Toward an Energy Frontier Muon Collider

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- The Long View
- Return to the Energy Frontier
- Staging Physics Milestones
- Summary

2013 Community Summer Study
"Snowmass on the Mississippi"
University of Minnesota
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WhitePapers
1. Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility In the USA
2. Muon Collider Higgs Factory

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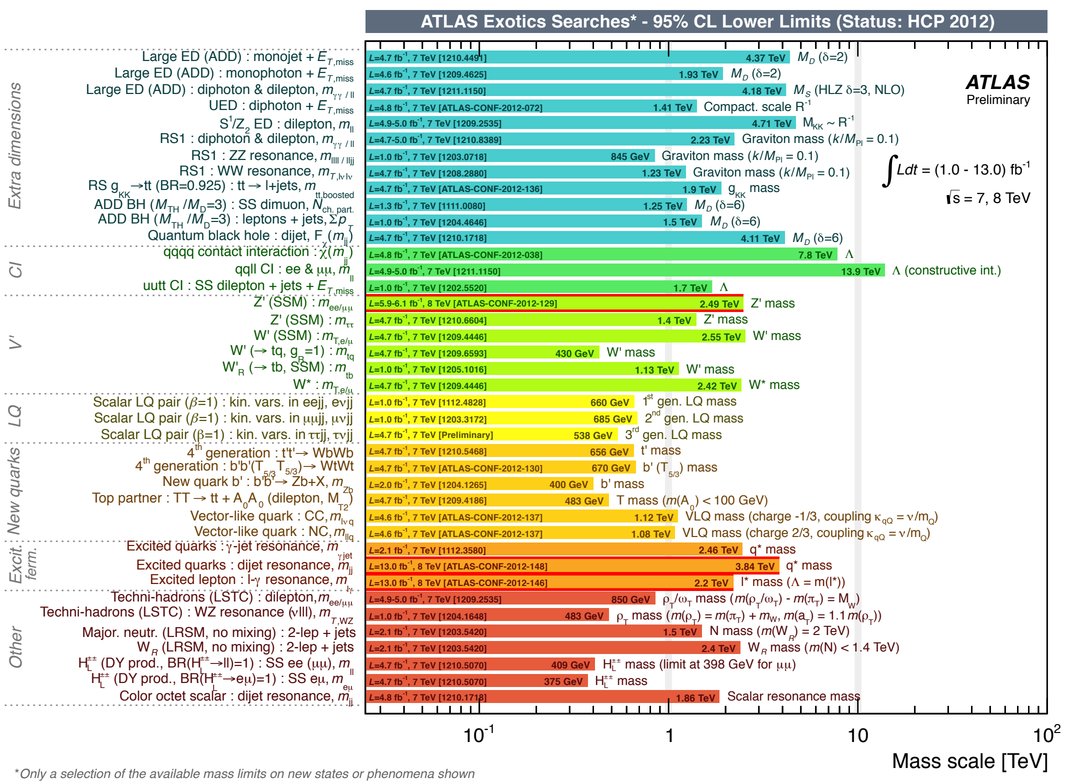
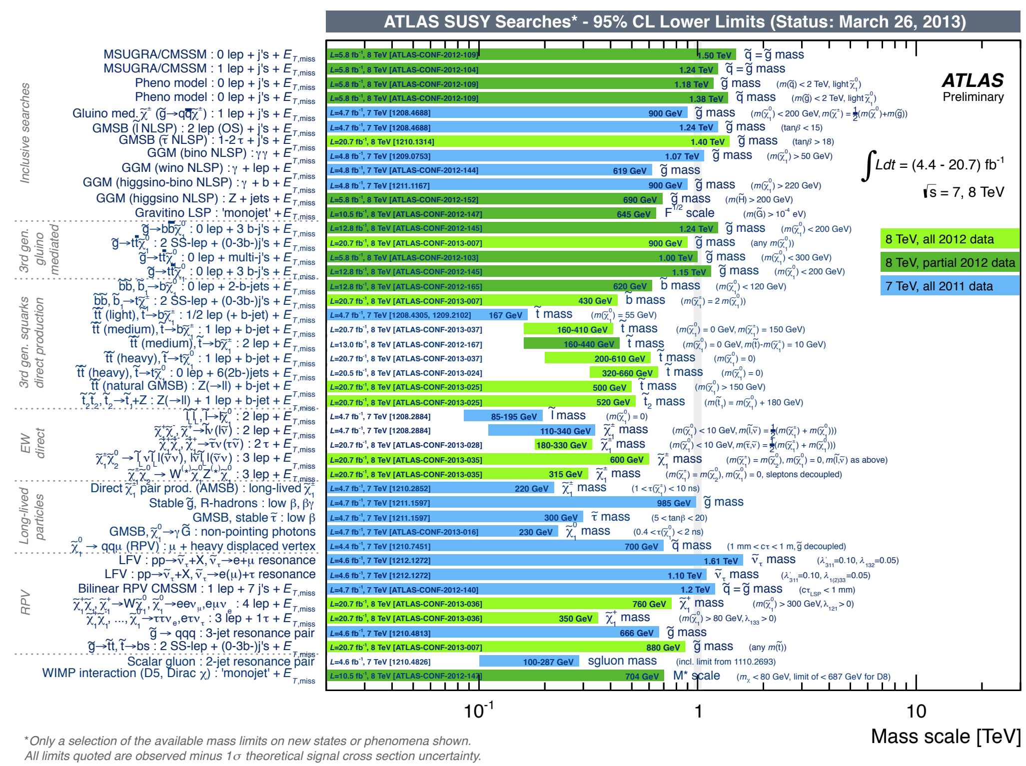
Implications of early LHC Results

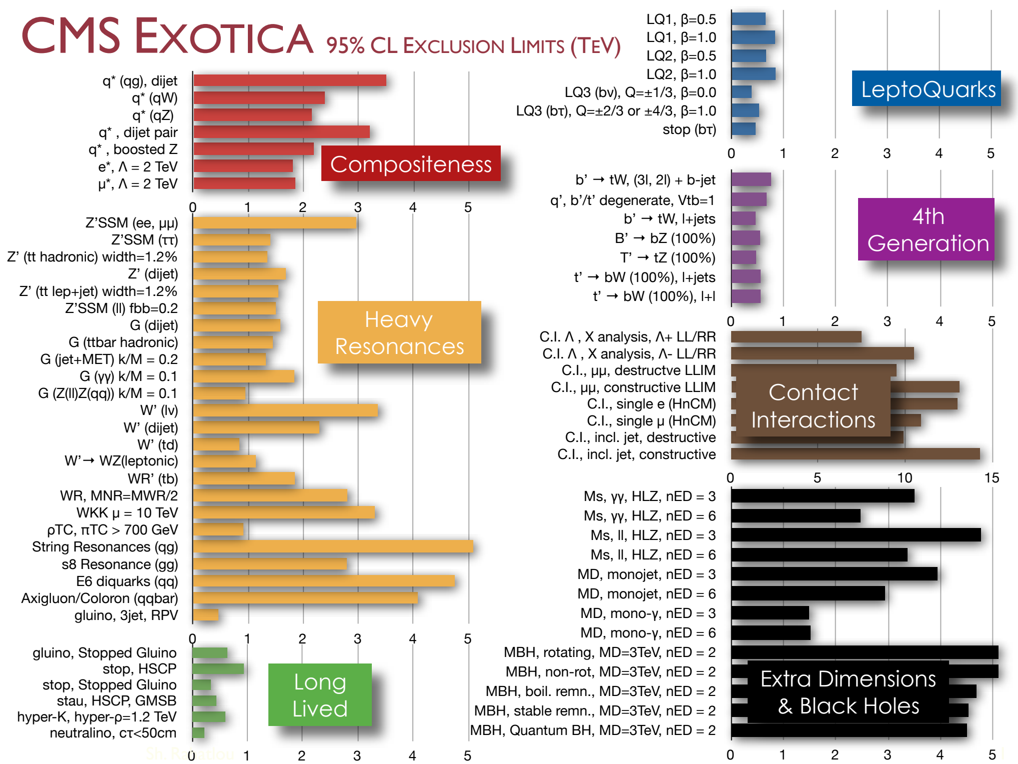
- No evidence for new physics beyond the Standard Model (BSM) to date:
  - BSM (SUSY, Strong Dynamics, Extra Dimensions, New fermions or gauge bosons,...)
    - ATLAS limits

