Search for anti-^{4}Li

and scouting on ^{3}He-p correlation function

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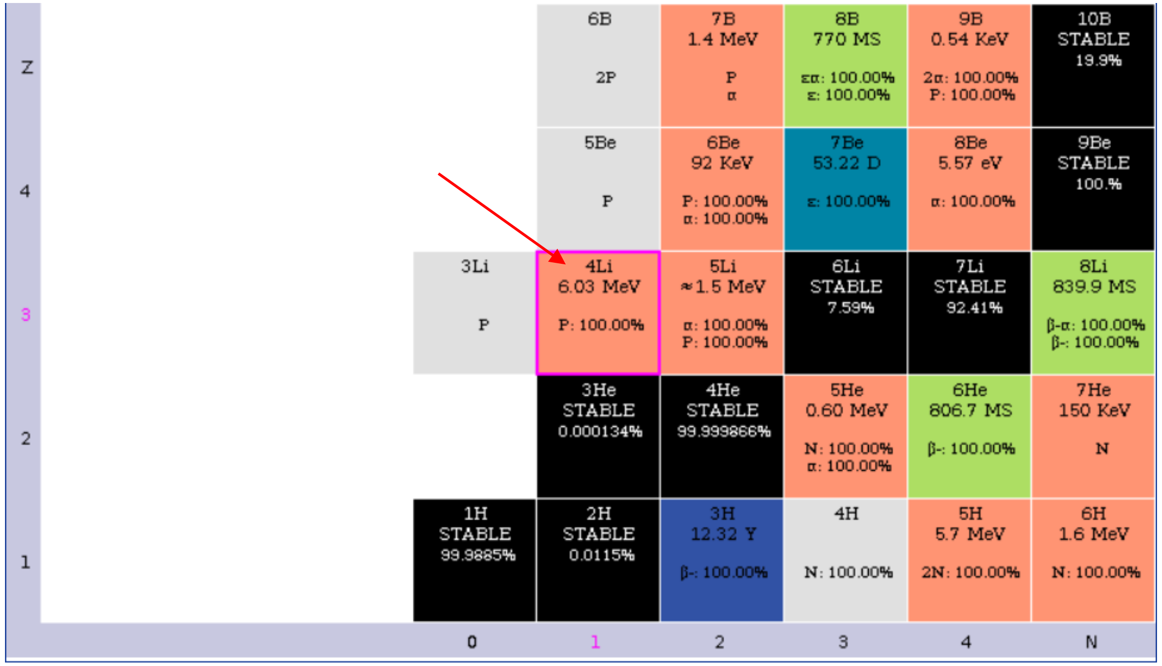
(Anti)Li-4

^{4}Li
Mass = 3749.76 MeV
Binding energy = 4.62 MeV
$J^P = 2^-$
Extremely unstable (Γ = 6 MeV)
$^4\mathrm{Li} \rightarrow {}^3\mathrm{He} + p$ (B.R. = 100%)

^{4}Li was first discovered in 1965, **PRL 15 (1965) 300**
More recently it was observed in:

- ^{40}Ar-induced reactions on ^{197}Au at E/A =60 MeV by measuring ^{3}He-p **correlation function**
  J. Pochodzalla et al. PRC 35 (1987) 1695
- 11.5A GeV/c Au-Pt at E864 (BNL-AGS) by measuring ^{3}He-p **invariant mass**
  T. A. Armstrong et al. PRC 65 (2002) 014906

Courtesy https://www.nndc.bnl.gov/nudat2/



Ground and isomeric state information for $^4_3$Li

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	2-	25.3231	6.03 MeV	p : 100.00 %

Antimatter partner ($^4\overline{\mathrm{Li}}$) has never been observed → we *might* have a chance to see it in ALICE

In this work the ^{3}He-p invariant mass technique has been used
Then I also looked at the ^{3}He-p correlation function (first look in slide 19)

Further motivation

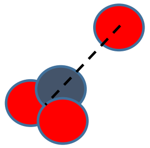
Both at LHC and RHIC the answer to the question if nuclei are produced only as a result of final-state interactions between nucleons (**Coalescence**) or also thermally in the fireball (**Thermal** model)

One issue is that Coalescence and Thermal models give similar predictions

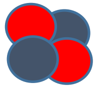
^{4}Li could be an exception. In **Mod. Phys. Lett. A 33 (2018) 25, 1850142** the authors proposed to measure the ^{4}Li/^{4}He ratio to probe the two models

In thermal models

$$\frac{{}^4\mathrm{Li}}{{}^4\mathrm{He}} \approx \frac{2J_{^4\mathrm{Li}}+1}{2J_{^4\mathrm{He}}+1} = \mathbf{5}$$



^{4}Li
Mass = 3749.76 MeV
Binding energy = 4.62 MeV
$J^P = 2^-$
R ≈ 2.5-3 fm



^{4}He
Mass = 3727.38 MeV
Binding energy = 28.3 MeV
$J^P=0^+$
R = 1.68 fm

Warning: additional complication may come from Li4 excited states
https://www.nndc.bnl.gov/nudat2/

Central PbPb: **R_s** (7 fm) from pions.
Here **protons (4 fm) are more appropriate**
See ALICE, PRC 92 (2015) 054908

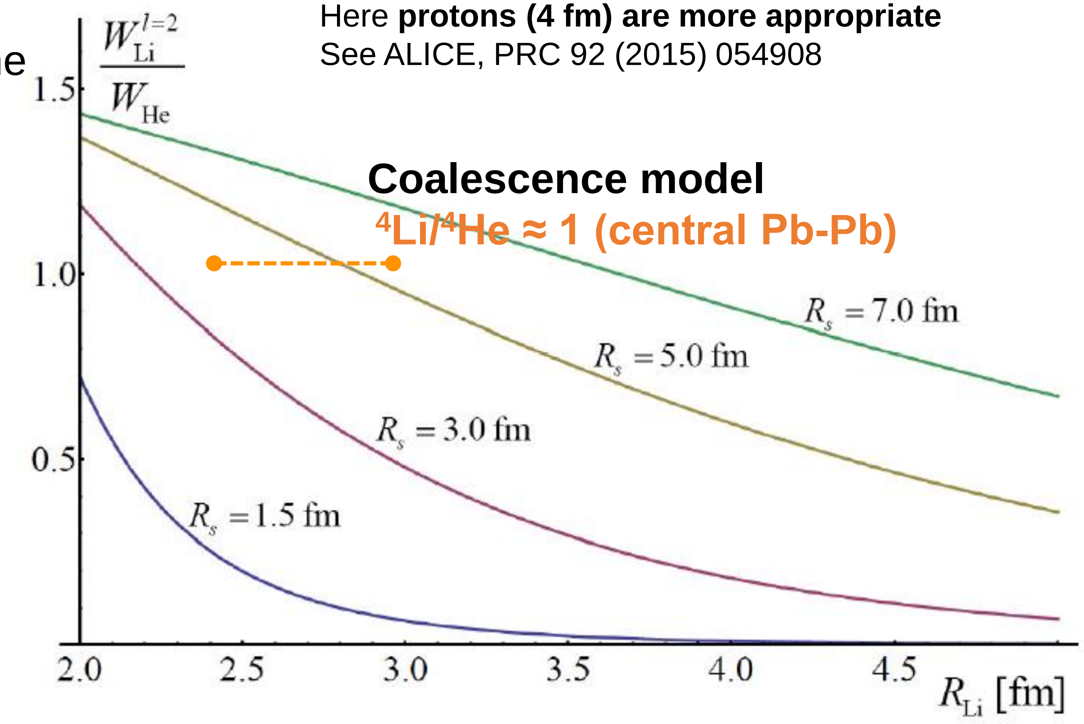


FIG. 1: The ratio of formation rates of ^{4}Li in $l = 2$ state and ^{4}He as a function of R_{Li} for four values of $R_s = 1.5,\ 3.0,\ 5.0$ and 7.0 fm.

S. Bazak and S. Mrowczynski, Mod. Phys. Lett. A 33 (2018) 25, 1850142

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How many (anti)Li-4 may we expect to count in ALICE?
(0-10% centrality)

Coalescence ($^{4}\overline{\mathrm{Li}}^{l=2}$)
$^{4}\overline{\mathrm{Li}}^{l=1} = 5/2\ ^{4}\overline{\mathrm{Li}}^{l=2}$

proton efficiency needs to be estimated with MC. Value taken from π/k/p analysis in Pb-Pb (p_T>0.6 GeV, TPC only)

$$^{4}\overline{\mathrm{Li}}^{raw} = \frac{^{4}\overline{\mathrm{Li}}^{raw}}{^{3}\overline{\mathrm{He}}^{raw}}\ ^{3}\overline{\mathrm{He}}^{raw} = \frac{^{4}\overline{\mathrm{Li}}\ \varepsilon_{^{3}\overline{\mathrm{He}}}\ \varepsilon_{\overline{\mathrm{p}}}}{^{3}\overline{\mathrm{He}}\ \varepsilon_{^{3}\overline{\mathrm{He}}}}\ ^{3}\overline{\mathrm{He}}^{raw} = \frac{^{4}\overline{\mathrm{Li}}}{^{3}\overline{\mathrm{He}}}\ ^{3}\overline{\mathrm{He}}^{raw}\ \varepsilon_{\overline{\mathrm{p}}} = \frac{^{4}\overline{\mathrm{Li}}}{^{4}\overline{\mathrm{He}}}\ \frac{^{4}\overline{\mathrm{He}}}{^{3}\overline{\mathrm{He}}}\ ^{3}\overline{\mathrm{He}}^{raw}\ \varepsilon_{\overline{\mathrm{p}}} \approx \begin{cases} 29, & \text{if } ^{4}\overline{\mathrm{Li}}/^{4}\overline{\mathrm{He}} = \mathbf{1} \text{ and } \varepsilon_{\overline{\mathrm{p}}} = 0.7 \\ 145, & \text{if } ^{4}\overline{\mathrm{Li}}/^{4}\overline{\mathrm{He}} = \mathbf{5} \text{ and } \varepsilon_{\overline{\mathrm{p}}} = 0.7 \end{cases}$$

Thermal model

$^{4}\overline{\mathrm{He}}$ / $^{3}\overline{\mathrm{He}}$ = 0.003 (i.e. 1/penalty factor)

$^{3}\overline{\mathrm{He}}^{raw} \approx$ 14000 from this analysis, see slide 8

This expression is just for having a rough estimation, it is not a precise determination

