ILCRoot Studies of a High Energy Muon Collider

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Fermilab

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Introduction

- LHC results seems to indicate new physics spectrum likely to be in the multi-Tev range.

- If narrow s-channel states exist in the multi-TeV region they will play an important role in precision studies for new physics.

- Increase of luminosity with energy. Needed for new physics. Wall power consumption is a major concern.

- A Muon Collider seems to be the only high luminosity lepton collider candidate capable to reach

  CM energies > 3 TeV.

- The physics potential of a multi-TeV Muon Collider is outstanding.
  It offers both discovery, as well as precision, measurement capabilities.

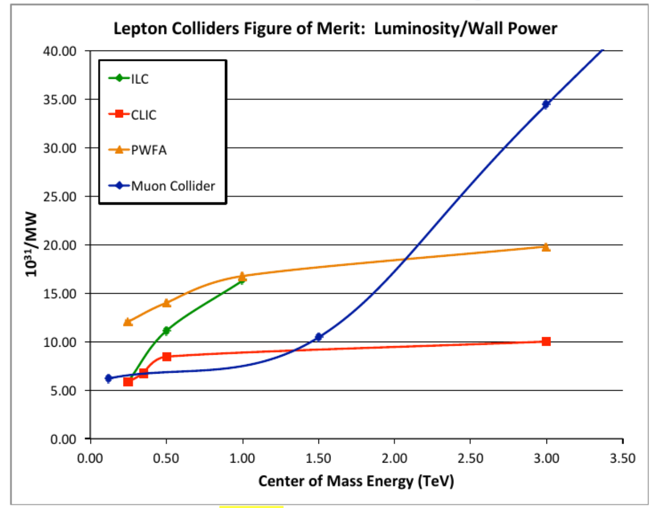


Figure A-4: Figure of merit: peak luminosity (within 1% colliding energy) normalized to wall-plug power

J-P. Delahaye,et al [arXiv:1308.0494]

- **BUT ... "Still need to prove that this is robust against machine backgrounds".**

  Snowmass 2013, Chip Brock & Michael Peskin

This talk will address this point.

Outline

- Muon Collider features.
- Muon Collider and detector challenges.
- Background and detector simulations: MARS and ILCroot frameworks.
- Background characteristics.
- Baseline detector for Muon Collider studies.
- Strategies to reduce the background in the detector.
- The Muon Collider as a H/A factory.
- H/A simulation with full background at 1.5 TeV.
- Conclusions and Remarks.

Muon Collider Features and Impact on Detector Design

- **COMPACT**
  Synchrotron radiation (1/mass^4) does not limit muon circular acceleration, a circular machine with multi-TeV beams can be realized and it fits on laboratory site.

- **TWO DETECTORS (2 Ips)**
  No need for "push and pull". → Detectors can be more "complicated" , no frequent reallignement.

- **MULTI-TEV MACHINE**
  Possibility to reach energy > 3 TeV. → $\lambda_I \geq 7$ calorimeter and $1/\sqrt{E}$ energy resolution.

- **NARROW ENERGY SPREAD**
  The beam energy resolution is not limited by beamstrahlung smearing, precision scans, kinematic constraints. → High resolution detector.

- **ΔT(BUNCH) ~ 10 μs … (e.g. 4 TeV collider)**
  Lots of time for readout. Backgrounds don't pile up. → Possible triple read-out calorimeter for neutron fluctuation compensation.

- **ENHANCED S-CHANNEL HIGGS PRODUCTION**
  Higgs coupling is proportional to mass and $(m_\mu/m_e)^2 =$ ~40000
  → Good detector resolution and PID.

Muon Collider Challenges

- **MUONS ARE PRODUCED AS TERTIARY PARTICLES**
  To make enough of them we must start with a MW scale proton source & target facility.

- **MUONS DECAY**
  Everything must be done fast and we must deal with the decay electrons (& neutrinos).

- **MUONS ARE BORN WITHIN A LARGE 6D PHASE-SPACE**
  For a MuC we must cool them before they decay.
  New cooling technique (ionization cooling) must be demonstrated, and it requires components with demanding performance (NCRF in magnetic channel, high field solenoids.)

- **AFTER COOLING, BEAMS STILL HAVE LARGE EMITTANCE**

S. Geer- Accelerator Seminar SLAC 2011

Main Detector Challenges: Muons Decay!

- The Muon Collider will be a precision machine: the detector performance must be very demanding.
- One of the most serious technical issues in the design of a Muon Collider experiment is the background.
- The major source come from muon decays:

  for 750 GeV muon beam with $2*10^{12}$ muons/bunch, ~ $4.3*10^{5}$ decays/m/bunchX.
- Electromagnetic showers induced by electrons and photons generate intense fluxes of particles in the collider components and in the detector.
- High levels of background and radiation are expected both in the detector and in the storage ring with a rate of 0.5-1.0 kW/m.
- The background will affect the detector performance: difficulties of track reconstruction because of extra hits in the tracking system and deterioration of jet energy resolution because of extra energy from background hits, aging and damage.
- The Muon Collider physics goals and the background will guide the choice of technology and parameters for the design of the detector.

Extensive and Detailed Simulation Studies: MARS and ILCroot Frameworks

- **MARS** – is the framework for simulation of particle transport and interactions in accelerator, detector and shielding components.
- New release of MARS15 is available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS).
- Background simulation in the studies shown in this presentation is provided at the surface of MDI (10° nozzle + walls).

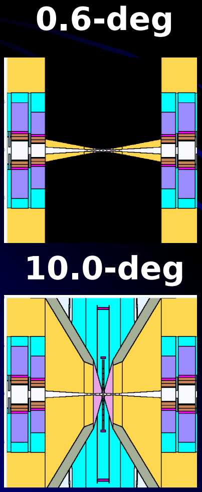
- **ILCroot** – is a software architecture based on ROOT, VMC & Aliroot:
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc).
  - Extremely large community of ROOT users/developers.
- It is a simulation framework <u>and</u> an offline system:
  - Single framework, from generation to reconstruction and analysis!!
  - Six MDC have proven robustness, reliability and portability
  - VMC allows to select G3, G4 or Fluka at run time (no change of user code).
- Widely adopted within HEP community (4th Concept, LHeC, T1015, SiLC, ORKA, MuC)
  - Detailed detector simulation, full simulation and physics studies are presented in this presentation.
- It is available at Fermilab since 2006.

Part of the Solution: Shieldings

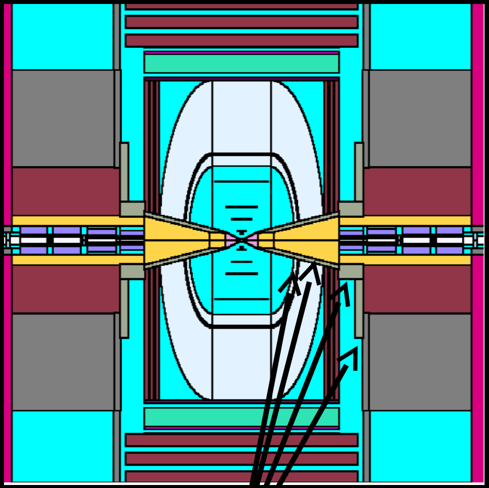
- Extensive studies (Mokhov et al., Fermilab) show a reduction of the background up to three order of magnitude using sophisticated shielding.
- Tungsten nozzle to stop gammas (generate neutrons), in Borated Polyethylene shell to absorb neutrons (and concrete walls outside the detector region)
- Detailed magnet geometry, materials, magnetic fields maps, tunnel, soil outside and a simplified experimental hall plugged with a concrete wall are simulated in MARS framework.

Number and species of particles per bunch crossing entering the detector, starting from S_{max}= 75m for a 1.5 TeV collider.

N.V. Mokhov



Particle	0.6-deg	10-deg
Photon	1.5×10^{11}	1.8×10^{8}
Electron	1.4×10^{9}	1.2×10^{6}
Muon	1.0×10^{4}	8.0×10^{3}
Neutron	5.8×10^{8}	4.3×10^{7}
Charged hadron	1.1×10^{6}	2.4×10^{4}

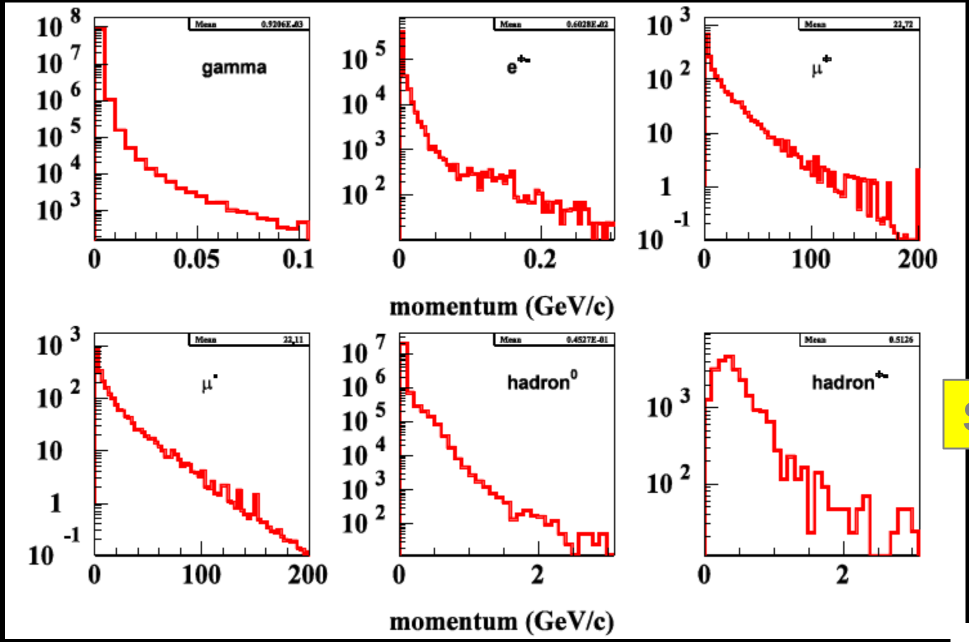


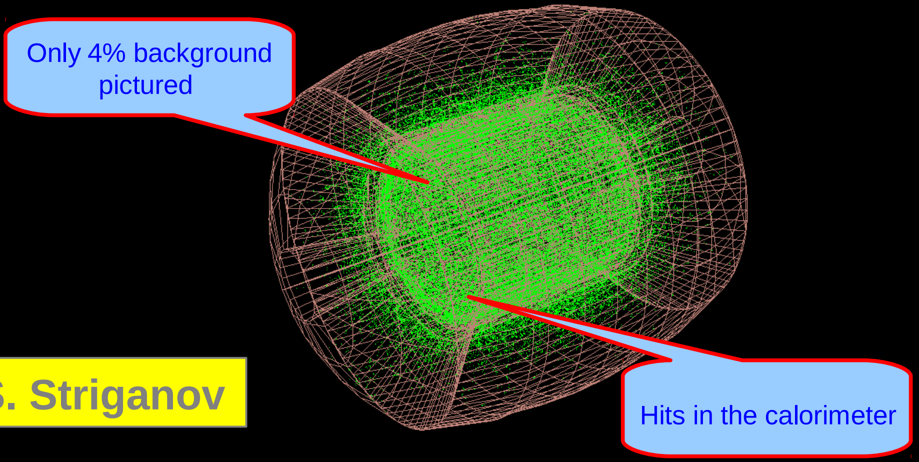
Sophisticated shielding: W, iron, concrete & BCH_2

No time cut applied, can help substantially (see next)
All results below are presented
for a 1.5 TeV collider and a 10° nozzle

MARS Simulation

The Background Entering the Detector



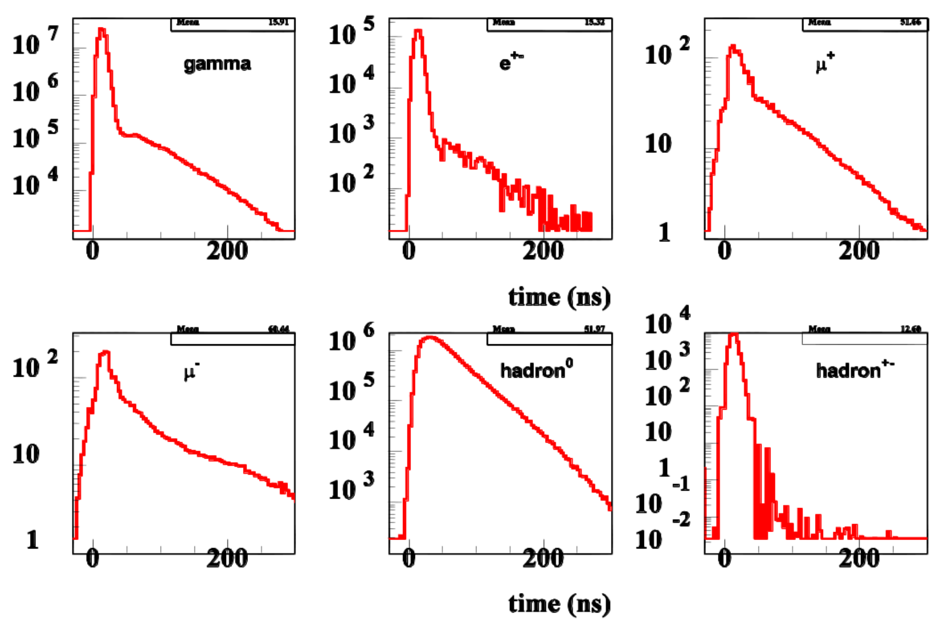


Only 4% background pictured

Hits in the calorimeter

S. Striganov

Most of the background is out of time
Timing cut can further reduce the background

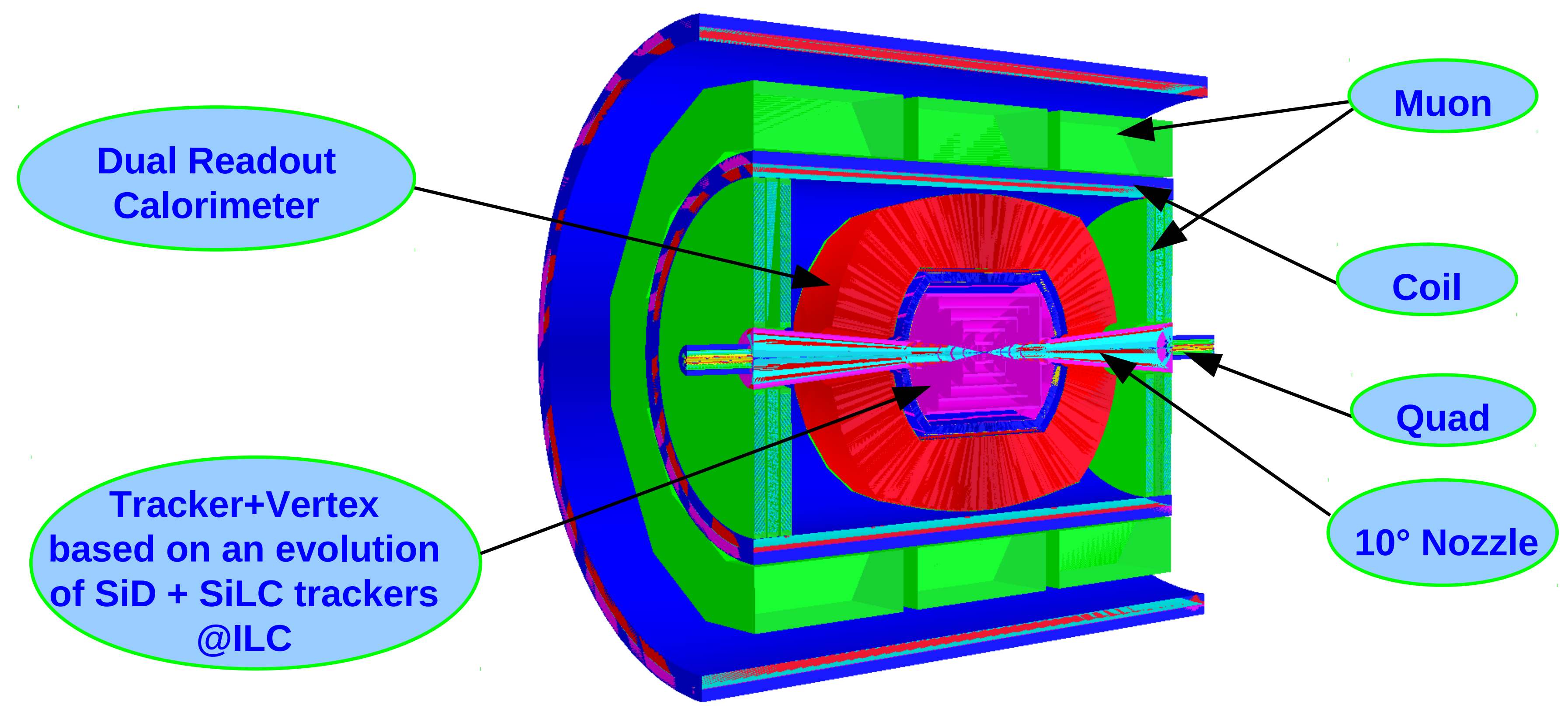


Most of the background are low momenta photons and neutrons

Still a lot of background!!!!!

