Imperial College London

Science & Technology Facilities Council

Perspectives on the route to a multi-TeV muon collider

K. Long, 3 June, 2019

Contents

- Ambition
- Muon accelerators for particle physics
- Muon collider
- nuSTORM
- To realise the ambition

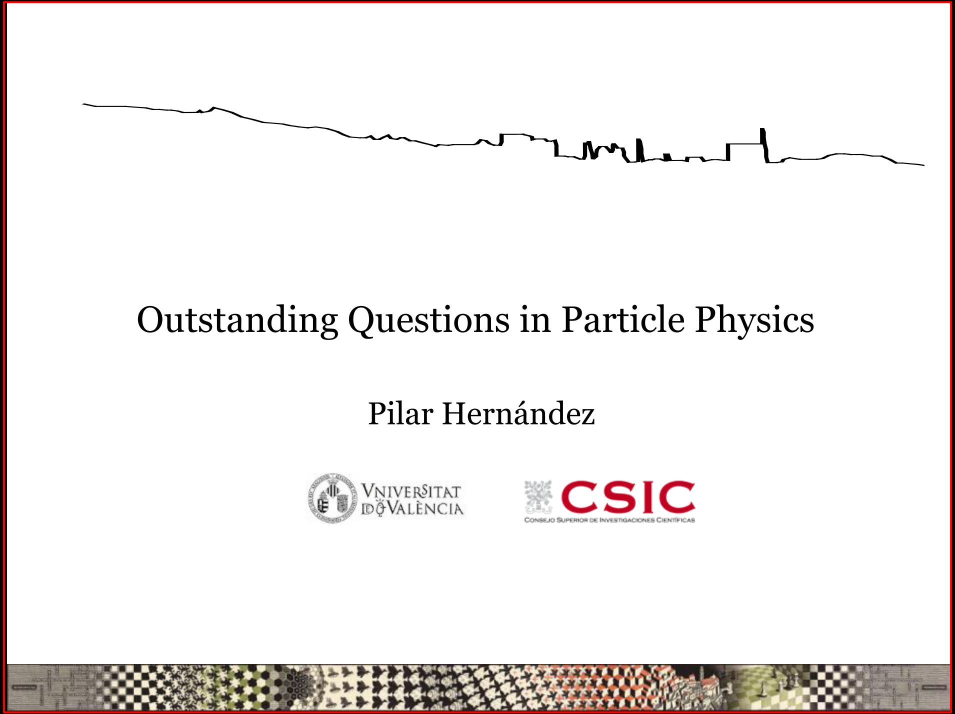
Perspectives on the route to a multi-TeV muon collider

AMBITION

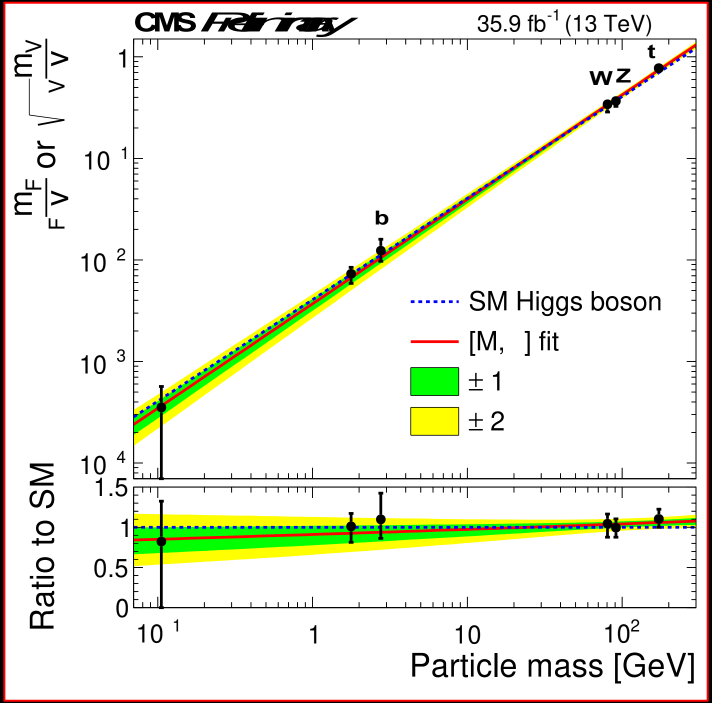
Outstanding questions …

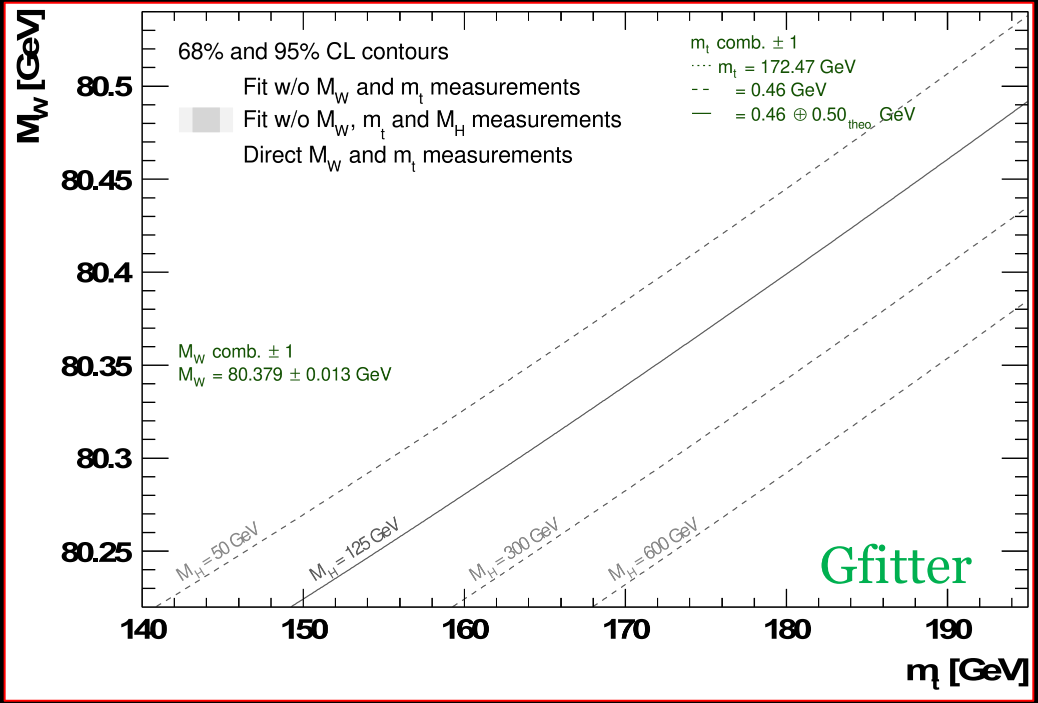
- … for the accelerator-based programme:

My take on part of P.Hernanez' excellent introduction to ESPPU



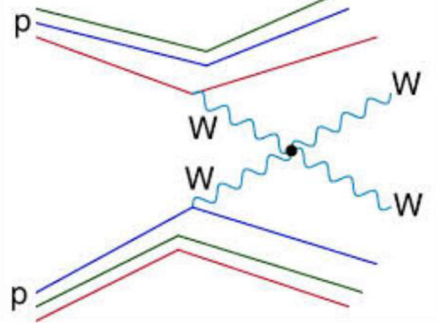
The Higgs as window on new physics

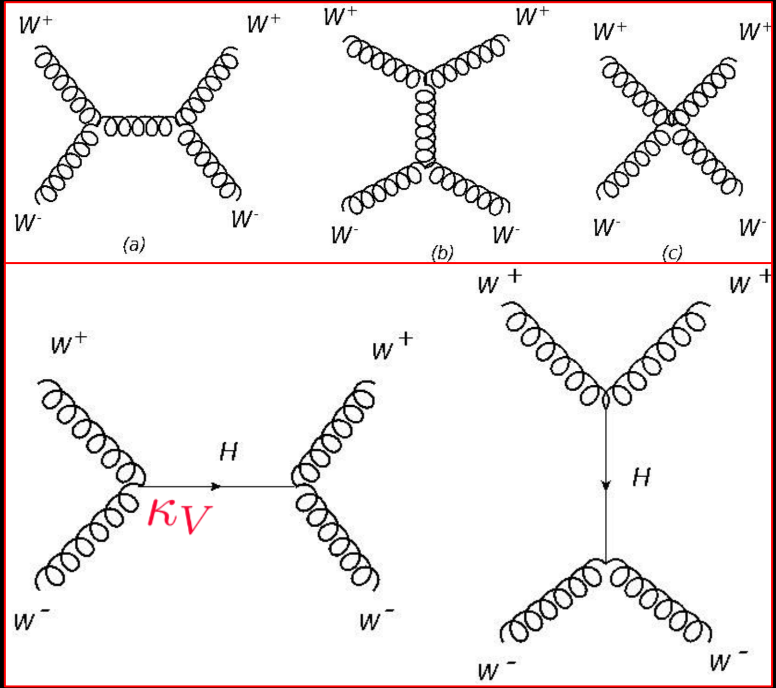


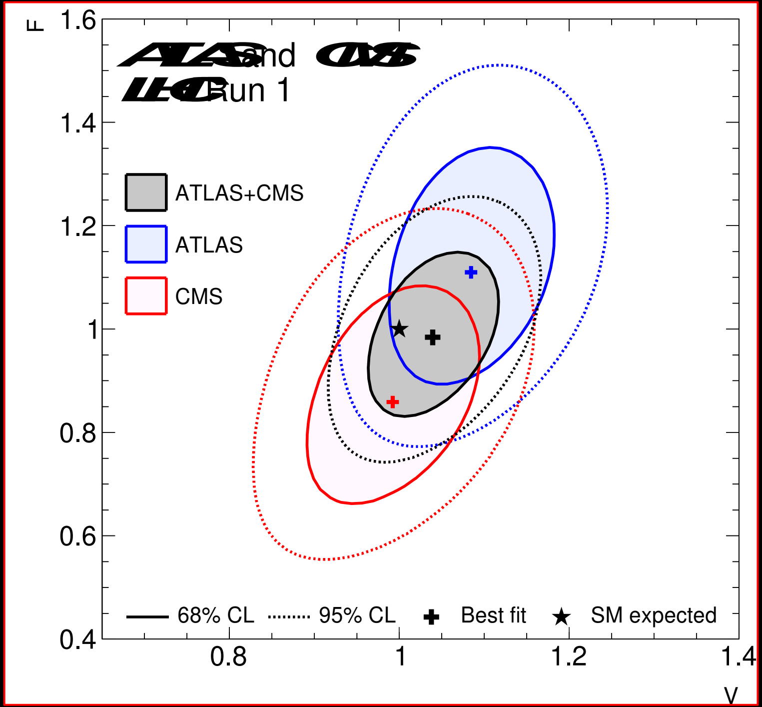


- m_{Higgs}= 125.09(24) GeV
  - Standard Model: predictive & verified at this level of precision

Higgs as window on new physics







SM within uncertainty

Motivates Higgs factory to reduce substantially

Statistical and systematic uncertainties

Neutrinos as window on origin of flavour

$SU(3) \rightarrow SU(2) \rightarrow U(1)_Y$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
⌫e, e L	u^i, d^i L	e_R	u^i_R	d^i_R
⌫μ, μ L	c^i, s^i L	μ_R	c^i_R	s^i_R
⌫☒, ☒ L	t^i, b^i L	☒R	t^i_R	b^i_R

$$V_{CKM} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

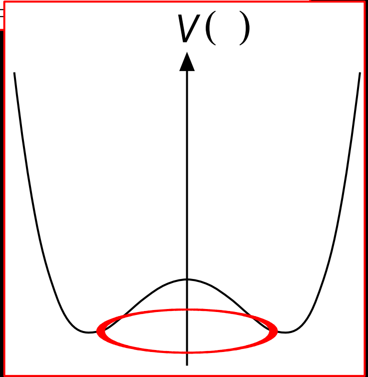
$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \rightarrow 0.844 & 0.516 \rightarrow 0.582 & 0.141 \rightarrow 0.156 \\ 0.242 \rightarrow 0.494 & 0.467 \rightarrow 0.678 & 0.639 \rightarrow 0.774 \\ 0.284 \rightarrow 0.521 & 0.490 \rightarrow 0.695 & 0.615 \rightarrow 0.754 \end{pmatrix}$$

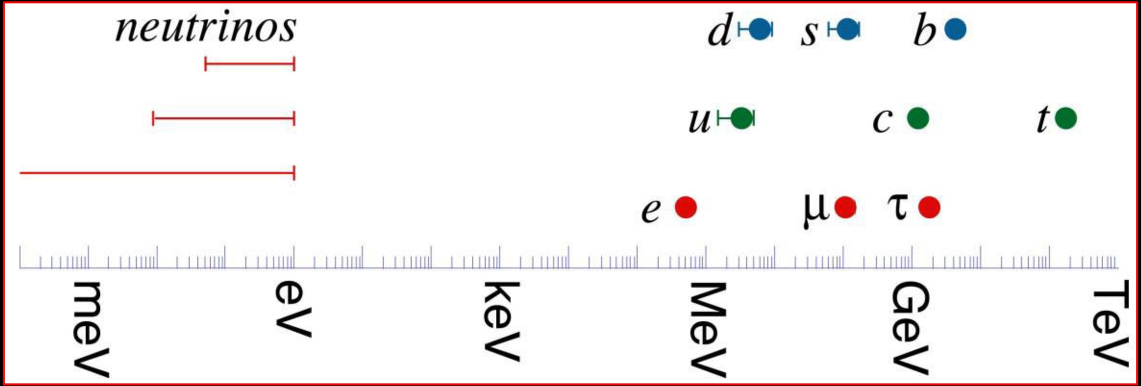
PMNS

Related to physics at very high energy scale

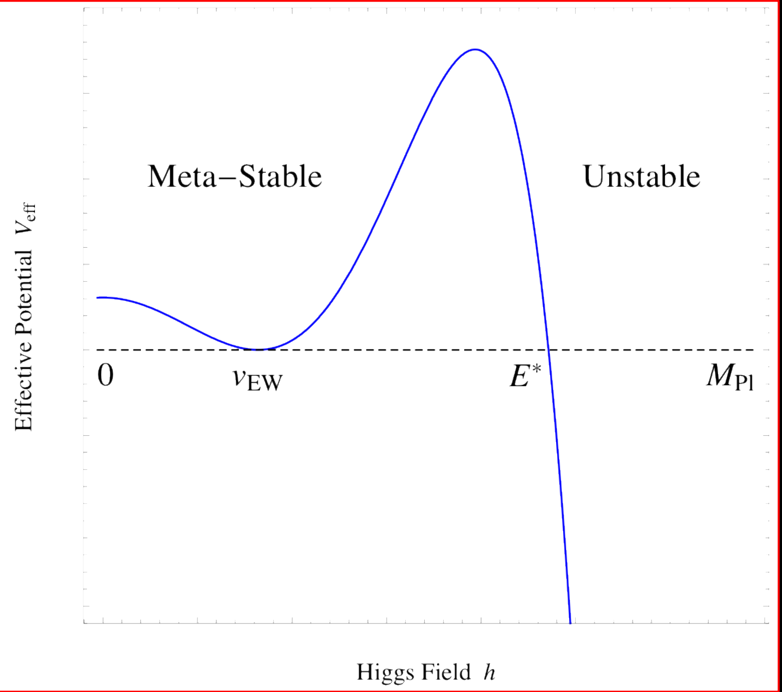
Motivates high-precision neutrino programme

Large event samples *and* low systematic uncertainties





Energy frontier to illuminate limit of SM



Degrassi et al ‘12

Measurement at highest possible energy

Experimental motivation clear!

