Ghost rate study of the tracking at LHCb

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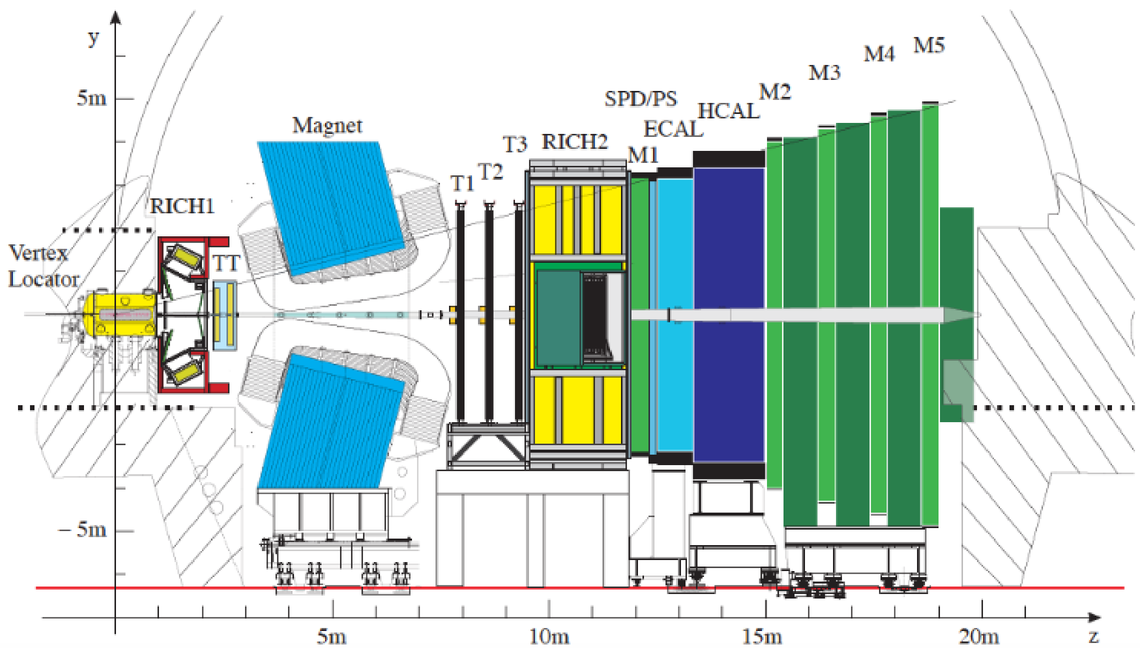
LHCb detector

- Single arm forward spectrometer: $2 < \eta < 5$
- Excellent detector performance:
  - **Track reconstruction efficiency >95%**
  - Momentum resolution dp/p ~[0.5%-1%]
  - Excellent particle identification

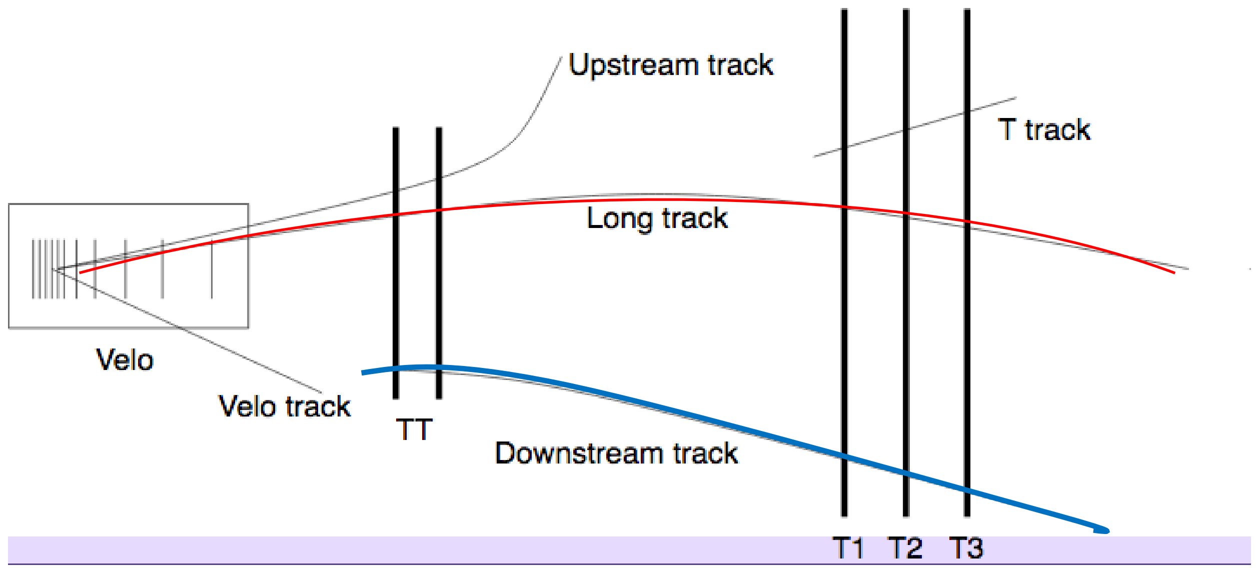


[JINST 3 (2008) S08005]

