A Future Muon Collider

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Outline

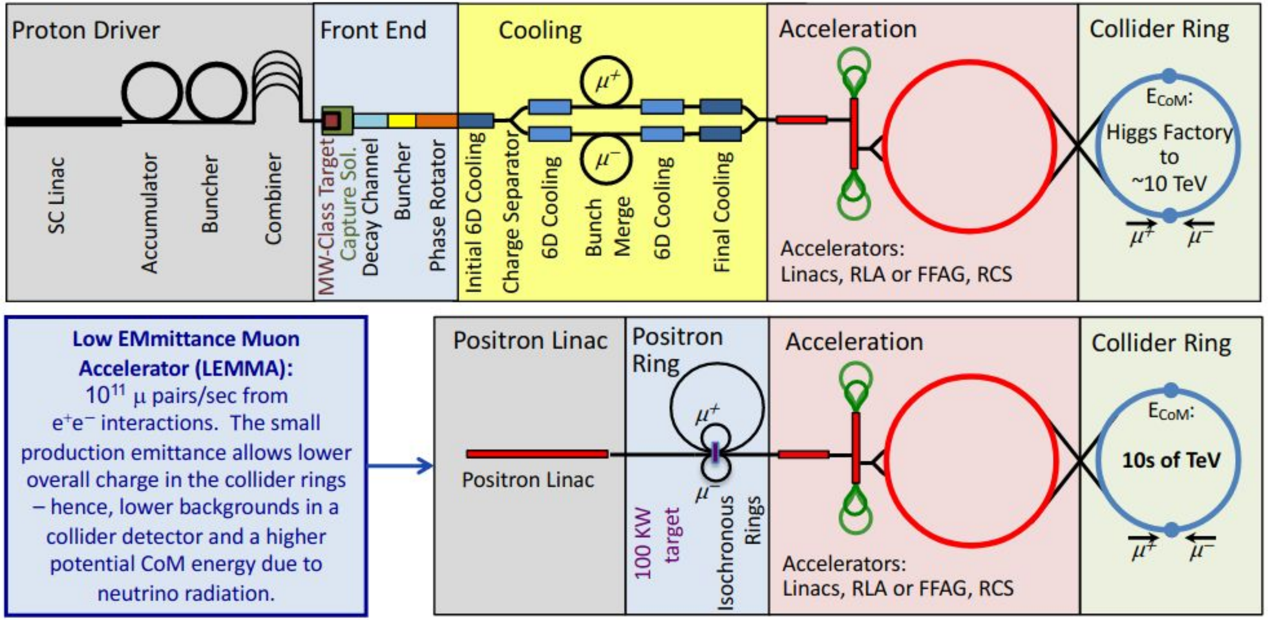
- Pro’s and cons of a muon collider
- Accelerator and muon production
- Detector concepts
- Physics reach

Wait you're trying to collide muons?

- Why would we prefer muons to electrons or protons?
- Compromise between ee or pp collider
  - High discovery potential with current tunnels due to higher mass
    - Radiative losses go like m^4
    - Circular muon colliders feasible
  - "Clean" environment
    - No underlying event/ hadronic mess to be concerned with
  - Full energy of muons available in collisions
    - No Bjorken x reduction in momentum of particles being collided

How do we get muon beams?

- Two main strategies for obtaining muon beams
- Proton driver vs. positron driver



Proton Driver

- Pro’s
  - Studied for a long period of time
  - Higgs factory is possible
- Con’s
  - Beam has large emittance
  - Many stages are required incl several cooling stages
- Mitigation techniques are being developed and investigated for the disadvantages and technical requirements
  - The Muon Ionizing Cooling Experiment (MICE) at RAL in UK is testing ionization cooling in preparation for a future muon collider
    - Combinations of absorber material and RF cavities homogenize momentum of beams

Positron Driver

- Dubbed Low Emittance Muon Accelerator (LEMMA) Scheme
  - 45 GeV e^+ incident on fixed electron (Be) target
  - At muon pair production threshold
  - Significantly lower emittance than proton based method but comparable luminosity
- Technical issues still to be worked out
  - Intense positron beam required (10^{16} e^+/s or 100x more intense the ILC requirements)
  - No strategy yet exists to concatenate groups of muons into single bunches

Don’t muons decay?

