Forward Neutron Production at MIPP Experiment

Analysis status report. Part I.

T.S. Nigmanov, D. Rajaram, M.J. Longo, H.R. Gustafson

University of Michigan

MIPP software/analysis meeting

January 19, 2010

neutron analysis outline

Part I, today

Event selection:

- good beam track
- trigger and tracking requirements
- counting of incident protons
- vertex position
- reduce straight through

Calorimeter energy scale

Neutron selection

Target-out subtraction

Trigger efficiency

MC neutron production properties

Calorimeter acceptance

Effect of calorimeter resolution

Neutron selection efficiency

Backgrounds

Neutron spectra

Part II, next meeting

Systematic uncertainties

Neutron production cross section

Target atomic weight dependence

What we want to measure?

Forward neutron production cross section:

$$\sigma(p_n > p_{min}) = \frac{n_n(t-in) - n_n(t-out) - n_n(backgr)}{N_{beam} \times \epsilon_{trig} \times \epsilon_{hcal} \times \epsilon_{cuts}} \times \frac{1}{n_t} \times 10^4, \text{ mb/(GeV/c)}$$

where, n_n is number of the neutron candidates passed the selection requirements, t-in and t-out are target-in and target-out respectively; $n_n(backgr)$ is the background, N_{beam} is the number of incident protons, ϵ_{trig} is the trigger efficiency, ϵ_{hcal} is the calorimeter acceptance and ϵ_{cuts} is the neutron selection efficiency, n_t is number of target particles per cm^2

Interaction target properties:

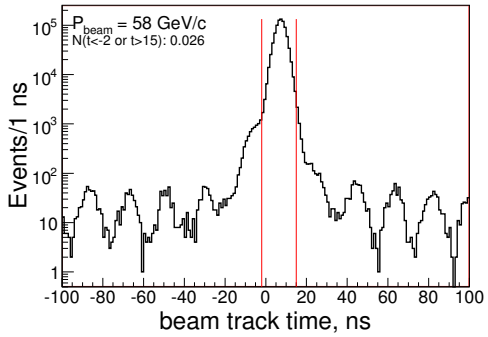
name	A	d, cm	m, g	AD, g/cm^2	IL, %	$n_t \times 10^{23}$cm^{-2}
H_2 liquid	1.008	14.0		0.991		5.922
Beryllium	9.012	0.399	14.4	0.71	0.94	0.4744
Carbon	12.011	1.003	34.0	1.677	1.94	0.8408
Bismuth	208.98	0.173	34.25	1.69	0.87	0.0487
Uranium	238.03	0.1	38	1.875	?	0.0474

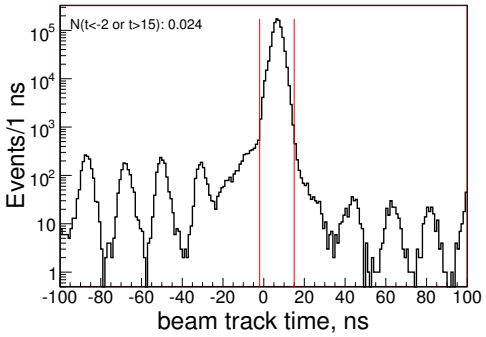
Table 1: The targets and their properties, where d - thickness in cm, m - mass in g, AD - areal density in g/cm^2, IL - interaction length and $n_t = \frac{N_A \times AD}{A}$ is a number of nucleus per cm^2.

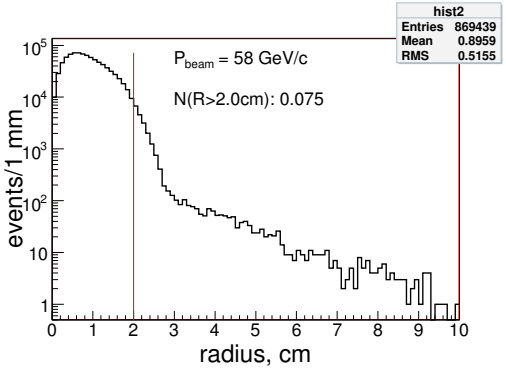
Event Selection

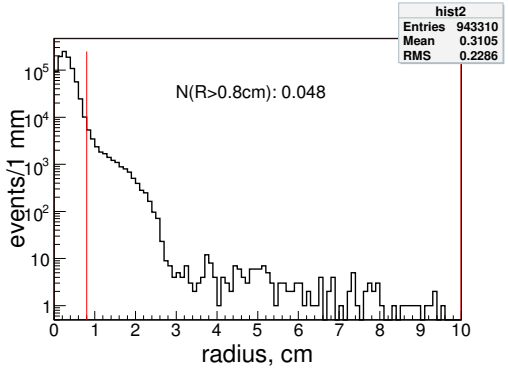
Use a “good” event sample:

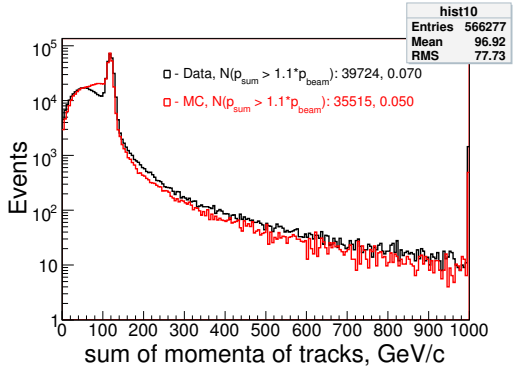
- $N_{trk} \leq$30 per event
- Calo should have readout
- “Good” beam track:
  - single beam track
  - avoid misreconstructed 2-nd trk
  - track position at target
  - track time
- Trigger scintillator is on
- Use events with reliable tracking conditions











Event and beam track selection cuts and efficiencies

Cut name	N(58-H_2)	EFF(58-H_2)	N(58-Tt)	EFF(58-Tt)	N(120-Tt)	EFF(120-Tt)
Total events	802616		1667211		2615429	
nTrks$\leq$30	772373	0.962	1543447	0.926	2518598	0.963
Calo status	772373	1.000	1543447	1.000	2518592	1.000
Is beam trk?	745447	0.965	1477568	0.957	2470960	0.981
Single beam trk	480130	0.644	869439	0.558	2011903	0.814
nCrossing $<$ 5	386237	0.804	685526	0.788	1674480	0.832
radius-1$<$2.0cm	300063	0.777	670633	0.978	1618680	0.967
radius-2$<$2.0cm			653655	0.975	1618680	1.000
track time	291234	0.971	646536	0.989	1610870	0.995
trk divergence	290707	0.998	645172	0.998	1610784	1.000
P_{sum} $<$1.1P_{beam}	275275	0.947	602133	0.933	1509270	0.937
Total efficiency		0.343		0.361		0.577
Proton fraction	92414	0.336	246413	0.409	1499105	0.993

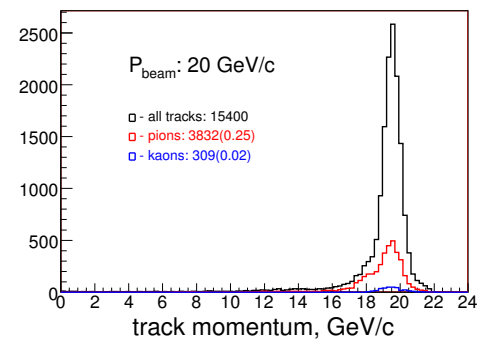
Table 2: Beam track selection cut efficiencies and proton fractions. All proton beam trigger events, which passed above requirements, are used in cross section calculation as an incident protons.

Incident proton sample sizes

target	p_{beam}	prescaler bit	direct scalers	ratio
H_2	20*	2215467	2063857	1.07
Empty Cryo	20*	397364	376001	1.06
H_2	58	17156645	16572320	1.03
Empty Cryo	58	2877699	2740163	1.05
Beryllium	58	2207422	2220883	0.99
Carbon	58	8751838	8603366	1.02
Bismuth	58	17164512	16274597	1.05
Uranium	58	32643688	30770547	1.06
Empty thin	58	12397130	11706104	1.06
H_2	84	31372847	28896245	1.09
Empty Cryo	84	10962656	9053908	1.21
Beryllium	120	19864149		0.08
Carbon	120	5542062		0.07
Bismuth	120	21559032		0.08

The number of incident protons calculated with two methods: accumulating the direct scaler and using the proton prescaler. Last column represents the ratio of two approaches.

Comparison for 120 GeV data done using about 80% of sample size where the direct scalers were reliable (run number $<$ 16044).



*RICH detector indicates that the pion fraction on 20 GeV/c proton beam is about 25%.

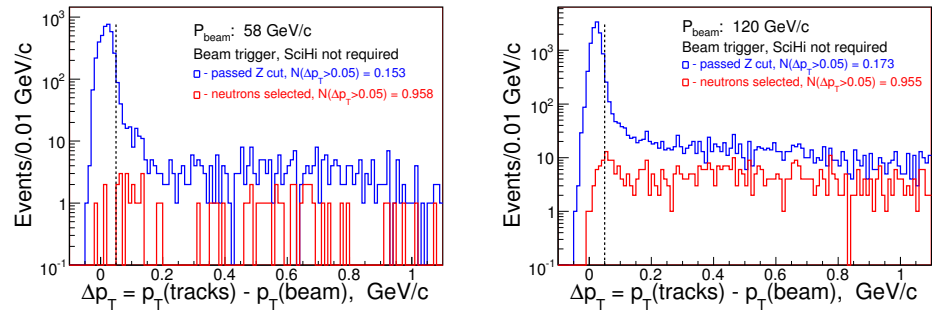
Some requirements prior neutron selection