Track reconstruction

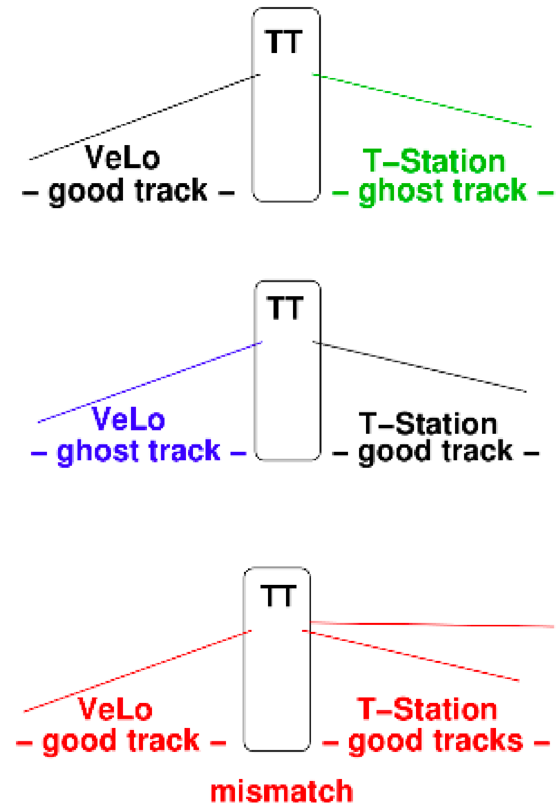
- The LHCb tracking reconstruction contains two steps:
  - Track finding - pattern recognition algorithm
  - Track fitting - Kalman filter

Track types in LHCb



Ghost sources

- Long tracks mis reconstruction:
  - **Hadronic interaction with detector material– main sources**
  - T station segments mis-reconstruction
  - VELO segments mis-reconstruction
  - mis-matched between VELO and T-station

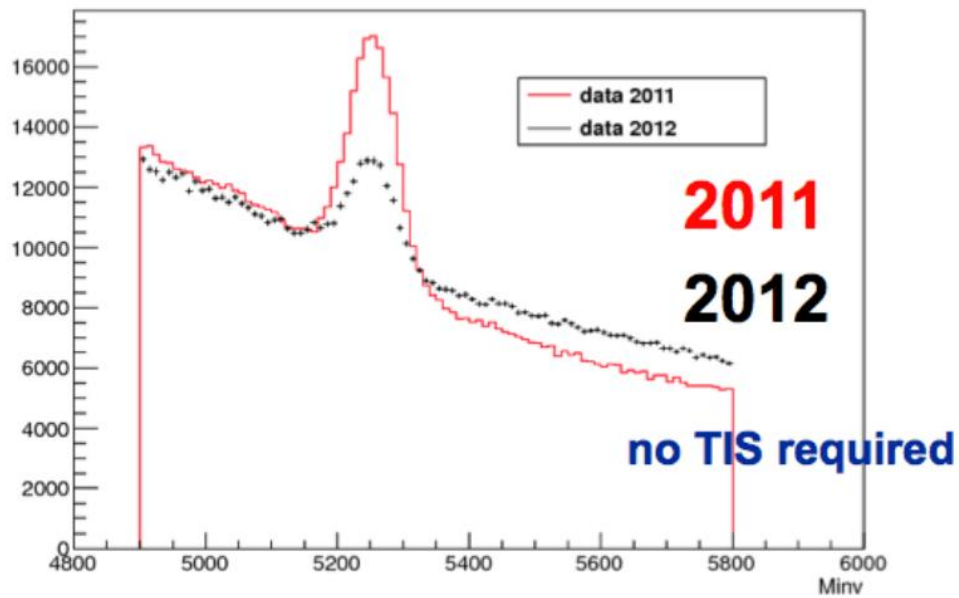


- Ghost tracks: Low probability of χ^2 from the track fit and missing hits

Motivation

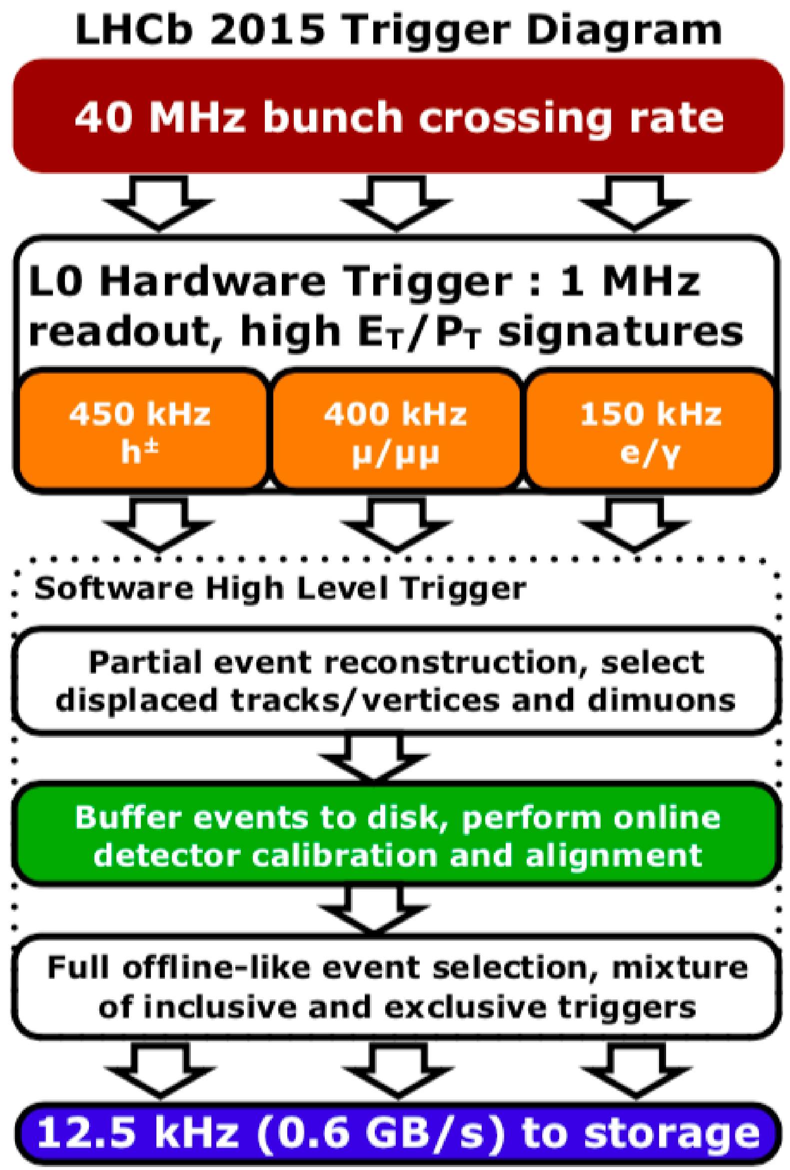
- 2012 data show more noise and worse S/B ratios than 2011 data
  - Problems are caused by background from mis-reconstructed **ghost tracks**

