The trigger system for the MEG II experiment

Marco Francesconi for MEG II collaboration

15th Pisa Meeting on Advanced Detectors, La Biodola, 23-27 May 2022

CLFV Golden channel: $\mu^+ \to e^+ \gamma$

Physics motivation:

Charged Lepton Flavour Violation are **key processes in SM:** lepton interactions can only couple within the same family

$$\overset{(-)}{\nu}_e \leftrightarrow e^{\pm}$$

$$\overset{(-)}{\nu}_\mu \leftrightarrow \mu^{\pm}$$

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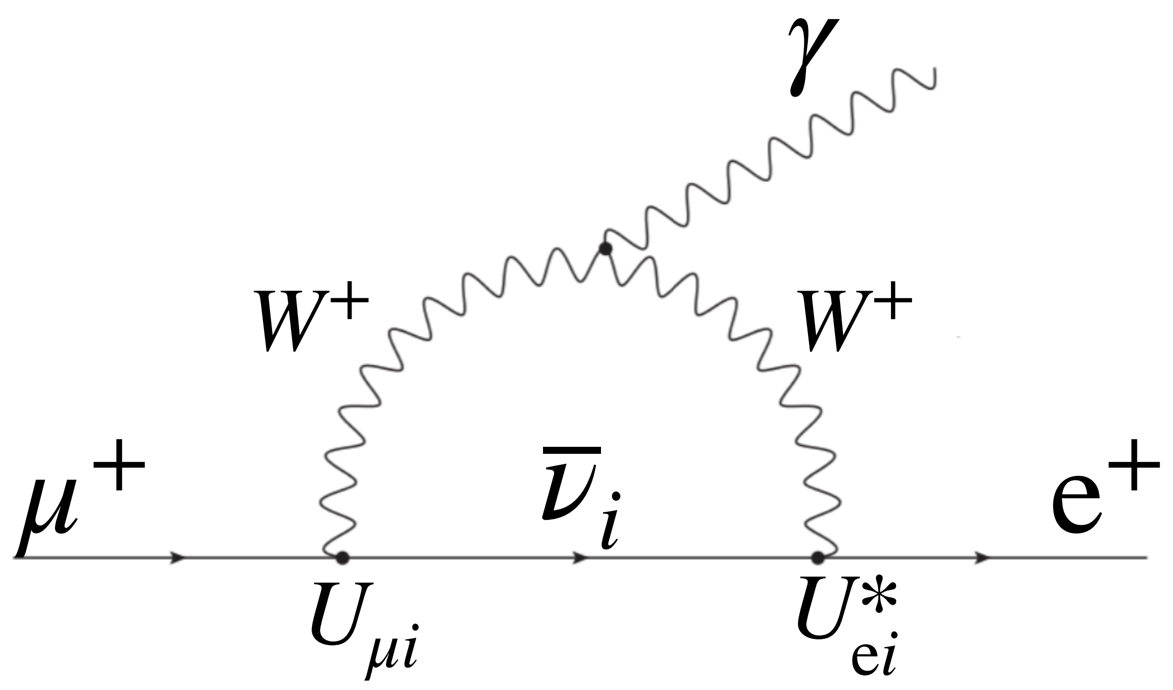
But neutrino oscillations shows that **Lepton family are violated**



PNMS matrix $U_{\ell i}$

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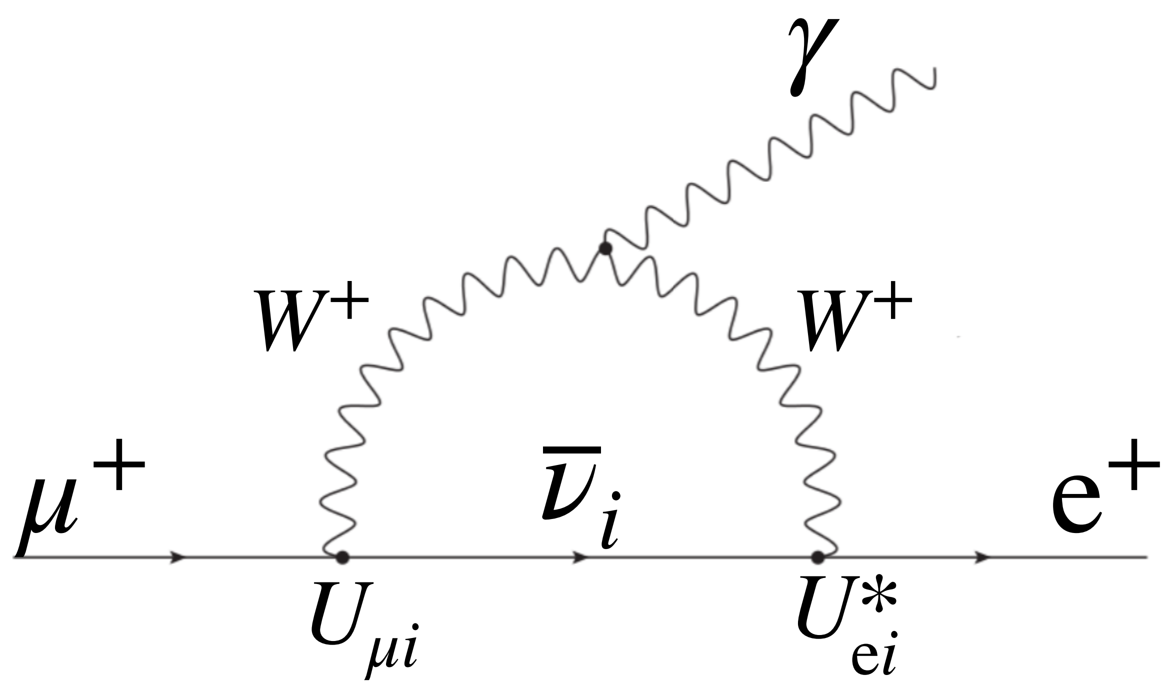

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World best upper limit by **MEG I**:

$$\mathrm{BR}(\mu^+ \to e^+ + \gamma) \leq 4.2 \cdot 10^{-13} \; (@ \; 90\,\% \; C.L.)$$

The European Physical Journal C 76.8 (2016): 434

MEG II experimental sensitivity:

$$\mathrm{BR}(\mu^+ \to e^+ + \gamma) \leq 6 \cdot 10^{-14} \; (@ \; 90\,\% \; C.L.)$$

Symmetry 13.9 (2021): 1591

One order of magnitude improvement!

Final statistic to be collected in **3 years**: $\sim 10^{16} \; \mu^+$ decays

Use world **most intense** continuous muon beam: $7 \cdot 10^7 \; \mu^+/s$ at PSI (CH)

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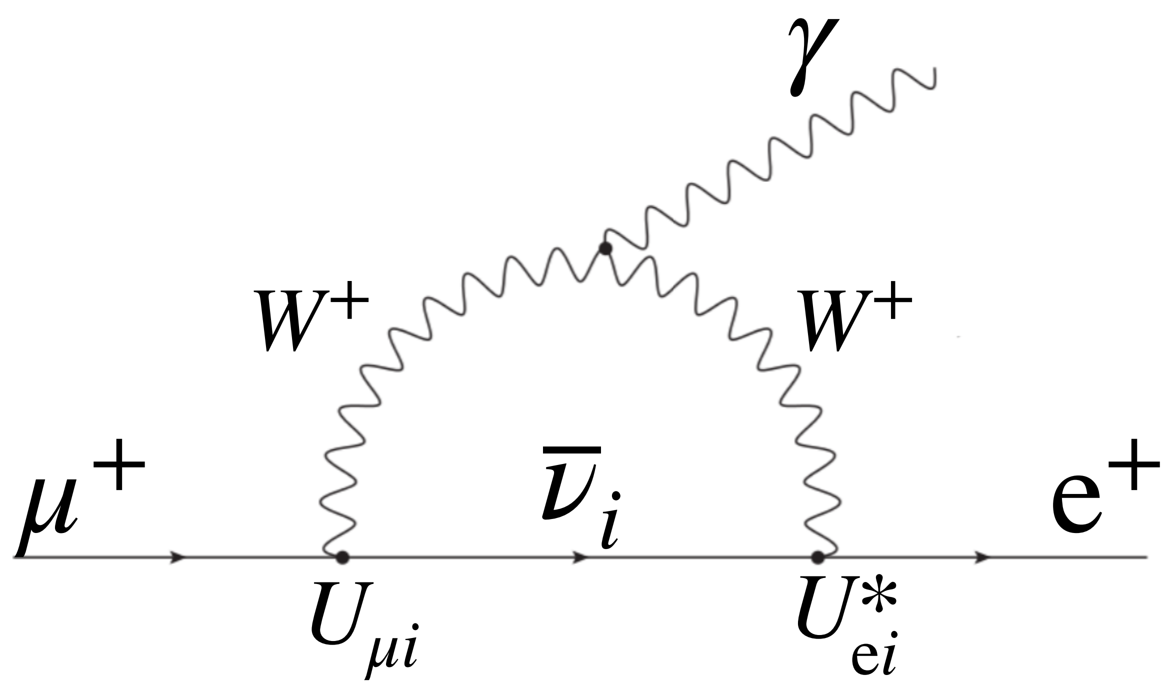

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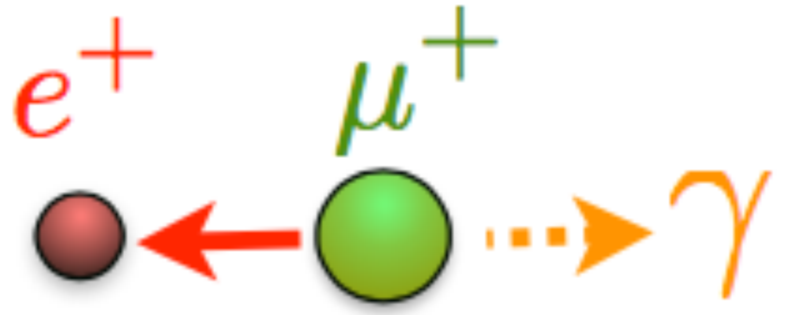
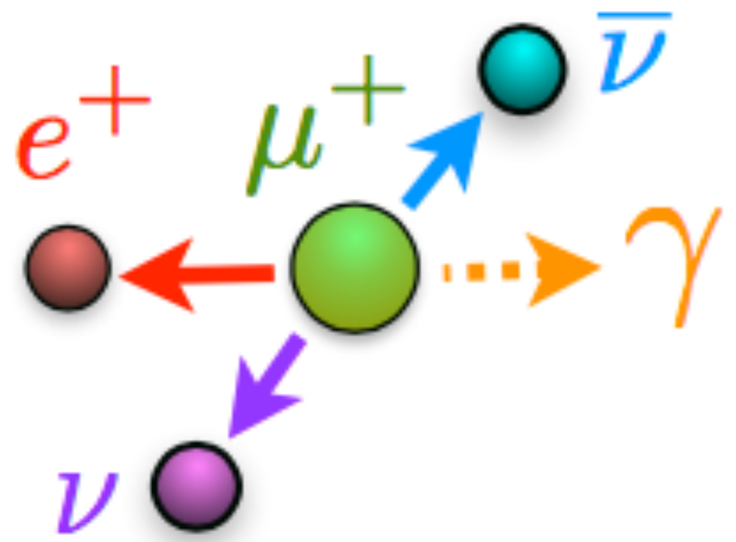
Signal

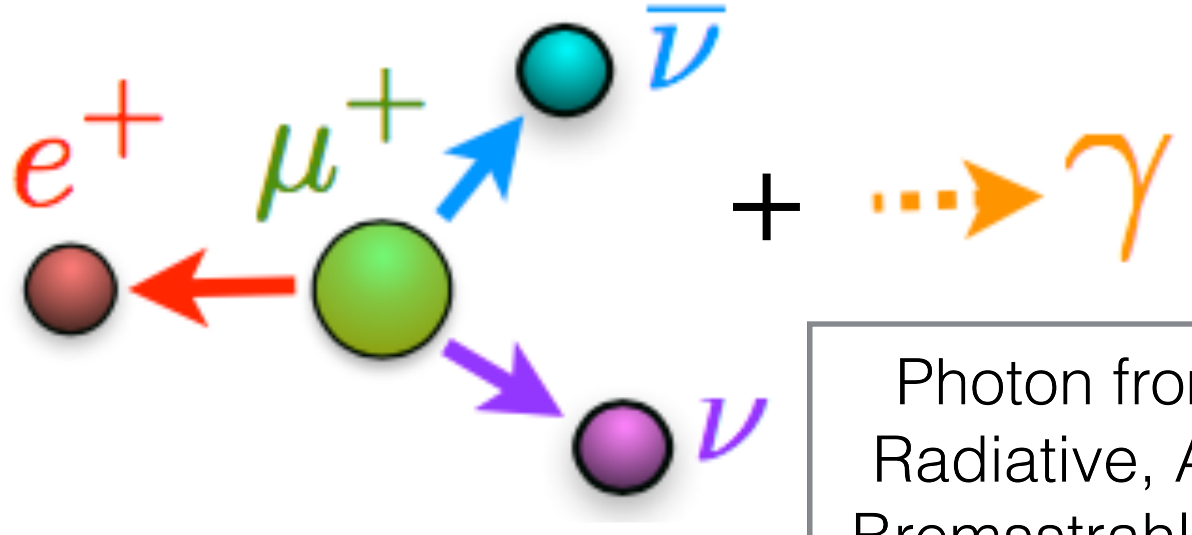


Physics Background:



$\propto R_\mu\ \mathrm{BR}(\mu \rightarrow e \nu \overline{\nu} \gamma)$

Accidental Background:



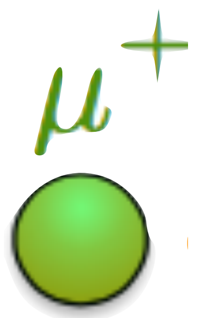
Photon from: Radiative, AIF, Bremsstrahlung

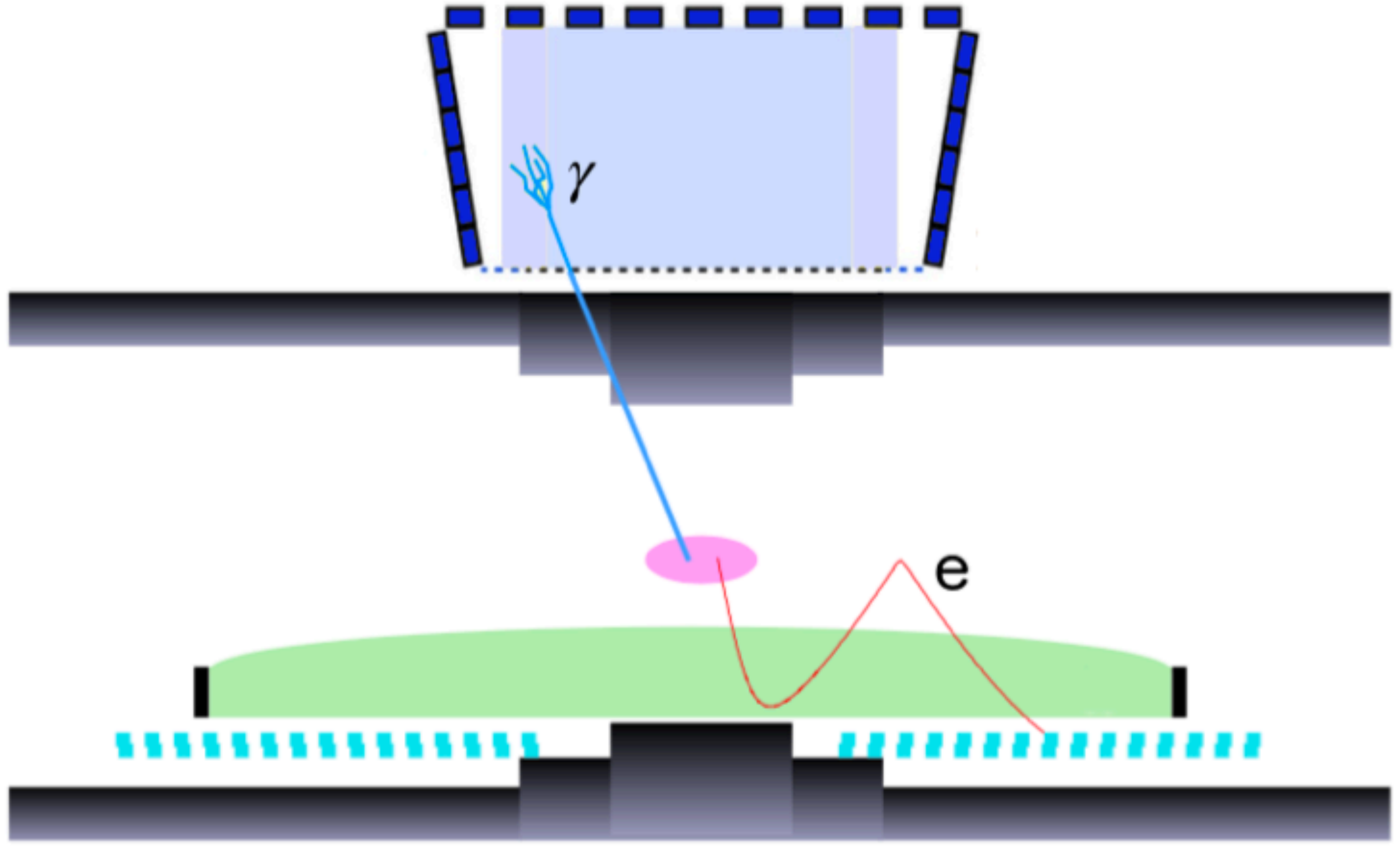
$\propto R_\mu^2\ \Delta T$

Design of MEG II Experiment

Experiment tailored to $\mu^+ \to e^+ \gamma$ search

- **Stop muon** at center of experiment
  → exploit the simple 2-body decay kinematics
  but harsh pileup environment from other muons





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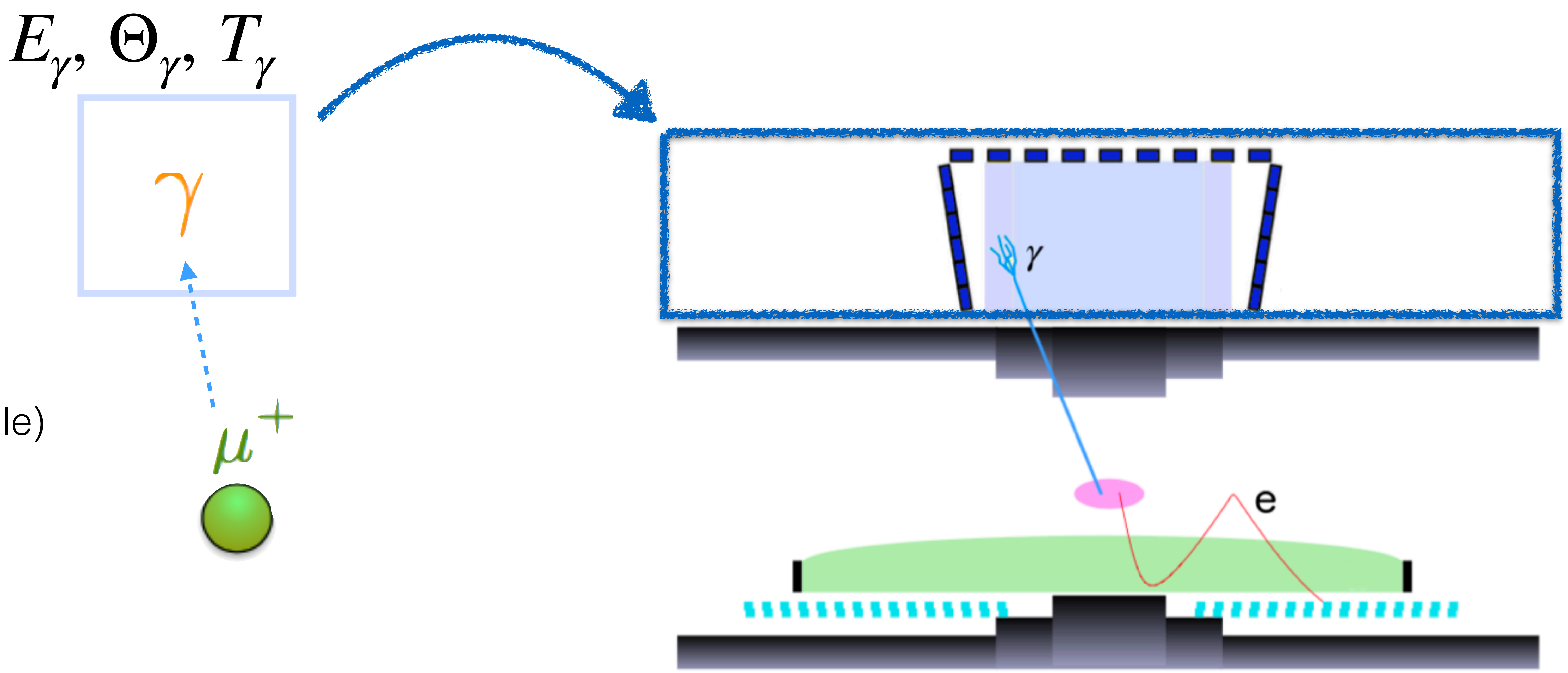

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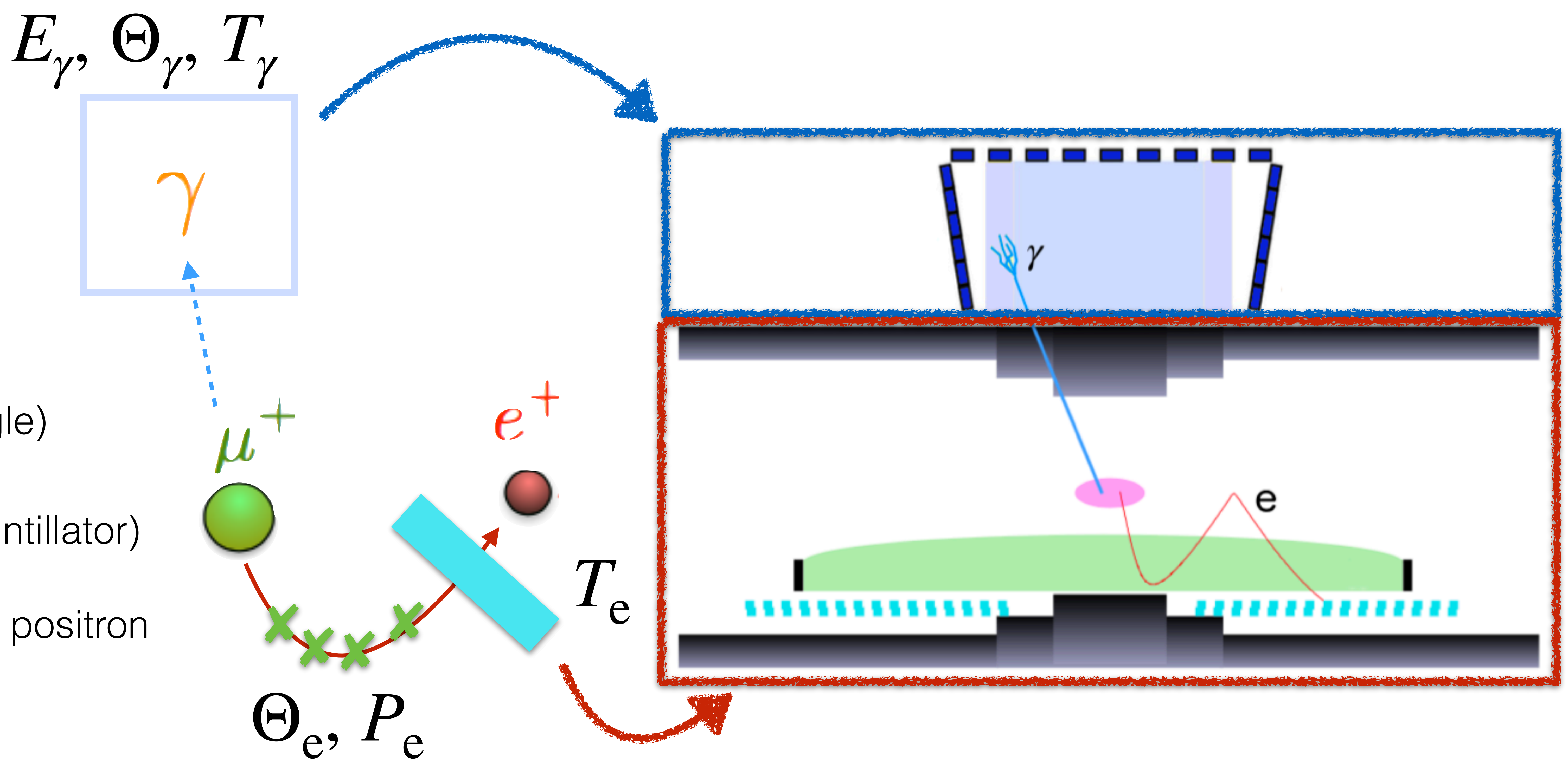

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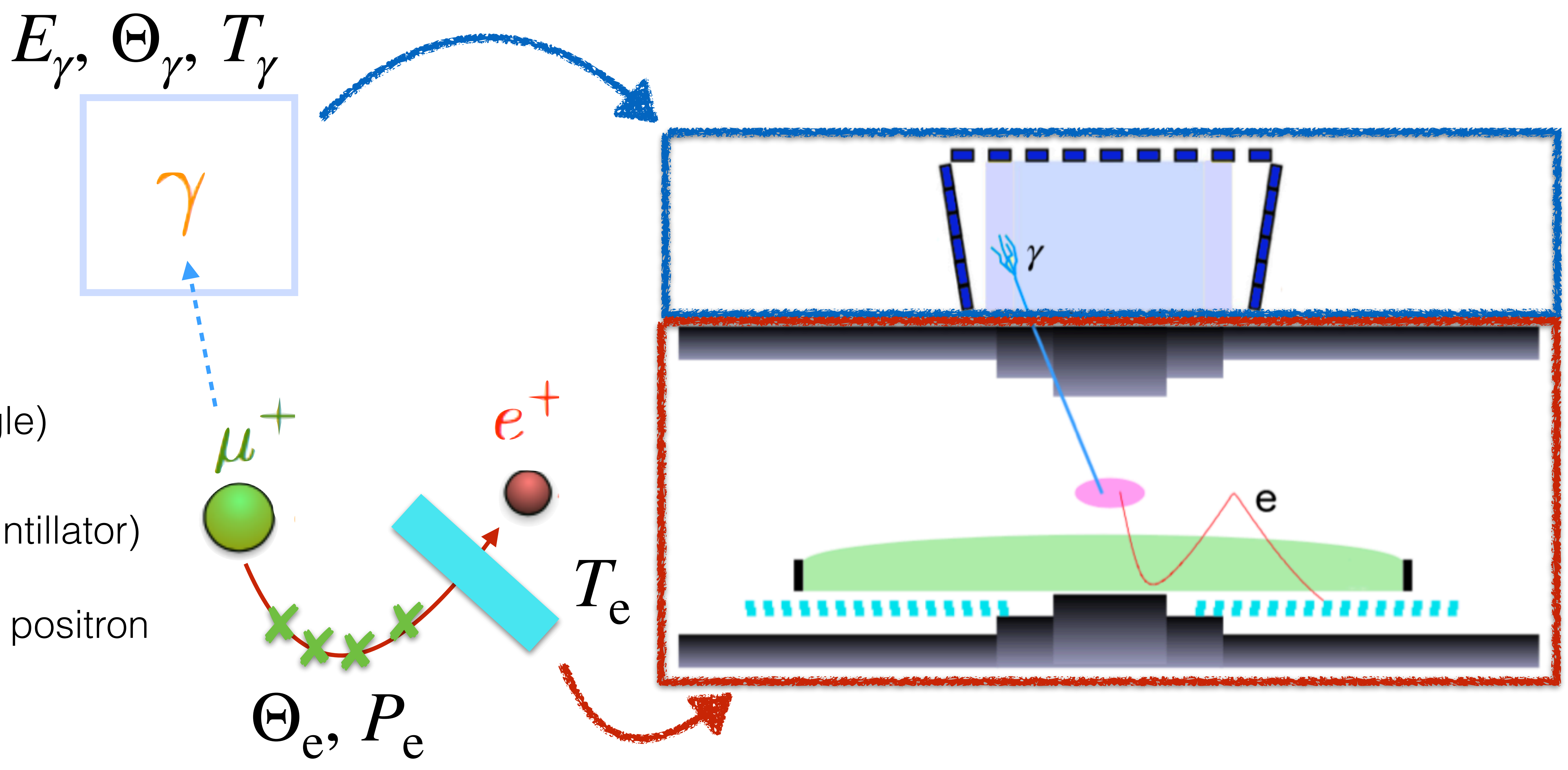


Detectors must provide high resolution **charge** and **time** reconstruction despite the extreme occupancy

All **signals sampled at >=1.4 GHz**
+
Full waveform stored for **offline processing**

- Noise rejection
- Pileup identification and subtraction
- Feature extraction
- Hit clustering
- …

