Forward Multiparticle Spectrometer at LHC

Talk is CMS-focused – but ATLAS & CMS have similar real estate here

Mike Albrow (Fermilab)

NEW PHYSICS AT THE LHC - introduction

Are we looking in the wrong direction?
Let’s look FORWARD to it!

A new subsystem for CMS Run 4 (HL-LHC)
80– 125m downstream of IR-5

Forward Multiparticle Spectrometer for LHC

A new subsystem for CMS Run 4 (HL-LHC)
80– 125m downstream of IR-5

Two operational modes:

BUY ONE, GET ONE FREE!

A) Charged and neutral TeV hadron production spectra
in p + p, p + O, O + O low pileup short runs.
Read out with full CMS detectors
35 Tm spectrometer magnet D1 (will be) already there!

SMP-HAD 03.20
Guaranteed physics in unexpored phase space

B) Search for new light long-lived decaying neutrals
in p + p at high luminosity (LLPs or WILPs)
Independent trigger & read out

EXO – LLP 03.27
BSM discovery potential

Steel absorber and 35 Tm sweeping magnet D1 (will be) already there!

Two half-day meetings on Forward Multiparticle Spectrometer April 16+17 2020

Purpose: present and discuss ideas. Critique and distinguish possible and not possible

Plan next level of studies and especially who will contribute to a write-up / note /doc

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Thursday 16th: Mainly search for penetrating but decaying LLPs - **$\gamma c\tau$ ~ 10 m → >~ few km**

CERN times

14:30	**Introduction to mode B - LLP search at HL**	*CERN*	*Michael Albrow*	14:30 - 15:00	
15:00	**LHC machine conditions**	*CERN*	*Francesco Cerutti* CERN	15:00 - 15:30	
	Iron toroidal magnets, front absorber and back calorimeter	*CERN*	*Vladimir Kashikhin* FNAL	15:30 - 15:45	
	FASER	*CERN*	*Felix Kling et al.*	15:45 - 16:10	Competition
16:00	**Proton Fixed-Target Experiments for LLP Searches**	*CERN*	*Yu-Dai Tsai*	16:10 - 16:35	Competition
	Detectors for CMS at HL	*CERN*	*Julie Hogan*	16:35 - 17:00	
17:00	**Introduction to dark portals (theory)**	*CERN*	*Gordan Krnjiac*	17:00 - 17:30	Theoretical
	Sensitivity to new penetrating LLP's	*CERN*	*Speaker To be determined*	17:30 - 18:00	Theoretical
18:00					

Friday 17th: Mainly measurement of very forward hadrons in pp, pO, OO at low luminosity

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

Beyond Standard Model Physics at LHC

Searches at high p_T – shortest distances & highest masses
Major effort – so far no discoveries since Higgs(125) – Standard Model

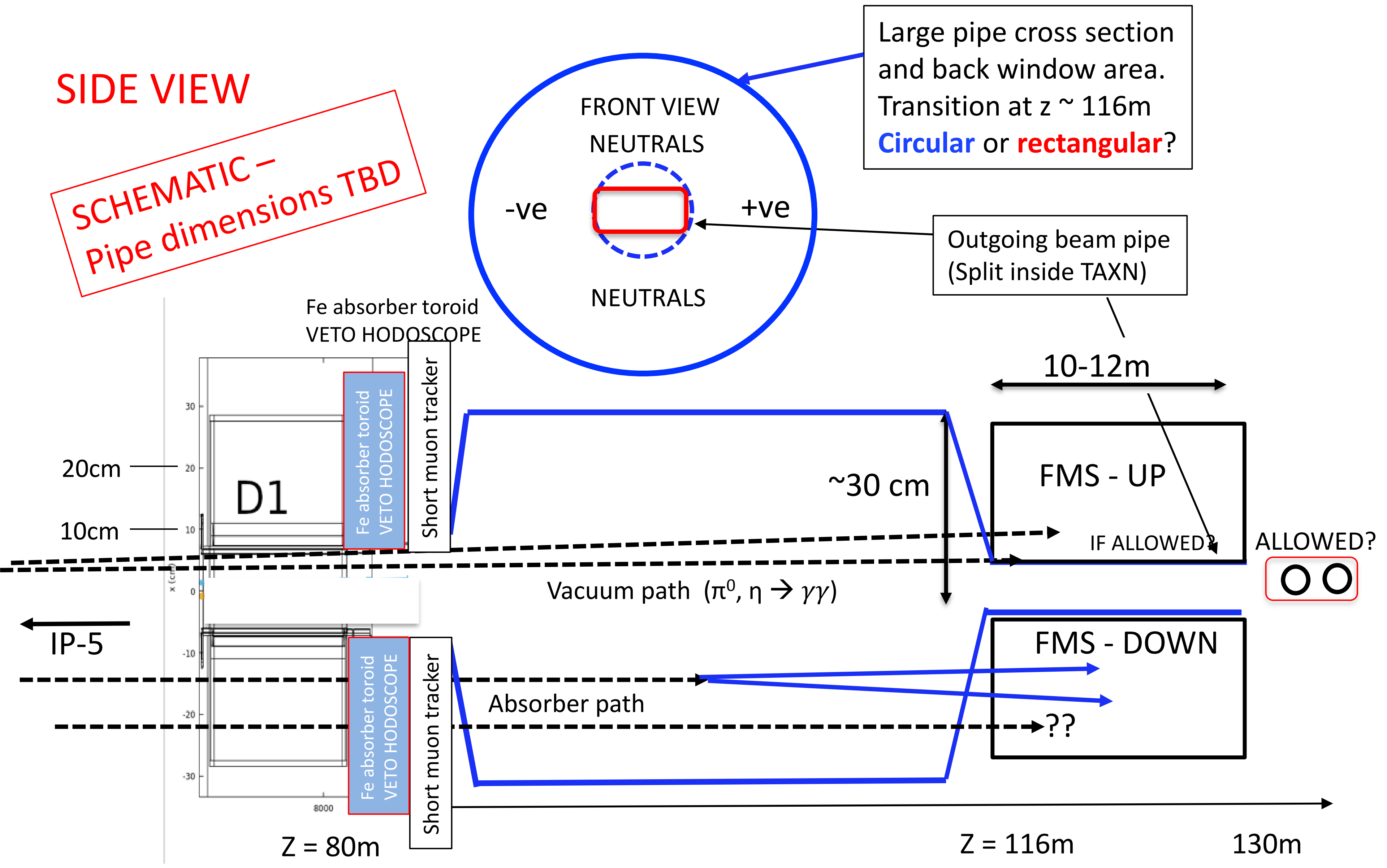
We know there must be new physics : dark matter at least, maybe portals to "dark side"

"Look elsewhere!"
Maybe new BSM particles are **light (< few GeV) but weakly interacting** (LLPs, WILPs)
Most produced light particles have **low p_T and large p_z : go along the beam pipes.**

++ Search at high luminosity for new particles e.g. dark photons, ALPs ("mode B")
Mostly penetrating ~ 40m steel before entering ~ 35m decay volume – Vacuum!
FASER (Felix Kling's talk) - similar goals but many differences. FMS closer, bigger, larger θ
Fixed Target expts (Yu-Dai Tsai's talk) similar goals but much lower √s – mass range

HL – LLP Decaying in vacuum search mode

Big pipe radius R = 30 cm



+ Friday 14:30 Beam pipe issues, Vincent Baglin (CERN)

Potentially* search for highly penetrating X^0 decaying in vacuum to:

$\gamma\gamma$ (no tracks - or conversion - to high granularity EM calorimeter)

e^+e^- if M(X) > 2 MeV (track pair and high granularity EM calorimeter)

$e^\pm\mu^\mp$ if M(X) > 108 MeV (Muon through calo & muon chambers) not from $\tau^+\tau^-$

$\mu^+\mu^-$ if M(X) > 212 MeV (Muon pair through calo & muon chambers)

$\tau^+\tau^-$ if M(X) > 3600 MeV (e^+e^- or $\mu^+\mu^-$ or $e^\pm\mu^\mp$ or e/μ + hhh ?)

$c\bar{c}$ if M(X) > ~ 4000 MeV (== e^+e^- charm factory event boosted to TeV!)

OR?? Not decaying but interacting in calorimeter (very good imaging!) ??

* All need proper study with simulation & realistic set-up and backgrounds.

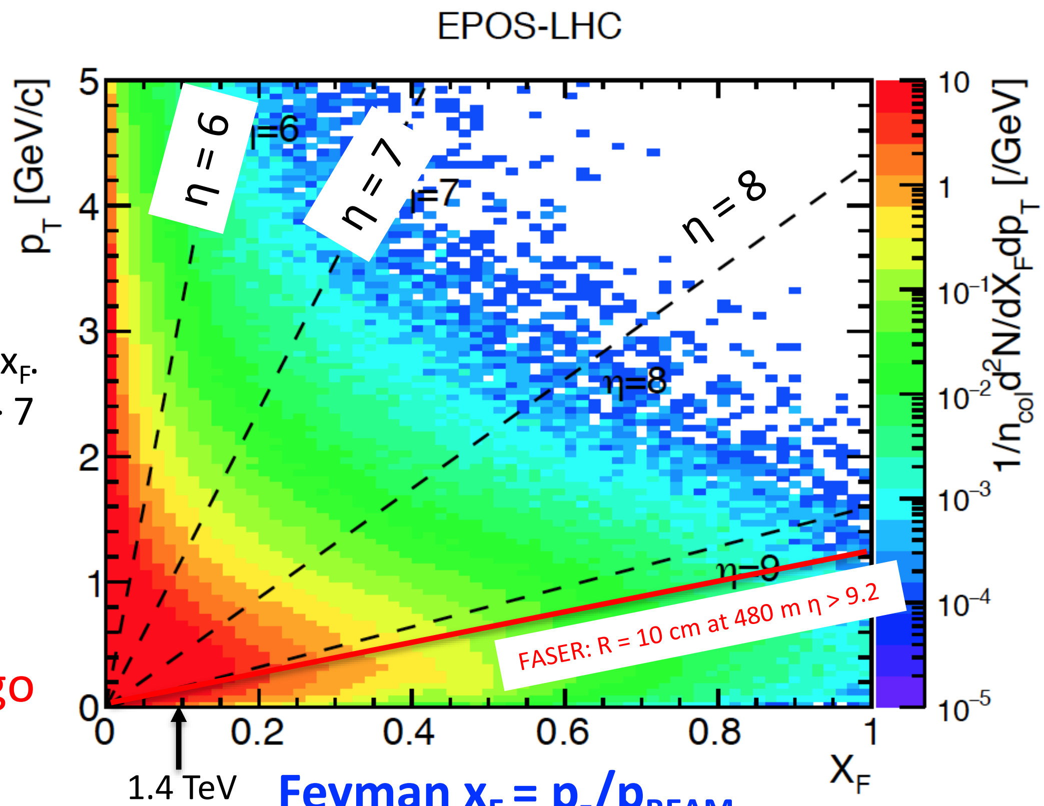
INVITATION!

