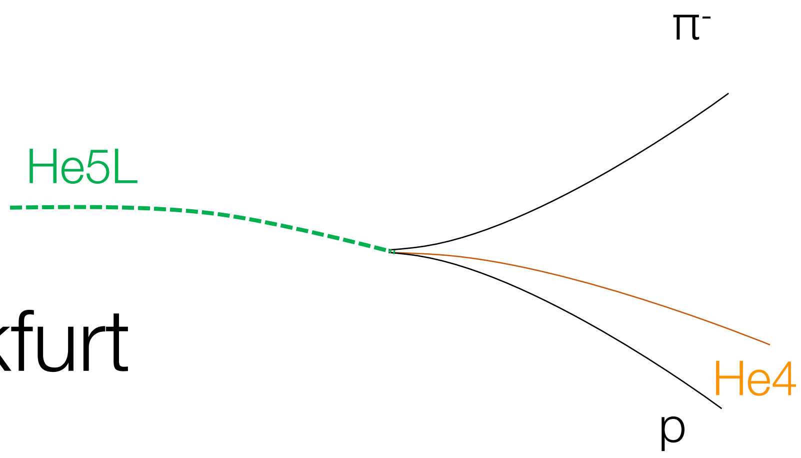
Hypernuclei reconstruction with CBM



Susanne Gläßel, IKF Frankfurt

Sept 26th 2024, FAIRNess, Croatia

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

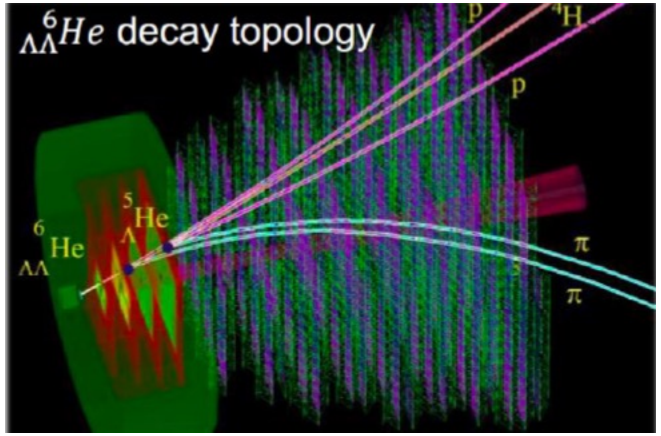
Bundesministerium für Bildung und Forschung

Agenda

Hypernuclei 3-body-decay

with $^{3}_{\Lambda}$H 3-body decay as test bed for the $^{6}_{\Lambda\Lambda}$He decay.

$$^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^{-} \quad \rightarrow \quad {}^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$$

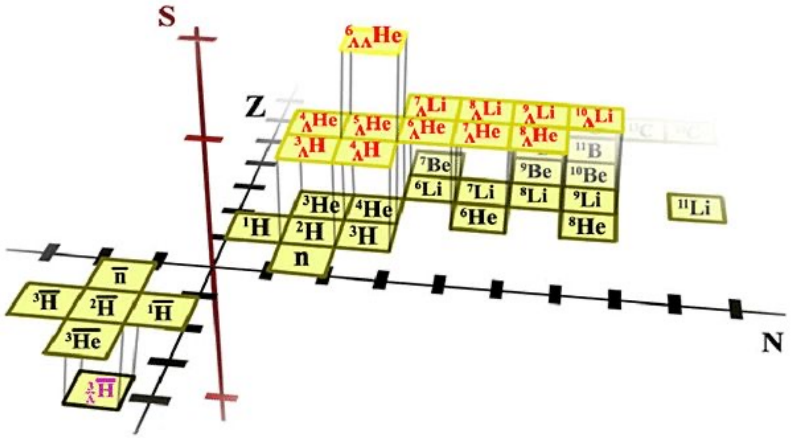


1) $^{3}_{\Lambda}$H reconstruction: Systematic error estimation for

- y-spectra
- lifetime measurement

2) $^{5}_{\Lambda}$He reconstruction: Improvement with Trd-dE/dx

Hypernuclei physics



- ✶ Properties of hypernuclei: lifetime, binding energy

  "Hypertrition liftetime puzzle"

- ✶ Hyperon-Nucleon(YN)- /Hyperon-Hyperon(YY) interactions "hyperon puzzle"

- ✶ Equation of state of hadronic matter at high density and low temperature

  → inner structure of neutron stars

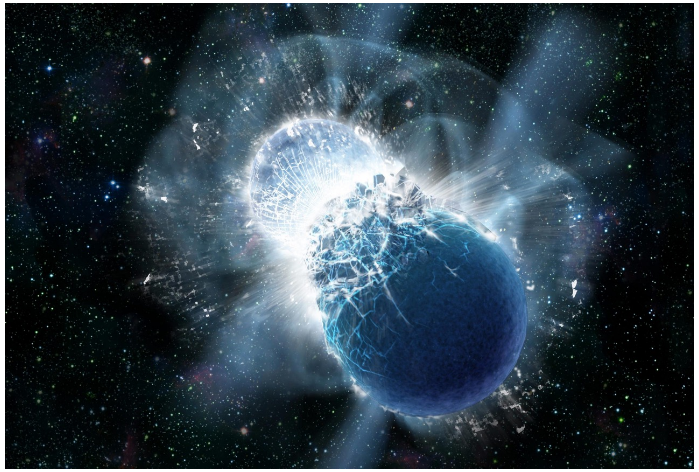
- ✶ Production mechanism of hypernuclei

  Thermal model: multiplicities ↔ masses, T, μ_B at chemical freezeout

  Colescence model: multiplicities ↔ phase-space-distribution of baryons

  at kinetic freezeout (coalescence radius)

  Dynamical model: PHQMD



Hyperon puzzle

Mass-radius relation for neutron stars: Depends on EOS of dense nuclear matter
Constraints form observation of MNS ≈ 2 M⊙

Hyperons should appear when density increases

⟹ EOS softens with hyperon matter

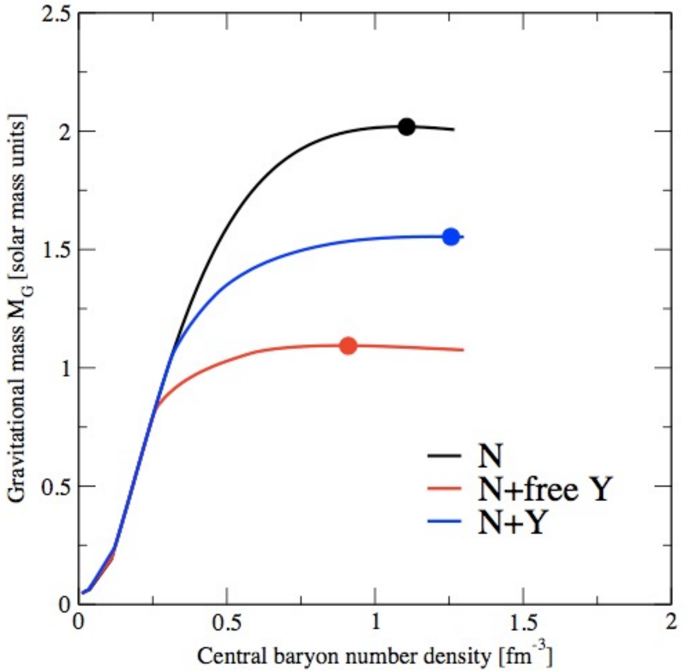
⟹ 2 $M_\odot$ cannot be reached

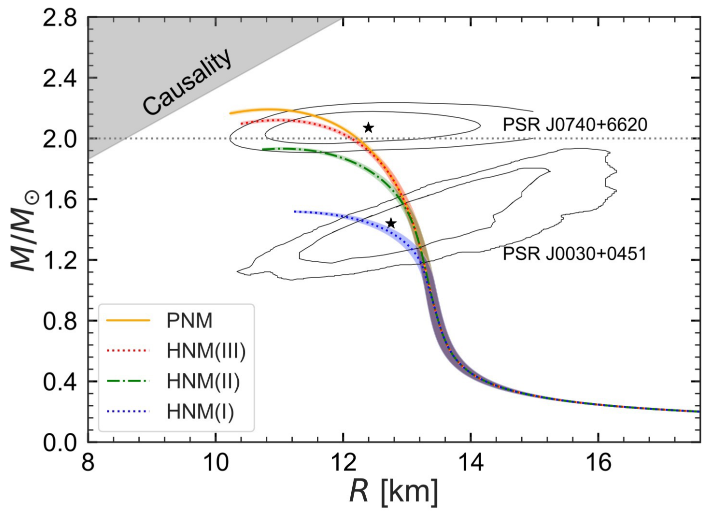
YN and YY interaction

- Repulsive YN and YY interactions ⟹ stiffer EOS

- 3-body forces between Ys to be studied

⟹ Important input from hypernuclei measurements





Tong, Elhatisari, Meißner, [arXiv:2405.01887 [nucl-th]]

Hypernuclei physics with CBM

CBM

Maximum in the production of hypernuclei

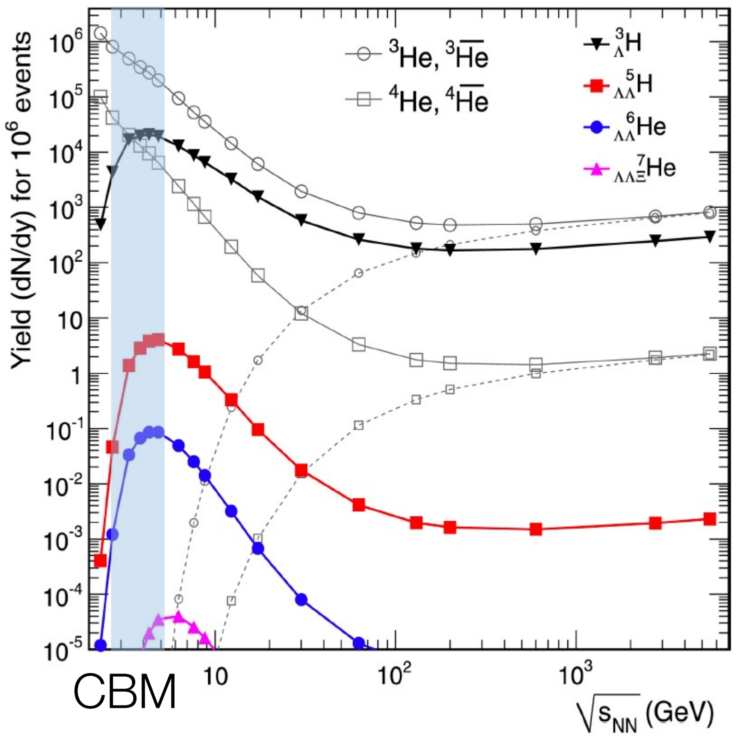
✶ Relatively low beam energies at FAIR & high interaction rates
✶ CBM detector design: clean identification

→ precise measurement of hypernuclei lifetime, branching ratios of decays, binding energy B_{Λ}, spectra and flow

→ sufficient statistics for double hypernuclei, e.g. ${}_{\Lambda\Lambda}{}^{6}He$

expected rates: ~10^{-6}/evt. — ~10^{-11}/evt. in CBM range

→ Search for the new hyper-nucleus or charmed nucleus ${}^{4}_{D}He$



*A. Andronic et al., Phys. Lett. B697 (2011) 203-207.

