Muon Collider Efforts at Fermilab

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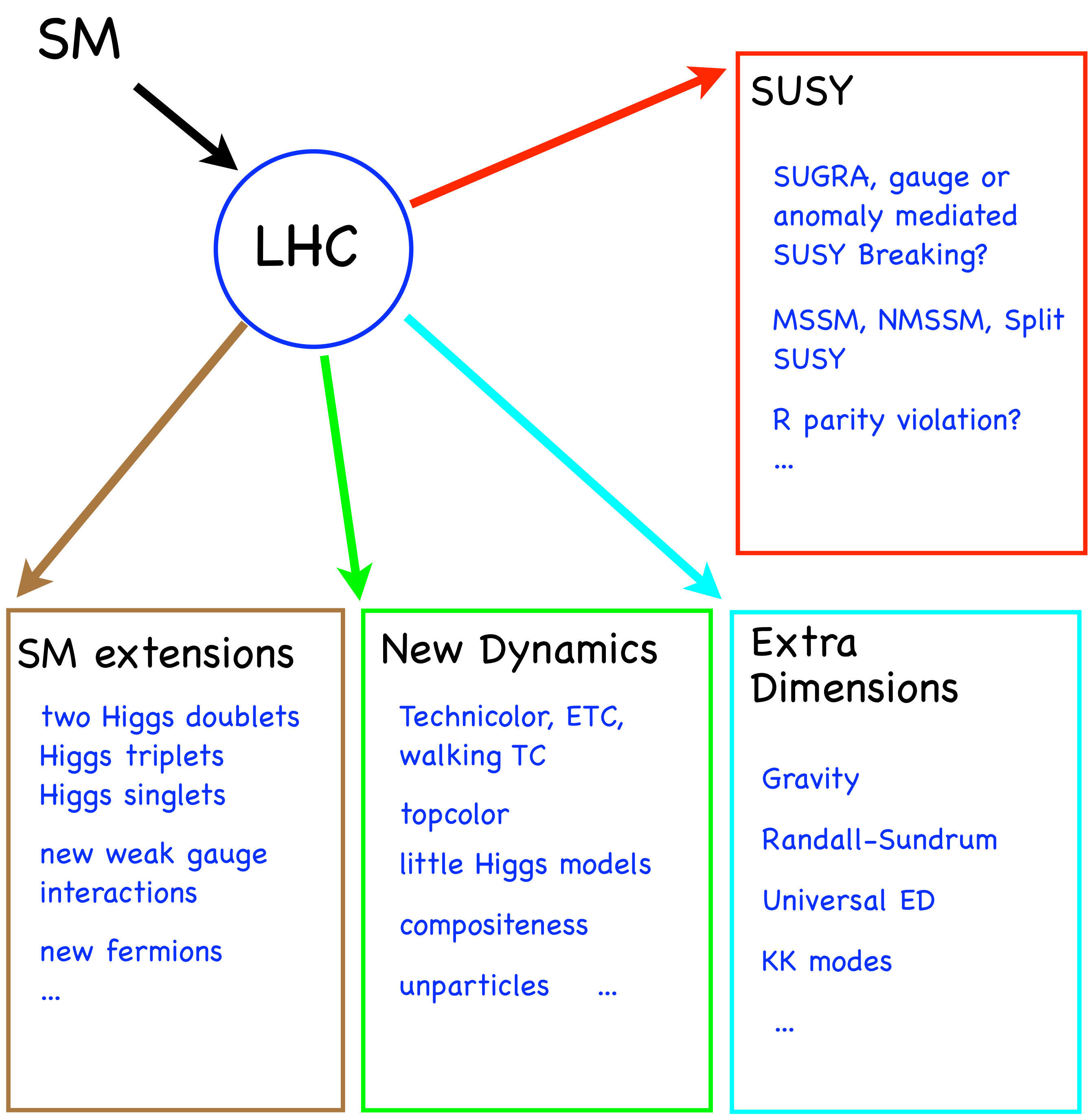
- Muon Collider Requirements
- Physics Benchmarks
- Simulation Efforts

Preparing for a Lepton Collider

- Existing facilities in 2020:
  - LHC with luminosity upgrade
- Options:
  - low energy lepton collider: ILC (500 GeV) (upgradable) or muon collider - Higgs Factory
  - lepton collider in the multi-TeV range: CLIC or muon collider
  - hadron collider in hundred TeV range: VLHC
- High energy lepton collider likely required for full study of Tevascale physics.



A Muon Collider

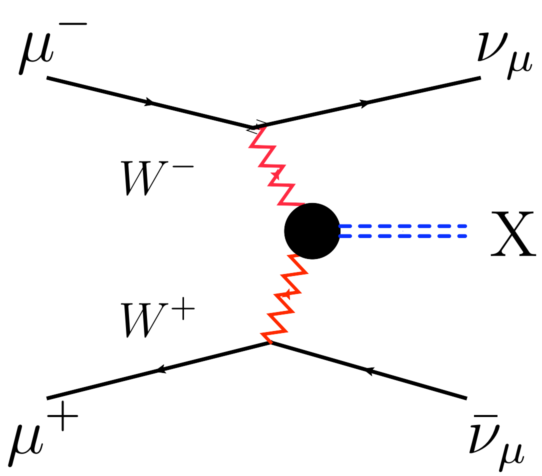
- Muon Collider:
  - Center of Mass energy: 1.5 - 5 TeV (focus 3 TeV)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (focus 400 fb^{-1} per year)

Abridged Parameter List

Machine	1.5-TeV $\mu^+\mu^-$	3.0-TeV $\mu^+\mu^-$	CLIC 3 TeV
$\mathcal{L}_{peak}$ [cm^{-2} s^{-1}]	7×10^{34}	8.2×10^{34}	8×10^{34} tot
$\mathcal{L}_{avg}$ [cm^{-2} s^{-1}]	3.0×10^{34}	3.5×10^{34}	3.1×10^{34} 99%
$\Delta p/p$ [%]	1	1	0.35
$\beta^{\star}$	0.5 cm	0.5 cm	35 μm
Turns / lifetime	2000	2400	
Rep. rate [Hz]	65	32	
Mean dipole field	10 T	10 T	
Circumference [m]	2272	3842	33.2 km site
Bunch spacing	0.75 μs	1.28 μs	0.67 ns

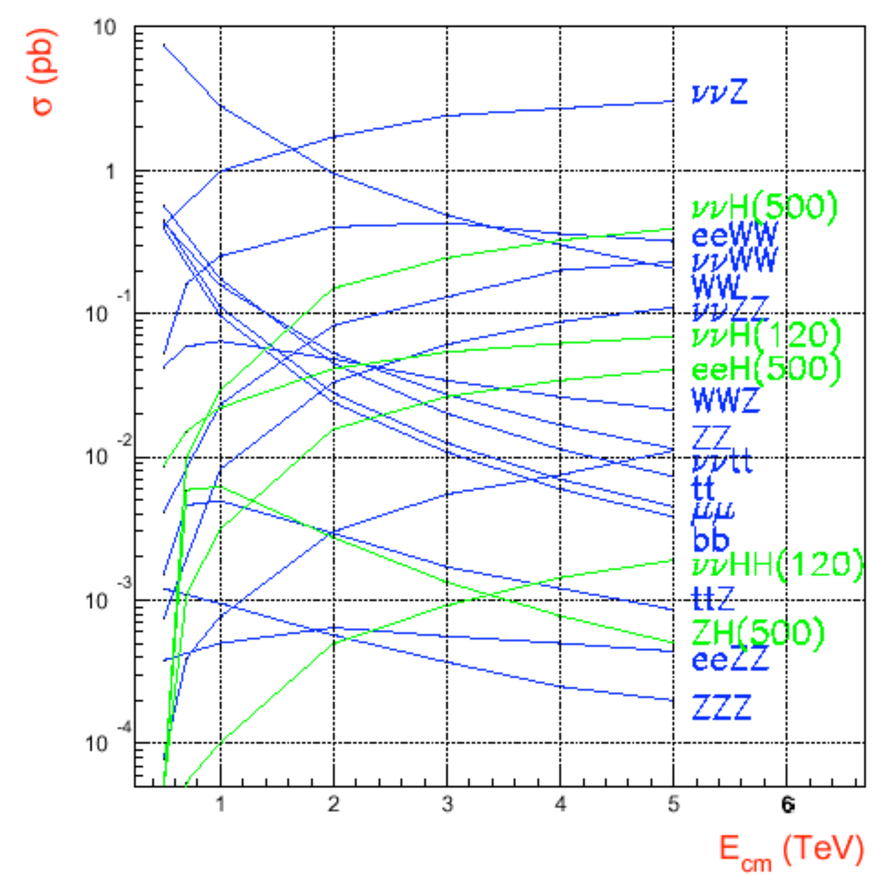
Muon Collider - Physics and Detectors

- The overall physics goals of a future lepton collider is similar for ILC/CLIC/MC. A coordinated program of detector research is appropriate. The 5 labs have proposed this to DOE.
- The Muon Collider (MC) physics effort is in the early stages. Needs much work to scope out the potential.
- The physics and backgrounds at significantly different for a 500 GeV ILC and a multiTeV CLIC/MC. For a MC there are additional backgrounds due to muon decays.
  - Fusion processes increasingly dominate s-channel processes.



