SAS@LHC: A Spectrometer for Multi-TeV Forward Particles at the LHC

Mike Albrow, Fermilab

EXECUTIVE SUMMARY

I present an idea for a **new LHC experiment**
Measure identified charged particles with **p_z = 2 TeV – 5 TeV : e, μ, π, K, p, Λ, D0, …**

They go down the beam pipes but are deflected sideways by separation dipoles (spectrometer magnets). Special vacuum chamber required – exit from vacuum.
This forward region has **not been measured above √s = 63 GeV (at ISR)**
Very important for understanding cosmic ray showers, VHE neutrinos, etc.
Cosmic ray community very supportive!
Possible **new physics from heavy flavor production** → SM &? BSM ?

Detectors: small, state-of-art precision rad hard tracking, calorimetry and **innovative PID transition radiation detectors** for **π, K, p** identification now being developed with this in mind.
Existing "big four" experiments could benefit in combination but busy with own programs and upgrades.
> **Form new collaboration** to propose and do this as **"independent" experiment** co-existing at a collision region with possibility of later combination.

Great opportunity for younger, energetic physicist to lead project!

SAS@LHC: A Spectrometer for Multi-TeV Forward Particles at the LHC

Introduction: **Terra Incognita!** Strong interactions and cosmic ray showers

Some physics topics: single- and two- particle inclusive production

TeV particles through 30 Tm spectrometer magnets, special vacuum chamber

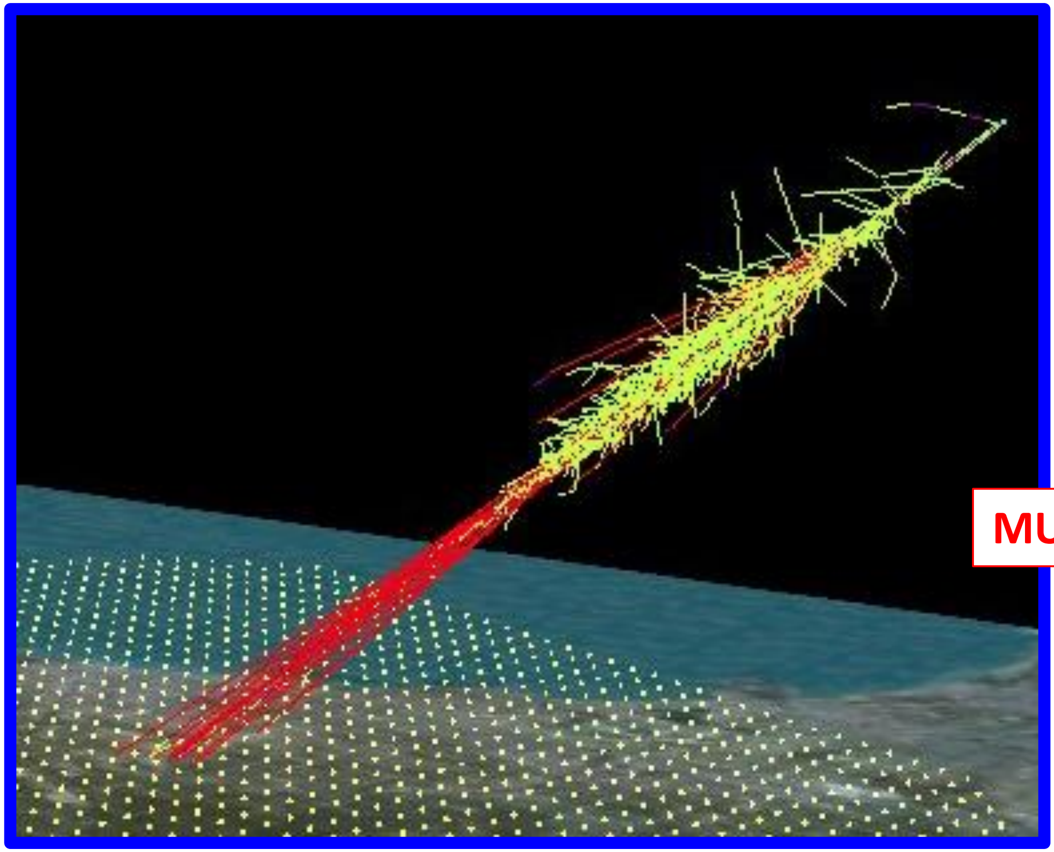
Tracking, Calorimetry and Muon detectors

Charged hadron identification : π, K, p with transition radiation detectors

What's next? Leadership needed : form a "collaboration" for studies
(acceptances, vacuum chamber design, set of detectors, costs, timescales)
- > Letter of intent - > proposal - > experiment.

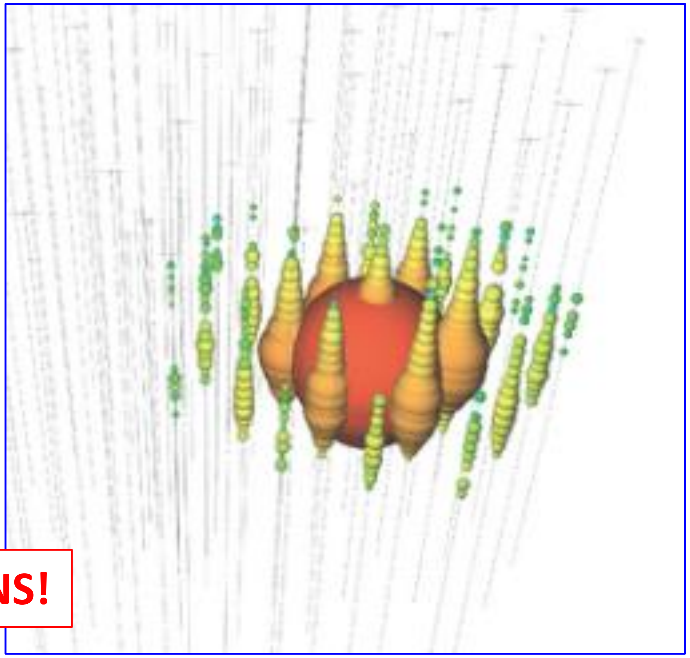
COSMIC RAY SHOWERs

Simulated UHE Cosmic ray shower over
Auger observatory in Argentina



Water Cherenkov tanks ~ 1 km spacing

ICECUBE Event 20 : 1140 TeV ν



MUONS!