$B \rightarrow hh$ channel in $B_s \rightarrow \mu\mu$ analysis



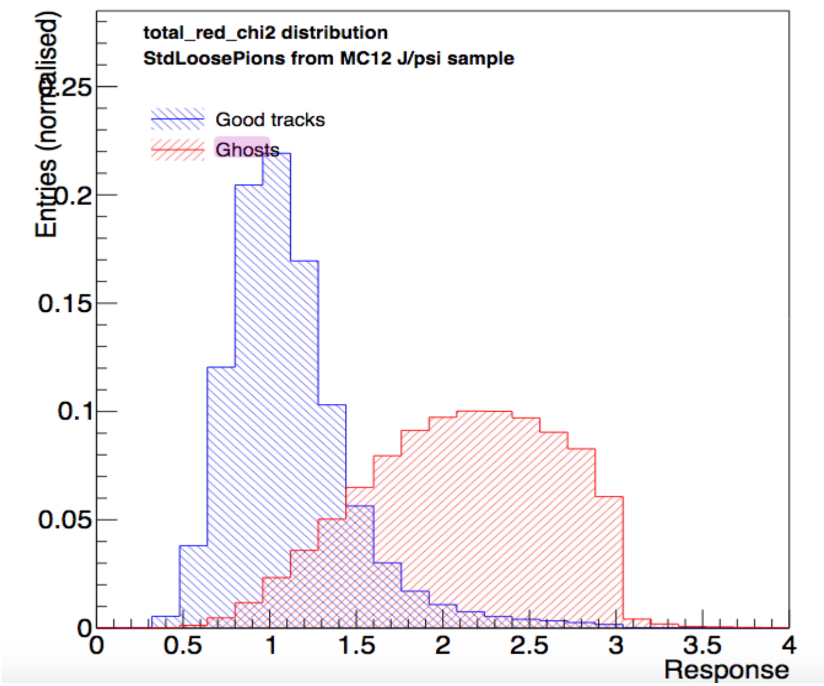
Reconstruction sequence in Run II

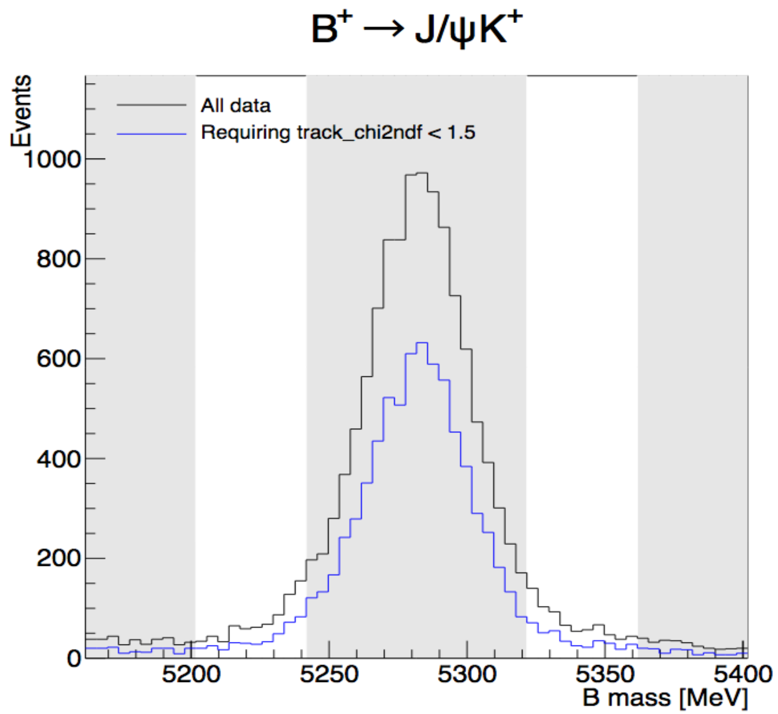
- Reconstruction in two stages
  - Fast stage (HLT1): partial event reconstruction
  - Full stage (HLT2): full offline-like selection
- The majority of the LHCb tracking algorithms efficiency is limited by the ghost rate
- **Need to make track reconstruction faster with low fake rate**



