# Sub-Threshold $\Lambda^0$ and $K^0_S$ Production

Analysis of $\Lambda^0$ and $K^0_S$ Production in Au+Au Collisions at $\sqrt{s_{NN}}$ = 2.4 GeV Measured with HADES

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FAIR Phase 0 Research Program

HADES

# Content

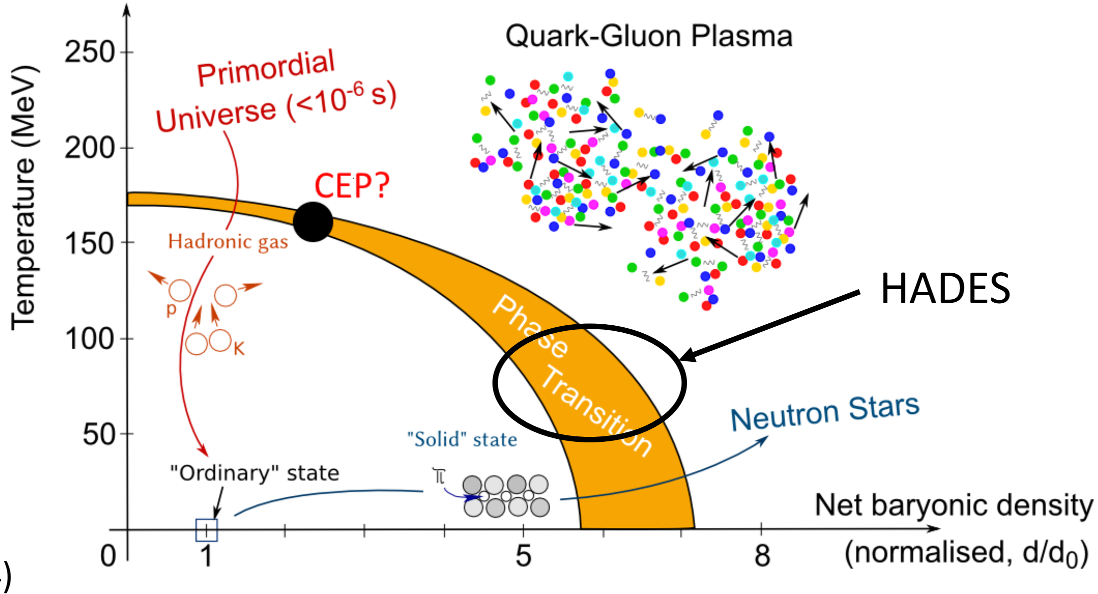
- Heavy Ion Collisions (HIC) at SIS18 Energies
  - Strangeness Production – Isolated vs. Coherent
- The HADES Detector System
- Analysis of Strangeness Production
  - Reconstruction of Weakly Decaying Particles
  - Differential Analysis
- Outlook: March 2019 - Ag+Ag at $\sqrt{s_{\mathrm{NN}}}$ = 2.6 GeV

# Heavy Ion Collisions at SIS18

Introduction and Motivation

# Heavy Ion Collisions at SIS18 Energies

- Investigation of the phasediagram of strongly interacting matter at highest $\mu_B$

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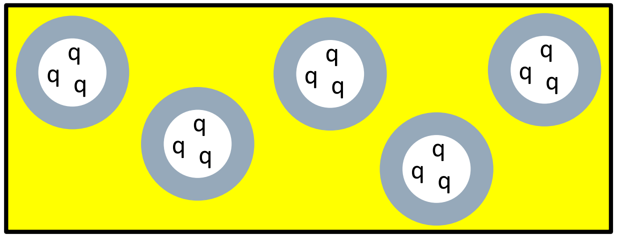
- Similar conditions as expected in Neutron Star Mergers
  (Phys. Rev. D96(2017) no.4, 043004)

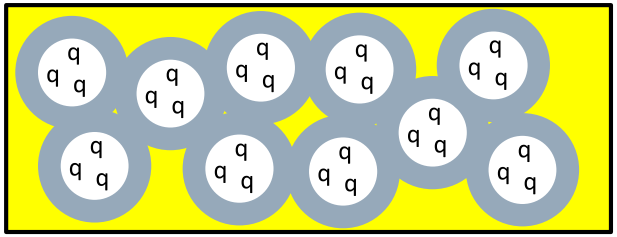
- Baryon dominated systems measured with HADES
  - Au(1.23A GeV)+Au → $\sqrt{s_{NN}}$ = 2.4 GeV

# Heavy Ion Collisions at SIS18 Energies

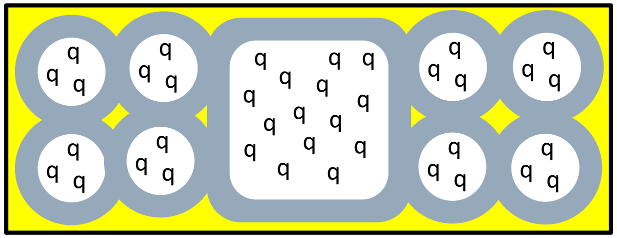
- Cloudy bag model
  (Phys. Rev. D24:216, 1981. 16, 25, 26)
  - Valence Quarks surrounded by Meson cloud
- Strangeness production in this picture:
  - Interactions of virtual $s\bar{s}$ pairs from the cloud with valence quarks
  - Probability increases with system lifetime
- Strangeness production ideal observable



Ground state density



Increased density (Clouds overlap)



Extreme density (Bag fusion)

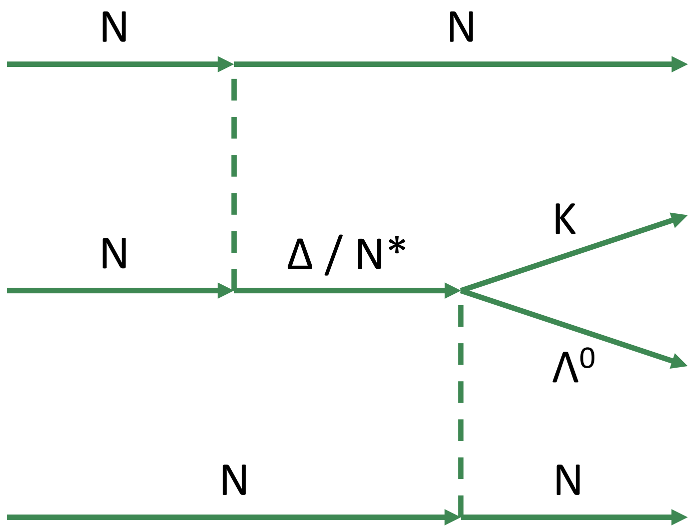
Less piktogrammatic, more solid: W. Weise - GSI-FAIR Colloquium „Phases of Strongly Interacting Matter - from Quarks to Nuclei and Neutron Stars” - 30.10.2018

# Strangeness Production

- Production channel in elementary NN collisions with lowest threshold: N + N → $\Lambda^0$ + K + N (NN Threshold 2.6 GeV)
  - $\overline{\mathrm{K}}$ production channel: N + N → N + N + K + $\overline{\mathrm{K}}$ (NN Threshold 2.9 GeV)
  - ϕ production channel: N + N → N + N + ϕ (NN Threshold 2.9 GeV)
- Production of particles with Strangeness content below free NN threshold energy ($\sqrt{s_{\mathrm{NN}}}$ = 2.4 GeV)
- Basically two options:
  - Production in isolated multistep processes via resonances (Δ, N*)
  - Coherent production with system acting as energy reservoir

# Sub-Threshold Strangeness Production

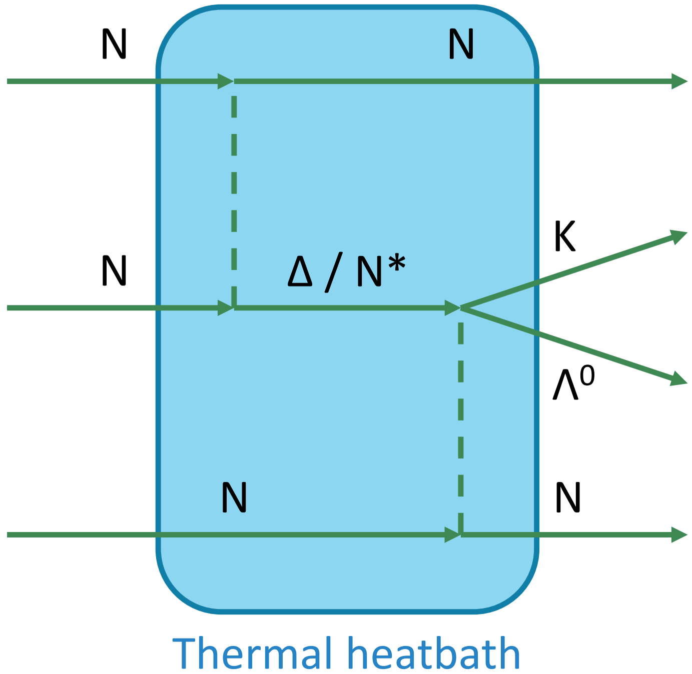
- Multi step processes
  - Accumulation of energy in isolated NN collision
  - Strangeness production in transport picture