Theorists motivated by ‘meta-stability’ of SM

And so, the ambition

Our ambition is to make measurements:

- **Of the properties of the Higgs**
  - **With the highest possible precision**
- **Of the properties of the neutrino**
  - **With the highest possible precision**
- **Of the properties of matter**
  - **At the highest possible energies**

What is the role of muon beams?

Perspectives on the route to a multi-TeV muon collider

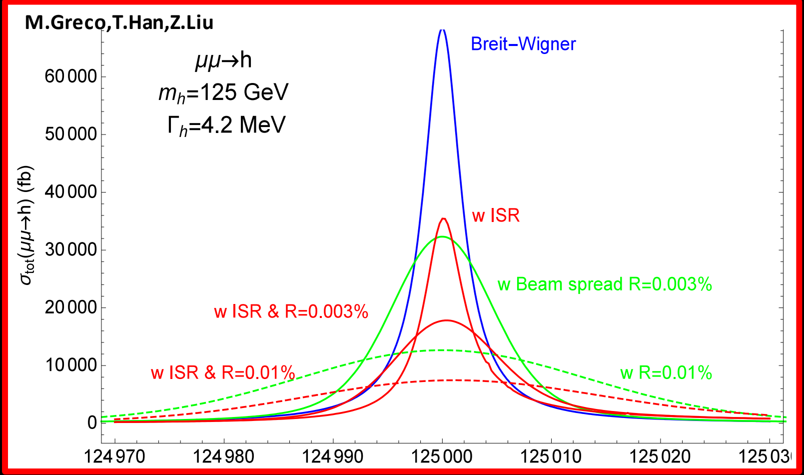
MUON ACCELERATORS FOR PARTICLE PHYSICS

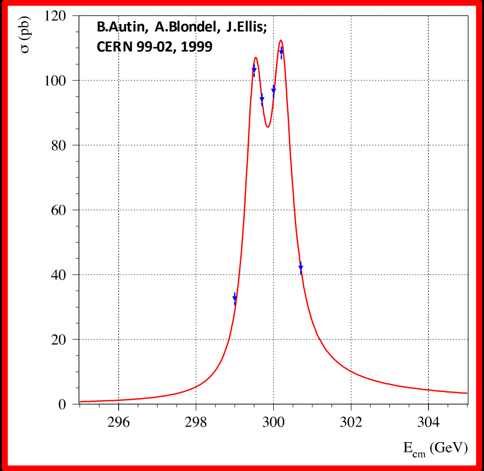
Basis of potential

- **Muon mass:**
  - $200 m_e \sim m_\mu \sim 0.1 m_p$
- **Energy frontier:**
  - No brem-/beam-sstrahlung
    - Rate $\propto m^{-4}$ [5×10^{-10} cf e]
  - Enhanced coupling to Higgs
    - Production rate $\propto m^2$ [5×10^4 cf e^+e^-]
  - Efficient acceleration
    - Favourable rigidity
- **Muon decay:**
  - ν_e, ν_μ
  - Precisely known energy spectrum
- **Physics of flavour:**
  - Precision neutrino physics
  - Sensitive cLFV searches

Line shape

- Standard Model Higgs:
  - *M* = 125 GeV; Γ=4.5 MeV
    - Exquisite resolution
      - R < 0.003%





- "Two-state" Higgs:
  - Deviation from SM line shape
  - Resolve states
    - Exquisite resolution!

Couplings/branching ratios

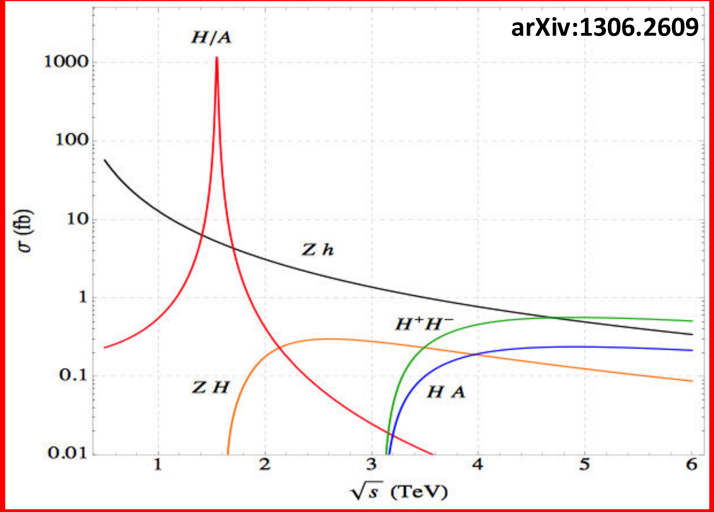
- **Standard Model Higgs**
  - Accurate threshold measurement
  - Exploiting accurate knowledge of (narrow) energy spectrum

R (%)	$\mu^+\mu^- \to h$	$h \to b\bar{b}$		$h \to WW^*$	
	$\sigma_{\rm eff}$ (pb)	σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
0.01	7.3	3.4	20	1.7	0.051
0.003	17	8.0		2.5	

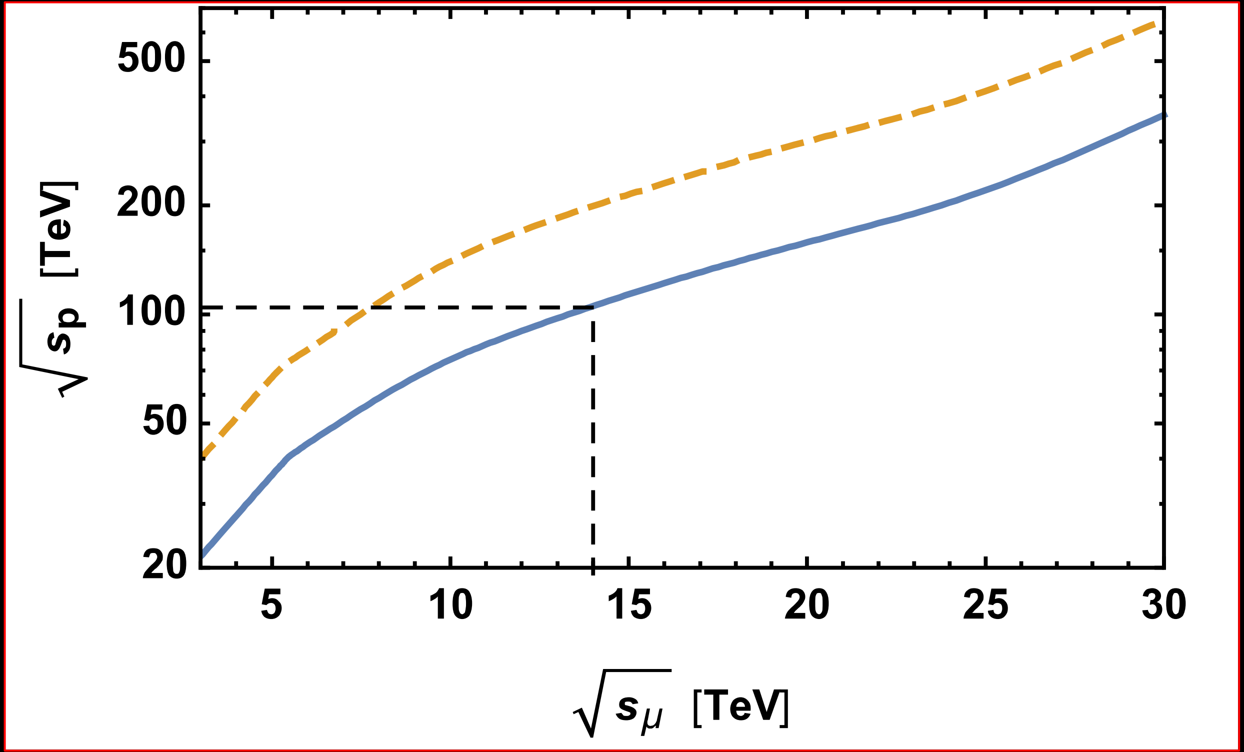
M.Greco,T.Han,Z.Liu

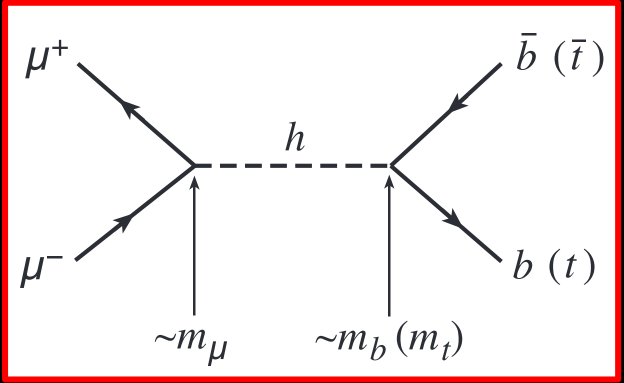
m_{bb} > 100 GeV

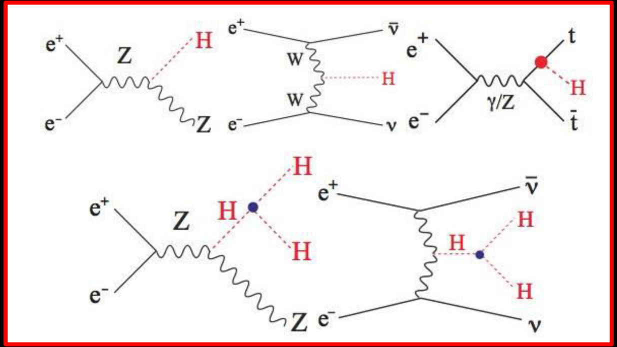
- **Beyond SM Higgs**
  - Exploit narrow energy spectrum to search for :
    - Narrow resonances
    - Unexpected thresholds



The Standard Model and beyond

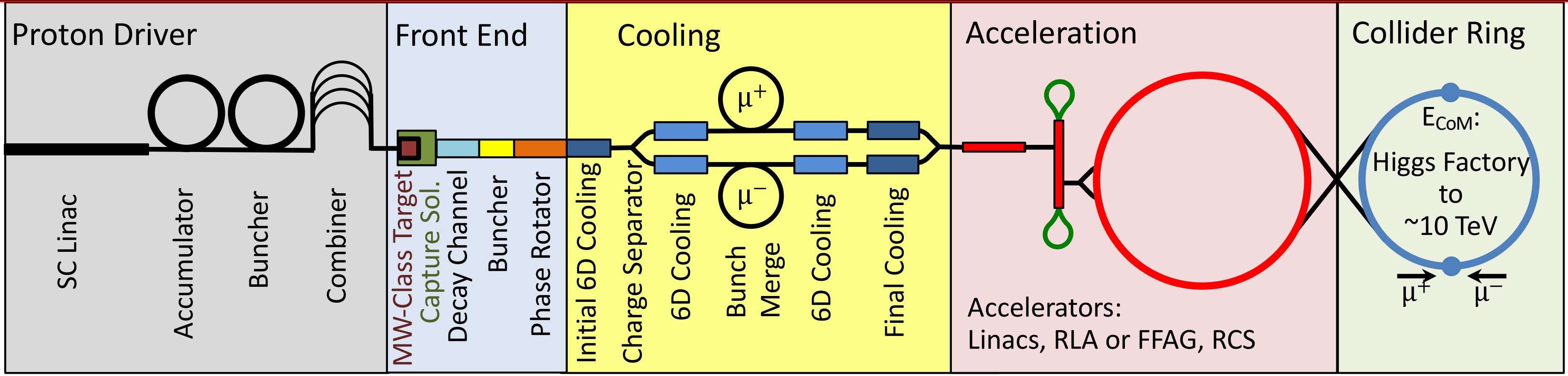




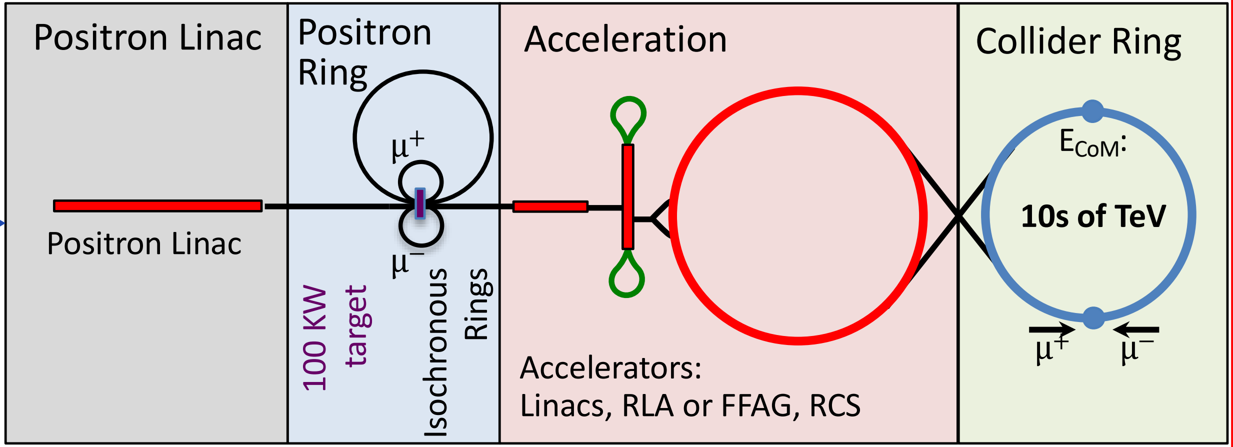


- Energy frontier: big advantage over pp because fundamental fermion
- Future study of the Higgs:
  - Line width; establish single resonance (?) in s-channel with $\mu^+\mu^-$
  - Couplings; requires > 1 TeV for complete, precise study

Resurgence of interest: Pastrone Panel



Low EMmittance Muon Accelerator (LEMMA):
10^{11} ∝ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



CERN
Horn and bubble chamber
First neutrino beam

BNL
first neutrino "beam"

IHEP
SKAT, INR

CERN
Horn #2 & Gargamelle

CERN
Gargamelle, Aachen/Padova, CDHS, CHARM, BEBC, CCFR, NOMAD, CHORUS

BNL/FNAL
CITF, HPWF, 7' BC, 15' BC, E605, E613, E734, E776, NuTEV

FNAL
MINOS, MINOS+, NOvA

CERN
OPERA, ICARUS

KEK/J-PARC
K2K, T2K

Global neutrino progamme
Hyper-K
LBNF/DUNE
CERN Neutrino Platform

1950 — 1960 — 1970 — 1980 — 1990 — 2000 — 2010 — 2020 — 2030

discovery (BNL)

e/ universality

Neutral Current discovery

Development of E/w SM, QPM, QCD

Development of Standard Neutrino Model

Discovery of CP-invariance violation?

