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Low Energy Beam Line for NA61/SHINE design status and plans

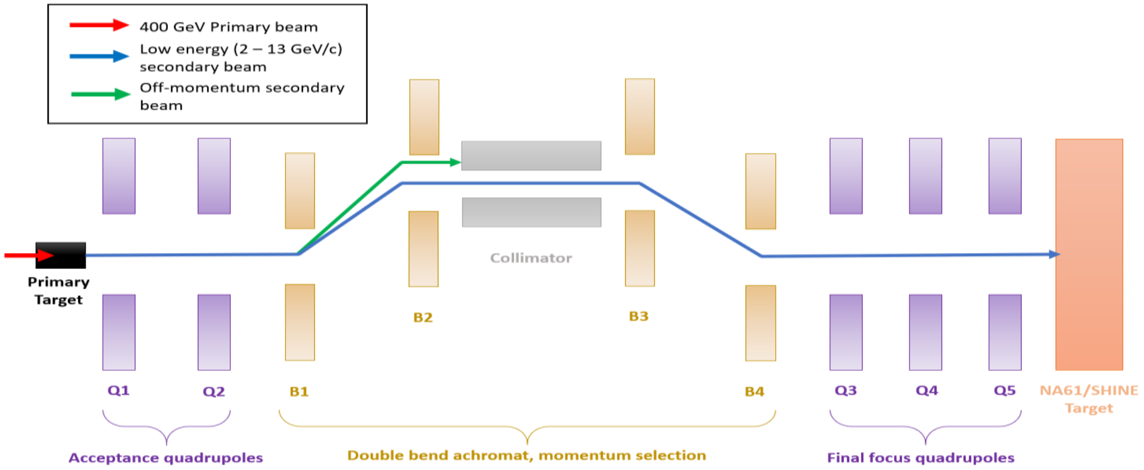
Need for a Low-Energy Beamline

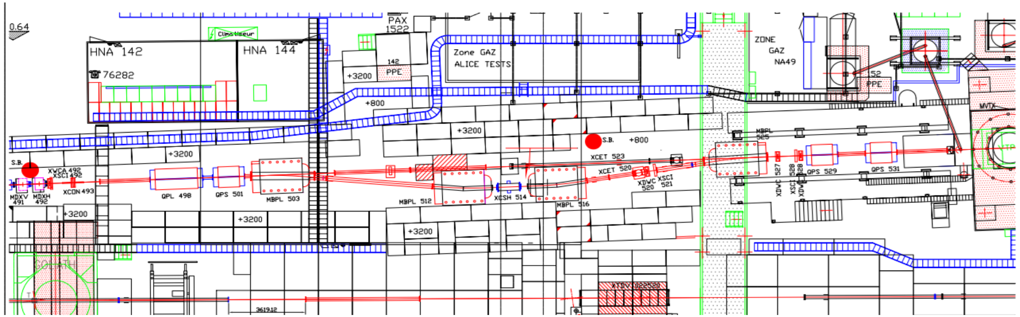
CERN's North Area beam facilities offer a unique place for test-beams and fixed target experiments, however low-energy particles are extremely challenging:

- SHINE's current H2 beamline is designed for momenta greater than 300 GeV/c
- Limitations on the magnets, the power supplies, and the acceptance
- Length is a limiting factor as beamline is too long for low energy particles and many of the pions and kaons decay before they reach the experiments (H2 length to NA61 is 600 m)

For these reasons, a new design is being studied, tailor-made for lower energy particles

Principle of a Low Energy Beam for SHINE

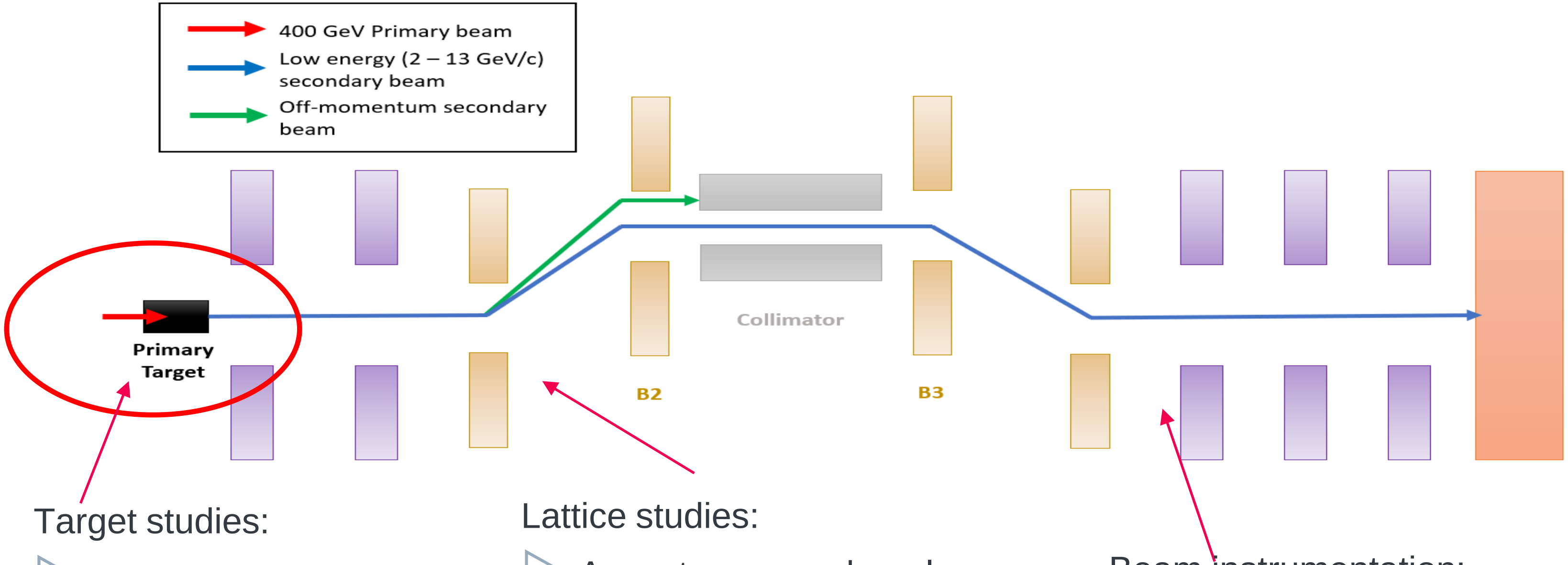




A low energy beam was there in ~2000 (NA49 times) serving CMS downstream

The current idea is to minimise disruptions to the existing beamline

Low-Energy Beamline Conceptual Design



Target studies:

- Particle yields
- Secondary beam composition
- Phase space

Lattice studies:

- Acceptance quadrupoles
- Momentum selection
- Beamspot studies
- Background studies

Beam instrumentation:

- BPMs
- Particle identification

1.

