Vertex reconstruction at the CMS experiment

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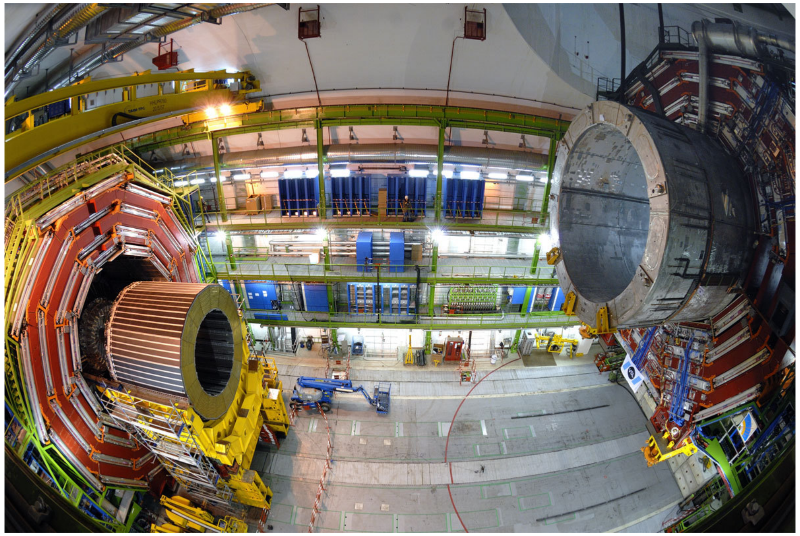
- Introduction
- (Robust) Algorithms
- Comparison of fitters
- Vertex finding
- Conclusions

Introduction: The CMS Experiment



Compact Muon Solenoid (CMS)

multi-purpose detector

full event reconstruction

LHC: pp collider, $\sqrt{s} = 14TeV$

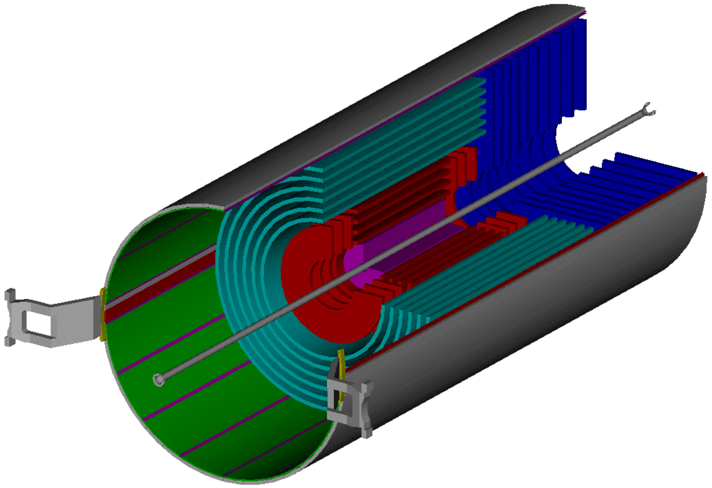
High luminosity $10^{34} cm^{-2} s^{-1}$

- 20 inelastic collisions
- 2000 tracks per bunch crossing

first collisions 2008

lower luminosity for the first years

CMS tracker



R=4cm . . . 110cm , L=5.4m

- 4 T solenoidal field
- 10 layers of silicon strips, 6 $r\phi$ and 4 $z$stereo
- 3 layers pixels (space points)
- disks in the forward region

3d tracking, comparable $r\phi$ and z resolution

Vertex Reconstruction: Finding + Fitting

Vertex Finding:

within a set of tracks (e.g. full event, jet):

- detect possible vertices (fixed or variable number)
- assign tracks to vertices

$\rightarrow$*examples: primary vertex, b-tagging*

Vertex Fitting:

for a given vertex hypothesis (set of tracks):

- best estimate of the vertex position

+ sometimes

- best estimate of track parameters at the vertex
- vertex quality, goodness of fit

$\rightarrow$examples: *exclusive decays*, $B \rightarrow J/\psi\Phi, \tau \rightarrow 3$-*prong*

