Articulating the MATHUSLA Cosmic Ray Physics Case

30 August 2018
MATHUSLA Workshop Simons Center

Carlos Arteaga-Velazquez
David Curtin
Juan Martin Alfonso Subieta Vasquez

Outline

1. What exactly can MATHUSLA measure and why is it good at it?

2. A few obvious physics targets and why they matter. *(Obviously there could be more)*

3. Big Picture Overview

1. What exactly can MATHUSLA measure and why is it good at it?

Comparison of MATHUSLA with other CR experiments in same E range

Observatory	Detector	Area (10^4 m^2)	Energy range (PeV)	Full coverage	Spatial resolution	Angular resolution	Energy precision	Composition capabilities	Test of models
MATHUSLA 100	Particle tracking	1	(1, 50)	Yes	Very good	Very good	Very good	Limited by statistics	Very good
HAWC	Water Cherenkov	2.2	(10^{-2} , 1)	62%	Good	Good	Good	In investigation	In investigation
KASCADE	Scintillators, muon tracking detector, calorimeter	4	(1, 10^2)	1.55%, 0.64%, 0.76%	Good	Good	Good	Very good	Very good
IceTop	Ice Cherenkov	100	(1, 10^3)	0.044%	Good	Good	Good	In investigation	Good
Tale (TA)	Scintillators, fluorescense telescopes	10^3	(30, 10^4)	O(%)	Good	Good	Excellent	In investigation	Good

MATHUSLA also has uniquely good time resolution and it also has directional tracking *(different from angular resolution of PRIMARY)*.