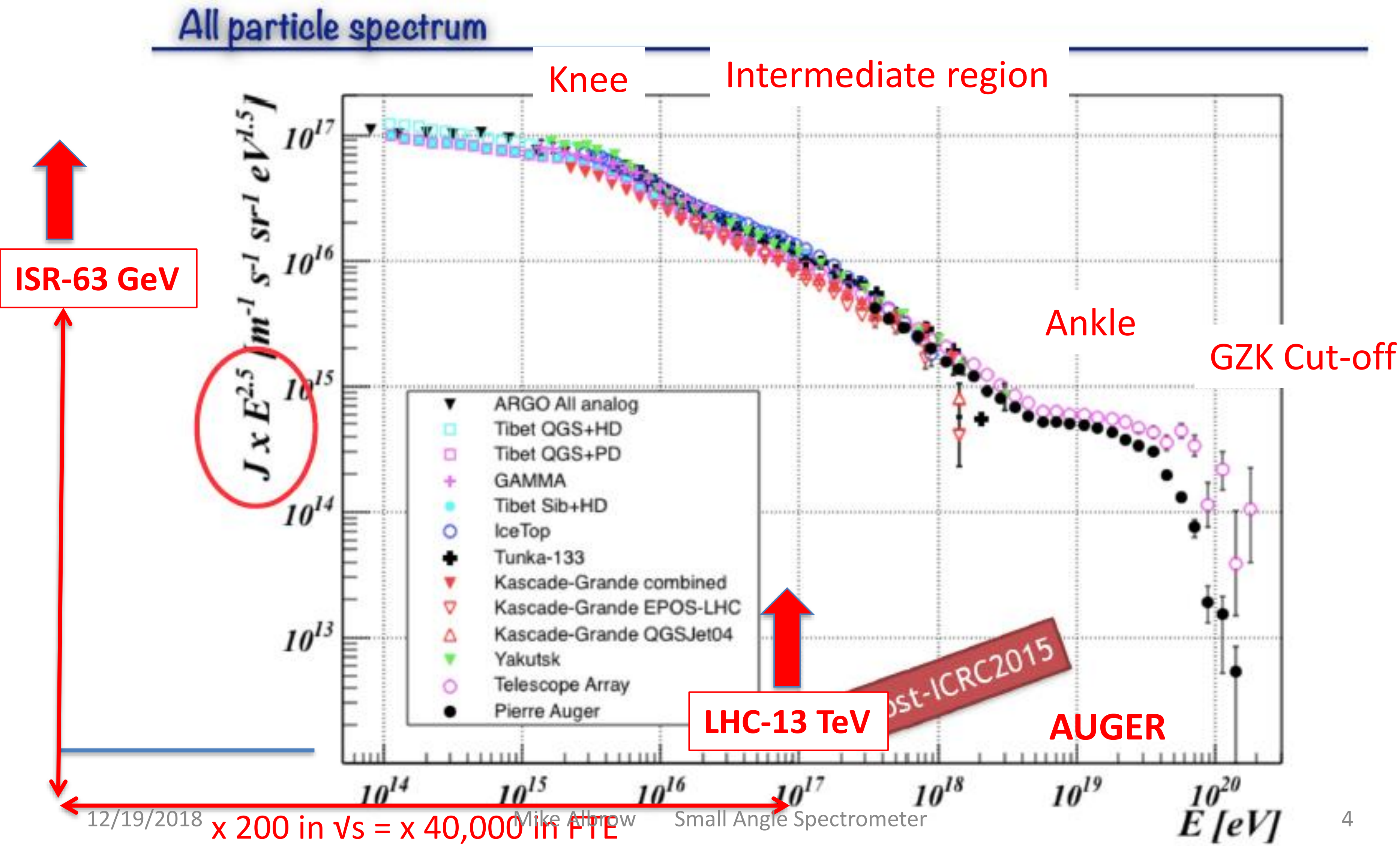
PMTs in Antarctic ice, 1 km^3

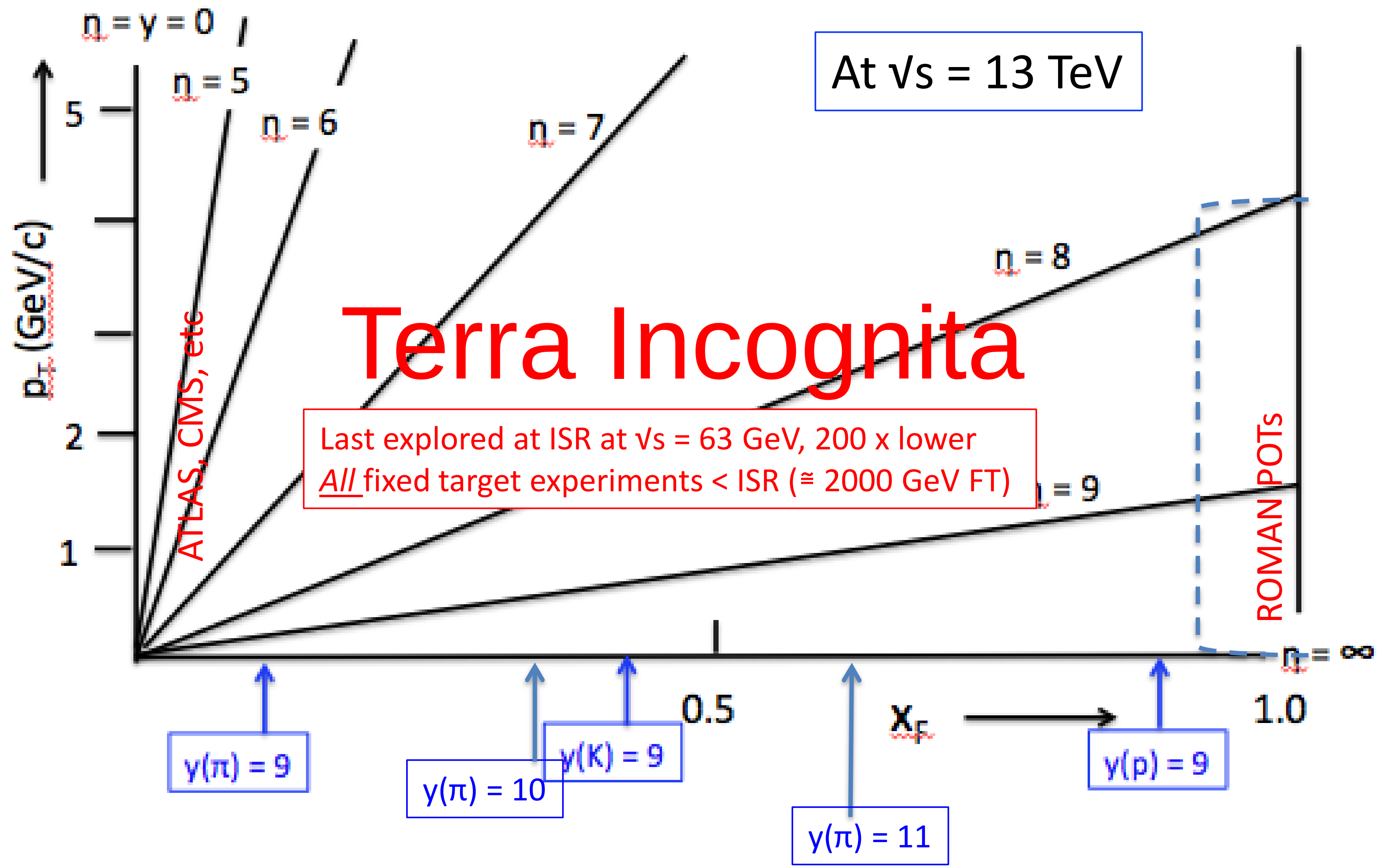
Simulating showers relies on particle production cross sections that are not well known

One day : p-N and N-N collisions at LHC?

COSMIC RAY SHOWERS: ASTROPHYSICS CONNECTION

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





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

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

40 years ago !

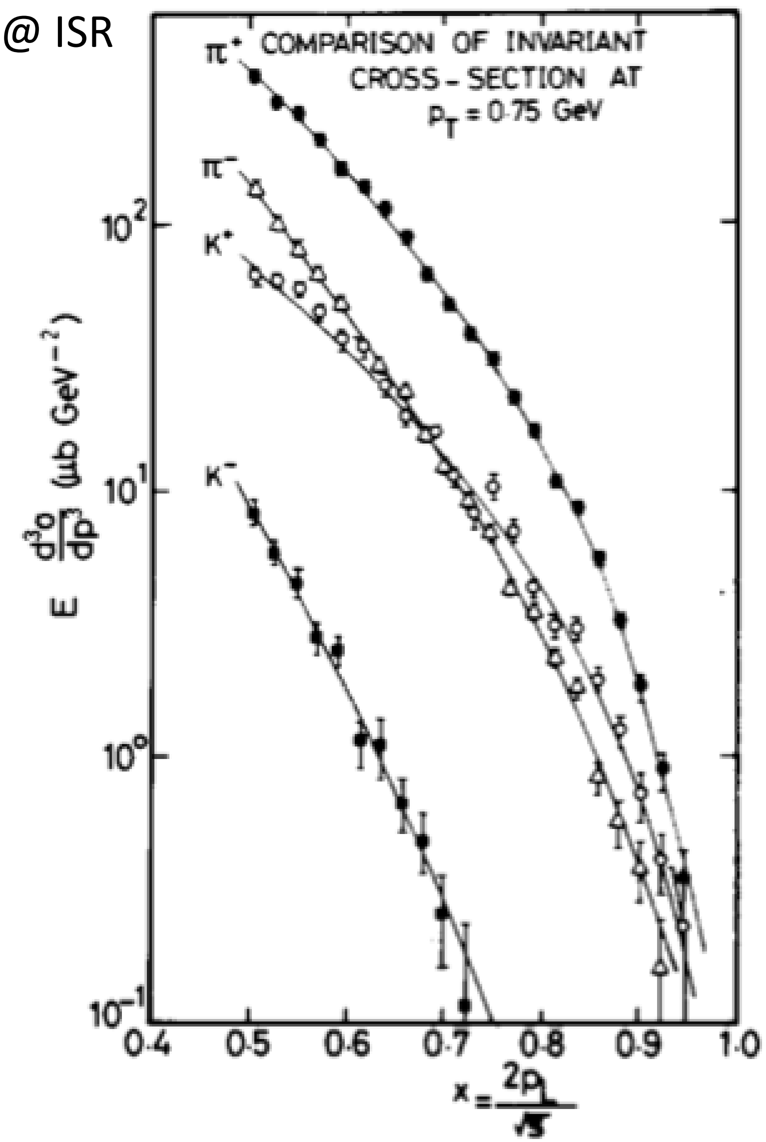


Fig. 2. Invariant cross sections for p + p → meson + X, for p_T = 0.75 GeV, a function of $x = 2p_L/\sqrt{s}$. The curves are empirical fits of the form $A \exp\{K(1-x)^C\}$ for $\pi^\pm$, K^+ described in the text. The curve for K^- is hand-drawn. The behaviour at other p_T values is similar.

Fixed pT, but want 2D $\sigma(x_F, p_T)$

3 different √s would be bonus.

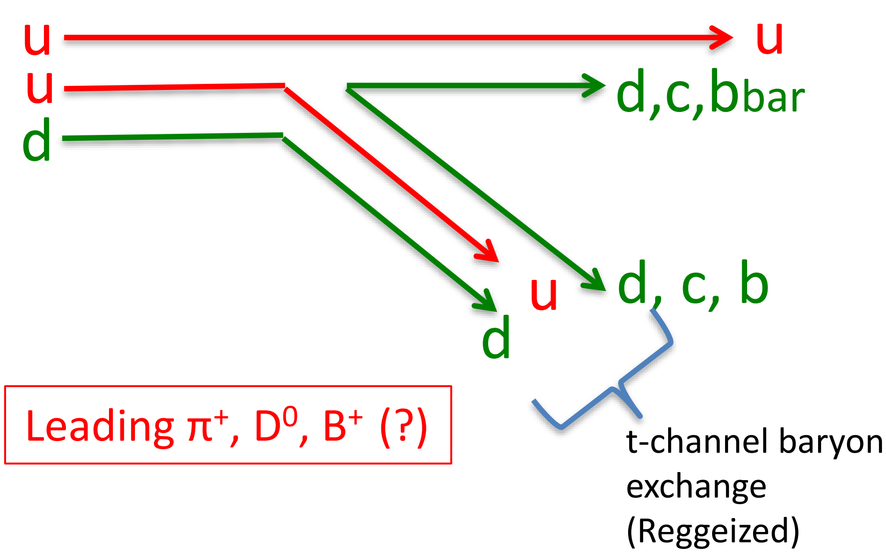
+ pA, AA

$x_{Feynman} = x_F$ = p_z(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

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



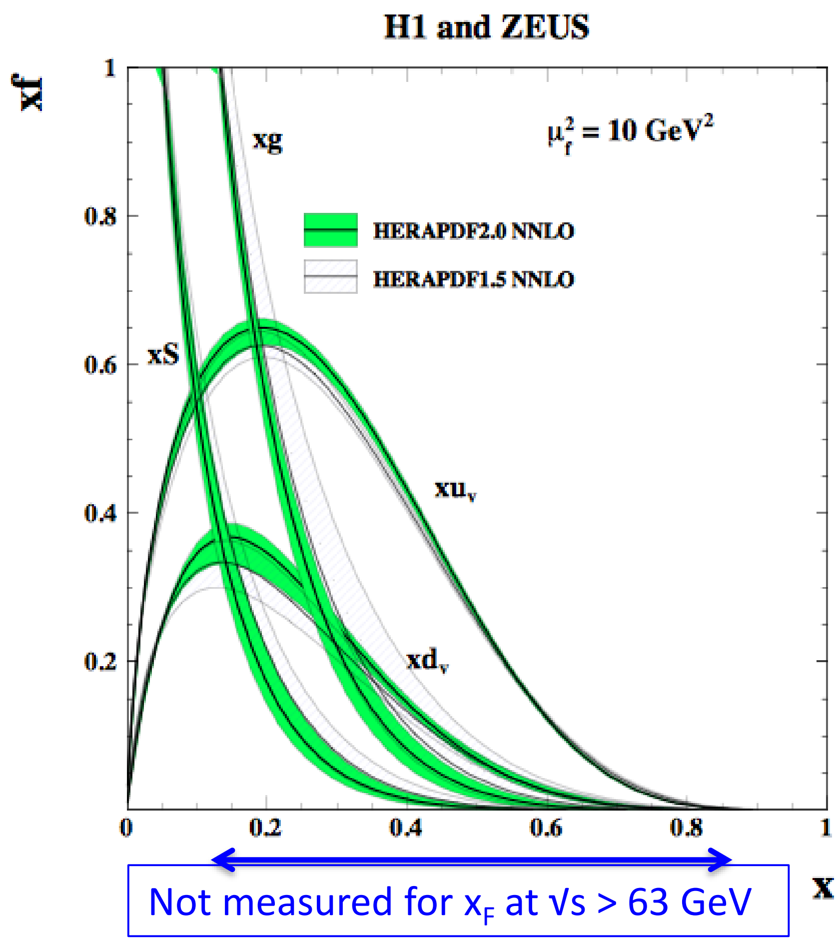


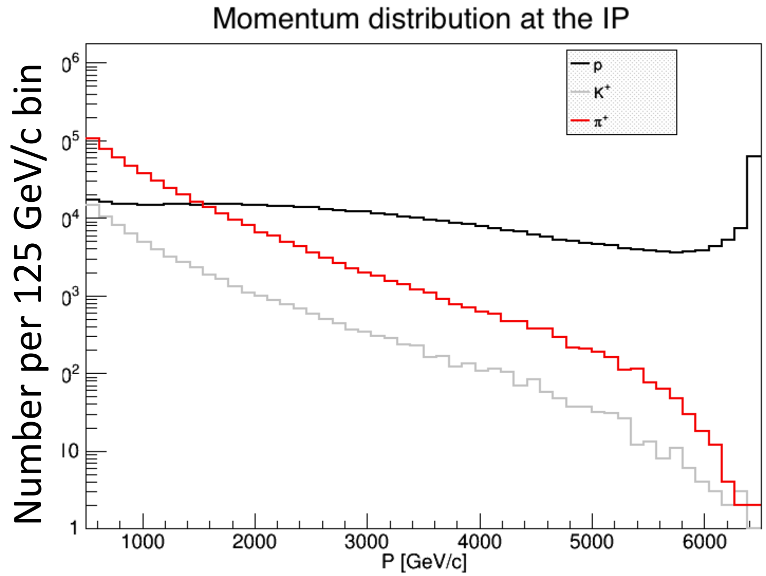
Figure 8: The parton distribution functions of HERAPDF2.0 NNLO, xu_v, xd_v, $xS = 2x(\bar{U} + \bar{D})$, xg, at $\mu_f^2 = 10\,\text{GeV}^2$ compared to HERAPDF1.5 NNLO on log (top) and linear (bottom) scales.

DPMJET prediction

Very uncertain!

Spectra generated by /DPMJET-MARS
With 10^6 pp events, $\sqrt{s}$ = 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.



