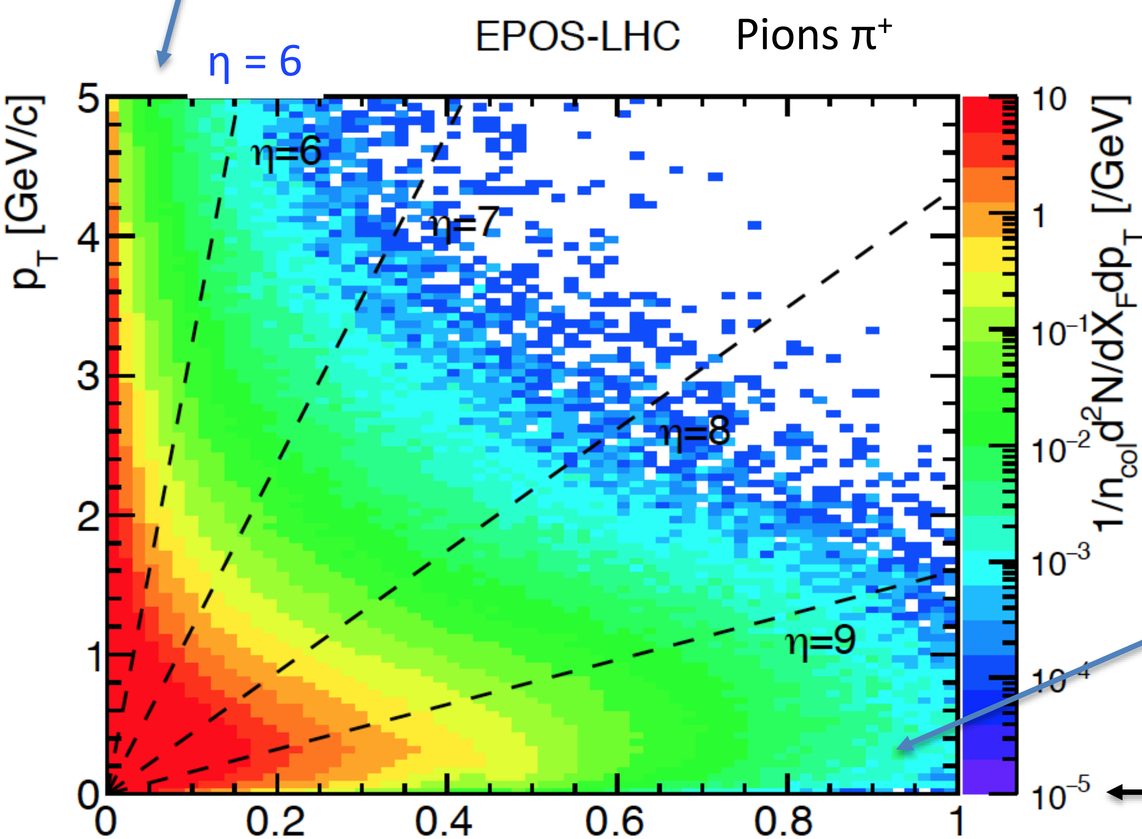
This region ~~should~~ must be measured before the LHC era ends!

This talk relates to CMS but is applicable to ALICE 3

CMS may be able to do it with new beam pipe & detectors
But I think ALICE may be a better fit (physics focus, luminosity not VH)

Most hadrons produced in p + p (and p+A, A+A) collisions at LHC
have small transverse momenta p_T < ~ 1 GeV/c and
Large longitudinal momenta p_Z ; $x_F = p_z / p_{BEAM}$ > ~ 0.05 so p_Z ~ 350 GeV/c

η = 4.5 (LHCb) is θ =1.3° not "very forward"



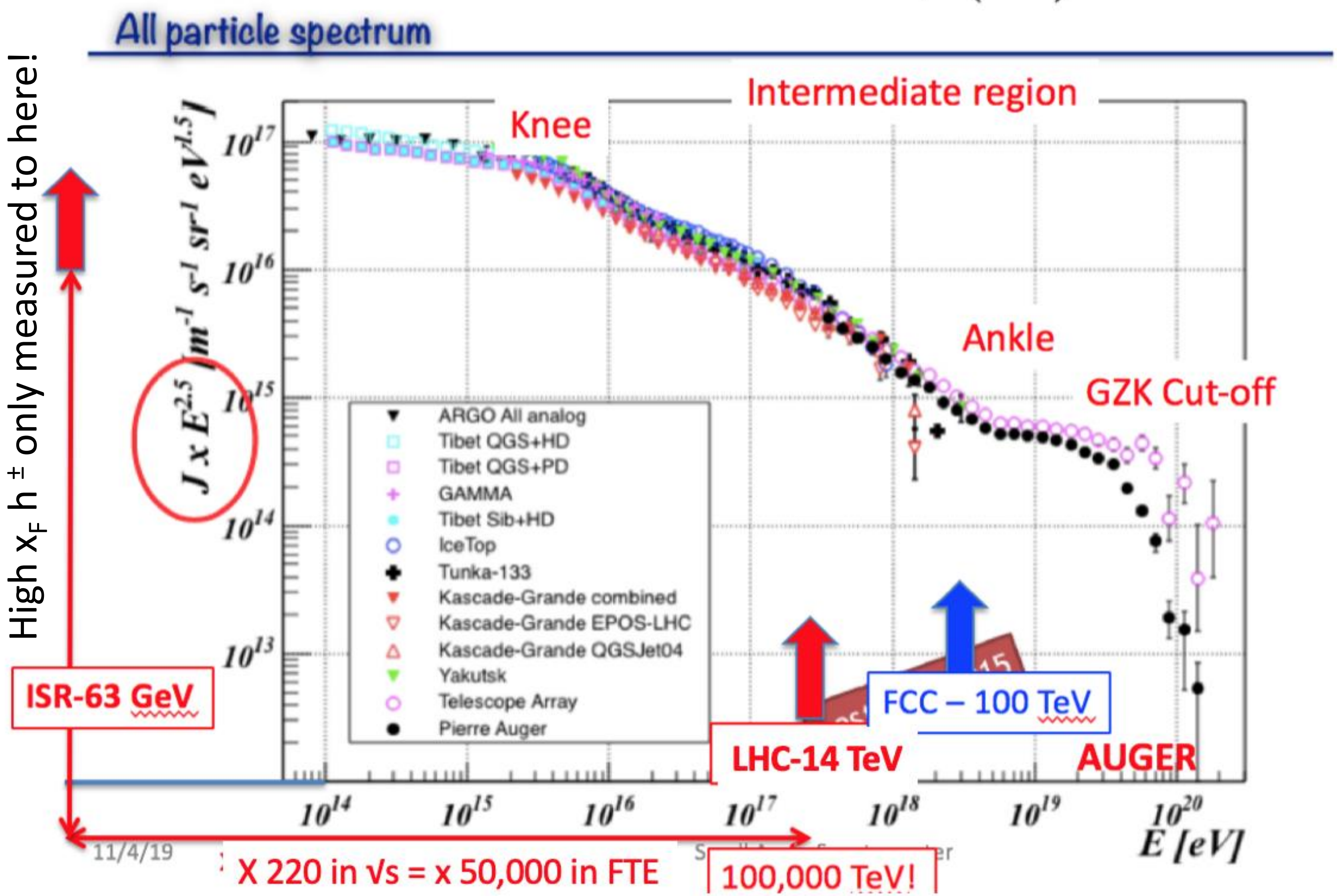
$x_F = p_z / p_{BEAM}$

Pseudorapidity $\eta = -\ln.\tan(\theta/2)$
very different from true rapidity y

x_F > ~ 0.9 protons
(Roman pots, PPS etc.)

Neutrals measured at θ = 0°
(ZDC etc)

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



√s = 45 GeV,
CHLM (MGA inter alia) SAS @ ISR
Nucl Phys B 140 (1978) 189

45 years ago !

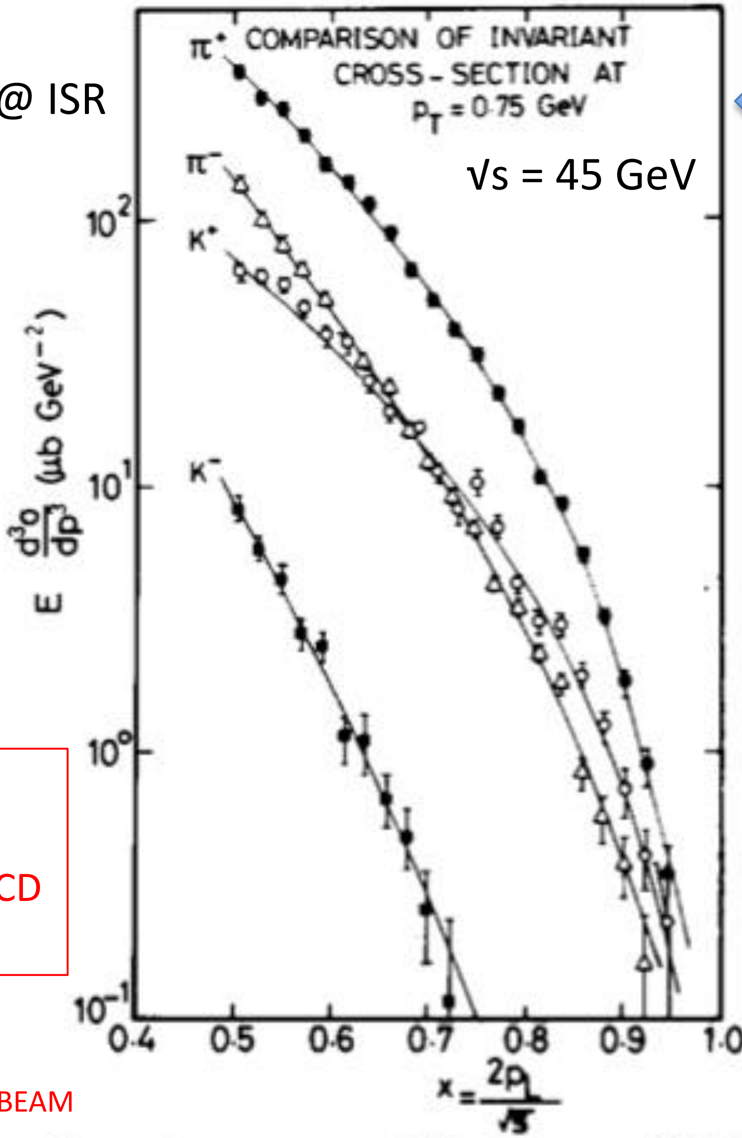


Fig. 2. Invariant cross sections for p + p → meson + X, for p_T = 0.75 GeV, a function of $x = 2p_L/\sqrt{s}$. The curves are empirical fits of the form $A\exp\{K(1-x)^C\}$ for $\pi^\pm$, K^+ described in the text. The curve for K^- is hand-drawn. The behaviour at other p_T values is similar.