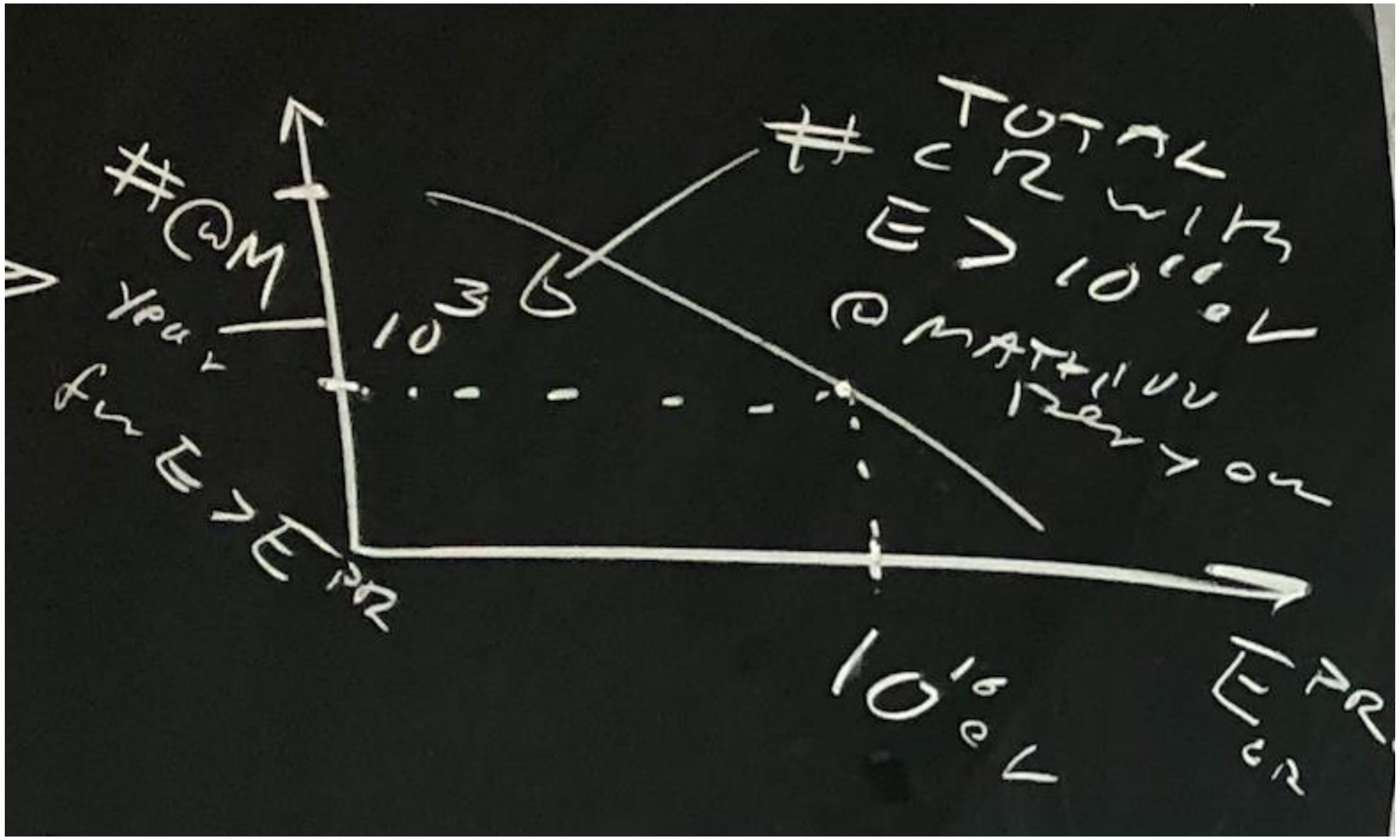
Describing CR's @ MATHUSLA

We want to first make a few really simple plots to describe "CR for dummies" at MATHUSLA.

All these plots are for MATHUSLA100, at its elevation.

Make these plots using existing Corsika MC samples!

1. Integrated flux plot (all compositions):



How many CR primaries above a certain energy hit 100mx100m area per year?

Describing CR's @ MATHUSLA

2. Properties of Extended Air Showers at MATHUSLA
(for θ = 0, 45, 60deg and different compositions separately)

Make plots of the following variables as function of $E^{Primary}$ (eV):
(using thresholds from LLP white paper, discuss?)

In MEV: pions 200, Kaons 600, muons 200, electrons 1000, protons 600

These will be various probes of the charged particle density at detector level, ρ(r).

More precisely, it is ρ(x, y, t, particle species, particle energy,…)
so MATHUSLA's time resolution will give important handles as well etc…

The shape of ρ(r) represents a projection onto the one spatial variable and is therefore somewhat detector-dependent (detection thresholds etc) but it should be approximately universal in shape for different primary energies, with normalization given by total number of charged particles (~ CR primary energy)

Describing CR's @ MATHUSLA

a) r_{width} = average shower width in meters
[STDEV of charged particle density ρ(r)]

b) $N_{charged}^{total}$
Usually this refers to only (e, mu) populations since that is most indicative of primary CR energy/composition, but if possible show this number for just (e+mu) AS WELL AS (all) so we can compare.

c) N_{μ}/N_{e} *to show dependence on composition*

d) S (~ exponent of ρ) *to show dependence on composition*

(c) and (d) are the two most obvious handles MATHUSLA could have on determining the primary CR composition, where (c) is a possible upgrade but (d) only depends on fine tracking