Parton-Hadron-Quantum-Molecular Dynamics

= n-body microscopic transport approach for the description of heavy-ion dynamics with dynamical cluster formation

PHSD + QMD + MST

Relativistic considerations

but: mean-field potentials
=> correlations are smeared out

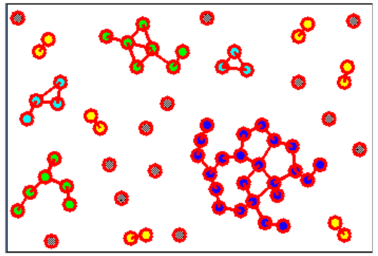
Correlations between baryons

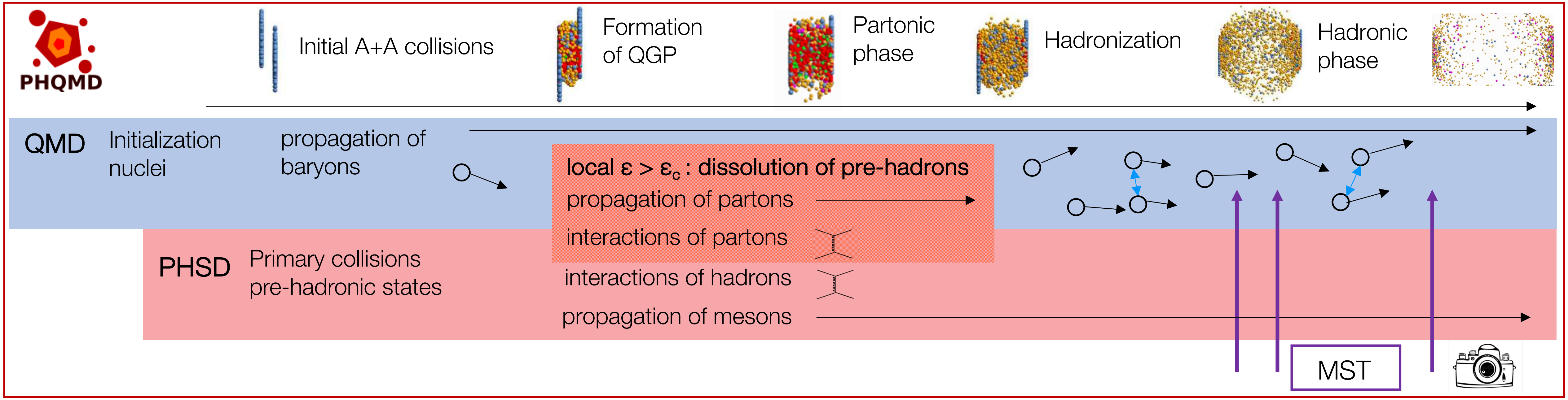
n-body transport approach

=> formation of clusters due to potential interactions

Cluster recognition

search for accumulations of particles in coordinate space





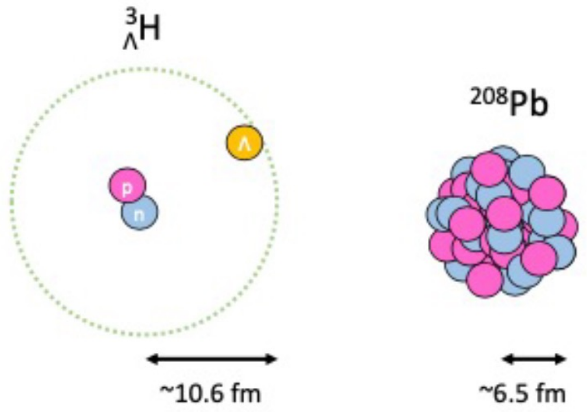
J. Aichelin et al., PRC 101 (2020) 044905 PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168(2009)

Hypertriton

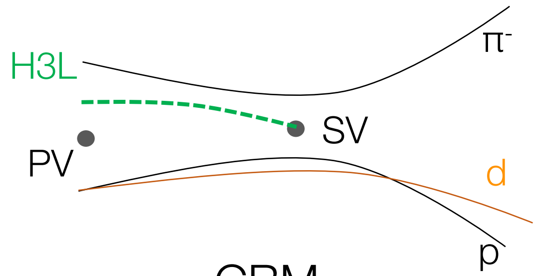
Loosely bound object

Λ binding energy: $B_\Lambda \approx 400$ keV
(compare $B_d = 2.2$ MeV)

Wavefunction is larger than Pb-nucleus

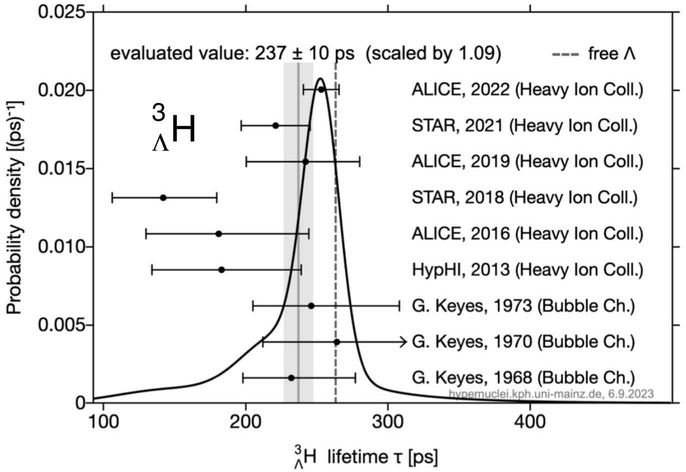


Reconstruction of 3-body-decay
1) reconstruct mother from π^- & p
2) Add d at SV of π^- & p

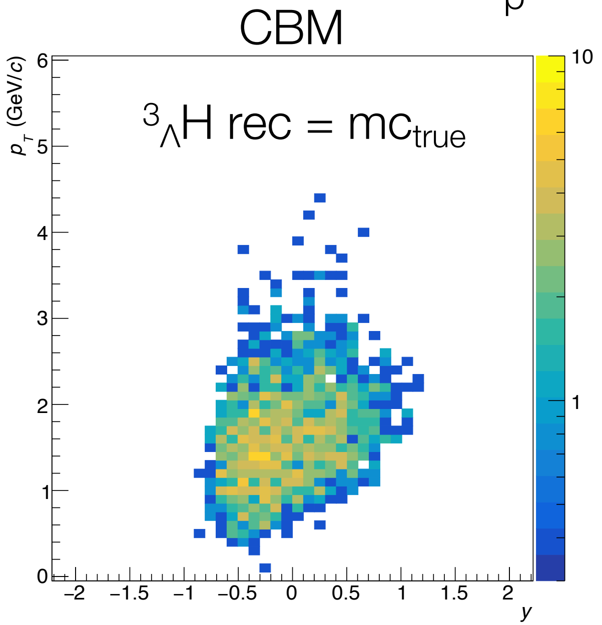


Hypertriton lifetime “puzzle”
- Lifetime smaller than the one of free Λ?
- Life-time particularly sensitive to YN interaction.

Worldwide lifetime measurements



https://hypernuclei.kph.uni-mainz.de



Decay modes:
$^3_\Lambda H \longrightarrow {}^3He + \pi^-$, $^3_\Lambda H \longrightarrow {}^3H + \pi^0$
$^3_\Lambda H \longrightarrow d + p + \pi^-$, $^3_\Lambda H \longrightarrow d + n + \pi^0$

Systematic error estimation for different simulation & reconstruction steps

1) different simulation input with different y- & pT-distributions ★

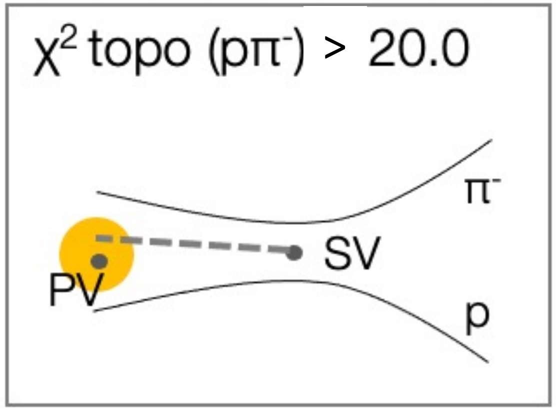
2) different cut sets for reconstruction

3) different invariant mass-cuts (2, 3 & 4 σ) ▽

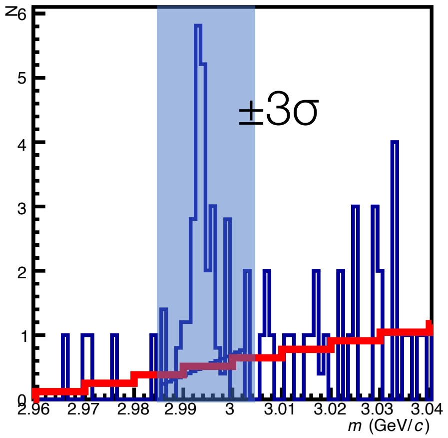
4) different input for efficiency correction ▲