MARS Simulation

Baseline Detector for Muon Collider Studies



- Detailed geometry (dead materials, pixels, fibers ..)
- Full simulation: hits-sdigits-digits. Includes noise effect, electronic threshold and saturation, pile up...
- Tracking Reconstruction with parallel Kalman Filter.
- Light propagation and collection.
- Jet reco

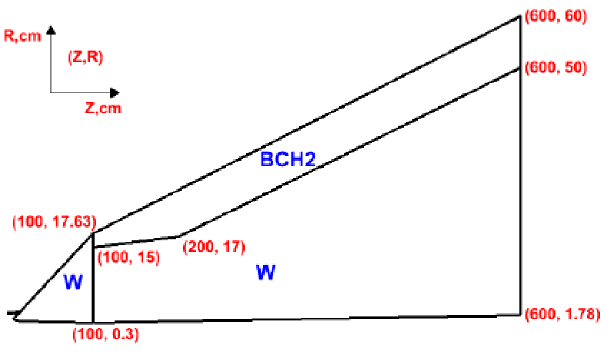
ILCroot Simulation

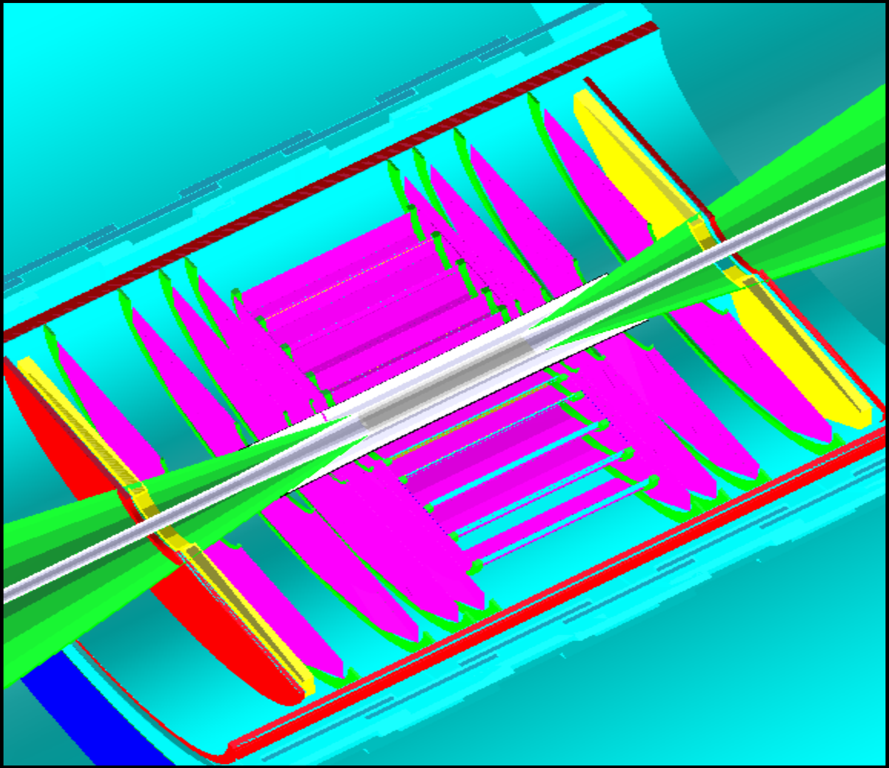
Vertex Detector (VXD)

10° Nozzle and Beam Pipe

VXD

- 75 µm thick Si layers in the barrel
- 100 µm thick Si layers in the endcap
- 20 µm x 20 µm Si pixel
- Barrel : 5 layers subdivided in 12-30 ladders
- R_{min}~3 cm R_{max}~13 cm L~13 cm
- Endcap : 4 + 4 disks subdivided in 12 ladders
- Total length 42 cm





NOZZLE

- W - Tungsten
- BCH2 – Borated Polyethylene
- Starting at ±6 cm from IP with R = 1 cm at this z

PIPE

- Be – Berylium 400 µm thick
- 12 cm between the nozzles

ILCroot Simulation

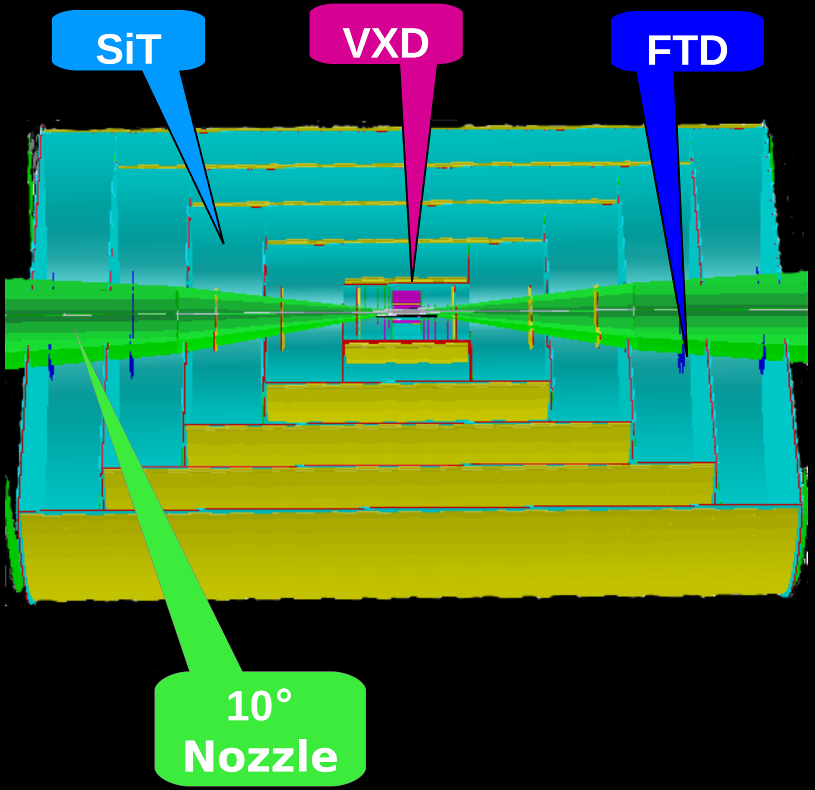
Silicon Tracker (SiT) and Forward Tracker Detector (FTD)

SiT

- 200 μm thick Si layers
- 50 μm x 50 μm Si pixel (or Si strips or double Si strips available)
- Barrel : 5 layers subdivided in staggered ladders
- Endcap : (4+3) + (4+3) disks subdivided in ladders
- R_{min}~20 cm R_{max}~120 cm L~330 cm

FTD

- 200 μm thick Si layers
- 50 μm x 50 μm Si pixel
- Endcap : 3 + 3 disks
- Distance of last disk from IP = 190 cm

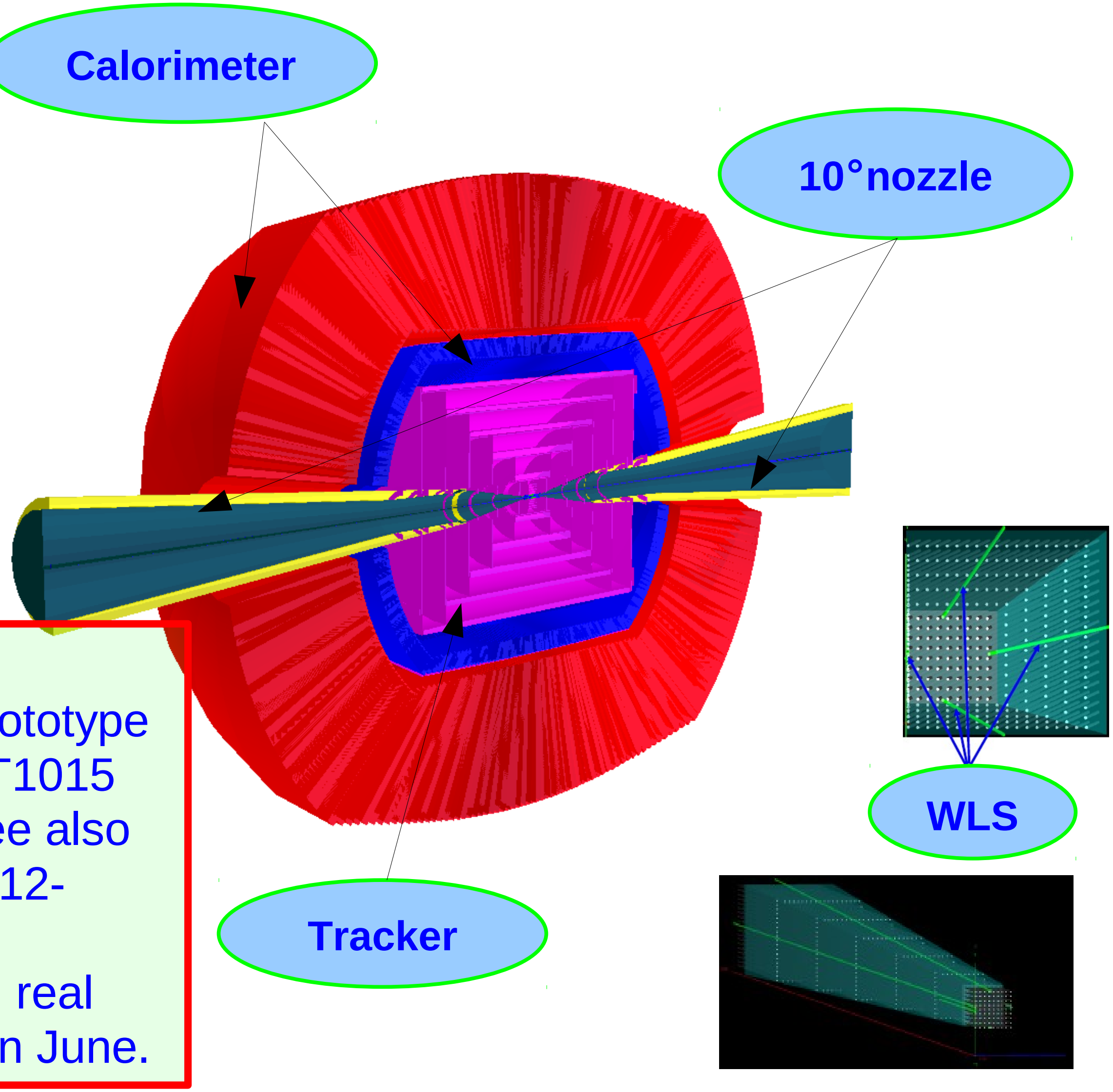


- Silicon pixel for precision tracking amid up to 10^5 hits
- Tungsten nozzle to suppress the background

ILCroot Simulation

Dual-Readout Projective Calorimeter

- **Lead glass + scintillating fibers**
- **~1.4° tower aperture angle**
- **Split in two sections**
- **Front section 20 cm depth**
- **Rear section 160 cm depth**
- **~ 7.5 λ_{int} depth**
- **>100 X_0 depth**
- **Fully projective geometry**
- **Azimuth coverage down to ~8.4° (Nozzle)**
- **Barrel: 16384 towers**
- **Endcaps: 7222 towers**

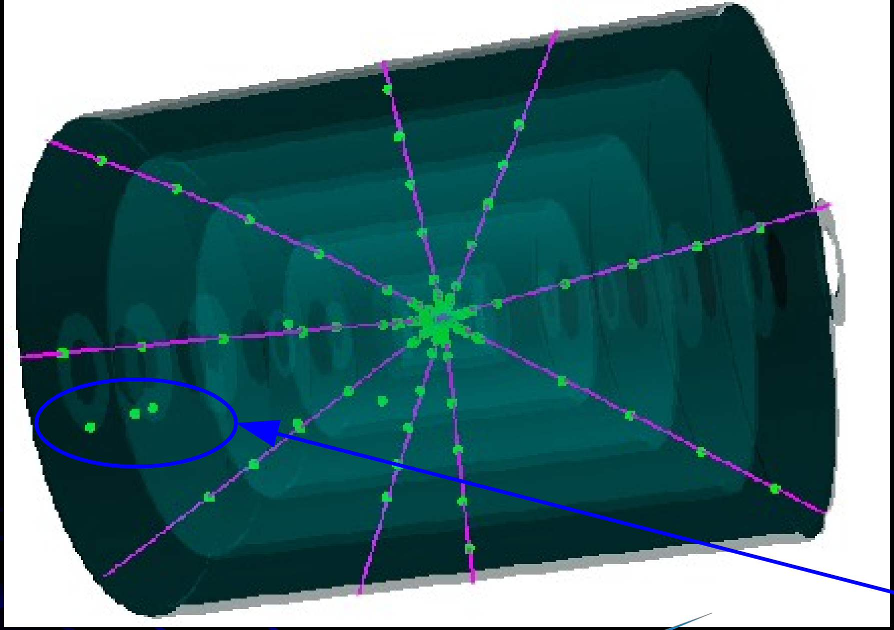


- ➢ All simulation parameters corresponds to **ADRIANO** prototype #9 beam tested by Fermilab T1015 Collaboration in Aug 2012 (see also T1015 Gatto's talk at Calor2012-Calor2014).
- ➢ 5 more prototypes tested with real beam. The 6th will be tested on June.