TARGET STUDIES

Particle Production

Simulation of targets

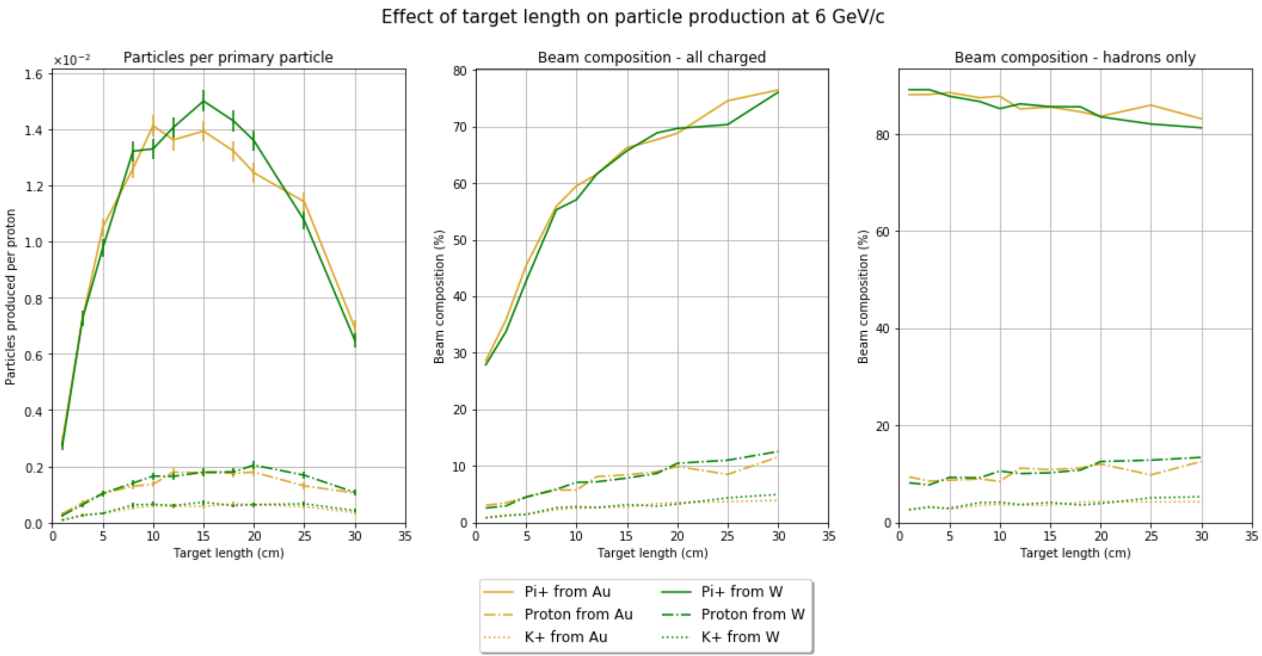
Low energy secondary particles are produced in an **intermediate** (secondary) **target**, for which the optimal **material** and **dimensions** have been studied via extensive simulations in G4Beamline.

Simulated different **materials** (both **high** and **low** Z), **lengths**, and **radii** using primary beams of **different energies** to estimate the expected:

- **Yield** – or secondary particles per incoming particle
- **Composition** – which percentage of the secondary beam does each particle make up

Assuming a ±10% momentum acceptance (Δp/p), a ±20 mrad angular acceptance ($\arctan(\frac{p_x}{p_z})$) and a length of 30 m for particle decay considerations. Considered particles at 1, 2, 4, 6, 8, and 13 GeV/c.

A large parameter space



Key findings

- There tends to be a trade-off between particle yields and beam composition
- There is no target which is optimal for the whole energy range for each particle
- A multi target station could be envisaged for the new beam line

Ranking of targets

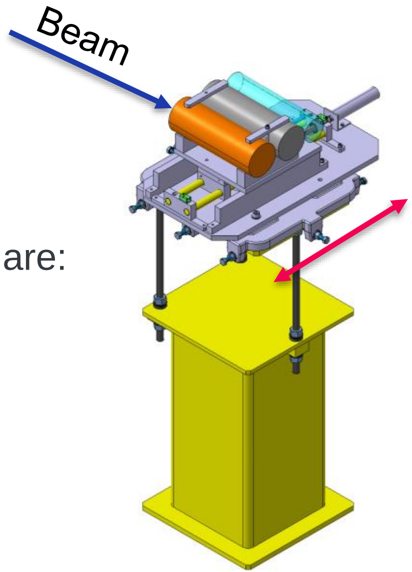
Due to the different parameters we were optimising for (yields and composition for different particles and at several different energies) the various targets need to be ranked

- Ranked the targets for each particle by giving a percentage score: best target has a score of 1, median target has a score of 0.5 and so on
- These rankings were then weighted by the ‘importance’ of the measurement and an overall ranking is returned
- Currently each energy is rated equally and pions, protons and kaons are given a score of [0.4, 0.4. 0.2] respectively

Optimal targets

Using this ranking formula, and limiting the choice to 3 optimal targets for ease of engineering of the switching system, the recommended targets are:

- For **high yields** : 20 cm W target with a 400 GeV primary
- For **balanced** : 30 cm W target with a 400 GeV primary
- For **high compositions** : 15 cm W target with a 70 GeV primary

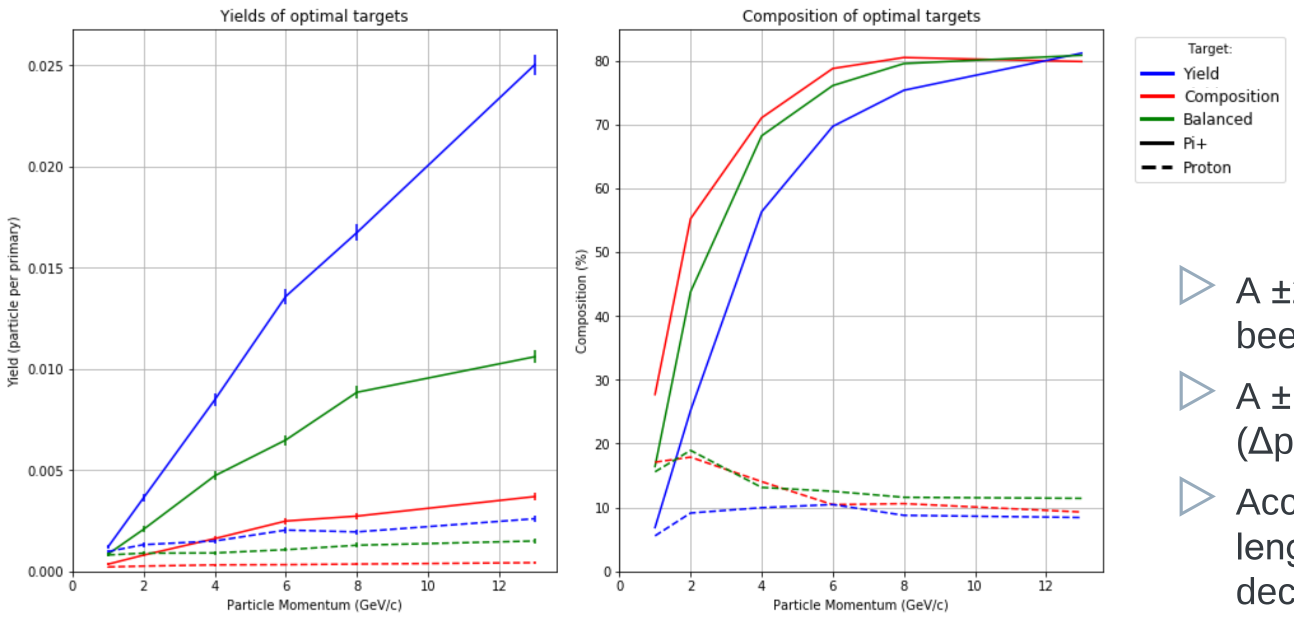


For these 3 targets the yield importance factor and the composition factor are:

[0.75, 0.25], [0.5, 0.5] and [0.1, 0.9] respectively.

Implementation trivial, remote exchange of target very easy

Differences between targets

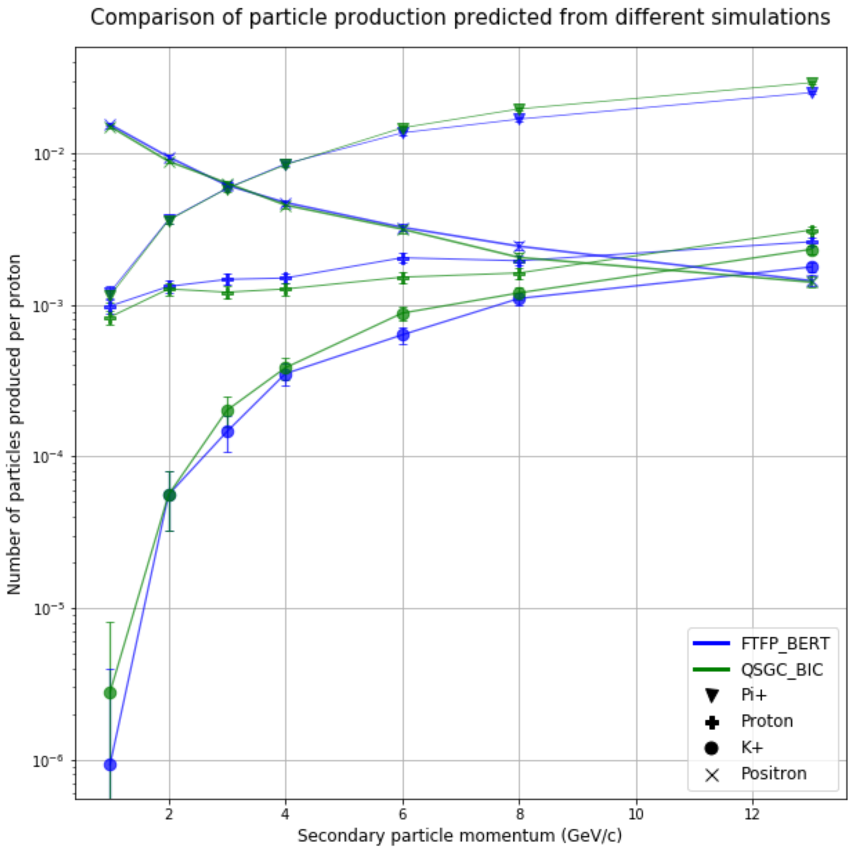


- A ±20mrad acceptance cut has been applied
- A ±10% momentum acceptance (Δp/p) cut has also been applied
- Accounting the 30 m beamline length's effects on particle decays