Production spectra of charged mesons at pp 13TeV

H.Menjo

(Dec 5th 2019)

- pp collisions with $\sqrt{s}$ = 13 TeV
- Event generation by CRMC for Pythia8, QGJSET2-4, EPOS-LHC, Sibyll 2.3c
- 10^7 collisions for each interaction model



Density of charged pions in p_T, x_F.
Most have p_T < 1 GeV/c & |η| > 7
– no measurements at LHC yet

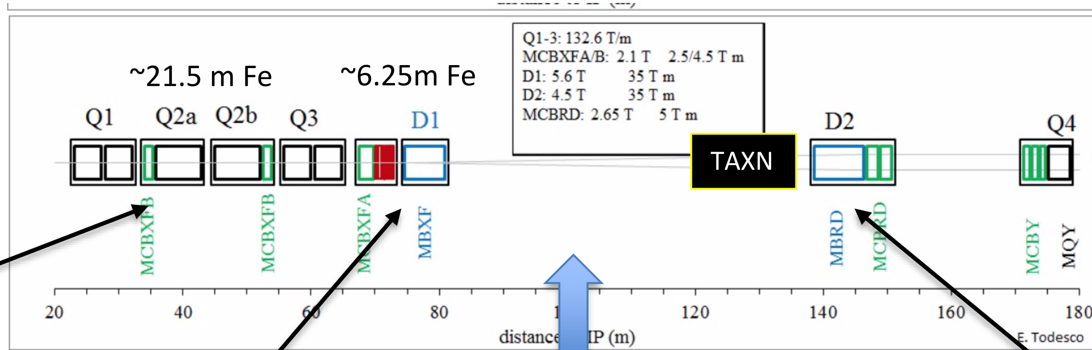
Light LLPs from π, η decay go where pions go
η = 7 is 1.8 mrad

Feyman $x_F = p_z/p_{BEAM}$

Note: η = 4.5 (LHCb charm) is not "very forward"

RUN 4 – HL LHC

IR5, IR1



BEAMS

Fig. 2.1: The lay-out of the LHC interaction region (upper part) and of the HL-LHC interation region (lower part)

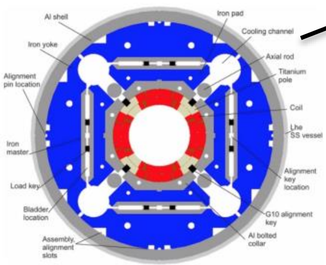
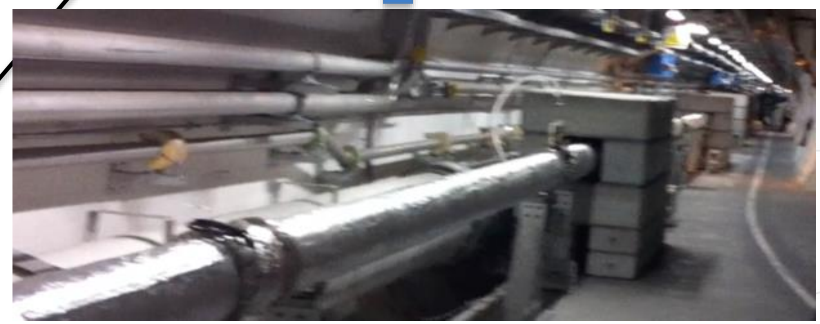
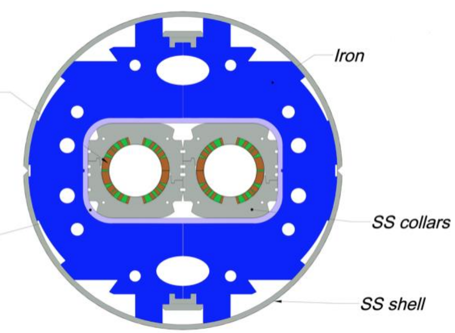


Fig. 3.3: Cross-section of the triplet quadrupole.



~46m bare pipe (now)



Recombination dipole D2
105 mm diameter bore
OD ~ 56 cm

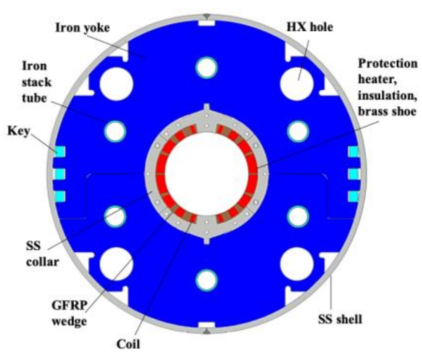
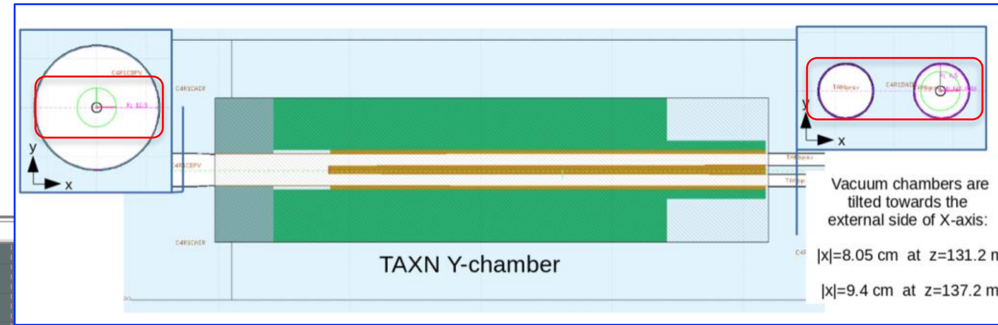


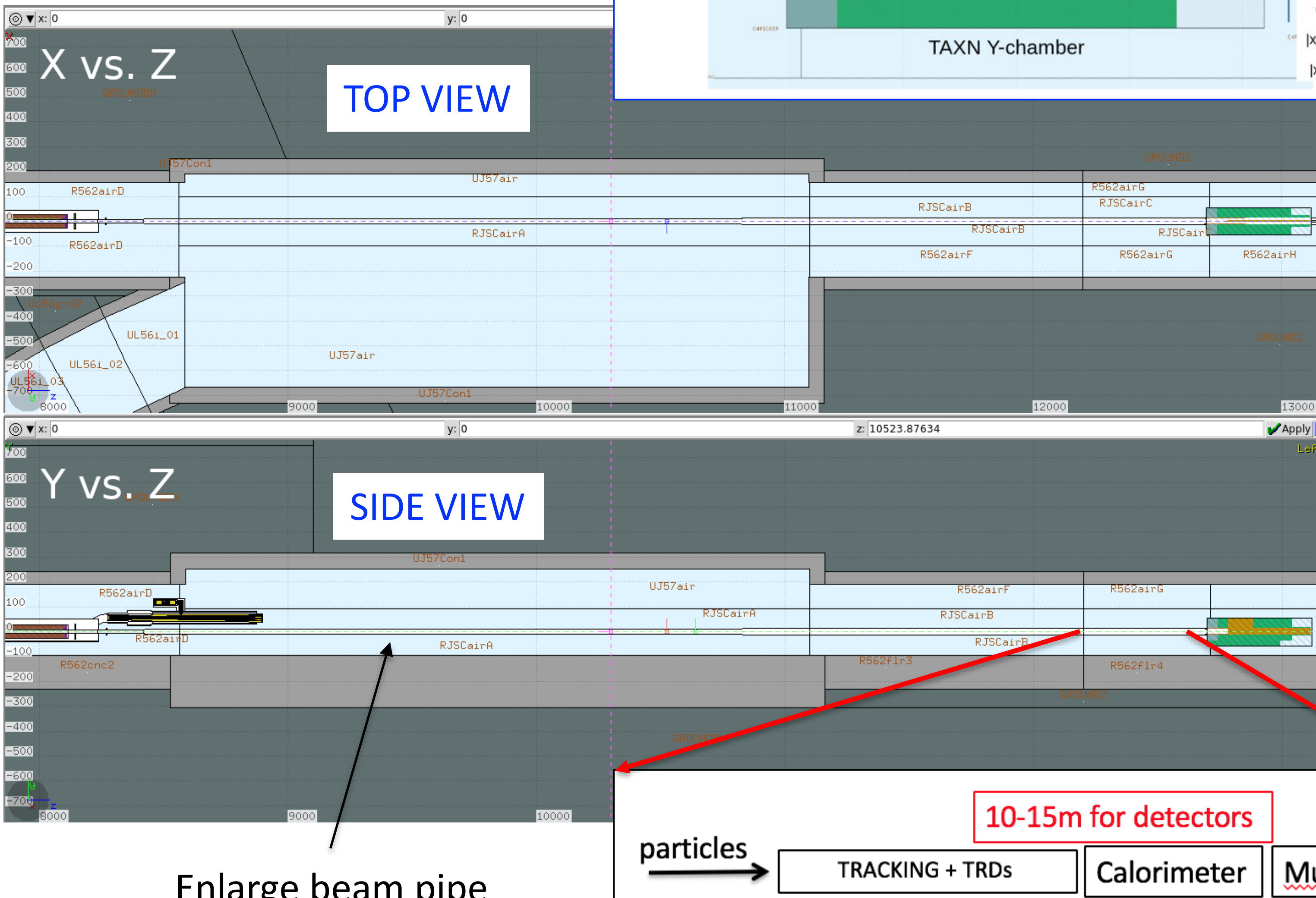
Fig. 4.1: Cross-section of the separation dipole.