# Sub-Threshold Strangeness Production

- Multi step processes
  - Accumulation of energy in isolated NN collision
  - Strangeness production in transport picture

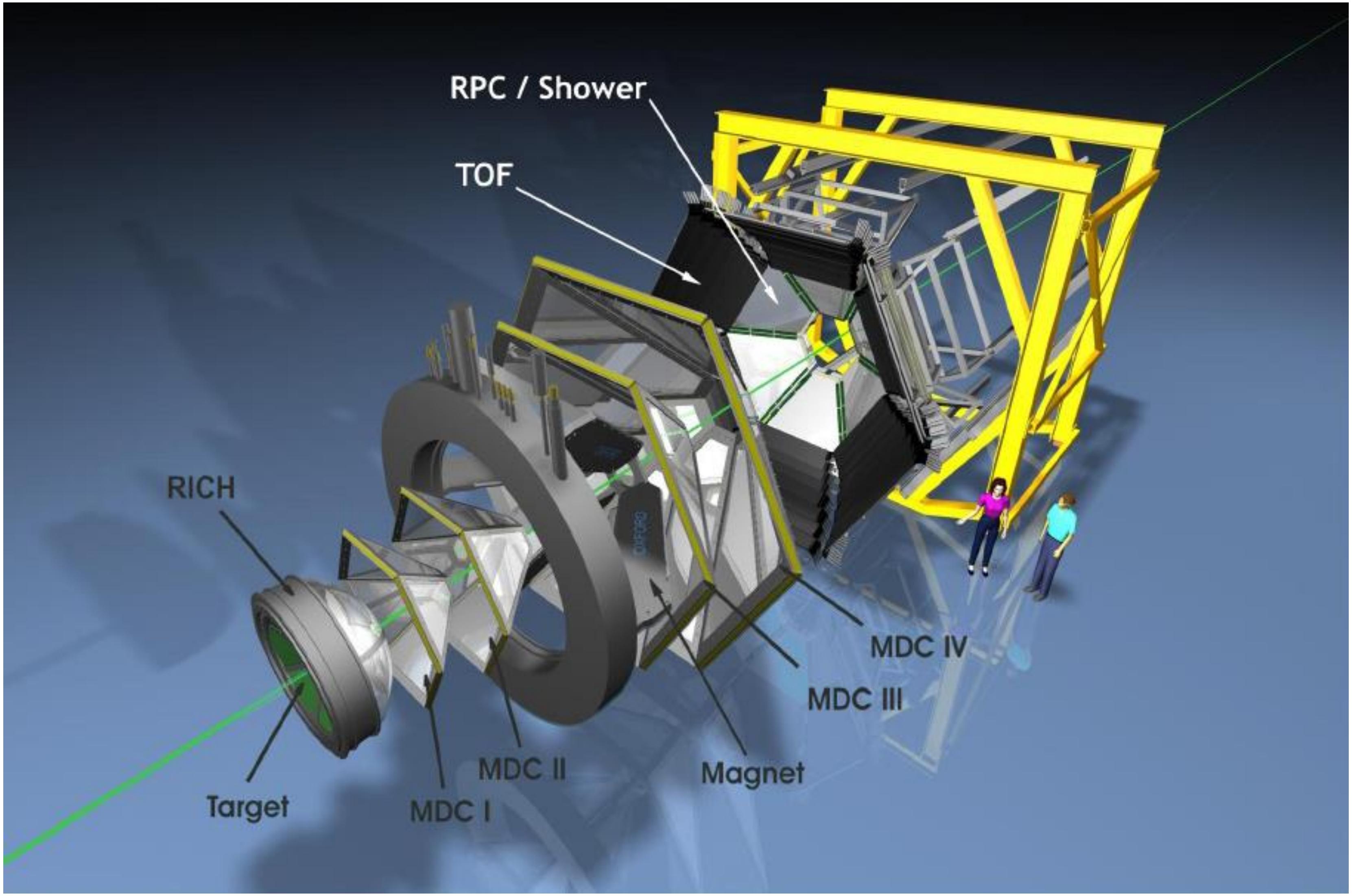
- Coherent production
  - Thermalized system provides energy as a heatbath
  - Strangeness production in thermal picture



# The HADES

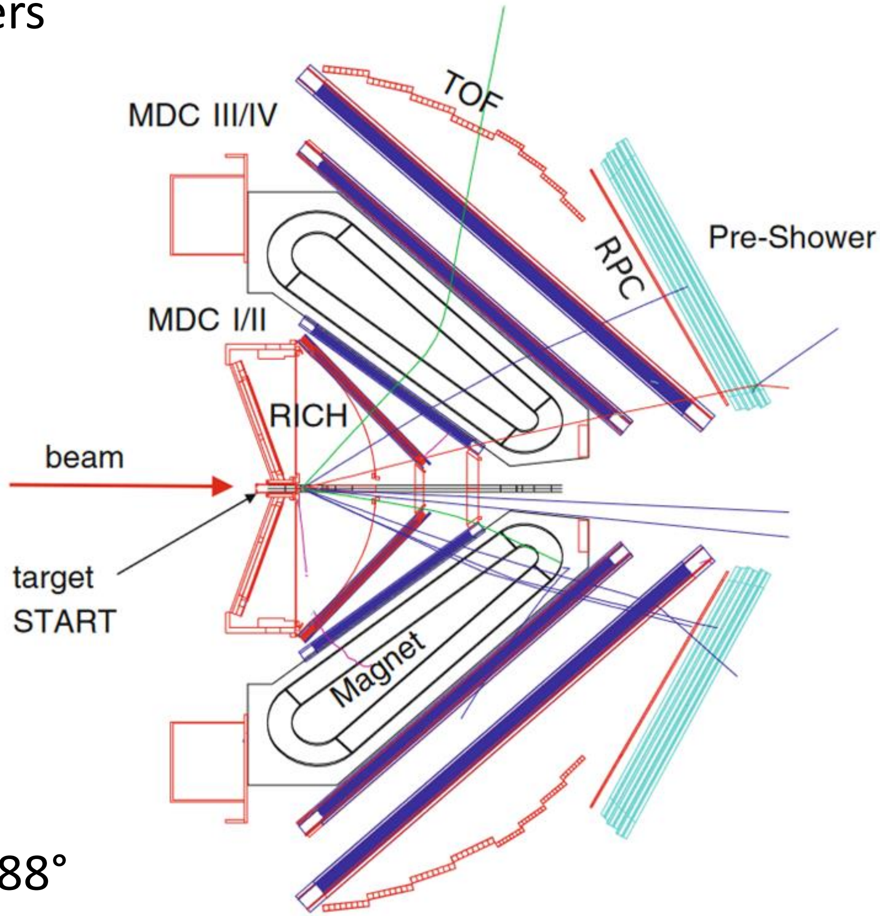
## The HADES Detector System – Setup and Functionality

# High Acceptance DiElectron Spectrometer



# High Acceptance DiElectron Spectrometer

- Segmented fixed target of 15 layers
- 4 layers of Mini-Drift-Chambers (MDCs) for tracking
- Superconducting magnet
- Resistive-Plate-Chamber (RPC) and Time-of-Flight (TOF) for particle identification
- Divided in 6 independent sectors
- Acceptance $\varphi = 2\pi$ and $18° \leq \vartheta \leq 88°$