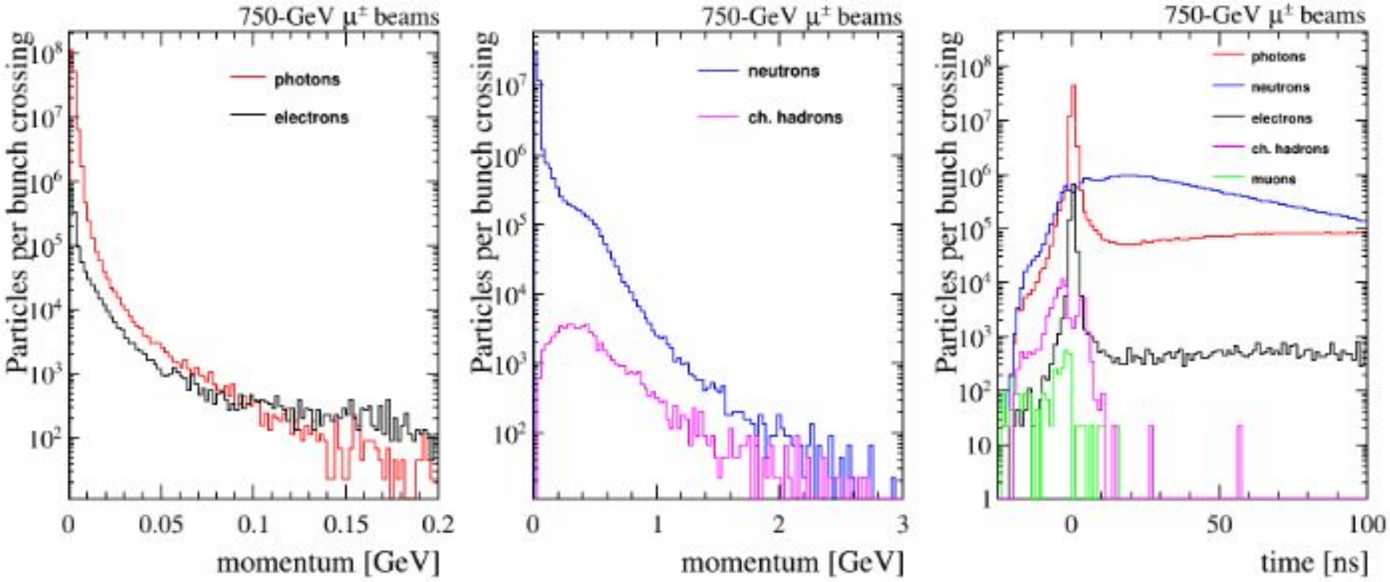
- Single biggest issue in muon collisions is the particle’s finite lifetime
- Muon lifetime is 2.2 μs (659 cτ)
- Backgrounds from muon decay generally referred to as beam induced backgrounds

Important consideration for beam induced bkg: optimal shielding of interaction point depends strongly on the energy

Left: Simulation of beam induced backgrounds at 1.5 TeV COM and associated optimal shielding cone (yellow)

Beam background composition

- In spite of shielding, beam induced backgrounds are unavoidable
- Simulation at 1.5 TeV COM for particular configuration of collision region

