Tracking and Vertexing at Future ~~Linear~~ Colliders: Applications in Flavour Tagging

Tomohiko Tanabe (U Tokyo)

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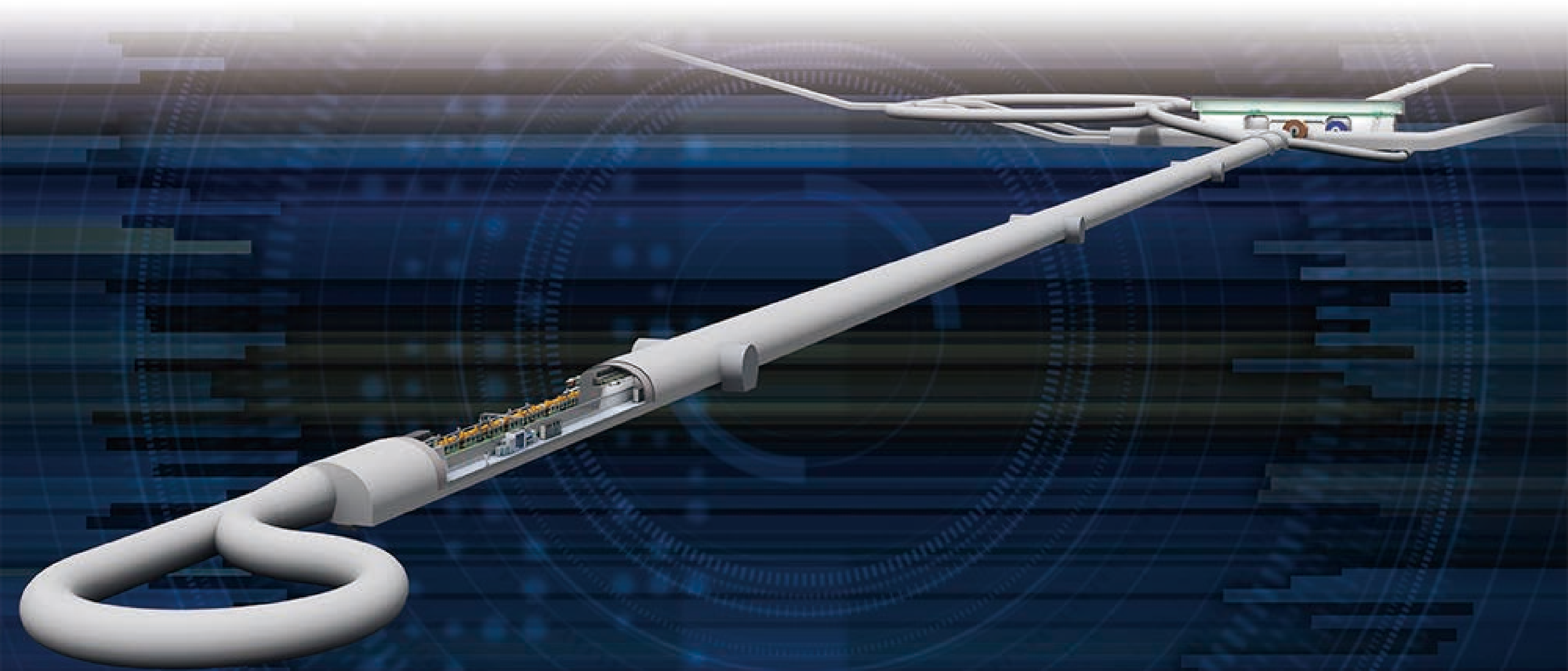


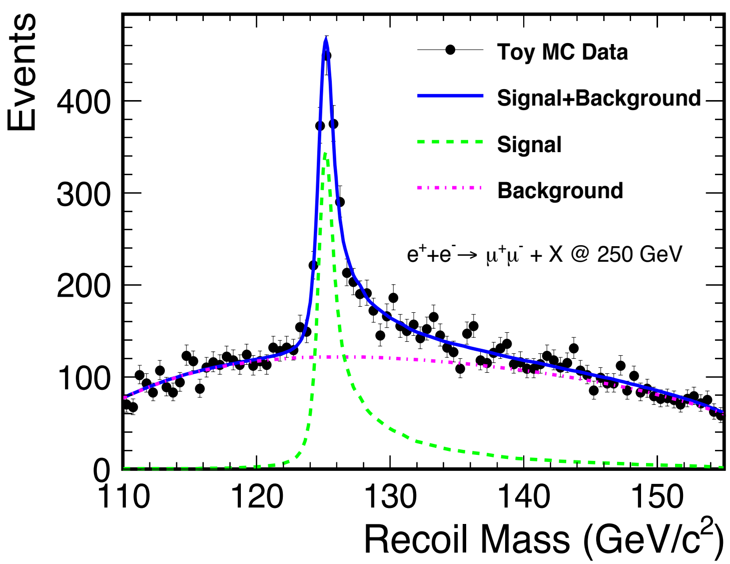
Outline

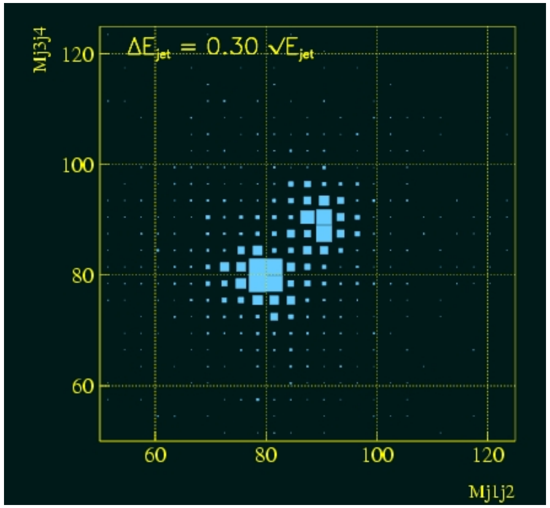
- **Introduction**
  - aspects of detector design
  - particle flow calorimetry
  - **Tracking detectors**
    - motivation and design
  - **Vertex detectors**
    - motivation and design
- **Application: Flavor Tagging**
  - vertex reconstruction
  - impact parameters
  - jet categorization

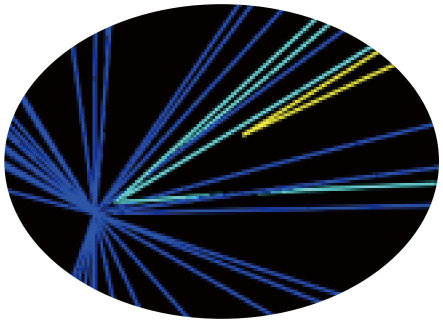
ILC Physics Goals

Reminder of ILC physics program:

- Precise measurements of **Higgs boson** and **top quark**
  - If there is new physics, their properties deviate from those predicted by the SM.
- Great potential for directly discovery of new particles, e.g.:
  - **Dark matter, supersymmetric (SUSY) particles…**
- Plenty of room for surprises!





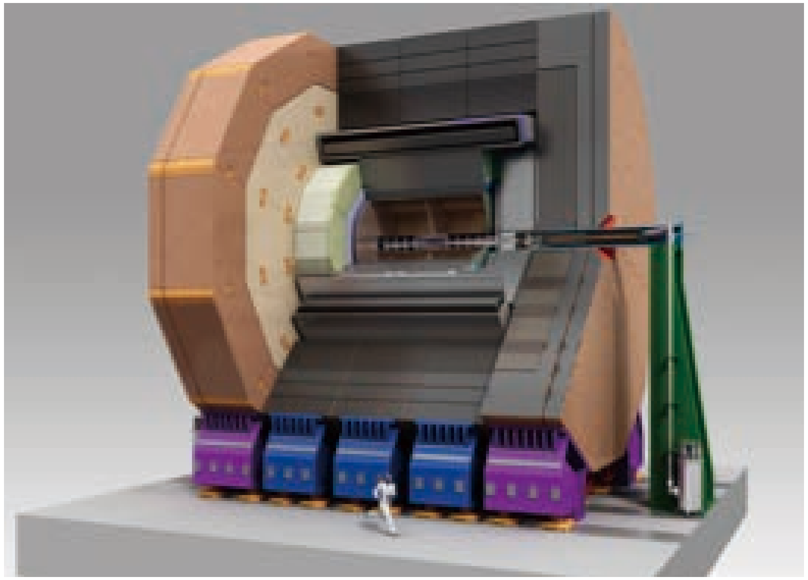


Aspects of Detector Design

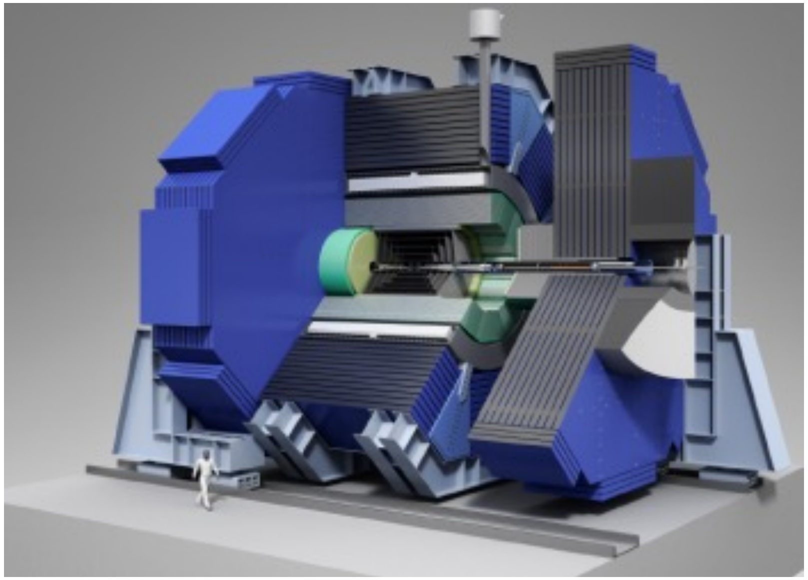
An ILC detector must:

- Be able to carry out the physics program
- Take into account the accelerator design (and provide feedback)
- Exploit and advance the latest sensor technology
- Fit in a reasonable budget profile (→ fixes the size of the detector)

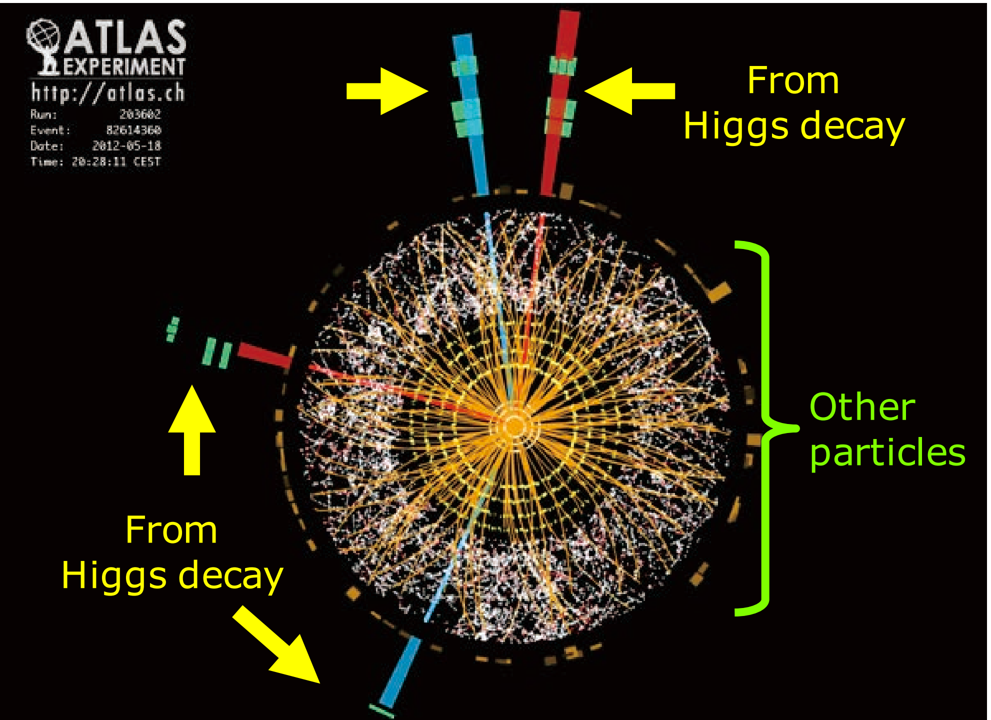
ILD



SiD

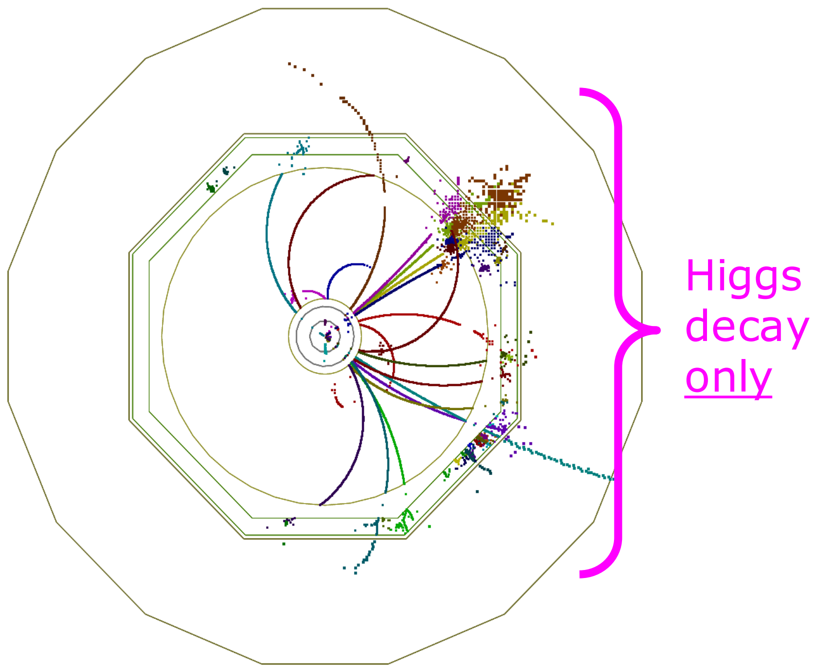


LHC/ILC Comparison: Higgs Detection



(ATLAS: H → ZZ* → μμee candidate)