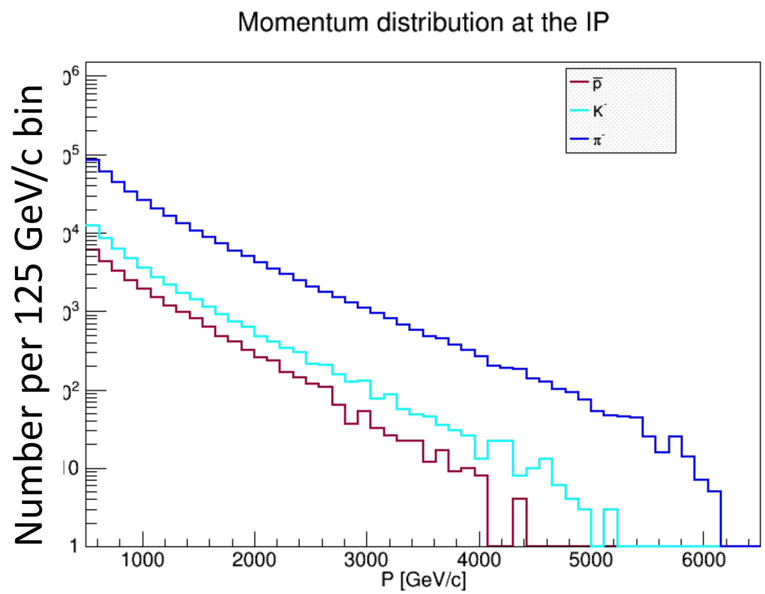
~ 100 x Acc/bin/sec if μ ~ 3

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)

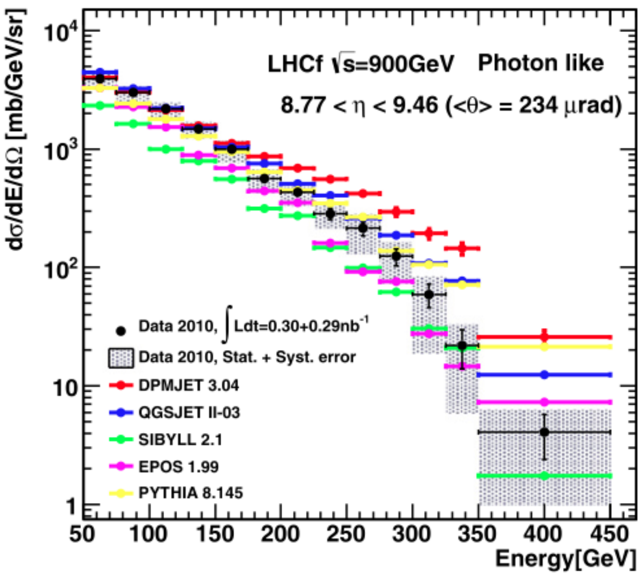
Antiprotons < K^- but only by a factor ~ 0.5



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

LHCf is a small 0° 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.

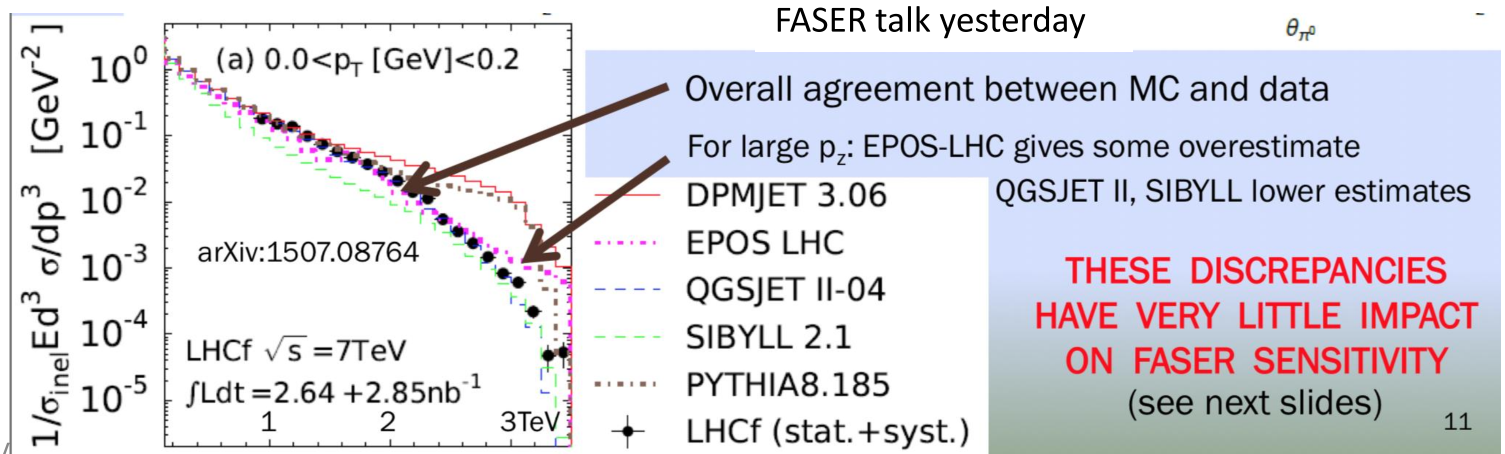
To illustrate the large spread in predictions even at much lower √s (900).



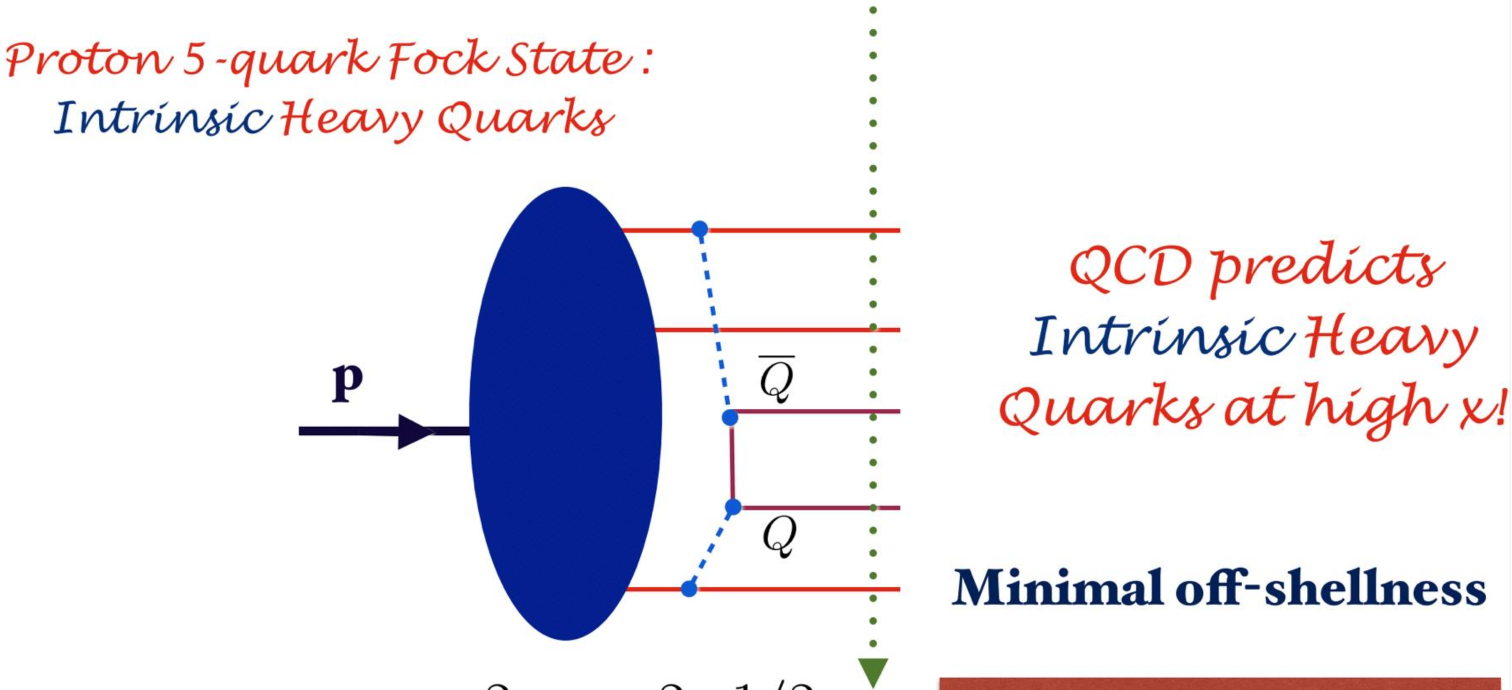
ZDC in CMS
7 λ_I and 8cm x 10 cm
Expect $\sigma(E)/E \sim 15\%$ at 3 TeV

Goal: A good 3D-imaging calorimeter for SAS : $\sigma(E)/E < \sim 4\%$

Sebastian Trojanowski
FASER talk yesterday



Brodsky et al.: Intrinsic heavy flavors



$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

This "Fock state" can then dissociate into a charm baryon + charm meson and even (rarer) B-baryon + B-meson.

Will feed high-x leptons (e.g. μ in cosmic ray showers)

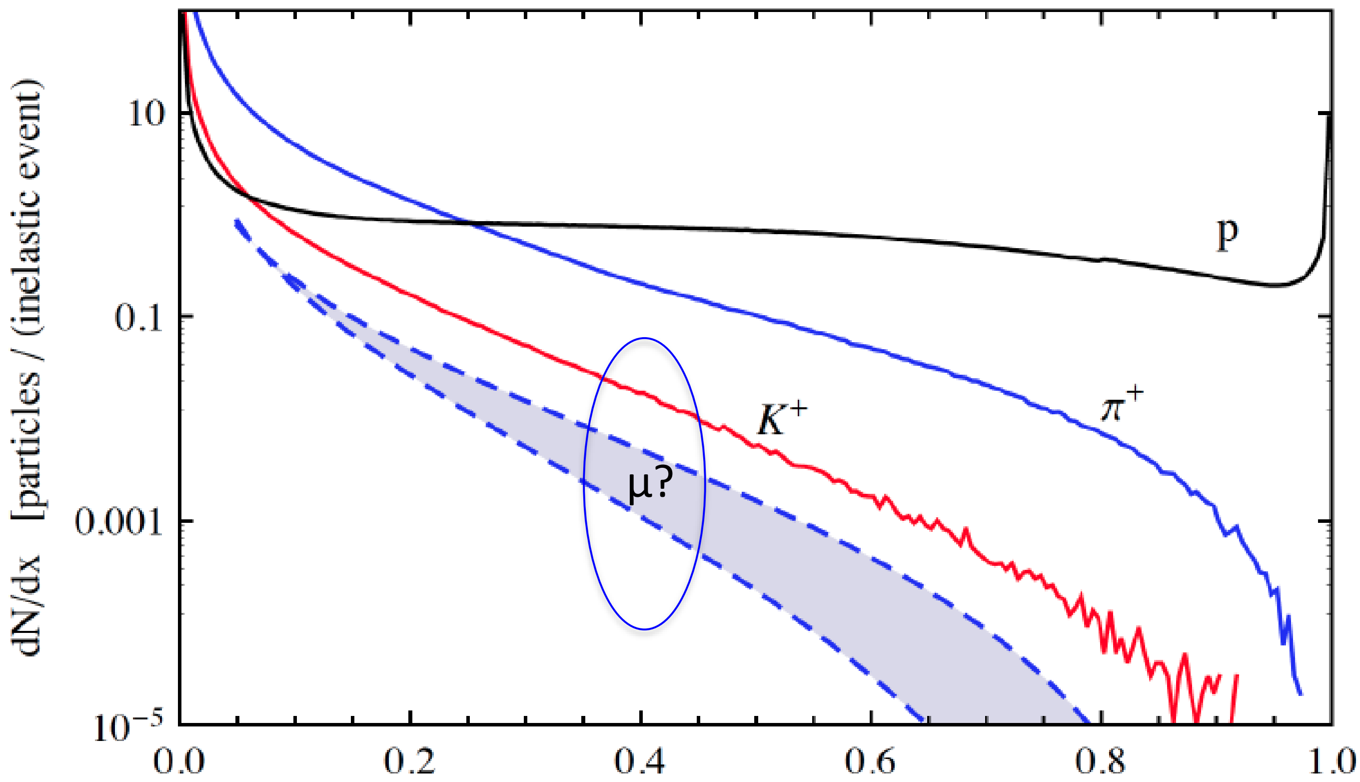
Charm and beauty hadrons only measured at LHC in central region.