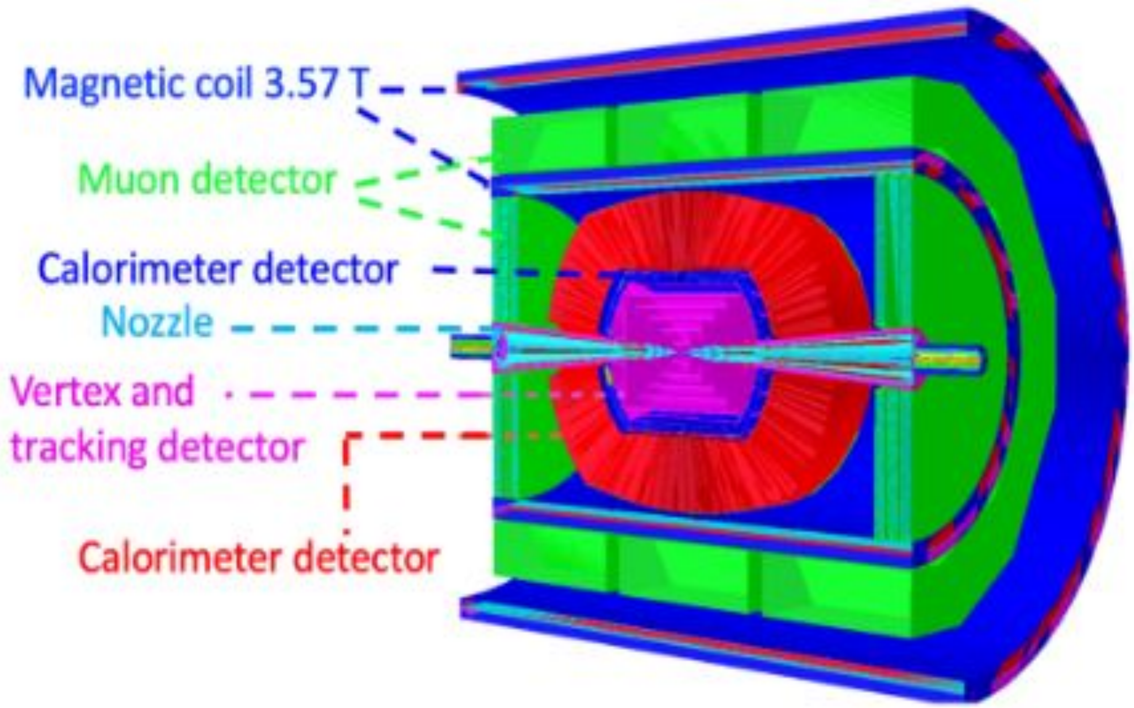


Beam induced bkgs
Left: e/gamma momentum spectrum
Avg ~ 5 MeV

Center: had momentum spectrum
Avg ~ 500 MeV

Right: arrival time of various bkgs
Largely asynchronous arrival

Detector concepts



Standard Detector lay out with few specifics determined

Tracking:
Assumed Si with inner, outer and forward substems

Calorimetry:
A Dual-readout Integrally Active Non-segmented Option

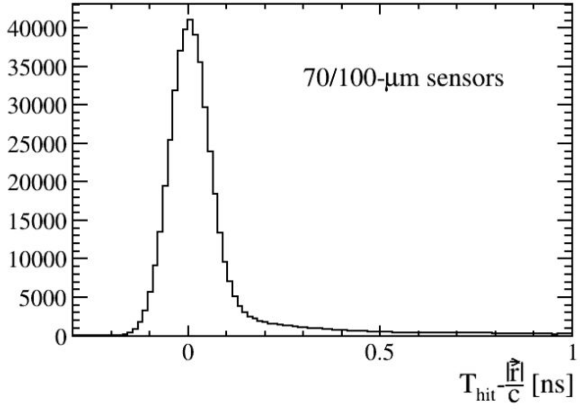
Tracking

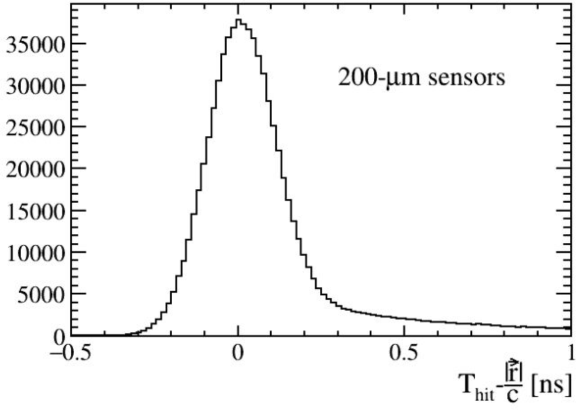
- 4D silicon sensor technology assumed ie silicon with timing
- Forward coverage will be limited by shield cones (and that in turn is determined by the COM energy)