# Analysis of Strangeness Production

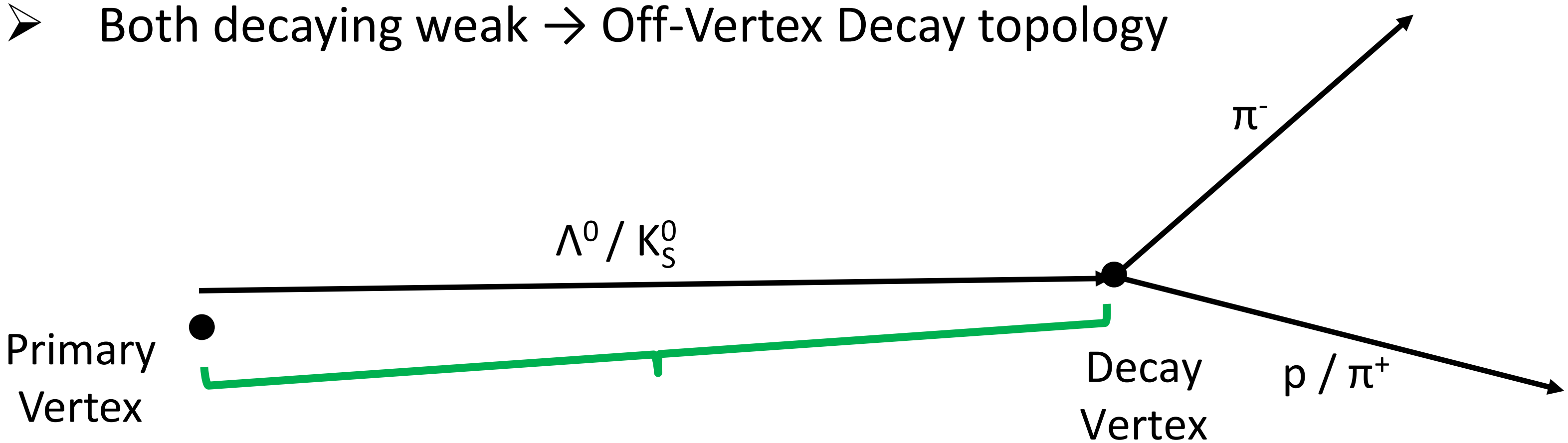
How is it done and what can we learn?

"Sub-threshold production of $K^0_S$ mesons and Λ hyperons in Au(1.23A GeV)+Au"
Phys. Lett. B 793 (2019) 457–463

# Off-Vertex Decay Topology

| | $K^0_S$ | $\Lambda^0$ |
|---|---|---|
| Quark composition | $1/\sqrt{2}\,(\lvert d\bar{s}\rangle + \lvert s\bar{d}\rangle)$ | $\lvert uds\rangle$ |
| Mass $m_0$ | 497 MeV/c² | 1115 MeV/c² |
| cτ | 2.68 cm | 7.89 cm |
| Primary decay products | $\pi^+ + \pi^-$ | $p + \pi^-$ |
| Branching Ratio | 69.2% | 63.9% |

- Both decaying weak → Off-Vertex Decay topology



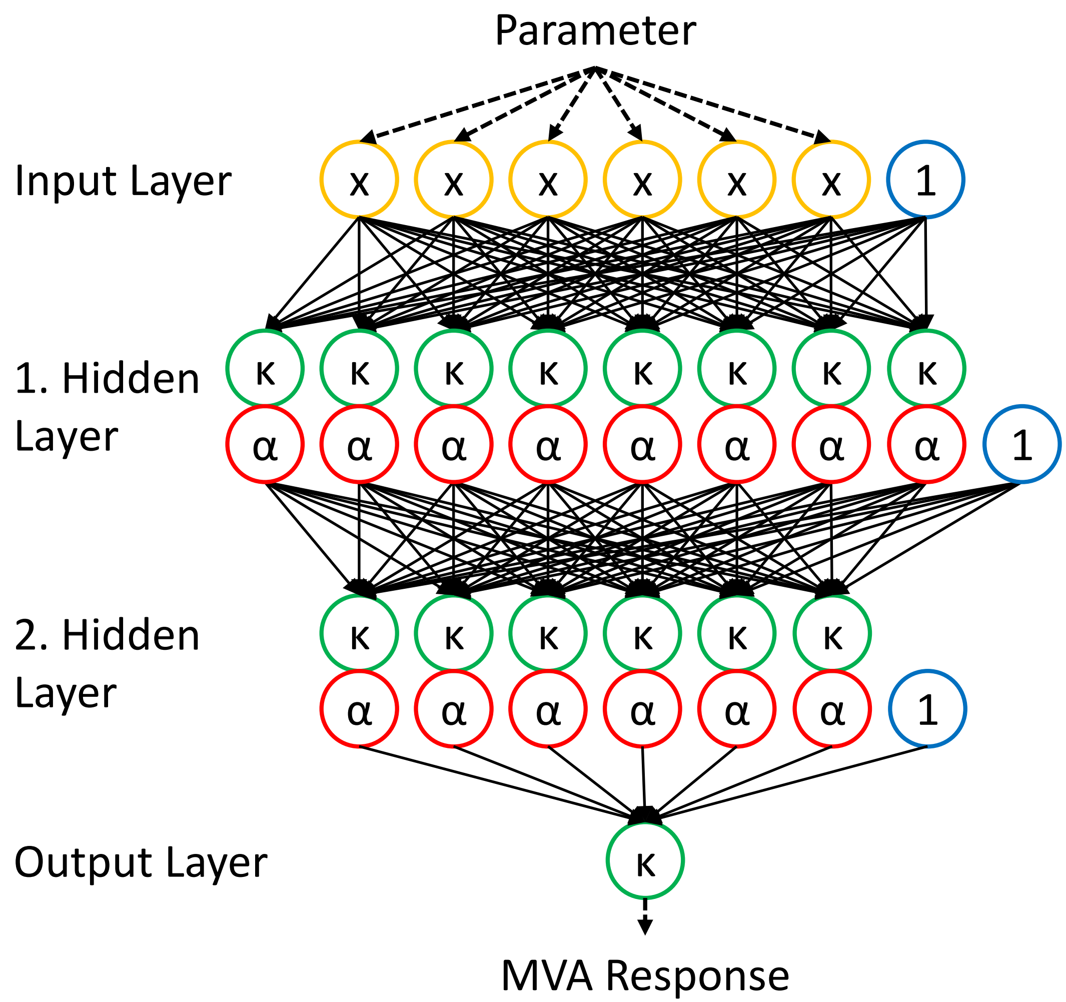
# Neural Network Analysis

- Toolkit for multivariant data analysis (TMVA) included in ROOT
  https://root.cern.ch/tmva
- Cut Parameter distributions for **simulated signal** and **mixed event background** used to train neural network
- MVA response treated as an additional cut parameter
- Preselection necessary for successful training
- Multi-Layer-Perceptron (MLP) amongst the best available methods
  - Performs even better than Tensor Flow with similar architecture

# MLP Setup and Functionality

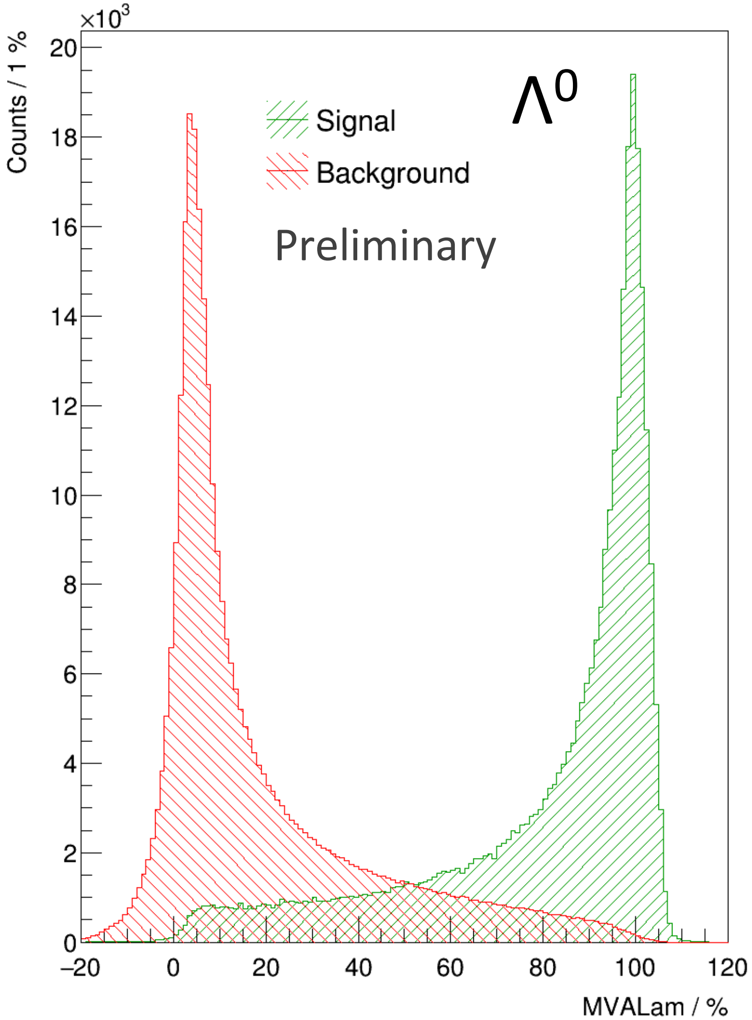
## Legend

- Neuron
- 1 – Constant 1
- x – Linear Function
- κ – Synapse Function
- α – Activation Function
- → Synapse
- - - → Input / Output



