# Overview of piE5 Beamline

Peter Kammel

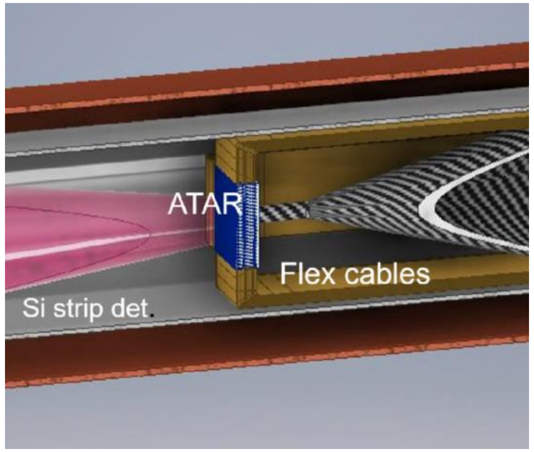
- Intro
- Test beam 2022 results
- Modelling the beamline
- Major upgrade studies

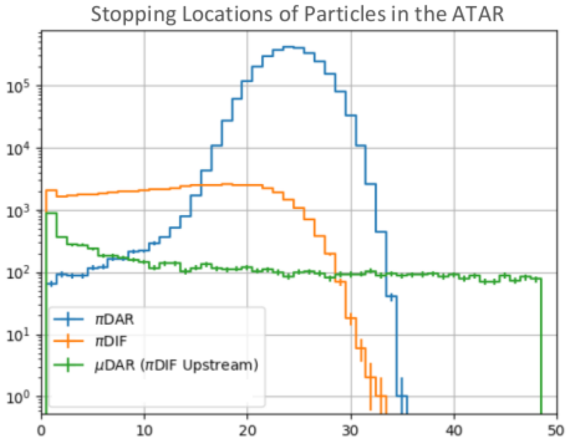
# Requirements Phase I

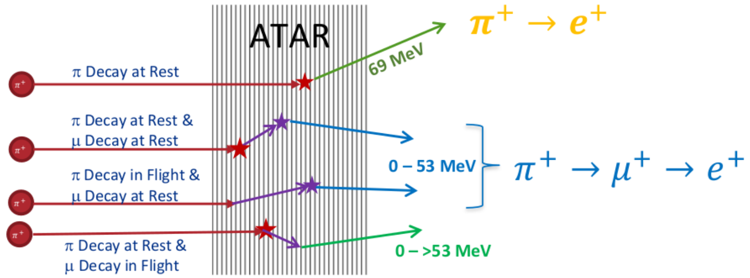
- Rate
  - 300k π/s stopped in ATAR

$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

- Momentum bite
  - $\Delta p/p < 2\%$
- Momentum
  - lowest p preferred 55-70 MeV/c
- Spot size
  - smaller than ATAR Size of 20mm x 20mm
- Particle contamination
  - μ/e less than 10% of π



# Requirements and achieved results from test run

- Rate 300k π/s stopped in ATAR
  Momentum lowest p preferred 55-70 MeV/c — ok at 65 MeV/c
- Momentum bite $\Delta p/p < 2\%$ — Probably not,
  requires more data analysis/beam modeling
- Spot size smaller than ATAR — No, difficult,
  requires beam design and modeling
  experimental design, active collimation
- Particle contamination μ/e less than 10% — Not yet, requires additional magnets,
  beam modeling and design

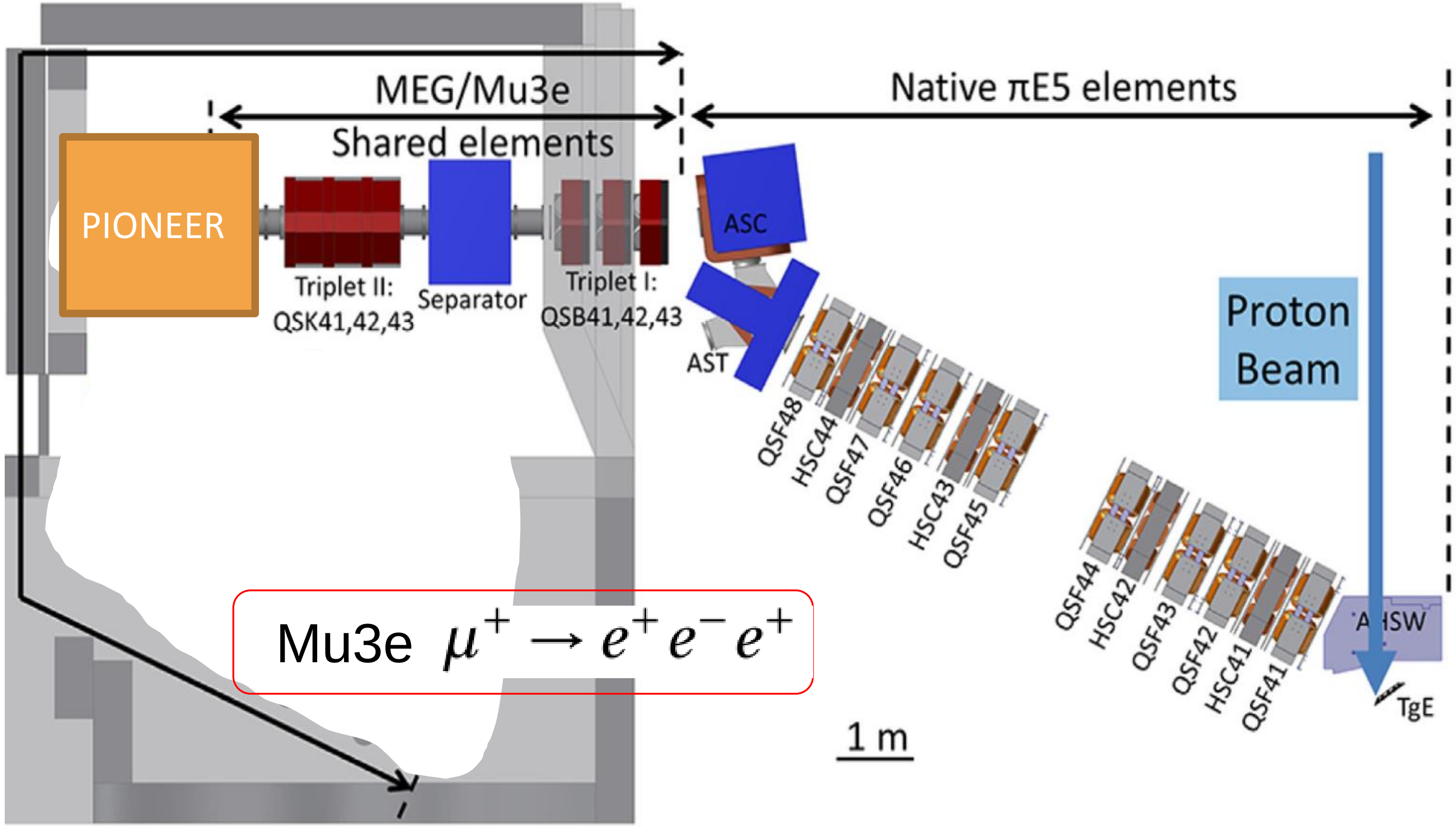
## Take away

- Serious effort and resources for beam team required, beam design and simulation
- Student can make a big difference, see Stefan's phase space analysis
- New machine learning approach, very promising
  but additional beam design effort required

# piE5 @ PSI - World's Brightest Stopped Pion Beam

MEG $\mu^+ \rightarrow e\gamma$

| Main properties of $\pi$E5 beam line | | |
|---|---|---|
| Solid angle | | 150 msr |
| Momentum range | | 10-120 MeV/c |
| Length | | ~~10.4 m~~ |
| Momentun | acceptance (FWHM) | 10% |
| | resolution (FWHM) | 2% |
| Angular divergence (FWHM) | horizontal | 450 mrad |
| | vertical | 120 mrad |
| Spot size (FWHM) | horizontal | 15 mm |
| | vertical | 20 mm |




- carefully studied for fundamental muon experiments
- still surprises for pions, unique PIONEER requirements

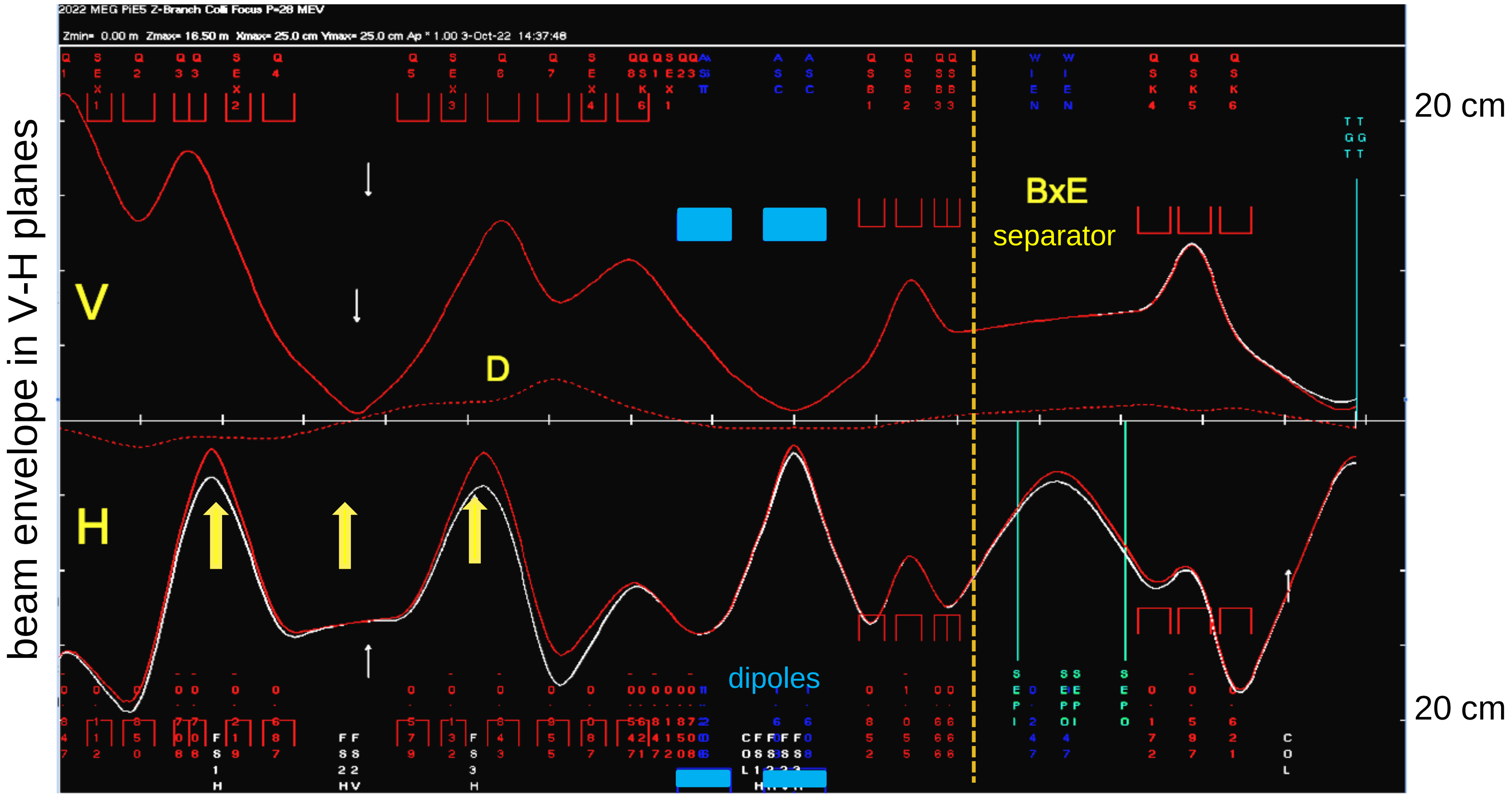
experimenters have full control over beam line (after first bend)

# Simple Transport Model

- Compare $\Delta p/p$= 3/0 %
- 1st order only
  - 2nd order diverges
  - other discrepancies to PIONEER Run ‘22
- upstream part in shielding
  - indirect diagnostics with slits