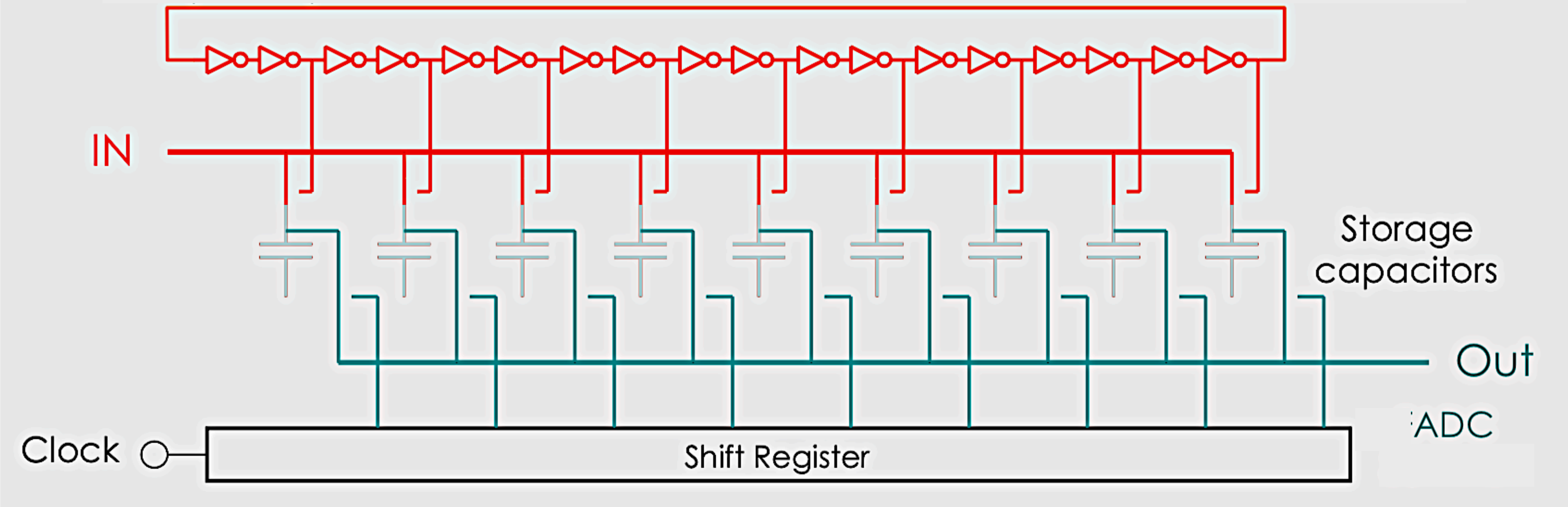
High speed digitization: the WaveDAQ system

Full MEG II experiment needs ~9000 channels: commercial FADCs too slow or too costly → **DRS4 ASIC Chip**

Analog switched capacitor array: analog memory with depth of 1024 sampling cells
Developed at PSI, provides a "**snapshot**" of signal before trigger time

Extensively used also in MEGI

800 MSPS ↔ 5 GSPS sampling speed



Strong constrain on trigger system:
decision must happen before 1024 samples are collected

$$T^{Max} = 1024/f_{sampl}$$

Trigger latency < 731ns @1.4 GHz

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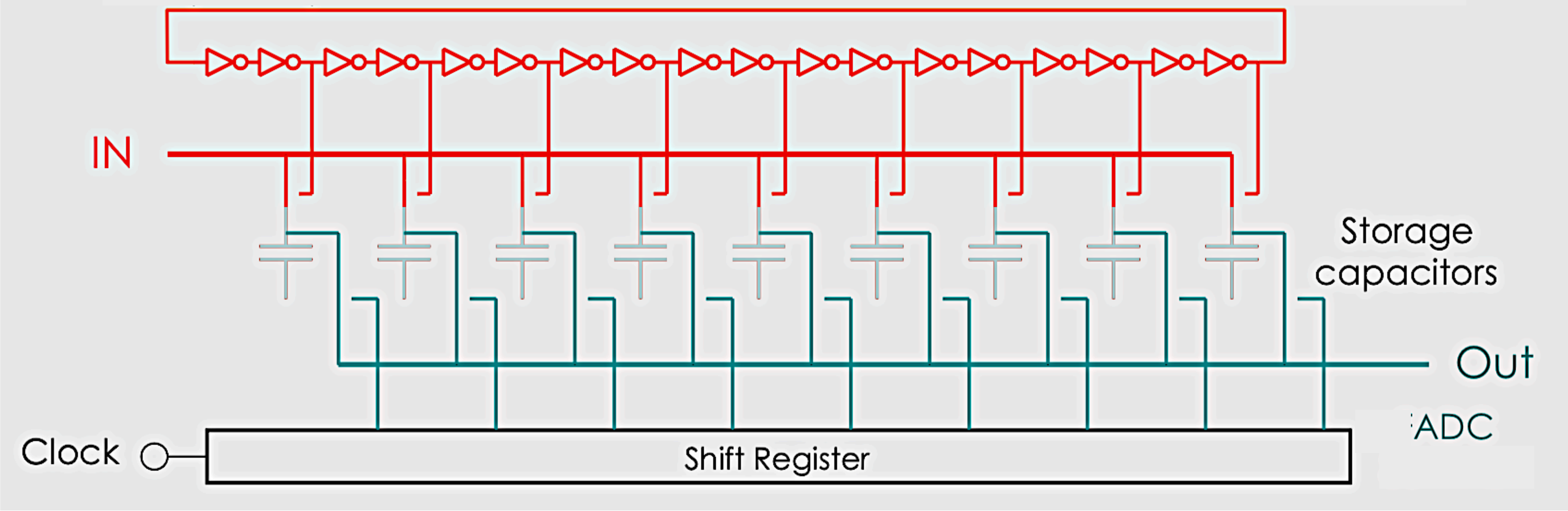
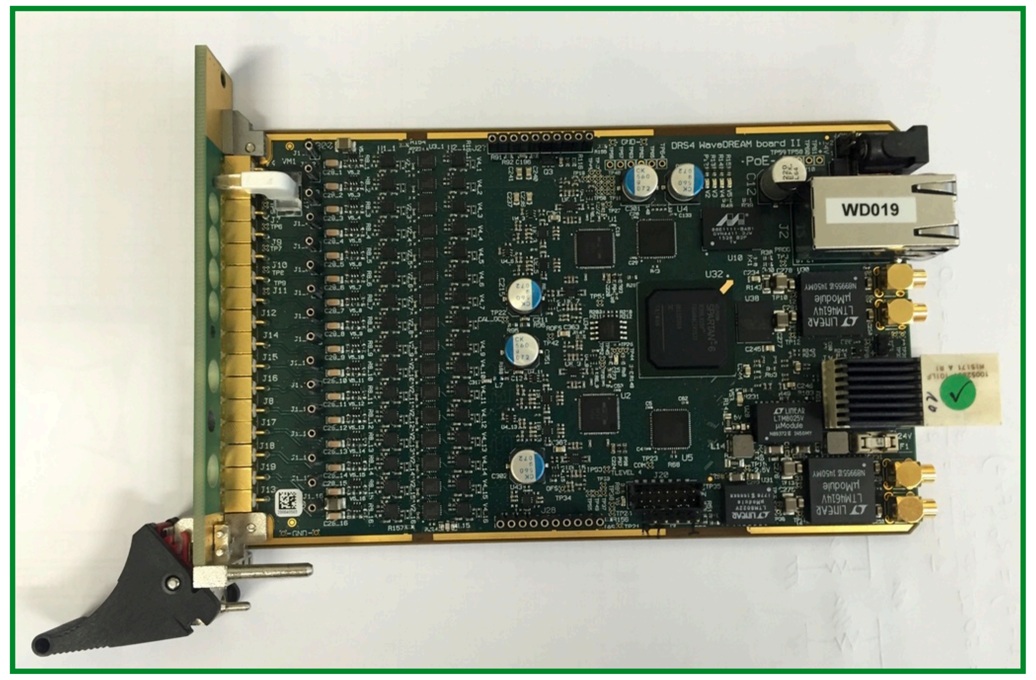


WaveDREAM board:
16 ch **D**rs4 **REA**dout **M**odule (10cm x 16 cm)
Waveform digitizer with two **DRS4** each with 80 MHz ADC for readout

Includes SiPM bias and amplification for Liquid Xenon detector and Timing Counter.



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More details: Poster #6
"Design of the WaveDAQ System"
by S. Ritt

How to reduce the event rate?

MEG event size is **3 MB** after **compression and data reduction**

At 20 Hz is ~500 TB every 3 month!

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Physics observables:

- Photon Energy E_γ
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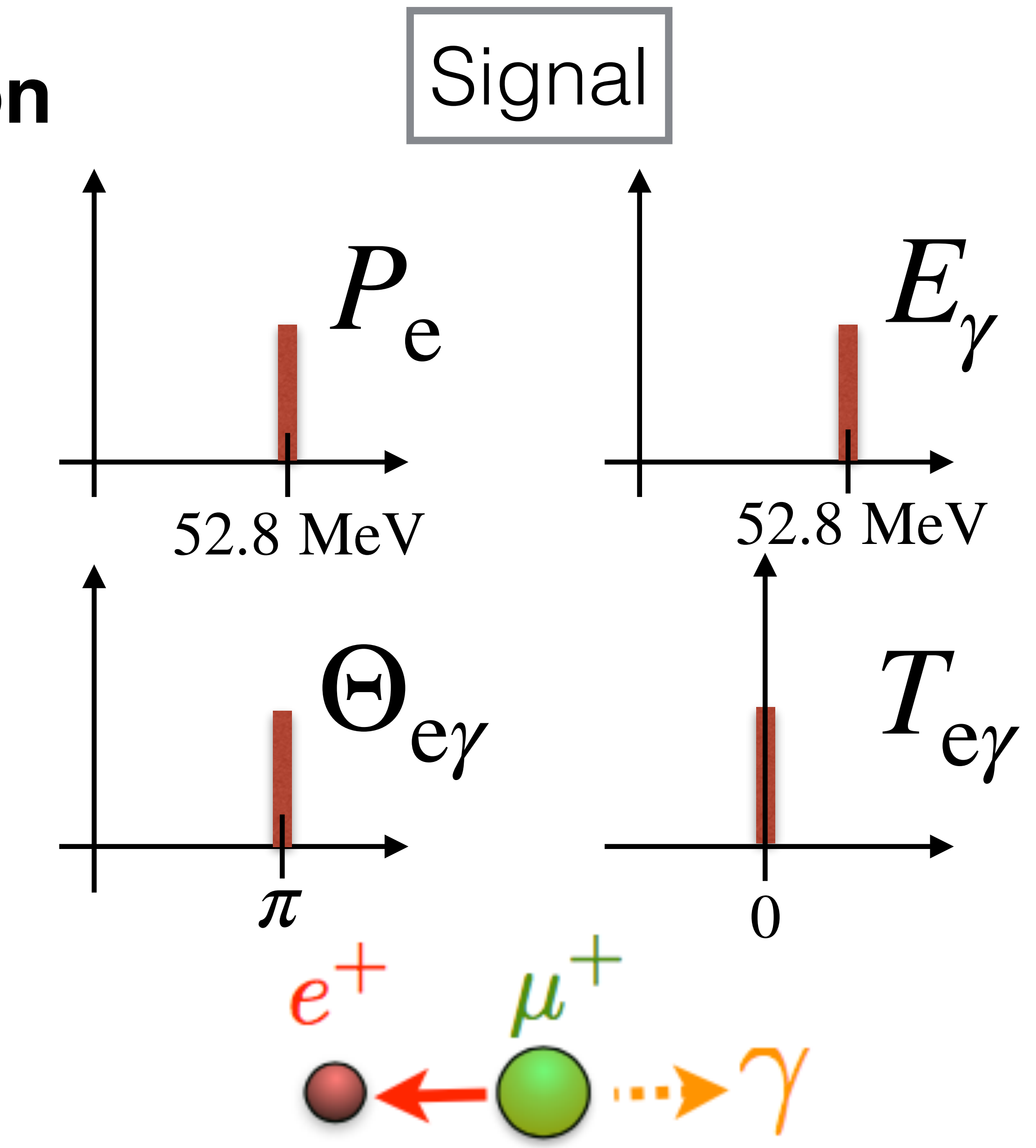
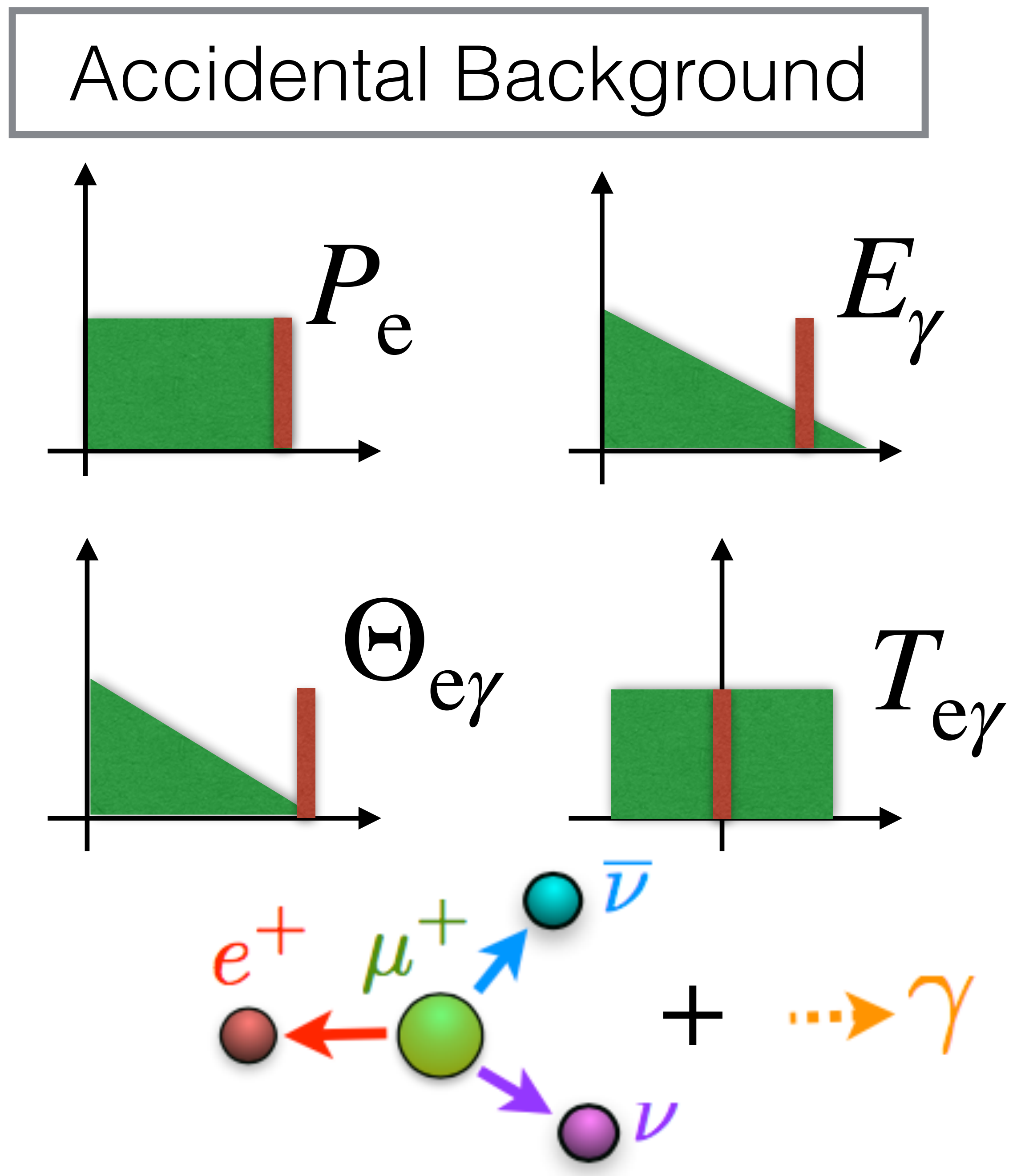
- Relative angle $\Theta_{e\gamma}$
- Time coincidence $T_{e\gamma}$

Require CDCH:
Cannot be fully exploited by trigger





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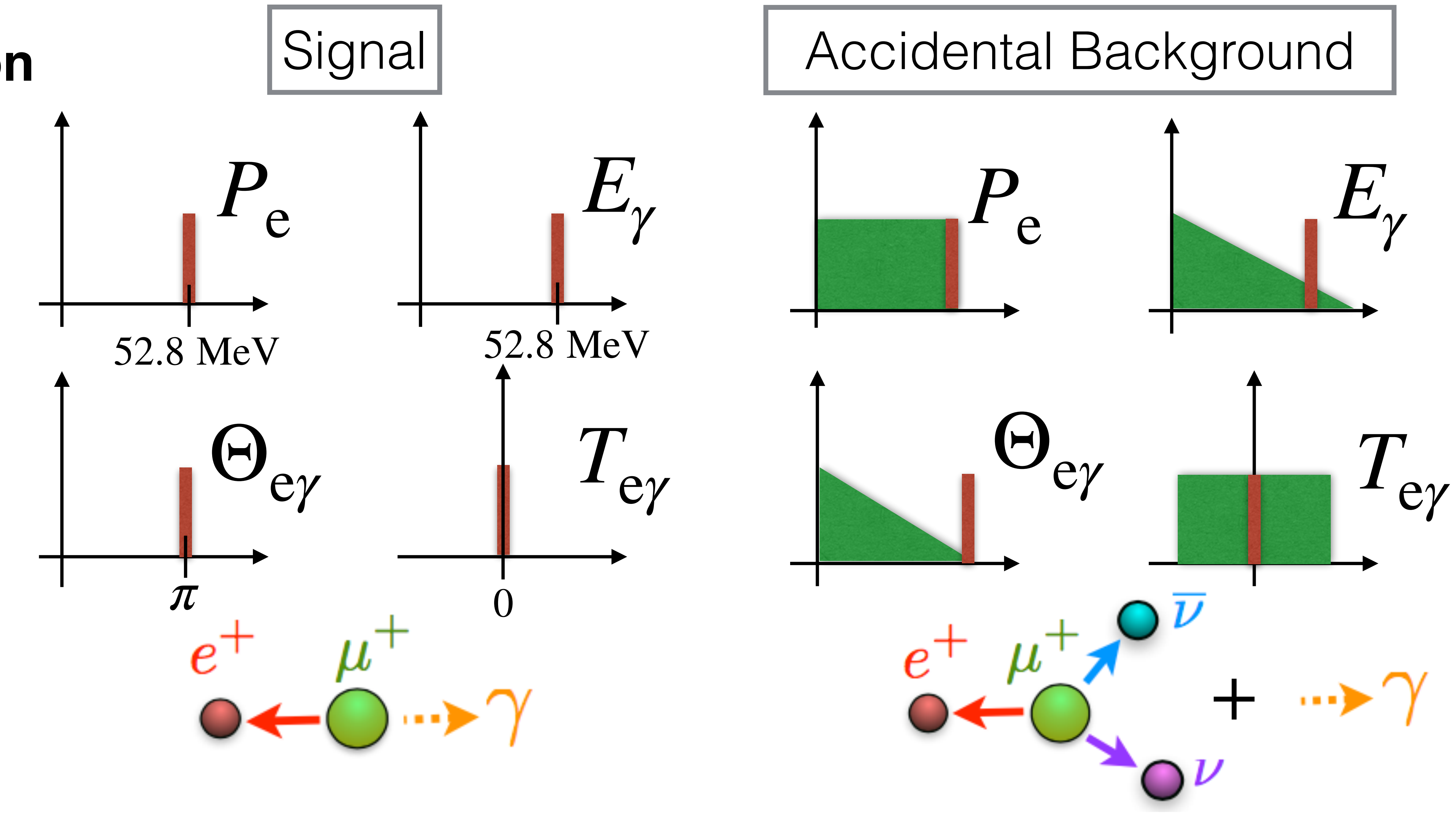
Trigger-level requests:

- Estimate E_γ through signals from Liquid Xenon photon detectors → **QSUM trigger**
- Estimate $T_{e\gamma}$ by comparing hit time in Timing Counter and in Liquid Xenon → **Time trigger**
- Combines $\Theta_{e\gamma}$ and P_e by checking if the pair of hits is compatible with signal topology → **DirectionMatch trigger**



Starting from ~100 kHz γ rate in Liquid Xenon

Reduction factor: ~100 → 1 kHz rate

Reduction factor: ~10 → 100 Hz rate

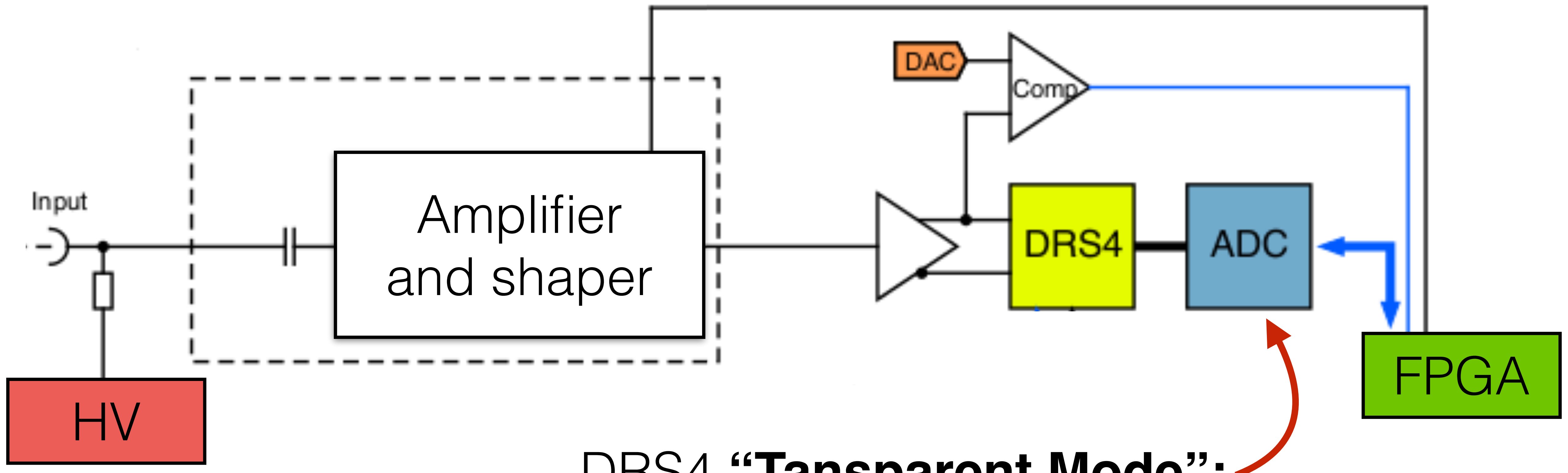
Reduction factor: ~10 → 10 Hz rate

WaveDAQ trigger inputs

Each WaveDREAM board contains a dedicated **ADC** and **Discriminator** for all input signals

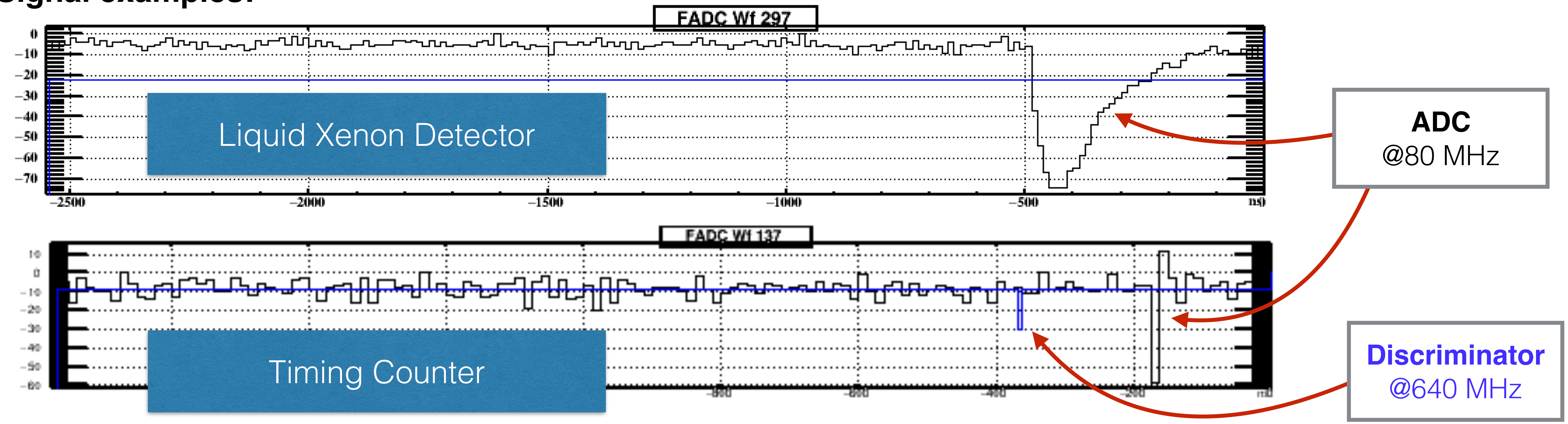
If possible prefer the discriminator:
ADC conversion takes ~100 ns

Flexibility to implement **charge** or **time** based selection within the onboard FPGA or on the global experiment



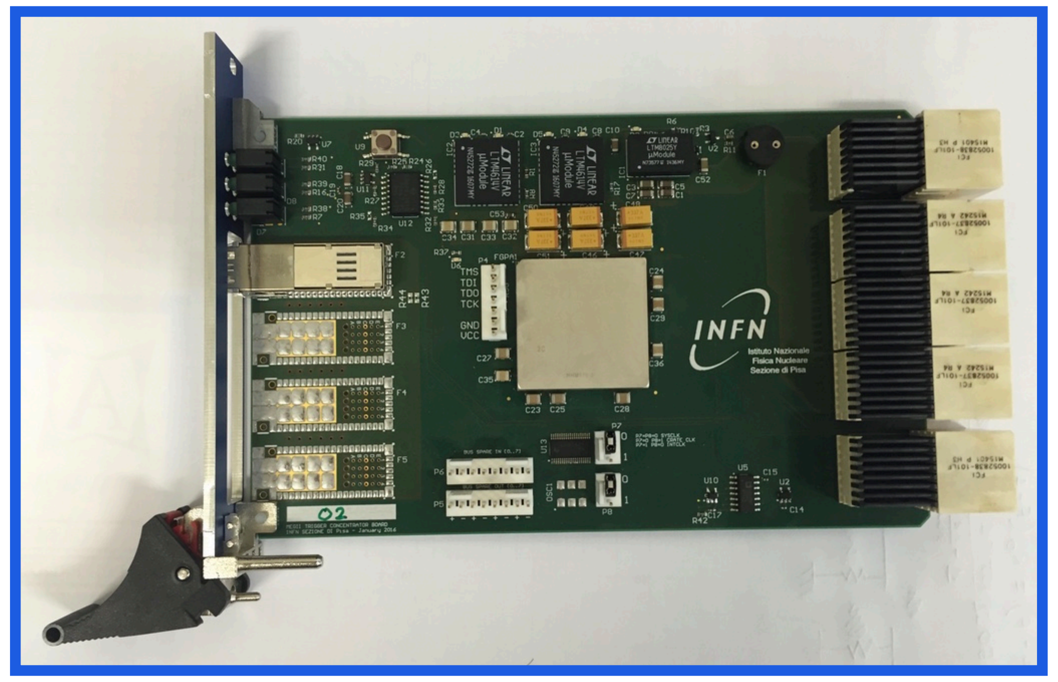
DRS4 **“Tansparent Mode”:**
same ADC for Trigger and readout

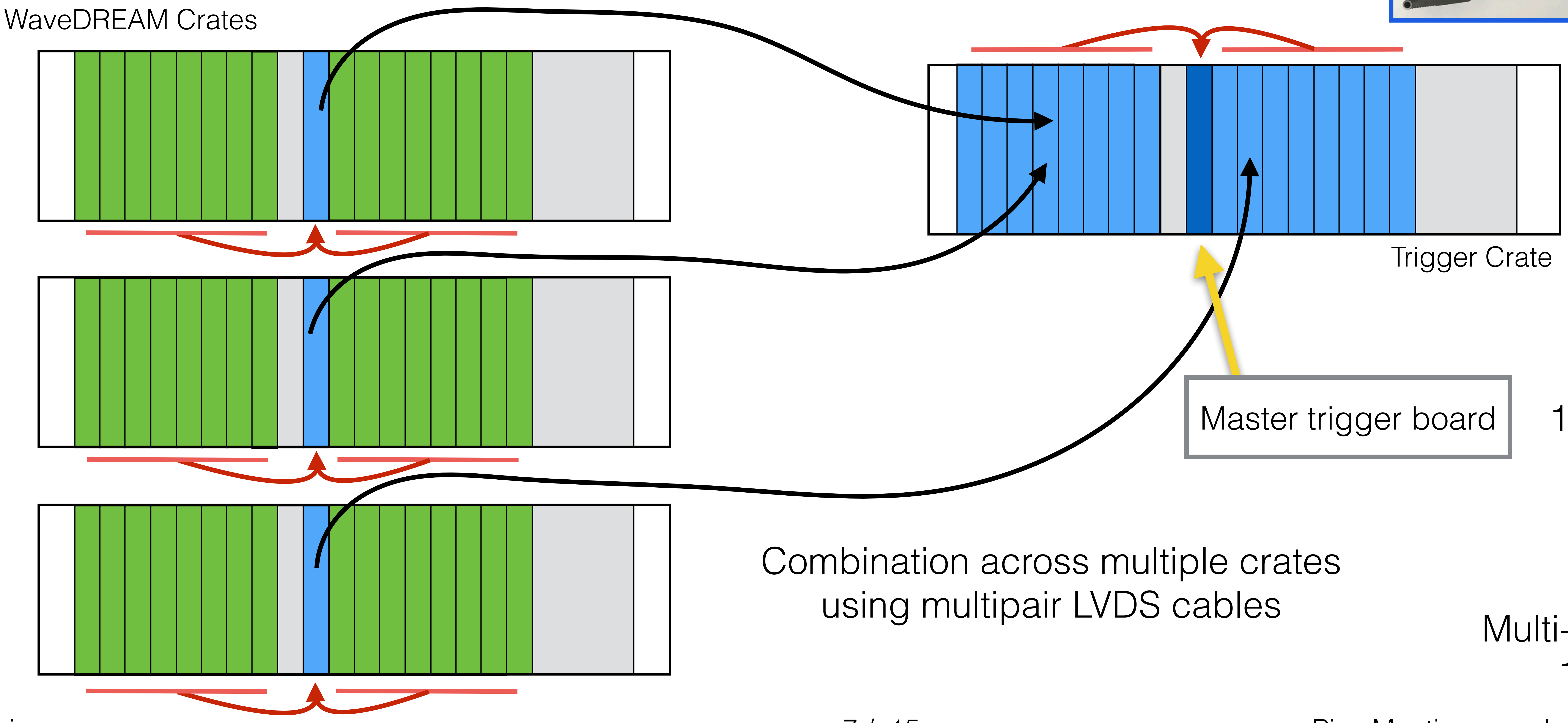
Signal examples:



WaveDAQ trigger subsystem

Trigger information merging by a 3-layer three made of 45 Kintex 7 **T**rigger **C**oncentrator FPGA **B**oard **TCB** using low latency **serial links**





1 custom crate
=
16 WaveDREAMs
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256 channels
↓
Multi-crate systems up to 16384 channels

