K. Long, 28 March, 2017

Muon Ionization Cooling Experiment

… and the future of muon beams for particle physics

Contents

MICE and the future of muon beams for particle physics

THE BENEFIT OF MUON BEAMS

The potential, pros and cons

- **Muon beams have the potential to:**
  - Revolutionise the study of the neutrino
  - Provide a route to multi-TeV lepton-antilepton annihilation

- **Unique potential arises because:**
  - Heavy: $200\,m_e < m_\mu < 0.1\,m_p$
    - Enormous (5×10^{-10} cf *e*) reduction be beam-/bremsstrahlung
    - Enhanced (5×10^{4} cf e^+e^-) *s*-channel coupling to Higgs
  - Decay: lifetime at rest 2.2 μs
    - ν_e, ν_μ – 50/50
    - Precisely known energy spectrum

- **Challenges:**
  - Tertiary beam
  - Decay: lifetime at rest 2.2 μs

Accelerator challenges

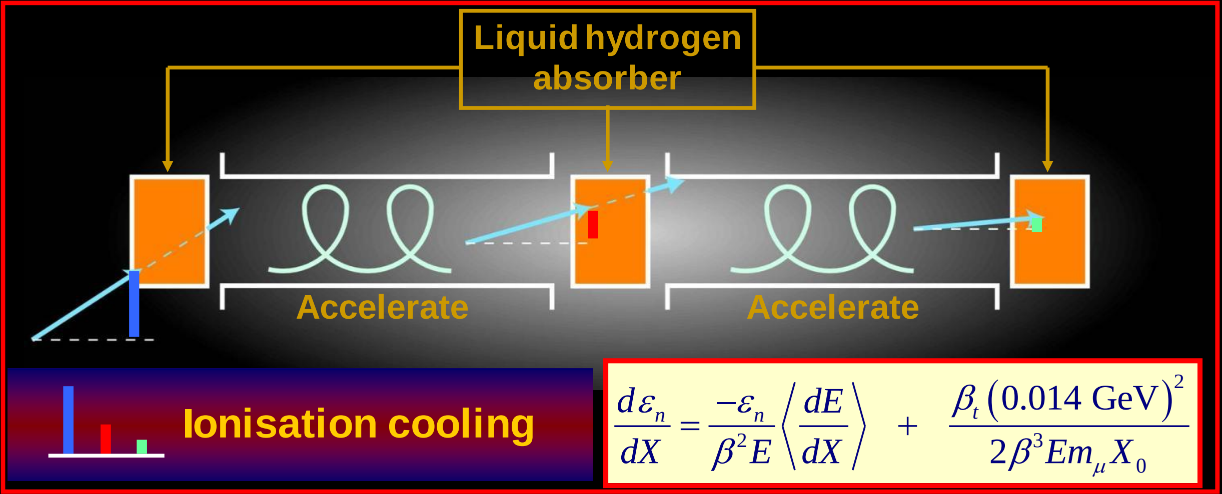
- **High-power, pulsed proton driver:**
  - “MW class”; e.g.:
    - FNAL Proton Improvement Plan
    - J-PARC Main Ring upgrade
- **Pion-production target:**
  - MERIT experiment [CERN]
- **Muon front end:**
  - MICE experiment [STFC Rutherford Appleton Laboratory]
    - Proof of principle of ionization-cooling technique
  - MuCool programme at FNAL
- **Rapid acceleration:**
  - EMMA experiment [STFC Daresbury Laboratory]

MICE and the future of muon beams for particle physics

MICE

THE MUON IONIZATION COOLING EXPERIMENT

The principle of ionization cooling



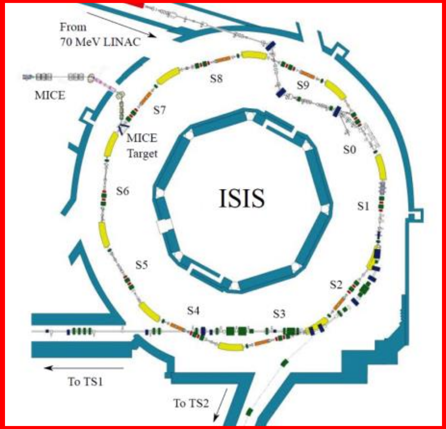
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX}\right\rangle + \frac{\beta_t \left(0.014\ \mathrm{GeV}\right)^2}{2\beta^3 E m_\mu X_0}$$

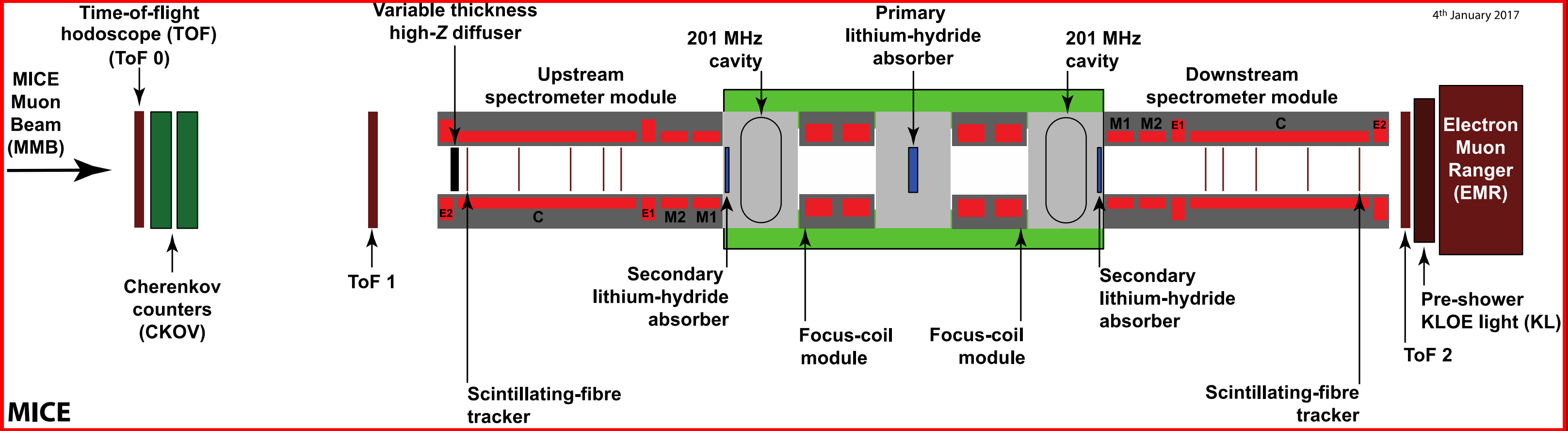
	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

- Competition between:
  - dE/dx [cooling]
  - MCS [heating]
- Optimum:
  - Low *Z*, large X_0
  - Tight focus
  - H_2 gives best performance

Mission

- Proof of principle:
  - Design, build commission and operate a realistic cooling cell;
  - Measure its performance in a variety of modes of operation and beam conditions

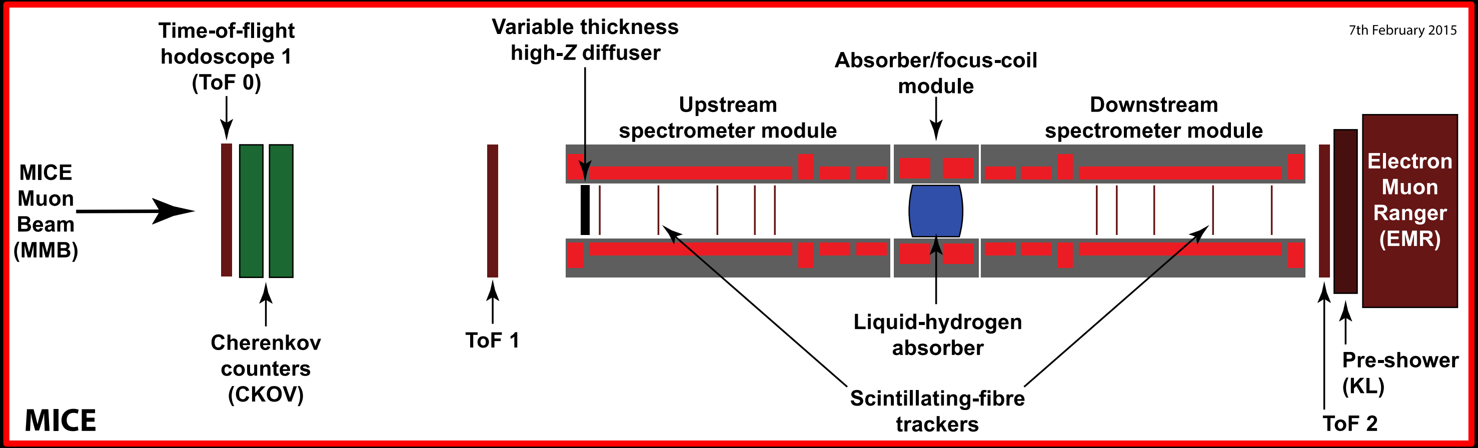




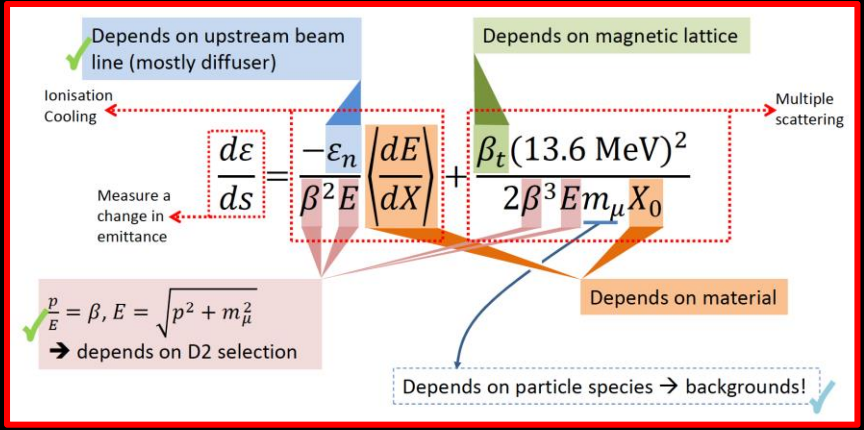
4th January 2017

Characterisation of the cooling equation

- Acceleration not required (Step IV):



- Emittance:
  - Vary beam optics/diffuser;
- Material:
  - Absorber change (LH2; LiH);
- *p*, *E* and β:
  - Vary beam momentum, optics



$$\frac{d\varepsilon}{ds} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (13.6\ \mathrm{MeV})^2}{2\beta^3 E m_\mu X_0}$$

Scientific programme

Step IV:

Material properties of LH_2 and LiH that determine the ionization-cooling performance

Observation of $\epsilon_{\perp}^{\mathrm{n}}$ reduction

MICE demonstration of ionization cooling:

Observation of $\epsilon_{\perp}$ reduction with re-acceleration

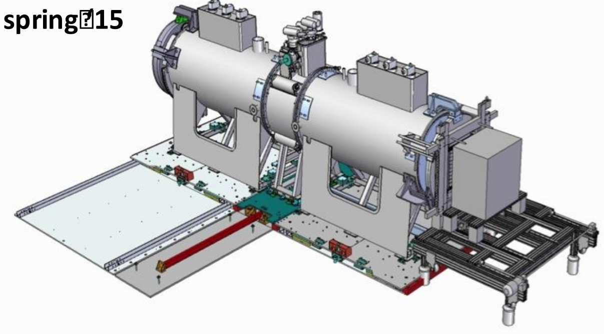
Observation of $\epsilon_{\perp}$ reduction and $\epsilon_{||}$ evolution

Observation of $\epsilon_{\perp}$ reduction and $\epsilon_{||}$ and angular momentum evolution†