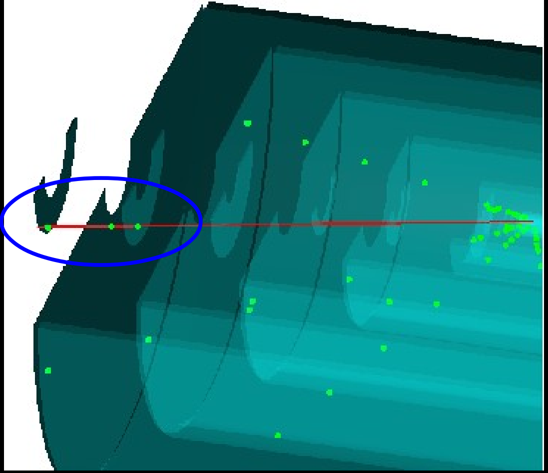
ILCroot Simulation

Effect of the 10° nozzle

ILCroot event display
for 10 muons up to 200 GeV



green - hits
purple – reconstructed tracks
red – MC particle



10 generated muons
9 reconstructed tracks

Tracking System Studies:
Nozzle Effects on Tracking Performance

Reconstruction Efficiency & Resolutions

$$\epsilon_{tot} = \frac{reconstructed \quad tracks}{generated \quad tracks} = \epsilon_{geom} * \epsilon_{track}$$

$$\epsilon_{geom} = \frac{reconstructable \quad tracks}{generated \quad tracks}$$

$$\epsilon_{track} = \frac{reconstructed\ tracks}{reconstructable \quad tracks}$$

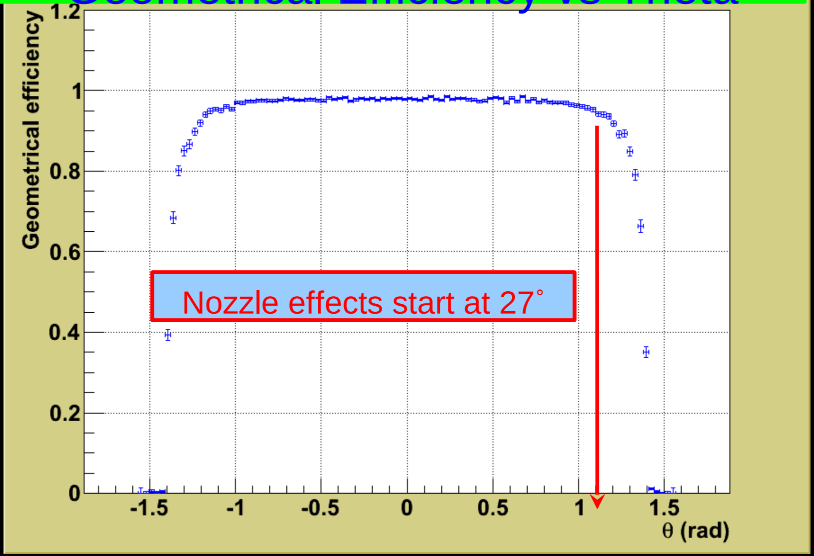
Defining “reconstructable tracks” (candidate for reconstruction)

tracks with DCA(true) < 3.5 cm

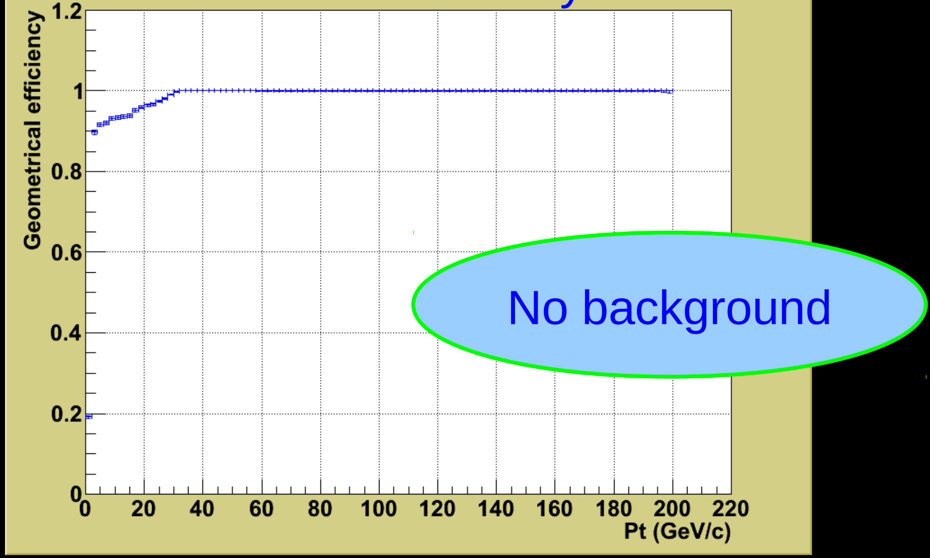
AND

at least 4 hits in the detector

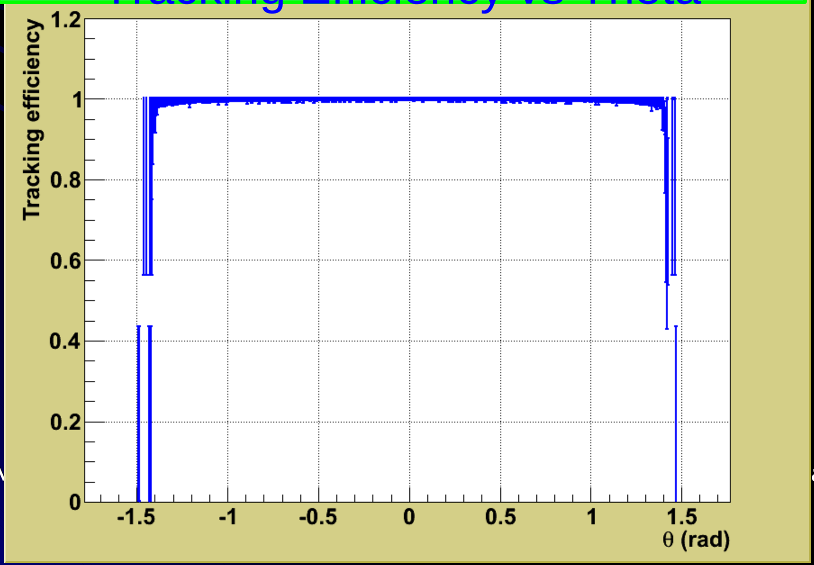
Reconstruction Efficieny for Single Muons

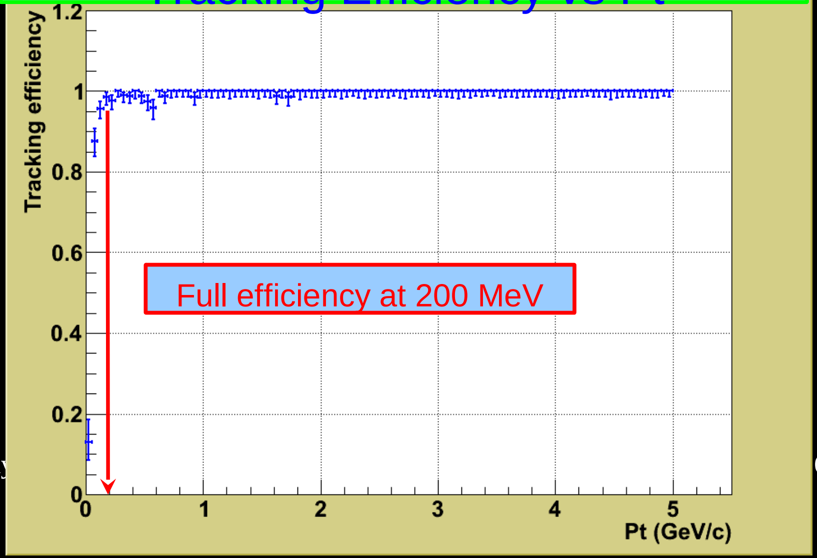

Geometrical Efficiency vs Theta

Nozzle effects start at 27˚


Geometrical Efficiency vs Pt

No background

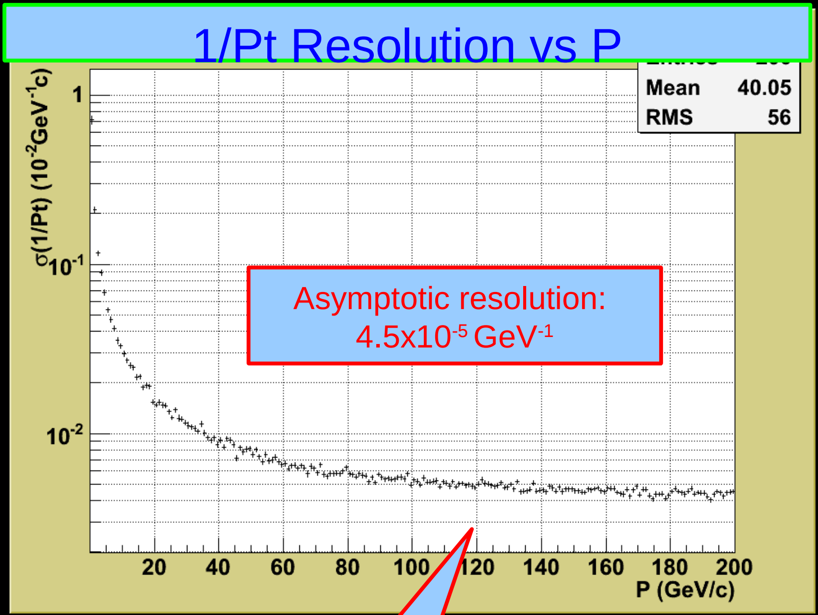

Tracking Efficiency vs Theta


Tracking Efficiency vs Pt

Full efficiency at 200 MeV

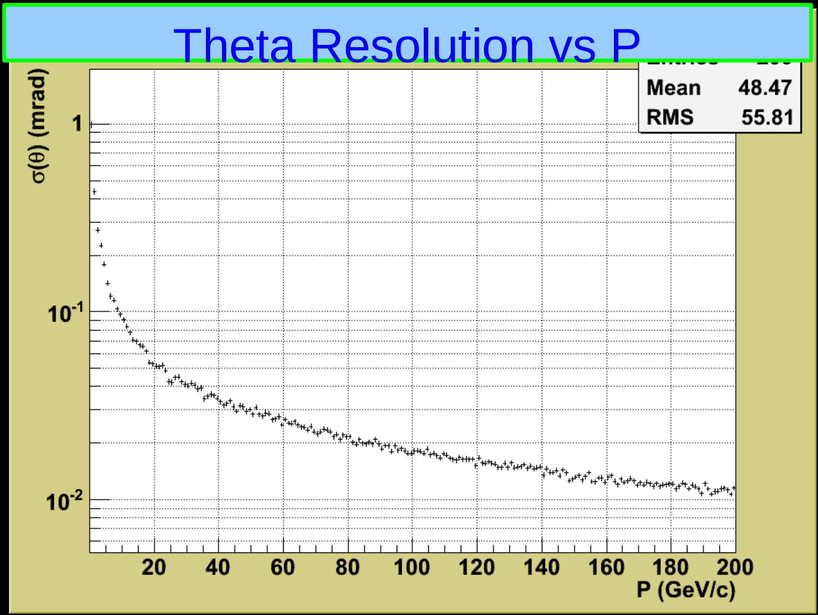
Resolutions for single muons

1/Pt Resolution vs P

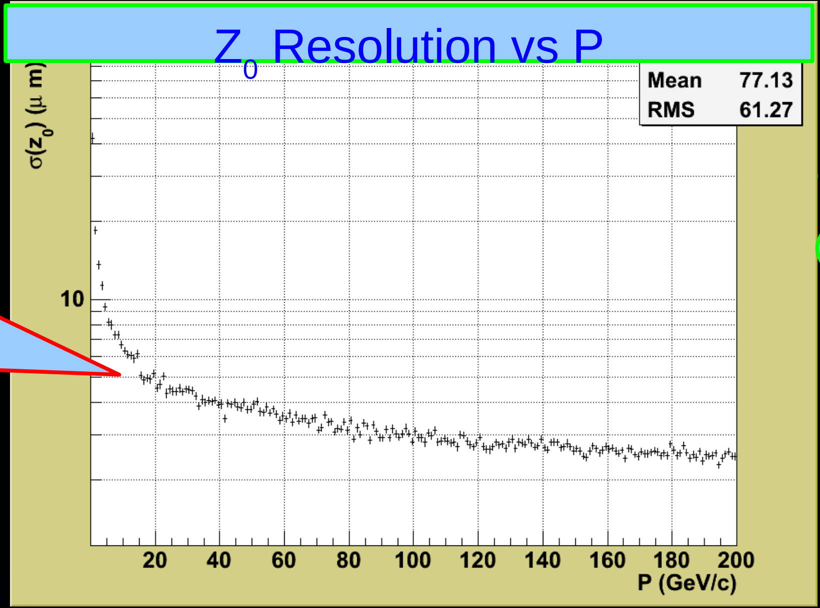


Asymptotic resolution: $4.5\mathrm{x}10^{-5}\ \mathrm{GeV}^{-1}$

Theta Resolution vs P



Z_0 Resolution vs P

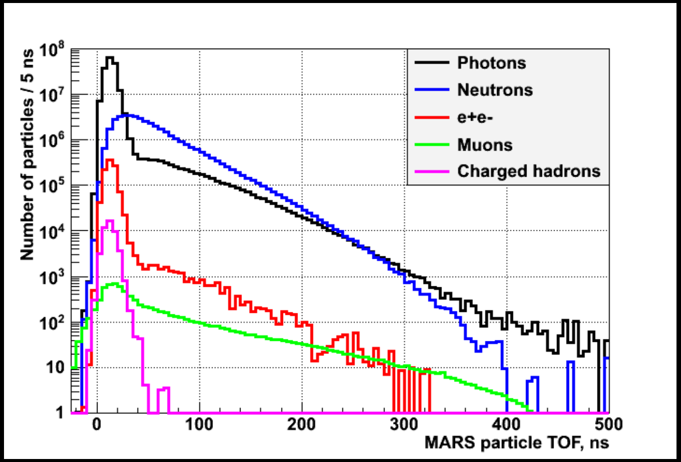


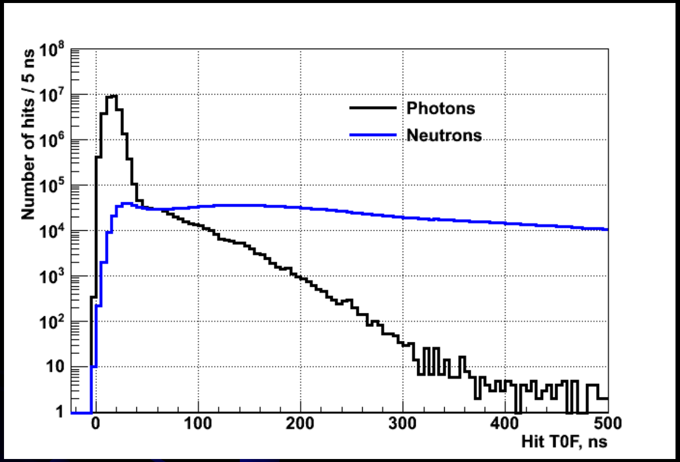
Well within requirements for precision physics

No background

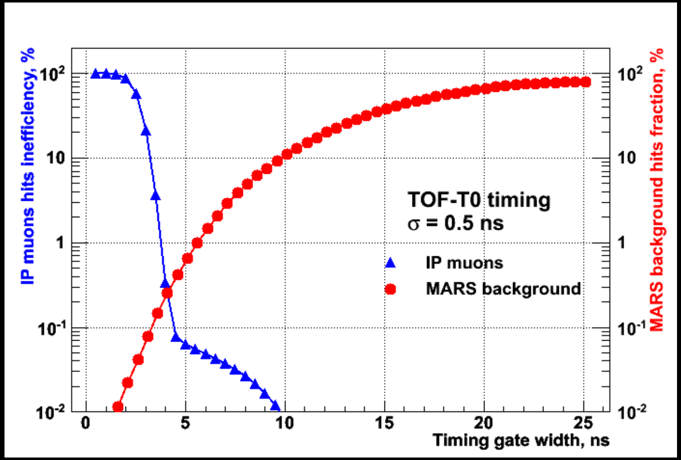
Timing Is The Key For Abating The Background

- **Timing for MARS background particles**
  - MARS background (on a surface of the shielding cone) up to ~1000 ns of TOF (time of flight w.r.t. BX)





- **Timing of ILCRoot MARS background hits in VXD and Tracker**
  - TOF for neutron hits has long tale up to a few ms (due to "neutron gas")



- **Time gate width of 4 ns can provide a factor of 300-500 background rejection keeping efficiency of hits from IP particles higher than 99% at hit time resolution σ=0.5 ns.**

N. Terentiev

With layer dependent time gate (TOF-T0) several times gain in MARS background rejection compared with global time gate (TOF)

Strategies To Reduce Clusters In The Tracking System Produced By The Machine Background