Previous method: cut on track $\chi^2/\mathrm{nd}of$

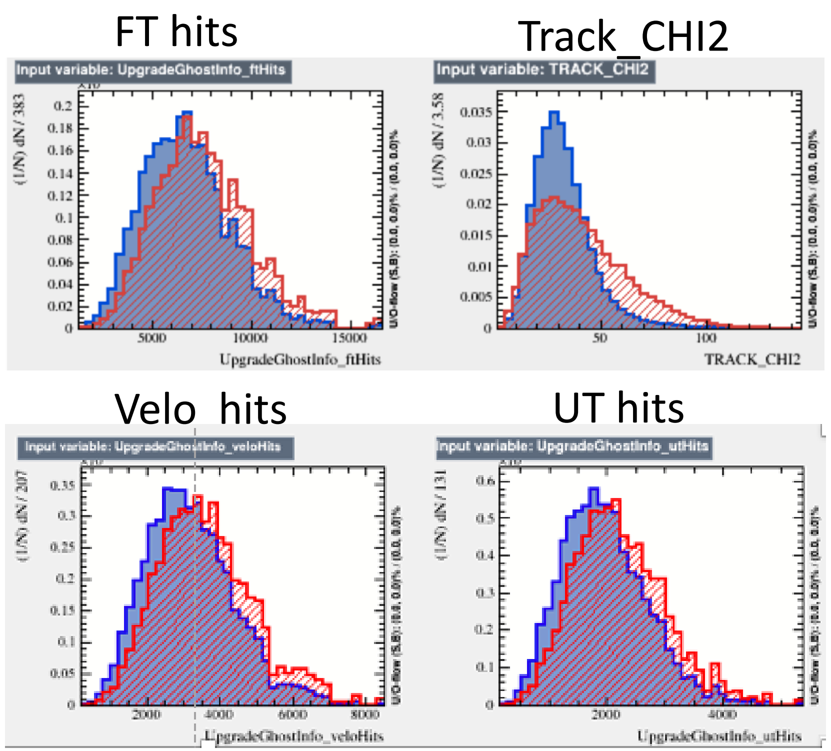
- Quality of fit is generally worse for ghosts than for real tracks
- Require $\chi^2/\mathrm{ndof} < 1.5$
  - Improves S/B ratio
  - Signal efficiency of 63.3%, **Signal loss too high**
- Need something more efficient to suppress ghost tracks





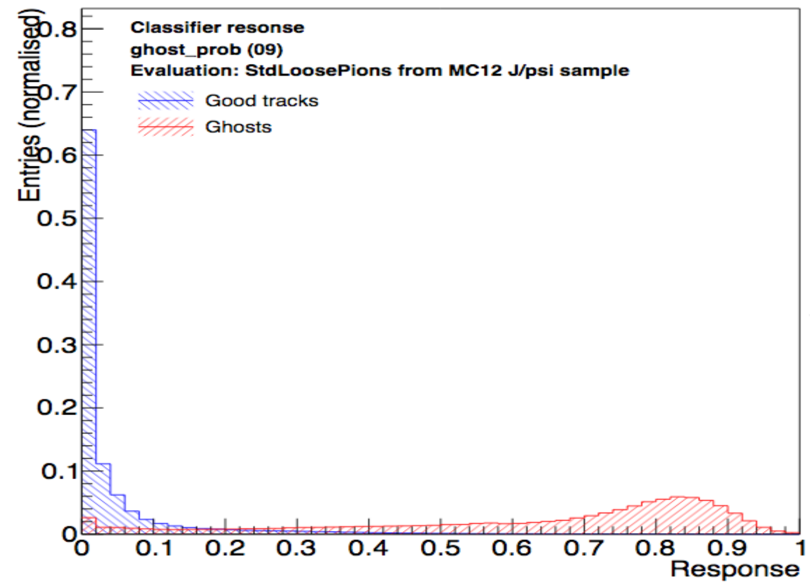
New algorithm: multivariate method

- **Multivariate classifier**: MLP neural network combines several weak discriminants into one strong classifier discriminate between ghost and good tracks
- Input files(B inclusive MC):
  - Signal: good tracks (>70% hits matched to a MC particle)
  - Background: ghost tracks (<70% hits matched to a MC particle)