Requirements for downstream tracking:

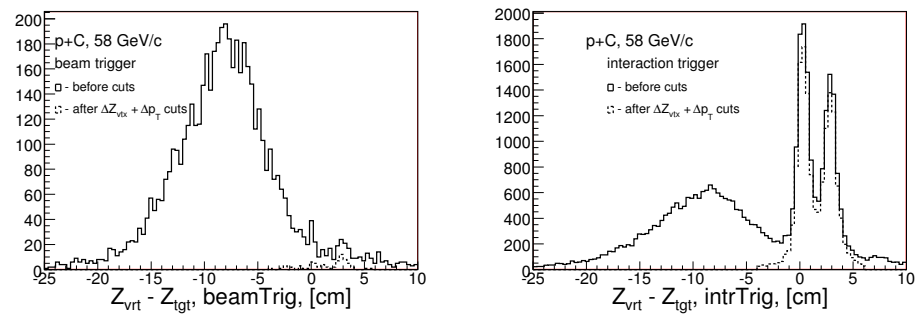
- use primary vertex
- vertex position cuts: R and Z
- reject straight through:
  - Δp_T <0.15 GeV/c
  - $p_{tot} > 0.7 \times P_{beam}$

p_{beam}	Be	C	Bi	U
58 GeV/c	0.093	0.072	0.067	0.046
120 GeV/c	0.019	0.015	0.021	

Table 3: The fraction of events when the transverse position of primary vertex was out of the beam spot.



Δp_T distributions for 58 GeV/c (left) and 120 GeV/c data (right).



Vertex Z positions for beam (left) and interaction (right) triggers.

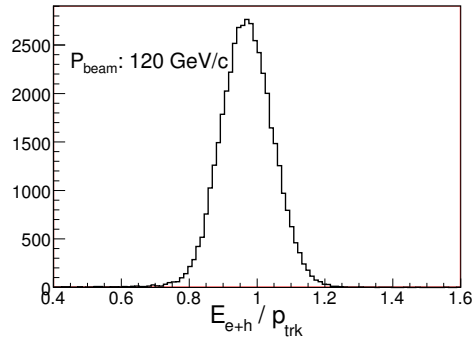
	thin	H_2 liquid
$Z_{vtx} - Z_{tgt}$	from -4 up to 6 cm	$\pm$15 cm

Cut values for the longitudinal position of the primary vertex, relative to the target center.

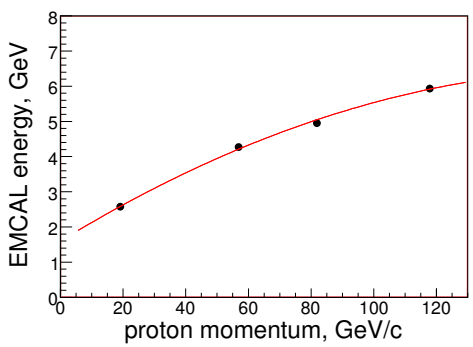
Calorimeter energy scale

Energy scale update:

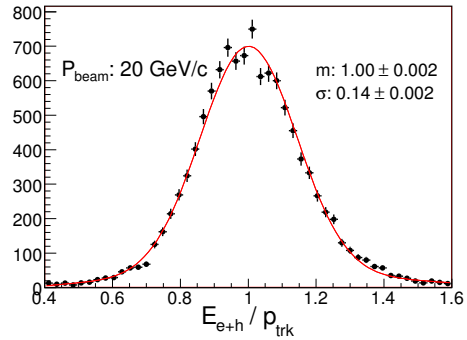
- HCAL energy with p4f release find to be off