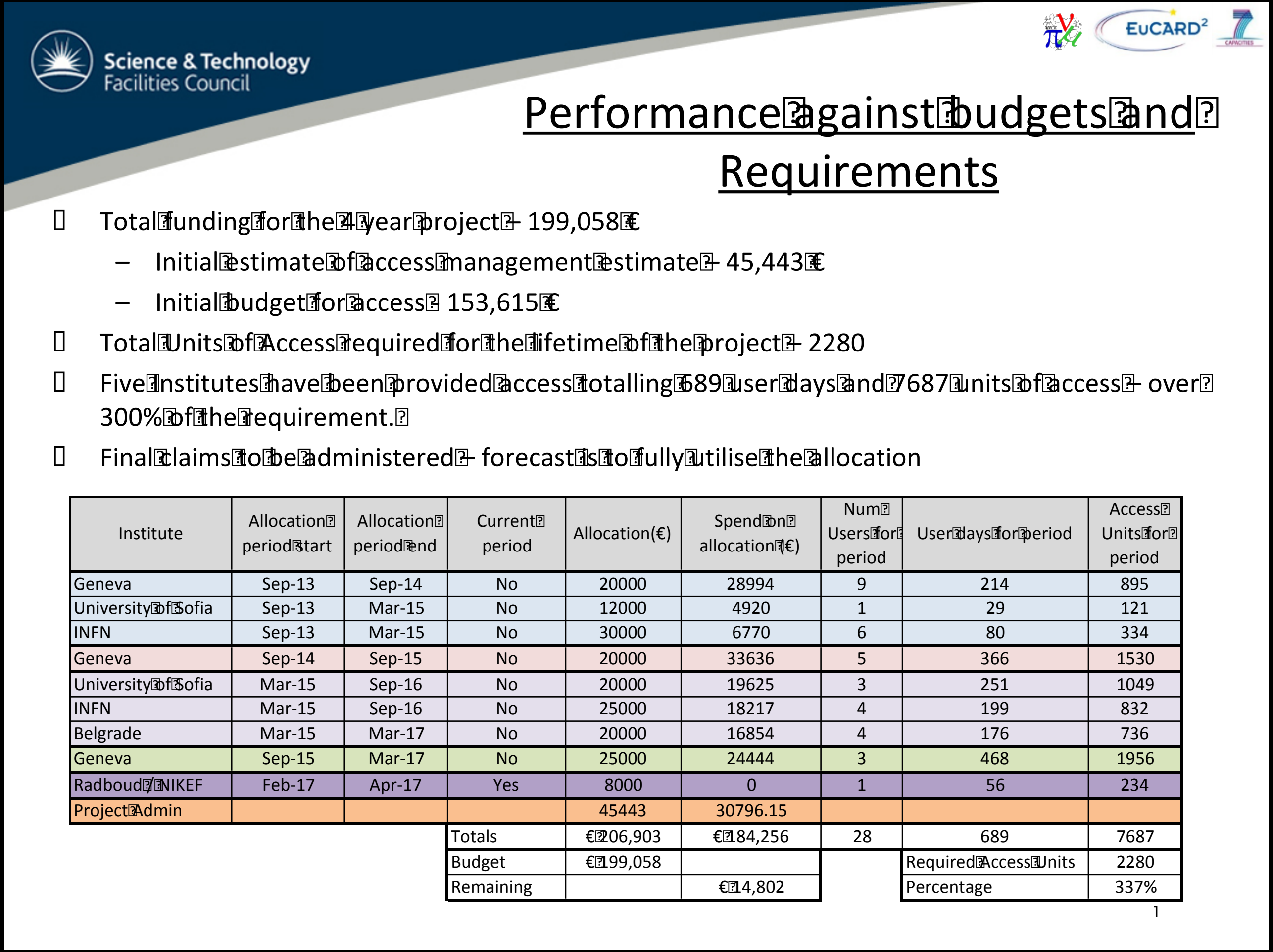
† Requires systematic study of “flip” optics.

MICE in 2013

Expected:
spring'15



Programme delivered with help from EUCARD-II



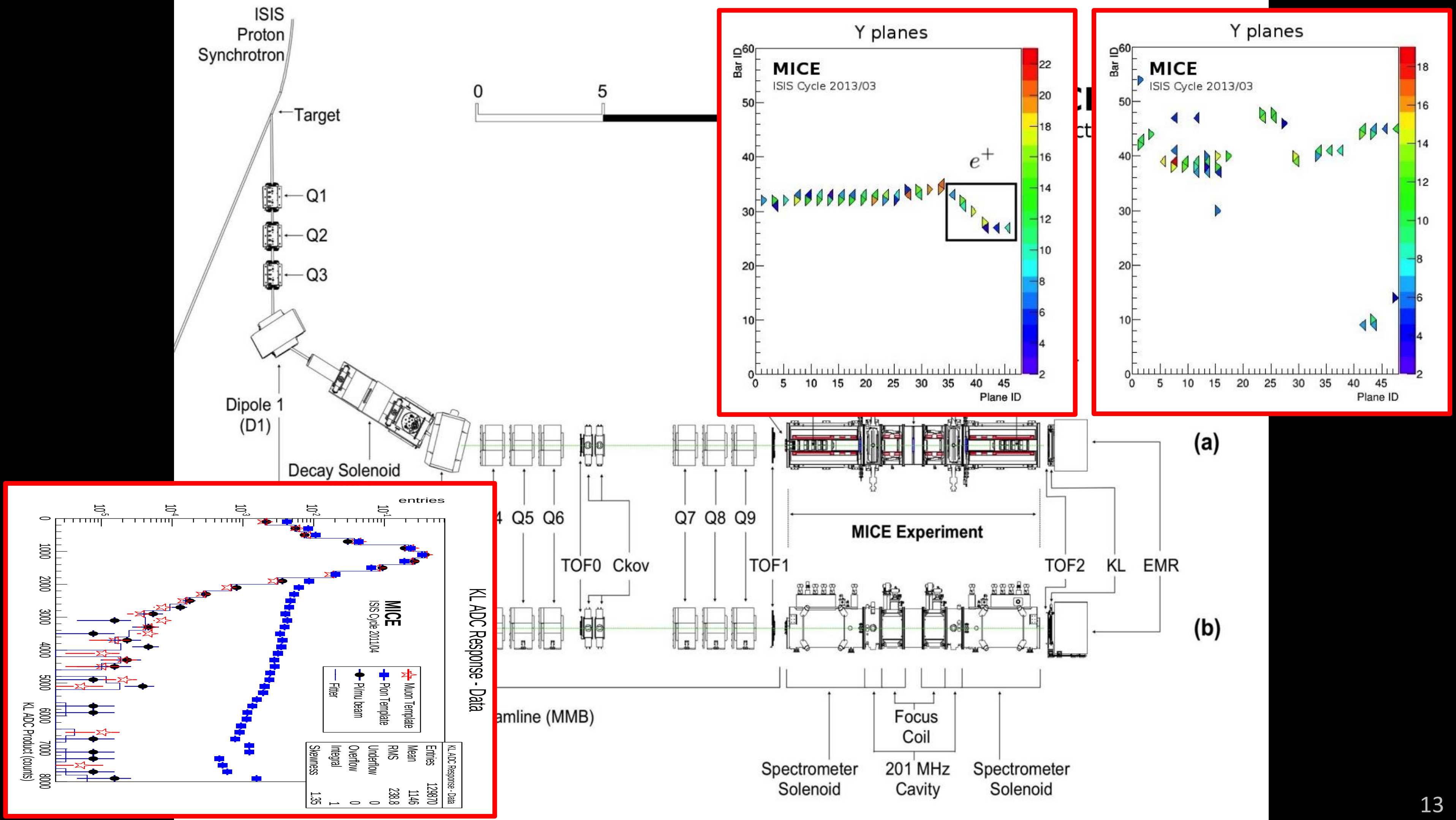
Science & Technology Facilities Council

Performance against budgets and Requirements

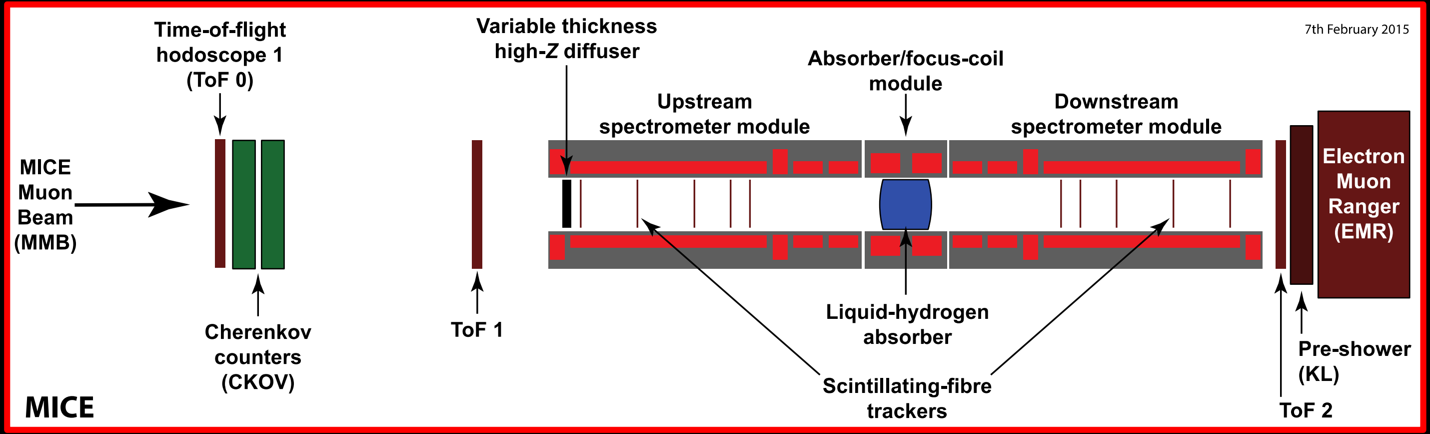
- Total funding for the 4 year project – 199,058 €
  - Initial estimate of access management estimate – 45,443 €
  - Initial budget for access 153,615 €
- Total Units of Access required for the lifetime of the project – 2280
- Five Institutes have been provided access totalling 689 user days and 7687 units of access – over 300% of the requirement.
- Final claims to be administered – forecast is to fully utilise the allocation

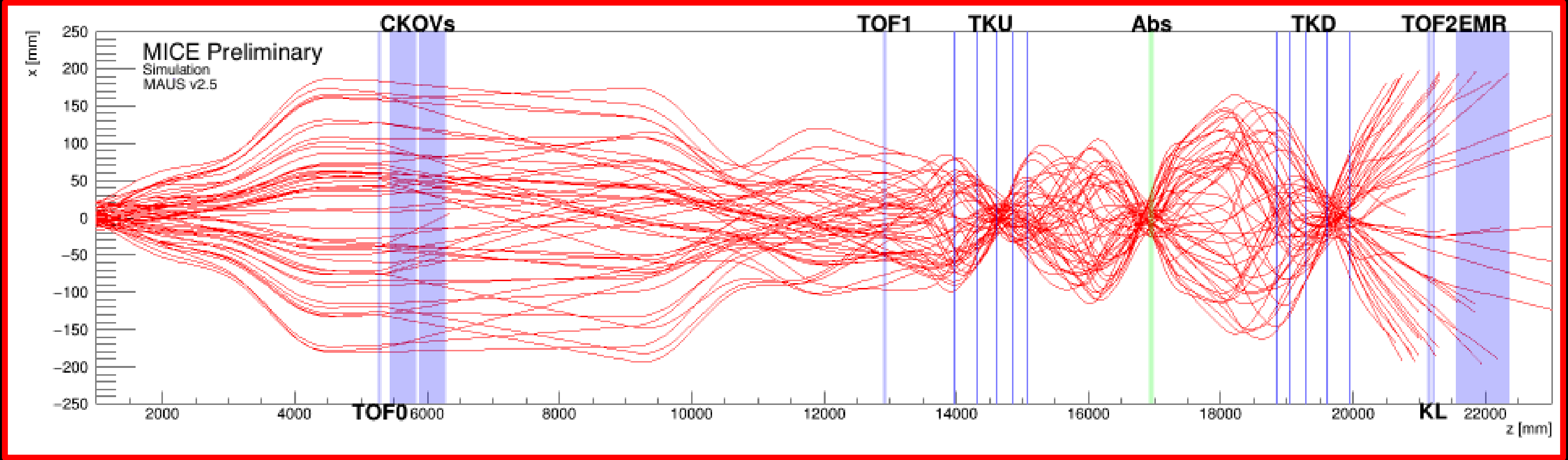
Institute	Allocation period start	Allocation period end	Current period	Allocation(€)	Spend on allocation (€)	Num Users for period	User days for period	Access Units for period
Geneva	Sep-13	Sep-14	No	20000	28994	9	214	895
University of Sofia	Sep-13	Mar-15	No	12000	4920	1	29	121
INFN	Sep-13	Mar-15	No	30000	6770	6	80	334
Geneva	Sep-14	Sep-15	No	20000	33636	5	366	1530
University of Sofia	Mar-15	Sep-16	No	20000	19625	3	251	1049
INFN	Mar-15	Sep-16	No	25000	18217	4	199	832
Belgrade	Mar-15	Mar-17	No	20000	16854	4	176	736
Geneva	Sep-15	Mar-17	No	25000	24444	3	468	1956
Radboud / NIKEF	Feb-17	Apr-17	Yes	8000	0	1	56	234
Project Admin				45443	30796.15			
			Totals	€ 206,903	€ 184,256	28	689	7687
			Budget	€ 199,058			Required Access Units	2280
			Remaining		€ 14,802		Percentage	337%