$\pi^+$

MEG tune adjusted to PIONEER geometry, P-R Kettle

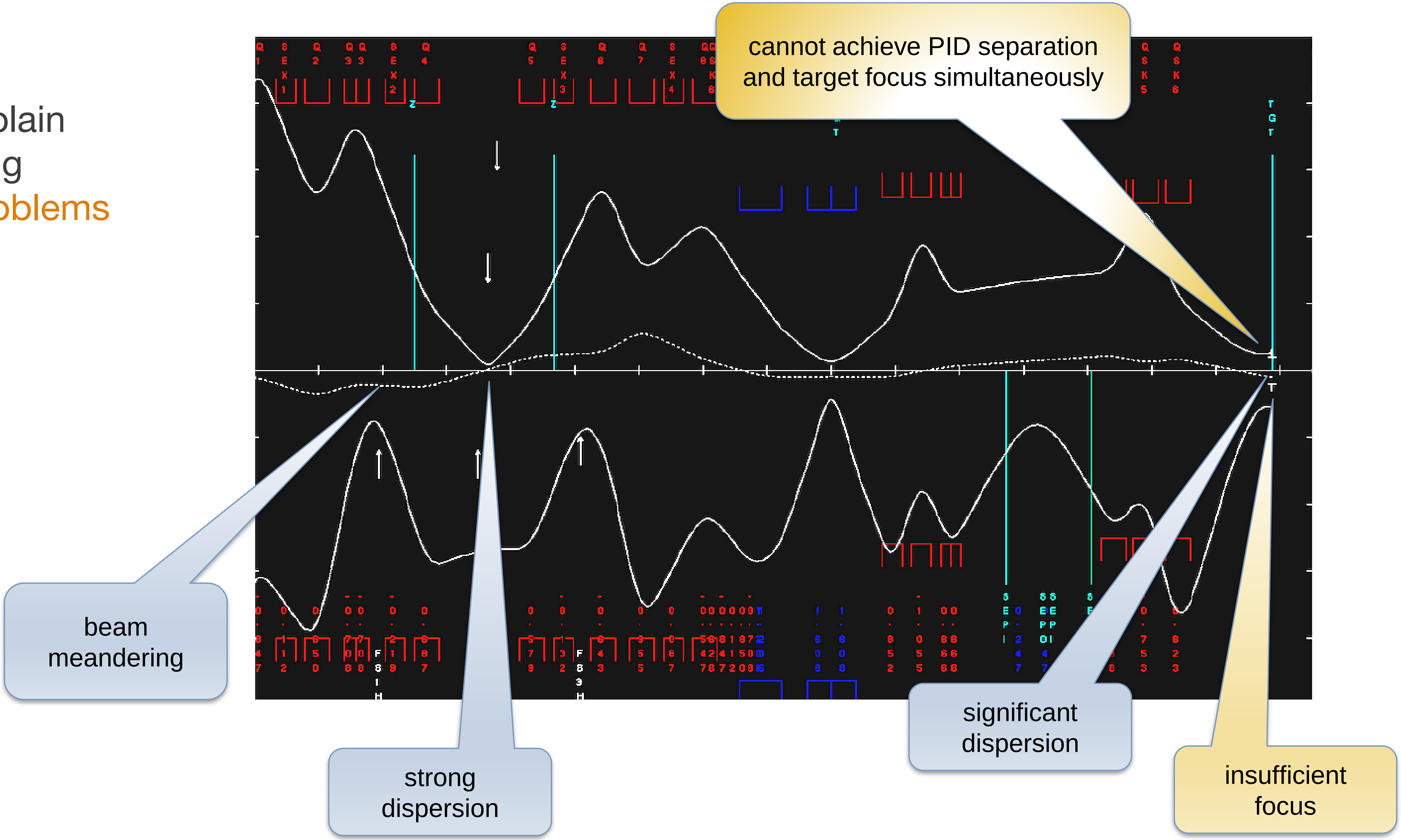



extraction, momentum selection and achromat

particle separation, focus on target

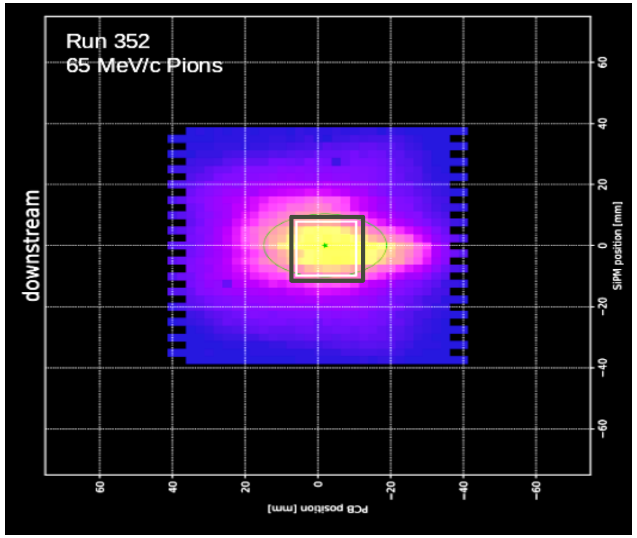
# Puzzles from beam test

- Explore/explain most striking puzzles, problems



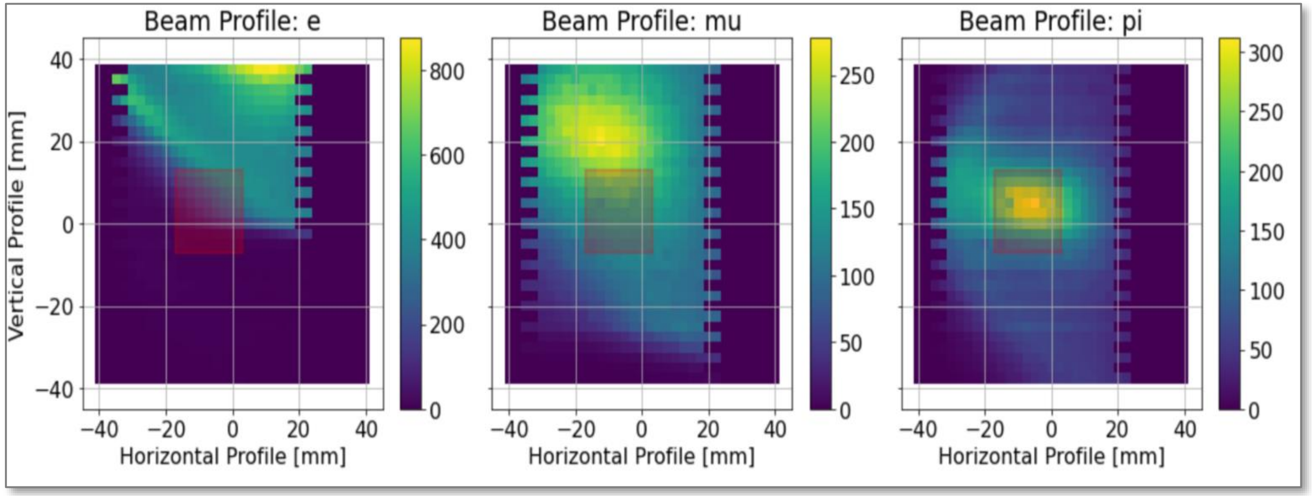
# Summary of findings

- Final focus

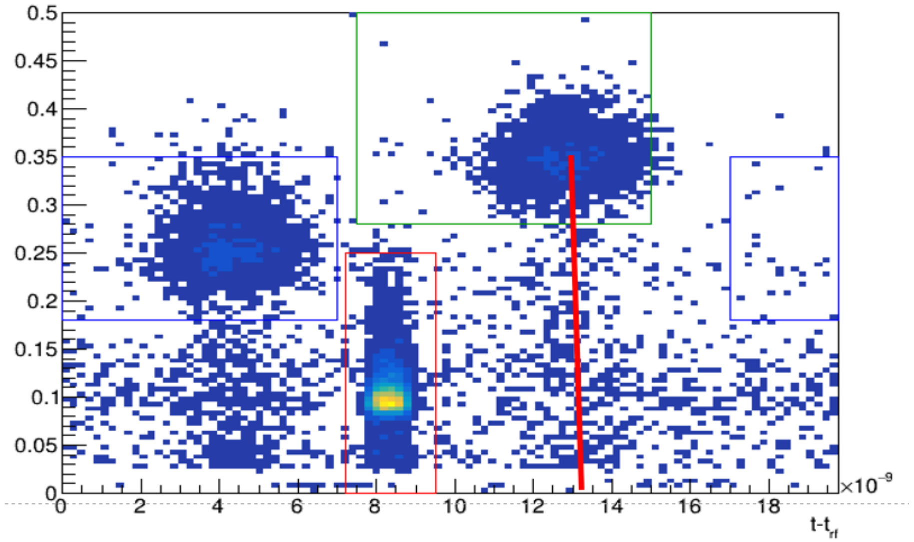



- Rate: 633 kH / 46 % in ATAR Box
- Mean X = 0.3 mm
- Mean Y = 0.2 mm
- Sig X = 23 mm
- Sig Y = 10.1 mm

- PID




- Dispersion? at target

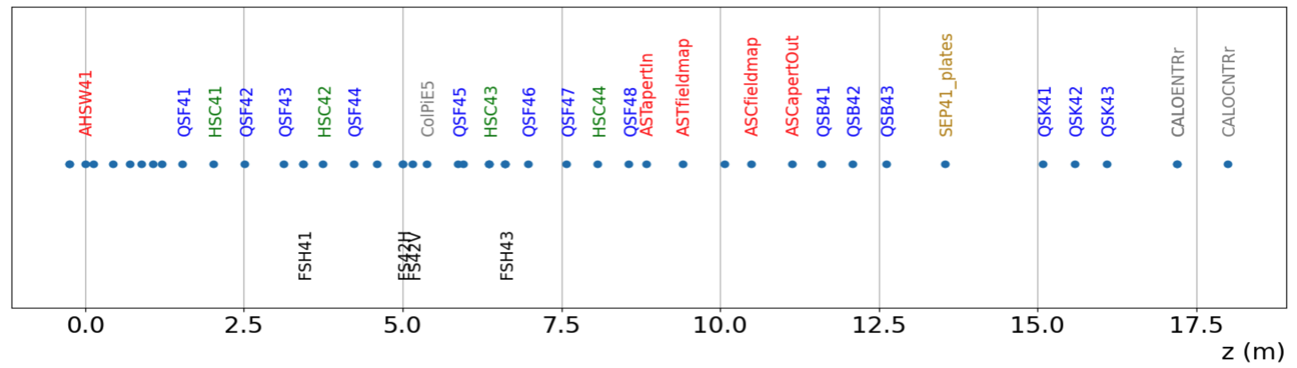



- Δp/p two methods
  - TOF
    - 16m beamline
    - 1% Δp/p ~ 1 ns (65 MeV/c)
  - Direct stopping measurement with range curve
    - pion signal amplitudes with different degraders
    - use π→ μ sequence to identity stops

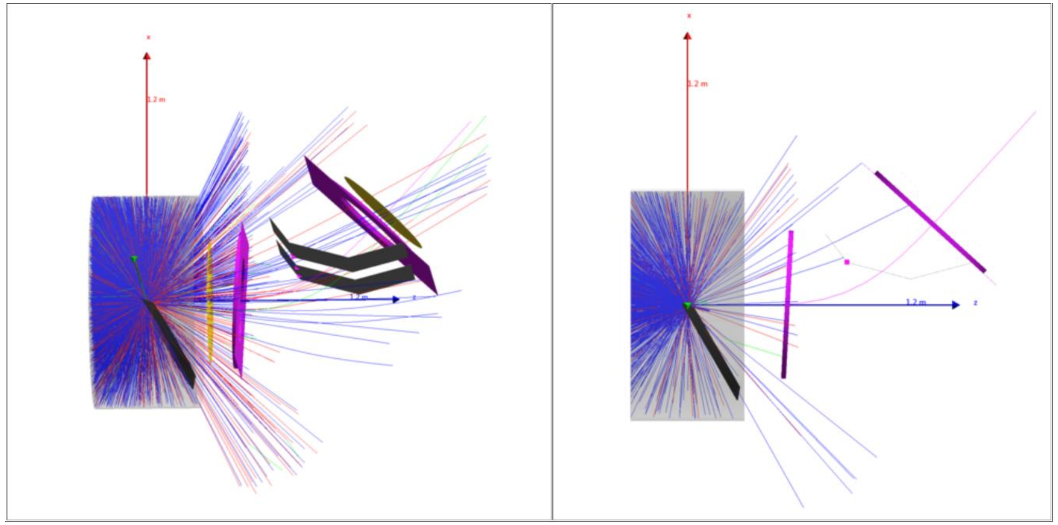
analysis needed

# G4BL steps

More resource links in backup

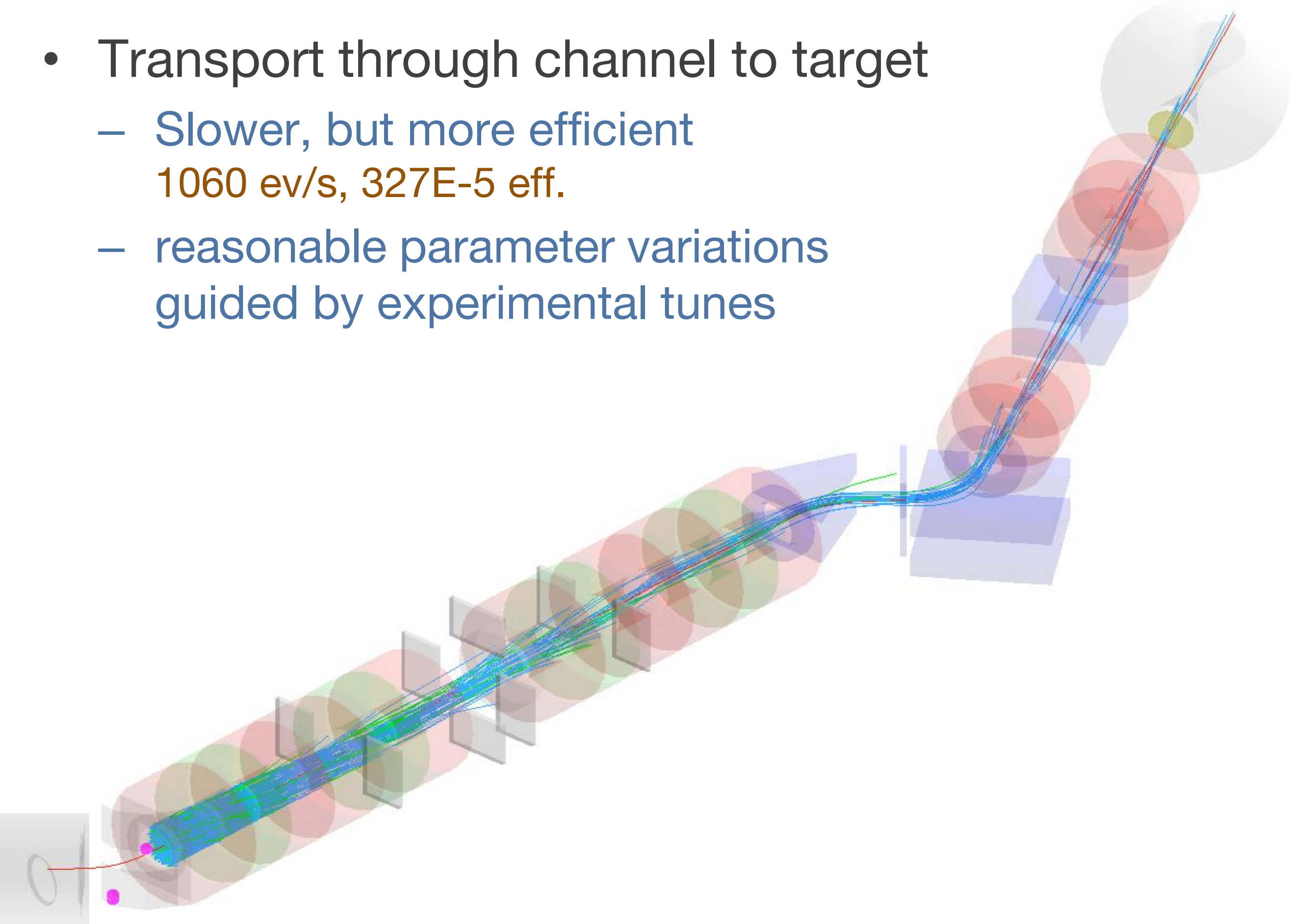



- Production



  - brute force high-statistics runs of (inefficient) pion production
    25k ev/s, but only 3E-5 eff.
  - phase space stored at virtual plane before first piE5 quad