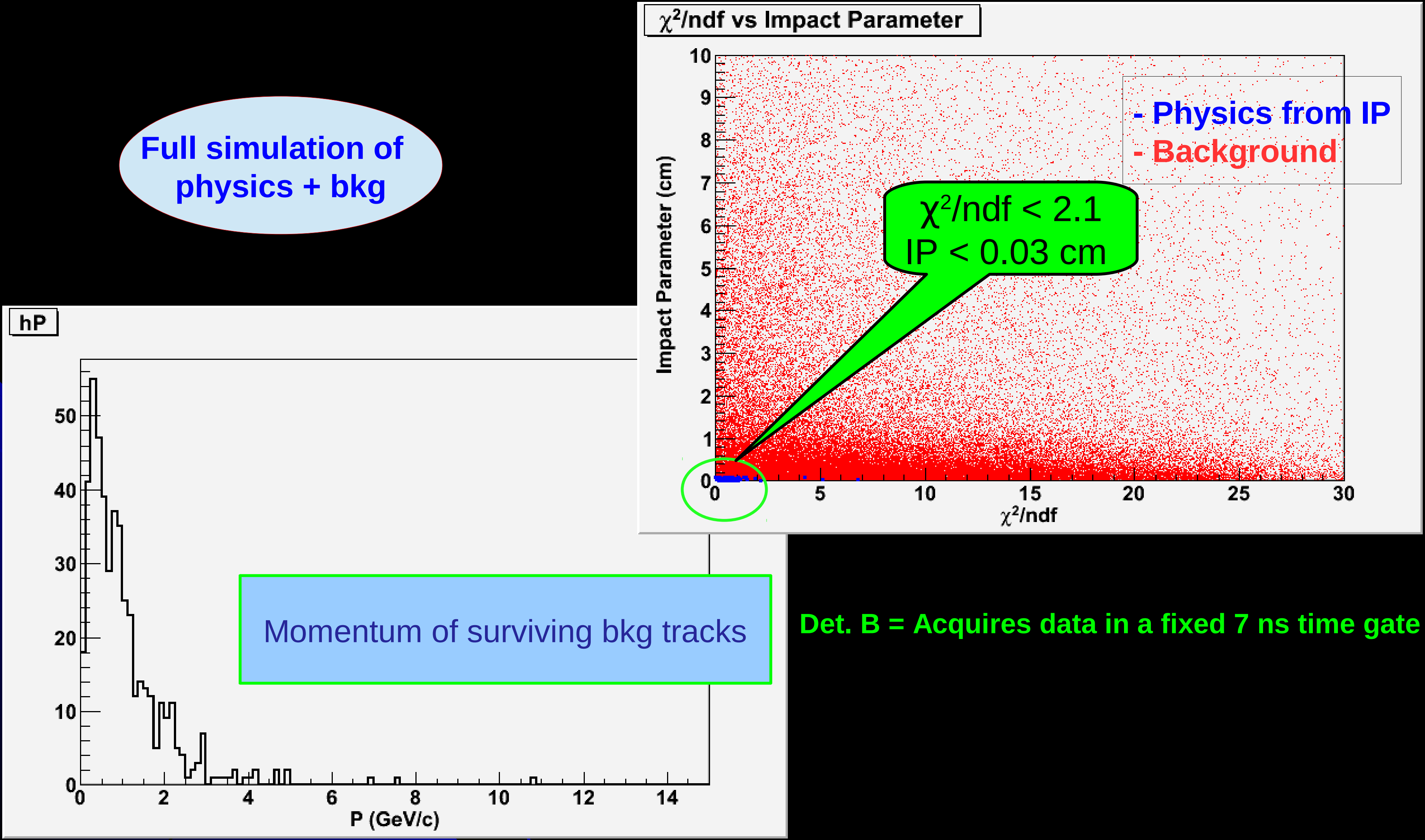
	Kalman Reconstruction	Clusters
Physics: 100 μ (0.2-200) GeV/c	92 (include geom. eff.)	1166
Machine Background	-	4 x 10^7

Simulated in ILCroot 4 detectors with different timing capabilities:

- **Det. A** – No time information (integrates all hits).
- **Det. B** – Acquires data in a fixed 7 ns time gate (minimal timing capabilities).
- **Det. C** - Acquires data in a 3 ns time gate tuned to distance from IP (advanced timing capabilities).
- **Det. D** - Acquires data in a 1 ns time gate tuned to pixel distance from IP (extreme timing capabilities.)

Physics vs Background in Det. B:
A strategy to disentangle reconstructed tracks from IP

Full simulation of physics + bkg



χ^2/ndf < 2.1

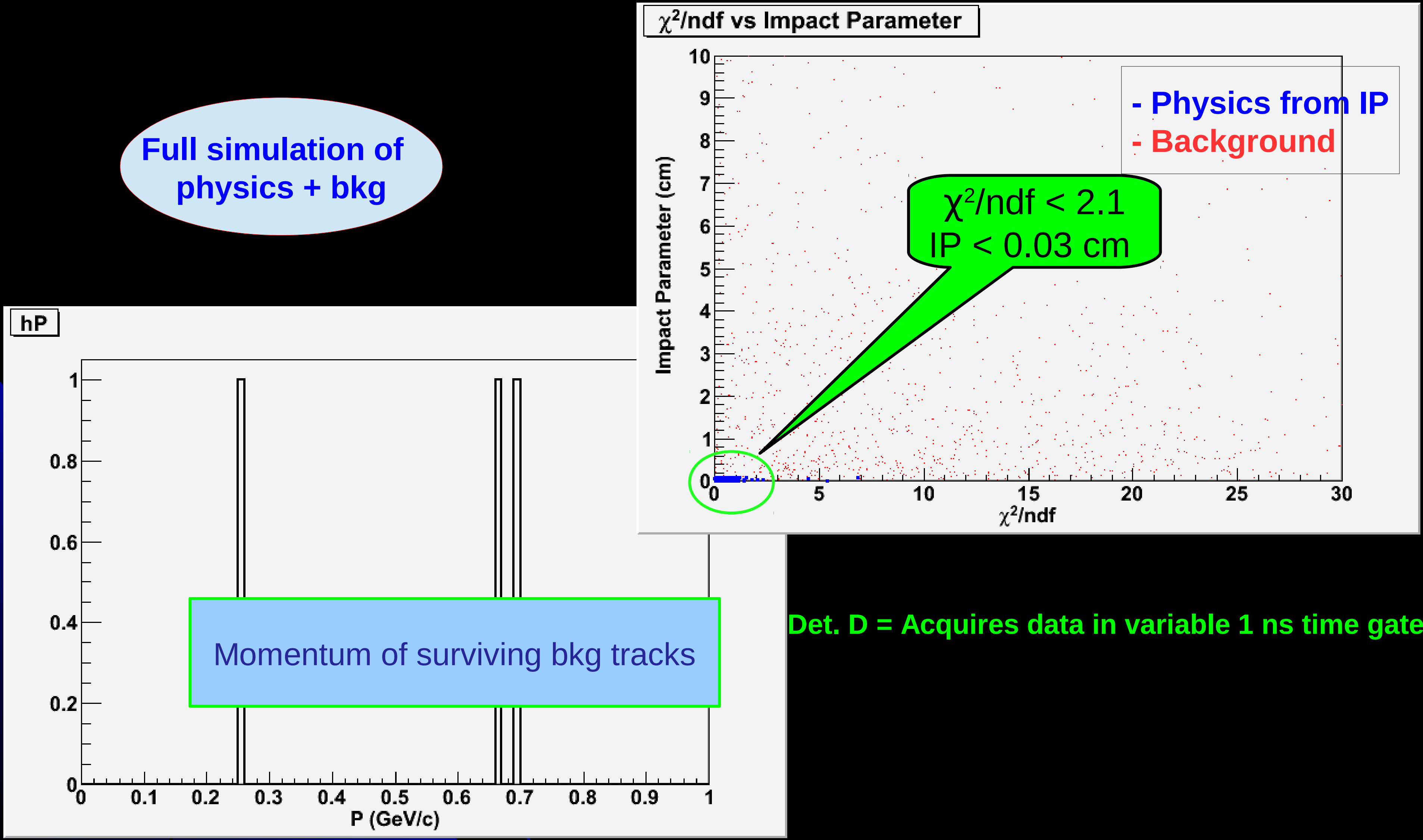
IP < 0.03 cm

Momentum of surviving bkg tracks

Det. B = Acquires data in a fixed 7 ns time gate

Physics vs Background in Det. D:
A strategy to disentangle reconstructed tracks from IP

Full simulation of physics + bkg



χ^2/ndf < 2.1
IP < 0.03 cm

Momentum of surviving bkg tracks

Det. D = Acquires data in variable 1 ns time gate

Reconstructed Background Tracks (from Kalman filter)

Full vs Fast simulation of the bkg

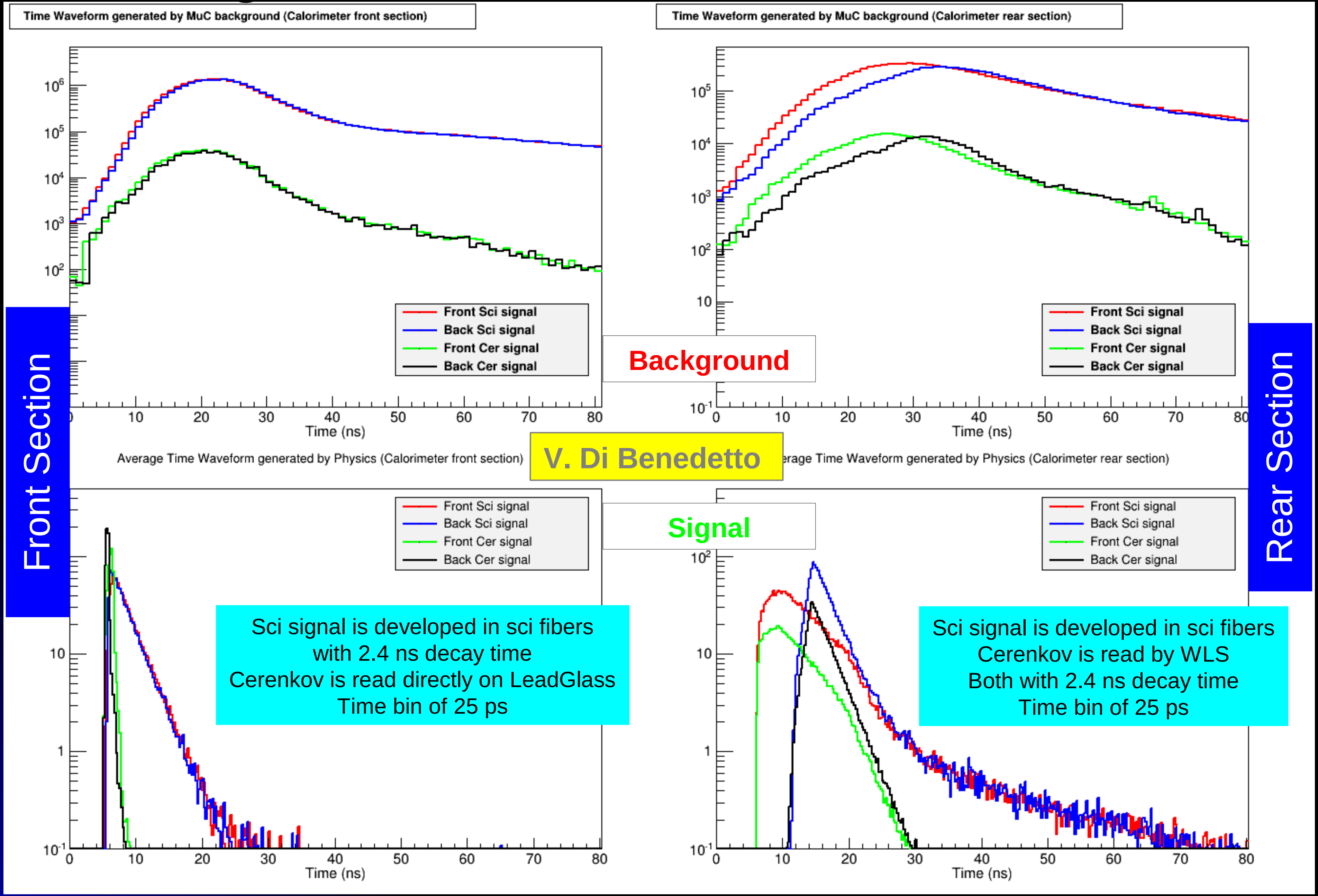
Detector type	Reconstructed Tracks (full simu)	Reconstructed Tracks (fast simu)
Det. A (no timing)	Cannot calculate	Cannot calculate
Det. B (7 ns fixed gate)	75309	64319
Det. C (3 ns adjusteble gate)	6544	4639
Det. D (1 ns adjusteble gate)	1459	881

After χ^2 and IP cuts

Detector type	Reconstructed Tracks (full simu)	Reconstructed Tracks (fast simu)
Det. A (no timing)	Cannot calculate	Cannot calculate
Det. B (7 ns fixed gate)	475	405
Det. C (3 ns adjusteble gate)	11	8
Det. D (1 ns adjusteble gate)	3	1

Full reconstruction is paramount when combinatorics is relevant

Timing Is Also The Key For Calorimetry



Time Waveform generated by MuC background (Calorimeter front section)

Time Waveform generated by MuC background (Calorimeter rear section)

Average Time Waveform generated by Physics (Calorimeter front section)

Average Time Waveform generated by Physics (Calorimeter rear section)

Front Section

Rear Section

Background

Signal

V. Di Benedetto

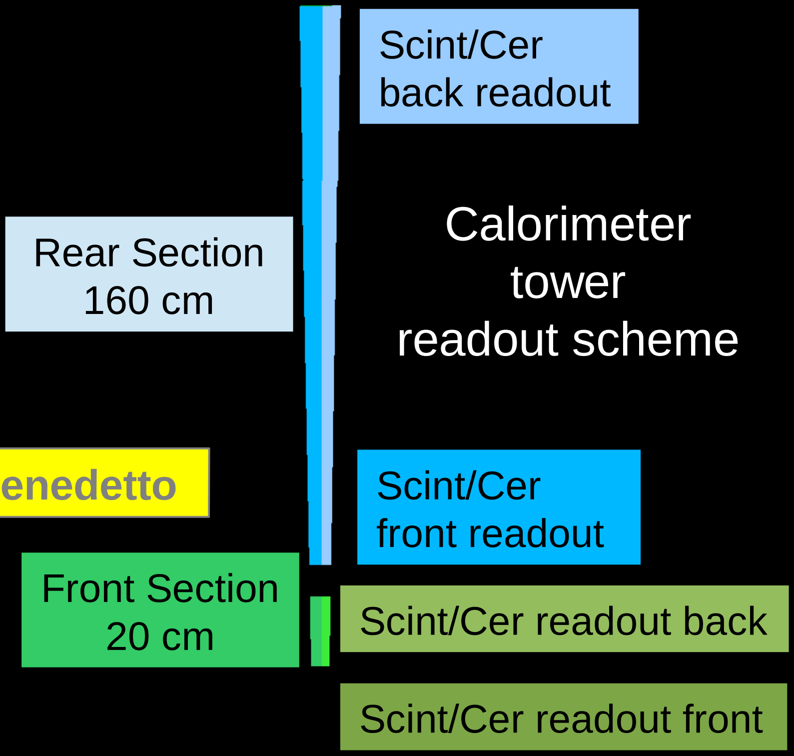
Sci signal is developed in sci fibers
with 2.4 ns decay time
Cerenkov is read directly on LeadGlass
Time bin of 25 ps

Sci signal is developed in sci fibers
Cerenkov is read by WLS
Both with 2.4 ns decay time
Time bin of 25 ps

Background Rejection In The Calorimeter

Time gate for each section				
	Front Section		Rear Section	
	Scint	Cer	Scint	Cer
Front readout	6.3 ns	1.5 ns	12.8 ns	10.3 ns
Back readout	5.7 ns	0.8 ns	8.5 ns	7.0 ns
Signal efficiency	83%		76%	
BG suppression	98.5%		97.3%	

V. Di Benedetto



BG energy	Front Section Rear Section	
Total	228 TeV	155 TeV
After time cut	3 TeV	4 TeV

Approach to reject machine background.

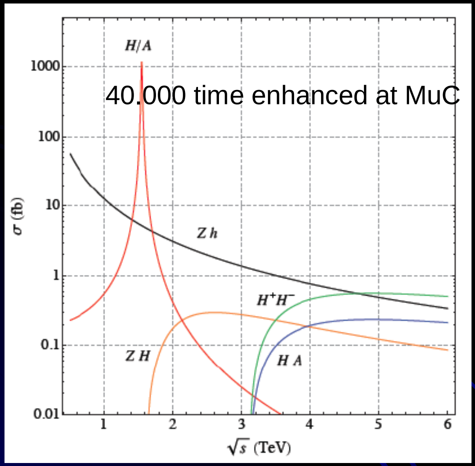
On going studies

- **Apply time cut.**
- **Individuate Region of Interest (RoI), i.e. regions where the energy is 2.5σ above the background level in that region.**
- **In the RoI apply soft energy subtraction, i.e. subtract the mean value of the background in that region.**
- **In the other regions apply hard energy cut, i.e. subtract 4σ of the background.**

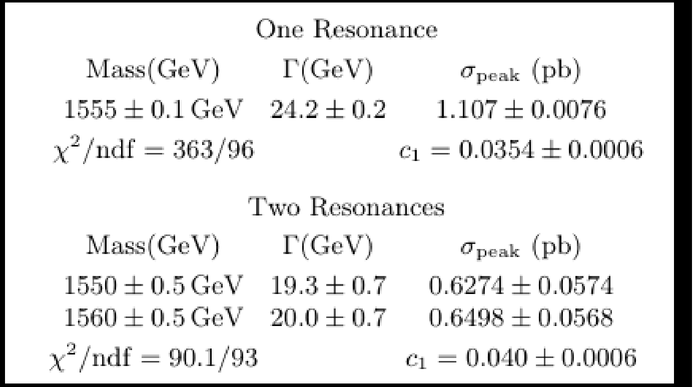
The Muon Collider as a H/A factory: Theory

- Heavy Neutral Higgses (H/A) and charged Higgses ($H^{\pm}$) are a simple possibility of new physics beyond the Standard Model.
- H/A are likely to be difficult to find at the LHC, and at e+ e- colliders are produced in association with other particles, such as Z, since the electron Yukawa coupling is too small for s-channel production.
- The H and A can be produced as s-channel resonances and direct measured at a Muon Collider (Eichten and Martin arXiv:1306.2609).