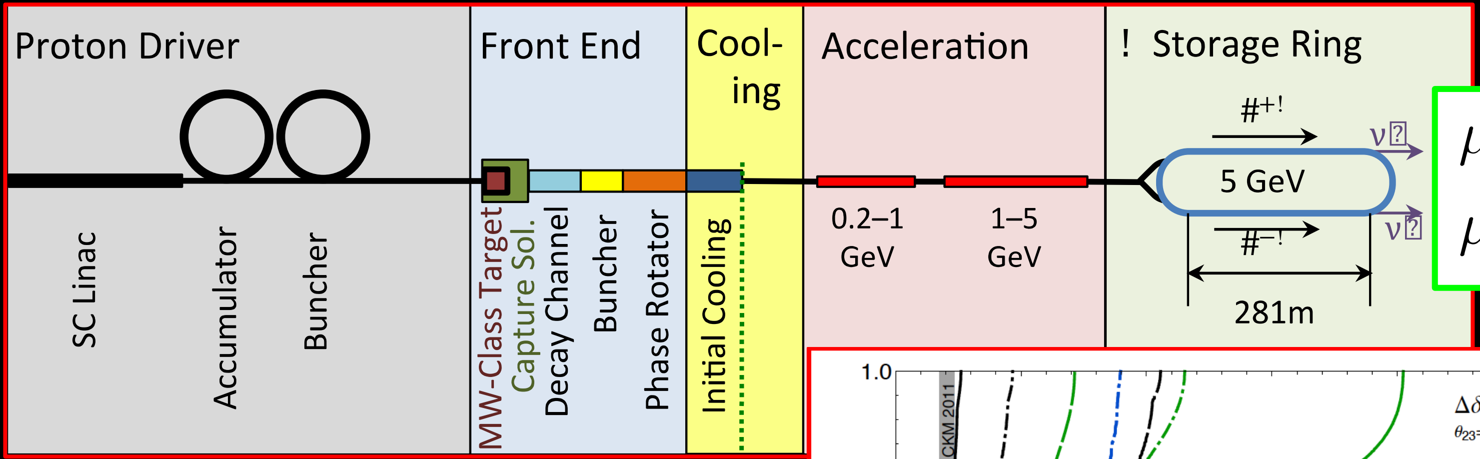
Fast extraction

Simon van der Meer
CERN, 1961

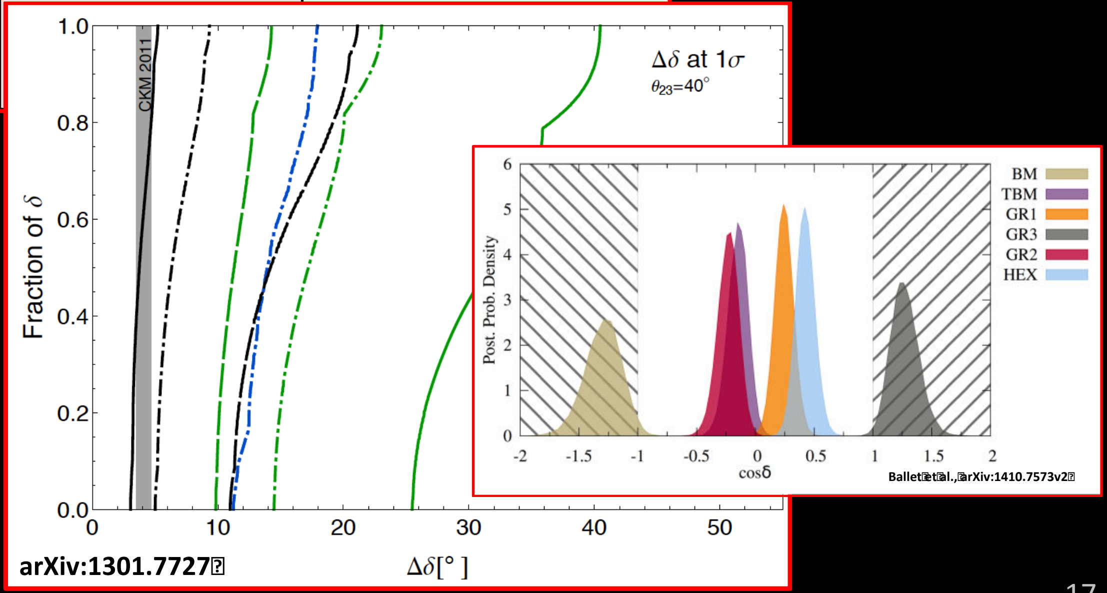
Innovation in detectors to provide:
- High-precision
- Large data sets
- Control of systematics

Innovation in accelerators to go beyond

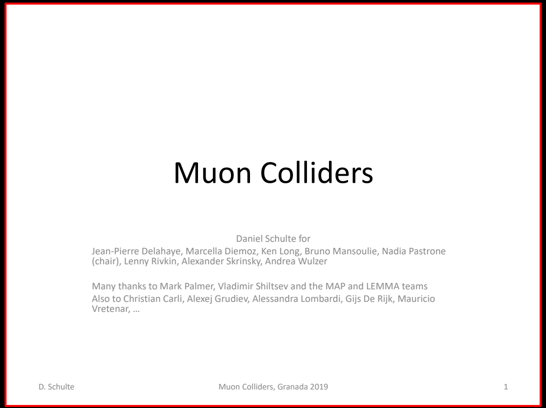
Neutrino Factory: sensitivity & precision



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



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



Perspectives on the route to a multi-TeV muon collider

MUON COLLIDER

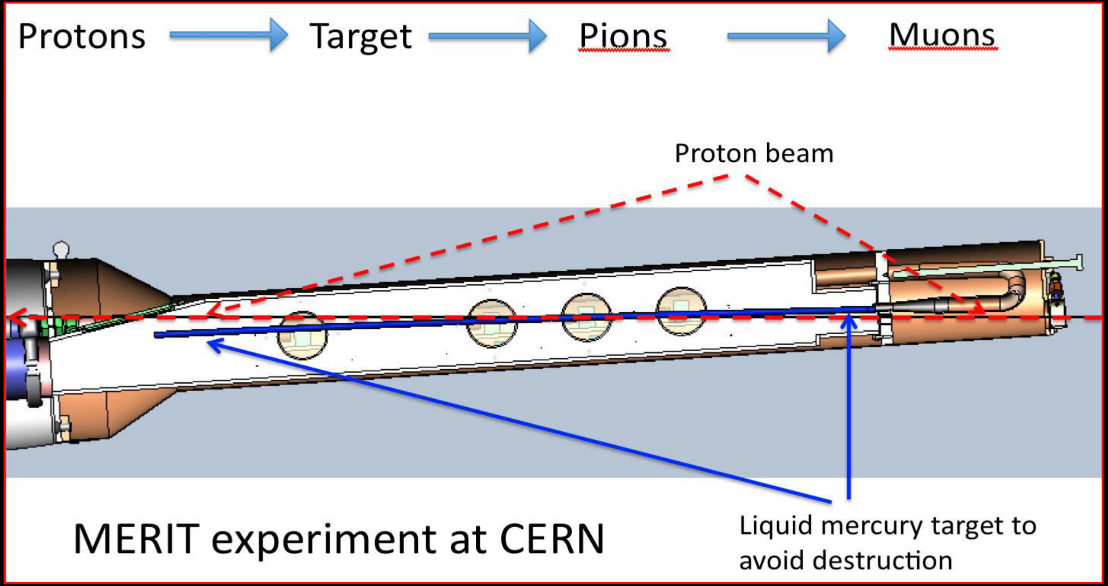
Collider Parameter Examples

From the MAP collaboration: Proton source

Muon Collider Parameters

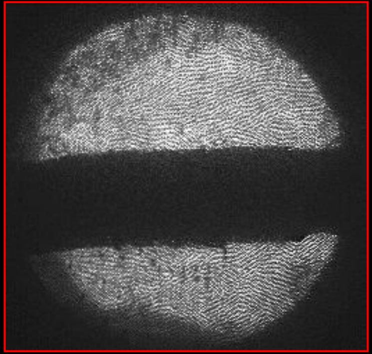
		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34} cm^{-2} s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, $_{TN}$	mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, $_{LN}$	mm-rad	1.5	70	70	70
Bunch Length, $_{s}$	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Source



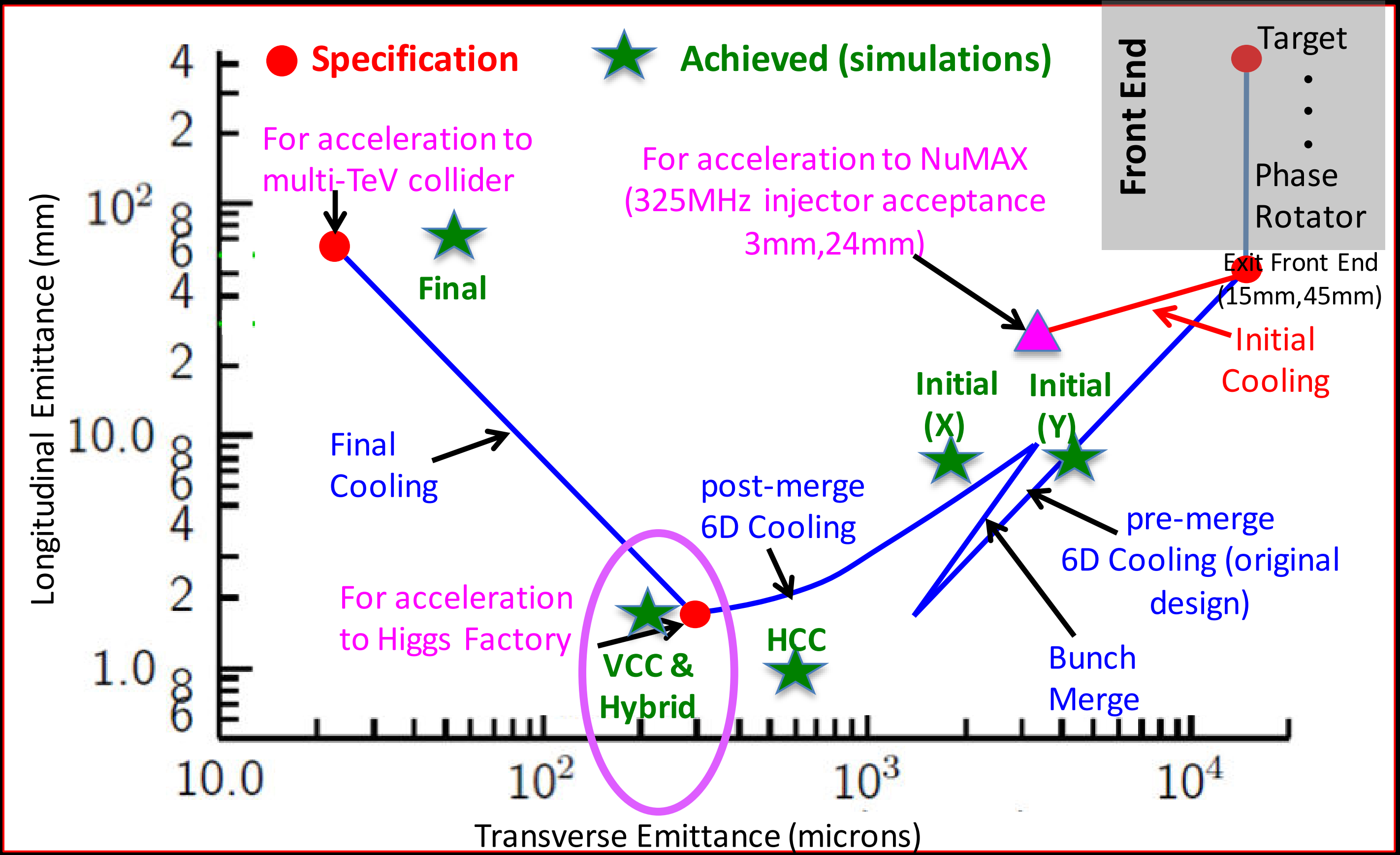
- **The MERIT Experiment at the CERN PS**
  - **Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!**

  ⇨ **Jets could operate with beam powers up to 8 MW with a repetition rate of 70 Hz**