Small transverse momentum p_T (Mean p_T ~ 350 MeV/c)

Valence quark counting:

$\pi^+ = u\,\bar{d}$ (2)
$\pi^- = \bar{u}\,d$ (1)
$K^+ = u\,\bar{s}$ (1)
$K^- = \bar{u}\,s$ (0)

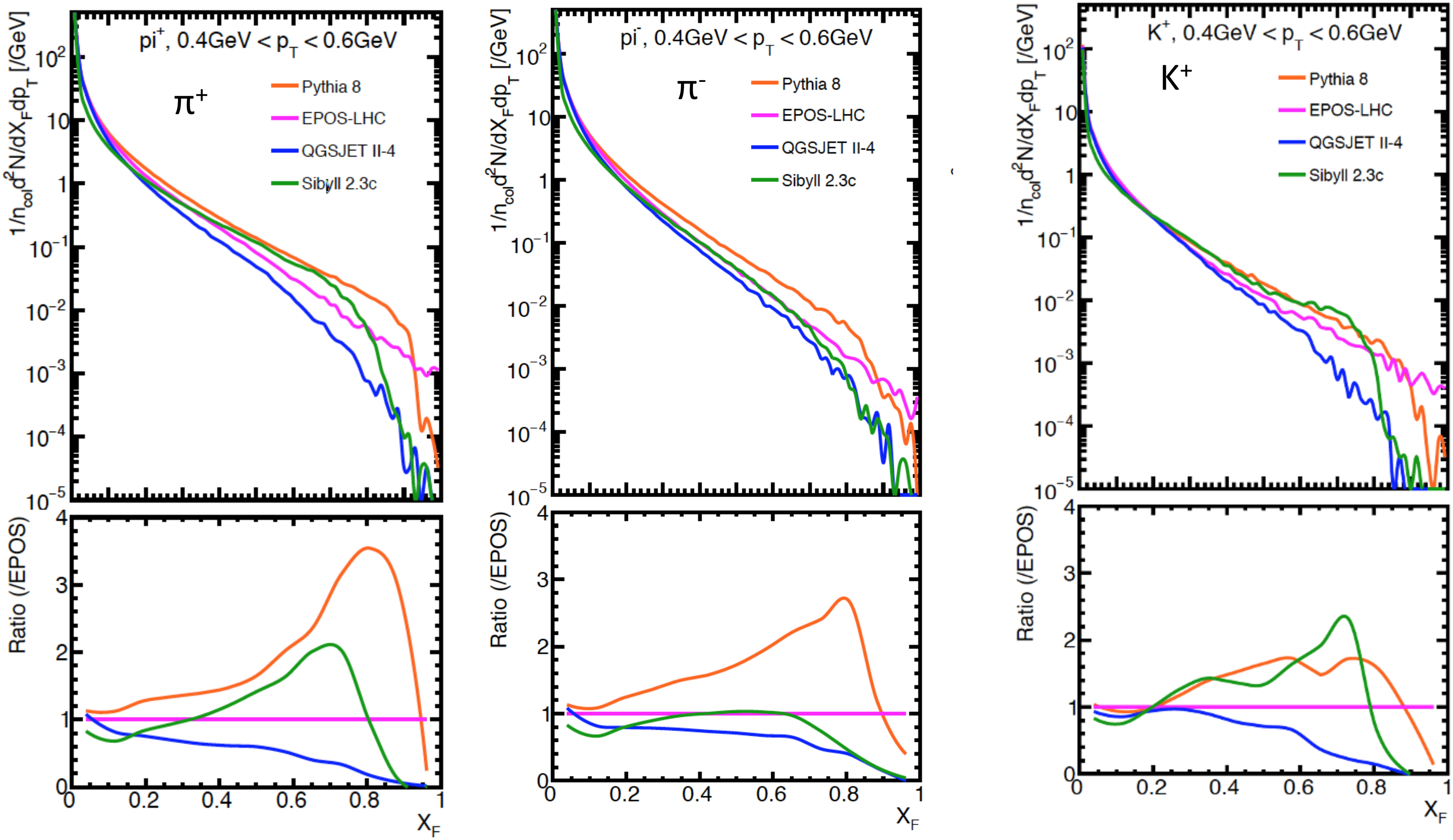
Feynman scaling (1969):
Spectra fn(p_T, x_F) not √s
Non-interacting partons, not QCD
Ignores thresholds (c,b)

Feynman $x_F = p_z/p_{BEAM}$

Low mass diffraction dissociation
e.g. **p → p $\pi^+\pi^-$**

At LHC p → charm, beauty !

Comparison of Monte Carlo generators, Low-p_T π and K (H. Menjo)