- Transport through channel to target
  - Slower, but more efficient
    1060 ev/s, 327E-5 eff.
  - reasonable parameter variations guided by experimental tunes



# Initial studies, January 2023

## Global properties

twiss and sigma

- twiss_mu3e_pion
- twiss orig_mu3e
- sigma mu3e_pion

## Histograms (all 65 MeV/c)

Tune Mu3e_22, HSC42 off MeV/c

- all vs pi
- pi vs pi_end

Pioneer_65 MeV/c

- all vs pi
- pi vs pi_end

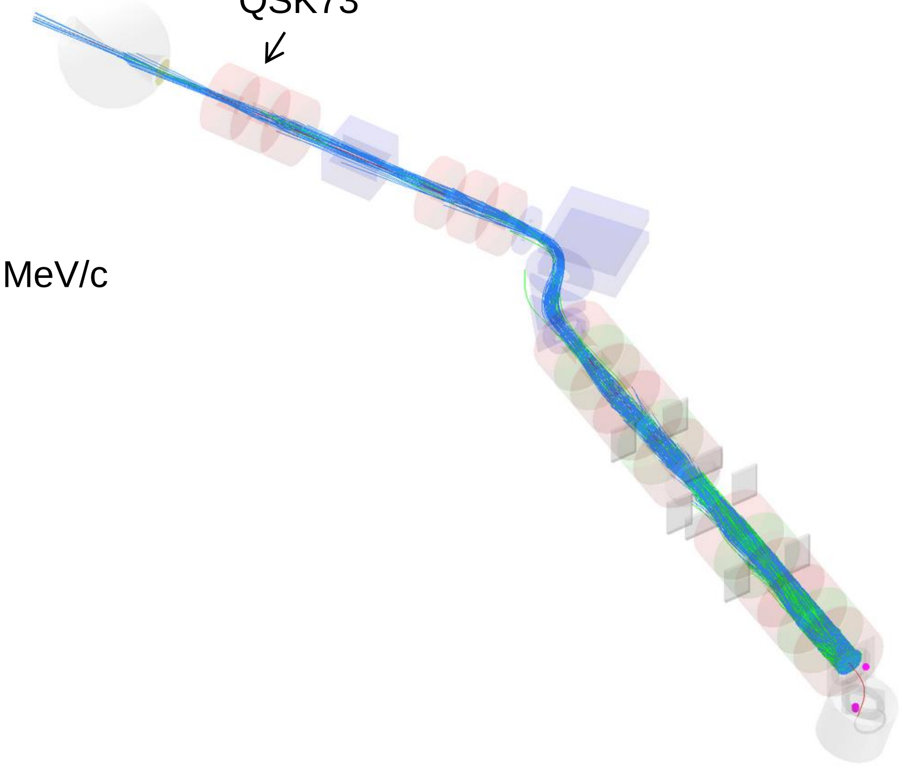
Pioneer_22 vs Mu3e_22

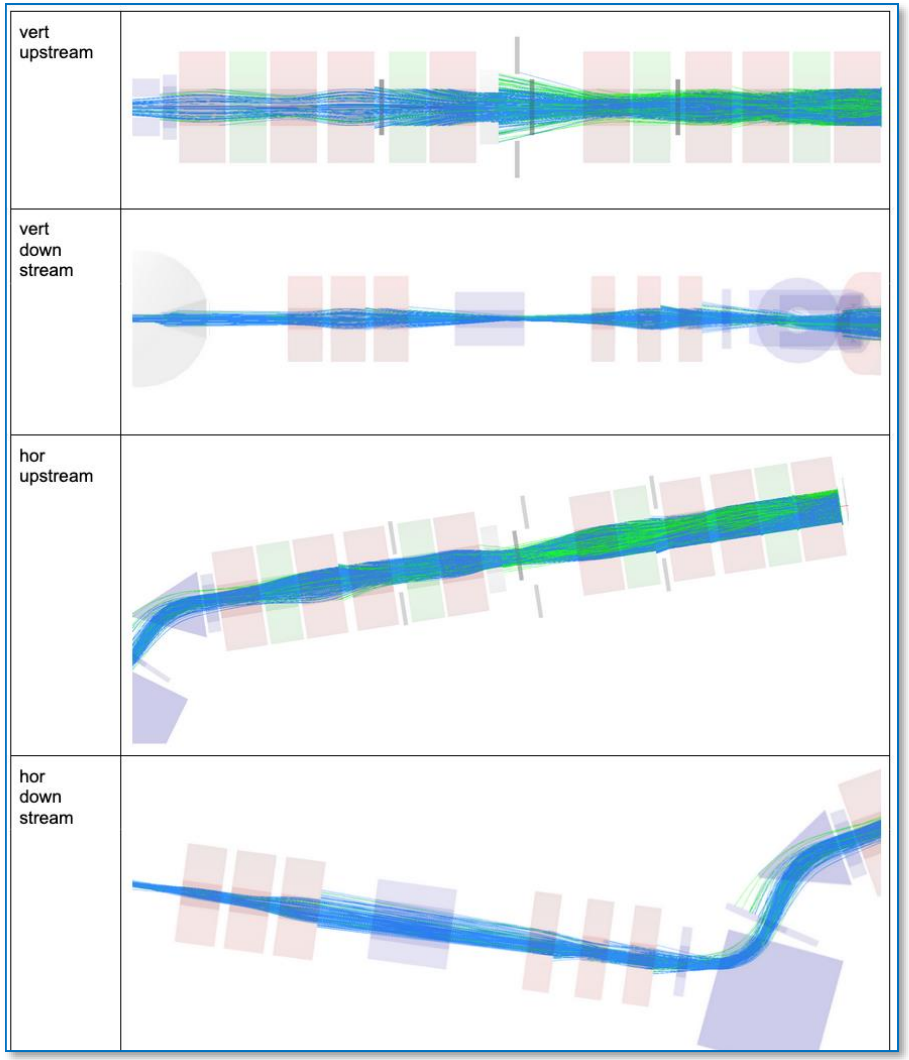
- pi
- pi_end

Orig_18 vs Mu3e_22

- pi
- pi_end

end QSK73



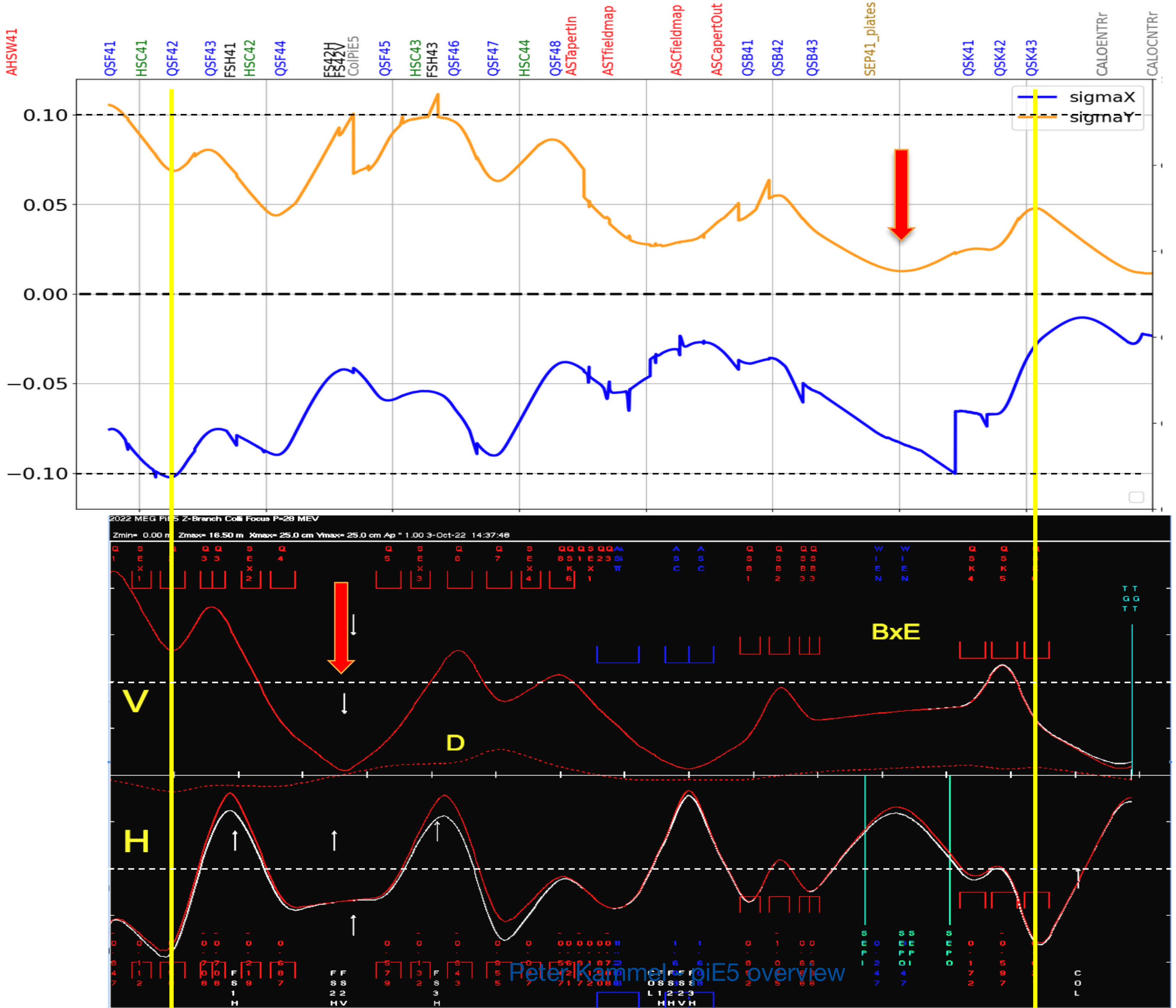



no strange beam effects a'la Zack

# Global properties: Envelopes

G4BL