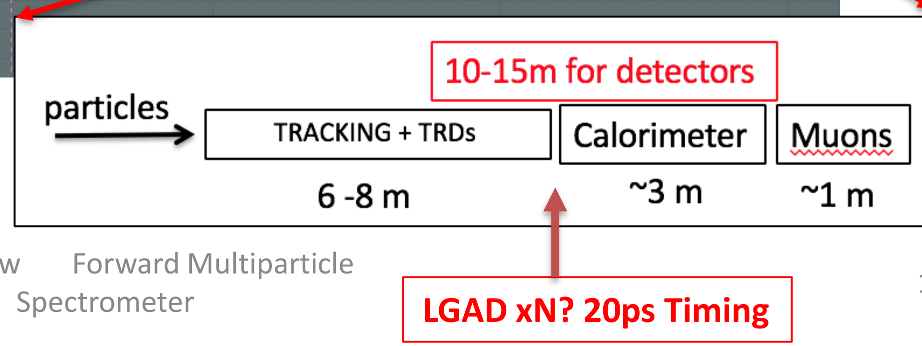
Separation dipole D1
150 mm aperture,
35 Tm integrated field
OD ~ 40 cm

Thanks G. Apollinari

D1 to TAXN in Run 4 as planned

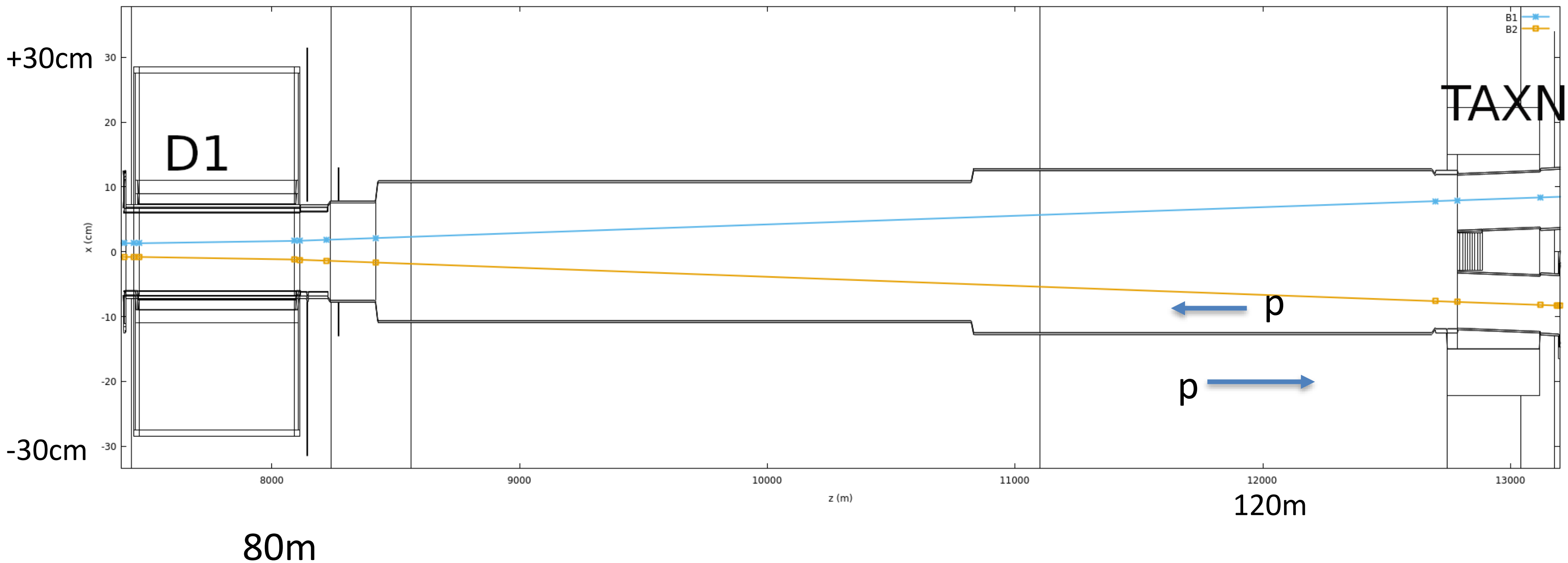






Pipe region as currently planned for Run 4
TOP VIEW

New superconducting
Dipole 35 Tm



Propose: new pipe with radius ~ 30 cm, length ~ 30 m

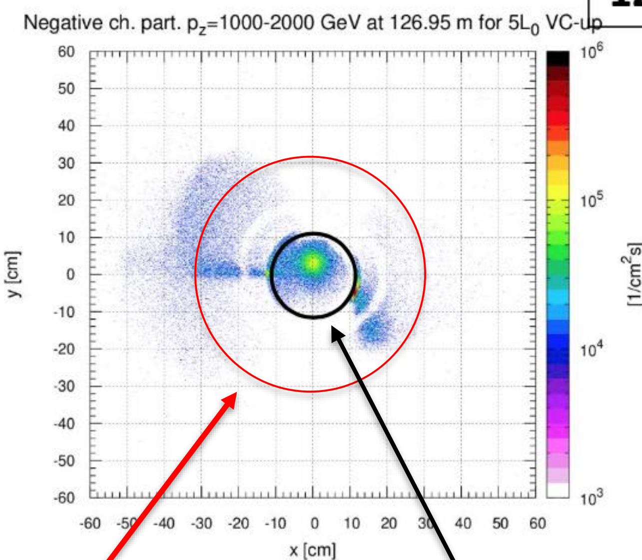
Vincent Baglin's talk tomorrow

Marta Sabate Gilarte's talk tomorrow

NEGATIVE particles 1 – 2 TeV
(through D1 aperture)

126.95 m

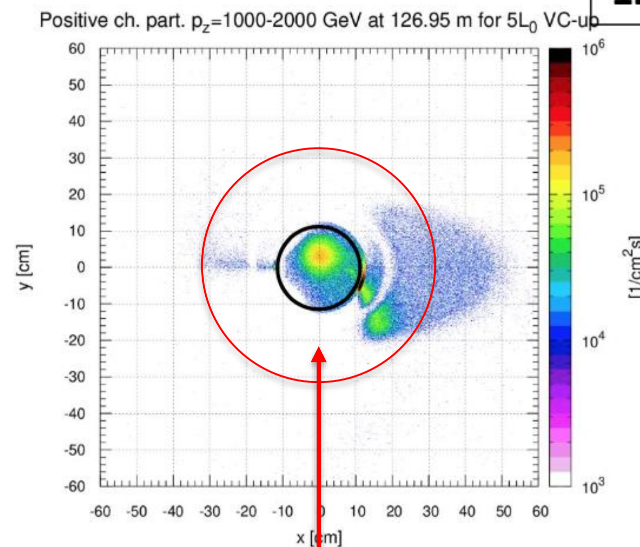
@ TAXN



POSITIVE particles 1 - 2 TeV
(through D1 aperture)

126.95 m

@ TAXN



R_{outer} (at 116m) = 30 cm
η = 6.65

R_{inner} (at 116m) = 10 cm
η = 7.75

No primary charged
Particles UP & DOWN

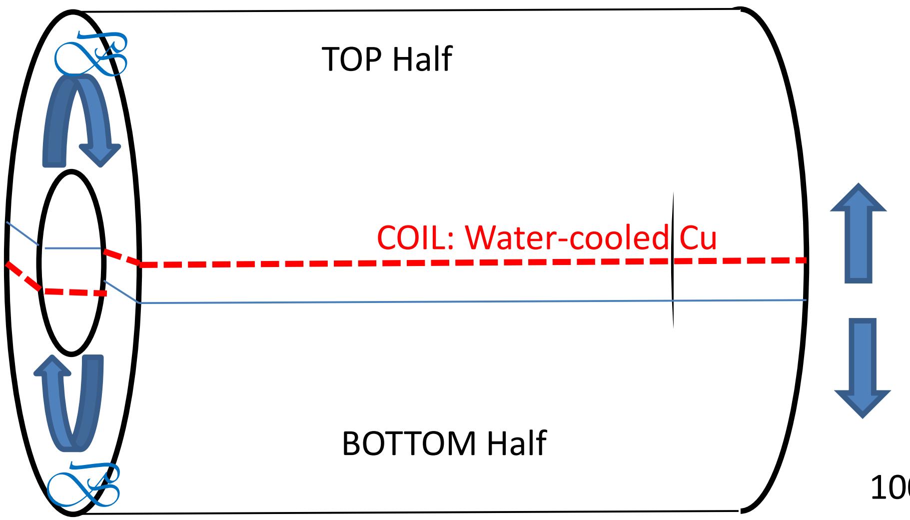
HADRON spectroscopy in L&R quadrants
in low pile-up short runs (Mode A)
LLP search in U&D quadrants in full HL Runs (Mode B)

Magnetised Fe Toroids around "small" beam pipe

At front as absorber, at back plates as calorimeter

Vladimir Kashikhin's talk

Fe cylinder (E.g. AISI 1010 ~0.1%C)



COIL: Water-cooled Cu
Field in Fe B ~ 2T at inner radius
~ 1T at outer radius

Field on beams small
Thanks to Vladimir Kashikhin

100 GeV Muons bend in 3m @ 2T = 18 mrad
& Mult. Scatt. θ_{RMS} ~ 2 mrad

R_{inner} ~ 10cm. R_{outer} ~ 30 cm → Area 0.25 m^2
Length ~ 3m = ~ 18 λ_{INT}
Top and bottom halves separate.
(Each half weighs ~ 3T if L = 3m)

FRONT CYLINDER @ z ~ 82m
Behind separation dipole D1 and Diode
BACK CYLINDER @ z ~ 120m = Calorimeter
Plates separated with detector layers