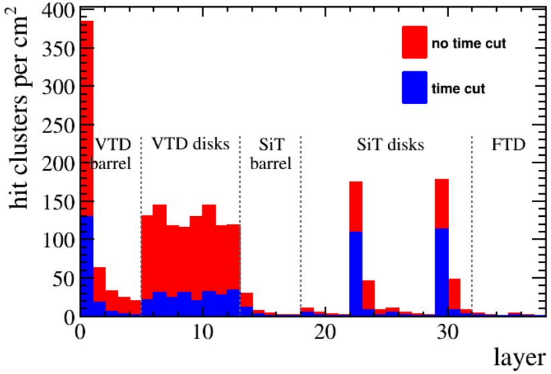
Subsystem	Number of layers	Pixel Size [μm]	Thickness [μm]	Distance [cm]
VTX (barrel)	5	20x20	75	3 - 12.9 (xy)
SiT (barrel)	5	50x50	200	25 - 160 (xy)
VTX (disk)	4	20x20	100	42 (z)
SiT (disk)	14	50x50	200	330 (z)
FTD	3	50x50	200	450 -520 (z)

Tracking and timing

- Even w/ optimized shield, lots of backgrounds in detector, specifically first few tracking layers
- Solution is 4D silicon sensors, that contain timing info as well as spatial info
- Use cut of 3σ w/in detector time resolution (left/center) and see reduction in hit clusters in various tracker subsystems

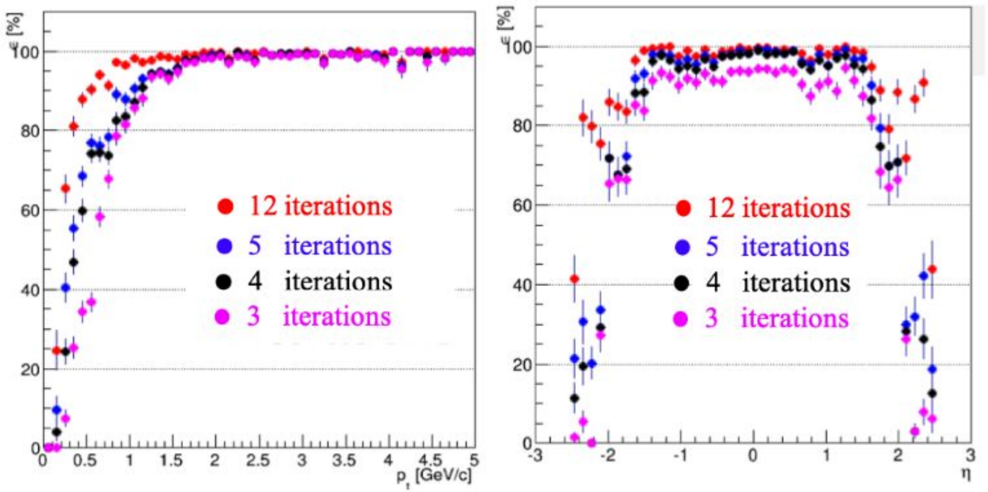






Tracking performance

- Standard Kalman filter track reconstruction assumed, based on simulation framework developed for ILC
- Tracking uses iterative procedure of increasing size search windows, where number of iterations is limited by compute time
- Preliminary results show optimal trade off of efficiency/ compute time at 4 of these iterations



Calorimetry tech: ADRIANO

- Cells are sandwiches of optical glass and scintillating fibers
- Design is meant to be a compensating calorimeter
  - Response of device to EM and hadronic components is equivalent
- Absorber is active material via the Cerenkov signal
- Two optically separate regions for the Cerenkov light and the light from scintillation