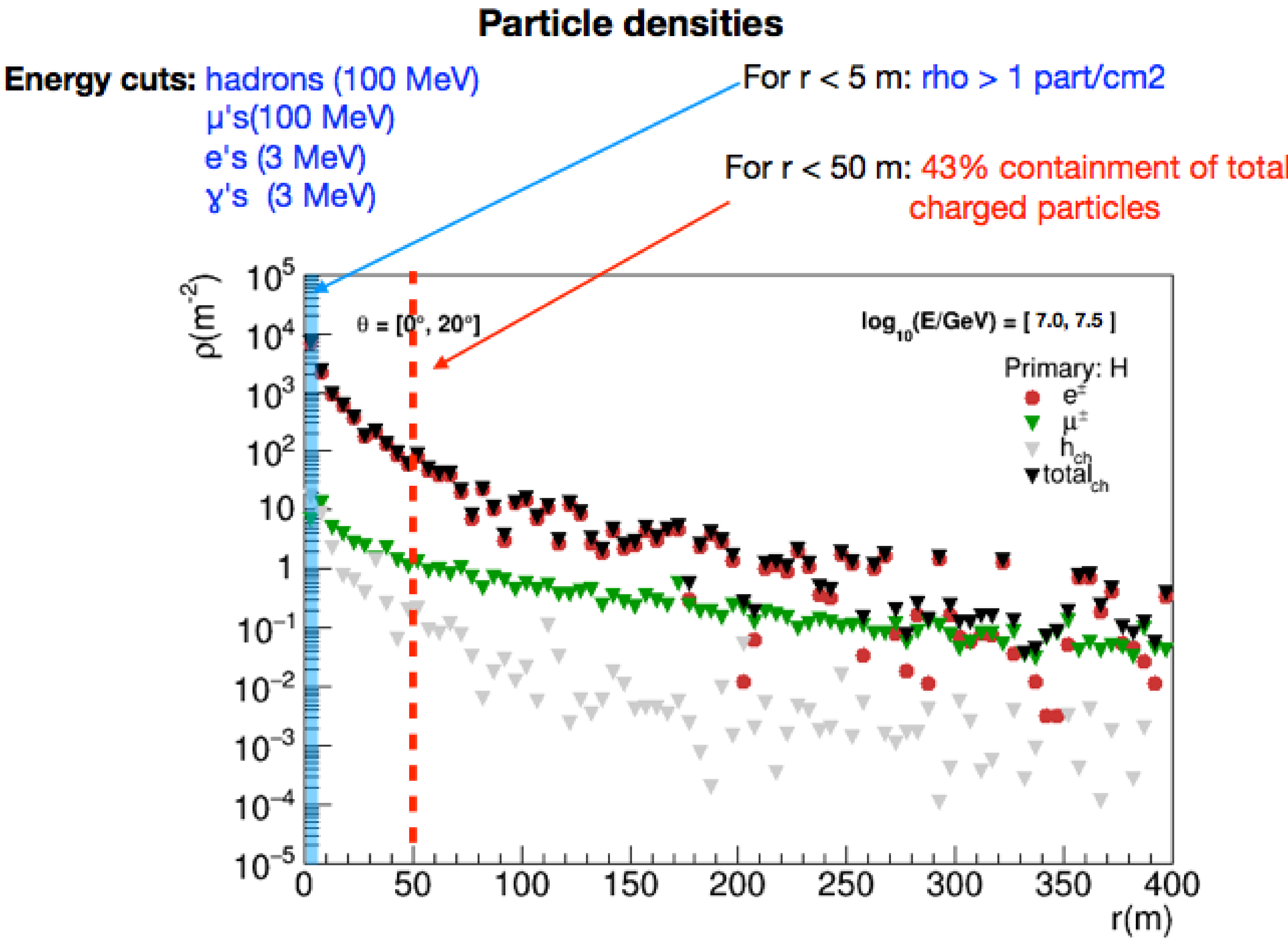
Describing CR's @ MATHUSLA

e) $r_{saturate}$ (meters) and $r_{saturate}/r_{width}$, where $\rho(r_{saturate}) = 1/cm^2$.
at both MATHUSLA and at elevation of 4km (ARGO)
This is to understand the approx radius of the shower core that would saturate a purely digital MATHUSLA detector, to understand the size scale of the shower region that analog readout would give us access to.

f) $r_{hadrons}$ (meters) and $r_{hadrons}/r_{width}$ where
$\rho_{e+mu}(r_{hadrons}) = \rho_{hadrons}(r_{hadrons})$
This is to understand where the shower starts being e/mu dominated, which is maybe (???) the region most useful for determining primary CR properties

g) Also just show a bunch of $\rho(r)$ examples.