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)

Idea, using 10 – 15 m of space in front of TAN:

Use **MBX dipoles** (Integral B.dL ~ 30 Tm) as **spectrometer magnets**.

Use straight section from ~ **85m to 140m** (TAN absorber) space.

Special vacuum chamber design for particles to emerge through minimal material

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

Transition Radiation Detectors for $\gamma = E/m$ in $10^3 – 3.\ 10^4$ region

Hadron Calorimeter for energy measurement

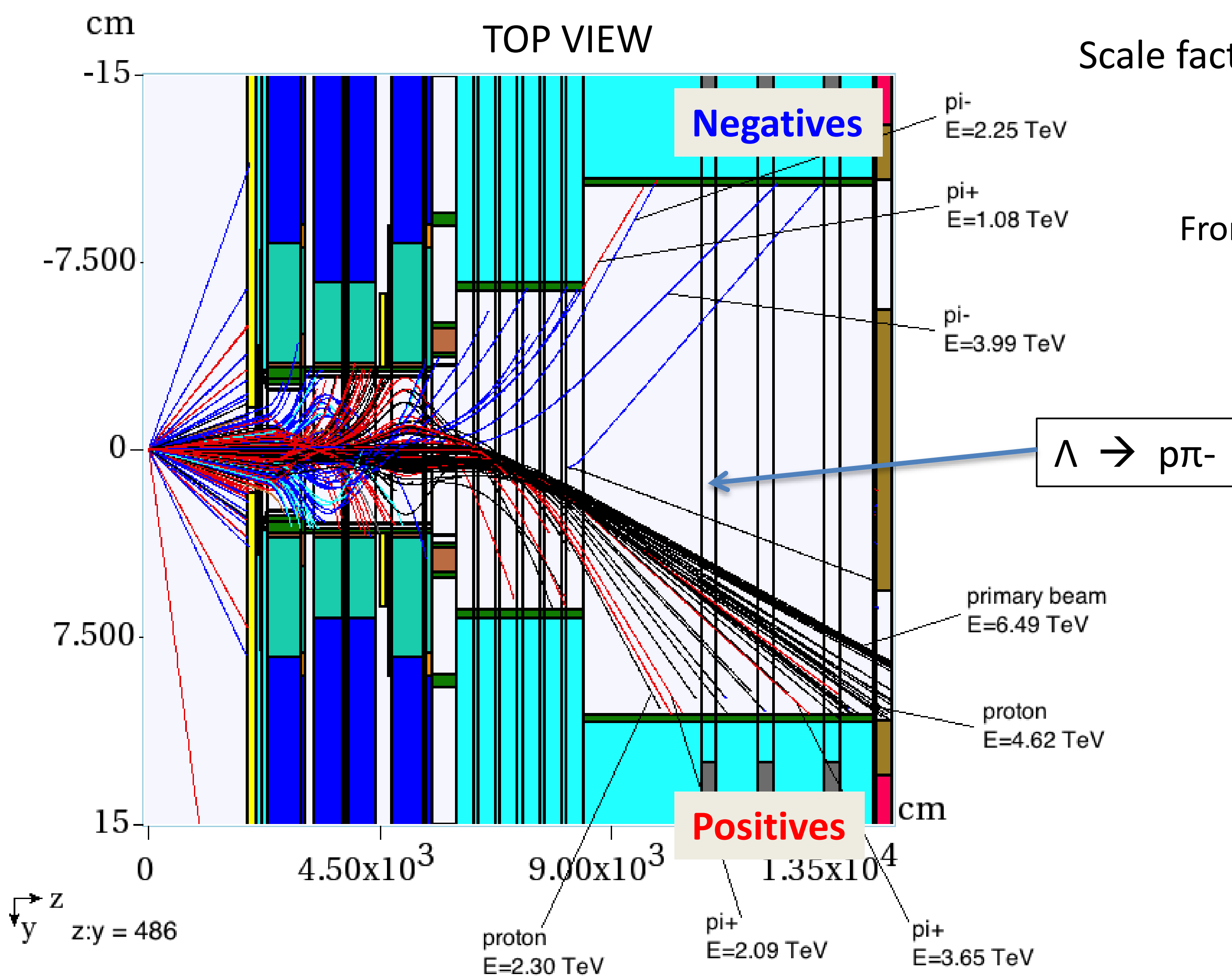
Muon tracking behind calorimeter

Possible addition (not discussed here):
Bent crystal to channel and so accept highest momenta (>~ 4.5 TeV, ~4 mrad bend)

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

Nikolai Mokhov
Ottavio Fornieri

If μ = 1 this is 200 bunch crossings = 6 μs



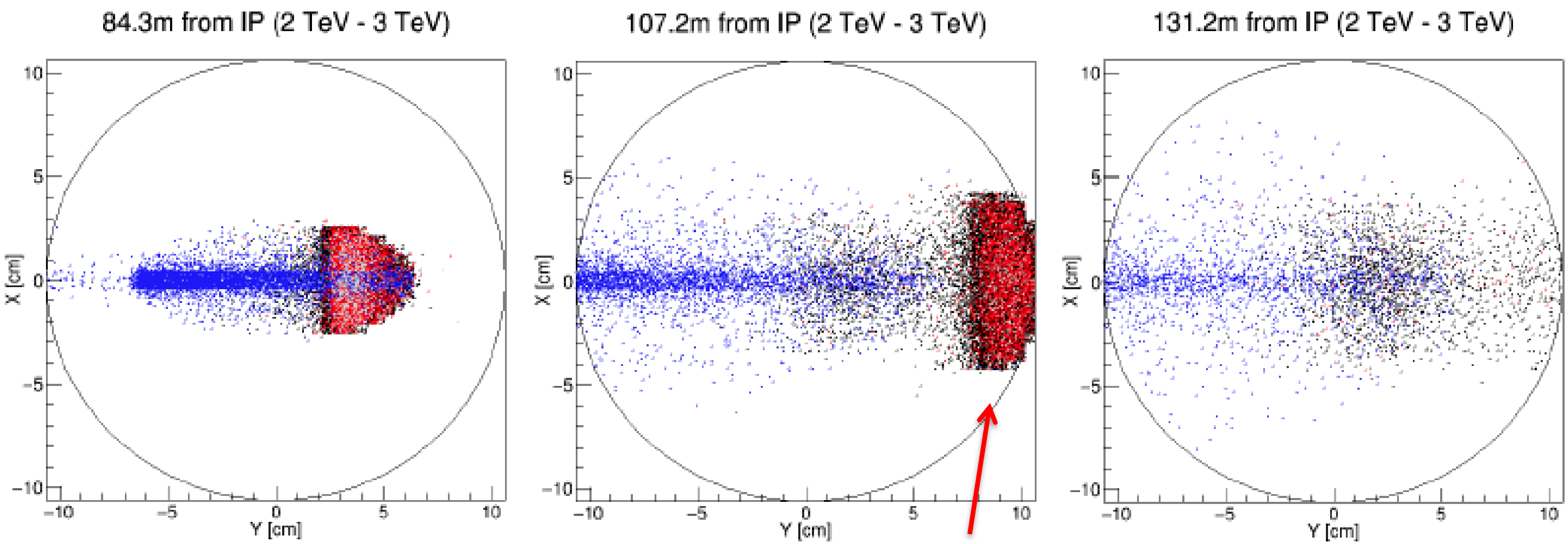
Hitting pipe: 2 π- and 4π+ and about 8 protons / 200 collisions. Mostly near horizontal plane

MARS simulation (Nikolai Mokhov and Ottavio Fornieri

For Pt.5 (CMS) with β* = 0.55m : need to do for β* = 5m at at LHCb, ALICE
Looking along 20 cm diam beam pipe: only particles inside pipe shown, at 3 distances

- ves
+ ves

2 TeV – 3 TeV particles



These all exit pipe between 107 and 131 m

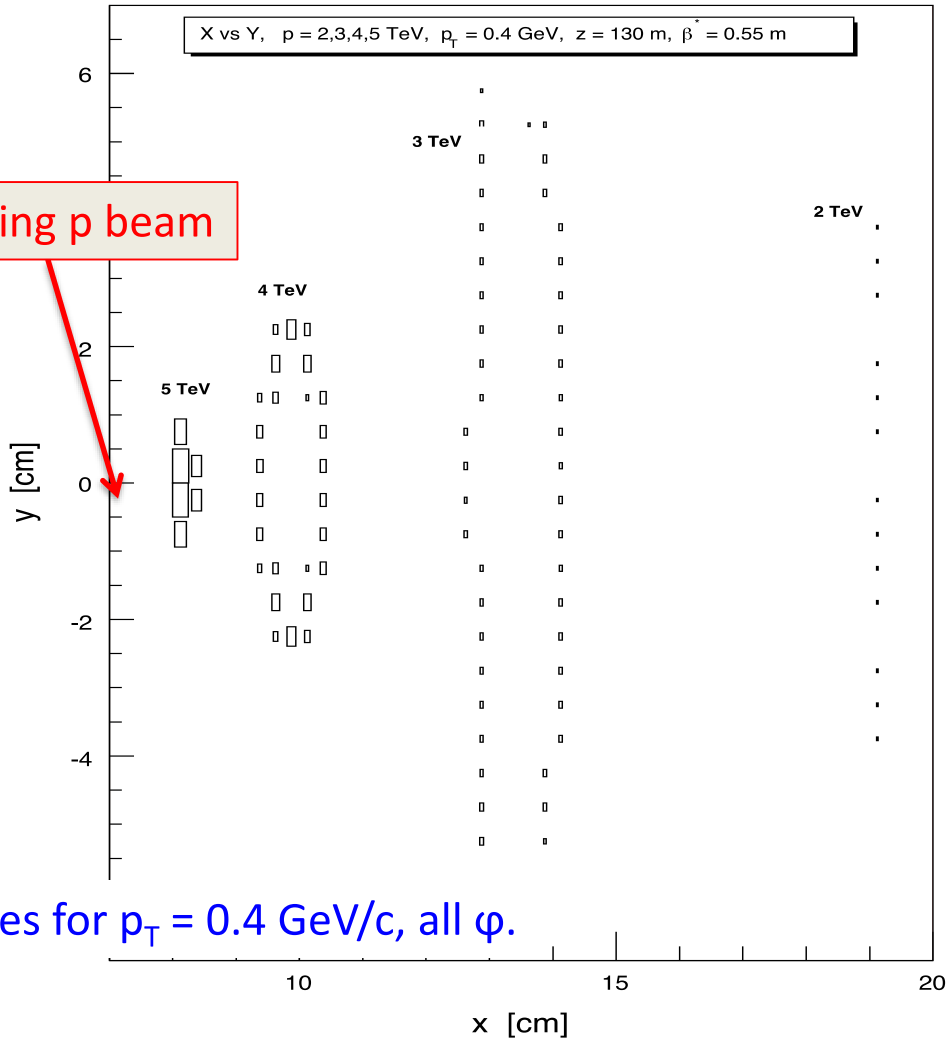
Rectangular shapes are due to the F/D quad field for given energy slice.

>> Only need to cover ~ 10 cm in y on L and R sides, not all φ

Particle transport calculations (Pt.5, β* = 0.55m) using MAD files

Jerry Lamsa

Outgoing p beam



Ellipses for p_T = 0.4 GeV/c, all φ.

