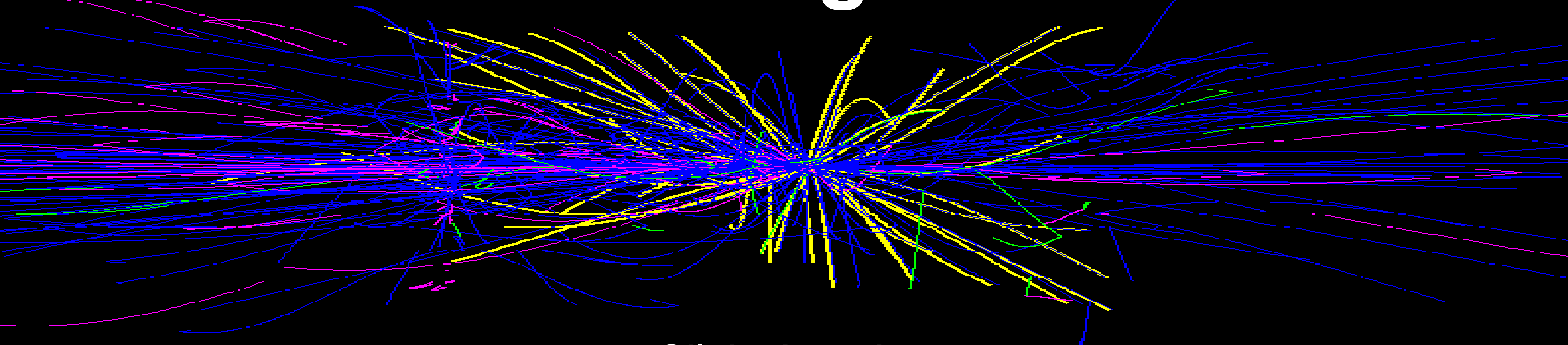
35th International Conference
on High Energy Physics
Paris, 22-28 July 2010

Online tracking at colliders



Silvia Amerio
INFN Padova

Why online tracking?

A good trigger system needs to combine **data reduction** with **sophisticated physics selection** to increase the purity of the collected sample.

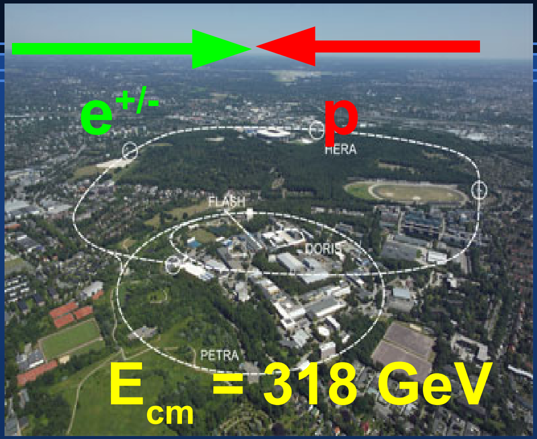
Online tracking allows accurate reconstruction of crowded events (high luminosity --> pile-up) in time for a trigger decision:

- a calorimetric tower integrates energy from all the particles in the event --> it cannot distinguish between hard scattering and pile-up
- online tracking **can distinguish particles based on their z and p_T**

Online tracking is challenging!

- Time constraints: track reconstruction in few μs at L1, ~ tens of μs at L2
- High number of readout channels
- High occupancy --> large combinatorics

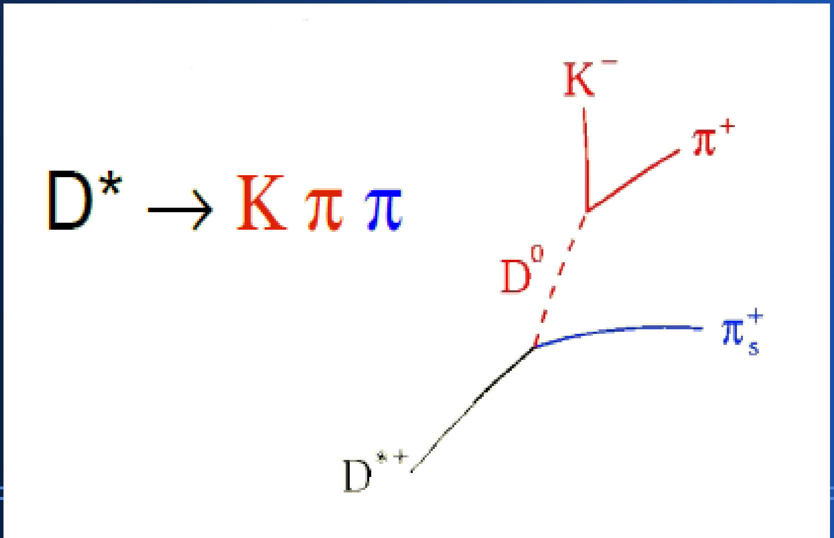
Why online tracking?



$L = 2\ 10^{31}\ cm^{-2}s^{-1}$

Fast Track Trigger

(FTT, 2004-2007)



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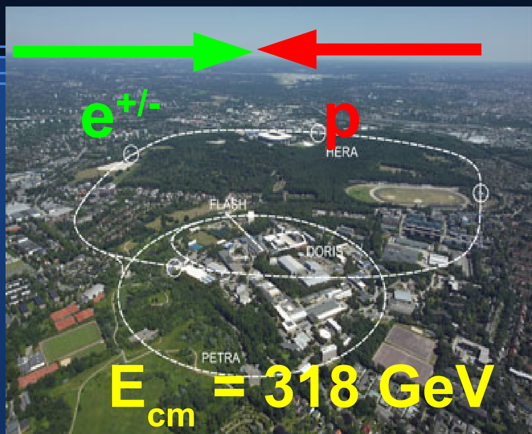
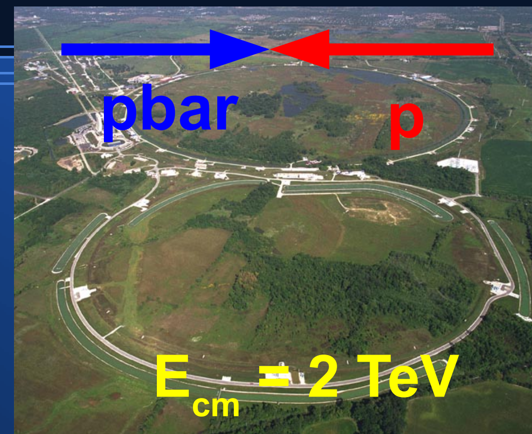




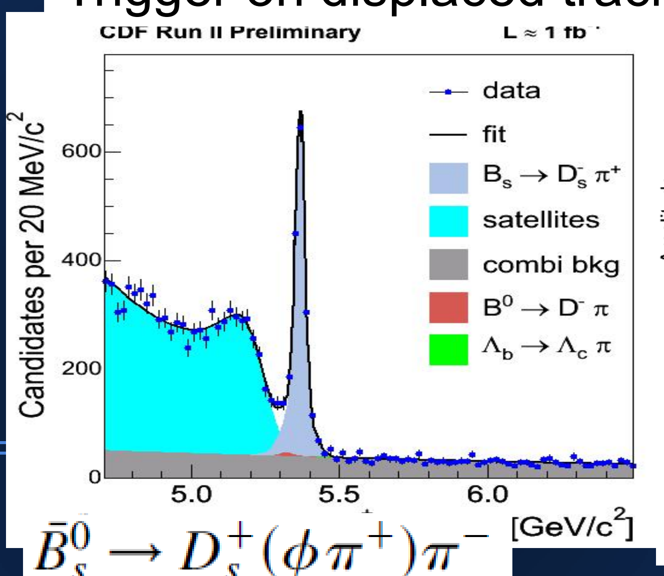
Silicon Vertex Tracker (SVT)

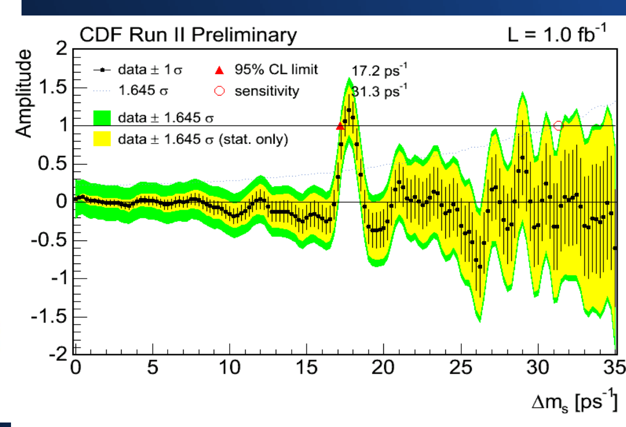
L = 2 10^{31} $cm^{-2}s^{-1}$

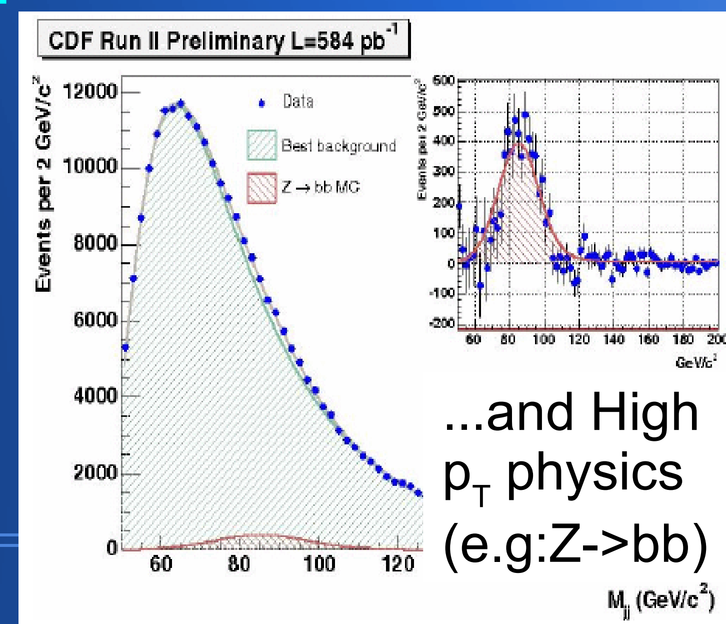
L = 3 10^{32} cm^{-2} s^{-1}

6 pp int/evt

Trigger on displaced tracks for B ....

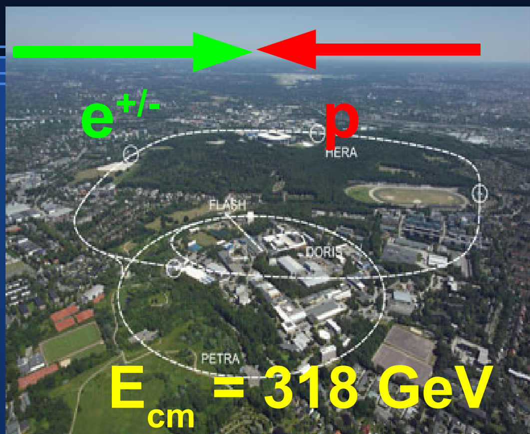


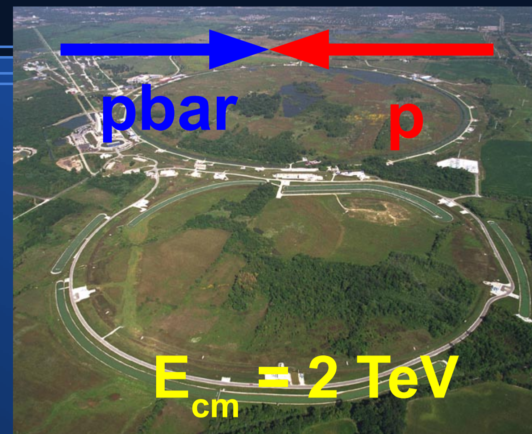


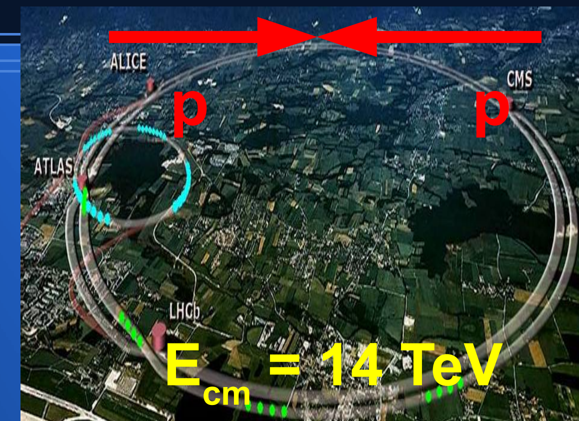


...and High p_T physics (e.g:Z->bb)

Why online tracking?







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$L = 3\ 10^{32}\ cm^{-2}\ s^{-1}$

6 pp int/evt

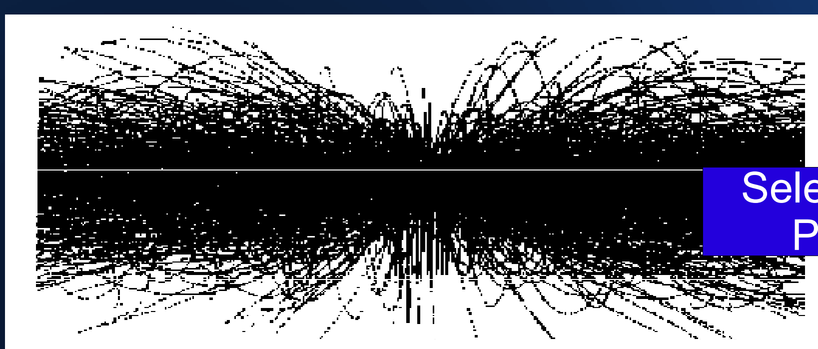
LHC : $10^{34}\ cm^{-2}\ s^{-1}$

SLHC: $3\ 10^{34}\ cm^{-2}\ s^{-1}$

$10^{35}\ cm^{-2}\ s^{-1}$

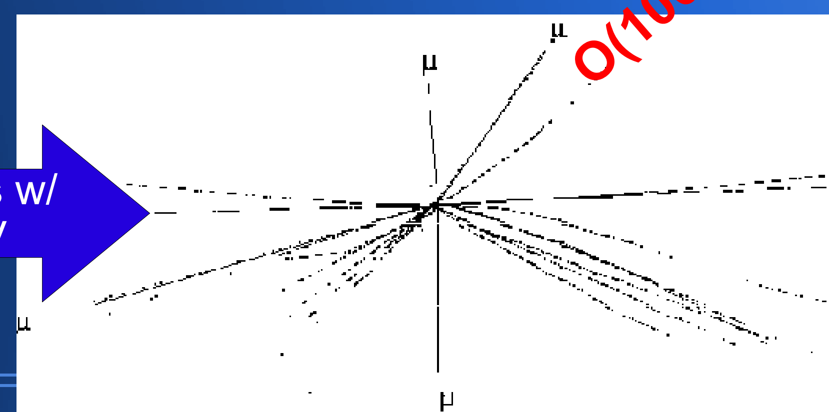
O(100) pp int/evt

ATLAS and CMS proposals for SLHC

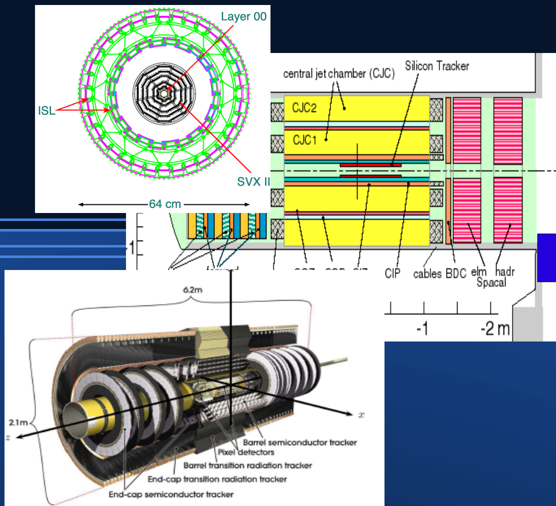


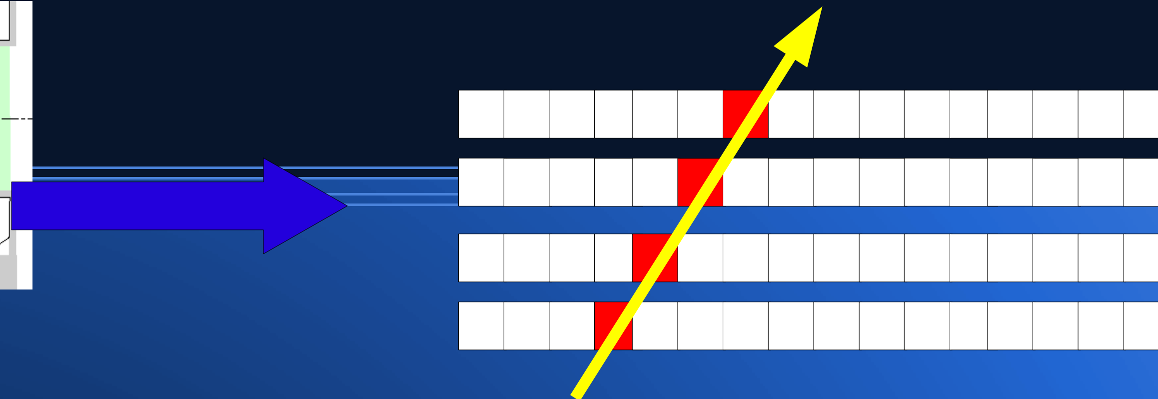
30 minimum bias events + H -> ZZ

Select tracks w/ Pt > 2GeV



Track identification: Pattern Matching





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- Each charged particle generates a **hit pattern**