Most algorithms do a bit of both

Vertex Fitting, Robust Algorithms

standard fitter Kalman filter (equiv. least square)

very sensitive to outliers

- **resolution tails**
  bad parameter track measurements/error estimates
  (pattern recognition, interactions with detector material)
- **wrong track–vertex assignment**
  often not a priori known

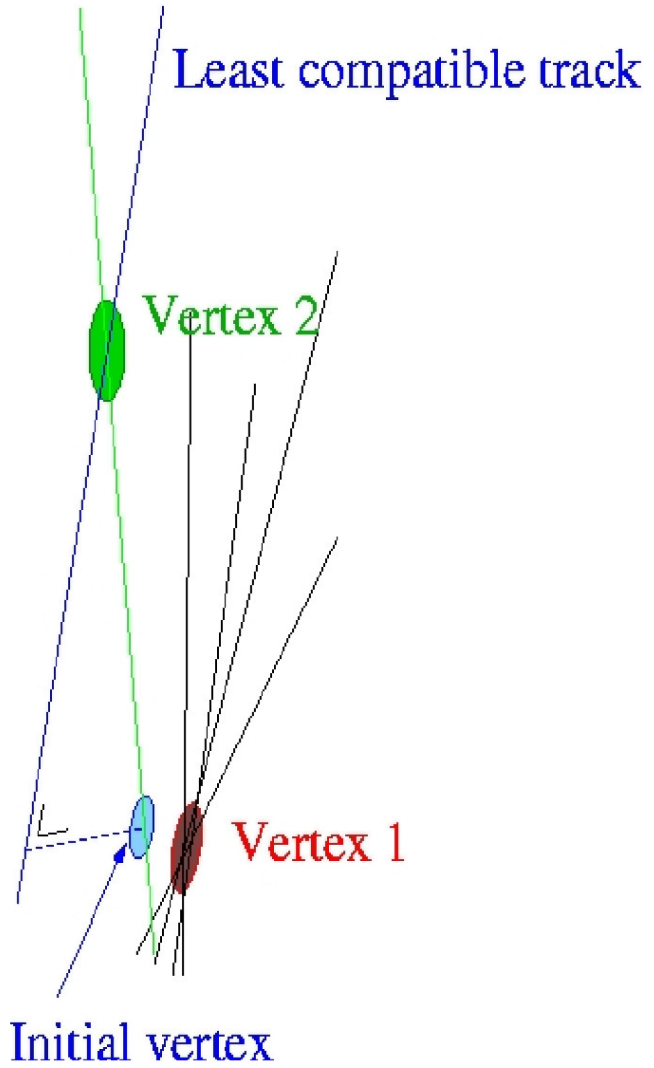
robust algorithms in CMS

	resolution tails	mis-assigned tracks
Trimmed Kalman Vertex Fit	remove outliers one by one	
Adaptive Vertex Fit	downweight outliers	
Gaussian Sum Fit	model tails	

a robustified Gaussian Sum Fit is also possible

Trimmed Kalman Vertex Fit

- robustification of the Kalman Filter
  - remove the least compatible track
    lowest Prob(χ^2)
  - iterate until all tracks above a given threshold (5%)
- hard assignment
  but final Vertex χ^2 biased
- used in Vertex Finders
- fails when too many tracks are rejected