E. Eichten & A. Martin



H/A production in the Natural Supersymmetry model compared with Z^0h, Z^0H and heavy Higgs pair production.

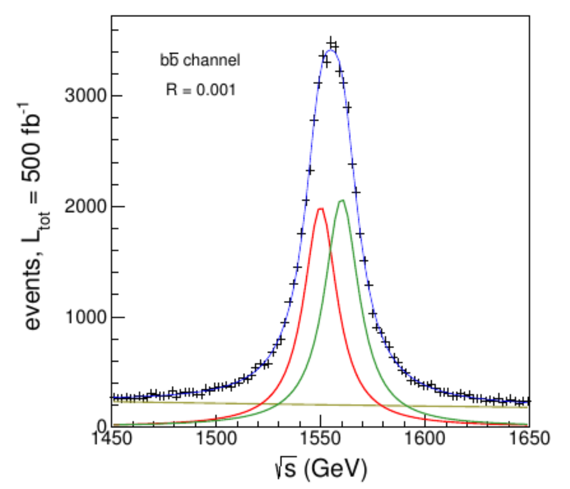


One Resonance

Mass(GeV)	Γ(GeV)	σ_{peak} (pb)
1555 ± 0.1 GeV	24.2 ± 0.2	1.107 ± 0.0076
$\chi^2/\text{ndf} = 363/96$		$c_1 = 0.0354 \pm 0.0006$

Two Resonances

Mass(GeV)	Γ(GeV)	σ_{peak} (pb)
1550 ± 0.5 GeV	19.3 ± 0.7	0.6274 ± 0.0574
1560 ± 0.5 GeV	20.0 ± 0.7	0.6498 ± 0.0568
$\chi^2/\text{ndf} = 90.1/93$		$c_1 = 0.040 \pm 0.0006$



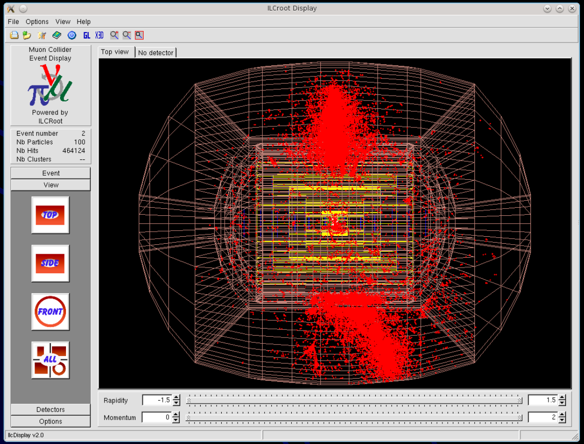
Pseudo-data (in black) along with the fit result in the bb channel. The peak signal is more than an order of magnitude larger than the physics background.

$$\sigma_B(\sqrt{s}) = c_1 \frac{(m_H m_A)}{s(\text{in TeV}^2)}$$

The Muon Collider as a H/A factory: “Reality”

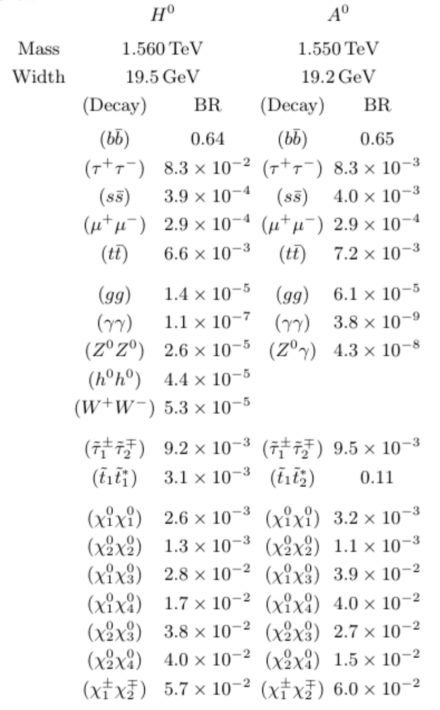
- **Fully simulated with track and calorimeter reconstruction** in ILCroot framework 4000 H/A events generated by Pythia at √s = 1550 GeV with a Gaussian beam energy smearing (R=0.001) (A. Martin)
- In these studies, considered the $b\bar{b}$ decay of the H/A which is the channel with the largest BR (64%).
- Applied a perfect b-tagging (using information from MonteCarlo truth).
- Reconstructed 2 jets applying PFA-like jet reconstruction developed for ILC benchmark studies.

ILCroot Event Display



Event number 2
Nb Particles 100
Nb Hits 464124
Nb Clusters --
Rapidity -1.5 1.5
Momentum 0 2

NO machine background



shown.

	H^0		A^0	
Mass	1.560 TeV		1.550 TeV	
Width	19.5 GeV		19.2 GeV	
	(Decay)	BR	(Decay)	BR
	$(b\bar{b})$	0.64	$(b\bar{b})$	0.65
	$(\tau^+\tau^-)$	8.3×10^{-2}	$(\tau^+\tau^-)$	8.3×10^{-3}
	$(s\bar{s})$	3.9×10^{-4}	$(s\bar{s})$	4.0×10^{-3}
	$(\mu^+\mu^-)$	2.9×10^{-4}	$(\mu^+\mu^-)$	2.9×10^{-4}
	$(t\bar{t})$	6.6×10^{-3}	$(t\bar{t})$	7.2×10^{-3}
	(gg)	1.4×10^{-5}	(gg)	6.1×10^{-5}
	$(\gamma\gamma)$	1.1×10^{-7}	$(\gamma\gamma)$	3.8×10^{-9}
	(Z^0Z^0)	2.6×10^{-5}	$(Z^0\gamma)$	4.3×10^{-8}
	(h^0h^0)	4.4×10^{-5}		
	(W^+W^-)	5.3×10^{-5}		
	$(\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp)$	9.2×10^{-3}	$(\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp)$	9.5×10^{-3}
	$(\tilde{t}_1\tilde{t}_1^*)$	3.1×10^{-3}	$(\tilde{t}_1\tilde{t}_2^*)$	0.11
	$(\chi_1^0\chi_1^0)$	2.6×10^{-3}	$(\chi_1^0\chi_1^0)$	3.2×10^{-3}
	$(\chi_2^0\chi_2^0)$	1.3×10^{-3}	$(\chi_2^0\chi_2^0)$	1.1×10^{-3}
	$(\chi_1^0\chi_3^0)$	2.8×10^{-2}	$(\chi_1^0\chi_3^0)$	3.9×10^{-2}
	$(\chi_1^0\chi_4^0)$	1.7×10^{-2}	$(\chi_1^0\chi_4^0)$	4.0×10^{-2}
	$(\chi_2^0\chi_3^0)$	3.8×10^{-2}	$(\chi_2^0\chi_3^0)$	2.7×10^{-2}
	$(\chi_2^0\chi_4^0)$	4.0×10^{-2}	$(\chi_2^0\chi_4^0)$	1.5×10^{-2}
	$(\chi_1^\pm\chi_2^\mp)$	5.7×10^{-2}	$(\chi_1^\pm\chi_2^\mp)$	6.0×10^{-2}

The Muon Collider as a H/A factory: "Reality" (cont'd)

Jet Reconstruction Strategy

Assume the jet made of 2 non-overlapping regions

Core: region of the calorimeter with overlapping showers

Outliers: hit towers separated from the core

Measure the Jet axis

using information from the tracker detectors

Measure the Core energy

using information from the calorimeter

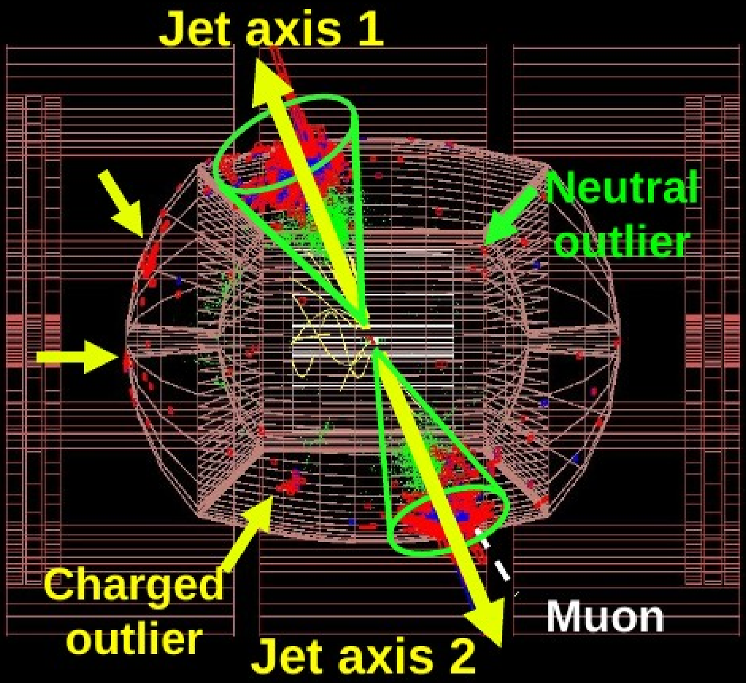
Reconstruct Outliers individually

using tracking and/or calorimetry

depending on the charge of the particle

Add Muons escaping from calorimeter

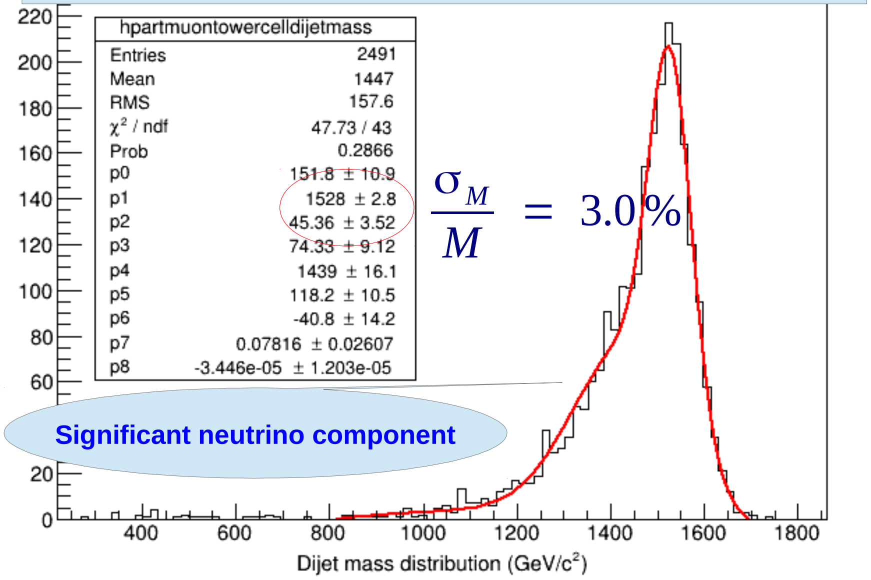
using muon spetrometer



ILCroot Simulation

The Muon Collider as a H/A factory: "Reality" (cont'd)

NO Time Gate NO Background



hpartmuontowercelldijetmass

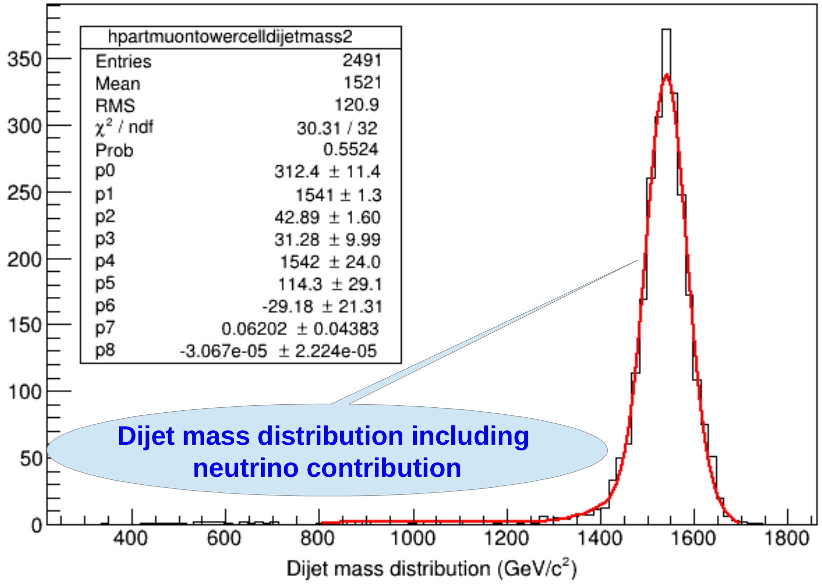
Entries	2491
Mean	1447
RMS	157.6
χ^2 / ndf	47.73 / 43
Prob	0.2866
p0	151.8 ± 10.9
p1	1528 ± 2.8
p2	45.36 ± 3.52
p3	74.33 ± 9.12
p4	1439 ± 16.1
p5	118.2 ± 10.5
p6	-40.8 ± 14.2
p7	0.07816 ± 0.02607
p8	-3.446e-05 ± 1.203e-05

$$\frac{\sigma_M}{M} = 3.0\%$$

Significant neutrino component

- Di-jet mass distribution obtained including the neutrino contribution

- There is a significant neutrino component



hpartmuontowercelldijetmass2

Entries	2491
Mean	1521
RMS	120.9
χ^2 / ndf	30.31 / 32
Prob	0.5524
p0	312.4 ± 11.4
p1	1541 ± 1.3
p2	42.89 ± 1.60
p3	31.28 ± 9.99
p4	1542 ± 24.0
p5	114.3 ± 29.1
p6	-29.18 ± 21.31
p7	0.06202 ± 0.04383
p8	-3.067e-05 ± 2.224e-05

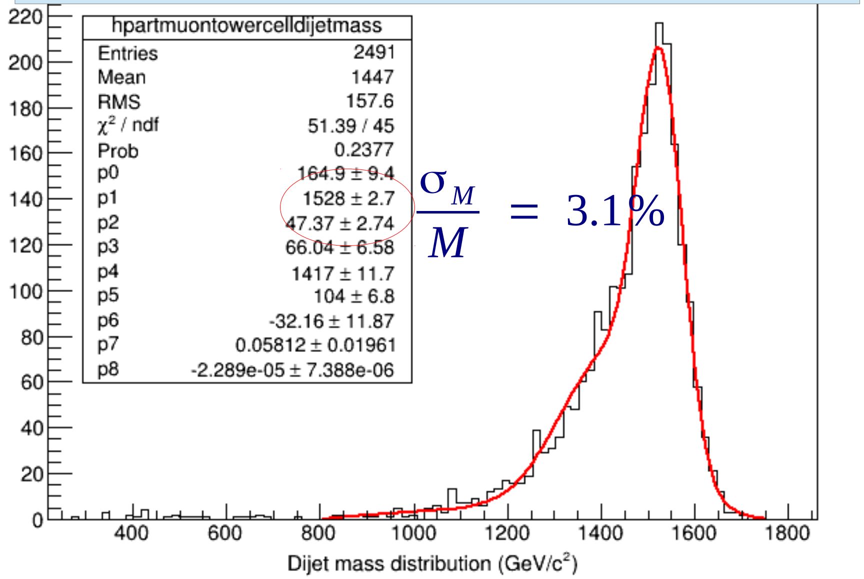
Dijet mass distribution including neutrino contribution

A. Mazzacane (Fermilab)

ILCroot Simulation

The Muon Collider as a H/A factory: “Reality” (cont'd)

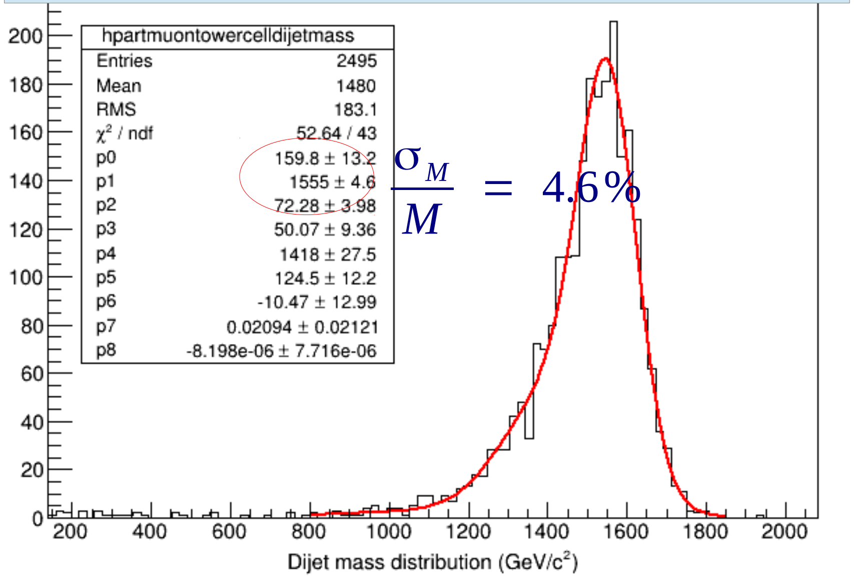
YES Time Gate NO Background



$$\frac{\sigma_M}{M} = 3.1\%$$

- Applied 3 ns layer dependent time gate in the tracking system and the time gate shown in slide #16 in the calorimeter.