10 Day Preliminary Number of Particles

Preliminary numbers for a 10 day run		High Composition Target		Balanced Target		High Yield Target	
		Number	Composition	Number	Composition	Number	Composition
2 GeV/c	Pion+	2,409,000	55.20%	6,237,000	43.80%	10,917,000	25.20%
	Proton	780,000	17.90%	2,700,000	18.90%	3,960,000	9.10%
	Kaon+	33,000	0.80%	93,000	0.70%	168,000	0.40%
4 GeV/c	Pion+	4,851,000	71.00%	14,163,000	68.20%	25,416,000	56.30%
	Proton	960,000	14.10%	2,730,000	13.10%	4,500,000	10.0%
	Kaon+	300,000	4.40%	633,000	3.00%	1,053,000	2.30%
6 GeV/c	Pion+	7,461,000	78.70%	19,476,000	76.10%	40,770,000	69.70%
	Proton	990,000	10.40%	3,210,000	12.50%	6,120,000	10.50%
	Kaon+	663,000	7.00%	1,266,000	4.90%	1,899,000	3.20%
13 GeV/c	Pion+	11,084,100	79.80%	31,800,000	80.80%	75,060,000	81.10%
	Proton	1,290,000	9.30%	4,500,000	11.40%	7,800,000	8.40%
	Kaon+	1,479,000	10.70%	2,451,000	6.20%	5,322,000	5.80%

Comparison of Physics lists



Different Physics lists:

- Simulations making different assumptions may have very different results
- G4Beamline's FTFP_BERT and QGSP_BIC lists. FLUKA will soon be added as well.
- Similar results and similar trends mean that we can be confident in our predictions
- There is a model uncertainty on the order of 10-15% according to various previous measurements
- **Measurements would be ideal to validate these models**

2.

OPTICS

Layout, Acceptance and Momentum Resolution

Requirements for the beamline

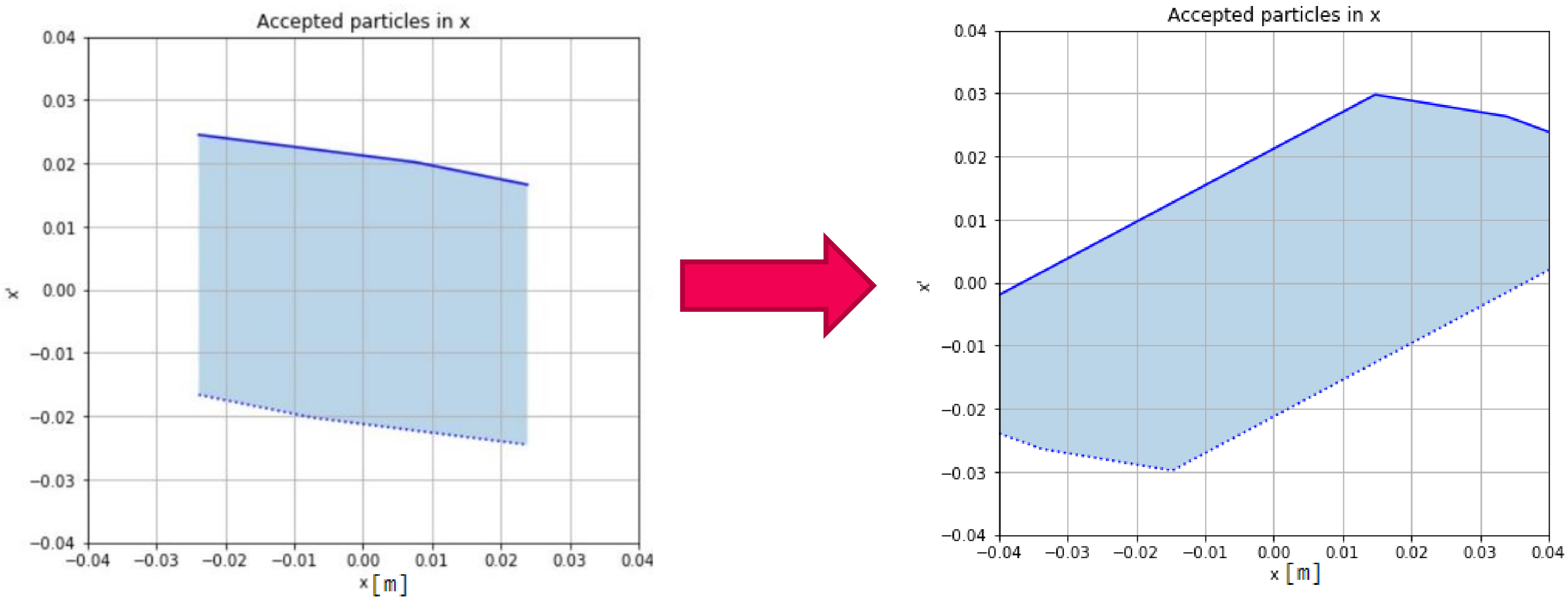
The beamline must:

- Have a large acceptance, for a sufficient rate
- Be short, to minimise particle decays
- Have a high acceptance
- Have a good momentum resolution
- Have a small spot size at the NA61 target
- Not be too contaminated by backgrounds

A full parameter scan

- Our approach to design this beamline has been to scan the parameter space and generate millions of beamline configurations, their acceptance and spot size at the end of the line.
- Using this information it is then possible to select the beamline that best matches the experiment's requirements, as every solution should be there
- Not affected by matching errors (as the conventional design process)

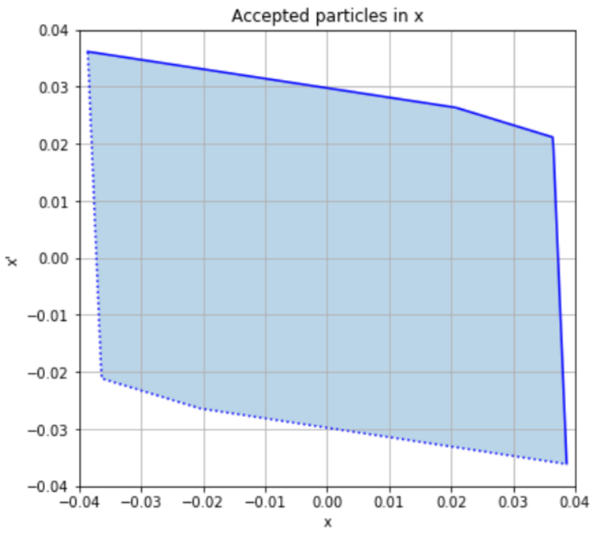
Improvements due to parameter scan



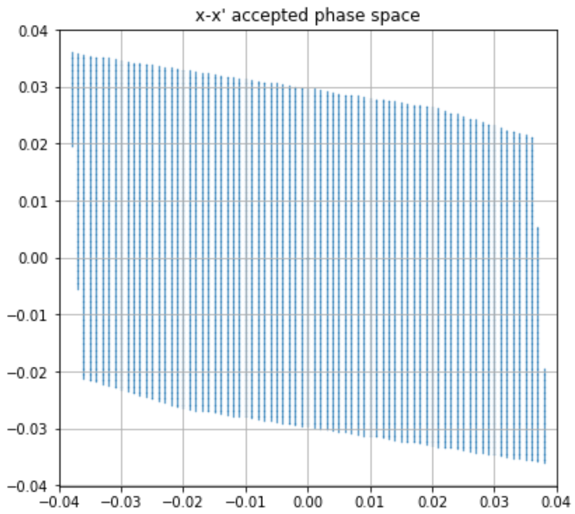
Difference in accepted phase space between current technique and the parameter scan for a doublet