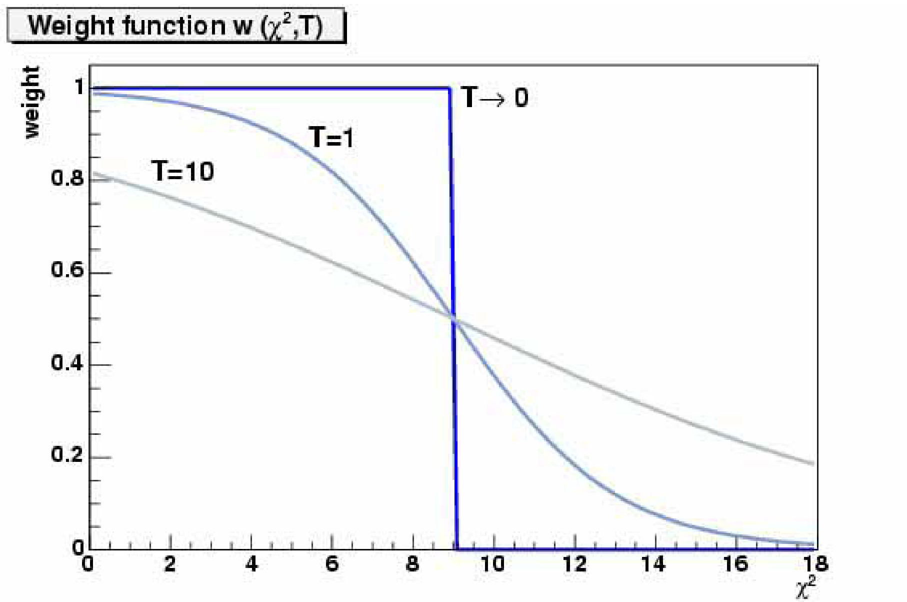


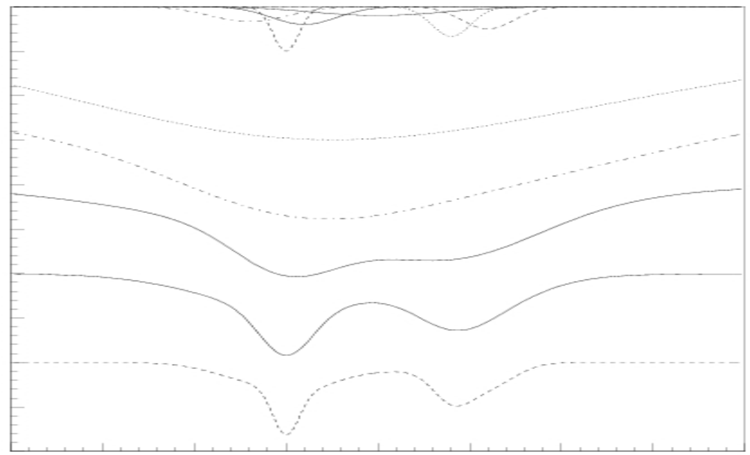
Adaptive Vertex Fit

- weighted tracks, "soft assignment"
- track weight based on distance to vertex
  → iterative procedure
- weight function

$$w_i = \frac{1}{1 + \exp \frac{\chi_i^2 - \chi_C^2}{2T}}$$

  - cut-off χ_C^2, e.g. 9
    $\chi_i^2 > \chi_C^2 \;\Rightarrow\; w < 0.5$
  - T ("Temperature"), sharpness of the weight function
- starts at high "T", avoid local minima
- T is decreased between iterations (annealing),stops at $T = 1$
- very robust against outliers