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

CLIC (or MC e<->μ)

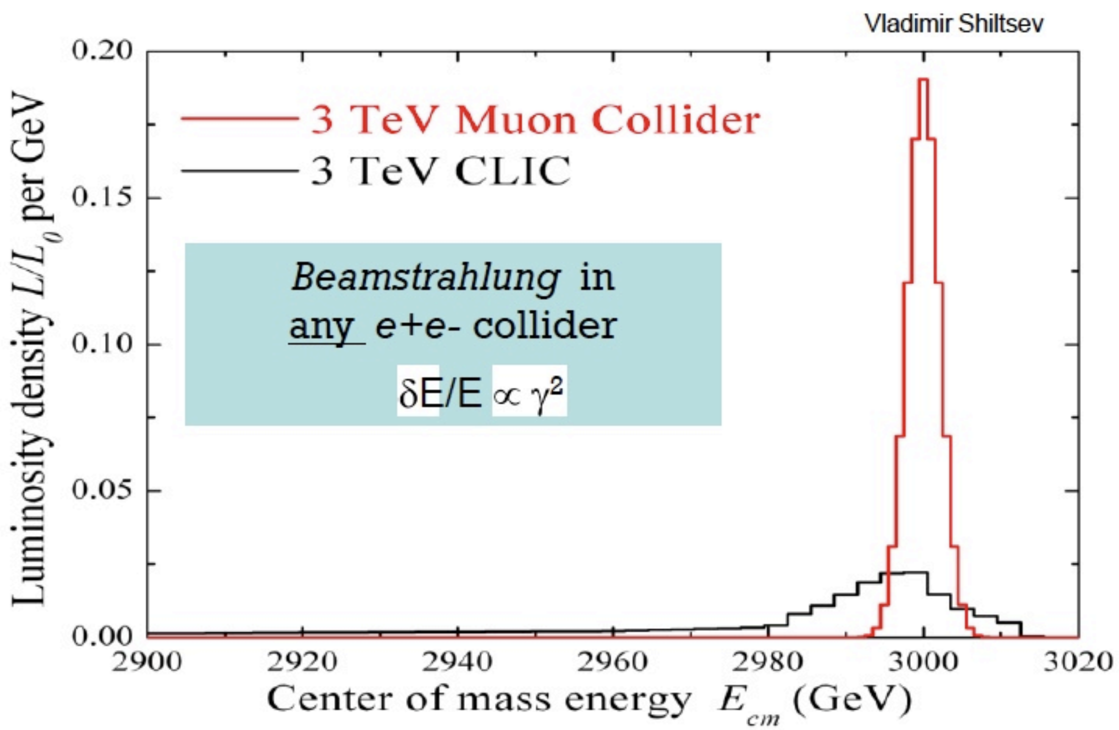


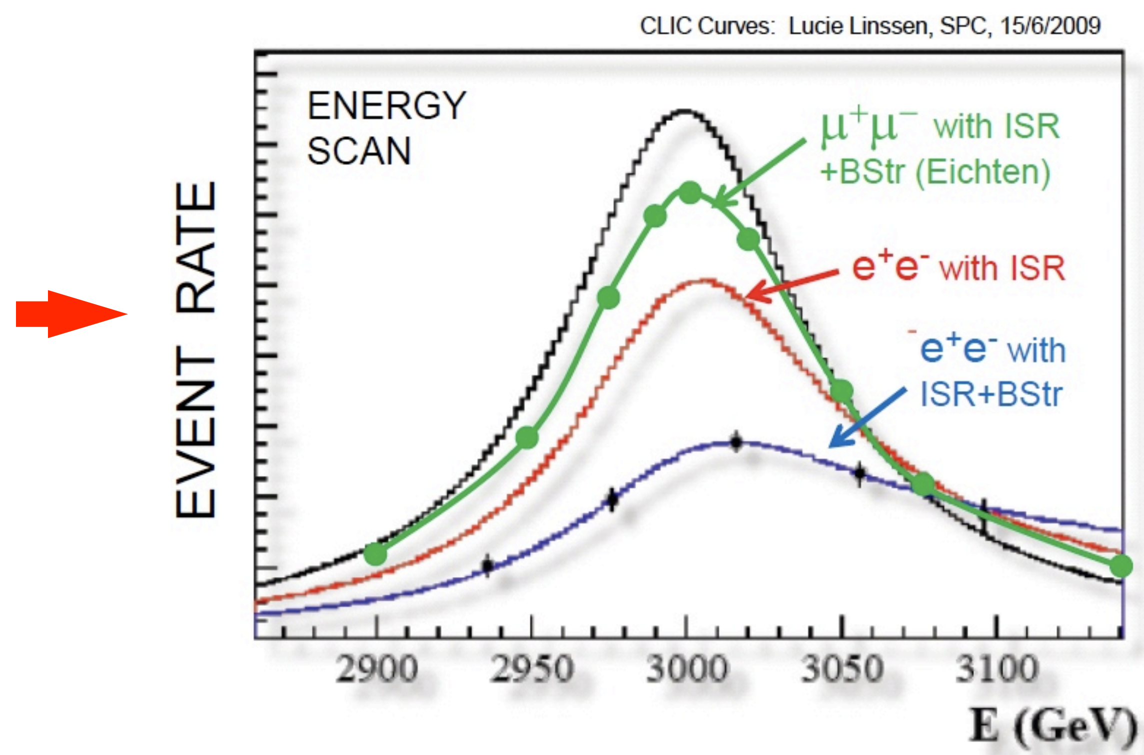
  - An Electroweak Boson collider

CLIC/MC

- Differences between MC and CLIC affects physics capabilities.

(+) Narrow energy spread → Precision scans, kinematic constraints
(+) Two detectors (2IPs)
(+) $\Delta T_{\text{bunch}} \sim 10\mu S$ → Lots of time for readout. Backgrounds don't pile up
(+) $(m_\mu/m_e)^2 \sim 40000$ → Enhanced s-channel rates for Higgs-like particles
(-) Beam polarization difficult





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MAP support

- Essential to match the research of the MAP program on accelerators with detector studies to determine the physics capability of a 1.5-4 TeV Muon Collider

FERMILAB-TM-2459-APC

R&D PROPOSAL FOR THE NATIONAL MUON ACCELERATOR PROGRAM
Revision 5b; February 24, 2010

Abstract
This document contains a description of a multi-year national R&D program aimed at completing a Design Feasibility Study (DFS) for a Muon Collider and, with international participation, a Reference Design Report (RDR) for a muon-based Neutrino Factory. It also includes the supporting component development and experimental efforts that will inform the design studies and permit an initial down-selection of candidate technologies for the ionization cooling and acceleration systems. We intend to carry out this plan with participants from the host national laboratory (Fermilab), those from collaborating U.S. national laboratories (ANL, BNL, Jlab, LBNL, and SNAL), and those from a number of other U.S. laboratories, universities, and SBIR companies. The R&D program that we propose will provide the HEP community with detailed information on future facilities based on intense beams of muons—the Muon Collider and the Neutrino Factory. We believe that these facilities offer the promise of extraordinary physics capabilities. The Muon Collider presents a powerful option to explore the energy frontier and the Neutrino Factory gives the opportunity to perform the most sensitive neutrino oscillation experiments possible, while also opening expanded avenues for the study of new physics in the neutrino sector. The synergy between the two facilities presents the opportunity for an extremely broad physics program and a unique pathway in accelerator facilities. Our work will give clear answers to the questions of expected capabilities and performance of these muon-based facilities, and will provide defensible ranges for their cost. This information, together with the physics insights gained from the next-generation neutrino and LHC experiments, will allow the HEP community to make well-informed decisions regarding the optimal choice of new facilities. We believe that this work is a critical part of any broad strategic program in accelerator R&D and, as the P5 panel has recently indicated, is essential for the long-term health of high-energy physics.