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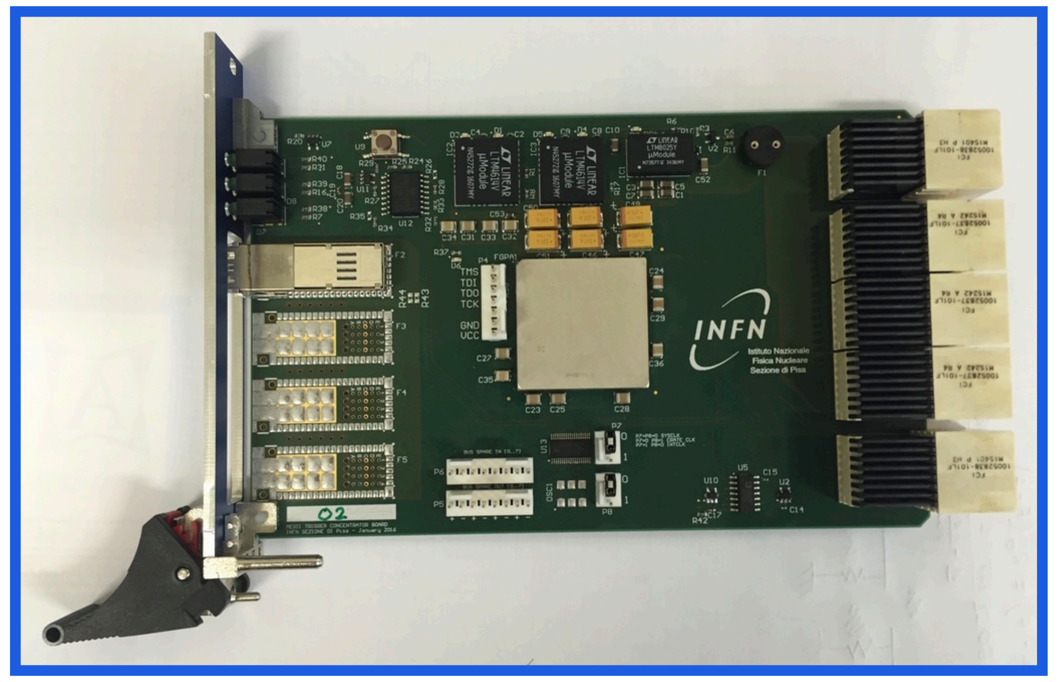
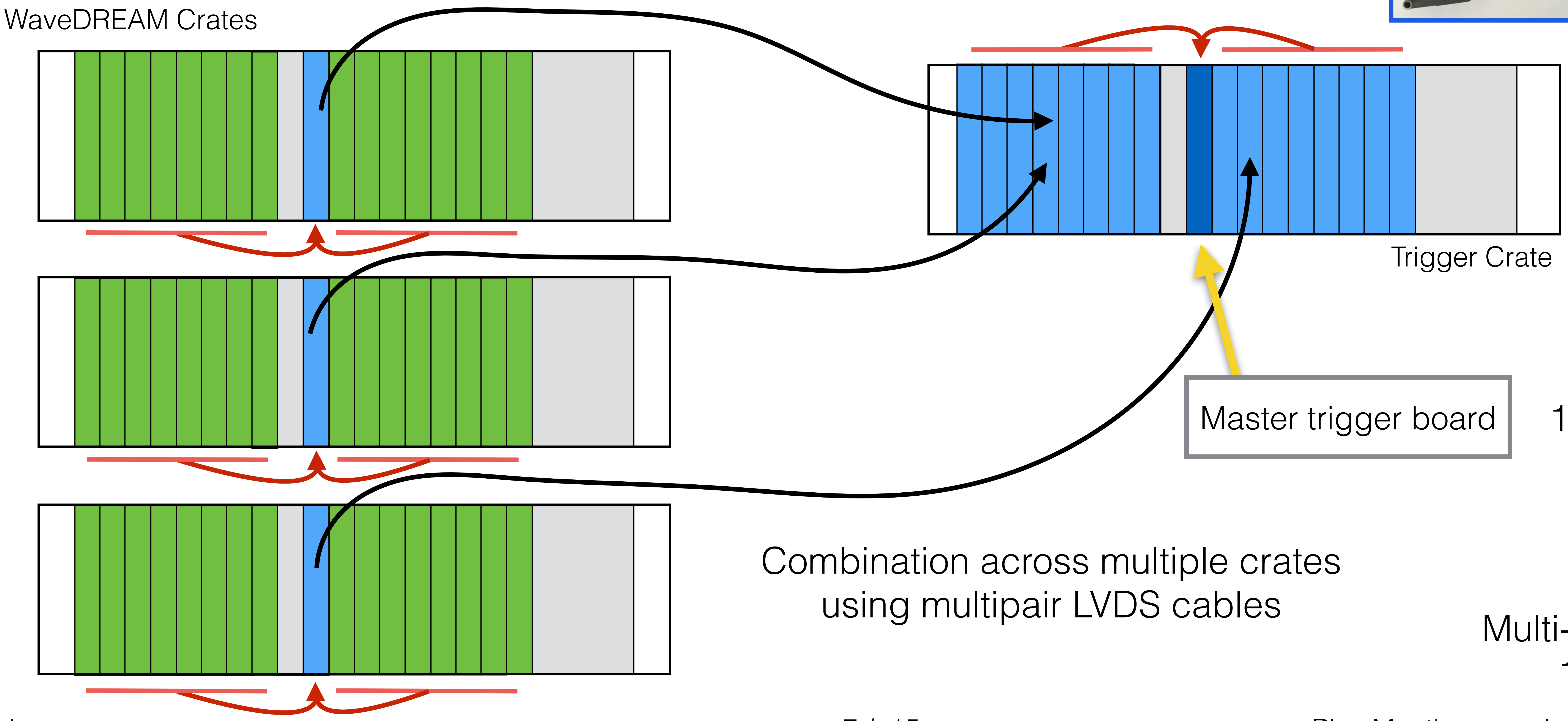


Every clock cycle is important: use shift registers instead of Multi-Gigabit Transceiver trade bandwidth (640 Mbit/s * 8 lines) for latency (~40 ns)



Combination across multiple crates using multipair LVDS cables

1 custom crate
=
16 WaveDREAMs
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Multi-crate systems up to 16384 channels

QSUM trigger: design

QSUM trigger computes the **weighted sum** of pedestal-subtracted signal amplitude

$$E_\gamma \approx \sum_{i \in LXe} g_i \left(V_i - V_i^{\text{pedestal}}\right)$$

This selection have to account for **ADC conversion time**
→ slowest path of trigger selection
→ use amplitude: cannot afford to integrate signal charge

Pedestal estimated "on the fly" from previous samples
to subtract low frequency noise

Channel-by-channel weight g_i to account for:

- Gain
- Detection efficiency
- Detector type (SiPM-PMT)
- Ageing speed
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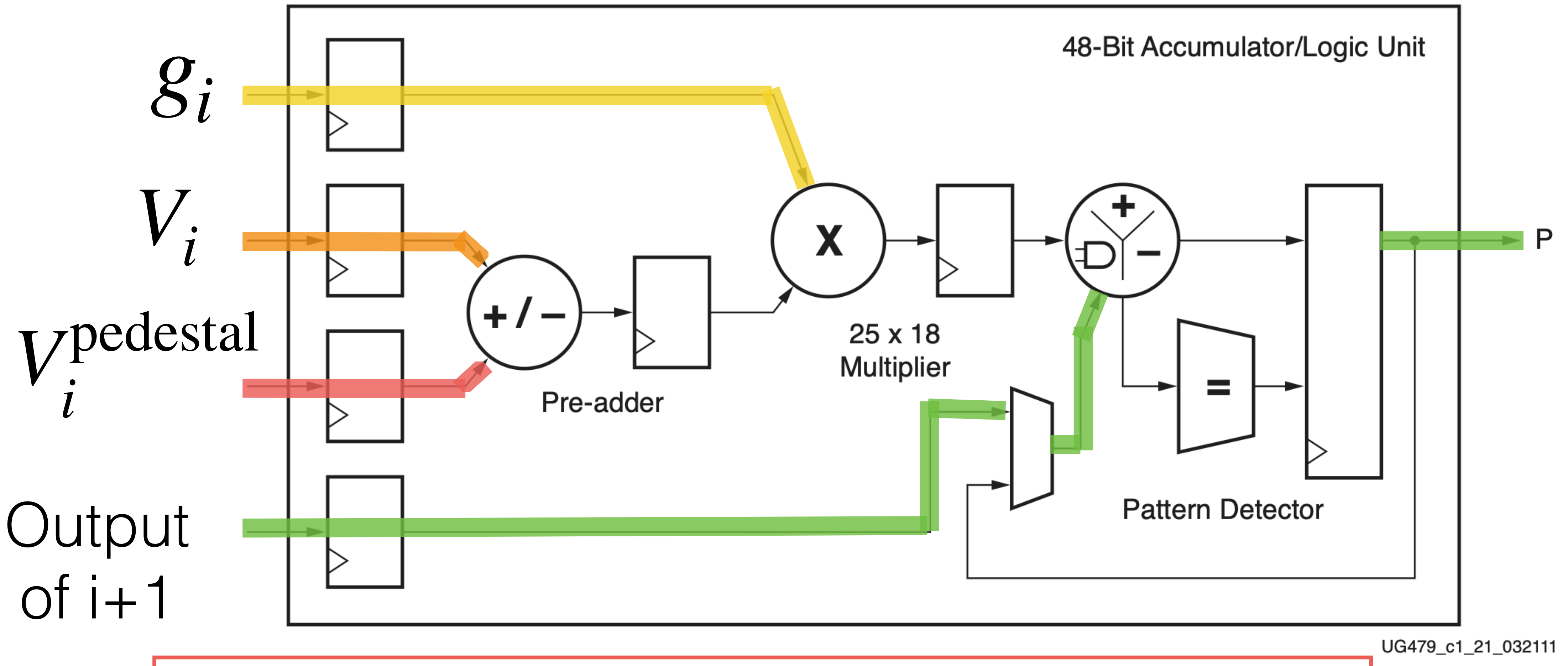
Use of **DSP48 primitives** of Xilinx FPGAs to compute difference, product and for the summation speedup



Lesson learn: Exploit your FPGA resources

QSUM trigger: performance

Two main **calibration sources** for Liquid Xenon detector

C-W proton accelerator

1 MeV proton on $\mathrm{Li\,BO_4}$ target

Energy calibration lines :

$$\mathrm{p}\ {}^{6}\mathrm{Li} \rightarrow {}^{7}\mathrm{Be}\ \gamma(17.6\ \mathrm{MeV})$$
$$\rightarrow {}^{7}\mathrm{Be}\ \gamma(14.6\ \mathrm{MeV})$$

Thee times a week

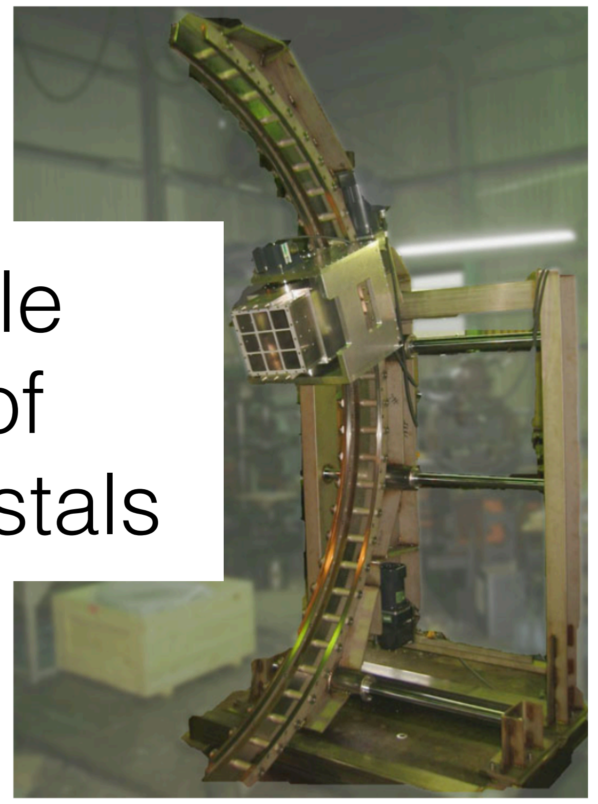
Charge Exchange reaction

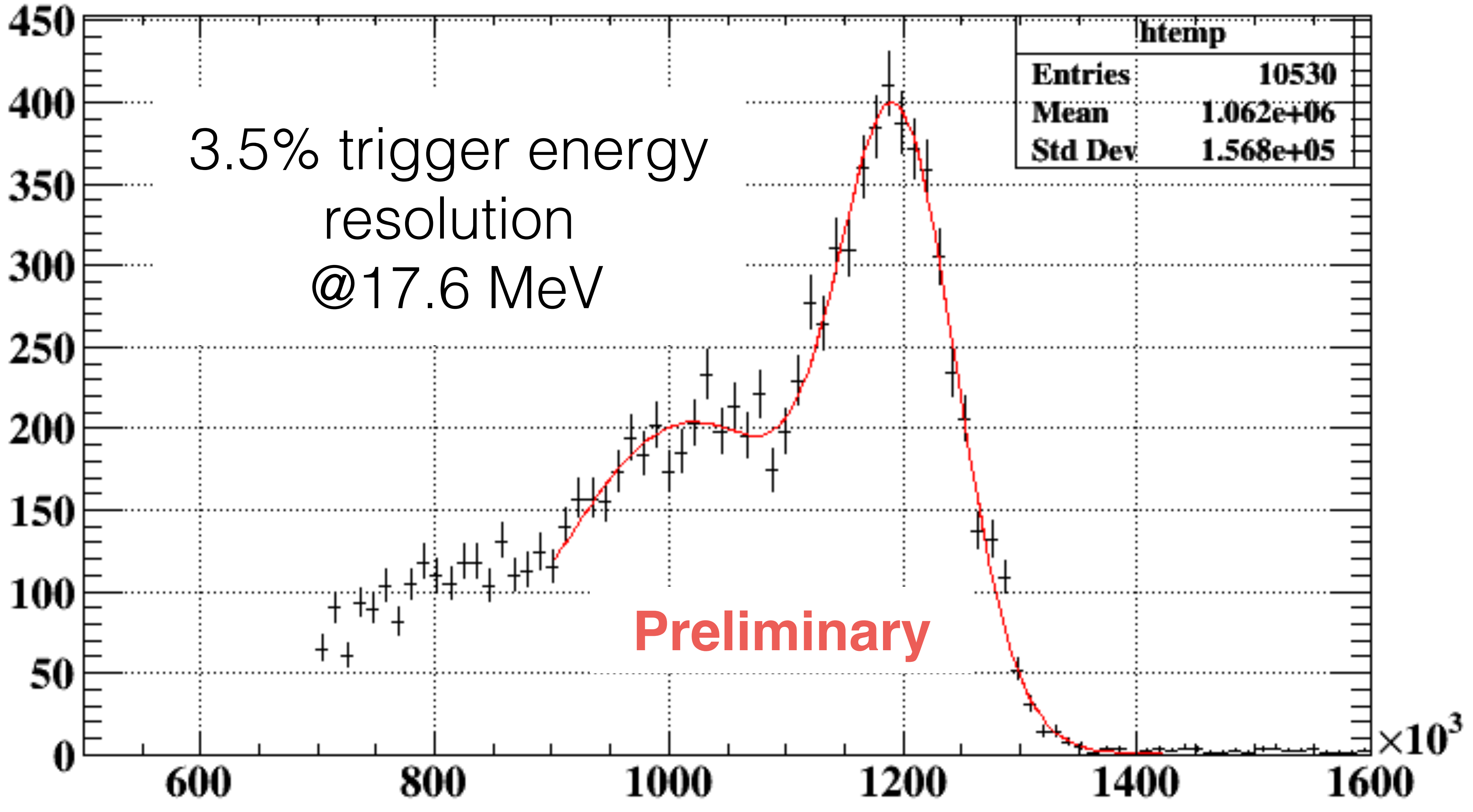
Change from μ^+ to π^-beam on liquid hydrogen target

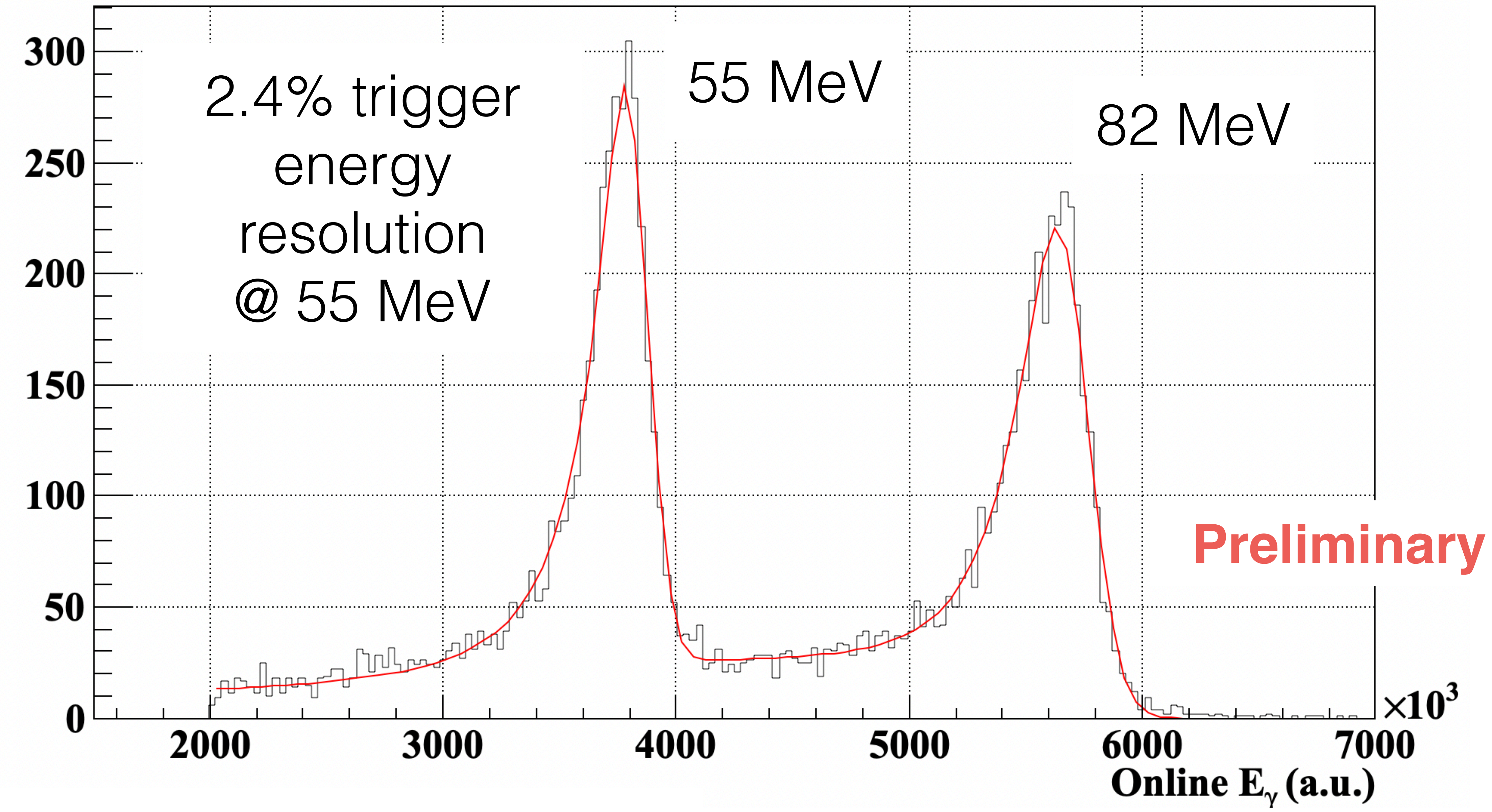
$$\pi^-\ \mathrm{p} \rightarrow \pi^0\ \mathrm{n}$$
$$\hookrightarrow \gamma\ \gamma$$

Once in the year

Movable array of BGO Crystals



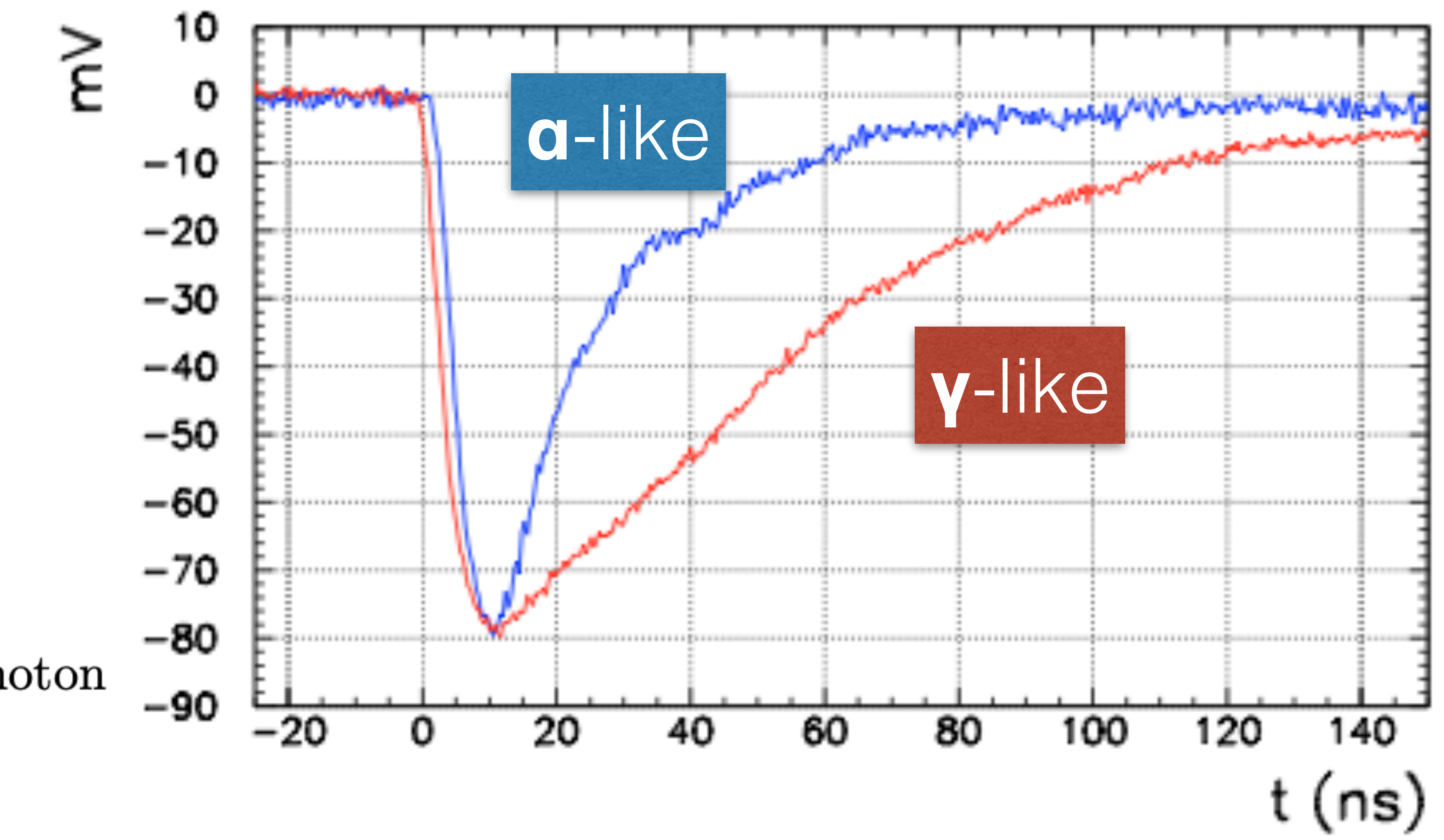




Current offline energy reconstruction: 1.8% @signal energy

QSUM trigger addendum: Q/A selection

Well-known property of Noble Gas scintillators:
Emission time of photons depends on **energy deposit mechanism**



α-like **Fast**

$\mathrm{Xe} + \mathrm{energy} \rightarrow \mathrm{Xe}^*$

$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^* \rightarrow 2\ \mathrm{Xe} + \mathrm{photon}$

γ-like **Slow**

$\mathrm{Xe} + \mathrm{energy} \rightarrow \mathrm{Xe}^+ + \mathrm{e}^-$

$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+$

$\mathrm{Xe}_2^+ + \mathrm{e}^- \rightarrow \mathrm{Xe}_2^{**} \rightarrow \mathrm{Xe}_2^* + \mathrm{heat}$

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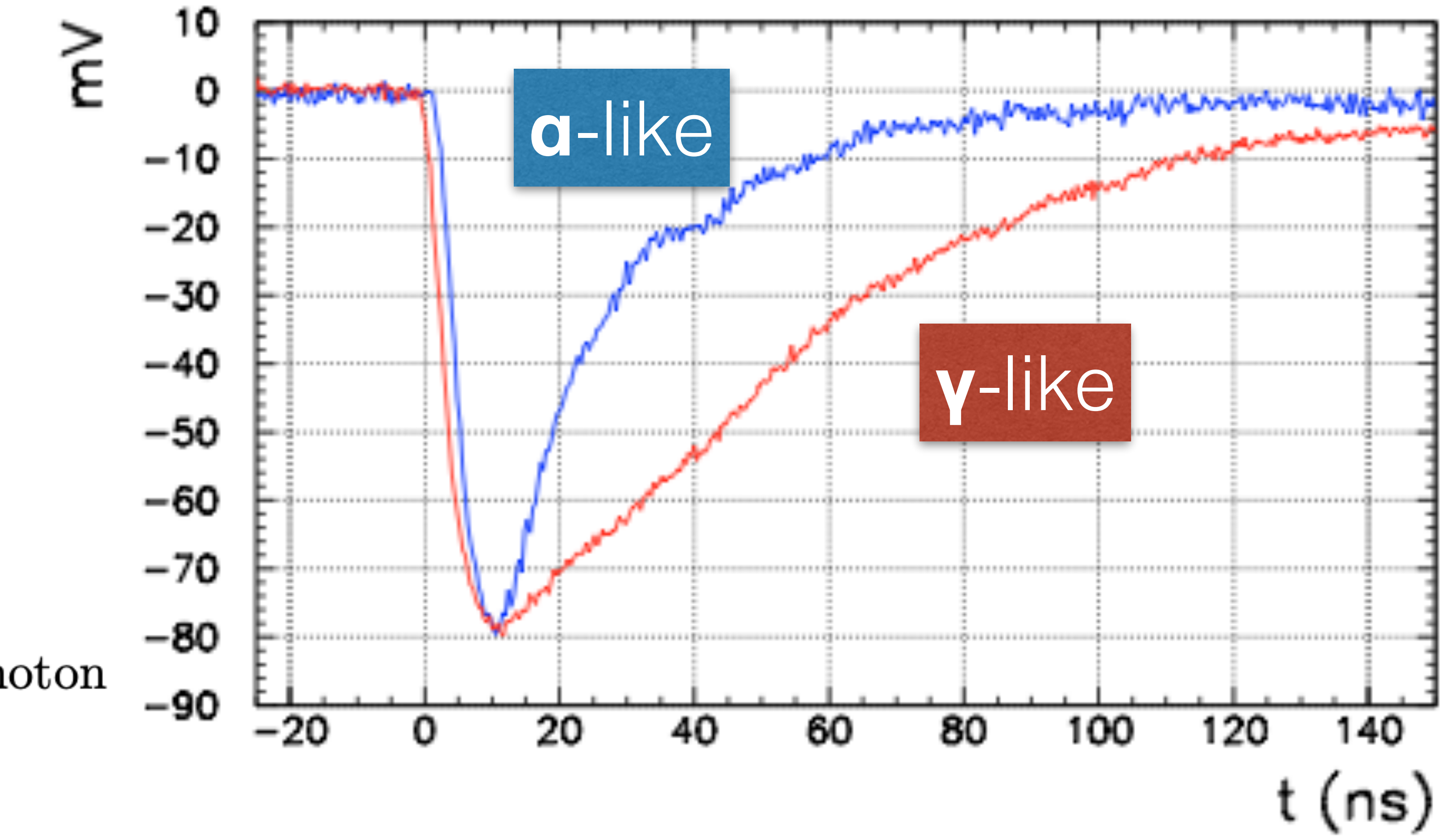
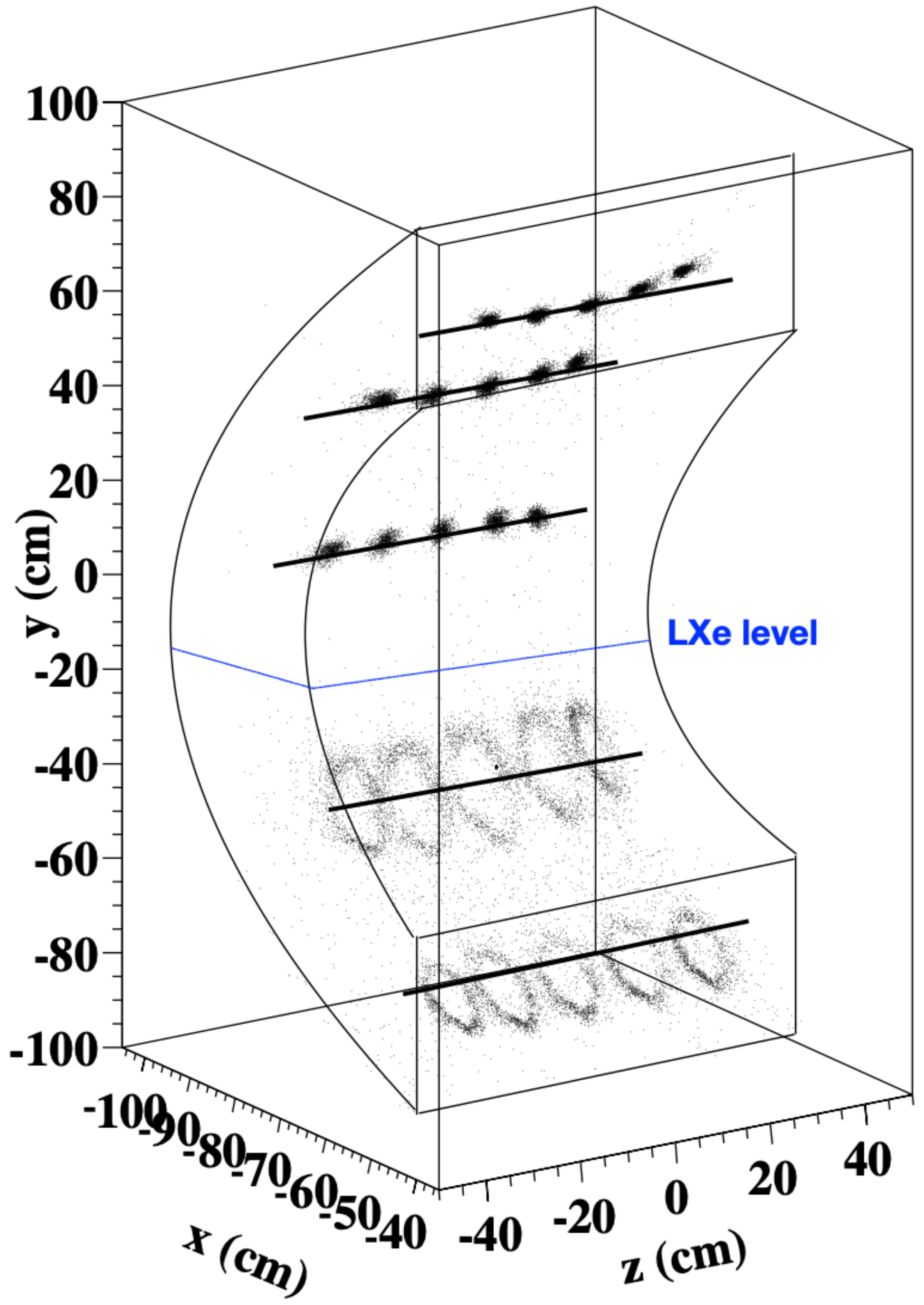
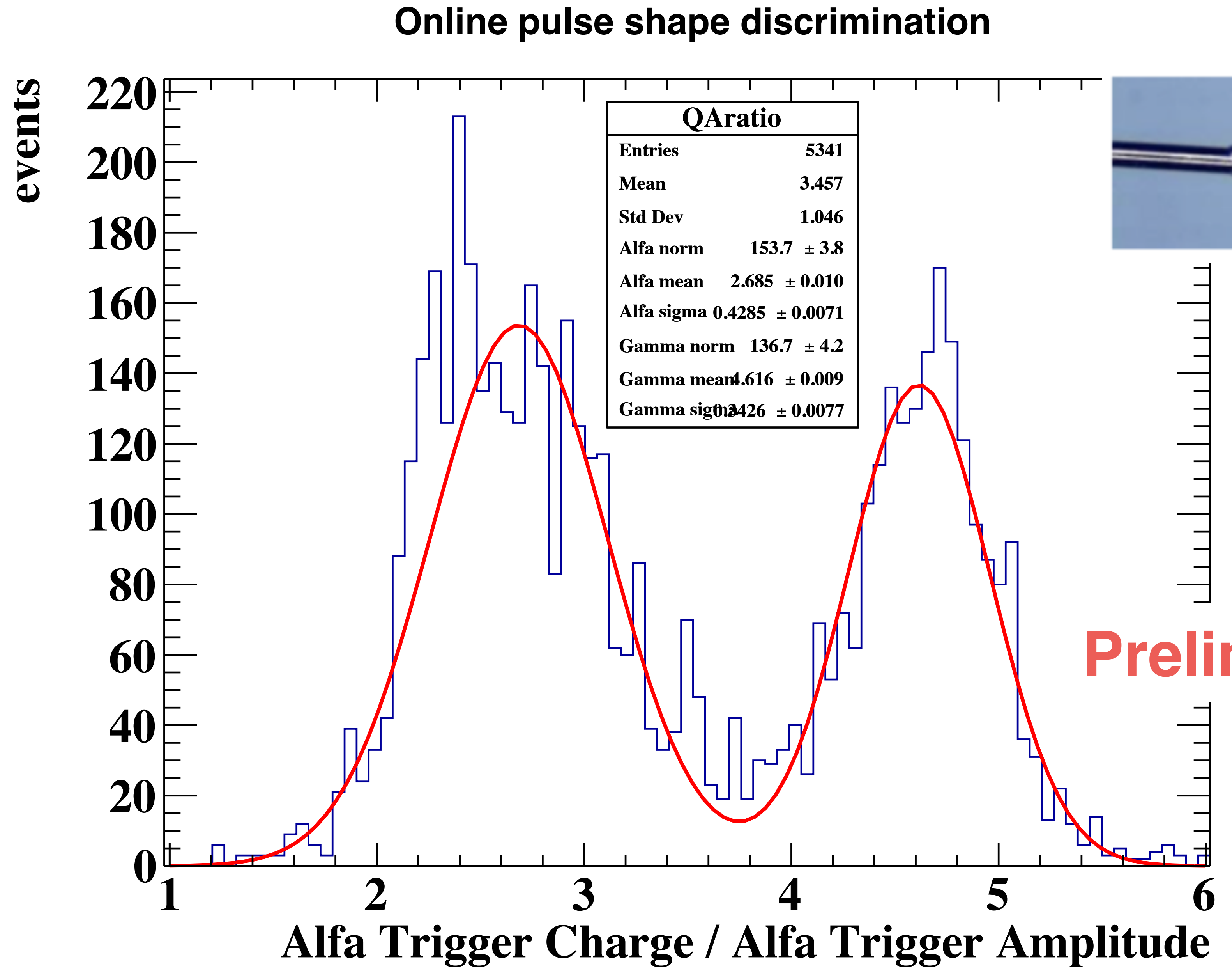