5) different fits for p_T-spectra to extrapolate to unmeasured regions

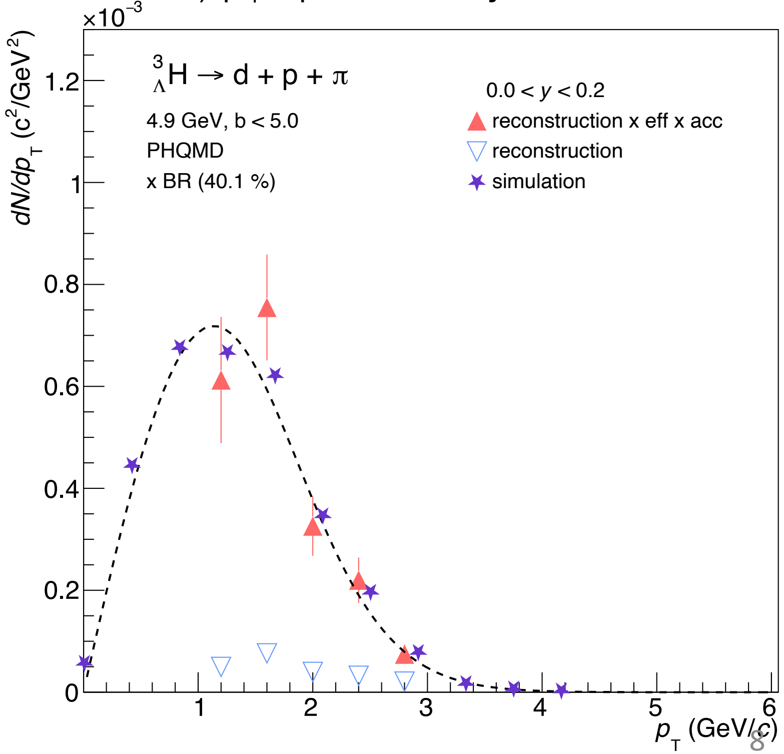
2) Cut variation (e.g.)



3) Mass spectrum for p_T-y-bin

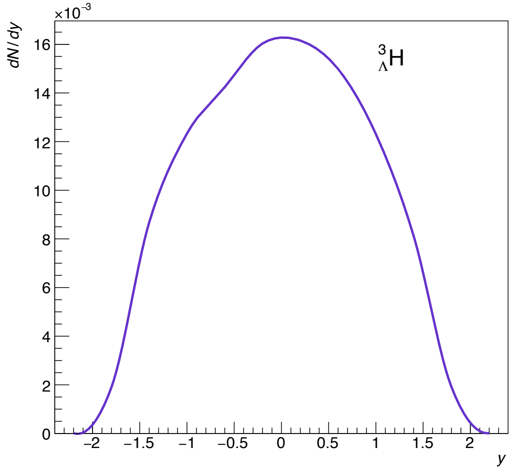


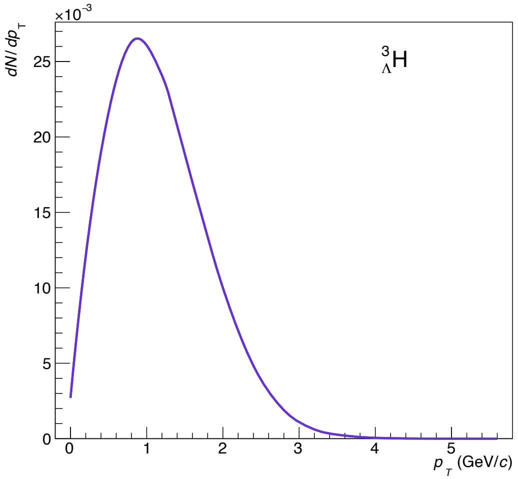
4) p_T-spectra for y-bin



Simulated datasets: different y- & p_T-distributions

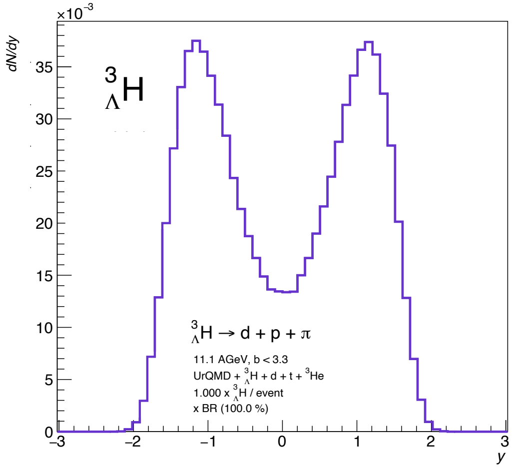
PHQMD (0.0427 $^{3}_{\Lambda}H$/event)

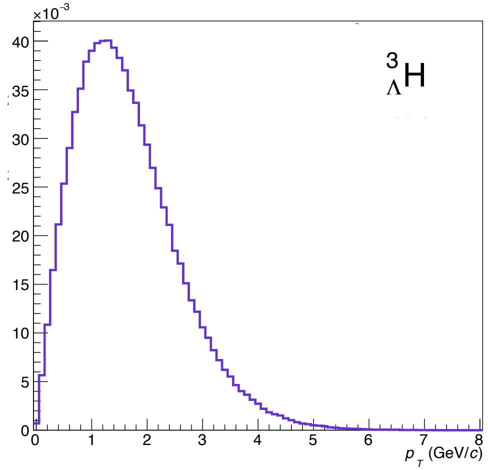




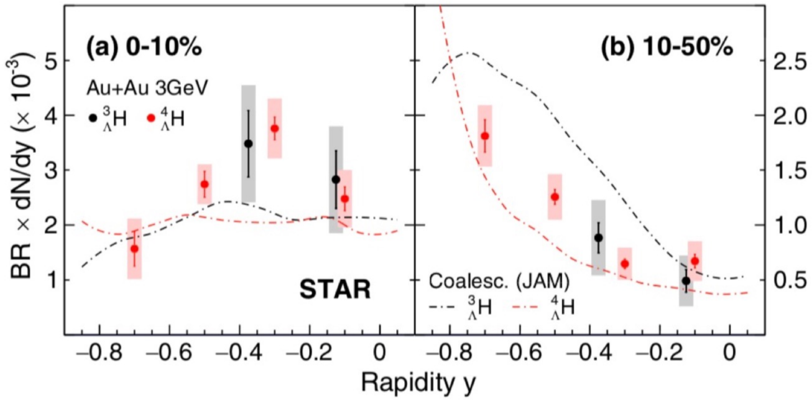
thermal signal (0.087 $^{3}_{\Lambda}H$/event) + UrQMD + d, t, ^{3}He

p_T- & y-distribution**: Experimental nuclei-shape from E864-data***





Shape of $^{3}_{\Lambda}H$ rapidity distribution is not 100% known yet.



=> Different distributions relevant for detector efficiencies.

=> Used for systematic error estimation of lifetime measurement.

*T. A. Armstrong et al., Phys. Rev. C 61 (2002) 064908 , **I. G. Bearden et al., Phys. Rev. Lett. 93 (2004) 102301, ***L. Adamczyk et al., Phys. Rev. C 97 (2018) 054909

Extrapolation of p_T-spectra to unmeasured regions

Fit p_T-spectra with:

1) Blast-Wave model fits*

$$\frac{1}{2\pi\, p_T}\frac{d^2N}{d p_T\, dy} \propto \int_0^R r\, dr\, m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) \times K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

Parameters:

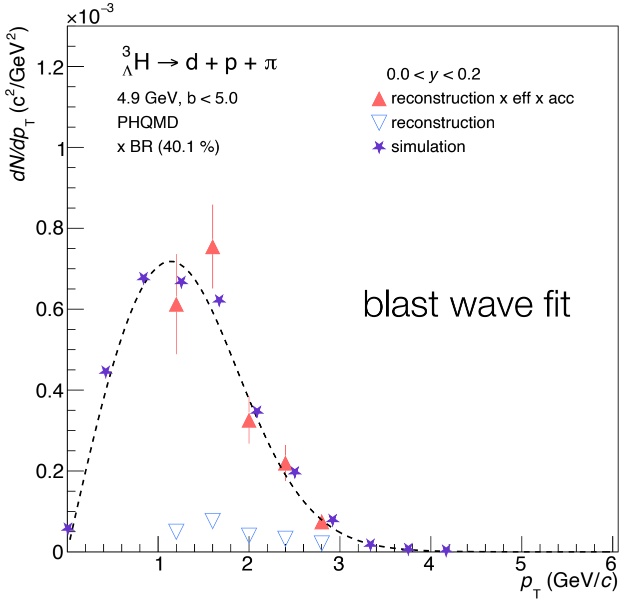
<β>: transverse expansion velocity (linear velocity profile)

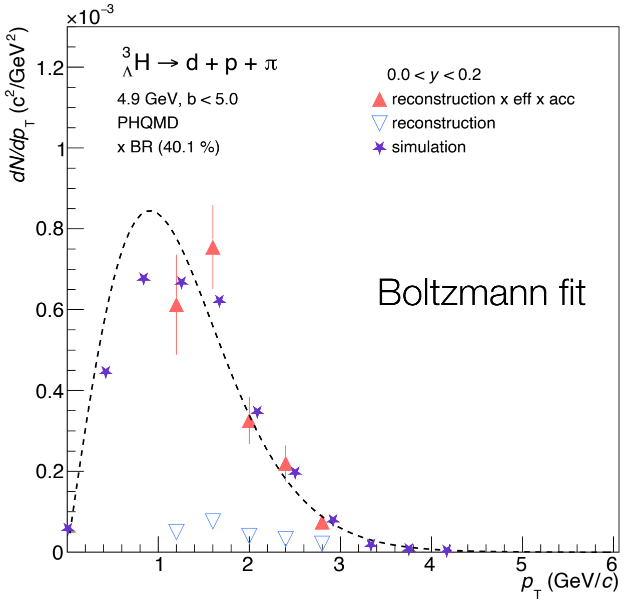
T: kinetic freeze-out temperature

2) Boltzmann fits

$$\frac{dN}{dp_T} \sim m_T \cdot e^{\left(-\frac{m_T}{T}\right)}$$

p_T-spectra for y-bin





*E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993).