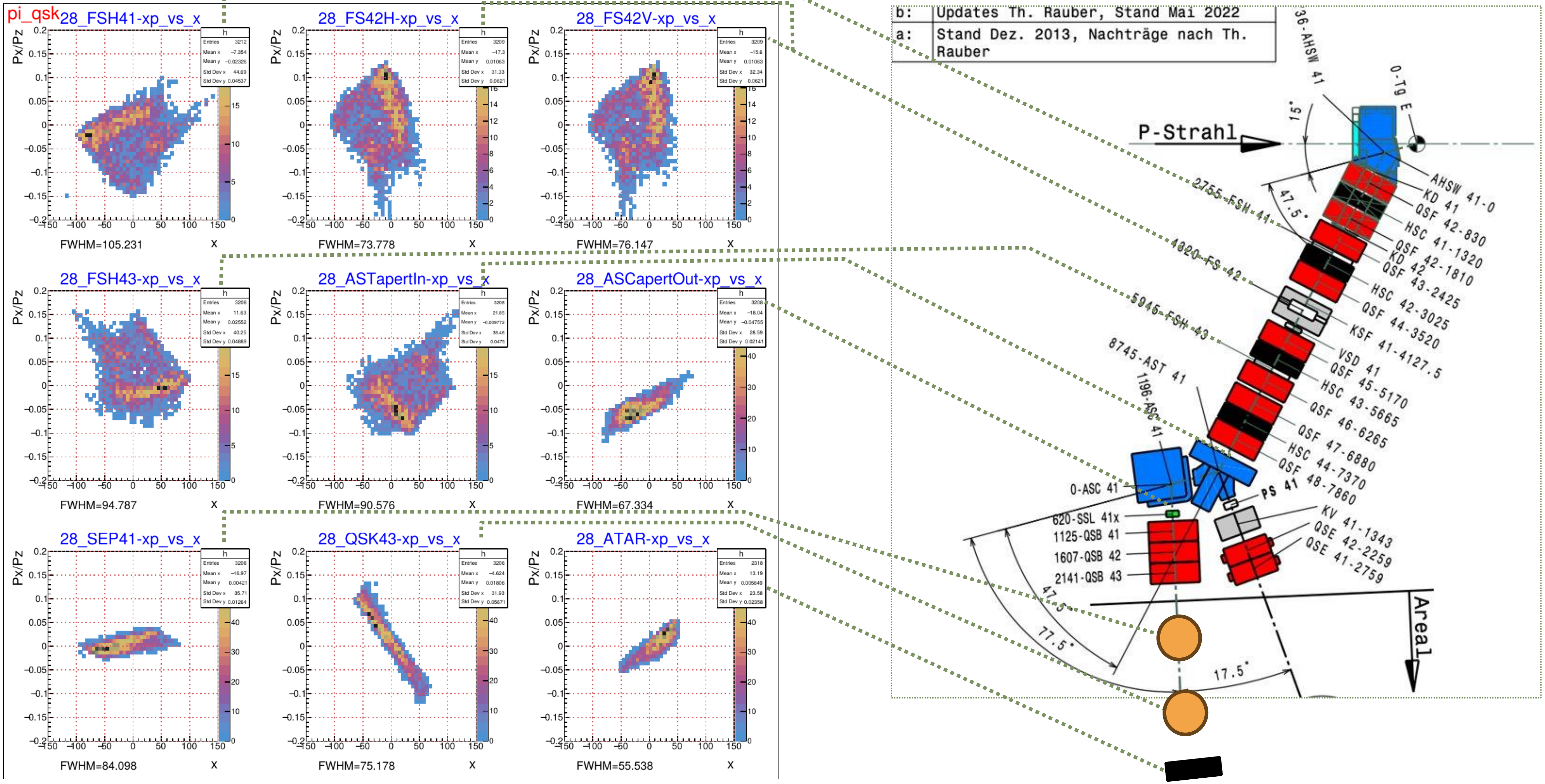
TRANSPORT



# Higher order effects: X vs X'

very preliminary

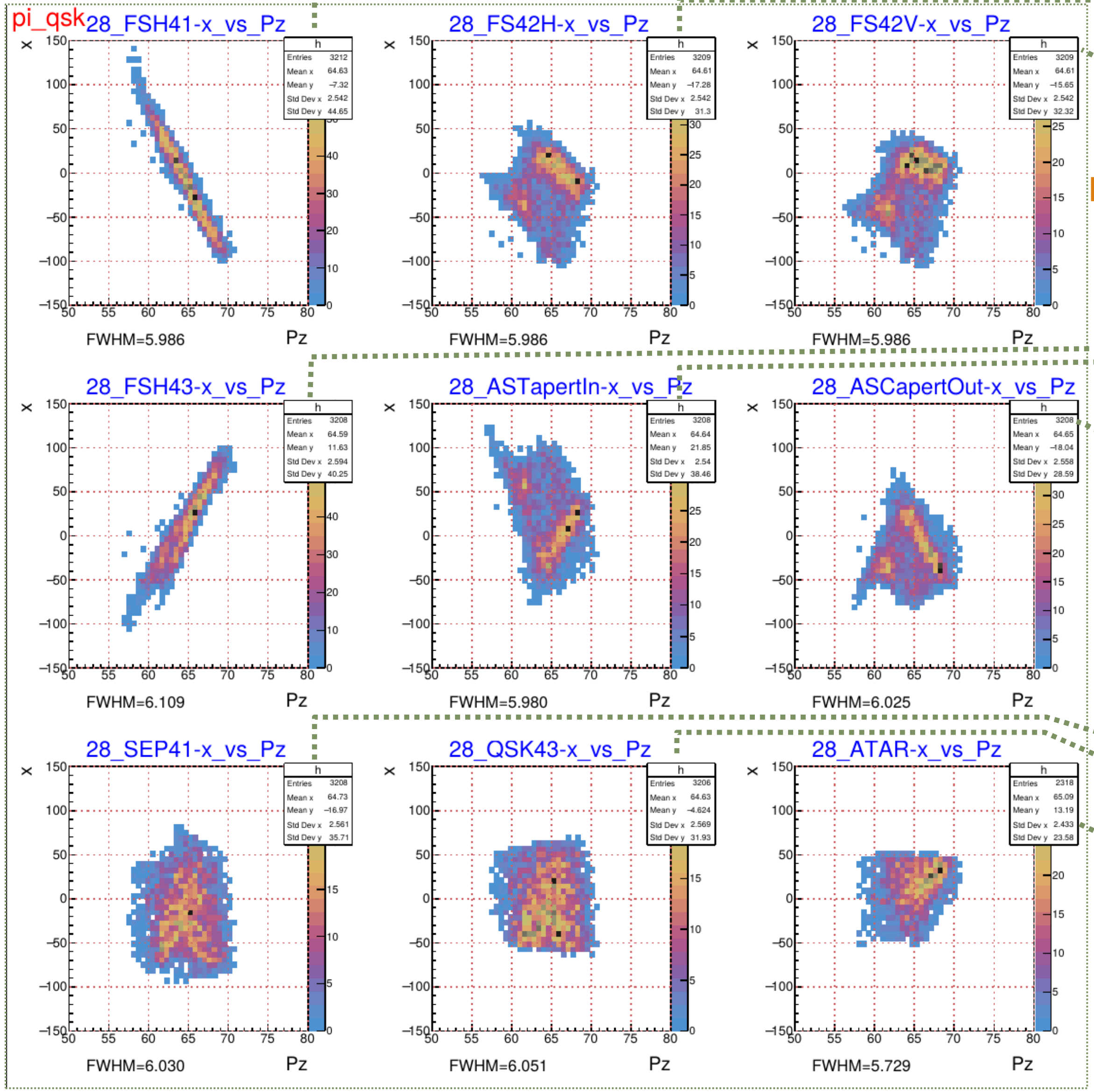
π to target cut



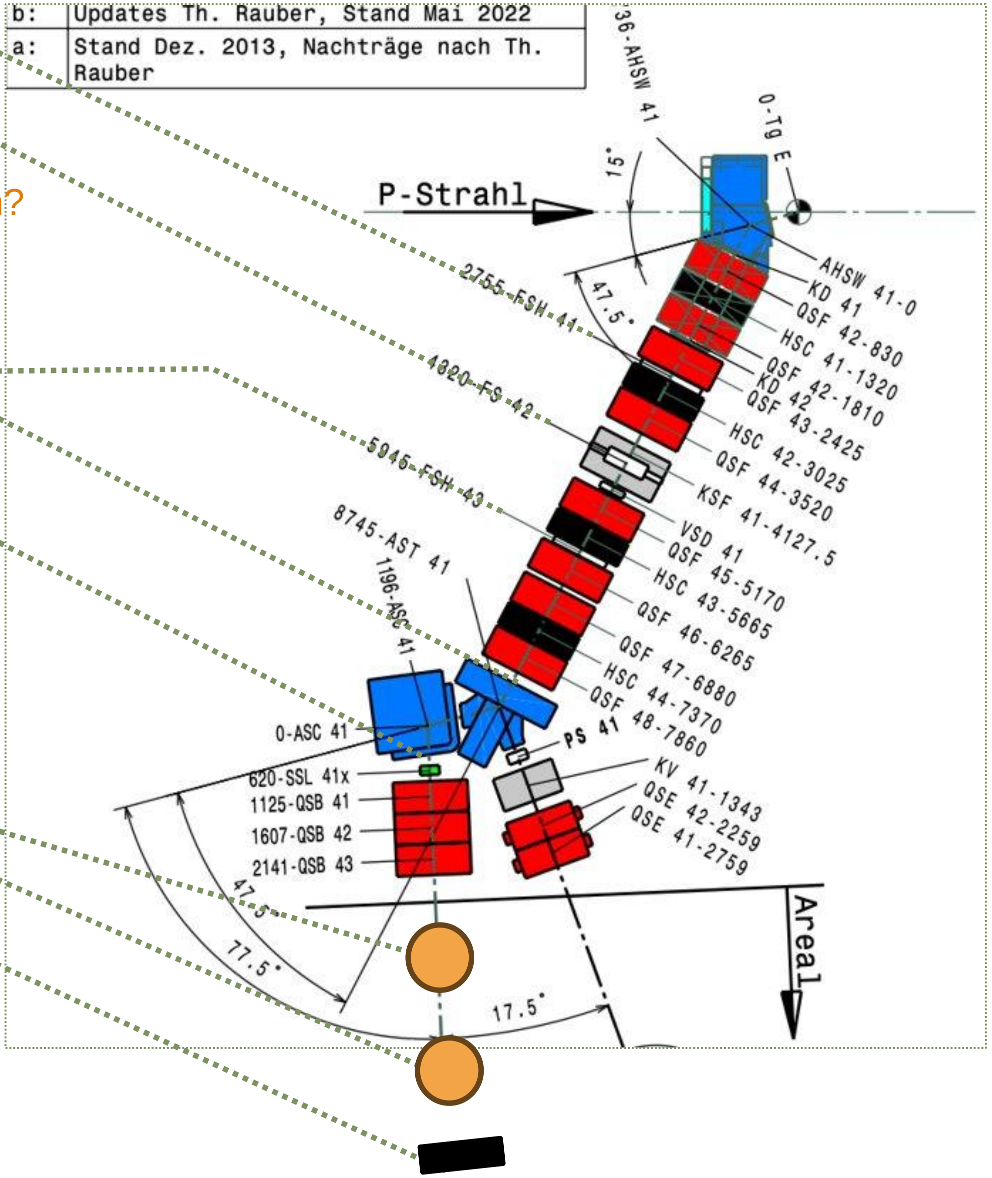
# Higher order effects: X vs $P_z$

π to target cut

very preliminary



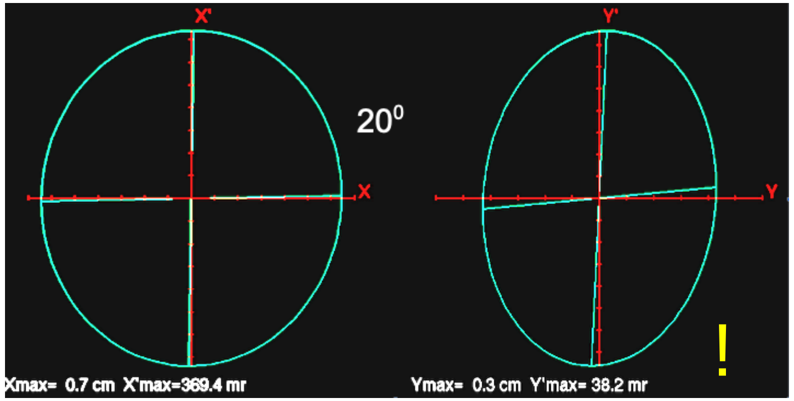

Dispersion?

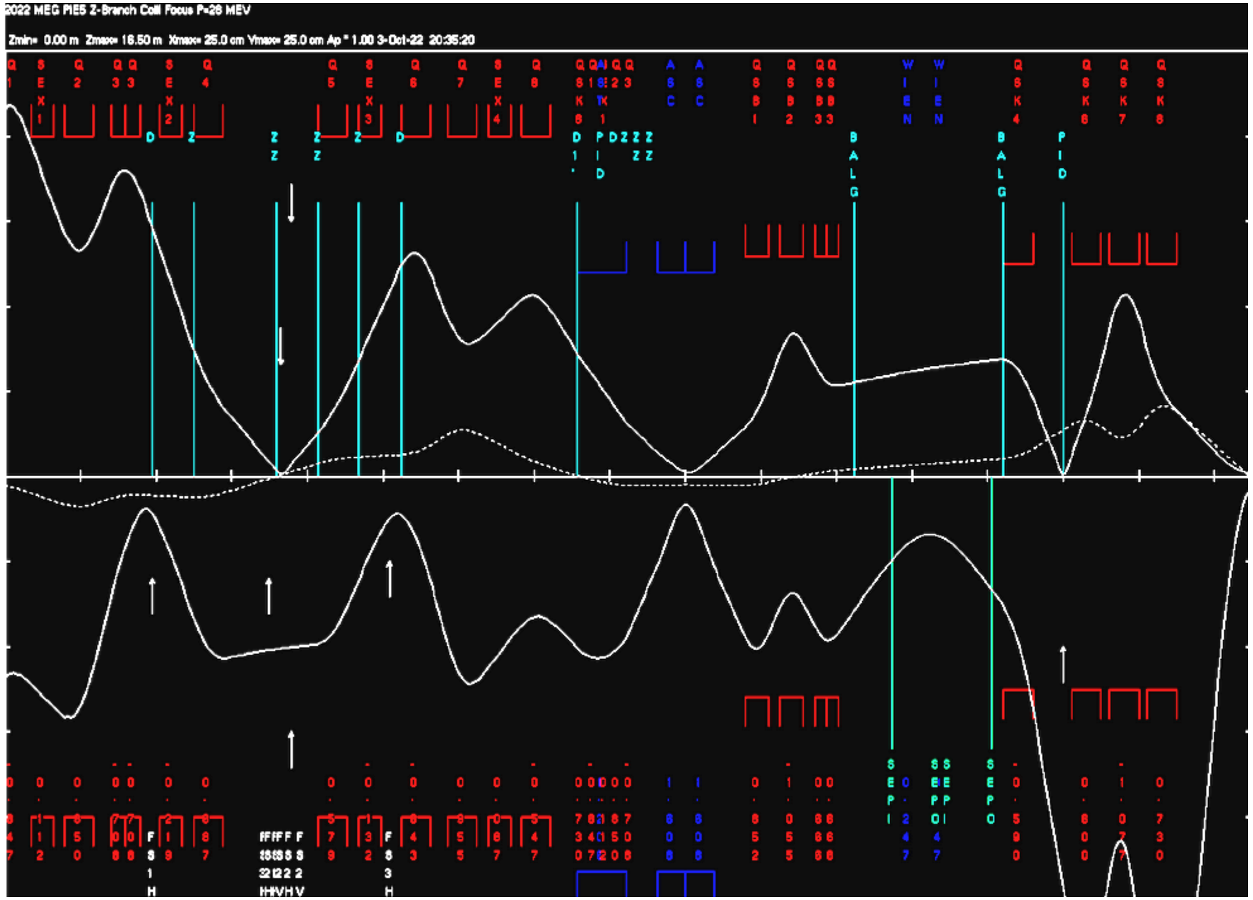


# Major upgrade: Extend Beam with Two Vertical Foci

- For particle separation and target focus two separate foci required, so that background is rejected outside of detector
  - 1st focus separates particles after ExB velocity filter and reject μ and e on collimator
  - 2nd focus is a double x/y focus aimed at ATAR