Positive particles contained in 40 cm diam pipe.
Only +/- 5 cm in y needed for p_T <= 0.4 GeV/c

Negatives on left side (not shown)
Less y coverage adequate (focusing)
x, y, θ_x and θ_y needed for p_T, p_z, φ

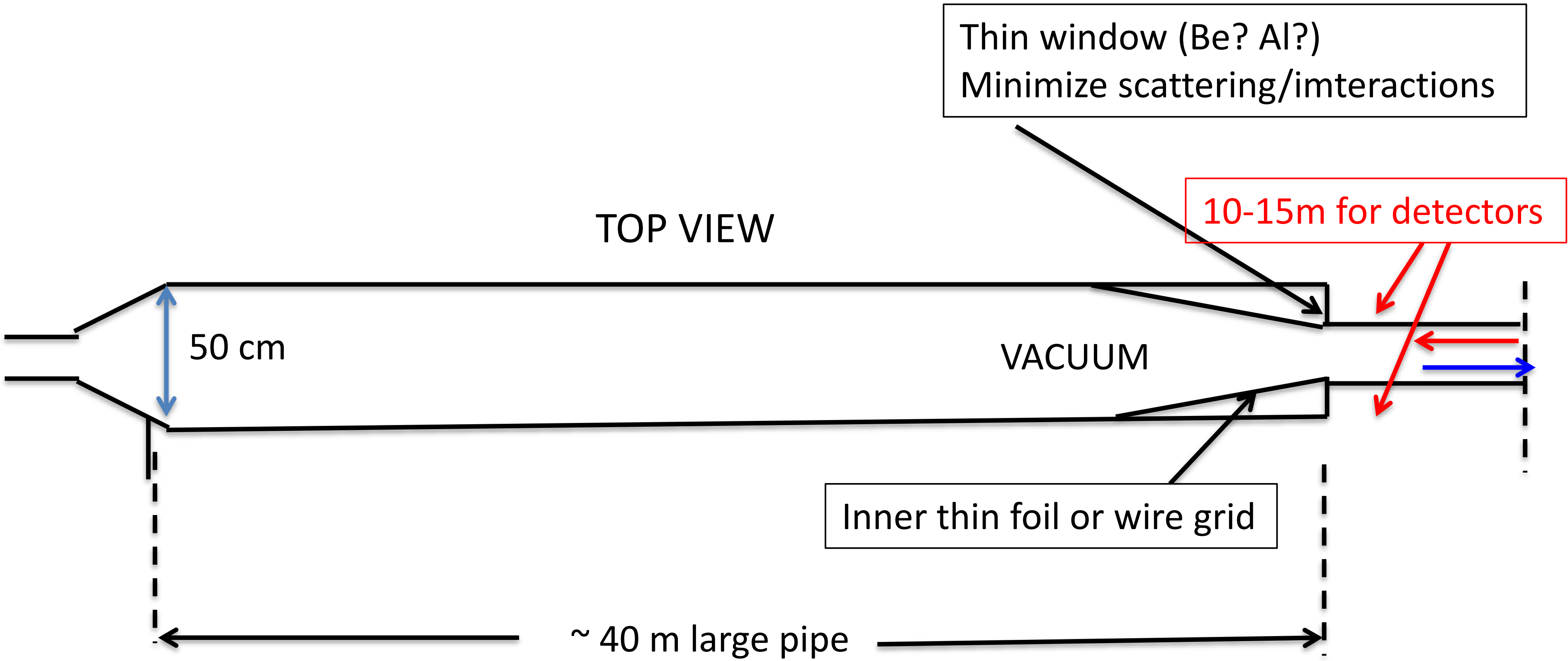
Calculations shown are for Pt.5 and specific optics.

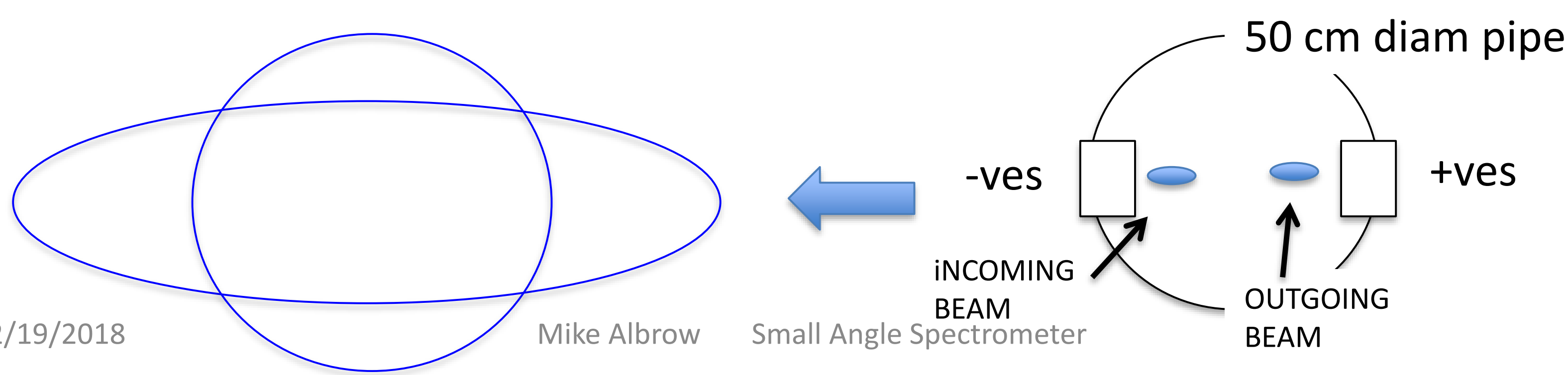
At Pts 2 and 8, larger β* and different, need specific calculations.

For single particle inclusive spectra do not need full φ – coverage, but valuable for correlations

Beam pipe design for small angle spectrometer (schematic)

50 cm (?) diameter pipe from 85m to 130m (from collision)



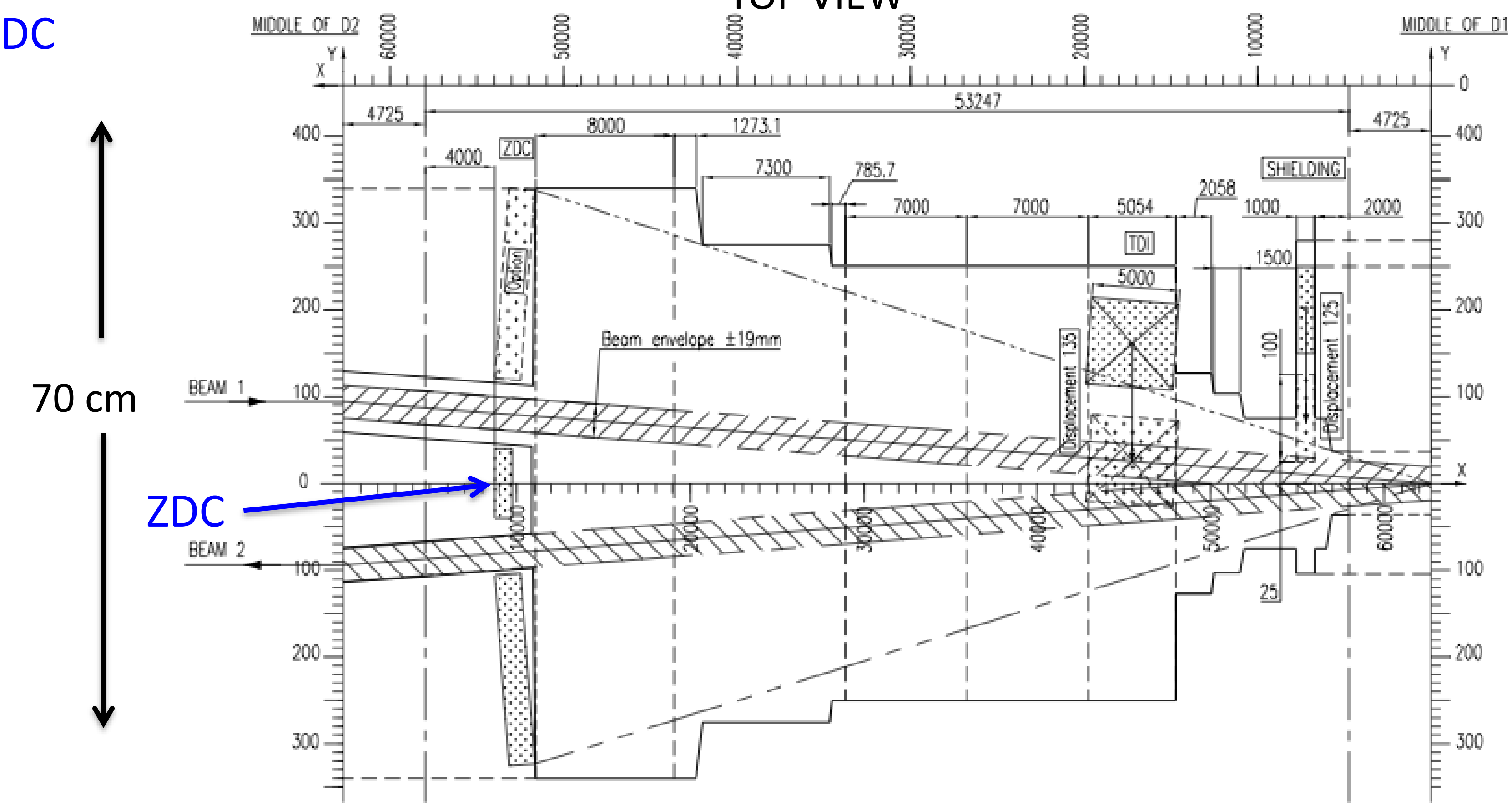


CERN / LHCC 99–5
ALICE TDR 3
5 March 1999

ZDC

ALICE : Early design had a large conical beam pipe for ZDC
> Centrality etc measurements in Heavy Ion (Pb+Pb) collisions

TOP VIEW



Make space in front of calorimeter (with "thin" window) for
tracking, TRDs, and behind calorimeter for muon measurement.

Muons	Calorimeter	-----------TRD-----------	Tracking	← particles
1m	2.5m	6 - 8m	2m	total = 12- 15m

SAS as a Multi-particle Spectrometer

Acceptance for 2 or more particles from same event.
Positive and negative particles on opposite sides of pipe, near horizontal plane.

Acceptances need to be calculated for realistic design.

Potentially:

J/ψ, $\psi(2S) \rightarrow \mu+\mu-$, $\chi_c \rightarrow J/\psi + \gamma$, Drell-Yan $\mu+\mu-$, $\gamma\gamma \rightarrow \mu+\mu-$
$K^0_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\,\pi$
$D^0 \rightarrow K^+\pi^-$ … $\chi_c \rightarrow \pi^+\pi$, K^+K^-, etc.

Very forward charm and beauty also measured with single leading e and μ
Leptons can be identified.

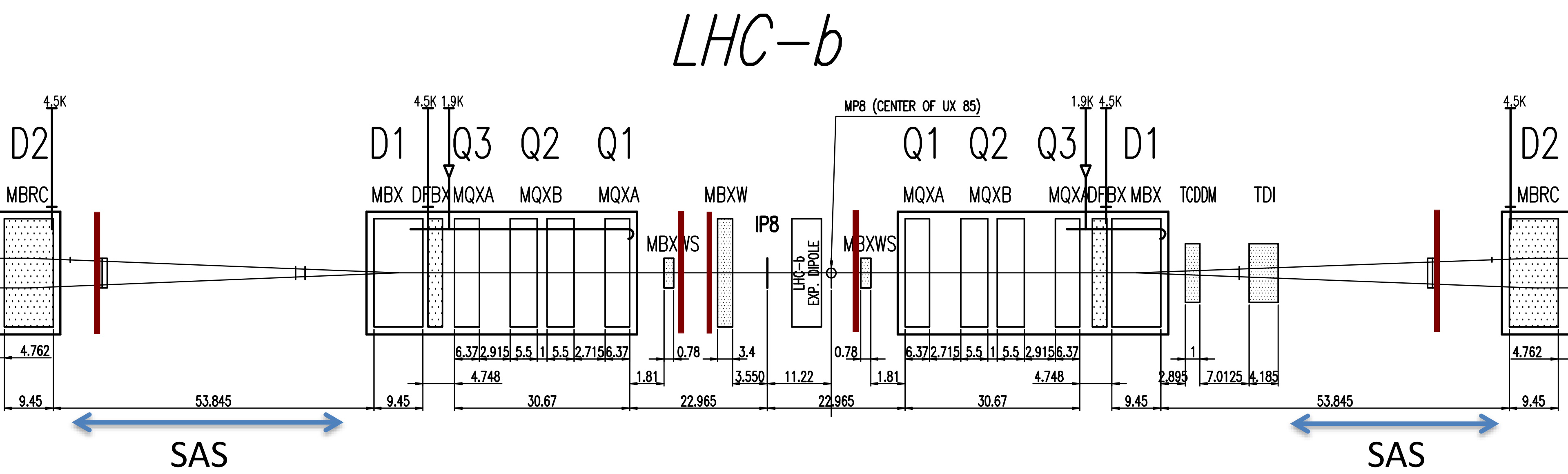
Leptons from π, K decay will be known, and their decay lengths are very long!