1


ISIS Proton Synchrotron
Target
Q1
Q2
Q3
Dipole 1 (D1)
Decay Solenoid
0
5
4
Q5
Q6
TOF0
Ckov
Q7
Q8
Q9
TOF1
MICE Experiment
TOF2
KL
EMR
(a)
(b)
amline (MMB)
Spectrometer Solenoid
Focus Coil
201 MHz Cavity
Spectrometer Solenoid
Y planes
MICE
ISIS Cycle 2013/03
Bar ID
Plane ID
e^+
Y planes
MICE
ISIS Cycle 2013/03
Bar ID
Plane ID
KL ADC Response - Data
MICE
ISIS Cycle 2011/04
Muon Template
Pion Template
Pi/mu beam
Fitter
KL ADC Response - Data
Entries 129870
Mean 1146
RMS 238.8
Underflow 0
Overflow 0
Integral 1
Skewness 1.35
entries
KL ADC Product (counts)

Emittance reconstruction





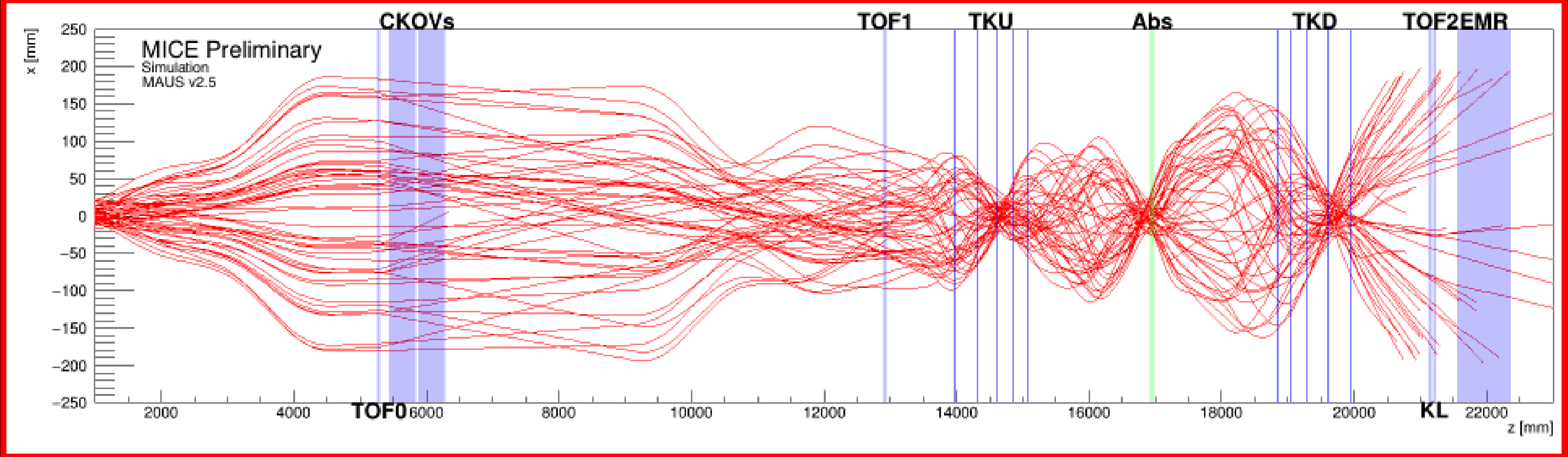
Emittance reconstruction

- Construct phase-space covariance matrix:
  - One track at a time

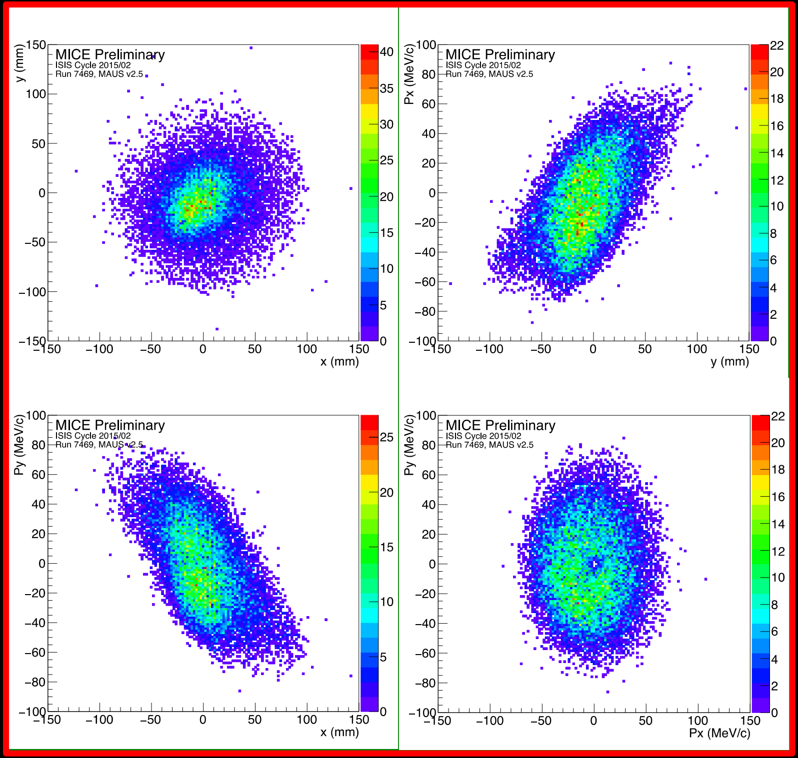
$$\hat{\ } = \begin{pmatrix} \sigma^2_{xx} & \sigma^2_{xp_x} & \sigma^2_{xy} & \sigma^2_{xp_y} \\ \sigma^2_{p_x x} & \sigma^2_{p_x p_x} & \sigma^2_{p_x y} & \sigma^2_{p_x p_y} \\ \sigma^2_{yx} & \sigma^2_{yp_x} & \sigma^2_{yy} & \sigma^2_{yp_y} \\ \sigma^2_{p_y x} & \sigma^2_{p_y p_x} & \sigma^2_{p_y y} & \sigma^2_{p_y p_y} \end{pmatrix}$$

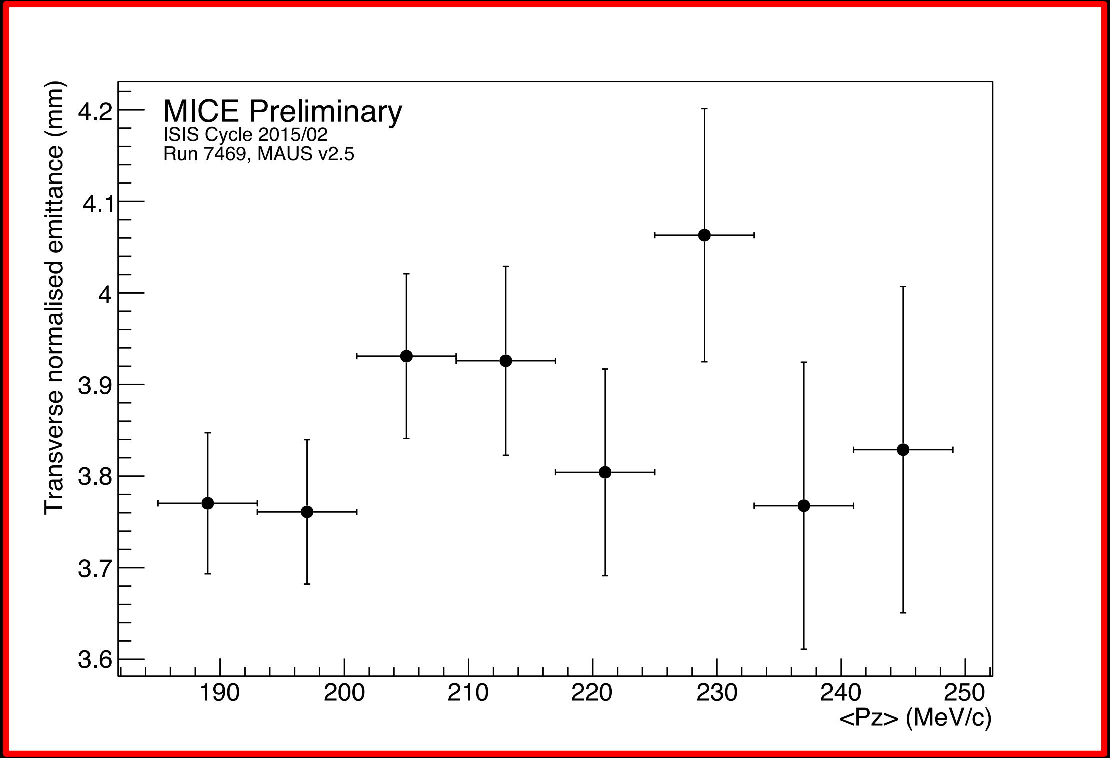
- Compute normalised transverse emittance

$$\varepsilon_n = \frac{1}{m_\mu} \sqrt[4]{\det \hat{\ }}$$



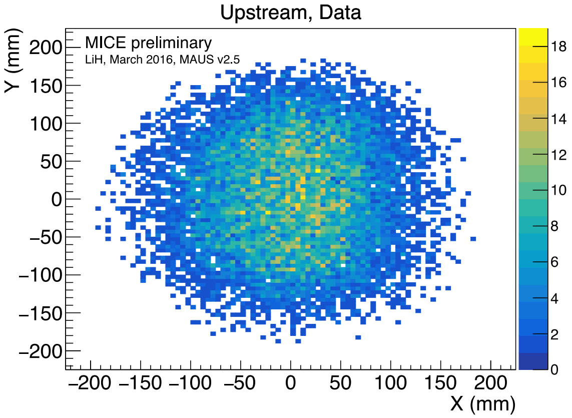
Emittance reconstruction

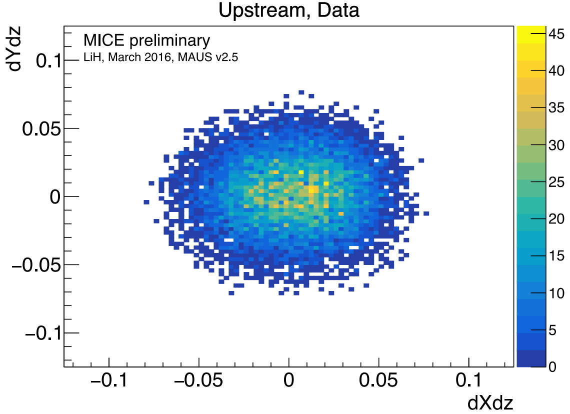


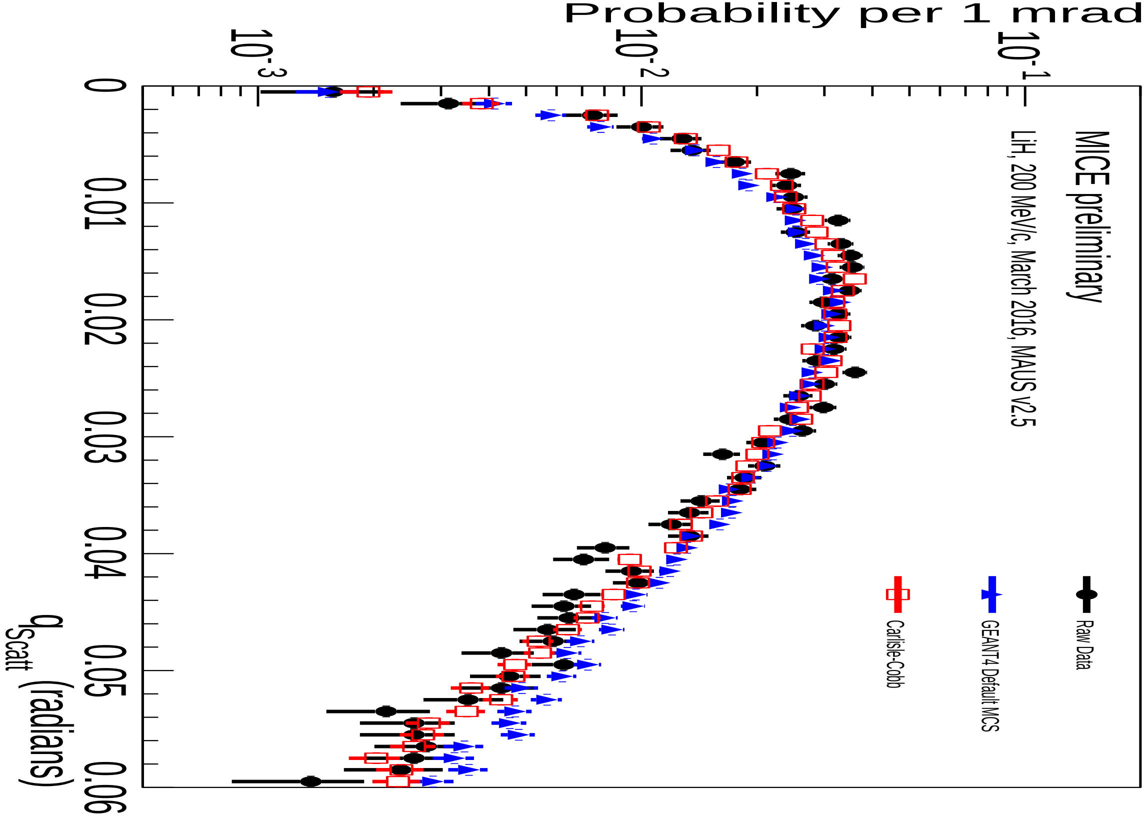


- **Reconstruction of emittance “particle-by-particle” in upstream tracker**
- **Validates MICE measurement approach**