LHC: Look for a striking signal in large background; high energy reach



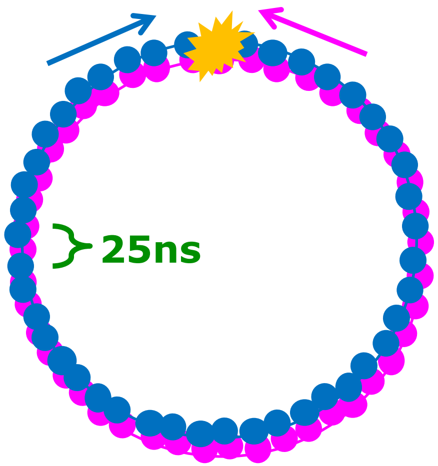
ILC: $e^+e^- \to \nu\nu H$ (simulation)

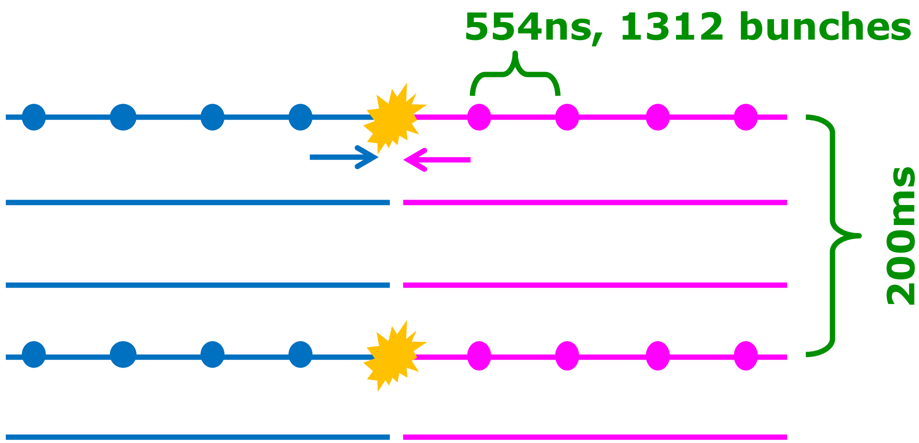
ILC: Detect everything, measure as precisely as possible

LHC/ILC Comparison: Collision Rate

LHC: high rate, continuous operation

ILC: low rate, with pause in-between bunch trains



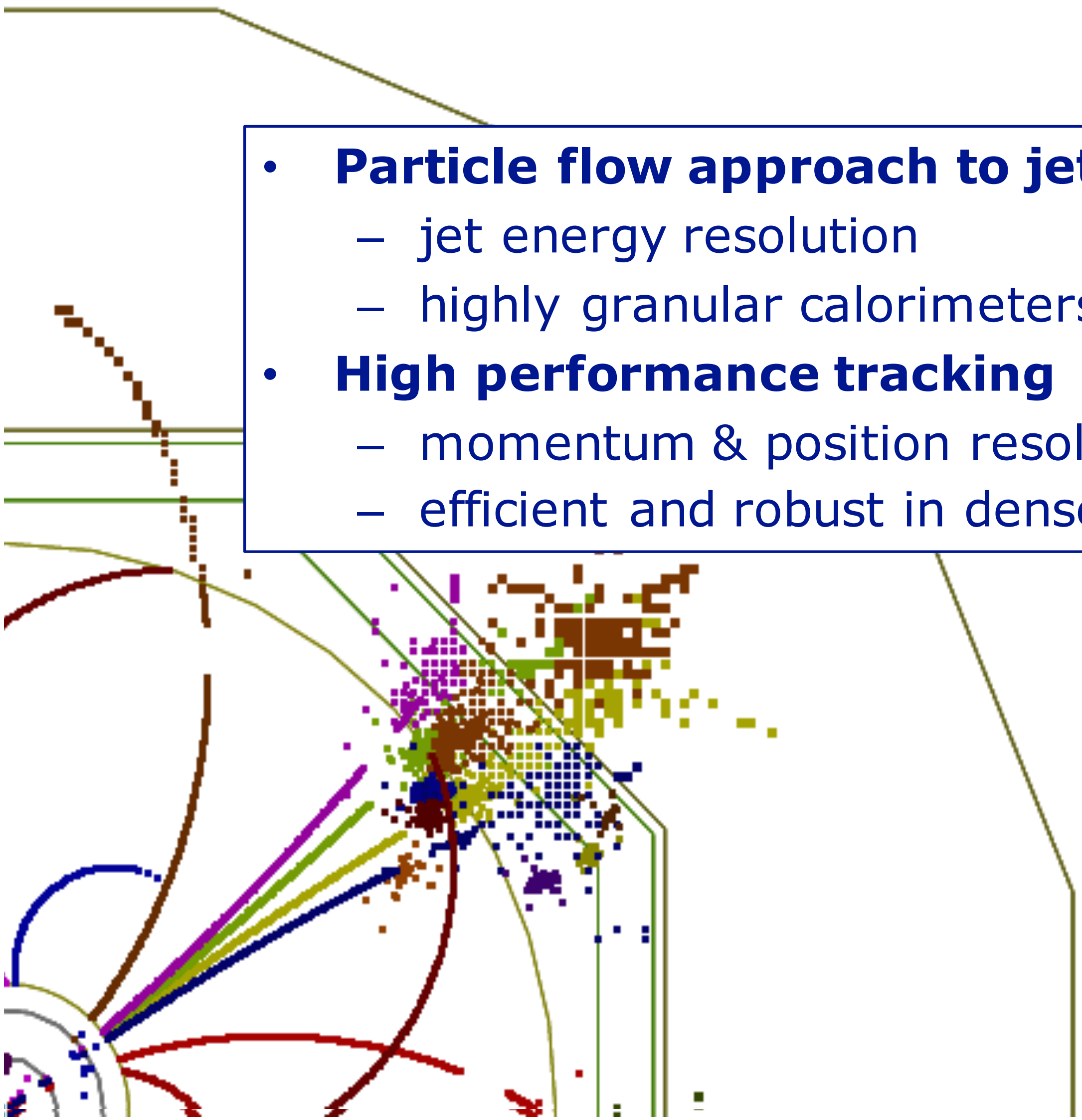


→ Detector requirements from the accelerator:

	LHC	ILC
Radiation hardness	★★★	★
Readout speed	★★★	★ (Trigger-free)
Number of sensors (Granularity/Thinness)	★	★★★

ILC Detector Design Philosophy

- **Particle flow approach to jet reconstruction**
  - jet energy resolution
  - highly granular calorimeters
- **High performance tracking**
  - momentum & position resolution
  - efficient and robust in dense environment

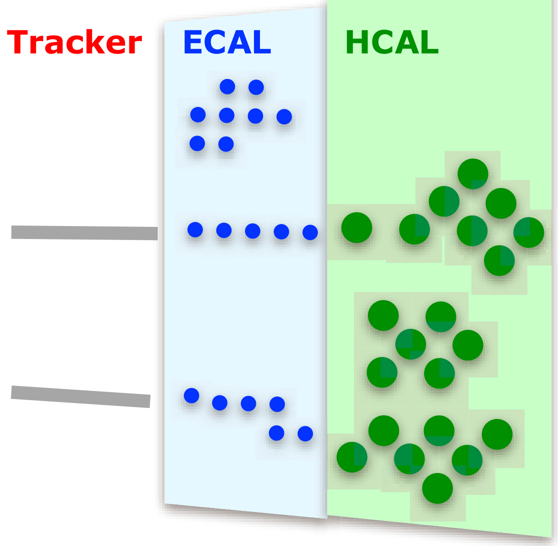


Particle Flow

	σ_E / E	@5 GeV	@50 GeV	@500 GeV
Tracker	0.00002 × E	0.01%	0.1%	1%
ECAL	0.2 / √E	9%	3%	1%
HCAL	0.6 / √E	30%	8%	3%

for single particles

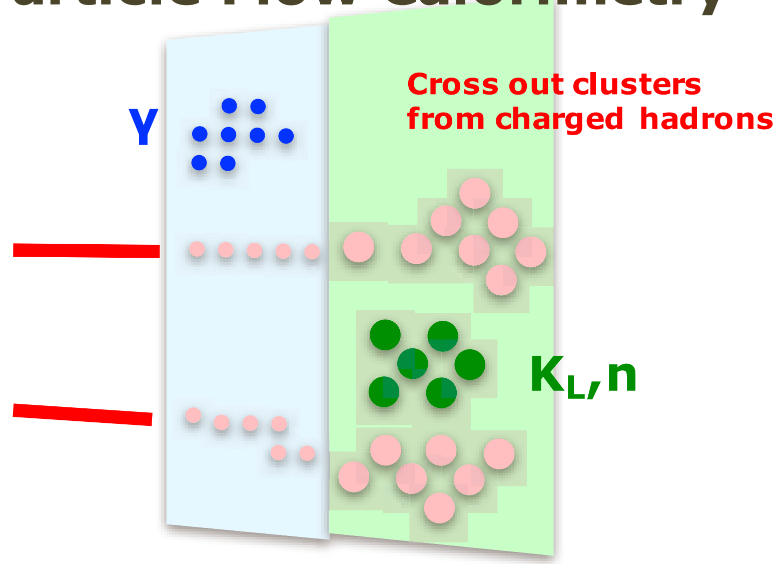
Traditional Calorimetry



E_{jet} = E(ECAL) + E(HCAL)

Composition ~30% : ~70%

Particle Flow Calorimetry

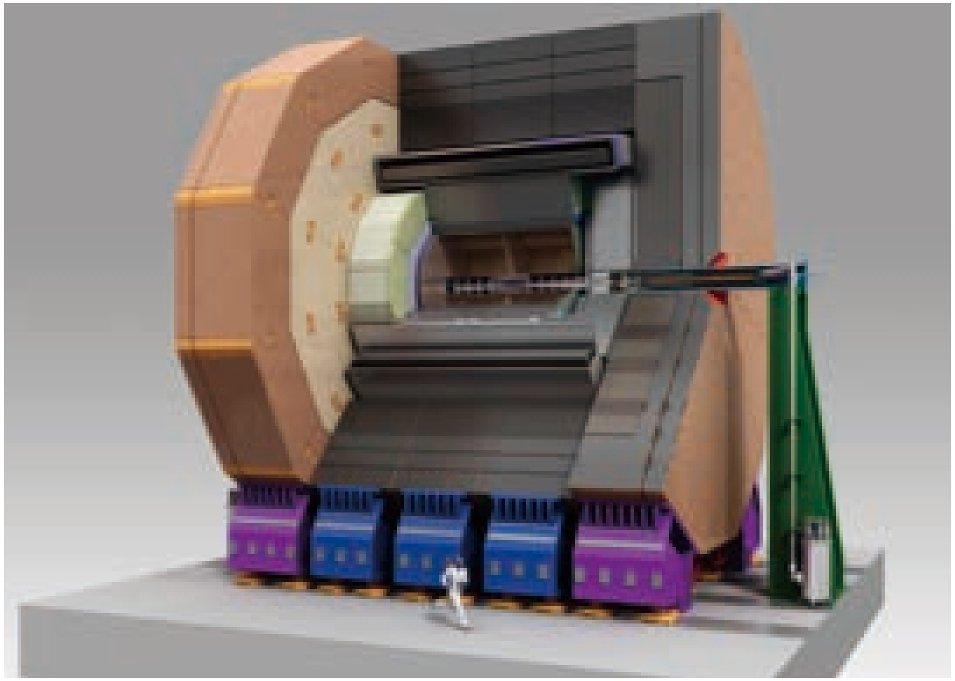


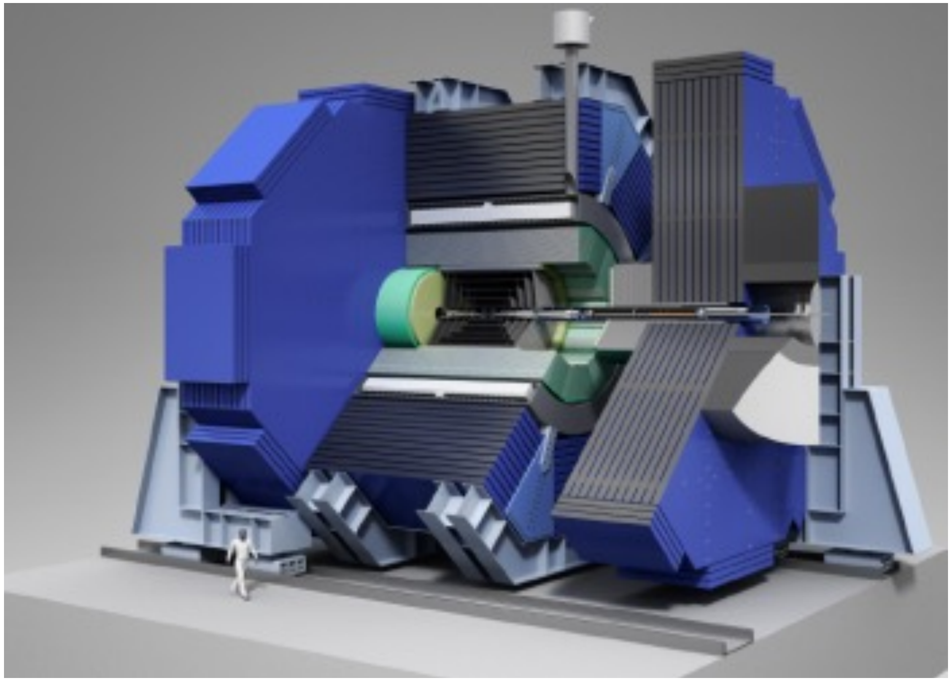
E_{jet} = E(Tracker) + E(γ) + E(K_L,n)