$\gamma c\tau\,(\pi)$ = 340 km at 2.5 TeV !

ALICE has pp collisions for most of the LHC running
Cannot compete with ATLAS and CMS for high mass/high p_T pp physics
Luminosity/pile-up much lower (good for SAS) and appropriate detectors.

Focus (pp) is on high multiplicity events, particle correlations, heavy flavor at low p_T …
Can have unique strong interaction program with SAS

LHCb focus is on charm and beauty, forward (but not ***this*** forward)
SAS extends spectrometer to y ~ 8, 9
Acceptances not yet calculated.



Muon Measurement behind calorimeter

Muons : from primary collision:

Drell-Yan pairs, photo-produced J/ψ, ψ(2S), $\Upsilon_{1,2,3}$ and γγ → $\mu^+\mu^-$ (especially in AA)

Some acceptance for measuring both!

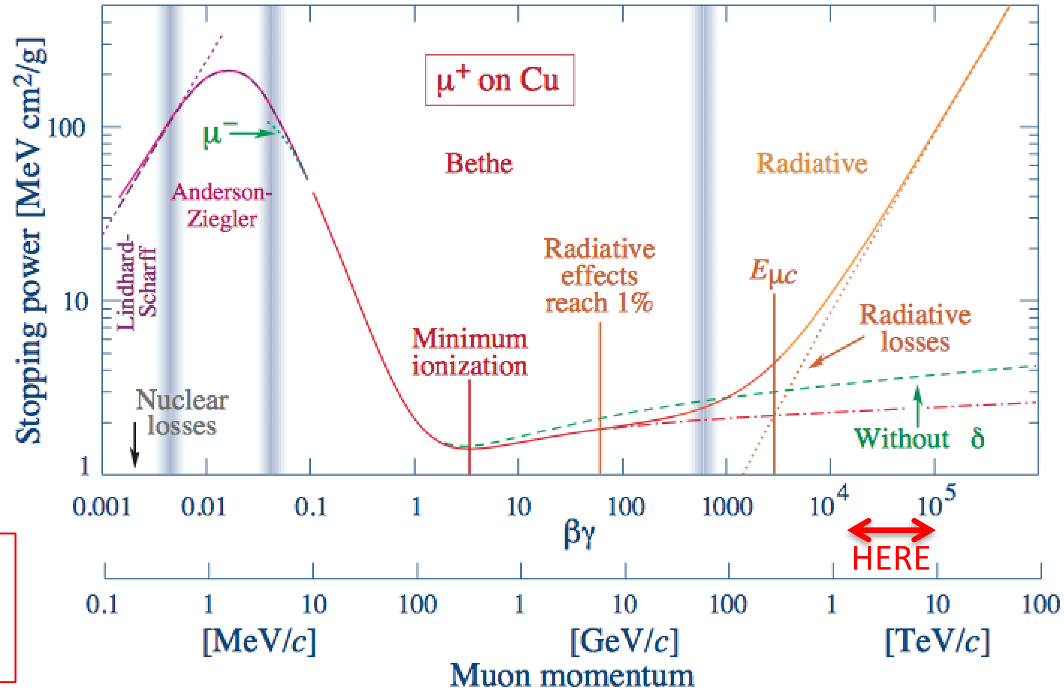
Almost prompt, from c, b decays. Note BR (D^0 → μ + X) = 6.7%

Background from π, K etc decays. γcτ(π) at 2.8 TeV = 150 km, . γcτ(K^+) = 70 km

Background from upstream interactions in pipes etc.

Momentum from upstream tracking, penetration and energy loss (fn(E)) through calorimeter

TRD signals consistent with m = p/γ = m(μ)   (= m(π) , no separation.)



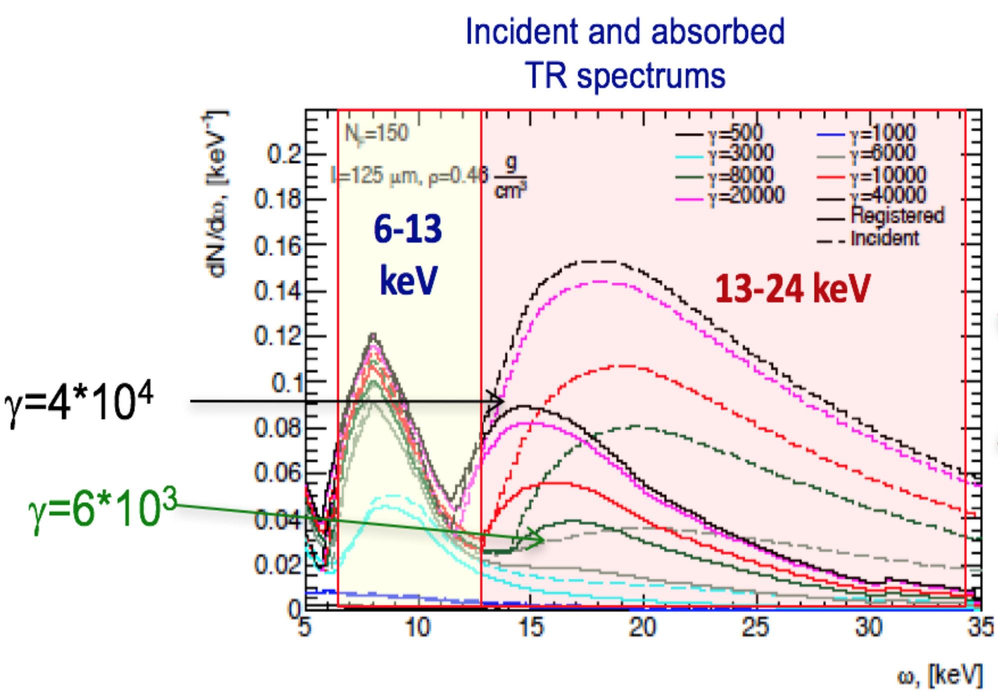
Many possible technologies
~ m^2 so high performance

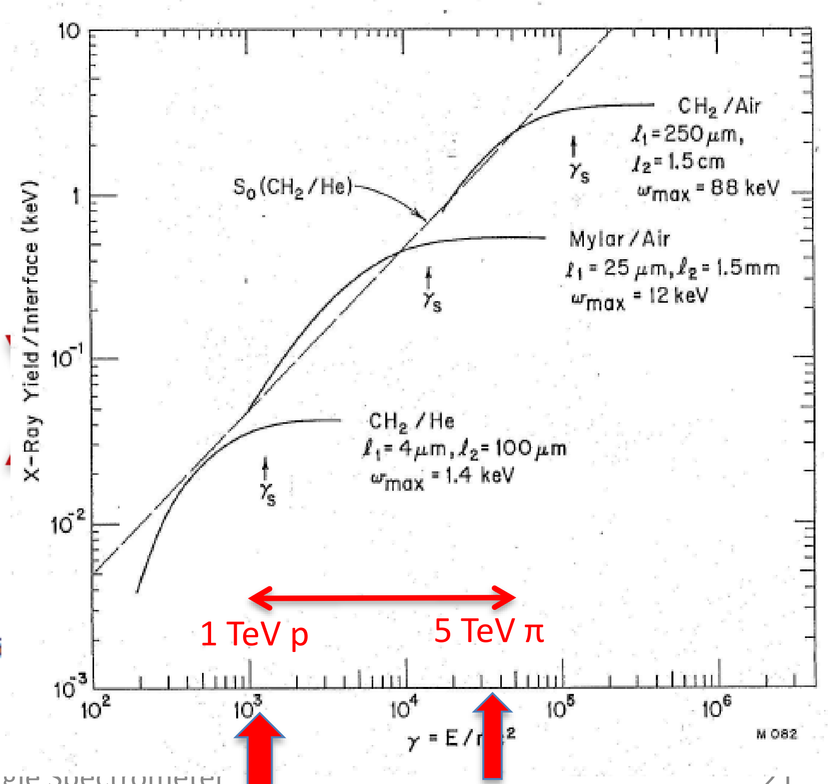
Transition Radiation Detectors - TRD

Anatoli Romaniouk, Mike Cherry et al.

Probably only technique for distinguishing **π / K / p** at multi-TeV energies
Main technical challenge for SAS@LHC.
Interface between two materials different ε → X-ray emission ~ 1/137
Function of $\gamma = E/m$ Know E = p from tracking and calorimeter, hence m.
Fastest hadrons in SAS ~ 5 TeV π; $\gamma = 5000/0.14 \sim 3.6\ 10^4$
Slowest in SAS ~ 1 TeV p; $\gamma = 1000/0.94 \sim 1.1\ 10^3$

Can "tune" design
for γ – range : higher γ longer





Development of Transition Radiation Detectors for hadron identification at TeV energy scale

N Belyaev[1], M L Cherry[2], F Dachs[3,4], S A Doronin[1,7], K Filippov[1,7], P Fusco[5,6], F Gargano[6], S Konovalov[7], F Loparco[5,6], V Mascagna[8,9], M N Mazziotta[6], D Ponomarenko[1], M Prest[8,9], D Pyatiizbyantseva[1], C Rembser[3], A Romaniouk[1], A A Savchenko[1,10], E J Schioppa[3], D Yu Sergeeva[1,10], E Shulga[1], S Smirnov[1], Yu Smirnov[1], M Soldani[8,9], P Spinelli[5,6], M Strikhanov[1], P Teterin[1], V Tikhomirov[1,7], A A Tishchenko[1,10], E Vallazza[11], K Vorobev[1] and K Zhukov[7]