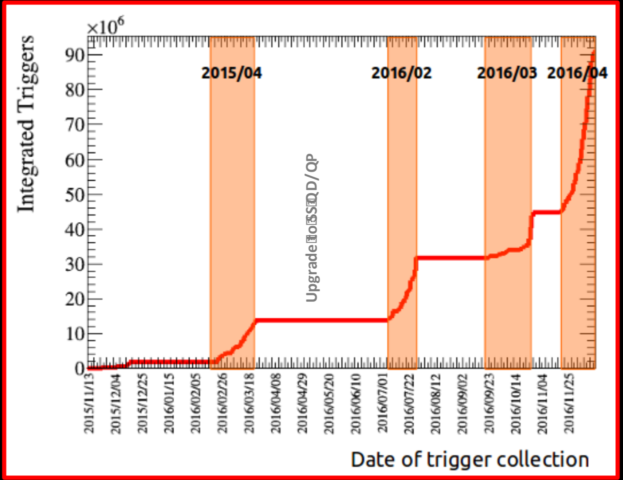
Measurement of muon-LiH MCS







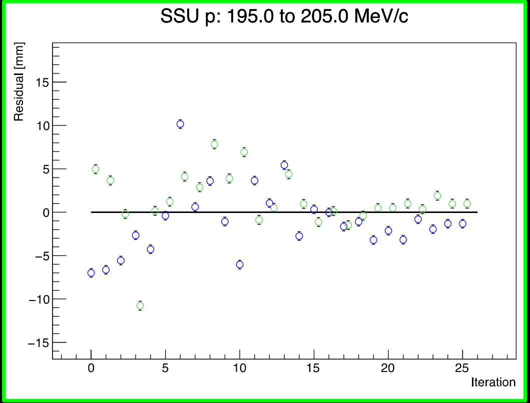
Step IV data taking to date



- **Lithium hydride:**
  - **Field-off scattering, complete**
  - **Field-on scattering, complete**
  - **Emittance evolution:**
    - **Solenoid mode**
    - **Flip mode**

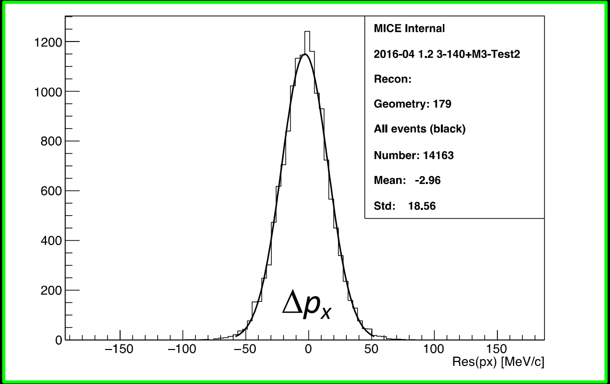
Beam-based alignment

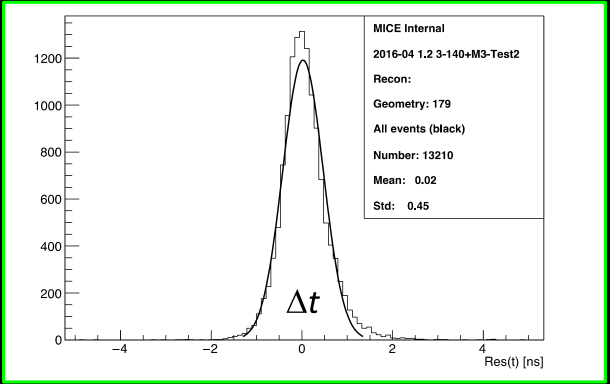
- **Magnetic field and instrumentation**



Towards normalised emittance evolution

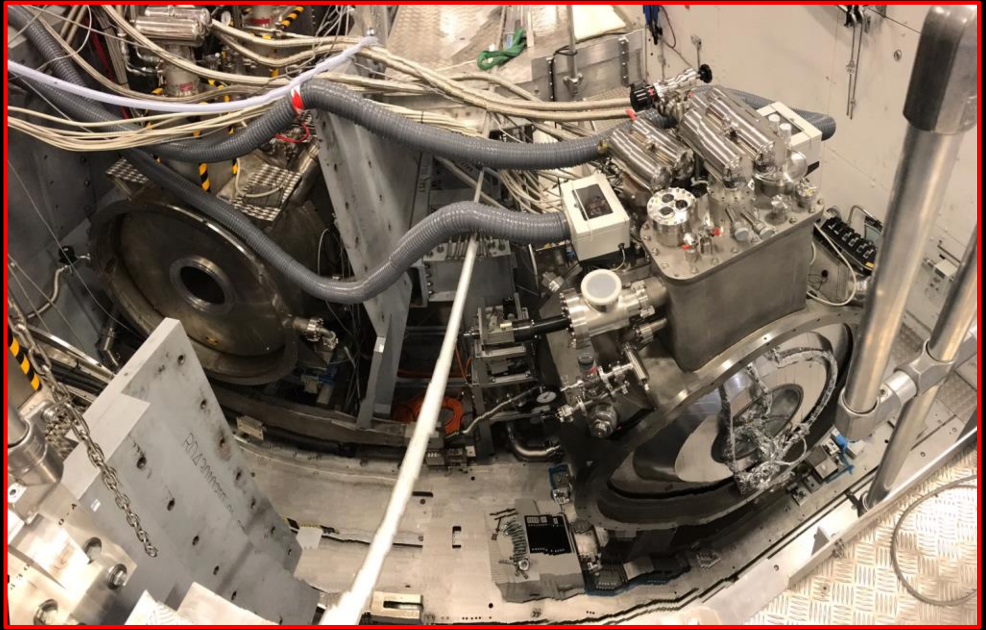
- **Residual: upstream vs downstream momentum and time**

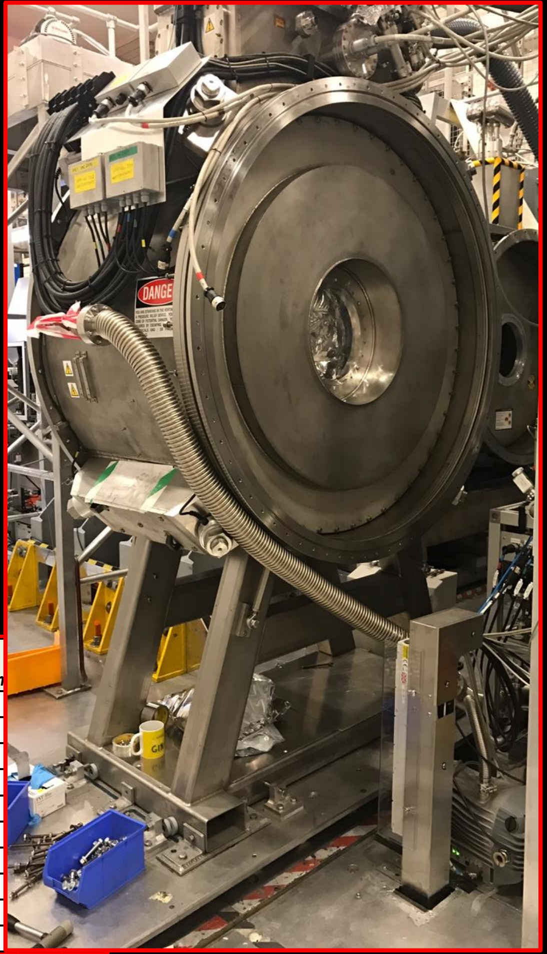




Liquid-hydrogen programme

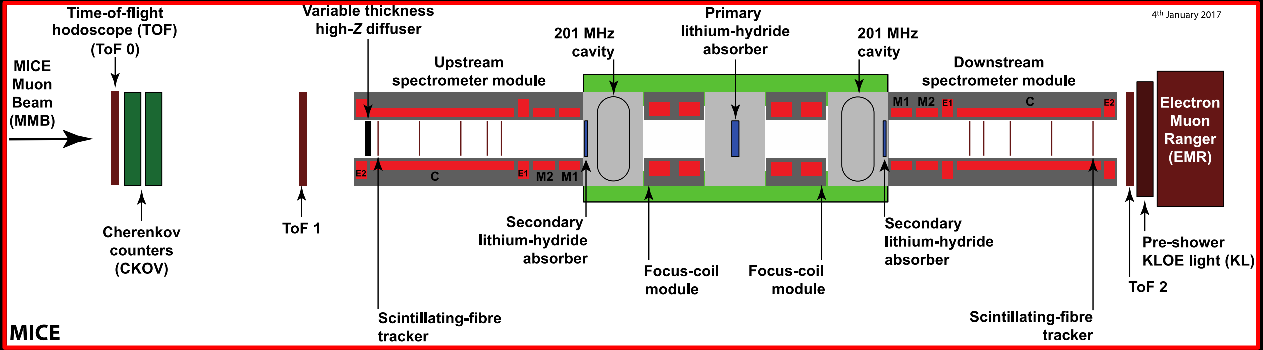
- Installation of LH2 absorber underway
- Goal: data taking start May 2017

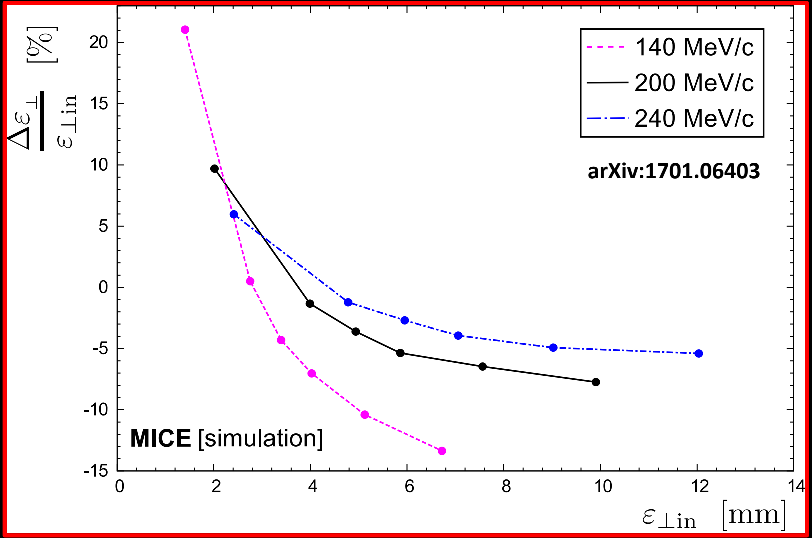


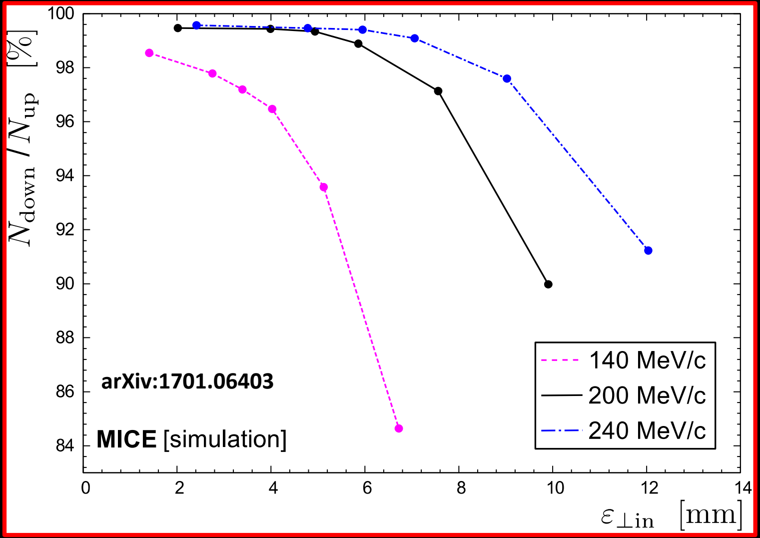


ISIS Cycle	From	To	2015/16			2016/17												2017/18									
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
2015/04	16-Feb-16	25-Mar-16		▨	▨																						
2016/01	12-Apr-16	20-May-16				🟩	🟩																				
2016/02	28-Jun-16	29-Jul-16							🟩																		
2016/03	13-Sep-16	28-Oct-16									🟩	🟩															
2016/04	15-Nov-16	16-Dec-16											🟩	🟩													
2016/05	14-Feb-17	31-Mar-17														🟩	🟩										
2017/01	02-May-17	02-Jun-17																	🟩	🟩							
2017/02	11-Jul-17	04-Aug-17																			⬛	⬛					
	19-Sep-17	27-Oct-17																					🟩	🟩			
2017/03	14-Nov-17	20-Dec-17																							▨	▨	