Event sample

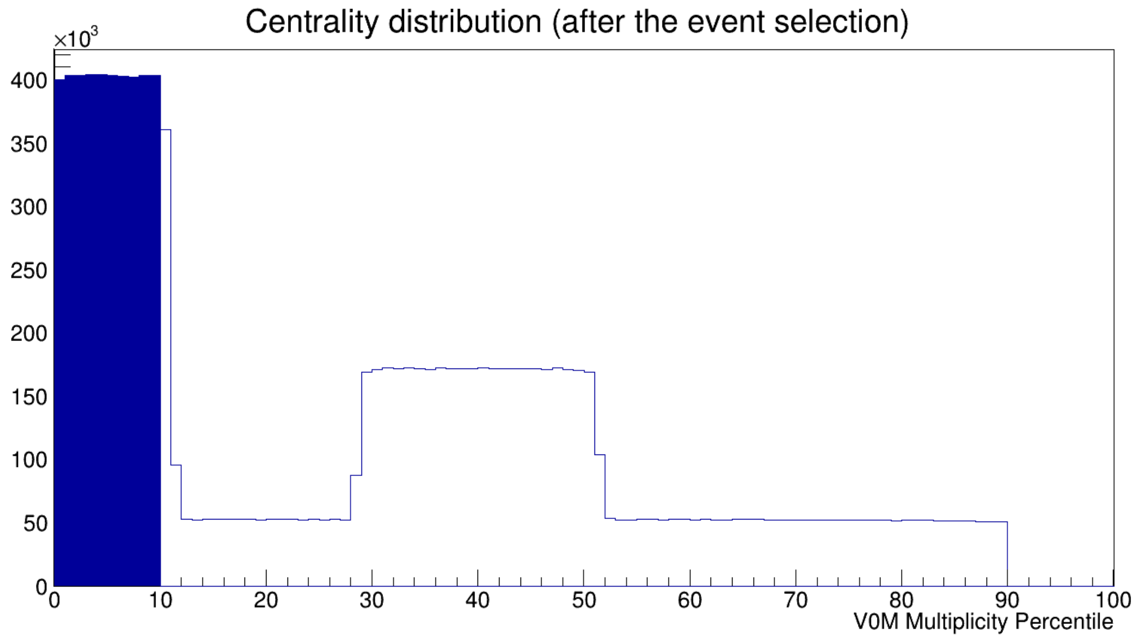
Full Pb-Pb 2018 statistics
(ESDs LHC18q+r pass1, DPG “Hadron PID” run list)

Analysis task runs only on a list of Chunks already filtered for (anti)He3
List in https://alice.its.cern.ch/jira/browse/ALIROOT-8432 (prepared by Max & Alexander, was great to have)
(filtered via PWGLF/NUCLEX/Utils/ChunkFilter/AliAnalysisTaskFilterHe3.cxx)

Events selected simply by `AliEventCuts::AcceptEvent`

In the following slides I show only results in **0-10% centrality**

I have also results on 0-90% centrality (slide 16)



Track cuts and PID

Track cuts	
GetStandardITSTPCTrackCuts2011(kFALSE, kTRUE)	ON
DCAxy(z)	< 0.1 cm
η	< 0.8

AliESDtrackCuts::GetStandardITSTPCTrackCuts2011(kFALSE, kTRUE)	
TPC crossed rows	> 70
TPC crossed rows / find. clusters	> 0.8
X^2 / TPC cluster	< 4
TPC refit	TRUE
SPD rec. points	≥ 1
X^2 / ITS cluster	< 36
ITS refit	TRUE

PID	
protons	
|nσTPC|	< 3
|nσTOF| (if TOF available)	< 3
He3	
|nσTPC|	< 3
dE/dx	> 150
|nσTOF| (if TOF available)	< 3

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protons	
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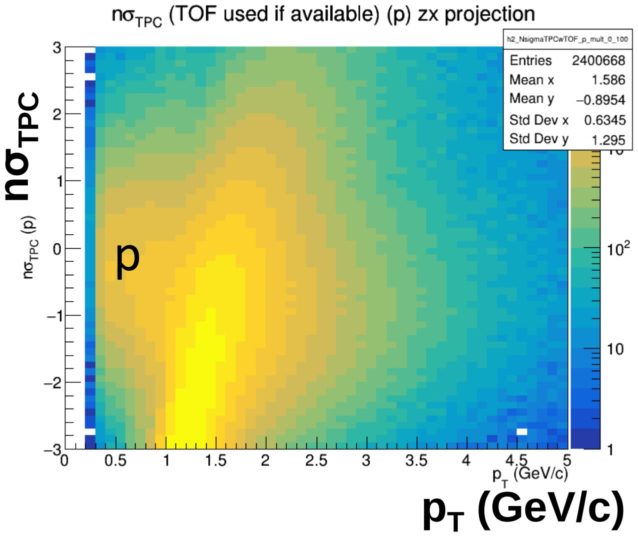
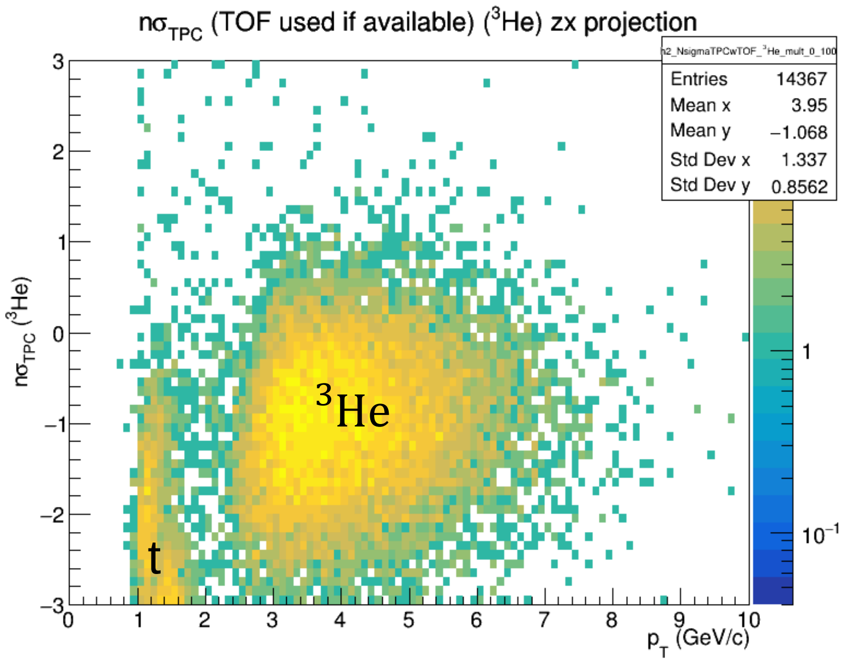
He3	
|nσTPC|	< 3
dE/dx	> 150
|nσTOF| (if TOF available)	< 3

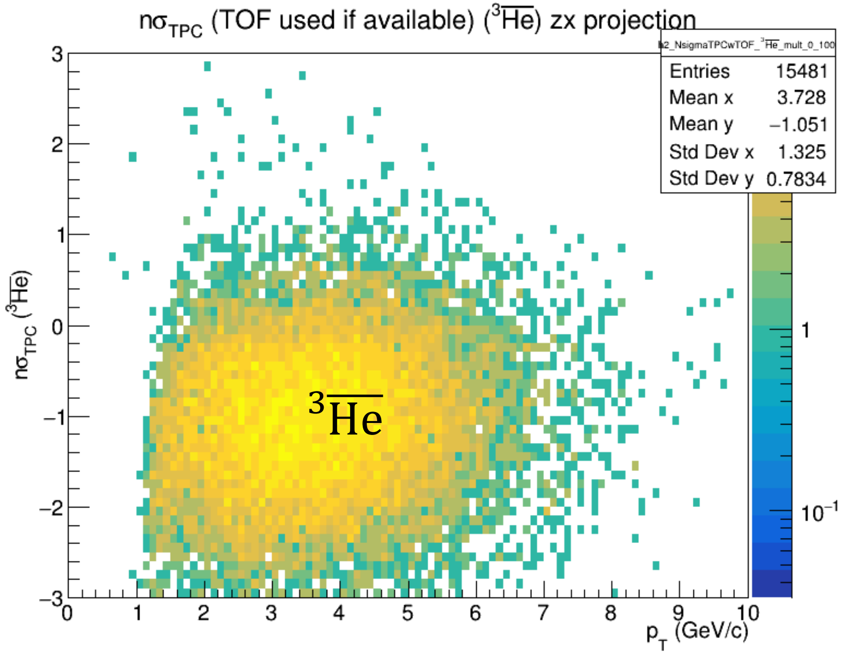


While I have a pure sample of He3 (see next slide), for protons I have huge contamination (at p_T>0.8 GeV) from pions and kaons

PID (He3)

PID	
He3	
$\|n\sigma TPC\|$	< 3
dE/dx	> 150
$\|n\sigma TOF\|$ (if TOF available)	< 3

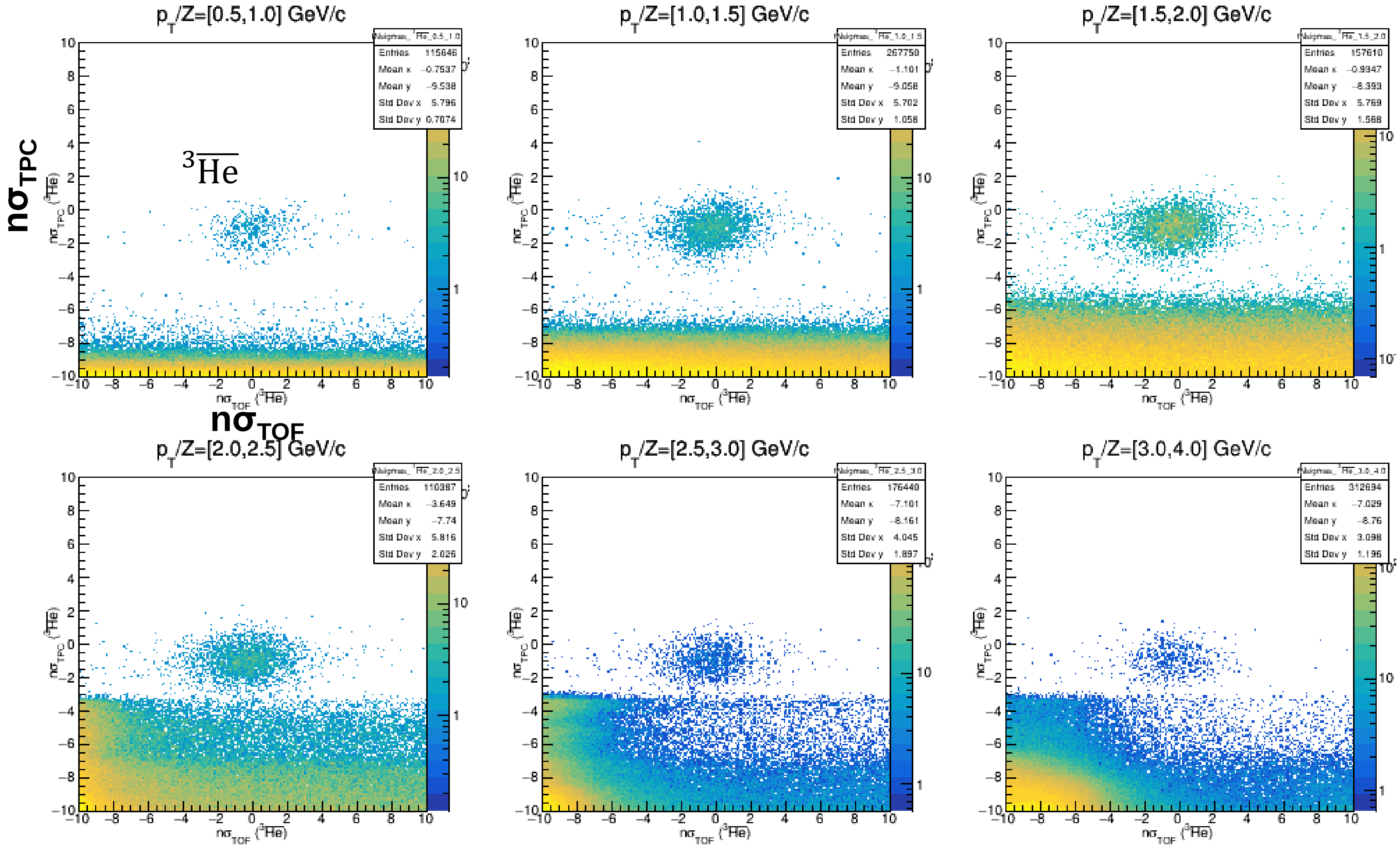




Counts	TPC	TPC+TOF (if available)	TPC+TOF (mandatory)
He3	15982	14387	7745
antiHe3	17340	15481	7492