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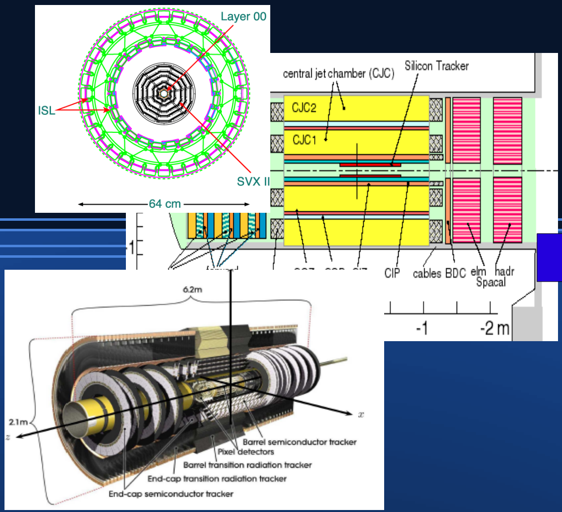

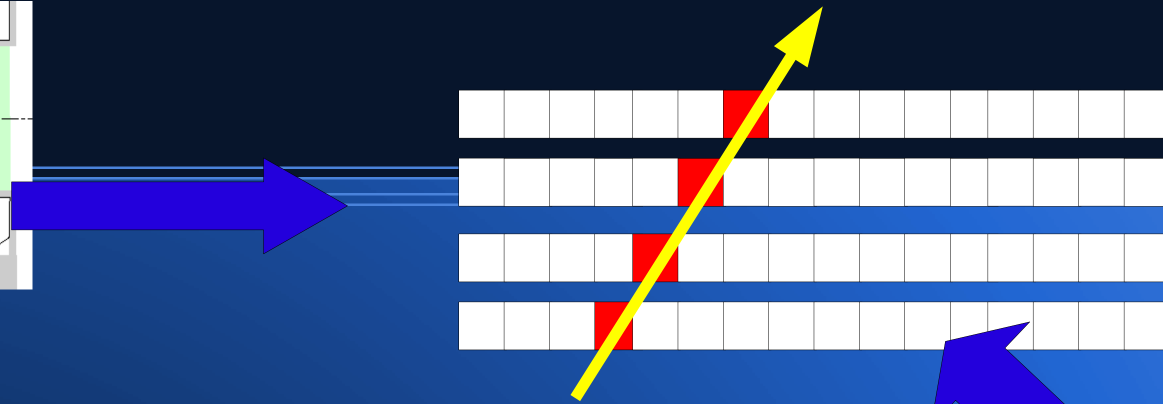

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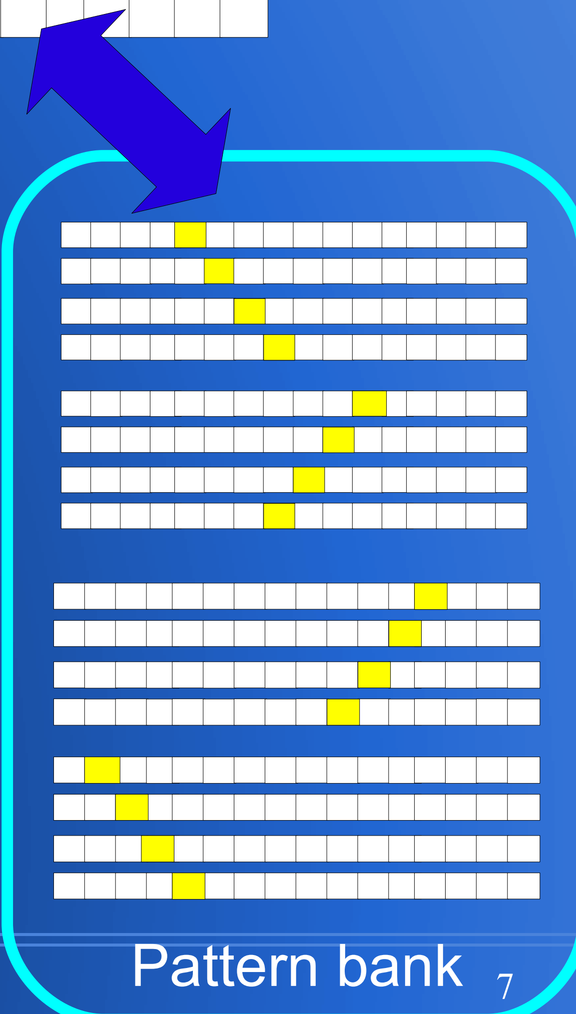
- All possible hit patterns stored in memory **(pattern bank)**

- Hit pattern matching a precomputed pattern = **Candidate Track**



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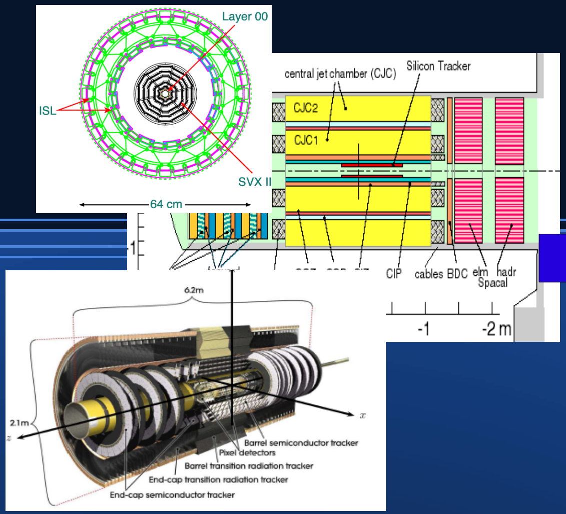

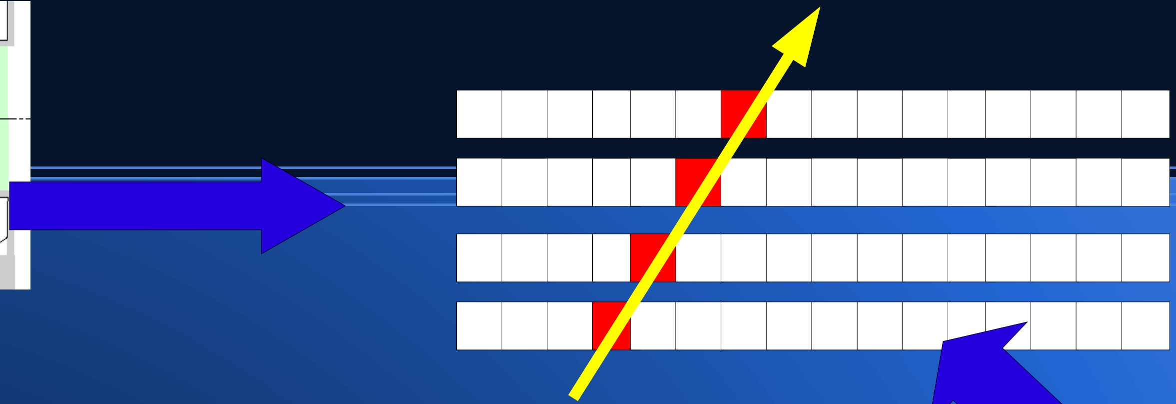

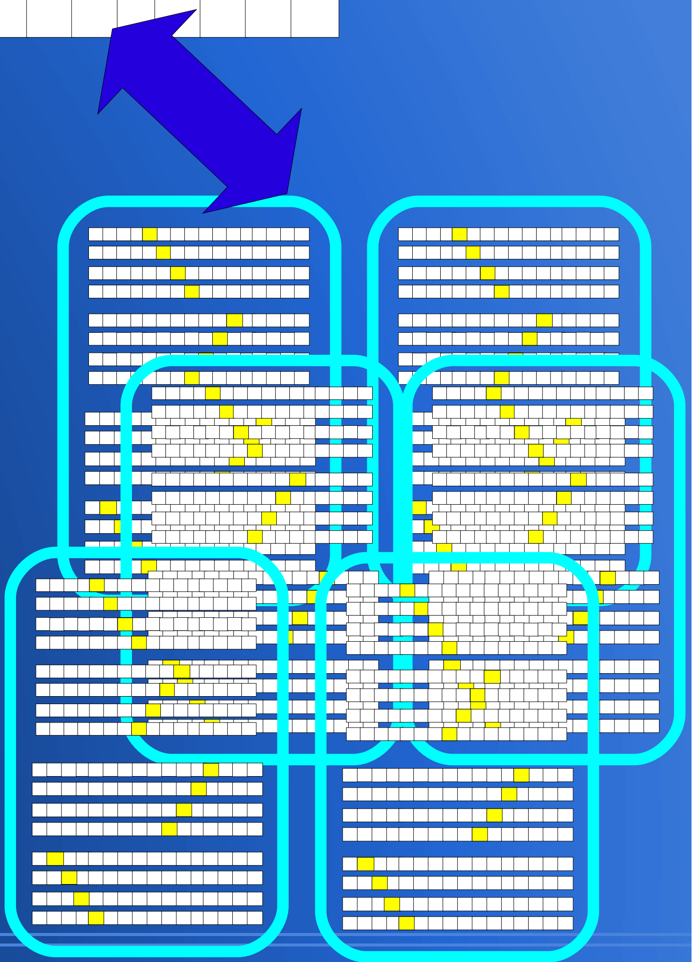

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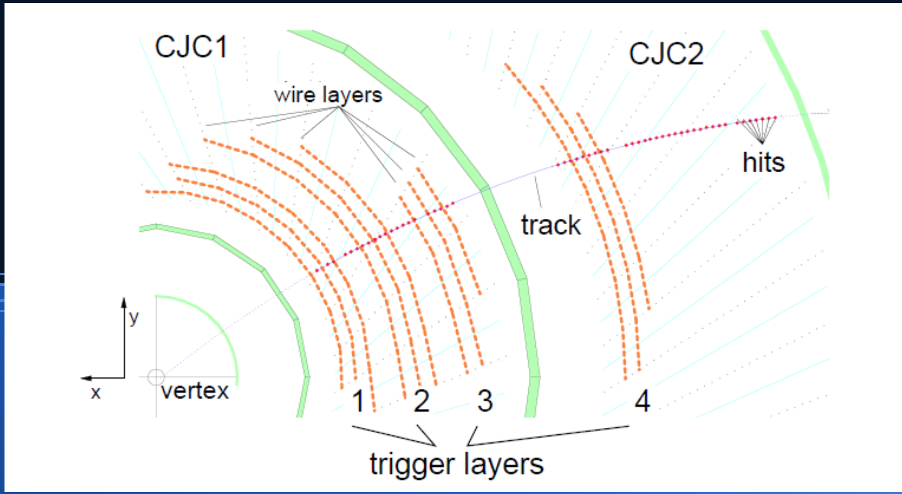
High degree of parallelism (Associative Memory or commercial Content Addressable Memories) to increase speed.

The Fast Track Trigger @ H1



L1 bandwidth is limited → use only a subsample (12/56) of the drift chamber layers

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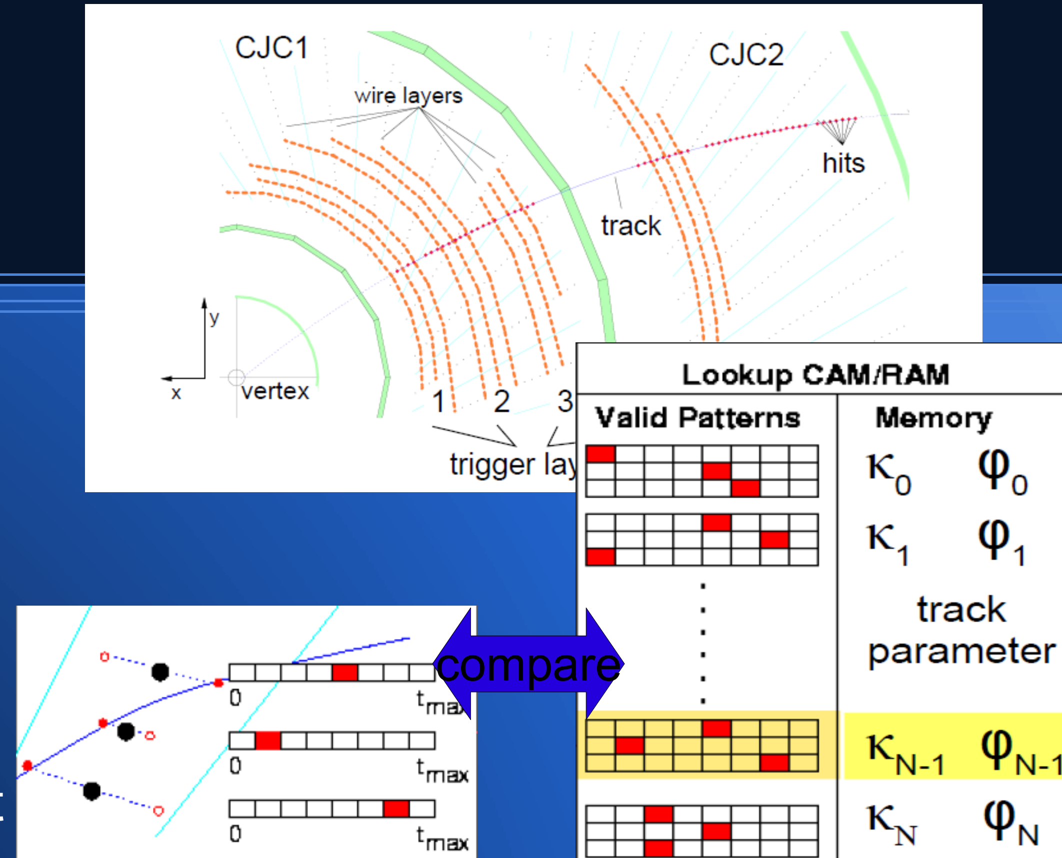

L1: Find **track segments** and **link them into tracks**.
L2: Repeat linking step at full resolution, **3D fit**
L3: reconstruct complex objects (invariant masses, jets)