(PYTHIA8: QGSJET II-4) ~ 50 at $x_F = 0.8$

No Data! FHS reach → ~ 0.4

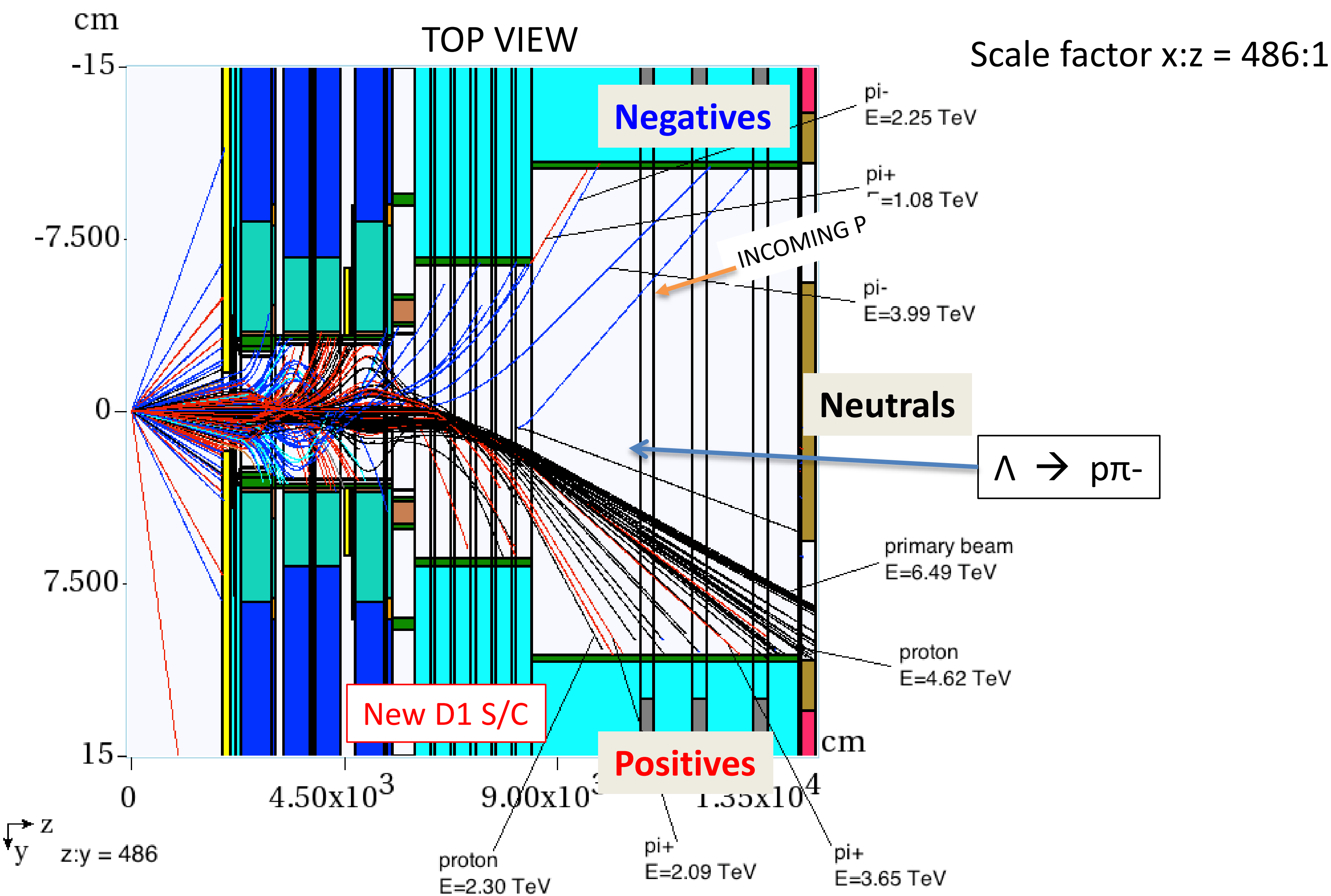
Feynman $x_F = p_z/p_{BEAM}$

May need updating

200 inelastic collisions at Pt 5 (CMS) **2018** (13 TeV, β* = 0.55 m): MARS

Nikolai Mokhov
Ottavio Fornieri

If μ = 50 this is 4 bunch crossings

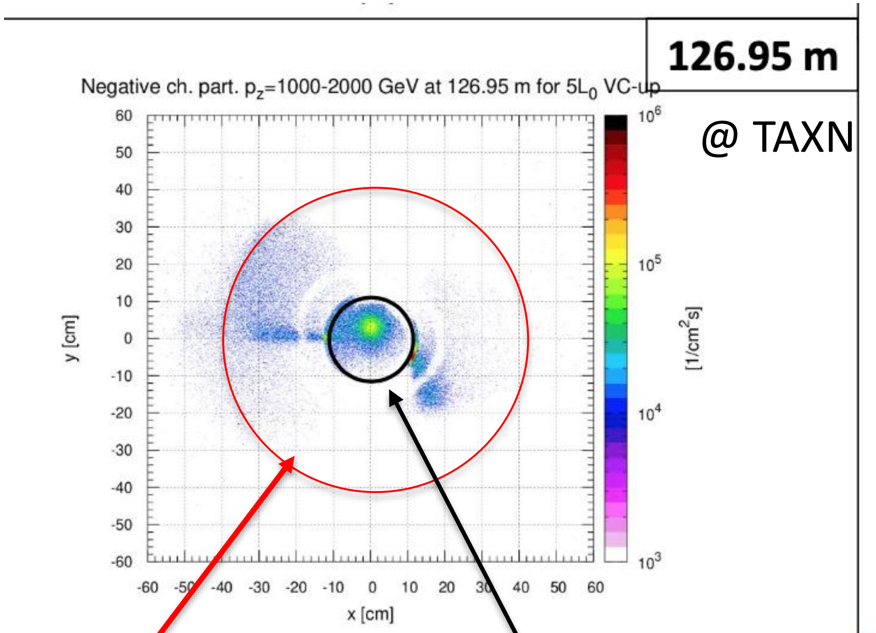


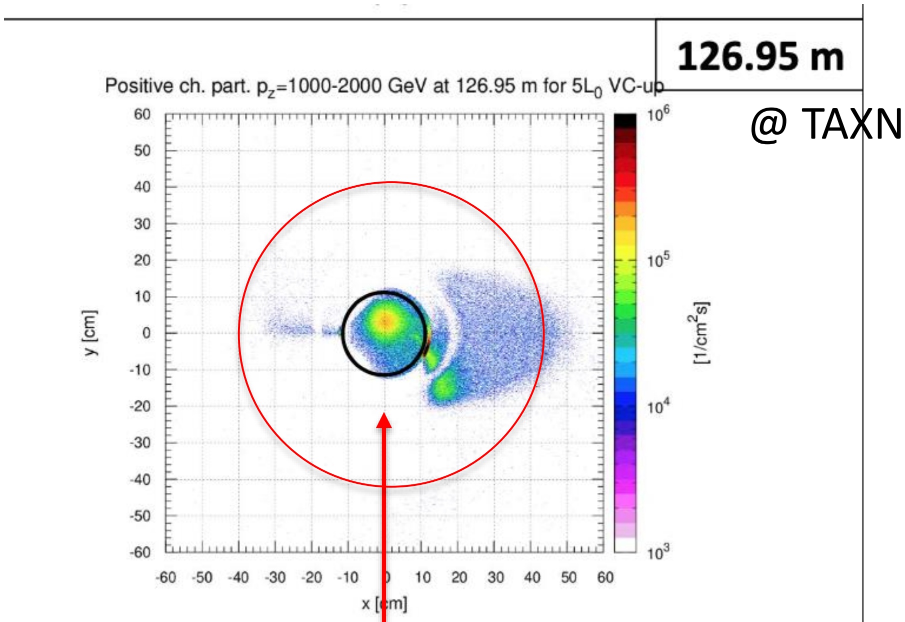
Hitting pipe: 0.5 π- and 1 π+ and about 2 protons / 50 collisions. Near horizontal plane

Marta Sabate-Gilarte and Francesco Cerutti

NEGATIVE particles 1 – 2 TeV (through D1 aperture - CMS)

POSITIVE particles 1 - 2 TeV (through D1 aperture - CMS)





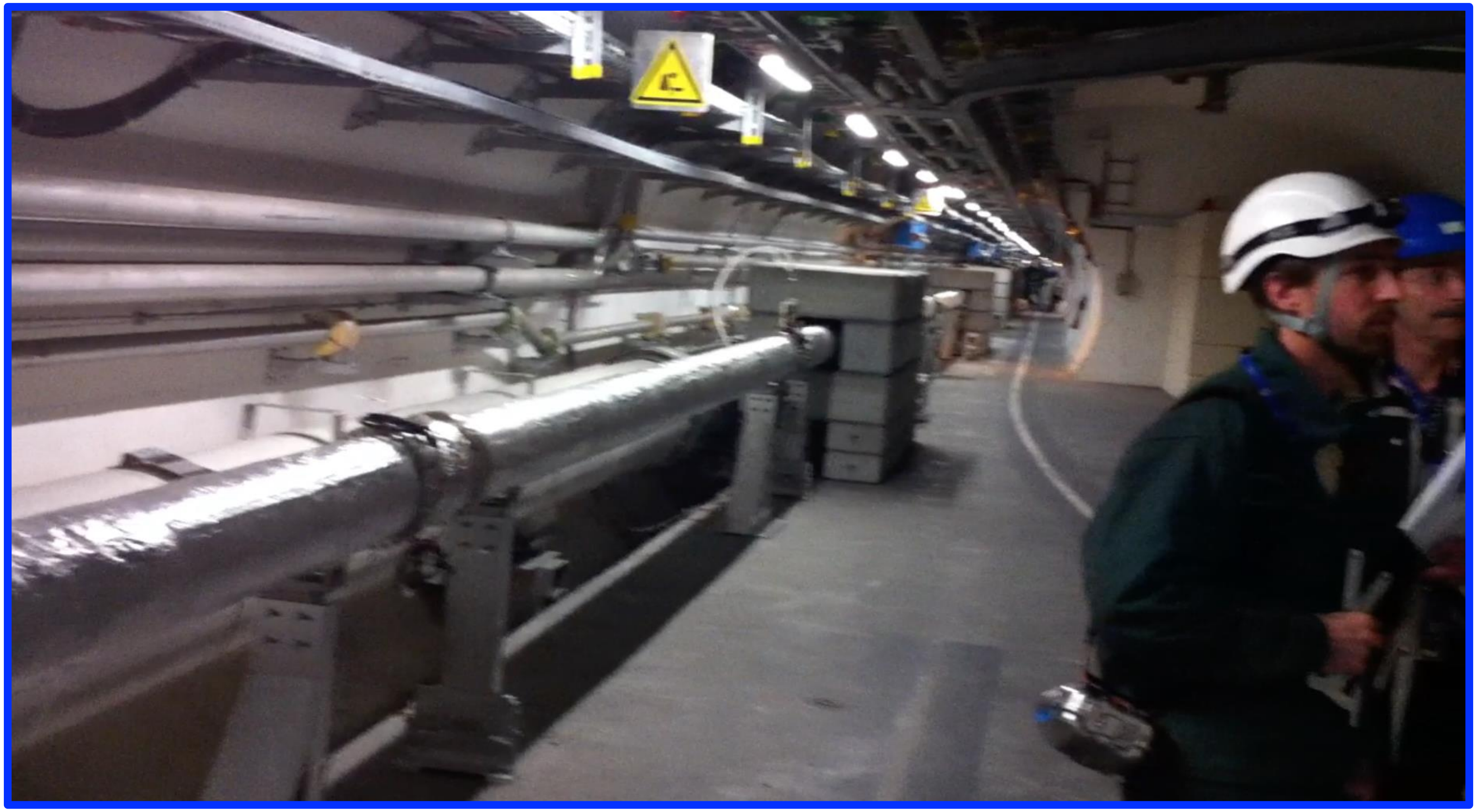
R_{outer} (at 116m) = 40 cm
η = 6.65

R_{inner} (at 116m) = 10 cm
η = 7.75

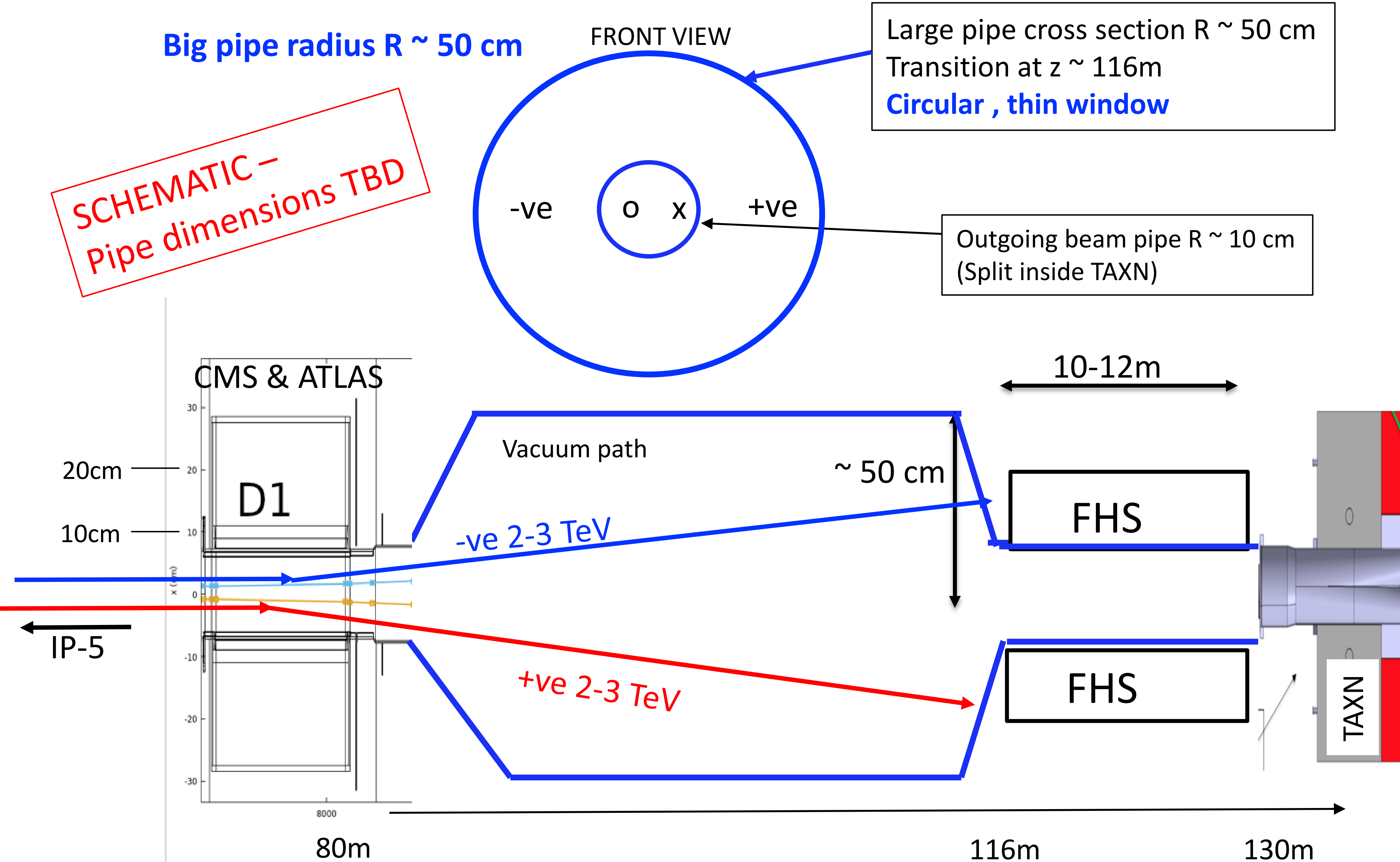
No primary charged
Particles UP & DOWN
Shielded by Quads and Dipole iron
Penetrating neutral particles
Neutrinos **+ to be discovered ? LLPs**