# Neural Network Analysis

- MVA Response can be interpreted as a probability of a given parameter set being signal
- Response close to 0% for background and close to 100% for signal
- Lower limit significantly reduces combinatorial background
- Neural Network working as expected

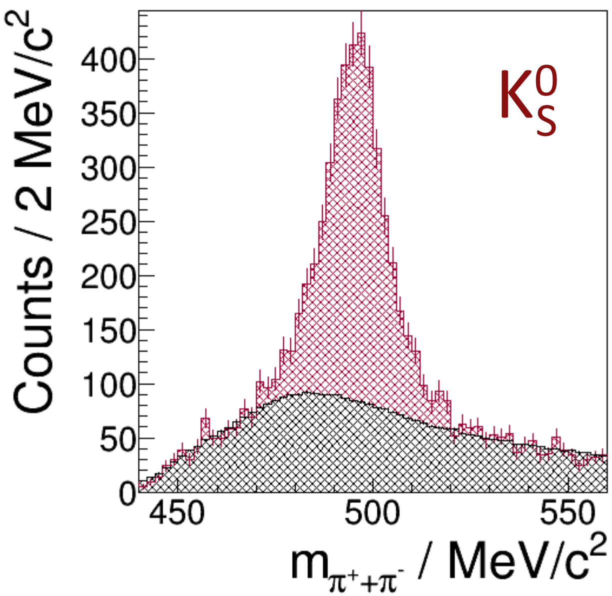


# Mass Spectra

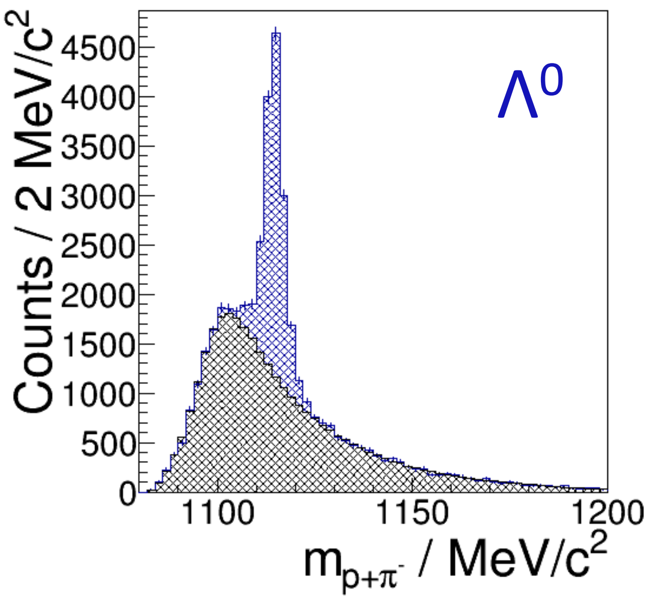
- Background estimated using Mixed-Event-Technique
- Extraction of yields in transverse mass, rapidity and centrality intervals
- Acceptance and efficiency correction of yields using simulated particles and Geant

$-0.05 < y_{cm} < 0.05$, 0 – 40% most Central

$m_t - m_0 \in [80, 120]$ MeV/$c^2$




$m_t - m_0 \in [100, 150]$ MeV/$c^2$

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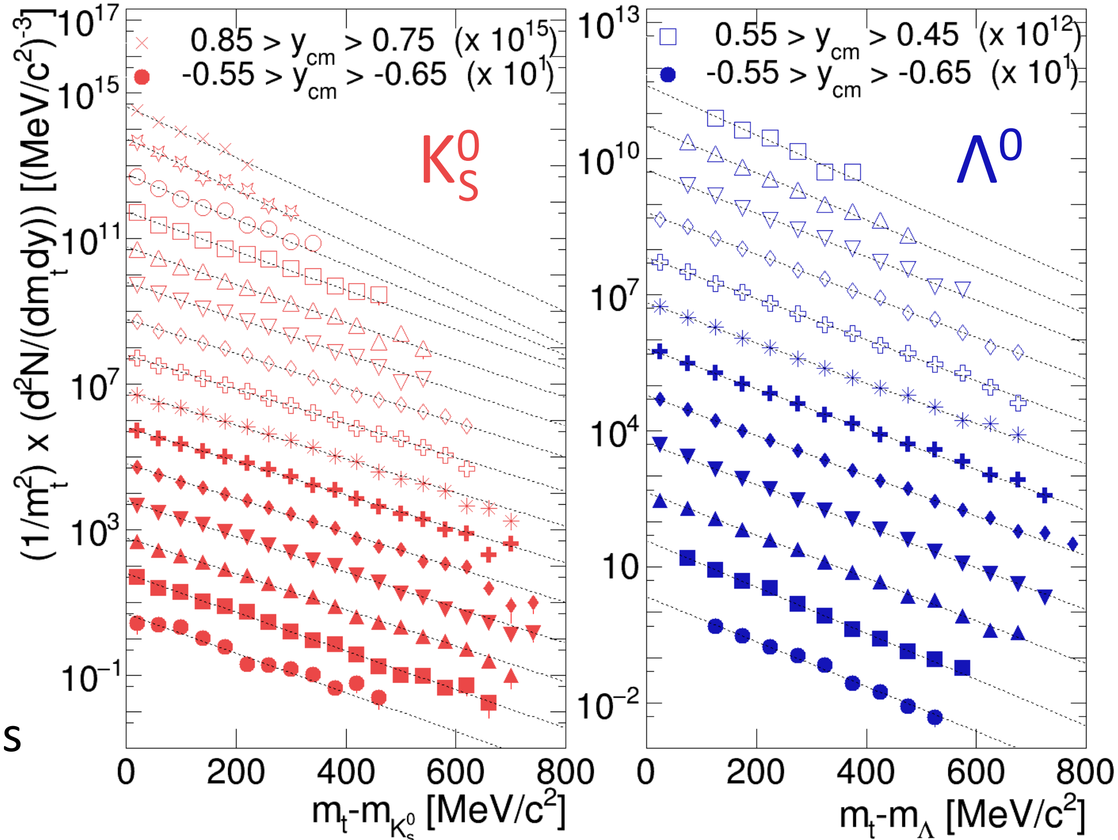
# Transverse Mass Spectra

- Spectra fitted with Boltzmann-functions
- Transverse Mass Spectra are thermal like
- Extrapolation to uncovered trans-verse mass regions by integrating Boltzmann functions