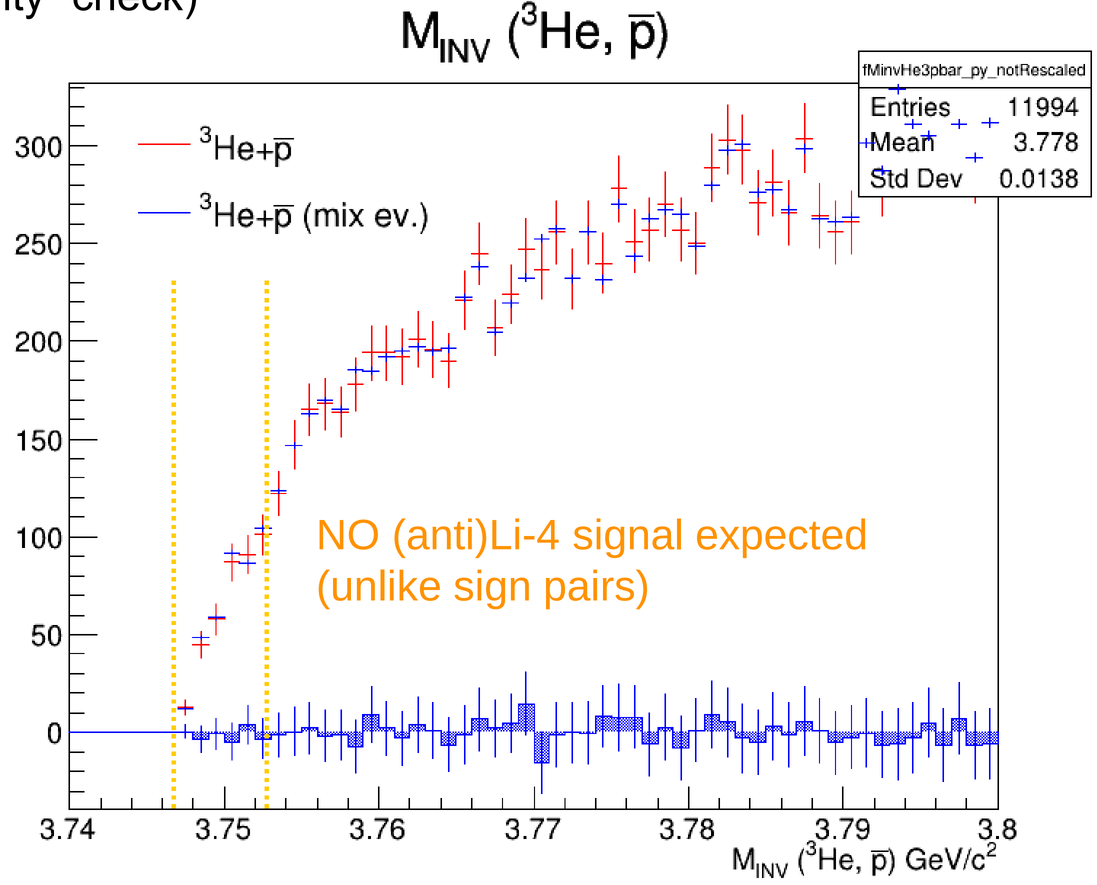
For each He3 found, I fill a tree entry with the array of protons (to "attach" to it) to reconstruct the invariant mass…

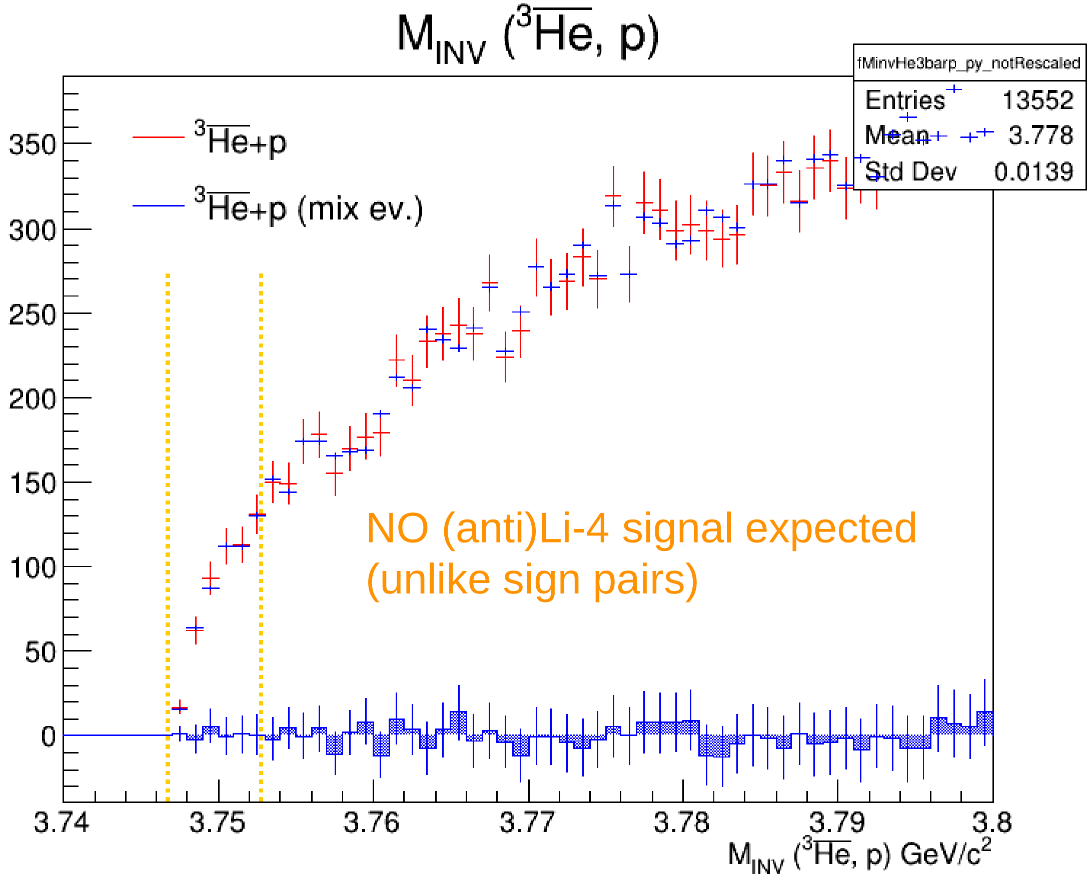
nσTOF ($^3\overline{\mathrm{He}}$)



Unlike sign pairs

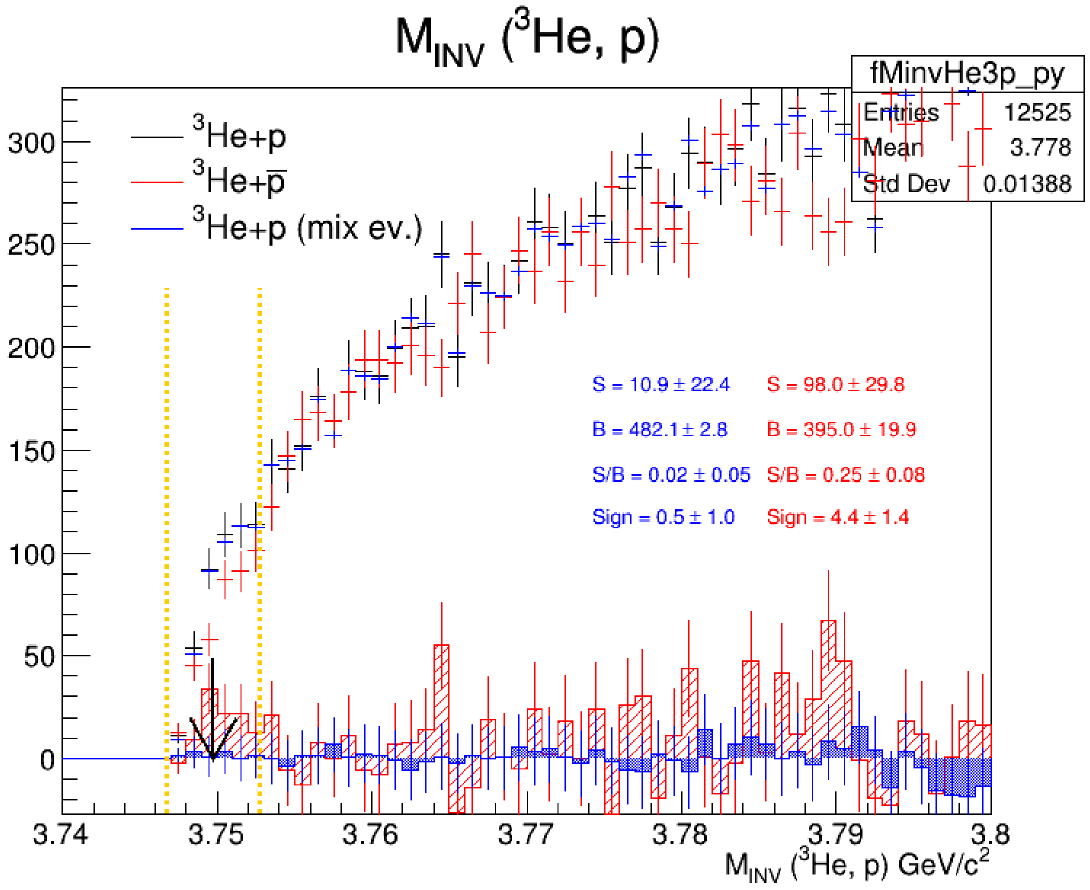
($He3$, $\bar{p}$) and ($^{3}\overline{\mathrm{He}}$, p) are uncorrelated pairs i.e. where I do NOT expect the Li4 signal.
I used them to check that the background estimated from those pairs and mixing events (from like sign pairs) is the same (“sanity” check)