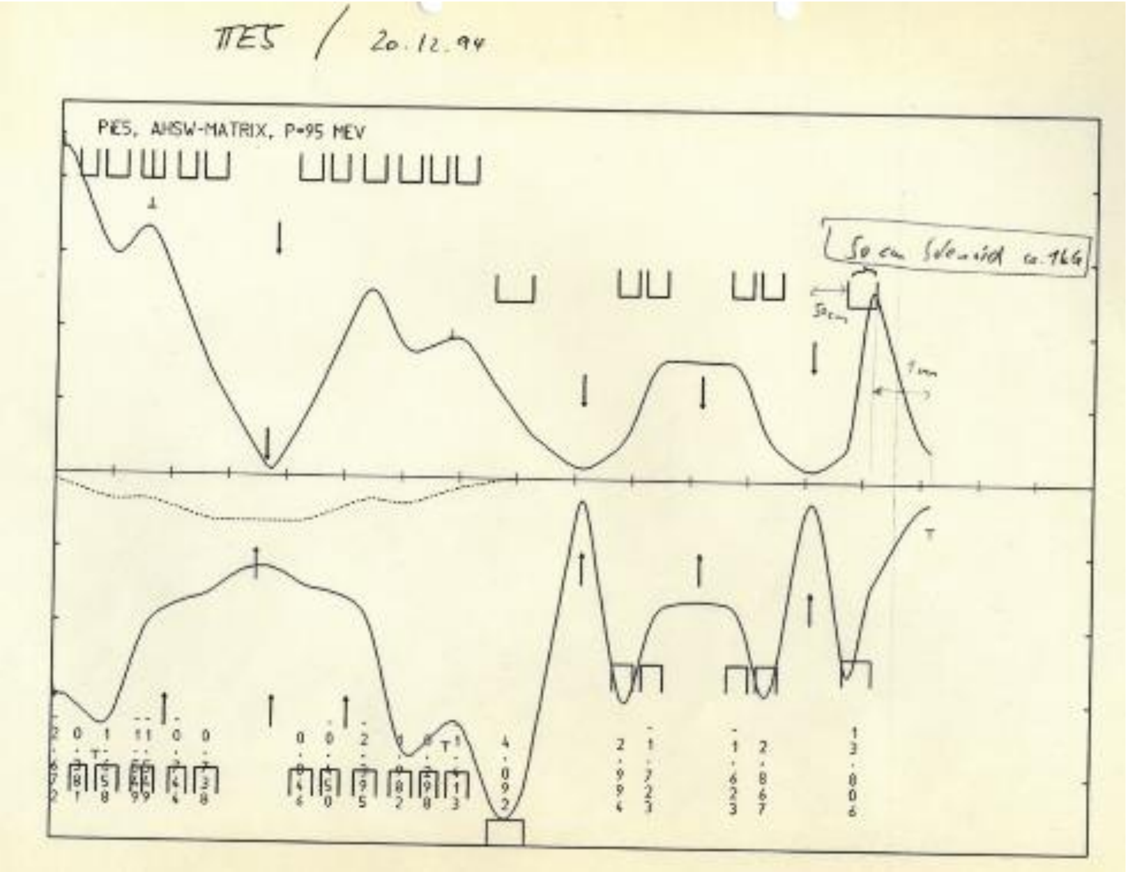
- First attempt with s-t promising
  - large final magnet
  - phase space
    - initial x: 2.40 π mm r
      y: 0.09 π mm r
    - promising final focus

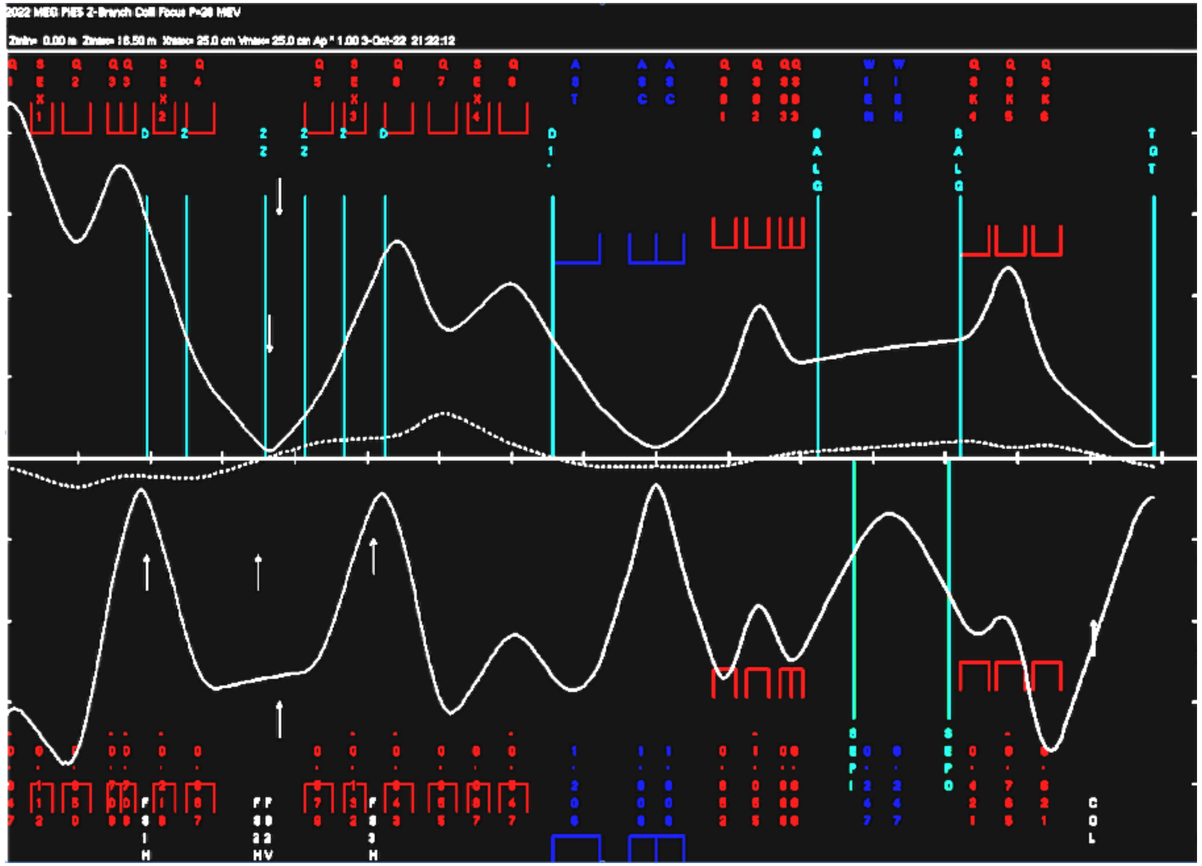


# Upgrade: Smaller Momentum Bite

exercise in history



# Beam Development Plan

- Higher order calculations and corrections
  - modern programs: G4BL,COSY
  - more careful G4BL
    - are non-linear effects **correct** and **real**?
- Beamline
  - downstream
    - easier as more accessible
    - measure phase space right after bends
    - Based on PIONEER run '22, we cannot improve quality with downstream tuning alone
  - upstream (Andy et al)
    - systematic **simulation** campaign
    - systematic **measurement** campaign to verify simulation and magnet characteristics
  - phase space measurements need large tracker

- Run analysis
  of low hanging ? fruits
  - Δp/p
  - dispersion dependencies

- Major upgrade studies
  needs beam designer
  - **Two vertical foci**
  - Large final magnet for small focus?
  - upstream retune for large dispersion
  - dE/dx π/μ/e separation?

# Backup

- 10/14/2023 1:25 PM

# G4BL overview

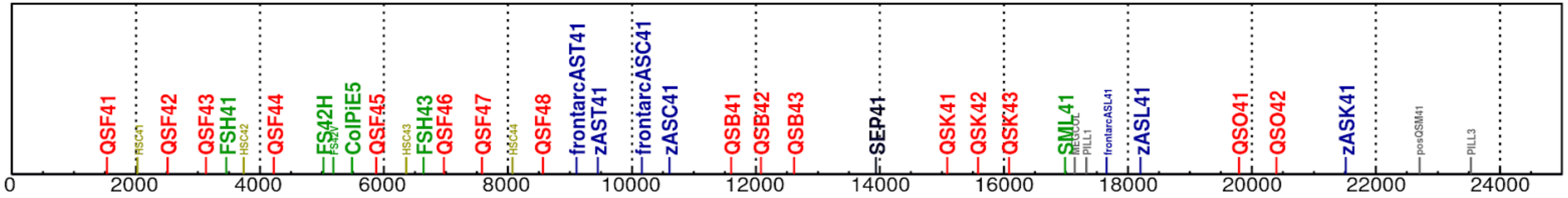
## Resource links

- Urs
- displays
- production

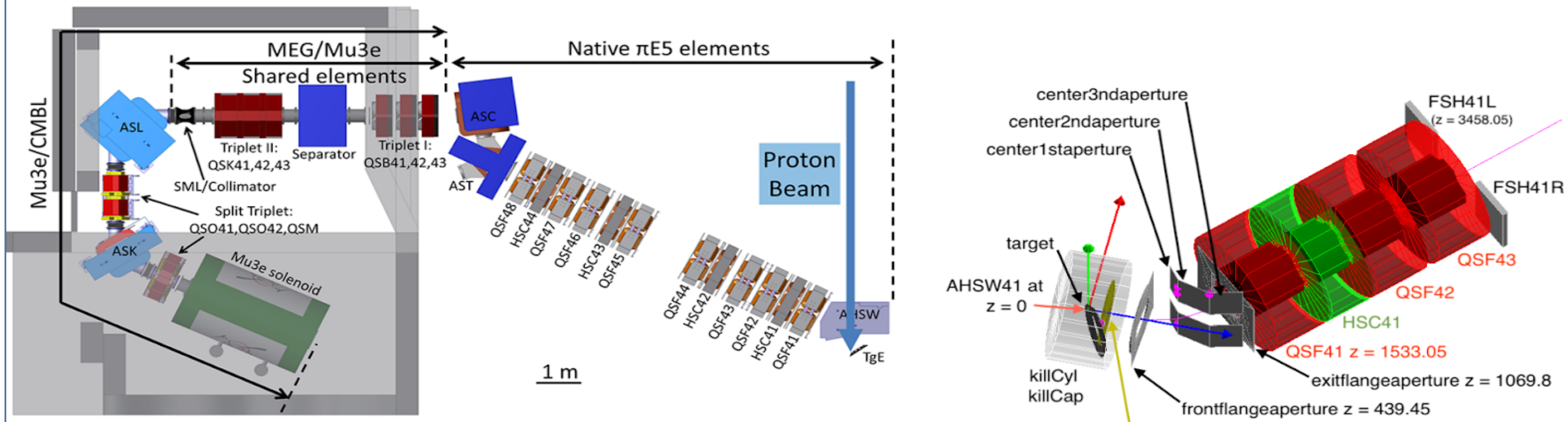
## Status

- complete model based on previous PSI work
- Repo of input field maps
- Reconstructed different historical I to B translations
- see beam team TWiki

- Beamline positions (g4bl)
  - AHSW (center) at $z = 0\,\mathrm{mm}$, (but) TargetCone at $z = 112.5\,\mathrm{mm}$




- Beamline illustrations

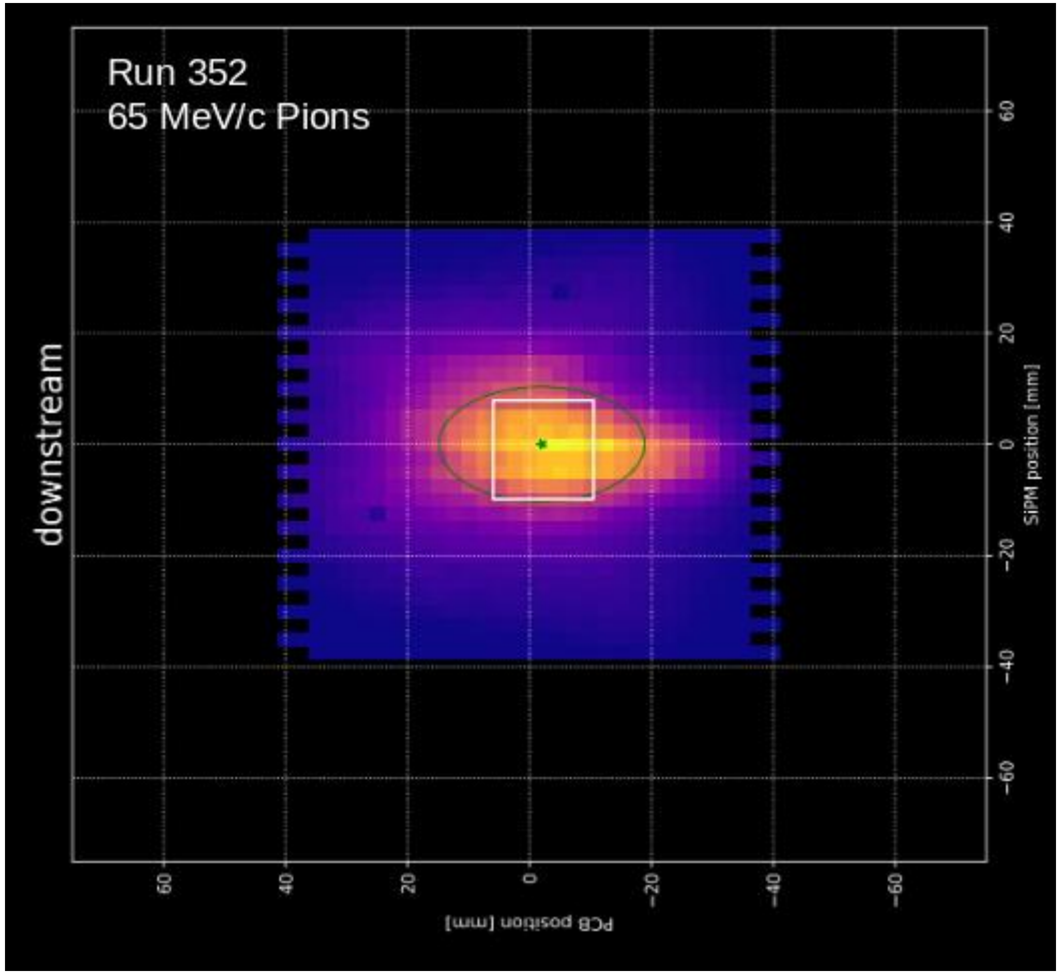



github repository: github.com/ursl/pioneer-g4bl

*Urs Langenegger* *pioneer g4bl (2022/12/xx)* *1*

# Good Enough Focus ?

- Beam behaves as expected (basic p scaling)
  - we measured 28 MeV/c muons and
  - pions of 55, 65 and 75 MeV/c
- Pions better focus than surface muons
- But only 46% of beam in ATAR box
- AST/ASC combination not problematic
- Not yet