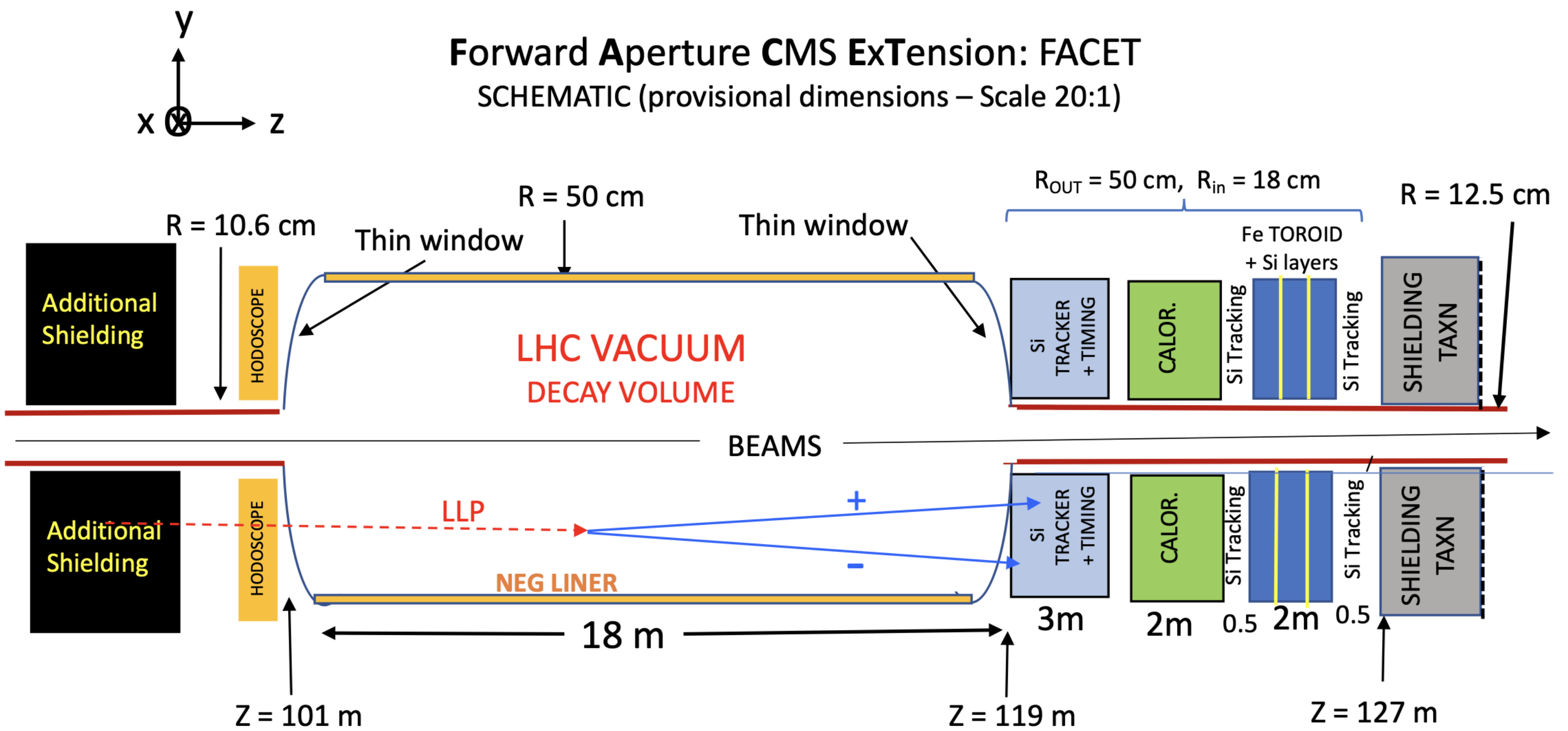
HADRON measurements in L&R quadrants in low pile-up short pp, pA, AA runs

Region NOW looking **along LHC tunnel**, beam separation dipoles & CMS way behind me.
20 cm diameter straight pipe with both beams for 50 m. (Cladding on pipe)



TOP (BENDING) VIEW





Search for penetrating (50 m Fe) neutral long-lived particles decaying to SM particles In large vacuum tank (replacing section of LHC vacuum pipe) which are detected in tracking, calorimetry, muon detectors – clones of CMS Run 4 upgrade detectors.

Sensitivity to LLPs (portals) in mass range to ~ 50 GeV (h) in coupling strength range.
Big vacuum tank Run 5+ only. Not yet formally proposed. Backgrounds high at μ = 140.
Possibility of initial test runs with existing pipe (no tank) in Run 4 – pipe interactions.

Meeting on Forward Multiparticle Spectrometer April 16+17 2020

https://indico.cern.ch/event/868473/

Context then: CMS Run 4?

14:30	**Beam pipe issues** — Considerations of a long, large diameter beam pipe — *CERN*	*Vincent Baglin*, CERN	14:30 - 15:00
15:00	**Introduction to Mode A: Hadron spectra** — High x_F low-p_T region – uncharted territory since ISR. Including charm and antinuclei — *CERN*	*Michael Albrow*	15:00 - 15:30
	Particle spectra, acceptances — Tracking through Q1-Q3 and D1 magnets – through big pipe to detectors — *CERN*	*Marta Sabate Gilarte*, CERN	15:30 - 16:00
16:00	**Transition Radiation Detectors for hadron ID** — How to identify multi-TeV π / K / p ? Not Cherenkov, TRD! — *CERN*	*Michael Cherry et al.*	16:00 - 16:30
	Cosmic ray showers & Forward hadrons — Why astroparticle physics needs these measurements — *CERN*	*Dr Tanguy Pierog*	16:30 - 17:00
17:00	**Way forward, plans** — How to make it real? Work (workers) needed to make a NOTE or LOI or similar. — *CERN*	*Mike Albrow, all*	17:00 - 17:20
	Next LHC forward physics meetings — *CERN*	*Christophe Royon et al.*	17:20 - 17:30

Now too late to make changes to LHC beam pipes for Run 4.
Should be done before end of LHC : Plan for Run 5 +
Can be done at any IR combined with any big central detector
Towards full event, central-forward correlations etc.

FHS – Charged L&R arms - OVERVIEW

Very forward charged particle production

Use beam separation dipole as a **spectrometer magnet** (+ focusing quads)

In CMS & ATLAS superconducting **D1 dipole** (Integral B.dL = 35 Tm) [**ALICE is different**]

Straight section in vacuum from ~ **80 m to ~ 127 m**.
Larger beam pipe R ~ 40 cm (cf R = 12 cm now)
for charged particles to emerge through thin windows: + & - sides - Low pile-up only

Detectors over 10 – 12 m in front of TAXN/TAN at 127 m:

Precision tracking (silicon strips or pixels) over ~ 2 m (θ_x, θ_y to a few μrad)

[Possible targets + tracking to study multi-TeV π, K, $\bar{p}$, p interactions]. --- bonus!

EM & Hadron Calorimeter for energy measurement and muon filter

Muon tracking behind calorimeter

Hadron ID: Transition Radiation Detectors for $\gamma = E/m$ in $10^3 – 3.\ 10^4$ region (novel)

PHYSICS GOALS for L&R Charged particles (not complete!)

Deuterons and antideuterons, tritons and antitritons

Precise measurements of Feynman-x (x_F) spectra at small p_T (< ~2 GeV) of:

$\pi+$, $\pi-$, K+, K-, p, $\bar{p}$, d, $\bar{d}$, t, $\bar{t}$, ... possibly $K^0_s \rightarrow \pi+\pi-$, $\Lambda^0 \rightarrow p\pi$ (acceptance?)

In p+p and p+O and O+O collisions (for cosmic ray showers in atmosphere)

Intrinsic charm: p = {uudcc} giving leading $D^0 \rightarrow K^+\pi^-$ & $K^-\pi^+$

Full reconstruction challenging but also → forward muons

Other reconstruct-able particles: $J/\psi \rightarrow \mu^+\mu^-$ (6%) ; $\Upsilon(1S) \rightarrow \mu^+\mu^-$ (2.5%)

These are 'intrinsically' important + to understand **μ and ν in cosmic ray showers.**

Very forward charm and beauty also inferred from single leading e or μ

Leptons can be identified : Track + EM calorimeter & muon chambers behind CAL.

Production of light nuclei and **antinuclei – antiprotons, antideuterons, antitritons**, $\overline{\mathbf{He}^3}$

Needed to understand background to Galactic Center γ-ray excess (Dark Matter Annihilation?)

Diffraction dissociation – products, e.g. $p \rightarrow n\,\pi+$, $p\,(\pi+\,\pi-)$, $\Lambda^0 K^+$

$\gamma c\tau$ (π) = 139 km at 2.5 TeV !
$\gamma c\tau$ (K+) = 18.5 km at 2.5 TeV !
$\gamma c\tau$ (D^0) = 16.5 cm at 2.5 TeV !

} **neutrinos!**

Low Q^2 frontier of QCD

Tracking

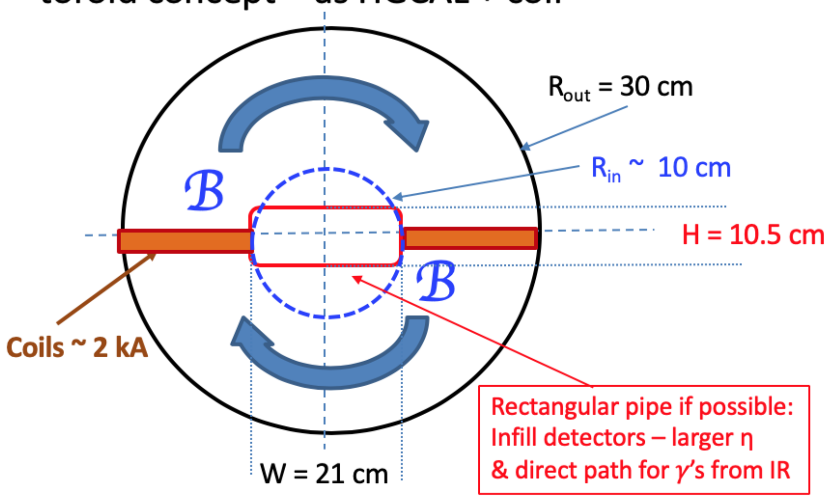
Precision (Si) tracking immediately behind vacuum pipe window – as thin as allowed (ribs)
No field region so straight tracks.