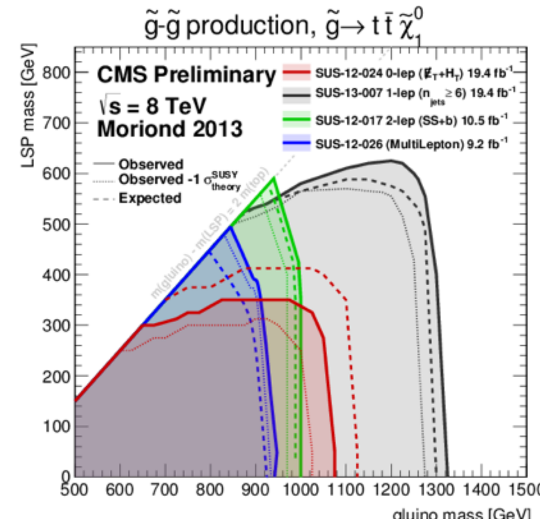


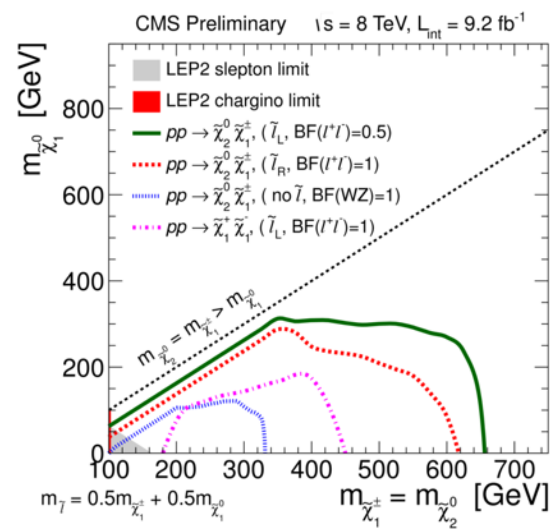


Implications of early LHC Results

- CMS limits







- Scales already probed at the LHC suggest that to study BSM new physics the next energy frontier collider must have $\sqrt{\hat{s}}$ in the multi-TeV range even for EW processes.
- However there must be new physics !!! WHY? Let me list the reasons

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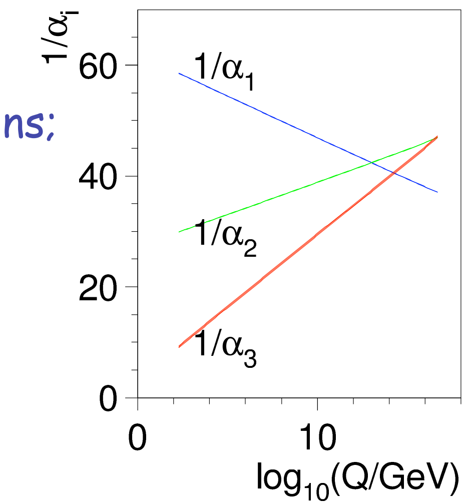
Implications of early LHC Results

1. The Standard Model is incomplete:
   - dark matter; neutrino masses and mixing -> new fields or interactions;
   - baryon asymmetry in the universe -> more CP violation
   - gauge unification -> new interactions;
   - gravity: strings and extra dimensions



2. Experimental hints of new physics: $(g-2)_\mu$, top A_{fb}, ...
3. Theoretical problems with the SM:
   - Scalar sector problematic:

     $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}^\dagger\psi_{jR}\Phi$ + h.c.

     $m_H^2/M_{planck}^2 \approx 10^{-34}$ Hierarchy problem — vacuum stability — large range of fermion masses
   - The SM Higgs boson is unnatural. (m_H^2/μ^2)
   - Solutions: SUSY, New Strong Dynamics, ...

muon (g-2)

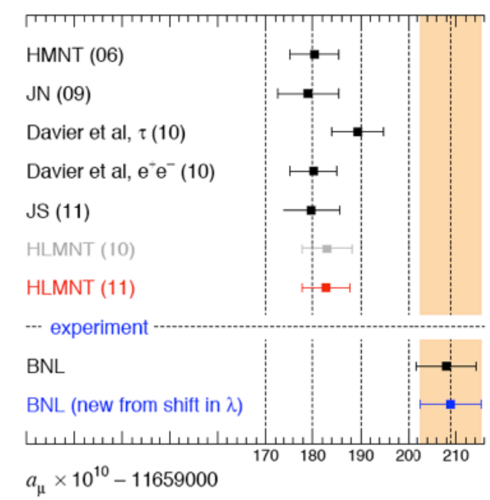
Davier, Hoecker, Malaescu, Zhang

Jegerlehner, Szafron

Hagiwara, Liao, Martin, Nomura, Teubner

hadronic VP contributions

$(685 \pm 4) \times 10^{-10}$



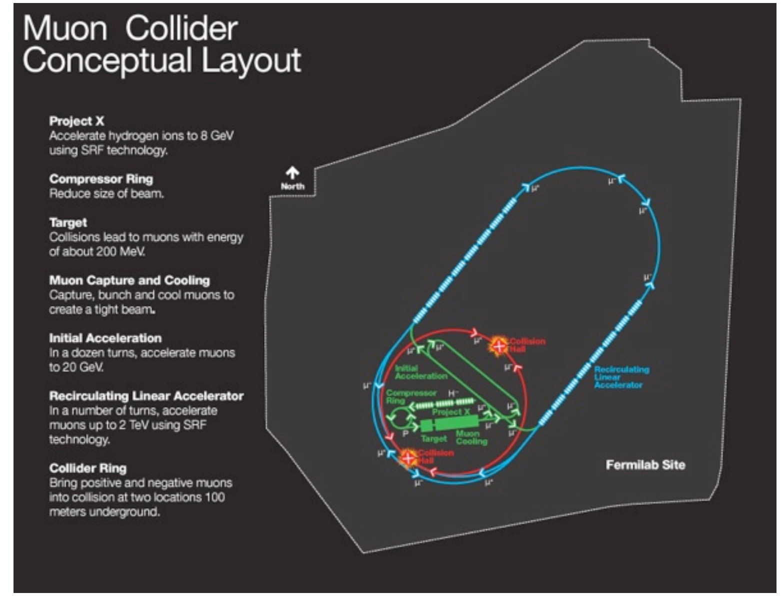
There remains a persistent discrepancy of 3.3-3.6 σ