MAP organization in place and functioning

Proposal Submitted by Pier Oddone on behalf of the MAP collaboration, 1st March 2010.
- 6-7 years long program (depending on funding level)
- Aims to establish feasibility and estimate cost range

214 MAP participants (at birth) from 14 institutions:

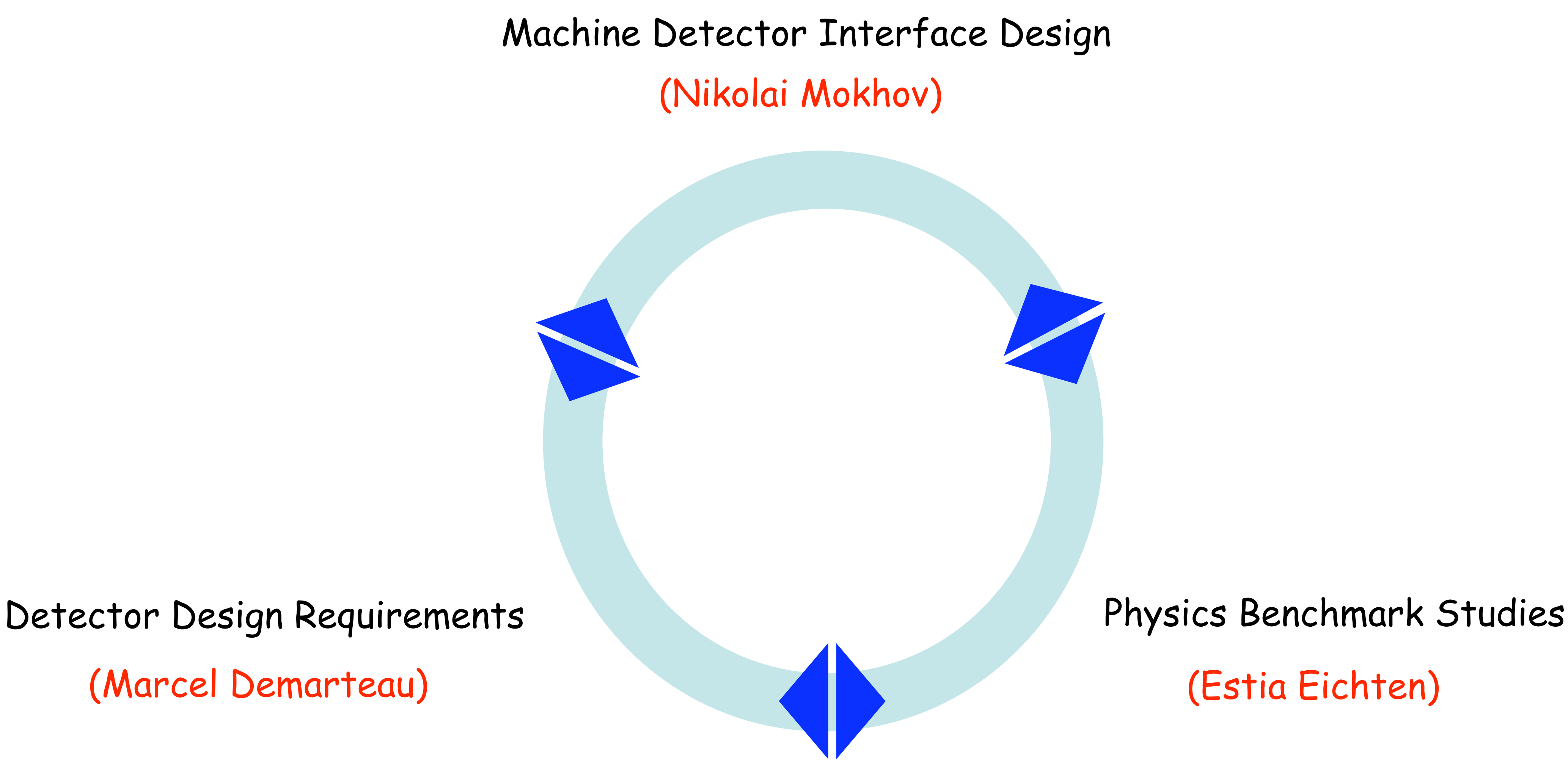
ANL, BNL, FNAL, Jlab, LBNL, ORNL, SNAL, Cornell, IIT, Princeton, UCB, UCLA, UCR, U-Miss.

Present Status

- Coordinated effort begun on physics and detector studies:
  - Machine-Detector Interface group within MAP will generate machine background files for physics-detector activity.
  - Physics-detector studies leader will participate in MAP "management council"
- Detailed detector and muon decay background studies from ~10yrs ago gave encouraging results, but since then:
  - New MC lattice design
  - A decade of detector development
  - Greater community expectations for detector performance
- New physics, detector and background studies have begun:
  - Kick-off workshop on Physics and Detectors held at Fermilab Nov. 10-12, 2009 [Ken Peach(UK), Jacobo Konigsberg (Florida), E.E.] (http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-muoncollider.html)
  - Rapid progress since then on shielding design (shielding cone angle reduced from 20° to 10°).
  - Started biweekly meetings including SLAC, Fermilab and other interested parties. Aim is to create an active detector simulation group. [Marcel Demarteau, EE (Fermilab), Norman Graf (SLAC)] (http://indico.fnal.gov/categoryDisplay.py?categid=137)
    - Began effort to develop a fast monte carlo sufficient for initial the physics studies.
    - Evaluating the existing SiD software framework as a starting point for more complete detector simulation.