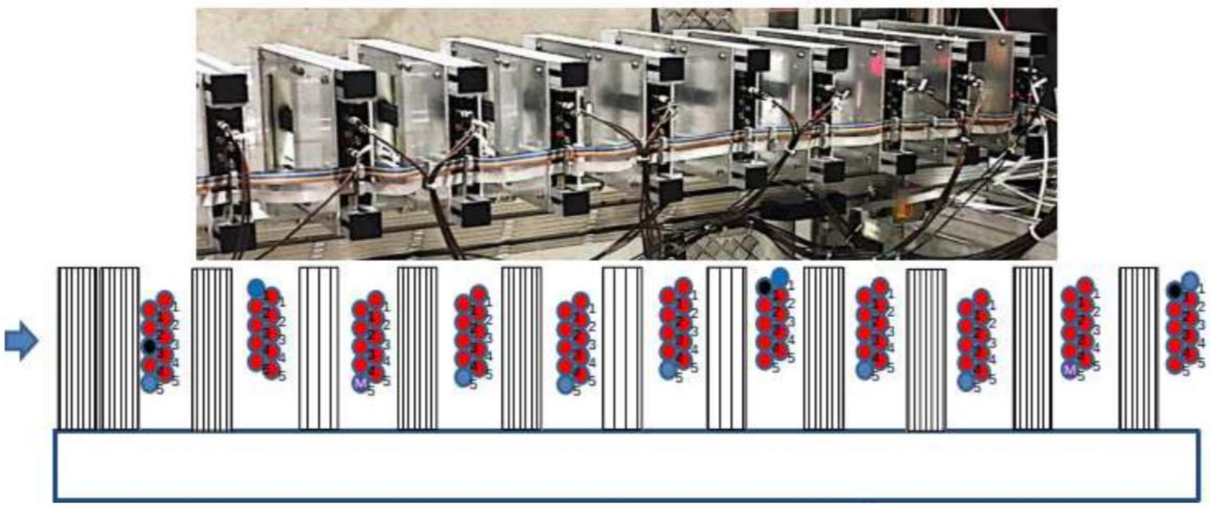
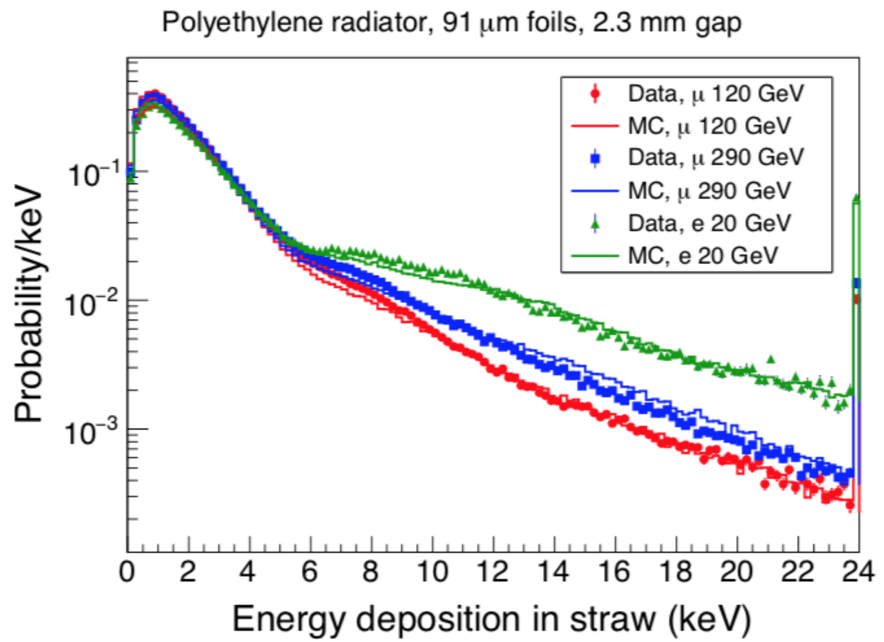


Figure 1. Photo and schematic view of the TRD straw prototype.

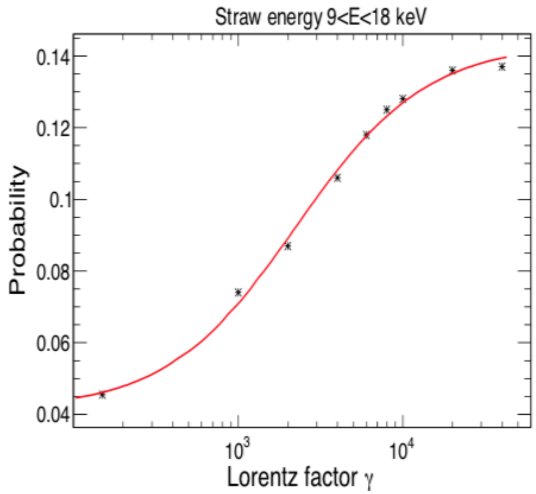
Belyaev et al. Beam tests of TRDs

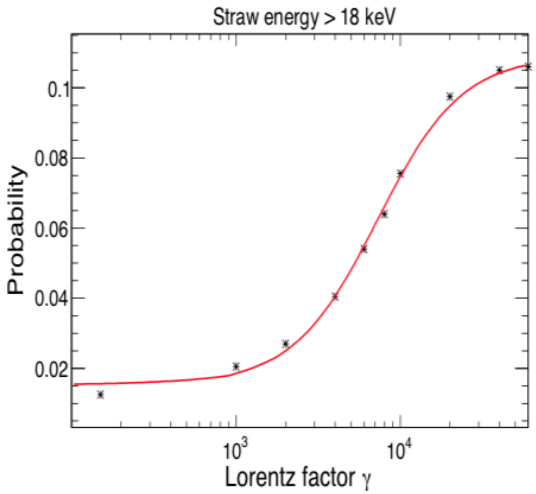
Comparison of signal in straws (keV)
between data and simulation.
Example of one configuration
Good agreement – understand detector



Necessarily not TeV hadrons but
20 GeV e's have γ = 4.10^4
& 5.5 TeV π's have same γ

Threshold in γ in E-band
(Simulation)





Thanks Anatoli Romaniouk

Example of input spectra (+ & - charged hadrons) compared with reconstructed spectra using MC simulation of realistic TRD detectors. Typically 1% - 2% agreement.
Electrons and muons well identified without TRD – excellent tests of system

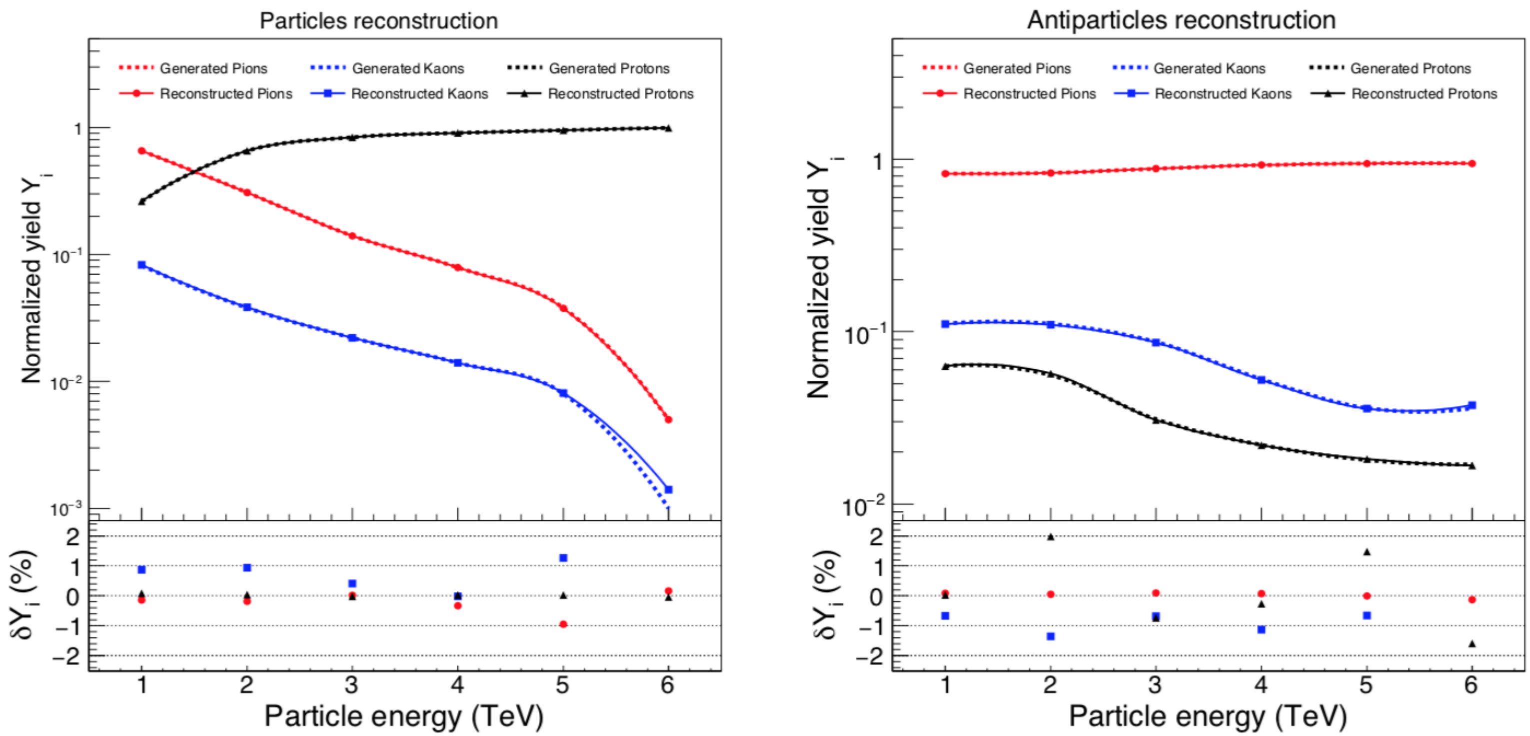
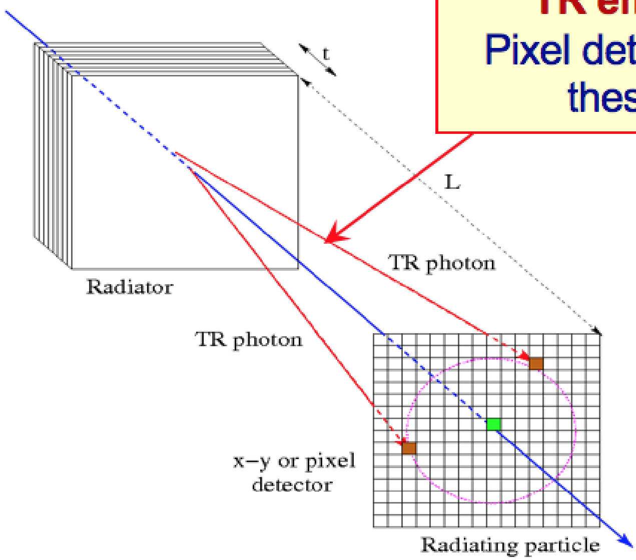
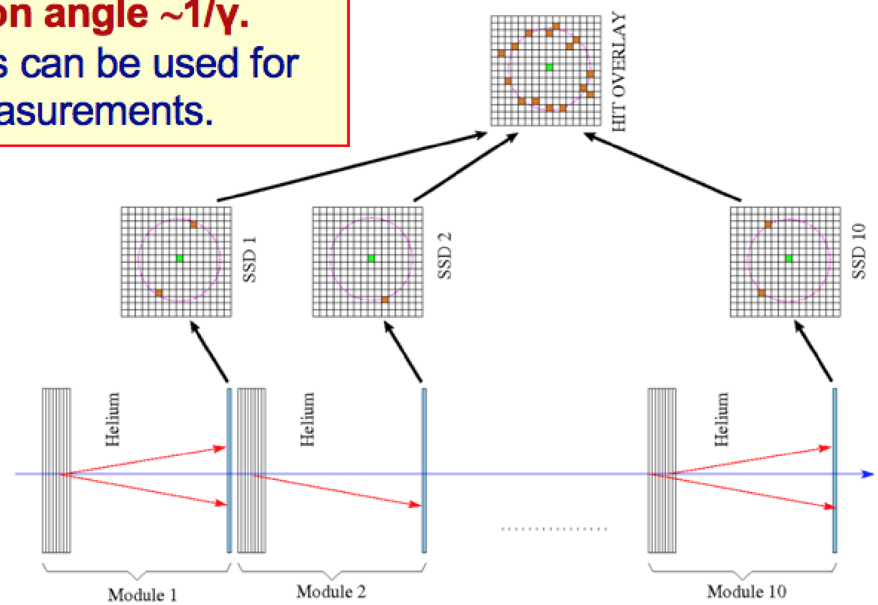


Figure 5. Particle composition reconstruction with the Bayesian method. The dotted lines indicate the fraction of particles generated in p-p collisions in SAS experiment (MC), the solid ones – reconstructed particle composition. Left plot – for positively charge particles, right one – for negatively. In the lower parts of the graphs, the relative errors of reconstruction are plotted.

Angle TRD: concept

Concept is based on the fact that
TR emission angle ~1/γ.
Pixel detectors can be used for
these measurements.