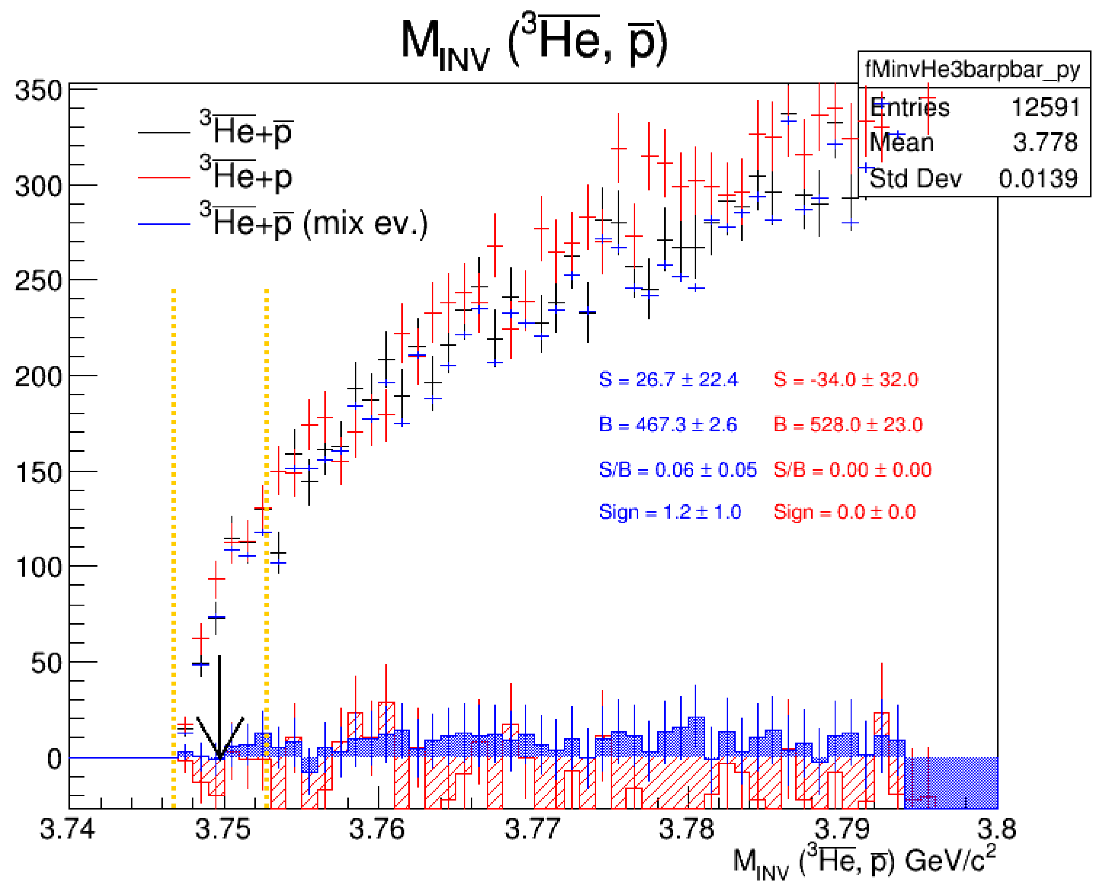




Ok, the background seems quite under control
Event mixing distribution renormalized using the integral (in the shown Minv range)

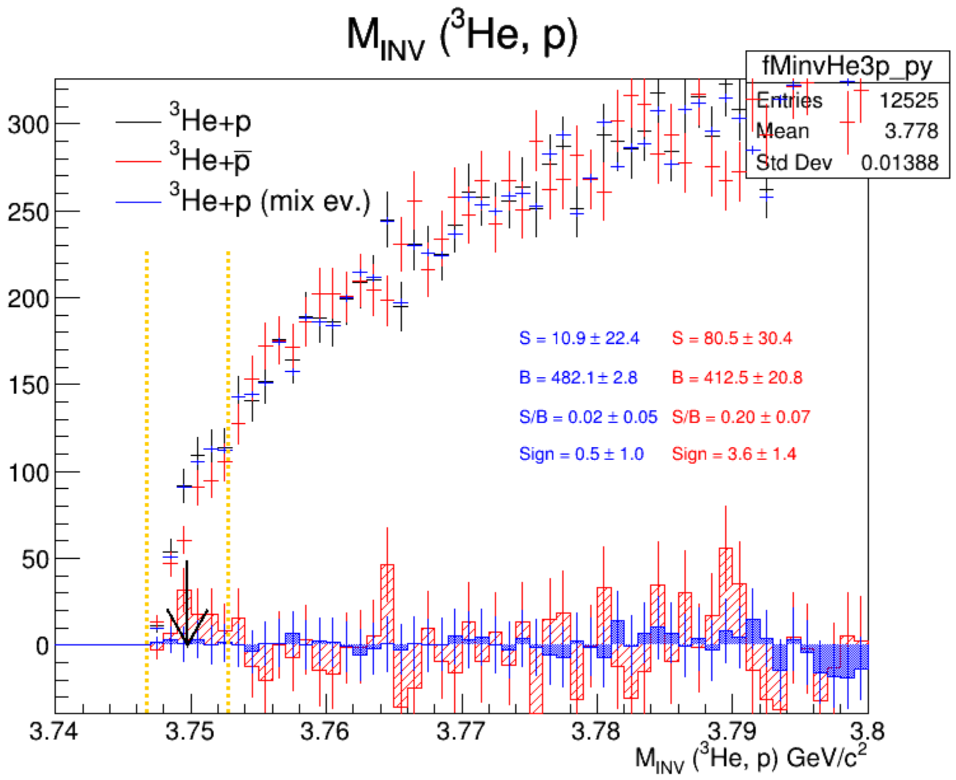
Like sign pairs

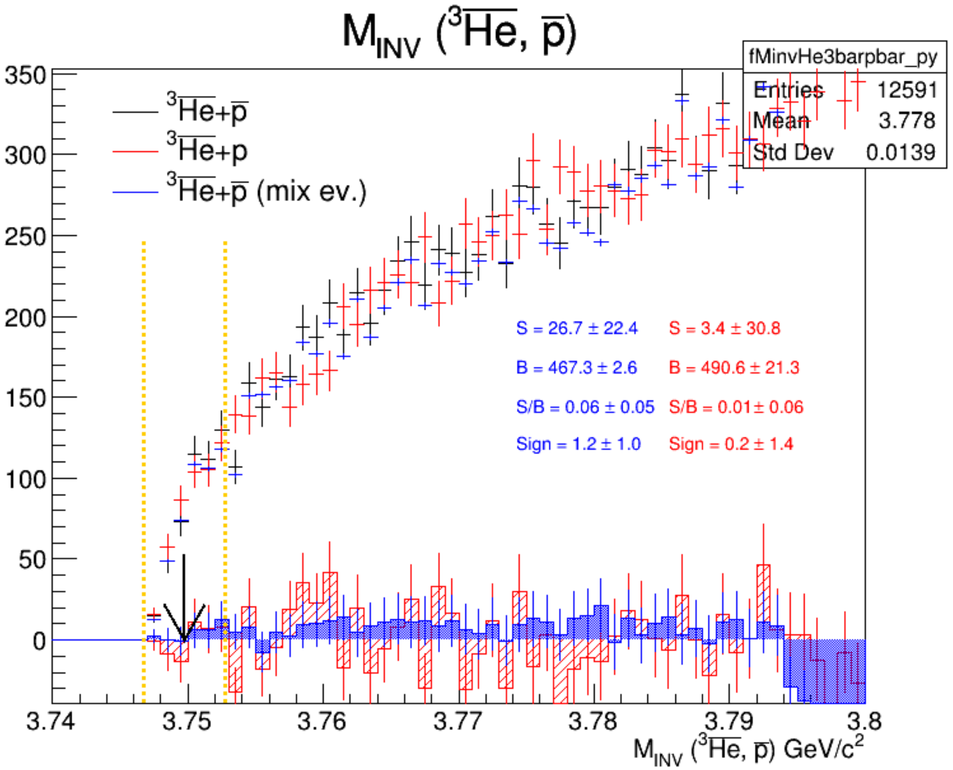




- **No evidence for (anti)Li-4 signal**
- Since I count more protons than antiprotons (see slide 14), I rescale also the unlike sign background using integral (in the shown Minv range) on the following slides
- Signal and background (see coloured text in the plot) estimated just by counting entries (as a “1st order approximation”)

Like sign pairs

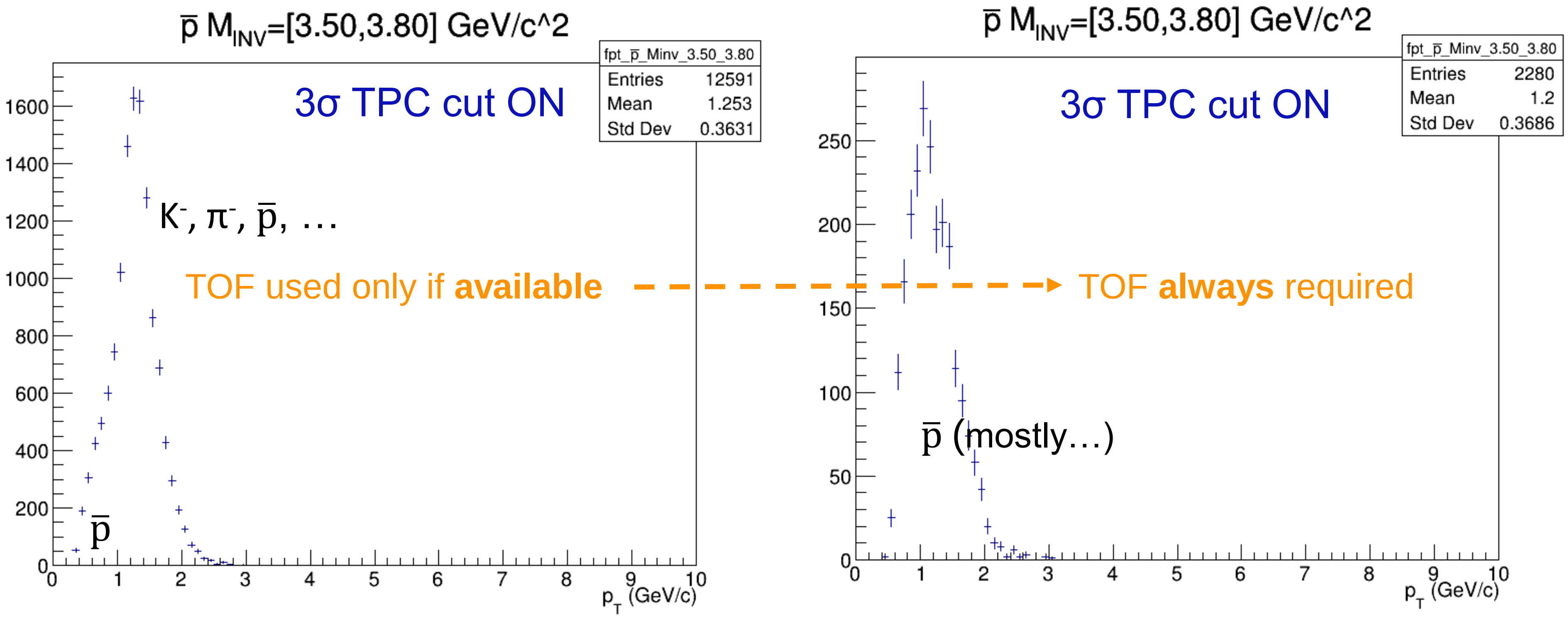




PID	
protons	
|nσTPC|	< 3
|nσTOF| (if TOF available)	< 3
He3	
|nσTPC|	< 3
dE/dx	> 150
|nσTOF| (if TOF available)	< 3