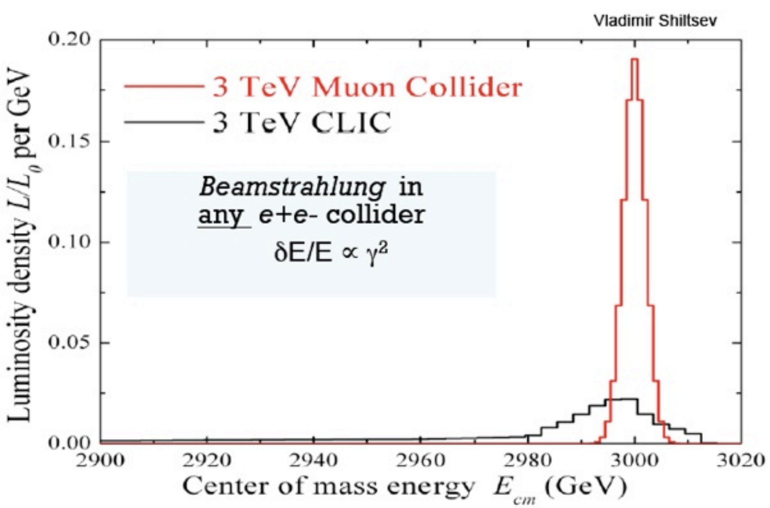
The SM Higgs and BSM

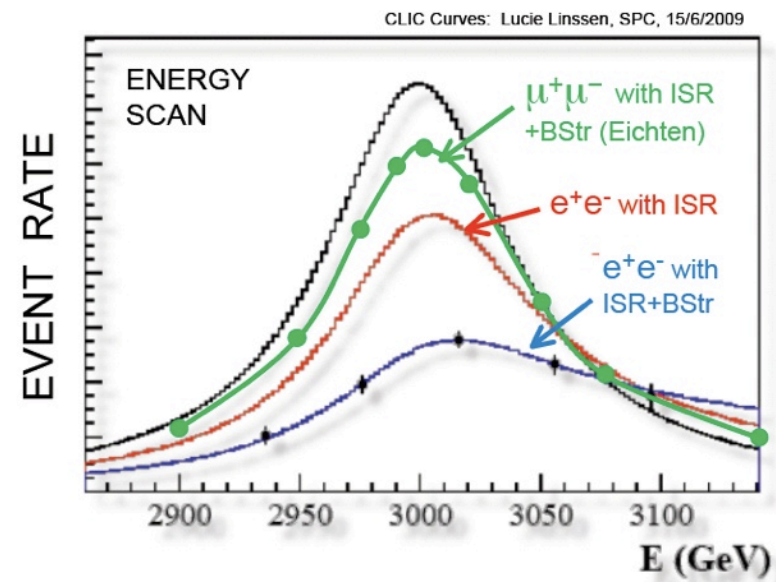
- The strong case for a TeV scale hadron collider rested on two arguments:
    1. Unitarity required that a mechanism for EWSB was manifest at or below the TeV scale.
    2. The SM is unnatural ('t Hooft conditions) and incomplete (dark matter, insufficient CP violation for the observed baryon excess, gauge unification, gravity and strings)
- If after the analysis of the 2012 CMS/ATLAS data, the 126 GeV state is found to be a 0+ state with couplings consistent with the SM Higgs, the first argument is satisfied.
    - The second argument remains strong. but is less strongly tied to the TeV scale.
    - **Scales already probed at the LHC suggest that any new collider (of LHC level costs) should be able the probe the BSM physics in the multi-TeV range.**

Muon Collider

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 10 TeV (3 Tev)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (440 fb^{-1}/yr)
  - Compact facility
    - 3 TeV - ring circumference 3.8 km
    - 2 Detectors
  - Superb Energy Resolution
    - MC: 95% luminosity in dE/E ~ 0.1%
    - CLIC: 35% luminosity in dE/E ~ 1%

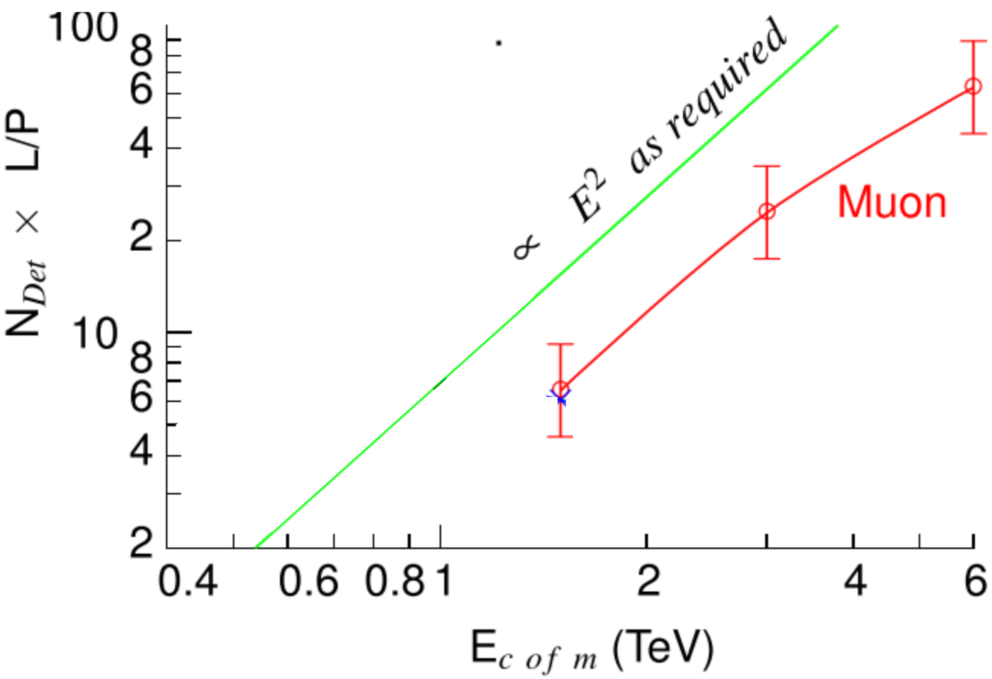


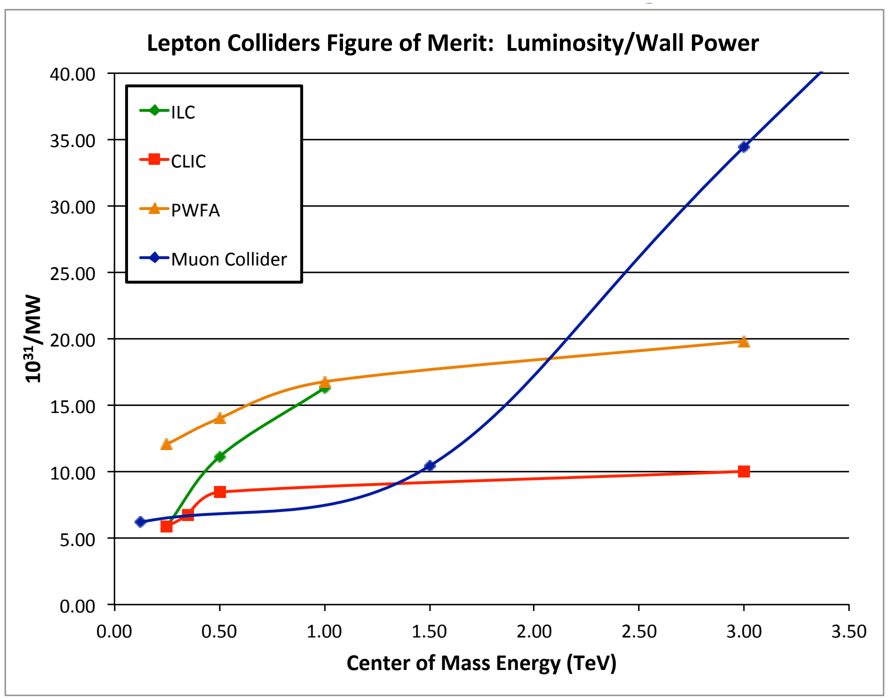




Muon Collider

- Comparison of Lepton Colliders at High Energy
  - Increase of luminosity with energy. Needed for new physics.
  - Wall power in operation.
  - Only a Muon Collider provides a path to the energy frontier.