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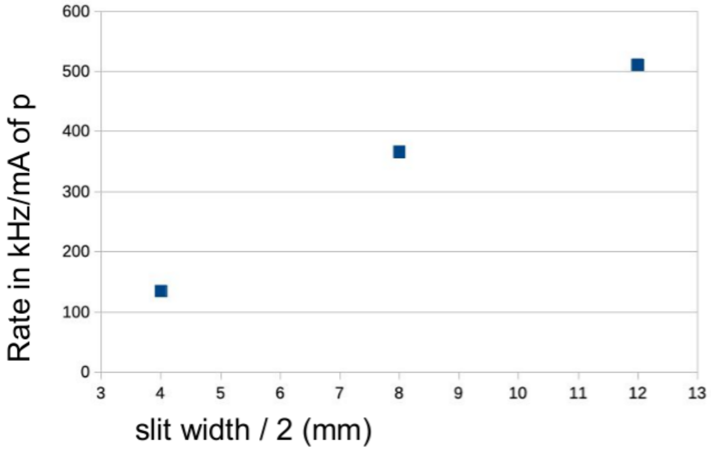
# Sufficient Rate and Small Δp/p ?

- Cannot answer without determination of Δp/p
- First impression
  - 55 MeV/c insufficient
  - 65 MeV/c enough rate




- Longitudinal phase space (i.e. Δp/p), two methods being analyzed

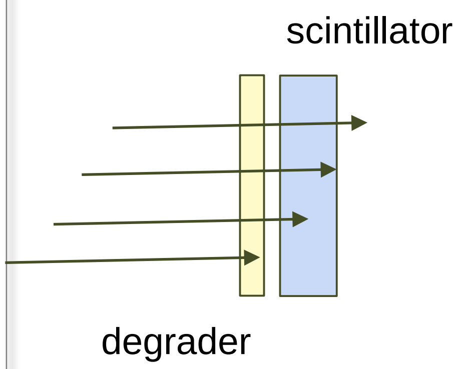
## Time of flight

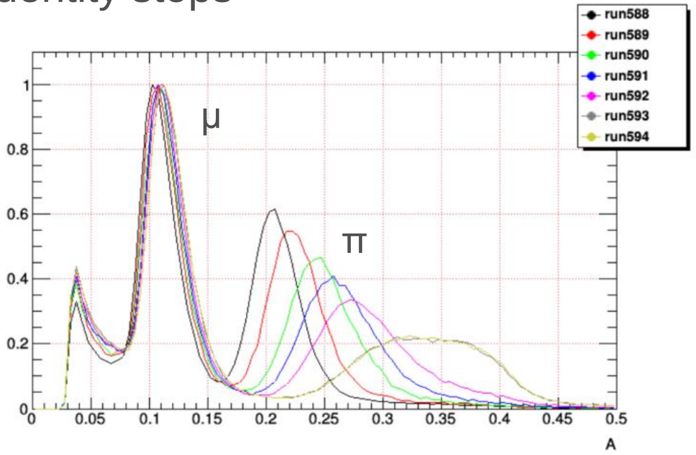
- 16m beamline
- 1% Δp/p ~ 1 ns (65 MeV/c)

| p (MeV/c) | 55 | 65 | 75 |
|---|---|---|---|
| TOF (ns) | 145.57 | 126.42 | 112.75 |

## Direct stopping measurement with range curve

- pion signal amplitudes with different degraders
- use π→ μ sequence to identity stops



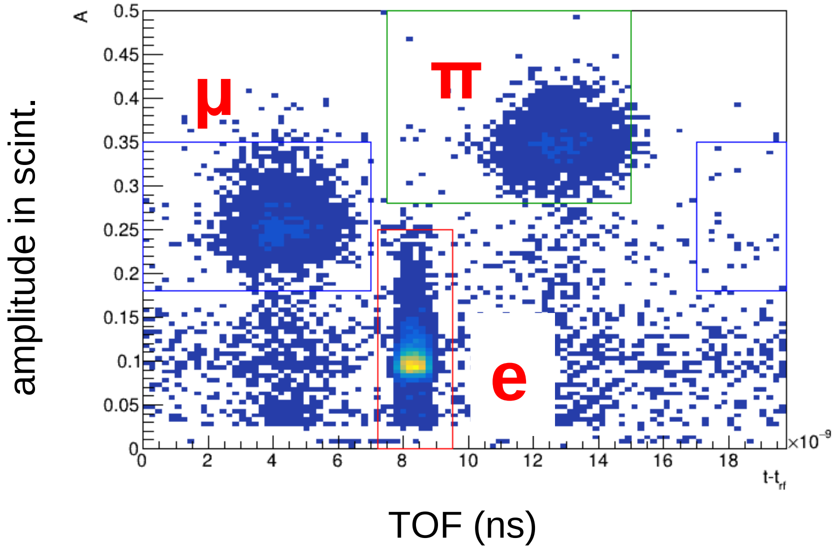



# Particle Separation Good Enough?

No

location of collimator !

Separator HV can be increased

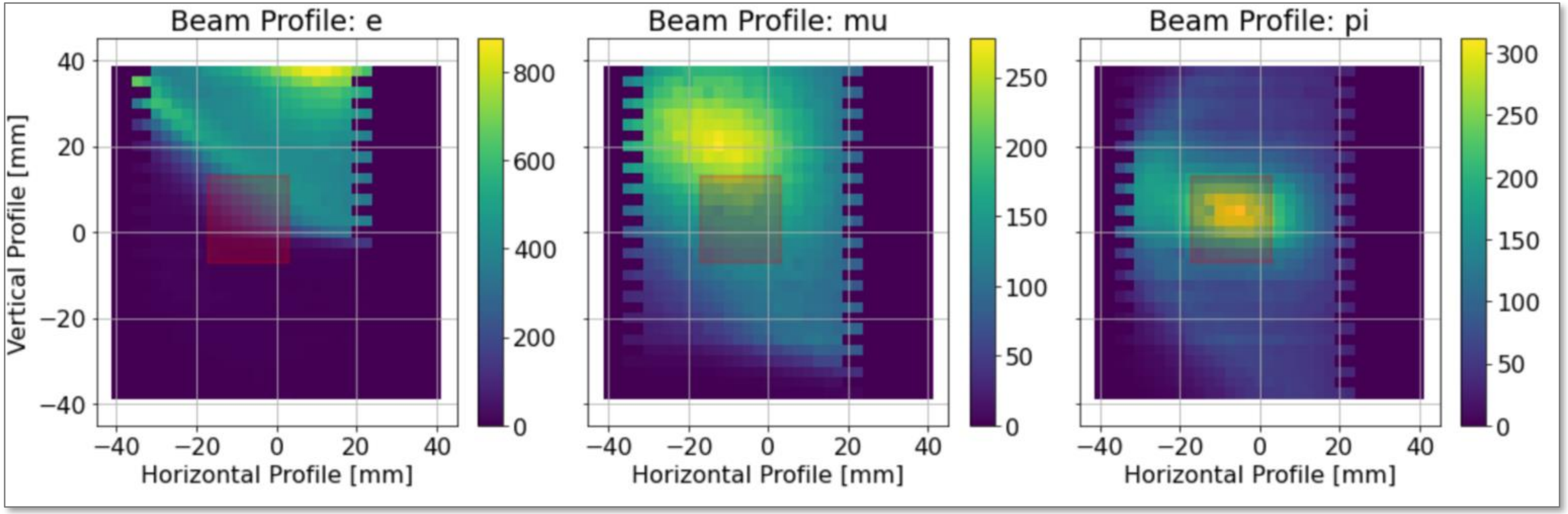



In area restricted to ATAR (optimistic accounting)

e: 25.0%

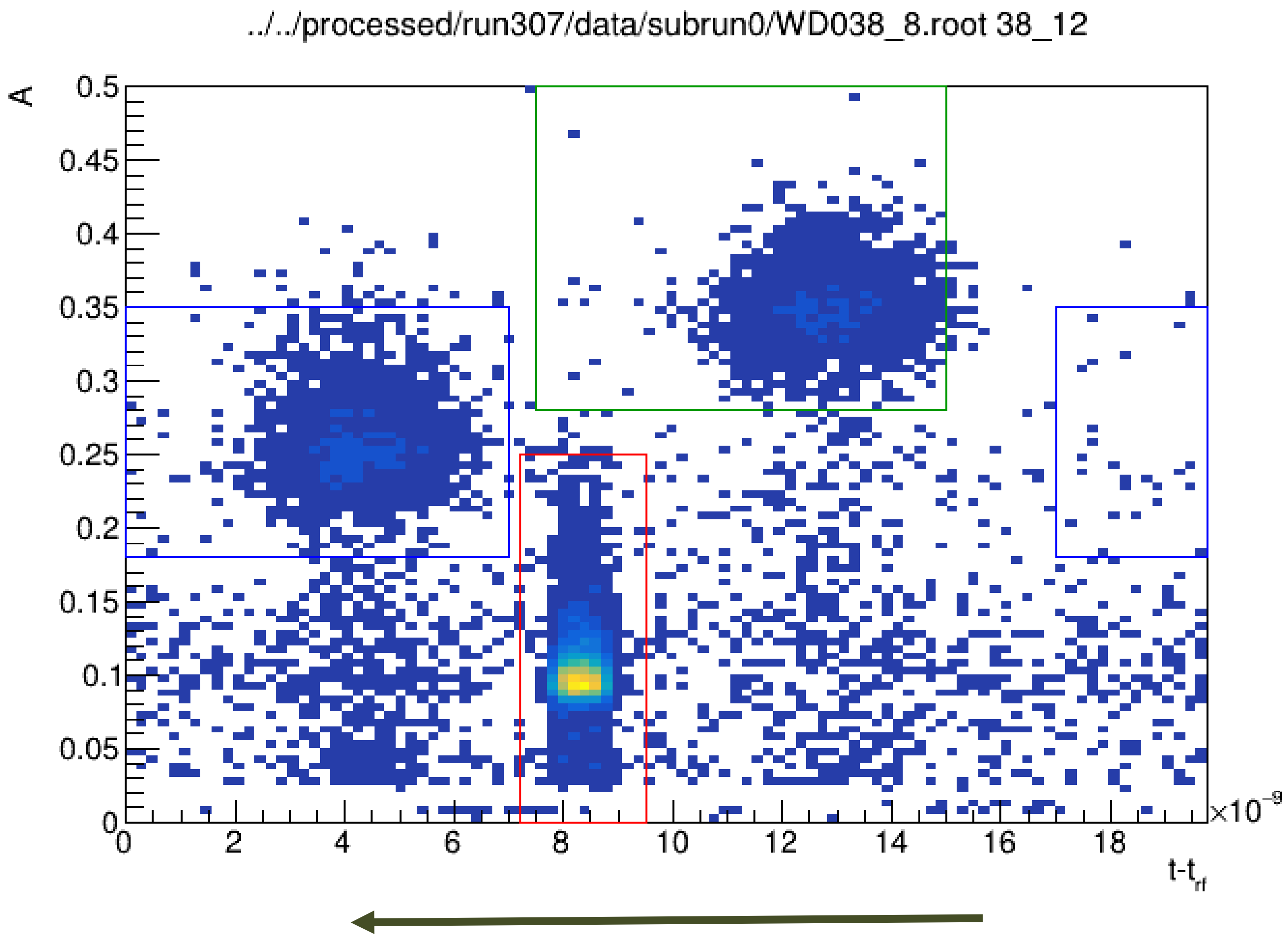
μ: 32.1%

π: 42.9%




Patrick
Josh

# Dispersion at Target Location?

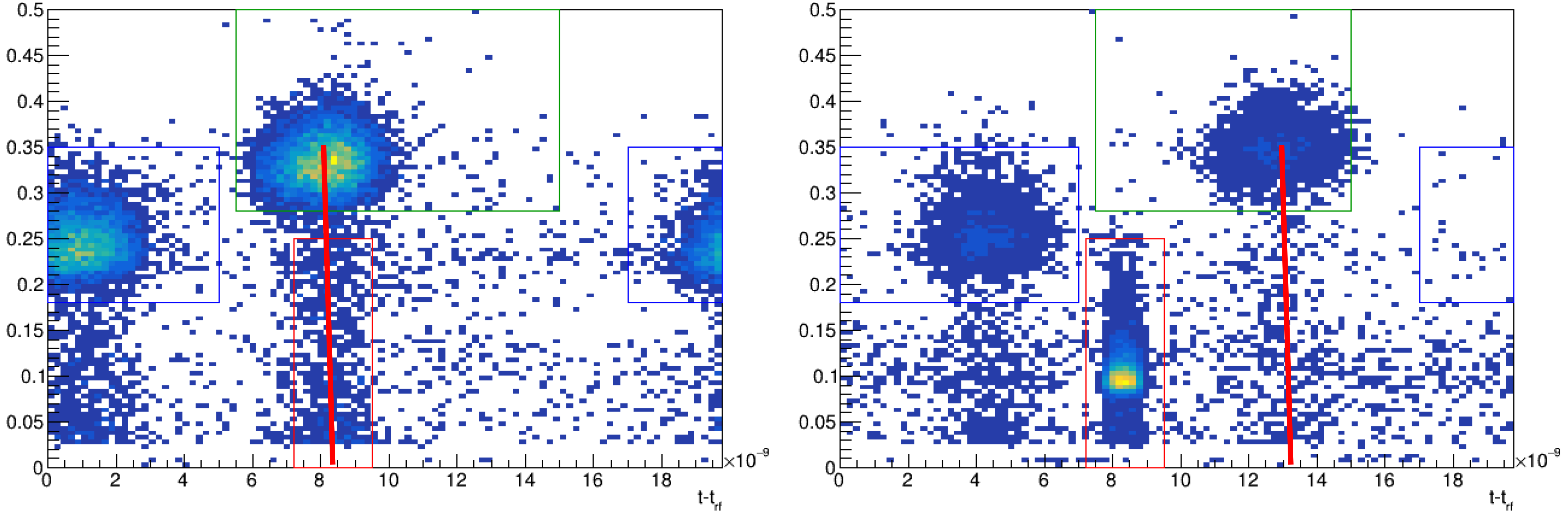



Patrick

TOF changes when when detector moves 5 cm to the left

X=X(P), significant dispersion D at target location, deteriorates focus.