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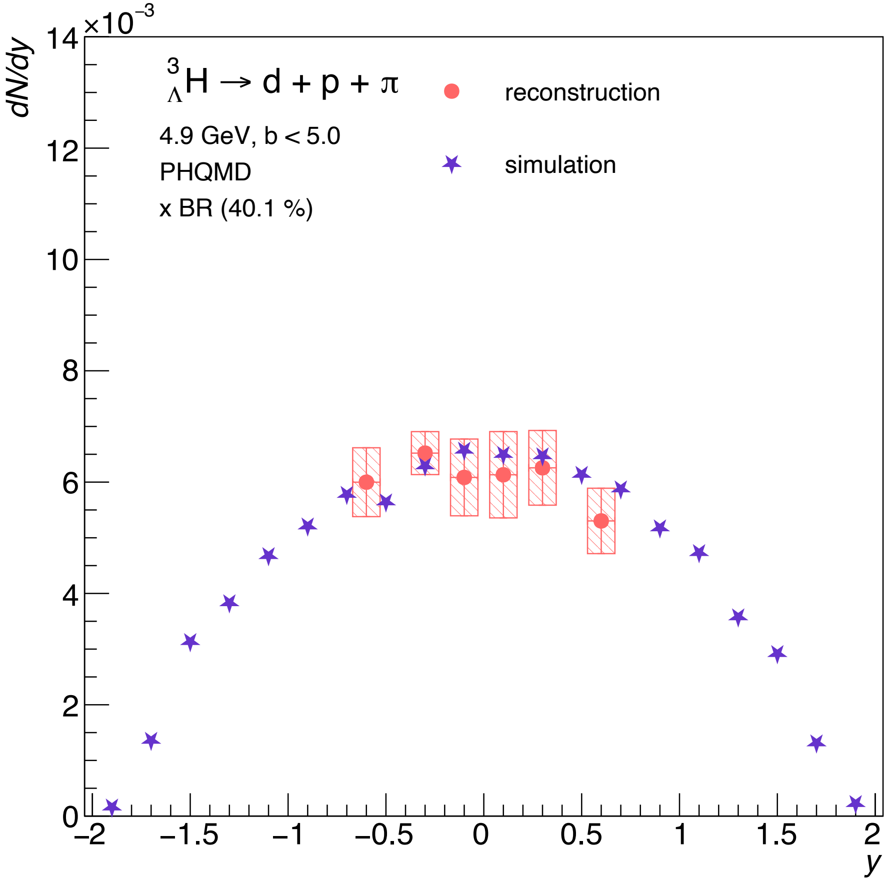
Systematic error for ${}^{3}_{\Lambda}H$ y-spectra

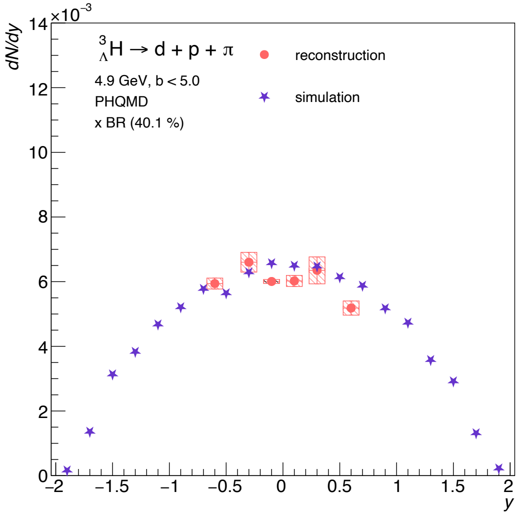
Total error



Systematic error most bins ~ 10%
maximum = 12.6 %.

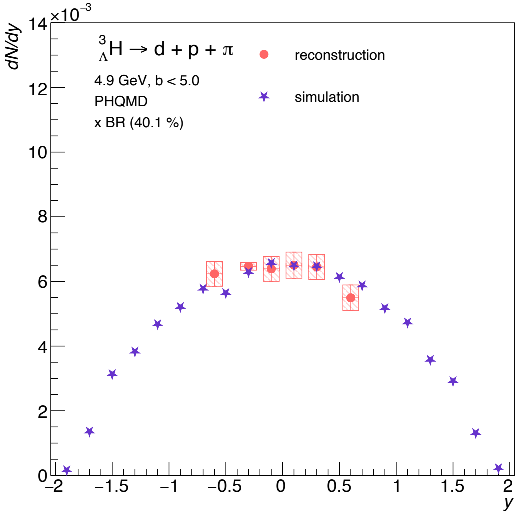
different contributions

Cut variations:
4 different cuts



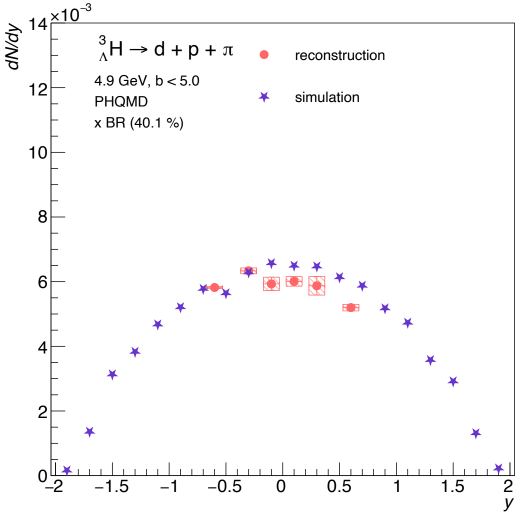
Sys. error most bins ~ 3%
maximum = 6.6 %.

Fit variations



Sys. error most bins ~ 6%
maximum = 7.23 %.

Mass cut variations
$m \pm n^{*}\sigma$



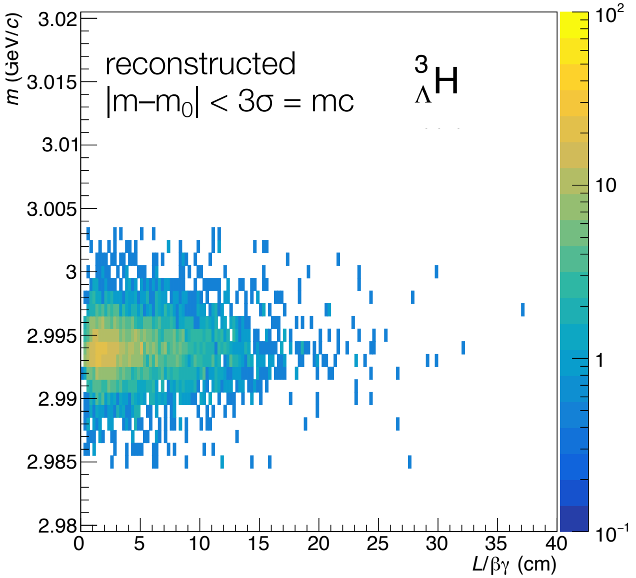
Sys. error most bins ~ 2%
maximum = 4.9 %.

Main contribution to systematic error comes from fit variations.

Lifetime measurement of $^{3}_{\Lambda}H$ with CBM

decay length L

after Lorentz-boost



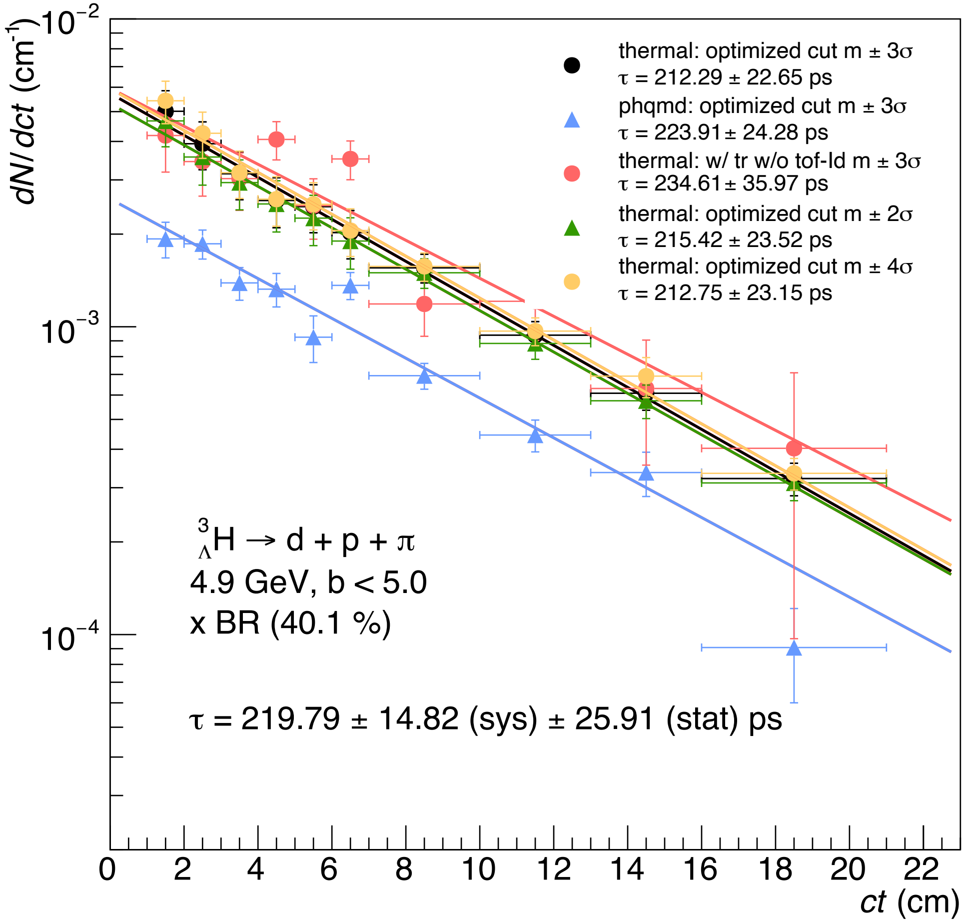
Fit dN/dct vs. ct with exponential decay law:

$$\frac{dN}{dct} = C \cdot e^{-ct \cdot \frac{1}{c\tau}}$$

where $\frac{L}{\beta\gamma} = ct$

Efficiency corrected decay-length distributions

after background substraction for different variations



- Statistical error is 11.7 % for 1 million events only.
- Estimated uncertainty the first year of data taking is $\sigma_{stat} = \pm\ 0.17$ ps.
- Total systematic error is 6.7 %.
- Lifetime is slightly underestimated.