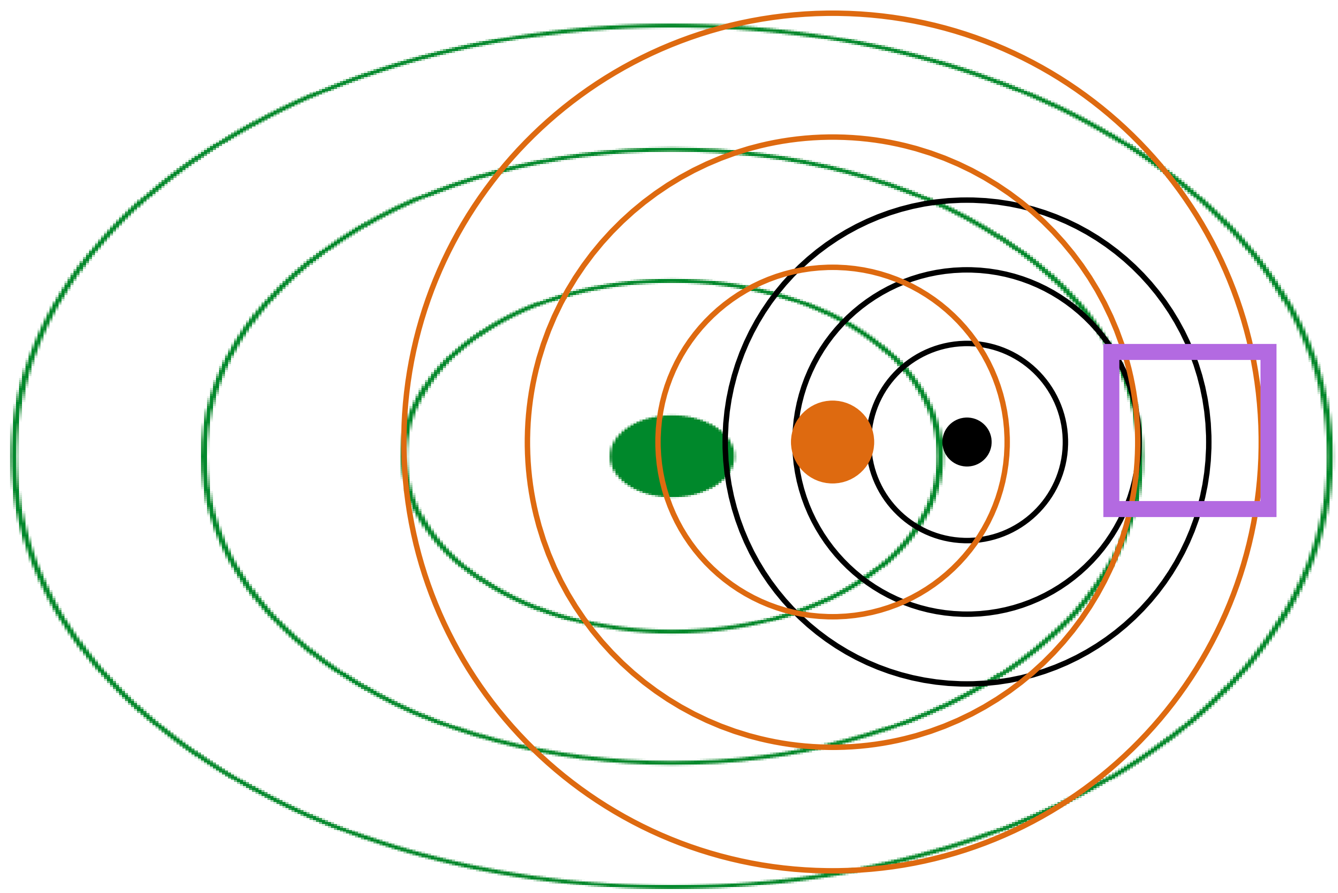
Preliminary Preview



Remarks

MATHUSLA's FULL coverage *(huge amount of data in detector area!!)* with fine tracking etc. This could give surprising capabilities to probe showers larger than the actual detector.

contours of N(r)



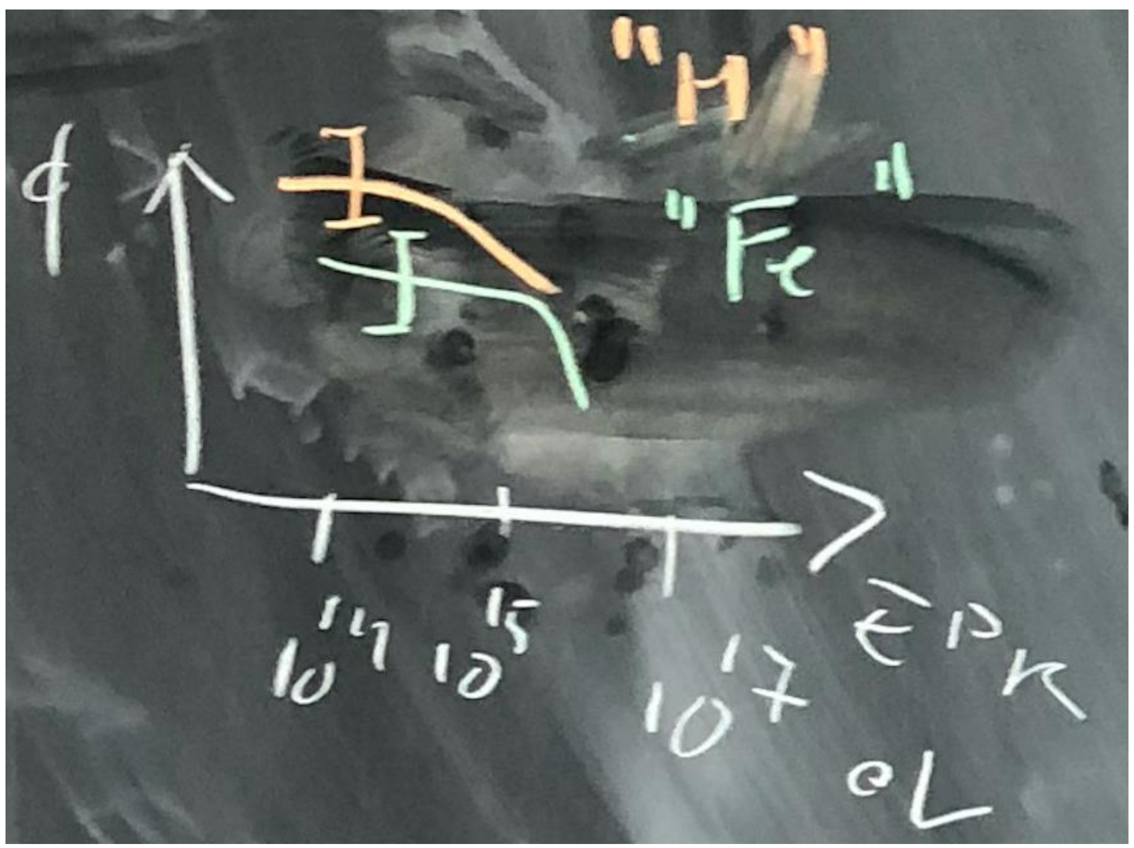
Time of arrival across shower front, "curvature" of two-dimensional N(x,y), .. should distinguish these possibilities and allow position of shower core to be fitted. Then you can fit shower shape with MATHUSLA sampled area.