YES Time Gate YES Background



$$\frac{\sigma_M}{M} = 4.6\%$$

- **Fully simulated signal and beam backgroud**
  Applied 3ns time gate and energy cut theta dependent to further reject the background

A. Mazzacane (Fermilab)

ILCroot Simulation

Why MuC Detector R&D Is Important

- Background vs Physics rejection has unprecedented characteristics compared to previous HEP experiments.
  - The background is huge but out-of-time and enter in the detector with a quite uniform distribution.
  - The Machine Detector Interface (MDI) has an important role and has to be considered an integral part of the detector: i.e. the geometry changes as the shielding strategy evolves.
  - The MDI affects the physics program, especially Susy signals, by the presence of forward shielding and instrumentation.
- New detector technologies need to be exploited. Push for a new detector generation.

  Tracking
  - Simulations indicate the Si detectors are a good solution, but many issues have to be addressed.
  - The inner radius of the vertex is set by the beam background and the shielding nozzle. But the impact parameter resolution and the physics reach are affected.
  - High granularity is required to low occupancy. But charge sharing limits the pixel size.
  - Fast timing is crucial. But power requirements need to be understood.
- Calorimetry
  - PFA disadvantaged at multi-TeV energies and in a MuC environment (Small λ_I, σ_E/E = cost. Higher confusion term).
  - Fast Dual/Triple-Readout can be a better option ($\lambda_I \geq 7$, $\sigma_E/E = 1/\sqrt{E}$, but the radiation hardness is crucial).
  - LAPPD for picosecond-level resolution and excellent photon-counting capabilities.

Software and Simulations

- We understood many things since these studies began thanks to simulations. Simulations are crucial:
  - to guide through technologies and help identifying the figure of merit for each subdetector.
  - to optimize parameters and to build prototypes to test.

- We need to unify efforts and expertise in order to make detector performance and physics studies for future colliders possible in a realistic time scale and man power.

- Software frameworks (MARS, ILCroot, SLIC) mature for advanced and realistic studies.

Conclusions

- A large background is expected into the detector from interactions of muon decay products with the beamline components and the accelerator tunnel.

- The background affects the detector performance and can spoil the physics program at a Muon Collider experiment.

- Sophisticated shielding have been proposed to suppress the machine background.

- MARS15 simulation shows a reduction of the machine background ~ 3 orders of magnitude (depends on the nozzle angle).

- The baseline detector configuration for a Muon Collider has been developed in ILCroot framework and studies on the performance are well advanced.

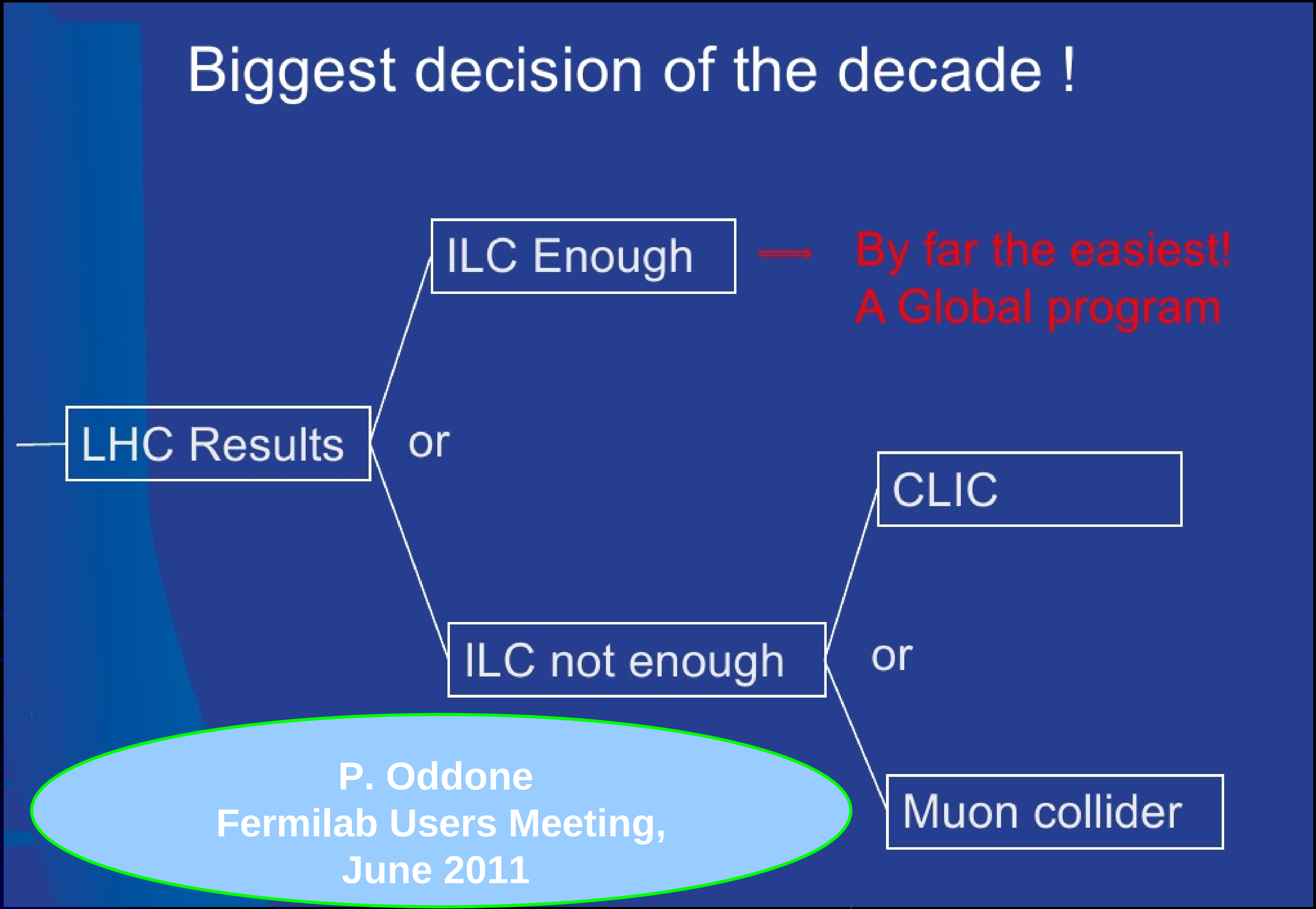
- Full simulation and reconstruction of Si-tracking detectors and a dual-readout calorimeter are implemented in ILCroot framework (thanks to previous and detailed studies at ILC).

Conclusions (cont'd)

- Both ad-hoc tracking and calorimetry simulation implemented in the current software framework.
- The background is very nasty, even with a 10° nozzle , but we have shown that we are on the right track to reach the physics goal at a Muon Collider experiment.
- Current studies show that timing cut is an effective tool to reducing the background to an acceptable level.
- However the needed timing for the Si detectors is at the limit of existing pixel devices (power consuption-cooling, material budget) and beyond the current calorimeter technology ⟹ Extensive R&D is needed.
- A second generation of detector and reconstruction algorithm are under consideration:
  - 3-D Si-pixel with precision timing
  - 4-D Kalman filter
  - segmented calorimeters with enhanced timing.

The Muon Collider is the opportunity to bring back collider physics to US soil.

Backup slides



Biggest decision of the decade !

LHC Results

or

ILC Enough ⟹ By far the easiest! A Global program

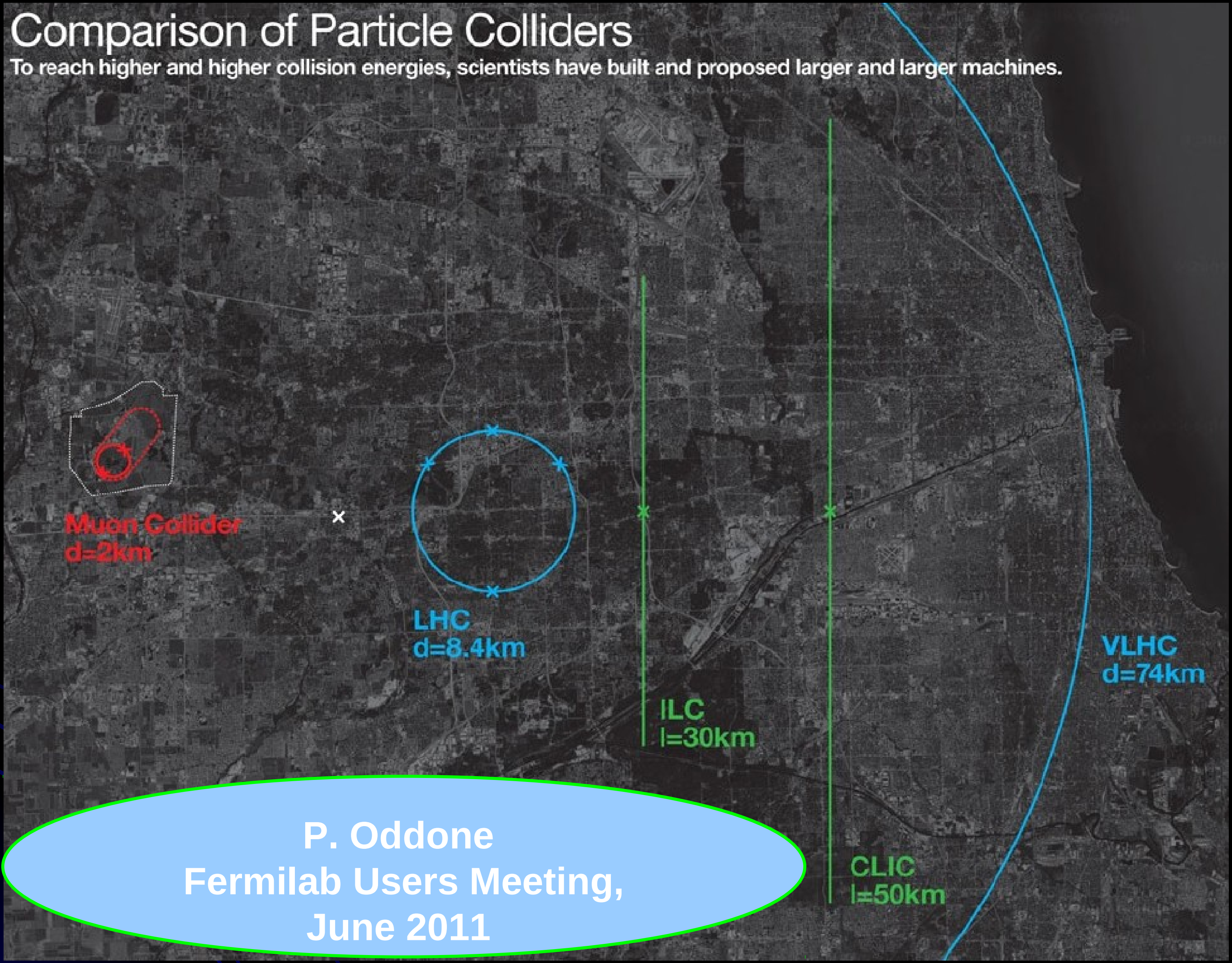
ILC not enough

or

CLIC

Muon collider

P. Oddone
Fermilab Users Meeting,
June 2011



Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.

P. Oddone
Fermilab Users Meeting,
June 2011

Potential Muon Collider Parameters

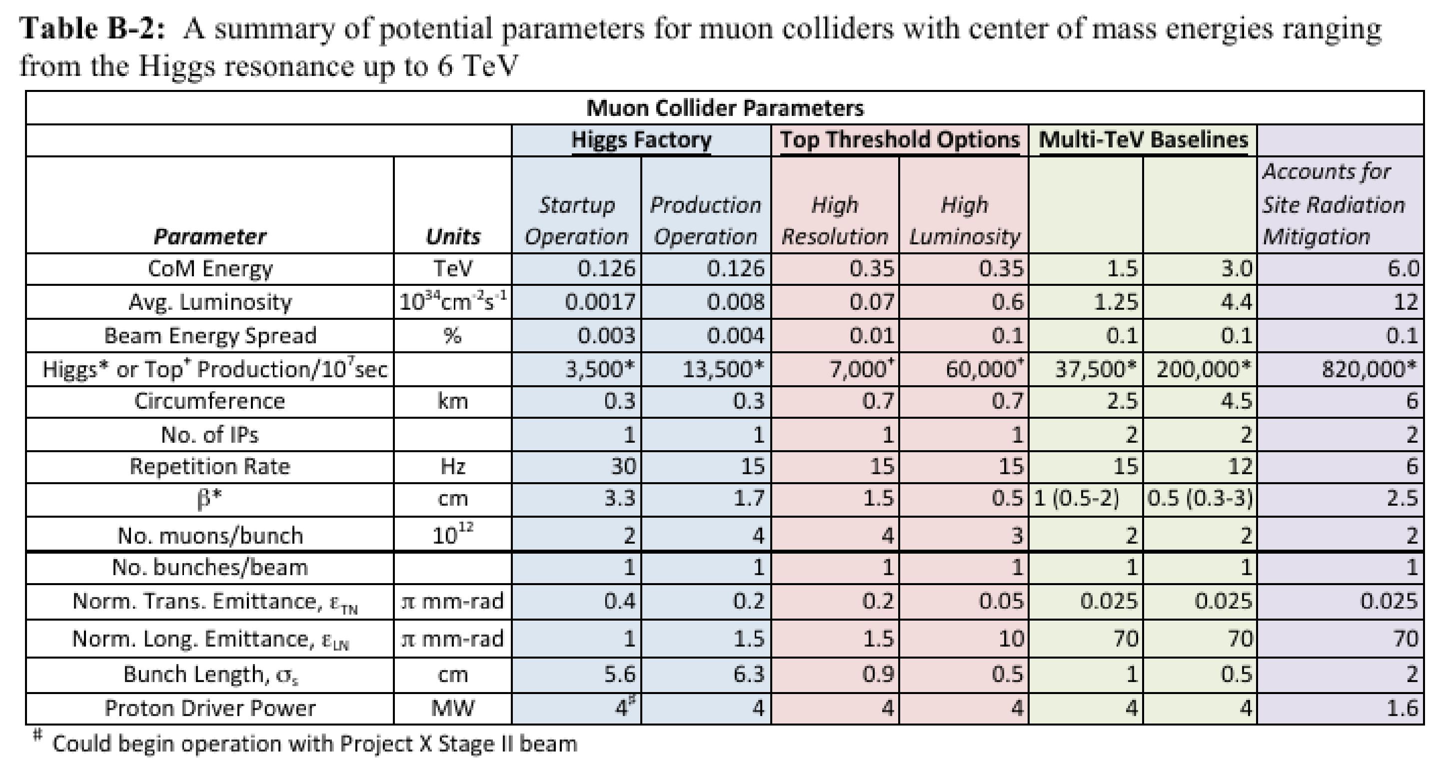


Table B-2: A summary of potential parameters for muon colliders with center of mass energies ranging from the Higgs resonance up to 6 TeV

Muon Collider Parameters								
		Higgs Factory		**Top Threshold Options**		**Multi-TeV Baselines**		
Parameter	***Units***	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top^{+} Production/10^7sec		3,500*	13,500*	7,000^{+}	60,000^{+}	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	2.5
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	2
Proton Driver Power	MW	4[#]	4	4	4	4	4	1.6

[#] Could begin operation with Project X Stage II beam

Introduction

Physics goals of a Muon Collider (MC) can only be reached with appropriate design of the ring, interaction region (IR), high-field superconducting magnets, machine-detector interface (MDI) and detector. All - under demanding requirements, arising from the short muon lifetime, relatively large values of the transverse emittance and momentum spread, unprecedented dynamic heat loads (0.5-1 kW/m) and background particle rates in collider detector.