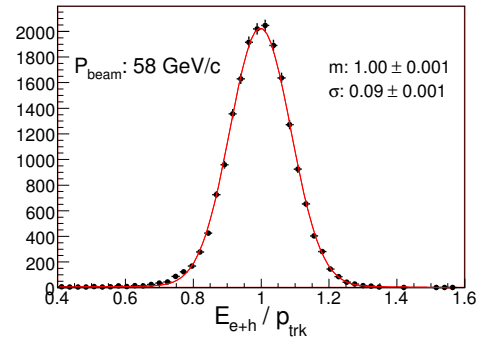


- add to E_n what was deposited into EMCAL

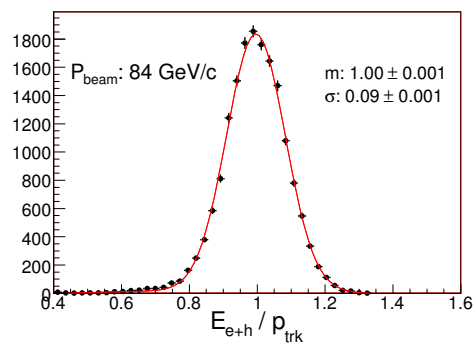


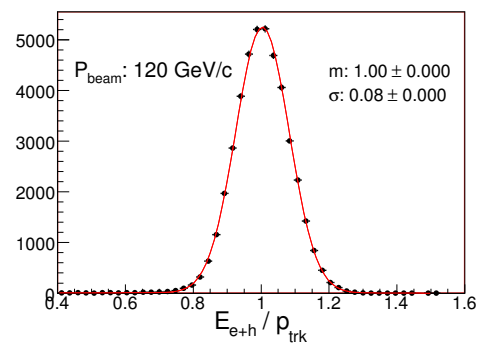
Mean values of proton deposited energy into EMCAL as a function of the proton momentum. Neutron deposition assumed to be same as protons.





E_{e+h}/p_{trk} ratio distributions for 20 GeV/c (left) and 58 GeV/c (right) protons.





E_{e+h}/p_{trk} ratio distributions for 84 GeV/c (left) and 120 GeV/c (right) protons.

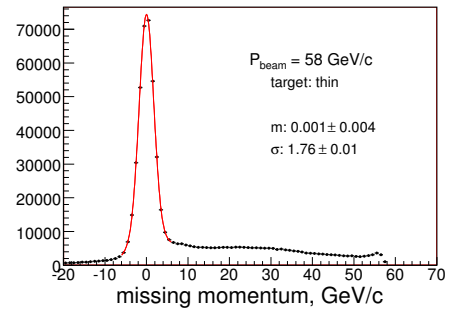
Neutron selection

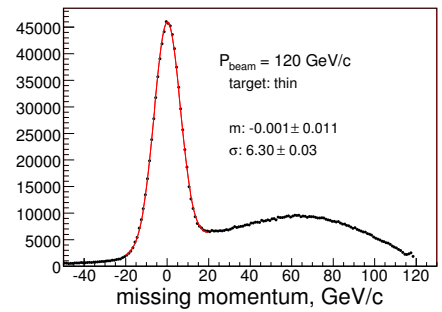
Neutron selection requirements:

- Proton interaction bit in the prescaled trigger word is on
- "SciHi" trigger bit in the raw trigger word should be on
- Lowest momentum values of neutron $P_n(min)$ are: 6, 12, 18 and 20 GeV/c for 20, 58, 84 and 120 GeV/c beam momentum, respectively
- Event rejected if there charged track with p_{trk} >0.7*P_{beam}
- Momentum balance: $(\sum P_{tracks}$ + $P_n)$ <1.2*P_{beam}, where $\sum P_{tracks}$ is the total momentum of all charged tracks in event, P_n is the neutron momentum.
- Candidate should have sufficient deposition to calorimeter compared with the sum of momenta of tracks pointing to calorimeter: $(P_n - P_{trkHcal}) > 3\sigma$, where σ represents the HCAL energy resolution

Neutron energy: $E_n = E_{e,pred} + E_{hcal} - E_{trkHcal}$, where $E_{e,pred}$ is the predicted energy loss by neutron in the lead of EMCAL, see plot on previous page. Term $E_{trkHcal}$ is the combined momentum of charged tracks pointing to the HCAL

Is any room for neutrals there?



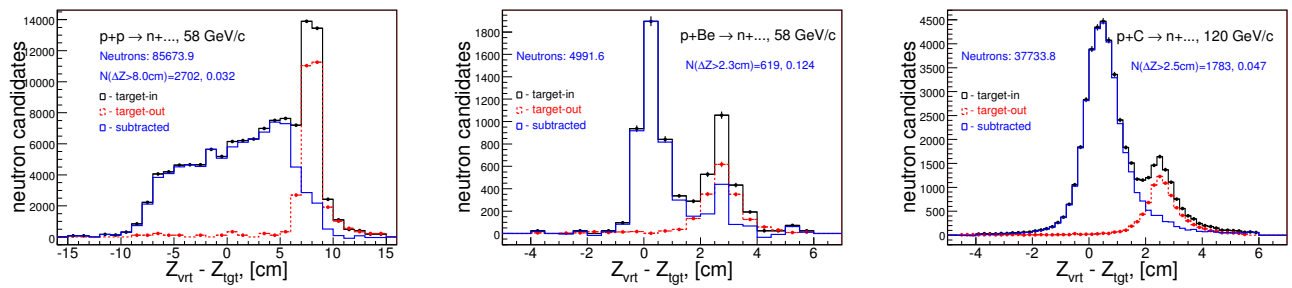


The missing momentum distributions for two proton beam momenta: 58 GeV/c (top) and 120 GeV/c (bottom).