CAMs in high density FPGA (Altera)
Working frequency 100 MHz

The Fast Track Trigger @ H1

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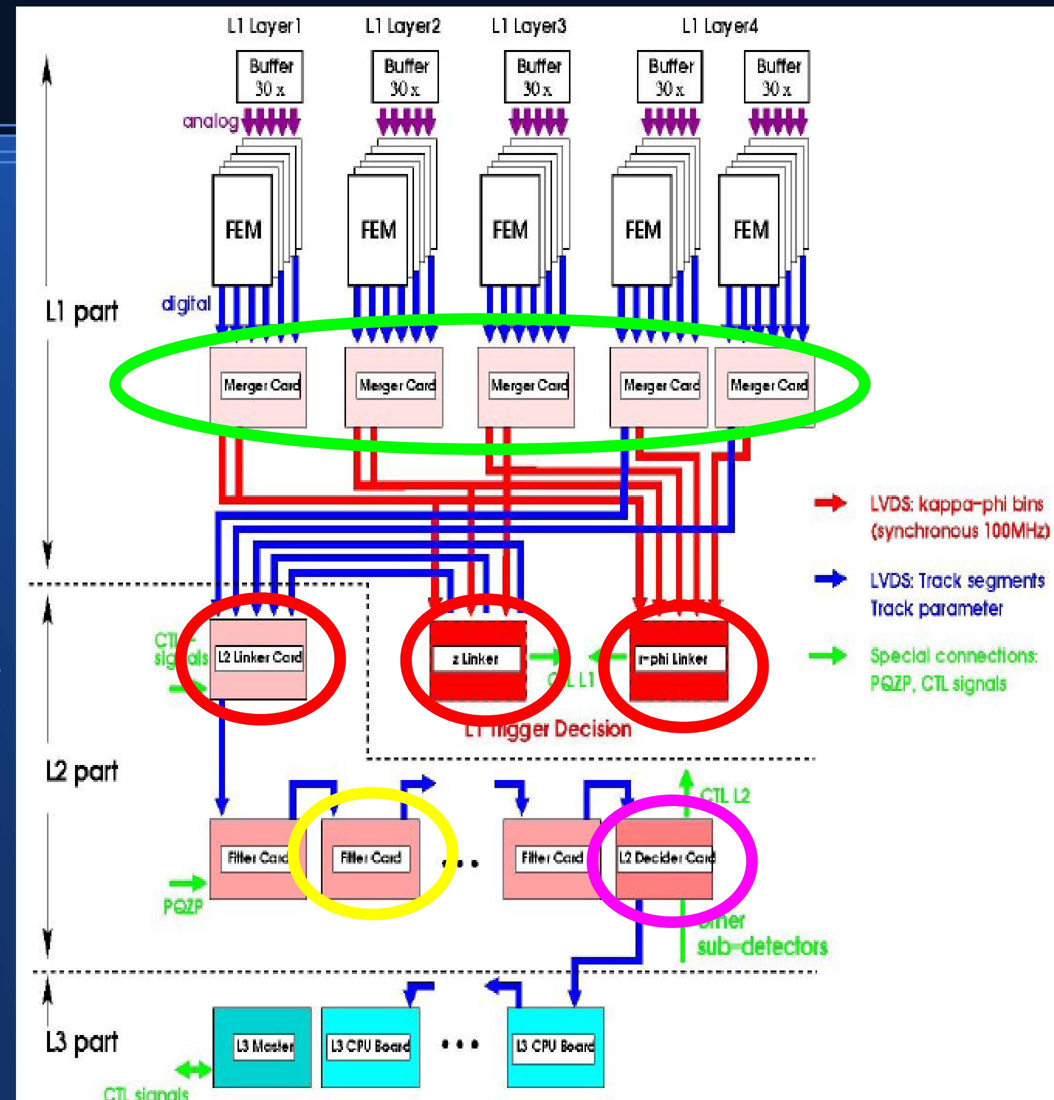
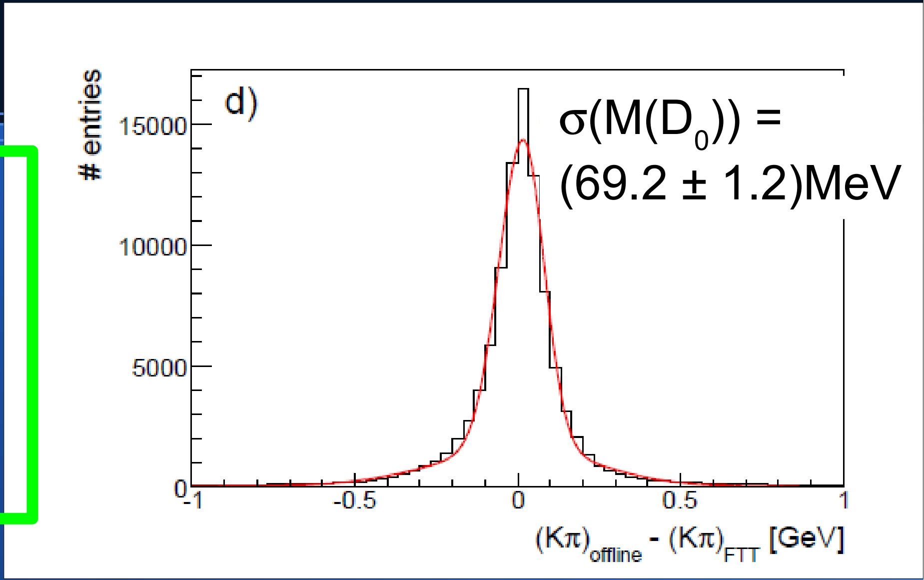


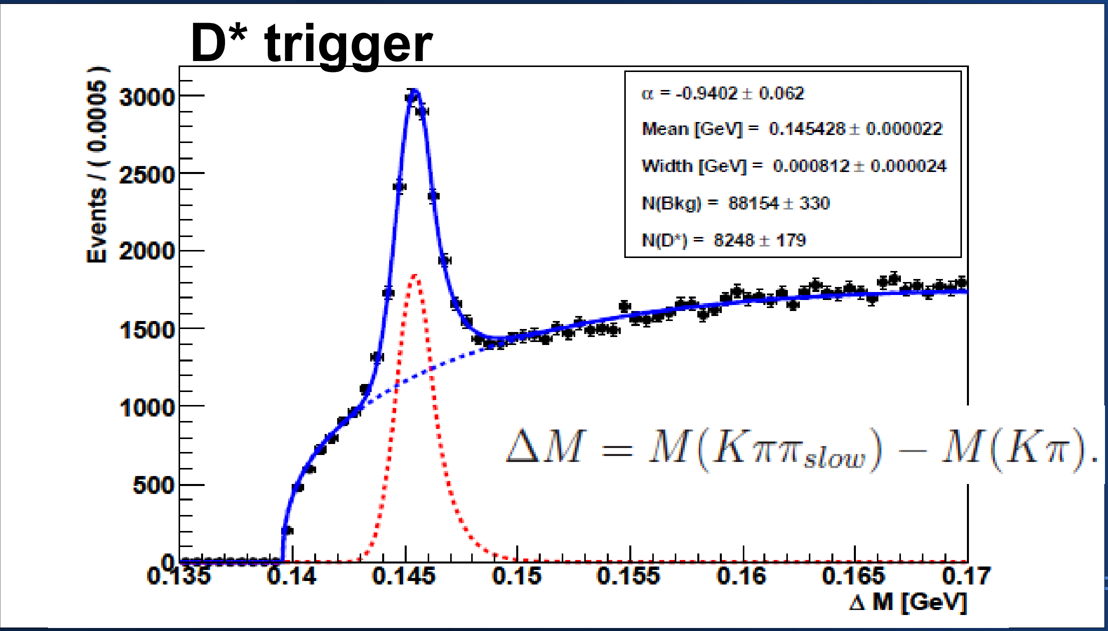
Based on a single flexible, multipurpose board (MultiFunctional Processing Board) that can

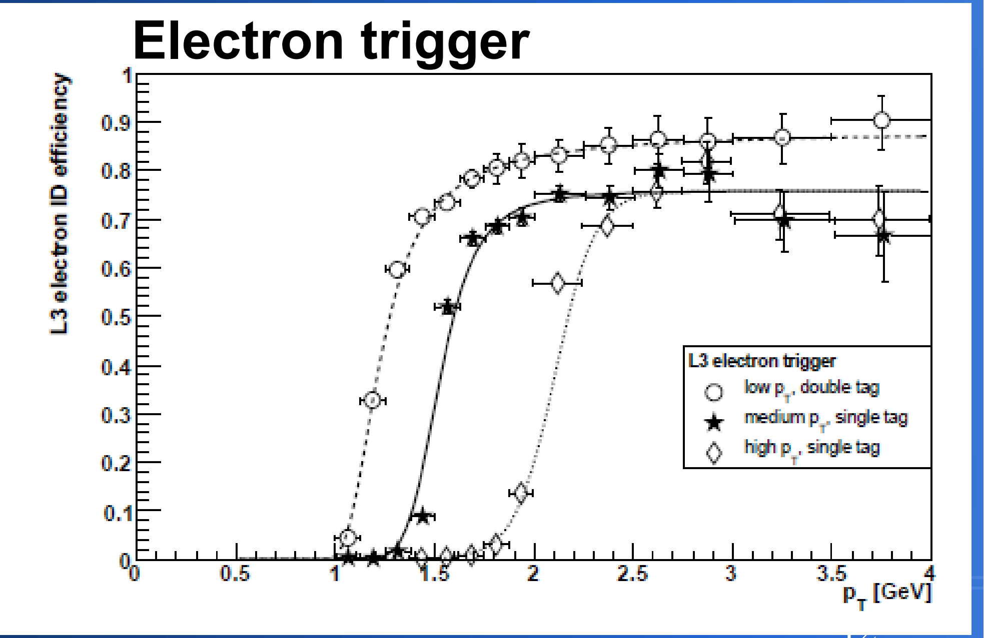
- Merge data streams
- Link track segments at L1 and L2
- Fit tracks at L2
- Make L2 decision

FTT performance

- Fit up to 48 tracks per event w/ pt > 100 MeV
- Resolutions:
  - $1/p_t \rightarrow 2.2\%/GeV$
  - $\vartheta \rightarrow 50$ mrad
  - $\phi \rightarrow 2.5$ mrad

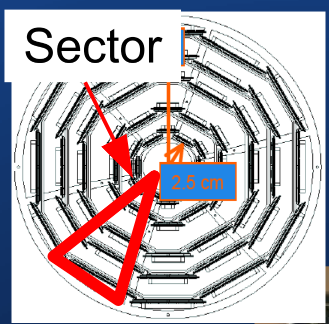




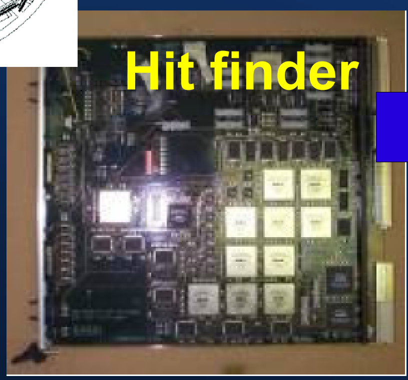


The Silicon Vertex Tracker @ CDF

1) HIGHLY PARALLEL ARCHITECTURE

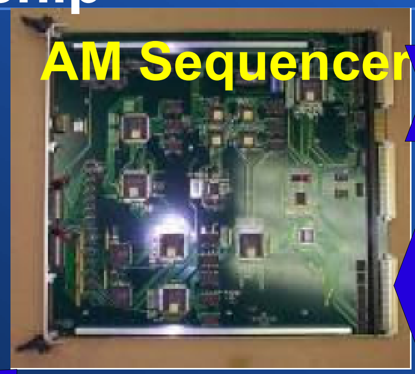


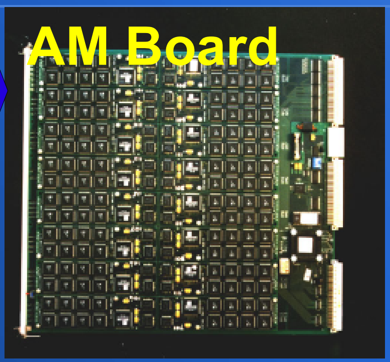
Detector Data



Hits

2) PATTERN RECOGNITION w/ custom VLSI Associative Memory chip





Matched patterns

Patterns + hits

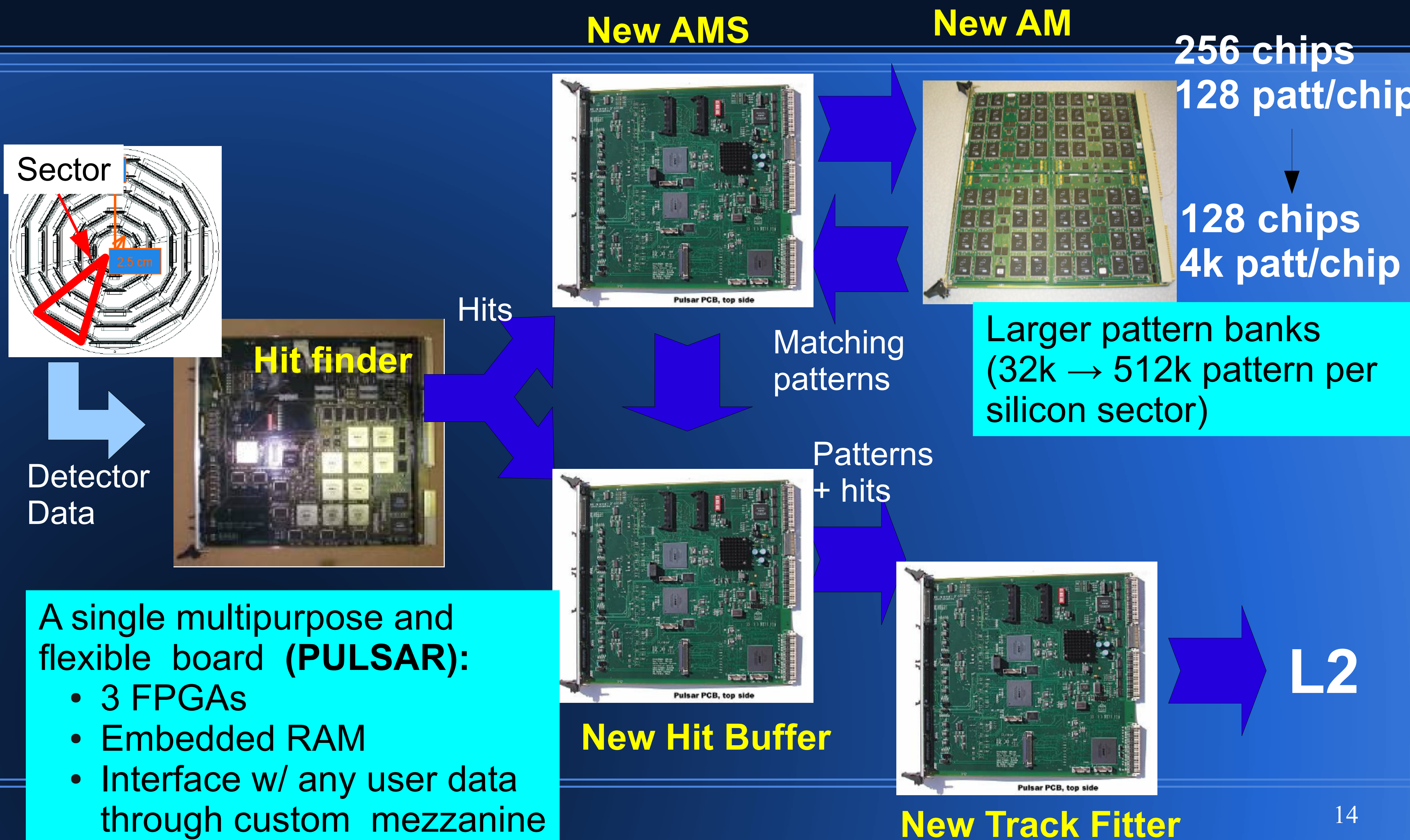
3) LINEARIZED FIT in fast FPGA

$$p_i = \vec{f}_i \cdot \vec{x} + q_i$$

L2

- Latency ~ 20 μs
- eff ~ 80% (p_T > 2 GeV, d_0 < 1 mm)
- **σ_{d0} ~ 35 μm**
- σ_{pT} ~0.003 pt^2
- σ_ϕ ~ 1 mrad

SVT (2006)



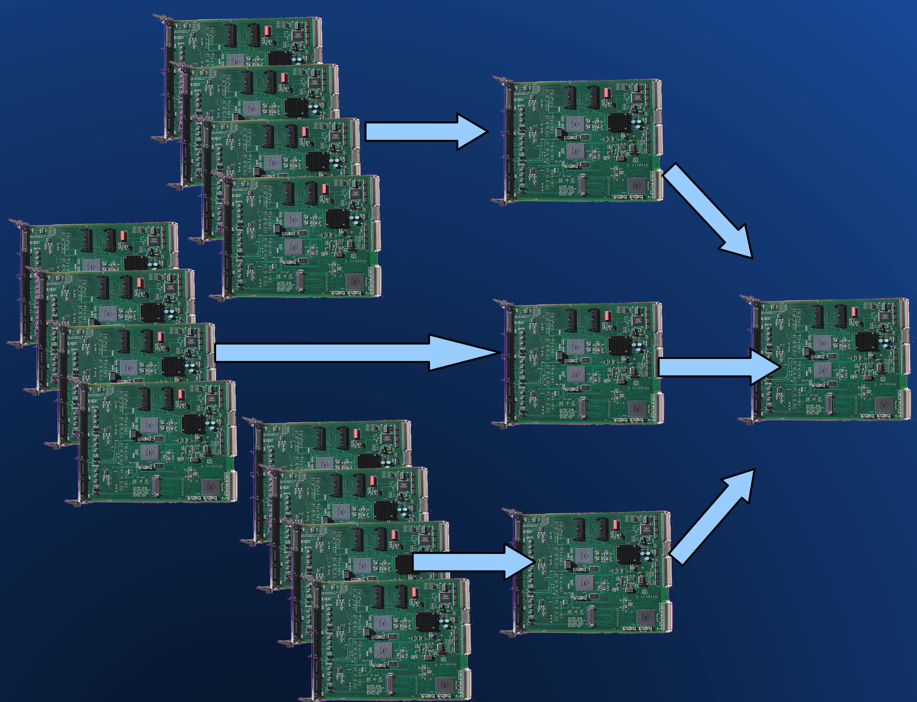
Larger pattern banks (32k → 512k pattern per silicon sector)