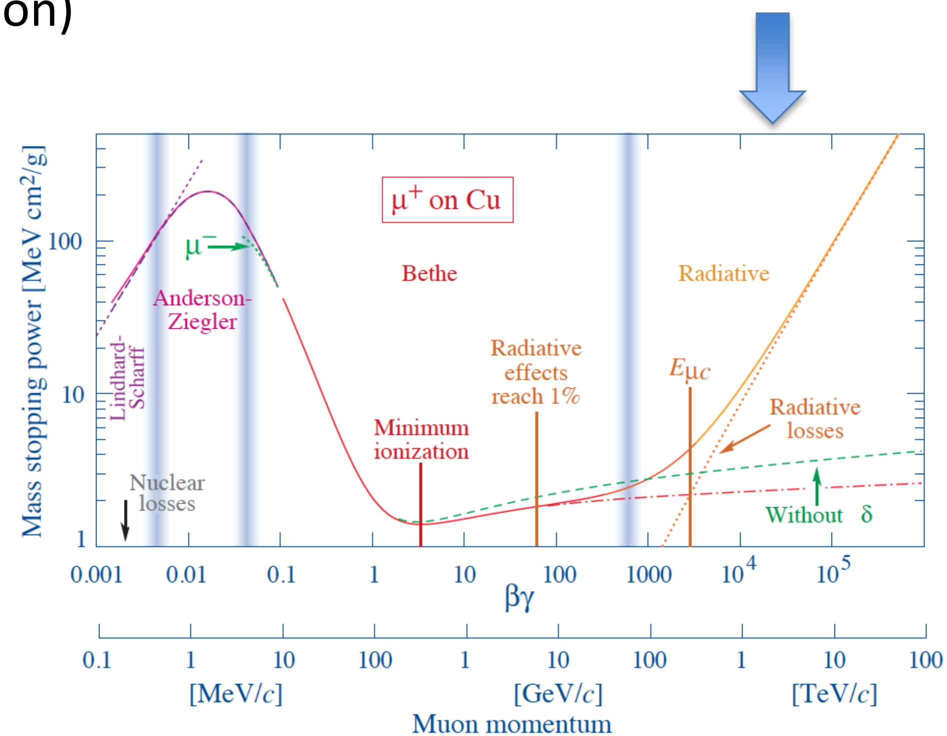
Hadron identification : π, K, p, d, .. **TRANSITION RADIATION DETECTOR**
- incorporates tracking

CALORIMETER (toroid for μ deflection)

MUON CHAMBERS

Magnetised hadron calorimeter
toroid concept – as HGCAL + coil





Identifying multi-TeV hadrons:

Nuclear Inst. and Methods in Physics Research, A 1055 (2023) 168535

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Full Length Article

Transition radiation detectors for hadron separation in the forward direction of LHC experiments

M. Albrow [a], N. Belyaev [b], M. Cherry [c], S. Doronin [b], P. Fusco [d,e], F. Gargano [e], S. Konovalov [f], F. Loparco [d,e], M.N. Mazziotta [d], D. Ponomarenko [b], C. Rembser [g], A. Romaniouk [b,*], S. Smirnov [b], Yu. Smirnov [b], P. Spinelli [d,e], L. Sultanaliyeva [f], P. Teterin [b], V. Tikhomirov [f], K. Vorobev [b], K. Zhukov [f]

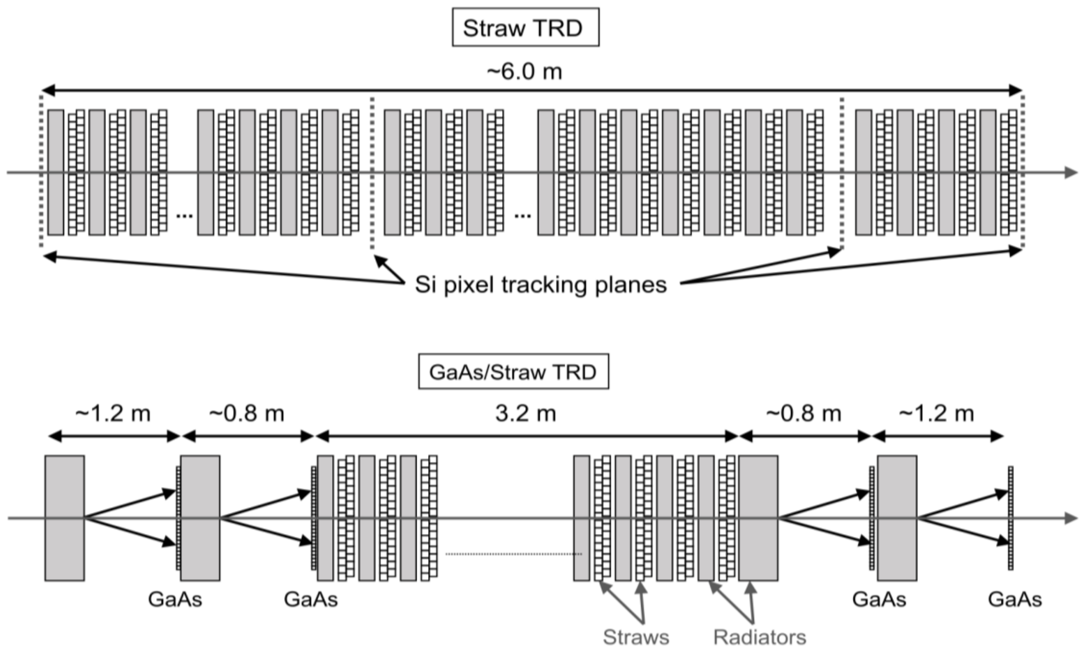
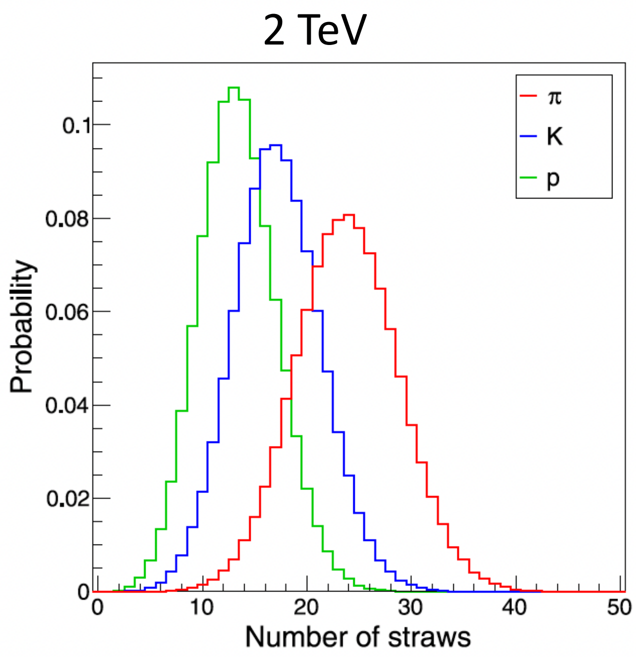


Fig. 8. Concepts of TRDs for forward-direction experiments at LHC. Top panel - "Straw TRD", bottom panel - "Hybrid GaAs/Straw TRD".

Test beam results with electrons and pions agree well With Monte Carlo

M. Albrow, N. Belyaev, M. Cherry et al. *Nuclear Inst. and Methods in Physics Research, A 1055 (2023) 168535*



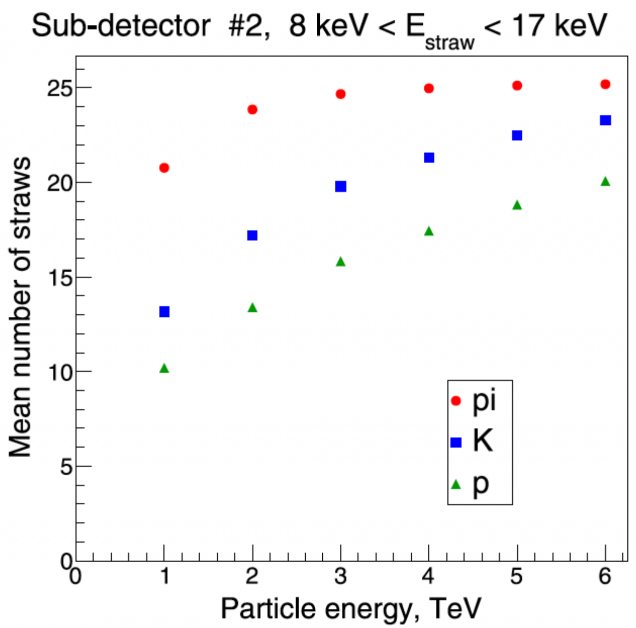


Fig. 11. Distributions of the number of straws for the particle energy of 2 TeV (left) and average number of straws for pions, kaons and protons as a function of their energy (right) for the second sub-detector, 8 keV< E_{straw} < 17 keV.

Forward production of antinuclei : antideuterons, anti-He?

Antideuterons discovered at the CERN PS (1965), seen at AGS, Serphukov, NAL.

Observed at the first pp-collider (ISR) at large angles:
B.Alper et al., Phys.Lett. 46B (1973) p.265 : dbar/π- = $(5 \pm 1)\ 10^{-5}$
and small angles:
M.G.Albrow et al., Nucl.Phys.B 97 (1975) p.189 : dbar/π- = $(7.6 \pm 2.3)\ 10^{-6}$

How produced in pp? Coalescence model.
pbar + nbar close in phase space (< p_0 parameter ~ 25 MeV?) stick together.

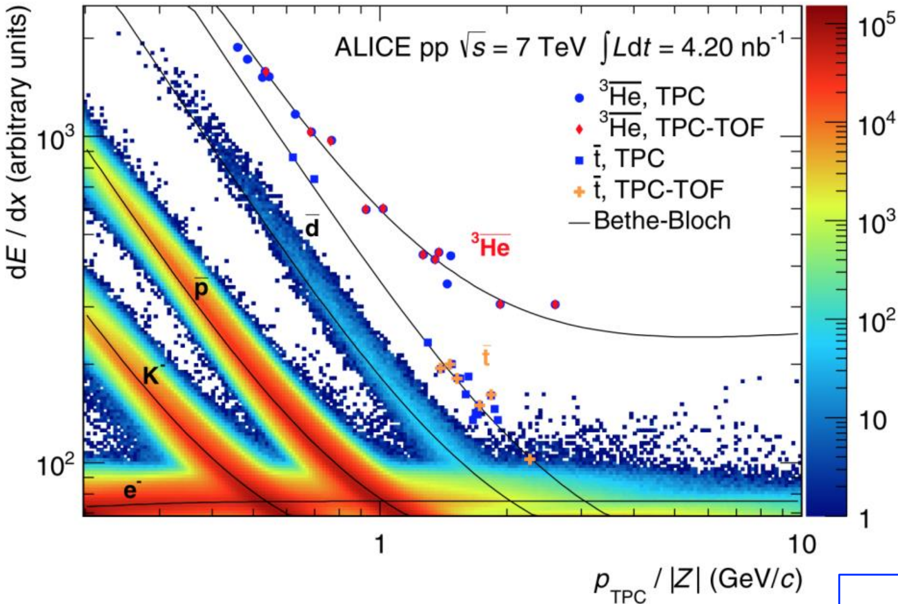
Renewed interest for **dark matter annihilations in galaxy center**
Need to know Standard Model production.
Very clean signature in FHS:
Negative curvature - > p/Q, dE/dx - > |Q|, Calorimeter - > E, TRD - > E/m

Anything novel? E.g. strangelets in heavy ion (pO and OO) fragmentation region?
(Light quasi-stable nuclei with s-quarks replacing d-quarks -unusual Q/M)

ALICE has best LHC data on antinuclei so far: Central region: |y|< 0.5 at $\sqrt{s} = 7$ TeV pp.

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



Topical interest, possible signals of dark matter annihilation in galaxy

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,*],

Can probably make a special trigger for « heavier than protons » & get high statistics. ??