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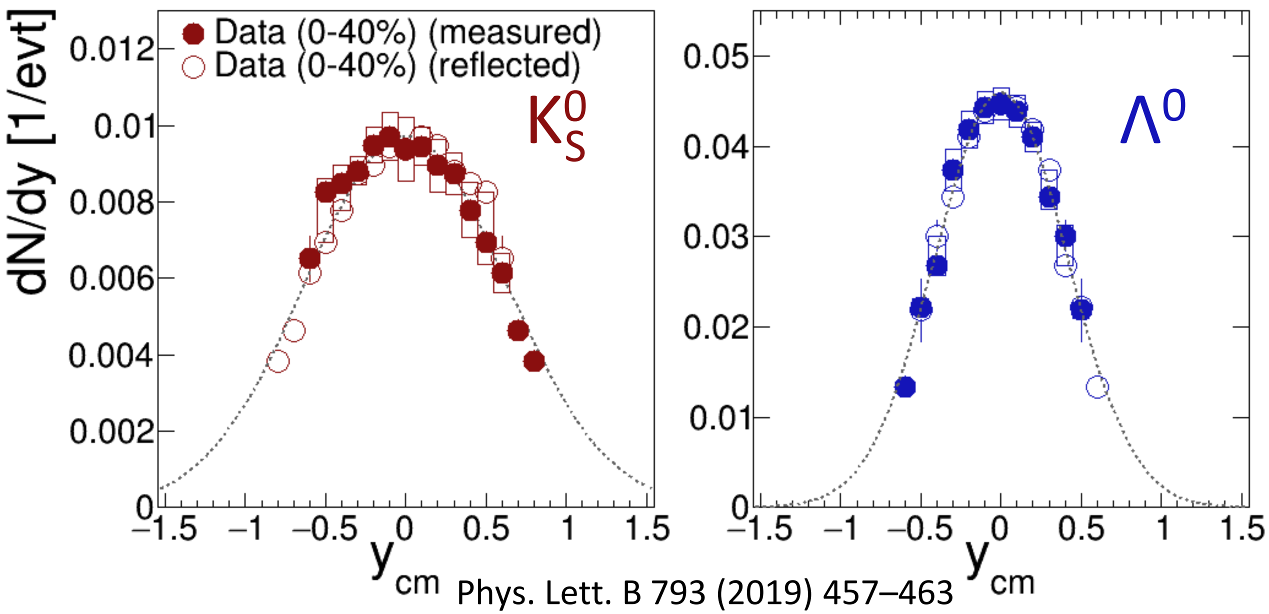
Boltzmann function: $\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = C \cdot \exp\left(-\frac{m_t - m_0}{T}\right)$

# Rapidity Spectra

- Each point represents one $m_t$ spectrum
- Symmetric collision system → Symmetric rapidity spectra
- Extrapolation to uncovered rapidity regions using gaussians

  → Extraction of total multiplicities

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# Conclusion

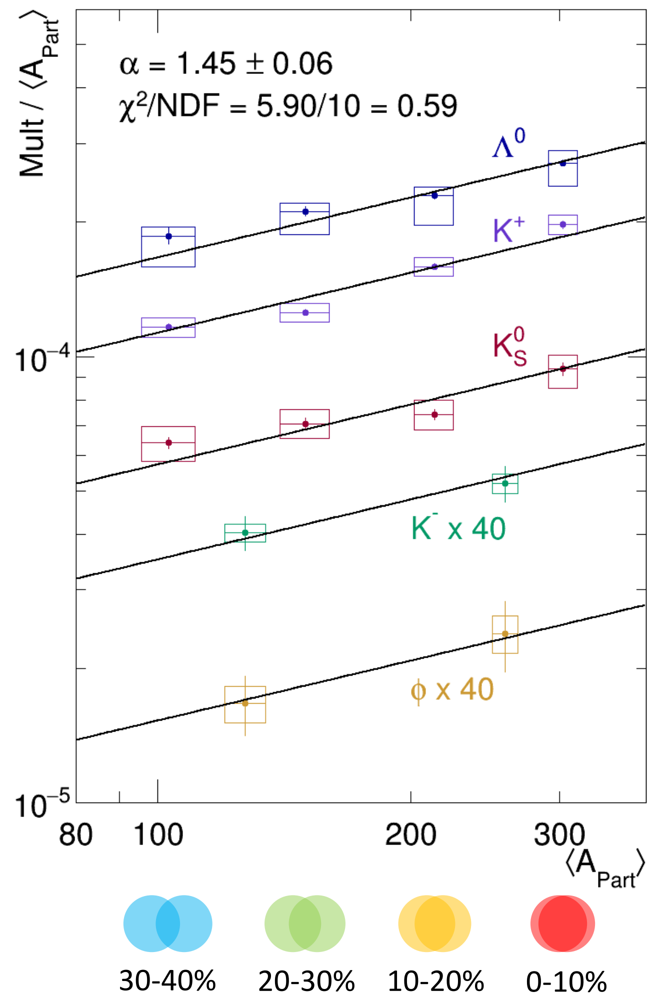
- Centrality and $\langle A_{part} \rangle$ estimated using Glauber model
  (Eur.Phys.J. A54 (2018) no.5, 85)

- Multiplicities of all strange particles show universal scaling

- Scaling of the multiplicities independent from production thresholds

  - $\Lambda^0$, $K^+$ and $K^0_S$: 2.6 GeV
    $K^-$ and $\phi$: 2.9 GeV

  - Energy provided by the system in a thermal like way

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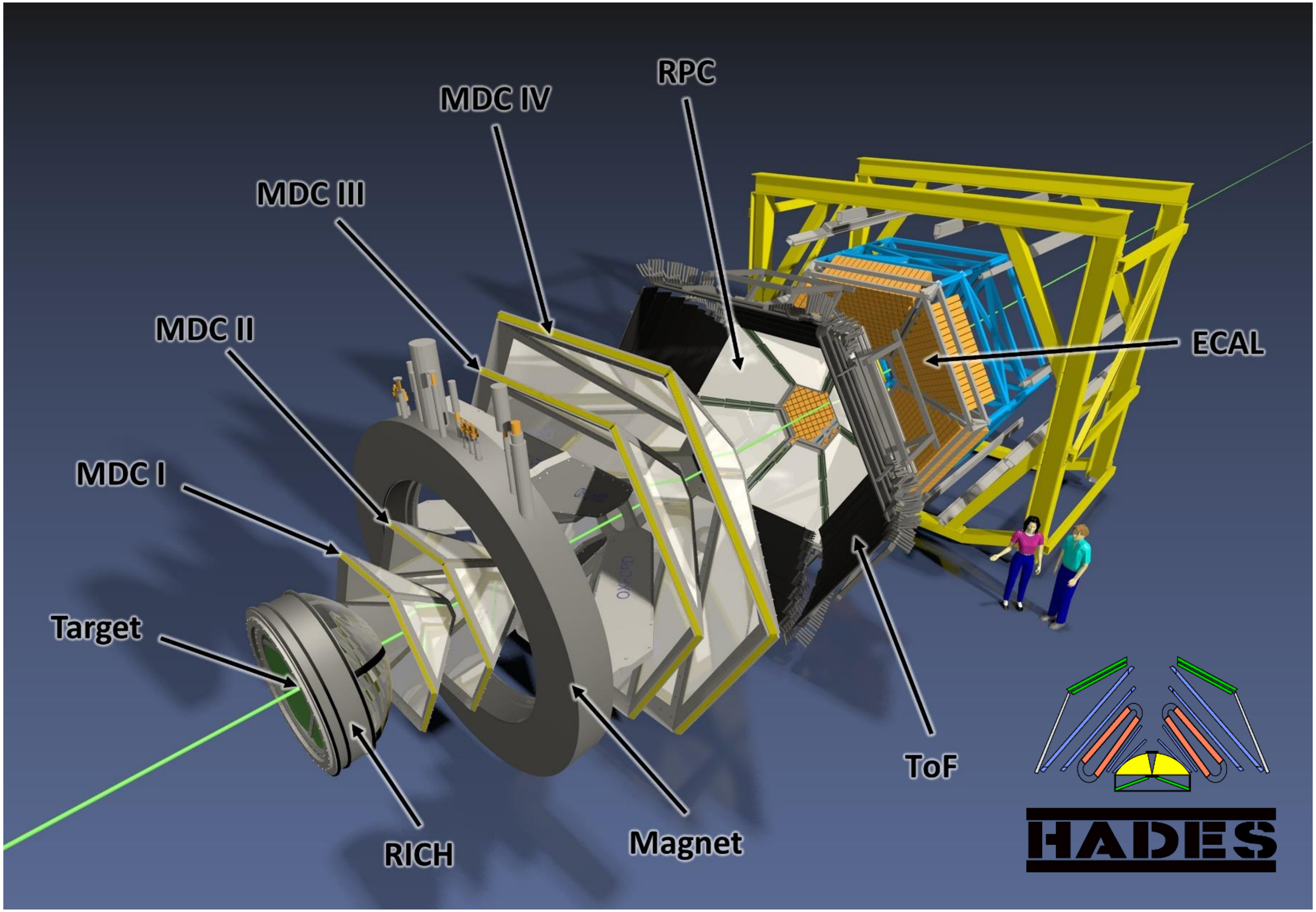
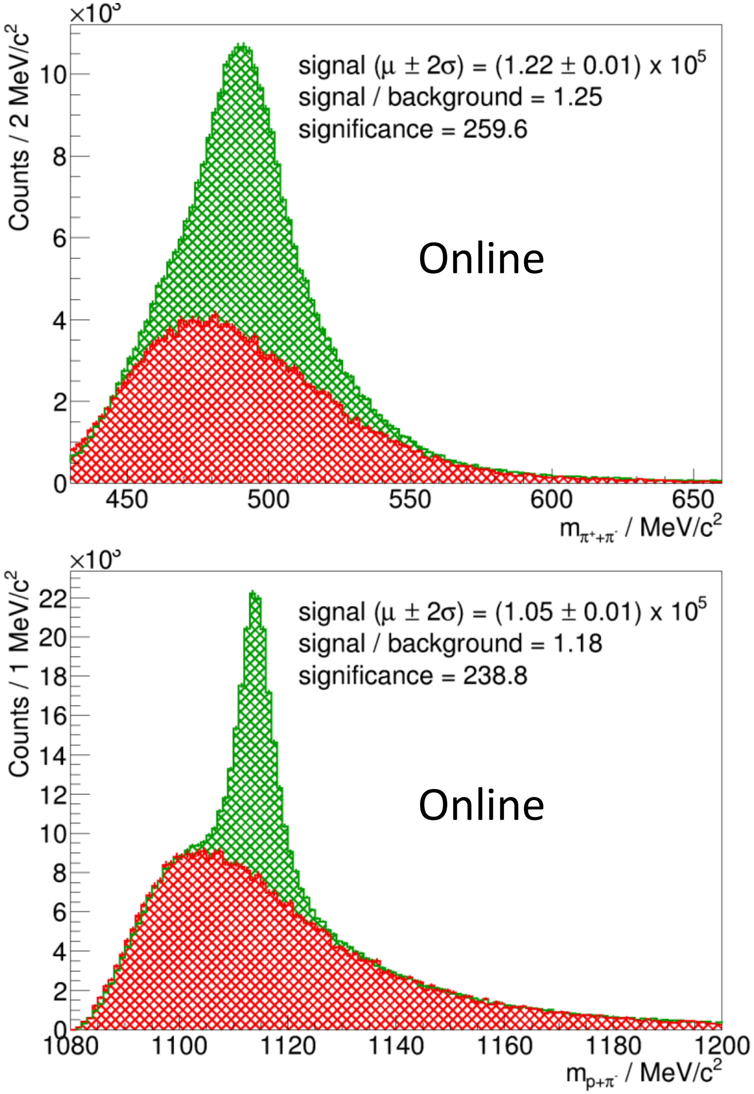
# HADES Ag+Ag March 2019