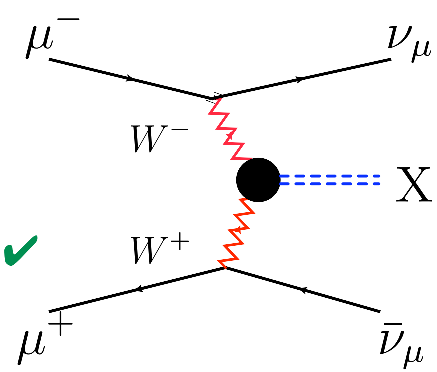




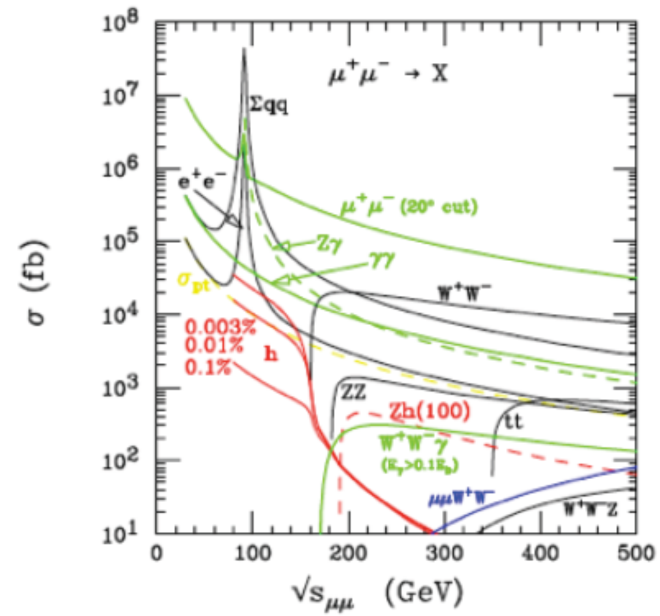
Muon Collider

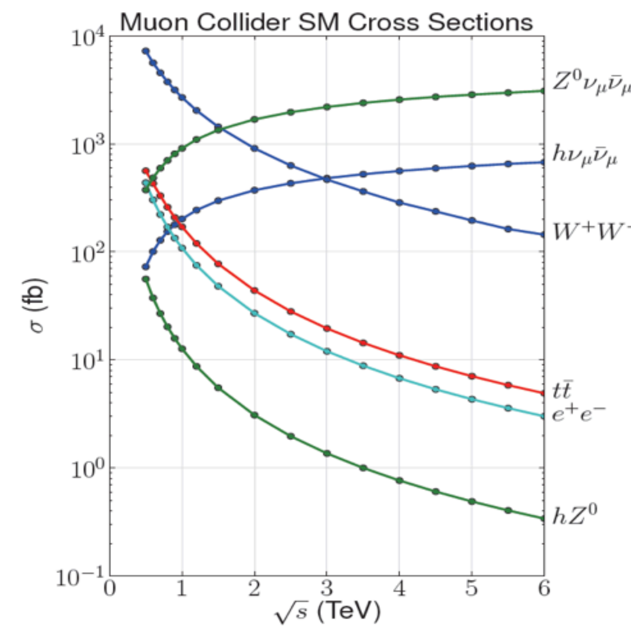
- For √s < 500 GeV
  - SM thresholds: Z^0h, W^+W^-, top pairs
  - Higgs factory (√s≈ 126 GeV) ✔
- For √s > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central (|θ| > 10°) pair production ~ R × 86.8 fb/s(in TeV^2) (R ≈ 1)
    - At √s = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)
- For √s > 1 TeV
  - Fusion processes important at multi-TeV MC

$$\sigma(s) = C\ln\left(\frac{s}{M_X^2}\right) + \ldots$$



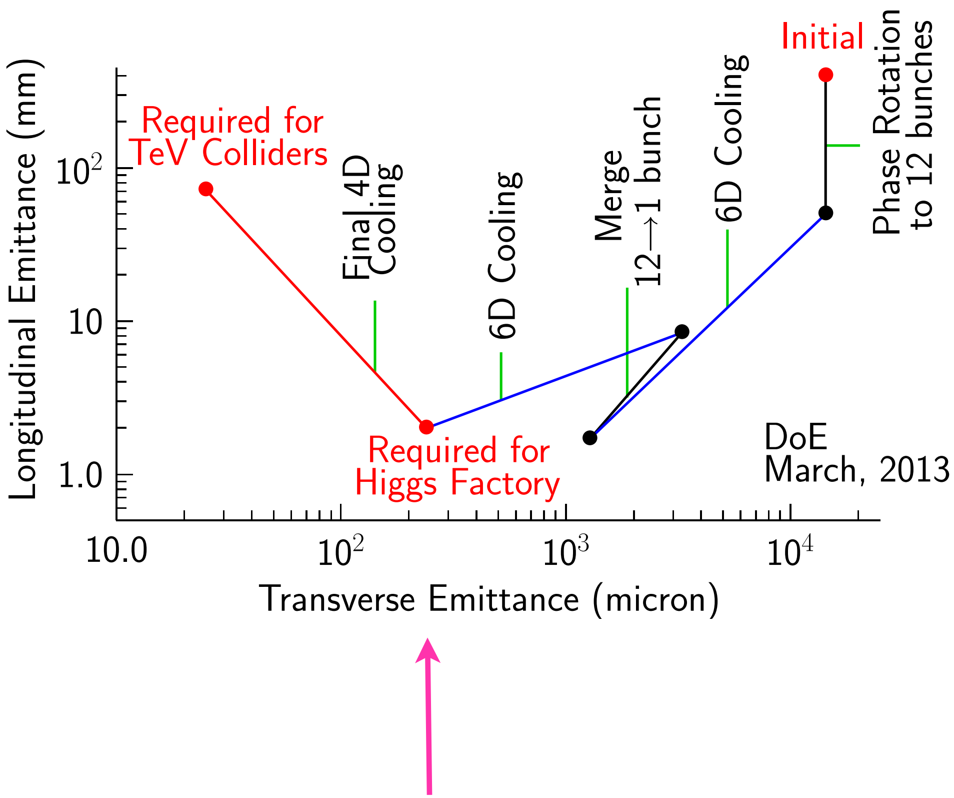
  - An Electroweak Boson Collider ✔





Muon Collider

- But muons decay:
  - The muon beams must be accelerated and cooled in phase space (factor ≈ 10^6) rapidly -> ionization cooling
  - requires a complex cooling scheme
  - The decay products ($\mu^- \rightarrow \nu_\mu \bar{\nu}_e e^-$) have high energies.
    - Detector background issues
    - Neutrino beam issue -> Ecm $\lesssim$ 10 TeV.
- The issues need dedicated R&D
  - MICE
  - MAP
  - nuStorm - Definitive 6D cooling demo.



Higgs Factory

Staging A Muon Collider

- Provide a flexible staging scenerio with physics at each stage.
  - Proton driver - Project X
    - LBNE, rare K decays, mu to e conversion, $(g-2)_{\mu}$, EDM, N-Nbar oscillations, cold muons, …
  - Neutrino Factory

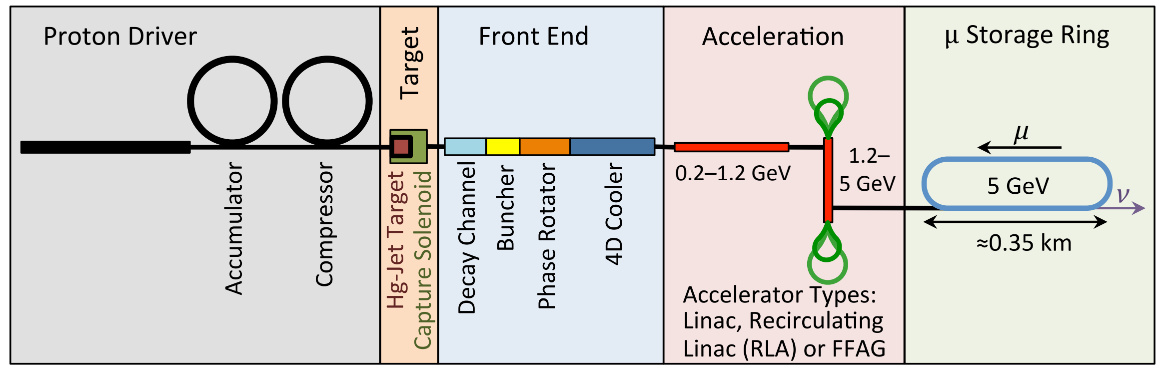


Figure 15: Functional elements of a 5 GeV Neutrino Factory

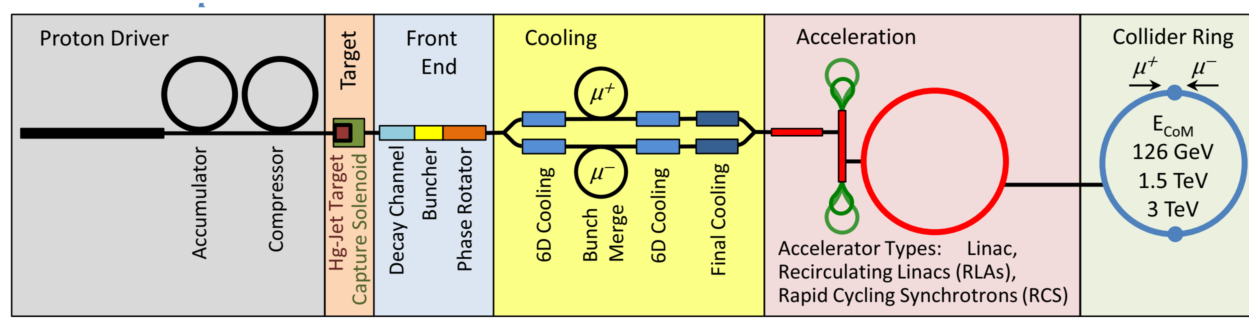


Figure 26: Functional elements of a Higgs Factory/Muon Collider complex

  - Higgs Factory
  - High Energy Muon Collider

- Staging plan has been developed.