Hodoscope and short tracker mounted on back, in front of decay volume

MGA 20200315

Same techniques as CMS-HL-LHC Forward detectors
Only small overall dimensions – 0.25m^2, shapes
Julie Hogan's talk

At back of big pipe, over R ~ 10 cm – 30 cm:
Detectors over 10 – 12 m in front of TAXN at 127 m:
Thin vacuum window (minimise mult.scatt. over most of area)
Precision tracking (pixels and/or strips) over ~ 2 m (θ_x and θ_y to few μrad)
Timing (~ 20 ps) to constrain track pairs (e.g. LGAD)
High granularity **EM calorimeter** (e^+e^- and $\gamma\,\gamma$)
Imaging **hadron calorimeter**: hadron E measurment and muon filter
== Fe toroid magnet full φ
Muon tracking behind calorimeter (e.g. GEMs)
== TAXN behind (shields the back)

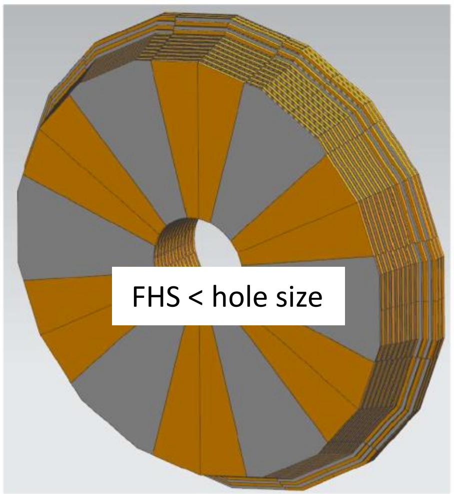
Transition Radiation Detectors only needed for Low PU spectra for Mode A (hadrons)
Not really essential (?) for HL LLP search – if assume h = π

At high P-U separate trigger and data stream – no need to combine with central
(Only in low – PU mode SMP-HAD)

Tracking

Julie Hogan's talk

Precision tracking immediately behind vacuum pipe window – as thin as allowed (ribs)
No field so straight tracks. Optimize vertexing – x_0 y_0 z_0 to be well inside vacuum
…and pointing



CALORIMETER

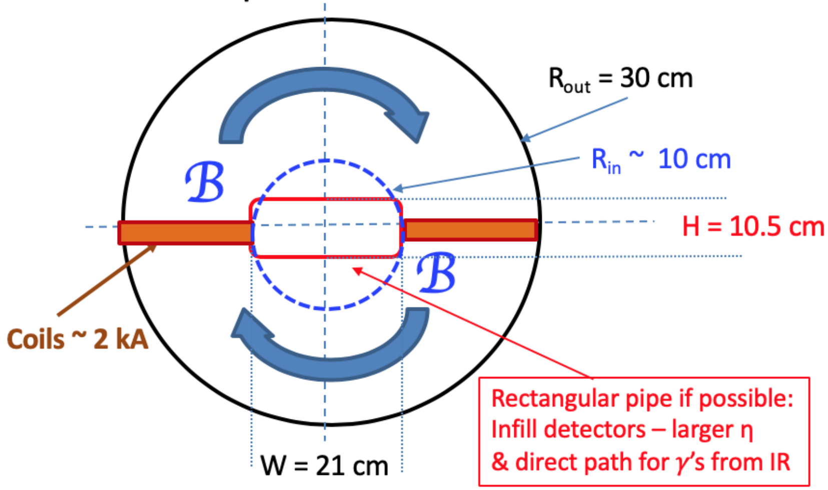
FH.	FMS
Imaging: readout with Si pads/cells ~ 1 cm^2	
R_{inn} ~ 40 cm.	Cf FHS 10 cm
R_{out} ~ 180 cm.	Cf. FHS 30 cm
Angled	Not angled
Area ~ 10 m^2.	^{i}Area ~ 0.25 m^2

TO DO: Layout a detector combination with Run 4 detectors as default and simulate.

M(X → μ+ μ-) in vacuum past D1

p(μ) from bend (dE/dx check)

Magnetised hadron calorimeter toroid concept – as HGCAL + coil

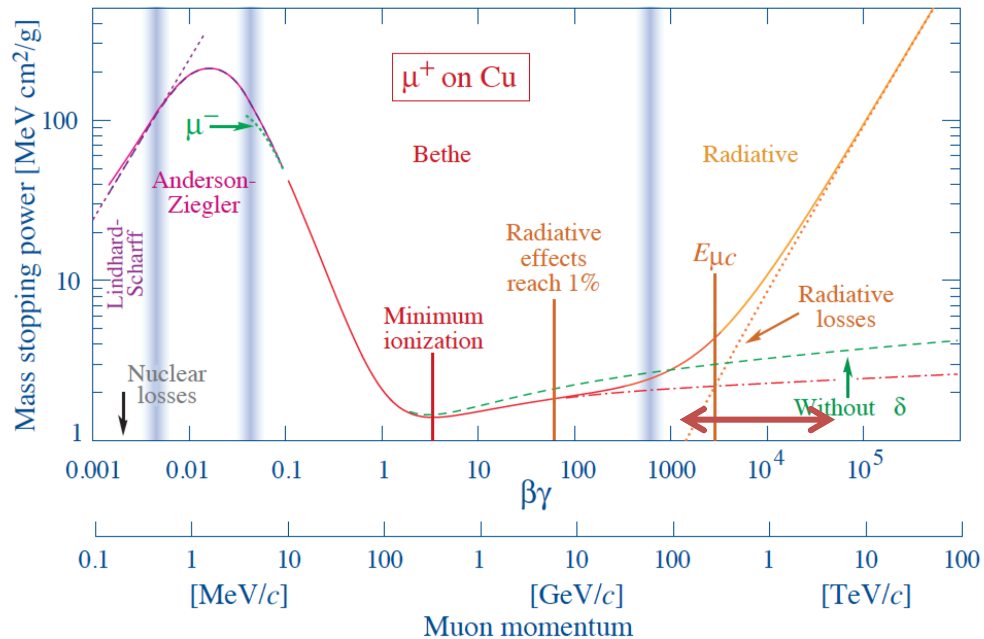


IRON Plate thickness = 12 x 35mm – (12-24) x 68mm
Field in Fe ~ 2T (saturation) at small R
Not uniform – decreases with R

TODO: Calculate bending with multiple scattering vs p(μ) over full range → M(μ+ μ-) resolution

Vladimir Kashikhin's talk

Total signal of μ-track through Calo



Several possible μ-tracking technologies
0.25 m² x N (~4?) layers
Alexei Safonov : GEMs suitable, and almost "off-the-shelf" now.

Note: shielded by TAXN at back

Calorimeter and tracking all azimuth also L&R
for charged hadrons : $\sigma(E)/E$ ~ 5%

Question: Why full azimuth for LLI Search?

Answers:

- Full azimuth needed for toroid magnet
- Perhaps search can be full ϕ even with charged particle background? Track multiplicity question.
- The low-PU Mode A is a strong SM motivation, and spectra are needed to understand expected fluxes, etc.
  That needs L & R sectors.

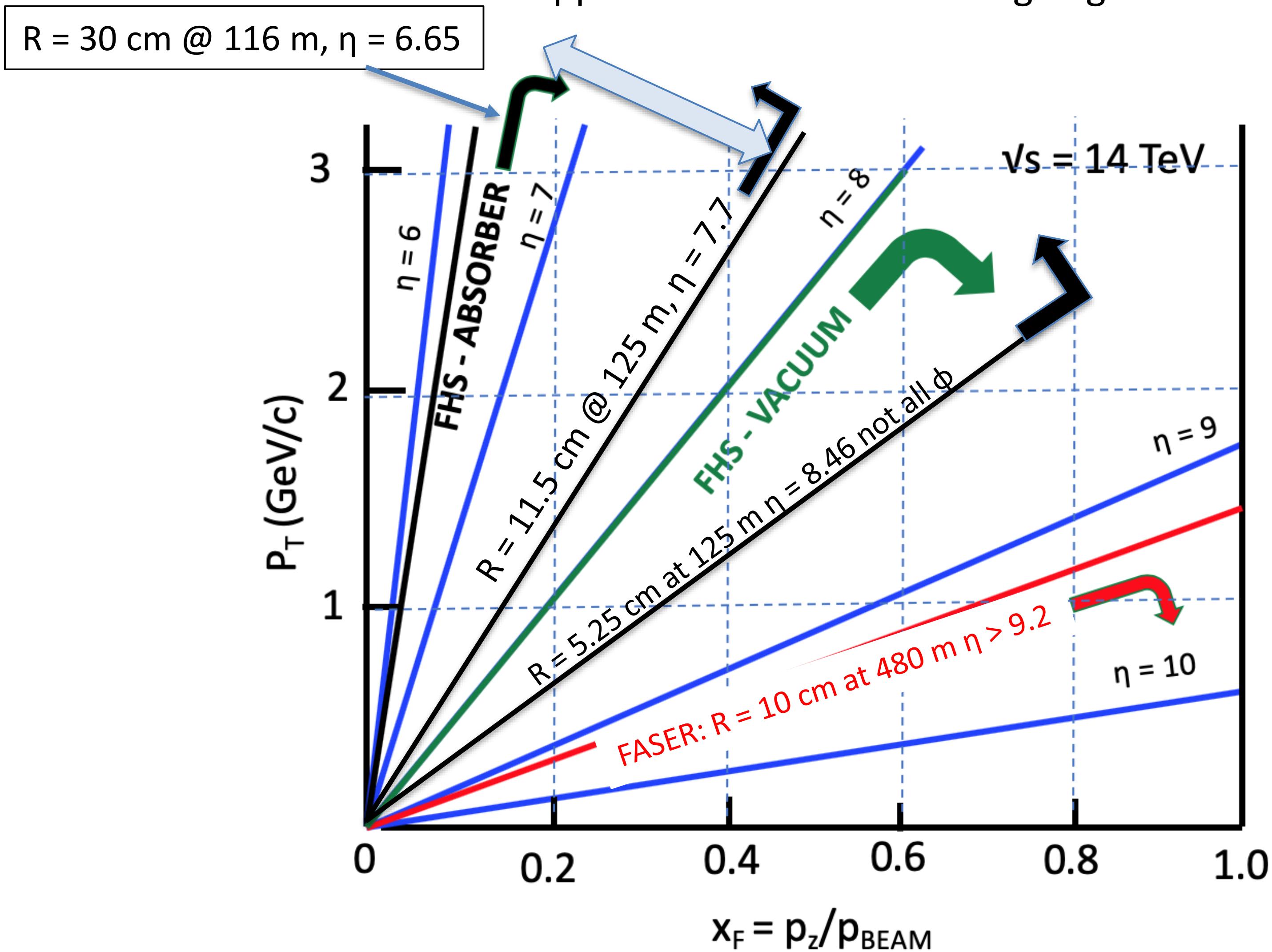
But can discuss value of TRD in the UP & DOWN sectors.