Agreement with MAD-X and PTC

Code



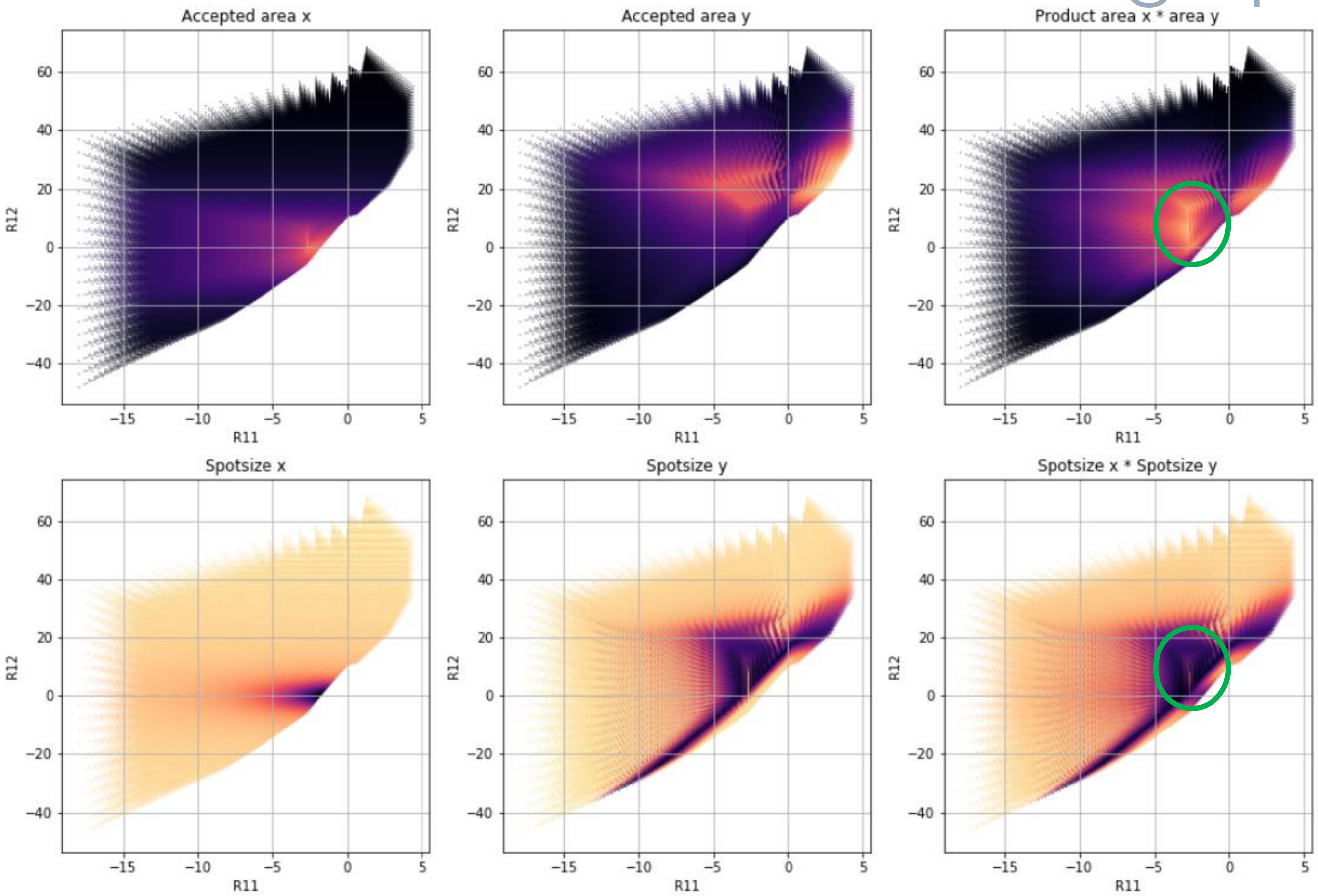
PTC



- Accepted areas of phase space, including the small features
- R-matrices: agreement to 8 decimal places

Overall this means that we can be confident in the results obtained by using this program to analyse possible beamlines

First results from new design process



Over 3 million doublets created and analysed, each dot represents a configuration.

Brighter means bigger, so want a bright spot in the top row and a dark spot in the bottom plot.

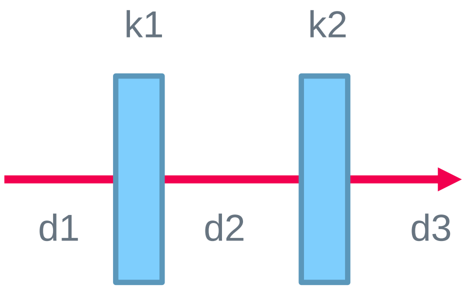
This shows the parameter region that we are interested in that can be reached with the available magnet strengths

First results from new design process

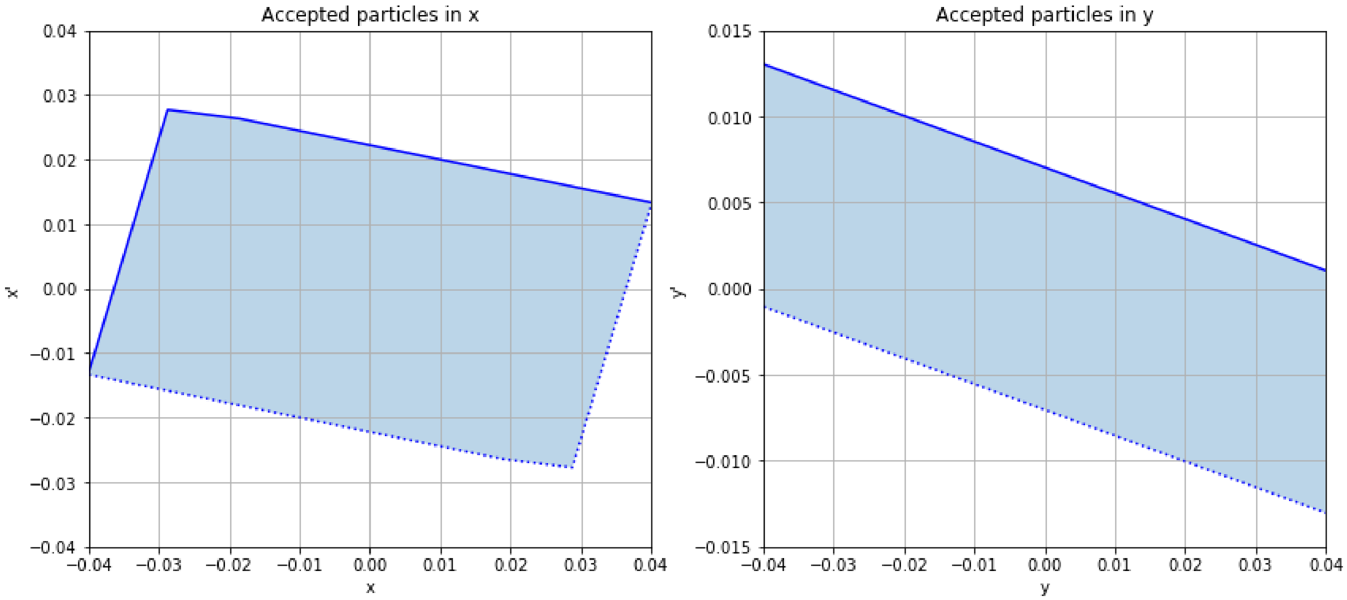
BLID	Area x	Area y	Product area	Spotsize x	Spotsize y	Product spotsize
3166800	0.003041	0.001127	0.000003	0.028379	0.025692	0.002291
3174800	0.002949	0.001147	0.000003	0.029536	0.019972	0.001853
3166801	0.002947	0.001127	0.000003	0.029238	0.024276	0.002230
2999200	0.003022	0.001097	0.000003	0.027024	0.029659	0.002518
3167200	0.003040	0.001086	0.000003	0.027317	0.025250	0.002167