2. A few obvious physics targets and why they matter.

1. Primary CR spectra + composition

In 10^{14} - 10^{17} eV range, should see about 1 Million showers per year at MATHUSLA100.

H ~ 90%, He ~ 10%, “heavier stuff” ~1%



Due to statistics,
“H” = H + He,
“Fe” = heavier

Obvious benefit of upgrades:
- MATHUSLA200 has 4x stat
- e/mu discrimination would hugely improve composition measurement.

We could get best resolution measurements on the market!

1. Primary CR spectra + composition

PHYSICS OUTCOMES

a) there is confusion amongst experiments about position of knee, and how many knees there are. Default assumption is one knee.

MATHUSLA could clear this up: how many knees? where are they?

Why? **If there are more knees, then there might be more populations of astrophysical CR accelerators**

1. Primary CR spectra + composition

PHYSICS OUTCOMES

b) this will constrain the galactic B field

This can be a detailed probe of spatial distribution of galactic accelerators.

Why care about Galactic Accelerators?
—> Supernovae, Neutron Stars, Galactic Center, …

Important Astrophysics!

Also has particle physics implications (e.g. NS are DM indirect detection backgrounds,….)

2. Look for Point Sources

MATHUSLA's excellent tracker will allow it to look for point sources with superior resolution.

PHYSICS OUTCOMES:

detection would imply presence of **nearby** (due to B field deflection/diffusion) galactic accelerator.

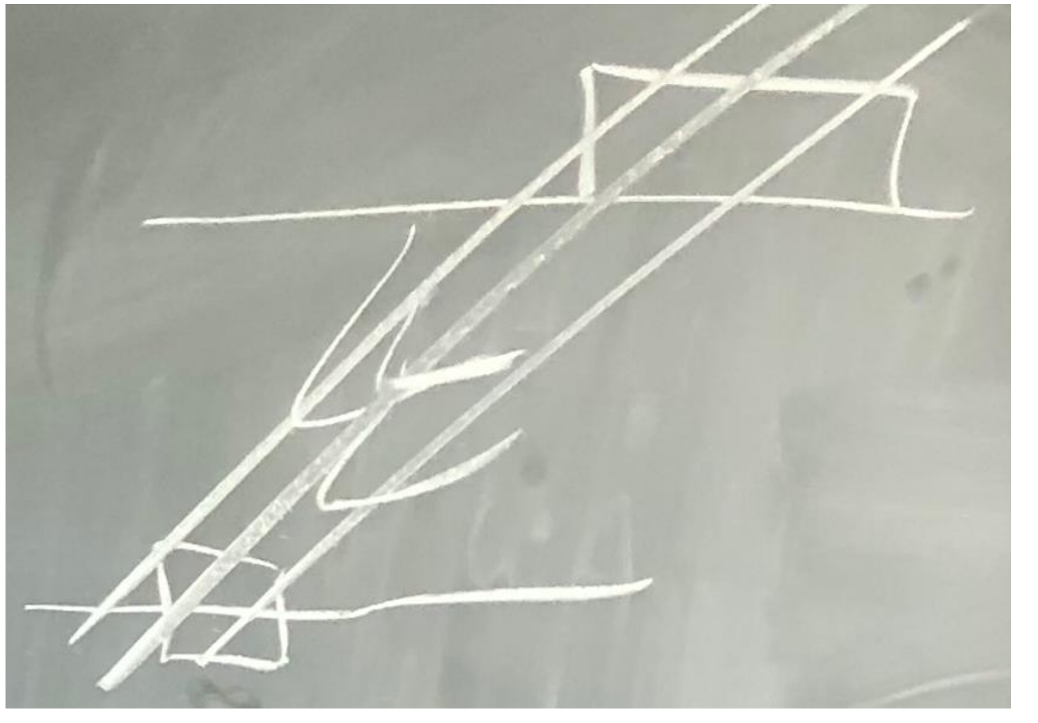
Important probe of G.A. properties, distribution, etc….
See (1)!

> Question: what is the "range" of point source searches for different Eprimary given galactic B-field?
>
> Question: is this a non-starter from statistics? Check literature…

3. Muon Bundles

MATHUSLA + CMS would be the only probe of these high-multiplicity muon bundles that correlates high-energy muon component with total air shower component.