Detector Backgrounds at Muon Colliders - N. Mokhov, S. Striganov

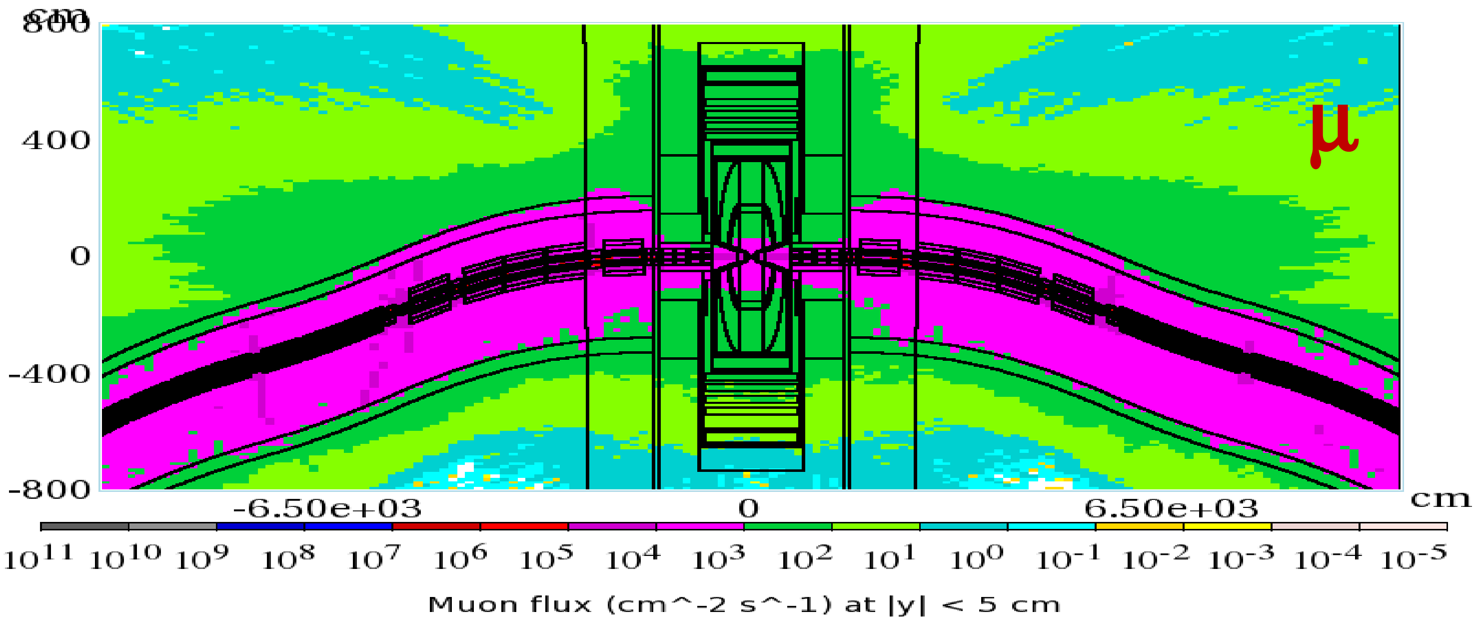
Sources of Background and Dynamic Heat Load

1. **IP $\mu^+\mu^-$ collisions:** Production x-section 1.34 pb at √S = 1.5 TeV (negligible compared to #3).
2. **IP incoherent e^+e^- pair production:** x-section 10 mb which gives rise to background of 3×10^4 electron pairs per bunch crossing (manageable with nozzle & detector B)
3. **Muon beam decays:** Unavoidable bilateral detector irradiation by particle fluxes from beamline components and accelerator tunnel – **major source** at MC: For 0.75-TeV muon beam of $2\text{x}10^{12}$, $4.28\text{x}10^5$ dec/m per bunch crossing, or $1.28\text{x}10^{10}$ dec/m/s for 2 beams; 0.5 kW/m.
4. **Beam halo:** Beam loss at limiting apertures; severe, can be taken care of by an appropriate collimation system far upstream of IP.

SUMMARY (1)

1. Backgrounds originated at IP are negligible compared to other sources: hadrons from $\mu^+\mu^-$ collisions; incoherent pairs are captured by nozzles in the solenoid field.
2. Backgrounds induced by beam halo losses exceed the limits by orders of magnitude, but can be suppressed with an appropriate collimation system.
3. Muon beam decays are the major source of backgrounds in the MC detectors. They can drastically be reduced by sophisticated collimating nozzles at IP, and sweep dipoles and collimators in a 100-m region upstream IP.

Background Suppression

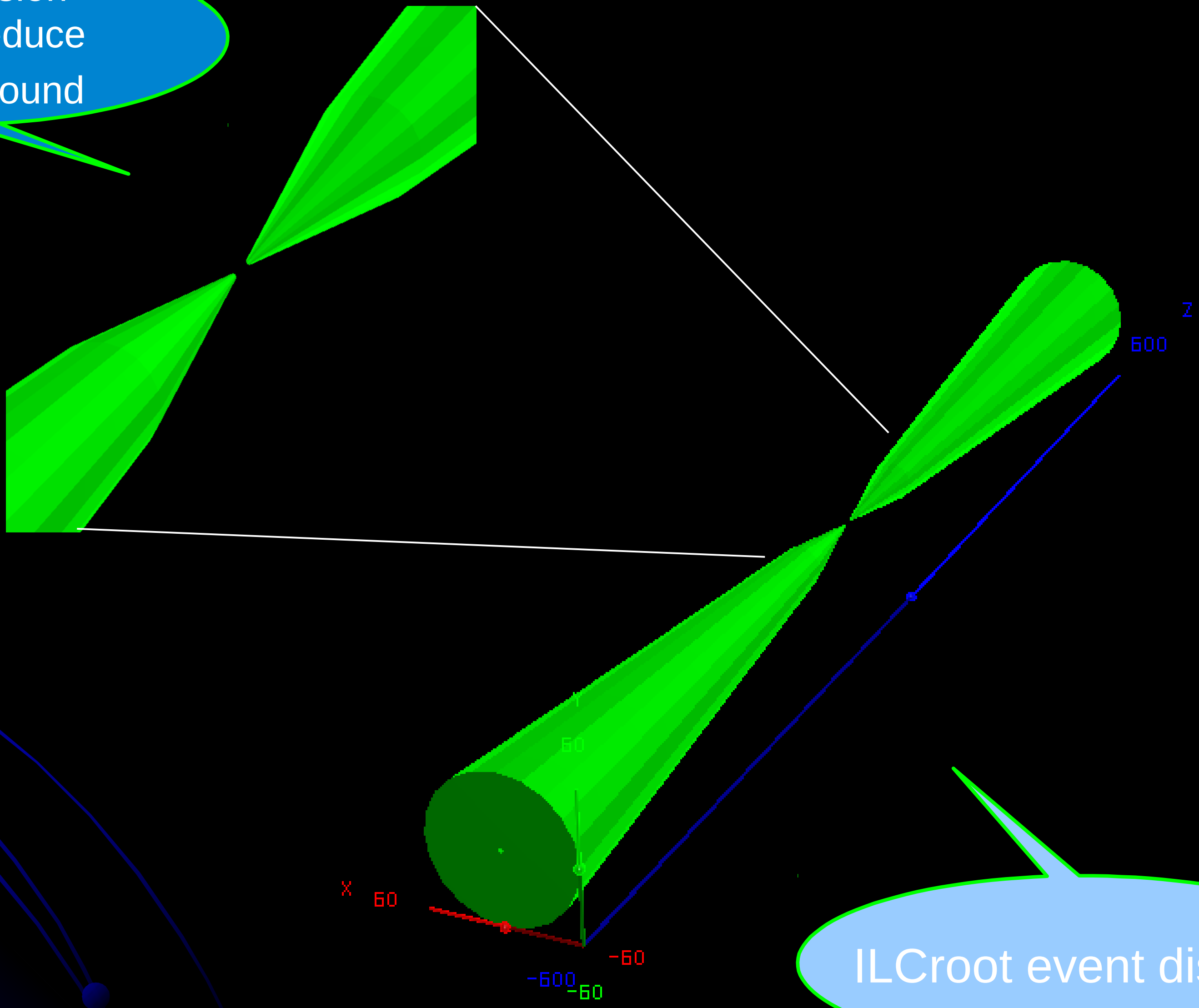


Dipoles close to the IP and tungsten masks in each interconnect region help reduce background particle fluxes in the detector by a substantial factor. The tungsten nozzles, assisted by the detector solenoid field, trap most of the decay electrons created close to the IP as well as most of incoherent e^+e^- pairs generated in the IP. With additional MDI shielding, total reduction of background loads by more than three orders of magnitude is obtained.

Detector Backgrounds at Muon Colliders - N. Mokhov, S. Striganov

10° Nozzle

Newer version
to further reduce
MuC background



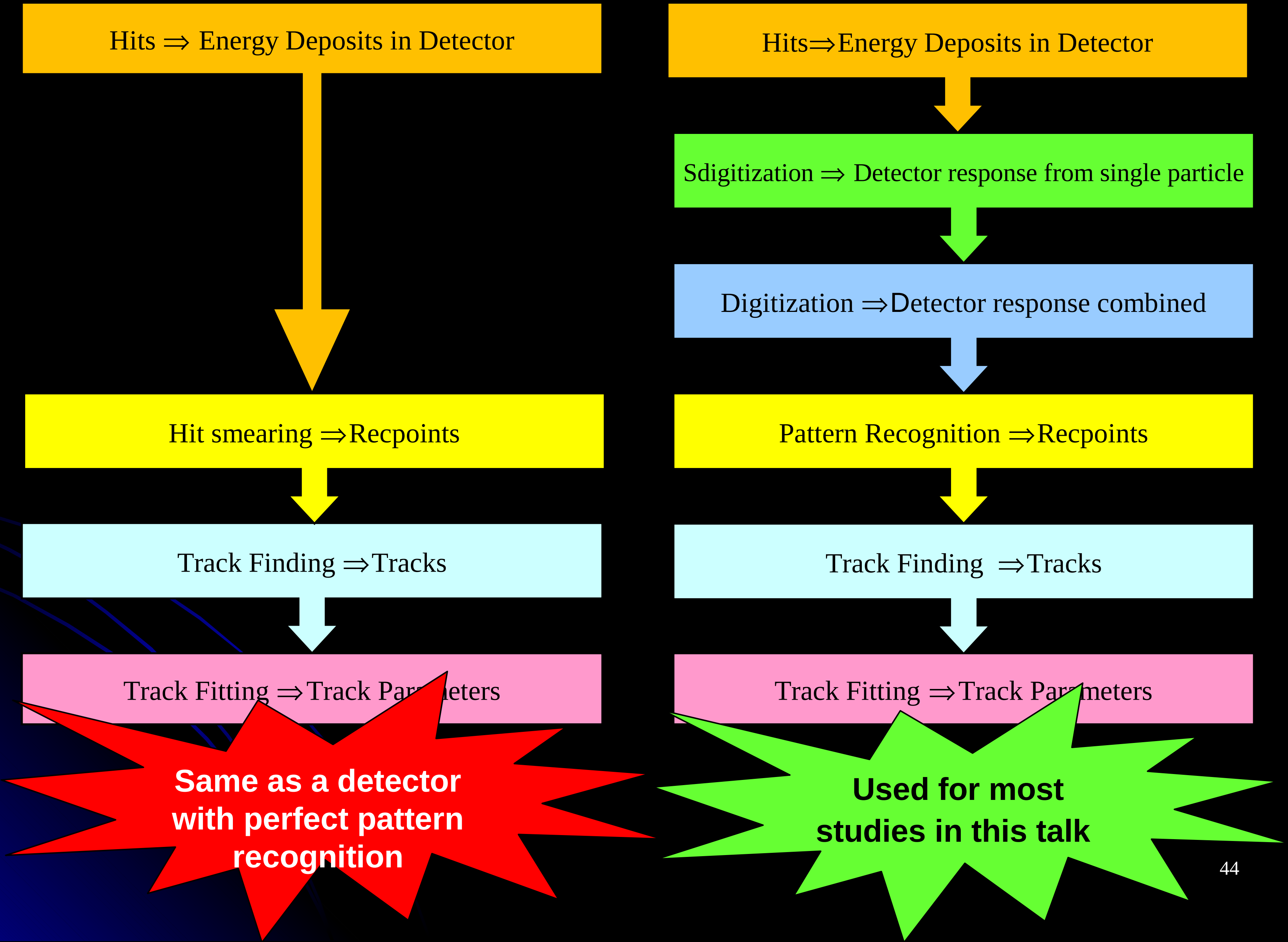
ILCroot event display

A. Mazzacane (Fermilab)

ILCroot: root Infrastructure for Large Colliders

- **Software architecture based on root, VMC & Aliroot**
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
- **Re-allignement with latest Aliroot version every 1-2 years (v4.17 release)**
- **It is a simulation framework and an Offline Systems:**
  - **Single framework, from generation to reconstruction through simulation. Don't forget analysis!!!**
  - It is immediatly usable for test beams
  - Six MDC have proven robustness, reliability and portability
- **Main add-ons Aliroot:**
  - Interface to external files in various format (STDHEP, text, etc.)
  - Standalone VTX track fitter
  - Pattern recognition from VTX (for si central trackers)
  - Parametric beam background (# integrated bunch crossing chosen at run time
- Growing number of experiments have adopted it: Alice (LHC), Opera (LNGS), (Meg), CMB (GSI), Panda(GSI), 4th Concept, (SiLC ?) and LHeC
- **It is Publicly available at FNAL on ILCSIM since 2006**
- **Used for ILC, CLIC and Muon Collider studies**