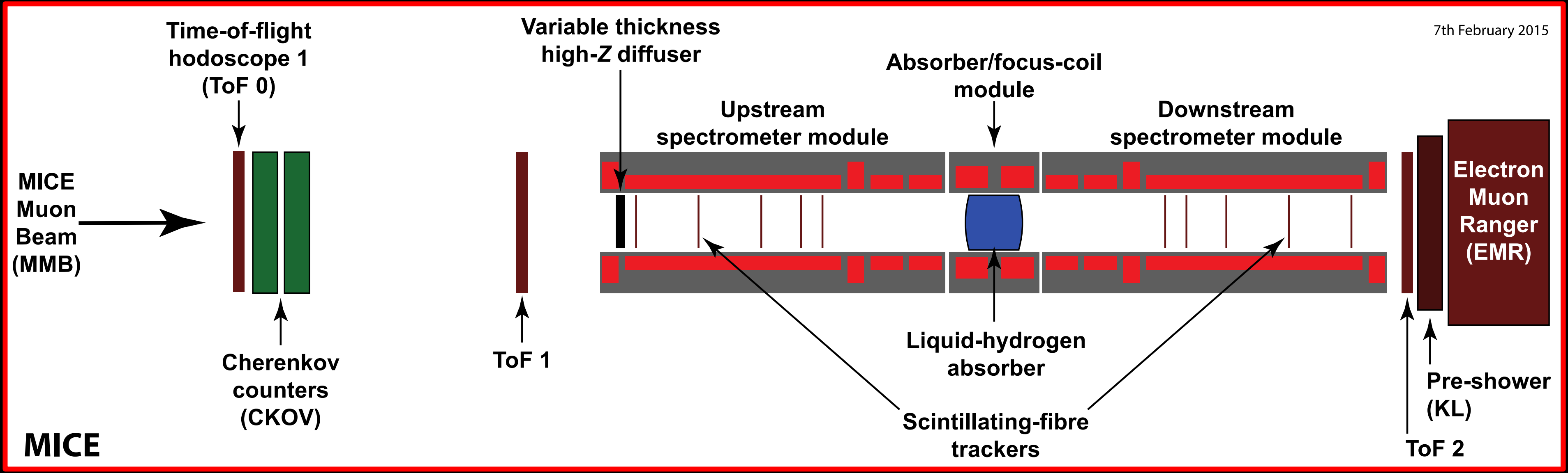


Hg jet in a 15 T solenoid: measured disruption length ~28 cm

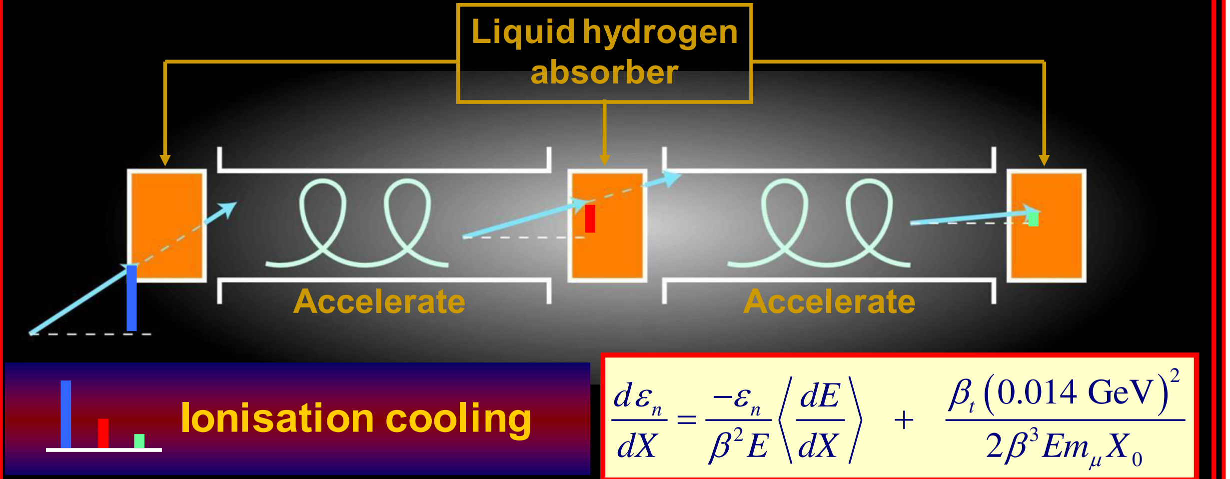
Cooling: the emittance path



Muon Ionization Cooling Experiment



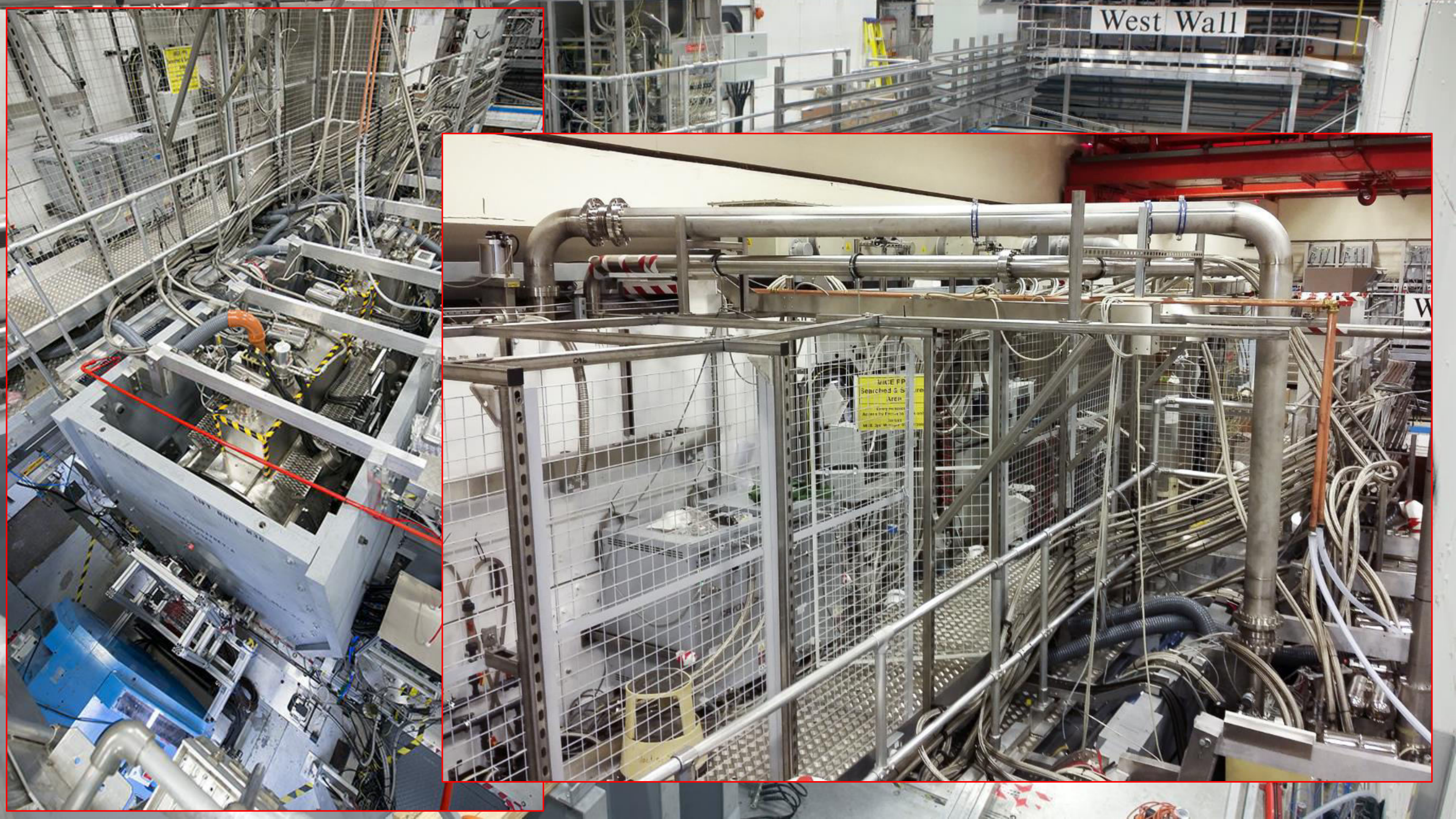
The principle of ionization cooling



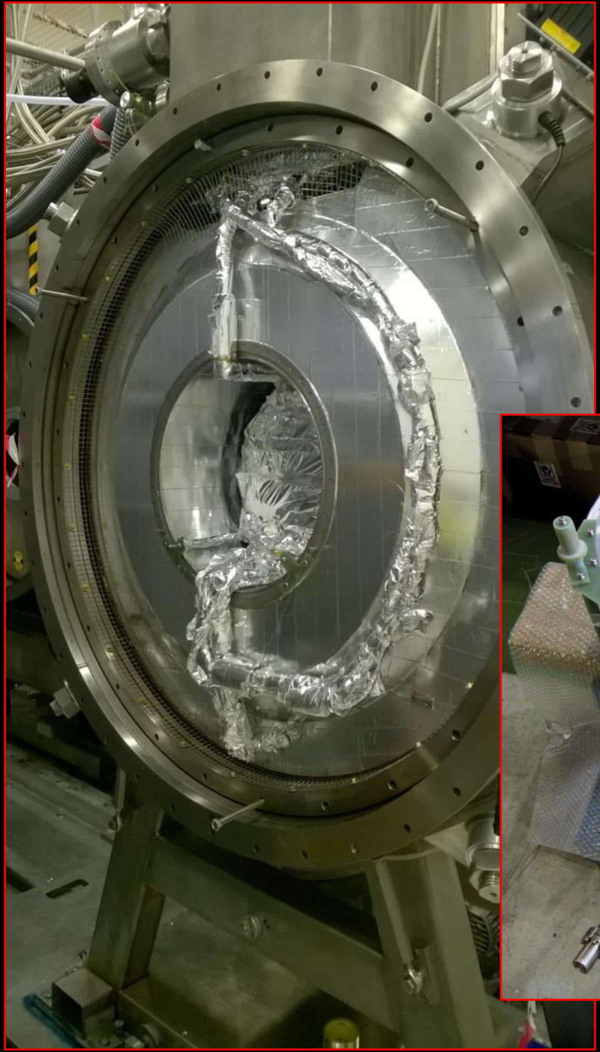
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

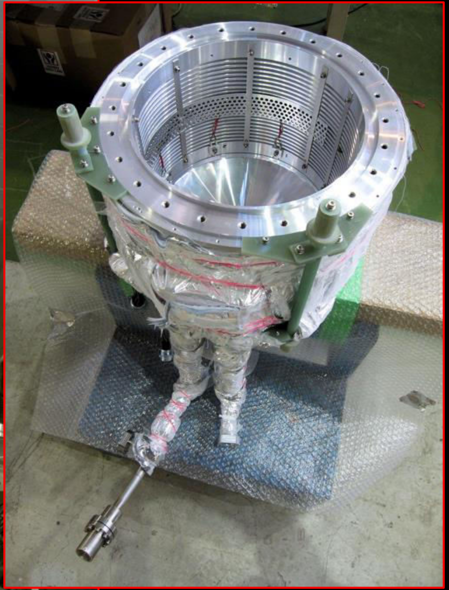
	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

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


West Wall

Liquid-hydrogen absorber

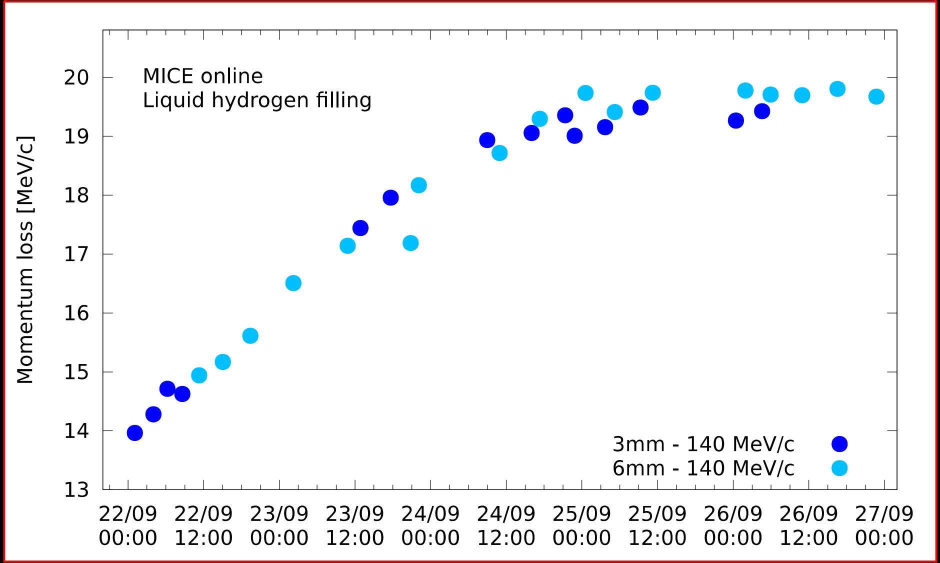




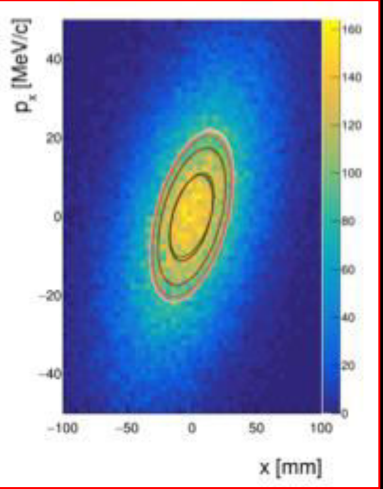
Online reconstruction:

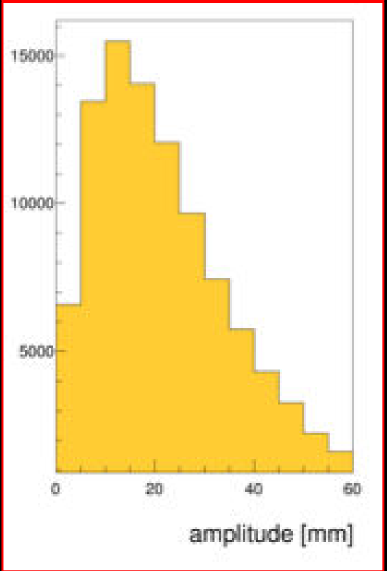
Mean momentum lost by muons as they pass through the liquid-hydrogen absorber.

The data were recorded while the absorber was filling.