Target-out subtraction

- the trigger scintillator about 2 cm downstream of the thin target
- the longitudinal vertex position resolution not allow to distinguish interactions at target versus interactions with the trigger scintillator
- due to of that we measured the neutron spectra also with the target-out case and then applied the subtraction procedure
- for this purpose the target-out sample is scaled-up to same size of the incident protons as in target-in case

Issue: the peak height on the trigger scintillator using the target-out sample is always below that the target-in case.



The relative longitudinal vertex position distributions for the neutron candidate events: target-in sample (black), target-out (red) and subtracted in blue.

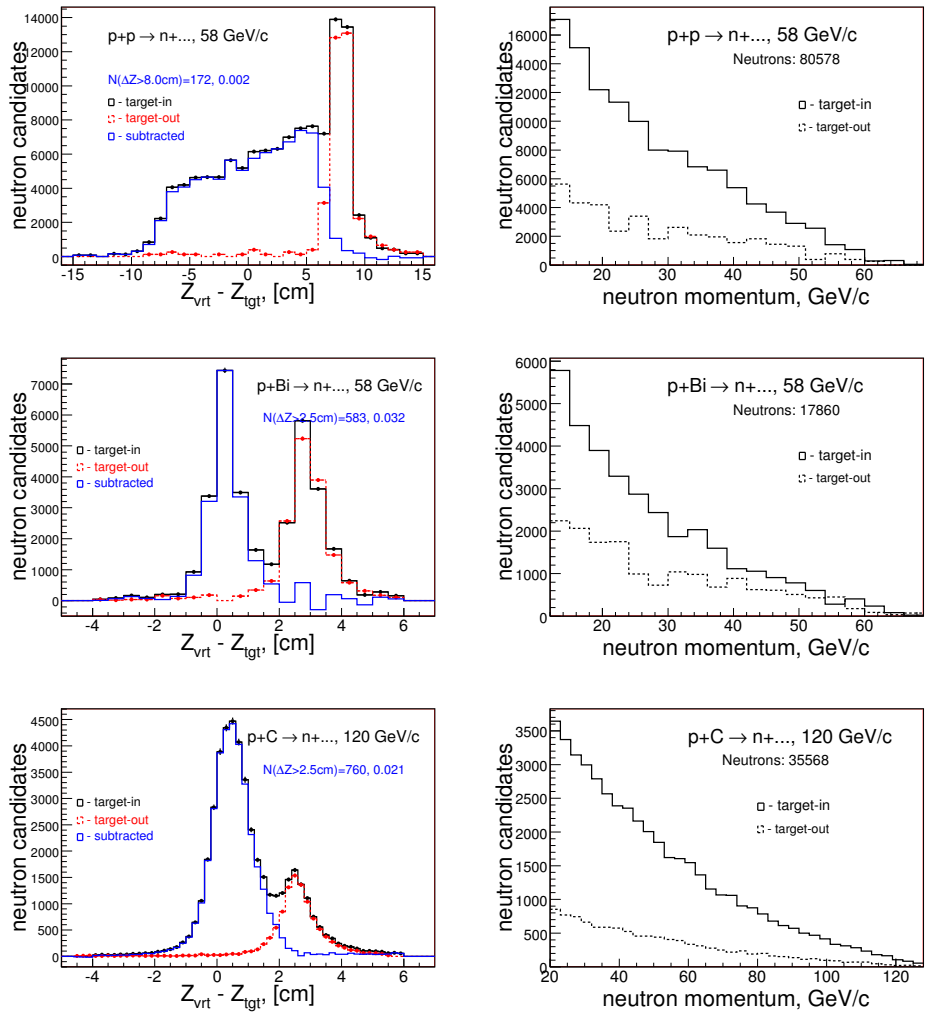
Possible options:

- There is no big issue there. Ignore it.
- Apply correction to the size of target-out sample in order to bring the scintillator height to the right level and assign the systematic uncertainty for it. In this approach we gain in the purity of neutron sample

Target-out subtraction, continue

target	p_{beam}	CF_{t-out}
H_2	20	0.50
H_2	58	1.16
Be	58	1.47
C	58	1.39
Bi	58	1.14
U	58	1.09
H_2	84	1.11
Be	120	1.09
C	120	1.25
Bi	120	1.04

Table 4: The correction factors for the target-out sample sizes.