  -> Reason might be: low efficiencies for particles with longer lifetime & decaylength -> stronger bending in magnetic field.

  -> Explore improvement by removing bins for longer lifetime from fit.

Reconstruction of $^{5}_{\Lambda}$He

- important also for the reconstruction the of $^{6}_{\Lambda\Lambda}$He decay

$$^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^{-}$$

- low multiplicities 0.003 $^{5}_{\Lambda}$He / event

  using PHQMD events is not possible (very high statistics needed)

  → embed thermal signal into UrQMD event + d + t + ^{3}He

  & mix signal-events with bg-events

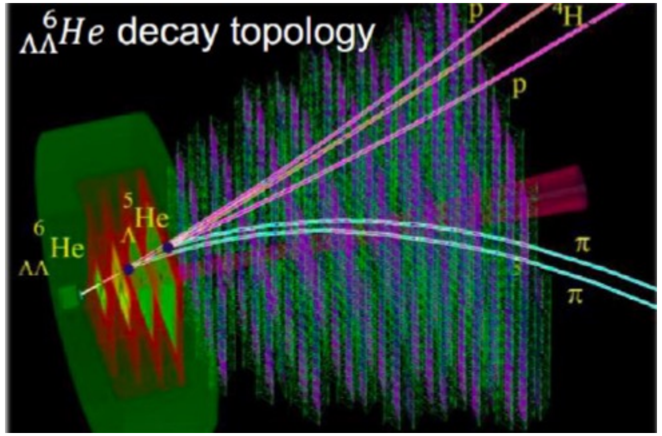
- separation of d & ^{4}He is very important to separate

$$^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$$

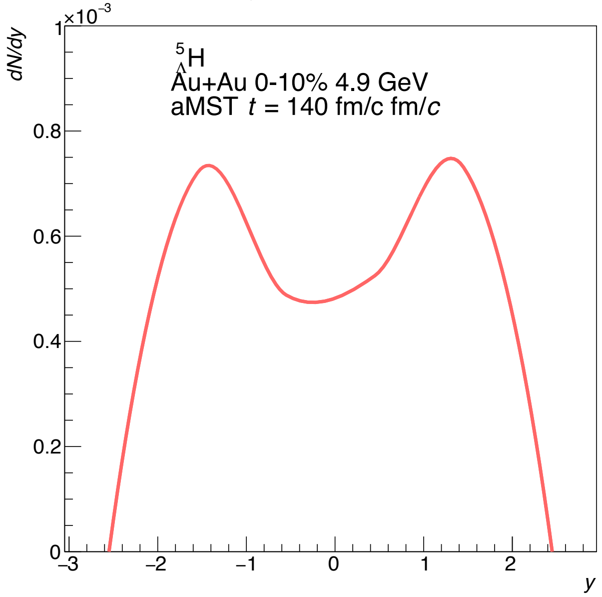
&

$$^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$$

→ use of Trd-dE/dx (PidTrd-software)



PHQMD simulation



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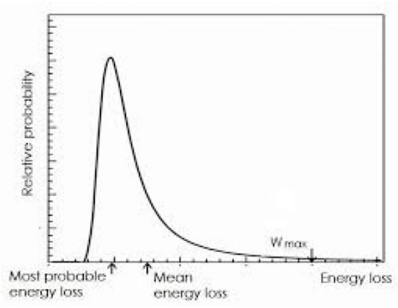
PID with TRD-dE/dx

TRD: Specific energy loss for every particle specie depending on momentum (Bethe-Bloch)



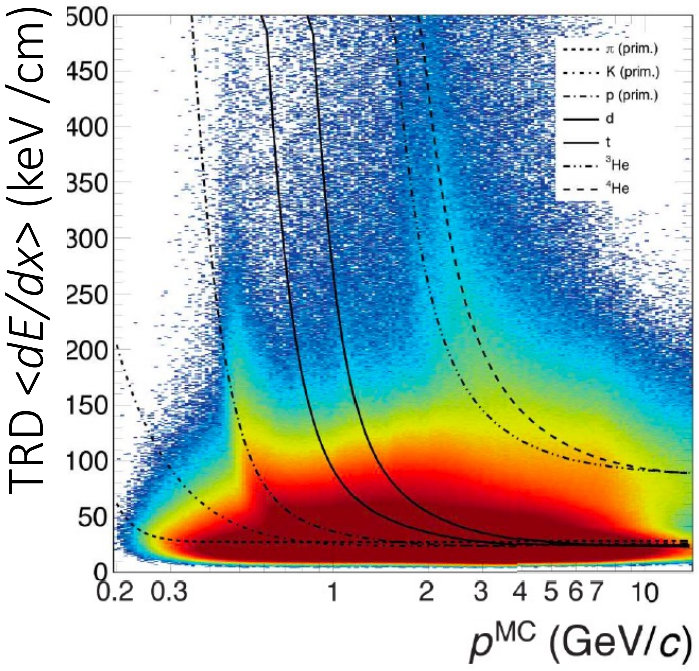
Calculation of <dE/dx> over 4 TRD-detector layers:

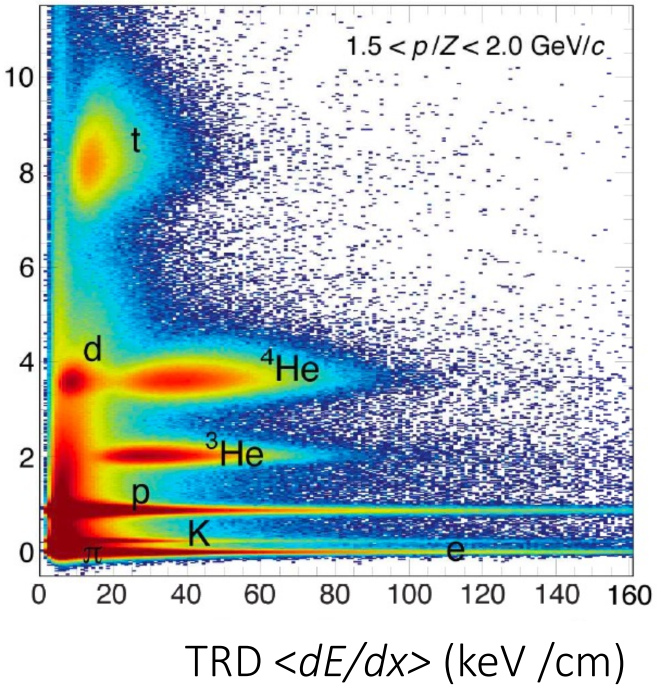
Truncation: reduce Landau-fluctuations => select 2 hits with smallest dE/dx

1) Separation of d & ^{4}He

- can not be separated with TOF alone (similar m/q)
- important for reconstruction of $_{\Lambda\Lambda}{}^6$He decay chain => very rare signal

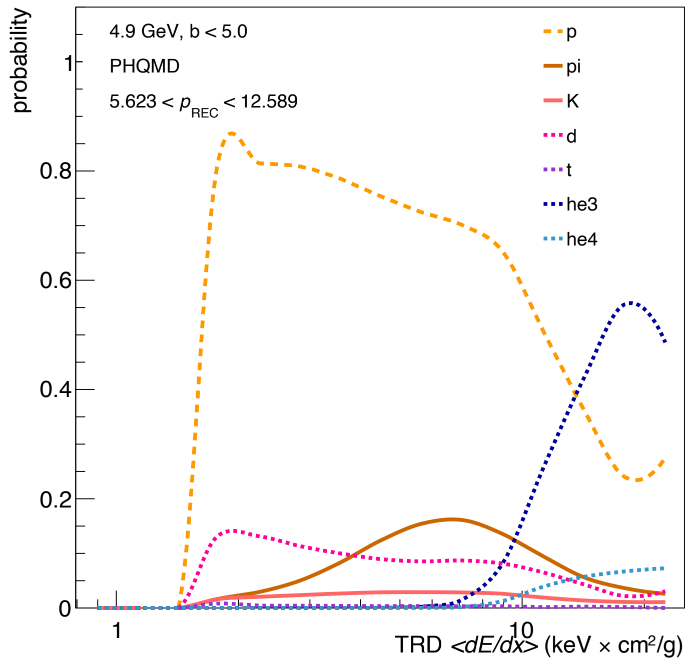
2) Pid for hadrons: Increase efficiency or s/b