Emittance and amplitude





Phase space, covariance, emittance and amplitude

Phase space: $\mathcal{P} = (x, p_x, y, p_y)^{\mathrm{T}}$

Covariance: $\mathcal{C} = \left\langle \Delta\mathcal{P}\Delta\mathcal{P}^{\mathrm{T}} \right\rangle$

Normalised transverse emittance: $\varepsilon_T = \frac{|\mathcal{C}|^{\frac{1}{4}}}{m_\mu}$

Transverse amplitude: $A_T = \varepsilon_T \mathcal{P}^{\mathrm{T}}\mathcal{C}^{-1}\mathcal{P}$

- **Emittance:**
  - Evaluated from RMS beam ellipse
- **Amplitude:**
  - Distance from core of beam
- **Mean amplitude ~ RMS emittance**

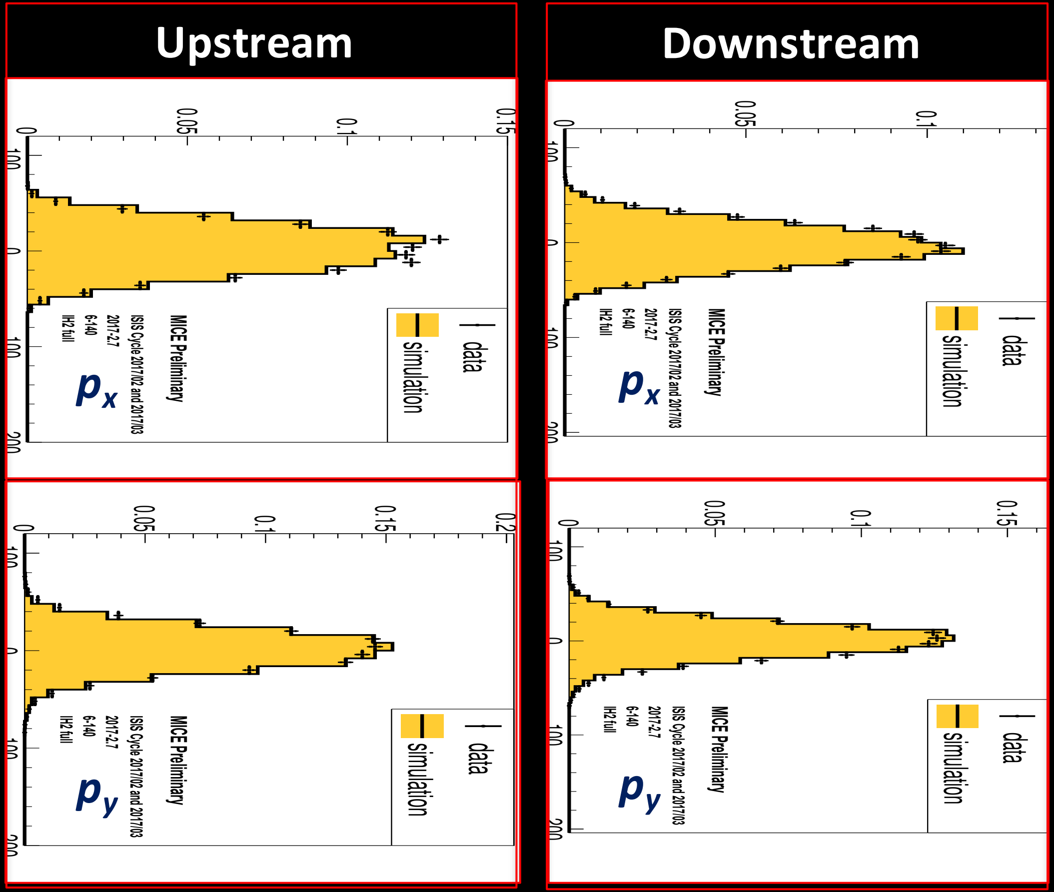
Effect of lithium-hydride absorber

Simulation in good agreement with data

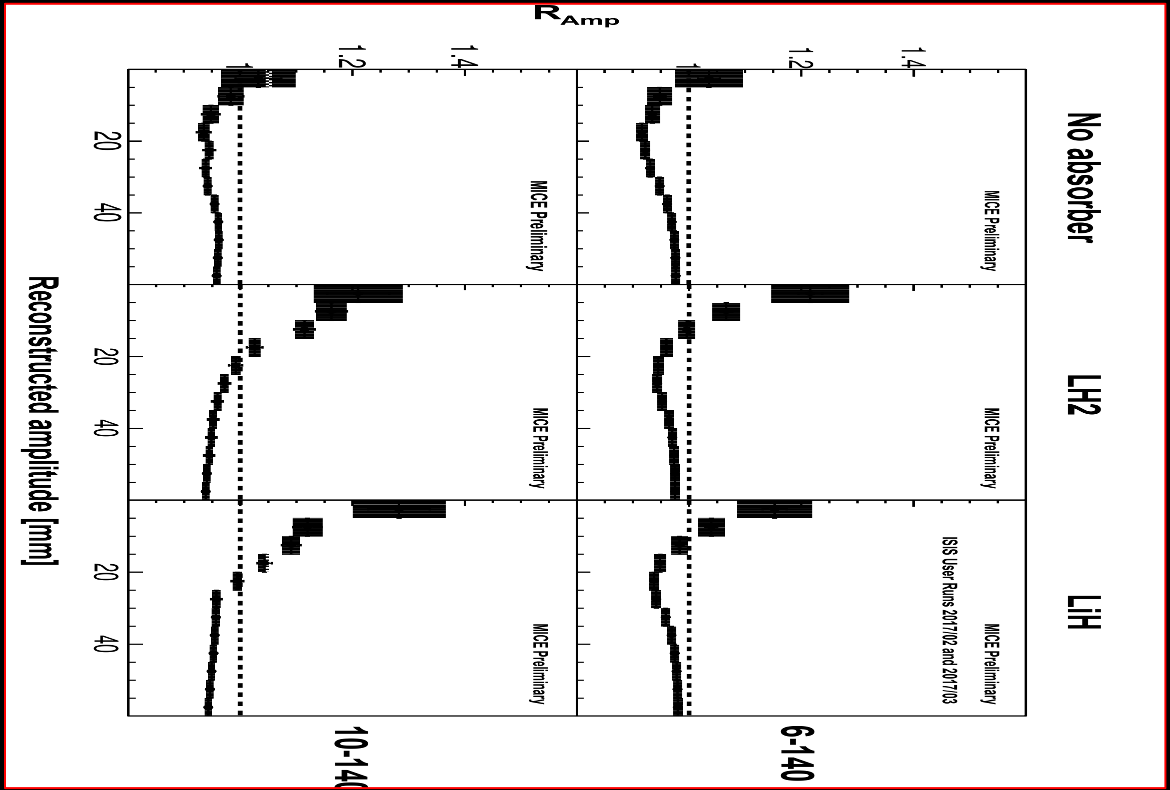
– Example:

- ε_T = 6 mm
- P = 140 MeV/c

Notation: P-ε_T = 6-140



Core-density change across absorber



R_{amp} = ratio of cumulative density downstream to upstream

Core-density:

- *Increases* with LiH and LH2 absorbers
- *Consistent with 'no change'* for no absorber

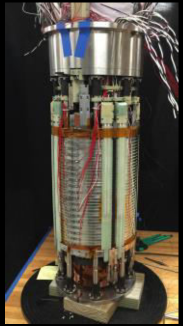
Ionization-cooling signal

Preparing submission to nature.

Other Tests

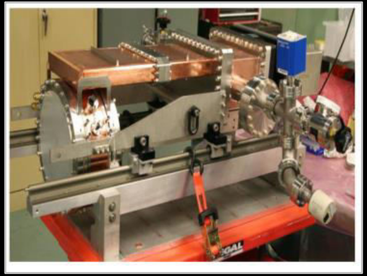
FNAL
Breakthrough in
HTS cables

NHFML
32 T solenoid with low-temperature HTS



FNAL
12 T/s HTS
0.6 T max

MuCool: >50MV/m in 5 T field

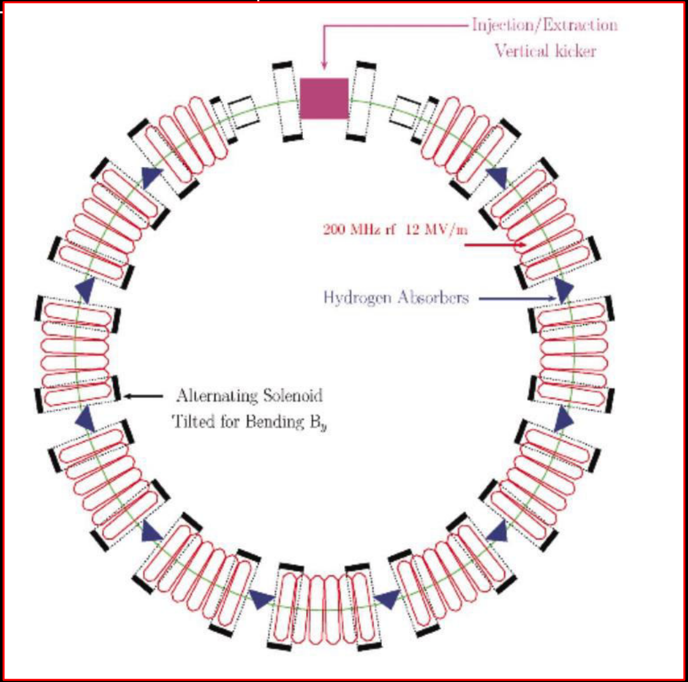


Mark Palmer

- ✓ 6D Ionization Cooling Designs
  - Designs in hand that meet performance targets in simulations with stochastic effects
  - Ready to move to engineering design and prototyping
  - Able to reach target performance with Nb_3Sn conductors (NO HTS)
- ✓ RF operation in magnetic field (MTA program)
  - Gas-filled cavity solution successful and performance extrapolates to the requirements of the NF and MC
  - Vacuum cavity performance now consistent with models
  - MICE Test Cavity significantly exceeds specified operating requirements in magnetic field
- ✓ Final Cooling Designs
  - Baseline design meets Higgs Factory specification and performs within factor of 2.2× of required transverse emittance for high energy MC (while keeping magnets within parameters to be demonstrated within the next year at NHMFL).
  - Alternative options under study

Test Facility Example

Carlo Rubbia: The experimental realization of the presently described μ+μ- Ring Collider may represent the most attractive addition of the future programs on the Standard Model to further elucidate the physics of the Ho, requiring however a substantial amount of prior R&D developments, which must be experimentally confirmed by the help of the Initial Muon Cooling Experiment(al) program.



6D cooling experiment; example
Use 100 ns ESS pre-pulse with 3×10^{11} protons
Yields 3×10^{7} μ^- and 6×10^{7} μ^+ around 250 MeV

Potential Approaches

Various options considered:

<u>Recirculating linacs</u>

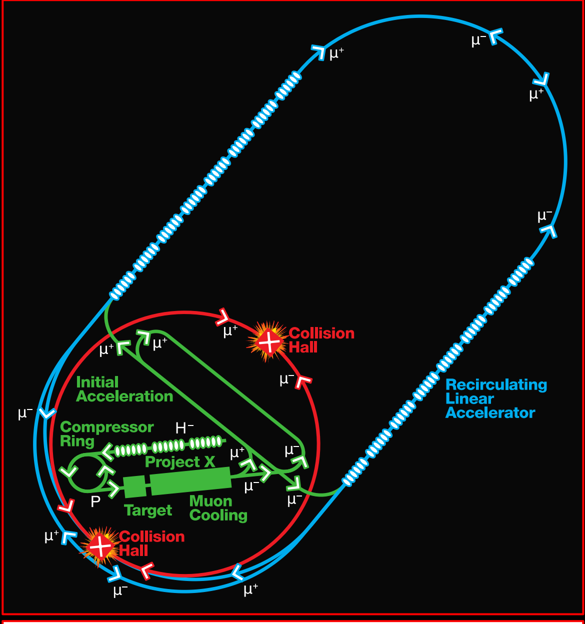
- Fast acceleration but typically only a few passages through RF, hence high RF cost

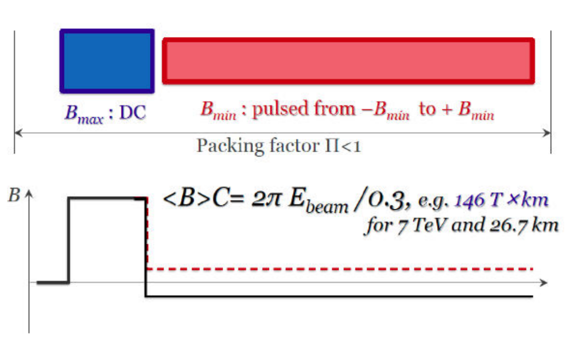
<u>FFAGs</u>

- Static magnets, but only limited increase in energy possible

<u>Rapid cycling synchrotron (RCS)</u>

- Potentially larger acceleration range at affordable cost
- Could use combination of static superconducting and ramping normal-conducting magnets
- But have to deal with energy in fast pulsing magnets

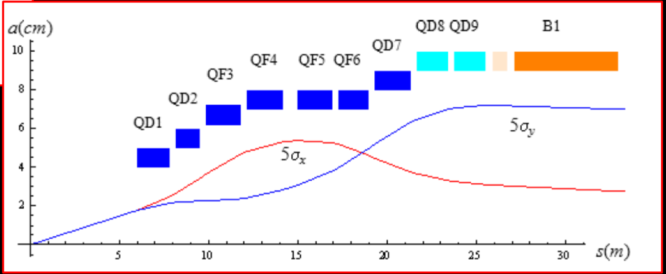




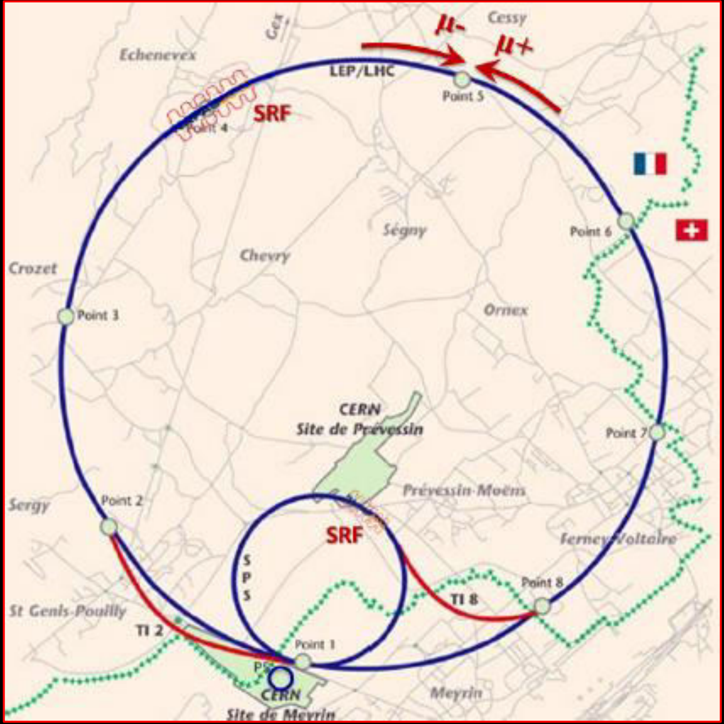
Collider Ring

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

$$\beta \propto \frac{1}{\gamma}$$



High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending



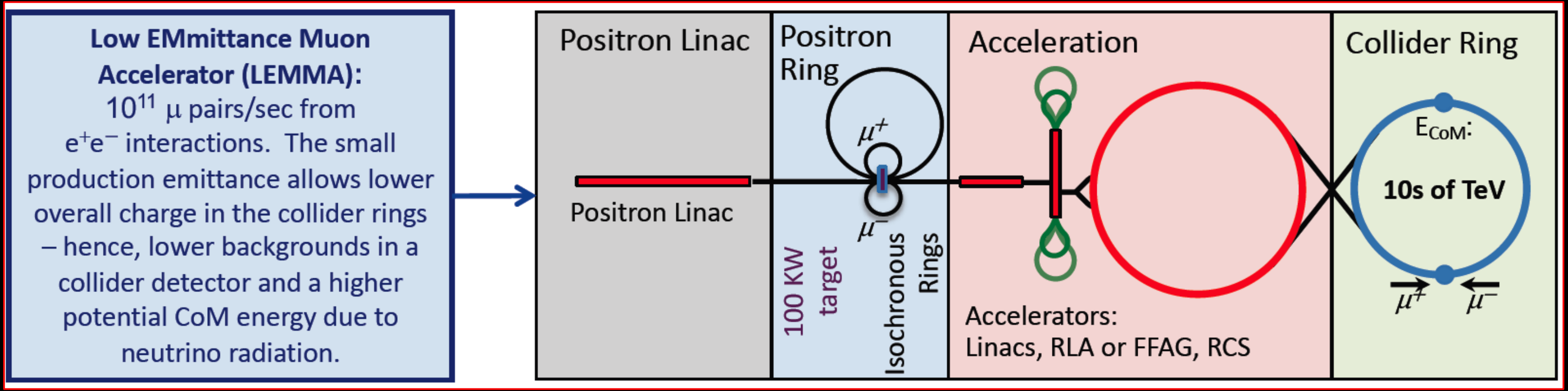
Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel

The LEMMA Scheme



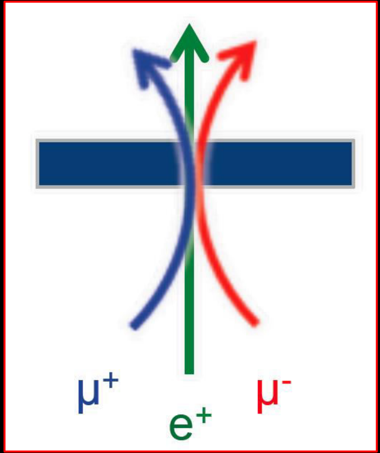
Muon beams produced with low emittance with positron beam (40 nm vs. 25 µm in proton scheme)

No cooling required, use lower muon current

- Positron beam:
  - 45 GeV, 3×10^{11} particles every 200 ns
  - Passes through target and produces muon pairs
- Muon bunches circulation O(2000) times muon accumulation (4.5×10^7)
- Every 0.5 ms, the muon bunches are extracted and accelerated

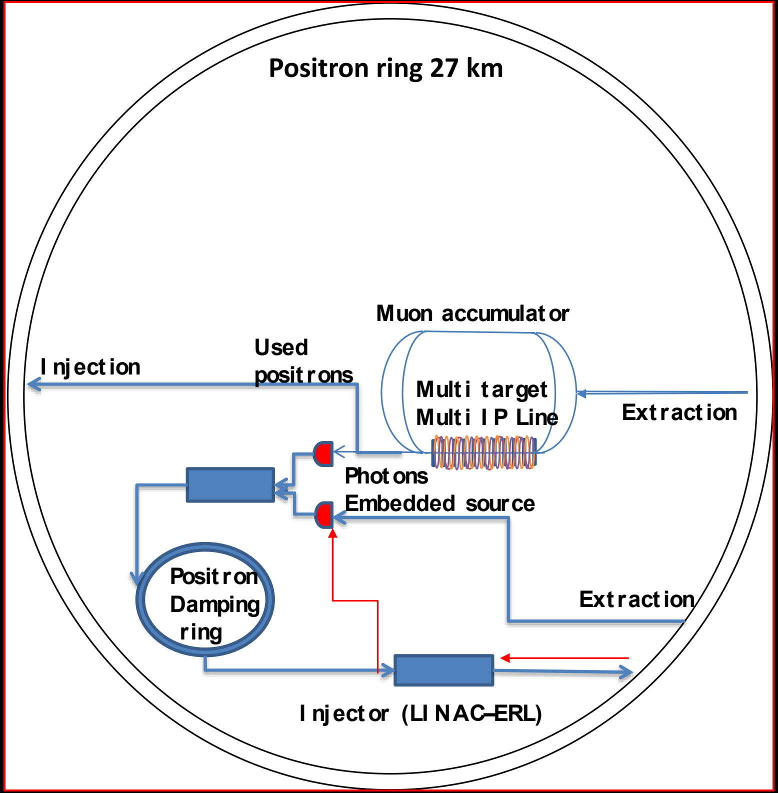
Key Issues

- Small efficiency of converting positrons to muon pairs:
  - Muon pair production small fraction of overall cross section (O(10-5))
  - Most positrons lost with no muon produced
  - Have to produce many positrons (difficult)
  - O(100MW) synchrotron radiation
  - High heat load and stress in target (also difficult)
- The multiple scattering of the muons in the target:
  - Theoretical best emittance of 600 nm (40nm assumed)
    - Reduction of luminosity by factor 15
- Small bunches to be accelerated and merged:
  - No design for the merger yet
  - Combination factor proportional to beam energy



Ongoing LEMMA Effort

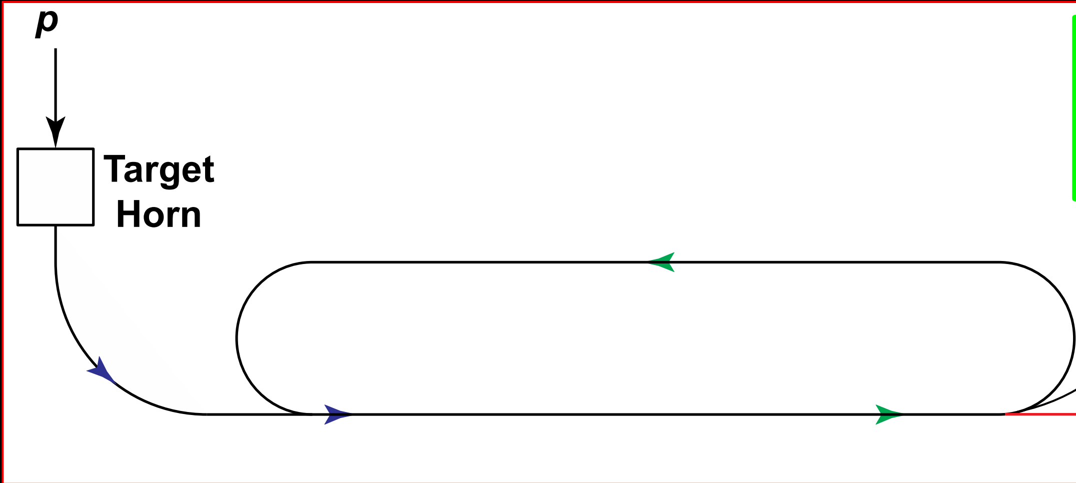
- Address issues identified:
  - Large emittance from target
    - Use sequence of thin targets
  - Combining bunches at high energy
    - Producing bunches in pulses fashion
  - Positron ring challenge
    - Larger ring
  - Positron production
    - Improved concepts
  - Did not yet reach competitive performance
    - Work is ongoing



Perspectives on the route to a multi-TeV muon collider

NUSTORM

Neutrinos from stored muons



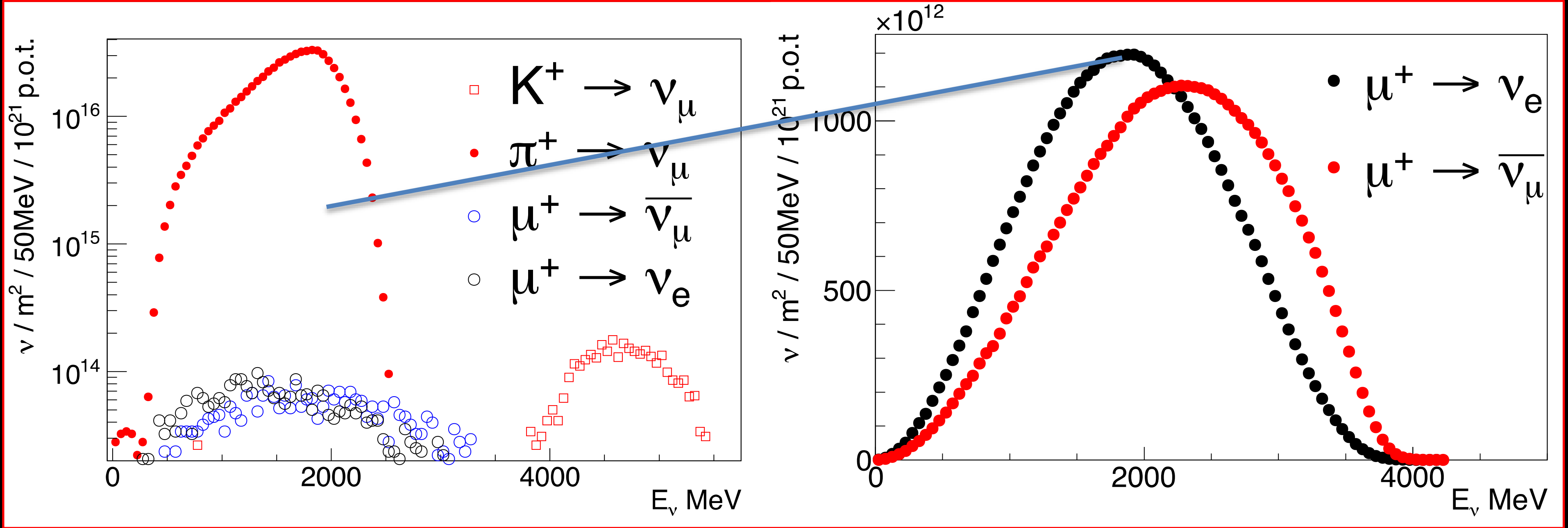
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- Scientific objectives:
  1. %-level ($\nu_e N$)cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN
  3. Muon-accelerator test-bed
     - E.g. 6D cooling experiment

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

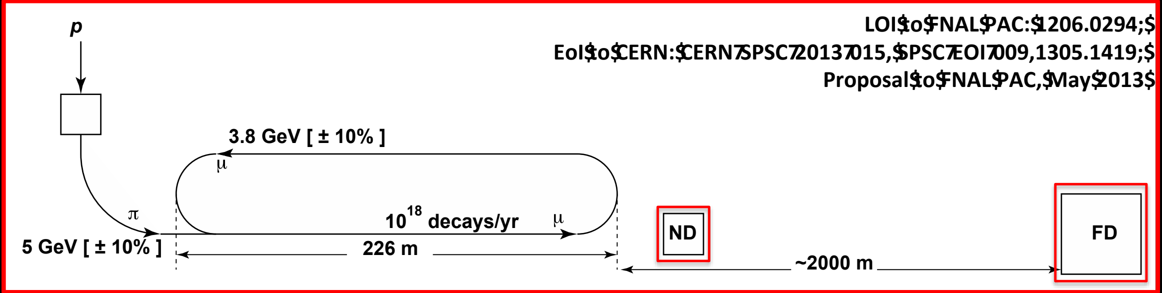
10.1146/annurev-nucl-102014-021930

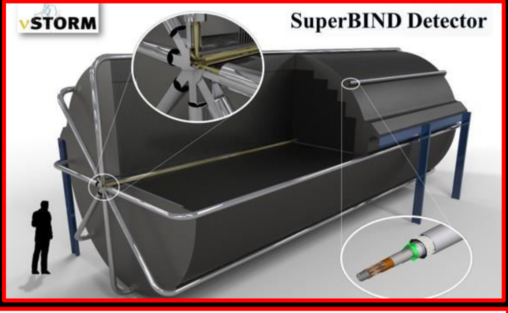
Neutrino flux

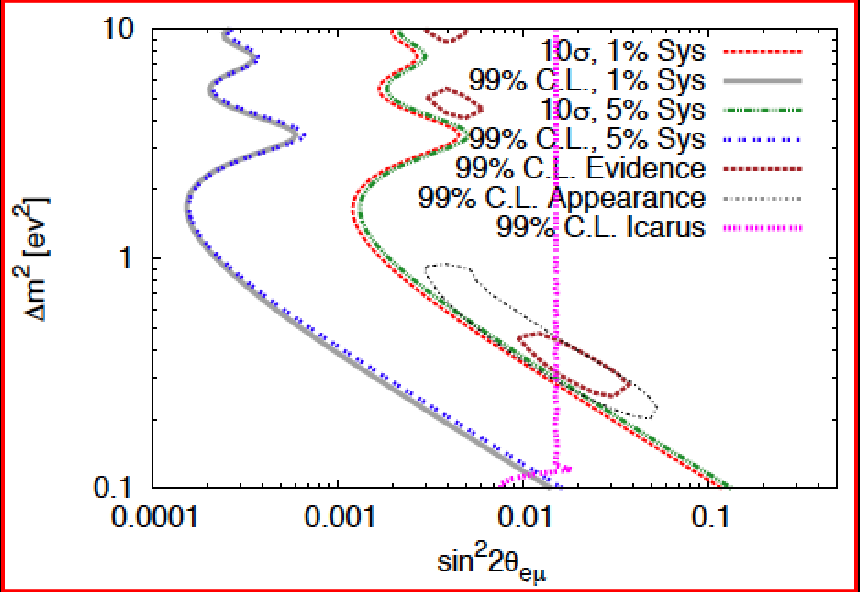


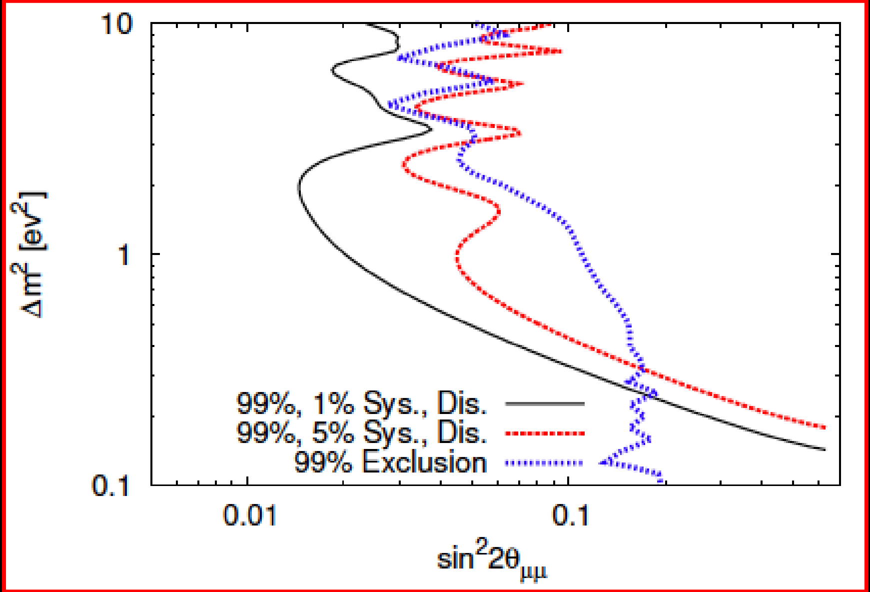
- ν_μ flash:
  - Pion: 6.3×10^{16} m^{-2} at 50m
  - Kaon: 3.8×10^{14} m^{-2} at 50m
    - Well separated from pion neutrinos
- ν_e and ν_μ from muon decay:
  - ~10 times as many ν_e as, e.g. J-PARC beam
  - Flavour composition, energy spectrum
    - Use for energy calibration