WhitePapers

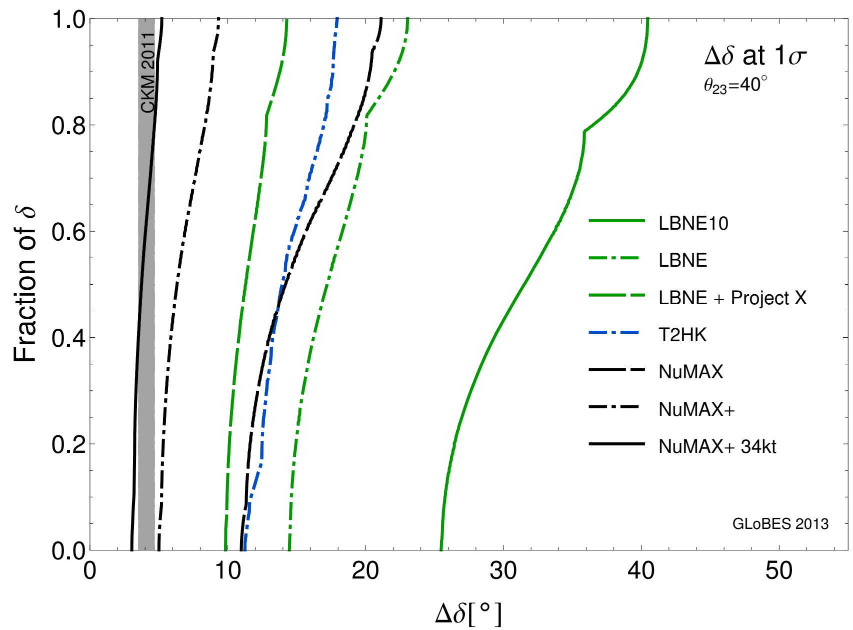
1. Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility In the USA.
2. Muon Collider Higgs Factory

Neutrino Physics Staging Scenerio

- Neutrino Physics Staging
  - Because θ_{13} is large a lower energy (5 GeV) and 1300 km works for a Neutrino Factory.
  - First a lower intensity (Project X phase 2) (2 x 10^{20} $\mu^{\pm}$/yr) neutrino factory NuMAX
  - Then higher intensity (1.2 x 10^{21} $\mu^{\pm}$/yr) NuMAX+
  - Unsurpassed performance is obtained for 34 kton magnetized LAr (TPC) at distance 1300 km (NuMAX+)

Table 1. Muon Accelerator Program baseline Neutrino Factory parameters for nuSTORM and two NuMAX phases located on the Fermilab site and pointed towards a detector at SURF. For comparison, the parameters of the IDS-NF are also shown.

System	Parameters	Unit	nuSTORM	NuMAX	NuMAX+	IDS-NF
Perfor-mance	Stored μ+ or μ-/year		8×10^{17}	2×10^{20}	1.2×10^{21}	1×10^{21}
	ν_e or ν_μ to detectors/yr		3×10^{17}	8×10^{19}	5×10^{20}	5×10^{20}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND
	Distance from Ring	km	1.9	1300	1300	2000
	Mass	kT	1.3	30 / 10	100 / 30	100
	Magnetic Field	T	2	0.5-2	0.5-2	1-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	2.7	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum (P_μ)	GeV/c	3.8	5	5	10
	Circumference (C)	m	480	600	600	1190
	Straight section	m	185	235	235	470
	Arc Length	m	50	65	65	125
Acceleration	Initial Momentum	GeV/c	-	0.22	0.22	0.22
	Single-pass Linac	GeV/pass	-	0.95	0.95	0.56
		MHz	-	325	325	201
	4.5-pass RLA — RLA I	GeV/pass	-	0.85	0.85	0.45
		MHz	-	325	325	201
	RLA II	GeV/pass	-	-	-	1.6
		MHz	-	-	-	201
Cooling			No	No	4D	4D
Proton Source	Proton Beam Power	MW	0.2	1	3	4
	Proton Beam Energy	GeV	120	3	3	10
	Protons/year	1×10^{21}	0.1	41	125	25
	Repetition Frequency	Hz	0.75	70	70	50



Muon Collider Staging Scenerio

- Staging Steps:
  - Higgs factory $\sqrt{s} = m_H \simeq 126$ GeV
    - $\mathscr{L} = 1.7 \times 10^{31} \sim 170\ pb^{-1}/yr$; $\Delta E/E = 0.003\%$
    - $\mathscr{L} = 8 \times 10^{31} \sim 800\ pb^{-1}/yr$; $\Delta E/E = 0.004\%$
  - High Energy Muon Collider:
    - LHC at $\sqrt{s} \simeq 14$ TeV after 300 fb^{-1}. Muon collider design energy is flexible. ($\Delta E/E = 0.1\%$)
    - $\sqrt{s} = 1.5$ TeV; $\mathscr{L} = 1.25 \times 10^{34} \sim 125\ fb^{-1}/yr$;
    - $\sqrt{s} = 3.0$ TeV; $\mathscr{L} = 4.4 \times 10^{34} \sim 440\ fb^{-1}/yr$
    - $\sqrt{s} = 6.0$ TeV; $\mathscr{L} = 1.6 \times 10^{35} \sim 1.6\ ab^{-1}/yr$

Muon Collider Baseline Parameters

		Higgs Factory		Multi-TeV Baselines	
Parameter	***Units***	Startup Operation	Production Operation		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4#	4	4	4

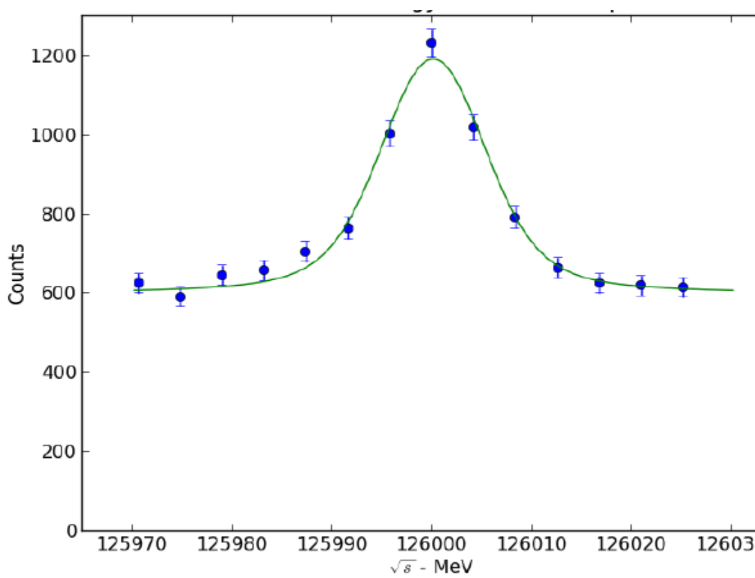
Could begin operation with Project X Stage 2 beam

Muon Collider Higgs Factory

- A muon collider can directly produce the Higgs as an s-channel resonance.
  - Higgs couples to mass so rate enhanced by $\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{4}$ so the cross section is $\sigma(\mu^+\mu^- \to h)$ = 26 pb (for $\Delta=\Gamma$ and including ISR and a 15° forward cut.
  - To obtain the same sensitivity to Higgs decay modes in a electron collider via Zh process as s-channel production at a MC requires more than 100 times the integrated luminosity.
  - The excellent energy resolution Δ of a muon collider makes the process observable.

$$\sigma_{\text{eff}}(s) = \int d\sqrt{\hat{s}} \, \frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}} \sigma(\mu^+\mu^- \to h \to X)$$
$$\propto \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2 + \Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B \exp[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \text{Br}(h \to \mu^+\mu^-)\text{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$



  - Results:

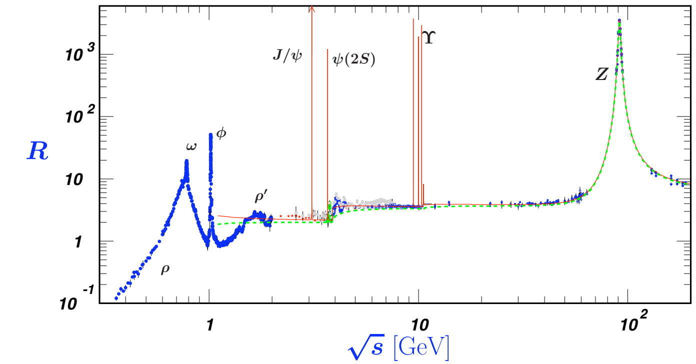
Channel	δM_H (MeV)	$\delta\Gamma_H$ (MeV)	$\delta Br(h \to X)$
$b\bar{b}$	0.1	0.4	0.05
WW^*	0.07	0.2	0.01
Combined	0.06	0.18	—

    - $\Delta\text{Br}(\mu^+\mu^-)\text{Br}(WW^*) \sim 2\%$

  - Finding the Higgs (5σ) requires 270 pb^{-1}.