# Outlook: March 2019 - Ag+Ag

- HADES beamtime measuring Ag(1.58A GeV)+Ag collisions at $\sqrt{s_{NN}}$ = 2.6 GeV in March 2019
- $\sqrt{s_{NN}}$ = 2.6 GeV – $\Lambda^0$ and $K^0_S$ production exaclty at threshold energy
- Online reconstruction shows already significant signals
- Cross-check universal $\langle A_{part} \rangle$ scaling




Thank you for your Attention!
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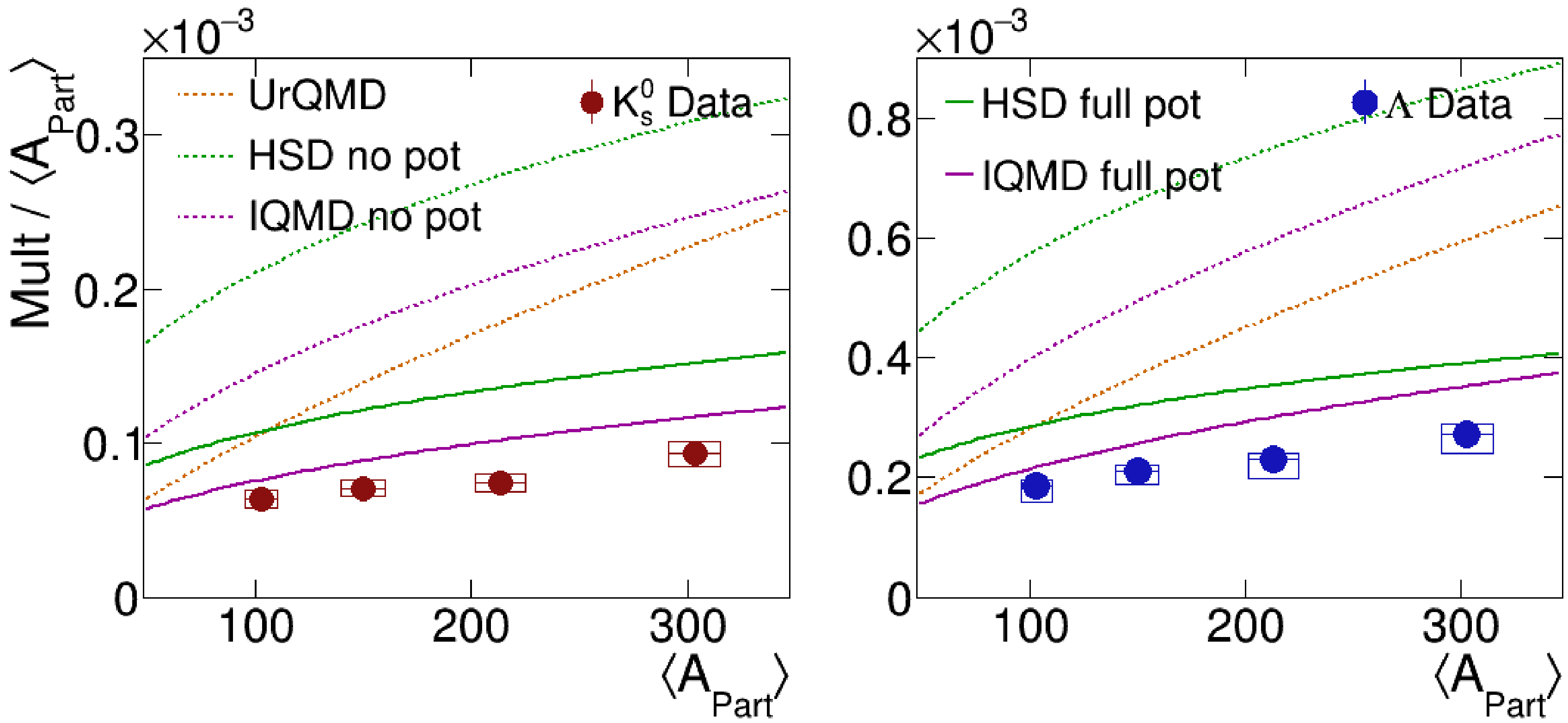
# Backup

Much more nice pictures

# Comparison with Models

- Absolute multiplicities of $\Lambda^0$ and $K^0_S$ not described by any of the tested models