- No evidence for (anti)Li-4 signal (as previous slide, nothing new)
- **How soft are the protons which enter in these plots? Next slide**
- p_T slices on backup

(Anti)proton spectrum

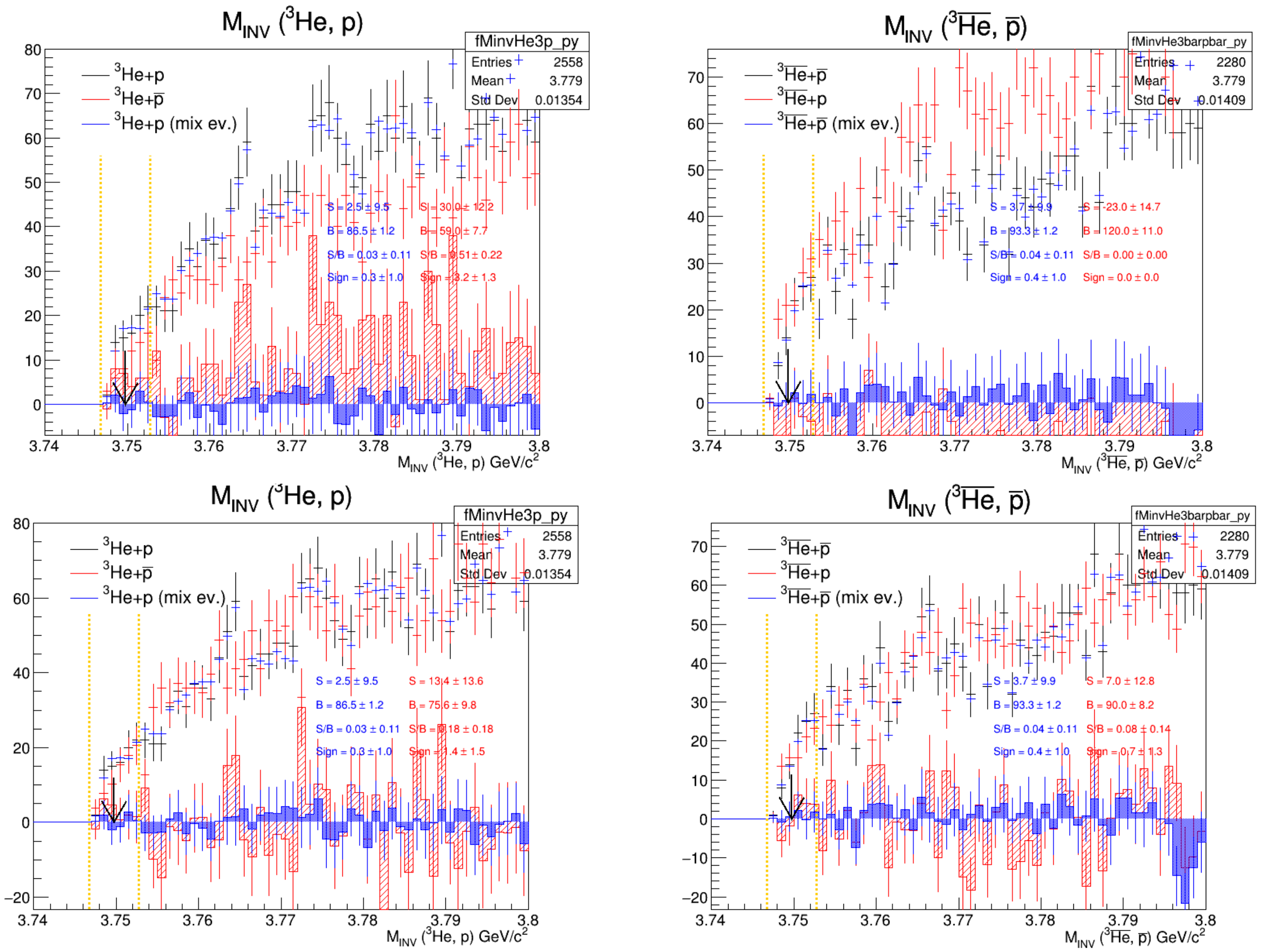


Then, I try to strictly require TOF PID (3σ) for (anti)protons (next slide)

Proton purity will significantly increase (the price to pay is a lower efficiency, to be estimated)

Like sign pairs (TOF always required for protons)

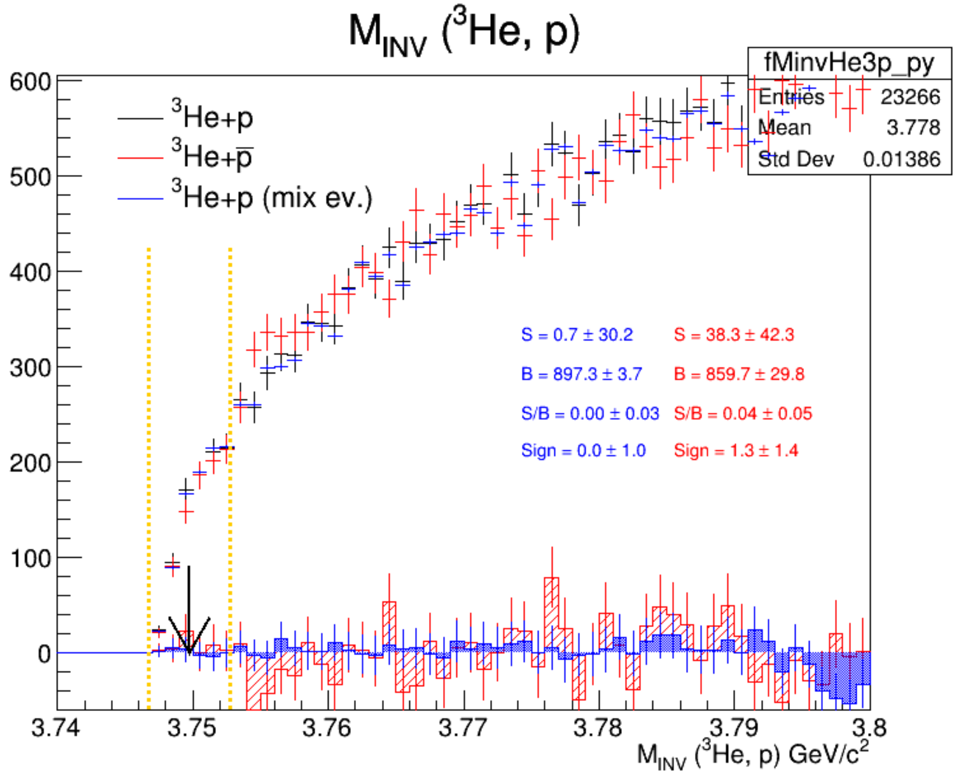
AFTER unlike sign bkg. renormalization

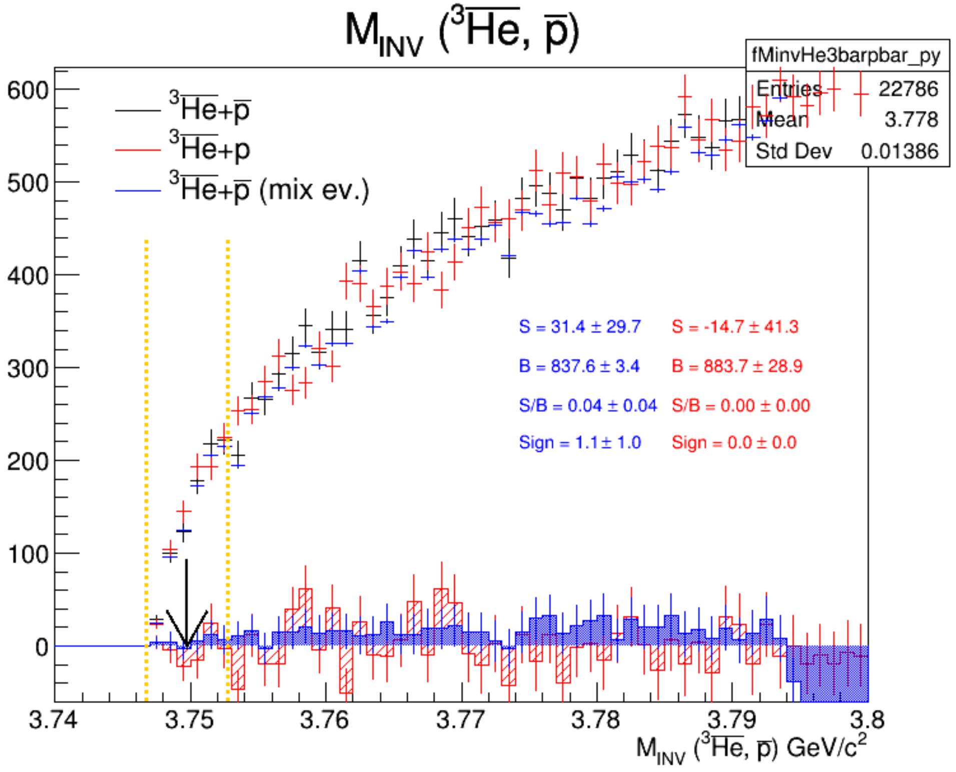


AFTER unlike sign bkg. renormalization

<table>
<tr><th>PID</th><th></th></tr>
<tr><td>protons</td><td></td></tr>
<tr><td>|nσTPC|</td><td>< 3</td></tr>
<tr><td>|nσTOF| <s>(if TOF available)</s></td><td>< 3</td></tr>
<tr><td>He3</td><td></td></tr>
<tr><td>|nσTPC|</td><td>< 3</td></tr>
<tr><td>dE/dx</td><td>> 150</td></tr>
<tr><td>|nσTOF| (if TOF available)</td><td>< 3</td></tr>
</table>

Like sign pairs (NO TOF info used for protons)





PID	
protons	
|nσTPC|	< 3
~~|nσTOF| (if TOF available)~~	~~< 3~~
He3	
|nσTPC|	< 3
dE/dx	> 150
|nσTOF| (if TOF available)	< 3

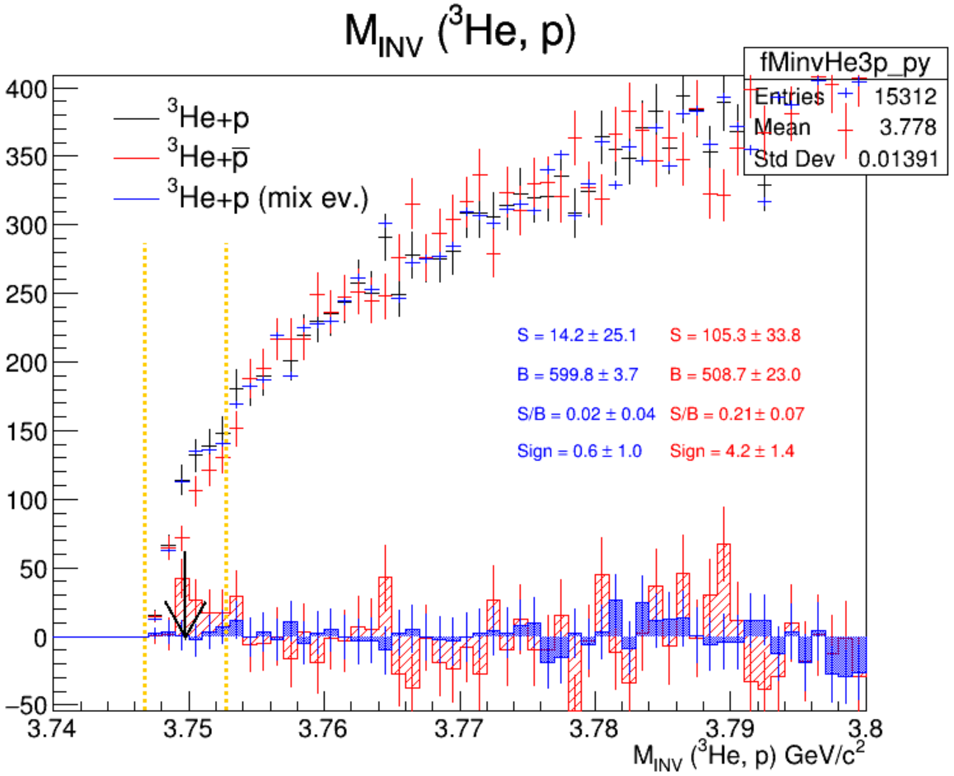
Rewording the Fermi paradox… “if there are so many Li4, where are all of them?!”