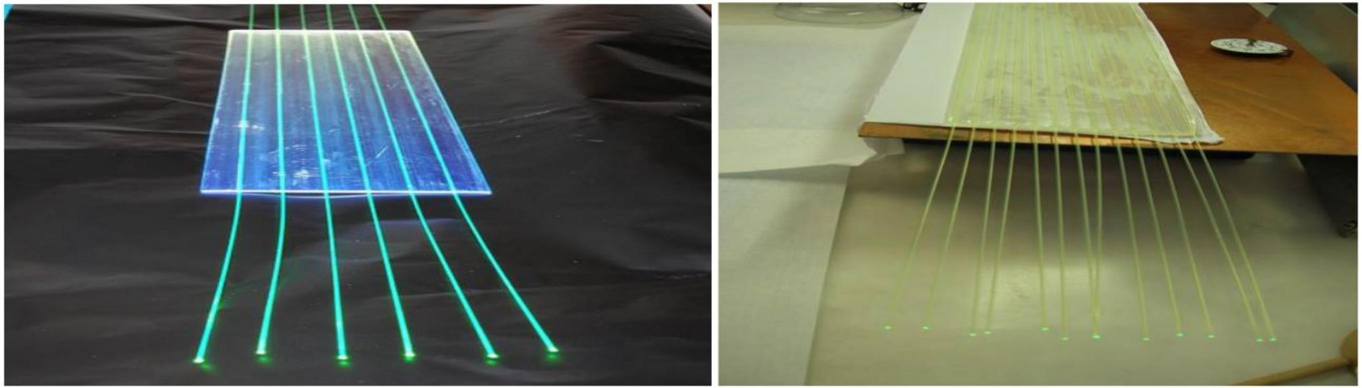
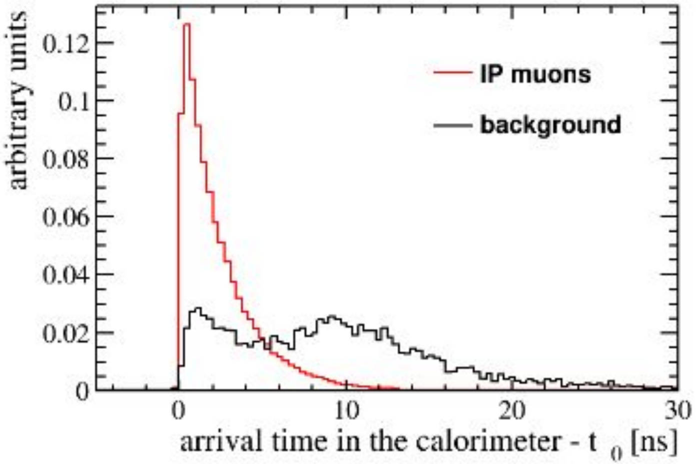


Figure 3. *Plastic scintillator (left) and glass (right) plates in the ADRIANO for High Intesity experiments.*

Beam induced bkg rejection w/ Calorimeter

- Two strategies
  - Timing information
  - Jet selection with energy clusters above pedestal



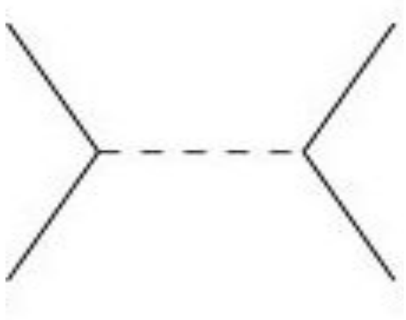
1. the calorimeter detector is divided in several pseudorapidity regions of equal width;
2. in each region the mean $\langle E \rangle$ and the standard deviation σ_E of the calorimeter cluster energies are calculated;
3. calorimeter clusters with an energy E higher than $\langle E \rangle + 2 \cdot \sigma_E$ are selected;
4. the energy of the selected clusters is corrected by subtracting the mean value $\langle E \rangle$ of the corresponding region.

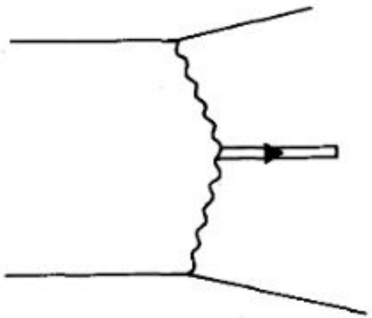
Left: Timing in Calo Towers
Above: Rejection of bkg by above pedestal selection

What do muon collisions look like?