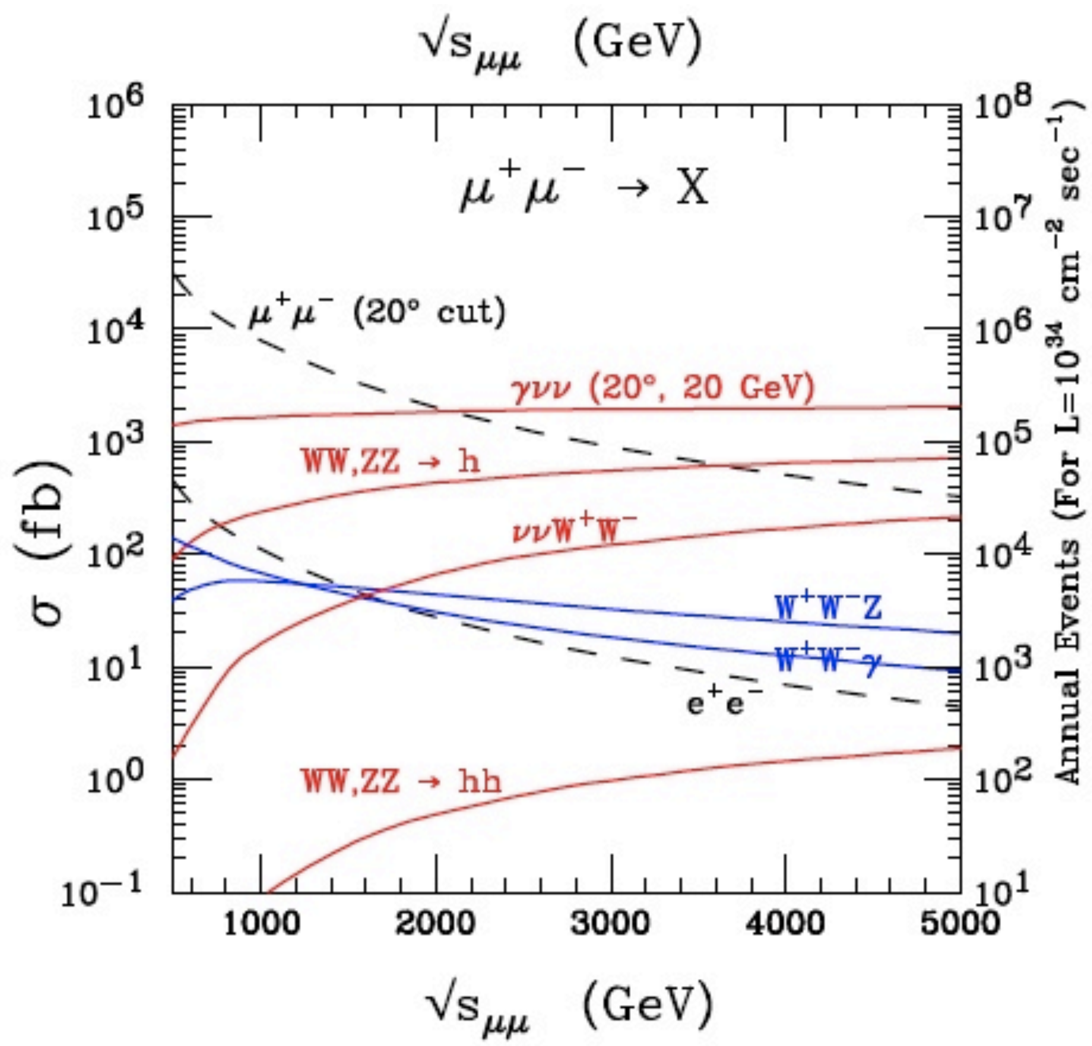
Iterative Process

- Three interconnected elements of Fermilab effort
  - Machine Detector Interface at the collision point
  - Physics benchmarks for studying the capabilities of the MC
  - Detector design to realize this physics



Muon Collider Benchmarks

- Physics processes similar CLIC/MC for 3TeV energy



Jets from W, Z decays
-> Must resolve W/Z

Many events have large missing energy
-> What is impact for SUSY?

No penalty for heavy flavors
-> Need excellent b and t tagging

Initial Benchmarks

- Ayres Freitas, Tao Han, E.E.: A first pass at benchmarks

Final states	Exp. considerations	Theo. considerations
$\ell^+\ell^-, \quad \ell = e,\ \mu,\ \tau$	Ecal, μ-chamber; τ-tagging at HE	Contact interaction
$q\bar{q}, \quad q = u,\ c,\ s,\ b$	Hcal, b-tagging at HE	Contact interaction
$\gamma\gamma$	Ecal	QED
$\gamma + \not{E}$	Ecal, missing energy	missing mass/dark matter
$W^+W^- \to q\bar{q}', q\bar{q}'$	Hcal: M_W-reconstruct	New resonances
$W^+W^- \to \ell\bar{\nu}, q\bar{q}'$	$\not{E}$, M_W-reconstruct	New resonances
$ZZ \to q\bar{q}, q\bar{q}$	Hcal: M_Z-reconstruct	New resonances
$ZZ \to \ell^+\ell^-, \nu\bar{\nu}$	Ecal; $\not{E}$	New resonances
$t\bar{t} \to bW^+\ \bar{b}W^+$	E,Hcal, b-tagging, mass reconstruct	New heavy quarks
ZHH	multiple $b\bar{b}$	Higgs self coupling
$W^+W^- \to HH$	multiple $b\bar{b}$	Higgs self coupling
$\nu\bar{\nu}W^+W^- \to 4j + \not{E}$	Hcal: M_W-reconstruct	WW scattering
$\nu\bar{\nu}ZZ \to 4j + \not{E}$	Hcal: M_Z-reconstruct	WW scattering
$\nu\bar{\nu}t\bar{t}$	Hcal: m_t-reconstruct	$WW \to t\bar{t}$
$\tilde{\chi}_i\tilde{\chi}_j$	leptons, jets+$\not{E}$	SUSY
$\tilde{\ell}_i\tilde{\ell}_j$	leptons+$\not{E}$	SUSY
$\tilde{q}_i\tilde{q}_j$	jets+$\not{E}$	SUSY

Z'

KK mode

Strong Dynamics

4th Generation,
Little Higgs Models

Strong Dynamics

SUSY

General Questions

- Should we adopt the ILC benchmarks for a multiTeV lepton collider?

Benchmarks for ILC Physics Study 2009-2010 (1 TeV) from Michael Peskin

1. $e^+e^- \to \nu\overline{\nu}h^0$ at $E_{CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson of mass 200 GeV, in the final states $h^0 \to b\overline{b}$ and $h^0 \to \mu^+\mu^-$. The goal is to measure the cross section times branching ratio for these reaction.
2. $e^+e^- \to t\overline{t}h^0$ at $E_{CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson of mass 200 GeV, in the final state $h^0 \to WW, ZZ$, in the 10 jet mode. The goal is to measure the Higgs boson coupling to $t\overline{t}$.
3. $e^+e^- \to \tau^+\tau^-$ at $E_{CM} = 1$ TeV. The goal is to measure the forward-backward asymmetry and the final-state τ polarization.
4. $e^+e^- \to b\overline{b}, c\overline{c}$ at $E_{CM} = 1$ TeV. The goal is to measure the cross section and the forward-backward asymmetry of each reaction.
5. $e^+e^- \to \nu\overline{\nu} + WW, ZZ$ at $\sqrt{s} = 1$ TeV. The goal is to measure the effective Lagrangian parameters α_4 amd α_5 in strongly interacting models of the Higgs sector.

- If a s-channel resonance is observed at LHC, how do CLIC/MC studies compare?
- What is the best way to determine the SUSY spectrum and couplings at a few TeV lepton collider?
- If the LHC results suggest a new strong dynamics, can we reach the scale?
- What if the LHC finds the SM Higgs (with possibly more scalars)?

A Start

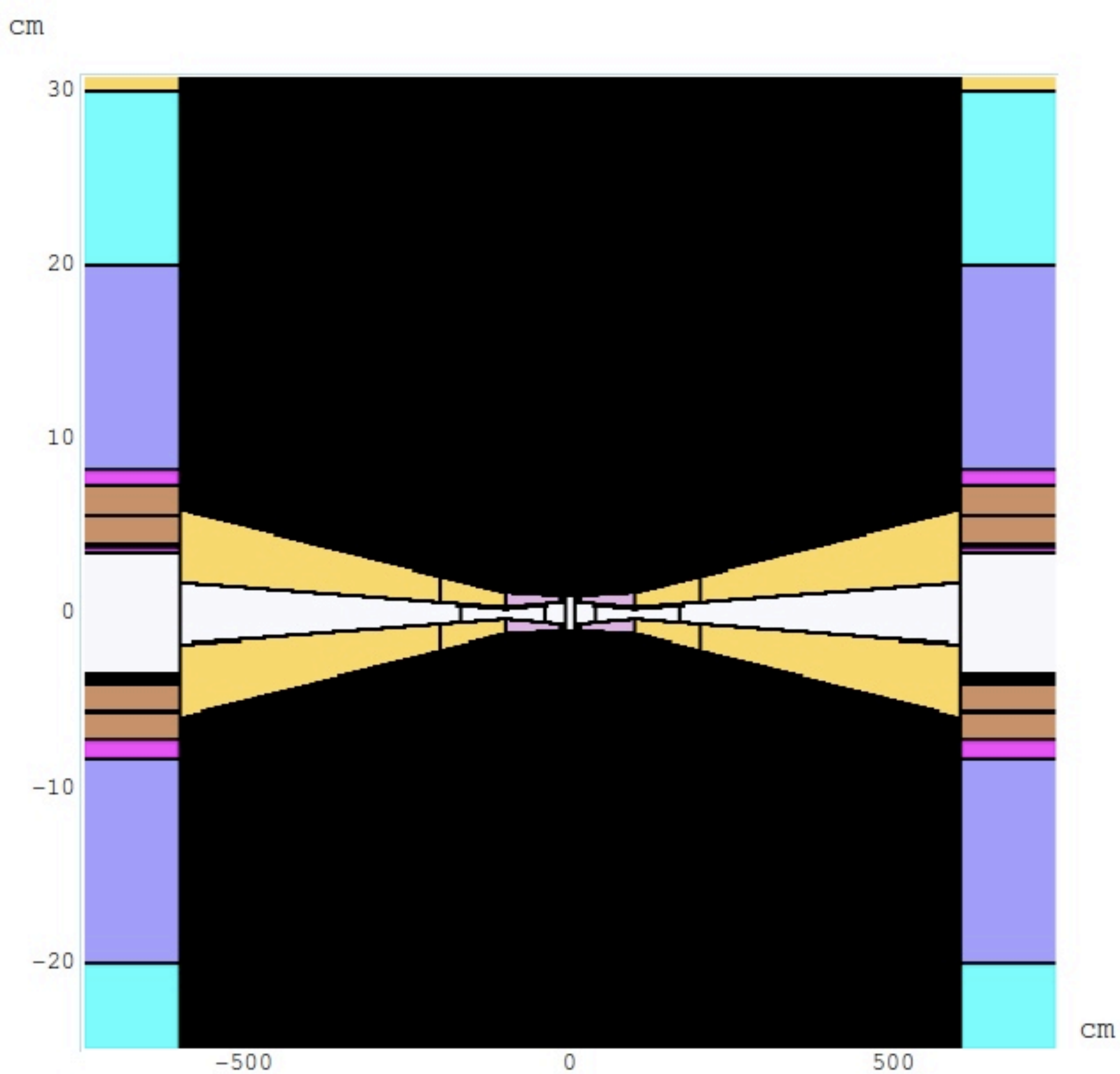
Toward Benchmark Processes for 3 TeV Muon Collider:

The SM with h(120) as reference point. Generate samples for 1 ab^{-1} total luminosity.

- $\mu^+\mu^-$ SM: reference process. BSM: Z prime, contact term sensitivity versus angular cuts.
- $(W^+W^-,\ ZZ,\ ZW^-\mu^+)\ +X$. Here X is anything not visible in detector (i.e. ν's, particles outside the detectors angular acceptance, ...).
  SM: W/Z resolution in jets. $W^+ \to c\bar{s}$, $Z \to b\bar{b}$, resolution in WW pair invariant mass.
  BSM: new strong dynamics (eg. ρ_T)
- $b\bar{b}$ + X. SM: resolve h from Z. BSM: Two Higgs doublet model - resolve H, A. (Use SUSY parameters with $m(H) = 400$ GeV.)
- $\tilde{\mu}^+\tilde{\mu}^-$ SUSY: Study decays. Find neutralino mass using edge effect

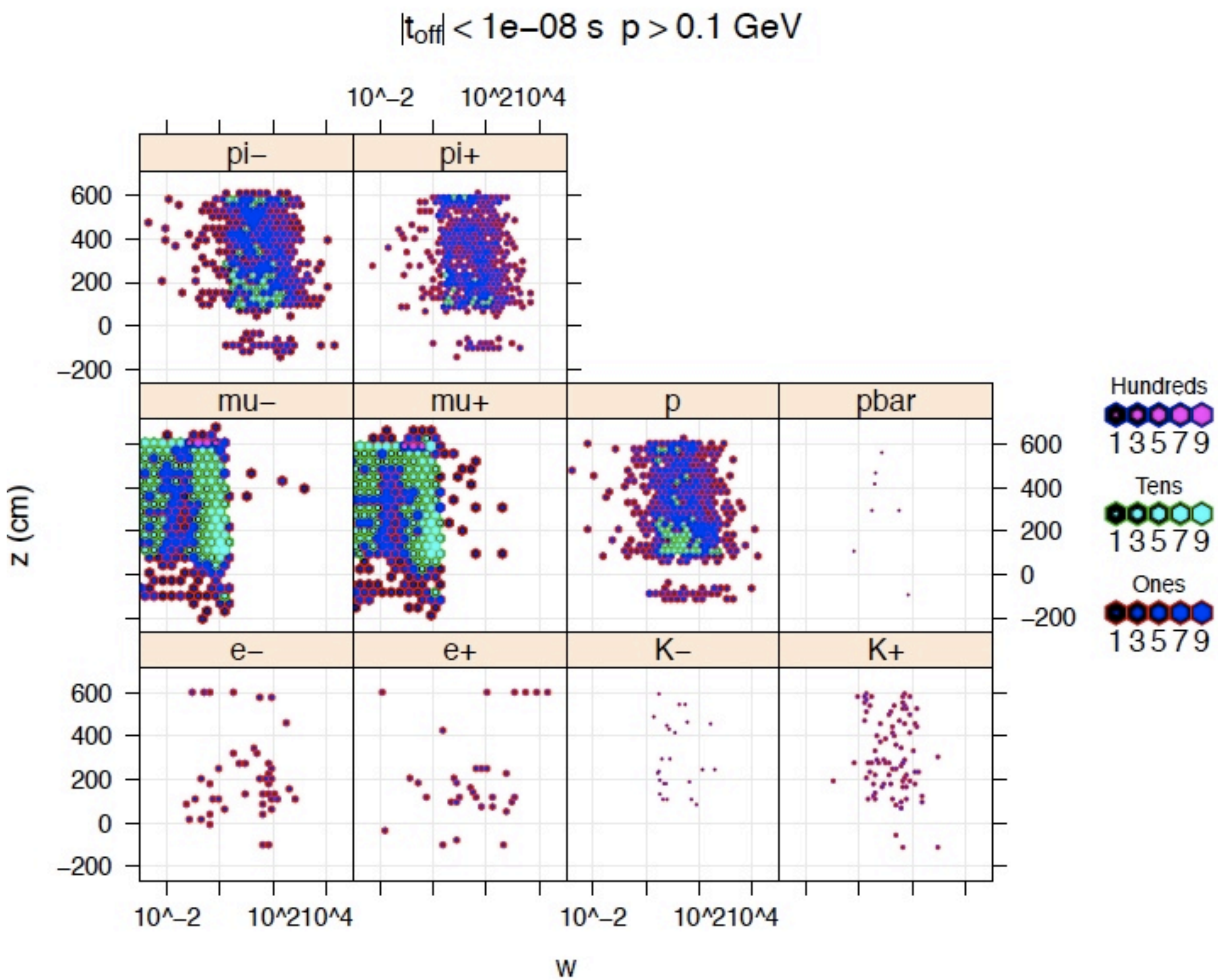
Fast Monte Carlo Effort

- Use the backgrounds from MARS15 simulations to feed into a detector area. Defined initially as a geometry with a cone of shielding 10 degrees about the beam axis. (20 degrees in old work 1997)