Cooling demonstration





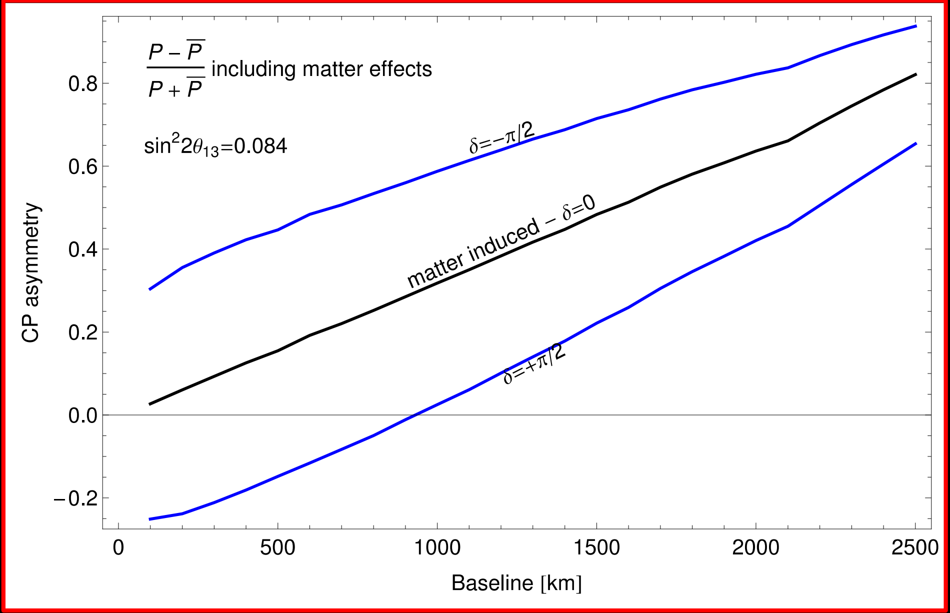


MICE and the future of muon beams for particle physics

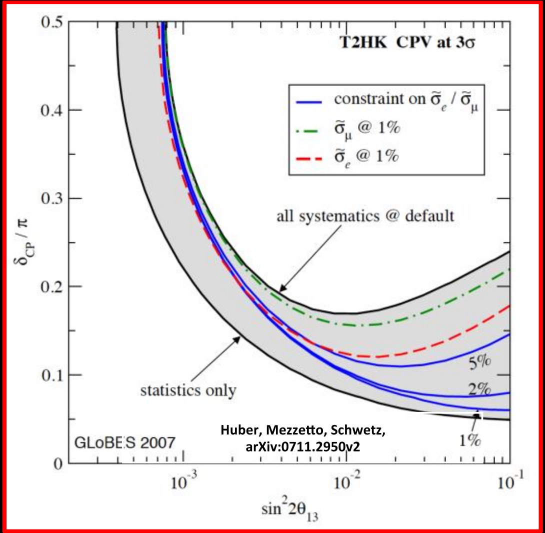
nuSTORM

Search for CPiV in lbl oscillations

- Seek to measure asymmetry:
  - $P(\nu_\mu \blacktriangleright \nu_e) - P(\bar{\nu}_\mu \blacktriangleright \bar{\nu}_e)$
    - For DUNE/Hyper-K, CP asymmetry < 25%
      - Matter effect contributes to observed asymmetry
      - Over much of parameter space, true CP asymmetry small (~5%)
  - → "few %-level" measurement of oscillation probabilities



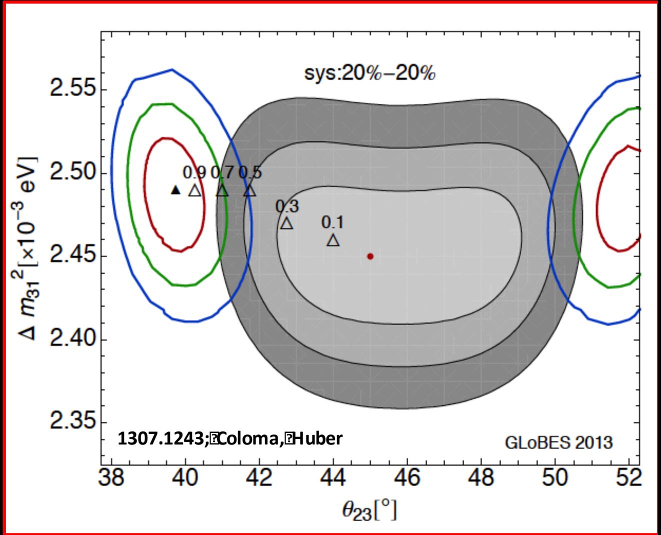
Systematic uncertainty and/or bias



Huber, Mezzetto, Schwetz, arXiv:0711.2950v2

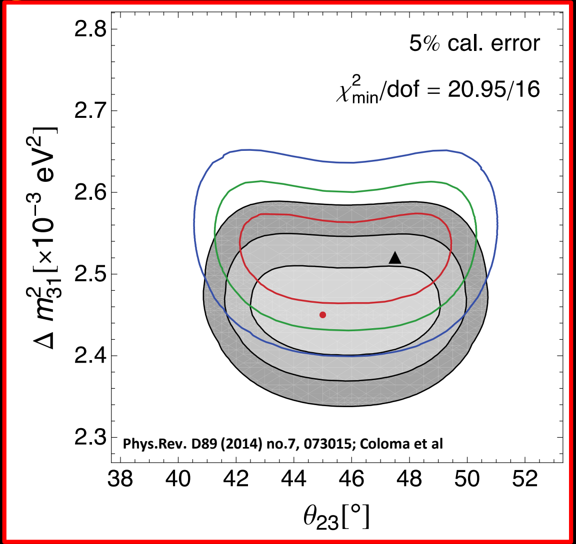
Uncertainty

(cross section and ratio)



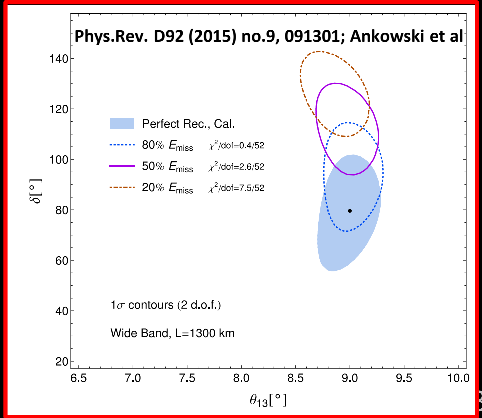
1307.1243; Coloma, Huber

Event mis-classification



Phys.Rev. D89 (2014) no.7, 073015; Coloma et al

Energy scale mis-calibration



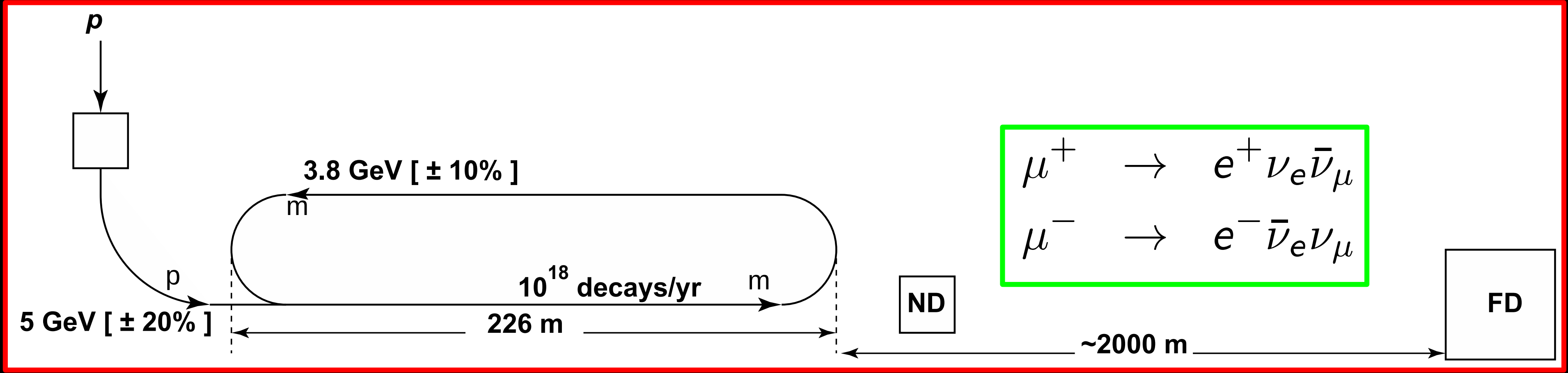
Phys.Rev. D92 (2015) no.9, 091301; Ankowski et al

Missing energy (neutrons)

Search for CPiV in lbl oscillations

- Seek to measure asymmetry:
  - $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Event rates convolution of:
  - Flux, cross sections, detector mass, efficiency, *E*-scale
    - Measurements at %-level required
- Lack of knowledge of cross-sections leads to:
  - Systematic uncertainties; and
  - Biases; pernicious if ν and $\bar{\nu}$ differ

Neutrinos from stored muons

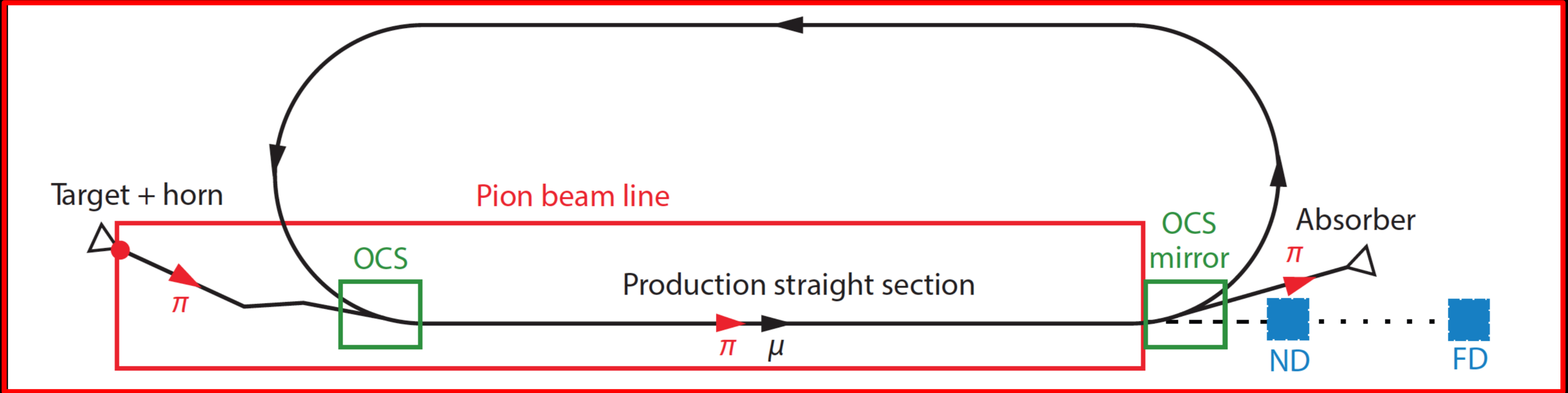


$$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$
$$\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$$

- Scientific objectives:
  1. %-level ($\nu_e N$)cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

- Precise neutrino flux:
  – Normalisation: < 1%
  – Energy (and flavour) precise
- π ➔ ↗injection pass:
  – "Flash" of muon neutrinos