- TRD can incorporate excellent tracking.
- GaAs more rad hard than Si

Mike Cherry's talk

Coverage through steel absorbers

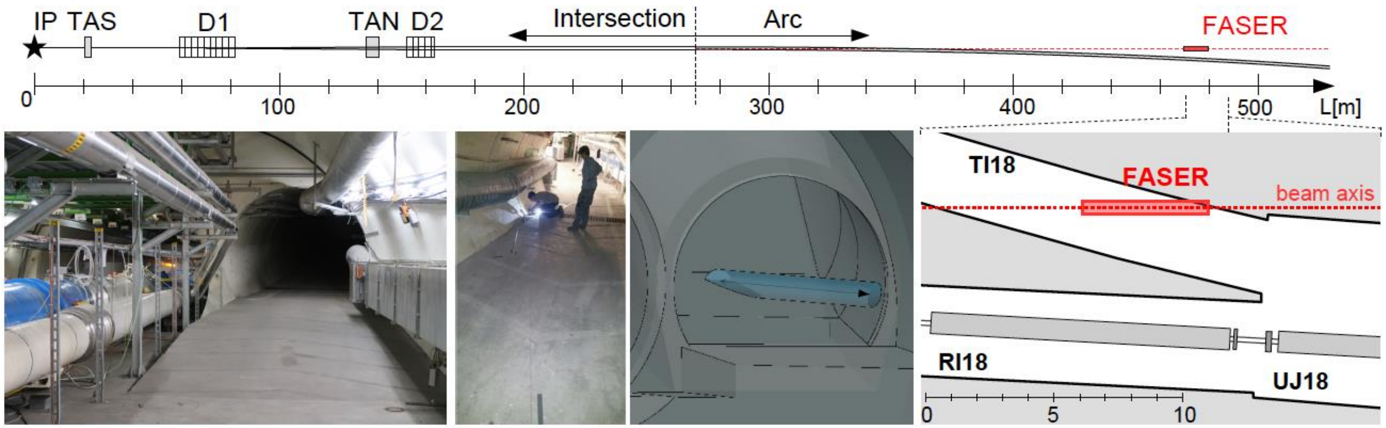
Approximation: Zero crossing angle



FASER
FORWARD SEARCH EXPERIMENT AT THE LHC

arXiv:1811.10243v1

Felix Kling's talk



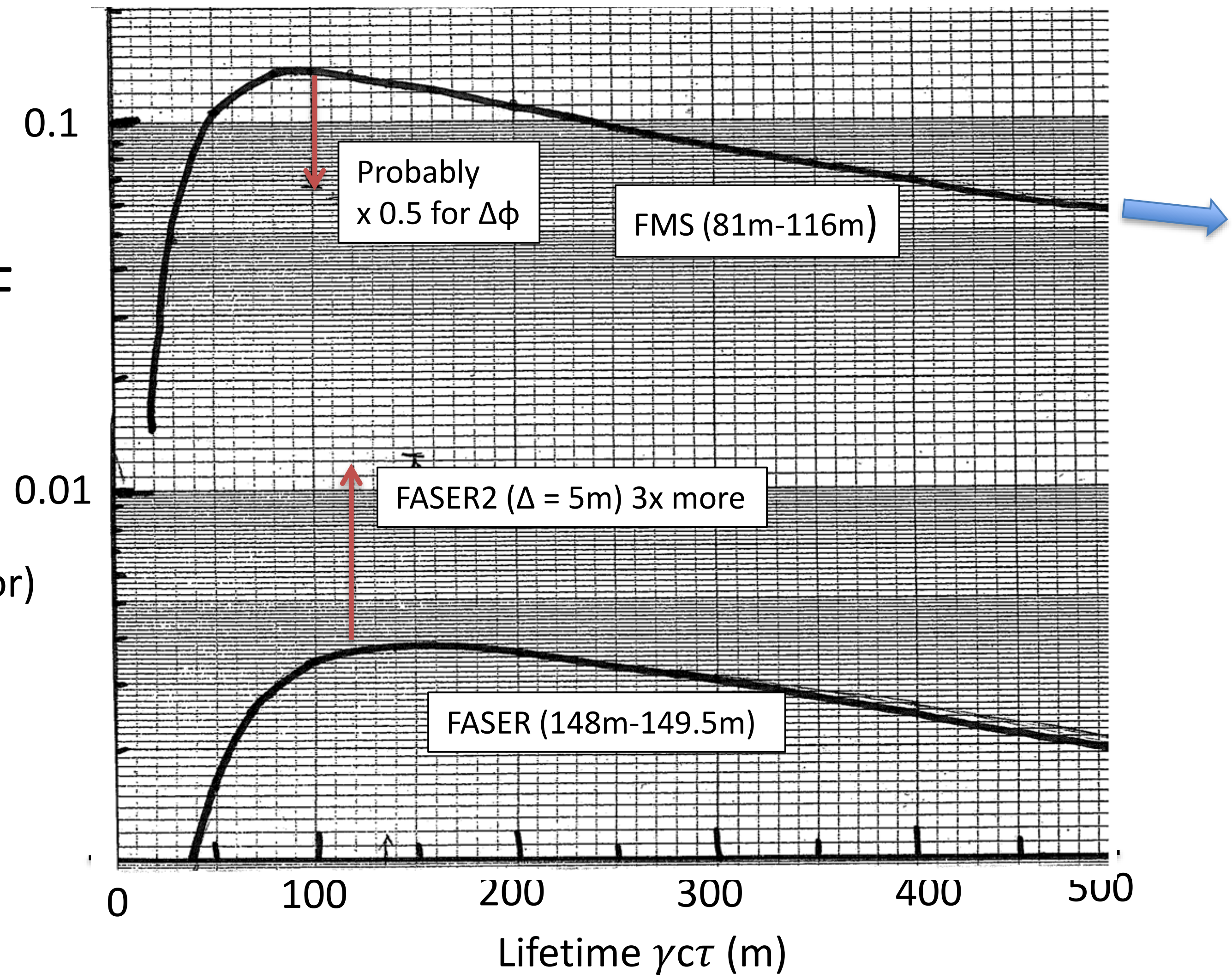
FASER: LoI July 2018 – quickly approved – Run 3
Decay volume at z = 480 m, R = 10 cm, and L = 1.5m
νFaser proposed (emulsion stacks)
Run 4 they propose FASER2 : R = 1m and L = 5m

Muons and ν from π, K, D decay can be known (FMS- hadrons), and their decay lengths are very long!

γcτ (π) = 139 km at 2.5 TeV !
γcτ (K+) = 18.5 km at 2.5 TeV !
γcτ (D^0) = 16.5 cm at 2.5 TeV !

But abundant and - > forward HE neutrinos! (FASERν)

Fraction of particles entering decay volume that decay vs. $\gamma c\tau$



F = Fraction decaying
in length of decay volume
in angular acceptance.

(Does not include flux factor)

FASER (Run 3/4) is a short decay volume far away : maximum decay fraction = 0.4% (1.2%)
FMS (Run 4) is much bigger volume closer: maximum decay fraction 13%

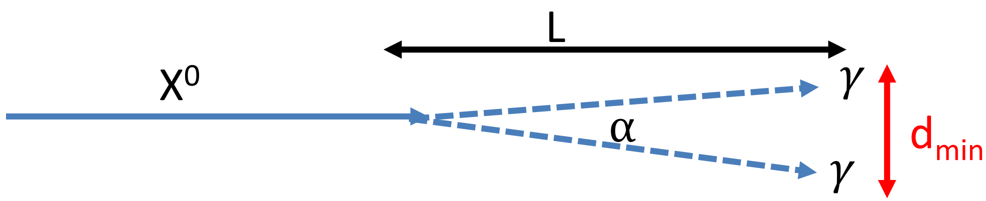
Can we see $X^0 \rightarrow \gamma + \gamma$? Axion-like particles

As for π^0 decay, the opening angle $\theta_{\gamma\gamma}$ (or α) has a minimum $\theta_{\gamma\gamma}$(min) $= 2\, M_X/E_X$ and a maximum opening angle 180^o .

For an isotropic decay the distribution in α is:

$$\frac{dN}{d\alpha} = \frac{1}{4\gamma\beta}\frac{\cos\alpha/2}{\sin^2\alpha/2}\frac{1}{\sqrt{\gamma^2\sin^2\alpha/2 - 1}}.$$

… which peaks at $\theta_{\gamma\gamma}$(min) - equal energy photons - and vanishes at 180^o (one is backwards)



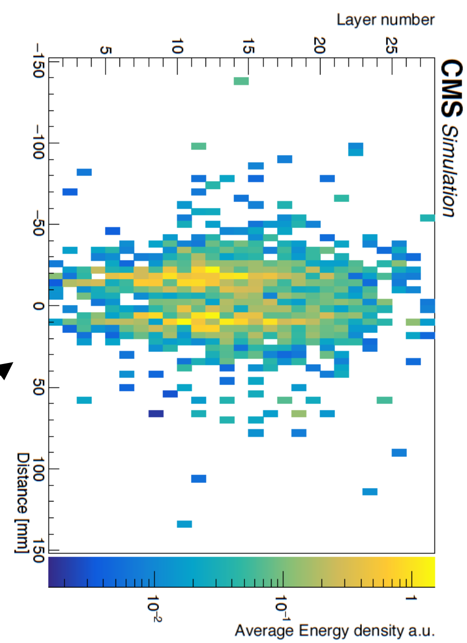
Some values, e.g.:

M_X(GeV)	E_X(GeV)	$\theta_{\gamma\gamma}$(min) mrad	
2	1000	4	= mm/m
2	2000	2	
5	1000.	10	
5	2000	5	
10	1000	20	
10	2000	10	

With 2-EM shower resolving d few mm and distances L ~ 3 – 30m looks OK, including mass M_X reconstruction.