Advantages:

- Combination angle and TR energy information would significantly improve identification power of such kind detectors.
- This approach would allow to minimize material budget
- It combines tracking and TRD functions in one detector

MGA: **A Very Forward Hadron Spectrometer for the LHC and Cosmic Ray Physics**
arXiv:1811.02047v1 [physics.ins-det] (November 2018)
Talk at Guadeloupe Workshop on DM and DE

Is there enough support both in this community (and outside e.g. cosmics, UHE neutrinos) to have a workshop/meeting at CERN (1 or 2 days) in April or May?

Needs an organizer and maybe a small organizing committee.
Establish web site / Twicki page …. Grow a collaboration.
Plan sections for a Letter of Intent - > Technical Proposal - > LHCC

Physics case
LHC – beam pipe conceptual (or better, real) design
Beam conditions scenario (standard running + ? pp & pO/N & OO/NN?
Detectors: Tracking, TRD identification, calorimeter, muon chambers
Electronics, DAQ and triggers.
Acceptances, especially for pairs (D0, J/ψ, etc …)
Time scale and rough costs
Collaboration, people, who & what?

Summary

Terra Incognita : large phase space (in x_F, p_T) unexplored from √s = 63 – 13,000 GeV !
Justification in itself, but …
Need to understand **Strong Interaction** in non-perturbative sector
Important to understand **UHE cosmic rays** : Sampled shower → primary, UHE collisions, muons

Spectrometer magnets and 85m vacuum chamber + 55m straight section
Need **special vacuum chamber** with thin exit windows. Feasible.
Technology for **tracking, calorimeter, muon** tracking exist
Particle ID with **transition radiation** possible (π,K,p) … interesting challenge to improve.
Open & accessible & small so evolution of techniques natural.

How and where?
I think now: Independent new experiment (possible later merger)

ALICE has good alignment with physics. pA and AA(A = O or N) & a unique pp program.
LHCb is a "forward" experiment – but not this forward – with c,b focus
Both should find addition of SAS enhances their physics program, both pp and nuclei

Crystal channeling experts are developing crystals – possible extension

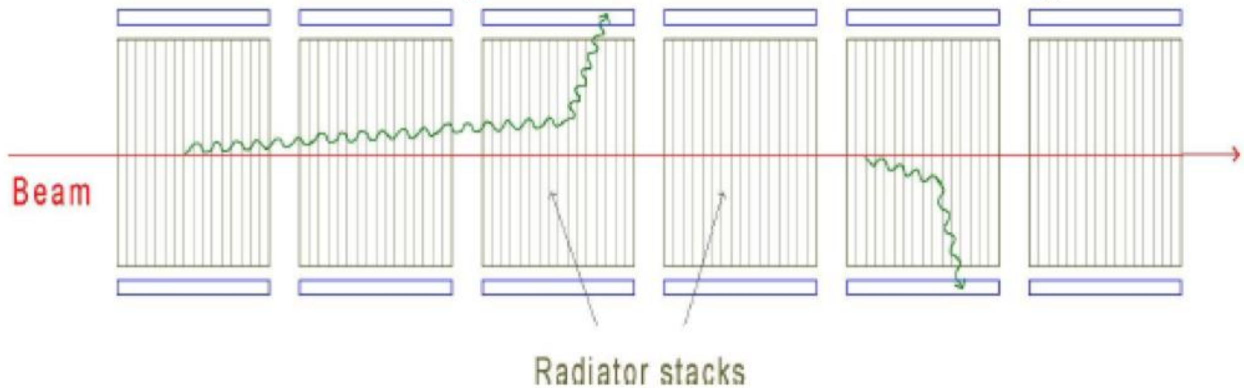
It can be done and it should be done!

Thank You

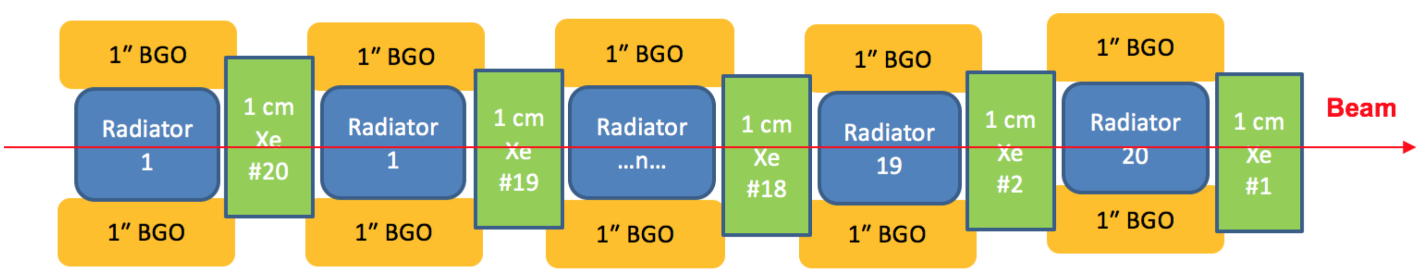
Back Ups →

SAS-TRD R&D Group formed : Test beams at CERN (2016, June 2017, 2018)
NRNU MEPhi (Russia), Louisiana Uni (USA), Bonn Uni. (Germany)
Como, Trieste, Bari Uni, (Italy), Lebedev Phys Inst. (Russia), CERN + Vienna (Austria)

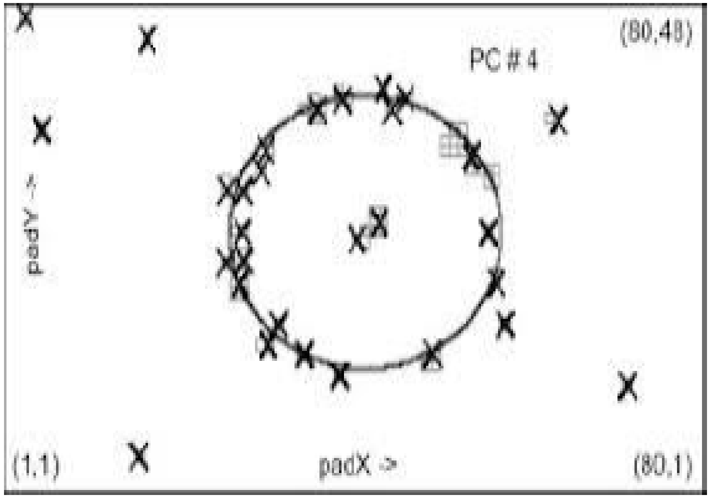
Compton TRD: concept.



20 modules (1-10 low γ_s configuration, 11-20 high γ_s configuration)
Radiator + Xe + Compton scintillators



Simulation work in progress



Can we envisage a "miniaturized"

ring imaging TRD = RITRD?

now we have more advanced pixel detectors !
(see next talk)

-we can collect with **10** sets radiator/pixel detector ≈ **20** TR photons (better than a conventional RICH) to **overlay** on a unique frame to reconstruct a ring

-conventional 15 μ foil radiators to let any hadron to radiate + 1 m *"espansion distance" in helium*→ L ≈ 10 m, still long, but X_0 and λ_I will be negligible!

-pixel size 50μ x 50 μ? (spatial resolution optimized by *centroid* calculation)

TRD also provides precision tracking information!

-the momenta , namely the rings radii per each kind of particle, are fixed by the calorimeter: at **1 m** of *espansion distance*→

R_p = 1mm @ γ= 1000 (1 TeV proton) or R_k = 0.5mm @ γ= 2000 (1 TeV kaon)

Mike Cherry, Louisiana State Univ., summary talk

Two day workshop at CERN October 2015, ~ 40 participants

Thursday, 1 October 2015

09:00 - 13:00 **Plenary**

Join | Salle Anderson

Convener: Michael Albrow (Fermi National Accelerator Lab. (US))

Location: 40-S2-A01 - Salle Anderson

09:00 **Welcome and Introduction** *20'*
Speaker: Michael Albrow (Fermi National Accelerator Lab. (US))

09:20 **Physics of forward particle production; event generators** *30'* No speaker?

09:50 **Cosmic ray showers and need for SAS** *30'*
Speaker: Paolo Lipari

10:20 **Coffee** *15'*

10:35 **Zero-degree neutral (n, K0, π0,...) measurements at LHC** *30'*
Speaker: Alessia Tricomi (Universita e INFN, Catania (IT))

11:05 **Studies towards the design of a Small Angle Spectrometer at the LHC** *25'*
Speaker: Ottavio Fornieri (Pisa)

11:30 **Particle optics and large pipe** *20'*
Speaker: Jerry Lamsa (Iowa State University (US)) (probably not)

12:10 **LHC Vacuum pipe and window issues** *30'*
Speaker: Benoit Salvant (CERN)

Thursday afternoon parallel session

14:00 - 17:30 **SAS calorimeter & Tracking**

Join

Convener: Michael Albrow (Fermi National Accelerator Lab. (US))

Location: 60-2-023

14:00 **High Granularity calorimeter (HGCAL) for CMS upgrade** *30'*
Speaker: Slawomir Marek Tkaczyk (Fermi National Accelerator Lab. (US))

14:30 **Test beam experiments with the CALICE scintillator tungsten HCAL** *30'*
Speaker: Eva Sicking (CERN)

15:00 **CT-PPS Tracking for SAS@LHC TBC** *20'*
Speaker: Nicolo Cartiglia (Universita e INFN Torino (IT))

15:20 **Muon track detection** *20'*
Speaker: Michael Albrow (Fermi National Accelerator Lab. (US))

15:40 **Discussion** *30'*
Speaker: All

Parallel Session: Workshop on TRDs for SAS

14:00 - 19:00 **TRD workshop**

Conveners: Christoph Rembser (CERN), Anatoli Romaniouk (National Research Nuclear University MEPhI (RU))

Location: 28-S-029

Join | 28-S-029

PRIMARY TECHNICAL CHALLENGE
Led to R&D project (Romaniouk +)

14:00 **Introduction** *10'*
Speaker: Christoph Rembser (CERN)

14:10 **Summary of Graphene radiator studies** *30'*
Speaker: Anatoli Romaniouk (National Research Nuclear University MEPhI (RU))

14:40 **GasPixel TRD tests in magnetic field** *20'*
Speaker: Jochen Kaminski (Universitaet Bonn (DE))

15:00 **Transition radiation from graphene in X-ray domain** *25'*
Speaker: Alexey Tischenko

15:25 **Discussion&future plans** *20'*
Speaker: ALL

15:45 **Coffee** *20'*

16:05 **Requirements and general considerations for SAS TRD** *25'*
Speaker: Anatoli Romaniouk (National Research Nuclear University MEPhI (RU))

16:30 **Possible configurations for TRD modules for pi/K/p separation in the TeV region** *2*
Speaker: Paolo Spinelli

16:55 **Straw based and solid state based TRDs for SAS** *25'*
Speaker: Mario Nicola Mazziotta (Universita e INFN, Bari (IT))

17:20 **Preliminary TRD simulations for Forward Scattering Experiment** *25'*
Speaker: Michael Cherry (Louisiana State University)

17:45 **Gas pixel TRD - what they can do?** *25'*
Speaker: Anatoli Romaniouk (National Research Nuclear University MEPhI (RU))

18:10 **Discussion of the TRD concepts for SAS** *45'*
Speaker: ALL

Friday Oct 2^{nd} Plenary

09:05 **Channeling for high-xF** *30'*

Speaker: Gianluca Cavoto (Universita e INFN, Roma I (IT))

crystal channeling

09:35 **Transition radiation summary report & plans** *40'*

Speaker: Michael Cherry (Louisiana State University)

SAS_CERN_Oct_20... SAS_CERN_Oct_20...

10:20 **Calorimeter summary report** *20'*

Speaker: Michael Albrow (Fermi National Accelerator Lab. (US))

calo-trk summary.... calo-trk summary....

10:40 **Coffee Break** *20'*

11:00 **LHCb very forward detectors** *30'*

Speaker: Paula Collins (CERN)

FSC_LHCb.pdf

11:30 **SAS at ALICE** *30'*

Speaker: Risto Orava (Helsinki Institute of Physics (FI))

ALICEZDC-worksh...

12:00 **Acceptance, rates, running conditions** *20'*

Speaker: ALL