The information stored in the background enables quick identification of interesting beamlines and the parameters that generated them

BLID	Magnet 1	Magnet 2	k1	k2	d1	d2	d3	Total length
3166800	QPL	QPL	0.242146	0.201694	4.502105	0.54	5.270000	14.312105
3174800	QPL	QPL	0.242146	0.211807	4.502105	0.54	5.270000	14.312105
3166801	QPL	QPL	0.242146	0.201694	4.502105	0.54	5.518947	14.561052
2999200	QPL	QPL	0.232033	0.191581	4.751053	0.54	5.270000	14.561053
3167200	QPL	QPL	0.242146	0.201694	4.751053	0.54	5.270000	14.561053



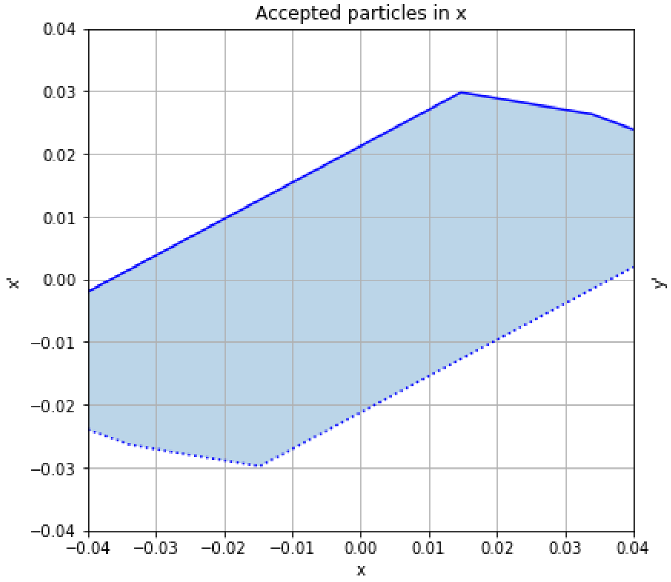
First results from new design process

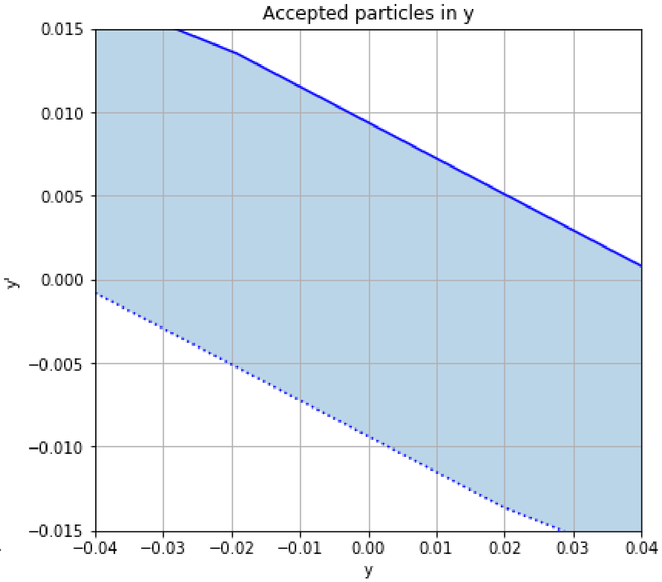



```
Phase space accepted area X: 3.04e-03
Phase space accepted area Y: 1.13e-03
```

Beamlines with spotsizes smaller than 3cm in both x and y were found. These both have larger acceptances and smaller spotsizes than what was found with the first iteration of simple matching

First results from new design process

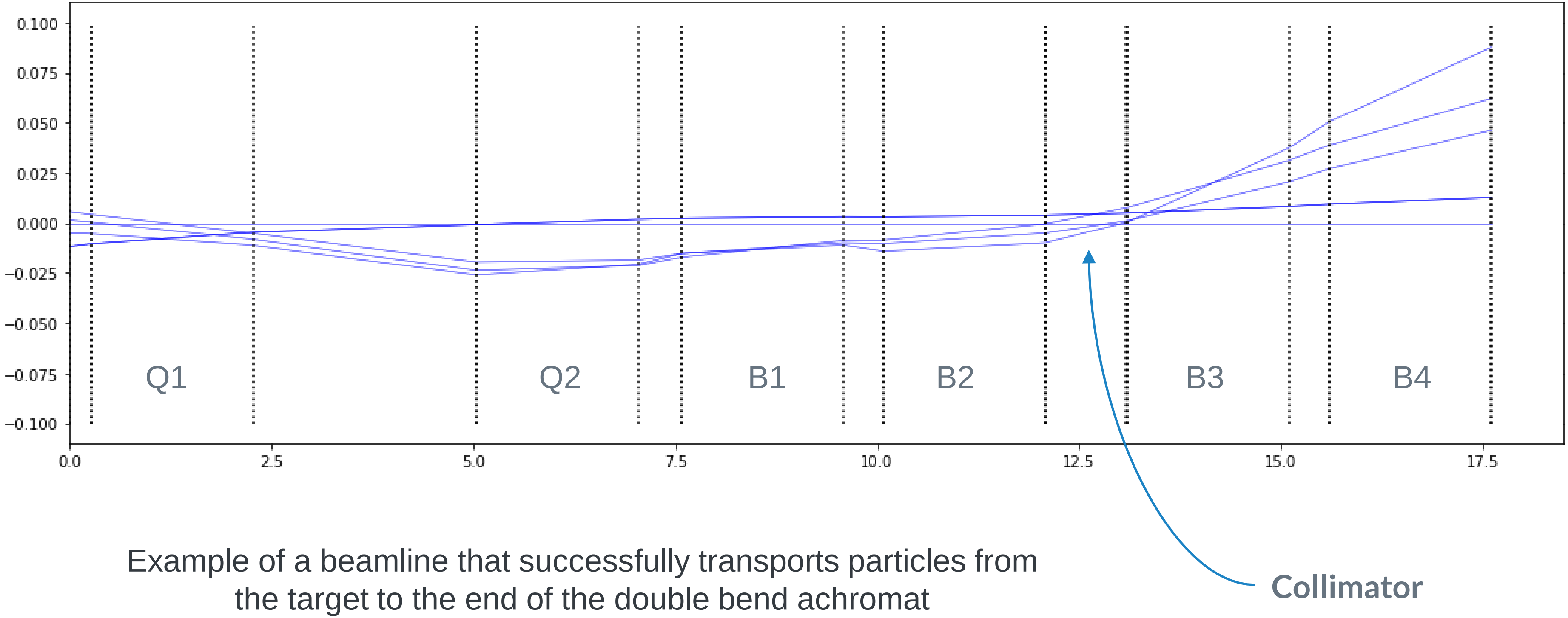





```
Phase space accepted area X: 2.90e-03
Phase space accepted area Y: 1.48e-03
```