Composition ~60% : ~30% : ~10%

Reducing HCAL dependence improves E_{jet} resolution
→ Require highly granular ECAL & HCAL

ILD and SiD





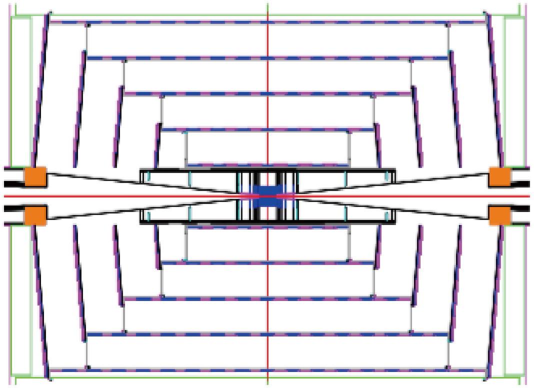
	ILD (International Large Detector)	SiD (Silicon Detector)
Height x Length	16 m x 14 m	14 m x 11 m
Weight	14,000 t	10,100 t
Magnetic field	3.5 T	5 T
ECAL inner radius	1.8 m	1.3 m
Tracker	TPC	Silicon strip

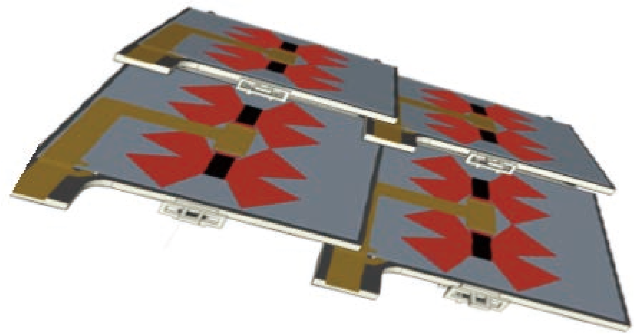
Both detectors optimized for particle flow performance

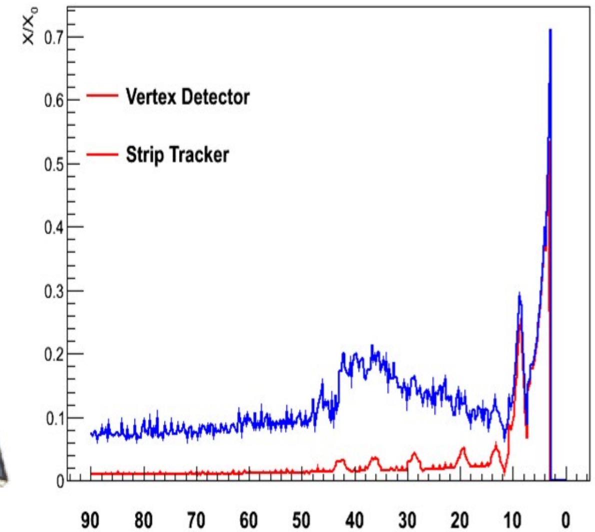
Tracker

SiD

5 layers of silicon strips
25 µm strips, 50 µm readout pitch

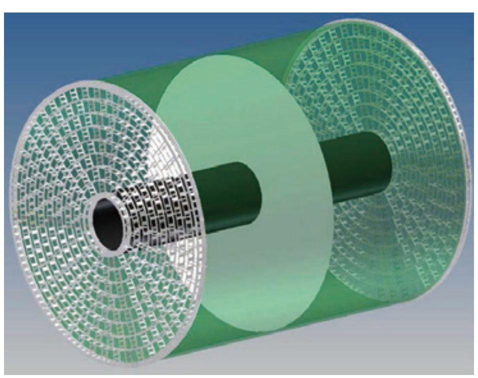


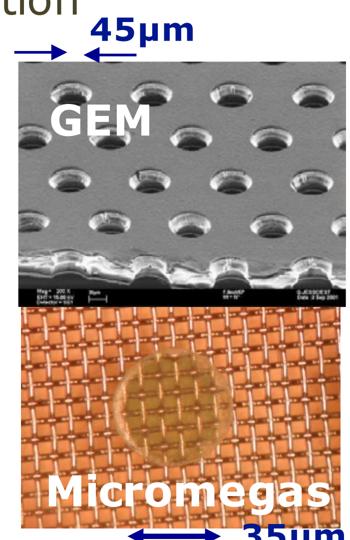


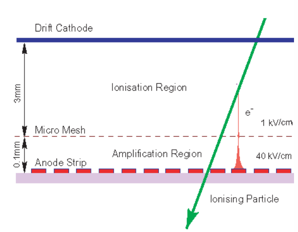


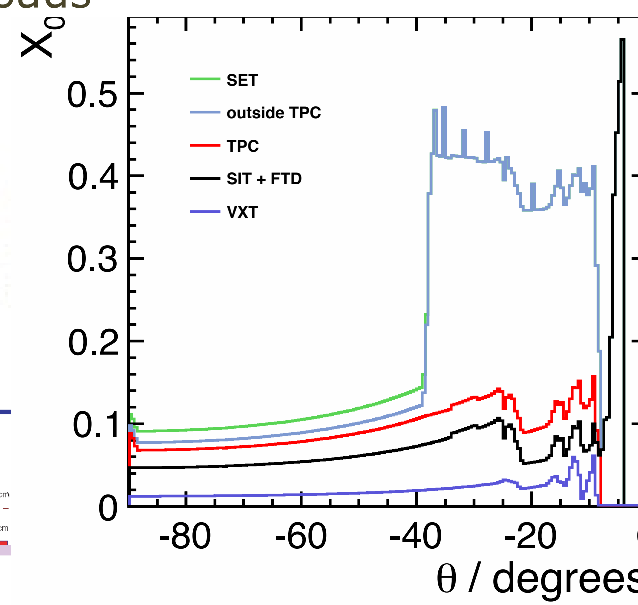
ILD

Time-Projection Chamber, 1x6mm^2 readout pads
~200 hits per track, 100µm resolution
dE/dx information









Momentum Resolution

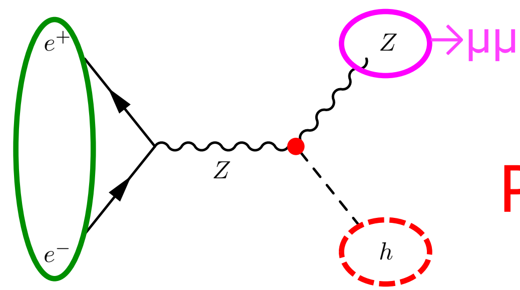
Track momentum resolution characterized by

$$\frac{\sigma_{p_T}}{{p_T}^2} = a \oplus \frac{b}{p_T \sin\theta}$$

track radius measurement (→ a)

multiple scattering (→ $\frac{b}{p_T \sin\theta}$)

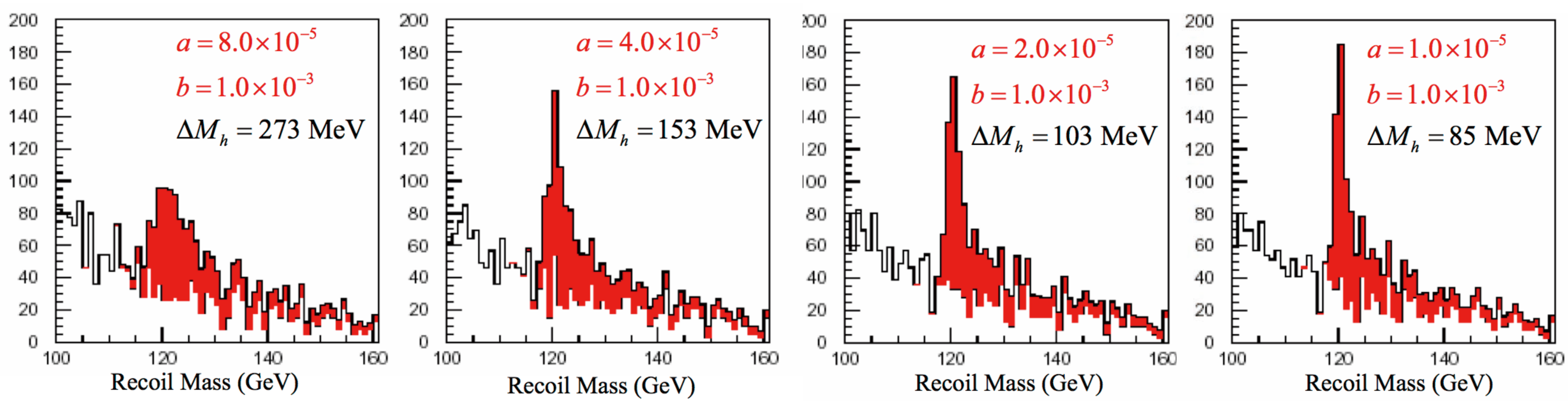
Requirement comes from the Higgs mass measurement via the recoil method:



$$P_H = P_{e+e-} - P_{\mu\mu}$$

beam spectrum (→ P_{e+e-})

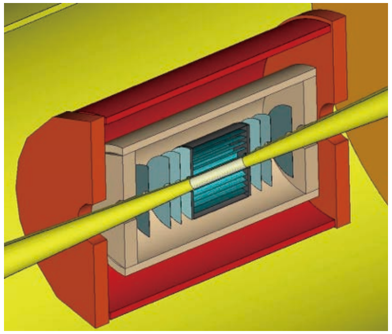
momentum resolution (→ $P_{\mu\mu}$)



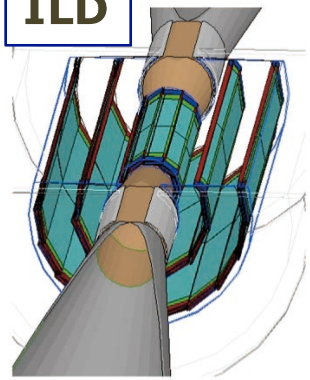
$a=8\times10^{-5}$ **$a=4\times10^{-5}$** **$a=2\times10^{-5}$ ILC goal** **$a=1\times10^{-5}$**

Vertex Detector

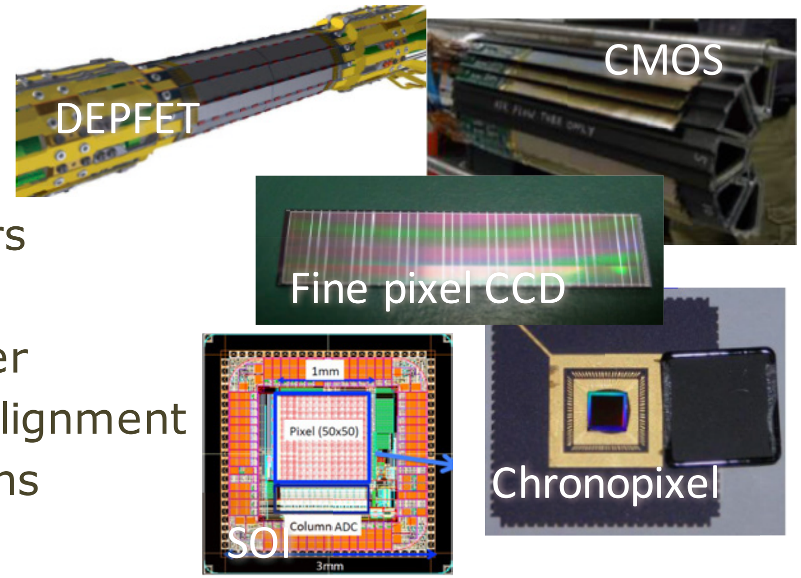
SiD



ILD



	R (mm)	$\lvert z \rvert$ (mm)	$\lvert\cos\theta\rvert$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100