25 point-like alfa sources on wires in LXe

Localized energy deposit (40μm range)
for **detection efficiency** monitoring & calibration

Charge/Height ratio provides discrimination
capability **online** using DSP48 resources in TCBs

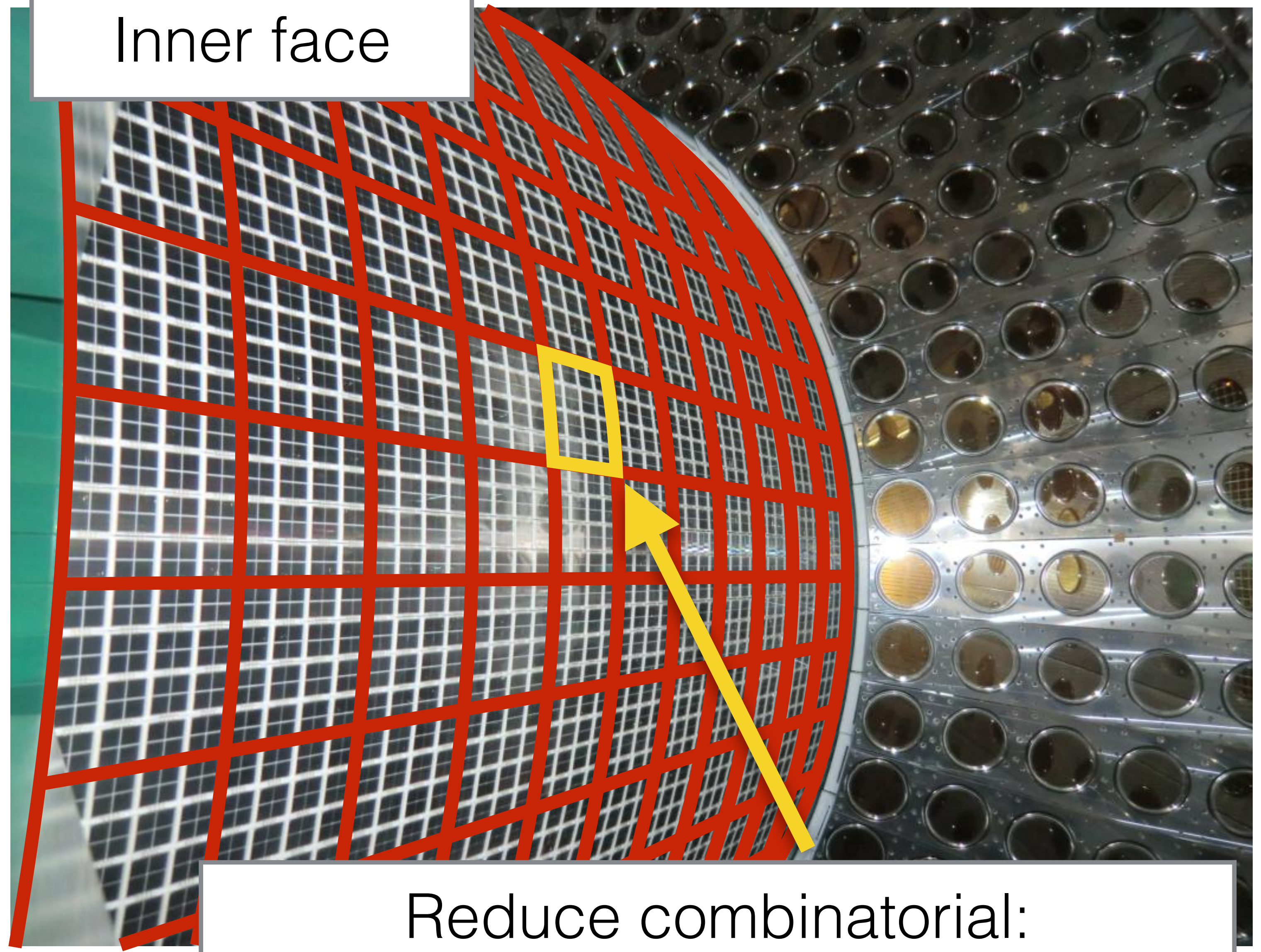
Good enough for triggering:
further selection offline with template fitting

DirectionMatch trigger: design

Online track fitting is not feasible: rely only on Liquid Xenon - Timing Counter **channel correlation**

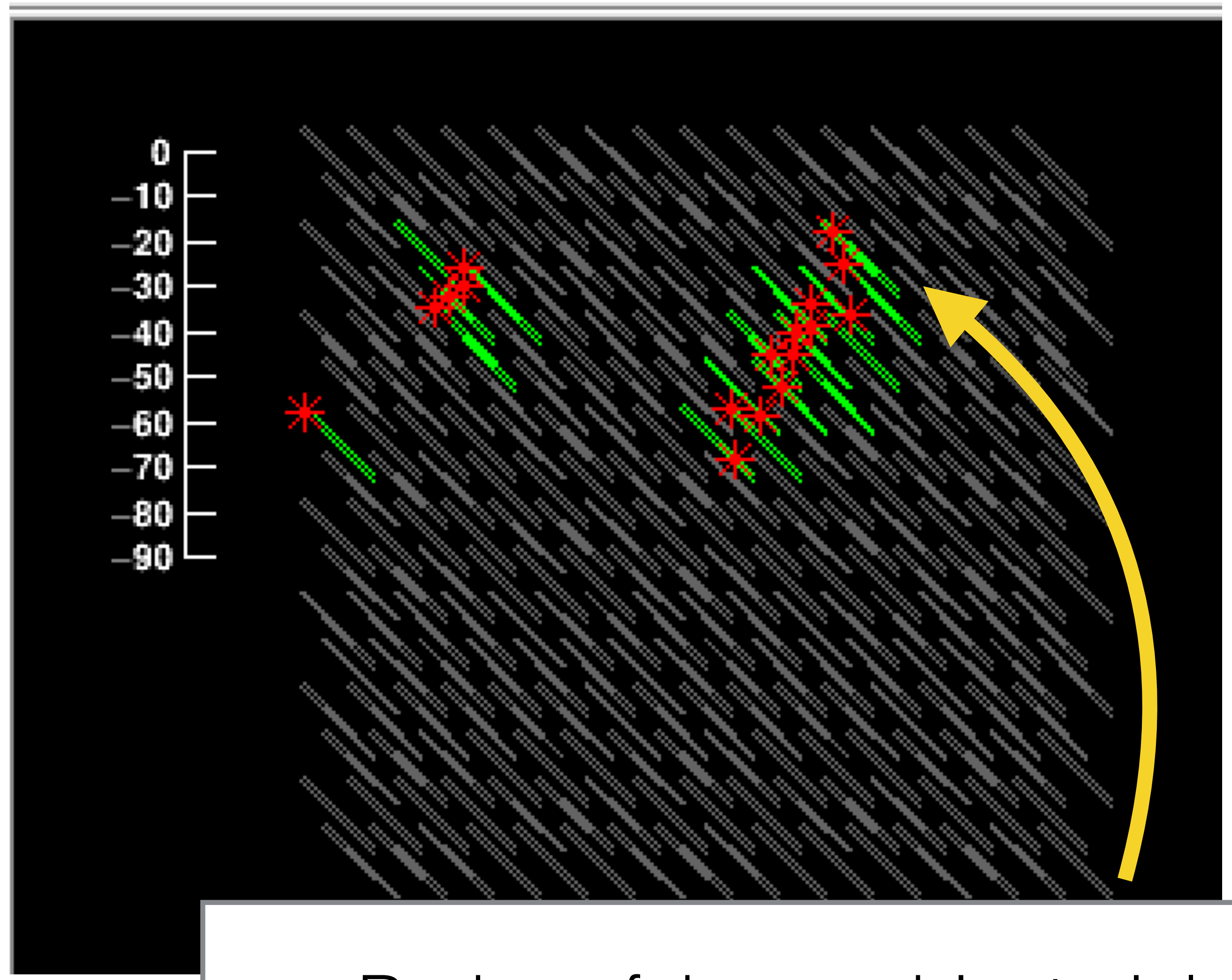
1 Search Max on the inner face of Liquid Xenon detector

Inner face



Reduce combinatorial: group channels in 4x4 SiPM **"Patches"** (6x6 cm)

2 Search Hit position in Timing counter



Reduce fake combinatorial: Select only first **"Tile"** hit

Single sensor in Liquid Xenon detector is sensitive to shower fluctuations ($R^{\mathrm{LXe}}_{Molière} = 5.2$ cm)

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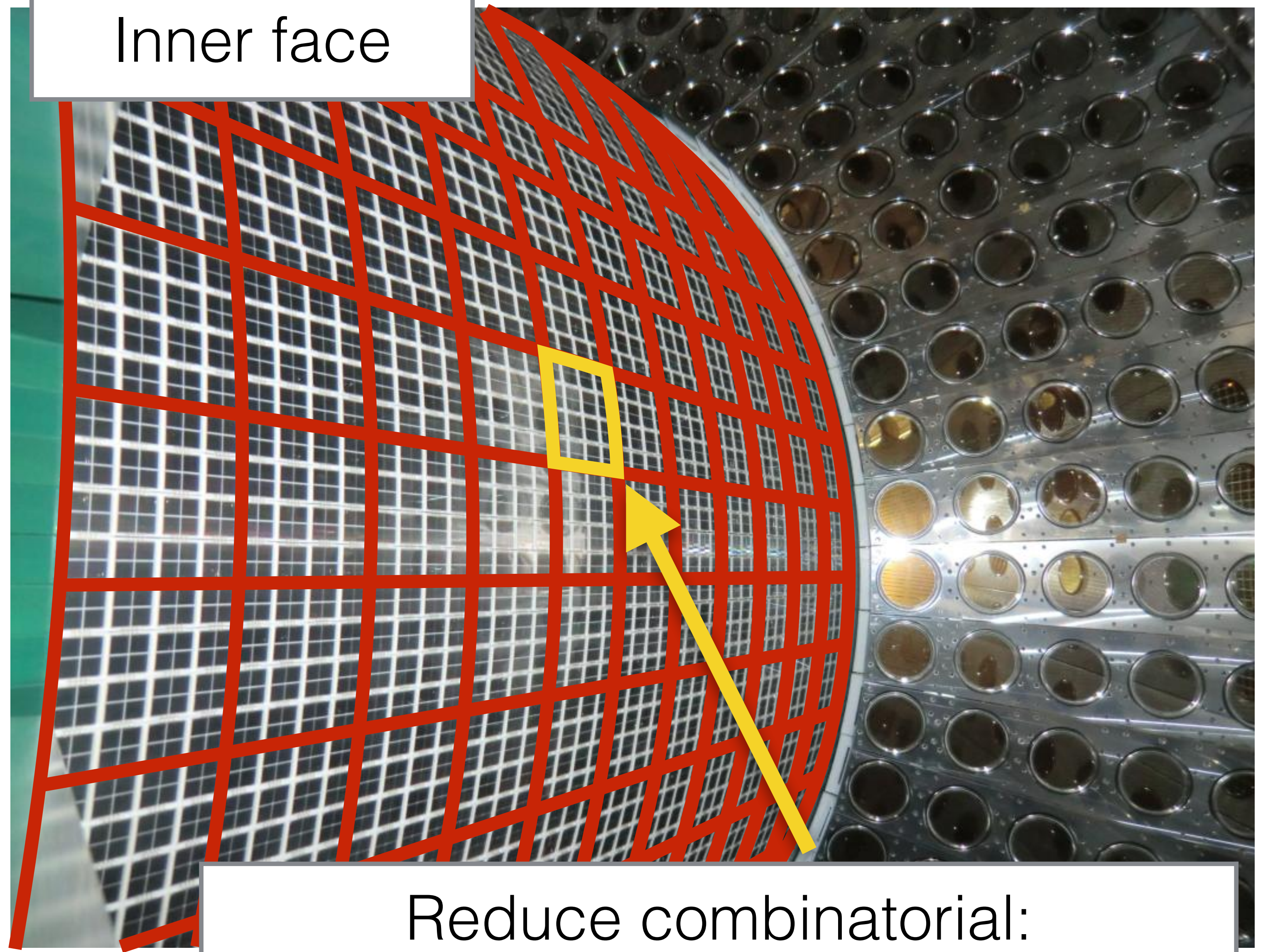

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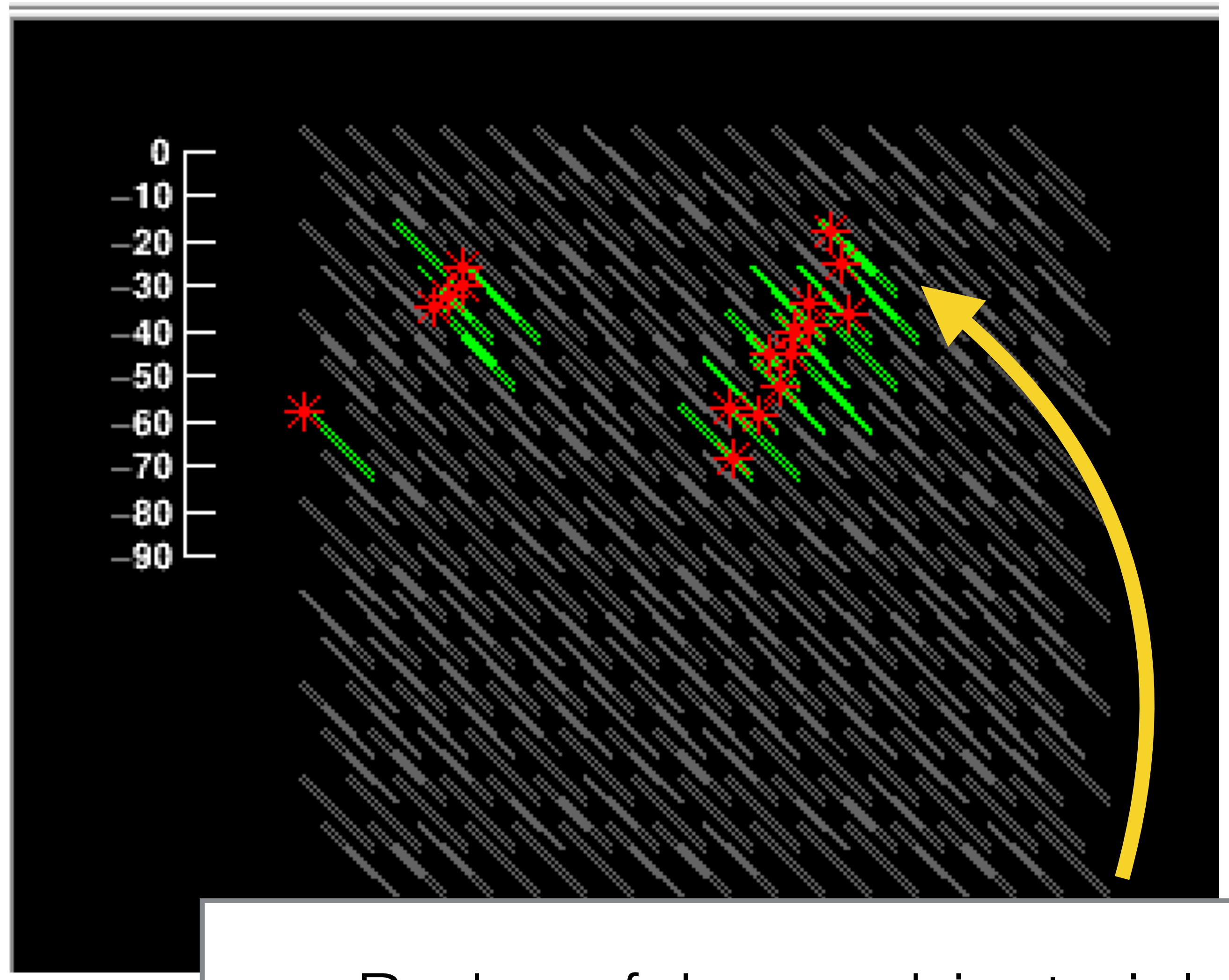

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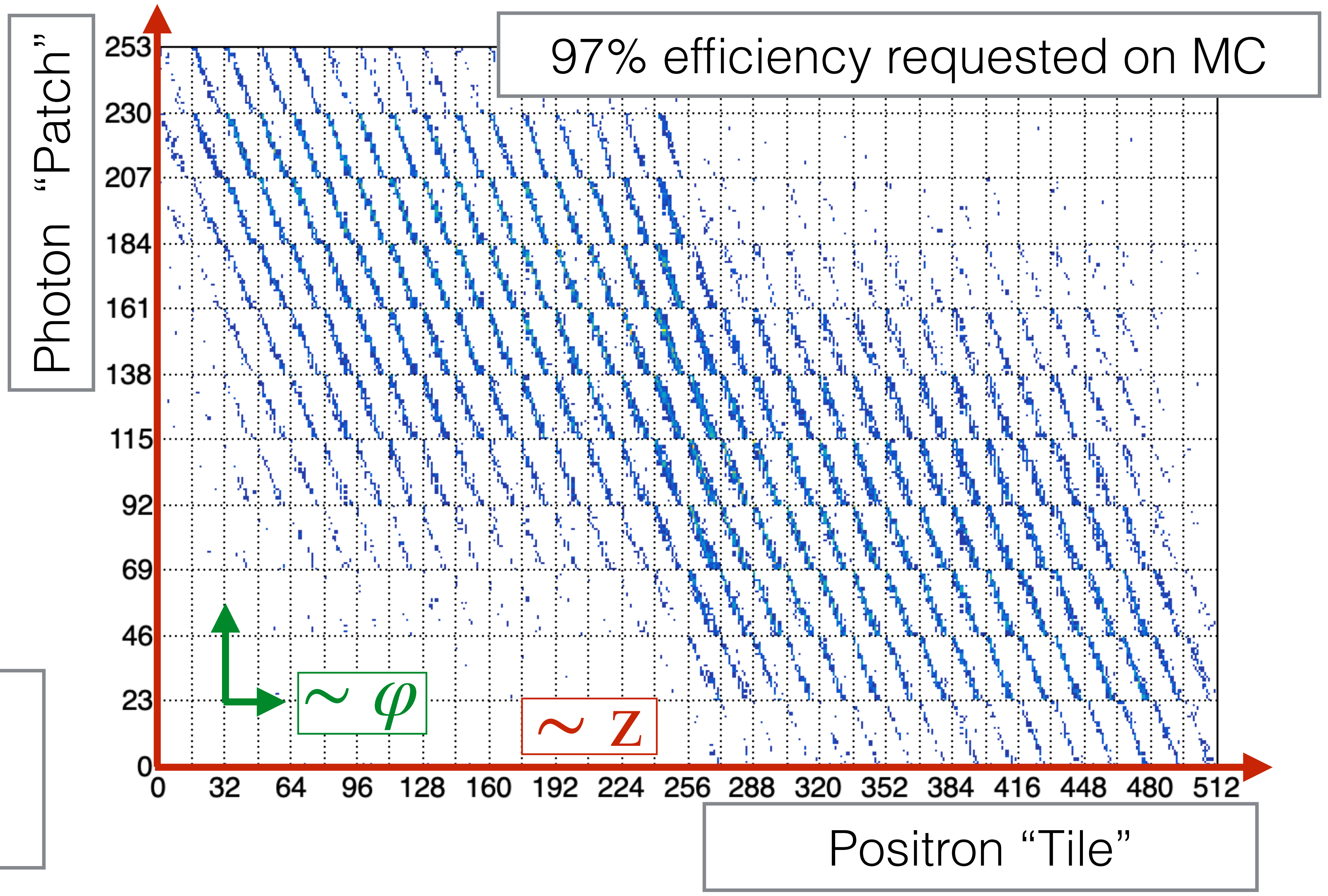
3 Check position of TC hit is consistent with **signal positrons** (Lookup Table from MC)



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Lesson learn: Exploit your detector strengths!

DirectionMatch trigger: performance

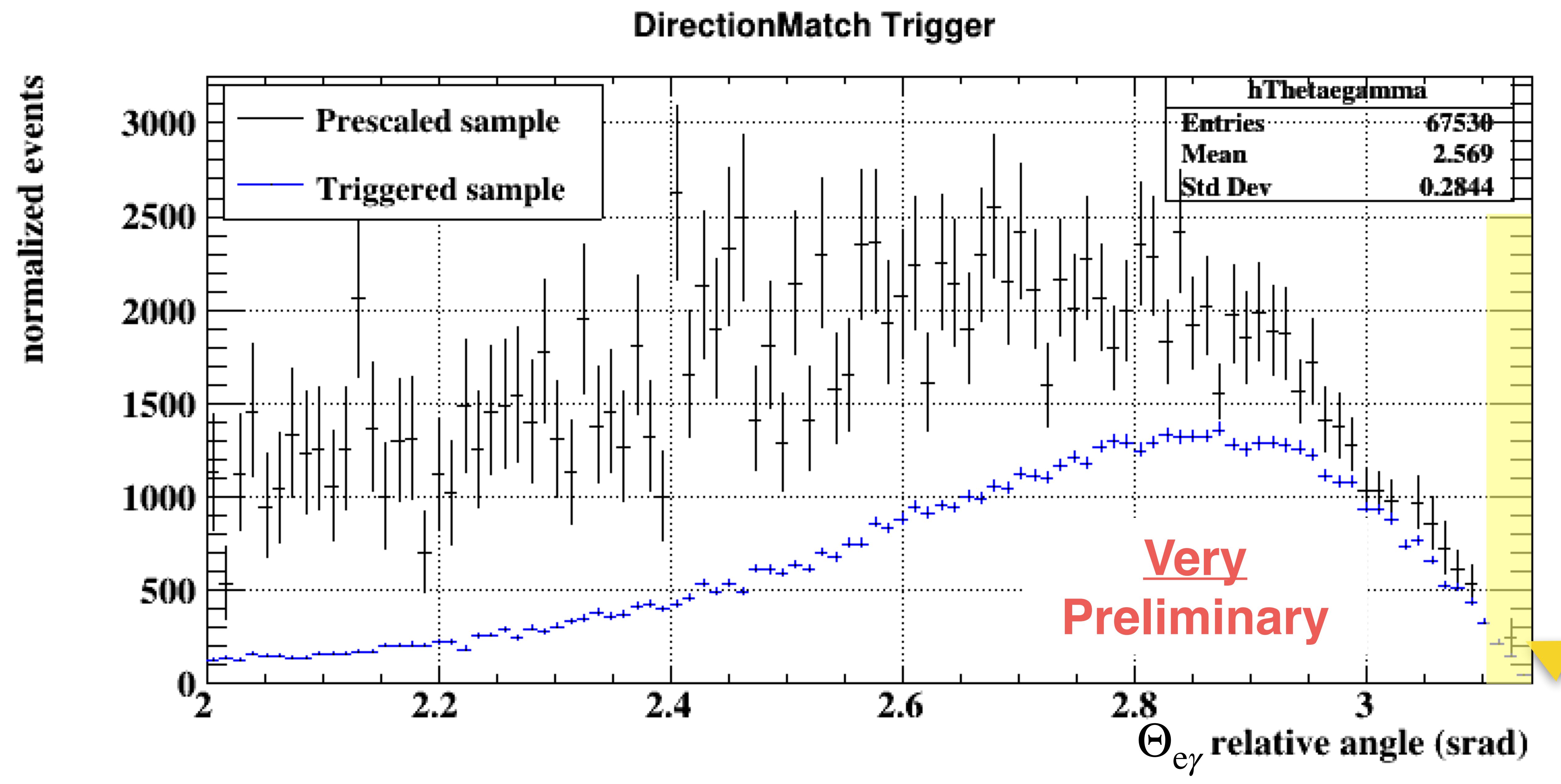
Operated **for the first time** in MEG II during 2021 beam time:
Availability of all electronics channel was crucia to explore the whole solid angle

Strategy: check bias induced using dedicated reduced bias trigger

Num	Trigger	Enabled	Prescaling	Rate
0	MEG	☑	2	16.308645
1	MEG low Q	☑	86	80.847122
2	MEG wide Angle	☑	60	60.56076
3	MEG wide Time	☑	31	28.639572

Physics trigger

“Reduced bias”



Signal region

<u>Caveat:</u> Sensitive to offline reconstruction performance of Liquid Xenon detector and Positron Spectrometer
Offline algorithm development still ongoing