ANOTHER POTENTIAL USE OF FHS:

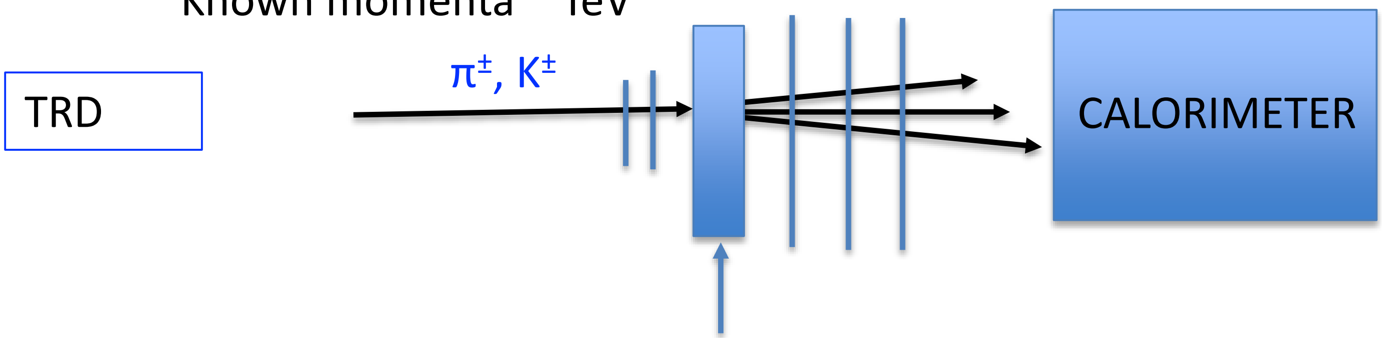
Inelastic (& elastic?) cross sections of multi-TeV $\pi^{\pm}$, $K^{\pm}$, etc.

IDEA:

Behind TRD-Tracker have multi-TeV identified $\pi^{\pm}$, $K^{\pm}$

Can put in front of calorimeter a thin target followed by short tracker:

Known momenta ~ TeV



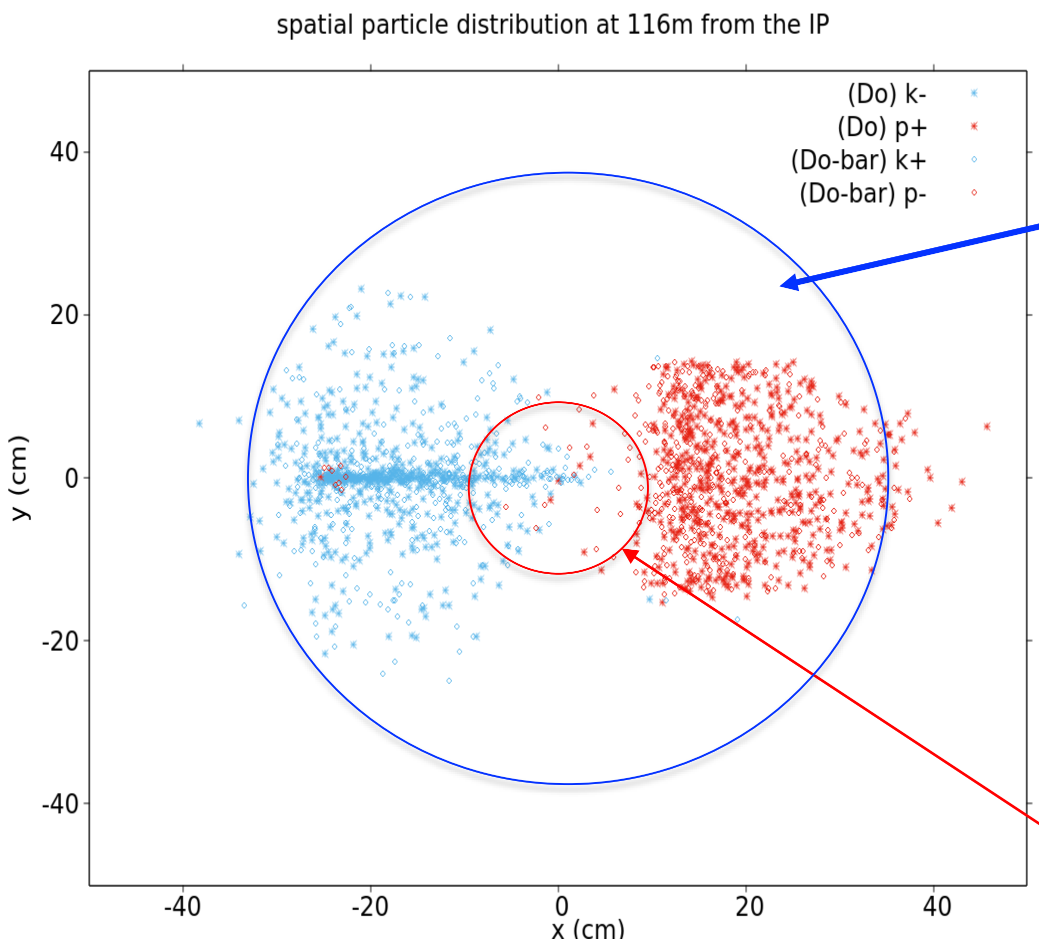
Thin TARGETs

CH_4, C - subtract

+ Simple addition: σ_{inel}, N_{ch}, σ_{el},

Can FHS measure $D^0 \rightarrow K+ \pi-$? Plot from Marta Gilarte (CERN)
Have some acceptance but is it possible?
Large pileup background unless low-luminosity single interactions
Displaced vertex very difficult since θ ~ 0

Relevant for FCC ν's
.... c, b ... ν's



Back big pipe
Thin window
R ~ 50 cm

Outgoing pipe
R ~ 12 cm

Preliminary study

Some acceptance for $D^0 \rightarrow K\,\pi$ but it is very challenging:

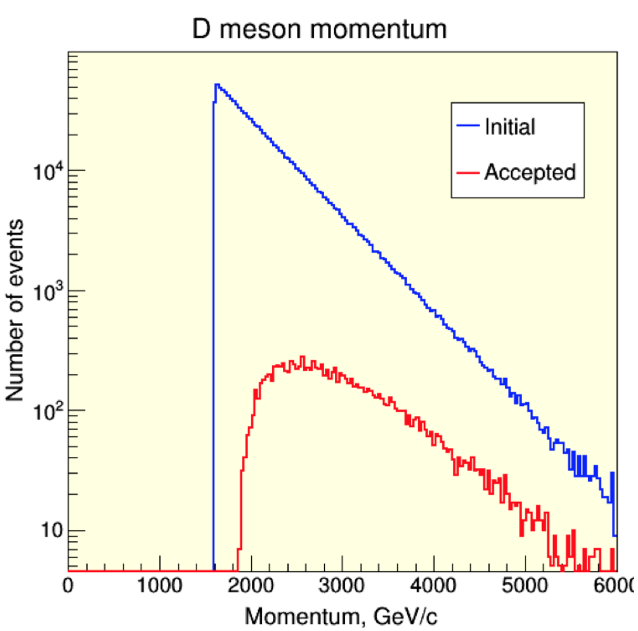
Acceptance small – OK if very well known – **signal could be much bigger (Brodsky)**

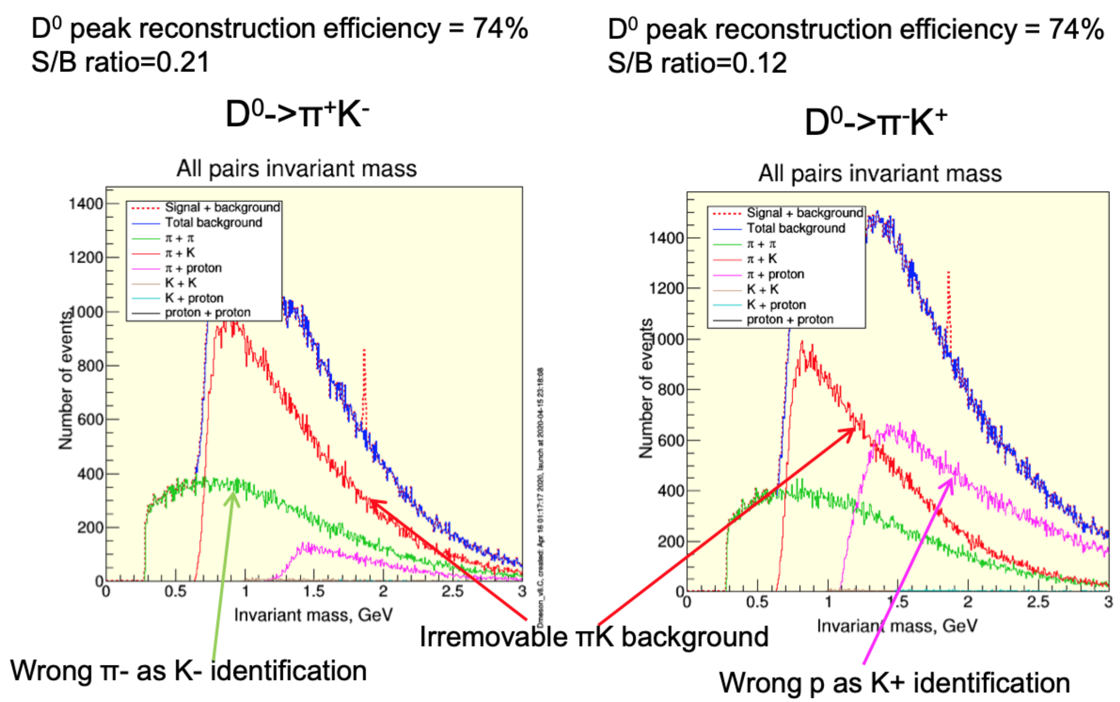
p >> π+ >> K+ so mis-identification critical … TRD challenge

Even with perfect identification, irremovable K π continuum is large.

Unlike central production, do not see decay vertex and $\gamma c\tau\ (D^0)$ = 16.5 cm at 2.5 TeV !