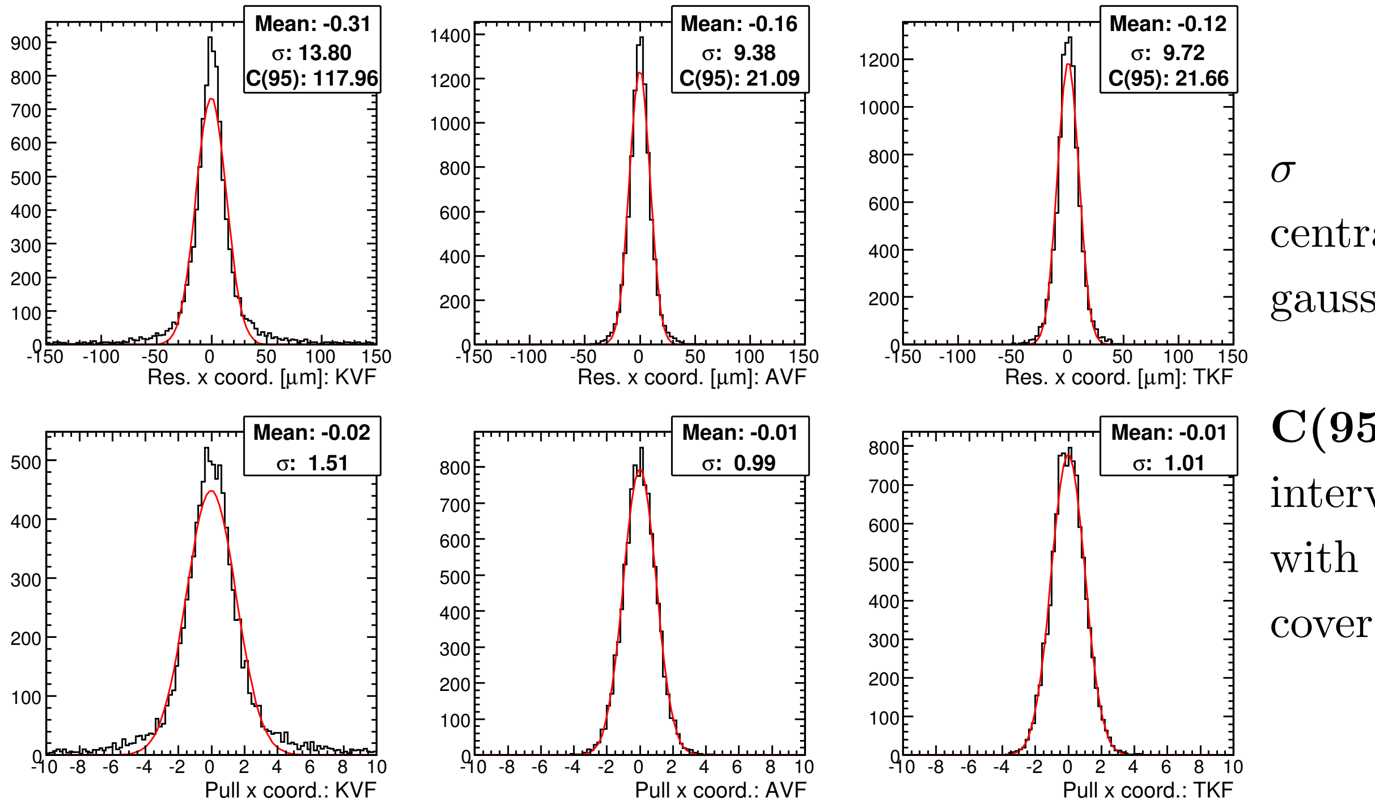


Comparison of Fitters, $t\bar{t}H(120\text{GeV})$ primary vertex

Kalman | Adaptive | Trimmed

x res. [μm]