WHY?
LEP and ALICE found muon bundle rates that are higher than expected from CR primary spectra that is dominated by light elements (as suggested by other measurements).



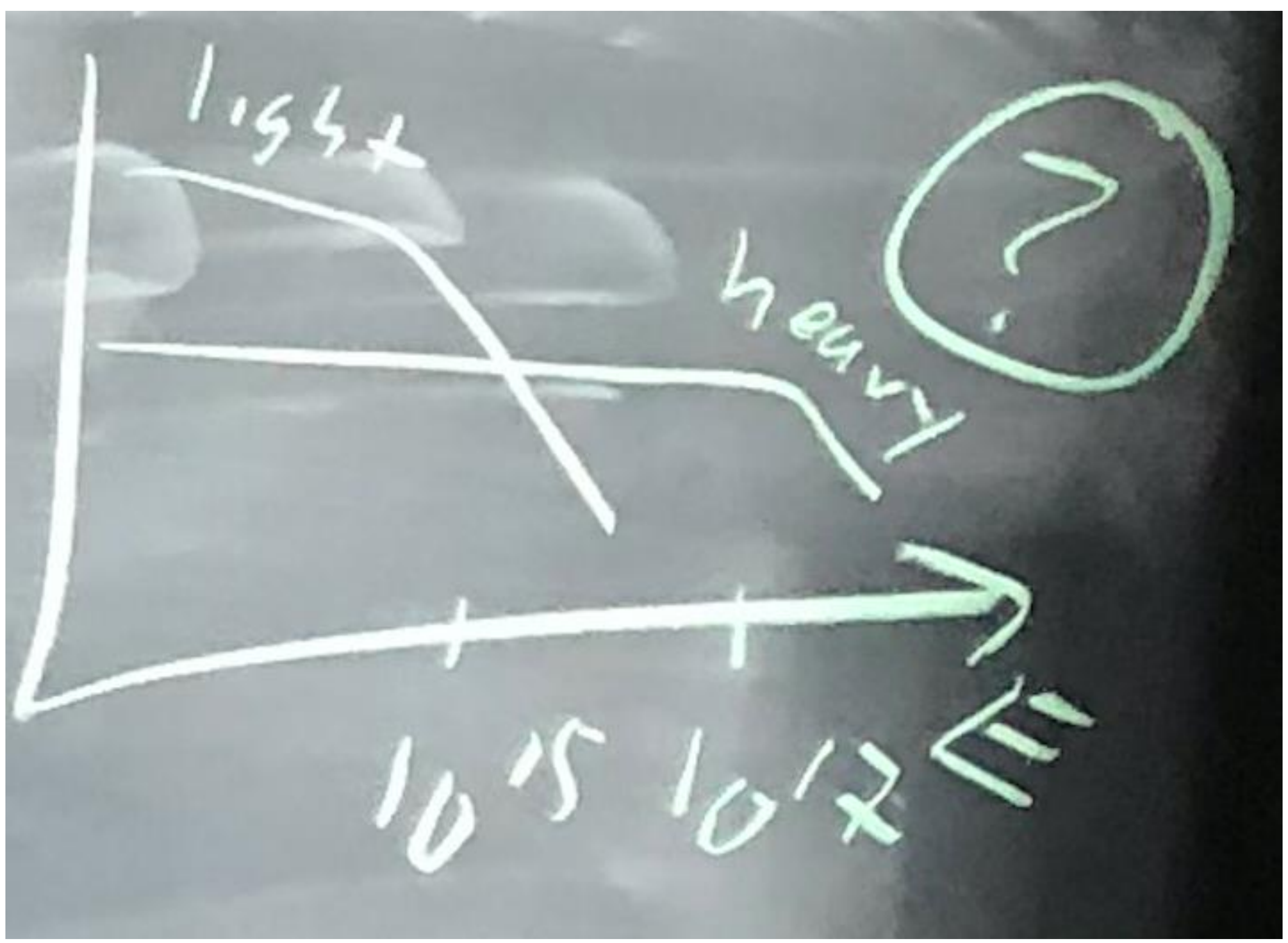
Ultimately, muon bundle origin is mysterious.

Obviously this would be helped A LOT by e/mu discrimination since then you wouldn't "need" the main detector

3. Muon Bundles

PHYSICS OUTCOMES of detailed muon bundle measurements:

a) could reveal detailed information on heavier CR component, which might dominate at higher energies, but which would be impossible for MATHUSLA see via conventional analysis.



Spectra & composition teach us about galactic accelerators! (see (1).