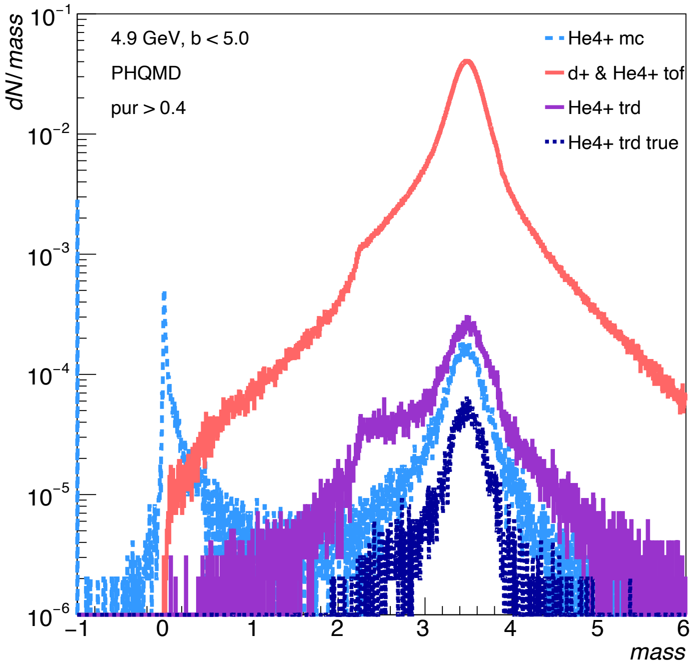


Separation of d & ^{4}He with TRD-dE/dx

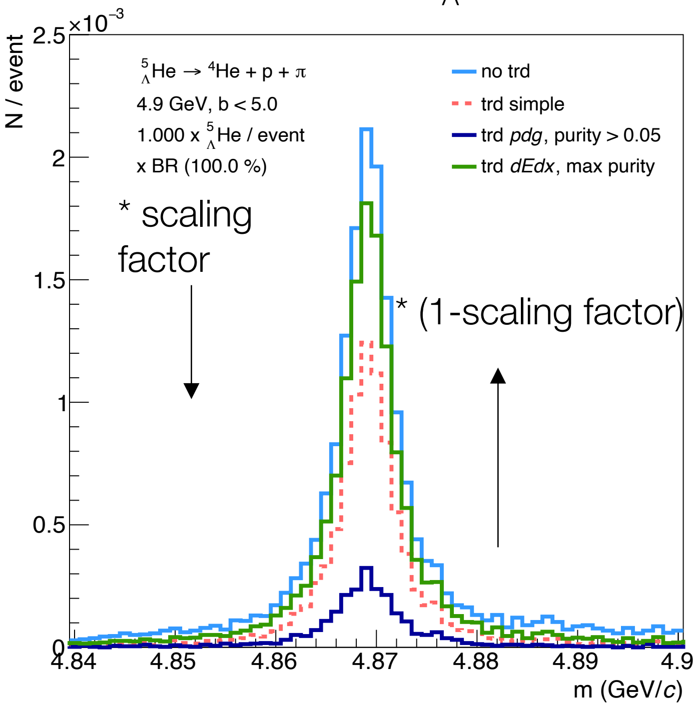
Track probability for particle species



^{4}He Mass spectrum w/ and w/o Trd



Reconstructed $^5_\Lambda$He



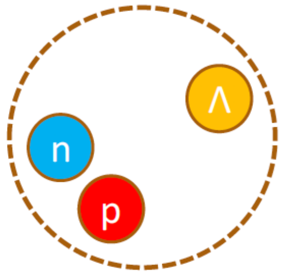
⇨ Background can be supressed with TRD (different settings for TRD cut possible).

! Results are for 1 ^{5}He / event. ! For scaling with bg-events more statistic is needed.
Scaling factor: ^{5}He / event * br = 0.03 * 0.323 =10^{-4}
⇨ Strong background supression is needed.

TRD <dE/dx> (keV /cm)

Summary & Conclusion

- Systematic error of ${}^{3}_{\Lambda}H$ y-spectra could be estimated to ~10% for PHQMD dataset.
- Systematic error of ${}^{3}_{\Lambda}H$ lifetime measurement could be estimated to 6.7 %, lifetime is slightly underestimated.
- Reconstruction of ${}^{5}_{\Lambda}He$ can be improved with Trd-dE/dx.



Next steps:

- Improve procedure to estimate systematic uncertainties by using different datasets for efficiency estimation.
- Improve estimation of lifetime value (e.g. remove particles with long lifetimes that might not reach detector).
- Realistic ${}^{5}_{\Lambda}He$ reconstruction with scaled background – high statistics needed.

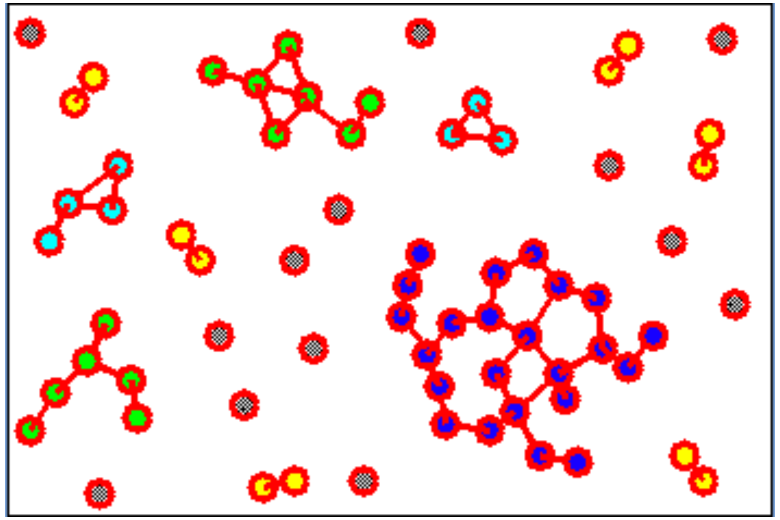
THANK YOU.

BACKUP

Minimum Spanning Tree (MST)

Cluster criterion: distance of nuclei

Algorithm: search for accumulations of particles in coordinate space



1. Two particles i & j are bound if:

$$|r_i - r_j| < 4.0 \text{ fm}$$

2. Particle is bound to cluster if bound with at least one particle of cluster

Remark: additional momentum cuts lead to a small changes: particles with large relative momentum are mostly not at the same position (V. Kireyeu, Phys.Rev.C 103 (2021) 5)

Reconstruction of rapidity spectrum

1. Mass spectra in y-p_T-bins: Calculation of dN/dp_T
   - N_{rec}: Integration for $| m - m_0 | < 3\sigma$
   - Subtraction of background with linear fit
   - Corrected for efficiency x acceptance in y-p_T-bin

$$\frac{dN}{dp_T} = \frac{N_{rec} - bg}{eff \cdot acc \cdot dp_T \cdot nevents}$$

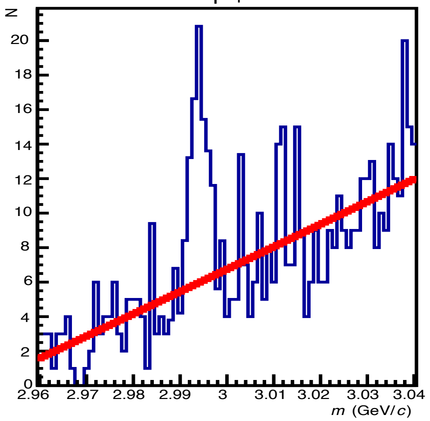
2. p_T-spectra in y-bins: Calculation of dN/dy
   - Sum over dN/p_T for reconstructed points
   - Extrapolation to unmeasured regions with Blast-Wave model fits*

$$\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh \rho}{T}\right) \times K_1\left(\frac{m_T \cosh \rho}{T}\right)$$

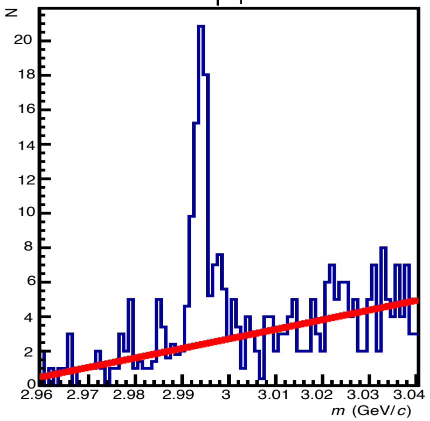
Parameters:
<β>: transverse expansion velocity (linear velocity profile)
T: kinetic freeze-out temperature