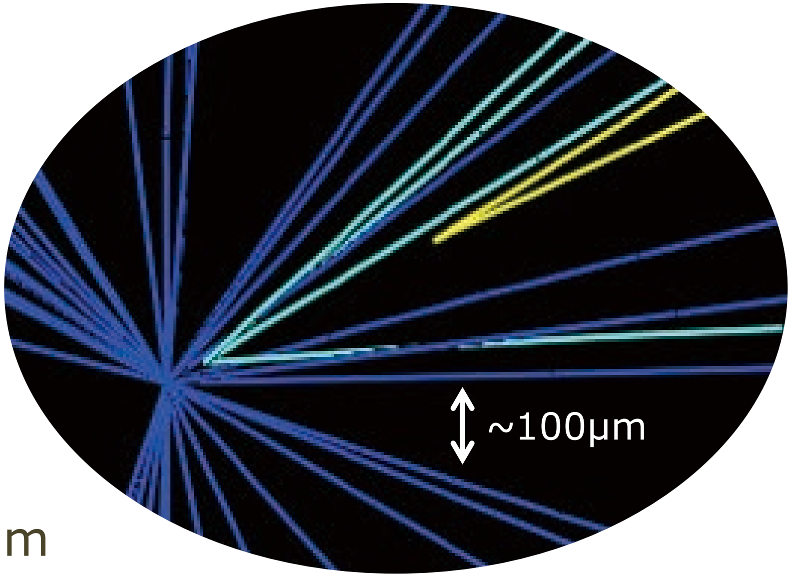
- Silicon pixels
  - 5 single layers or 3 double-sided layers
  - e.g. $\sigma_{r\varphi}$ ~3 μm → ~17μm pitch
- Low material budget: O(0.15%X_0) per layer
- Challenges: beam backgrounds, cooling, alignment
- Last detector to be installed; several options currently exist

- Readout strategies: exploiting the ILC duty cycle O(10^{-3}):
  - Slow readout (low power) in-between trains
    - either ~5μm pitch for occupancy or in-pixel timestamping
  - Fast readout with power cycling
    - mechanical stress from Lorentz forces in high B field

Vertexing and Flavor Tagging

Identifying the flavor of the originating quark helps with the reconstruction of the parent particle:

H → **bb**, **cc**, gg
t → **b**W
W → **c**s, ud
Z → **bb**, **cc**, ss, dd, uu



Key signature of heavy quarks:
secondary vertices

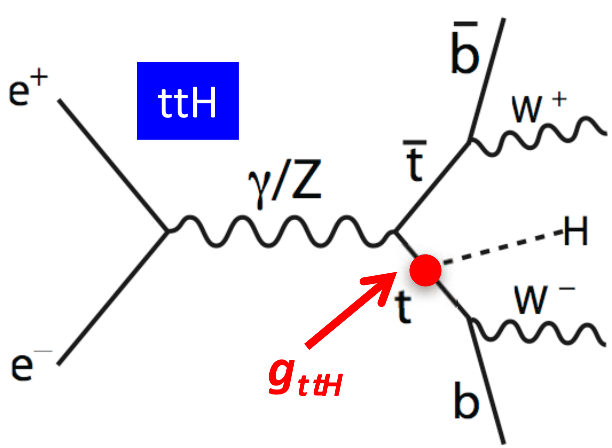
Lifetime of charm hadrons: cτ ~ 80μm
bottom hadrons: cτ ~400μm

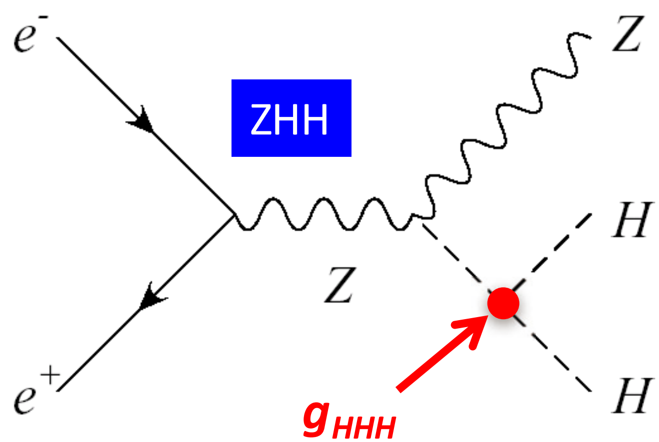
→ Requirement on spatial resolution of sensors close to the interaction point (=vertex detectors)

Flavor Tagging

- Many important physics processes have multiple heavy flavor jets
  - Higgs hadronic BRs: H → **bb**,**cc**,gg
  - Higgs self-coupling: ZHH → qq**bbbb**
  - Top-Yukawa coupling: ttH → **b**W**b**W**bb**

H→**bb** (58%)
Z→qq (70%)
W→qq (65%)

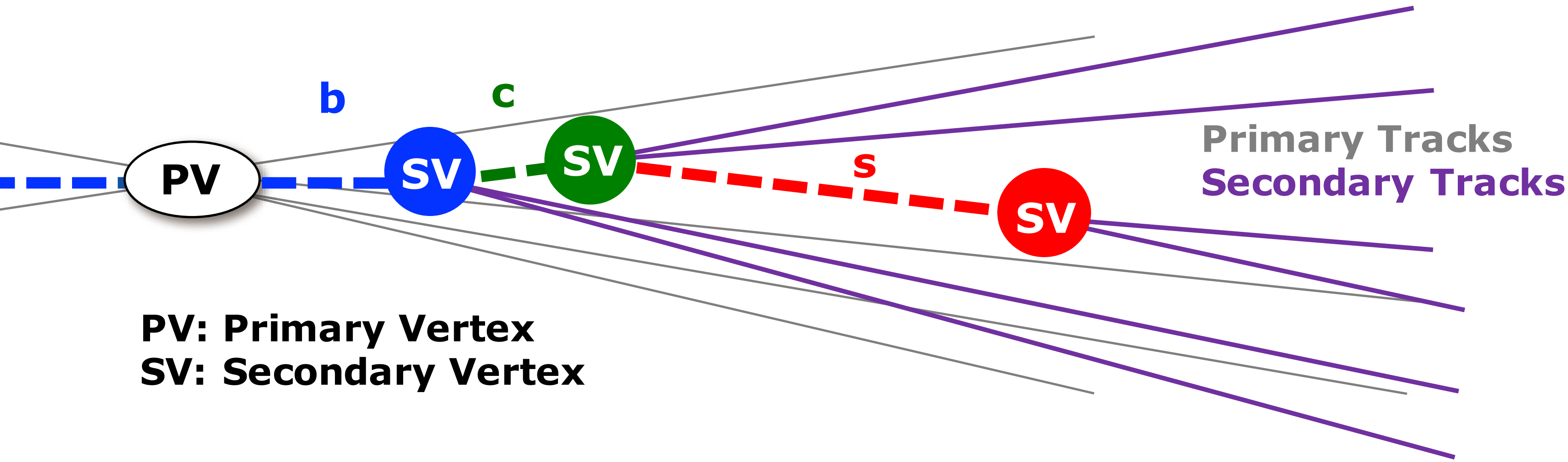




If single b-tag efficiency improves from 80% to 85% (+6%)
efficiency of **4b** improves 40% → 52% (+30%)
Large impact on final states with many b jets

Decay Chain

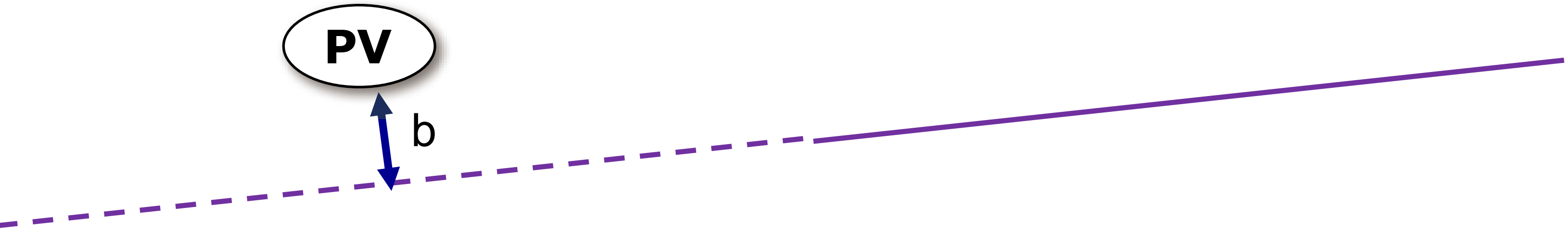
- Ideally want to reconstruct the entire decay chain in a jet:



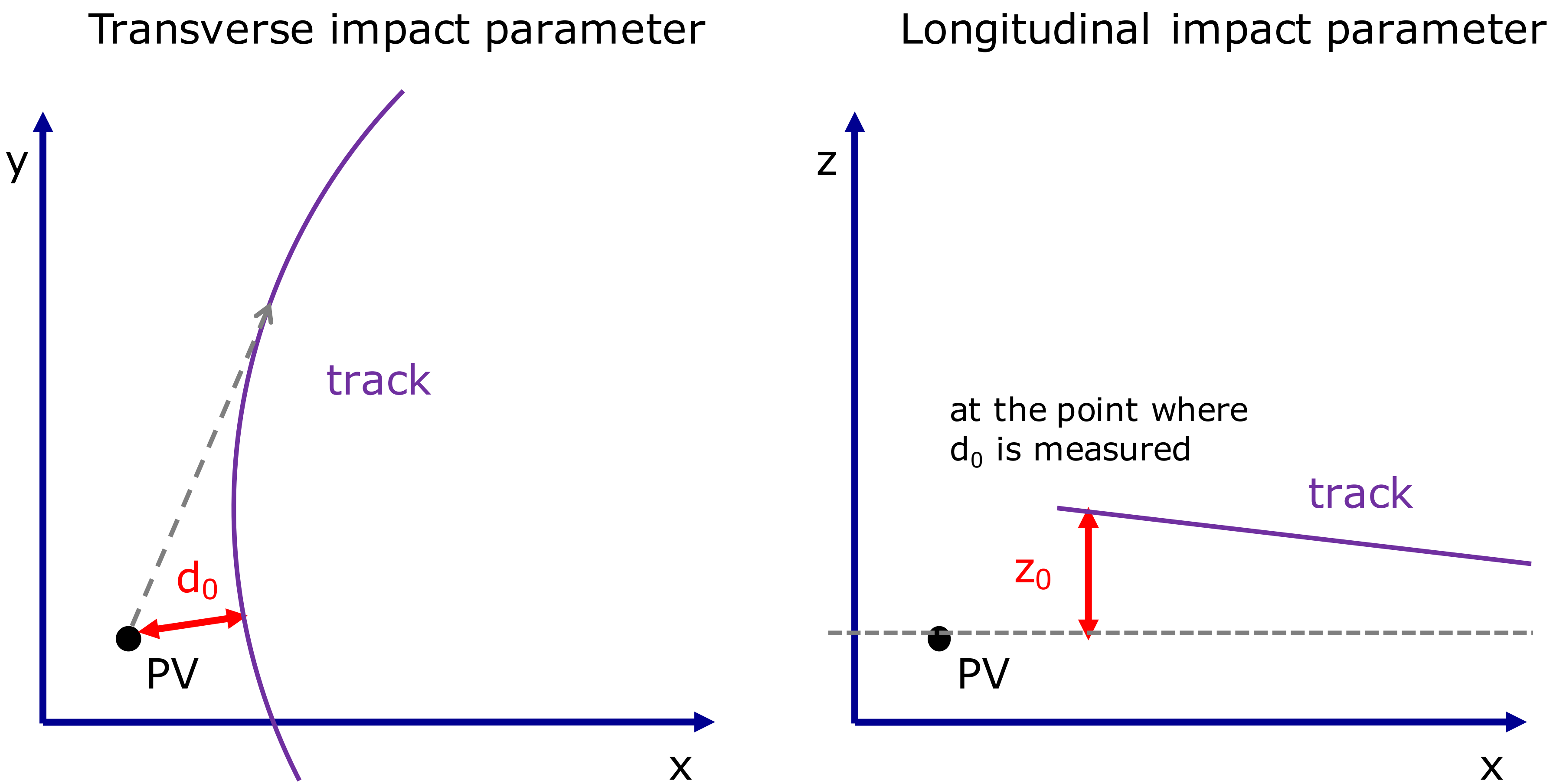
PV: Primary Vertex
SV: Secondary Vertex

Vertex reconstruction is key to flavor tagging

- Require at least two reconstructed tracks
- Use track impact parameter if vertex reco. not possible