Sterile neutrino search @ FNAL





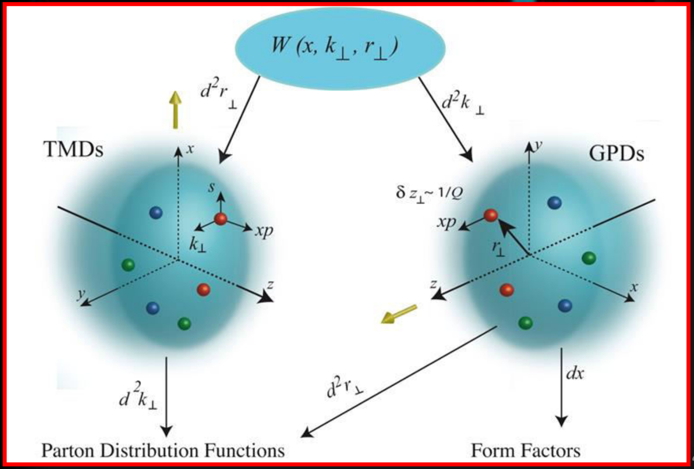




Adey et al., PRD 89 (2014) 071301

To understand the nucleon and the nucleus

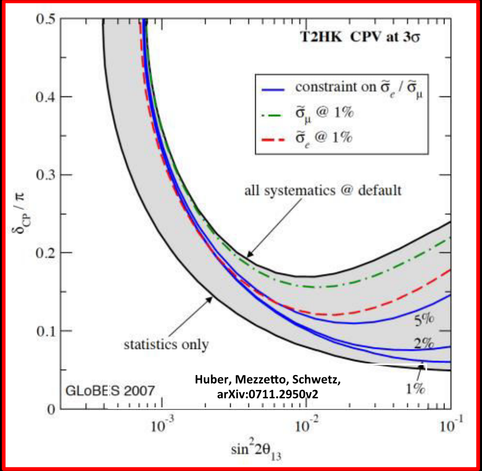
- **Neutrino unique probe: weak and chiral:**
  - Sensitive to flavour/isospin and 100% polarised
- **How could neutrino scattering help?**
  - Development of understanding of nucleus/nucleon (e.g.):
    - Multi-nucleon correlations
    - Precise determination of:
      - Model parameters or, better,
      - Theoretical (ab initio) description
- **Precise νN scattering measurements to:**
  - Constrain models of nucleus/nucleon:
    - Exploiting isospin dependence, chirality, …
- **Benefit of nuSTORM:**
  - Precise flux and energy distribution

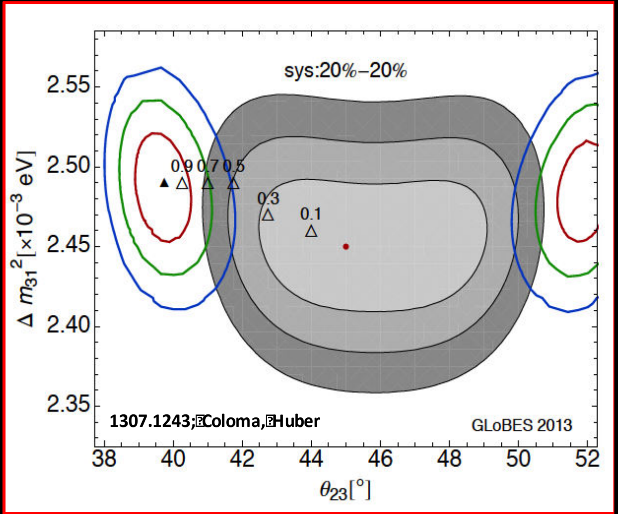


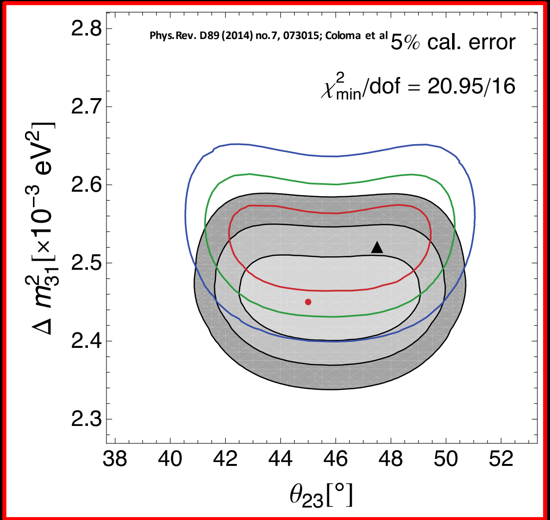
Search for CPiV in lbl oscillations

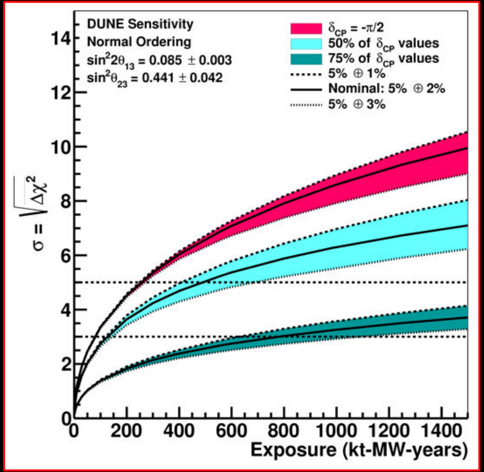
- Seek to measure asymmetry:
  - $P(\nu_\mu \succ \nu_e) - P(\bar{\nu}_\mu \succ \bar{\nu}_e)$
- Event rates convolution of:
  - Flux, cross sections, detector mass, efficiency, *E*-scale
    - Measurements at %-level required
  - Theoretical description:
    - Initial state momentum, nuclear excitations,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

Systematic uncertainty and/or bias







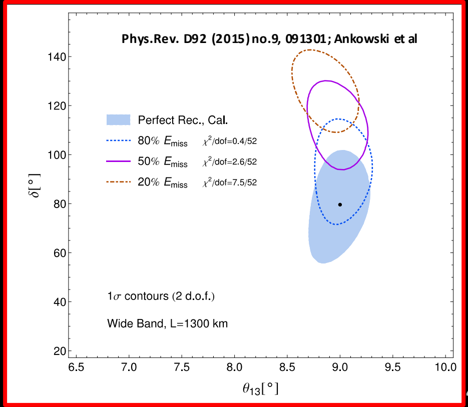


Event mis-classification

Energy scale mis-calibration

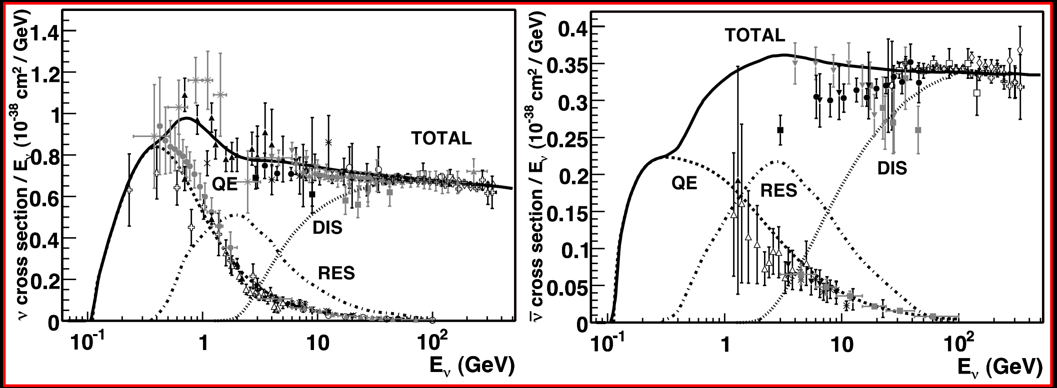
Uncertainty
(cross section and ratio)

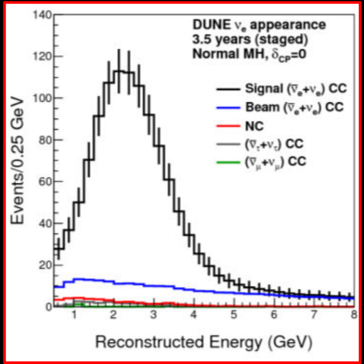
Missing energy (neutrons)

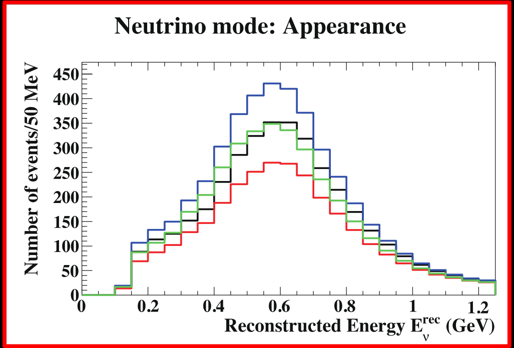


Specification: energy range

- Guidance from:
  - Models:
    - Region of overlap 0.5—8 GeV
  - DUNE/Hyper-K far detector spectra:
    - 0.3—6 GeV







- Cross sections depend on:
  - Q^2 and W:
    - Assume (or specify) a detector capable of:
      - Measuring exclusive final states
      - Reconstructing Q^2 and W
    - → $E_\mu < 6$ GeV
- So, stored muon energy range:

$$1 < E_\mu < 6 \text{ GeV}$$

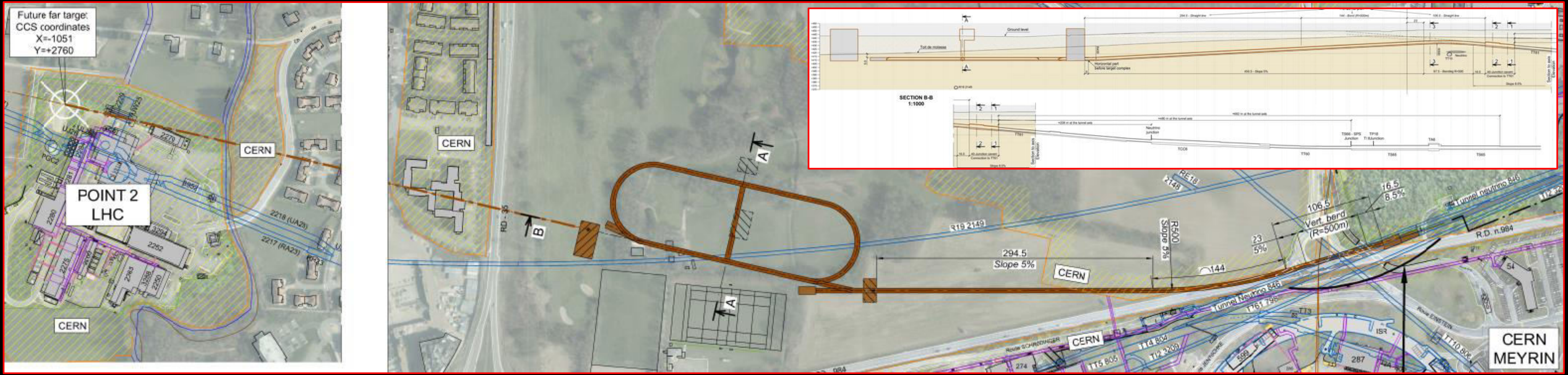
nuSTORM for νN scattering @ CERN — parameters

- **New specification!**
  - **Design update:**
    - **$1 < E_\mu < 6$ GeV**
  - **Challenge for accelerator design!**
  - **Benefit:**
    - **Calibration via energy spectrum**
    - **Statistical 'mono-energetic beam'**
- **SPS requirements table**

Table 1: Key parameters of the SPS beam required to serve nuSTORM.