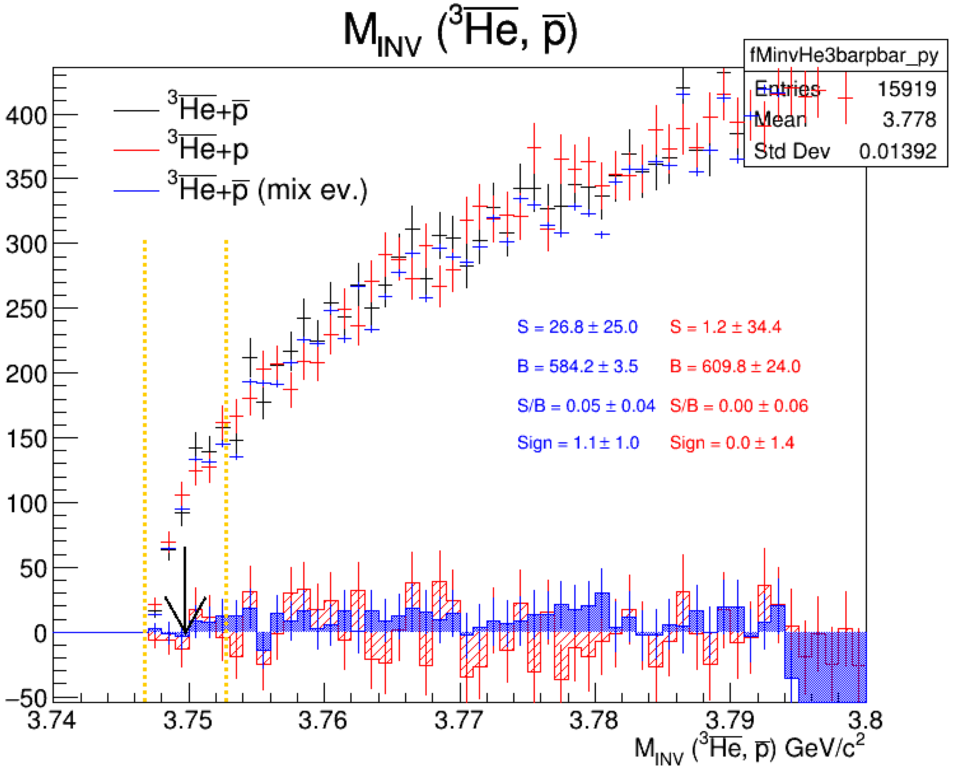
There is also the possibility (to verify) that we have no enough momentum resolution to see such a narrow (6 MeV) resonance (see Summary slide)

Like sign pairs **(0-90% centrality)**

Counts (raw)	0-10% centrality	**0-90% centrality**
$^{3}\overline{\mathrm{He}}$ (TPC+TOF if av.)	15481 →	23959

PID	
protons	
|nσTPC|	< 3
|nσTOF| (if TOF available)	< 3
He3	
|nσTPC|	< 3
dE/dx	> 150
|nσTOF| (if TOF available)	< 3





He3-p correlation function C(k*)

Both in

- S. Bazak and S. Mrowczynski, **arXiv:2001.11351v1** [Jan 2020]
- B-S Xi, Z-Q Zhang, S. Zhang and Y-G Ma, **arXiv:109.03157** [Sep 2019]

the authors proposed to search for $^{4}\overline{\mathrm{Li}}$ by studying the $^{3}\overline{\mathrm{He}}\text{-}\bar{\mathrm{p}}$ correlation function at small relative momenta

Correlation function is defined as follows:

$$C(\boldsymbol{k}^*) = \frac{A(\boldsymbol{k}^*)}{B(\boldsymbol{k}^*)}$$

→ He3-p pairs in the **same event**

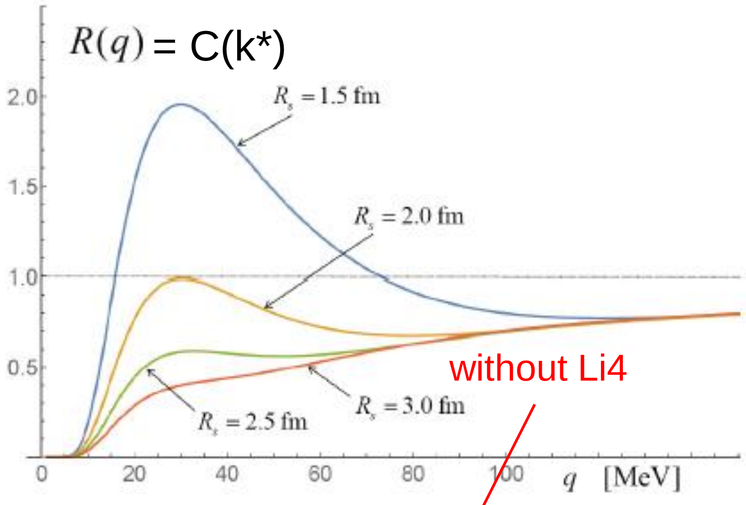
→ He3-p pairs from mixed events

$\boldsymbol{k}^* = \frac{1}{2}(\boldsymbol{p}_{\mathrm{He3}}\text{-}\boldsymbol{p}_{\mathrm{p}})$ in the *pair rest frame*

He3-p correlation function C(k*)

S. Bazak and S. Mrowczynski, **arXiv:2001.11351v1** [Jan 2020]

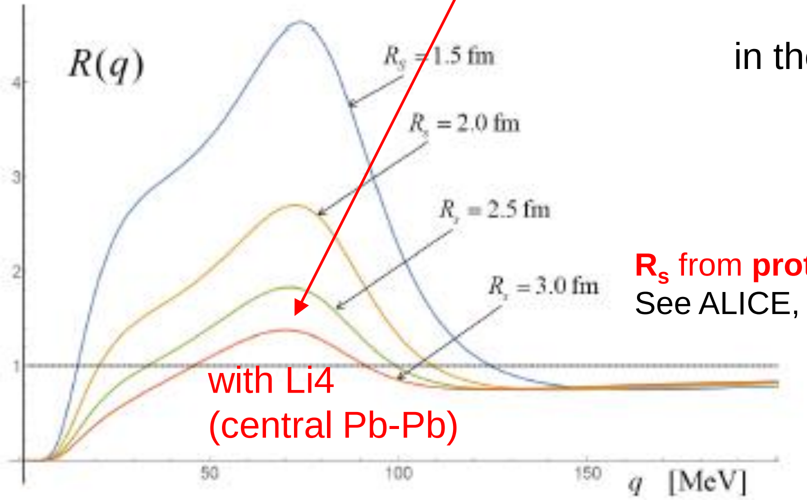
B-S Xi, Z-Q Zhang, S. Zhang and Y-G Ma, **arXiv:109.03157** [Sep 2019]



without Li4

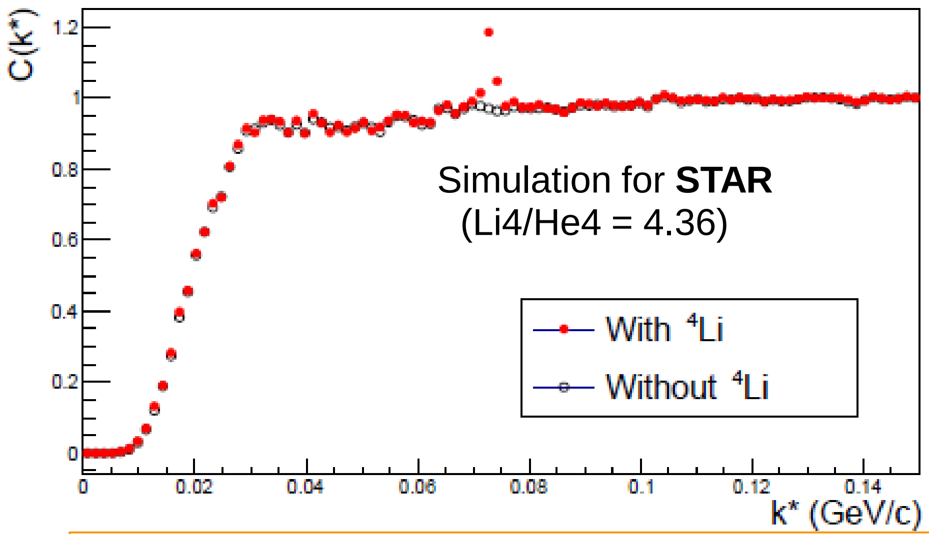
$$q = k^* = \frac{1}{2}\left(p_{He3}-p_{p}\right)$$

in the pair rest frame

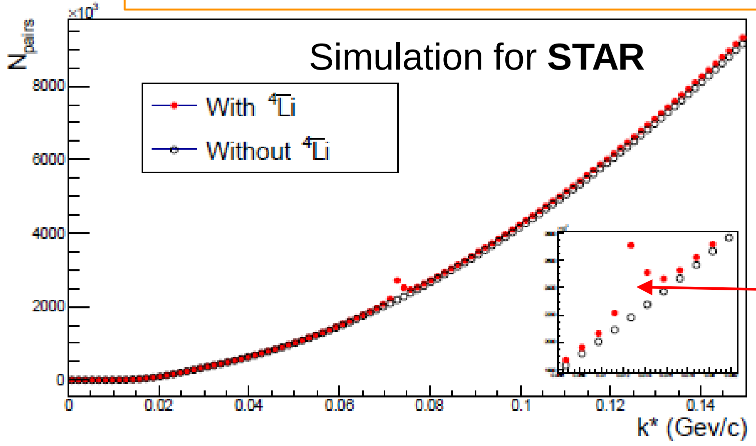


with Li4
(central Pb-Pb)

R_s from **protons** (4 fm in central PbPb)
See ALICE, PRC 92 (2015) 054908



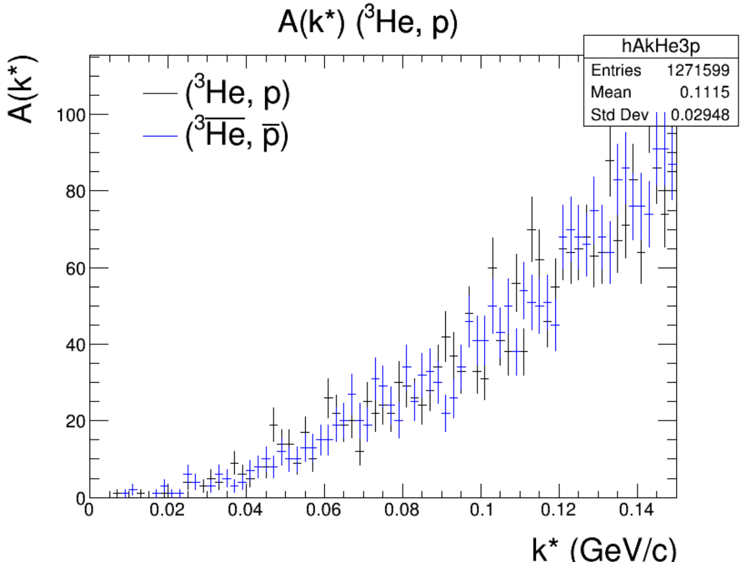
Yep, very different shape...