Critical issue probably shower pointing vertex resolution and X^0 trajectory.

Simulation two 80 GeV parallel photons separated by about 30mm.
From CMS-TDR-019 Fig 5.1



Can we see $X^0 \rightarrow \gamma + \gamma$?

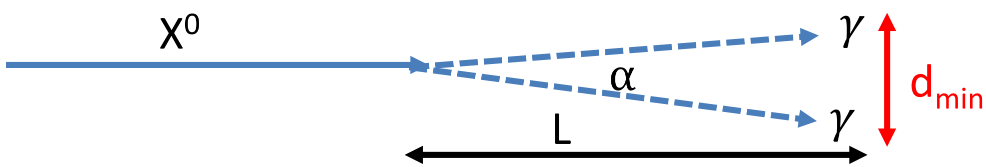
From CMS-TDR-019

Critical issue probably shower pointing:
vertex resolution, X^0 trajectory and α

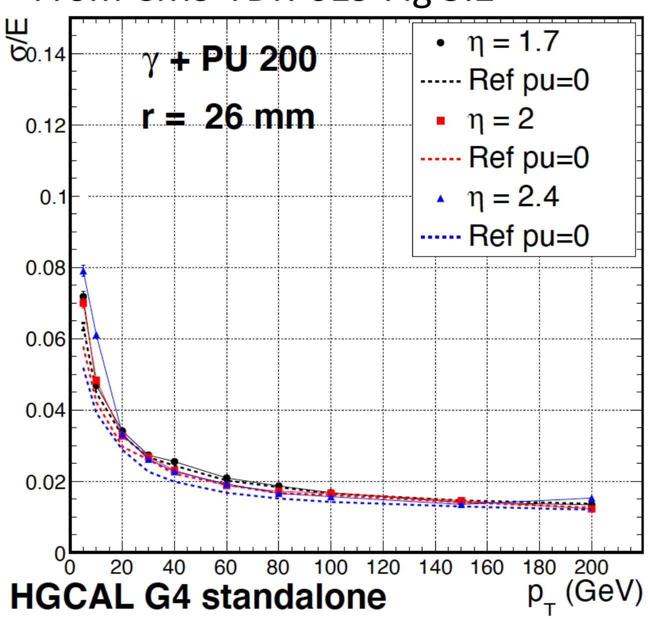
Single shower position resolution ~ 1mm

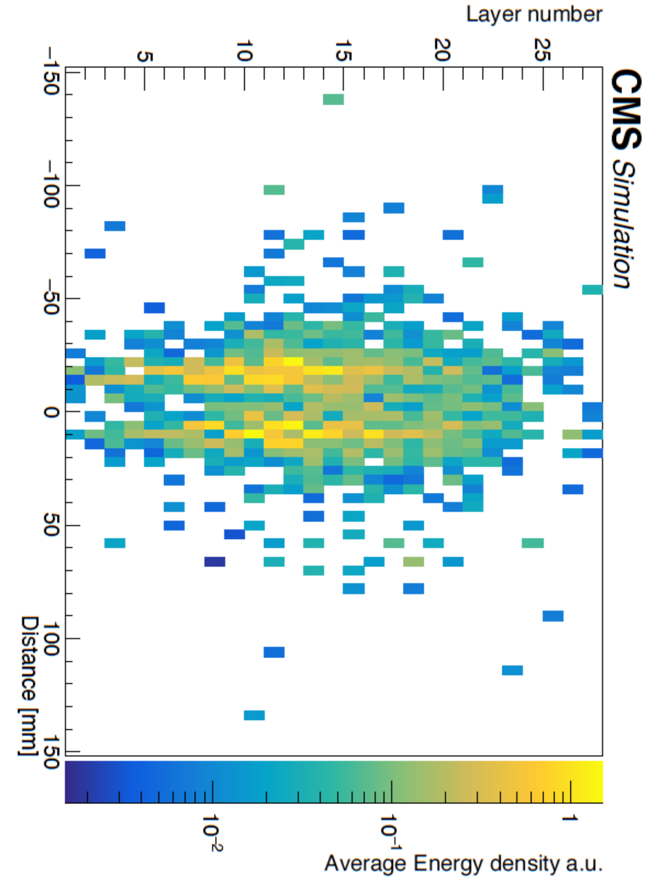
Angle resolution < 7 mrad (25 GeV showers)

σ(M) probably < ~ few %
> Needs proper simulation



From CMS-TDR-019 Fig 5.2



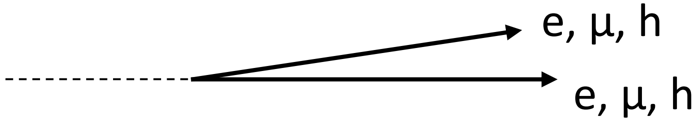


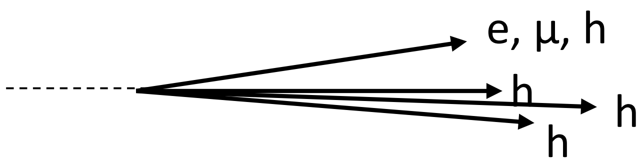
Simulation two 80 GeV parallel photons separated by about 30mm.
From CMS-TDR-019 Fig 5.1

If conversion in tracker – no field so no spread

Can we see $X^0 \rightarrow \tau + \tau$?

$M(\tau)$ = 1776.86 MeV → M(X) > ~ 3600 MeV
Main decays: μ ν ν & e ν ν each about 0.175 so μ μ, e e 3% each, e μ = 6%
Non-pointing because neutrinos missing.
BR (h ν) = 0.115 (mostly π).
BR (h + ≥ 1 neutrals) 37%
BR (h h h + ≥ 0 neutrals - 3 prong) 15%



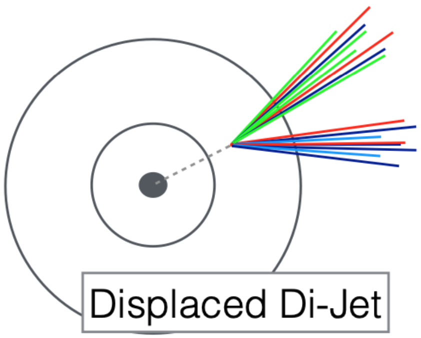


Can we see $X^0 \rightarrow c + c$?

Consider e+e- events above open charm threshold 2 x $M(D^0)$ = 3730 MeV
Boosted to high p_z (acceptance?) and decay in pipe

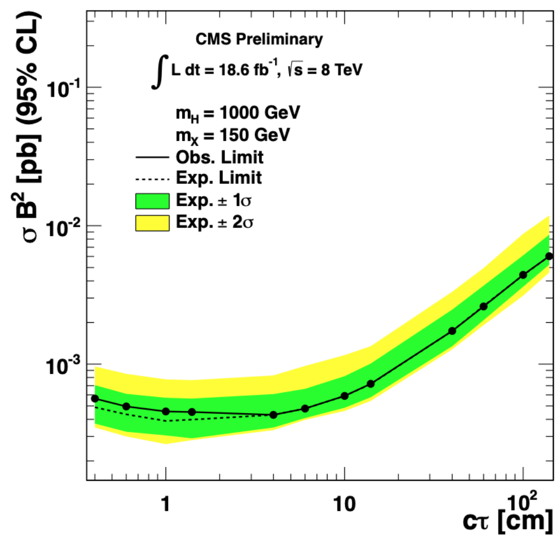
All need simulation

Can we see $X^0 \rightarrow$ Jet + Jet?



CMS Central

CMS Collaboration, Phys.Rev.D.91, 012017 (2015) [arXiv:1411.6530].

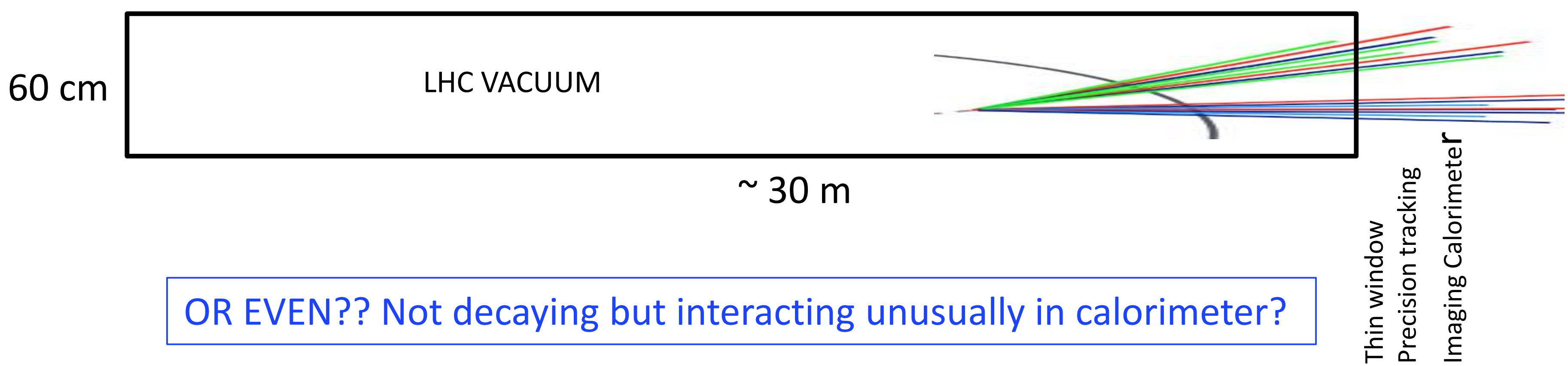


1 m $\rightarrow$ 10 m – 1000 m+

Require di-jets all coming from a single displaced vertex.