Stephen Mrenna
Ray Culbertson

Particle Fluxes at Boundaries

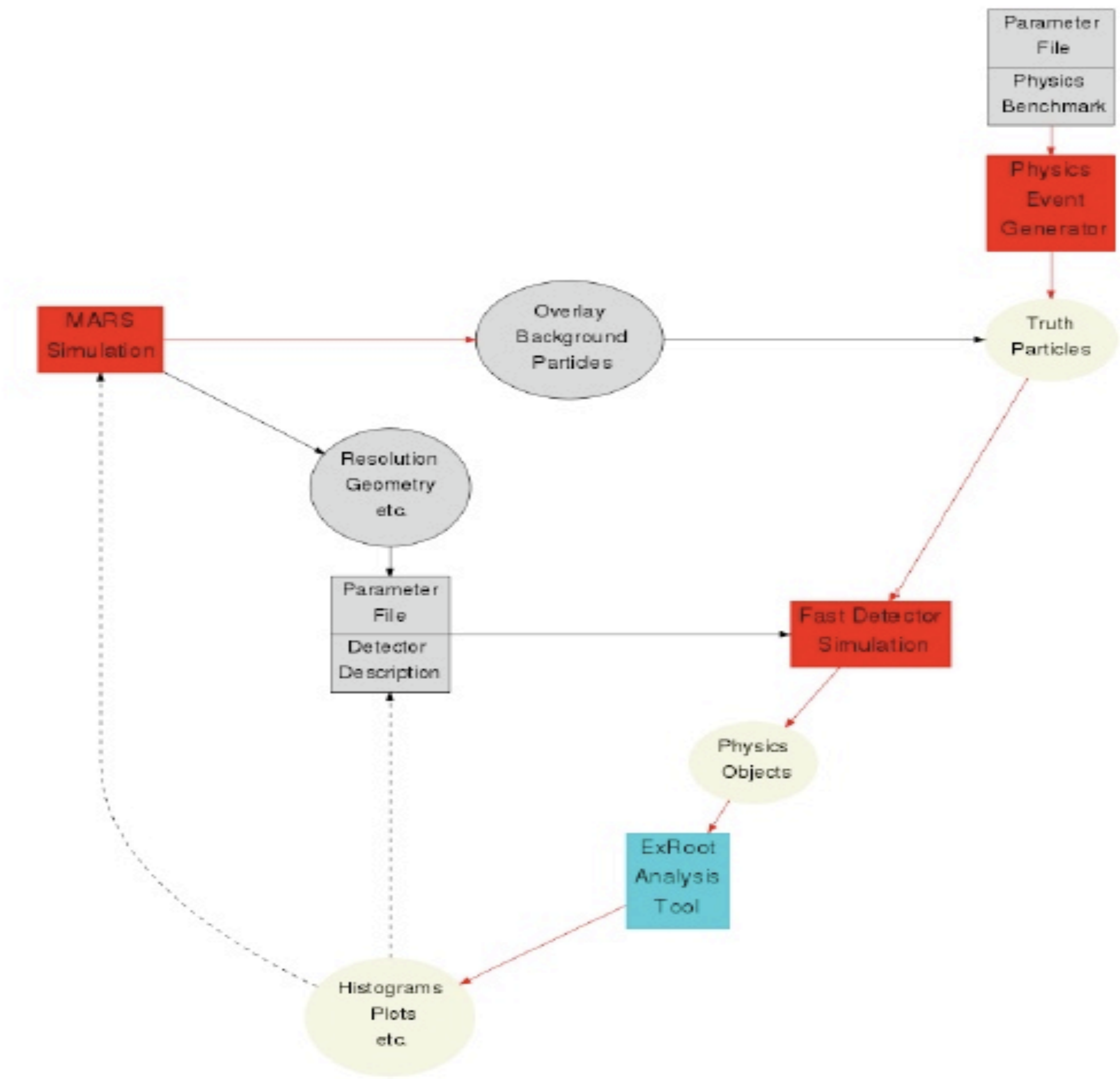


Using Backgrounds in Fast Simulation

- For the calorimetry can use the heat load from backgrounds
- Tracking more difficult: particles entering the detector away from IP
- For Vertex detector - determine occupancy
- Fast MC should be available in PGS form so theorists can use it for physics simulation.
- Will allow the identification of issues for retuning of MDI and help set

the focus for detector component research.

Monte Carlo Development Flow Chart



Summary of plan for 2011-2013

- Complete a fast Monte Carlo for physics simulations
- Develop an initial physics and detector report by the end of 2011. Allows input to the design parameters of the MAP study.
  - This study should set requirements on luminosity, energy, determine acceptable background event rates and suggest feasible methods of attaining these levels.
  - The impact of the polarized beams, energy spread, and detector fudicial volume should be evaluated.
  - The physics opportunities should be compared to the CLIC option and take account of the substantial running of LHC after a luminosity upgrade.
  - Synergies with the ILC/CLIC and LHC detector R&D should be exploited.
- Using an existing framework (e.g. SiD framework) to do a more detailed detector study to identify the needs for detector development.

Backup slides

		ILC	CLIC	CLIC	MC	MC
E_{cms}	TeV	0.5	0.5	3	1.5	4
f_{rep}	Hz	5	50	50	12	6
f_{RF}	GHz	1.3	12	12	n/a	n/a
G_{RF}	MV/m	31.5	80	100	n/a	n/a
n_b		2625	354	312	1	1
Δt	ns	369	0.5	0.5	10000	27000
N	10^9	20	6.8	3.7	2000	2000
σ_x	nm	655	202	40	5900	2000
σ_y	nm	5.7	2.26	1	5900	2000
ε_x	μm	10	2.4	0.66	25	25
ε_y	μm	0.040	0.025	0.020	25	25
L_{total}	10^{34} cm^{-2}s^{-1}	2.0	2.3	5.9	1.0	4.0
$L_{0.01}$	10^{34} cm^{-2}s^{-1}	1.45	1.4	2.0	1.0	4.0

Muon Collider Motivation

- If we can build a **muon collider**, it is an **attractive multi-TeV lepton collider option because muons don't radiate as readily as electrons** $(m_\mu / m_e \sim 207)$:

COST

- COMPACT
  Fits on laboratory site
- MULTI-PASS ACCELERATION
  Cost Effective
- MULTIPASS COLLISIONS IN A RING (~1000 turns)
  Relaxed emittance requirements & hence relaxed tolerances

PHYSICS

- NARROW ENERGY SPREAD
  Precision scans, kinematic constraints
- TWO DETECTORS (2 IPs)
- $\Delta T_{bunch} \sim 10\ \mu s$ … (e.g. 4 TeV collider)
  Lots of time for readout
  Backgrounds don't pile up
- $(m_\mu/m_e)^2 = \sim 40000$
  Enhanced s-channel rates for Higgs-like particles

A 4 TeV Muon Collider would fit on the Fermilab Site

Challenges

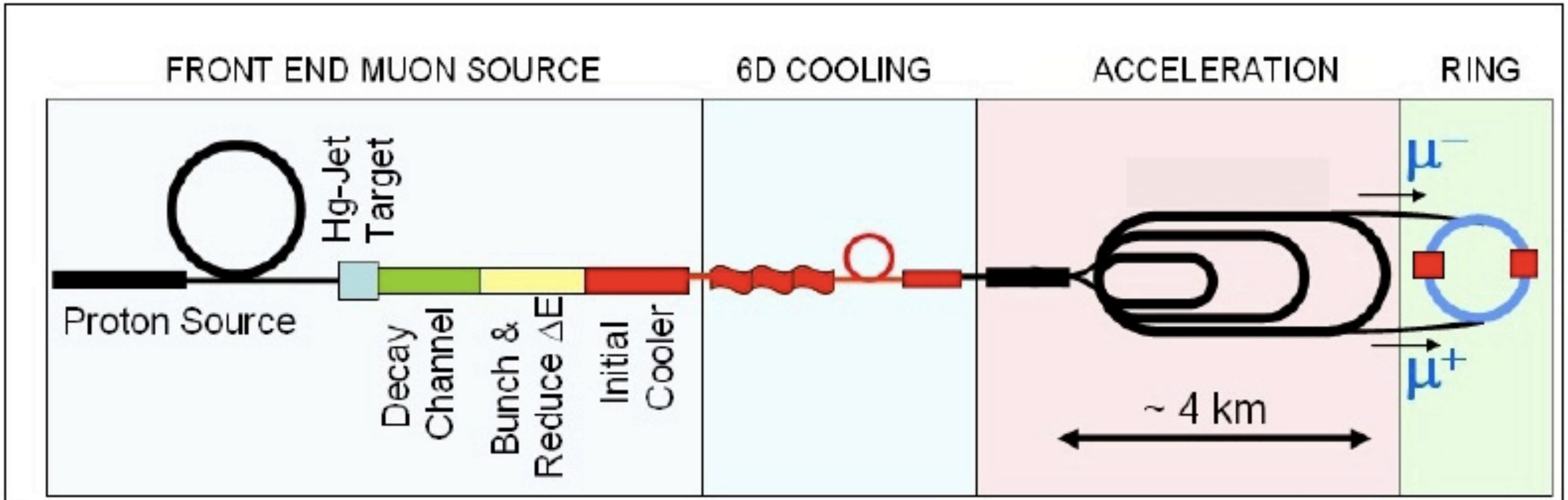
Muons are born ($\pi \rightarrow \mu\nu$) within a large phase space

- To obtain luminosities $O(10^{34})$ $cm^{-2}s^{-1}$, need to reduce initial phase space by $O(10^6)$

Muons Decay (τ_0 = 2μs)

- Everything must be done fast
  → need ionization cooling
- Must deal with decay electrons
- Above ~3 TeV, must be careful about decay neutrinos

Muon Collider Schematic



Proton source: Upgraded PROJECT X (4 MW, 2±1 ns long bunches)

10^{21} muons per year that fit within the acceptance of an accelerator

In present MC baseline design, Front – End is same as for Neutrino Factory

$\sqrt{s}$ = 3 TeV
Circumference = 4.5km
$\mathcal{L} = 3\times10^{34}$ cm^{-2}s^{-1}
μ/bunch = 2×10^{12}
σ(p)/p = 0.1%
$\varepsilon_{\perp N}$ = 25 μm
β* = 5mm
Rep Rate = 12Hz