A single multipurpose and flexible board **(PULSAR):**

- 3 FPGAs
- Embedded RAM
- Interface w/ any user data through custom mezzanine cards

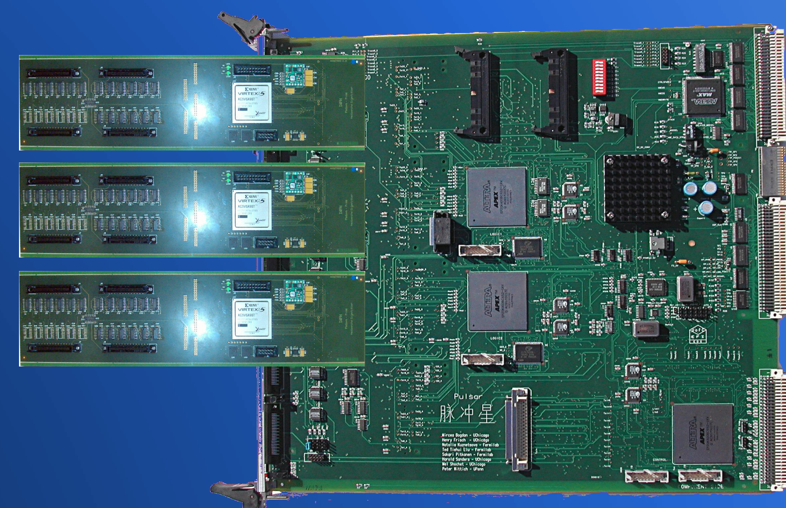
SVT (2010) : the Gigafitter upgrade

Old Track Fitter system



16 boards

New



1 Pulsar board + 3 Mezzanine cards

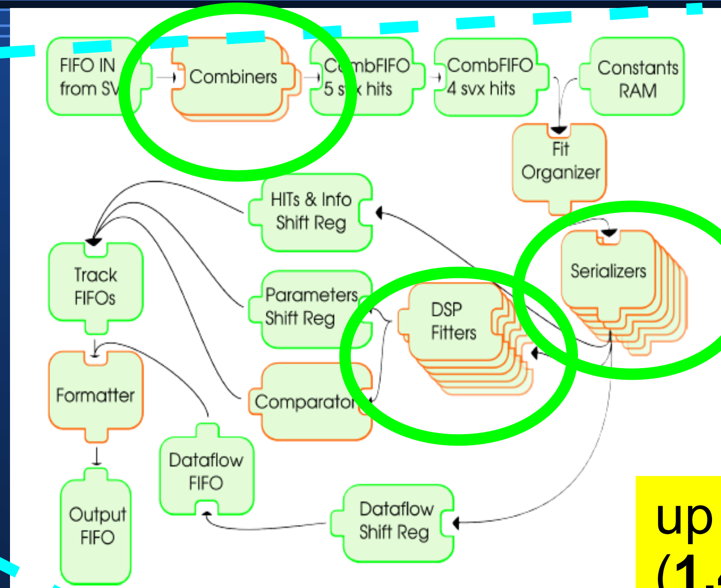
equipped with

Xilinx Virtex-5 FPGA with

- 640 DSP (**25 x 18 bit multiplier + 48 bit adder)**
- **8.2 Mb Ram**

The Gigafitter: advantages over the old system

Faster:



640 DSPs → many tasks in parallel

up to **12 fits / clock cycle**
(**1.4 fits/ns** at 120 MHz internal clock)

More available memory:

- **Extension of the SVT acceptance in track Pt and impact parameter d**

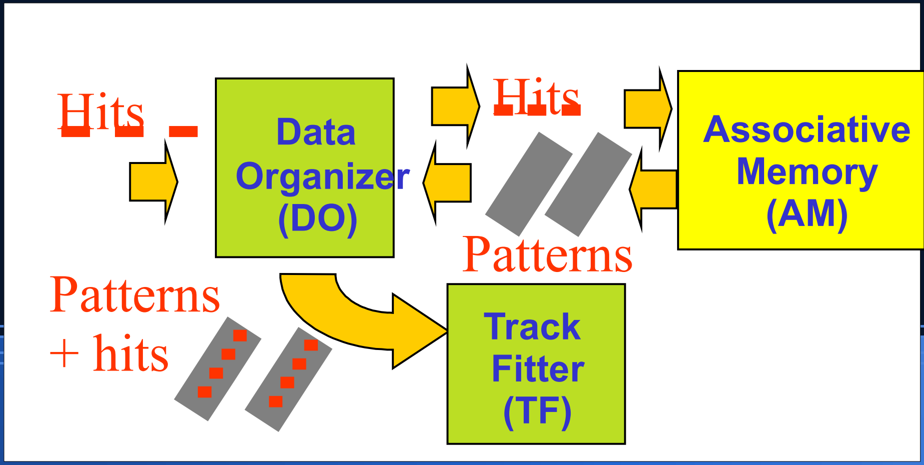
d < 1.5 mm → d < 2-3 mm **Pt > 2 GeV → Pt > 1.5 GeV**

Improvement in b-tagging capabilities and lifetime measurements

Fast TracKer (FTK) @ Atlas

Goal: reconstruct offline-like tracks in time for **L2 decision** @ 100 kHz (L1 rate).

How: adapt SVT (+GF) experience to Atlas



	SVT	FTK
L1 output rate	30 kHz	100 kHz
Detector layers	5	11 (3 pixel+8 SCT)
# patterns	6M	>800M

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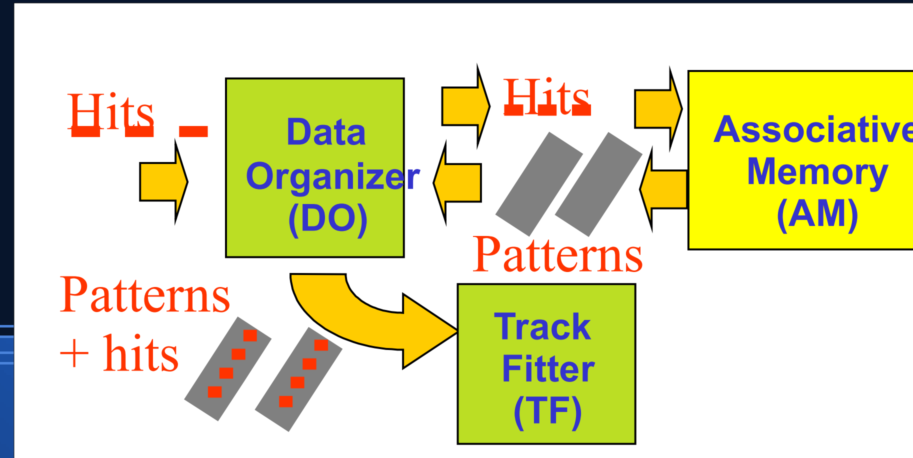

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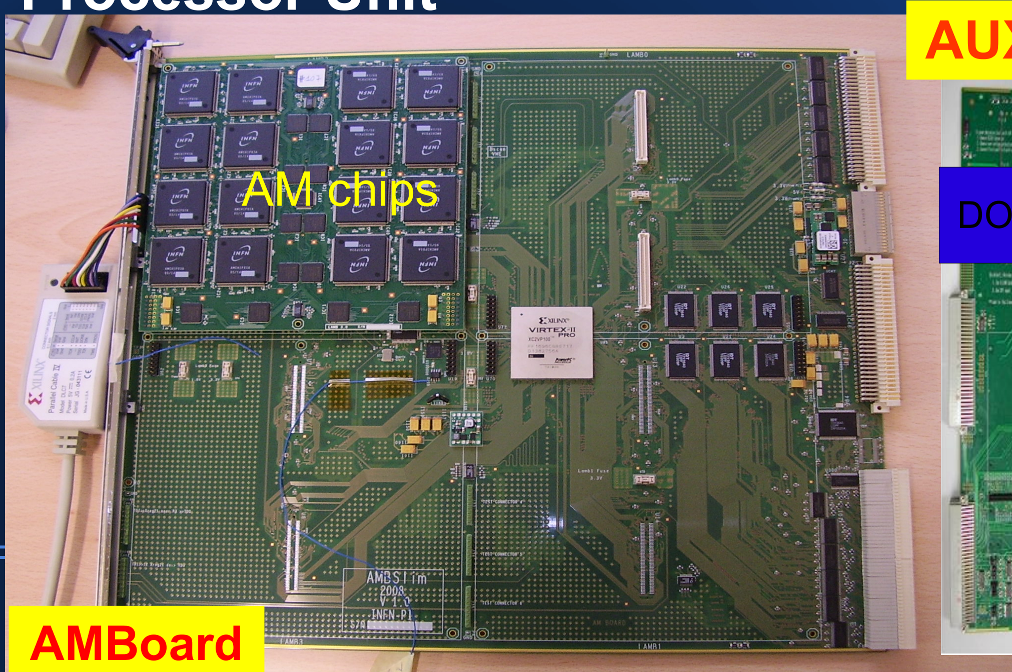
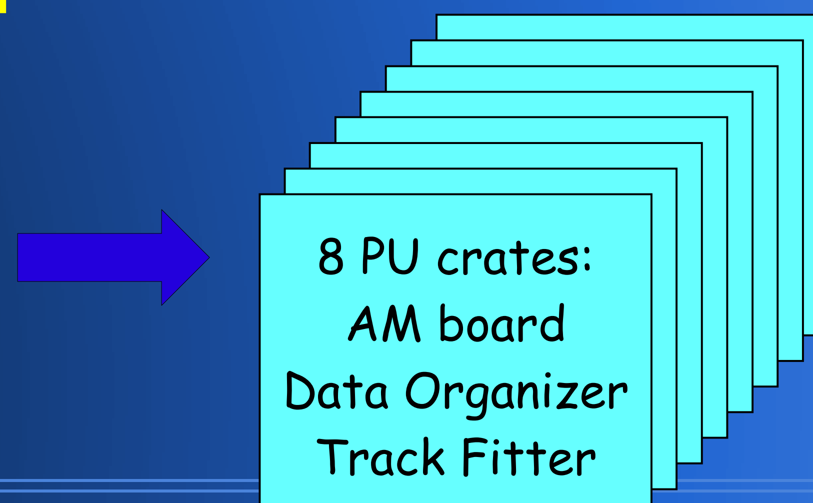
Processor Unit



AUX card

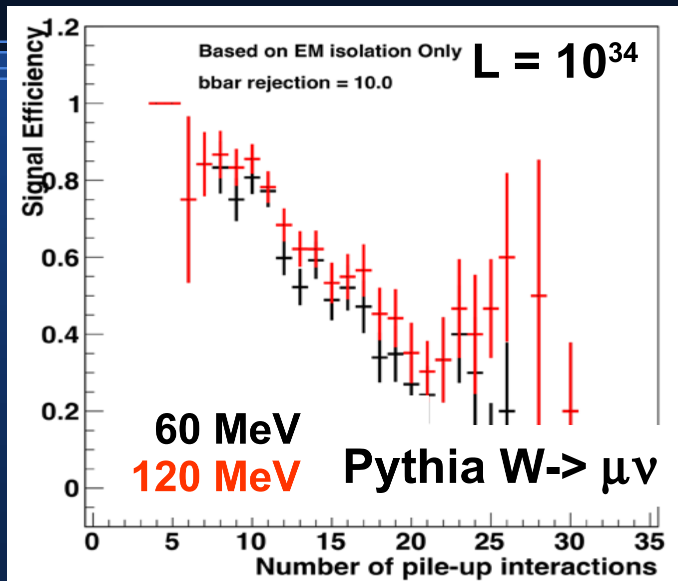


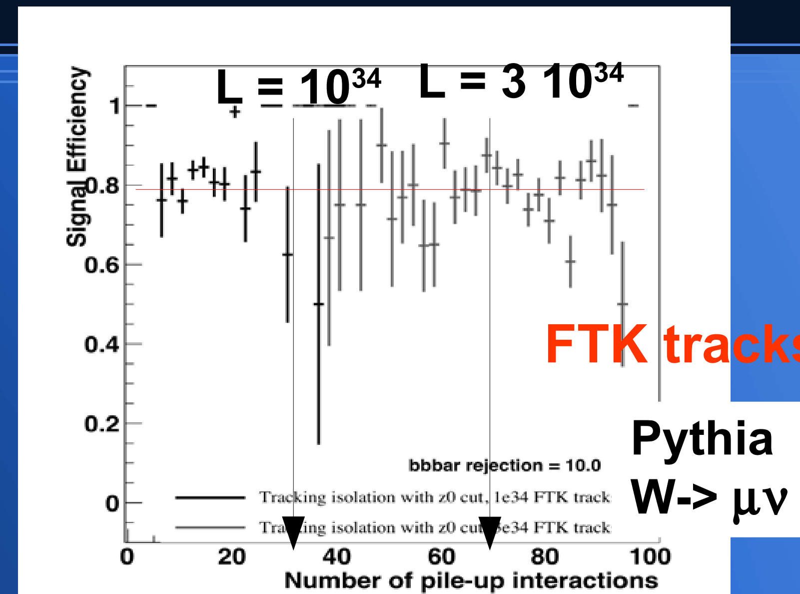
FTK expected performances

EM calorimeter isolation only

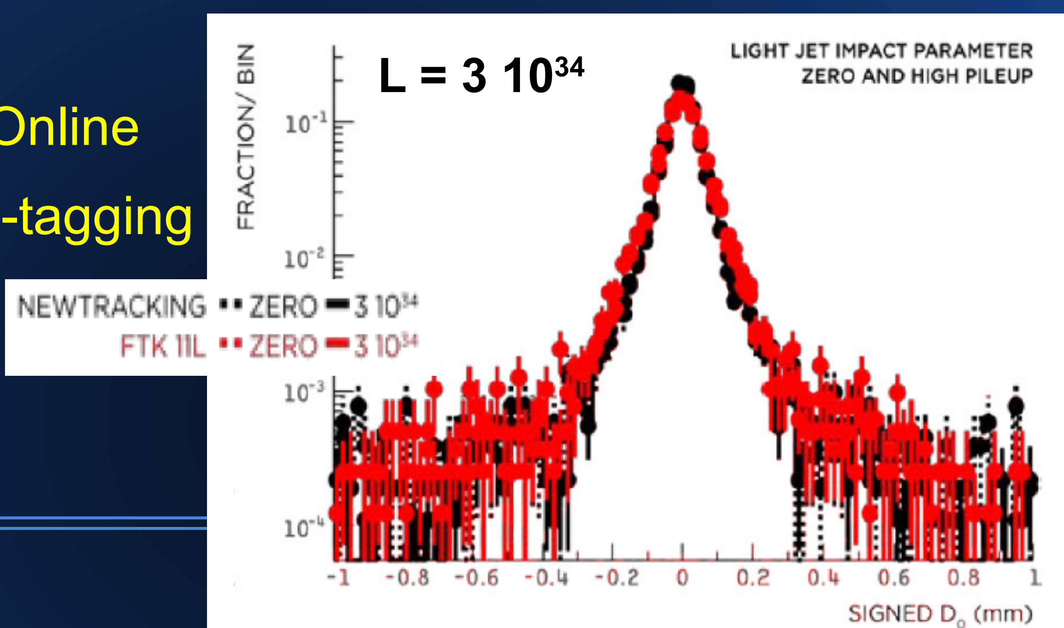
Track isolation (w/ z_0 cut)

Isolated muon triggers

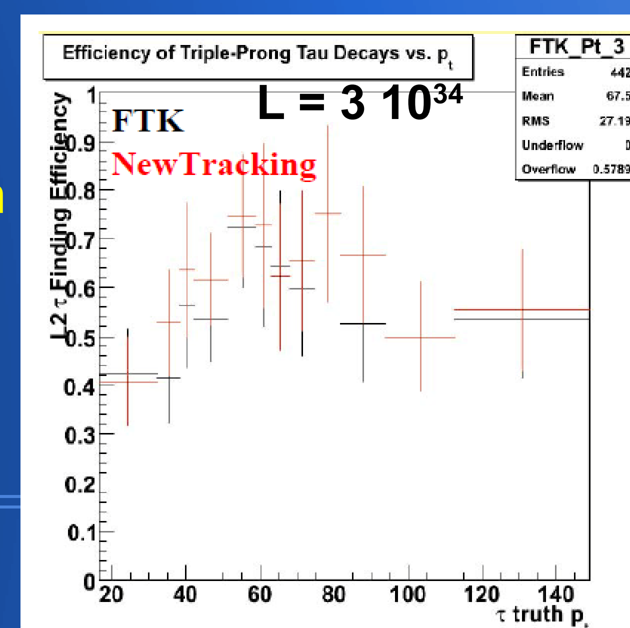




Online b-tagging



Online tau reconstruction



CMS tracking @ L1

LHC

L1
- Calorimeters
- Muon detectors

100 MHz, 4 μs

→

High level Trigger (HLT)
- Offline-like objects

100 Hz, 40 ms

SLHC new tracker & **new L1 track trigger**

Main challenge is data volume: data rates ~ 10-20Gb $cm^{-2}s^{-1}$ to read out a silicon detector layer at 10 cm! *On-detector data reduction* is needed.