Physics at muon colliders falls into 2 categories

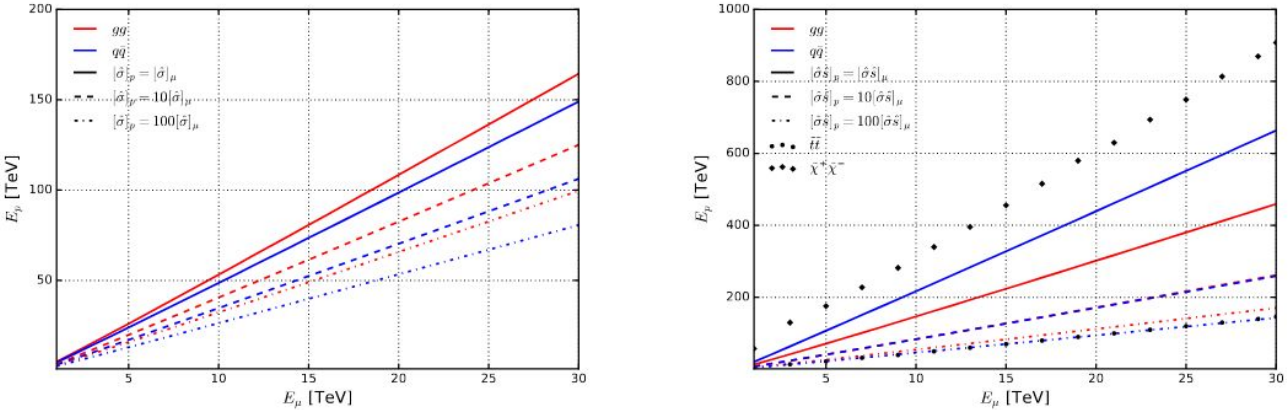
- Direct production
  - s channel processes that lead to direct discovery of high mass states
- Vector Boson Fusion (VBF)
  - Associated production of weak boson moderating the interactions of interest





Direct production compared to pp

- Partons inside proton means muons can be competitive at lower energy



(a) (b)

Figure 1. The equivalent proton collider energy $\sqrt{s_p}$ [TeV] required to reach the same beam-level cross section as a $\mu^+\mu^-$ collider with energy $\sqrt{s_\mu}$ [TeV] for (a) $2 \to 1$ and (b) $2 \to 2$ parton-level process, for benchmark scaling relationships between the parton-level cross sections $[\hat{\sigma}]_p$ and $[\hat{\sigma}]_\mu$ as well as for pair production of $\tilde{t}\bar{\tilde{t}}$ and $\tilde{\chi}^+\tilde{\chi}^-$ through their leading $2 \to 2$ production modes.