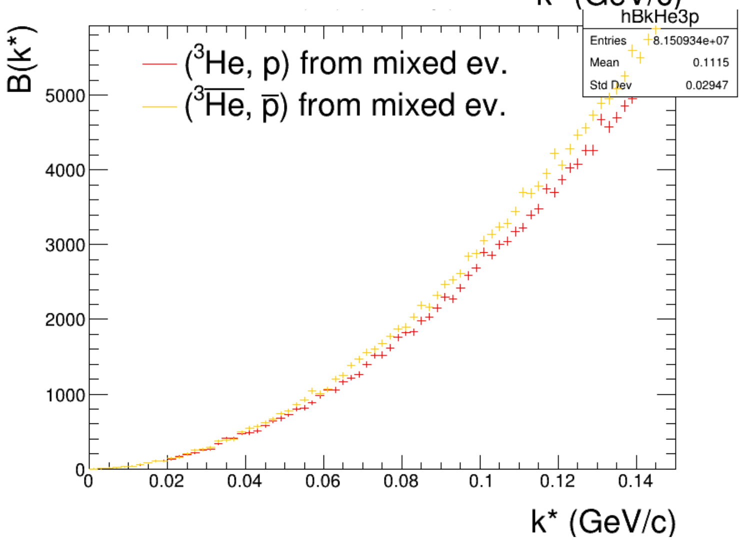


500k Li4 in input?!

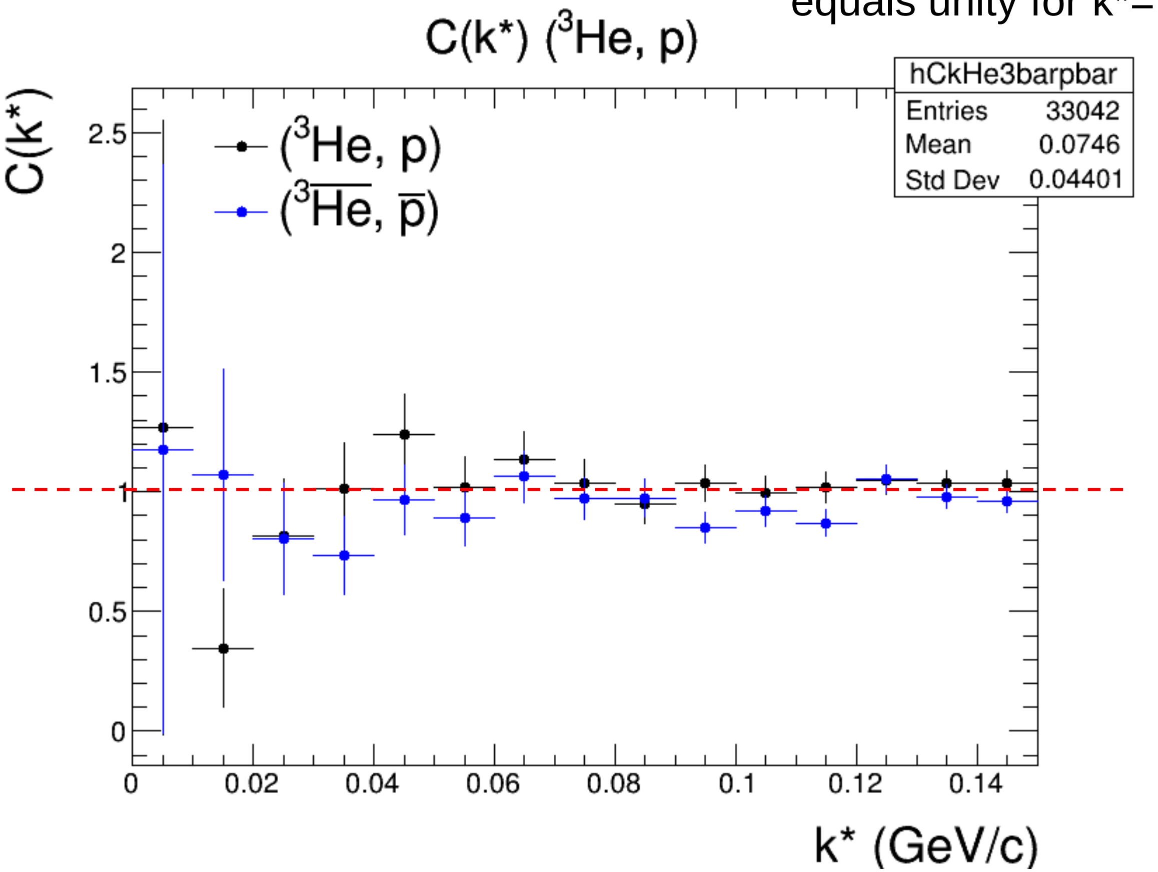
He3-p correlation function in ALICE (1st look)

- Independently on the Li-4 could be interested to have a look at He3-p CF



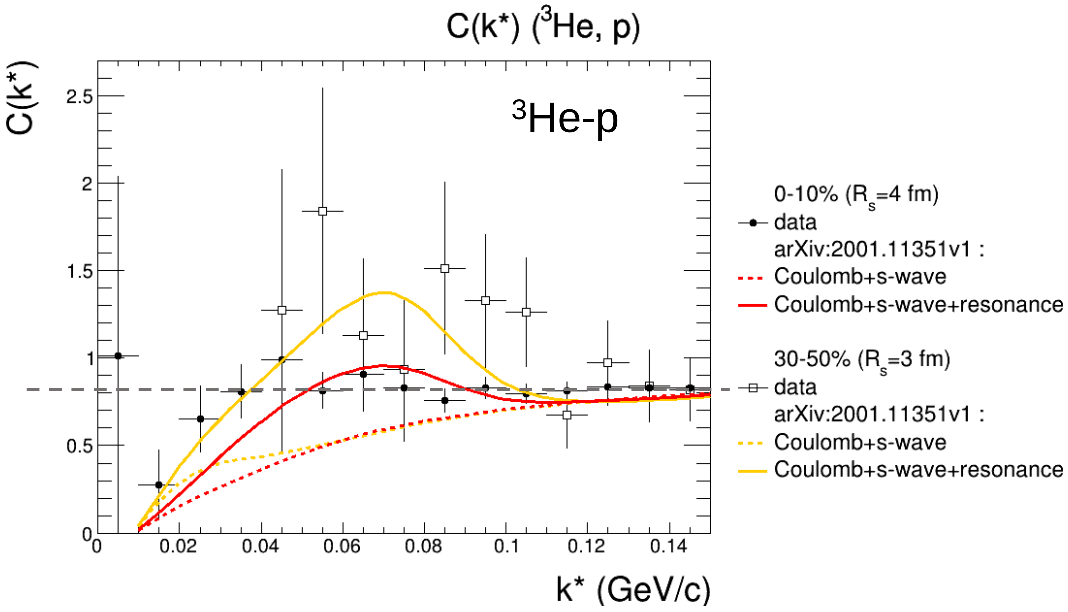


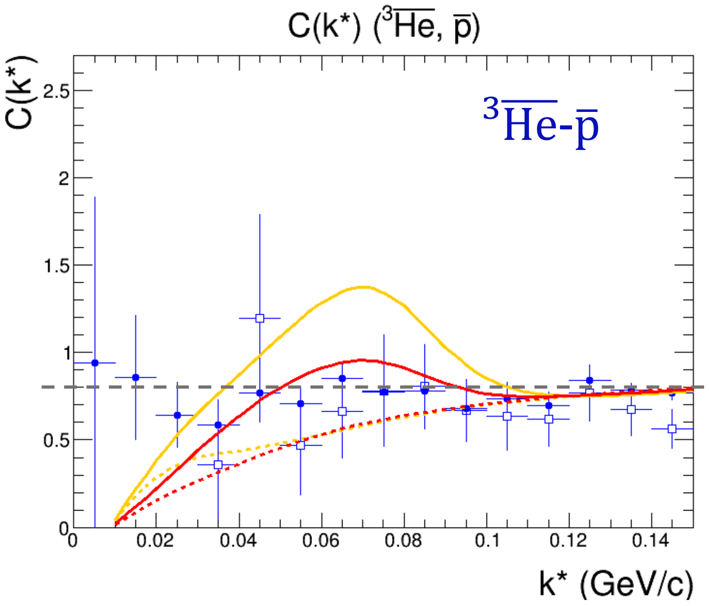
C(k*) renormalized such that equals unity for k*=[0.5, 1] GeV/c



- Too large stat. uncertainties for a physics message (low k* are relevant)

Do we see any (expected) centrality dependence?