x pull



σ central gauss

C(95) interval with 95% coverage

non-gaussian tails of track parameters affect (linear) Kalman Vertex Fitter

robust algorithms : 30% improved resolution, reduced tails, correct covariance

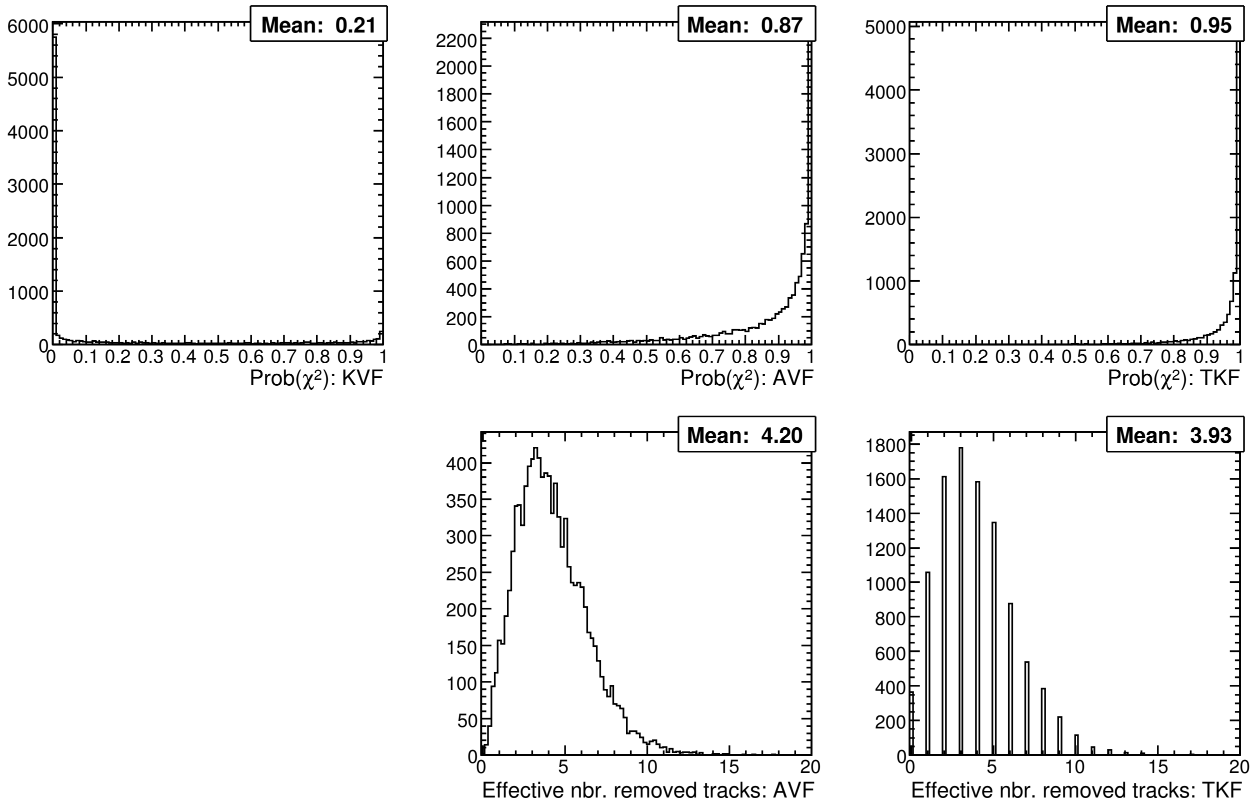
small failure rate ($< 0.1\%$), CPU time $\mathcal{O}(5\times)$

Properties of Fitters, $t\bar{t}H(120\text{GeV})$ primary vertex

Kalman | Adaptive | Trimmed

prob(χ^2)

removed tracks



Kalman Vertex Fitter: up to 80% of high multiplicity vertices have Prob(χ^2) < 0.01

robust algorithms : reject/downweight outliers $\Rightarrow$ "pseudo χ^2"

$\mathcal{O}(10\%)$ tracks removed (Adaptive Vertex Fitter: $\sum(1 - w_i)$)

Comparison of Fitters

CMS, full simulation, ORCA framework. Kalman, Adaptive, Trimmed

event sample	rec. tracks	coordinate	Std. Dev. [μm]			pull		
$B_s \to J\psi\Phi$, secondary	4	x	54.4	53.1	53.6	1.08	1.02	1.04
		z	72.9	72.3	74.2	1.08	1.02	1.05
$H \to \gamma\gamma$(GF), primary	23.2	x	27.9	21.9	22.8	1.11	0.9	0.93
		z	54	48.3	49	1.07	0.94	0.95
$udsg$–jets	33.3	x	19	13.2	13.5	1.45	0.97	0.99
		z	23.7	18.3	18.8	1.32	0.96	0.98
$Drell - Yan$	22.7	x	15.3	12.6	13.3	1.51	1.21	1.21
		z	26.4	22.3	22.8	1.48	1.18	1.18
$t\bar{t}H$	44.3	x	13.8	9.38	9.72	1.51	0.99	1.01
		z	17.7	12.9	13.2	1.46	1	1.02

no difference for low multiplicity

robust fitters significantly better for high multiplicities:

improved resolution and error estimates

Gaussian Sum Fit

Gaussian Sum:

- sum of gaussians models non-gaussian pdf
- successfully used in CMS for
  electron track reconstruction