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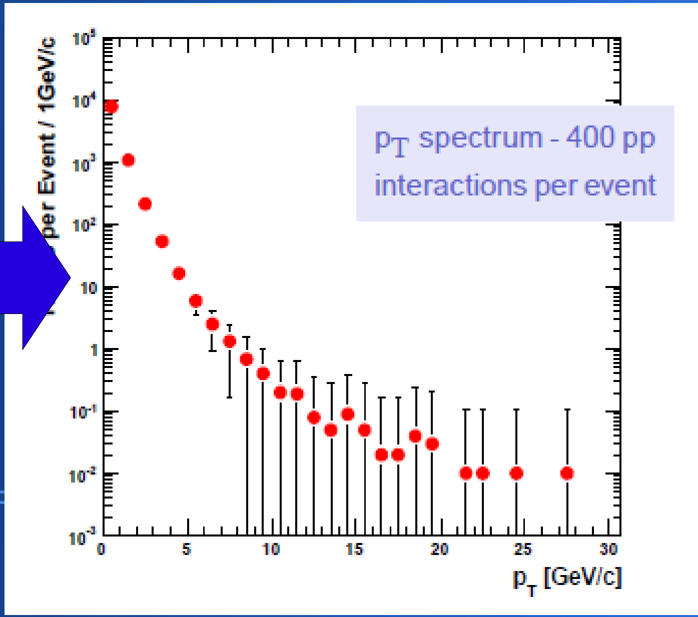
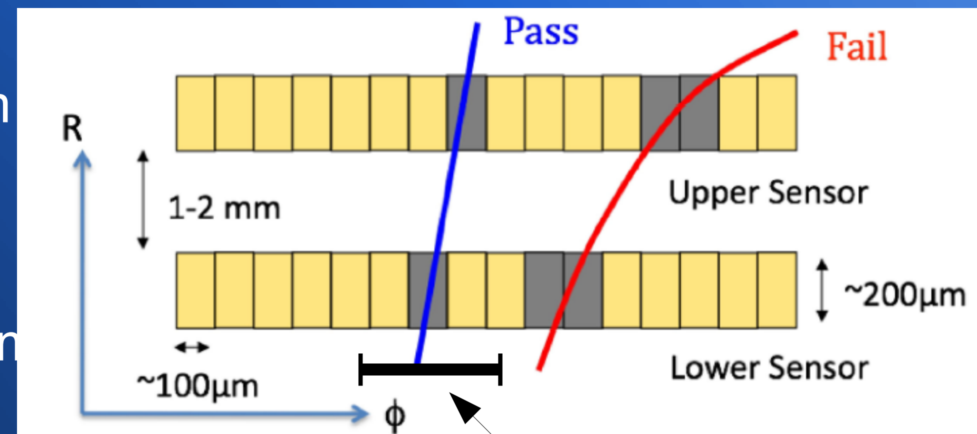
Possible solution: use for L1 decision only tracks with Pt > 1 GeV/c, reject low momentum ones.



CMS tracking @ L1: possible solutions

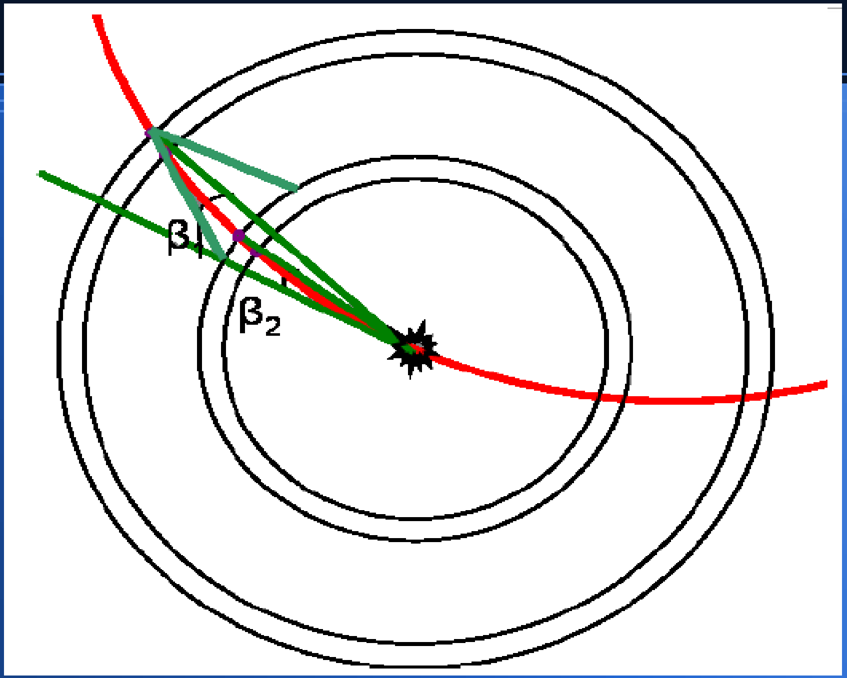
STACKED TRACKING

- Correlate hits between closely separated sensors using a simple matching algorithm
- High Pt tracks = hits within a specific search window.
- With multiple sensors pairs, matched hits from different pairs can be correlated to form raw tracks.



Search window

CMS tracking @ L1: possible solutions



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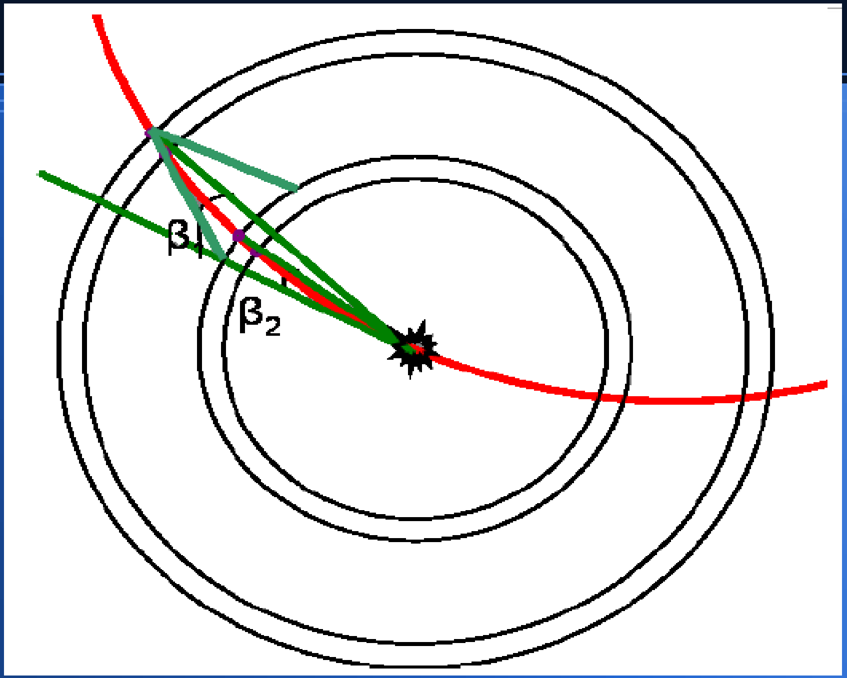
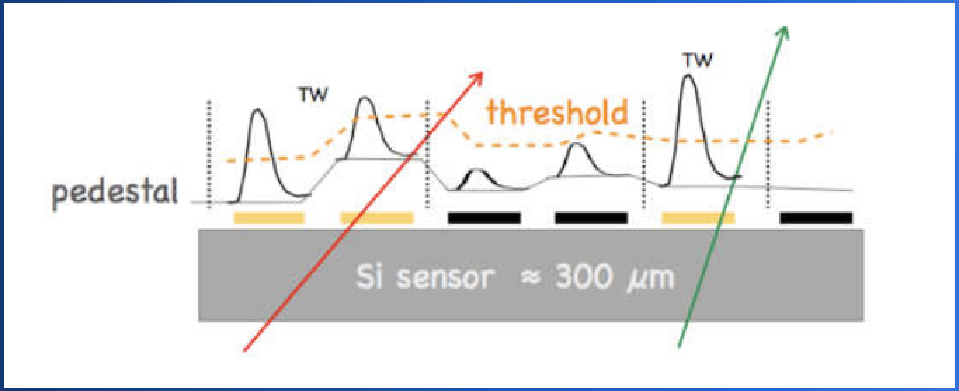


CLUSTER WIDTH DISCRIMINATION

- Four strip sensor layers at radii 25-50 cm.
- Cut on cluster width to reduce data rate.
- Correlate clusters from 3 out 4 layers using CAM or FPGAs



Conclusions

A good online tracking system is important to increase the physics reach of experiments at hadron colliders.

What do we learn from the past (H1) and the present (CDF)?

The online tracking system has to be

- FAST and EFFICIENT → *data reduction, pattern recognition, parallelism, high density FPGAs*
- FLEXIBLE, to be easily adapted to different luminosity conditions → *multipurpose boards*.

Both CMS and ATLAS are facing the challenge: R&D activity ongoing for SLHC.

References

FTT

- A. Baird et al, *A Fast High Resolution Track Trigger for the H1 Experiment*, arXiv:hep-ex/0104010v1
- D. Meer et al, *A Multifunctional Processing Board for the Fast Track Trigger of the H1 experiment*, arXiv:hep-ex/0107010v1
- A.W.Jung et al, *First Results from the Third Level of the H1 Fast Track Trigger*, Proceedings of 15th IEEE-NPSS Real Time Conference (2007)

SVT

- M.Dell'Orso, L.Ristori, VLSI Structures for Track Finding, NIM A278 (1998) 436-440
- J.Adelman et al., The Silicon Vertex Trigger Upgrade at CDF, NIM A572 (2007) 361
- S.Amerio et al., The Gigafitter: Performance at CDF and Perspectives for Future Applications, 2010 J.Phys.: Conf.Ser. 219 022001

FTK

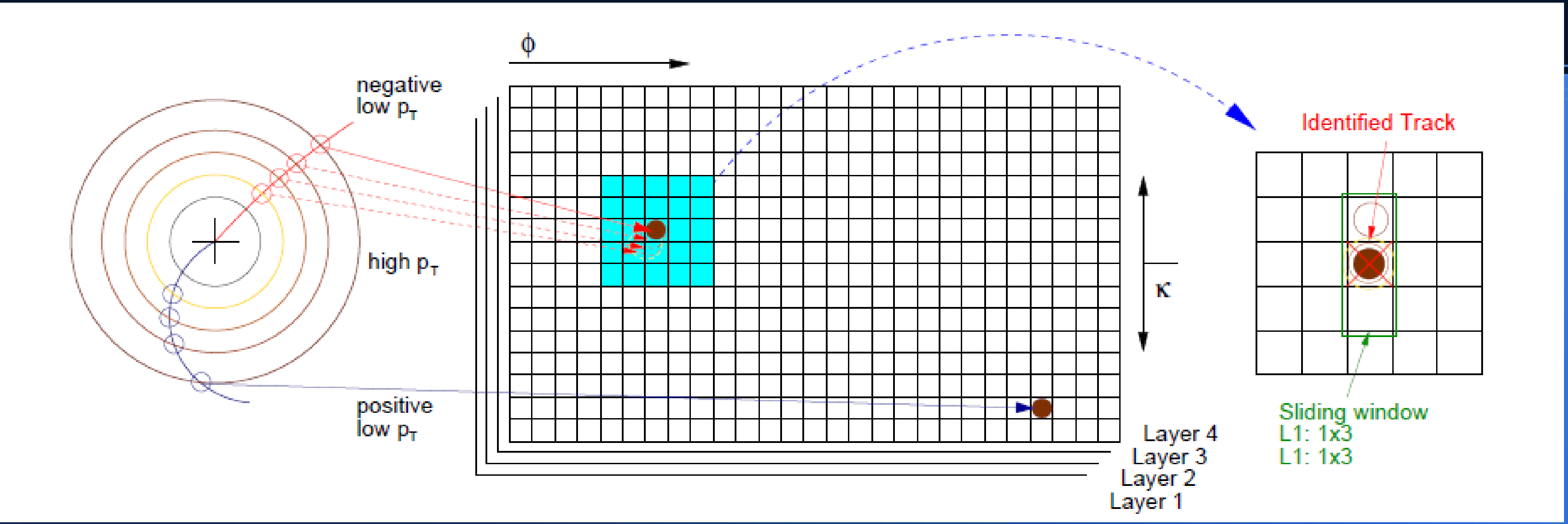
- A.Annovi et al., Associative memory design for the Fast TracK Processor (FTK) at Atlas
- A.Andreani et al., The FastTrack Real Time Processor and Its Impact on Muon Isolation, Tau and b-jet Online Selections at ATLAS, both in Proceedings of 17th IEEE NPSS Real Time Conference, Lisbon, Portugal, 24-28 May 2010

CMS

- G.Hall, *Design of a trigger module for the CMS tracker at SLHC*, Proceedings of TWEPP-09
- F. Palla, *Proposal for a First Level Trigger using Pixel Detector for CMS at Super-LHC*, 2007 JINST 2 P02002
- J. Jones et al, *A Pixel Detector for Level-1 Triggering at SLHC*, arXiv:physics/0510228