Fast vs Full Simulation



Hits ⇒ Energy Deposits in Detector

Hit smearing ⇒Recpoints

Track Finding ⇒Tracks

Track Fitting ⇒Track Par eters

Hits⇒Energy Deposits in Detector

Sdigitization ⇒ Detector response from single particle

Digitization ⇒Detector response combined

Pattern Recognition ⇒Recpoints

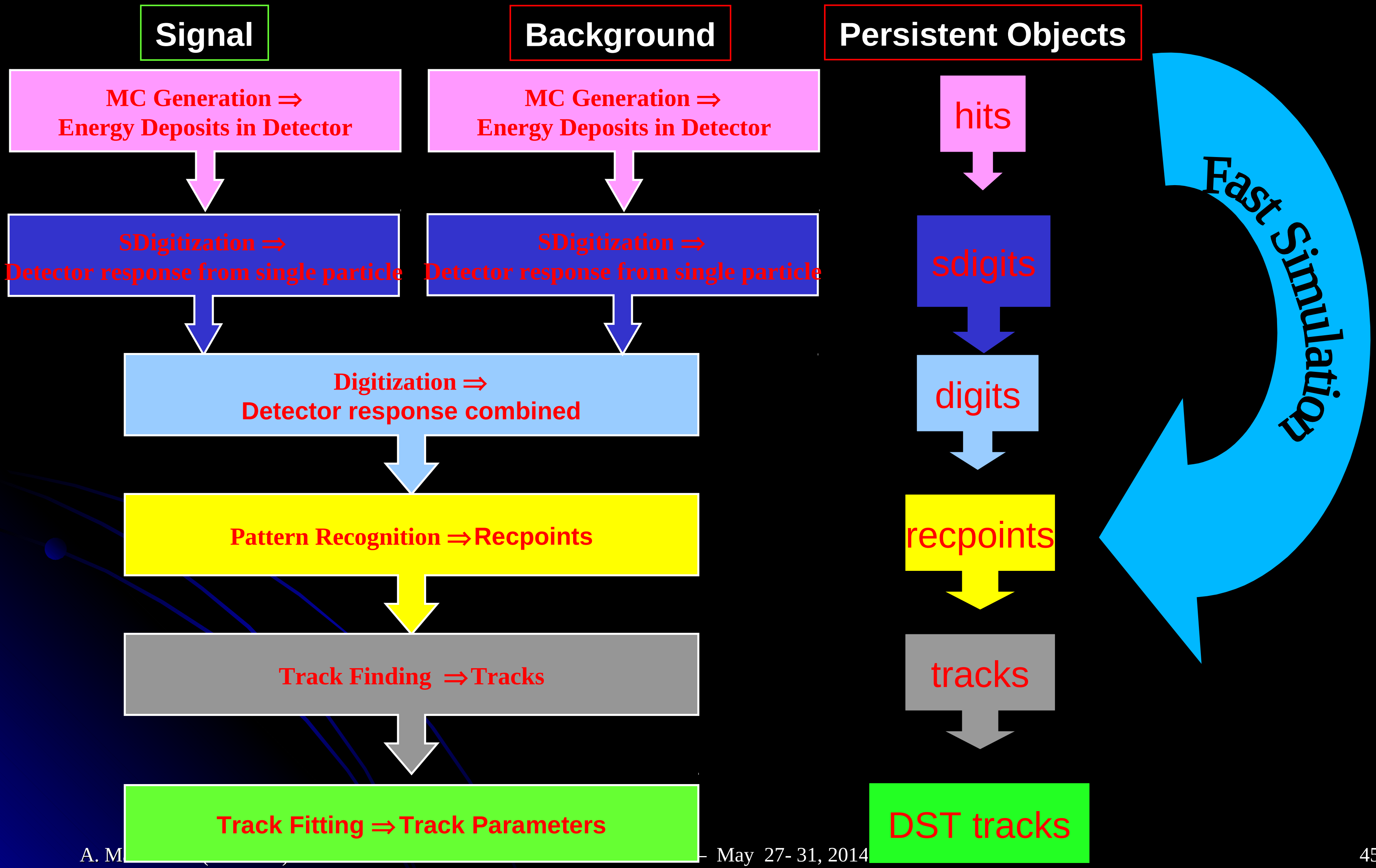
Track Finding ⇒Tracks

Track Fitting ⇒Track Par meters

Same as a detector with perfect pattern recognition

Used for most studies in this talk

Simulation steps in ILCroot: Tracking system



Signal

Background

Persistent Objects

MC Generation ⇒ Energy Deposits in Detector

MC Generation ⇒ Energy Deposits in Detector

hits

SDigitization ⇒ Detector response from single particle

SDigitization ⇒ Detector response from single particle

sdigits

Digitization ⇒ Detector response combined

digits

Pattern Recognition ⇒ Recpoints

recpoints

Track Finding ⇒ Tracks

tracks

Track Fitting ⇒ Track Parameters

DST tracks

Fast Simulation

Fast simulation and/or fast digitization also available in ILCroot for tracking system

- Fast Simulation = hit smearing
- Fast Digitization = full digitization with fast algorithms
- Do we need fast simulation in tracking studies?

  Yes!

  - Calorimetry related studies do not need full simulation/digitization for tracking
  - Faster computation for quick answer to response of several detector layouts/shielding
- Do we need full simulation in tracking studies?

  Yes!

  - Fancy detector and reconstruction needed to be able to separate hits from signal and background

Digitization and Clusterization of Si Detectors in Ilcroot: a description of the algorithms available for detailed tracking simulation and studies

Technologies Implemented

- 3 detector species:
  - Silicon pixels
  - Silicon Strips
  - Silicon Drift

Used for VXD SiT and
FTD
in present studies

- Pixel can have non constant size in different layers
- Strips can also be stereo and on both sides
- Dead regions are taken into account
- Algorithms are parametric: almost all available technologies are easily accomodated (MAPS, 3D, DEPFET, etc.)

Full Simulation of Si Detectors

SDigitization

- Follow the track in steps of 1 μm
- convert the energy deposited into charge
- spreads the charge asymmetrically (B-field) across several pixels:

$$f(x,z) = Errf(x_{step}, z_{step}, \sigma_x, \sigma_z)$$

$$\sigma_x = \sqrt{T \cdot k / e \cdot \Delta l / \Delta V \cdot step}$$

$$\Delta l = Si\,tickness, \quad \Delta V = bias\,voltage, \quad \sigma_x = \sigma_z \cdot fda$$

- Parameters used:
  - Eccentricity = 0.85 (fda)
  - Bias voltage = 18 V
  - cr = 0% (coupling probability for row)
  - cc = 4.7% (coupling probability for column)
  - threshold = 0 electrons
  - electronics noise = 0 electrons
  - T° = 300 °K

Digitization

Merge signals belonging to the same channel (pixel)

- Add threshold
- Add saturation
- Add electronic noise
- Save Digits over threshold
  - threshold = 0 electrons
  - electronics noise = 0 electrons

typical Si threshold corresponds to 10-20 KeV E_{dep}

Cluster Pattern recognition

- Create a initial cluster from adjacent pixels (no for diagonal)
- Subdivide the previous cluster in smaller NxN clusters
- Get cluster and error matrix from coordinate average of the cluster
- Kalman filter picks up the best Recpoints

Track Fitting in ILCRoot

Track finding and fitting is a global tasks: individual detector collaborate

It is performed after each detector has completed its local tasks (simulation, digitization, clusterization)

It occurs in three phases:

- Seeding in SiT and fitting in VXD+SiT+MUD
- Standalone seeding and fitting in VXD
- Standalone seeding and fitting in MUD

Two different seedings:

- Primary seeding with vertex constraint
- Secondary seeding without vertex constraint

Not yet implemented

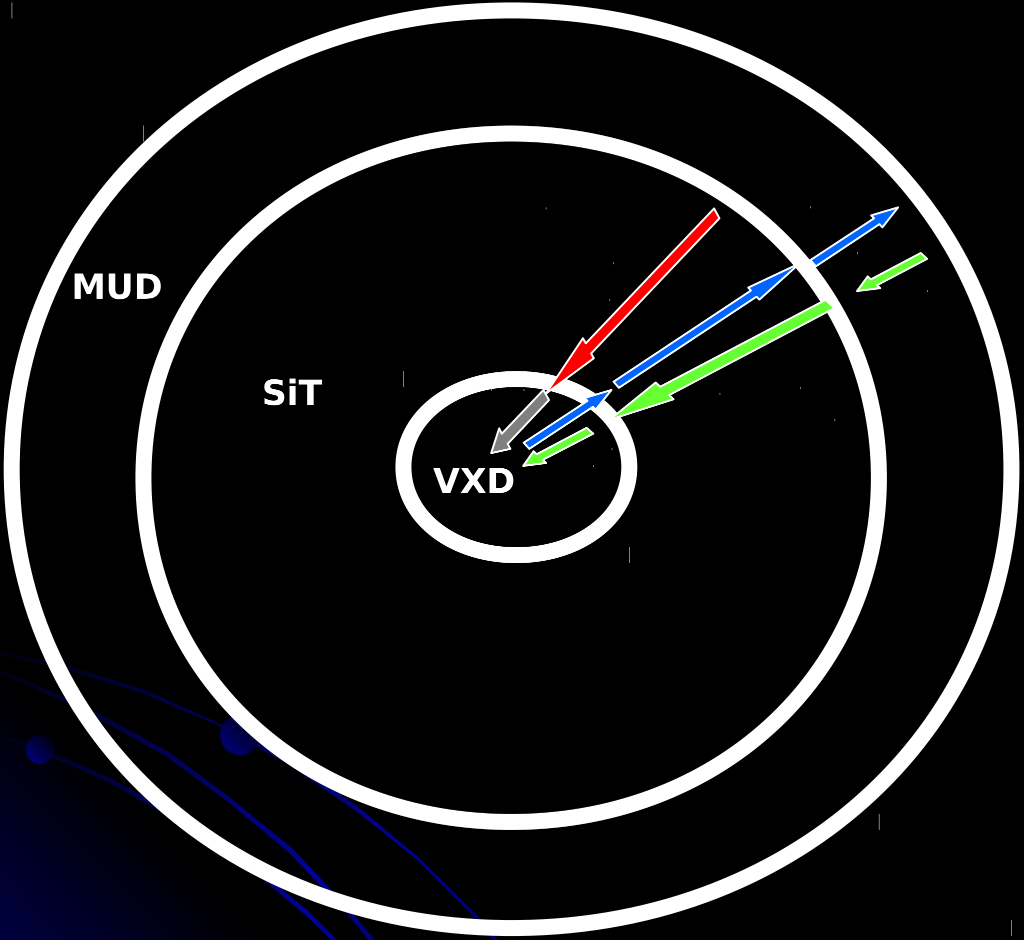
Kalman Filter (classic)

- Recursive least-squares estimation.
- Equivalent to global least-squares method including all correlations between measurements due to multiple scattering.
- Suitable for combined track finding and fitting
- Provides a natural way:
  - to take into account multiple scattering, magnetic field inhomogeneity
  - possibility to take into account mean energy losses
  - to extrapolate tracks from one sub-detector to another

Parallel Kalman Filter

- Seedings with constraint + seedings without constraint at different radii (necessary for kinks and V0) from outer to inner
- Tracking
  - Find for each track the prolongation to the next layer
  - Estimate the errors
  - Update track according current cluster parameters
  - (Possible refine clusters parameters with current track)
- Track several track-hypothesis in parallel
  - Allow cluster sharing between different track
- Remove-Overlap
- **Kinks and V0** fitted during the Kalman filtering

Tracking Strategy – Primary Tracks



- Iterative process
  - Seeding in SiT
  - Forward propagation towards to the vertex

    SiT → VXD
  - Back propagation towards to the MUD

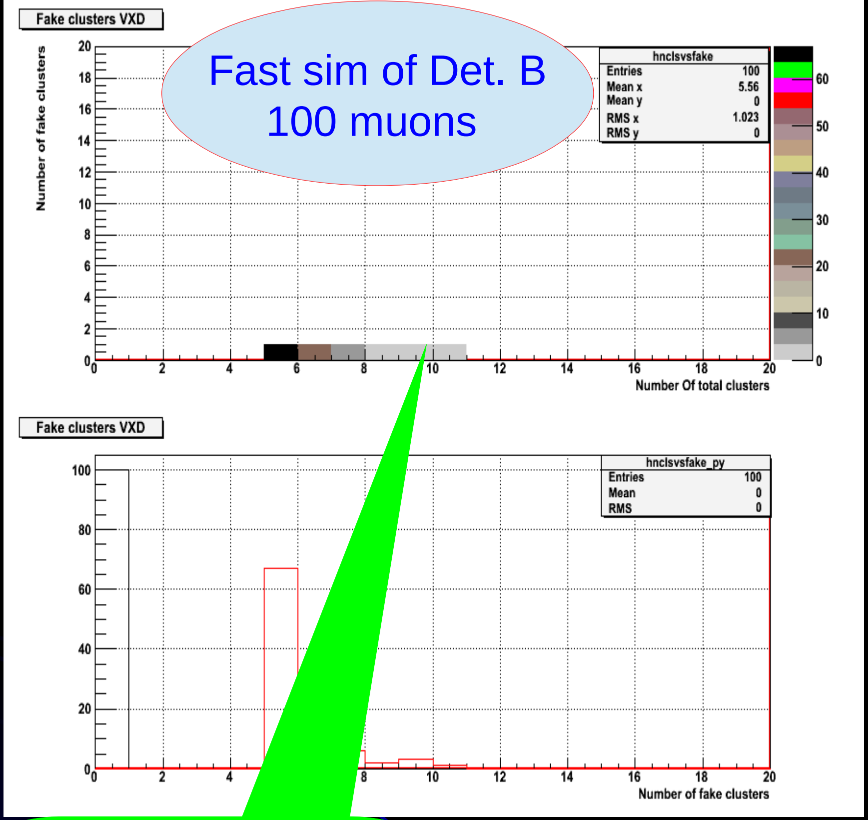
    VXD → SiT → MUD
  - Refit inward

    MUD → SiT → VXD
- Continuous seeding –track segment finding in all detectors

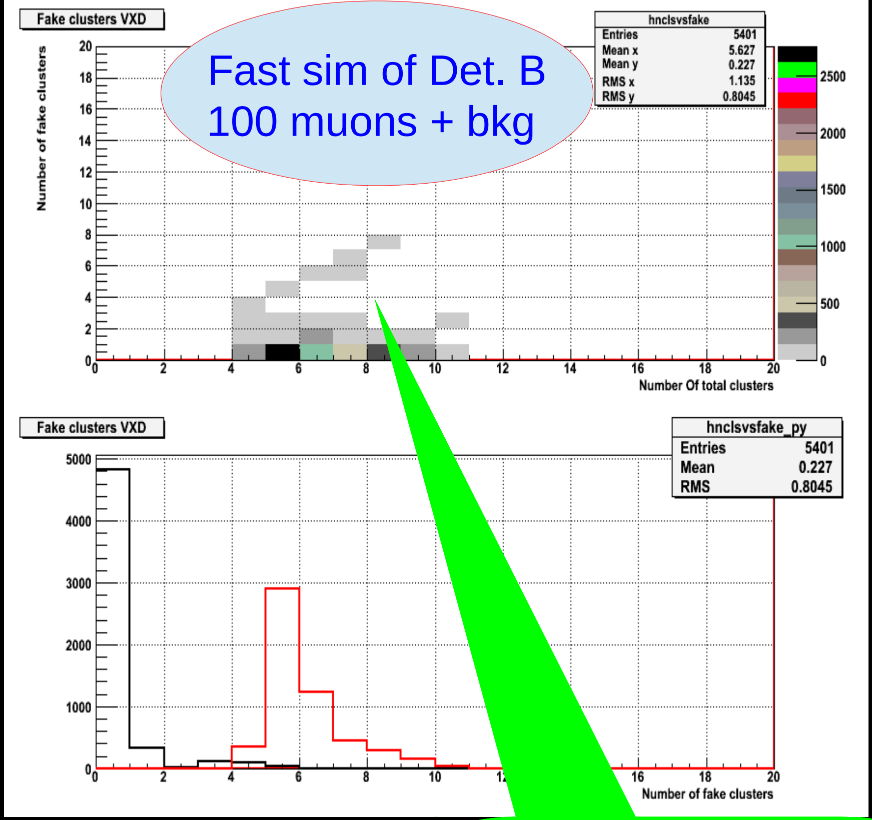
VXD Standalone Tracking

- Uses Clusters leftover in the VXD by Parallel Kalman Filter
- **Requires at least 4 hits to build a track**
- Seeding in VXD in two steps
  - Step 1: look for 3 Clusters in a narrow row or 2 Clusters + IP constraint
  - Step 2: prolongate to next layers each helix constructed from a seed
- After finding Clusters, all different combination of clusters are refitted with the Kalman Filter and the tracks with lowest χ^2 are selected
- Finally, the process is repeated attempting to find tracks on an enlarged row constructed looping on the first point on different layers and all the subsequent layers
- In 3.5 Tesla B-field $P_t > 20$ MeV tracks reconstructable

Effects of background Hits on Physics



Fast sim of Det. B
100 muons



Fast sim of Det. B
100 muons + bkg

no fake cluster

< 5% of tracks
have > 1 fake cluster

Effects on track parameter resolution are unaffected by background