Impact Parameter

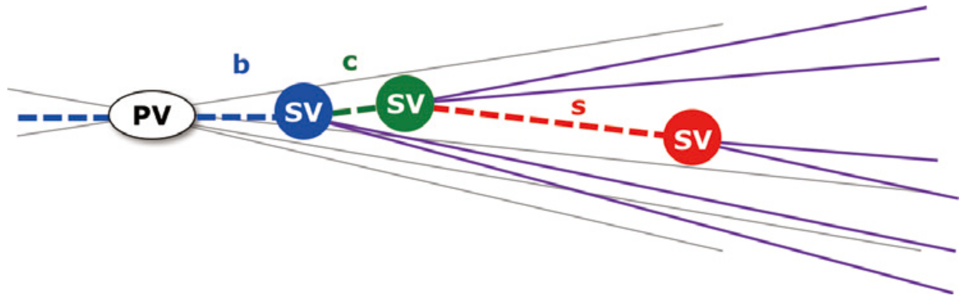


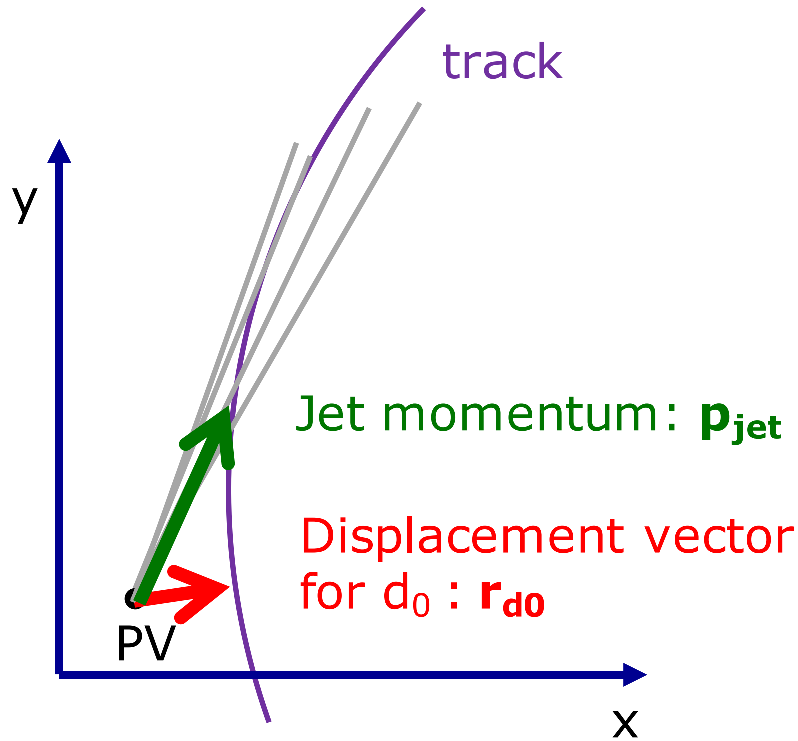
Impact parameter significance:
$S(d_0) = d_0/\sigma_{d0}$, $S(z_0) = z_0/\sigma_{z0}$

Uncertainty taken from track fit: σ_{d0} , σ_{z0}

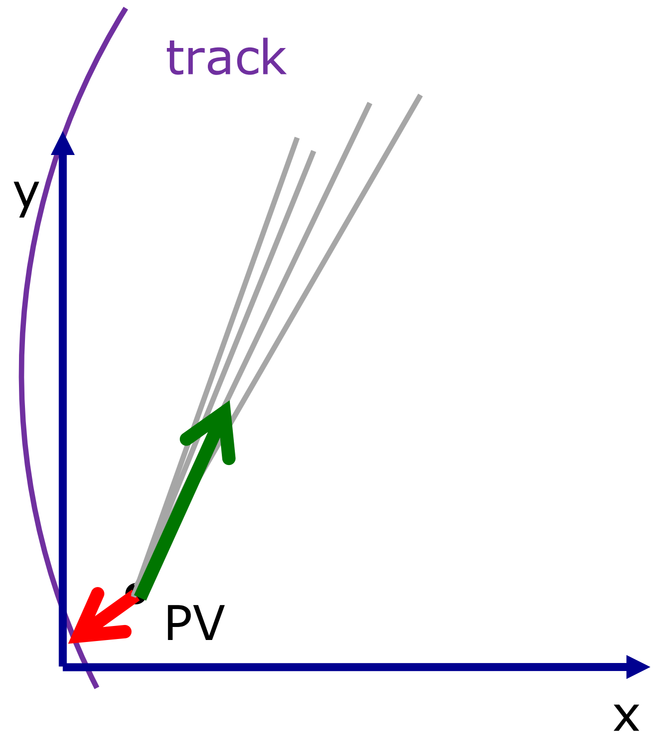
Signed Impact Parameter

Secondary decays should be in the direction of the jet

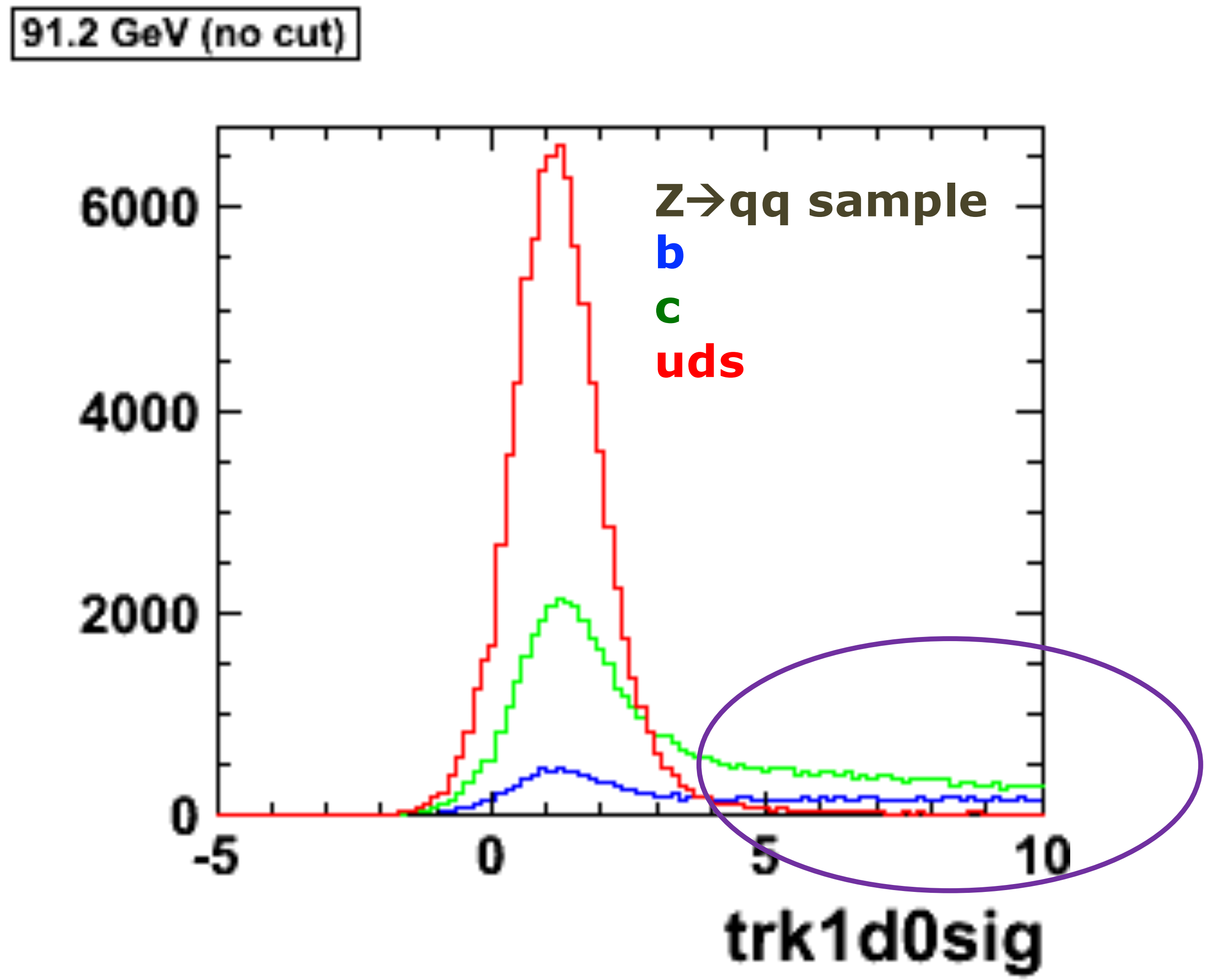




Positive if $(\mathbf{p}_{\mathbf{jet}} \cdot \mathbf{r}_{\mathbf{d0}}) > 0$

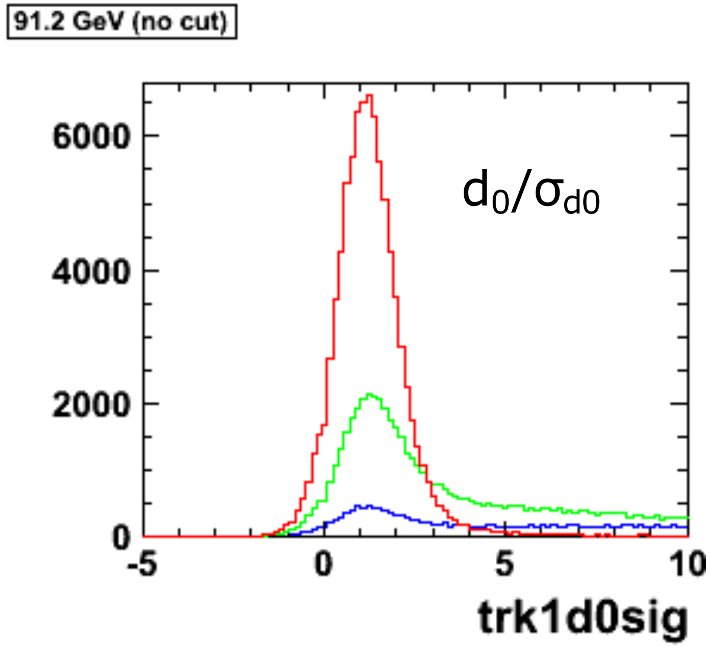


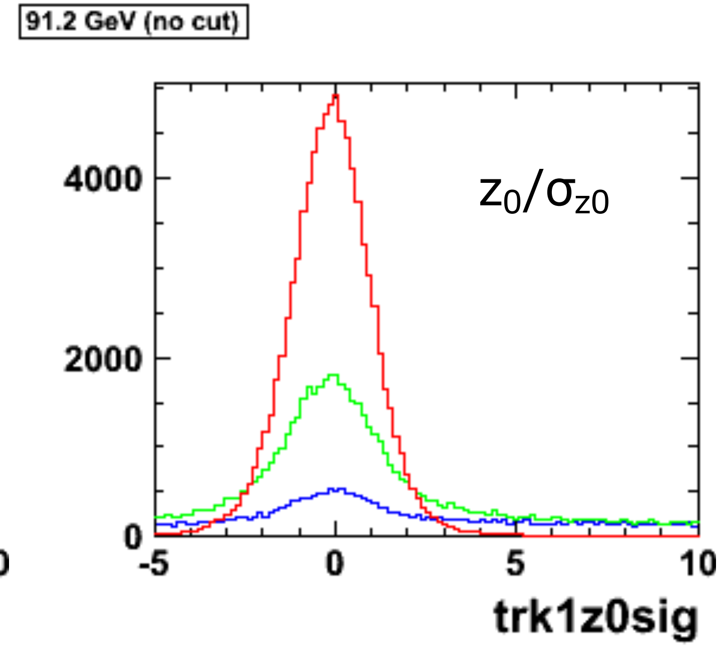
Negative if $(\mathbf{p}_{\mathbf{jet}} \cdot \mathbf{r}_{\mathbf{d0}}) < 0$



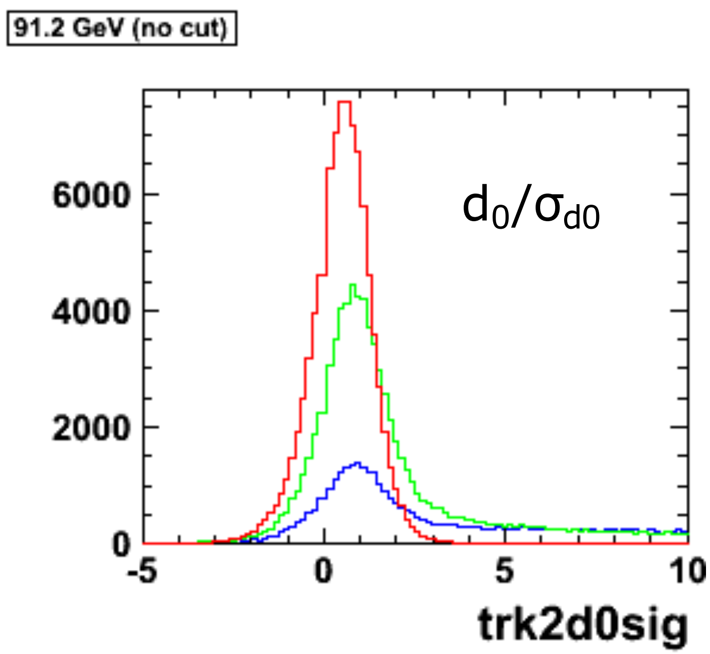
Signed transverse impact parameter significance
Track having the highest value is chosen to represent the variable per jet