Neural network

Ghost probability



Variable Selection

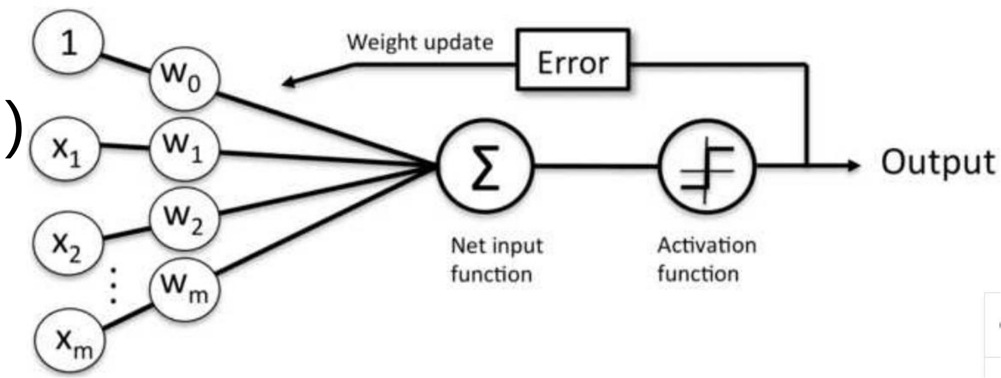
☐ Various tracking variables, no PID

- Track fit quality, number of hits, momentum, detector occupancies

	Velo Track	Upstream Track	Downstream Track	Long Track	T Track
Total hit multiplicitie in VELO	√	√	√	√	√
Total hit multiplicitie in UT	√	√	√	√	√
Total Track fit χ^2	√	√	√	√	√
Total Track fit NDOF	√	√			√
η	√	√	√	√	√
p_T		√	√	√	√
FitVeloCHi2	√	√		√	
FitVeloNDOF	√	√		√	
FitTChi2			√	√	√
FitTNDOF			√	√	√
Observed hits in VELO	√	√		√	
Observed hits in UT		√	√	√	
Observed hits in FT		√	√	√	√
UT Hits not used for the fit		√	√	√	
Match fit χ^2				√	
Exp VPHits	√	√		√	
Exp UTHits			√	√	
Exp FTHits					√

Activation function

- Introduces non-linear factors to compute nontrivial problems using only a small number of nodes
  - **Hidden layer**: Tanh(RunI) → Sigmoid(RunII)
  - **Last layer**: exponential function(RunI+RunII)

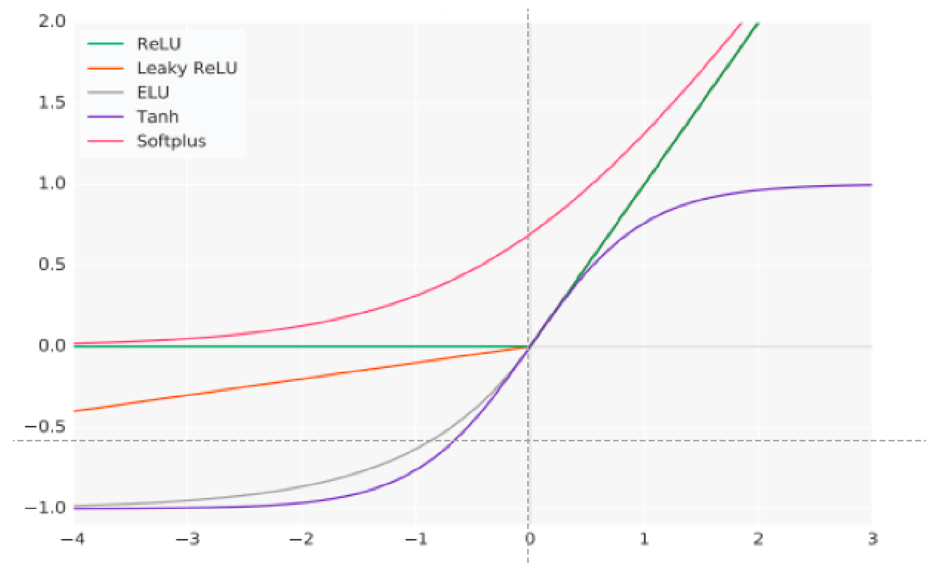


Tanh: $f(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$

Sigmoid: $f(x) = \frac{1}{1+e^{-x}}$

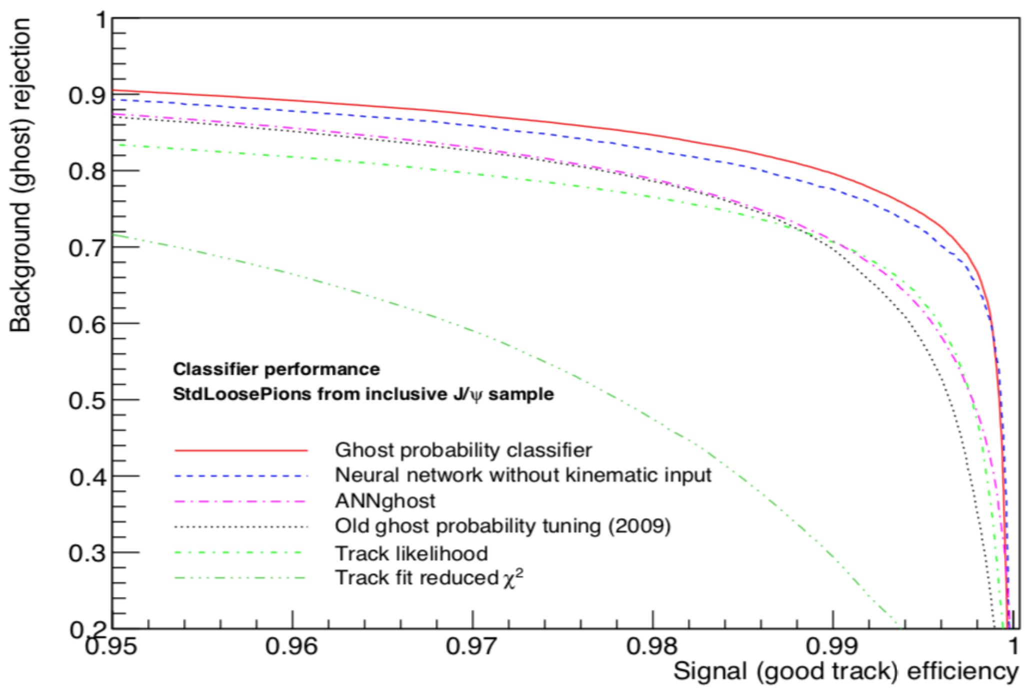
Simple-Sigmoid: $f(x) = \frac{1}{1+x^2}$