# Dispersion at Target Location?

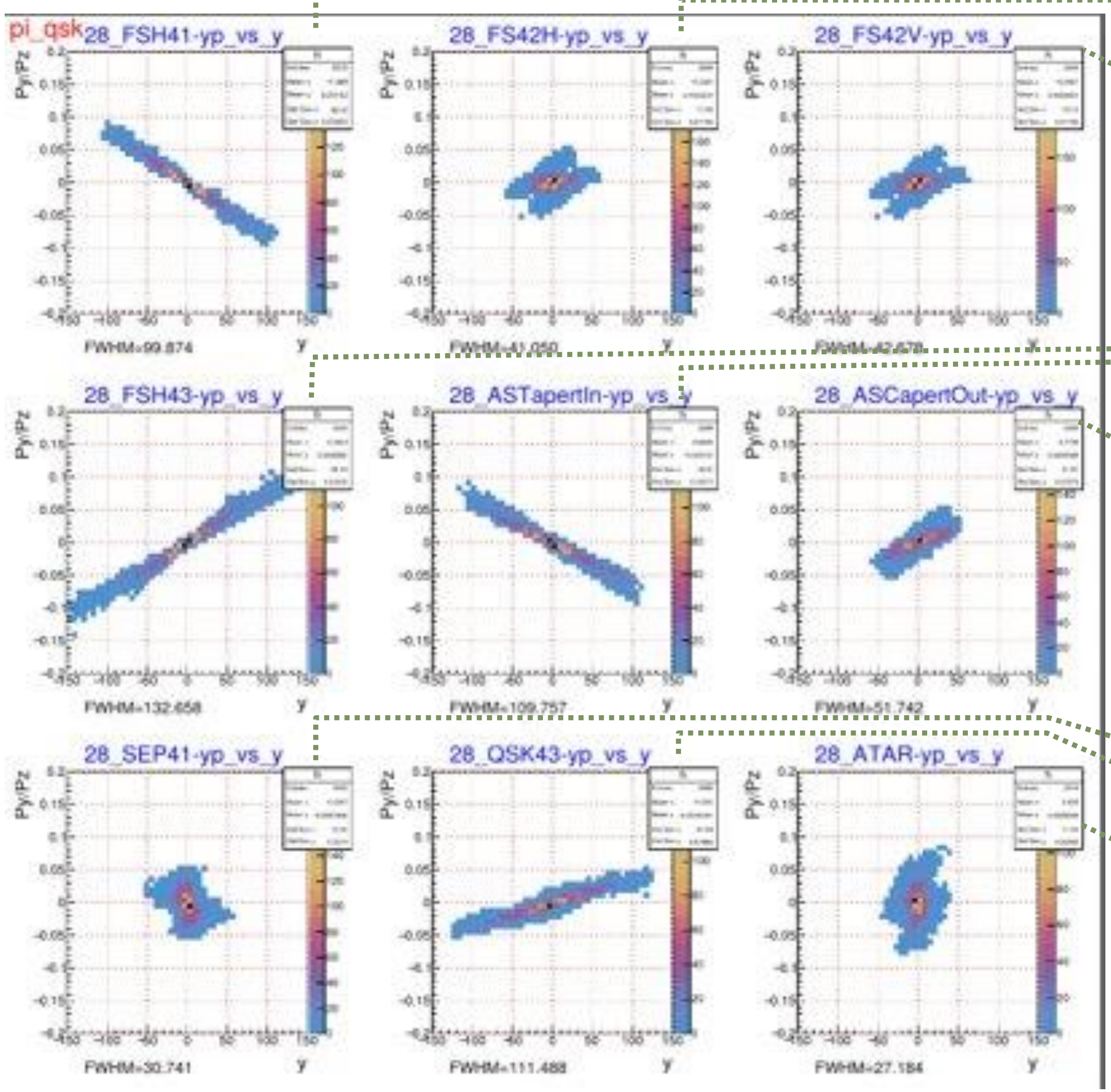


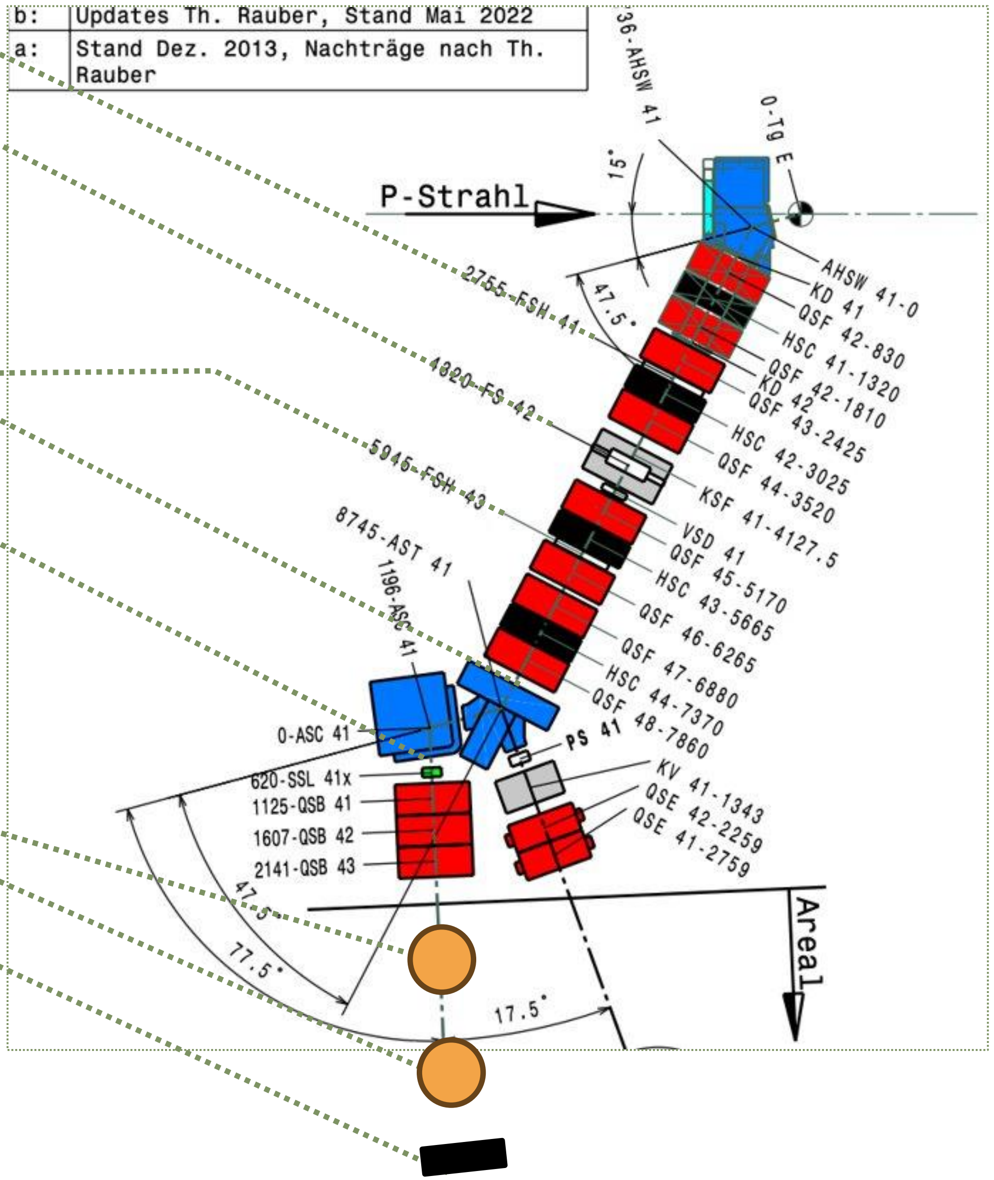

$$\frac{dTOF}{dx} \approx 0.9 \text{ ns/cm}$$

D~1 cm/%
similar to dispersive section??