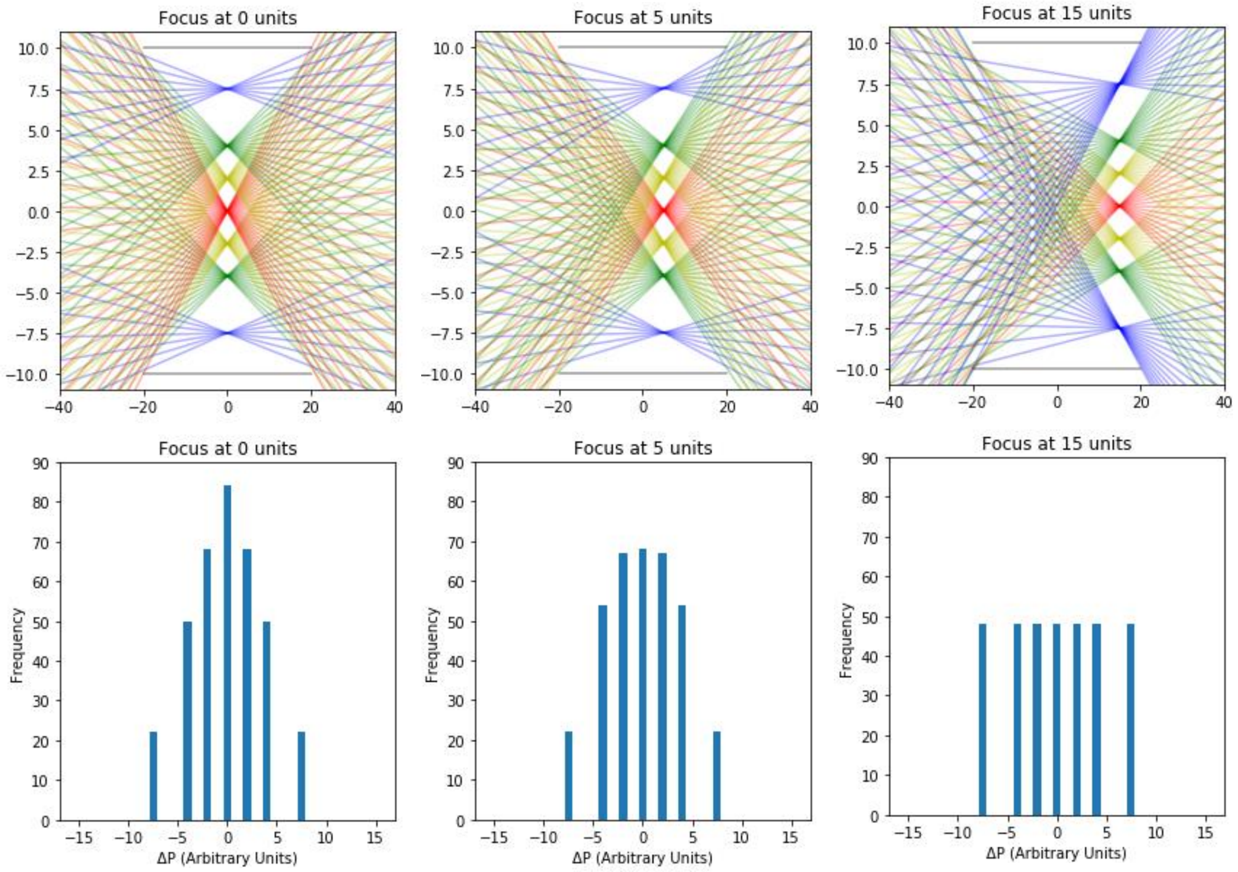
It is possible to sacrifice momentum resolution to increase acceptance. This flexibility will allow the design of a beamline that can closely match the needs of NA61 and other possible users

First results from new design process



Example of a beamline that successfully transports particles from the target to the end of the double bend achromat

Better momentum resolution



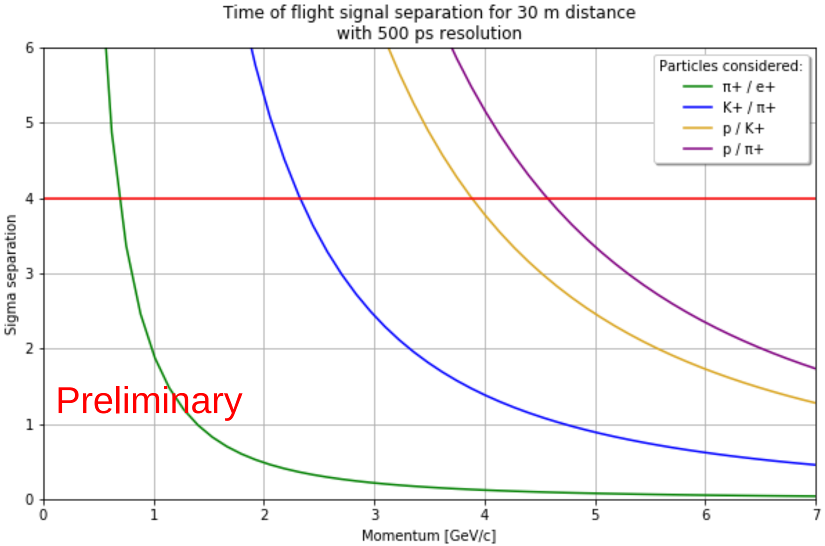
Currently in the process of changing the metric for momentum resolution to distance of focusing point from the centre of the collimator. These are functionally equivalent as measures of momentum resolution, but the distance is faster to calculate and more accurate

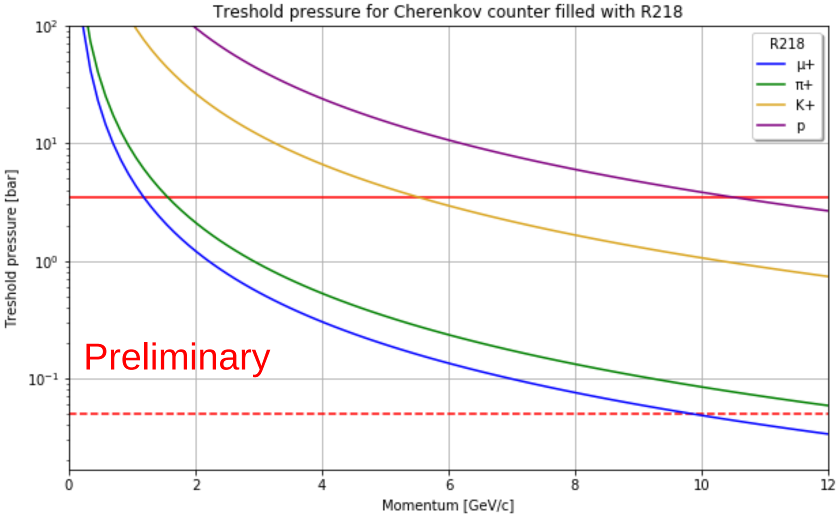
3.
INSTRUMENTATION

For tracking and particle identification

Beam instrumentation

- Particle identification across the wide energy range will be of vital importance
- Studies on possible instrumentation for the low energy beamline ongoing
- Currently considering a combination of Time of Flight for lower energies and threshold Cherenkov detectors for higher energies
- More info on instrumentation in Sakashita-san's talk





4.
IN CONCLUSION

And Future Work

Future work

- Continue investigating beamline designs aiming to maximise the acceptance, minimise beamline length and minimising cost
- While considering the various physical limitations (magnet strengths, spacing etc) and requirements (e.g. a focal point to enable momentum selection and electron suppression)
- Find correlations between parameters and acceptances, to reduce the parameter space that needs to be scanned to improve the granularity of the scan
- With the aim of having a first ‘feasible design’ in May
- Continue to investigate various options for particle identification in the beamline
- Begin background studies to assess the impact of other particles on the measurements at NA61

Conclusion

- Steady progress is being made towards the completion of the Low Energy beamline
- Preliminary targets have been chosen which optimise for different types of beams
- With the recommendation of a switching station to easily swap between these
- Beam optics are being studied with a focus on acceptance and momentum resolution
- Using a parameter scan to ensure the optimal configuration I found
- Discussions for beam instrumentation are beginning, your input on requirements would prove extremely useful

Thank you for your attention

Any questions?