ReLu: $f(x) = \max(0,x)$

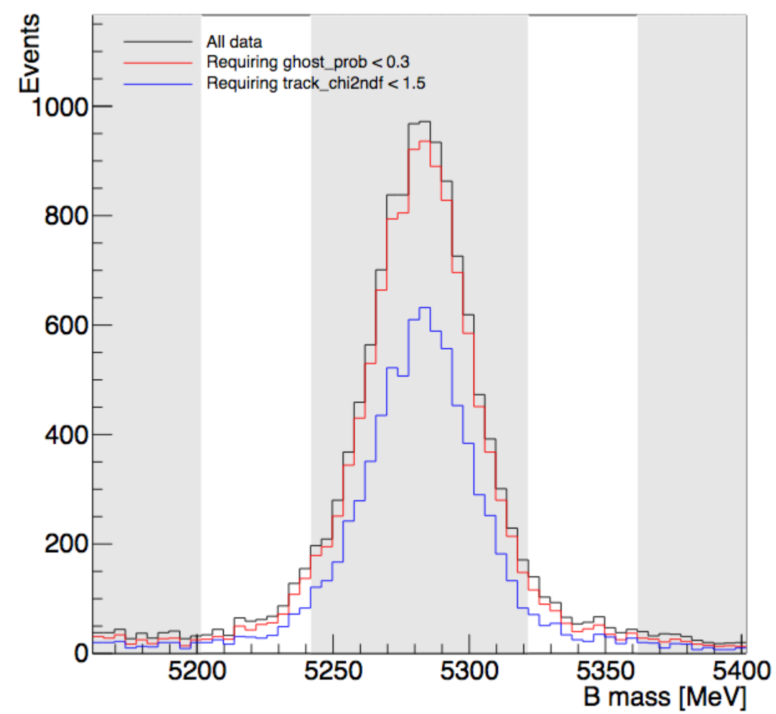


Discrimination power

- Good performance
  - For the same signal efficiency, **cutting on ghost probability is most efficient**
  - With similar ghost rejections, the signal efficiency of the ghost prob cut is much better
    - ✓ $\chi^2/ndof < 1.5$: 63.3%
    - ✓ Ghost prob < 3 : 96.1%



$B^+ \to J/\psi K^+$



Impact on trigger CPU consumption

- offline→online quantity:
  - RunI+2015(50ns) : offline quantity
  - 2015(25ns): all tracks in HLT2 had to pass ghost probability selection, **speed-up by a factor ~90**
  - Since 2016: processing in HLT1+HLT2, HLT2 input rate reduced by **4%**

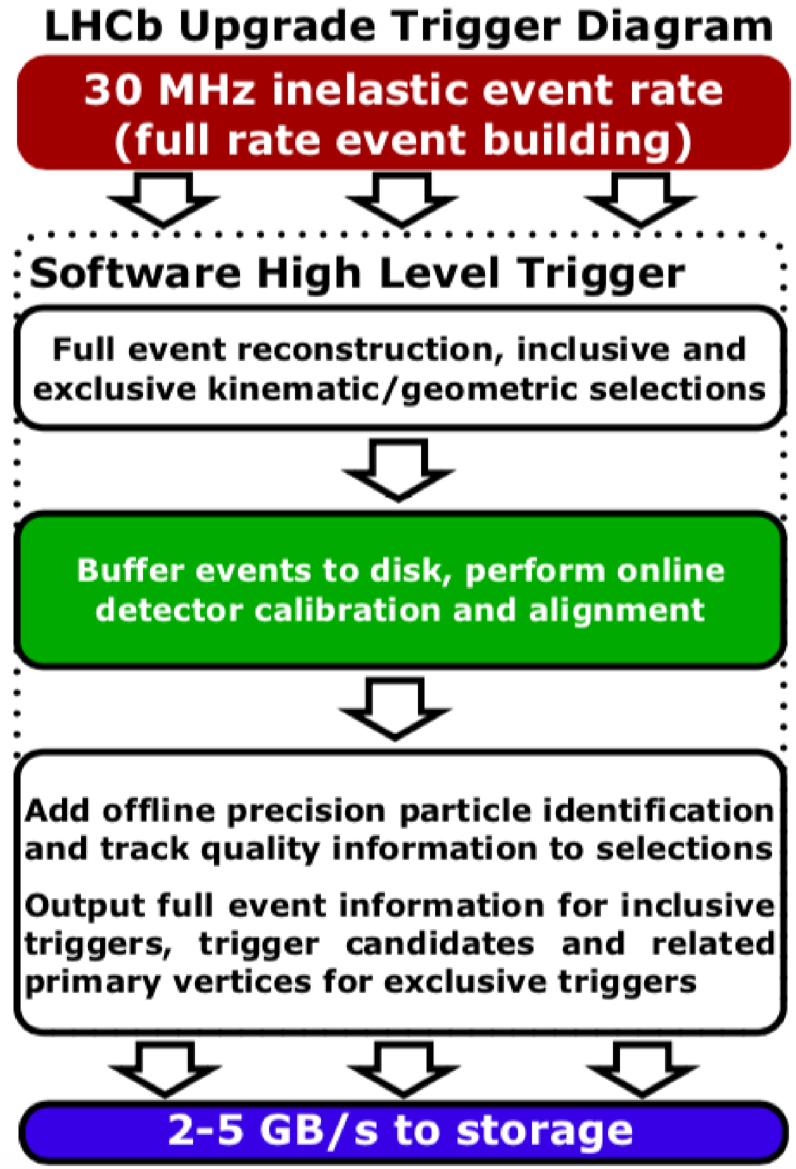
- CPU consumption decreased
  - ghost probability computation itself is **0.2%** of HLT CPU budeget
  - **22%** fewer tracks, **23%** less CPU time in RICH PID
  - Overall saving of **16%** entire HLT CPU