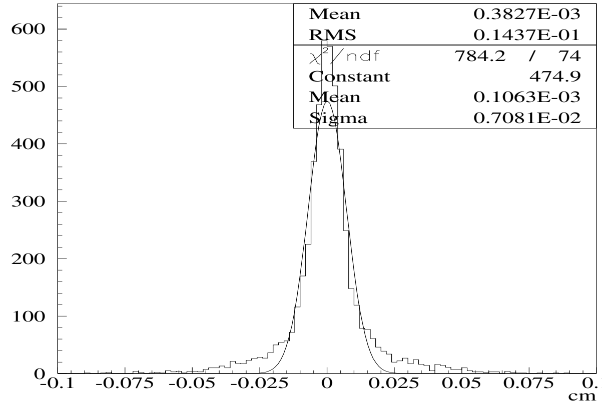
Gaussian Sum Vertex Fit:

- implemented as parallel Kalman filters
- improves resolution
  reduces tails of vertex coordinates
- combinatorial growth of components while adding tracks
  can be reduced without much degradation
- vertex fit recently implemented in CMS

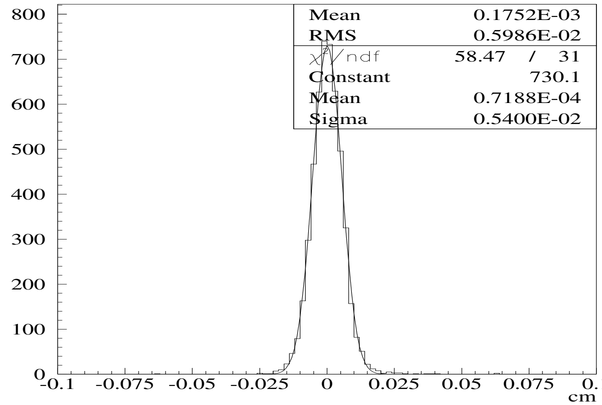
toy model: 4 tracks,

90% 100μm $\oplus$10%1000μm

Kalman Vertex fit:



Gaussian Sum Vertex Fit:



-0.1cm 0 $+0.1$cm

x residuals

Vertex Finding in Jets

Trimmed Kalman Vertex Finder

- like trimmed fitter, but re-use rejected tracks to form new vertices
- b vertex finding efficiency 63.3%
  b-jets, p_T=20–70GeV , ℓ_T=100μm –2cm
  vertex rate in uds events $\mathcal{O}(1\%)$