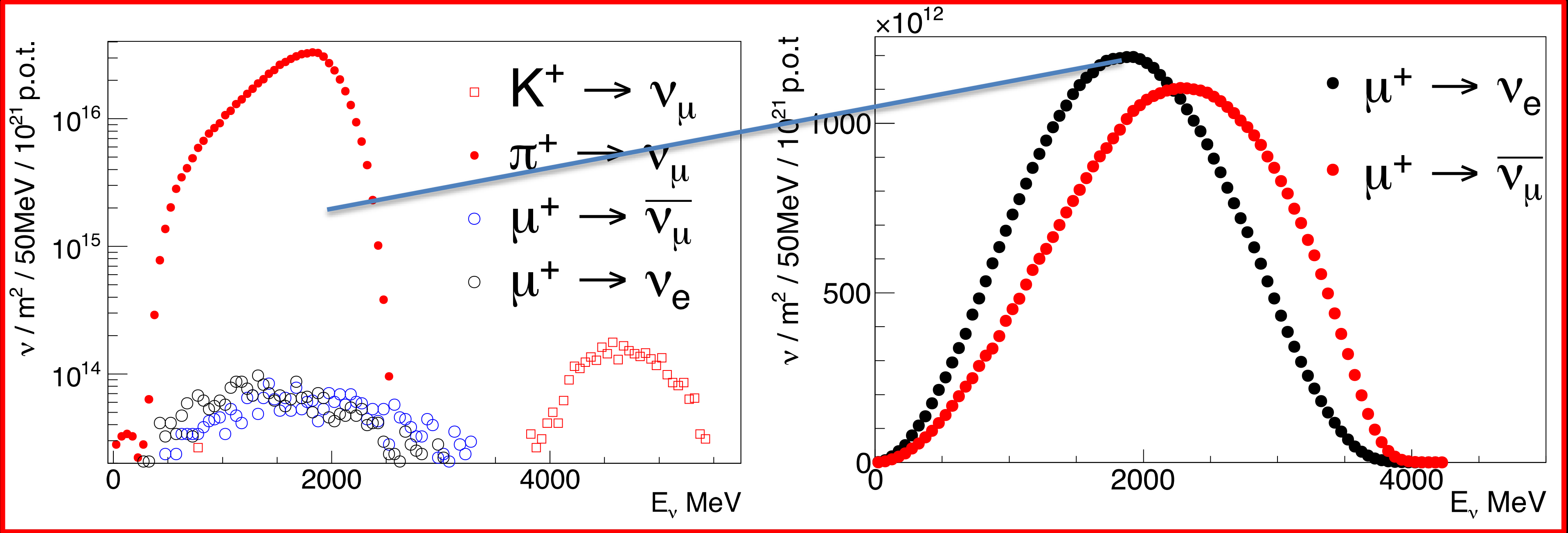
nuSTORM oveview



- **Fast extraction at >~ 100 GeV**
- **Conventional pion production and capture (horn)**
  - **Quadrupole pion-transport channel to decay ring**
- **“Stochastic injection” in “orbit combination section”**
  - **52% of pions decay before first bend**

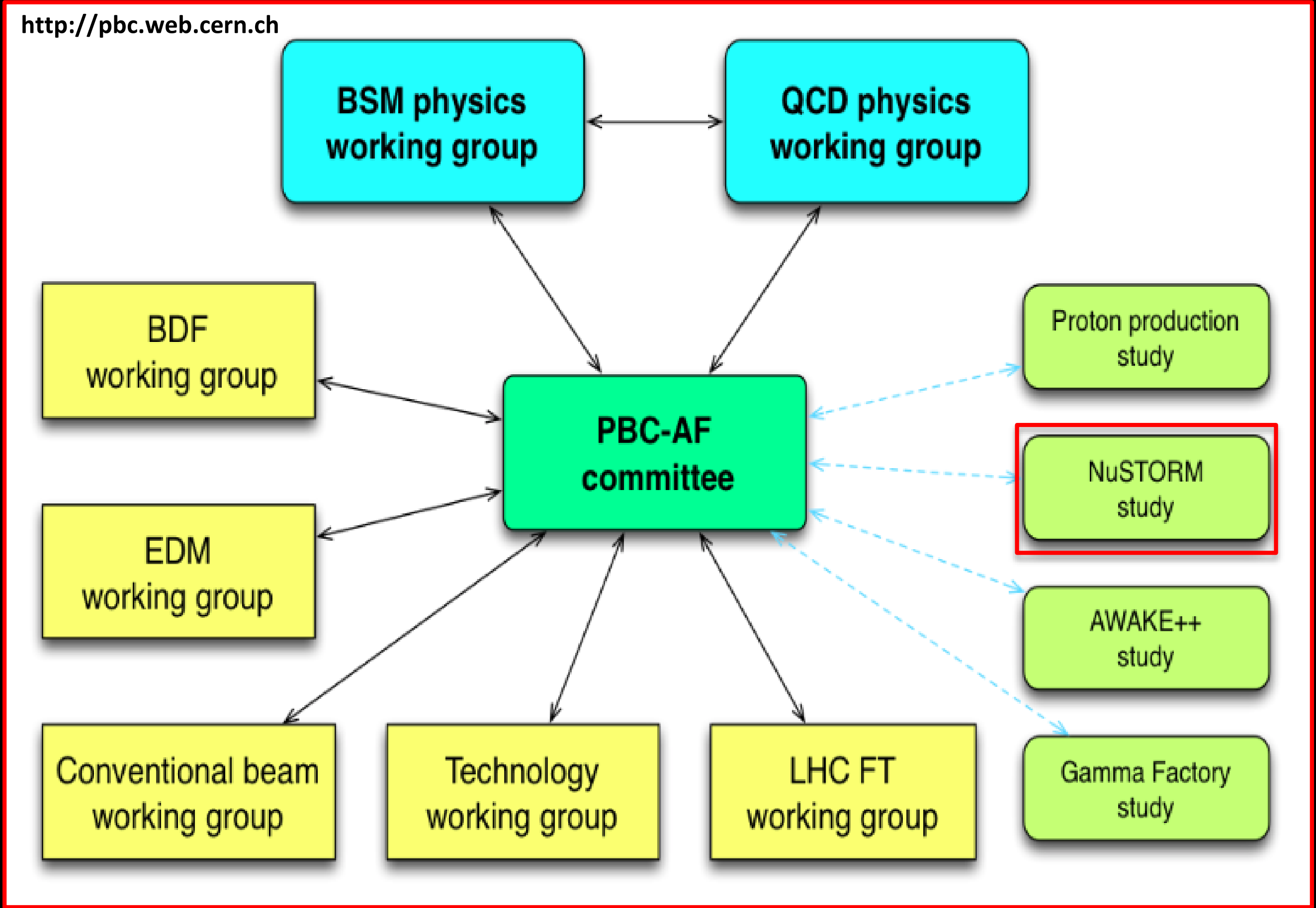
10.1146/annurev-nucl-102014-021930

Neutrino flux



- ν_μ flash:
  - Pion: 6.3×10^{16} m^{-2} at 50m
  - Kaon: 3.8×10^{14} m^{-2} at 50m
    - Well separated from pion neutrinos
- ν_e and ν_μ from muon decay:
  - ~10 times as many ν_e as, e.g. J-PARC beam
  - Flavour composition, energy spectrum
    - Use for energy calibration

Physics Beyond Colliders study group



http://pbc.web.cern.ch

To be studied

- **Physics case:**
  - **Neutrino-scattering for:**
    - **Oscillation**
    - **Nuclear**
- **Accelerator:**
  - **Full simulation that demonstrates <~1% flux precision**
  - **Energy range (i.e. sweep down from max)**
- **Implementation:**
  - **Feasibility at CERN (see next slide)**
- **Detector:**
  - **Others are "on this", so:**
    - **Adopt performance of typical, or assumed, detector**

“Exploratory study”

- A credible proposal for siting at CERN taking into account:
  - SPS requirements POT/year, beam parameters, potential users
  - Fast extraction, beam-line
  - Target and target complex, absorber
  - Horn: engineering, simulation, energy deposition
  - Siting of target and target complex, ring
    - radiation protection considerations…, interference...,
  - Civil engineering
    - preliminary study might be possible – resources required
  - RP implications, target, environment, fluxes near surface …

MICE and the future of muon beams for particle physics

CONCLUSIONS

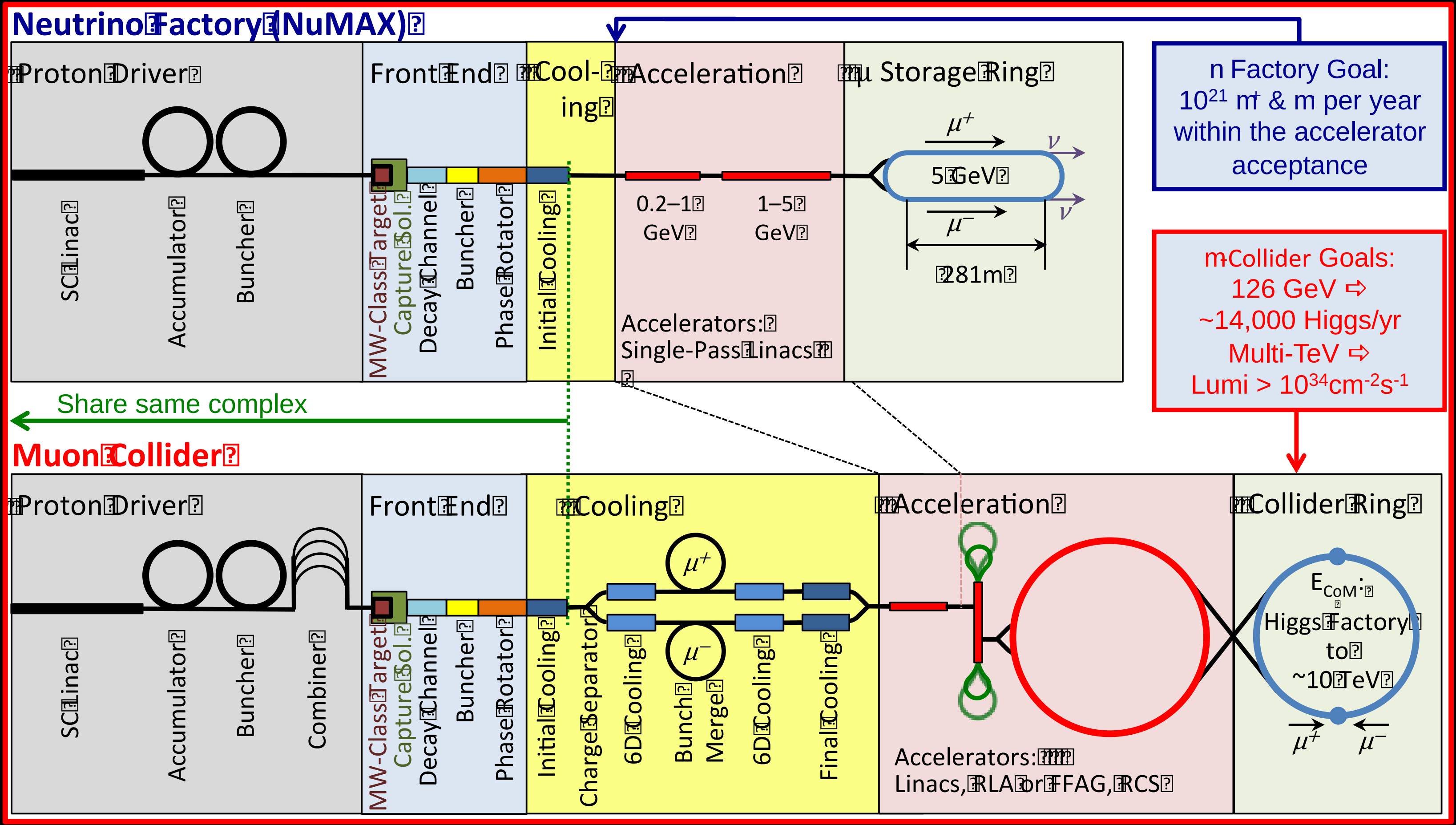
Conclusions

- MICE:
  - Successfully executing its experimental programme:
    - Measuring of multiple Coulomb scattering
    - Study of energy loss
    - Study of evolution of normalised transverse emittance
- Intense stored muon beams have the potential to:
  - Revolutionise neutrino physics
  - Provide multi-TeV lepton-anti-lepton collisions
- nuSTORM can deliver:
  - n*N* scattering measurements with precision required to:
    - Serve the long- and short-baseline neutrino programmes
    - Provide a valuable probe for nuclear physics
- CERN PBC study: opportunity to define innovative programme:
    - nuSTORM:
      - Delivers critical measurement: ν_e/ν_μ *N* scattering;
      - Has discovery potential: sterile neutrinos;
      - Potential for 6D ionization-cooling programme to follow MICE