Clear effect of reduction of events with opening angle < 3 srad

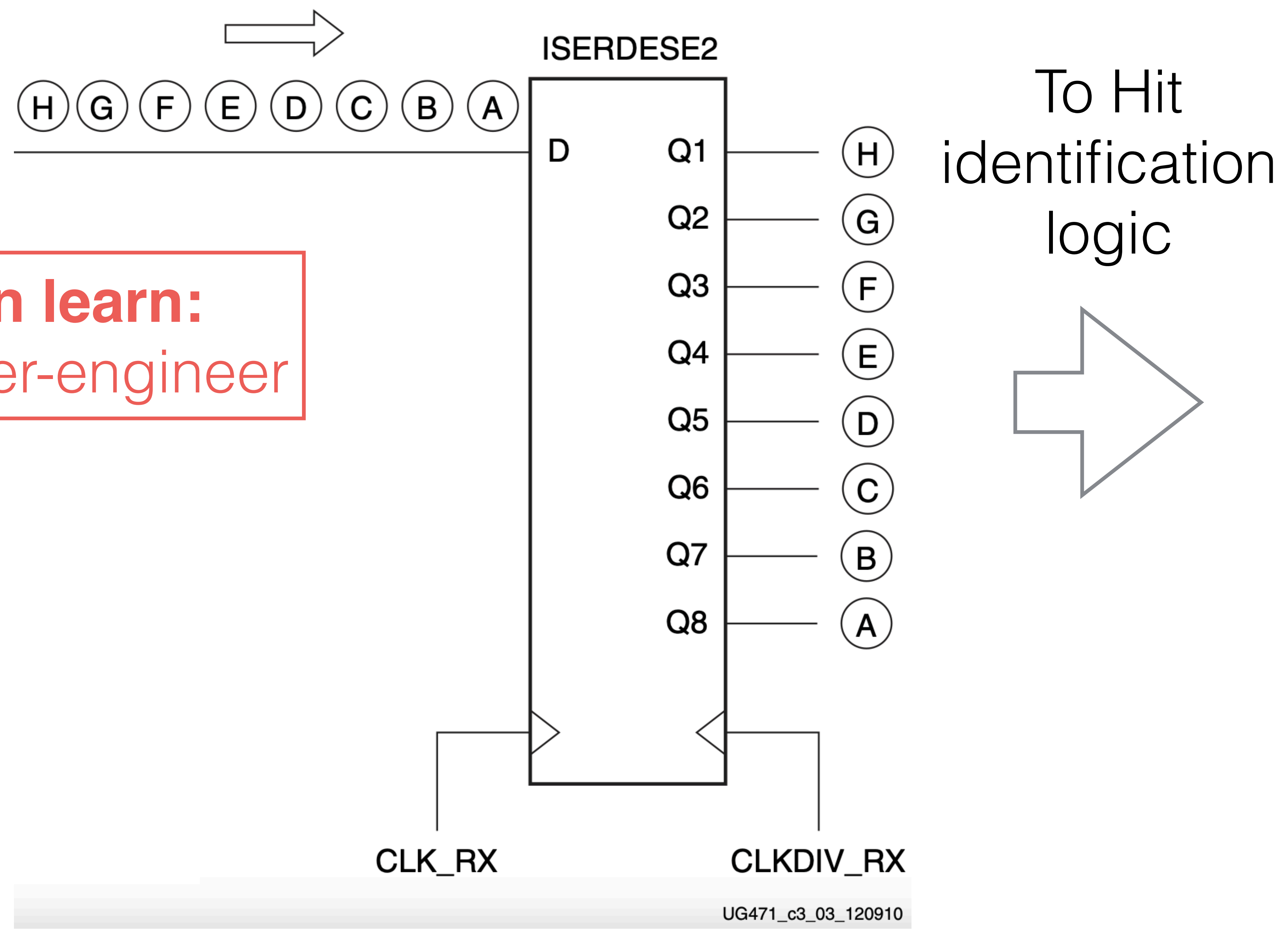
Time trigger: design

Modern FPGA input tiles have integrated shift registers:
Oversampling of input signals

Can get signal timing timing
at 1/n of the clock cycles resolution (n=8)

Minimal logic and latency need:
encoder at output to identify transitions

Lesson learn:
Do not over-engineer



Resolution @80 MHz: $12.5; \mathrm{ns}/8 \sim 1.56\ \mathrm{ns}$

Single channel $\sigma = \dfrac{1.56\ \mathrm{ns}}{\sqrt{12}} \sim 450\ \mathrm{ps}$

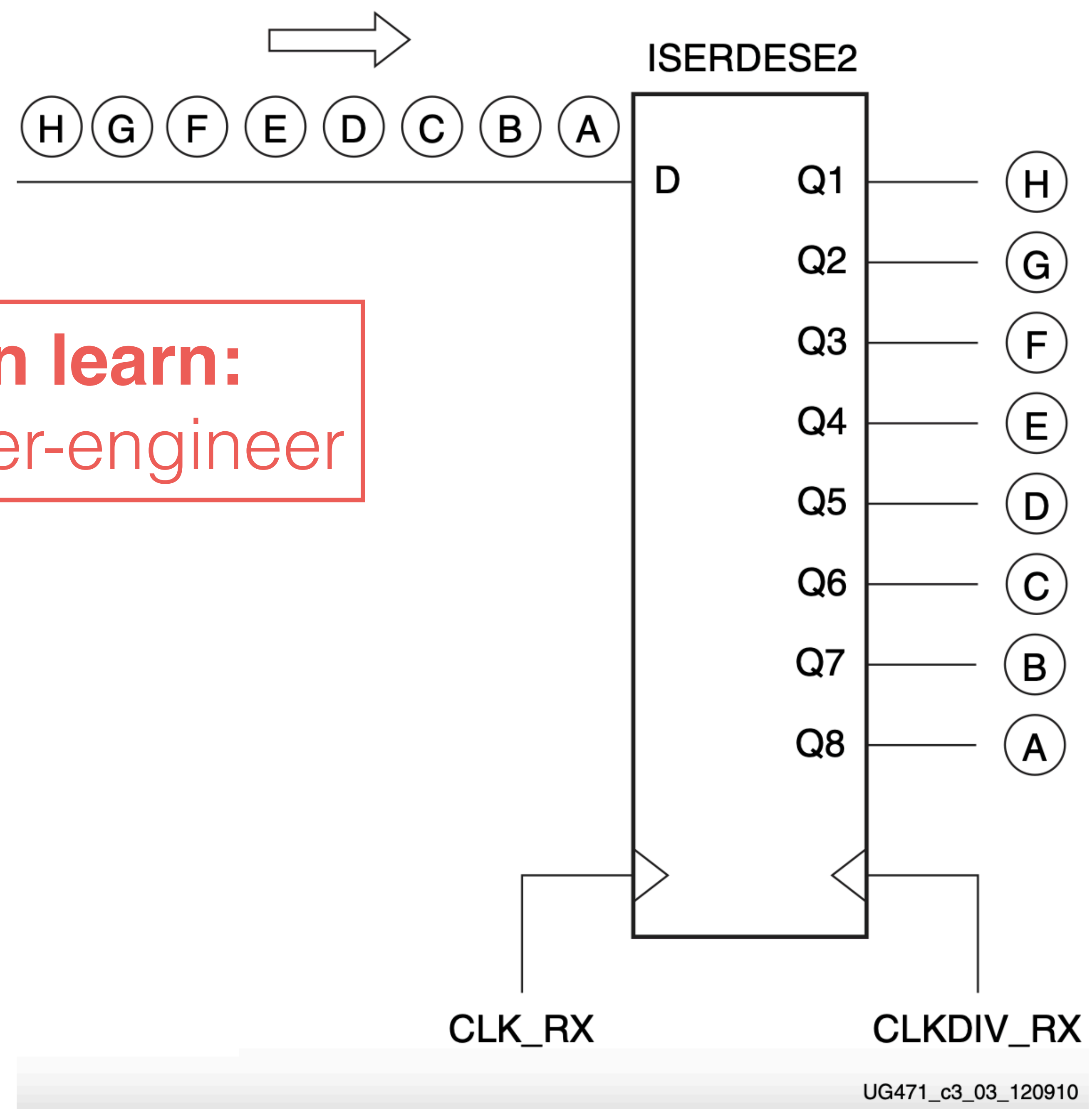
Time trigger: design

Modern FPGA input tiles have integrated shift registers:
Oversampling of input signals

Can get signal timing timing
at 1/n of the clock cycles resolution (n=8)

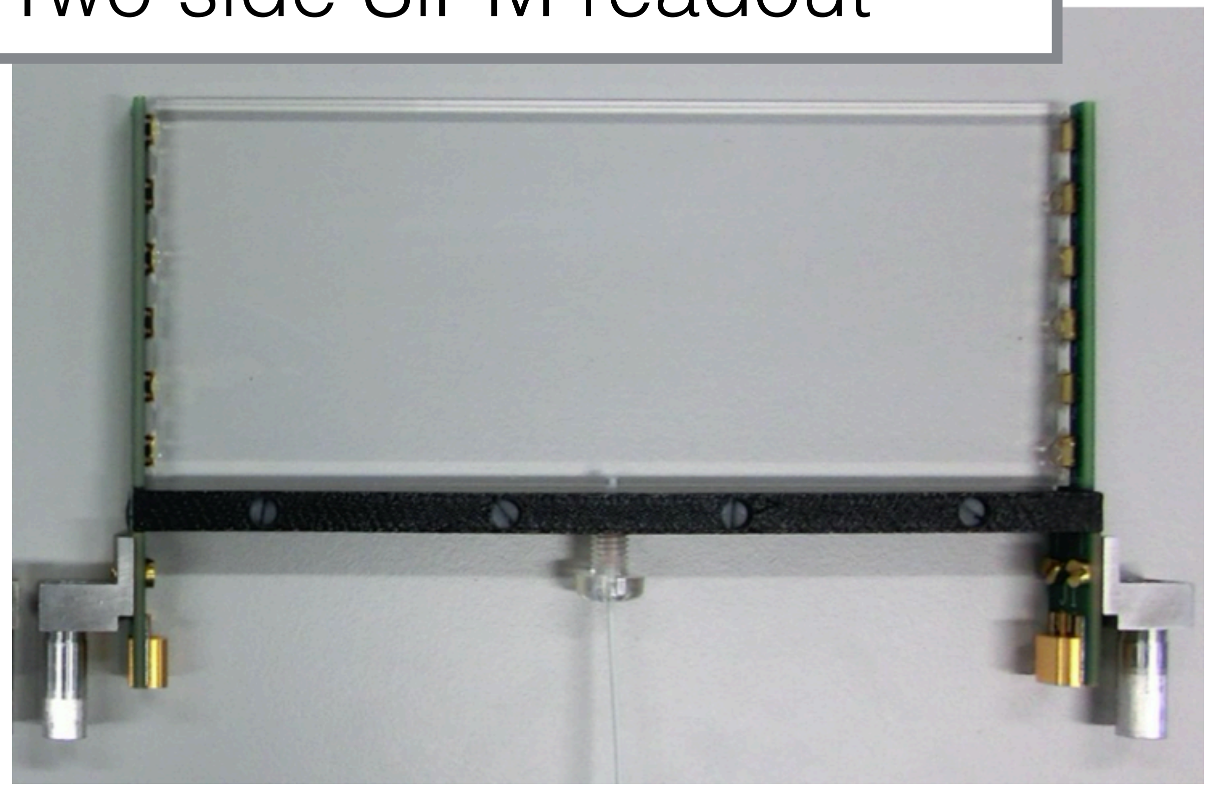
Minimal logic and latency need:
encoder at output to identify transitions

Lesson learn:
Do not over-engineer



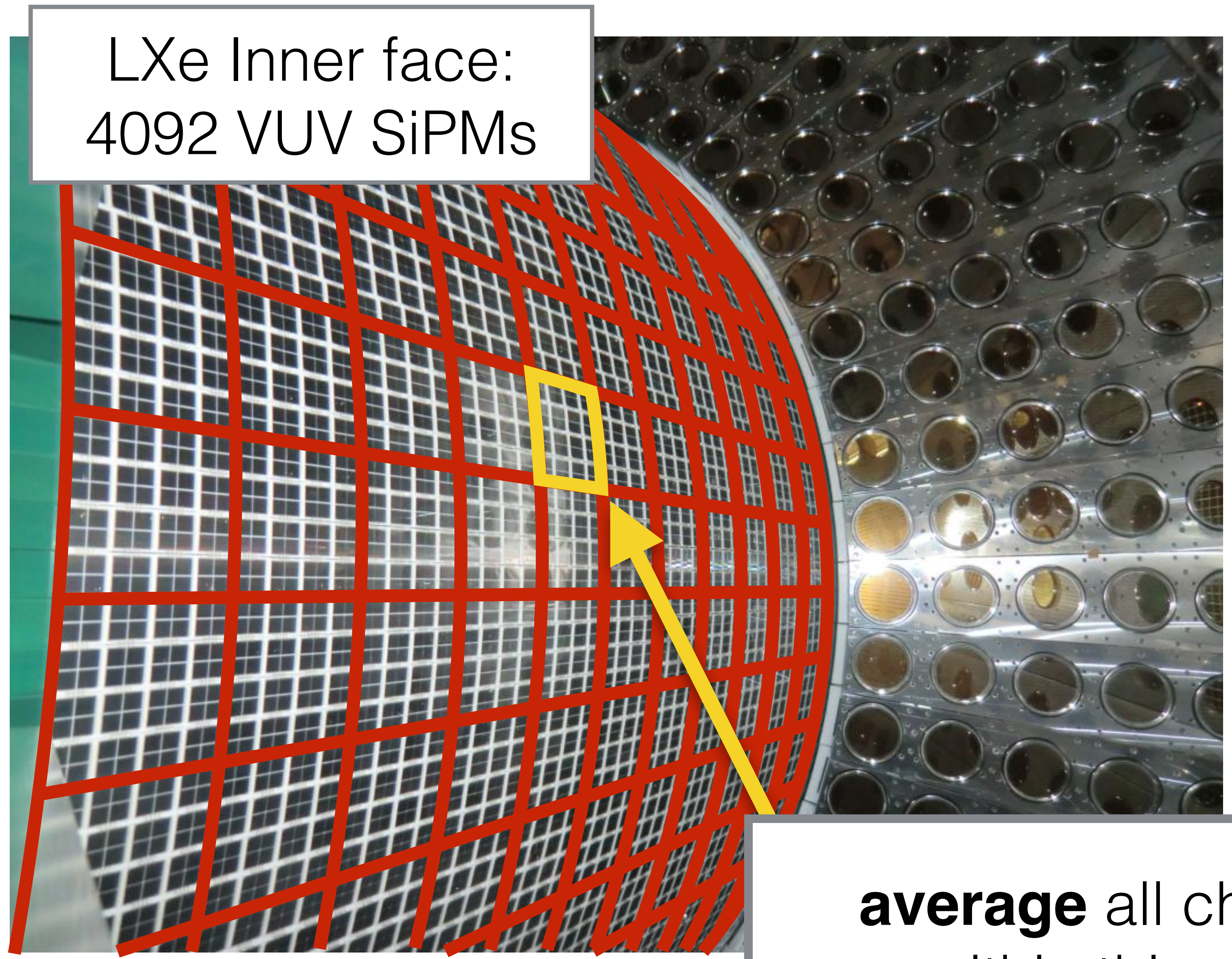
To Hit identification logic

Timing counter scintillator:
Two side SiPM readout



average both ends

LXe Inner face:
4092 VUV SiPMs



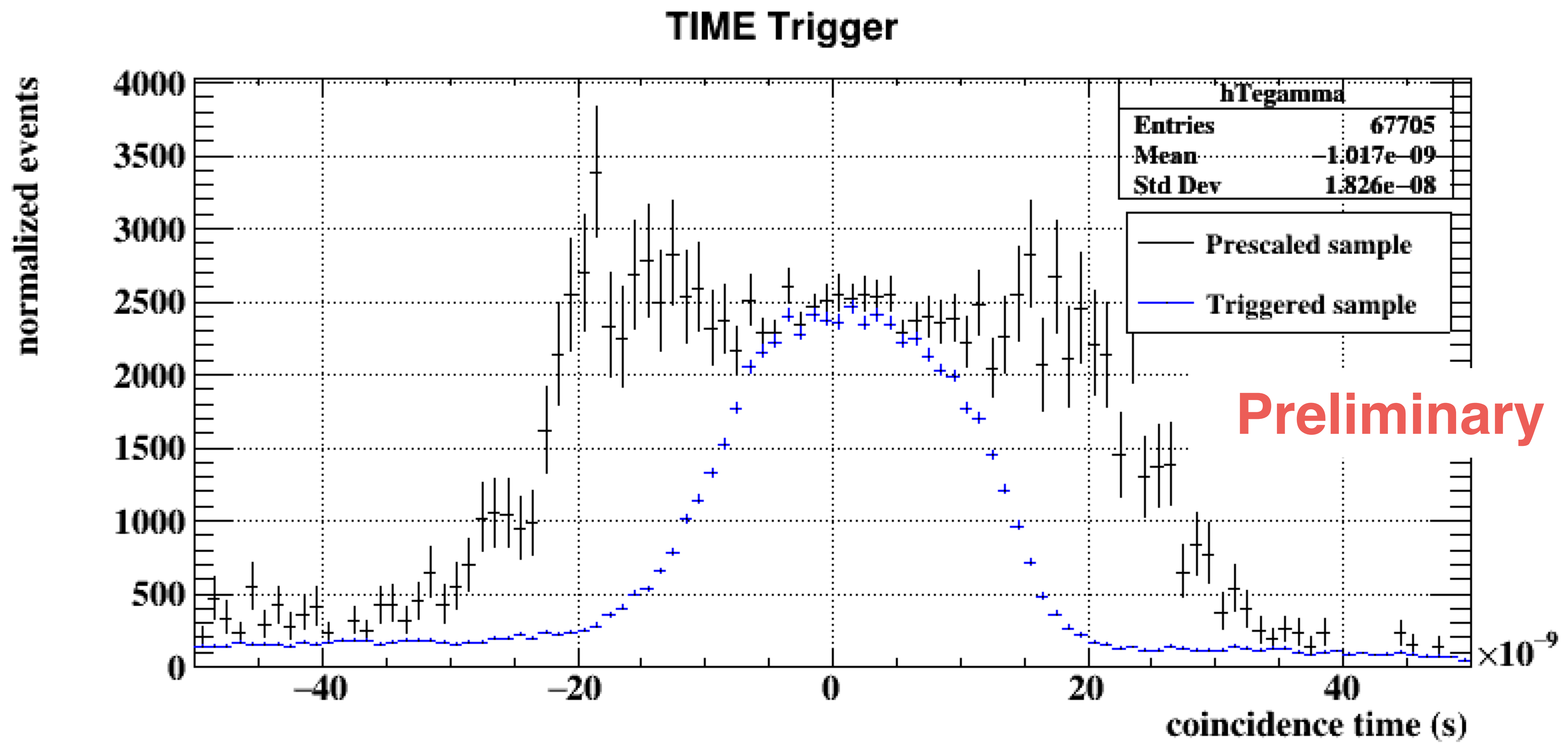
average all channels
within this region

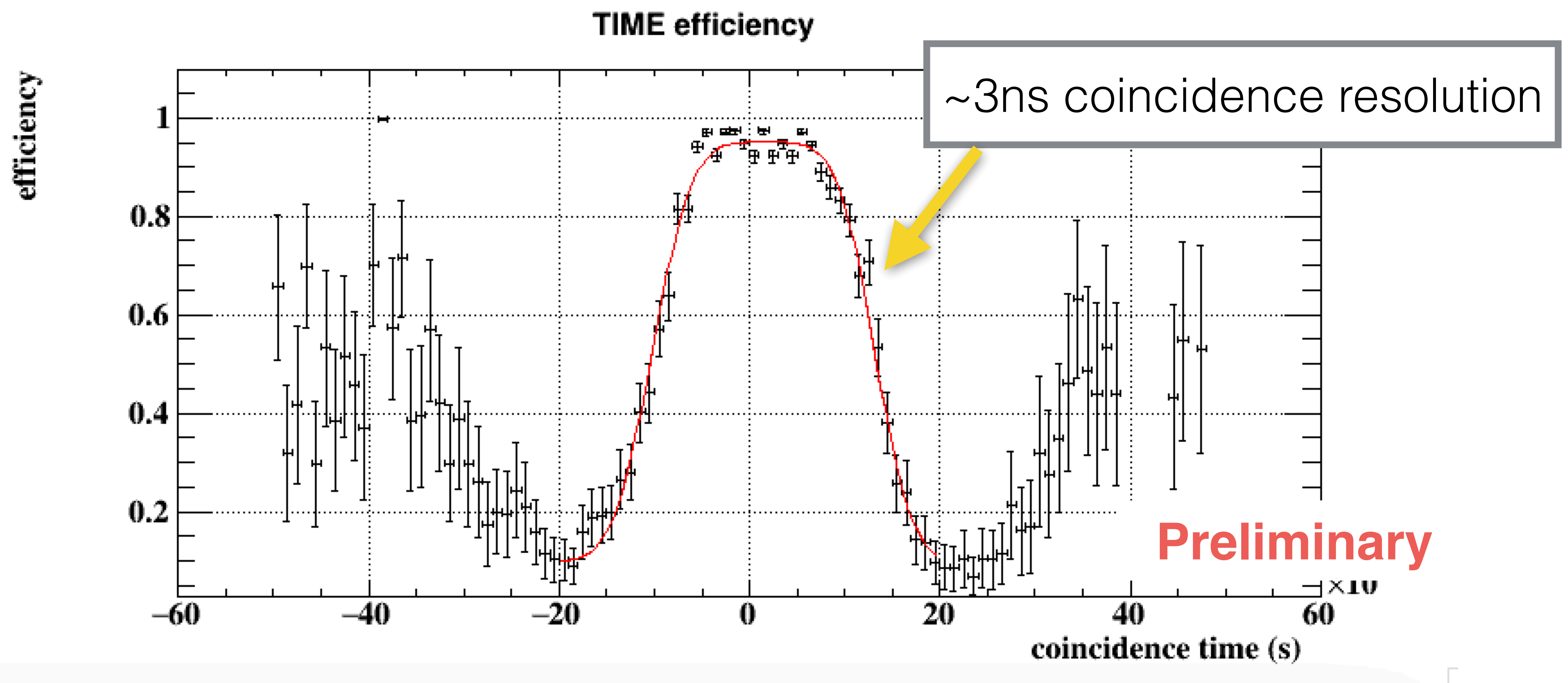
Resolution @80 MHz: $12.5; \mathrm{ns}/8 \sim 1.56\ \mathrm{ns}$

Single channel $\sigma = \dfrac{1.56\ \mathrm{ns}}{\sqrt{12}} \sim 450\ \mathrm{ps}$

Time trigger: performance

Detector time resolution (<100ps) much better than trigger one: only relevant effect is trigger

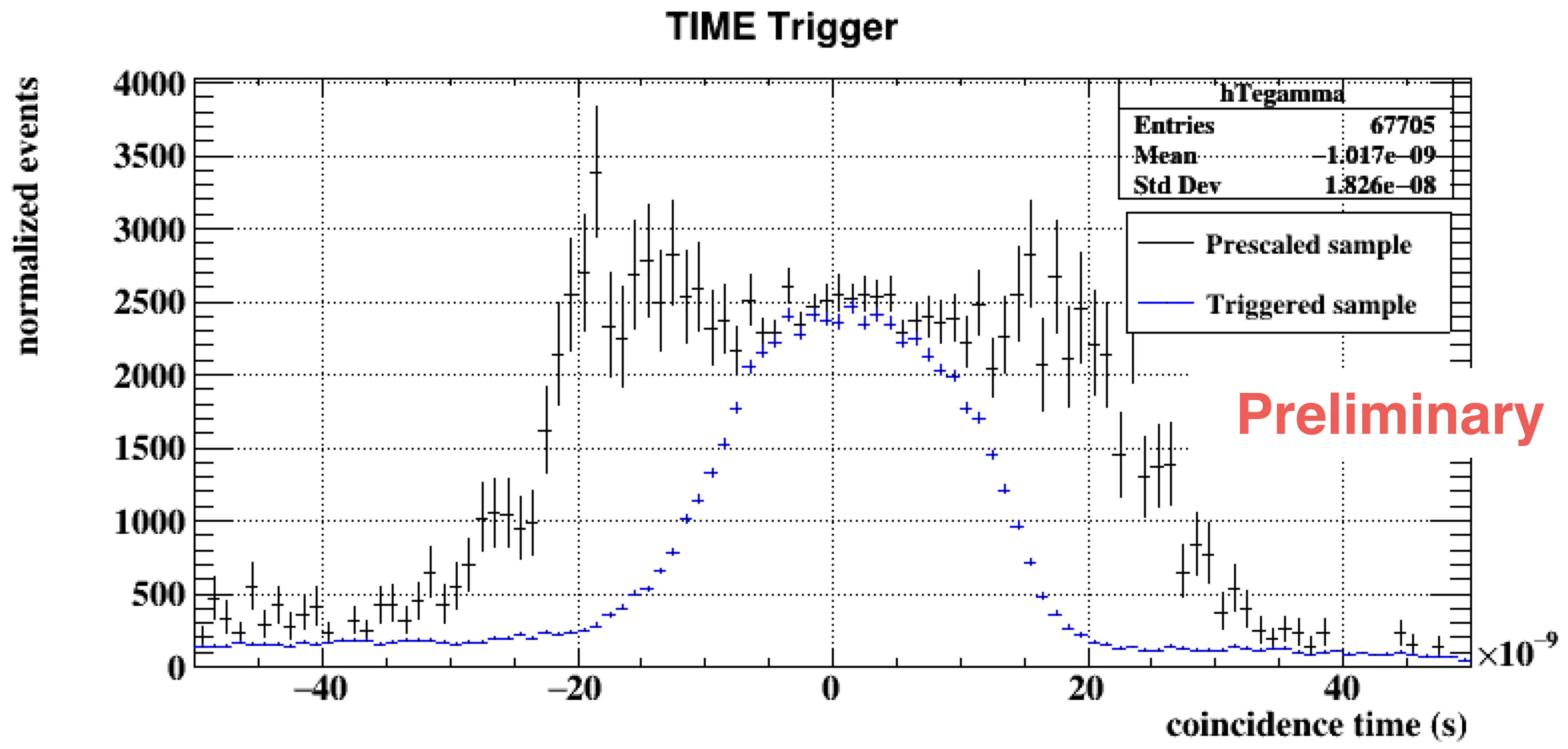


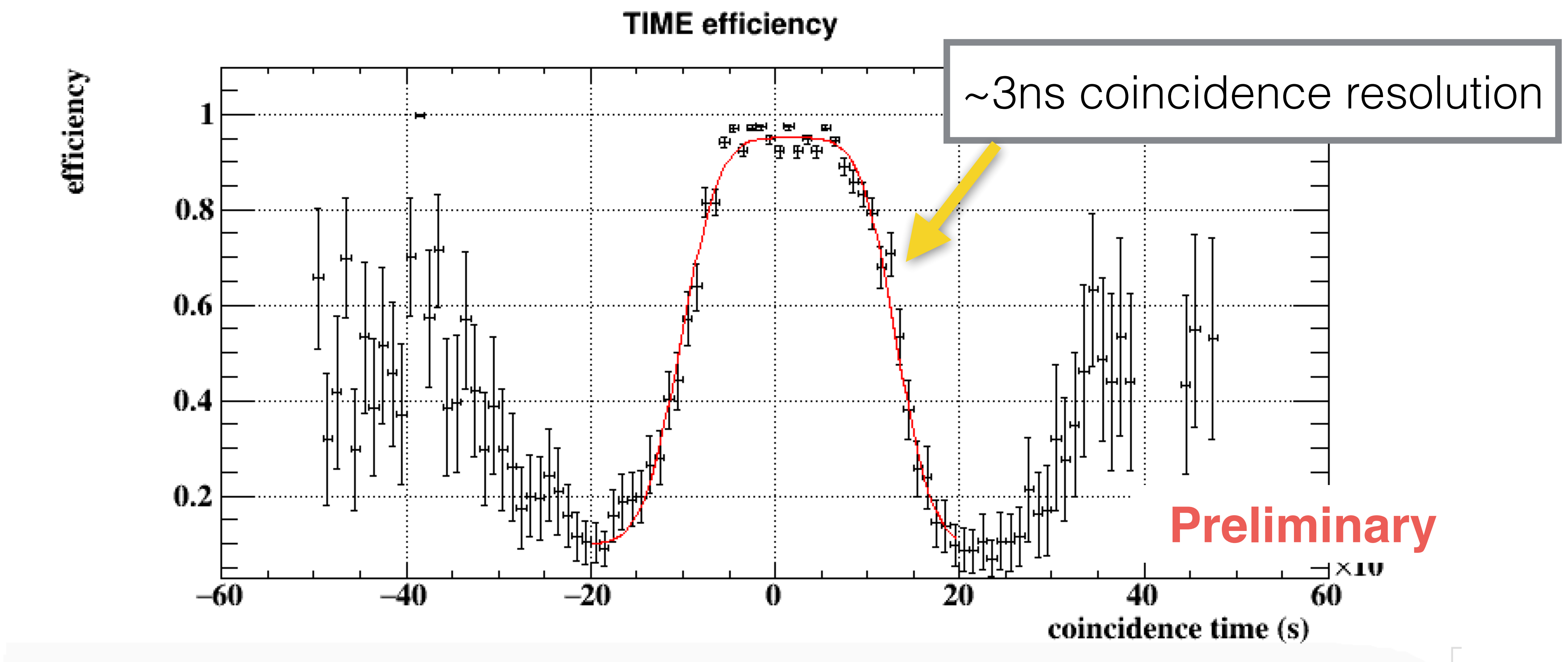


Extract trigger effect from ratio of two distribution

Time trigger: performance

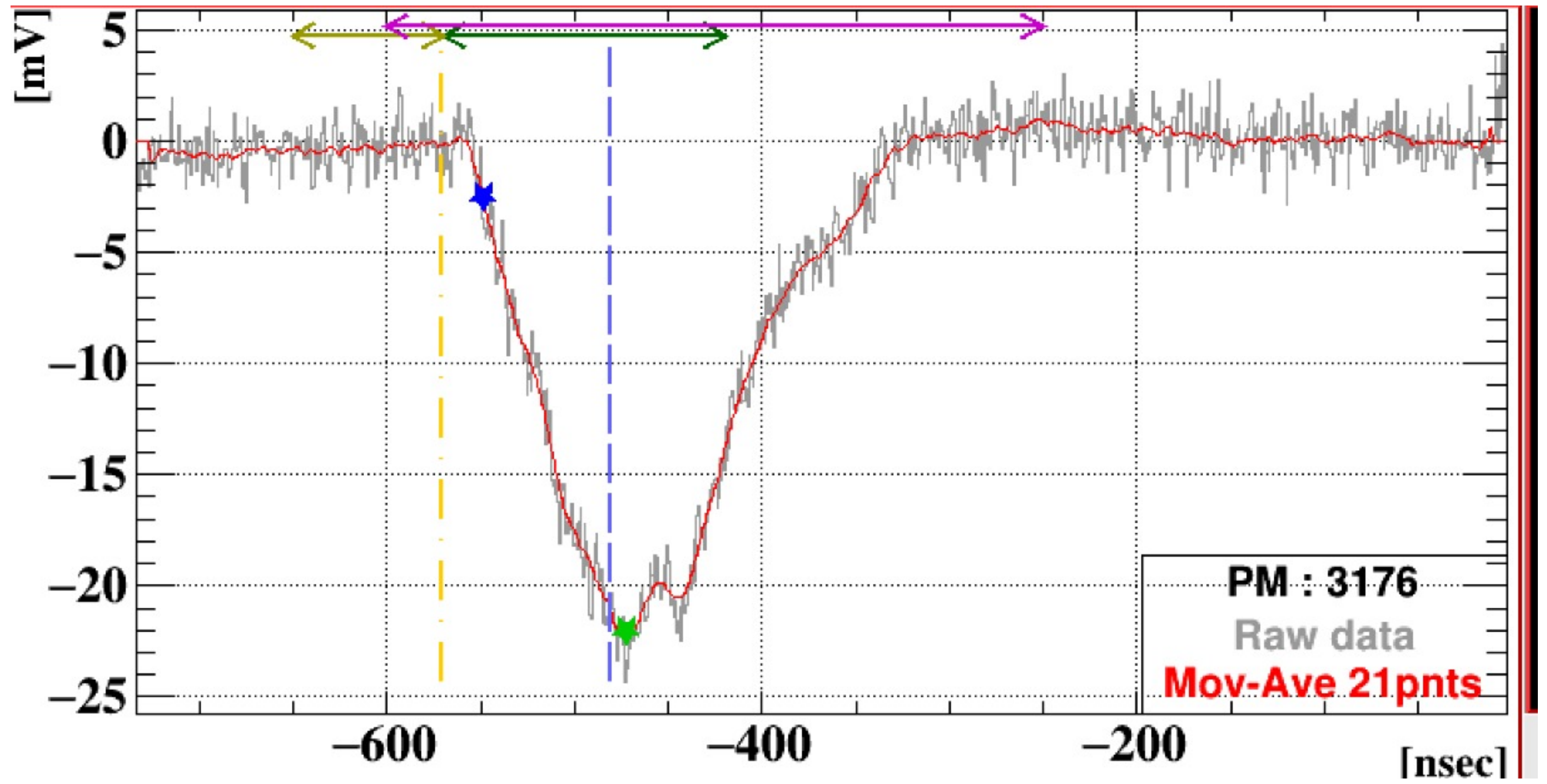
Detector time resolution (<100ps) much better than trigger one: only relevant effect is trigger