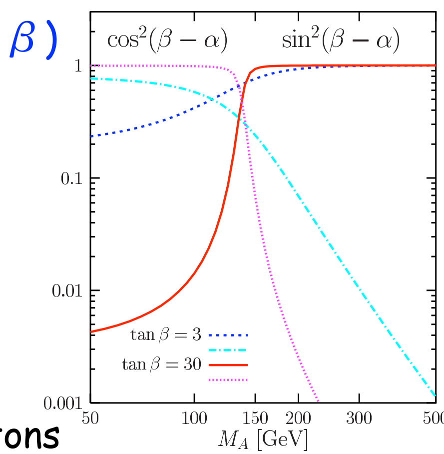
Beyond the Standard Model

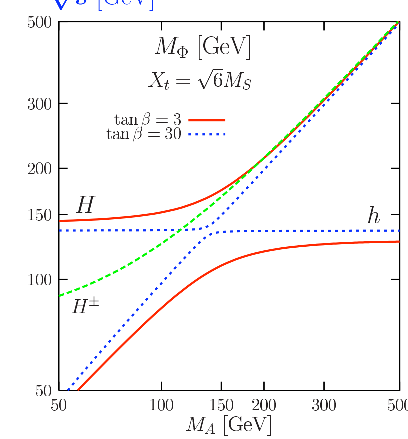
- New Z', W'
  - S-channel resonances - factories for lepton colliders



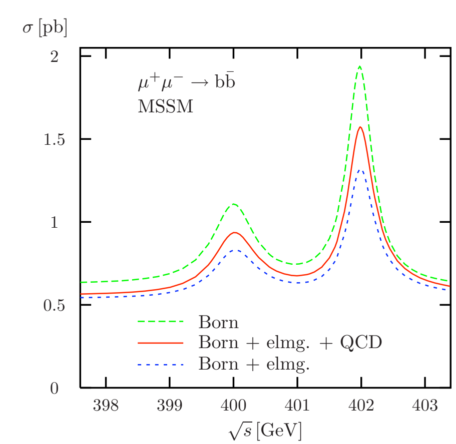
- Additional scalars in all BSM ideas.

- Two Higgs doublets (MSSM):
  - Five scalar particles: h^0, H^0, A^0, $H^\pm$
  - Decay amplitudes depend on two parameters: (α, β)
  - decoupling limit $m_{A^0} \gg m_{Z^0}$:
    - » h^0 couplings close to SM values
    - » H^0, $H^\pm$ and A^0 nearly degenerate in mass
    - » H^0 small couplings to VV, large couplings to ZA^0
    - » For large tanβ, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by tanβ. Couplings to top quarks suppressed by 1/tanβ factor.
  - The LHC has difficulty in discovering H/A above 900 GeV even at $\sqrt{s}$ = 14 TeV and 300 fb^{-1}





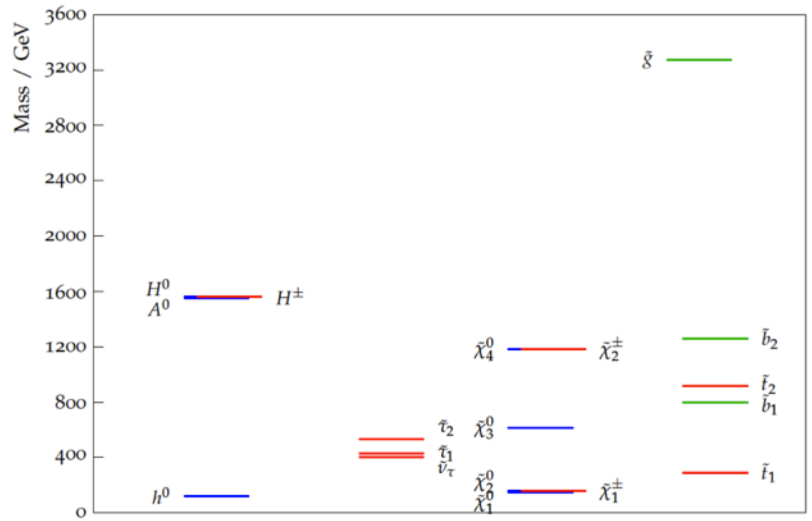
- If H/A near present LHC bounds (≃300 GeV). The states can be cleanly separated because of the excellent energy resolution of the muon collider.

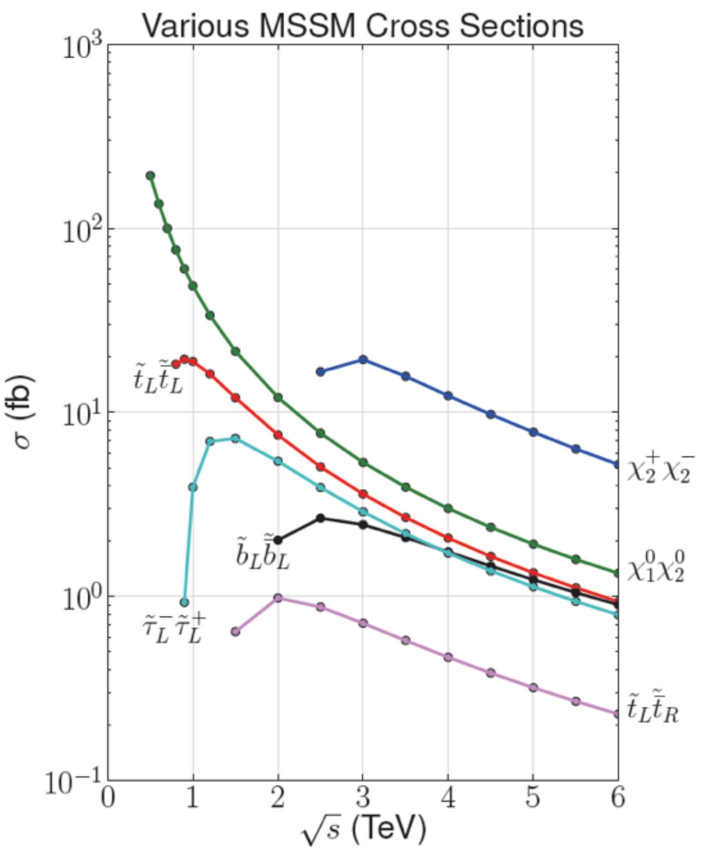


Dittmaier and Kaiser [hep-ph/0203120]