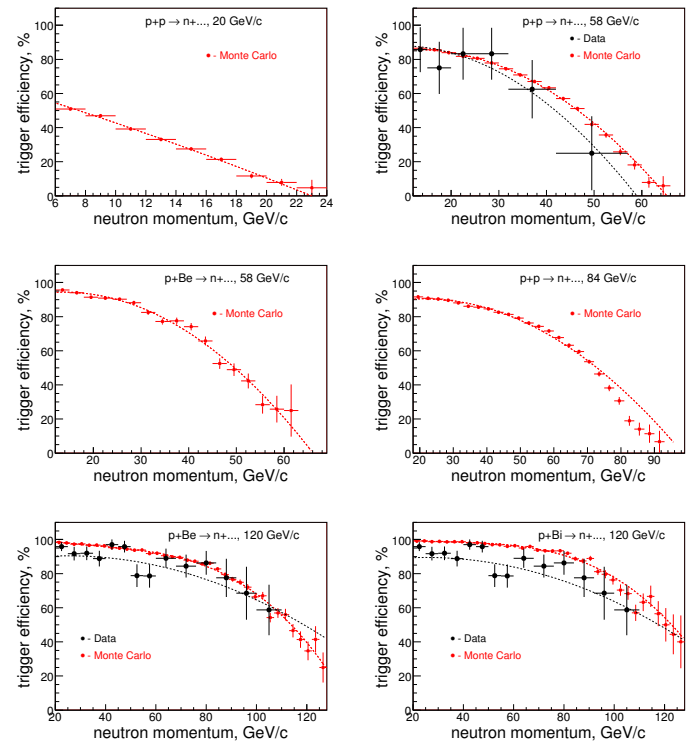
The vertex Z (on left) and measured neutron spectrum (on right) distributions. Plots illustrate the target-out contributions.

Trigger efficiency

- Use unbiased beam triggers and select neutrons
- Count SciHi trigger fires

tgt,p_b	N_n	ϵ_{trig}(data)	ϵ^{mc1}_{mc2}	ϵ^{avr}_{trig}	ass $syst$	M^{dat}_{mc}
H_2,20	19	0.53±0.12	$\frac{0.38}{0.39}$	0.46	0.10	$\frac{2.0}{2.5}$
H_2,58	43	0.67±0.07	$\frac{0.72}{0.74}$	0.71	0.10	$\frac{4.9}{4.6}$
Be, 58	3	1.00±?	$\frac{0.83}{0.82}$	0.82	0.10	$\frac{n/a}{5.9}$
C, 58	5	0.80±0.18	$\frac{0.85}{0.84}$	0.84	0.10	$\frac{n/a}{6.6}$
Bi, 58	9	0.67±0.16	$\frac{0.91}{0.91}$	0.845	0.10	$\frac{n/a}{9.8}$
U, 58	40	0.78±0.07	$\frac{0.92}{0.91}$	0.845	0.10	$\frac{5.3}{10.0}$
H_2,84	137	0.66±0.04	$\frac{0.82}{0.80}$	0.73	0.10	
Be, 120	235	0.85±0.03	$\frac{0.92}{0.92}$	0.885	0.07	$\frac{7.1}{8.2}$
C, 120	129	0.88±0.03	$\frac{0.93}{0.93}$	0.905	0.05	$\frac{7.7}{9.3}$
Bi, 120	193	0.77±0.03	$\frac{0.96}{0.97}$	0.87	0.10	$\frac{8.6}{14.2}$

Table 5: Why trigger efficiency in MC is higher than in data? Answer: number of particles passing through scintillator in MC is higher (last column).