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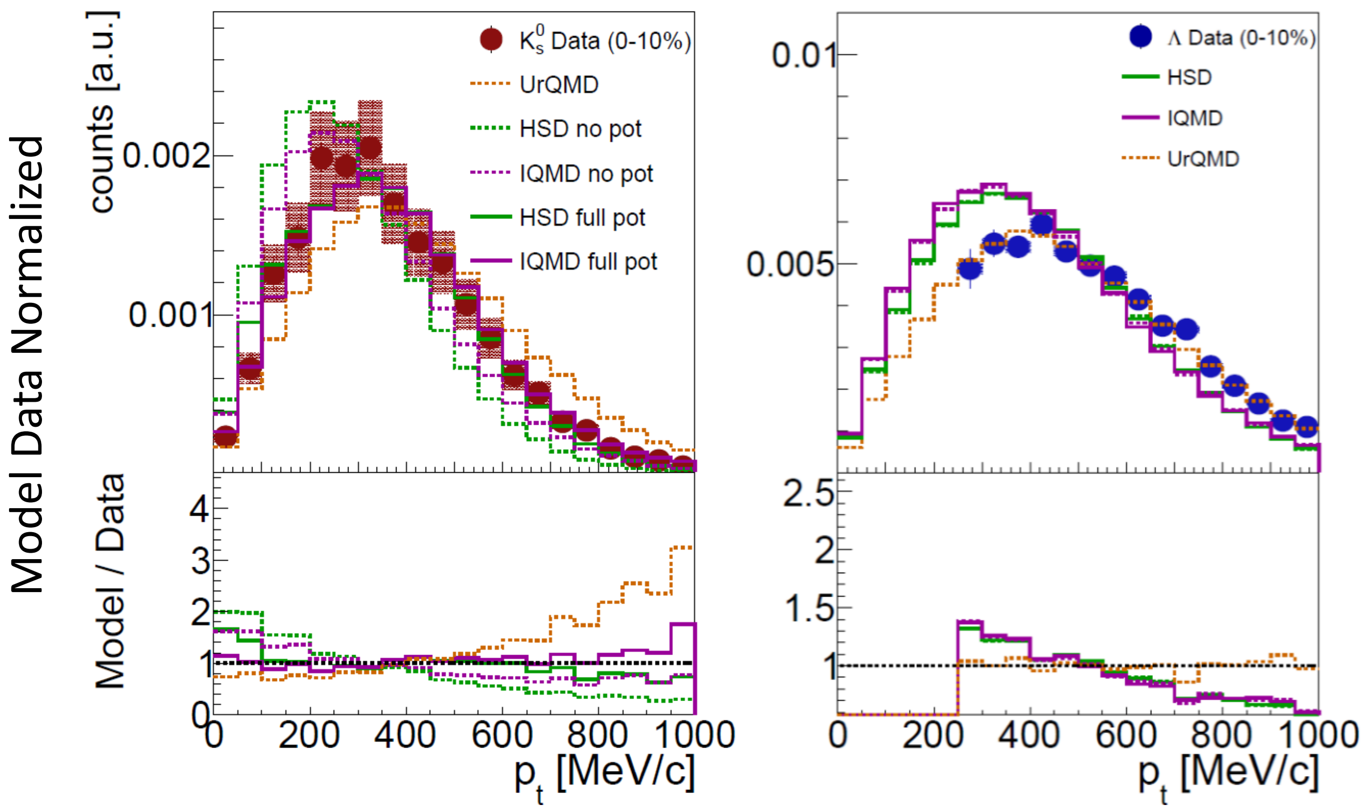
# Comparison with Models

- Compare shape of transverse mass spectra
  - Still models cannot describe production of $\Lambda^0$ and $K^0_S$ simultaneously

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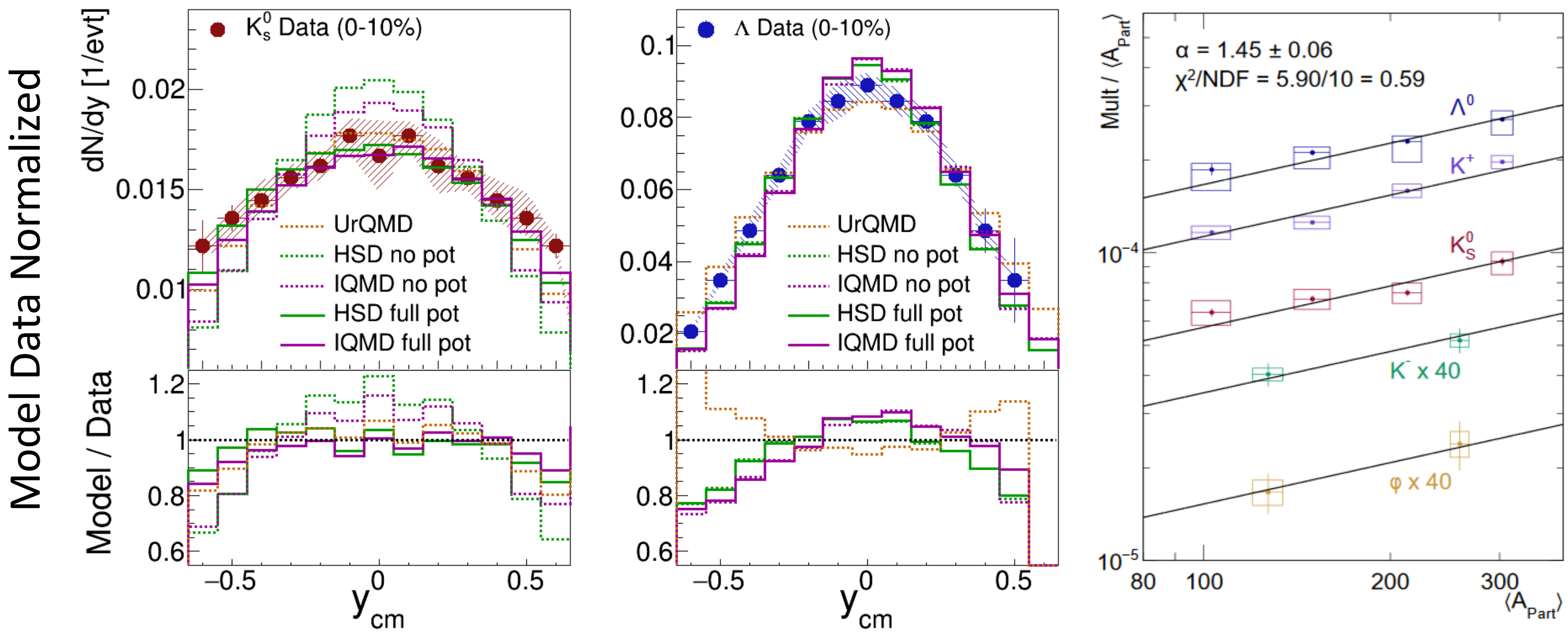
# Sub-threshold Strangeness Production

- Associated production of particles carrying strangeness
  - Still models cannot describe production of $\Lambda^0$ and $K^0_S$ simultaneously
- Universal scaling of multiplicities with $\langle A_{Part} \rangle$

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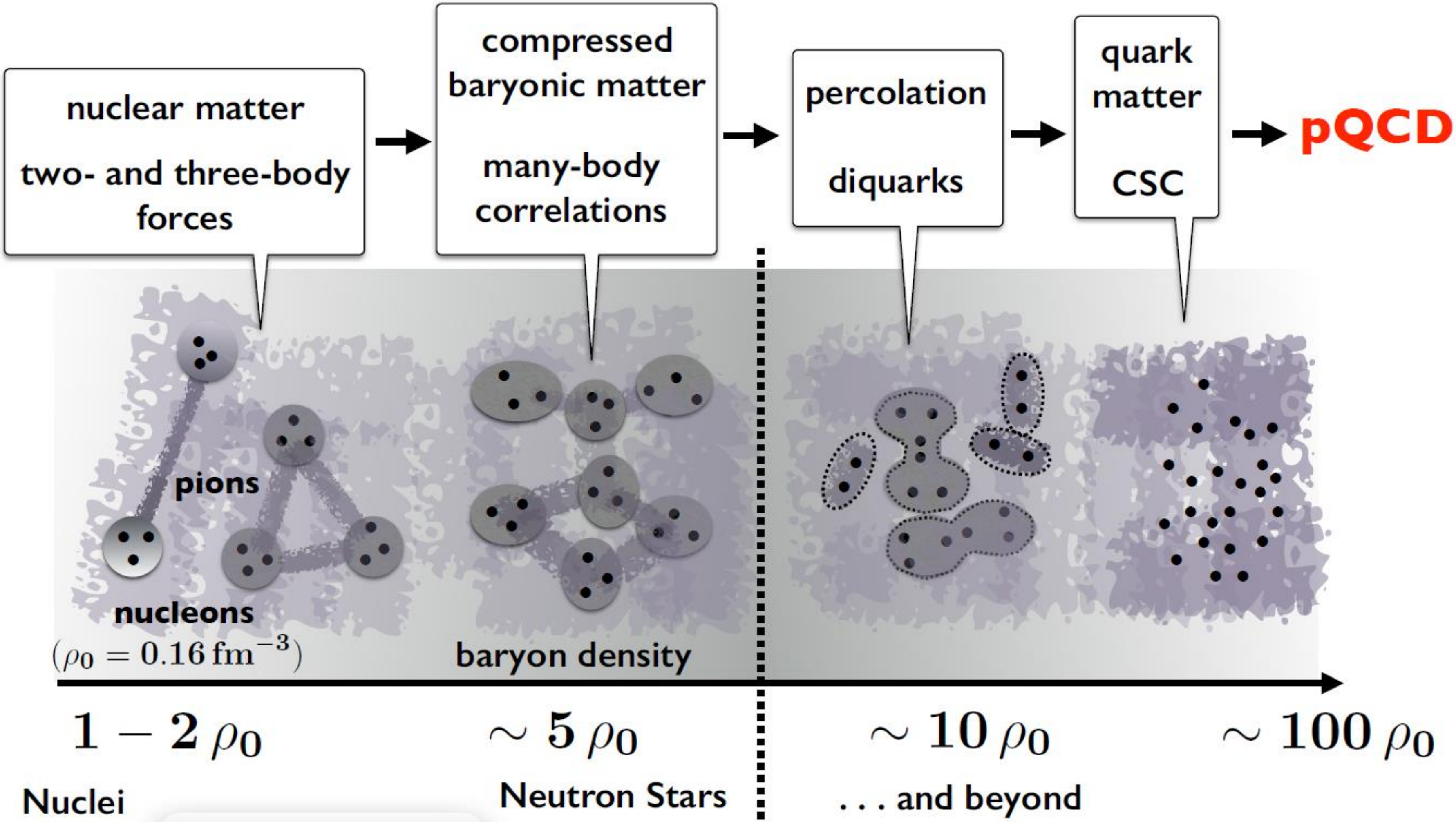
# PICTORIAL SUMMARY : COLD BARYONIC MATTER