3. Muon Bundles

PHYSICS OUTCOMES of detailed muon bundle measurements:

b) Could be BSM (Strangelets, weird QCD plasma, non-perturbative EW physics, …)

c) could be weird air shower properties, but then we still need to know & understand, see (4).

4. Probing Hadron Interaction Models

“Fact”: MATHUSLA would make super-detailed EAS measurements that are highly sensitive to hadron interaction models:

- time structure of EAS
- muon production height
- general distribution of directional tracks and detailed spatial structure (not just position&time)
- highly inclined showers (mu rich, more atmospheric absorbtion)
- detailed measurements of very center of shower cores (see Rinaldo’s slides, c.f. analog readout)
- etc

Question: can we find out how interesting the cores are for this?

4. Probing Hadron Interaction Models

PHYSICS OUTCOME:

a) may help make **ALL OTHER (!!)** CR measurements (spectra, composition, ..) more reliable, including at much larger telescopes that probe higher energy, **extra-galactic CRs**

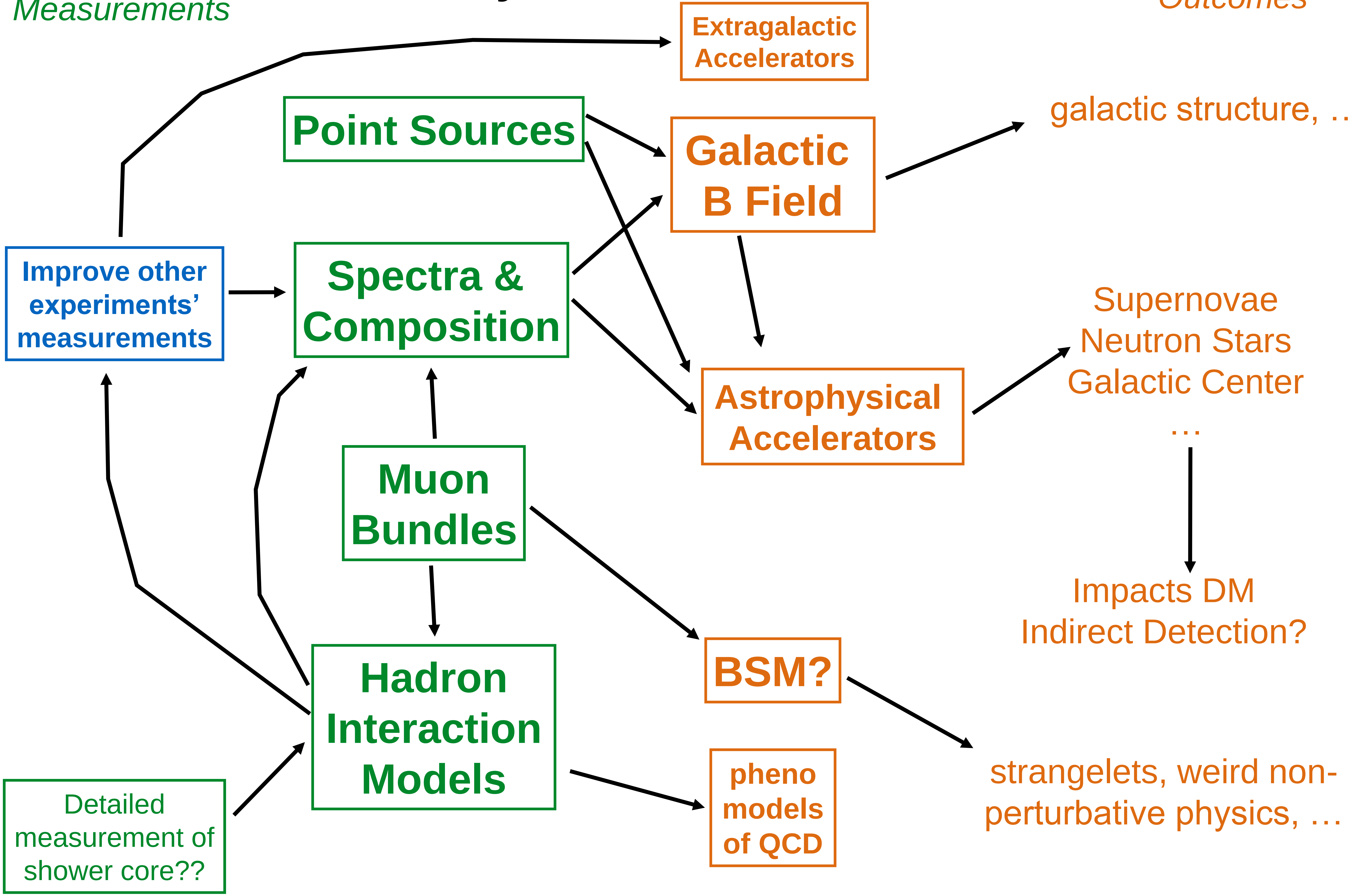
b) constrain QCD in highly forward, high $\sqrt{s}$ region?
—> this might be mostly non-perturbative QCD, or regions where perturbative calculations are possible in principle but very difficult? **Phenomenological models of QCD?**

(Perhaps a good analogy here is that it’s like a Pythia tune?!)