- **Ghost probability can not only suppress background but also decrease CPU consumption**

LHCb Upgrade

- CPU timing decreased is expected
  - Detector upgrades to copy with increased luminosity
    - ✓ Run III: $2 \times 10^{33}\ \mathrm{cm}^{-2} s^{-1}$ **(~5 factor larger than RunII)**
  - Remove hardware trigger, increase output rate to storage

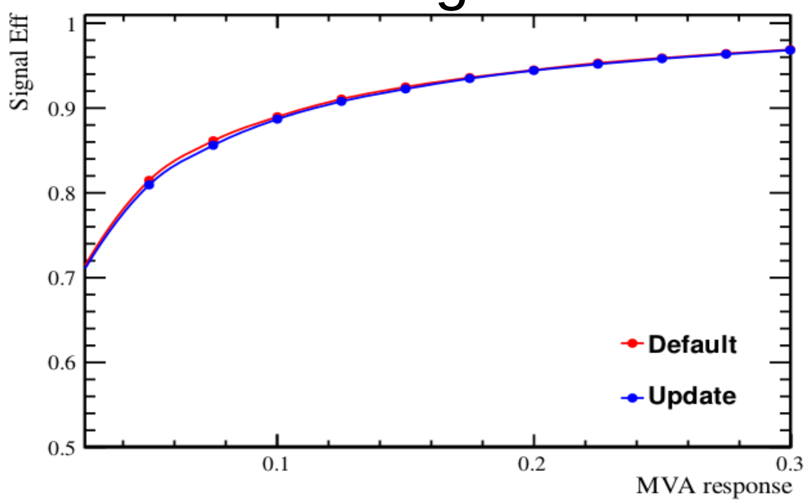
Integrated luminosity			
LHC era		**HL_LHC era**	
Run2 (2015-18)	**Run3 (2021-24)**	**Run4 (2027-30)**	**Run5+ (2031+)**
9 fb^{-1}	**23 fb^{-1}**	**46 fb^{-1}**	**>300 fb^{-1} ??**



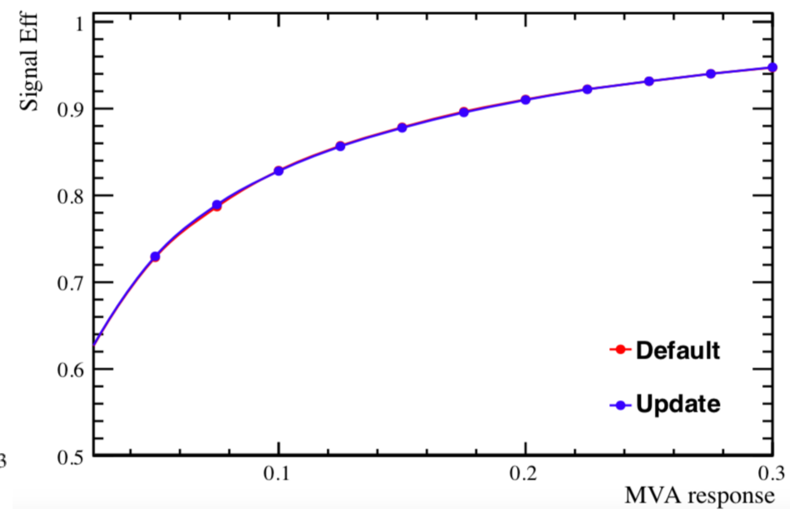
Improvements in the upgrade

- Upgrade:
  - Removed time-consuming variables(hit estimation)
  - Activation functions at hidden layer: Sigmoid→ ReLU
    - ✓ Efficient gradient propagation
    - ✓ Fast computation: Only comparison, addition and multiplication
  - Activation functions at Last layer: exponential → finite exponential
    - ✓ Replace the exponential operation with the finite number of multiplications
- The efficiency performance is almost the same
- Reduced timing of ghost probability algorithm by **97%**