Throw away energy of tracks not reconstructed from vertex.

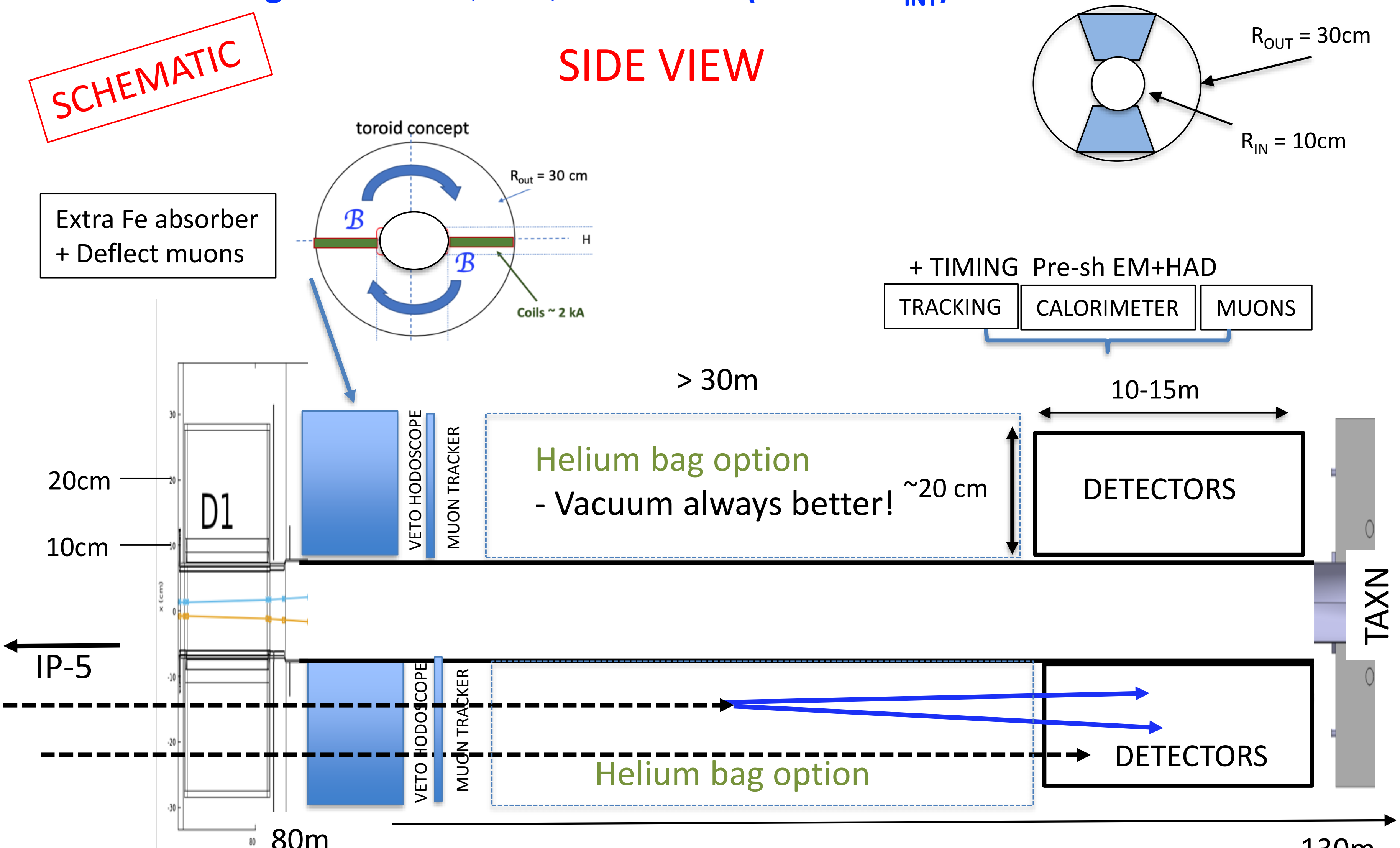
Unlikely to be sensitive to emerging phenomenology.



OR EVEN?? Not decaying but interacting unusually in calorimeter?

FMS Both sides? Or other side LLP search only?
Existing absorbers Q1 – Q3 & D1. + Fe (2m ~ 12 λ_{INT})

FRONT VIEW
AREA ~ 0.1 m^2



If almost no background events (?) a few makes a discovery [cf Z (6 events)]

What backgrounds make a pointing-back vertex in this large fiducial volume?

SUMMARY: Propose Forward Multiparticle Spectrometer for CMS Run 4

Low PU charged mode : many valuable measurements in unexplored region
High Lumi neutral mode: important discovery potential

Many opportunities to participate towards a CMS Note or other documents (theory paper too)

Simulate beam line, magnets as absorbers etc.

Assemble a possible configuration of Run 4 detectors as spectrometer elements

Simulate vertexing (x, y, z) from track pairs (or 4?) in tracker, resolutions

Calculate hadron (including c) production spectra in this region with PYTHIA et al. –other MCs

Simulate sensitivity to LLIs as fn (M, $\varepsilon^2 / \tau, \sigma$) … including $\tau^+ \tau^-$, c-cbar? (LHC > SPS-FT)

Opportunity for participation and also leadership!

Thank you

Back-ups →

Thursday 16th: Mainly search for penetrating but decaying LLPs - $\gamma c\tau$ ~ 10 m → >~ few km

CERN times

14:30	**Introduction to mode B - LLP search at HL**	*Michael Albrow*	*CERN*	14:30 - 15:00
15:00	**LHC machine conditions**	*Francesco Cerutti* CERN	*CERN*	15:00 - 15:30
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16:00	**FASER** (Competition)	*Felix Kling et al.*	*CERN*	15:45 - 16:10
	Proton Fixed-Target Experiments for LLP Searches (Competition)	*Yu-Dai Tsai*	*CERN*	16:10 - 16:35
	Detectors for CMS at HL	*Julie Hogan*	*CERN*	16:35 - 17:00
17:00	**Introduction to dark portals (theory)** (Theoretical)	*Gordan Krnjiac*	*CERN*	17:00 - 17:30
	Sensitivity to new penetrating LLP's (Theoretical)	*Speaker To be determined*	*CERN*	17:30 - 18:00
18:00				

From IR5 to first quadrupole Q1

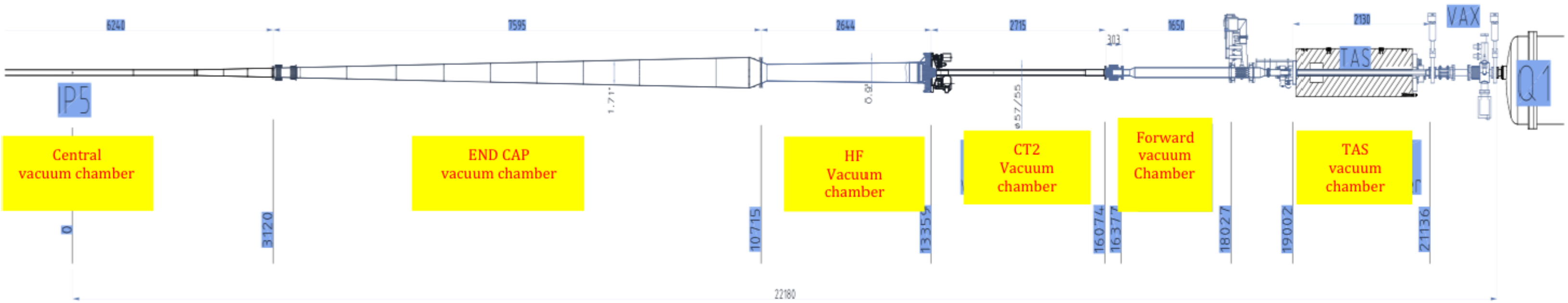
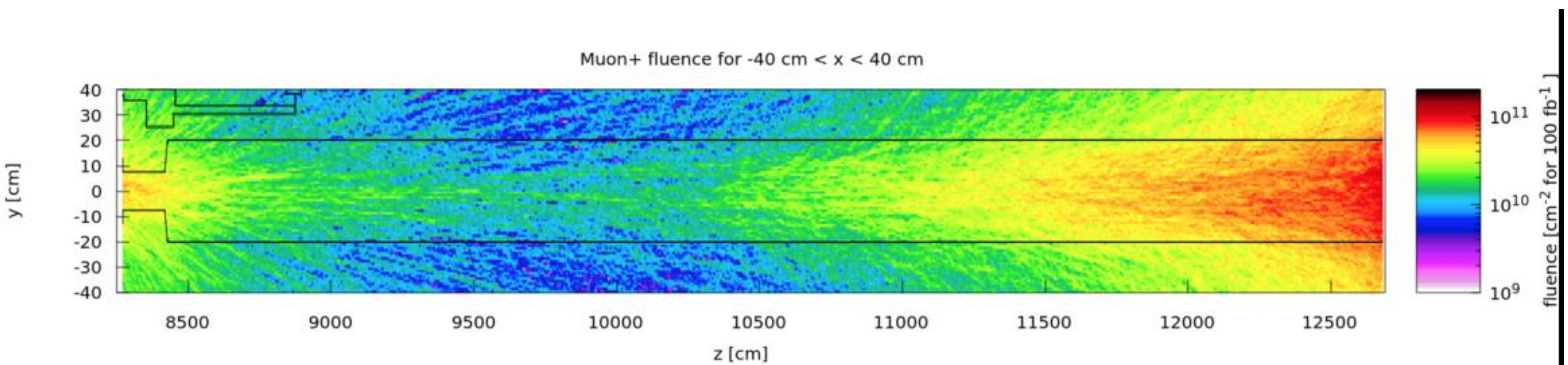


Figure 11.9: Layout of CMS beam-pipe from interaction point to first quadrupole. All dimensions are in millimeters.