… which smears mass resolution from ~ 6 MeV to ~ 16 MeV





Implications for the FCC = Future CERN Colliders
100 TeV pp and heavy ion colliders FCC

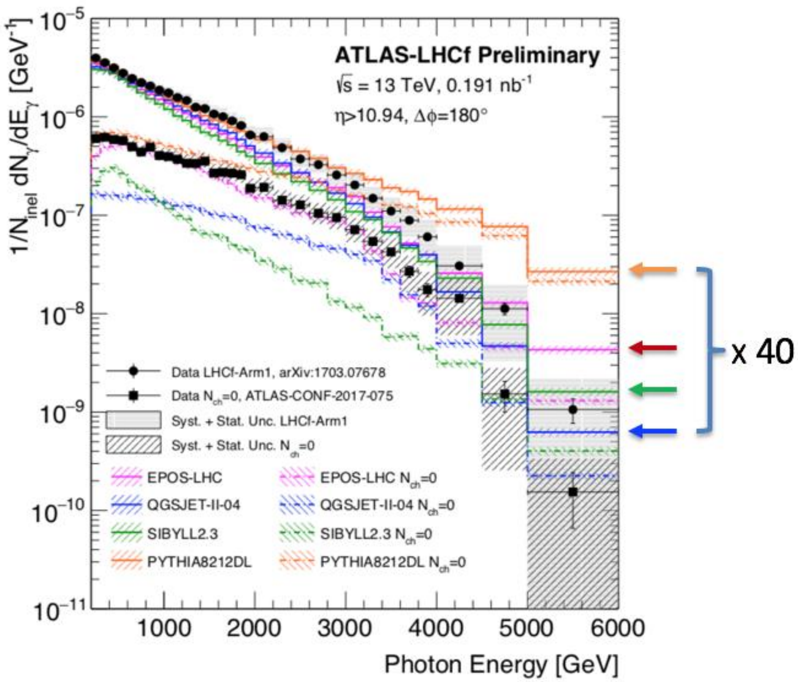
Designing such machines requires advanced knowledge of very forward very energetic particles.
Beam particles hitting pipes and collimators etc.
Also particles produced in the collisions – all x_F (tens of TeV) and small angles (p_T)

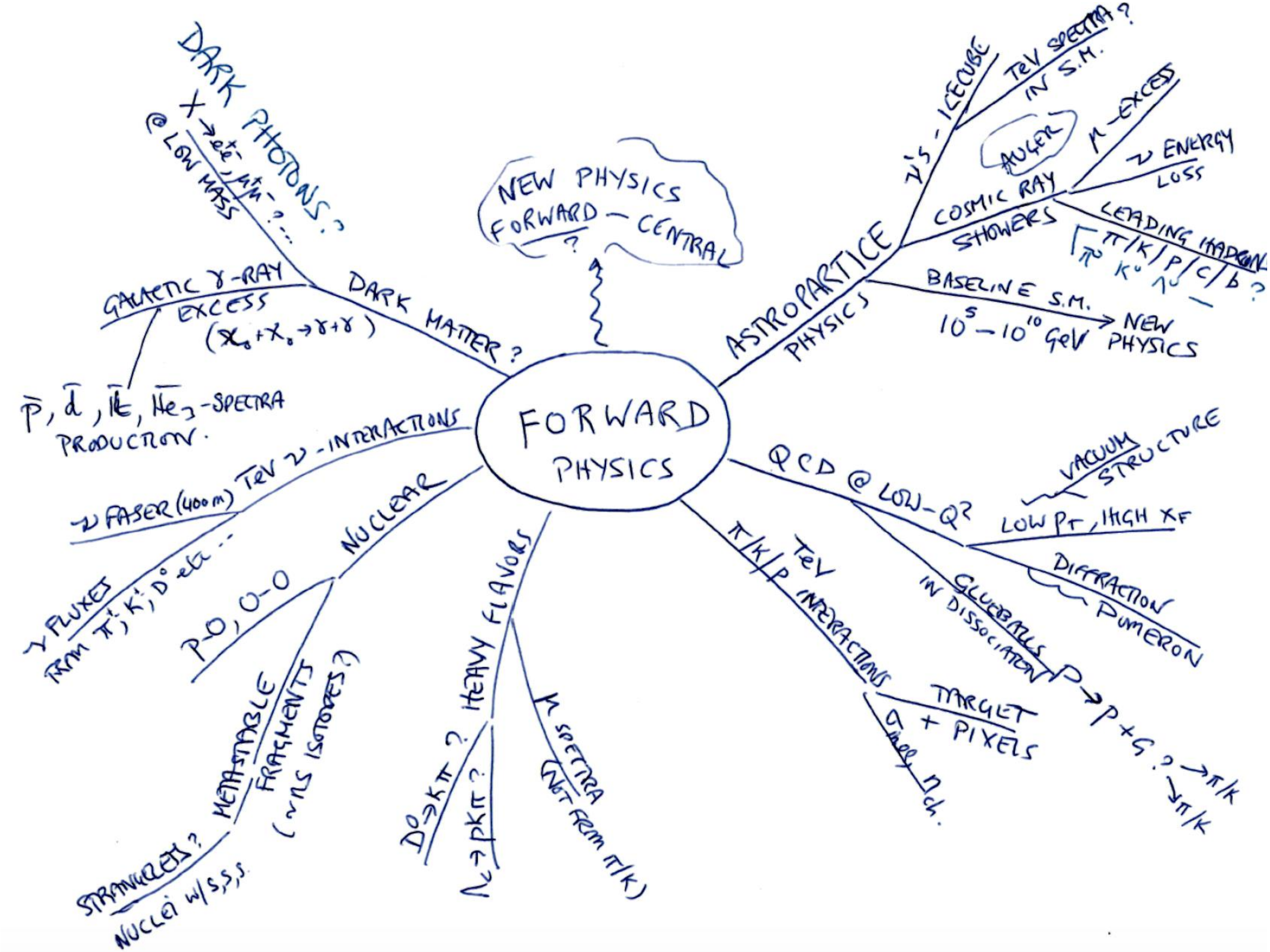
Not only protons (dominant at high x_F) and neutrons but also pions, kaons, etc.

We need these spectra, presently very uncertain!

So FHS will be a service to CERN's future FCC!

> CERN should support it! ?




FORWARD PHYSICS
NEW PHYSICS FORWARD — CENTRAL ?
DARK MATTER ?
DARK PHOTONS ?
@ LOW MASS
GALACTIC γ-RAY EXCESS
p̄, d̄, H̄e, He3 -SPECTRA PRODUCTION.
TeV ν - INTERACTIONS
ν FASER (400 m)
ν FLUXES FROM π±, K±, D° etc ...
NUCLEAR
P-O, O-O
METASTABLE FRAGMENTS
STRANGELETS ?
NUCLEI W/ s,s,s.
HEAVY FLAVORS
μ SPECTRA (NOT FROM π/K)
ASTROPARTICLE PHYSICS
ν's - ICECUBE
TeV SPECTRA IN S.M. ?
AUGER
COSMIC RAY SHOWERS
μ - EXCESS
ν ENERGY LOSS
LEADING HADRONS
BASELINE S.M.
10^5 — 10^10 GeV
NEW PHYSICS
QCD @ LOW-Q²
VACUUM STRUCTURE
LOW pT, HIGH xF
DIFFRACTION
POMERON
GLUEBALLS IN DISSOCIATION
TeV π/K/p INTERACTIONS
TARGET + PIXELS

SUMMARY

In RUN 5 with new vacuum pipe, and new detectors ~ 10 m (?):
TRD's with tracking for hadron ID, calorimeter for E and muon toroid for μ
LHC magnets as spectrometer for momenta
→ Forward Hadron Spectrometer. Modest size (L + R < ~ 0.5 m^2)

FHS can measure spectra small p_T & up to p_z ~ 3 TeV
of identified charged : π, K, p, d, t, (and anti-d,t) – μ
and decaying neutral : π, K, ρ, φ, n, Λ, …. & $D^0 \rightarrow K^- \pi^+$ & $K^+ \pi^-$ (some acceptance)
Could combine with 0^o calorimeter for π^0, η^0, K_L, n

in p + p, p + O, O + O low pileup short runs.
Independent or events combined with full central detectors

Spectrometer magnet (will be) already there! (35 Tm in CMS & ATLAS – ALICE different?)

Conceptual now – needs full study to check feasibility etc.
Possible part of ALICE 3 ???

Thank you

Back-ups →

DPMJET prediction (Prob. Too high)

Very uncertain! Illustration only

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

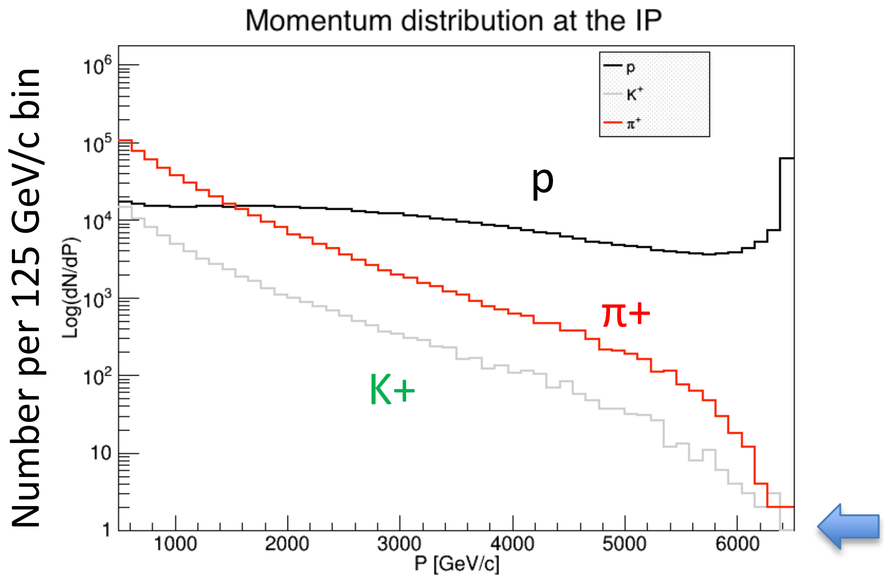
In 1 second, with 2808 bunches,
Have 30 x 10^6 bunch crossings and
30 x 10^6 x μ(= interactions/X) events.

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

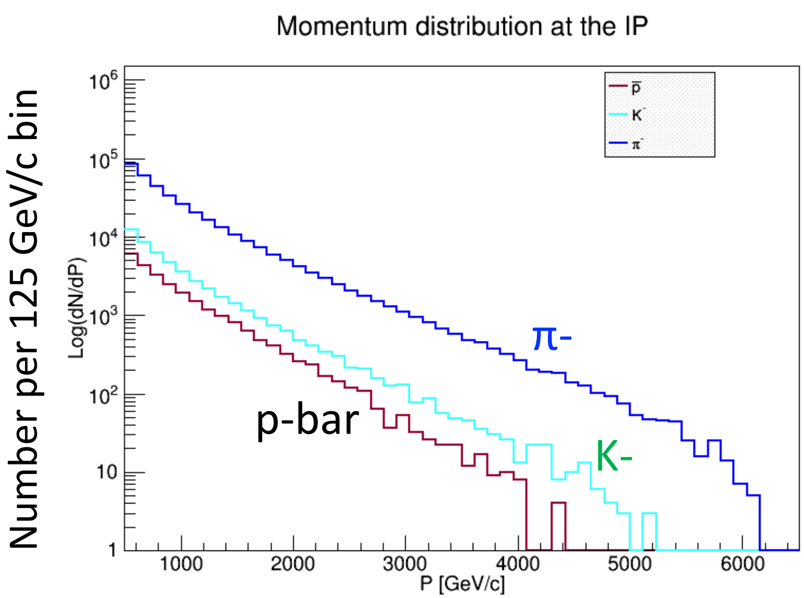
p's > π^+ above 1.5 TeV and flattish;
High x_F peak from diffraction

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

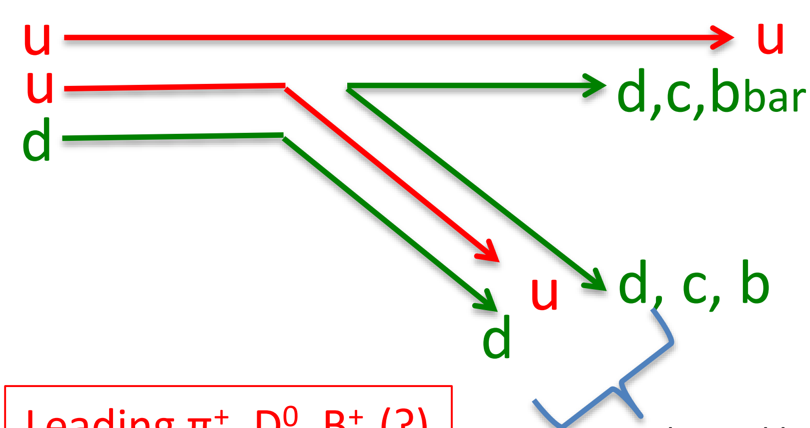


Neutrons not = protons, K^0 not = $K^{+/-}$

$x_{Feynman} = x_F$ = p(hadron)/p(proton)

$x_F - x_{Bj}$ relationship, but less direct than in deep inelastic scattering.