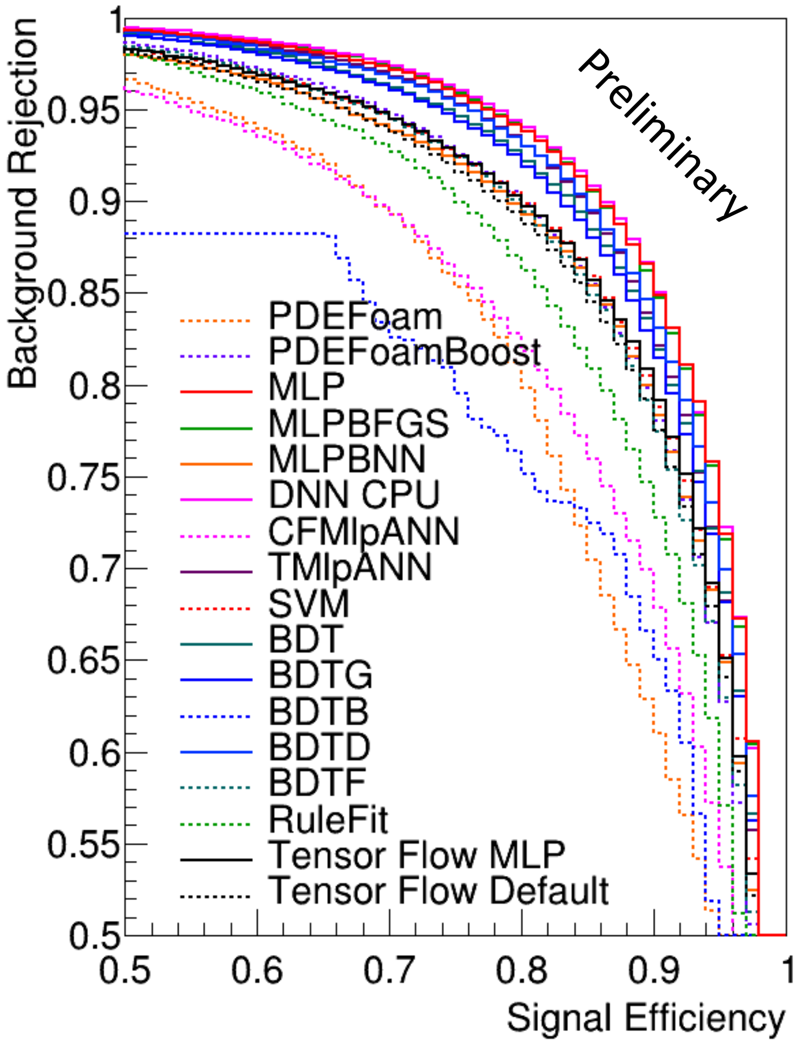



FERMI LIQUID

hadron - quark continuity ?

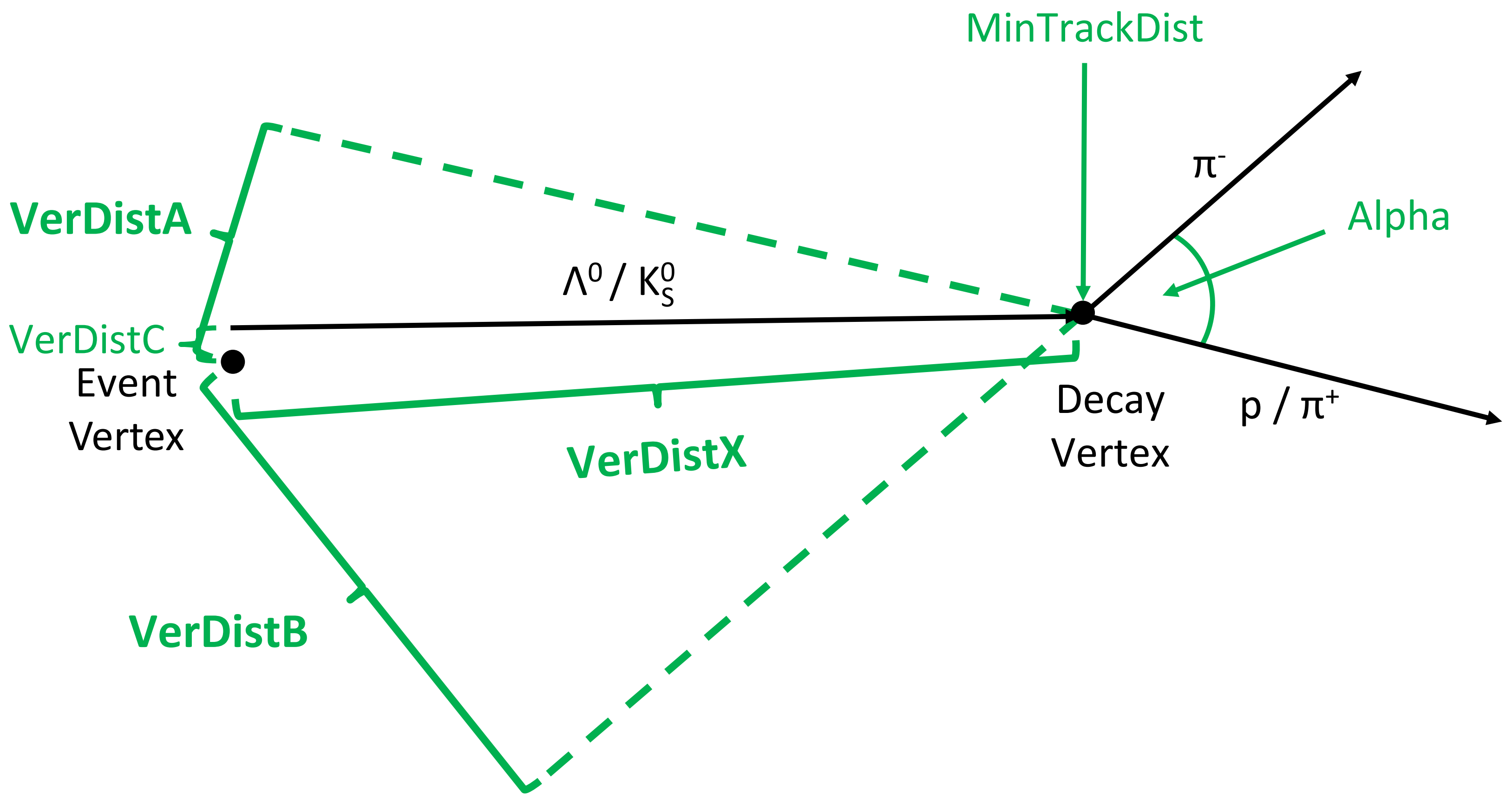
# Comparison of MVA Methods

- Using settings from examples provided by TMVA
- Trained on a sample of 50.000 $\Lambda^0$s
- Tensor Flow not as good as it‘s reputation might imply
- Multi Layer Perceptron (MLP) amongst the best Methods



# Off-Vertex Decay Topology

- Weak Decay → Long mean Lifetime → Off-Vertex-Topology



# MLP Setup and Functionality

- Every synapse has a weight $w_{ij}^{l}$
  - Passing Input Value × Weight
  - Weights define state
- Neurons sum input values with synapse function κ
- Hidden Neurons pass value of Activation Function α for summed value $y_i^l = \alpha\big(\kappa(input)\big)$
- Bias Neurons always pass 1
- Output Neuron solely sums