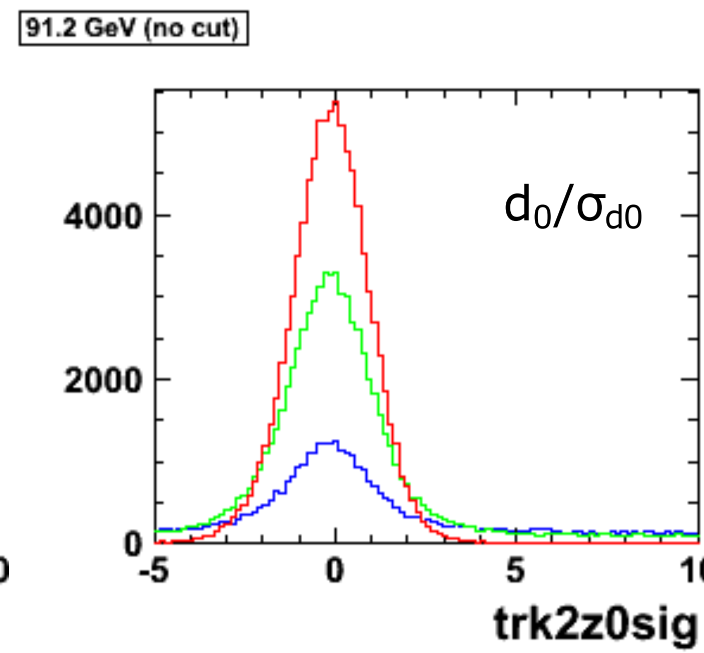
for track with
highest d_0/σ_{d0}





for track with
<u>second</u> highest
d_0/σ_{d0}

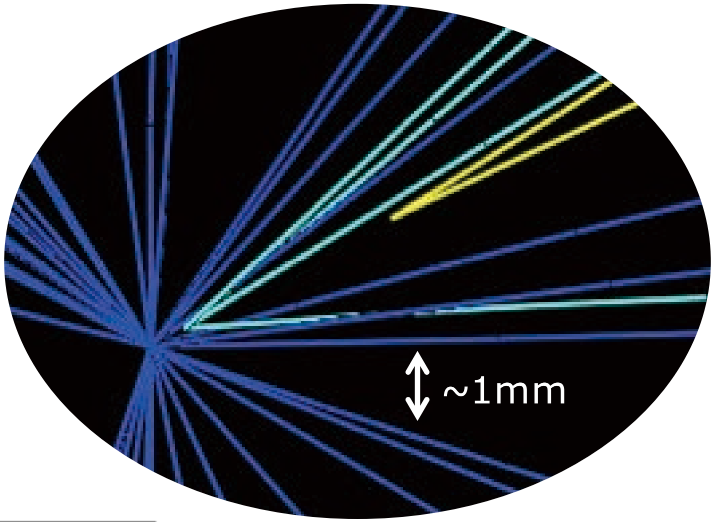




Secondary Vertex

Identifying the flavor of the originating quark helps with the reconstruction of the parent particle:

H → **bb**, **cc**, gg
t → **b**W
W → **c**s, ud
Z → **bb**, **cc**, ss, dd, uu



Key signature of heavy quarks:
secondary vertices

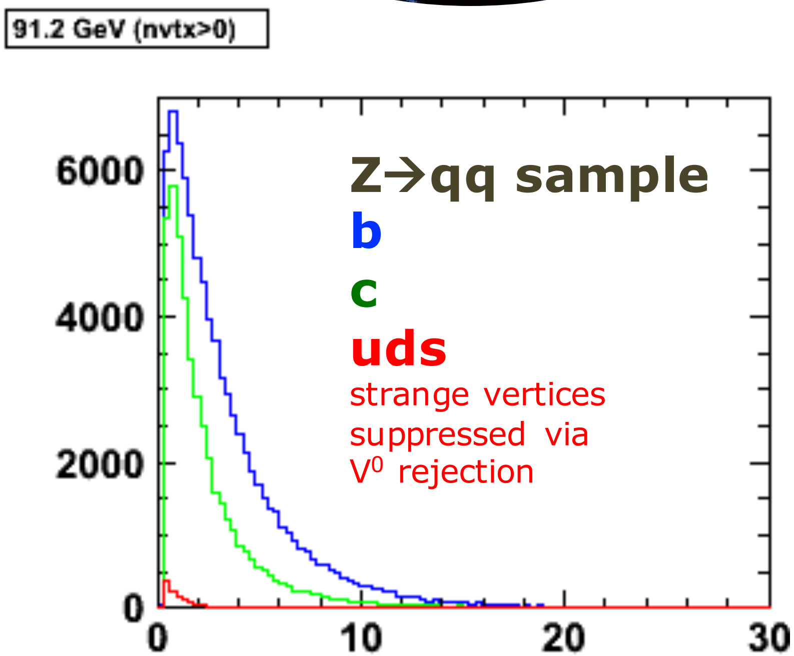
Lifetime of **c** hadrons: cτ ~ 80μm
b hadrons: cτ ~400μm

Exponential decay
Not Gaussian peaks!

Mean secondary vertex distance:

$$\langle L_{vtx} \rangle = \gamma\beta c\tau$$

e.g. for B meson (m_B~5 GeV) with E=45 GeV, γ~9, β~1 → L~3.6mm



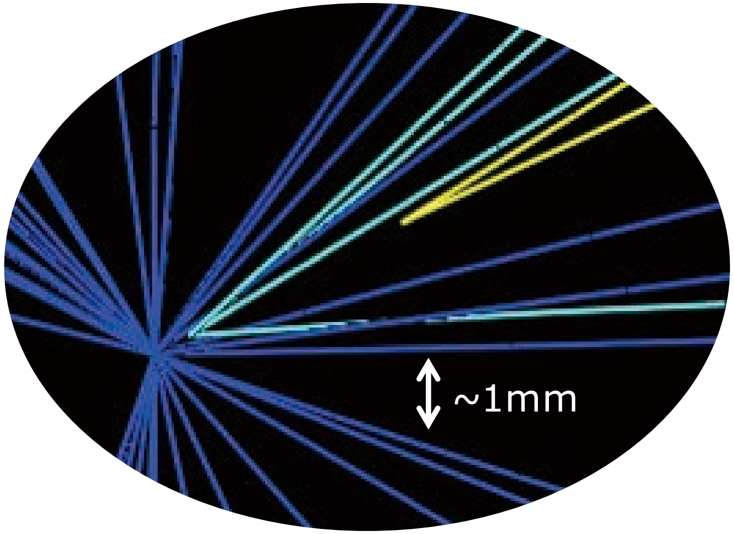
Distance between secondary vertex and primary vertex (reco.) [mm]

Vertex Reconstruction

Two standard approaches to vertex reconstruction:

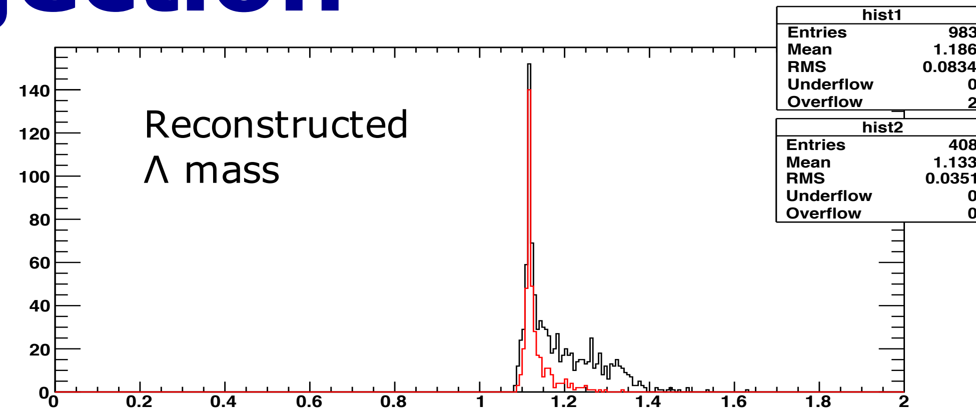
- "**tear down**" method – used for finding **primary** vertex
  - Start with all tracks
  - Fit the tracks to a vertex
  - Remove track which is most inconsistent with the vertex
  - Repeat until all tracks are consistent with the vertex, i.e. χ^2 contribution is smaller than some threshold value

- "**build up**" method – used for finding secondary **vertices**
  - Create vertex "seeds" from track pairs
  - Try to add more tracks to the vertex, accept if the vertex fit is good
  - Repeat until there are no more tracks to add



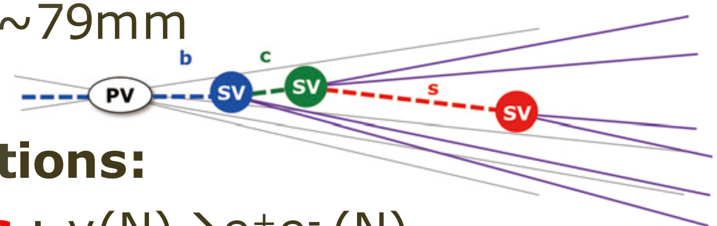
V^0 Rejection

Long-lived neutral particles "V^0 particles" decaying to two charged tracks are backgrounds in flavor tagging.



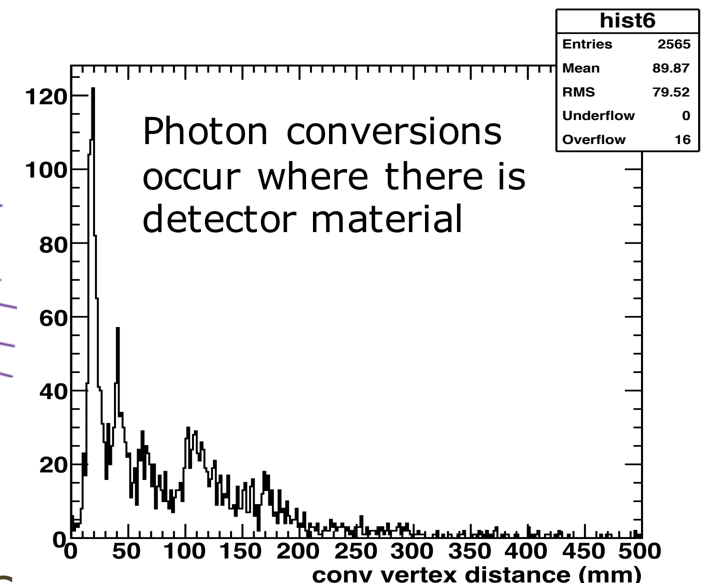
Strange neutral hadrons:

- **K_S** : lifetime cτ ~26mm
  - $K_S \rightarrow \pi^+\pi^-$
- **Λ** : lifetime cτ ~79mm
  - $\Lambda \rightarrow p\pi$



Material interactions:

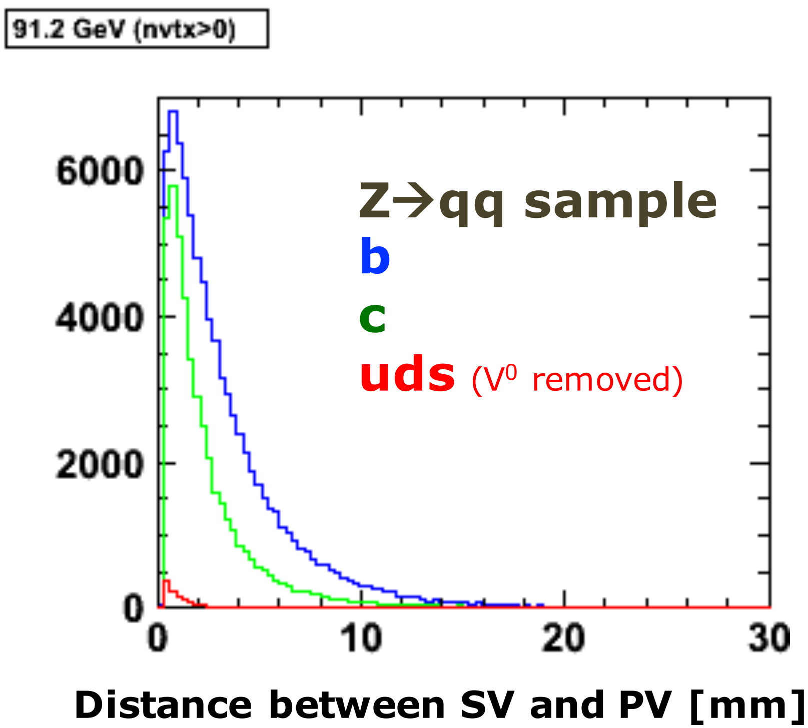
- **γ conversions** : $\gamma(N) \rightarrow e^+e^-(N)$

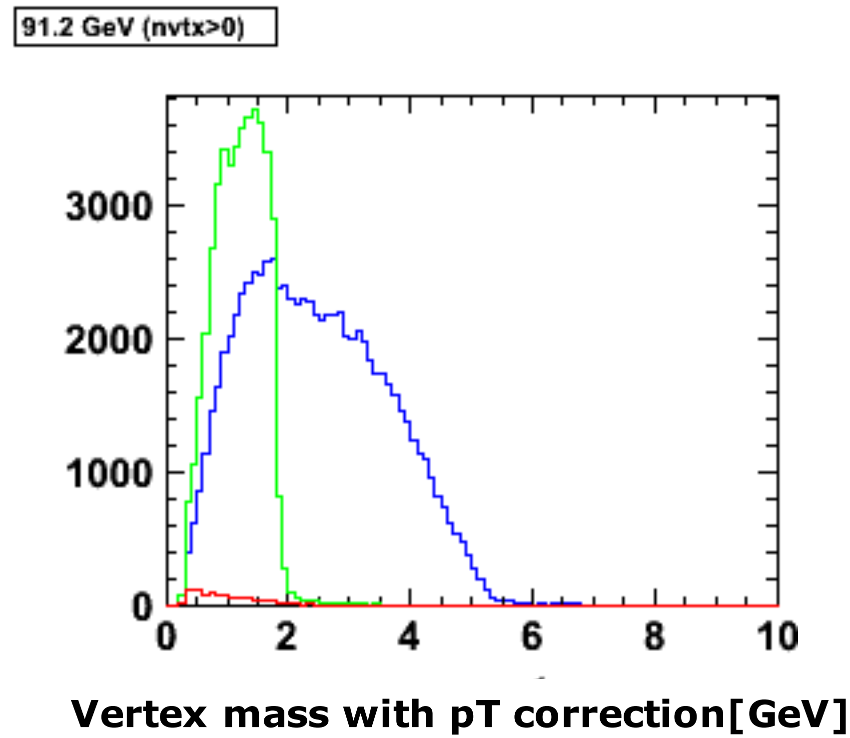


V^0 particles are removed by applying selections on the mass and direction to the primary vertex.