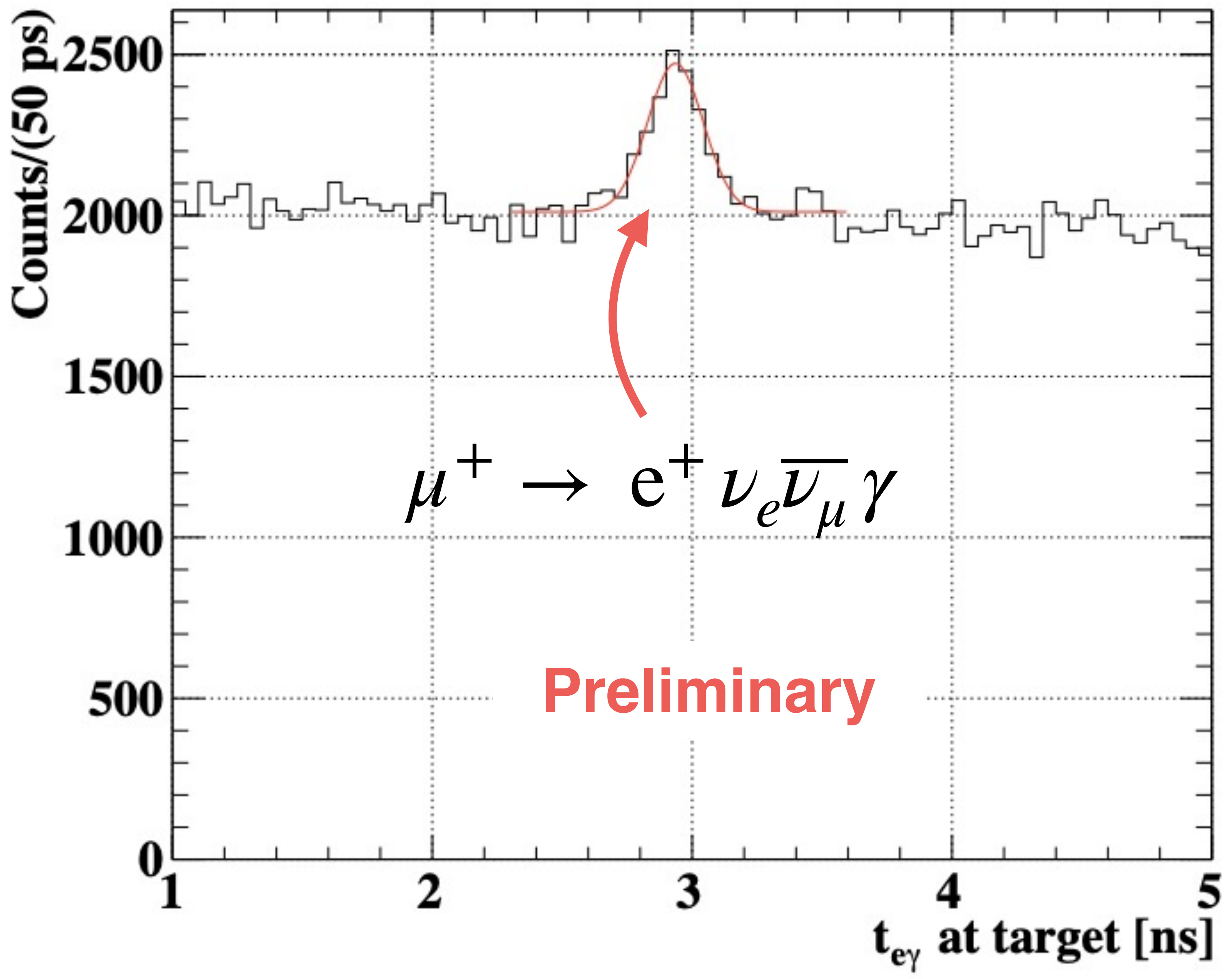
Extract trigger effect from ratio of two distribution

Source of bias observed in depth dependence of time reconstruction:
Time walk on discriminator because of slow MPPC risetime (0.1 mV/ns)



Conclusions and prospects

MEG II ended its first **Physics run** in 2021.
Data sanity check: radiative decays observed!



Definitely a major step toward the
μ→eγ physics data taking next years

The **WaveDAQ system** was successfully deployed (x8 more channels than 2020) and the DAQ side performed extremely well.

MEG II trigger system performed very smoothly for the first time with all electronics.
Refinements planned for 2022, especially on the timing of the Liquid Xenon signals.

WaveDAQ application to other experiments:
poster #49 → "The fragmentation trigger of the FOOT experiment"
poster #257 → "Looking for Cherenkov light in liquid Xenon with LoLX"

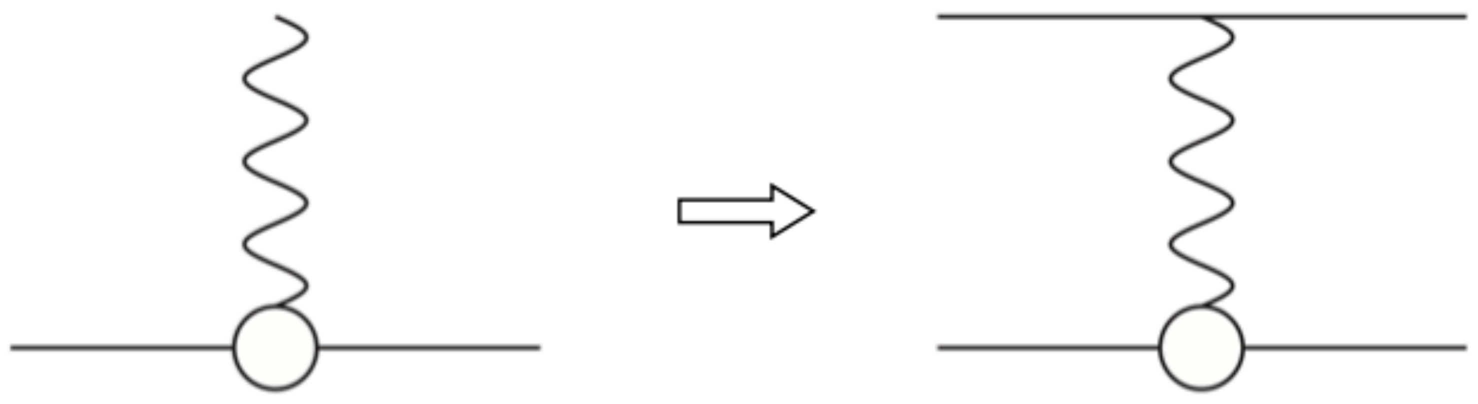
Backup

Dipole and 4-lepton operator

Additional EM vertex needed to convert an operator to the other

dipole operator

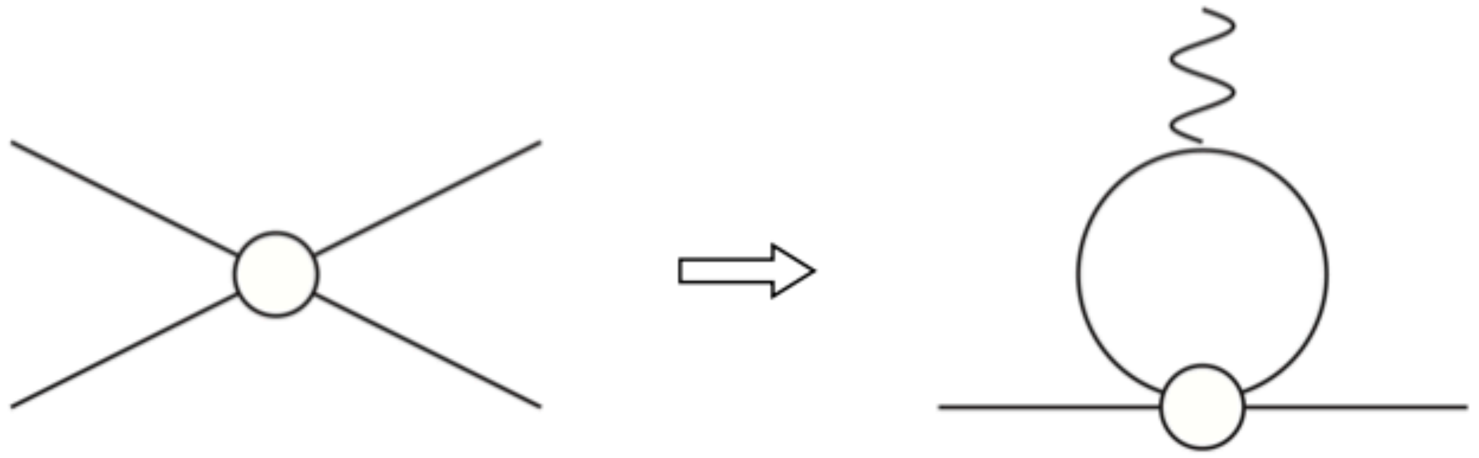
μ→eγ



4 lepton operator

μ→eee

μN→eN



Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6\times10^{-3}$	$10^{-3}-10^{-2}$
Type-I seesaw	Loop*	Loop*	$3\times10^{-3}-0.3$	$0.1-10$
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop*†	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05-0.5$	$2-20$

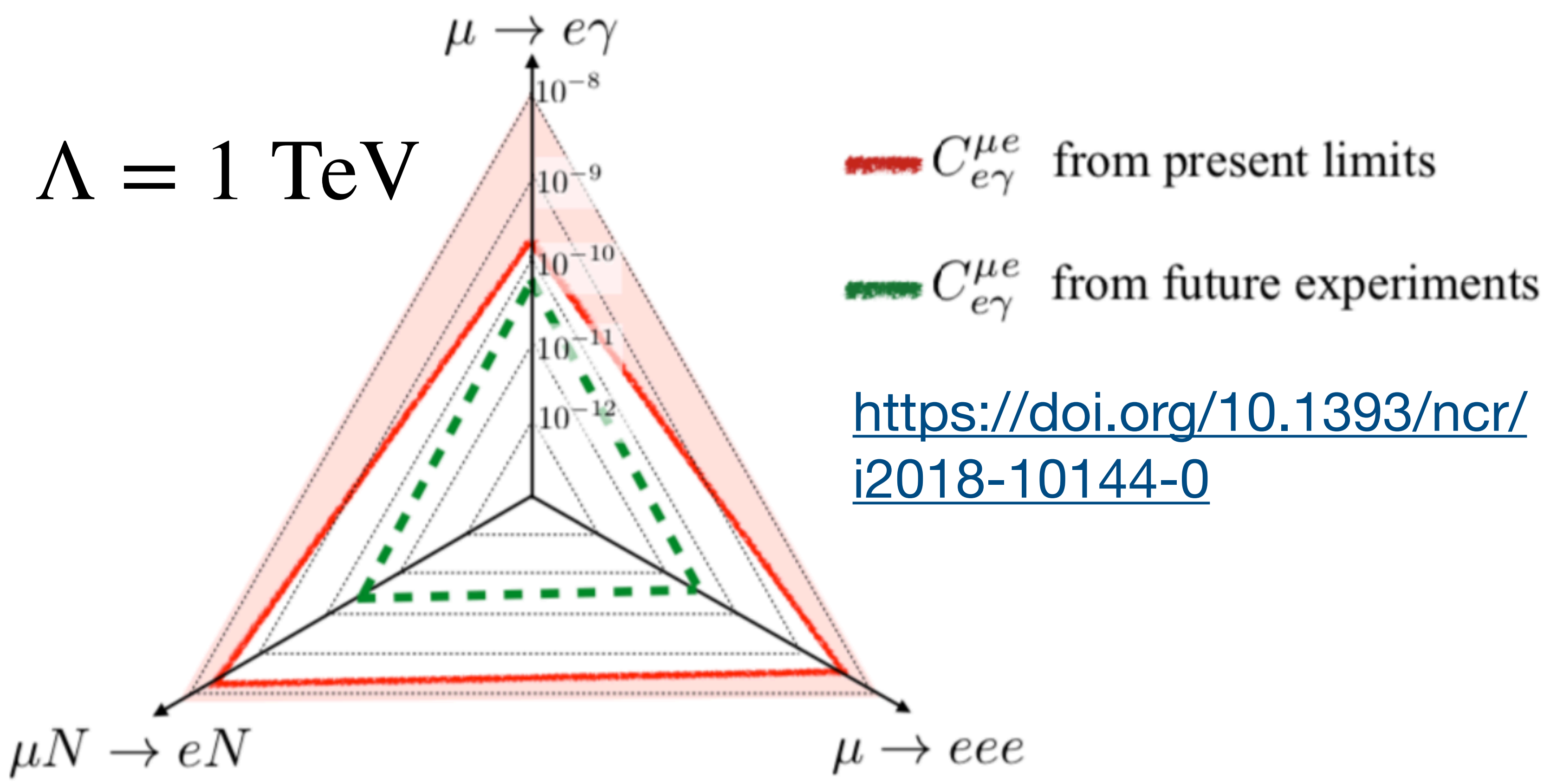
Huge theoretical effort on combining results from various processes

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_\alpha C_\alpha^{(5)}O_\alpha^{(5)} + \frac{1}{\Lambda^2}\sum_\alpha C_\alpha^{(6)}O_\alpha^{(6)} + \dots$$

$O_\alpha^{(i)}$ = operator of i-th order in SM field

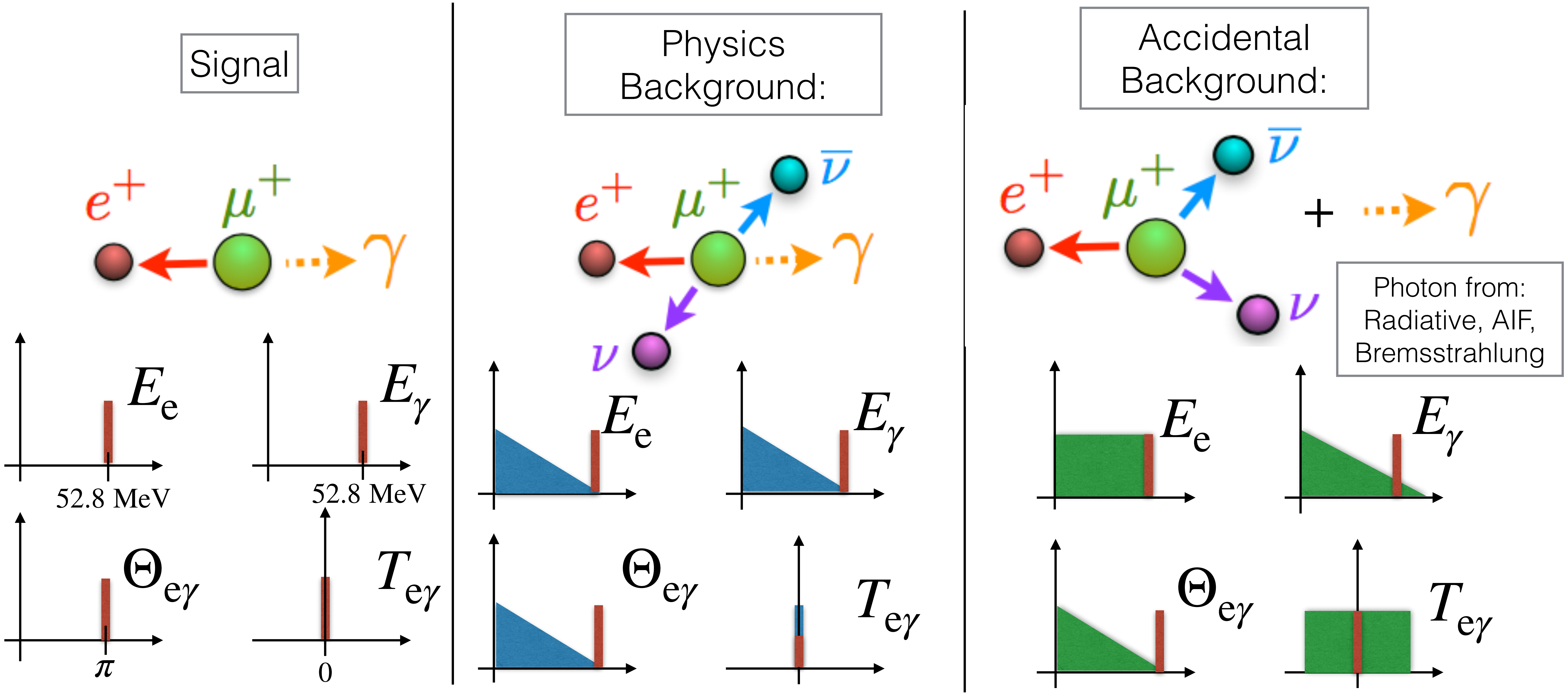
$C_\alpha^{(i)}$ = coupling associated to operator $O_\alpha^{(i)}$

Λ = scale of physics being integrated



https://doi.org/10.1393/ncr/i2018-10144-0

MEG experiment: signature and backgrounds

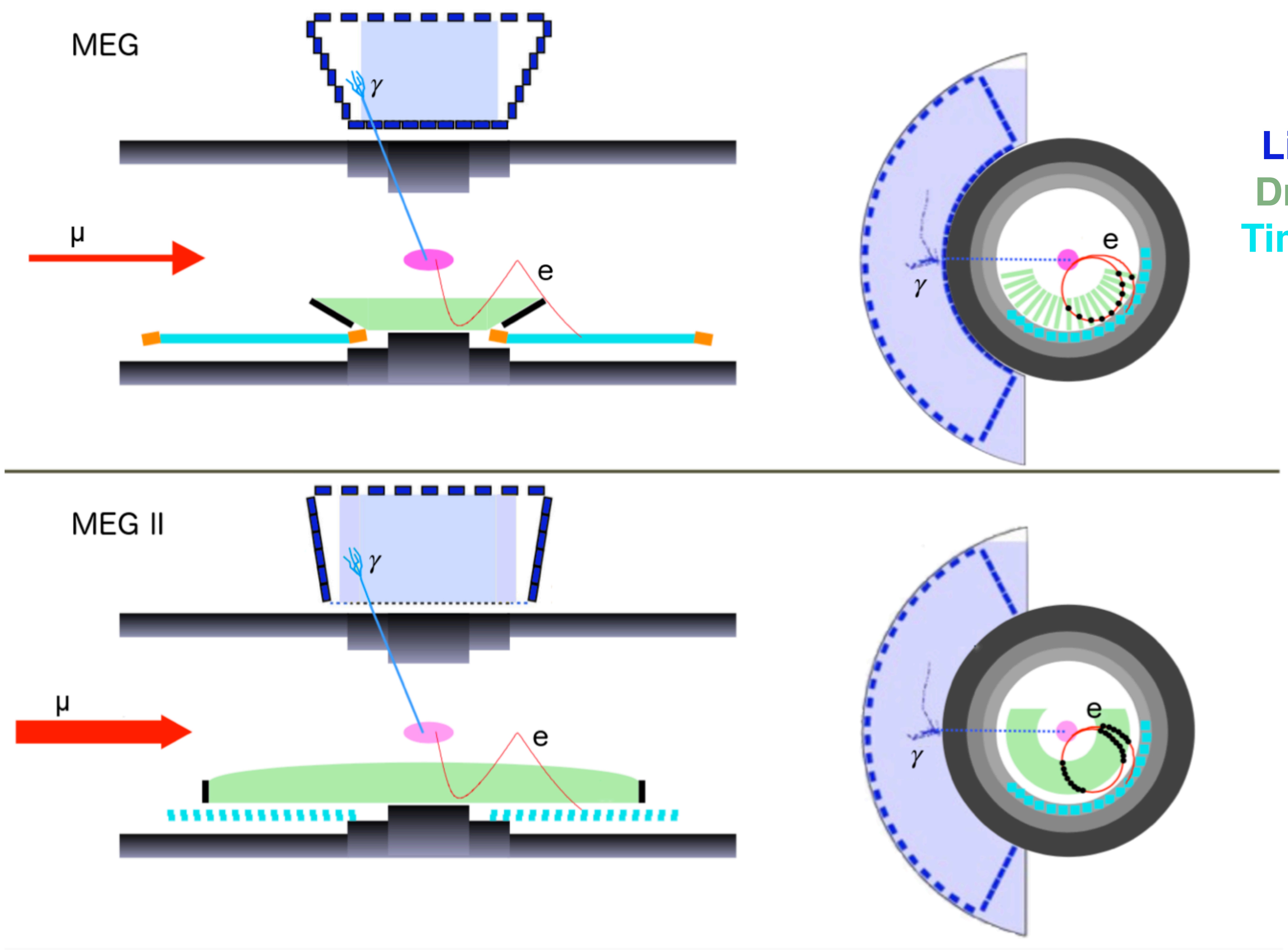


$$\boxed{R_{\mathrm{Rad}} = R_\mu \mathrm{BR}(\mu \to \mathrm{e}\nu\bar{\nu}\gamma \,|\, \Delta E_\gamma, \Delta E_\mathrm{e}, \Delta\Theta_{\mathrm{e}\gamma})}$$

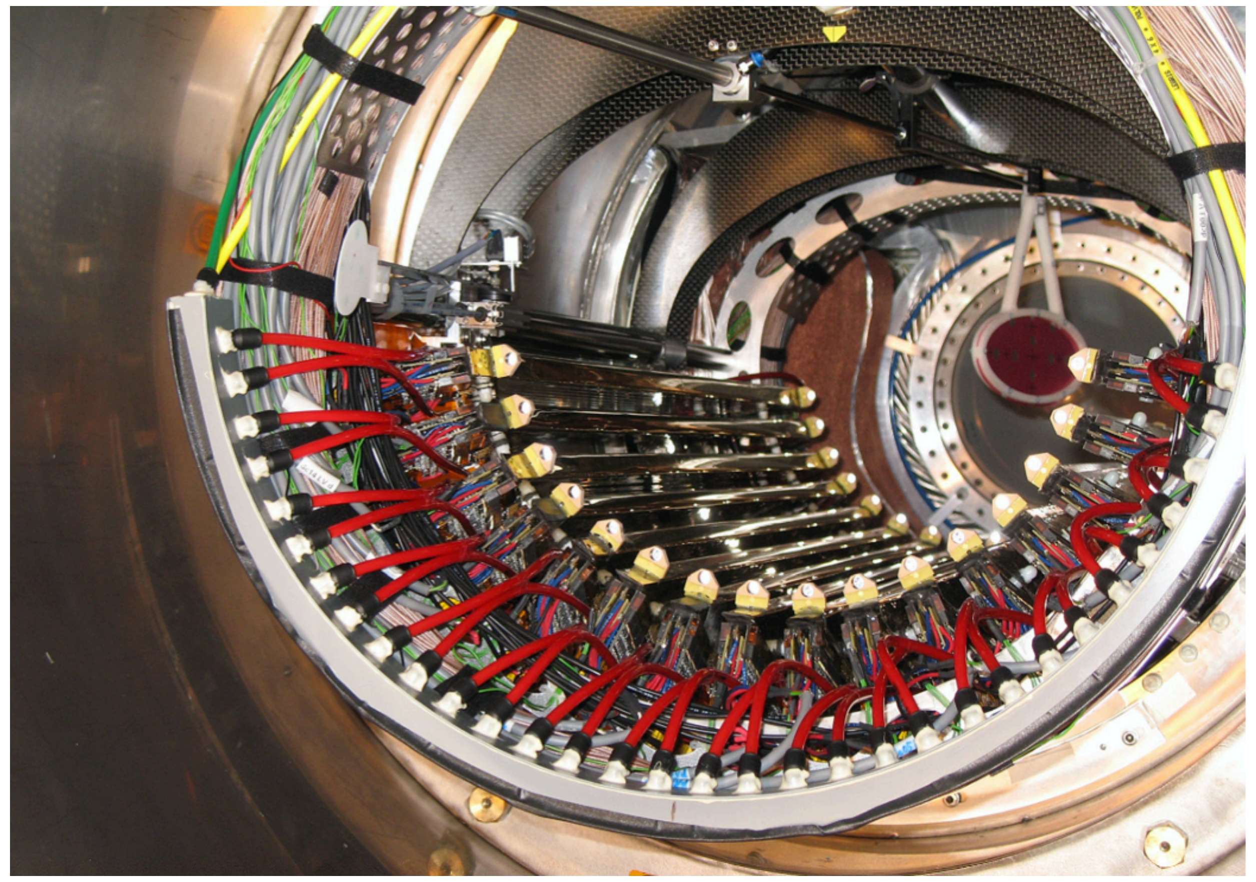
$$\boxed{R_{\mathrm{Acc}} \approx R_\mu^2 \cdot \Delta E_\mathrm{e} \cdot \Delta E_\gamma^2 \cdot \Delta\Theta_{\mathrm{e}\gamma}^2 \cdot \Delta T_{\mathrm{e}\gamma}}$$

Dominating for high muon rates R_μ

MEG I - MEG II comparison



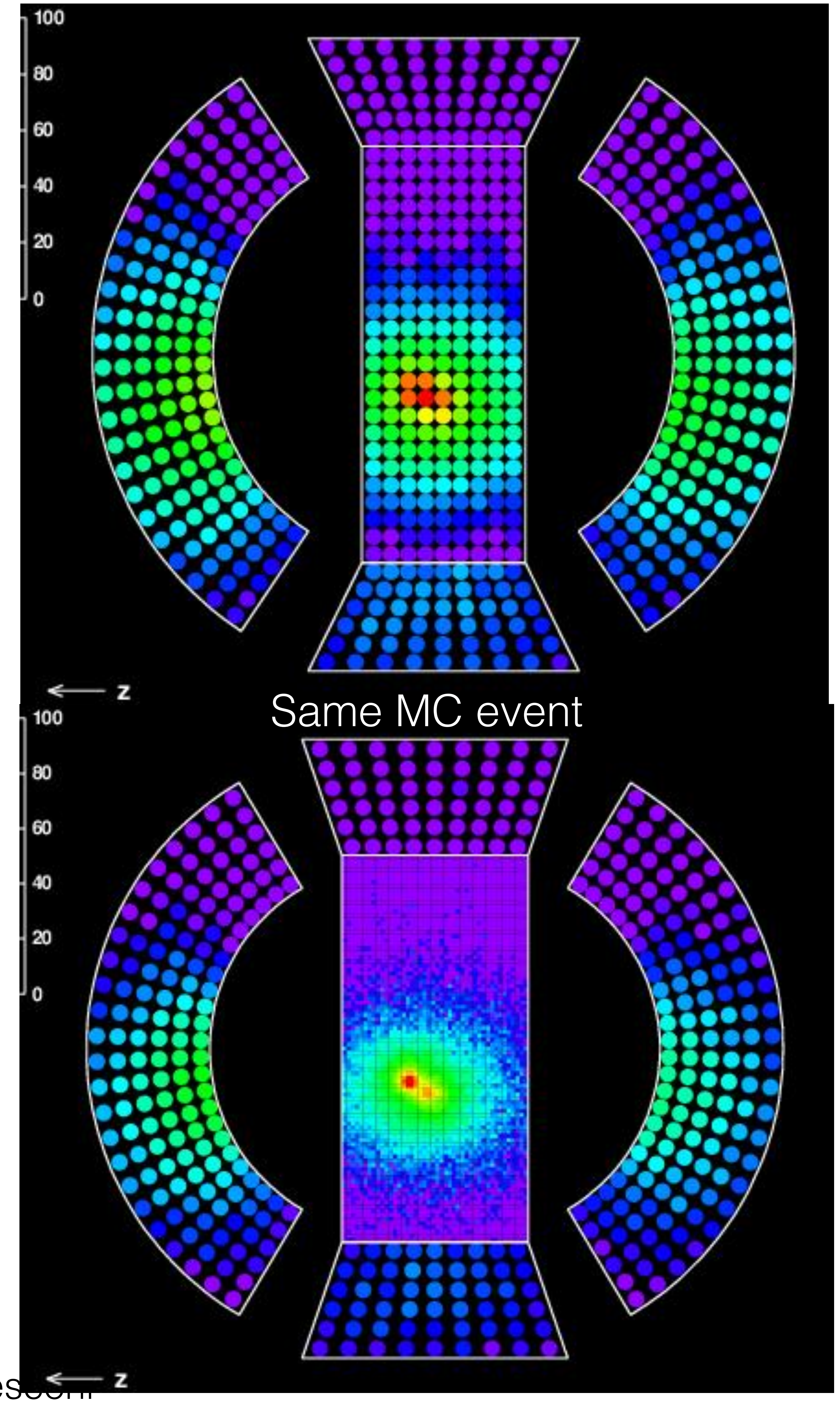
Liquid Xenon
Drift Chamber
Timing Counter