EXTRA SLIDES

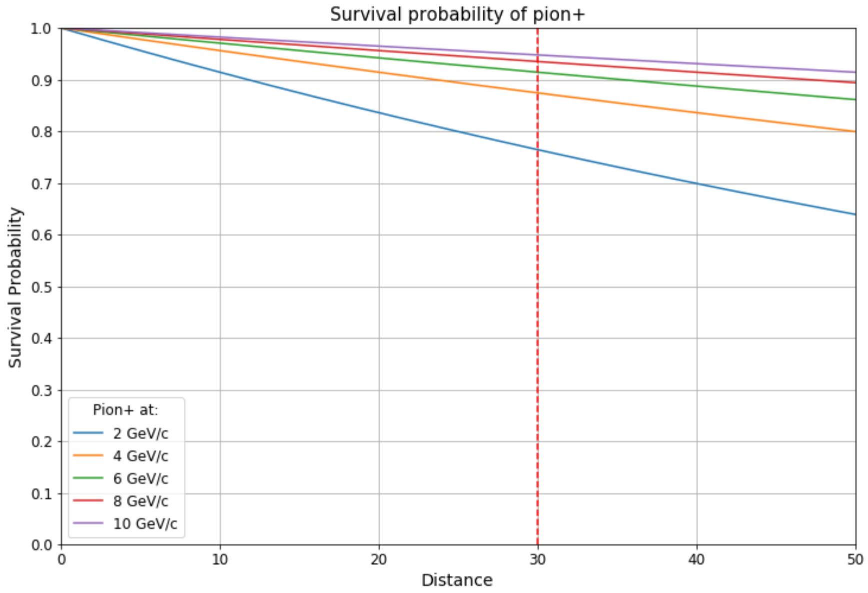
Simulation of targets

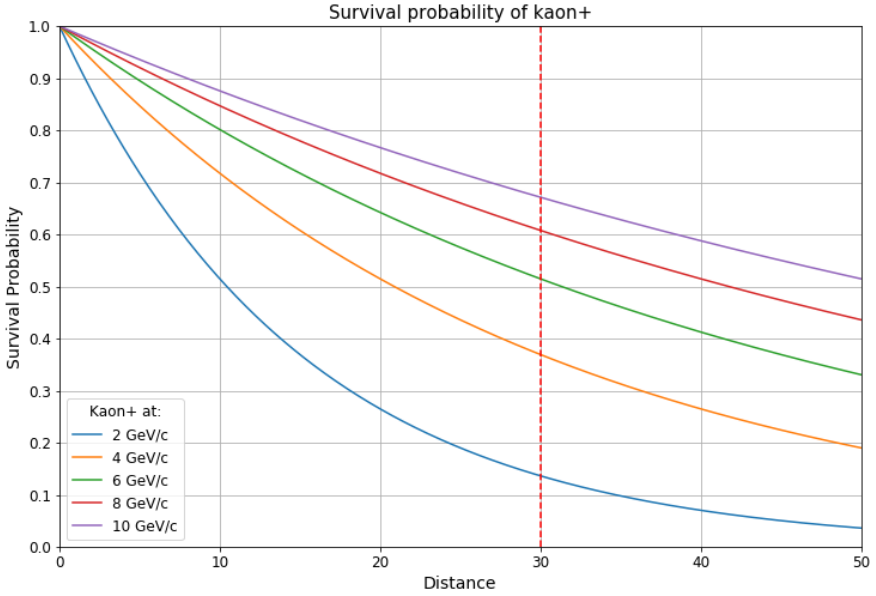
Primary protons with momenta of 40, 70,150, 240, 400 GeV/c impinging on:

- **Beryllium, Carbon, Graphite** and **Inconel** cylindrical targets (low Z)
  - With a length of 5, 10, 20, 35, 50, 80, 110, 140 cm
  - A radius of 10, 15, 20, 25, 30 mm
- **Tungsten, Gold** and **Copper** cylindrical targets (high Z)
  - With a length of 1, 3, 5, 8, 10, 12, 15, 18, 20, 25, 30 cm
  - A radius of 10, 15, 20, 25, 30 mm

All simulations with 100 000 primary protons each. In the analysis we have assumed a ±10% momentum acceptance (Δp/p) and a ±20 mrad angular acceptance ($\arctan(\frac{p_x}{p_z})$) for the low energy beam line. All plots shown in the body of the presentation also take into consideration particle decay, assuming a length of 30 m

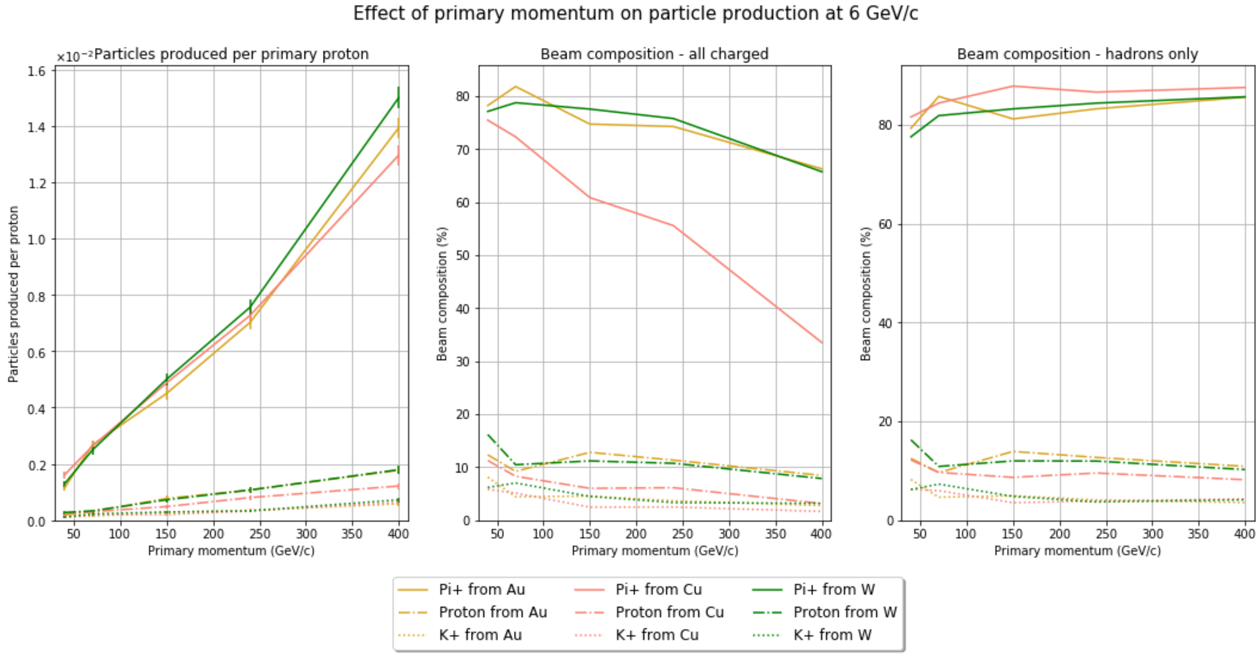
Expected survival in beamline





- With a 30 meter beamline we expect a survival of above 75% for pions at all energies
- For Kaons, we expect a survival of 13.6% @ 2 GeV/c, 36.9% @ 4 GeV/c, 51.4% @ 6 GeV/c

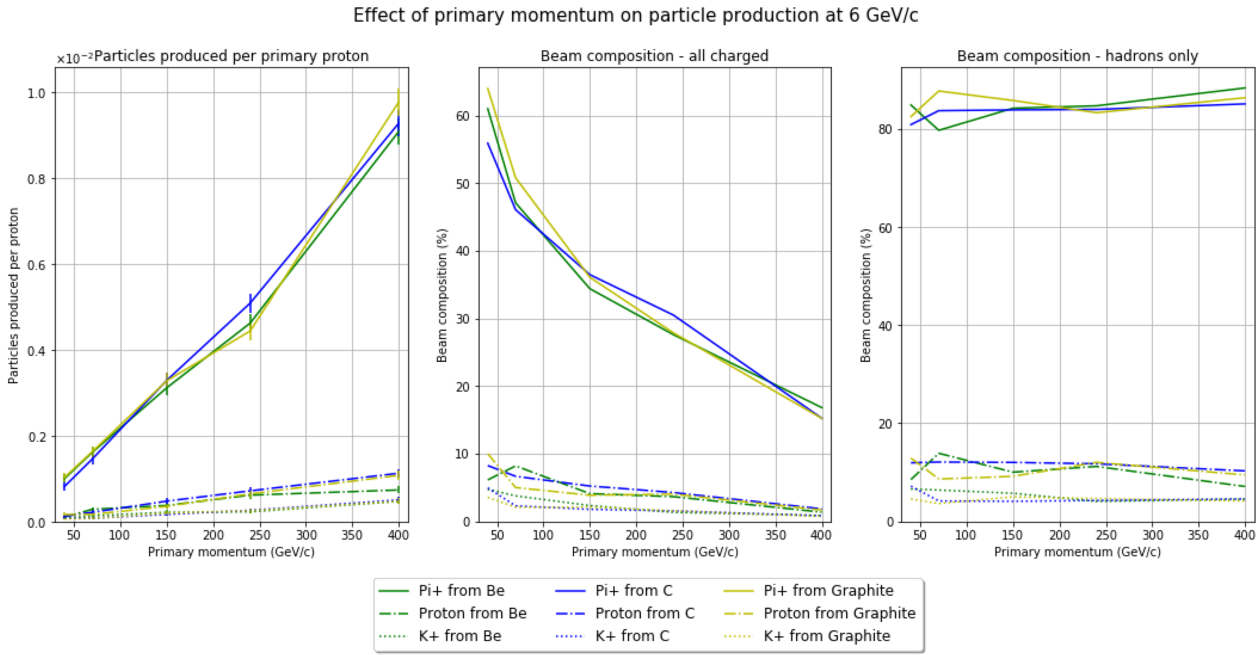
Effects of primary momentum (High Z)