MICE and the future of muon beams for particle physics

BACKUP

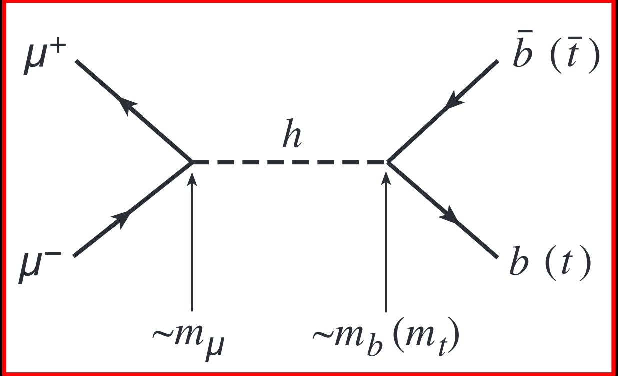
Muon Collider and Neutrino Factory

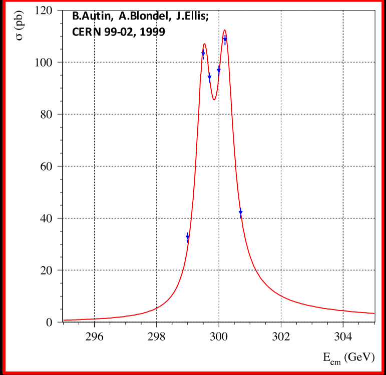


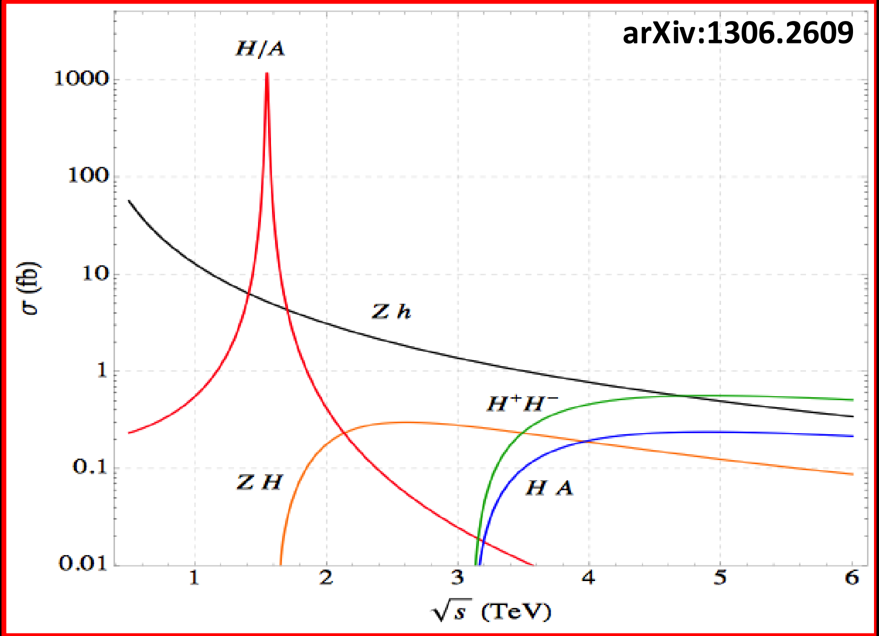
n Factory Goal:
10^{21} mt & m per year
within the accelerator
acceptance

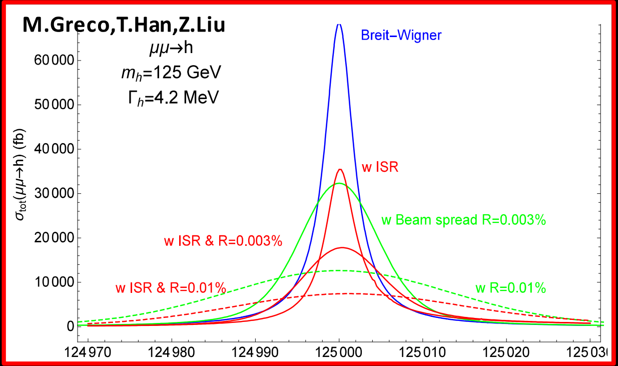
m-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

Energy frontier




B.Autin, A.Blondel, J.Ellis; CERN 99-02, 1999


arXiv:1306.2609


M.Greco,T.Han,Z.Liu

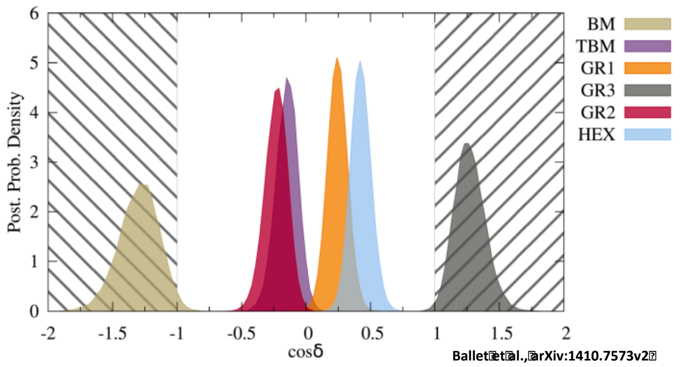
- **Example: Higgs studies**
  - **Line width; single resonance? Scan in *s*-channel**
  - **Couplings; require > 1 TeV for complete, precise study**

Neutrino Factory

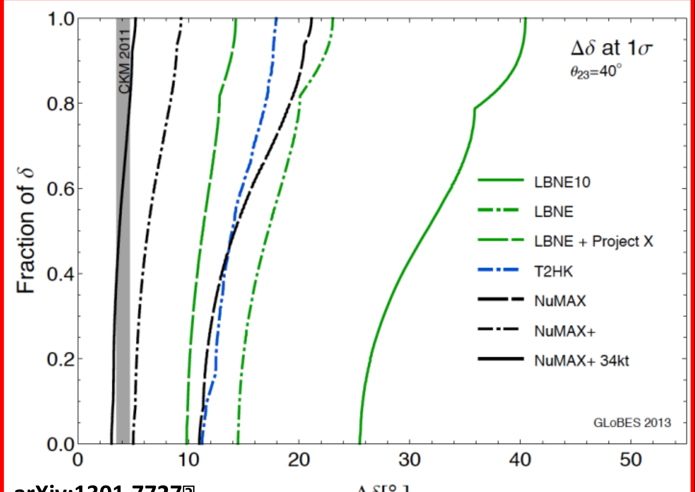
- Optimise sensitivity & precision:
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
    - Detailed study of sub-leading effects

$$\boxed{\begin{array}{lcl} \mu^+ & \rightarrow & e^+\nu_e\bar{\nu}_\mu \\ \mu^- & \rightarrow & e^-\bar{\nu}_e\nu_\mu \end{array}}$$

- Unique:
  - Large, high-energy ν_e ($\bar{\nu}_e$) flux
    - Muon-beam cooling
  - Favourable rigidity:
    - Optimise *E* for given *L*