E.g. p → π^+ is from leading u adding a dbar
p → π^- is from leading d adding a ubar
Ratio at high x reflects u:d in p

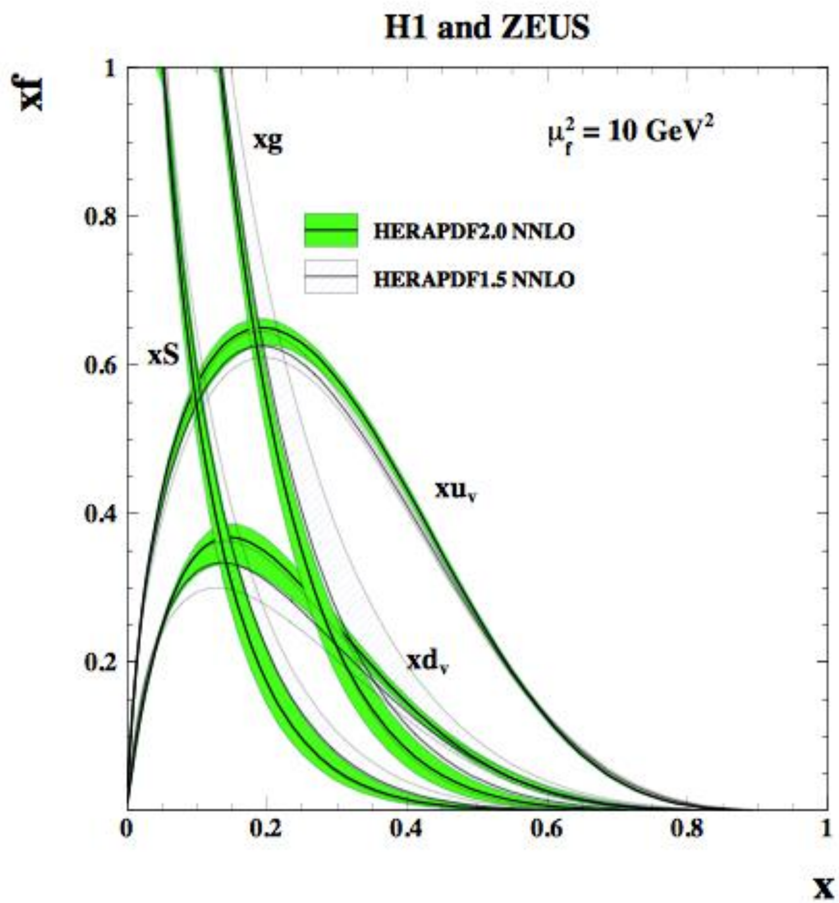


Leading π^+, D^0, B^+ (?)

t-channel baryon exchange

Diffraction dissociation

$x_{Bjorken} = x_{Bj}$ = p(parton)/p(proton)
Major industry at HERA, and these PDFs needed for hard (partonic) interactions at LHC



Brodsky: Intrinsic charm – p has {$uudc\bar{c}$} component (1-2%?) → high x_F Λ_c and D^0

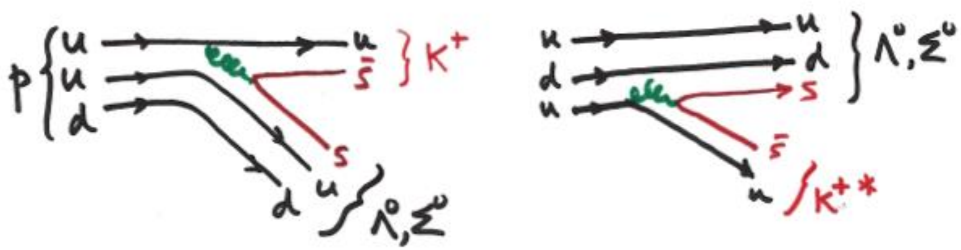
Challenge to theorists

Strong Interactions at low-Q^2

Hadron level ~ Regge theory ⟷ Parton level ~ QCD (non-perturbative)

Leading (high x_{Bj}) u-quark or [ud] di-quark picks up an sbar or s in "string-breaking" or from s-sbar sea, to make a leading K^+ or Λ^0, Σ^0

$\gamma c\tau(\Lambda)$ at 4.4 TeV is 316 m, → $p\pi^-$ (acceptance?). $\Sigma^0 \to \Lambda^0 + \gamma$ (100%, prompt)



Dissociation products sharing beam momentum (p opposite?)

Quark line description of leading K^+ or Λ^0, Σ^0

8 *J. Singh et al. / Production of high-momentum mesons*

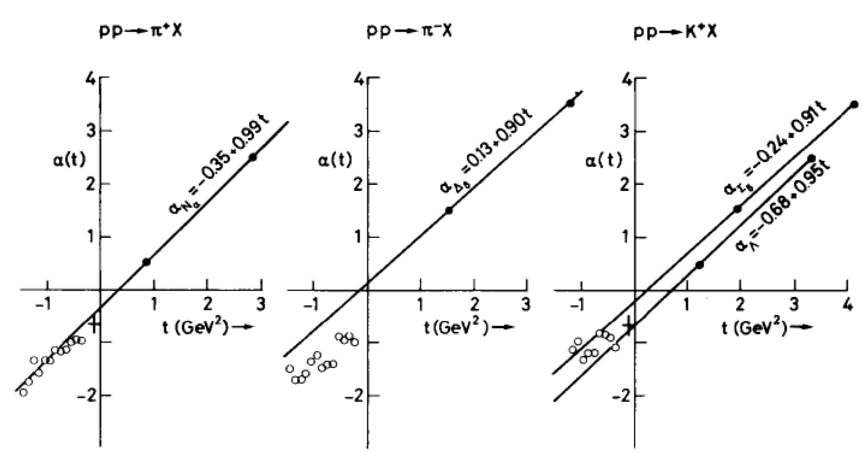


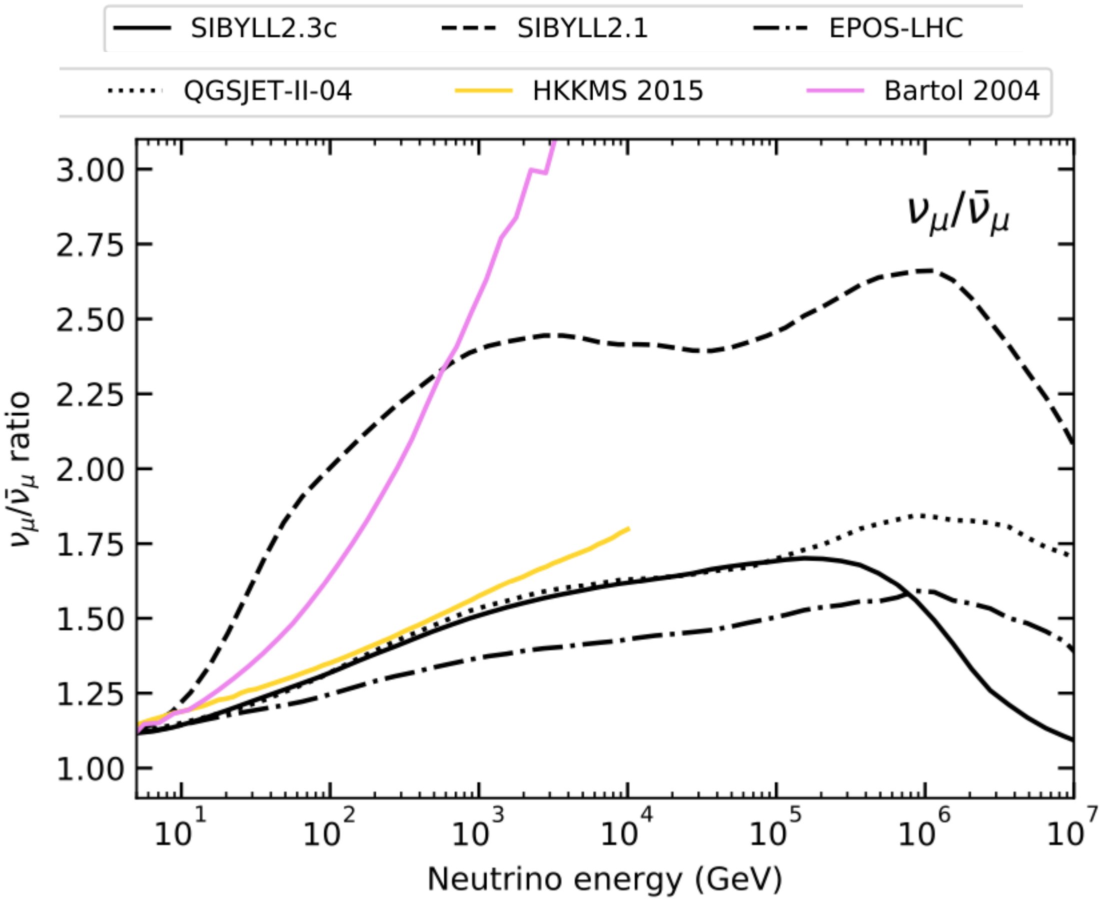
Fig. 9. Effective trajectories $\alpha(t)$ obtained from a one-term triple-Regge fit, see text.

Virtual (negative mass^2, t-channel) exchanged baryon or meson described in Regge phenomenology :
Analyticity, unitarity and crossing symmetry
+ continuous complex angular momentum.

Derive it from QCD !! ?

The hadronic interaction model SIBYLL 2.3C and inclusive lepton fluxes

A. Fedynitch, F. Riehn, R. Engel, T.K.Gaisser and T. Stanev, arXiv:1806.04140



To illustrate the uncertainties in expected ν fluxes from cosmic ray showers

Refining and tuning the models will impact UHE CR and ν physics