Primary momentum

- Considering **a realistic** beam on 15 cm long targets
- Trade off between high particle yields and beam composition
- Electron suppression may be necessary

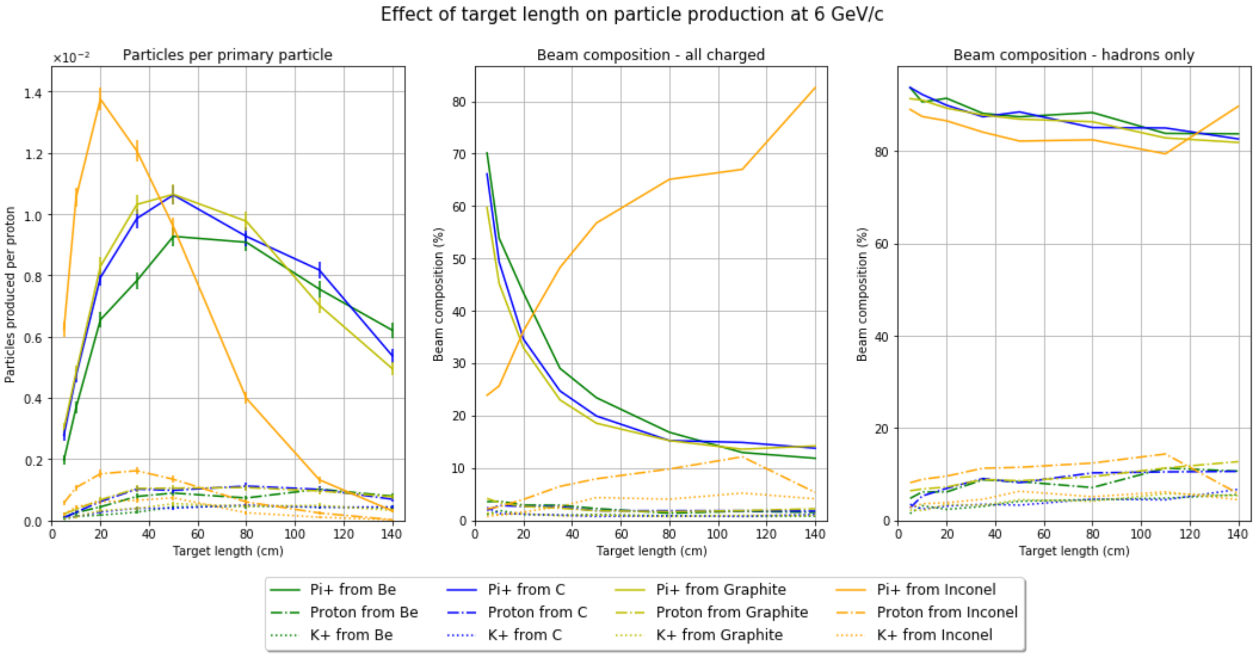
Effects of primary momentum (Low Z)



Primary momentum

- Considering **a realistic** beam on 80 cm long targets
- Trade off between high particle yields and beam composition
- Electron suppression may be necessary

Effects of length (Low Z)



Target Length

- Considering **a realistic** beam at 400 GeV/c
- Trade off between high particle yields and beam composition
- Electron suppression may be necessary

High yield target

W 20 cm 400 GeV/c beam		Yield	Composition
2 GeV/c	Pion+	363.9E-5	25.2 %
	Proton	132.0E-5	9.1 %
	Kaon+	5.6E-5	0.4 %
4 GeV/c	Pion+	847.2E-5	56.3 %
	Proton	150.0E-5	10.0%
	Kaon+	35.1E-5	2.3 %
6 GeV/c	Pion+	1359E-5	69.7 %
	Proton	204.0E-5	10.5 %
	Kaon+	63.3E-5	3.2 %
13 GeV/c	Pion+	2502E-5	81.1 %
	Proton	260.0E-5	8.4 %
	Kaon+	177.4E-5	5.8 %

In these tables:

- The yields are per proton, expecting approx. 3e9 particles per day – 3000 spills with 1e6 particles per spill
- A ±20mrad acceptance cut has been applied
- A ±10% momentum acceptance (Δp/p) cut has also been applied
- The acceptance seems reasonable and any difference may be compensated by increasing intensity on target
- Accounting the 30 m beamline length's effects on particle decays
- The composition column includes positron

Balanced target

W 30 cm 400 GeV/c beam		Yield	Composition
2 GeV/c	Pion+	207.9E-5	43.8 %
	Proton	90.0E-5	18.9 %
	Kaon+	3.1E-5	0.7 %
4 GeV/c	Pion+	472.1E-5	68.2 %
	Proton	91.0E-5	13.1 %
	Kaon+	21.1E-5	3.0 %
6 GeV/c	Pion+	649.2E-5	76.1 %
	Proton	107.0E-5	12.5 %
	Kaon+	42.2E-5	4.9 %
13 GeV/c	Pion+	1060E-5	80.8 %
	Proton	150.0E-5	11.4 %
	Kaon+	81.7E-5	6.2 %

In these tables:

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- A ±20mrad acceptance cut has been applied
- A ±10% momentum acceptance (Δp/p) cut has also been applied
- The acceptance seems reasonable and any difference may be compensated by increasing intensity on target
- Accounting the 30 m beamline length's effects on particle decays
- The composition column includes positron

High composition target

W 15 cm 70 GeV/c beam		Yield	Composition
2 GeV/c	Pion+	80.3E-5	55.2 %
	Proton	26.0E-5	17.9 %
	Kaon+	1.1E-5	0.8 %
4 GeV/c	Pion+	161.7E-5	71.0 %
	Proton	32.0E-5	14.1 %
	Kaon+	10.0E-5	4.4 %
6 GeV/c	Pion+	248.7E-5	78.7 %
	Proton	33.0E-5	10.4 %
	Kaon+	22.1E-5	7.0 %
13 GeV/c	Pion+	369.47E-5	79.8 %
	Proton	43.0E-5	9.3 %
	Kaon+	49.3E-5	10.7 %

In these tables:

- The yields are per proton, expecting approx. 3e9 particles per day – 3000 spills with 1e6 particles per spill
- A ±20mrad acceptance cut has been applied
- A ±10% momentum acceptance (Δp/p) cut has also been applied
- The acceptance seems reasonable and any difference may be compensated by increasing intensity on target
- Accounting the 30 m beamline length's effects on particle decays
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Limitations of the classic method

- Starting assumptions (eg. point like target) do not closely describy the starting conditions of our beamline
- Without having these starting assumptions it is unclear what to match for to minimise the spotsize at the end of the beamline
- Even if we could find a beamline that minimses the spotsize, the acceptance of the beamline will not be maximised, so we may be losing a significant portion of particles compared to another configuration
- So overall there is no guarantee that you find a beamline that is optimal in any way
- Furthermore, it is highly dependant on numerical methods and may converge to different results

Overall there are limits of the conventional approach for such a low energy beam, due to the characteristics of the target production phase space, so a new way to design beamlines may prove to be valuable