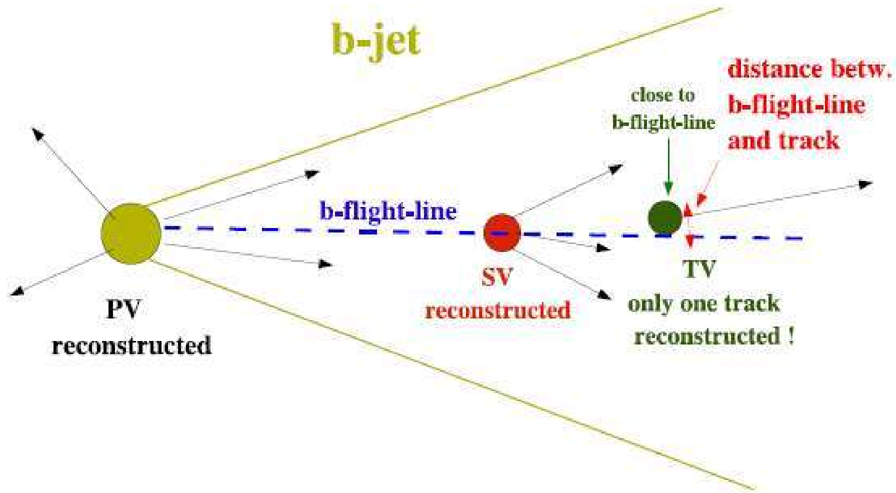
Tertiary Vertex Finder

- find $b \rightarrow c$ daughter tracks
  to improve b–tagging/ c rejection

Adaptive Multi-Vertex Fit in preparation

- primary and secondary vertex "compete" for for tracks

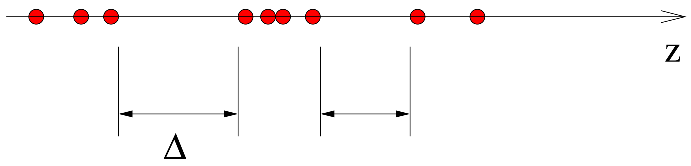
b-tagging → presentation of Ian Tomalin



Primary Vertex Reconstruction

- track selection
  select tracks compatible with the beam-line
  distance of closest approach $< 3\sigma$ (5σ)

- cluster tracks according to their z-coordinate at the point of closest approach



  split clusters where $\Delta > 1$mm

- fit tracks of a cluster to a common vertex
  Kalman Filter (Adaptive Vertex Fit)

- clean-up cuts
  - distance of vertex to beam-line $< 200\mu$m
  - vertex fit χ^2 probability $> 1\%$ (not needed for adaptive fit)

- sort vertices by $\sum p_T^2$, “signal “ vertices usually have much highest $\sum p_T^2$

Primary Vertex Reconstruction

efficiency = ϵ_{tag} = prob. of true primary within 500μm of tagged primary

- full detector simulation
- low luminosity pile-up
- including possible track mis-assignment

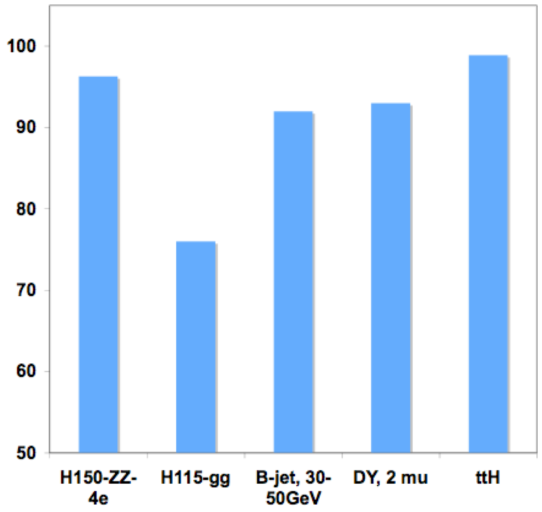
efficiency and resolution improve when the p_T cut is lowered

beam constraint under study

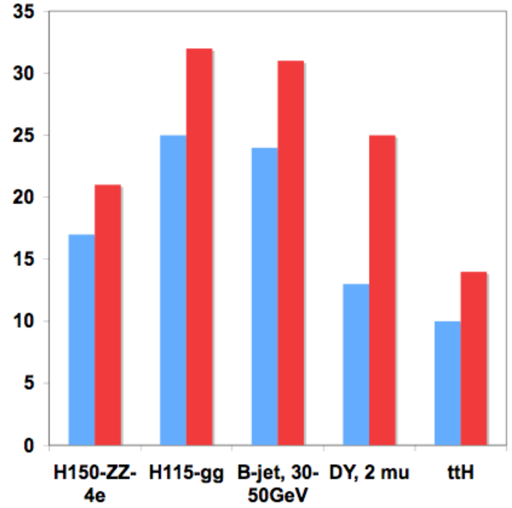
Online Pixel Primary Vertex Reconstruction

- based on pixel tracks (triplets)
- provides z-coordinate of the Primary Vertex in High Level Triggers
- similar clustering, no fit
- high efficiency, resolution better than 50 μm

ϵ_{tag} [%]



primary vertex resolution [μm]



Conclusions/Outlook

Vertex Reconstruction in CMS

- convential Kalman Vertex Fitter ok for low multiplicity vertices
- Adaptive vertex fit superior for high multiplicity vertices
- Gaussian Sum fitter promising for special cases (electrons)
- primary and secondary vertex finding ported to new CMS software framework
- several ongoing developments