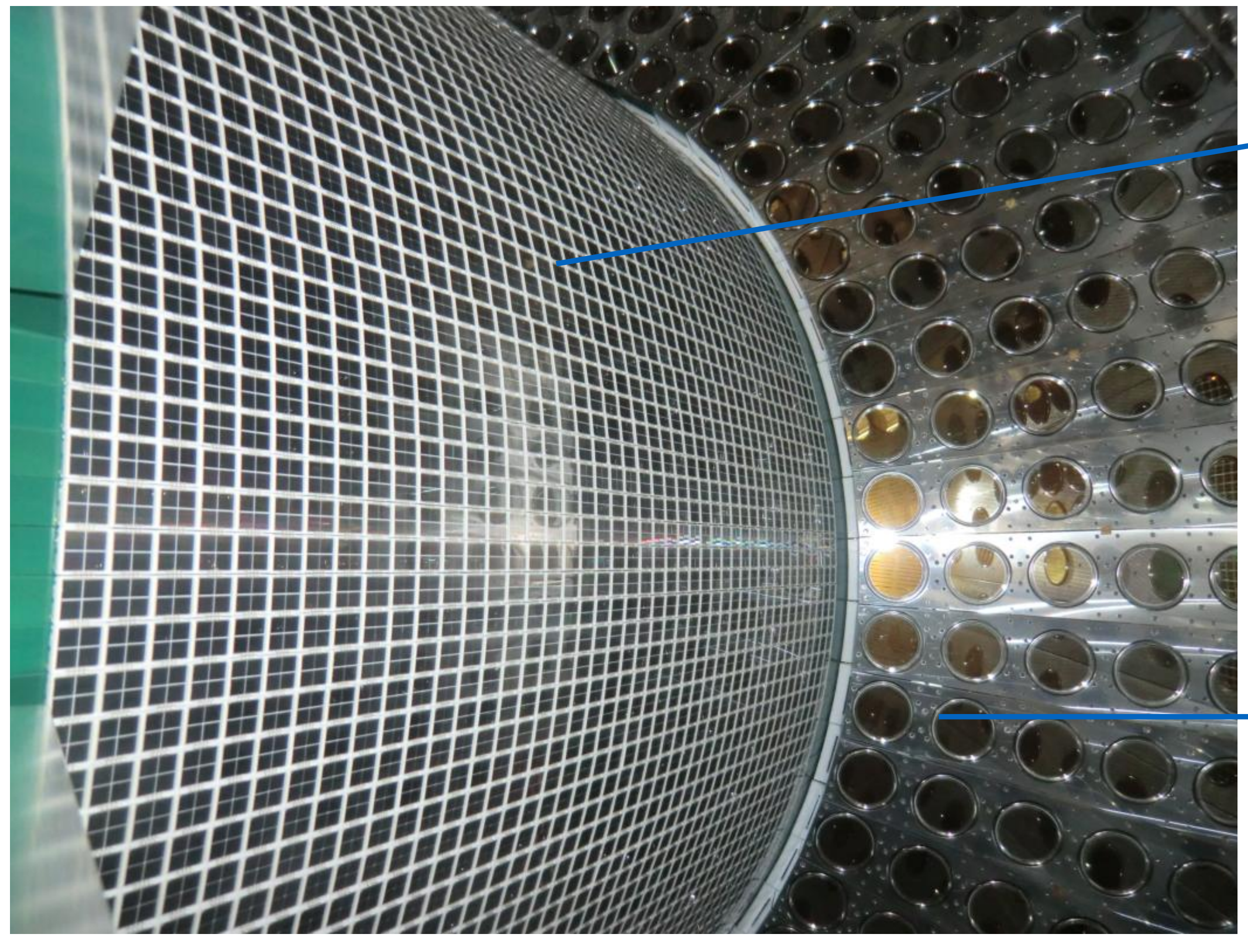


Design performances

	MEG I	MEGII
E_{e^+} (keV)	380	130
θ_{e^+} (mrad)	9.4	5.3
ϕ_{e^+} (mrad)	8.7	3.7
$E_\gamma\ w_\gamma > 2;\mathrm{cm}(\%)$	1.7	1.1
$E_\gamma\ w_\gamma < 2;\mathrm{cm}(\%)$	2.4	1.0
u_γ (mm)	5	2.6
v_γ (mm)	5	2.2
$t_{e^+\gamma}$ (ps)	122	84

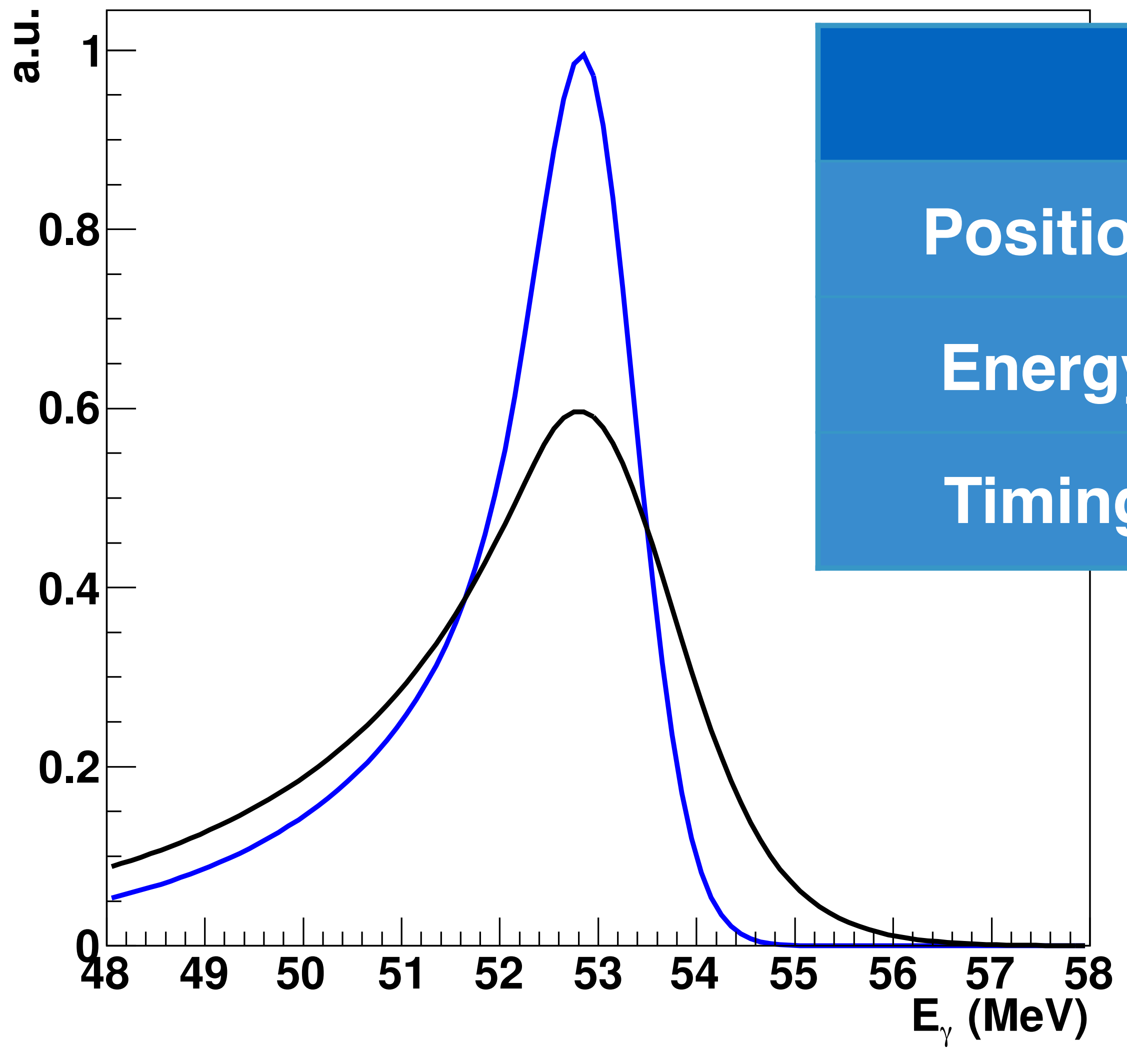
Photon detector: the Liquid Xenon detector





4092 UV SiPMs
12mmx12mm

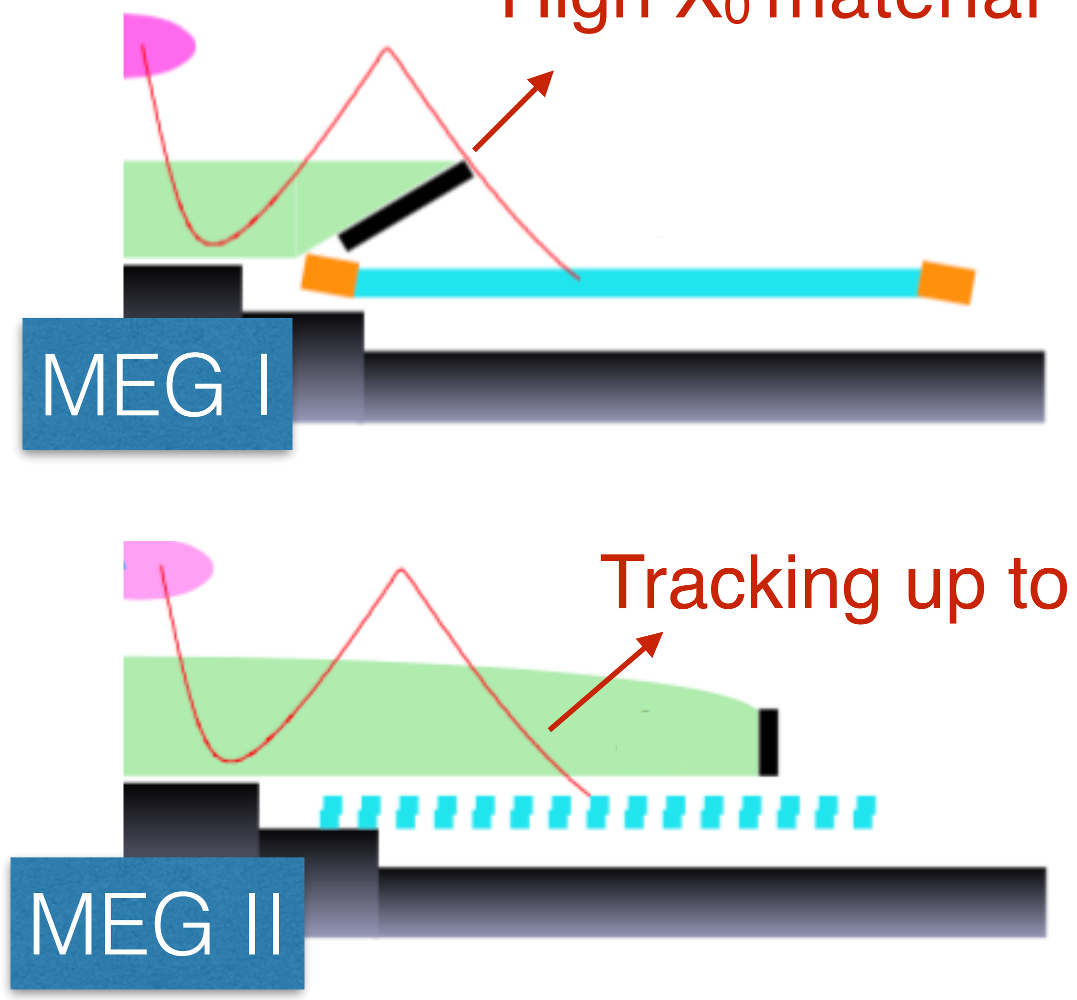
optimised positions
of the remaining
668 PMTs



	MEG	MEG II
Position	5 mm	2.4 mm
Energy	2.4%-1.7%	1.7%
Timing	67 ps	60ps

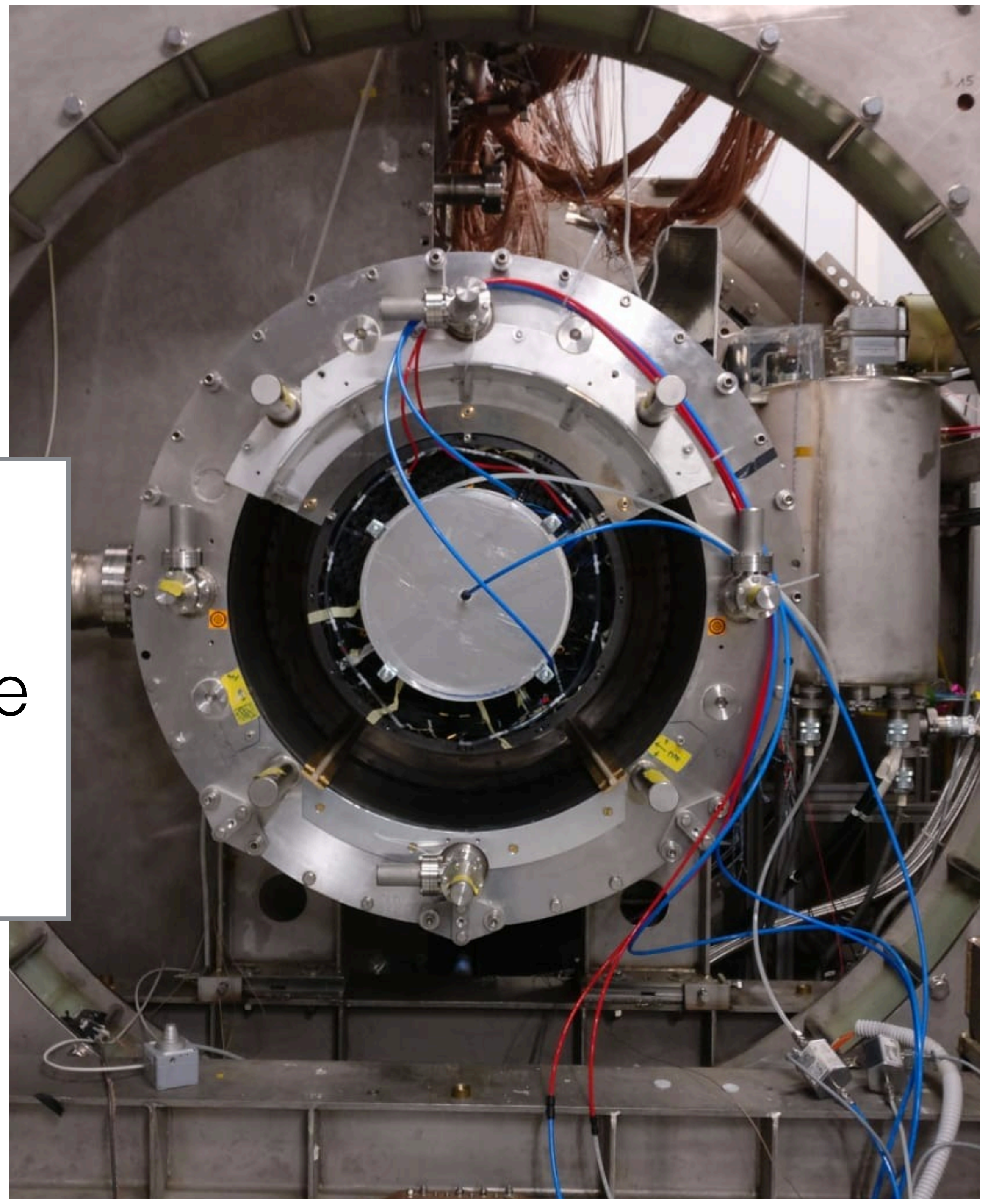
More details: Poster #332
“Commissioning of Liquid Xenon Gamma-Ray Detector for MEG II Experiment”
by A. Matsushita

The Cylindrical Drift Chamber

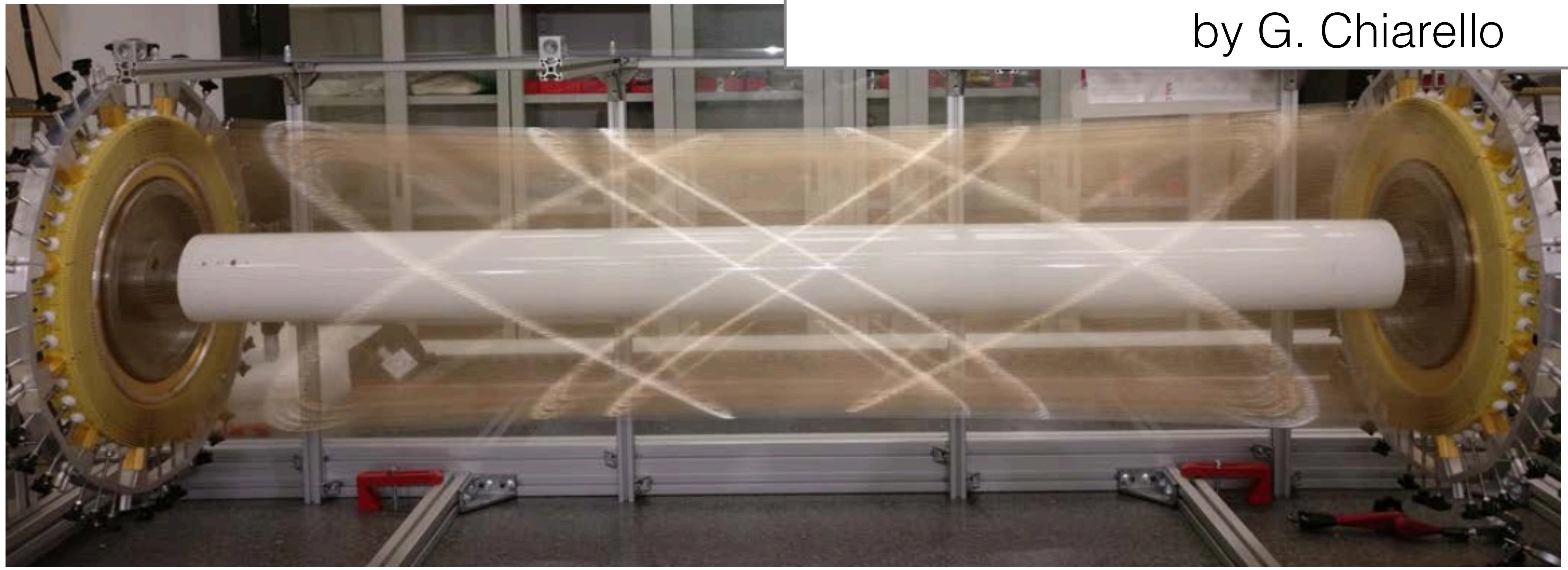


Single volume stereo drift chamber with He:Isobutane

- 1.5 10^{-3} X_0 per turn
- Drift cells 6mm x 6mm to cope with pileup (PCB-based construction)
- ~65 hits per track (MEG: ~12)

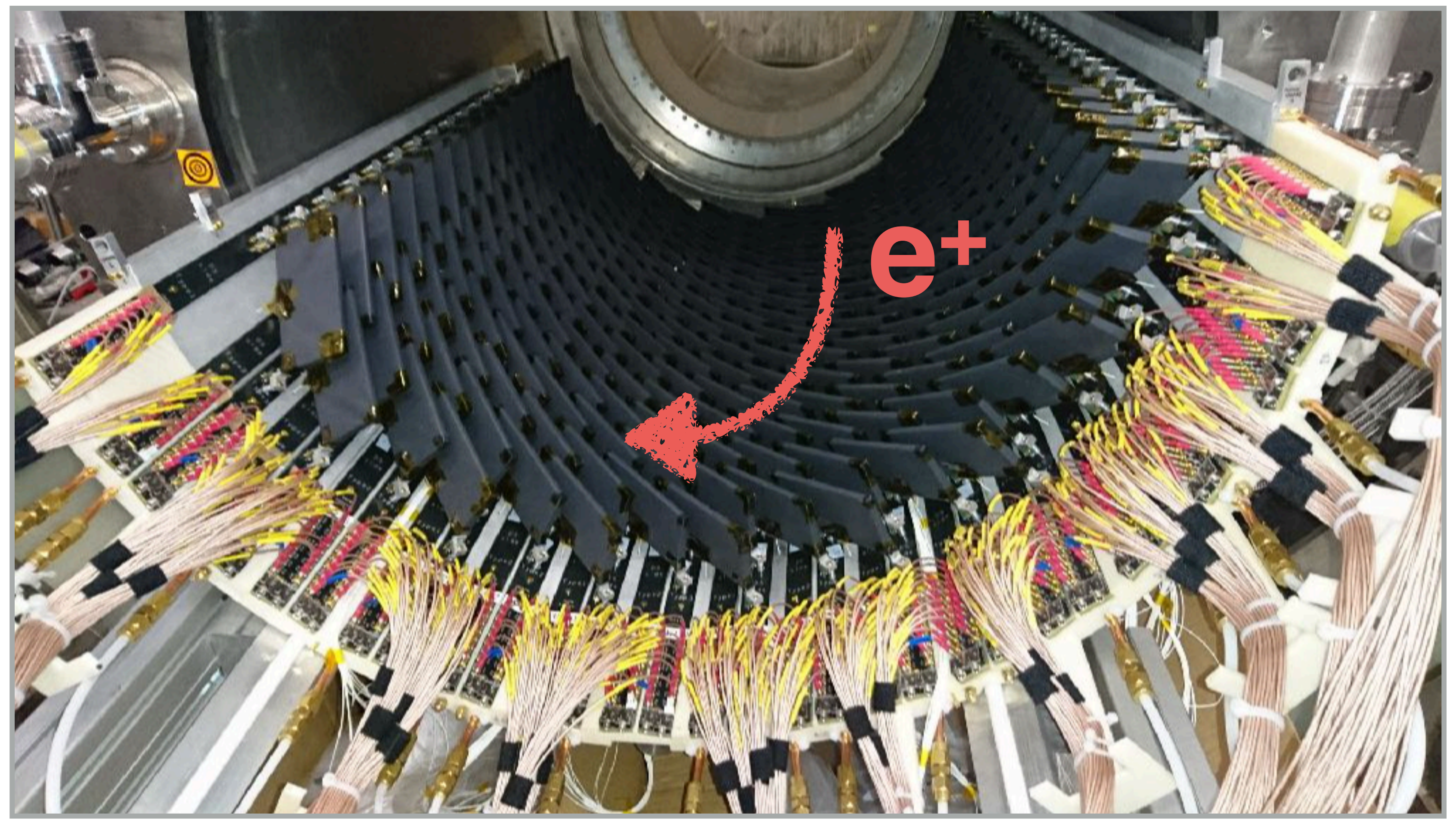


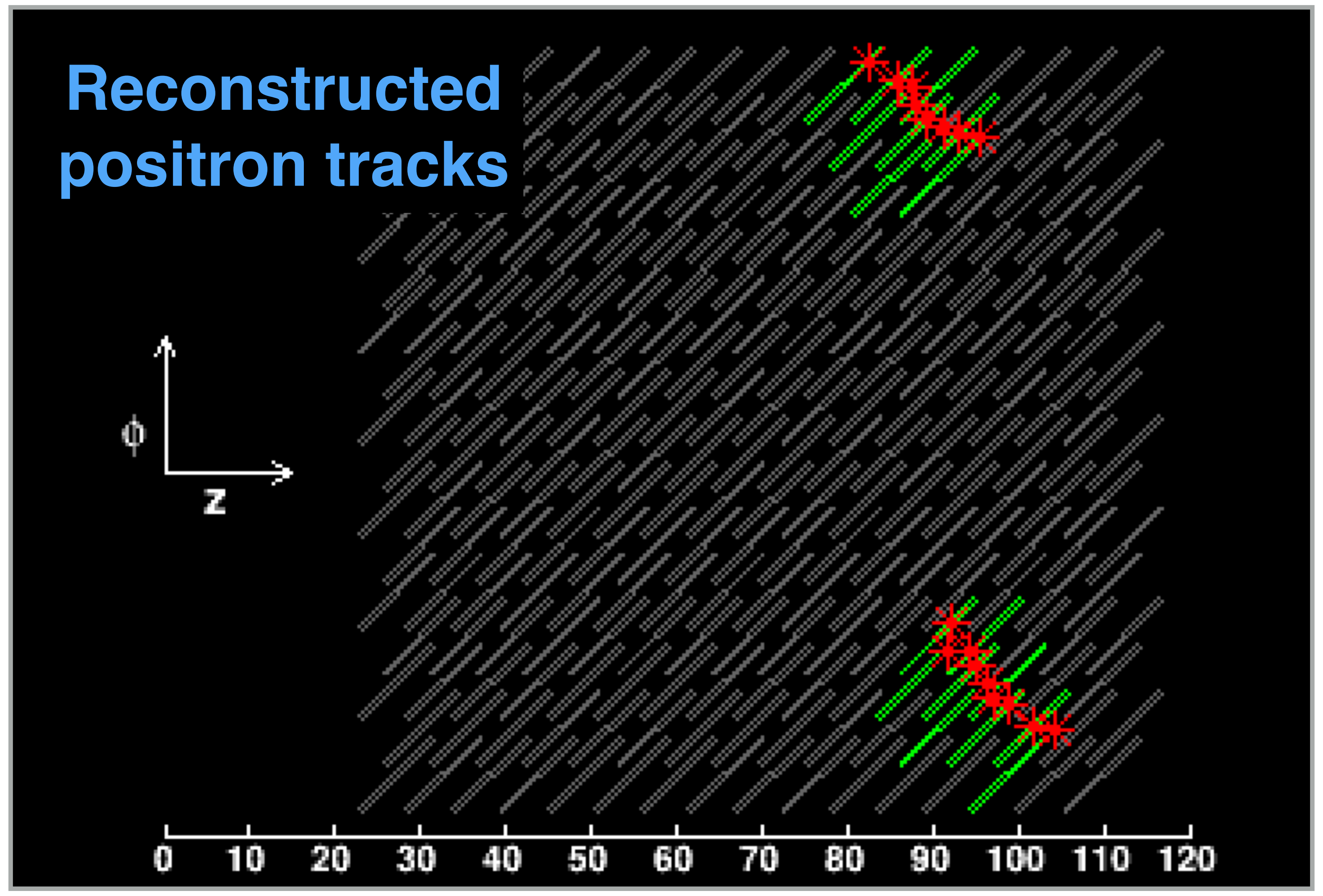
More details: Poster #236
"Analysis and study of the problems on the wires used in the MEG CDCH and the construction of the new drift chamber"
by G. Chiarello



	MEG	MEG II
Efficiency	29%	65%
Theta	9.4 mrad	6.7 mrad
Momentum	306 keV/c	100 keV/c

The pixelated Timing Counter



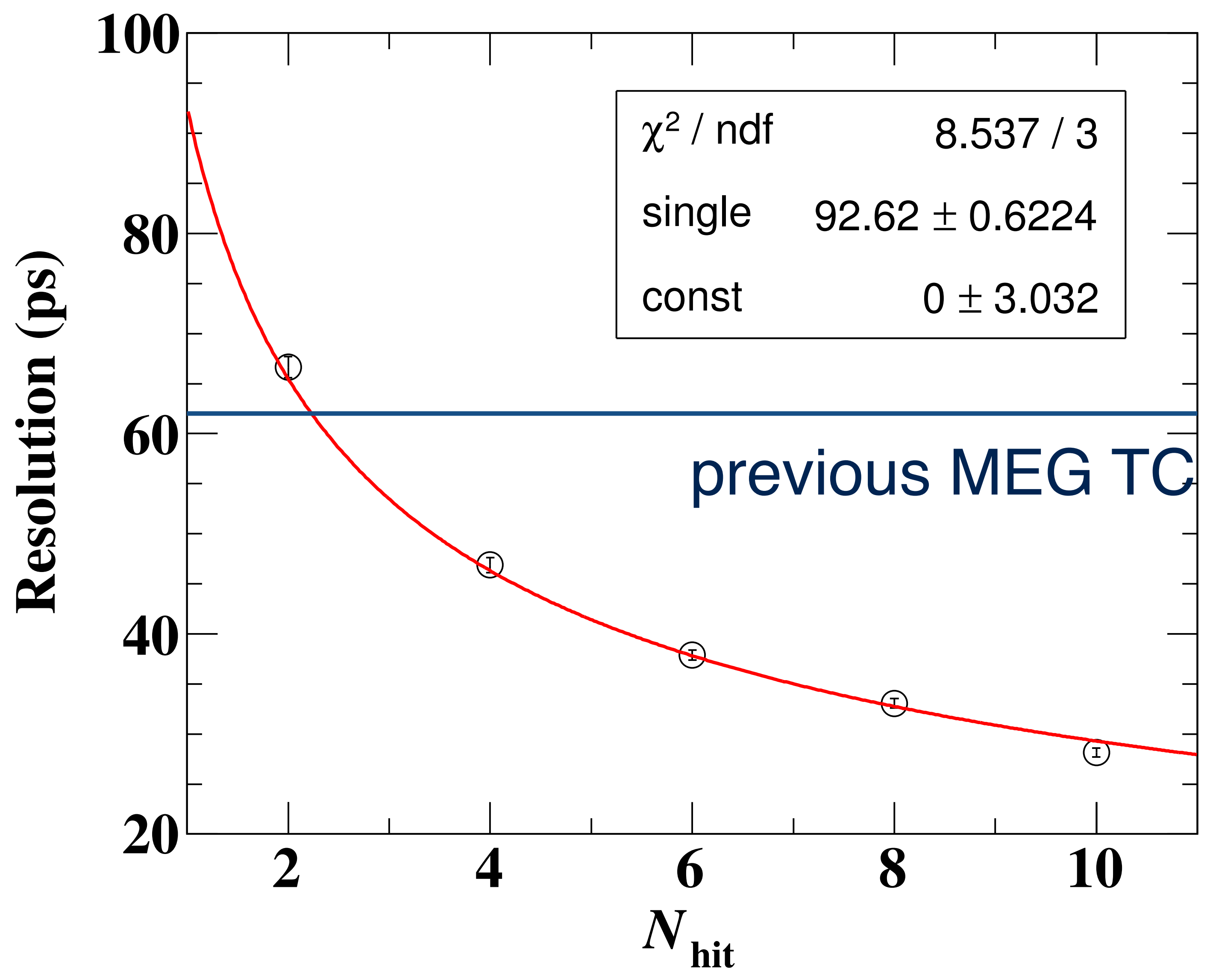


More details: Poster #184
“Operational results with the pixelated timing Counter (pTC) of the MEGII experiment during the first year of physics data taking”
by P.W. Cattaneo