Momentum	100 GeV/c
Beam Intensity per cycle	4 ◊ 10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4 ◊ 10^{19}
Total PoT in 5 year's data taking	2 ◊ 10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance (1 ‡)	8 mm.mrad
Max. normalised vertical emittance (1 ‡)	5 mm.mrad
Number of extractions per cycle	2
Interval between extractions	50 ms
Duration per extraction	10.5 μs
Number of bunches per extraction	2100
Bunch length (4 ‡)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	2 ◊ 10^{-4}

Overview

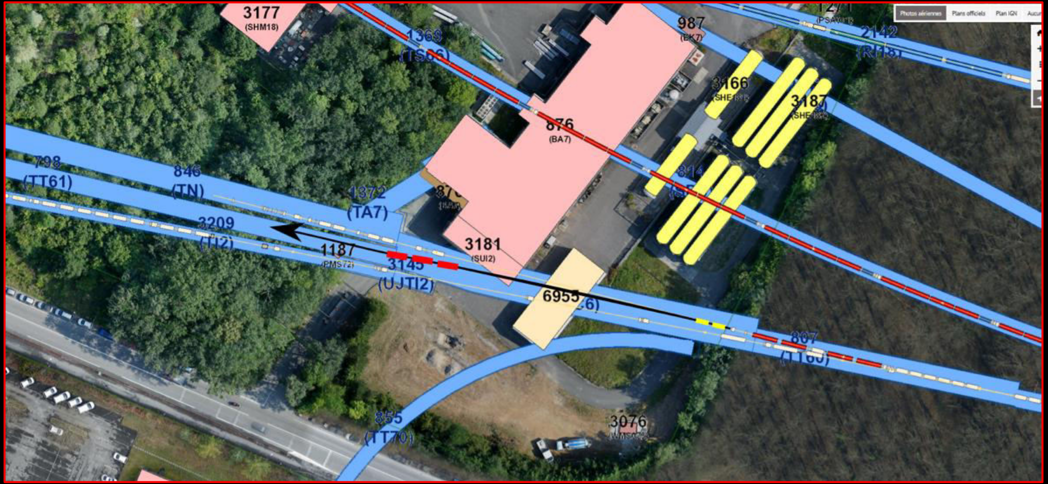


- **Extraction from SPS through existing tunnel**
- **Siting of storage ring:**
  - **Allows measurements to be made 'on or off axis'**
  - **Preserves sterile-neutrino search option**

Extraction and *p*-beam transport to target

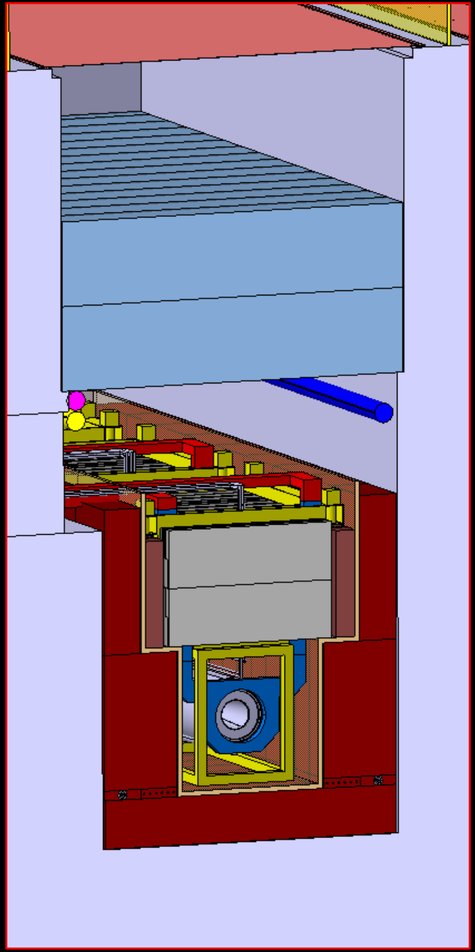
- **Fast extraction at 100 GeV:**
  - CNGS-like scheme adopted;
    - Apertures defined by horizontal and vertical septa reasonable
    - Pulse structure (2 x 10.5 ms pulses) requires kicker upgrade

- **Beam transport to target:**
  - Extraction into TT60:
    - Branch from HiRadMat beam line at 230 m (TT61)
  - Require to match elevation and slope
  - New tunnel at junction cavern after 290 m
  - 585 m transport to target



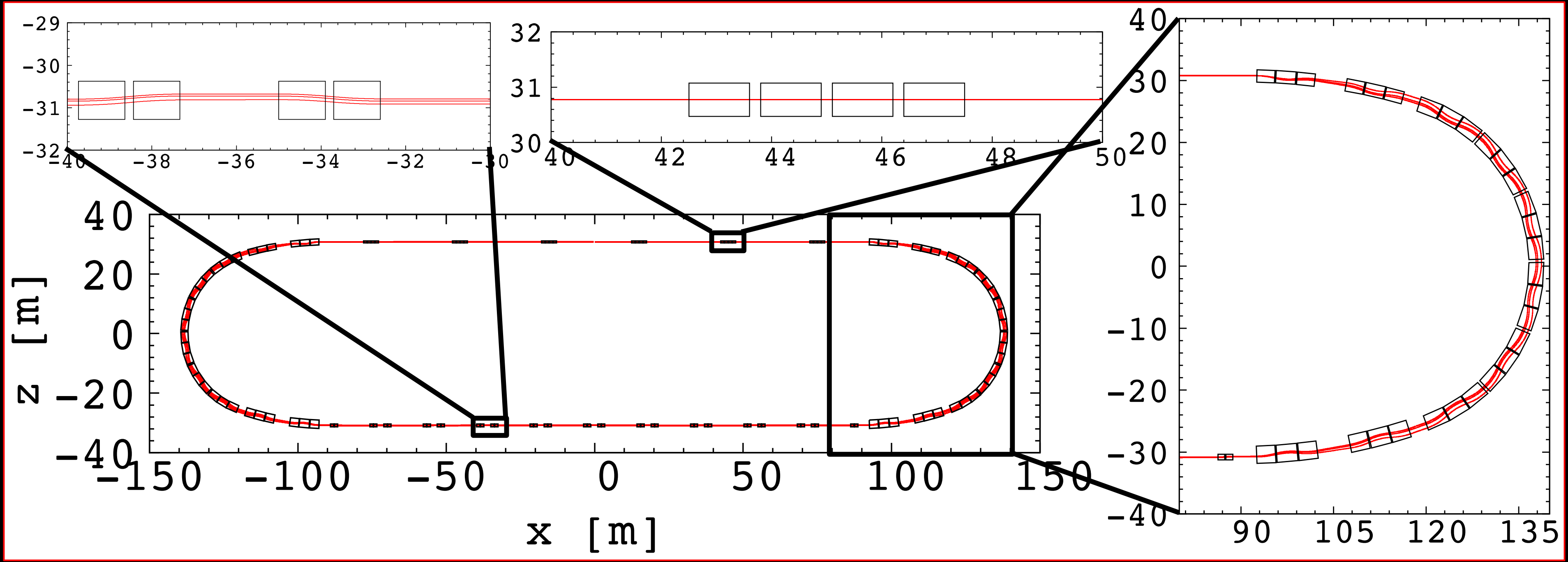
Target and capture

- FNAL scheme adopted:
  - Low-Z target in magnetic horn
  - Pair of quadrupoles collect particles horn focused
  - Target and initial focusing contained in inert helium atmosphere
- Graphite target, based on CNGS experience:
  - Radiation-cooled graphite target embedded in water-cooled vessel
- Containment and transport of pion beam with a 10% momentum spread:
  - Base on scheme used successfully for AD in PS complex
- Target complex design:
  - Exploit extensive work done for CENF



Storage ring

- **New design for decay ring:**
  - Central momentum between 1 GeV/c and 6 GeV/c;
  - Momentum acceptance of up to ±16%



nuSTORM feasibility

- **Goal of PBC nuSTORM study:**
  - ***"A credible proposal for siting at CERN …"***

  achieved.

> *" … the SPS can provide the beam and offers a credible fast extraction location allowing the beam to be directed towards a green field site at a suitable distance from existing infrastructure. Initial civil engineering sketches have established a potential footprint and the geology is amenable to an installation at an appropriate depth."*

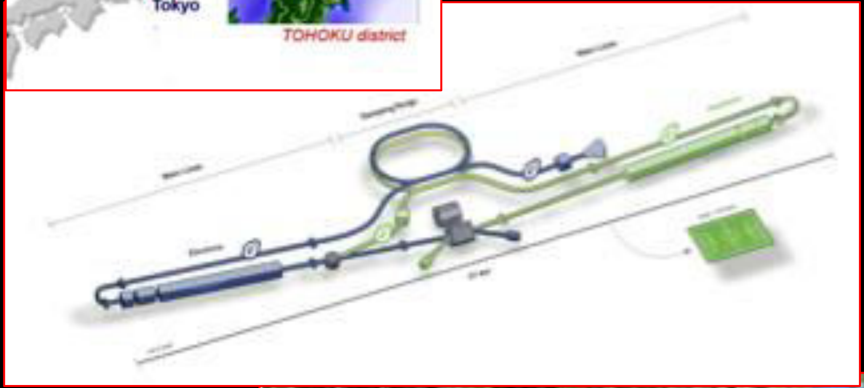
- **Challenges:**
  - **Muon decay ring:**
    - **FFA concept though feasible**
    - **Require magnet development to allow production at a reasonable cost**
  - **Detailed evaluation of:**
    - **Proton-beam extraction, target and target complex**
    - **Civil engineering studies and radiological implications**

Perspectives on the route to a multi-TeV muon collider

TO REALISE THE AMBITION

Options


Site-A
KITAKAMI
IWATE
Tokyo
TOHOKU district

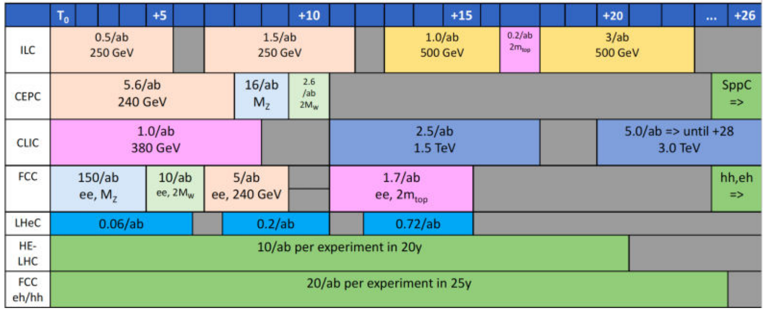



Legend
CERN existing LHC
Potential underground siting :
CLIC 380 GeV
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
Geneva
Google


LHC
Jura
Prealps
Schematic of an
80 - 100 km
long tunnel
Aravis

Timescales are long

Proposed Schedules and Evolution



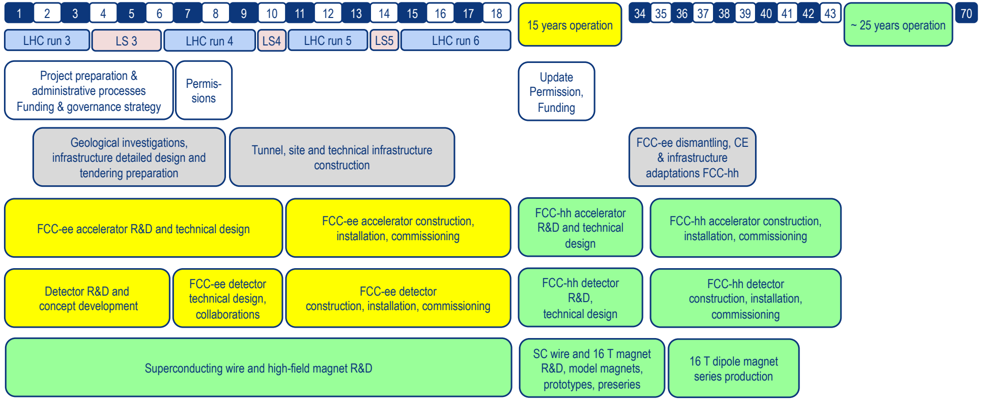
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

D. Schulte 2019

FCC integrated project technical schedule



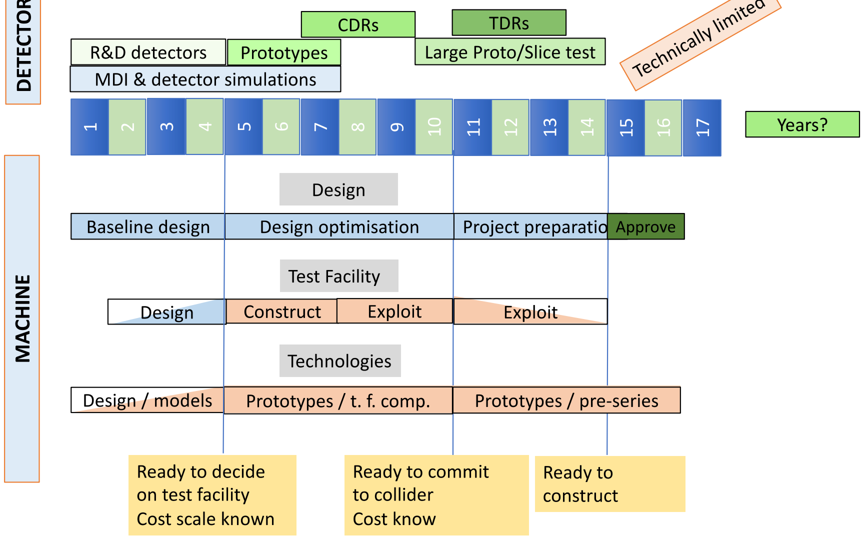
FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

Muon collider

Answers to the Key Questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged on positron one
  - But at this moment not mature enough for a CDR, need a careful design study done with a coordinate international effort
- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - **Should not miss this opportunity?**
- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
    - Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source
  - **R&D in a strongly coordinated global effort**

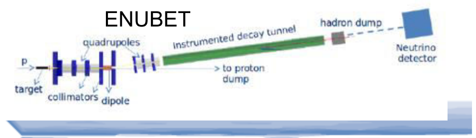
Proposed tentative timeline

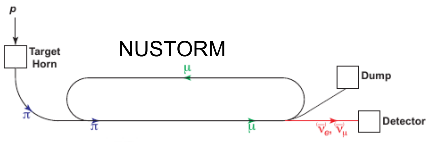


Neutrinos

Precision program in Europe

- Squeezing every bit of information out of the future experiments requires a complementary program (special rôle for Europe) to
  - Measure hadroproduction for the neutrino flux prediction (NA61)
  - Understand the neutrino-nucleus cross-section at the % level, both theoretically and with new facilities (Enubet, Nustorm)
  - Collaboration to be developed with nuclear physicists
- Next-to-next generation facilities (ESSnuSB, …) are also under study





Neutrino oscillations

- Vibrant program (DUNE, Hyper-Kamiokande, JUNO, ORCA) to fully measure the PMNS mixing matrix and especially the Mass Ordering and the CP violation phase delta, with strong European contribution. Perceived by the community as a priority.
- Neutrino experiments need cutting-edge detectors and % precision on the flux and cross-sections: leading rôle for Europe (NA61, Neutrino Platform). New facilities currently under study.
- Long term future for high precision LBL measurements with new techniques. Time to prepare for it !

Neutrino Physics
(accelerator and non-accelerator)
summary of the session

Conveners: Stan Bentvelsen, Marco Zito

ESPPU Open Symposium Granada
May 16, 2019

In the session we also covered astroparticle physics

Conclusions

- Muon accelerators have the potential to:
  - Contribute to the study of the Higgs boson
  - Deliver multi-TeV lepton-antilepton collisions
    - Bringing forward the exploration of the very highest energies
  - Revolutionise the study of the neutrino

- Energy-frontier R&D programme should therefore:
  - Include muon collider R&D:
    - A new test facility is an essential part of this effort
      - Synergy with front-rank particle-physics should be exploited

- nuSTORM:
  - A front-rank neutrino facility based on stored muon beams
  - A demonstrator for muon beams for particle physics
  - Capable of serving the 6D-cooling demonstration crucial for muon collider