	K_S^0 tight	K_S^0 loose	Λ^0 tight	Λ^0 loose	γ_{conv} tight	γ_{conv} loose
Mass (GeV)	[0 493 0 503]	[0 488 0 508]	[1 111 1 121]	[1 106 1 126]	< 0 005	< 0 01
r (mm)	> 0 5	> 0 3	> 0 5	> 0 3	> 9	> 9
p r	> 0 999	> 0 999	> 0 99995	> 0 999	> 0 99995	> 0 999

Secondary Vertex Reconstruction





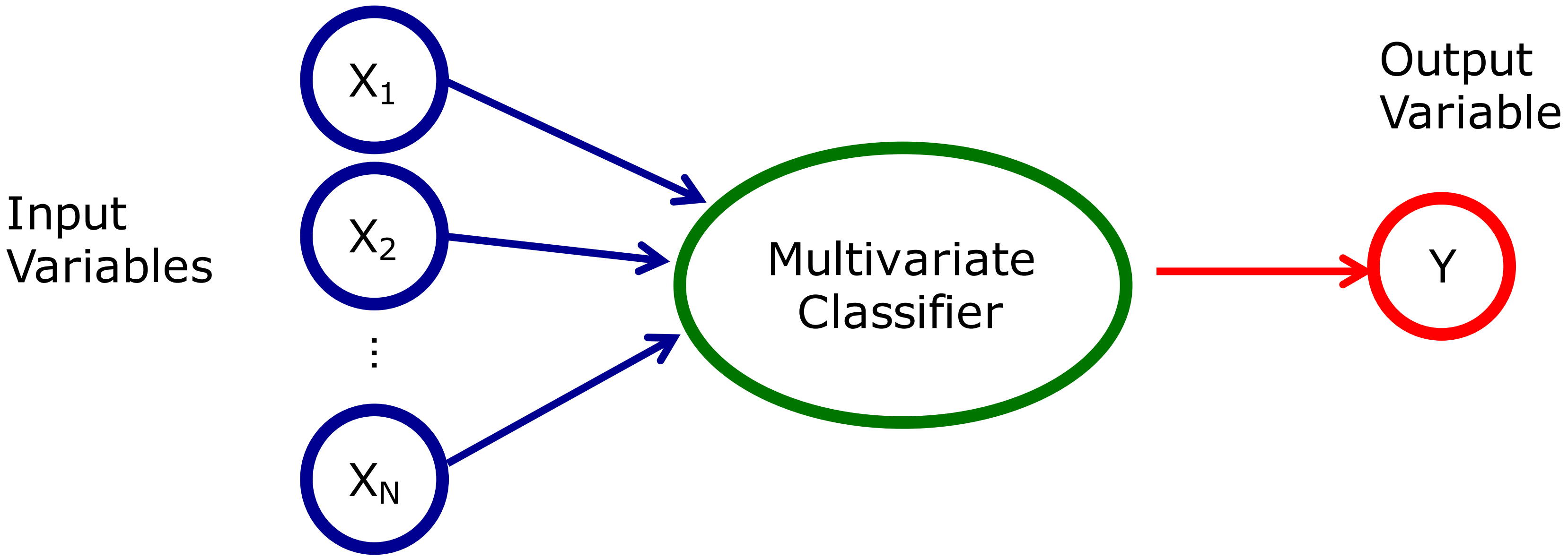
Add minimum amount of pT to the vertex (contribution from neutral particles) needed to make the vertex momentum direction consistent with the primary vertex

m_b ~ 5 GeV, m_c ~ 2 GeV
Vertex mass powerful discriminant for b/c separation

Track origin	Primary	Bottom	Charm	Others
Total number of tracks	496897	258299	247352	56432
Tracks in secondary vertices	0.6%	57.5%	64.3%	2.5%
... from the same decay chain		56.6%	63.4%	1.9%
... from the same parent particle		32.2%	38.9%	1.2%

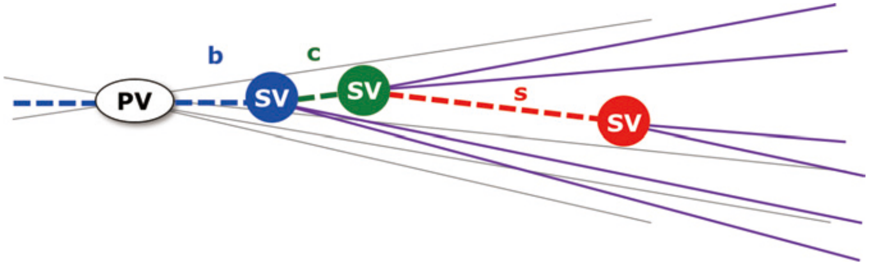
Multivariate Analysis

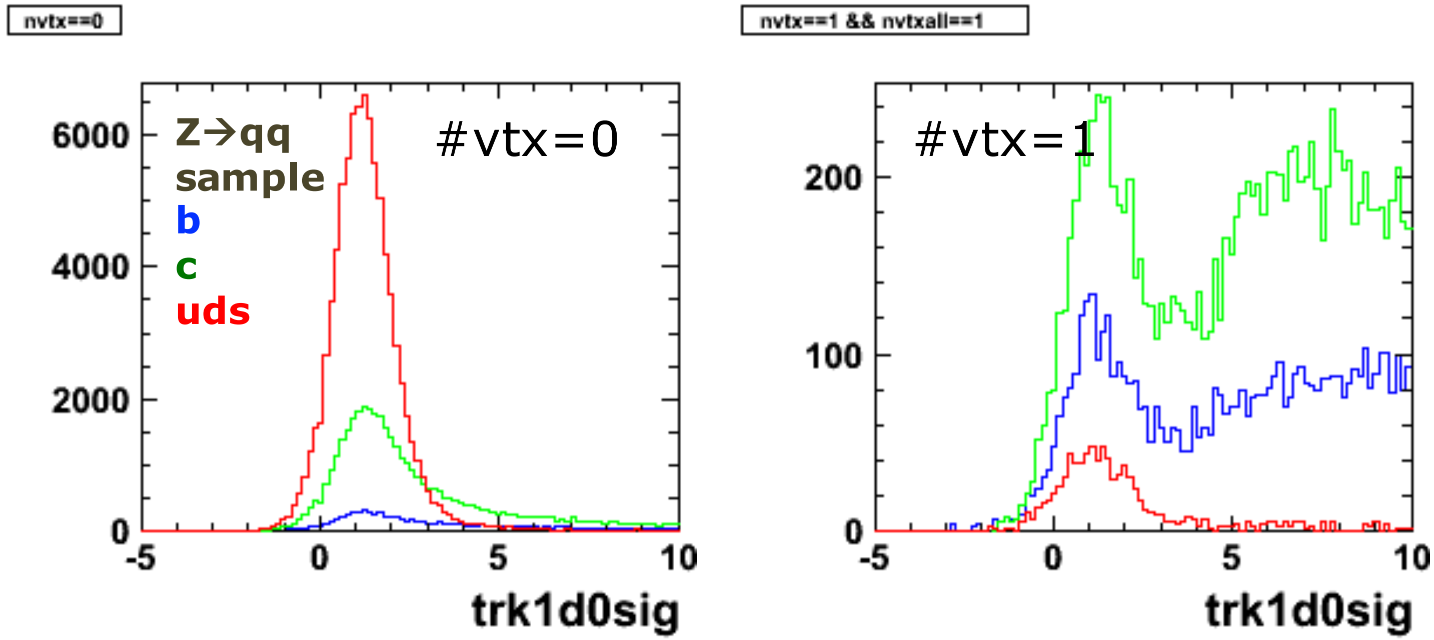
- We construct discriminating variables for each jet.
- We then perform a **multivariate analysis** (as implemented in the **TMVA** package of ROOT):
  - To fully take advantage of the shape of the distributions, while taking into account the correlations among the variables
- We "train" the multivariate classifier by using samples which we already know the "correct answer". The algorithm learns how to use the variables to arrive at the "correct answer".
  - We need to ensure that "training" and "testing" datasets are statistically independent when giving the results.



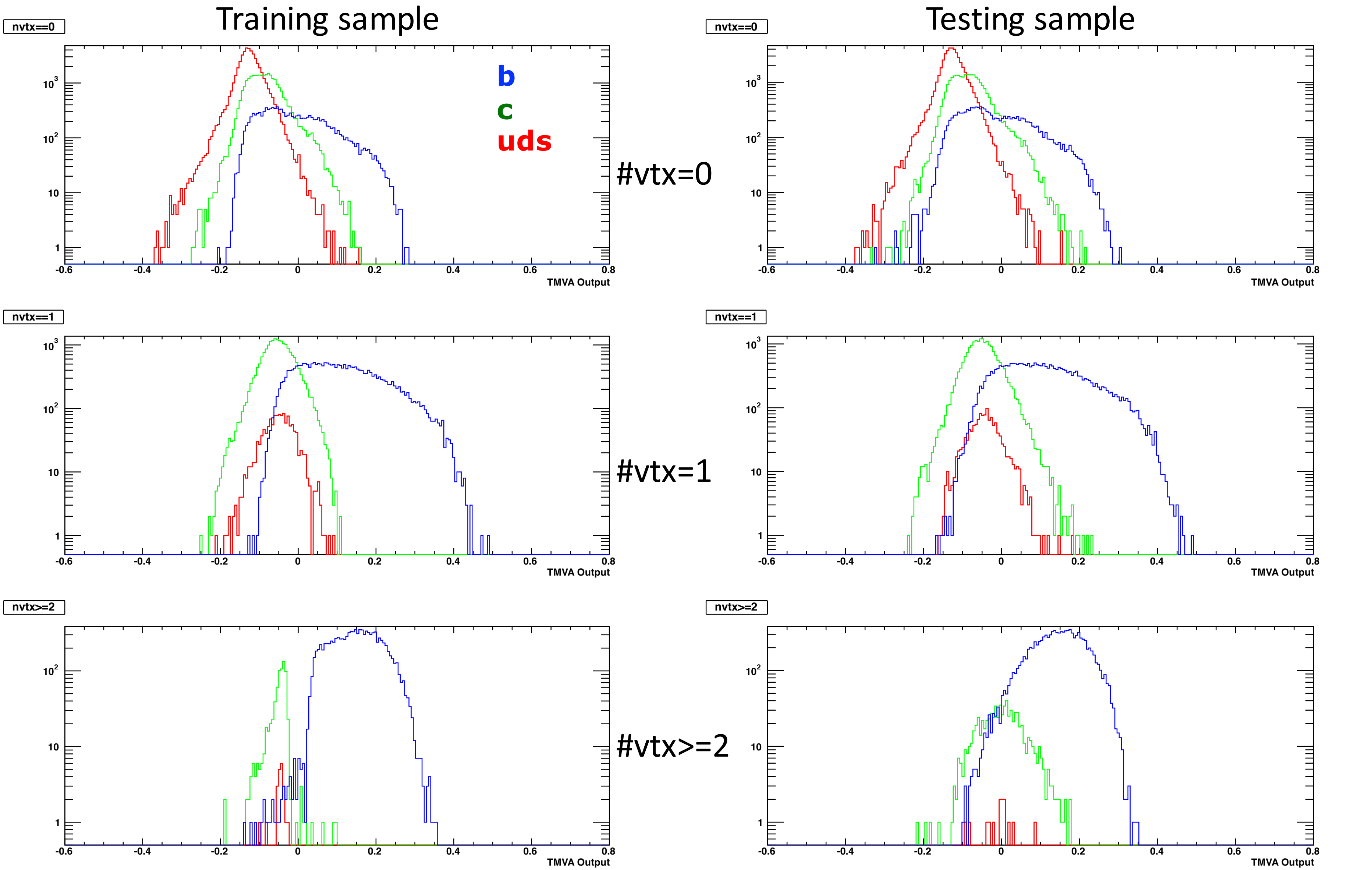
Categories

- For the training of the multivariate analysis, it is often helpful to divide the dataset into different parameter spaces. This is especially the case if we <u>know</u> that they will be very different. Then the algorithm can focus on the differences within the restricted space, rather than finding the boundaries of this parameter space which gives the large difference.
- In our application, we divide the dataset according to the number of reconstructed vertices:
  - Category 1: # of vertex = 0
  - Category 2: # of vertex = 1
  - Category 3: # of vertex = 2