Final detector fully tested with **full beam intensity** (7 10^7 μ/s):

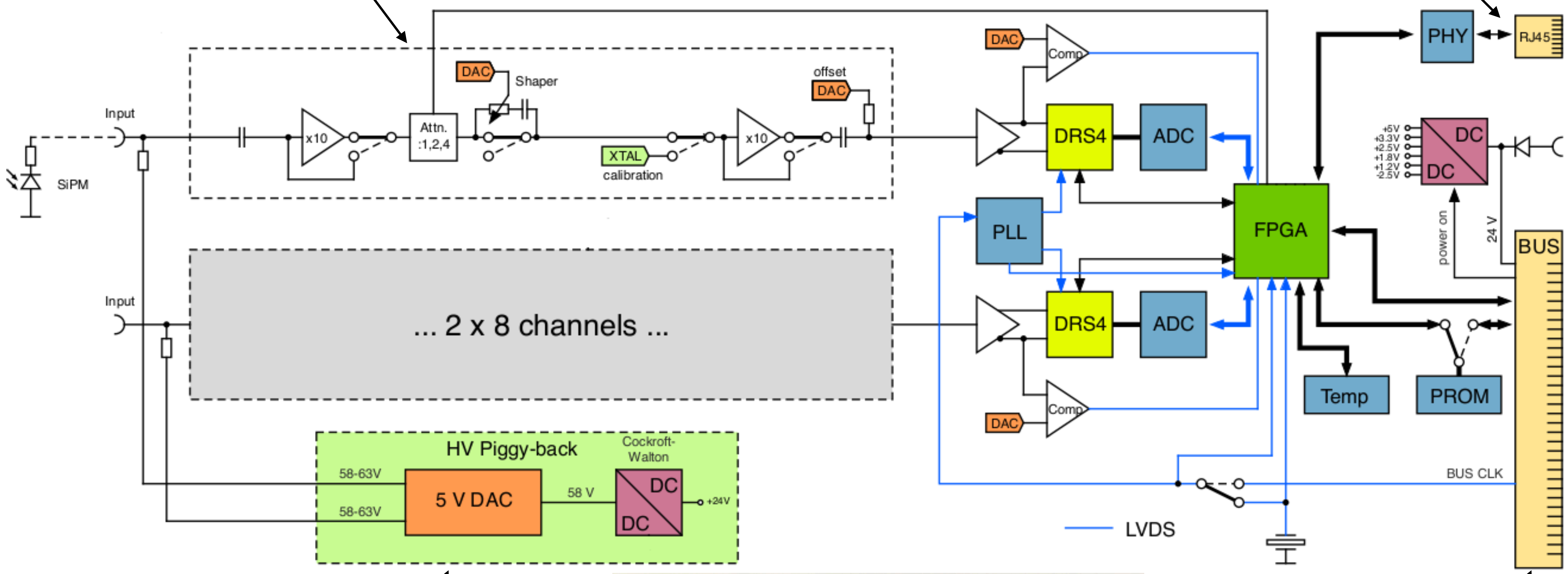
- 256 scintillating “Tiles” per module
- Multiple hits belonging to the same **positron track**
- Tracking capability to seed CDCH tracks
- Auxiliary Laser for stability monitoring

	MEG	MEG II
Timing	62 ns	30 ns

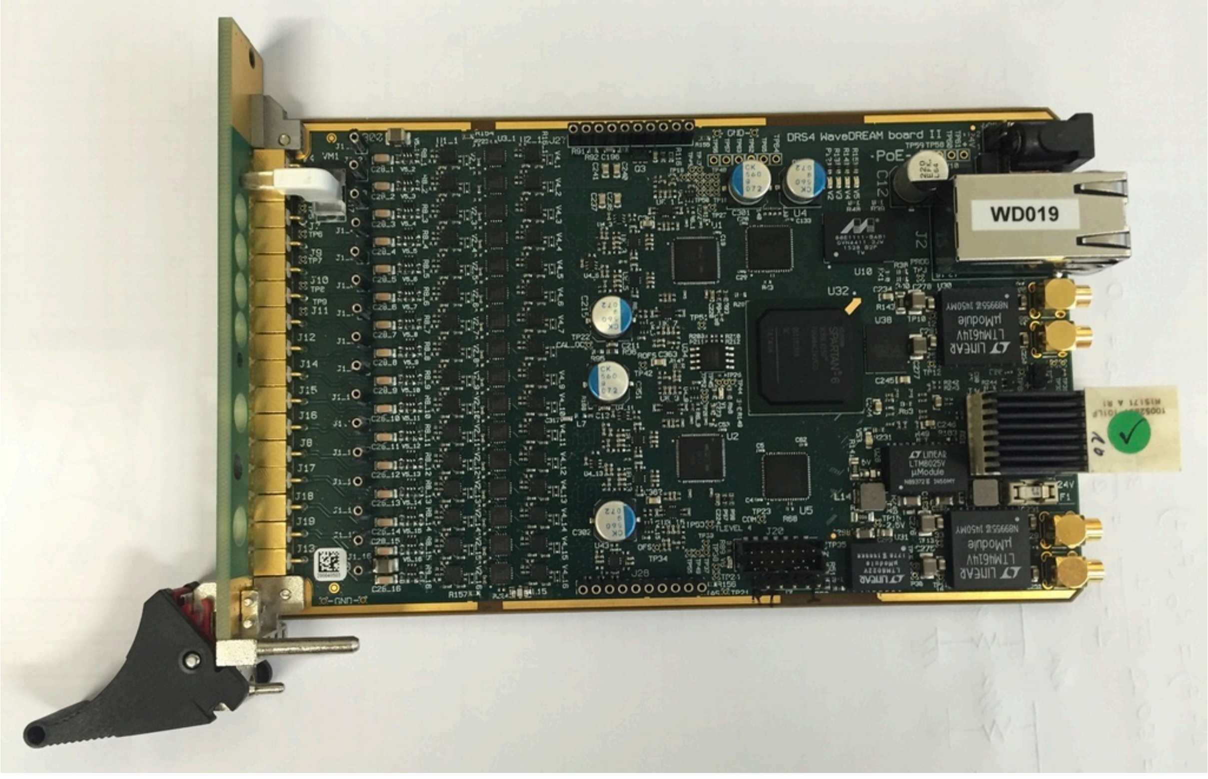


Analog Frontend

Ethernet readout

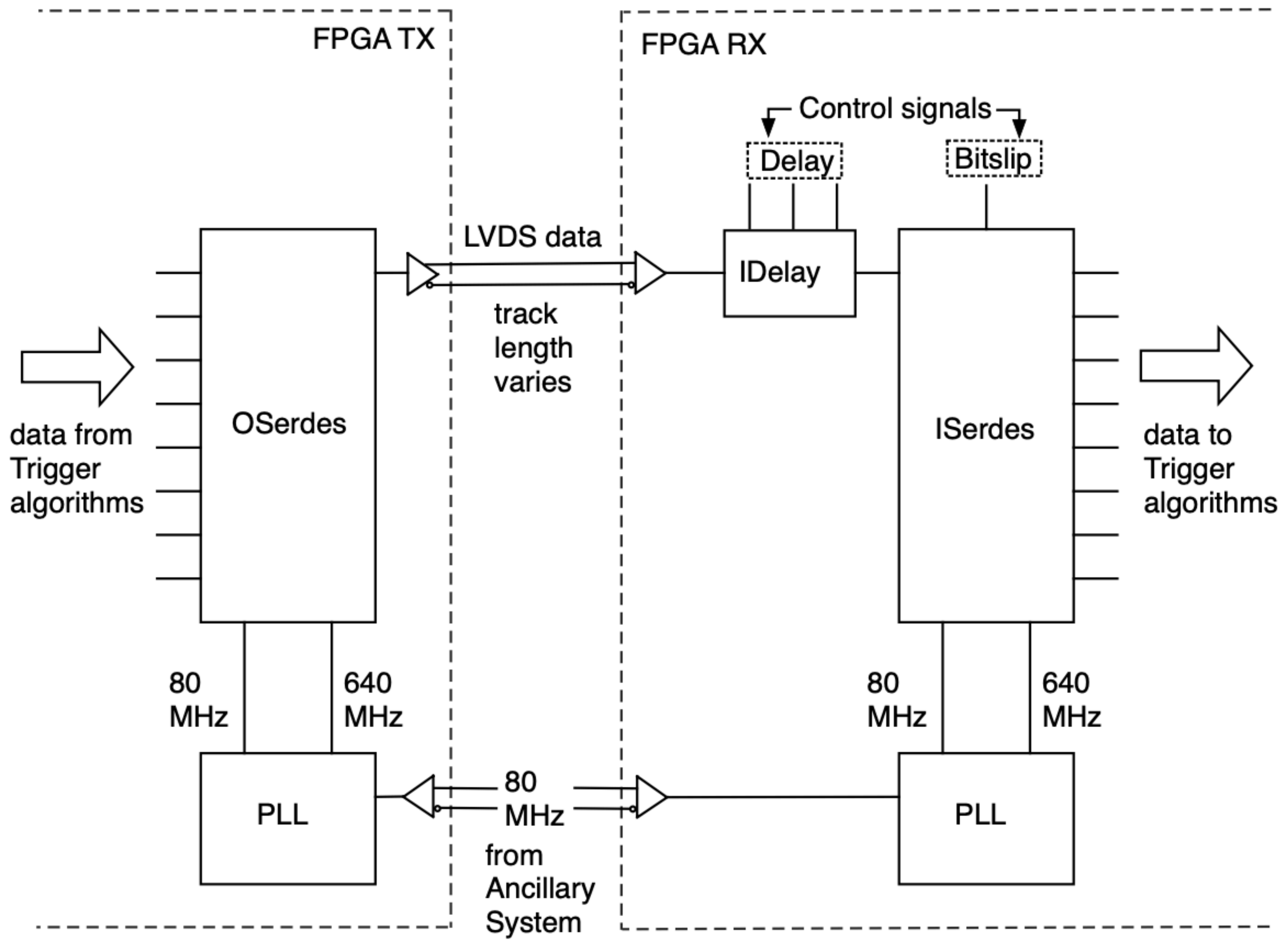


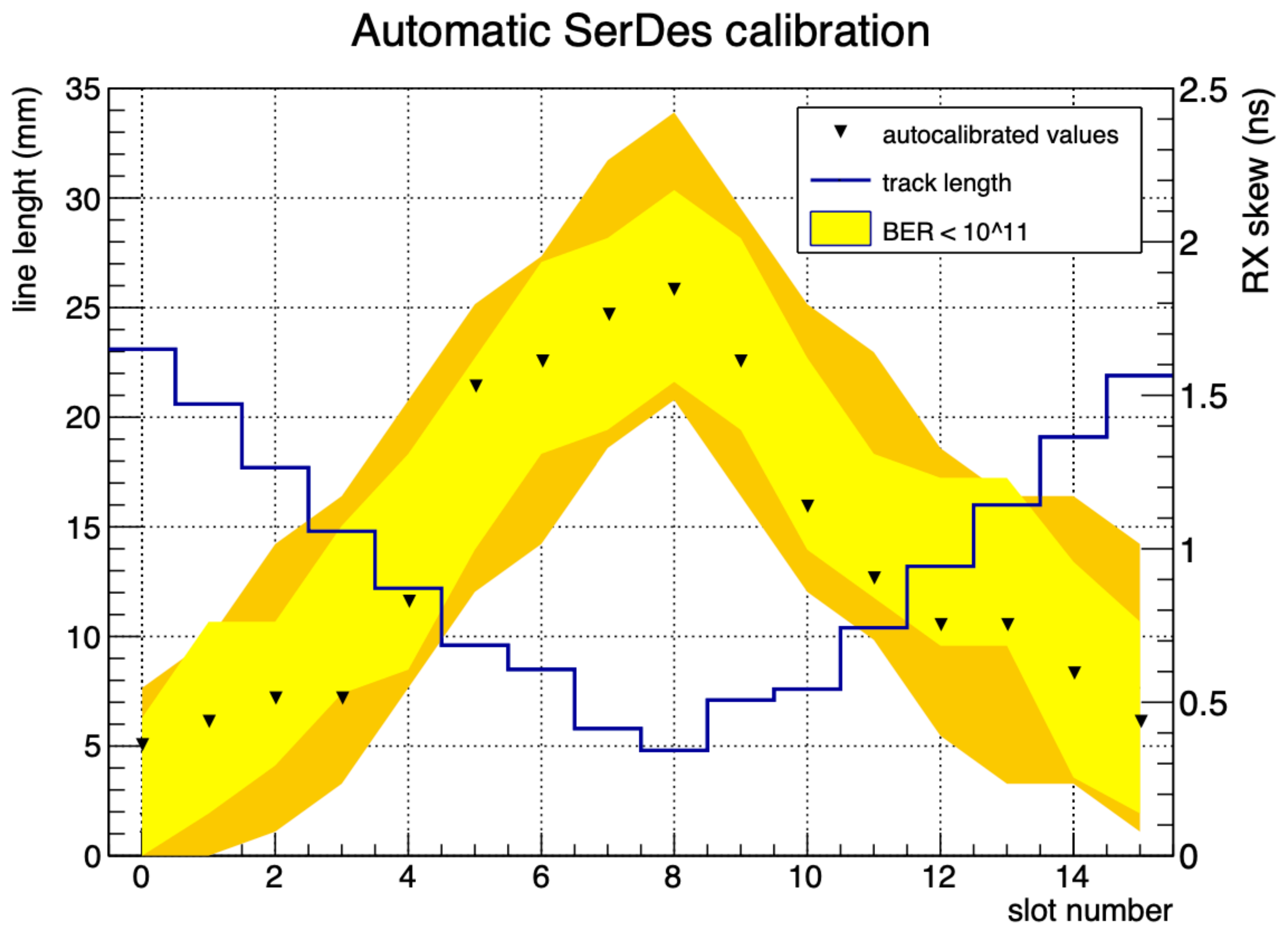
SiPM biasing



Crate connector

Serial links





8 bit word sent each clock period: 640 Mbps with 3 clk cycles latency

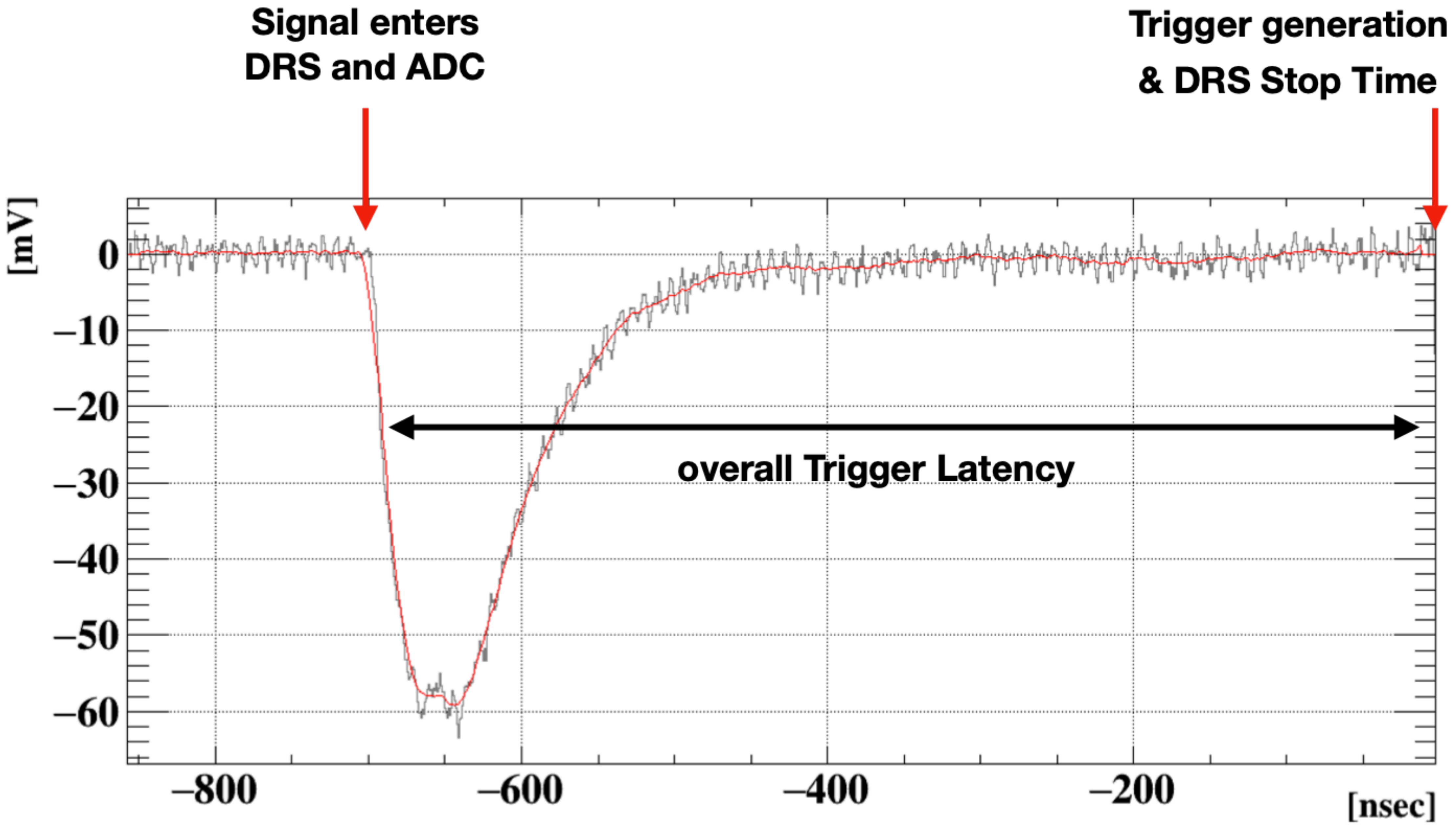
Backplane track length different for each slot

Delay to sample “value" stable moment

Bitslip to align characters whitin each word

Automatic slot by slot calibration needed → Finite State Machine

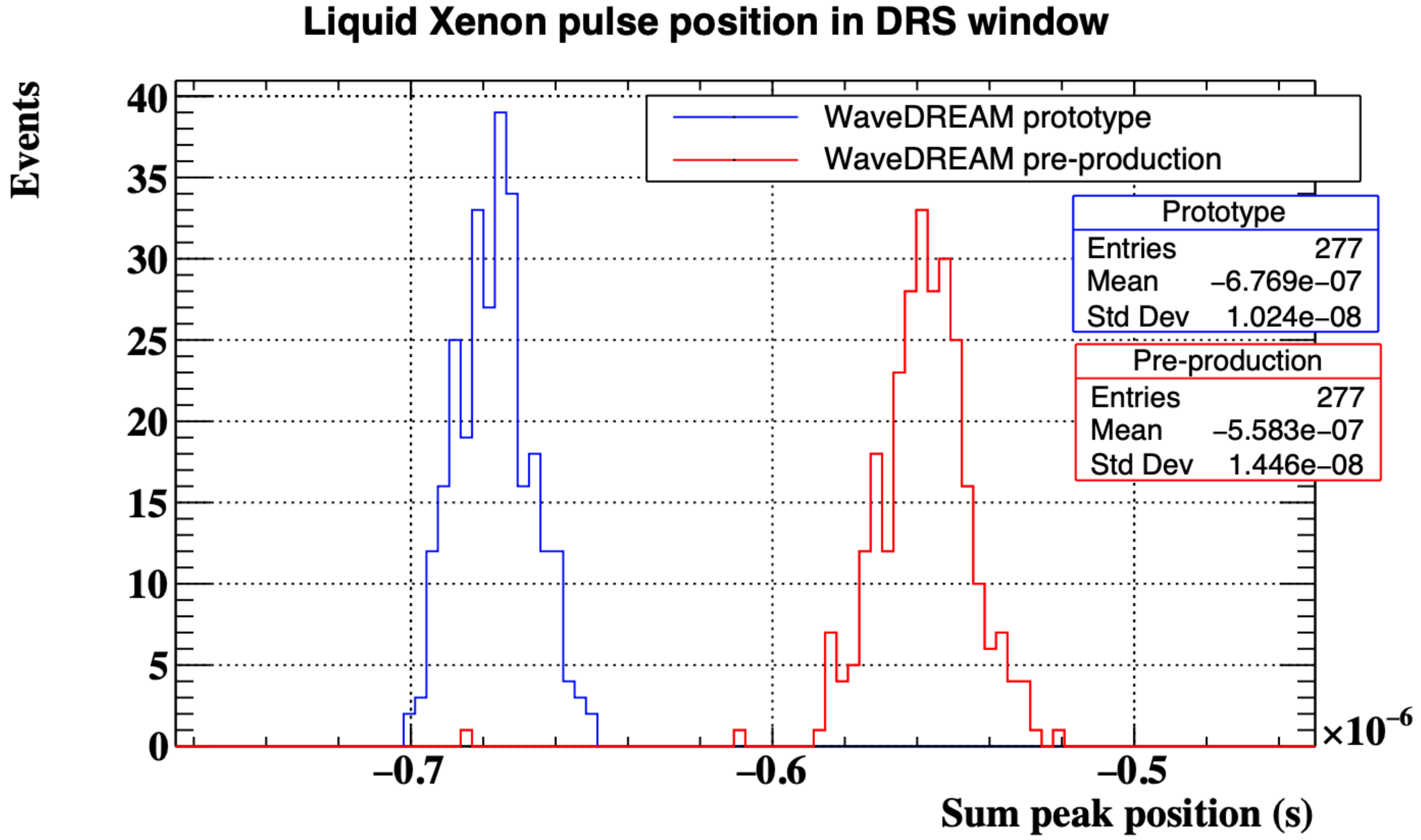
Trigger latency



Constraint on additional baseline for offline analysis

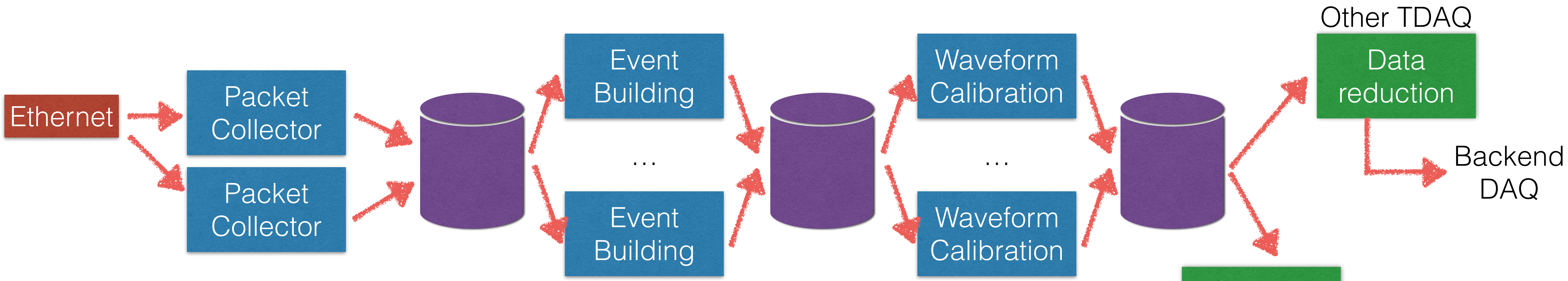
Trigger latency translate in peak position in the DRS4 window

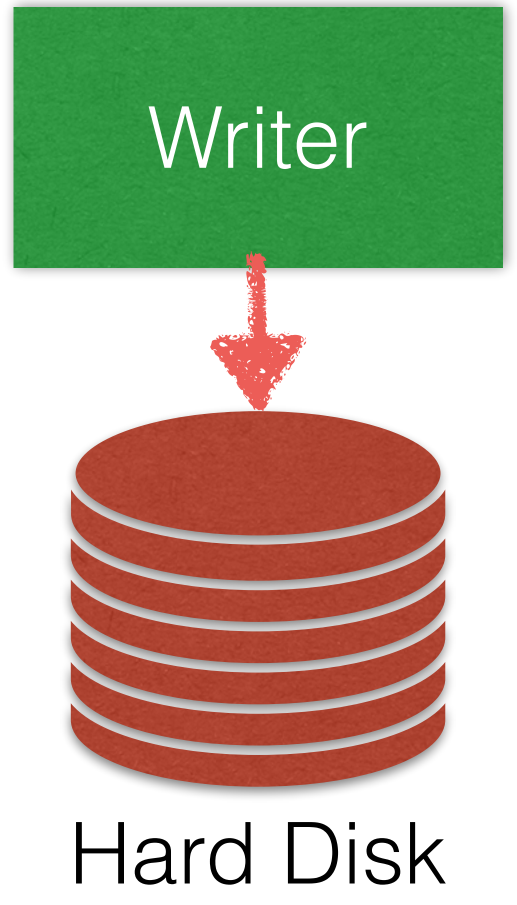
If it exceed 1024/f_{DRS} the signal falls outside DRS snapshot window



Final WaveDREAMs have a **quicker ADC**:
Still 80 MHz speed but smaller latency
Trigger latency improved by ~120 ns
Current algorithms run in 560 ns
  1.8 GHz sampling speeds possible

Multithreaded DAQ system





TDAQ Software completely written in c++11:

- High parallelization
- Tailored to MEG II TDAQ needs
- Use new c++ thread interface
- Provides key-value storage of board parameters
- Can add other stages
  (zero suppression, feature extraction…)
- Optional disk writing or interface with other DAQ software (MIDAS for MEG II)
- Flexibility to face system scaling:
  - More packet collectors
  - More Waveform Calibration threads

The challenge of datasize and dead time

Main drawbacks of high speed digitizers approach:

Huge single-channel data size:
1.5 KB/waveform

↓

Enormous uncompressed event:
12.4 MB/event

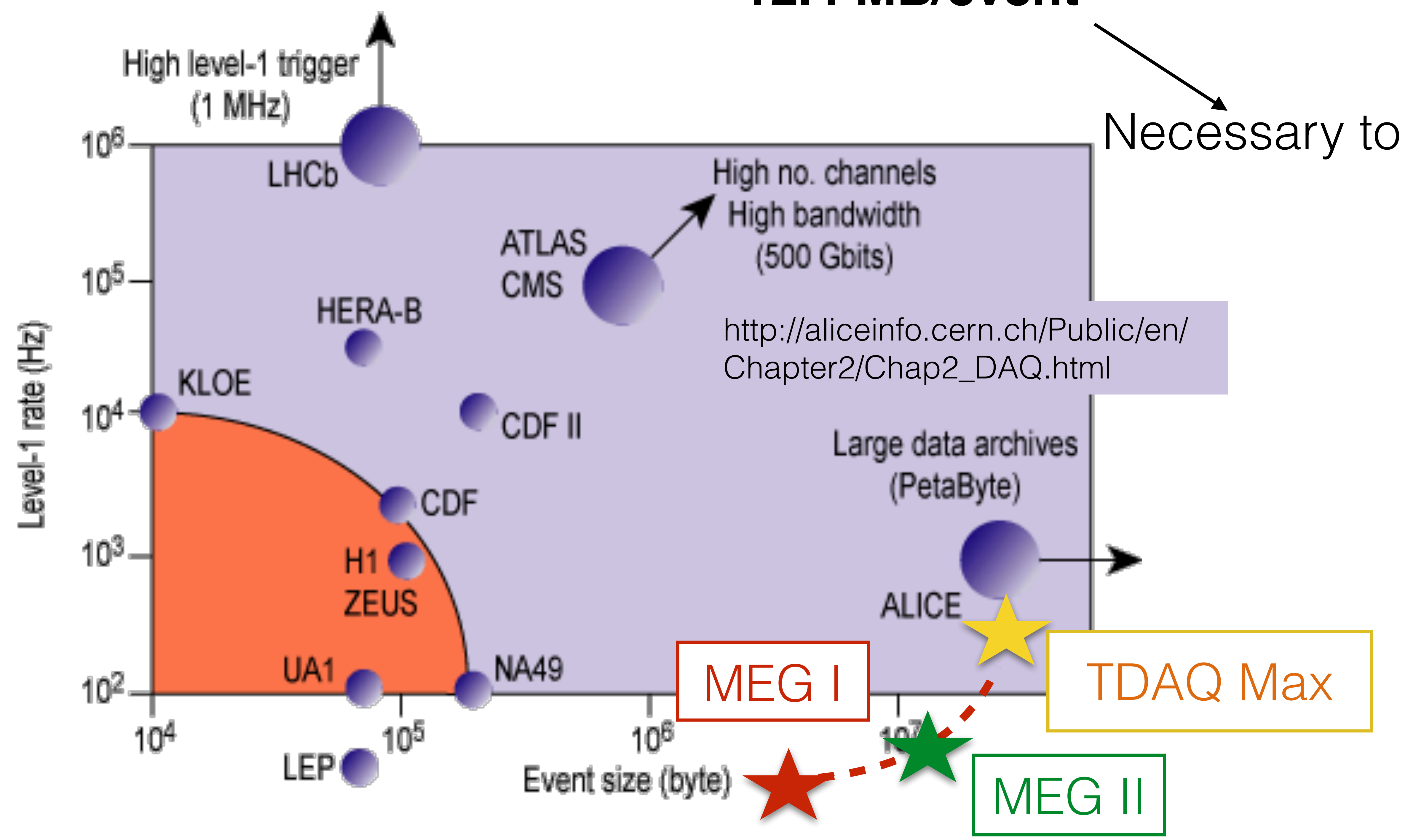
DRS4 does not convert data in real time

↓

Takes 375 μs to download the samples after a trigger is generated

Continuous beam:
dead time = event loss

Necessary to limit the DAQ rate



Goal 24 Hz Trigger rate:
Live time fraction is 99%

Data taking perspectives, depending on annealing