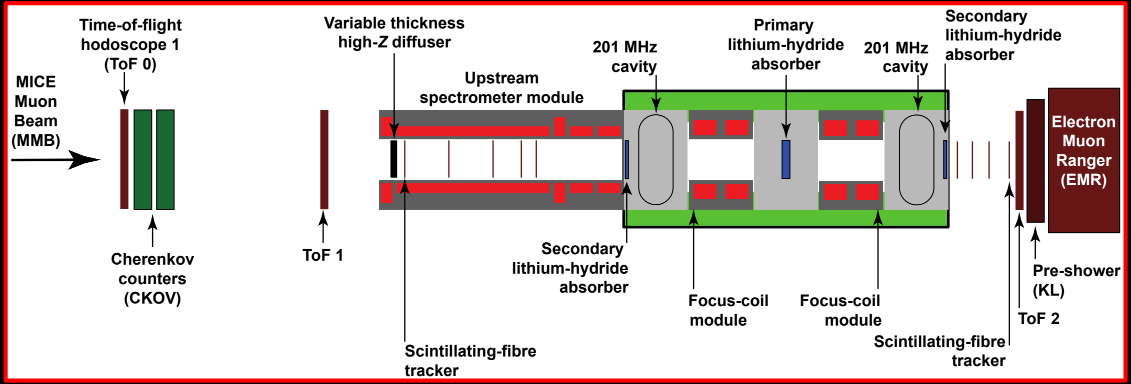


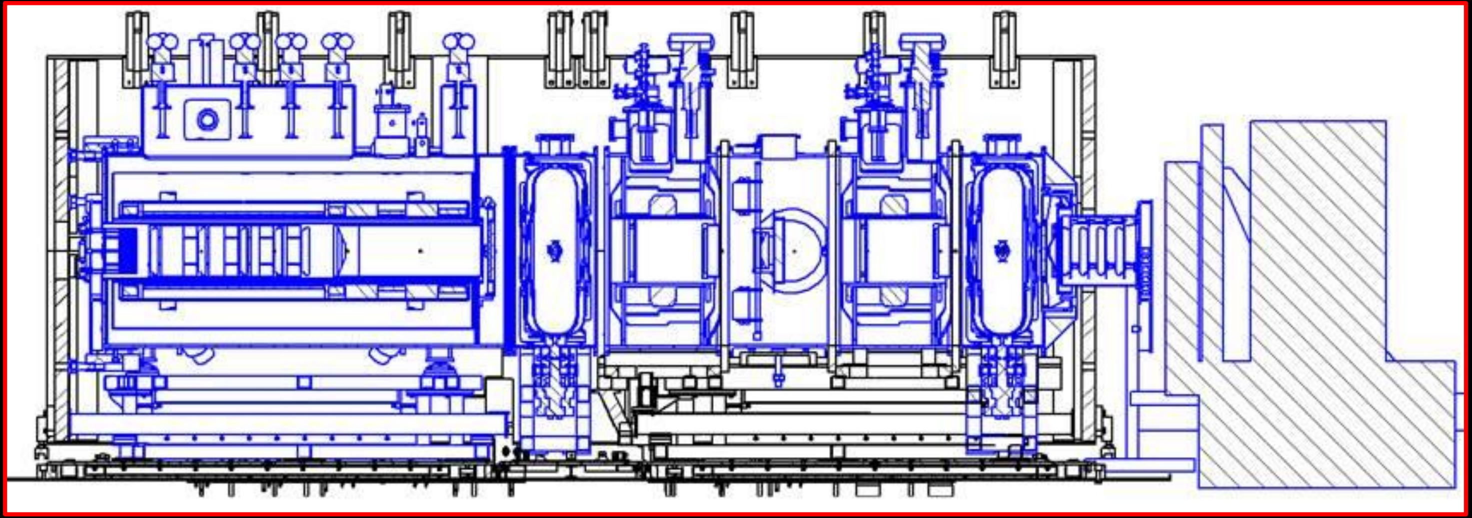
Ballet et al., arXiv:1410.7573v2



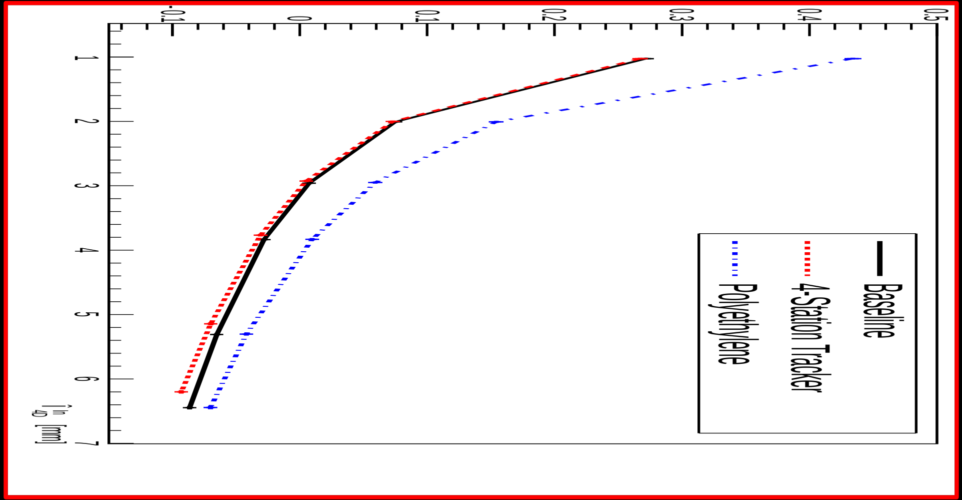
arXiv:1301.7727

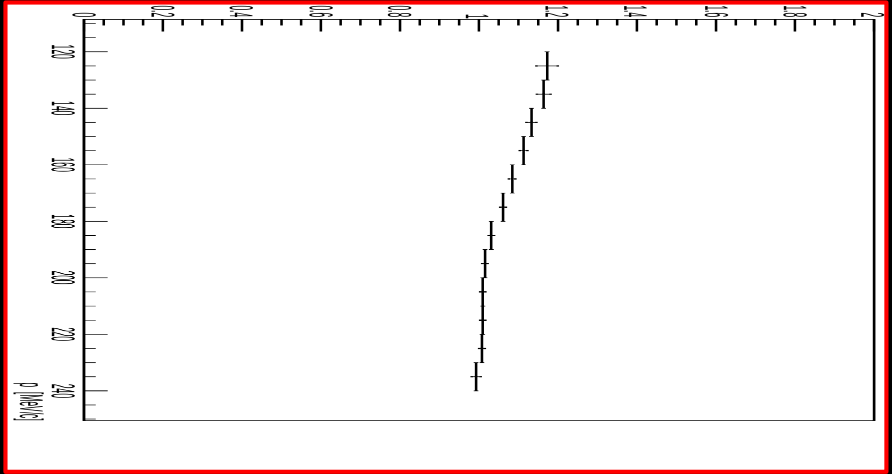
Upgraded configuration

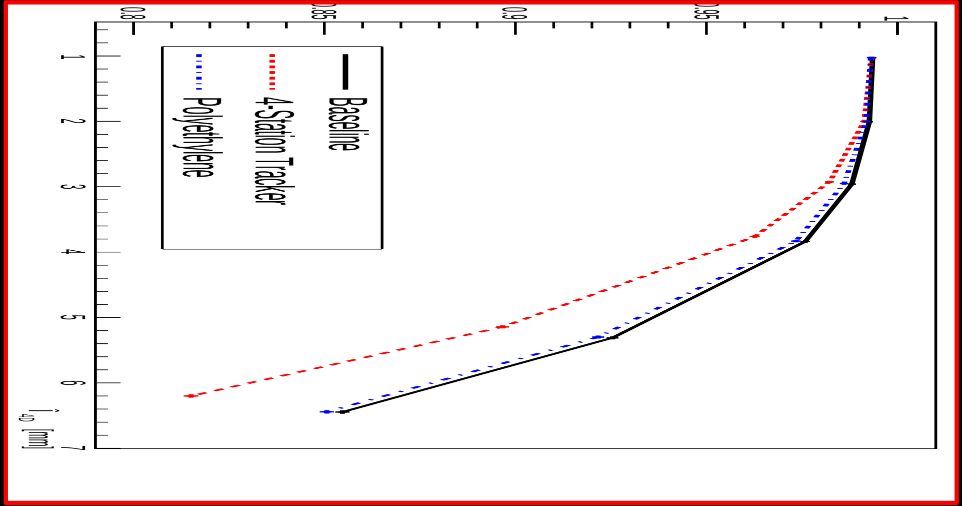


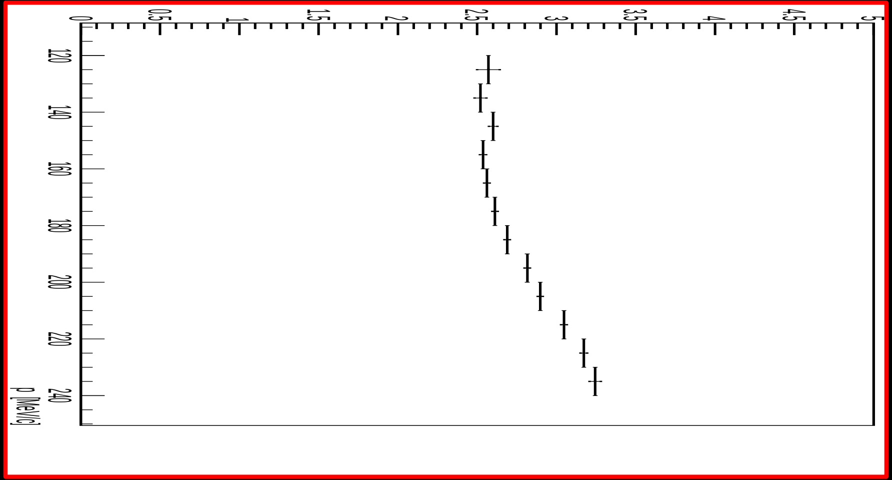


Performance



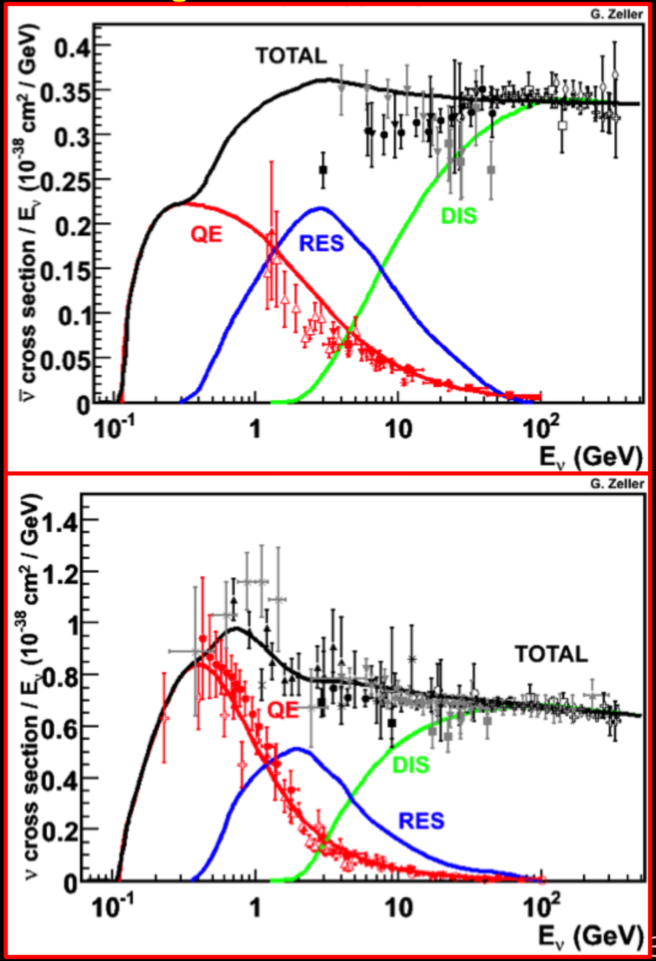


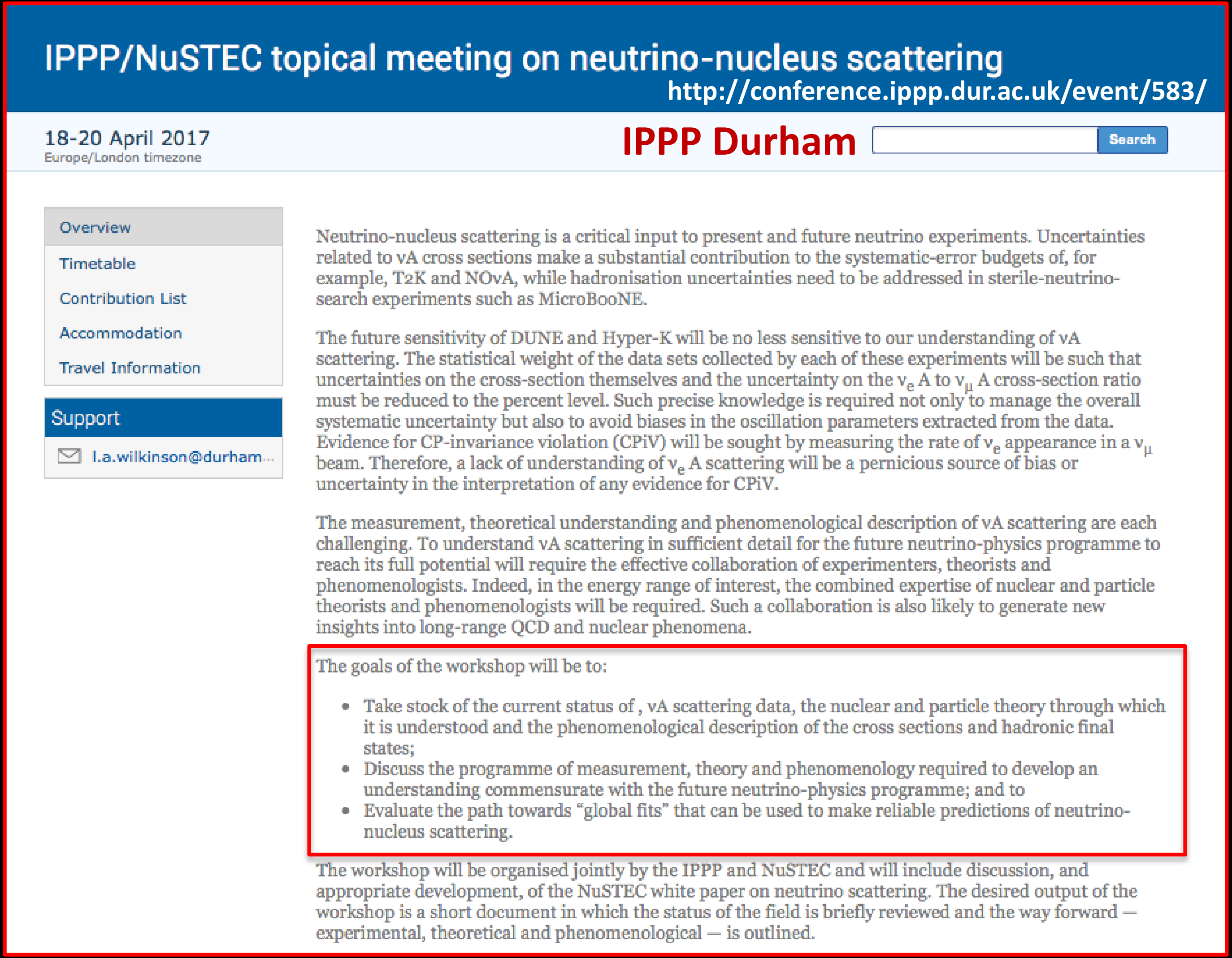




Specification

- Considerations:
  - Energy range:
    - Long- and short-baseline neutrino
    - Nuclear and particle physics
  - Acceptance:
    - Rate
    - Neutrino-energy calibration
  - Experiment:
    - Migration/feed-down





IPPP/NuSTEC topical meeting on neutrino-nucleus scattering

http://conference.ippp.dur.ac.uk/event/583/

18-20 April 2017
Europe/London timezone

IPPP Durham

Neutrino-nucleus scattering is a critical input to present and future neutrino experiments. Uncertainties related to νA cross sections make a substantial contribution to the systematic-error budgets of, for example, T2K and NOνA, while hadronisation uncertainties need to be addressed in sterile-neutrino-search experiments such as MicroBooNE.

The future sensitivity of DUNE and Hyper-K will be no less sensitive to our understanding of νA scattering. The statistical weight of the data sets collected by each of these experiments will be such that uncertainties on the cross-section themselves and the uncertainty on the ν_e A to ν_μ A cross-section ratio must be reduced to the percent level. Such precise knowledge is required not only to manage the overall systematic uncertainty but also to avoid biases in the oscillation parameters extracted from the data. Evidence for CP-invariance violation (CPiV) will be sought by measuring the rate of ν_e appearance in a ν_μ beam. Therefore, a lack of understanding of ν_e A scattering will be a pernicious source of bias or uncertainty in the interpretation of any evidence for CPiV.

The measurement, theoretical understanding and phenomenological description of νA scattering are each challenging. To understand νA scattering in sufficient detail for the future neutrino-physics programme to reach its full potential will require the effective collaboration of experimenters, theorists and phenomenologists. Indeed, in the energy range of interest, the combined expertise of nuclear and particle theorists and phenomenologists will be required. Such a collaboration is also likely to generate new insights into long-range QCD and nuclear phenomena.

The goals of the workshop will be to:

- Take stock of the current status of , νA scattering data, the nuclear and particle theory through which it is understood and the phenomenological description of the cross sections and hadronic final states;
- Discuss the programme of measurement, theory and phenomenology required to develop an understanding commensurate with the future neutrino-physics programme; and to
- Evaluate the path towards "global fits" that can be used to make reliable predictions of neutrino-nucleus scattering.

The workshop will be organised jointly by the IPPP and NuSTEC and will include discussion, and appropriate development, of the NuSTEC white paper on neutrino scattering. The desired output of the workshop is a short document in which the status of the field is briefly reviewed and the way forward — experimental, theoretical and phenomenological — is outlined.

Will provide i/p to:

- **Nuclear physics case**
- **Energy**