Output Variable from Multivariate Analysis

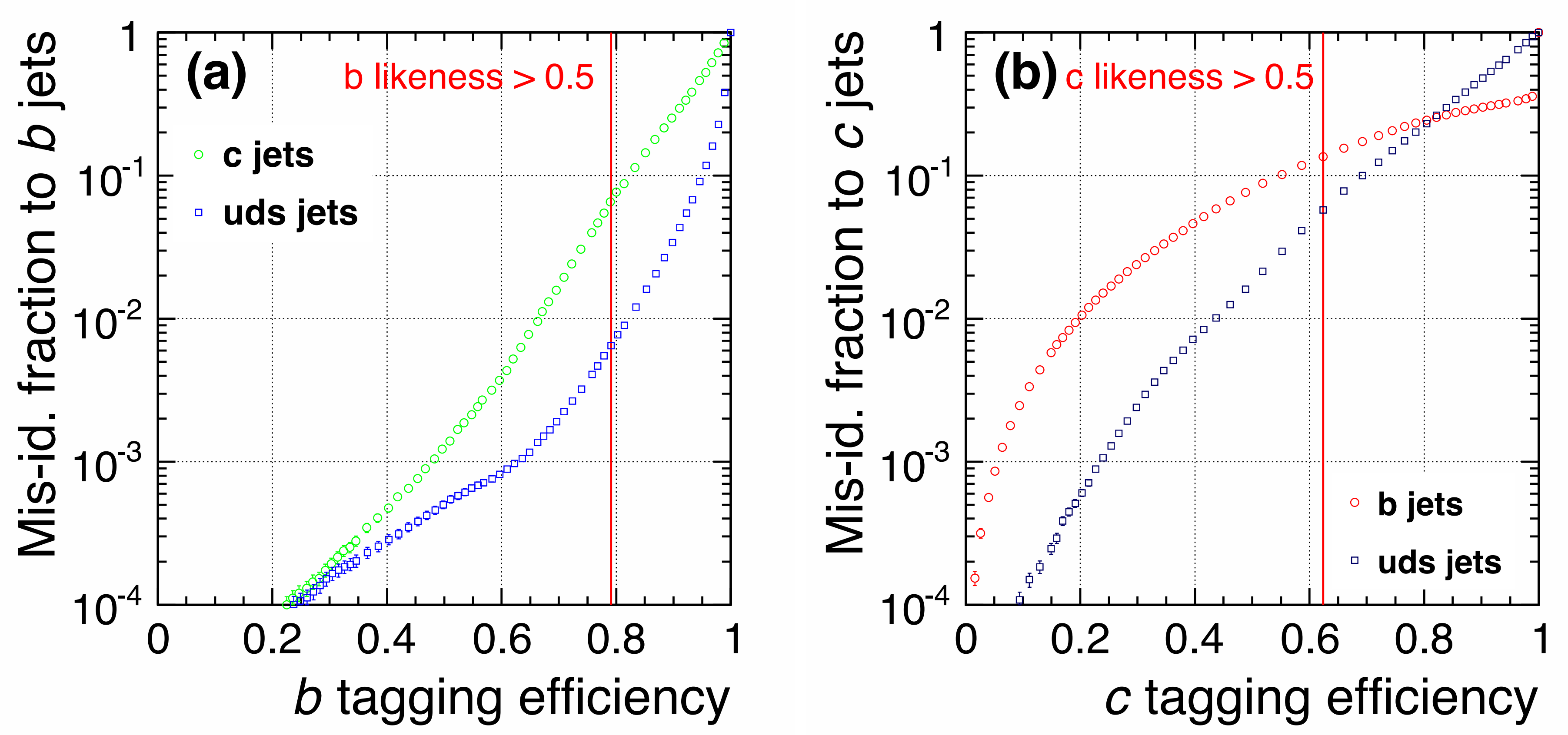


The output value is used to assign a likelihood that a jet is of a given flavor

Flavor Tagging Performance

b tagging
i.e. b signal, c/uds background

c tagging
i.e. c signal, b/uds background

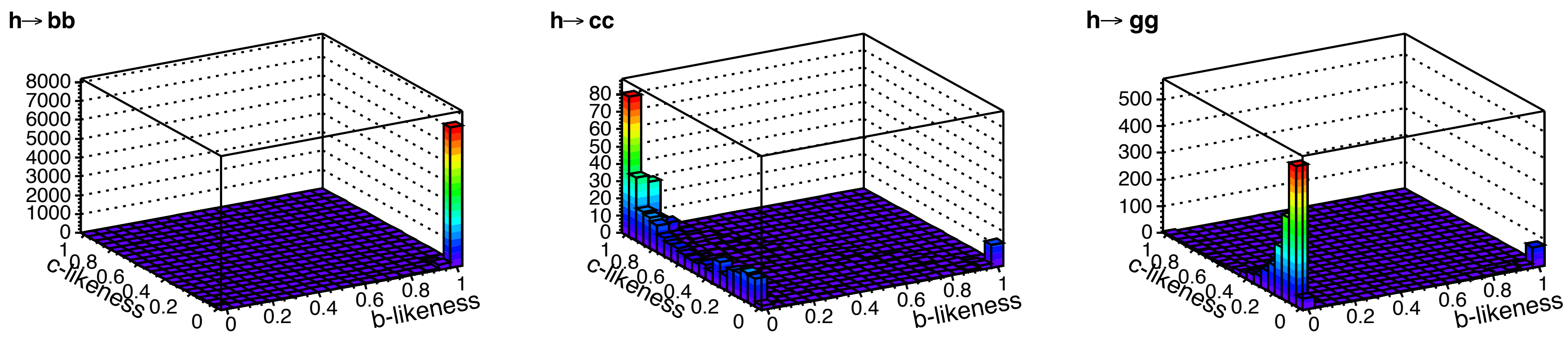


avor assignment	true b jet	true c jet	true uds jet
b jet	80.1%	7.28%	0.94%
c jet	16.2%	67.4%	9.56%
uds jet	3.72%	25.3%	89.5%

Application: Higgs hadronic decays

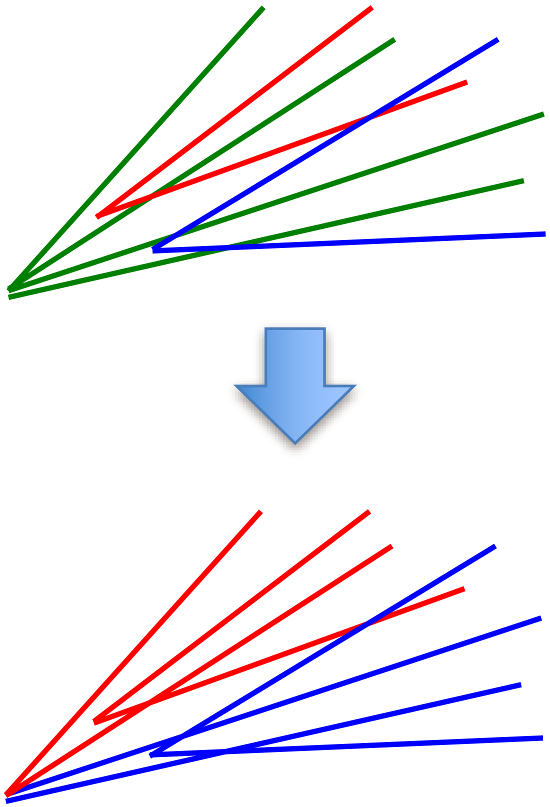
Template distributions for H→bb,cc,gg:

ILC 250 GeV [H.Ono]

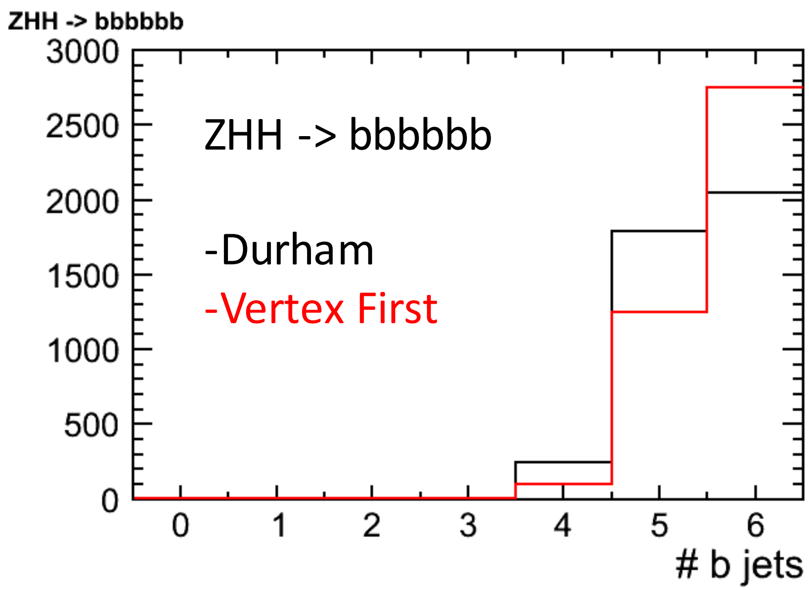


→ **Flavor tagging makes it possible to measure Higgs BRs to bb/cc/gg**

Jet Finding and Vertex Splitting

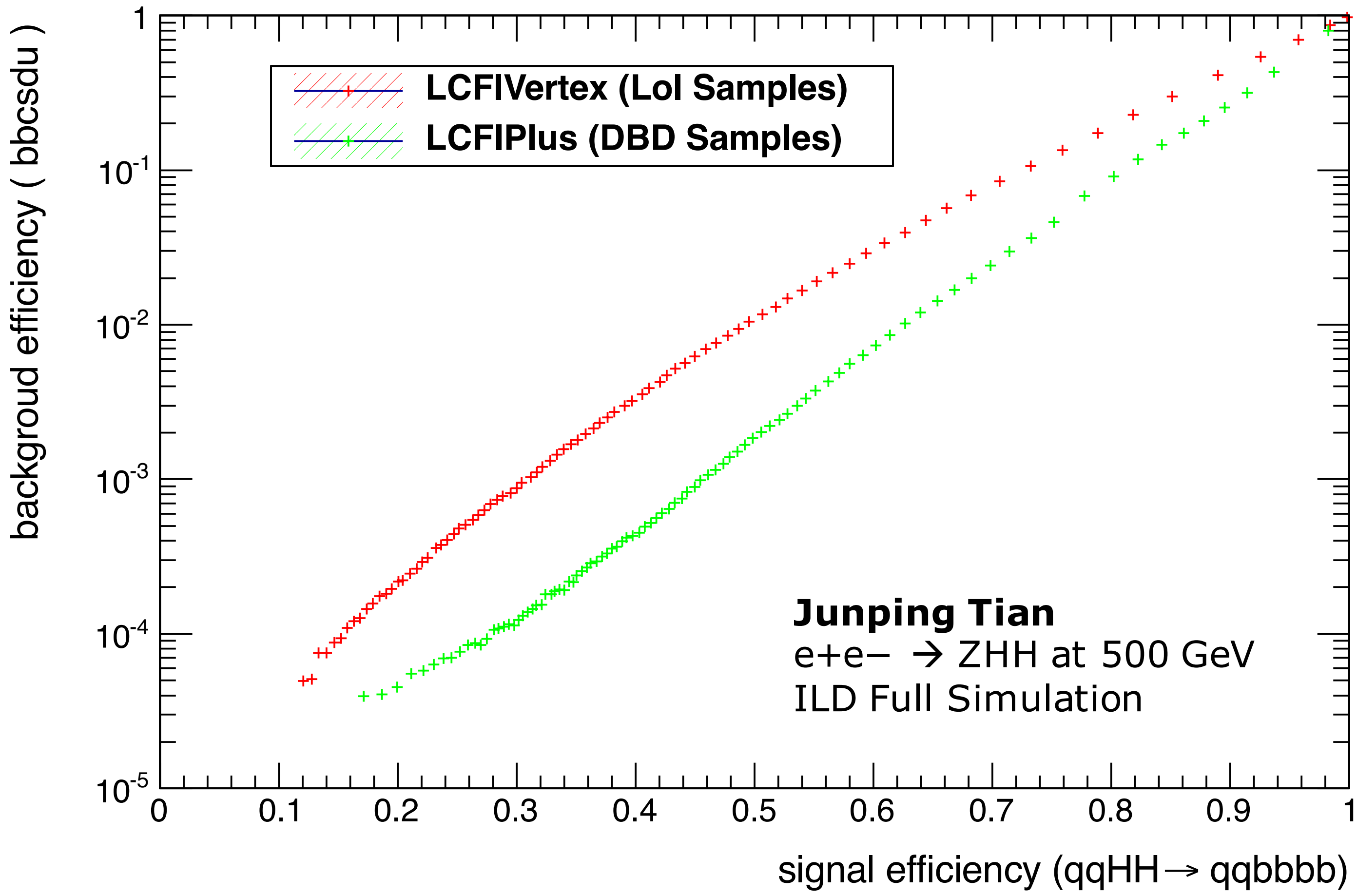


- So far, assumed that jet finding is done prior to flavor tagging
- HOWEVER, secondary tracks can get combined into different jets
  - effect significant in events with many jets
- **Solution:** perform vertex finding <u>before</u> jet clustering
  - computationally more challenging but doable



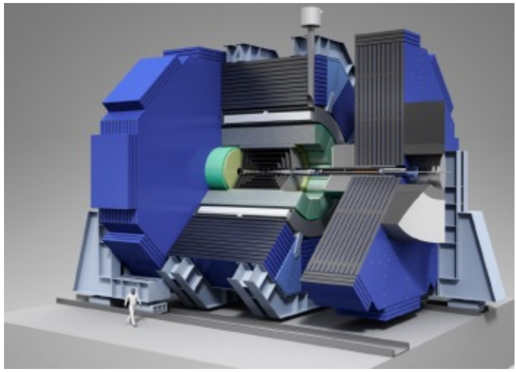
Shown to increase b finding efficiency in ZHH events

Performance: ZHH at 500 GeV



Summary

ILC detector concepts: SiD & ILD



- Requirements driven by physics
- Both concepts based on **particle flow** with high granularity sensors
- High performance tracking
  - ILD: TPC as main tracker
  - SiD: all silicon
- Vertexing essential for flavor tagging

Flavor tagging

- Reconstruction of decay chain
- Secondary vertices and tracks with large impact parameters are key objects
- Multivariate analysis with event categorization essential for performance
- b tagging and c tagging demonstrated for linear collider studies