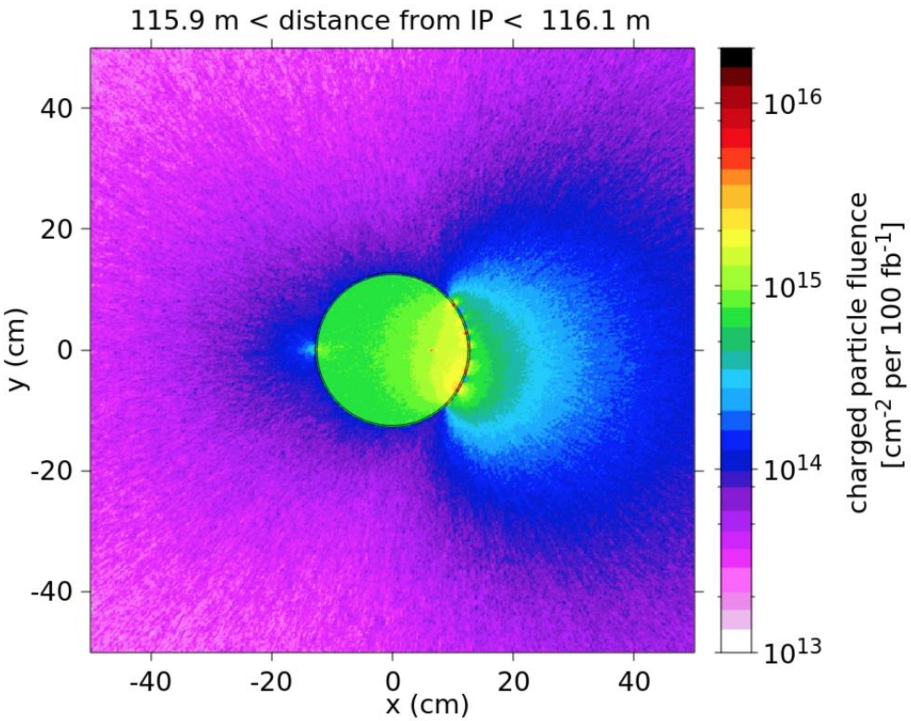


Francesco Cerutti & Marta Gilarte. FLUKA

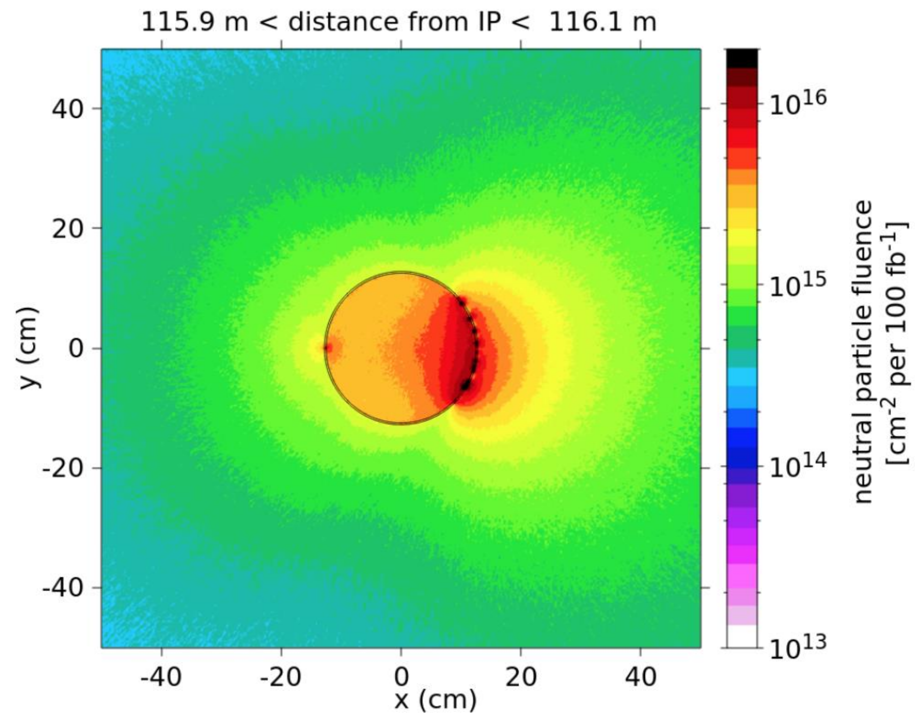
100 fb^{-1} Does not include additional Fe absorbers

Fluence cm^{-2} per 100 fb^{-1} down to low energies (100 keV - 1 MeV) – all momenta
Calculations by Marta Gilarte, CERN (FLUKA)
At z = 116m where transition to small pipe could be.

CHARGED PARTICLES



NEUTRAL PARTICLES



Very low levels above and below
'small' beam pipe

WITHOUT EXTRA ~3m Fe "PLUG"
Or n-absorber

arXiv:2001.06522v1 [hep-ph] 17 Jan 2020

A Light Scalar Explanation of $(g-2)_\mu$ and the KOTO Anomaly

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(Dated: January 22, 2020)

Not dark photon but …?

Abstract

The KOTO experiment has recently performed a search for neutral Kaons decaying into neutral pions and a pair of neutrinos. Three events were observed in the KOTO signal region, with an expected background of about 0.05. Since no clear signal of systematic errors have been found, the excess of events in the decay $K_L \to \pi^0 \nu\bar{\nu}$ is quite intriguing. One possibility to explain this anomaly would be the presence of a scalar ϕ with mass of the order of the pion mass and inducing decays $K_L \to \pi^0 \phi$ which mimic the observed signal. A scalar with mass of the order of the pion mass and a coupling to muons of the order of the Standard Model Higgs coupling could also explain

$K_L \to \pi^0 + \phi$

K^0_L too long lived for FMS
$\gamma c\tau$(1 TeV) = 30 km but
$K^0_S \to \pi^+ \pi^- \phi$ is allowed (Carlos Wagner)
$\gamma c\tau$(1 TeV) = 53 m & $\phi \to e^+e^-$
Lifetime in reasonable range

Consider “dark photons” – popular candidate, not for dark matter if they decay but maybe “portals” to the dark sector.

If 1 Mev < M(A’) < 140 MeV then $\pi^0 \to$ A’ + γ and then A’ $\to$ e+e-
If 1 Mev < M(A’) < 547 MeV then $\eta^0 \to$ A’ + γ and then A’ $\to$ e+e-
If 210 Mev < M(A’) < 547 (958) MeV then η^0 (η’) $\to$ A’ + γ and then A’ $\to$ e+e- & μ+ μ-

Look where the π^0 and η^0 (η’) go …

Key is **extremely good tracking** (behind thin window) to find **vertex in vacuum** (consider He or air but … pipe exists – make it bigger) pointing back to collision region through ~ 30m of steel.

If almost no background events (?) a few makes a discovery [cf Z (6 events)]
What backgrounds make a pointing-back vertex in this large fiducial volume?

Food for thought (& simulation) - enhanced coupling to heavy flavors:

X → $\tau^+ \tau^-$ → 3% e+μ, ~5% (e or μ)+ 3-tracks - but missing ν's smears pointing

X → $c\text{-}\bar{c}$, $b\text{-}\bar{b}$?

SM Particles decaying to $\mu^+\mu^-$

Name	IGJPC	M(MeV)	Width MeV	BR-mumu	
rho(770)	1+1--	775.26 +- 0.25	149.1 +/- 0.8	4.55 +- 0.28	10^-5
omega(782)	0-1--	782.65 +- 0.12	8.49 +- 0.08	7.4 +- 1.8	10^-5
phi(1020)	0-1--	1019.461 +- 0.016	4.249 +- 0.013	2.86 +- 0.19	10^-4
J/psi(1S)	0-1--	3096.900 +- 0.006	0.0929 +- 0.0028	5.961+-0..033	10^-2
psi(2S)	0-1--	3686.097 +- 0.025	0.294 +- 0.008	8.0 +- 0.6	10^-3
psi(4160)	0-1--	4191 +- 5	70 +- 10	seen	
Upsilon(1S)	0-1--	9460.30 +- 0.26	0.05402 +- 0.00125	2.48 +- 0.05	10^-2
Upsilon(2S)	0-1--	10023.26 +- 0.31	0.03198 +- 0.00263	1.93 +- 0.17	10^-2
Upsilon(3S)	0-1--	10355.2 +- 0.5	0.02032 +- 0.00185	2.18 +- 0.21	10^-2
K0_S		497.611		< 8	10^-10
K0_L		497.611		6.84 +- 0.11	10^-9


FORWARD PHYSICS
NEW PHYSICS FORWARD — CENTRAL ?
DARK PHOTONS ?
@ LOW MASS
DARK MATTER ?
GALACTIC γ-RAY EXCESS
(χ₀+χ₀→γ+γ)
p̄, d̄, H̄e, H̄e₃ -SPECTRA PRODUCTION.
TeV ν -INTERACTIONS
ν FASER (400 m)
ν FLUXES FROM π±, K±, D° etc. ..
NUCLEAR
P-O, O-O
METASTABLE FRAGMENTS (w/ ISOTOPES?)
STRANGELETS ?
NUCLEI w/ s,s,s
HEAVY FLAVORS
D°→Kπ ?
Λc→pKπ ?
μ SPECTRA (NOT FROM π/K)
π/K/p TeV INTERACTIONS
TARGET + PIXELS
σinel, nch.
QCD @ LOW-Q²
VACUUM STRUCTURE
LOW pT, HIGH xF
DIFFRACTION
POMERON
GLUEBALLS IN DISSOCIATION
P → P + G ? → π/K → π/K
ASTROPARTICLE PHYSICS
ν's - ICECUBE
TeV SPECTRA ? IN S.M.
AUGER
COSMIC RAY SHOWERS
μ-EXCESS
ν ENERGY LOSS
LEADING HADRONS
π/K/p/c/b ?
BASELINE S.M.
10⁵ – 10¹⁰ GeV
NEW PHYSICS