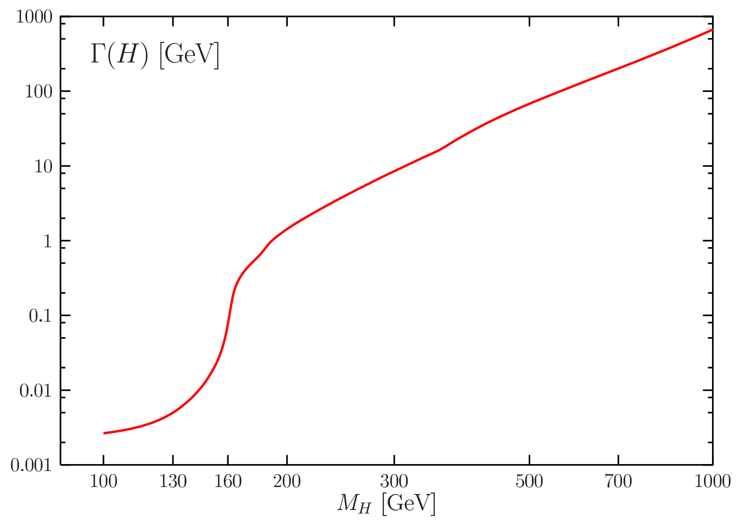
Low Energy Muon Collider Basics

- For $\sqrt{s} < 500$ GeV lepton collider
  - SM threshold regions: top pairs; W^+W^-; Z^0Z^0; Z^0h production
- For low energy muon collider
  - s-channel Higgs production
    - Coupling $\propto$ lepton mass

$$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^4$$

    - Narrow width

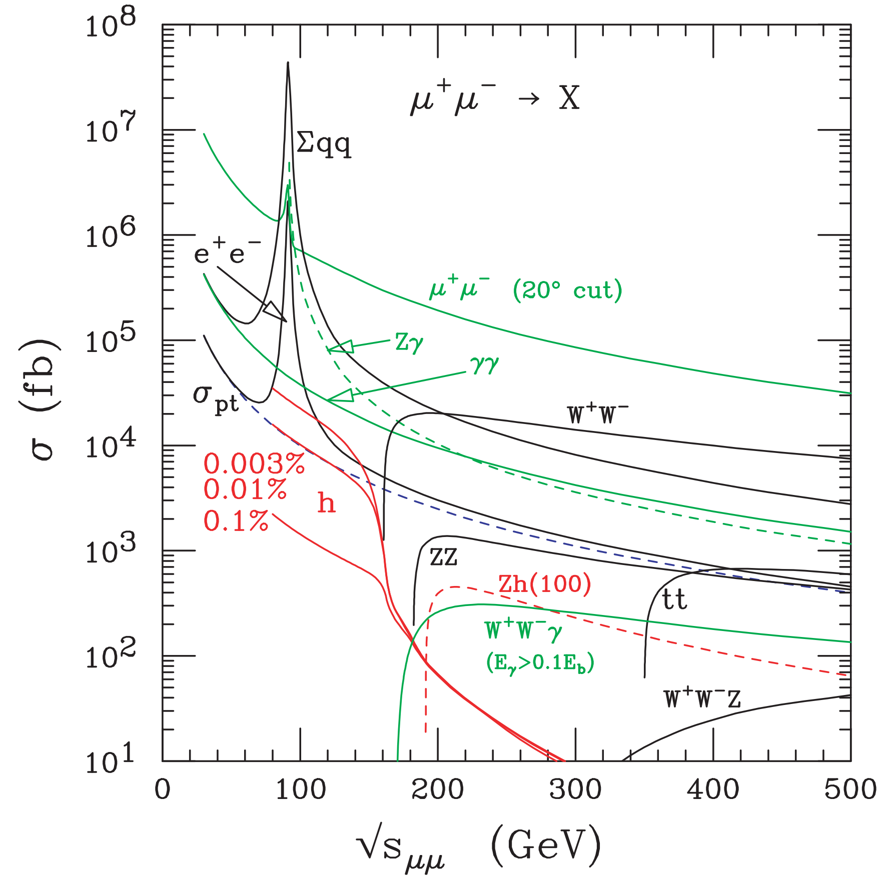
$$\Gamma = 3.6 \text{ MeV} \quad (m_h = 120 \text{ GeV})$$