Long Track

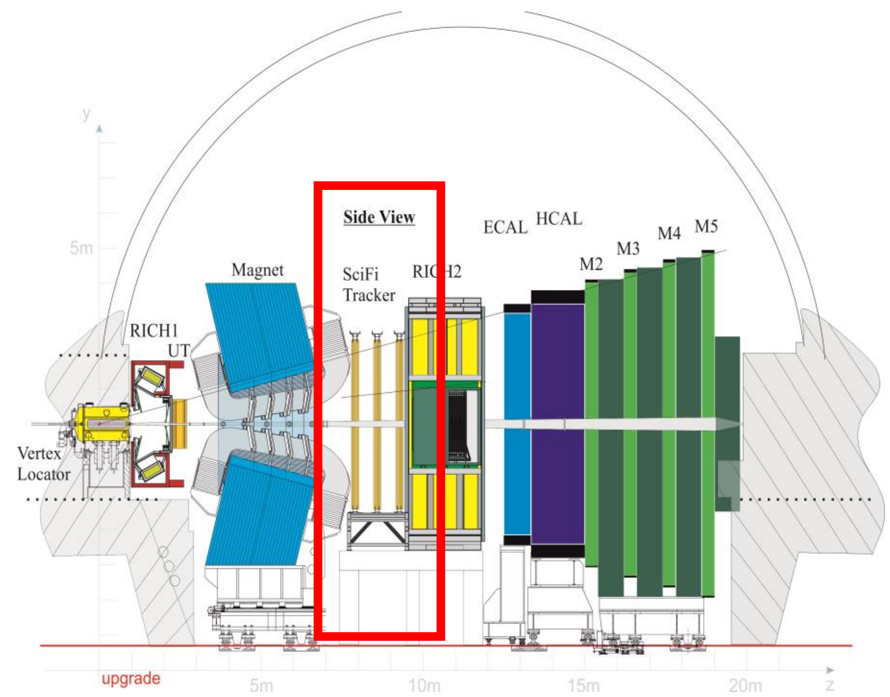


Downstream Track



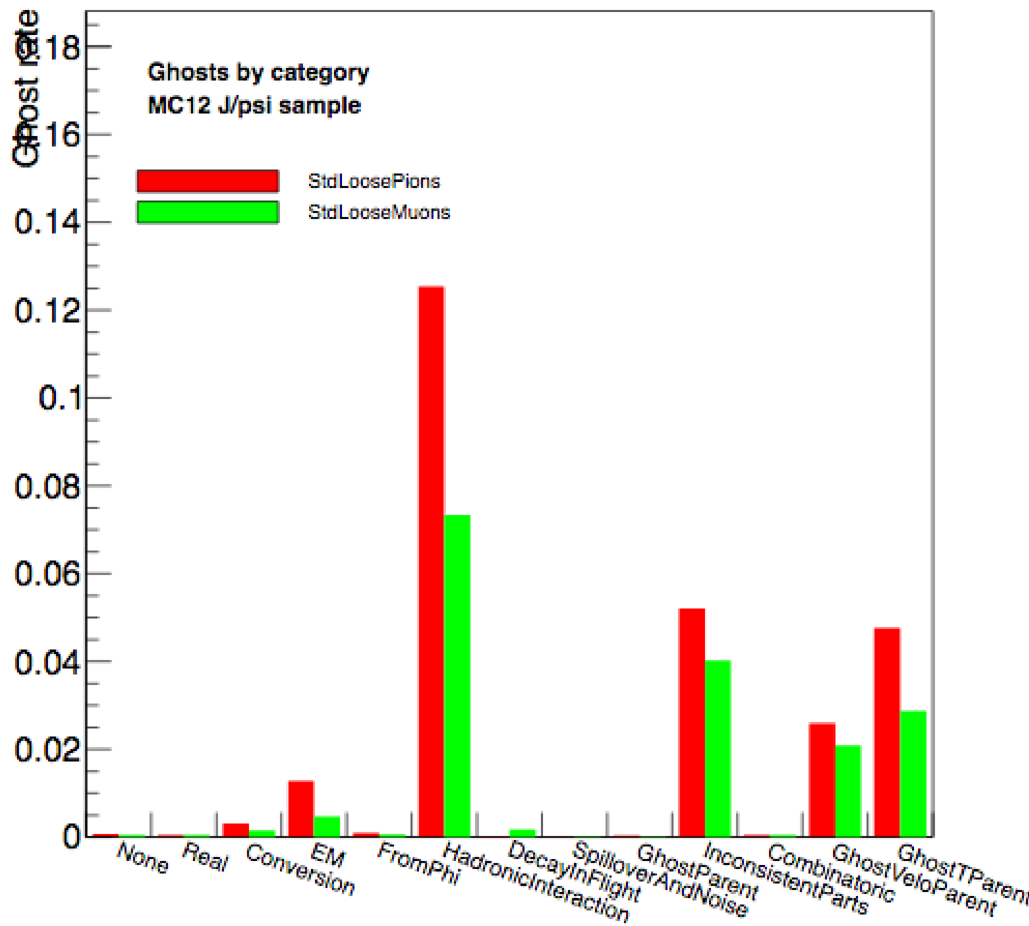
Conclusion

- ☐ Ghost tracks are a significant source of background
- ☐ Ghost probability: important part online reconstruction
  - excellent ghost reduction with minor signal loss
  - Highly decrease the CPU timing
- ☐ Room for improvement
  - fast VDT-like implementations for SIMD types
  - add Scifi track position information in neural work



Backup

Ghost types



Ghost rate
Ghosts by category
MC12 J/psi sample
StdLoosePions
StdLooseMuons
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
None
Real
Conversion
EM
FromPhi
HadronicInteraction
DecayInFlight
SpilloverAndNoise
GhostParent
InconsistentParts
Combinatoric
GhostVeloParent
GhostTParent