VBF overtaking direct production

- VBF will outpace direct production for all processes at some energy

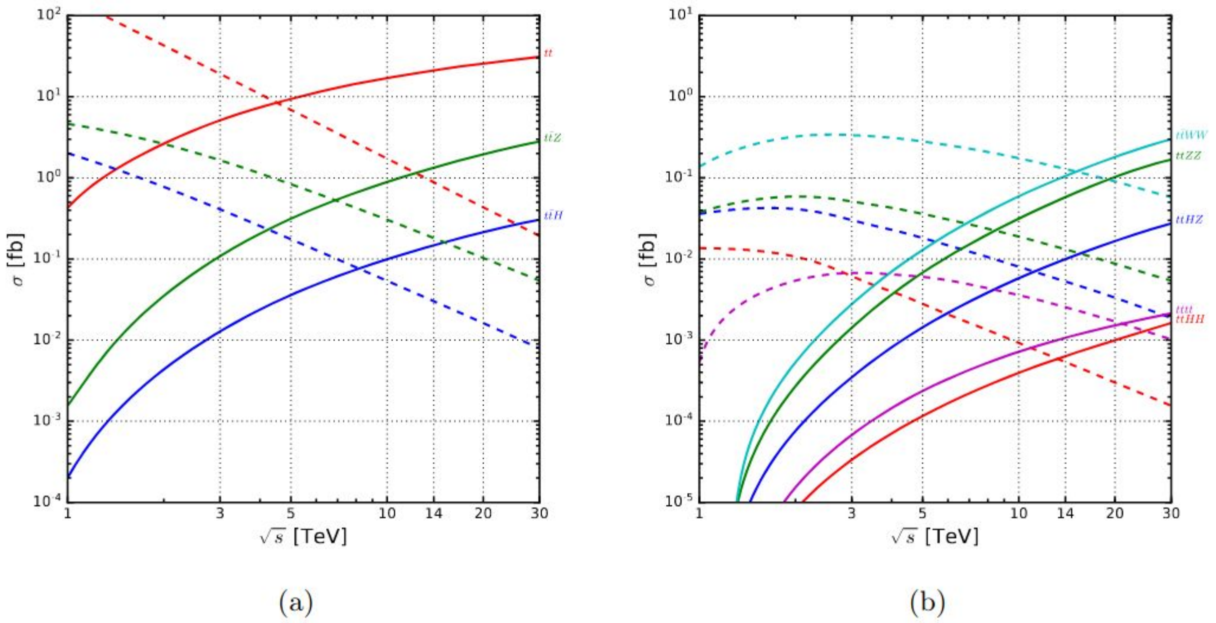
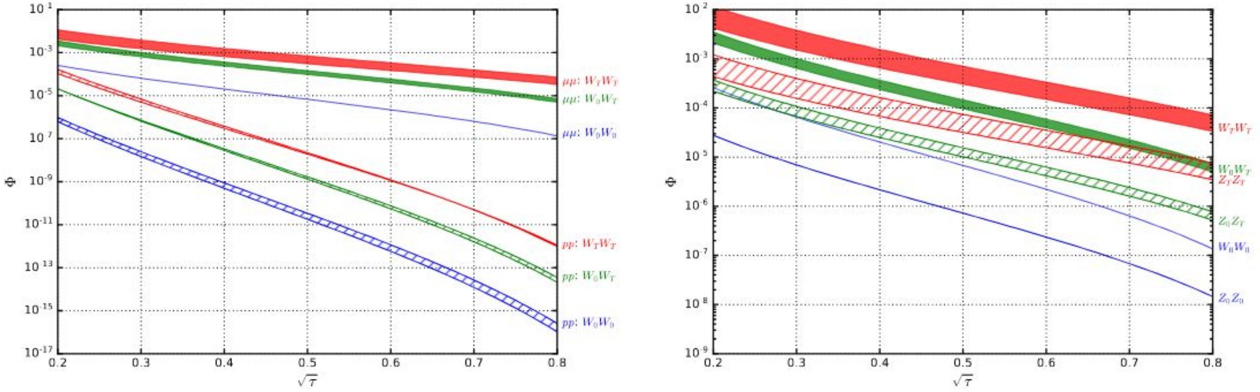


Figure 3. W^+W^- fusion (solid) and analogous s-channel annihilation (dashed) cross sections σ [fb] for (a) $t\bar{t}X$ and (b) $t\bar{t}XX$ associated production as a function of collider energy $\sqrt{s}$ [TeV].

VBF compared to pp collisions

- Simulations use Effective W approximation
- Similar results for direct production with certain advantage over pp

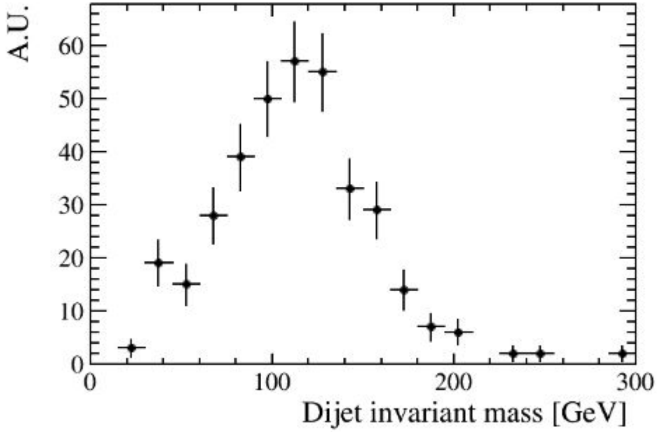


(a) (b)