BACKUP

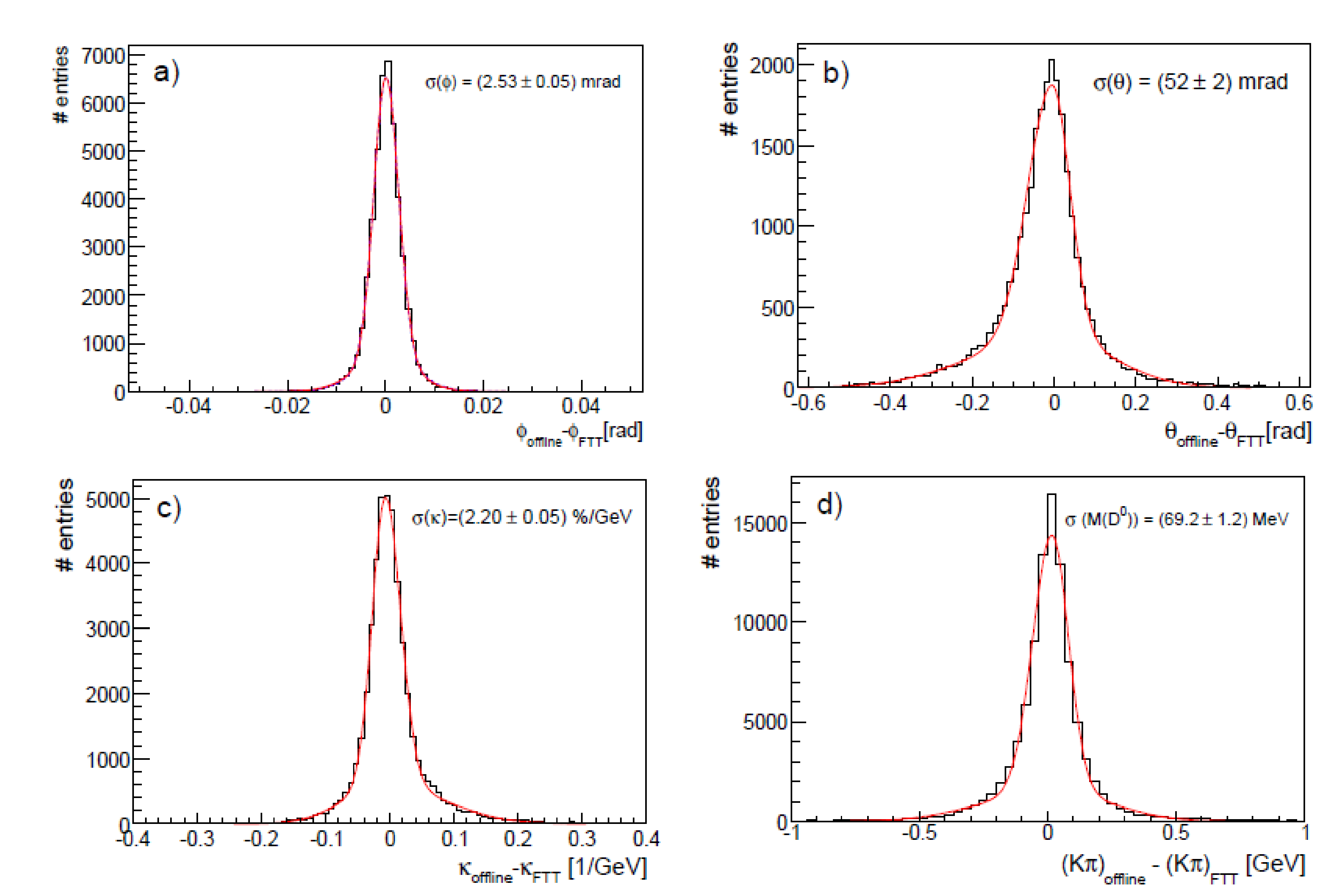
FTT track linking and fit



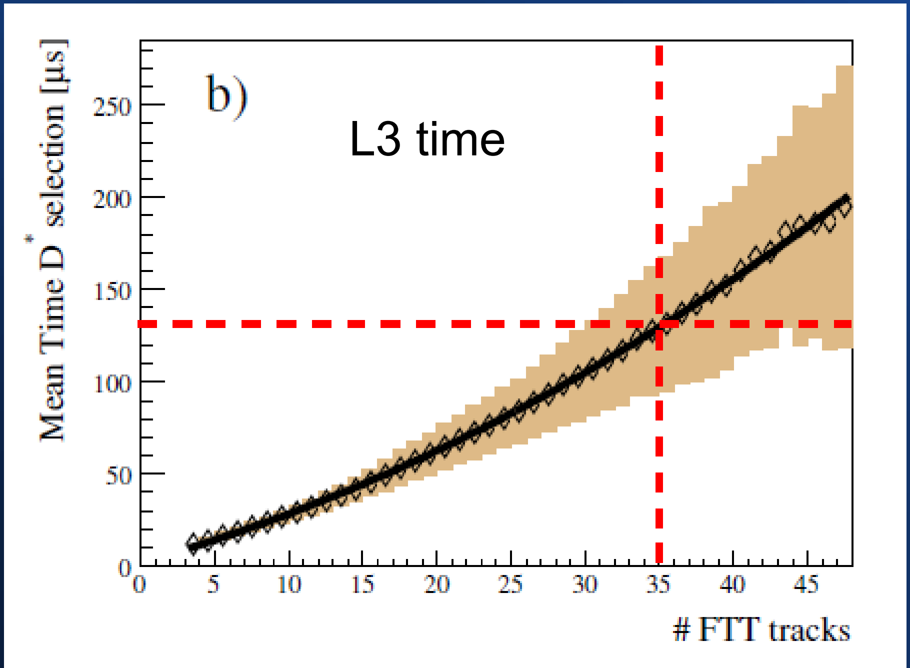
- Track segments from the 4 trigger layers are filled into four corresponding k-phi histograms (size 16 x 60 @ L1, 60 x 640 @ L2).
- A sliding window technique is used to link track segments to tracks: coincidence of at least 2 out of 4 trigger layers.

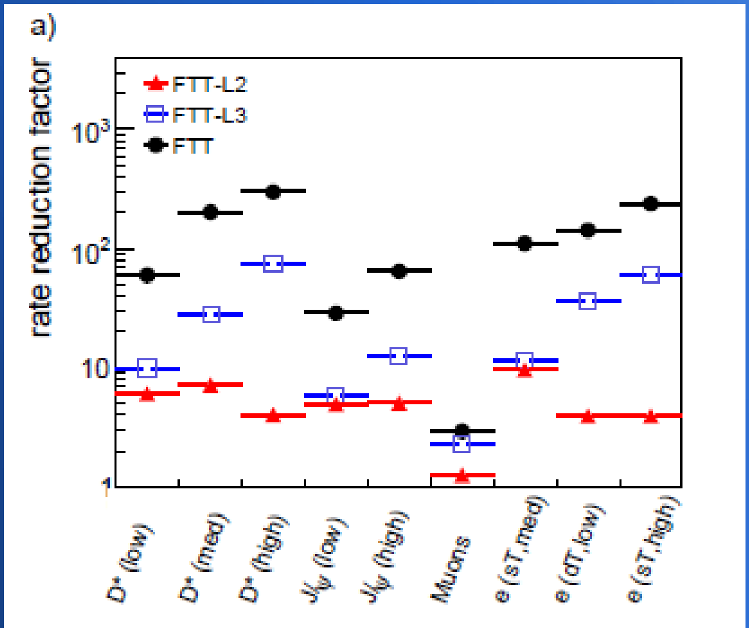
- @ L2 the track is fitted. A primary vertex constraint is applied. Each DSP performs up to 2 track fits.

FTT L2 track resolution



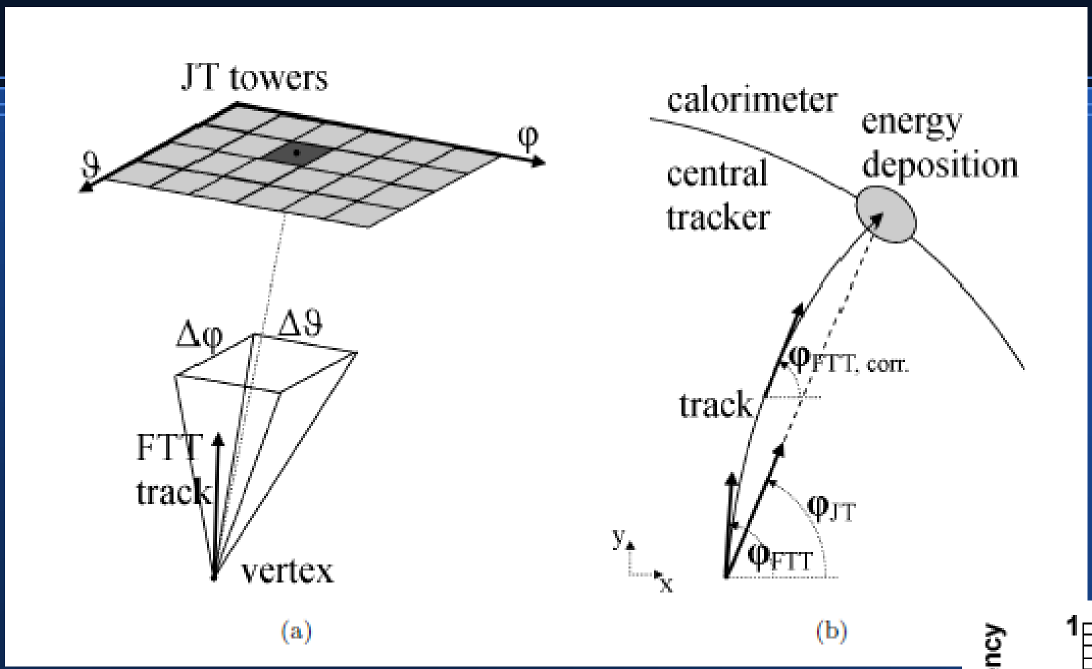
FTT timing and reduction rate

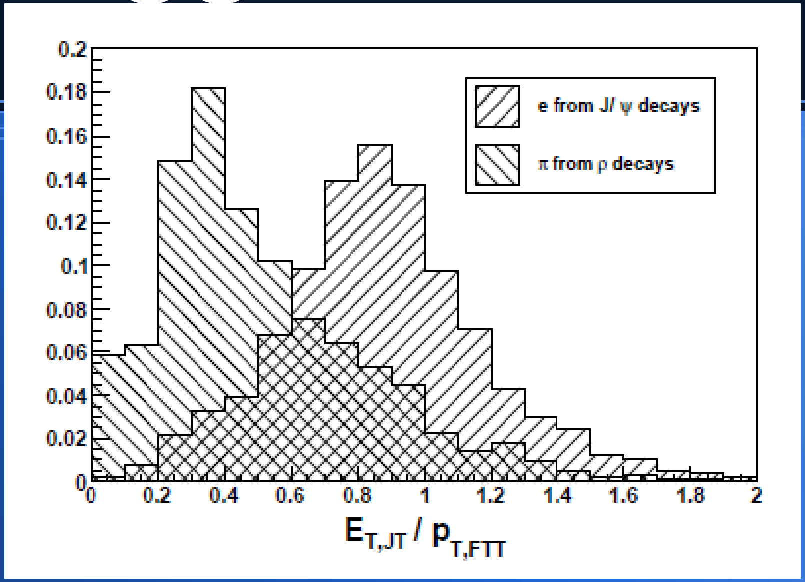


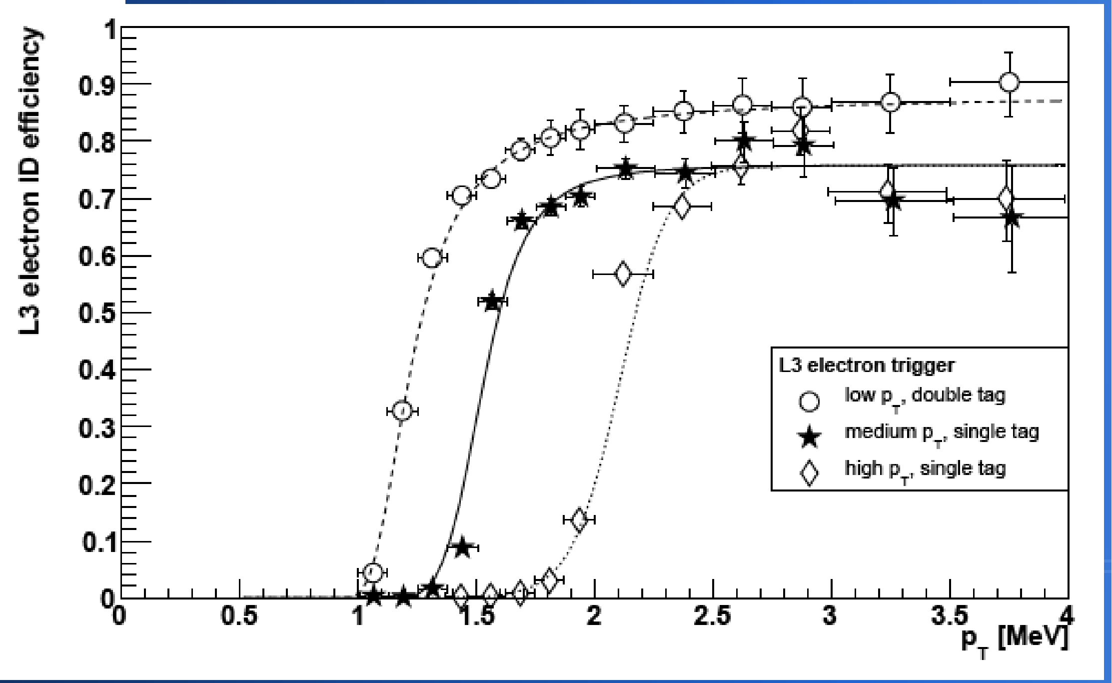


Rate reduction factors

FTT electron trigger







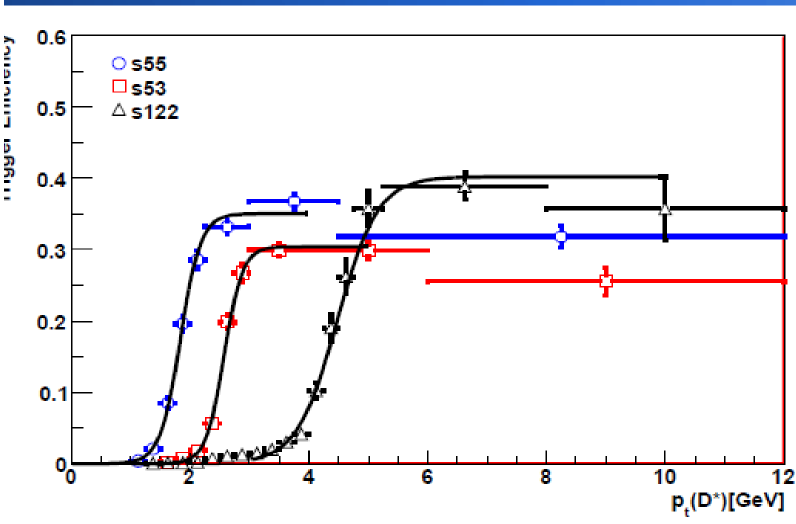
D* reconstruction @ H1

Subtrigger	*triggerelement*	*definition*
	level 1	
s55, s53, s122	cipmul>4	$N(ctr) + N(bwd) + N(fwd) > 10$
	& cipsig>2	$N(ctr) > 2 \cdot (N(bwd) + N(fwd))$
	& FTT_mul_Ta>5	#tracks > 5, with $p_t > 100$MeV
	& FTT_mul_Tc>2	#tracks > 2, with $p_t > 400$MeV
	& FTT_mul_Td>1	#tracks > 1, with $p_t > 900$MeV
	& FTT_mul_Te>0	#tracks > 0, with $p_t > 1.8$GeV
	level 2	
s55	& FTT_Et_1	total transverse energy > 5.0GeV
	& FTT_mul_Te>1	#tracks > 1, with $p_t > 900$MeV
	& FTT_zVtx>2	
s53	& FTT_Et_2	total transverse energy > 6.5GeV
	& FTT_mul_Te>1	#tracks > 1, with $p_t > 900$MeV
	& FTT_zVtx>2	
s122	& FTT_mul_Te>1	#tracks > 1, with $p_t > 900$MeV
	& FTT_zVtx>2	
	level 3	
s55	& low_pt_D^*_untagged	$p_t(D^*) > 1.5$ GeV with $\Delta M \leq 180$ MeV
s53	& medium_pt_D^*_untagged	$p_t(D^*) > 2.5$ GeV with $\Delta M \leq 180$ MeV
s122	& high_pt_D^*_untagged	$p_t(D^*) > 4.5$ GeV with $\Delta M \leq 280$ MeV

@L3:

- 2 tracks with mass consistent with D0 meson mass
- 3rd track corresponding to $\pi+$ mass
- Mass difference (around 145 MeV)

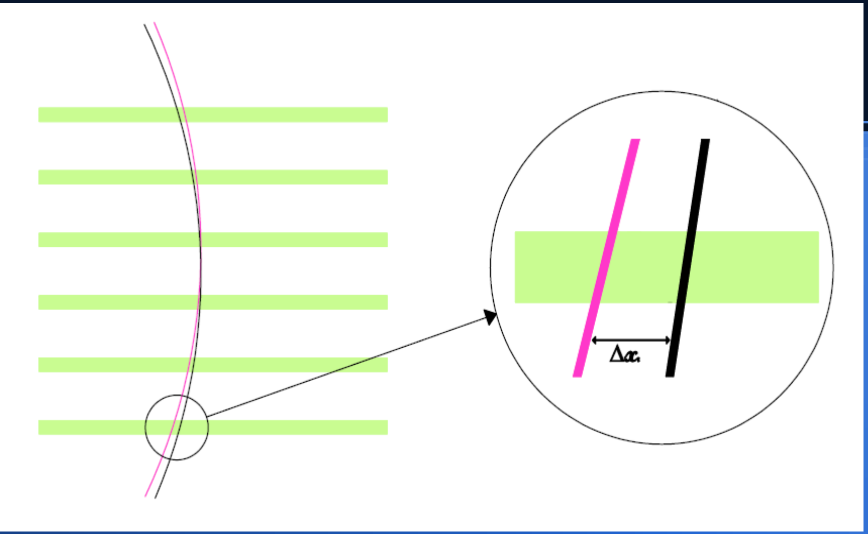
- Trigger efficiency vs D* pt for 3 different triggers (low, medium and high transverse momenta)