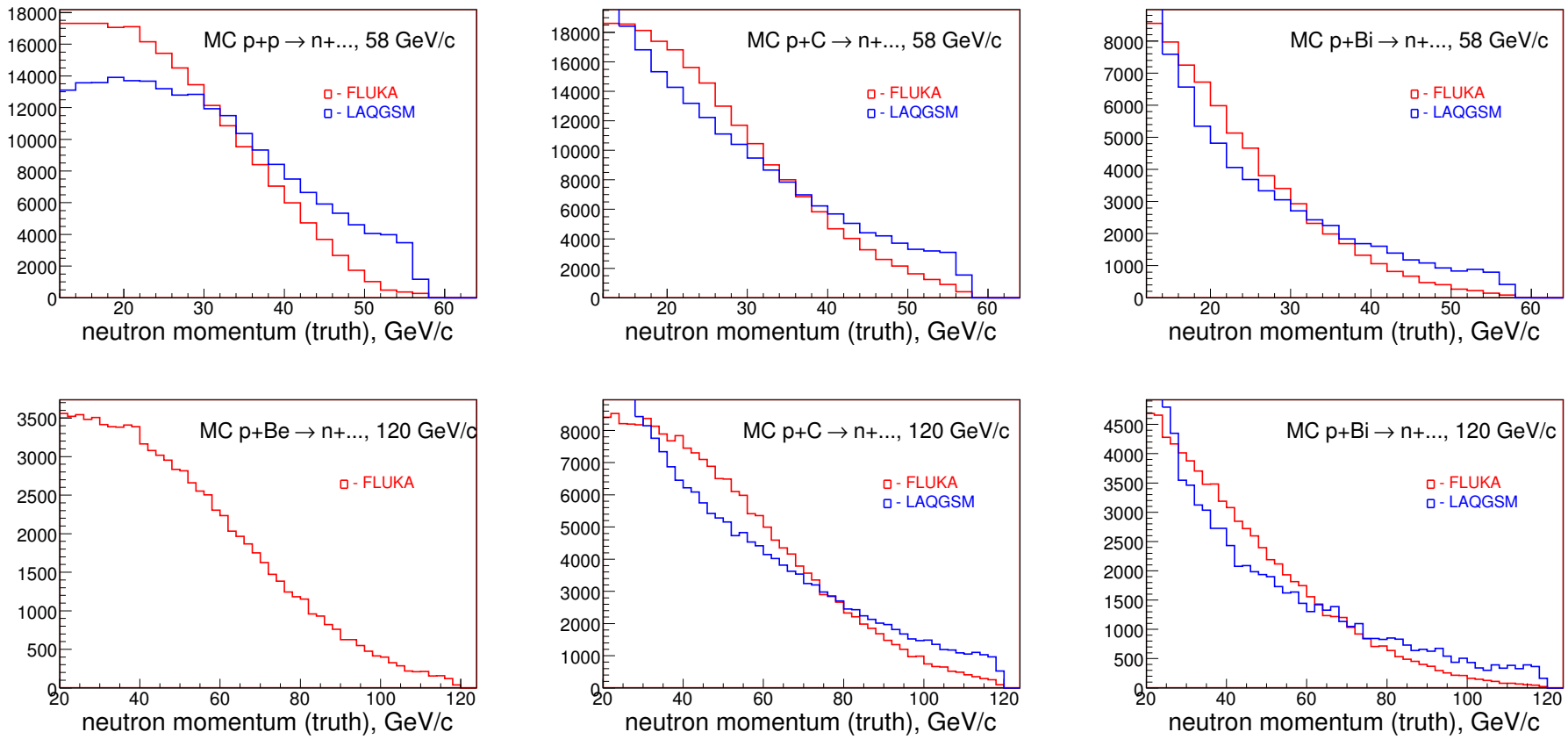


How it was applied to data?

The momentum dependence follows according to Monte Carlo prediction (red dashed curve).

The level of each predicted curve was adjusted. For an example, Bi-58 efficiency in each bin has been multiplied by factor 0.845/0.91