# Higher order effects: X vs X'

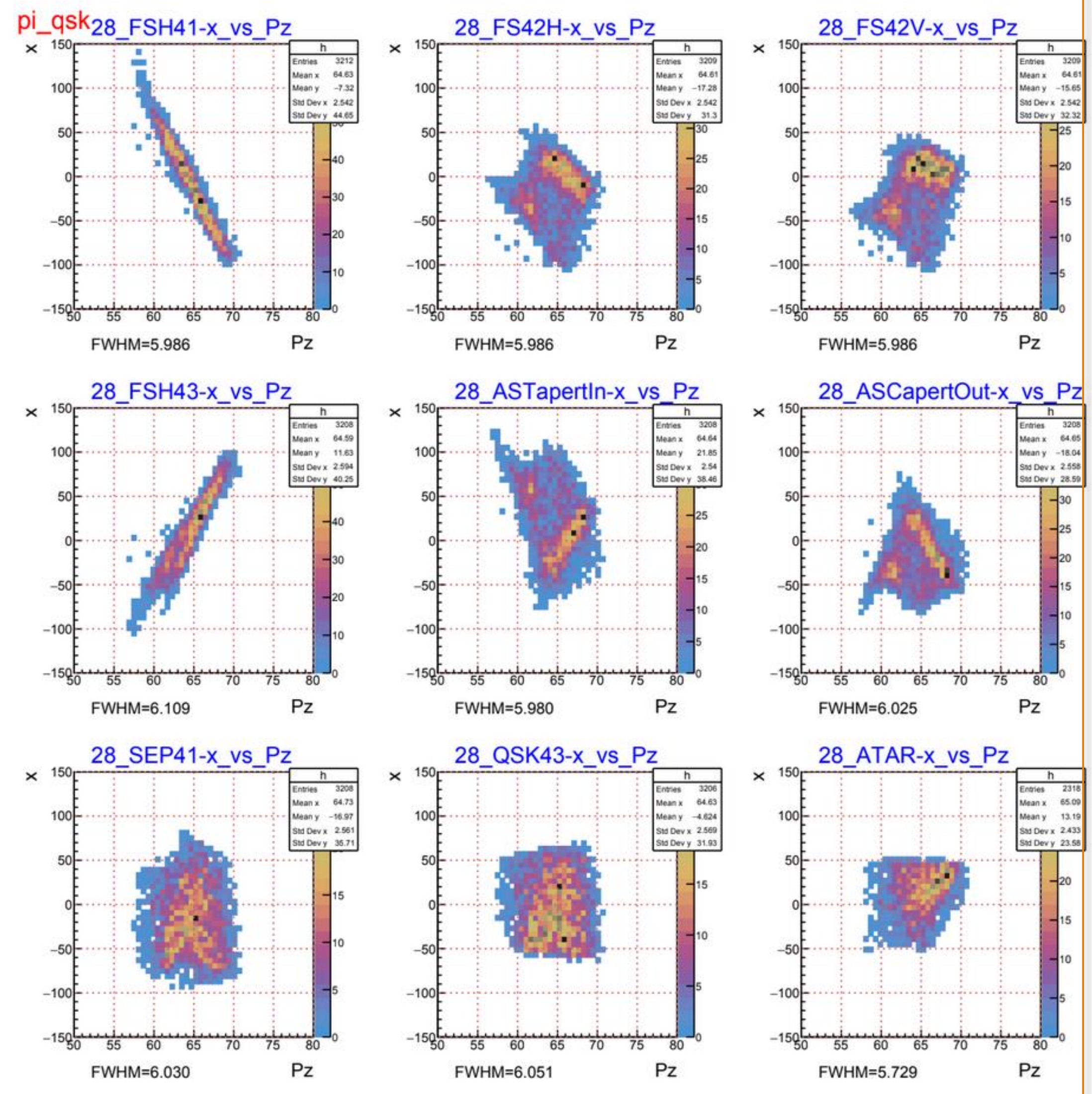
very preliminary



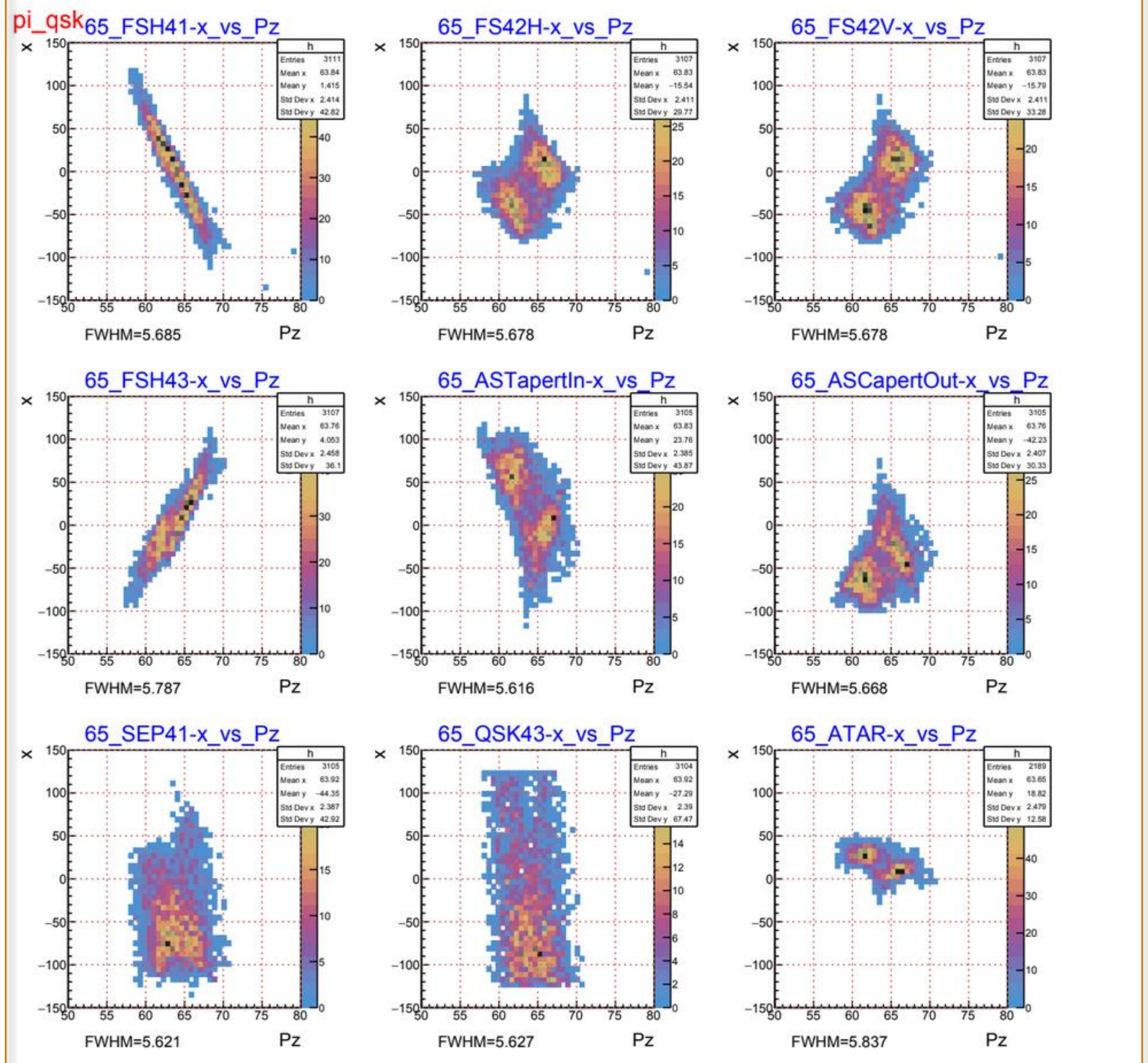



# Dependence on tune

## Mu3e tune

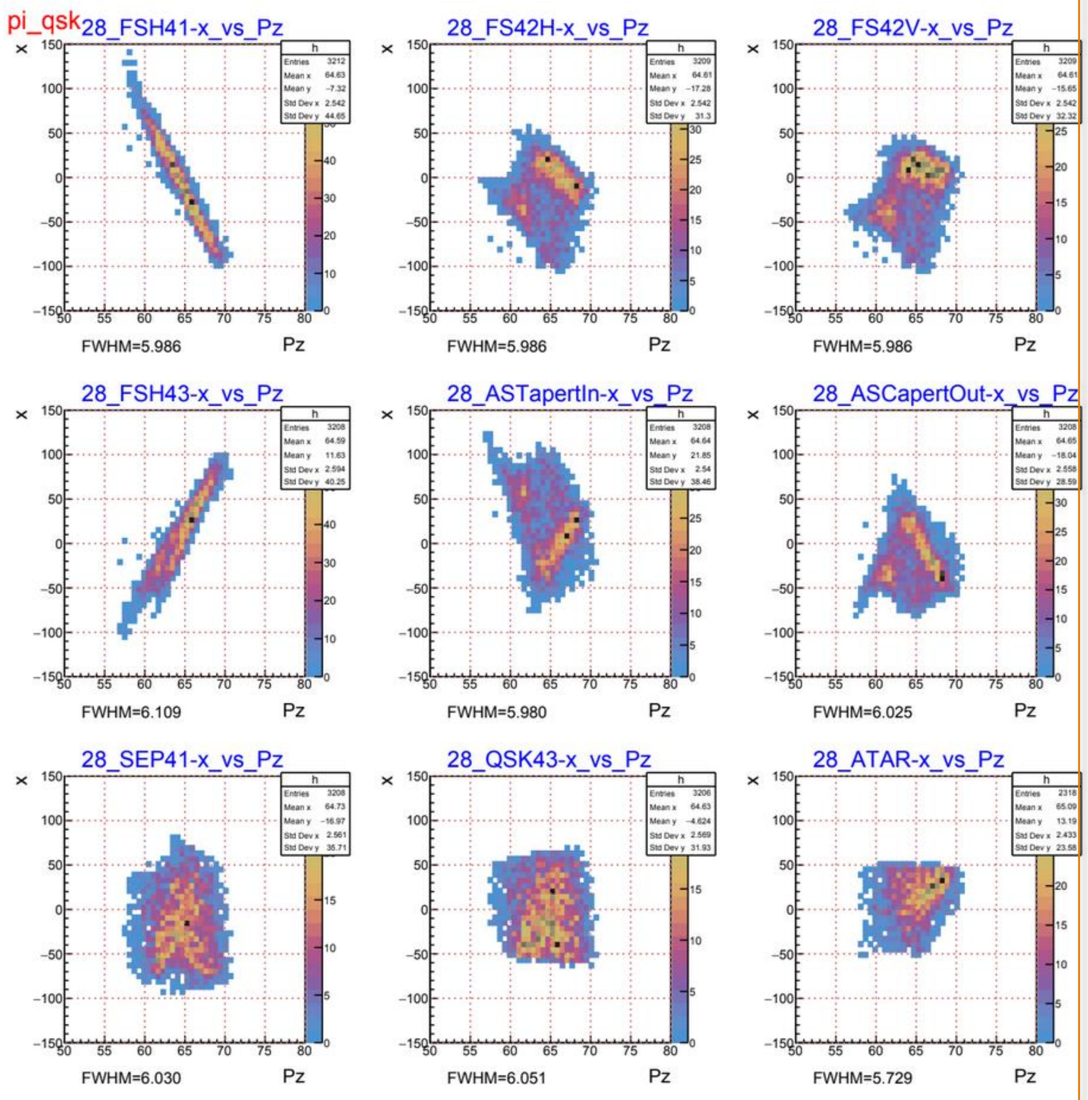



## Pioneer tune

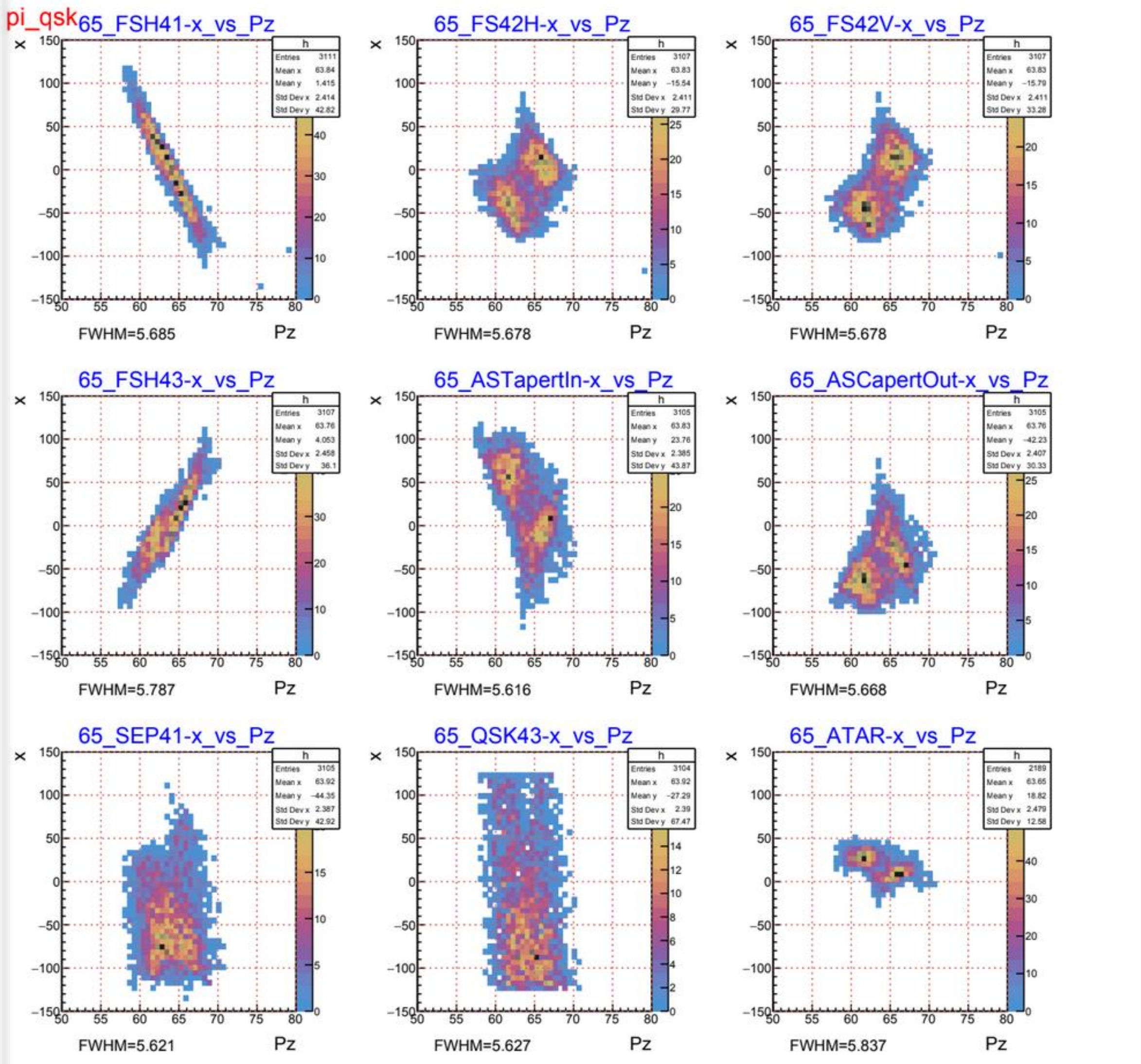


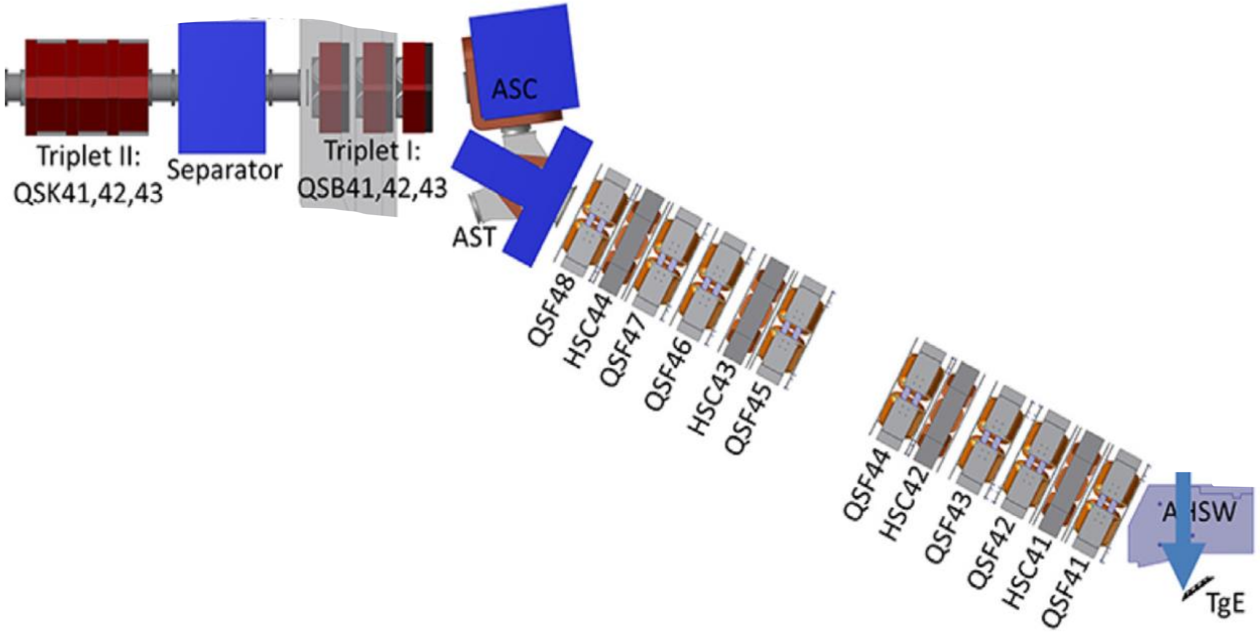
# Dependence on tune

## Mu3e tune




## Pioneer tune




Triplet II:
QSK41,42,43
Separator
Triplet I:
QSB41,42,43
ASC
AST
QSF48
HSC44
QSF47
QSF46
HSC43
QSF45
QSF44
HSC42
QSF43
QSF42
HSC41
QSF41
AHSW
TgE