Beyond the Standard Model

- Example of Natural SUSY
  - Low-lying spectrum





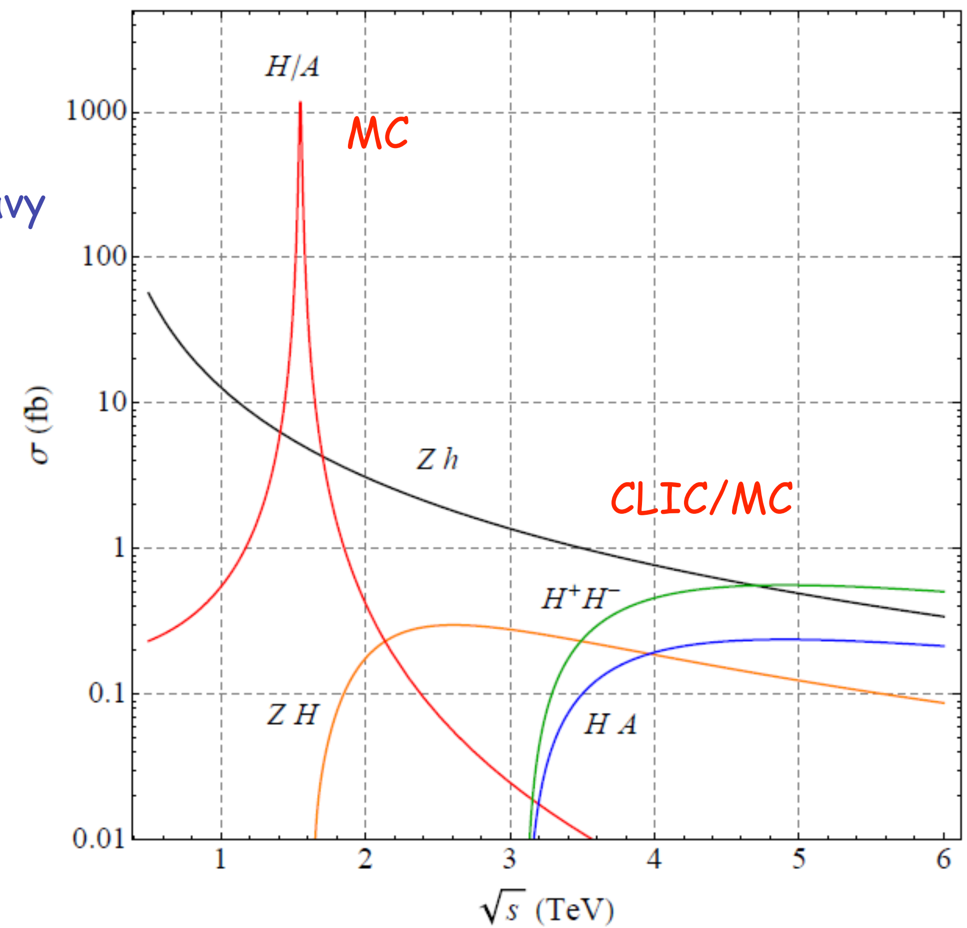
  - For electroweakinos, sleptons, …

    A ≥ 3TeV muon collider has discovery reach beyond a 100 TeV pp collider !

Beyond the Standard Model

- Generally expect very heavy: $H^{\pm}$, H^0 and A^0
  - LHC limits on $H^{\pm}$: ~ 300 (ATLAS) (CMS)
  - SUSY models that evade the all present experimental constraints often have very heavy THDM scalars
- The H/A are observable as s-channel resonances at a MC!
  - $M_H = M_A \sim 1.5$ TeV/c^2 , $\Gamma \sim 15$ GeV
  - Large $\tan\beta \sim 20$
  - Limited spectrum of SUSY particle decays.
  - Expect 10^6 H/A decays per 1 ab^{-1}
- The H/A resonances are a factory for study BSM physics.

E.E and A. Martin (arXiv:1306.2609)



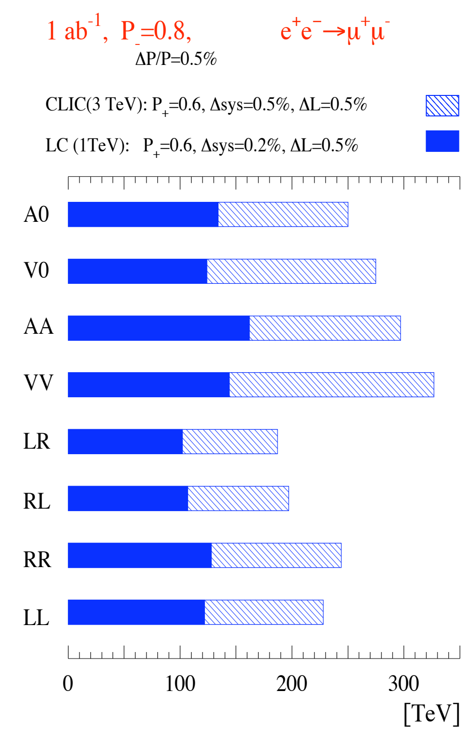
Beyond the Standard Model

- Electroweak Symmetry Breaking is generated dynamically at nearby scale
  - Technicolor, ETC, walking TC, topcolor, Two Scale TC, composite Higgs models, ...
  - New strong interaction at the Terascale:
    - What is the spectrum of low-lying states? s-channel production π_T (technipion) (0^-), ρ_T, ω_T (technirho, techniomega) nearly degenerate - needs good energy resolution
    - What is the ultraviolet completion? Gauge group? Fermion representations?
    - What is the energy scale of the new dynamics?
    - Any new insight into quark and/or lepton flavor mixing and CP violation?

- Contact interactions
  - e.g. Compositeness, broken flavor symmetries, ...
  - Present LHC bounds (~ 10 TeV)

$$\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)(\bar{\Psi}\Gamma'\Psi)$$

  - Muon collider sensitive to scales > 200 TeV
    - Forward cone cut not important
    - Polarization useful in determining chiral character of the interaction.



Summary

- The path from the intensity frontier back to the energy frontier has physics at each step.
- A staged Muon Collider can provide a Neutrino Factory to fully disentangle neutrino physics.
- The observation of a new state at 125 GeV by both ATLAS and CMS revitalizes consideration of a Higgs factory as part of a staged multi-Tev muon collider. This is particularly attractive if there is an enlarged scalar sector (eg. THDM, SUSY)
- The unique measurements of the Muon Higgs factory (4.2 fb^{-1})
  - Most precise measurement of Higgs mass: Δm_H = 0.06 MeV; direct Higgs width measurement: $\Delta\Gamma_H$ = 0.18 MeV; measurement of BR($\mu^+\mu^-$) BR(WW*) to 2% and can separate nearly degenerate scalar resonances.
- A multiTeV lepton collider will be required for full coverage of Terascale physics.
  - The physics potential for a muon collider at $\sqrt{s}$ ~ 3 TeV and integrated luminosity of 1 ab^{-1} is outstanding. Particularly strong case for SUSY and new strong dynamics.
  - Narrow s-channel states played an important role in past lepton colliders. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics.

BACKUP SLIDES

What Happened to Naturalness?

Fermilab

- Concept of naturalness.
  - K. Wilson, G. 't Hooft
  - A theory [L(μ)] is natural at scale μ ⇔ for any small dimensionless parameter ʎ (e.g. m/μ) in L(μ) the limit ʎ -> 0 enhances the symmetries of L(μ)
- The SM Higgs boson is unnatural. (m_H^2/μ^2)
  - Maybe no large gap in scales (Extra Dimensions)
- Two potential solutions:
  - scalars not elementary
    - New strong dynamics (TC, walking TC, little Higgs, top color, ...)
  - fermion masses are natural
    - Symmetry coupling fermions and bosons (SUSY)
- Quest for the "natural" theory to replace the SM has preoccupied theorists since the early 80's
- Is a third way required after the discovery of a Higgs boson?

G. 't Hooft in Proceedings of Recent Developments in Gauge Theories, Cargese, France (1980)

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

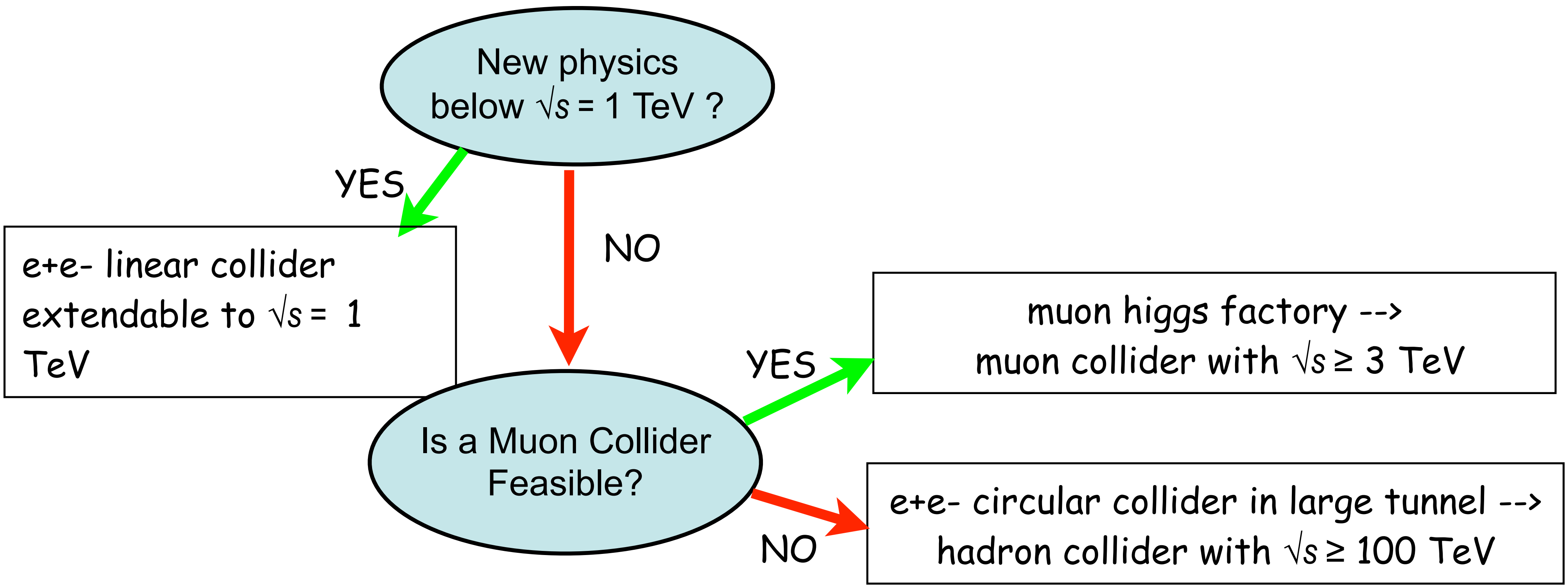
Utrecht, The Netherlands

ABSTRACT

A properly called "naturalness" is imposed on gauge theories. It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for elementary particles one needs more types of confining gauge theories besides quantum chromodynamics. We propose a search