Figure 2. (a) As a function of fractional scattering scale $\sqrt{\tau} = M_{VV'}/\sqrt{s}$, the (dimensionless) parton luminosities Φ for $W_T^+W_T^-$ (red), $W_T^\pm W_0^\mp$ (green), $W_0^+W_0^-$ (blue) in both pp (hatched shading) and $\mu^+\mu^-$ (solid shading) collisions. (b) The same but for $W_\lambda^+W_{\lambda'}^-$ (solid shading) and $Z_\lambda Z_{\lambda'}$ (hatched shading) in $\mu^+\mu^-$ collisions with $(\lambda, \lambda') = (T, T)$ (red), $(0, T) + (T, 0)$ (green), and $(0, 0)$ (blue). Band thickness corresponds to the μ_f dependency as quantified in the text.

Physics processes: H->bb

- Significantly less background than hadronic machine
- Dedicated beam bkg reduction can lead to a clear mass peak in early toy simulation



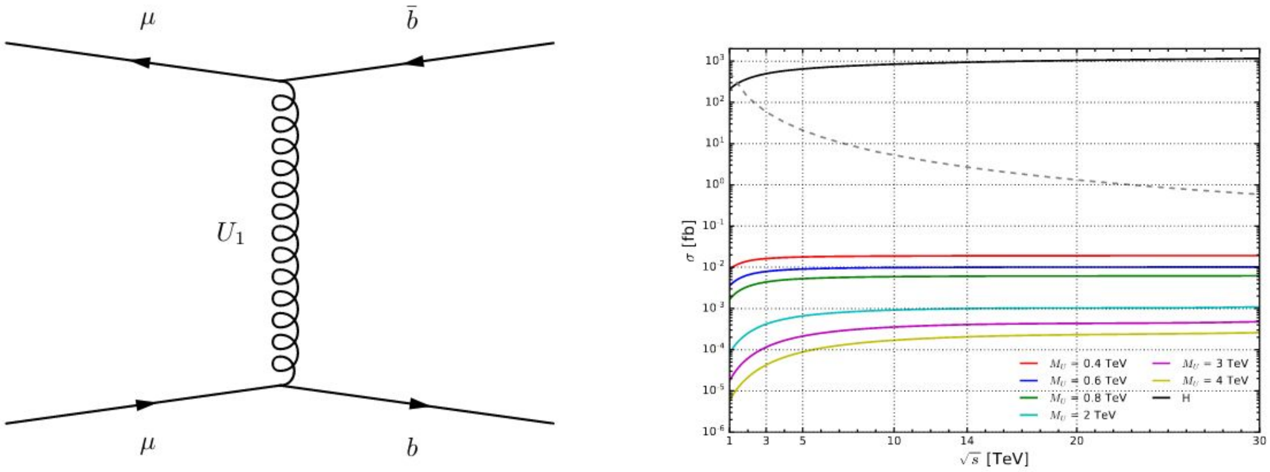
Toy simulation of bb resolution for truth matched bjets, including simulation of beam induced backgrounds

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

Relative significance for H->bb at CLIC and Muon Collider

Physics process: vector lepto-quarks

- Exciting based on recent lepton flavor universality violation results from LHCb



(a) (b)

Figure 13. (a) Diagrammatic representation of $b\bar{b}$ production in $\mu^+\mu^-$ collisions via the t-channel exchange of the vector leptoquark U_1^μ. (b) The associated cross section [fb] as a function of collider energy $\sqrt{s}$ [TeV] for representative M_U. Also shown is SM $\mu^+\mu^- \to b\bar{b}$ production (dashed curve).

References

[1] arXiv:1901.06150

[2] arXiv:1603.00909

[3] arXiv:2005.10289

[4] Status of muon collider research and development and future plans
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