Mass spectra -0.4 < y < -0.2

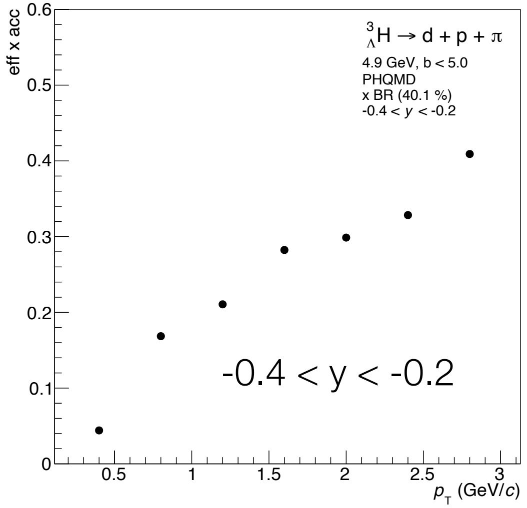
$1.0 < p_T < 1.4$



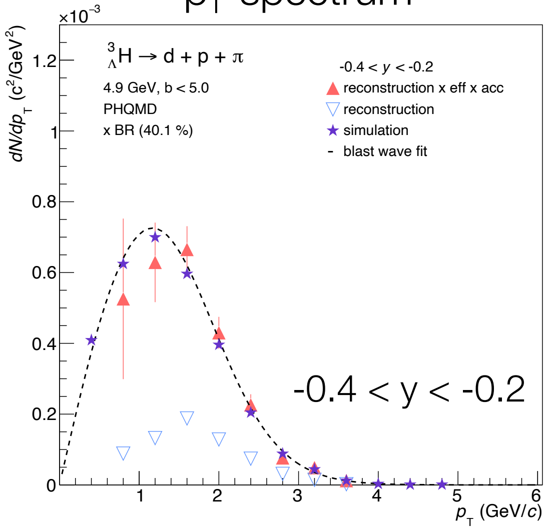
$1.4 < p_T < 1.8$



efficiency x acceptance



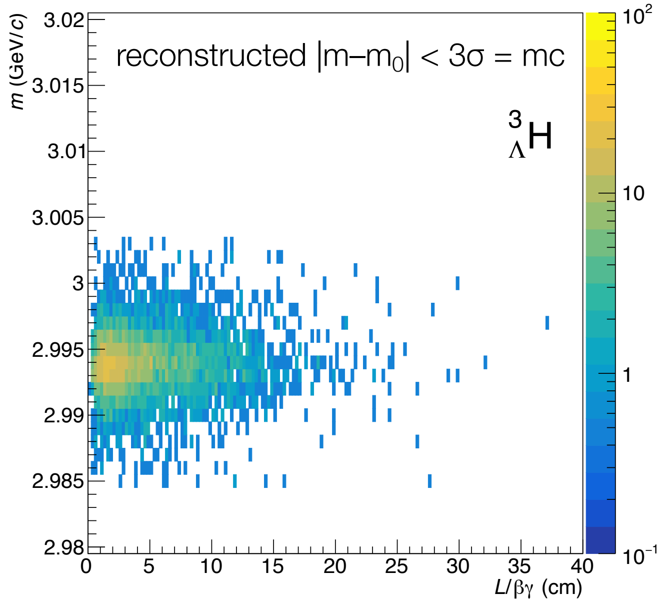
p_T-spectrum



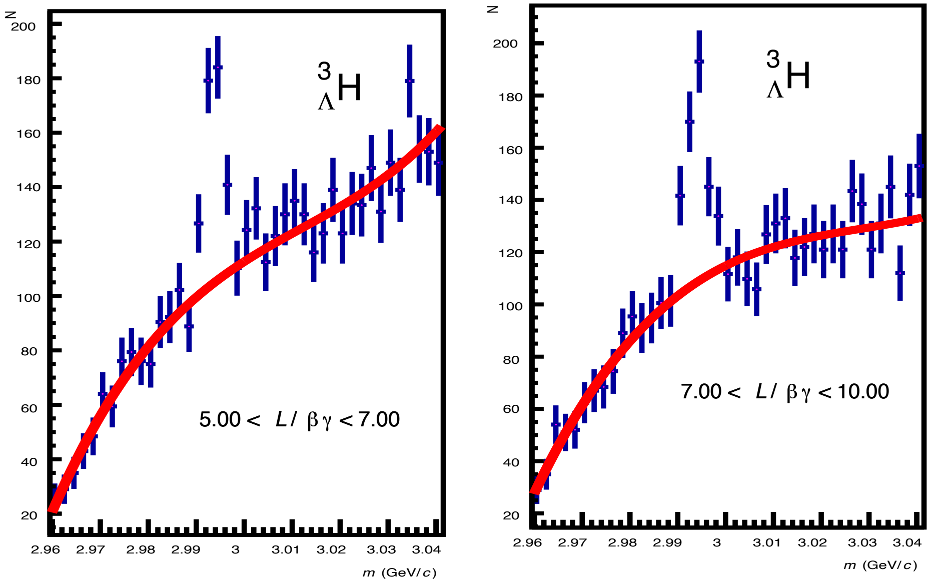
*E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993).

Lifetime measurement of $^{3}_{\Lambda}$H with CBM

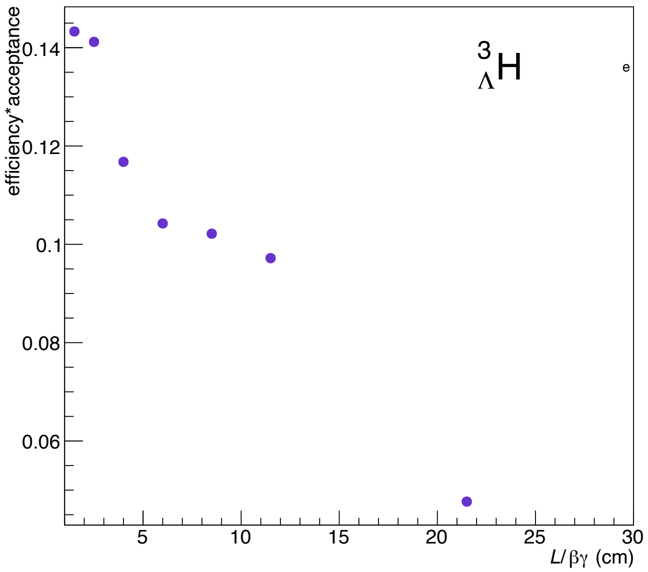
mass vs. L / βγ



mass spectra for L/βγ-bins



efficiency x acceptance



1. decay length L → after Lorentz-boost $\frac{L}{\beta\gamma}$
2. mass projections in $\frac{L}{\beta\gamma}$ -bins: calculation of dN/d$\left(\frac{L}{\beta\gamma}\right)$
   - Sum up signal in 3σ-mass-window
   - Fit background with polynomial function
   - Scale with efficiency

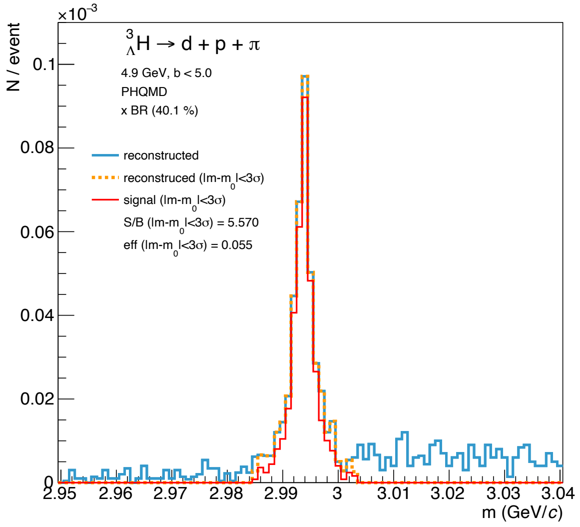
Reconstructed hypertritons in $\frac{\mathrm{L}}{\beta\gamma}$ -bin:

$$\frac{\mathrm{dN}}{d\left(\frac{L}{\beta\gamma}\right)} = \frac{\mathrm{N_{rec}} - \mathrm{bg}}{\mathrm{d}\left(\frac{L}{\beta\gamma}\right) \cdot \mathrm{eff} \cdot \mathrm{nevents}}$$

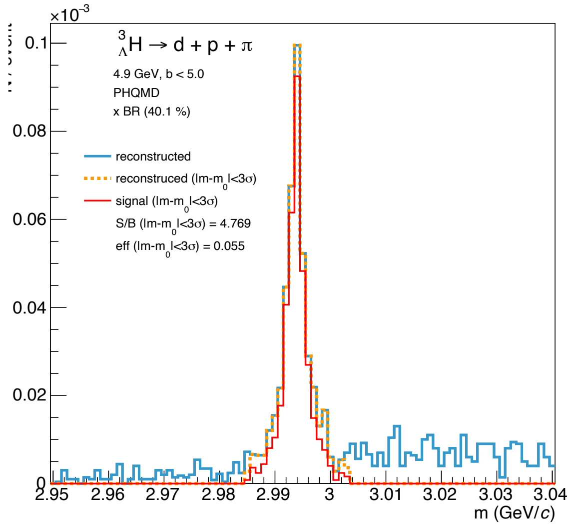
with efficiency: $$\mathrm{eff}\left(\frac{L}{\beta\gamma}\right) = \frac{\mathrm{N_{mc}}\left(\frac{L}{\beta\gamma}\right)}{N_{sim}^{tot} \cdot \mathrm{e}^{-\Delta\frac{\mathrm{L}}{\beta\gamma}\cdot\frac{1}{\mathrm{c\tau}}}}$$

Cut selection for systematic error estimation

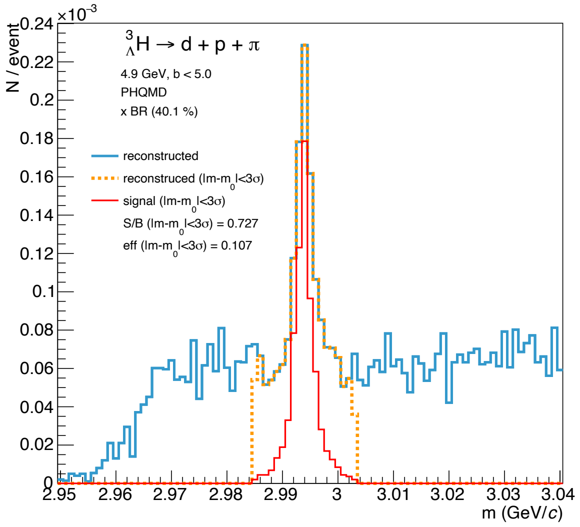
“optimized”