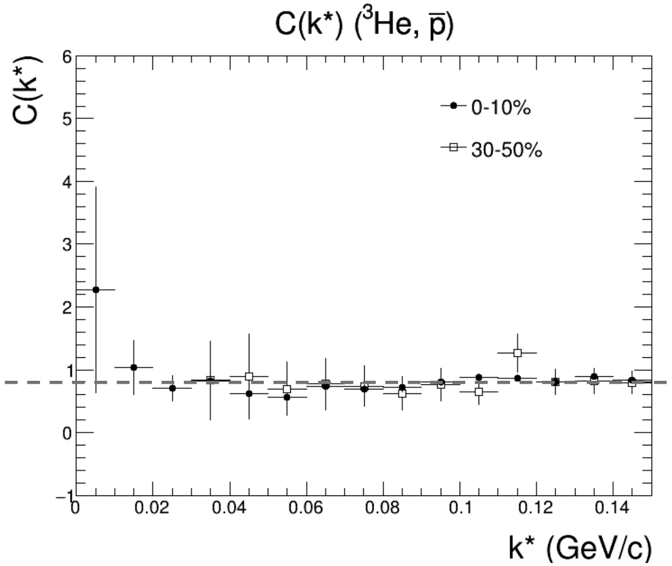


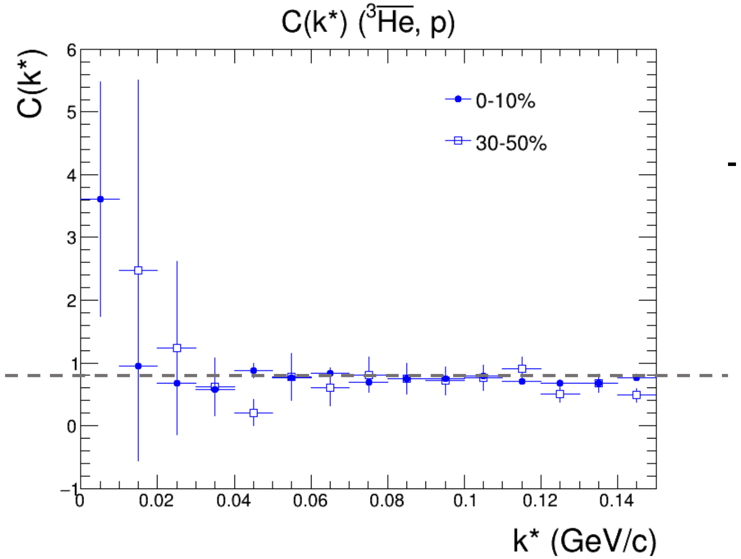


C(k*) renormalized such that they equal expectations (arXiv:2001,11351v1) at large where there is no correlation

- Speculations on for ^{3}He-p
  - centrality dependence
  - He3-p interaction (Coulomb repulsion at low k*)

- Interpretation got complicated with $^{3}\overline{\mathrm{He}}$-$\bar{\mathrm{p}}$ data. Argh…





- Unlike sign pairs (warning: larger Y axis)

Summary and outlook

[done] (Anti)Li4 has been searched in He3-p invariant mass
[done] He3-p correlation function has been measured (just scouting!)

What did we learn?

- (Anti)Li4 signal - if present - is not visible in Pb-Pb data
- Independently of Li4... stat. uncertainties are too large for constraining He3-p CF
  Future LHC runs could give us a better chance

Why I don't see (anti)Li4 signal?

- We have a too scarce momentum resolution? Indeed the resonance width - 6 MeV - is too narrow (but… in ALICE hadron resonances with similar widths like ϕ... are measured)
  → MC with injected Li4 (and if possible with a realistic Li4/He4 ratio) should answer

- Li4 - if produced - are too few → do we publish an upper limit (depending on the answer to A)?

Next steps:

- Further investigation on He3-p Minv (with MC) *to have a chance* to publish an upper limit (?)
- Other options I don't see?
- Possibity to refine the analysis

Backup

Li4 (NOT anti-Li4) in heavy-ion collisions

T. A. Armstrong et al. PRC 65 (2002) 014906
on 11.5A GeV/c Au-Pt at E864 (BNL-AGS)

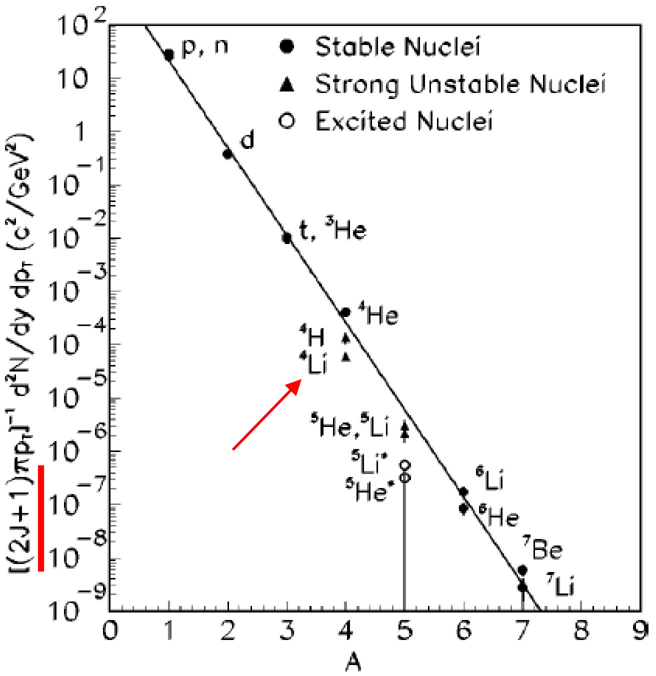


FIG. 9. Invariant multiplicities divided by $(2J+1)/2$ for stable and unstable nuclei in the range $1.8 \leq y \leq 2.0$. For the unstable nuclei and ^{6}He, $p_t/A \leq 400$ MeV/c. For the remaining nuclei, $p_t/A \leq 300$ MeV/c. The curve is an exponential fitted to the stable nuclei.

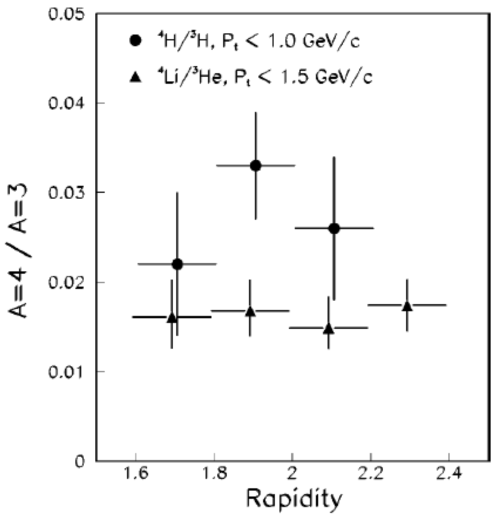


FIG. 5. Ratios of invariant multiplicities of $A=4$ unstable nuclei to invariant multiplicities of the heavy decay daughter species. Data points for different species are offset slightly from rapidity bin centers for clarity.

J. Pochodzalla et al. PRC 35 (1987) 1695
on ^{40}Ar-induced reactions on ^{197}Au at E/A =60 MeV

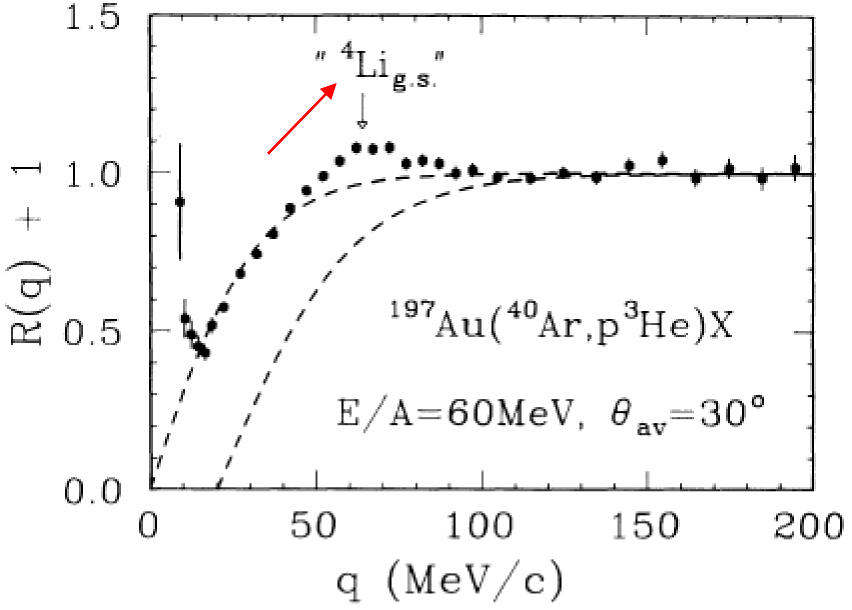


FIG. 6. p-^{3}He correlation function. The location of the "ground state" of ^{4}Li is marked by the arrow. The dashed lines are extreme bounds for the background correlation function.

Source radius (R_s)

ALICE, PRC 92 (2015) 054908

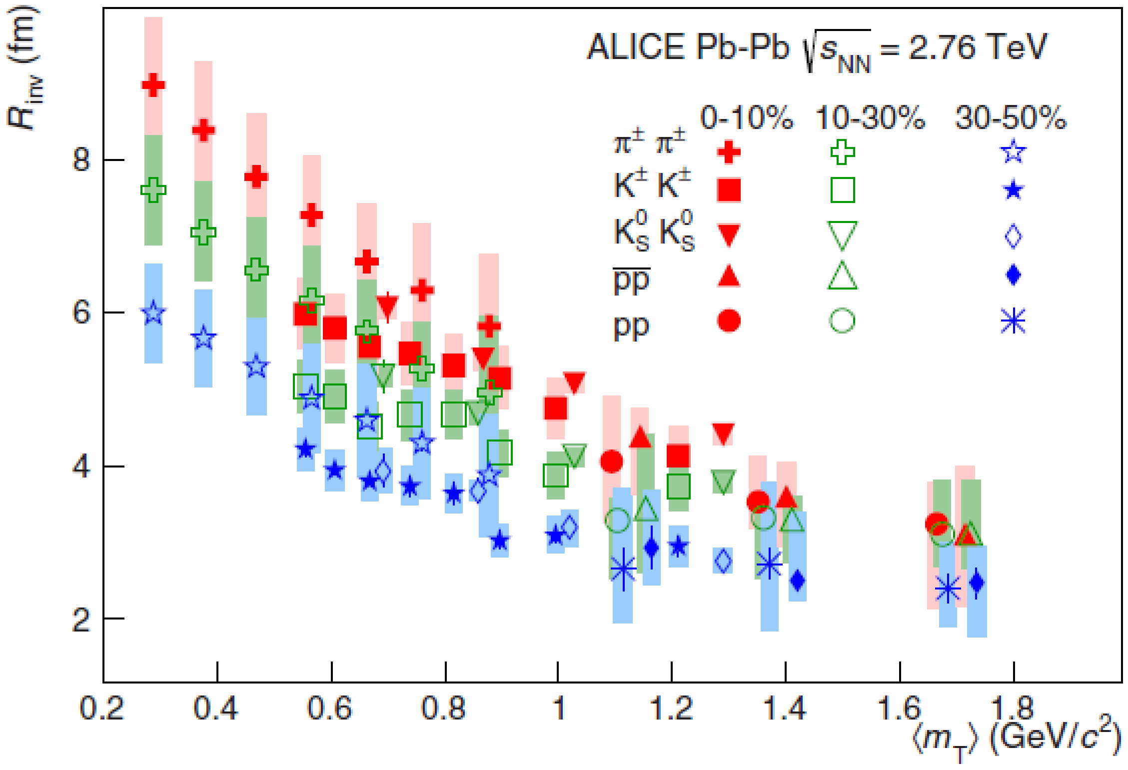


FIG. 8. (Color online) R_{inv} parameters vs m_T for the three centralities considered for $\pi^{\pm}\pi^{\pm}$, $K^{\pm}K^{\pm}$, $K^0_S K^0_S$, pp, and $\overline{p}\overline{p}$. Statistical (thin lines) and systematic (boxes) uncertainties are shown.

Like sign pairs (p_T slices)