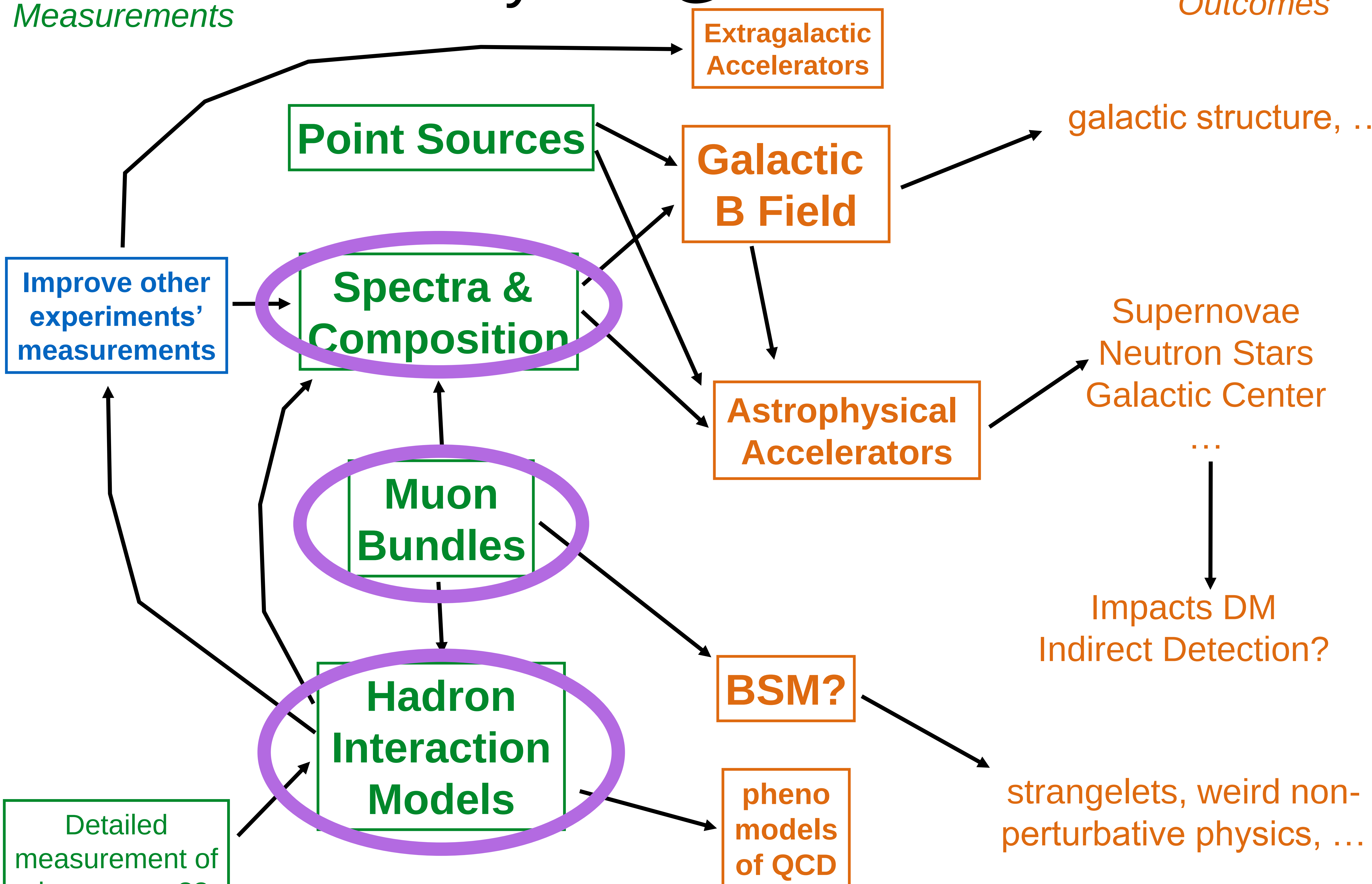
To do: is there a way of quantifying (a) a bit more?

3. Big Picture Overview

CR Physics @ MATHUSLA



CR Physics @ MATHUSLA



Improves a lot with e/mu discrimination