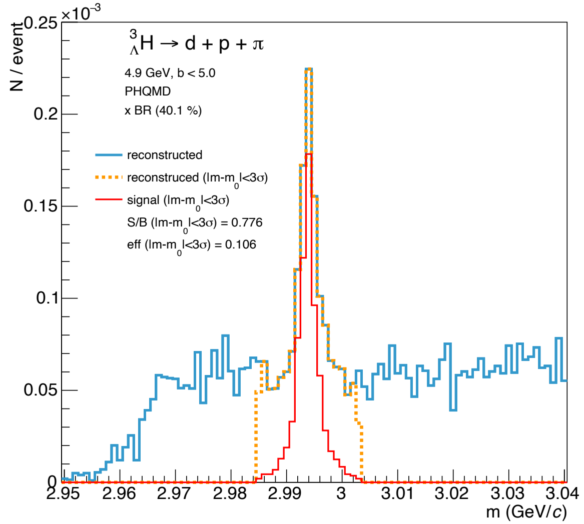
variation 2



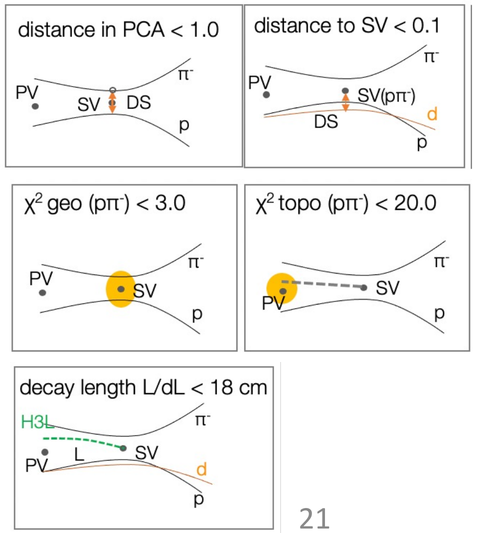
“optimized” incl. tracks w/o tof id



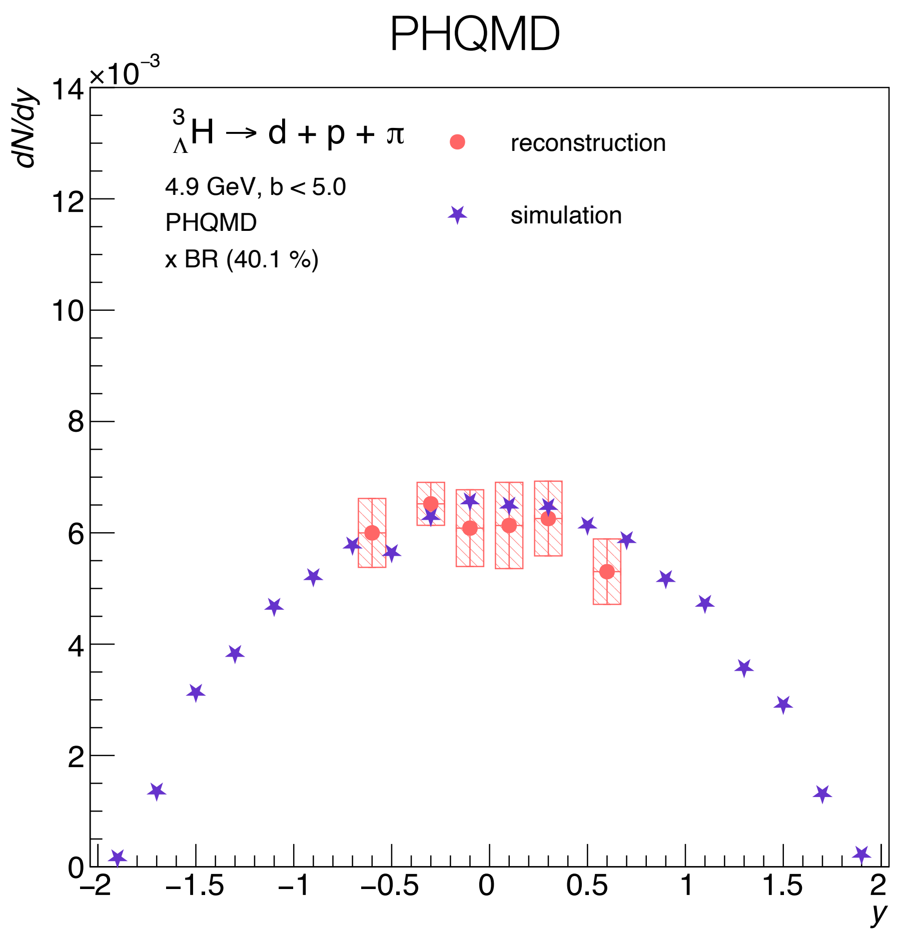
variation 2 incl. tracks w/o tof id



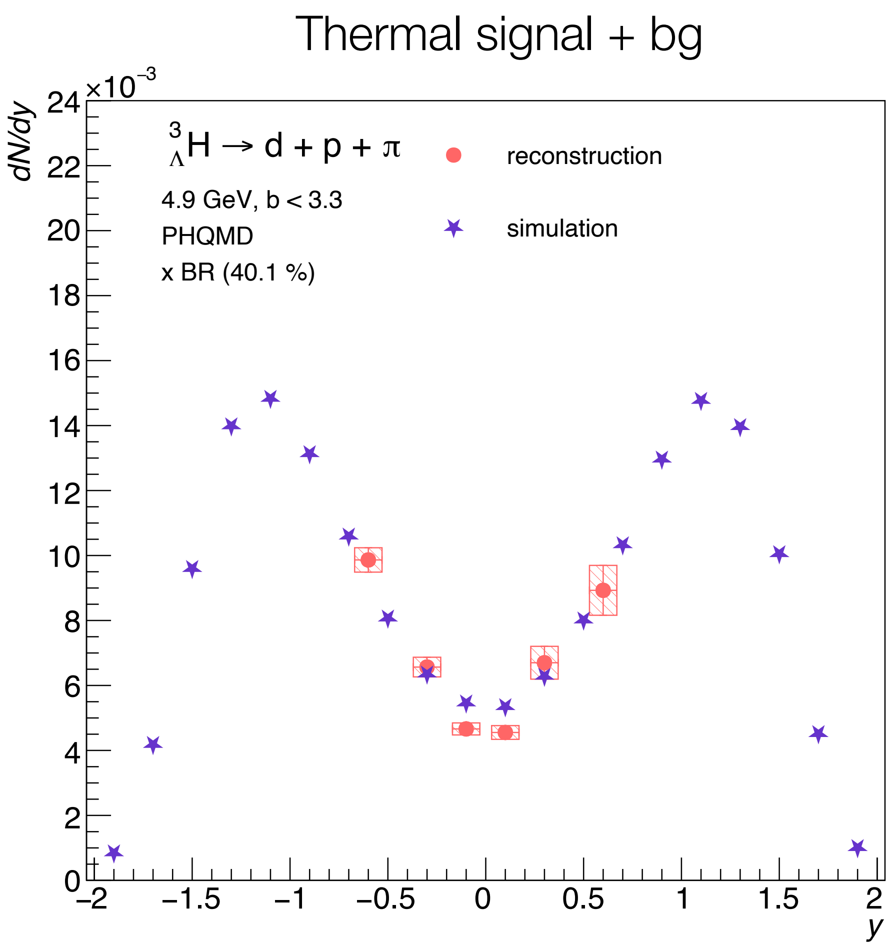
	“optimized”	variation 2	“optimized” w/ tr w/o tof id	variation 2 w/ tr w/o tof id
χ^2 to PV p/π/d	40/90/10	40/90/10	40/90/10	40/90/10
distance p & π	1.0	1.0	1.0	1.0
distance d to SV	0.1	0.1	0.1	0.1
χ^2 geo p-π-mother	3.0	3.0	3.0	3.0
χ^2 topo p-π-mother	20.0	5.0	20.0	5.0
decaylength L/dL	18.0	18.0	18.0	18.0
efficiency	0.055	0.055	0.107	0.106
s/b ratio	5.570	4.769	0.727	0.776



Total systematic error for $^{3}_{\Lambda}H$ y-spectra



Systematic error most bins ~ 10%
maximum = 12.6 %.

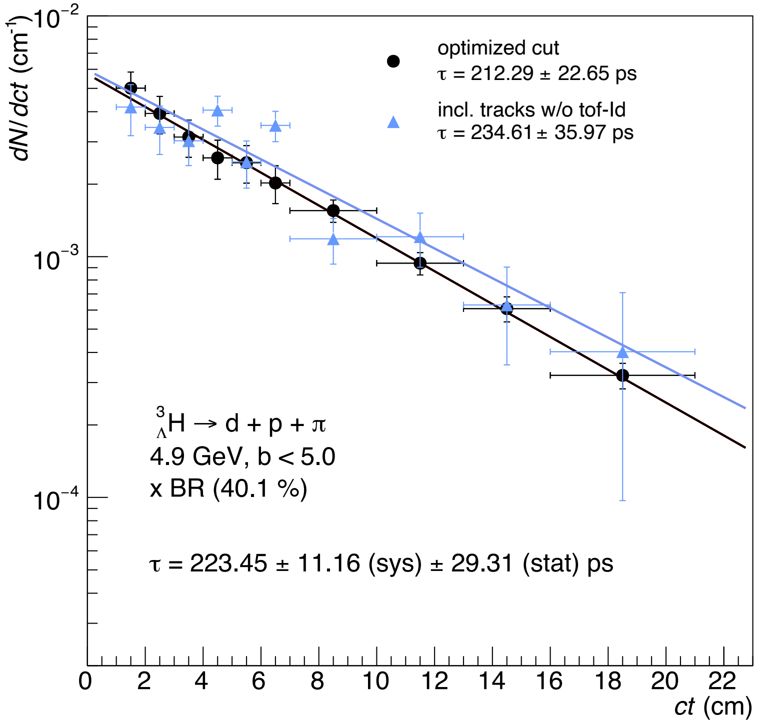


Systematic error most bins ~ 4%
maximum = 8.6 %.

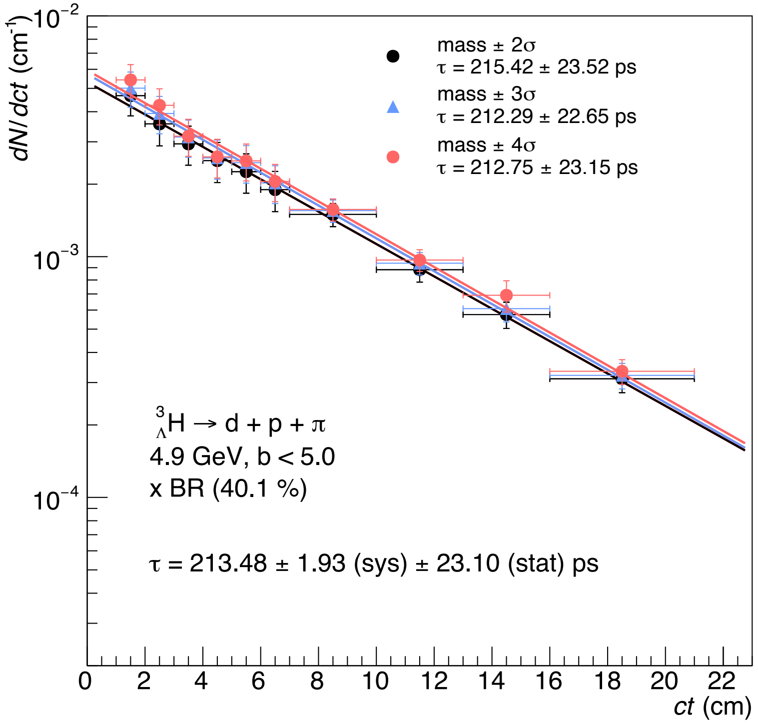
Lifetime measurement systematic error: different contributions

Exampes:

Cut variations
for thermal signal + bg



Mass cut variations ($m \pm n^*\sigma$)
for thermal signal + bg



Thermal + phqmd
for optimized cut