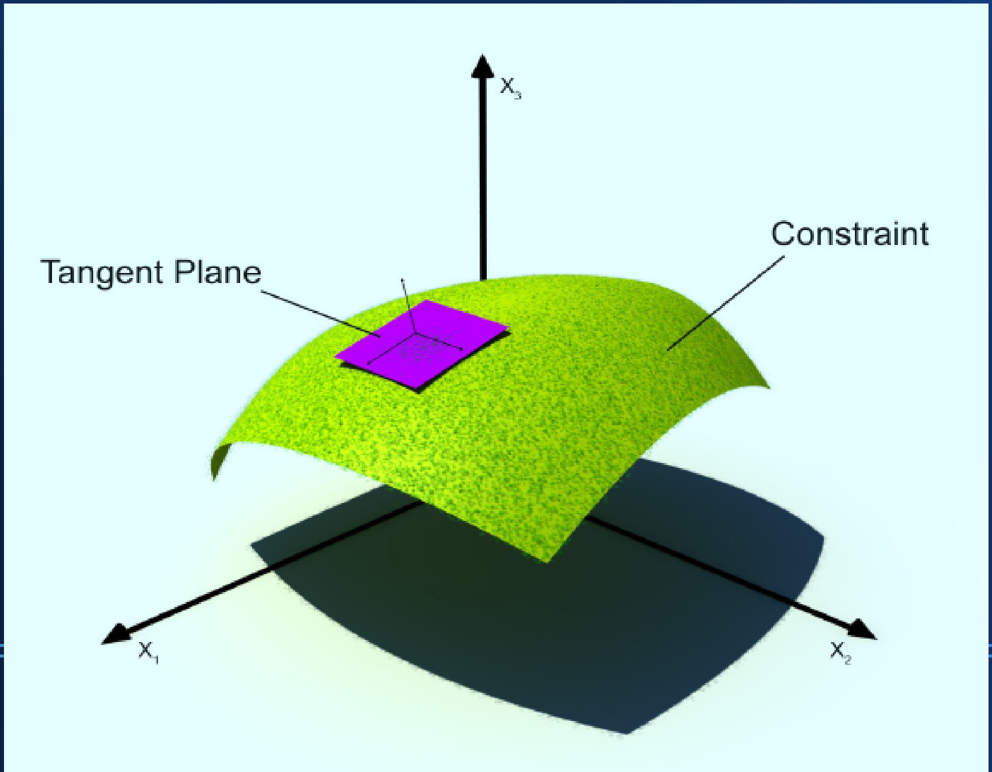


SVT – Track Fitter

Non linear geometrical constraint for a circle → F(x1, x2, ...) = 0

For small displacements → F(x1, x2, ...) ∼ a0 + a1 Δx1 + a2 Δx2... (ai = constant)



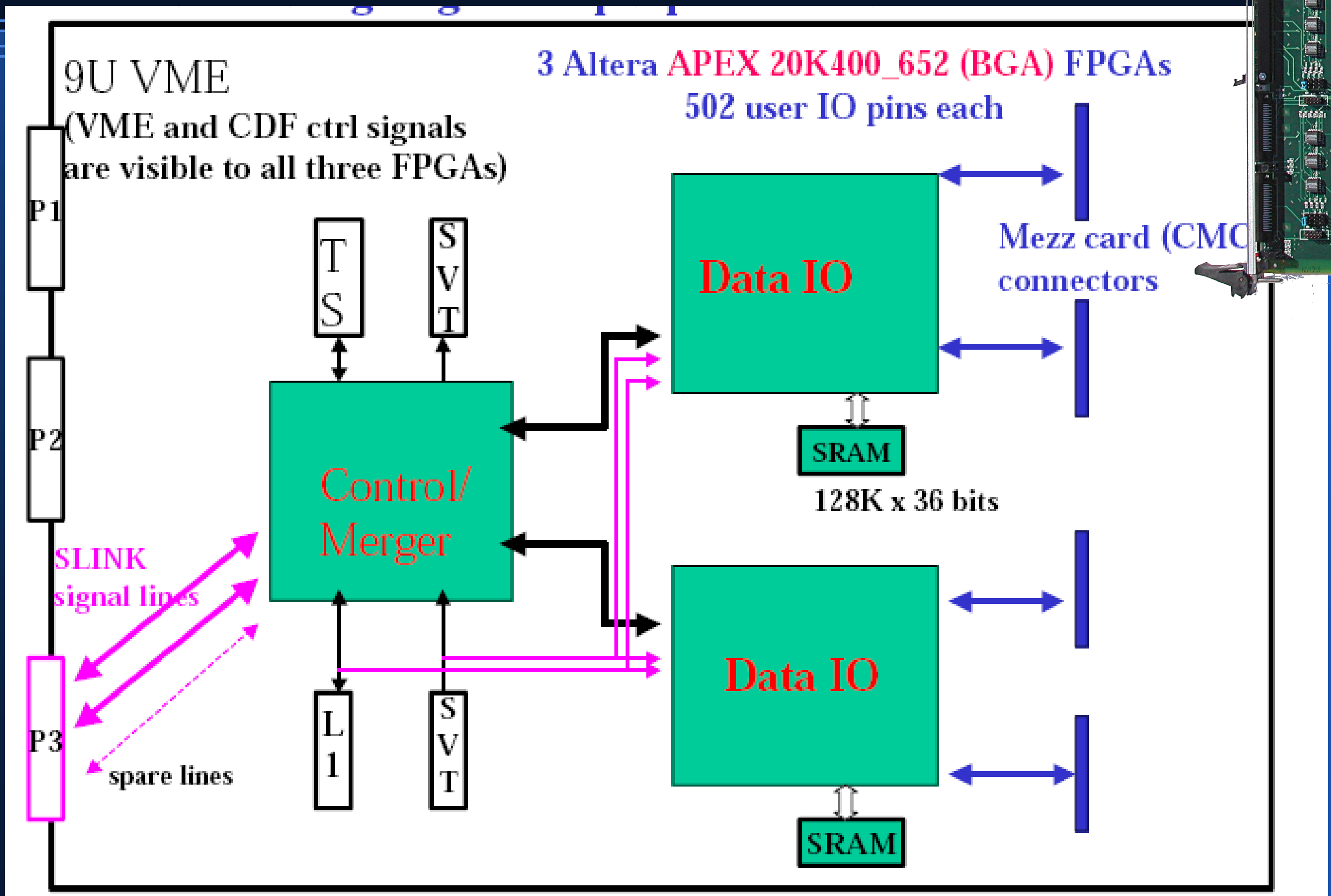


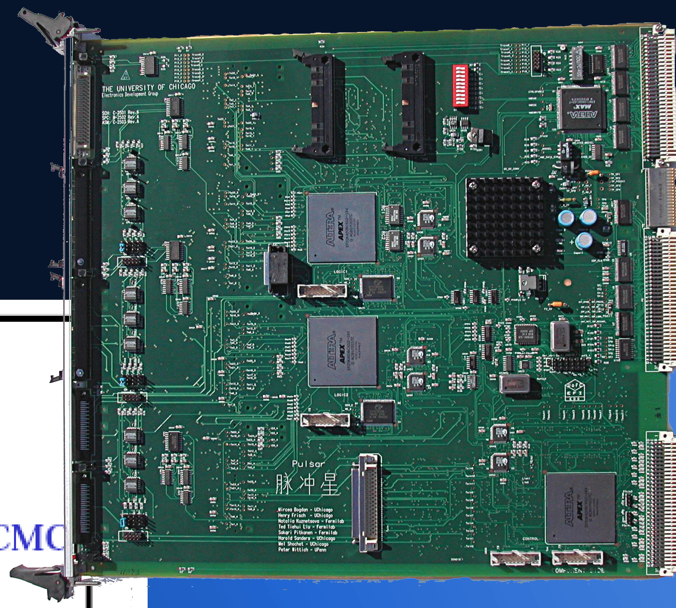
6 coordinates (4 SVX hits + Pt and Phi from XFT) – 3 parameters to fit → 3 constraints that can be locally linearized

Track parameters →
$p \sim c_0 + \Sigma_{i=1,6}\, c_i x_i$

A single set on constants c_i is good for a whole detector wedge (30° in φ)

The Pulsar board

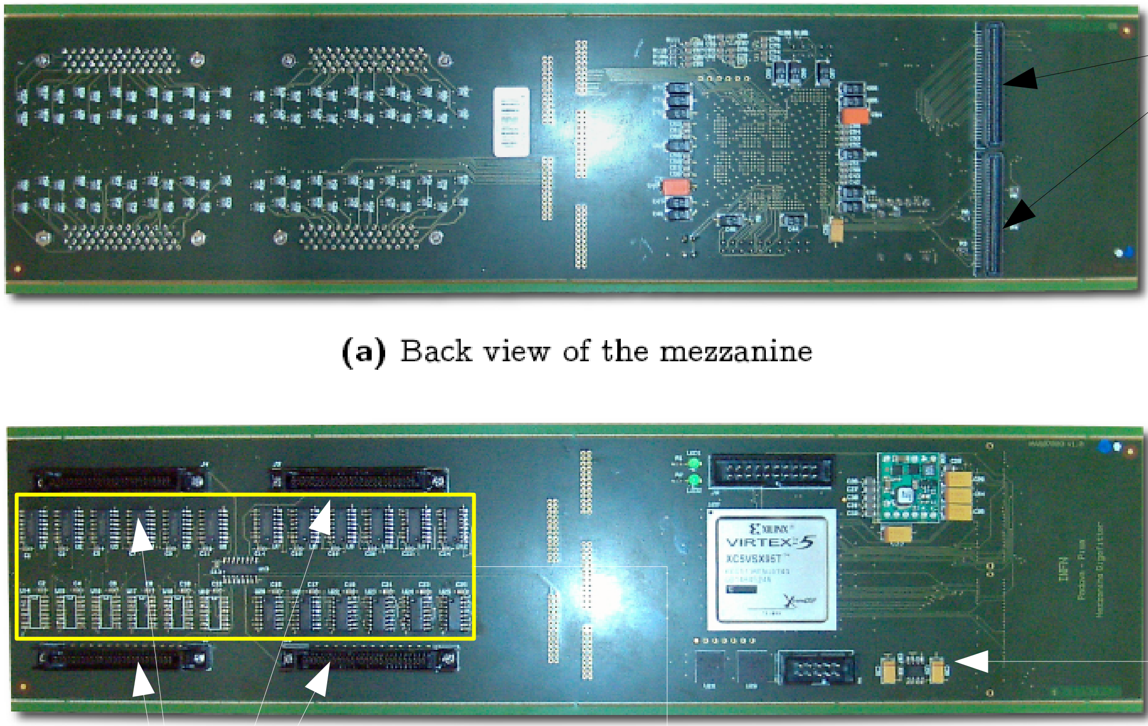




3 APEX20K400-1XV FPGAs on board = 3 Million system gates/80KB RAM per board
2 128K x 36 pipelined SRAMs with No Bus Latency: 1 MB SRAM (~5ns access time)

The GF mezzanine

Interface with the Pulsar based on 2 64 pins PMC IEEE 1386 connectors



(a) Back view of the mezzanine

(b) Front view of the mezzanine

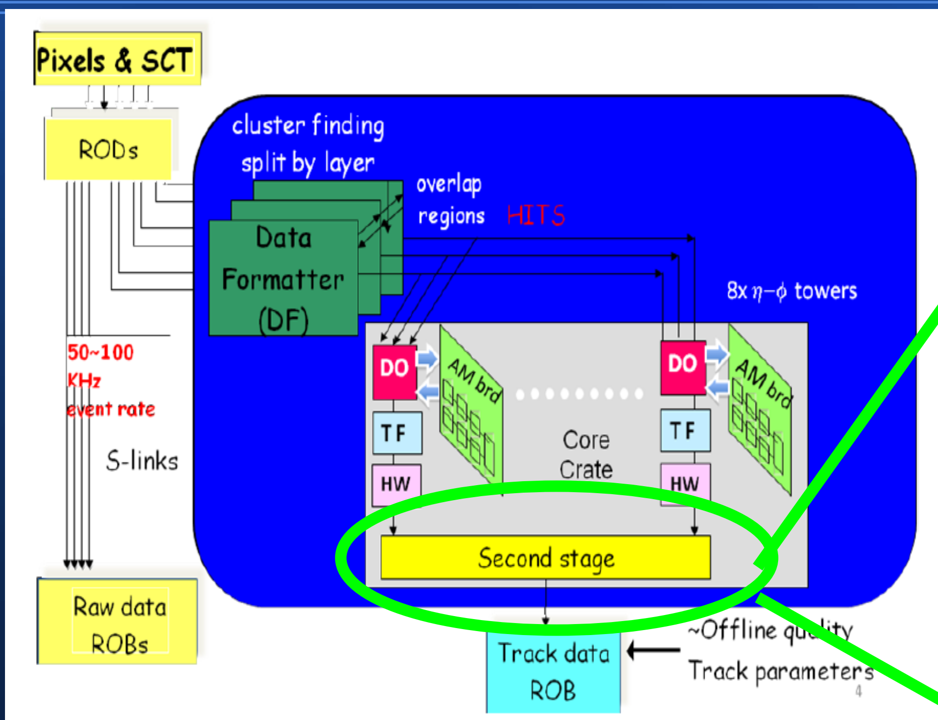
EEPROM to program the FPGA at every startup

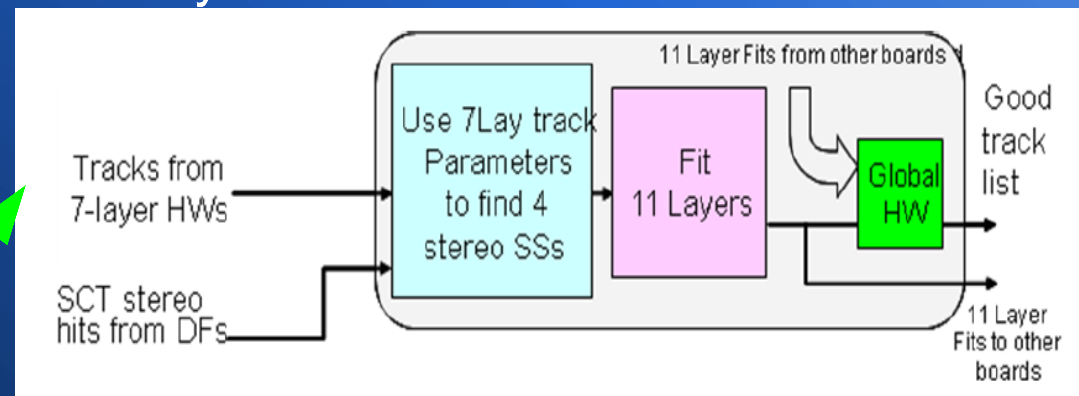
Connectors (52 pins KEL_8830E-052-170S) to receive the SVX + XFT inputs

24 receivers and 1 driver to allow the translation from LVDS to TTL signals

FTK architecture

Option A:
- Pattern matching w/ 3 pixel + 4 SCT axial layers.
- Chi2 cut --> extrapolation into the SCT stereo layers
- 11-layers fit



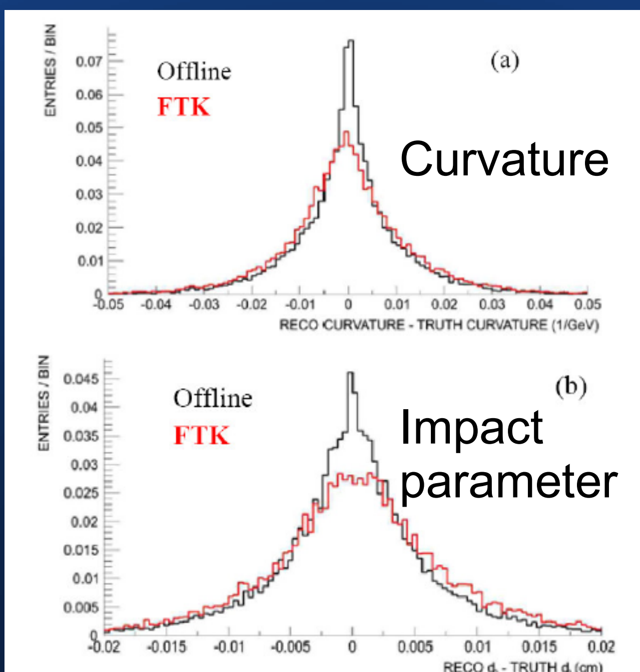


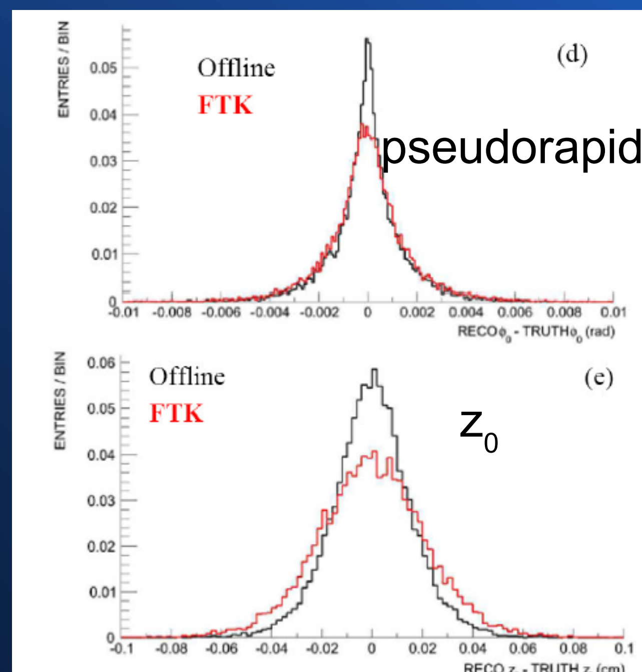
Pattern matching and track fitting with 11 layers not feasible at high lumi (3 $10^{34}cm^{-2}s^{-1}$) : AM size and # of fits increase rapidly with the number of layers.
Need to divide the track reconstruction in 2 stages.