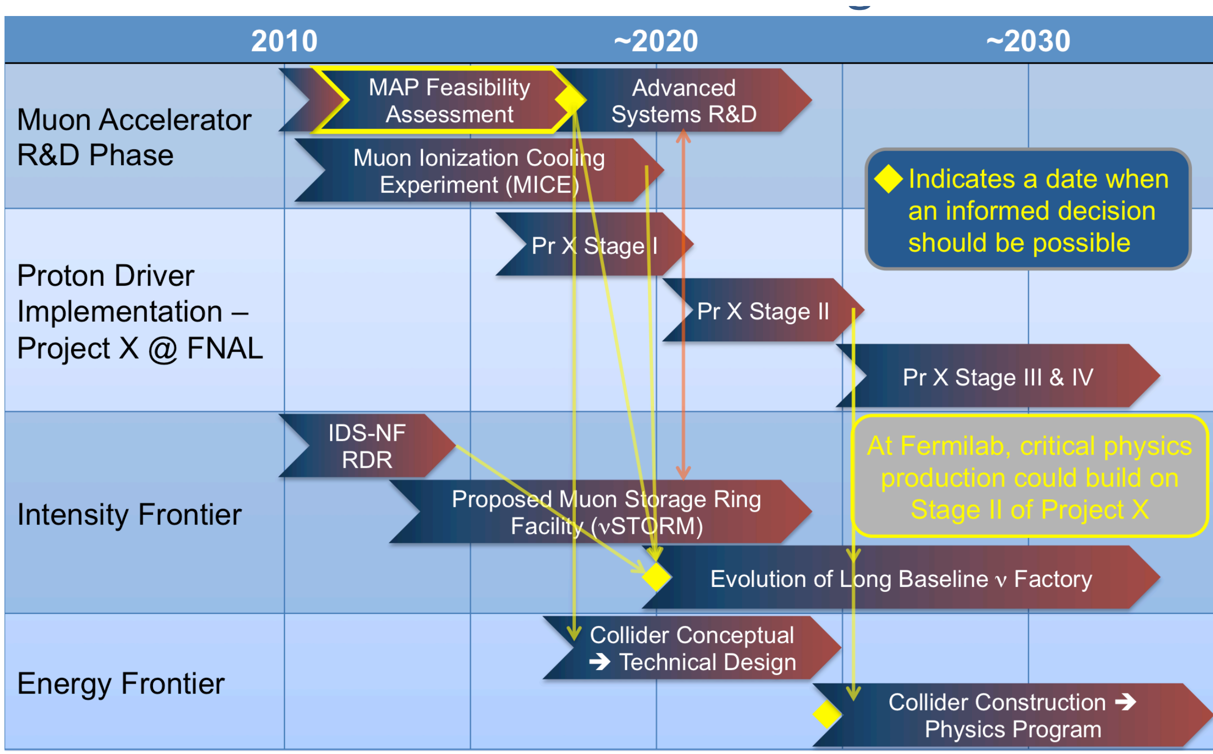
Which Accelerator for Higgs Physics?

1. The LHC is the Higgs Accelerator - Continue -> HL-LHC
2. Continue research and development of lepton colliders. In particular the muon collider needs a convincing proof of 6D cooling.
3. Push neutrino physics - Lepton sector
4. After 300 fb^{-1} of ~14 TeV running OR the discovery of BSM physics, chose the next accelerator for Higgs physics.



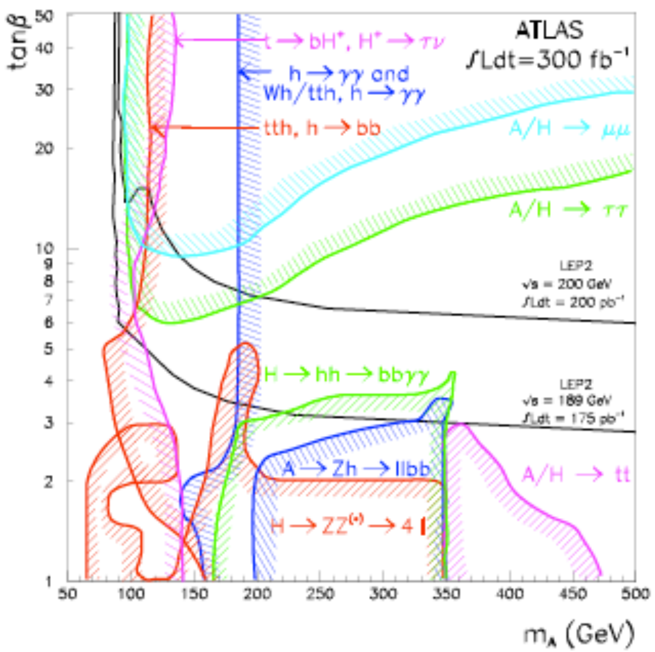
Staging Scenerio

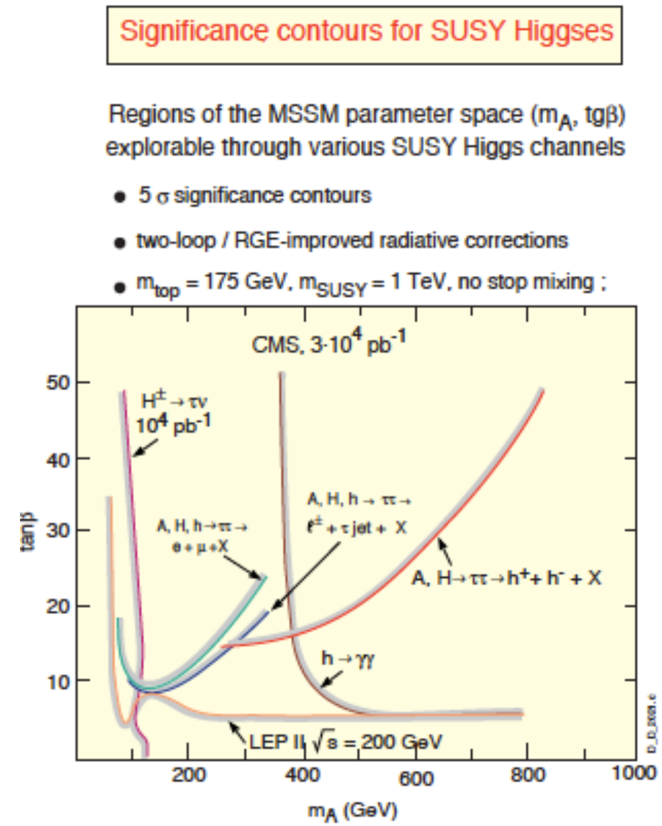
- A possible timeline
  - Project X Stages:
    - Stage I -> 1 GeV, 1 mA
    - Stage II -> 3 GeV, 3MW
    - Stage III -> 8 GeV
    - Stage IV -> 4MW
  - Decision points:
    - Finish of MAP Feasibility Assessment ~ 2018
    - Advanced System R&D makes use of nuSTORM muon ring.
    - Decision point middle of 2020's on collider program.
    - Program X Stage II can start physics of neutrino or collider program.



Beyond the Standard Model

- The LHC has difficulty observing the H, A especially for masses > 500 GeV. Even at $\sqrt{s}$ = 14 TeV and 300 fb^{-1}.





- Pair produced with easy at a multi-TeV lepton collider.

100 TeV pp Collider

- 100 TeV pp Collider (EHLQ)

1 TeV slepton pair ≈ 1 fb
2 TeV wino pair ≈ 4 fb