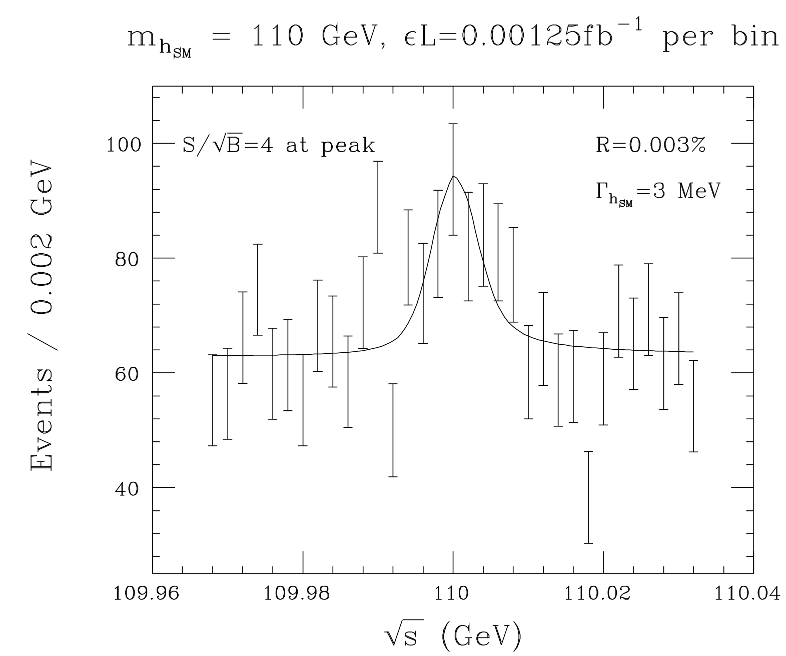


    - Direct width measurement

$$\Delta E/E \approx 0.003\% \text{ and } 100\ pb^{-1}$$

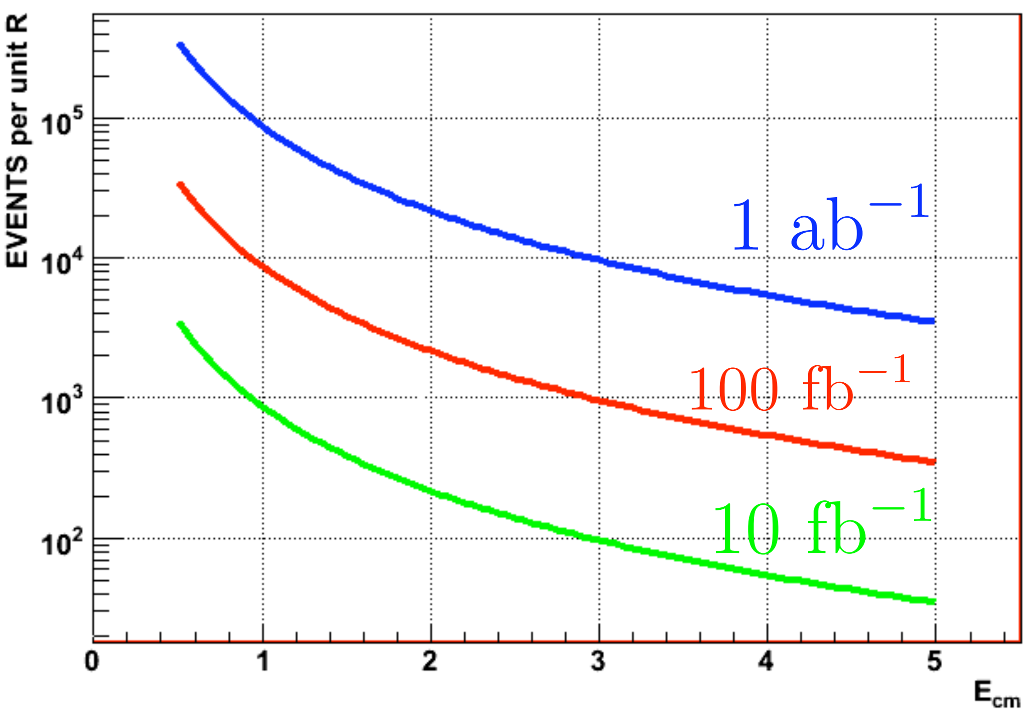
Standard Model Cross Sections





Multi-TeV Muon Collider Basics

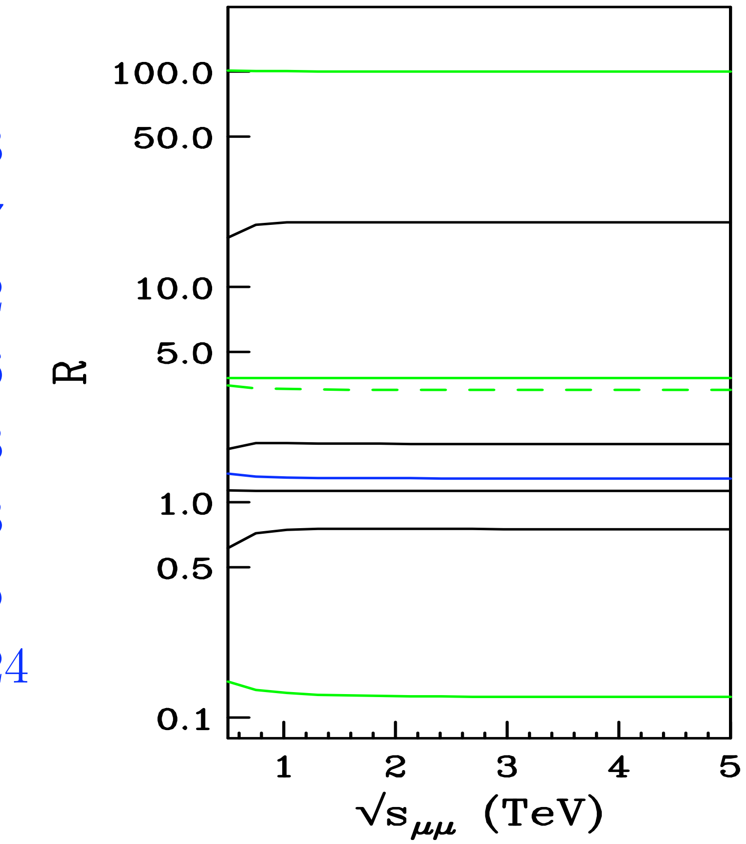
- For $\sqrt{s}$ > 500 GeV
  - Above SM pair production thresholds: R ≡ σ/σ_{QED} ($\mu^+\mu^- \to e+e-$) flat
- Luminosity Requirements



R at $\sqrt{s}$ = 3 TeV

O(α_{em}^2) O(α_s^0)

$$\mu^+\mu^-(20^o\ \mathrm{cut}) = 100$$
$$W^+W^- = 19.8$$
$$\gamma\gamma = 3.77$$
$$Z\gamma = 3.32$$
$$t\bar{t} = 1.86$$
$$b\bar{b} = 1.28$$
$$e^+e^- = 1.13$$
$$ZZ = 0.75$$
$$Zh(120) = 0.124$$



(one unit of R)

$$\sigma_{\mathrm{QED}}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \mathrm{fb}}{s(\mathrm{TeV}^2)}$$

For example: $\sqrt{s} = 3.0\ \mathrm{TeV}$ ⇒ 965 events/unit of R

$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \rightarrow 100\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$$

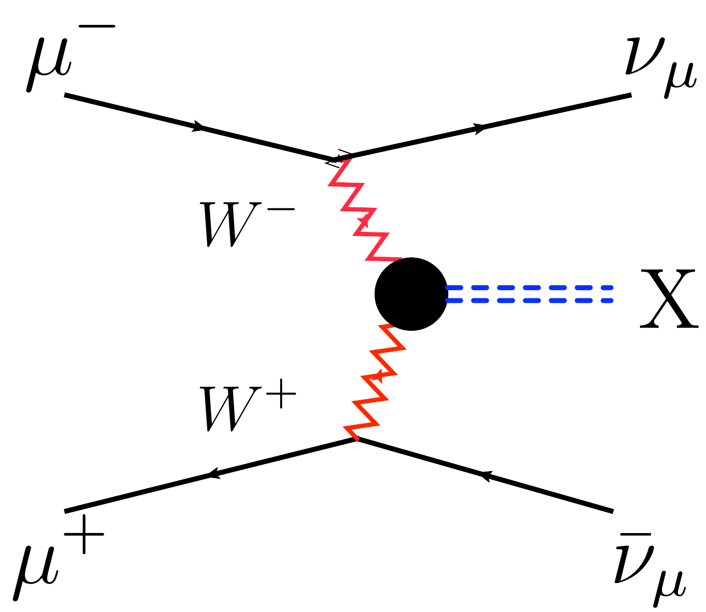
Processes with R ≥ 0.1 can be studied

Total - 128 K SM events per year

Fusion Processes

- Large cross sections
- Increase with s.
- Important at multi-Tev energies
- $M_X^2 < s$

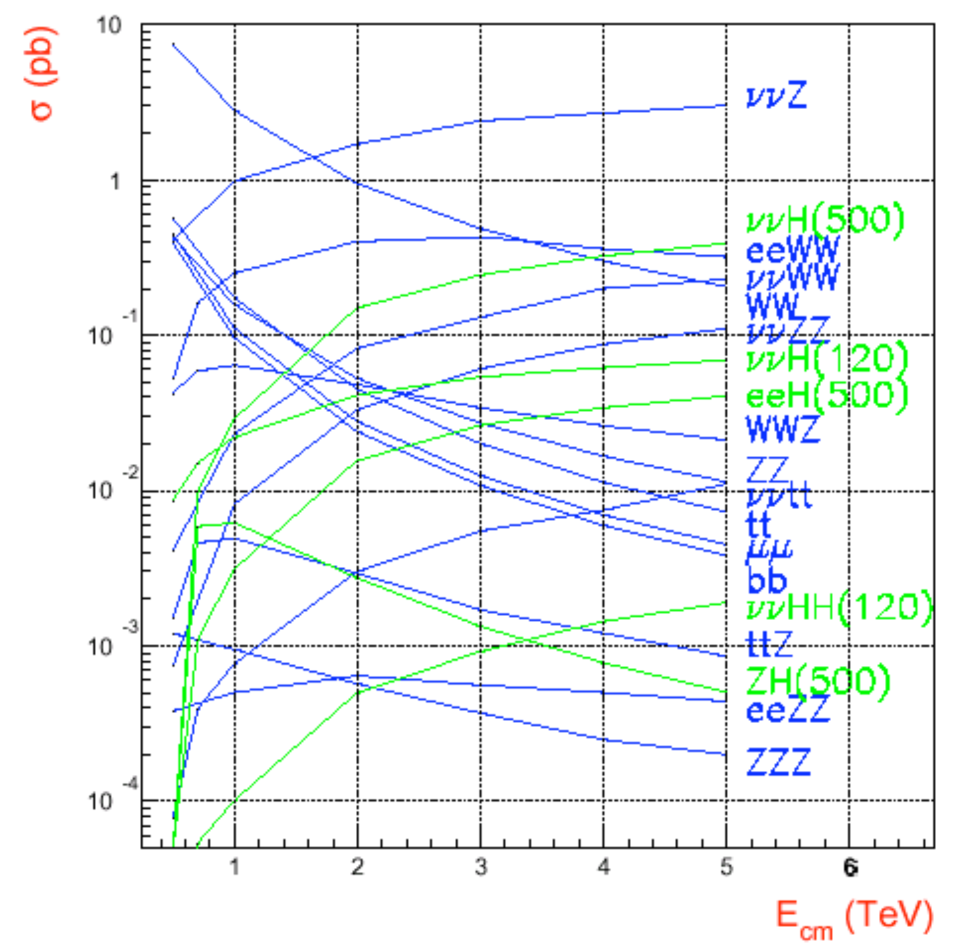
- Backgrounds for SUSY processes
- t-channel processes sensitive to angular cuts



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

❑ An Electroweak Boson Collider

CLIC (or MC e<->μ)



X	R (@ 3 TeV)
Z^0	230
$h^0(500)$	25
W^+W^-	19.8
Z^0Z^0	5.8
$h^0(120)$	5.5
$t\bar{t}$	0.6
$h^0h^0(120)$	0.1