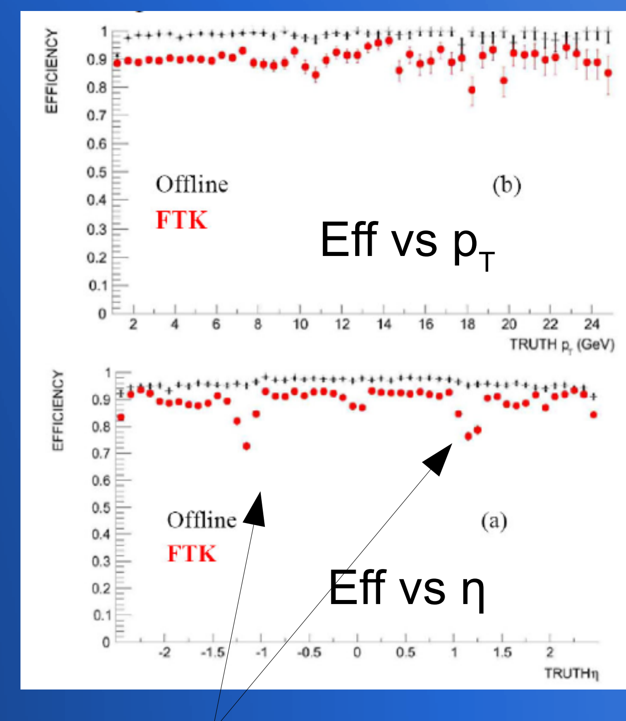
Option B:
- Pattern matching w/ 8 SCT layers
- Chi2 cut --> track = “pseudohit”
- 4 layers AM (pseudohit + 3 pixel layers)
- 11-layers fit

FTK expected performances (I)

Single track efficiency and resolution





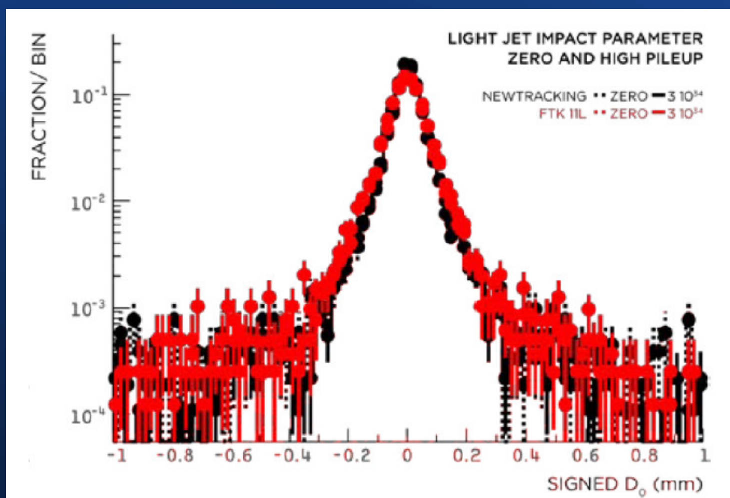


Single muon events, no pile-up
FTK settings to be used at high lumi.

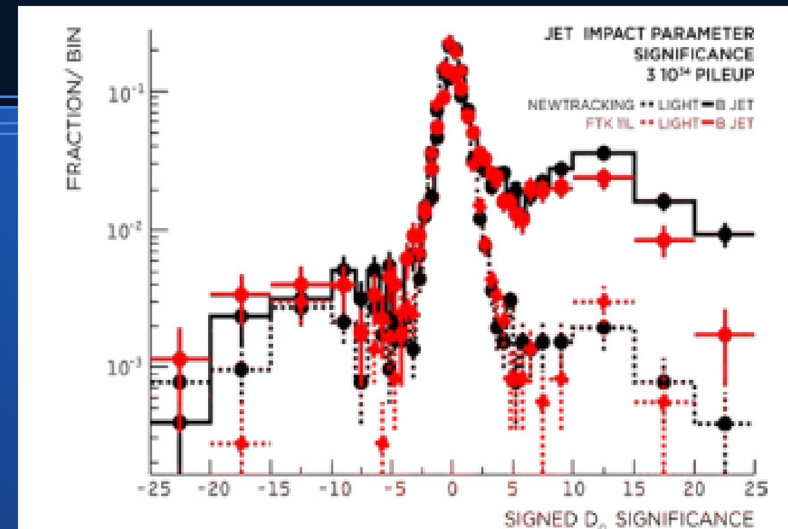
Drop in efficiency between barrel and forward regions

FTK expected performances (II)

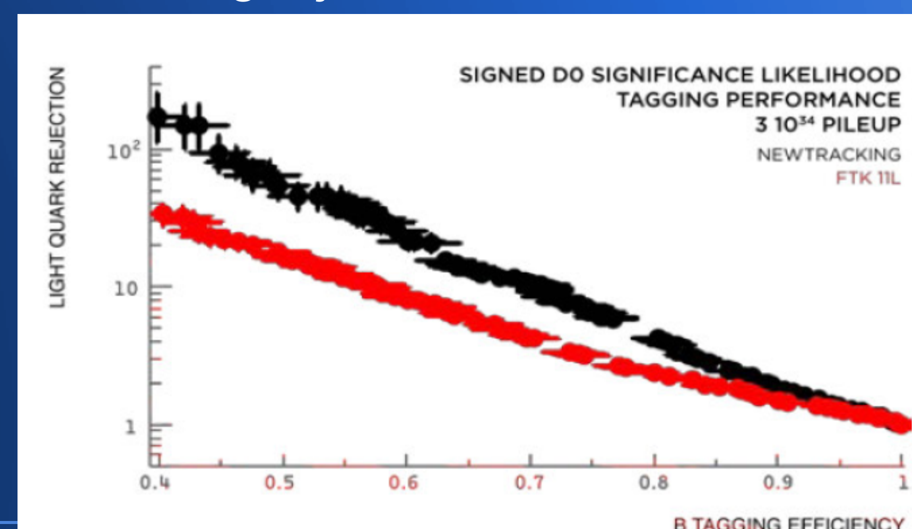
B-tagging



Impact parameter for tracks in light quark jets.



Impact parameter significance for b- and light jets.

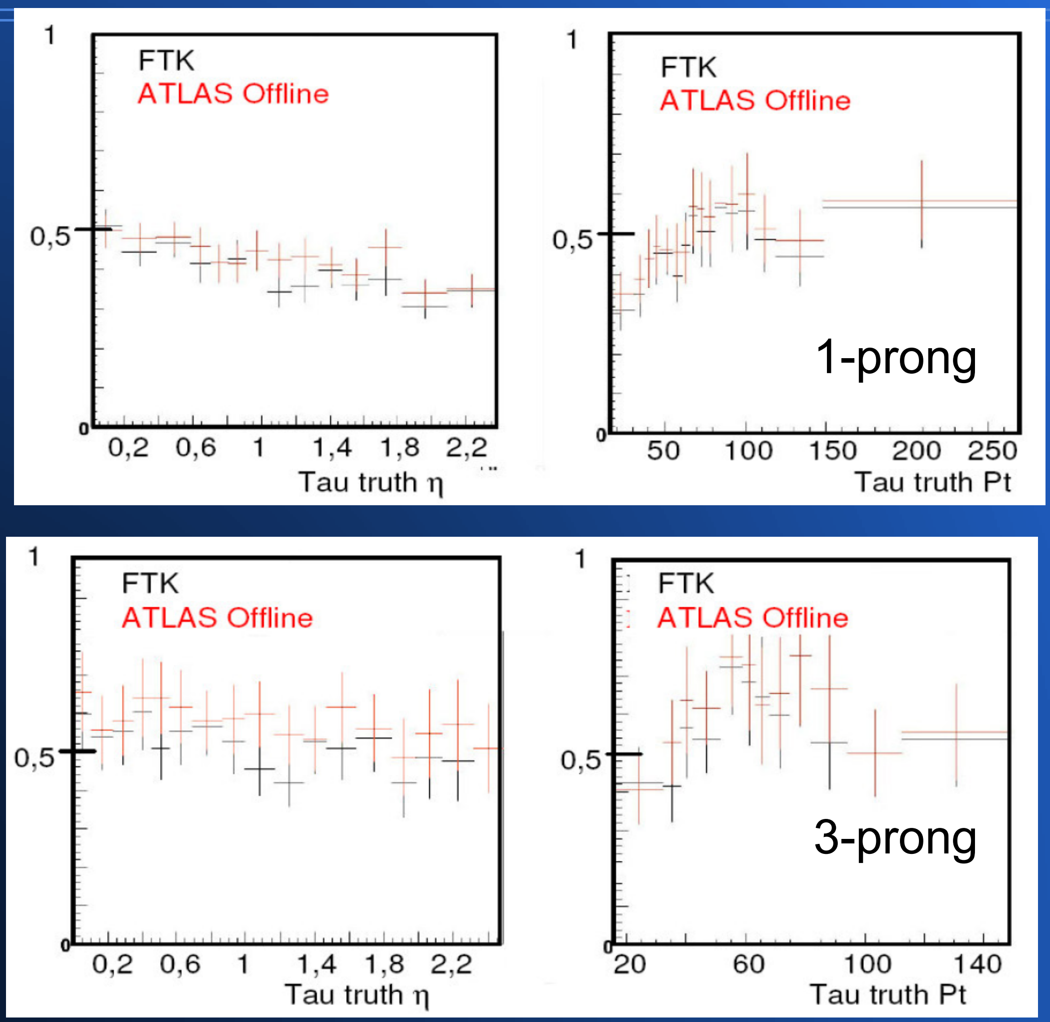


Light quark rejection vs b-tagging efficiency

WH sample (M_H = 120 GeV, H->bb/uu)
Offline cuts for very high lum: Nhits ≥ 9, Npixel holes = 0, NSCT holes ≤ 2, $|d_0| < 1$ mm, $|z_0| < 15$ cm)

FTK expected performances (III)

Tau reconstruction



Vector-boson-fusion Higgs --> tau_{had} tau_{had}

CMS stacked tracker module

Pixel size = 100 μm x 2.5 mm
1 module = 256 rows x 32 columns
Active sensor size = 25.6 mm x 80 mm = 8192 pixels

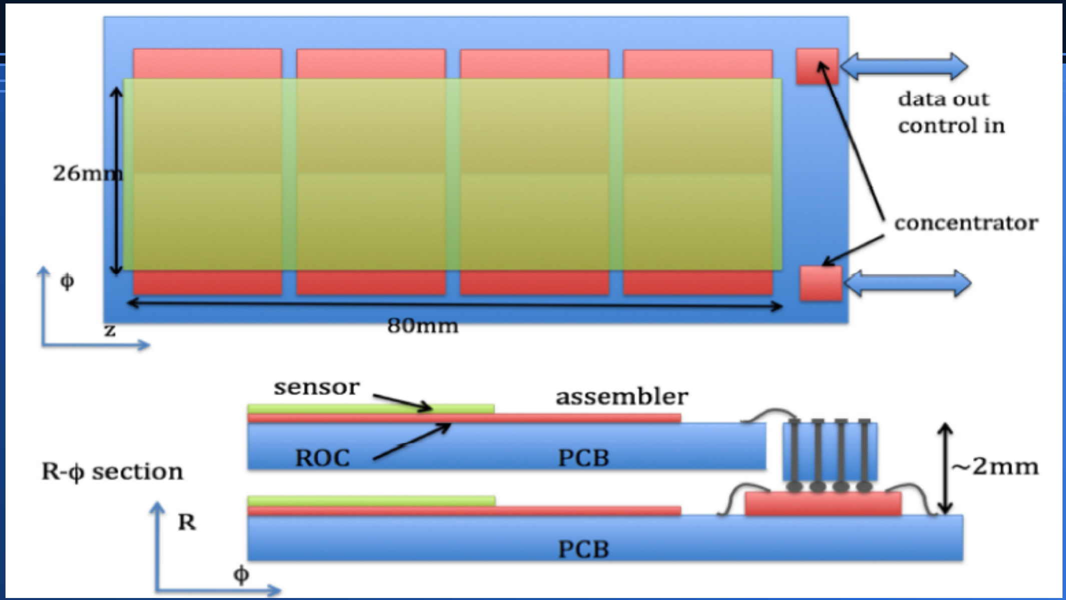
Sensors thickness = 200 μm

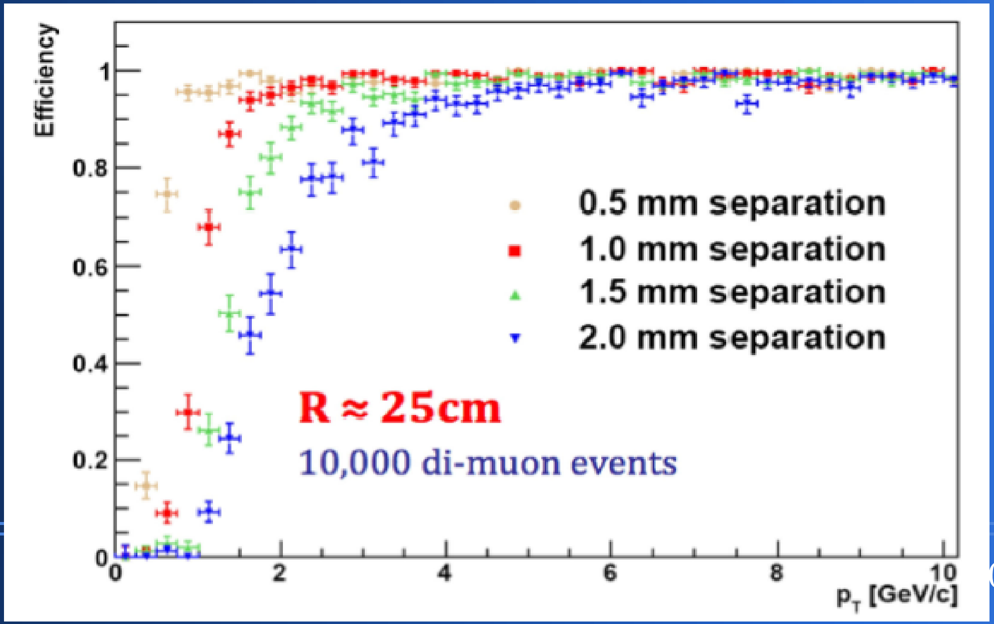
Read out from a column of 128 pixels

Readout Asic = 128 channel front- end element + assembler where comparison of patterns between the two layers are made.

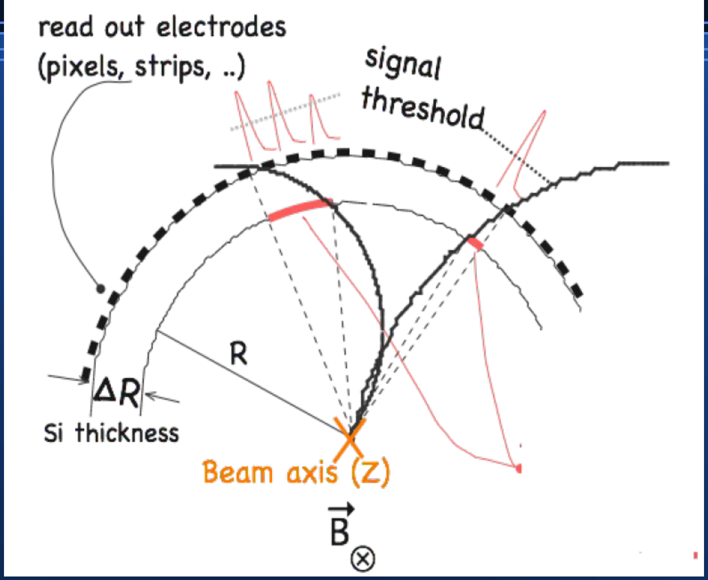
High speed radiation hard bidirectional optical links

Power consumption: 250 μW/channel,
10 kW for 40M pixels at 25 cm radius





CMS L1 tracker based on cluster width discrimination



4 layers between R = 25 cm and R = 50 cm

Hybrid pixel modules equipped with radiation hard fibers

Independent engines working on different azimuthal sectors
Each engine receives hits from each layer and produces track candidates using Associative Memory.

25kpatterns per engine for tracks with Pt > 5 GeV/c
To sustain data flux from the detector, 40 AM chips per engine working in parallel on 40 events at the same time.
160 boards with 40 AM chips (new generation) each.