MC neutron production properties: spectrum

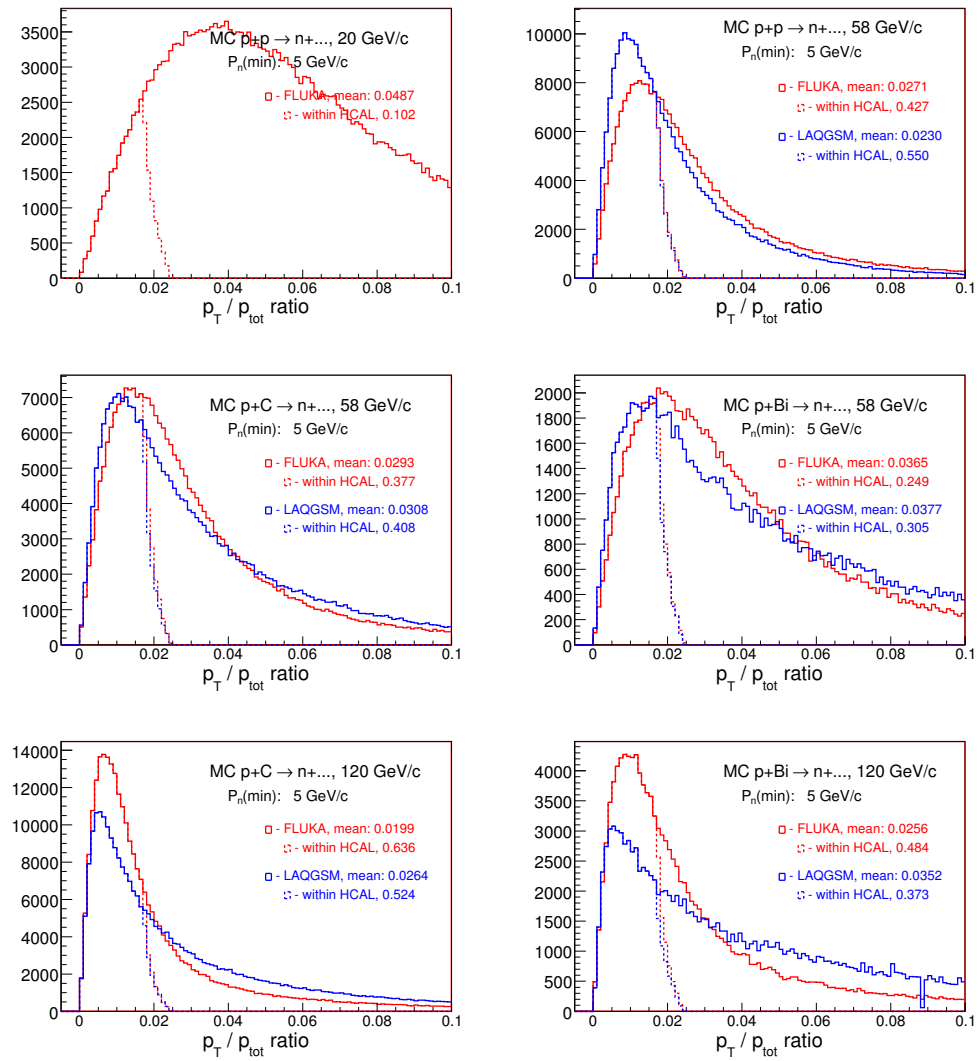


MC true neutron production spectra from p+A interaction using FLUKA and LAQGSM models.

The number of LAQGSM events are normalized to same size as FLUKA.

Distributions tells that LAQGSM generate harder neutron spectrum than FLUKA

MC true neutron an angular distribution



MC true neutron angular distributions

target	p_{beam}	FLUKA	LAQGSM
H_2	20	0.10	
H_2	58	0.43	0.55
Be	58	0.39	
C	58	0.38	0.41
Bi	58	0.25	0.31
U	58	0.25	
H_2	84	0.57	
Be	120	0.65	
C	120	0.64	0.52
Bi	120	0.48	0.37

Table 6: Predicted average calorimeter acceptance.

Hadron calorimeter acceptance

Typical issue: detector coverage for neutrons depends on neutron p_T spectrum.

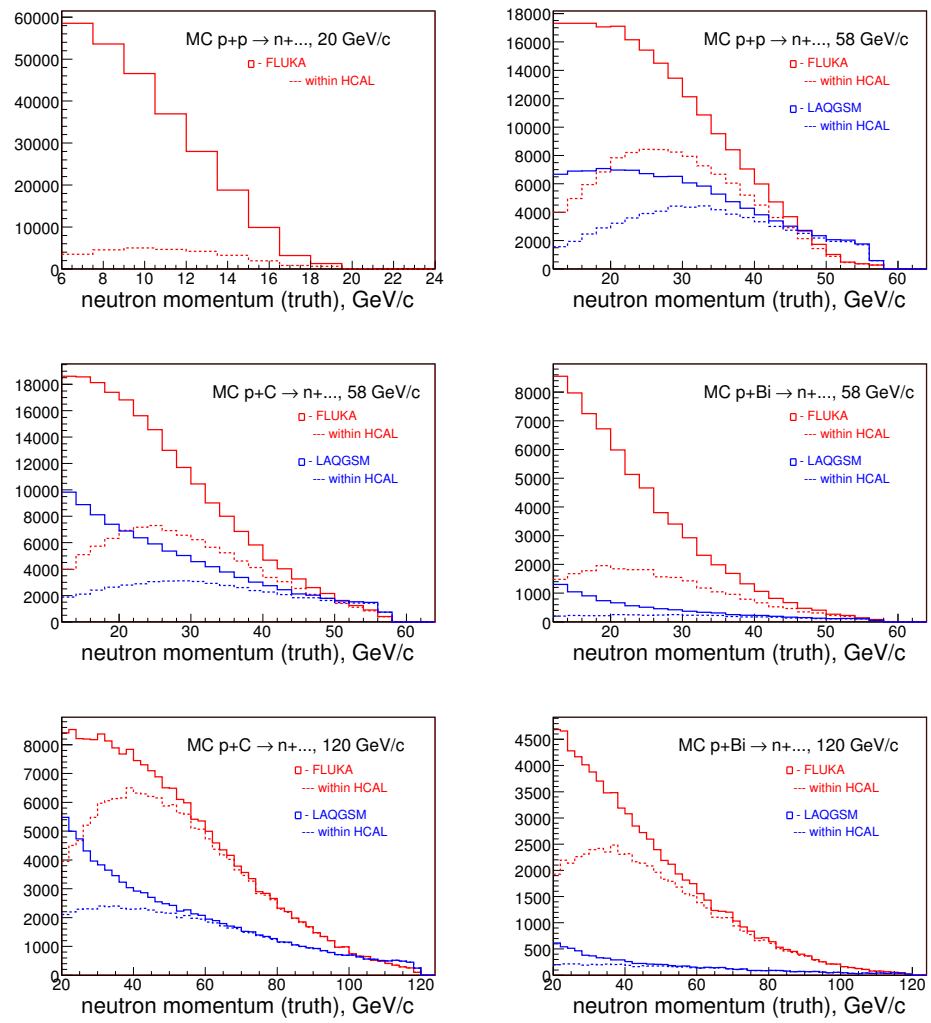
How to solve this issue?

Only one choice: use Monte Carlo. Better use several models. Variations in models might give us some estimate. We might get an idea what the uncertainty assign for it.

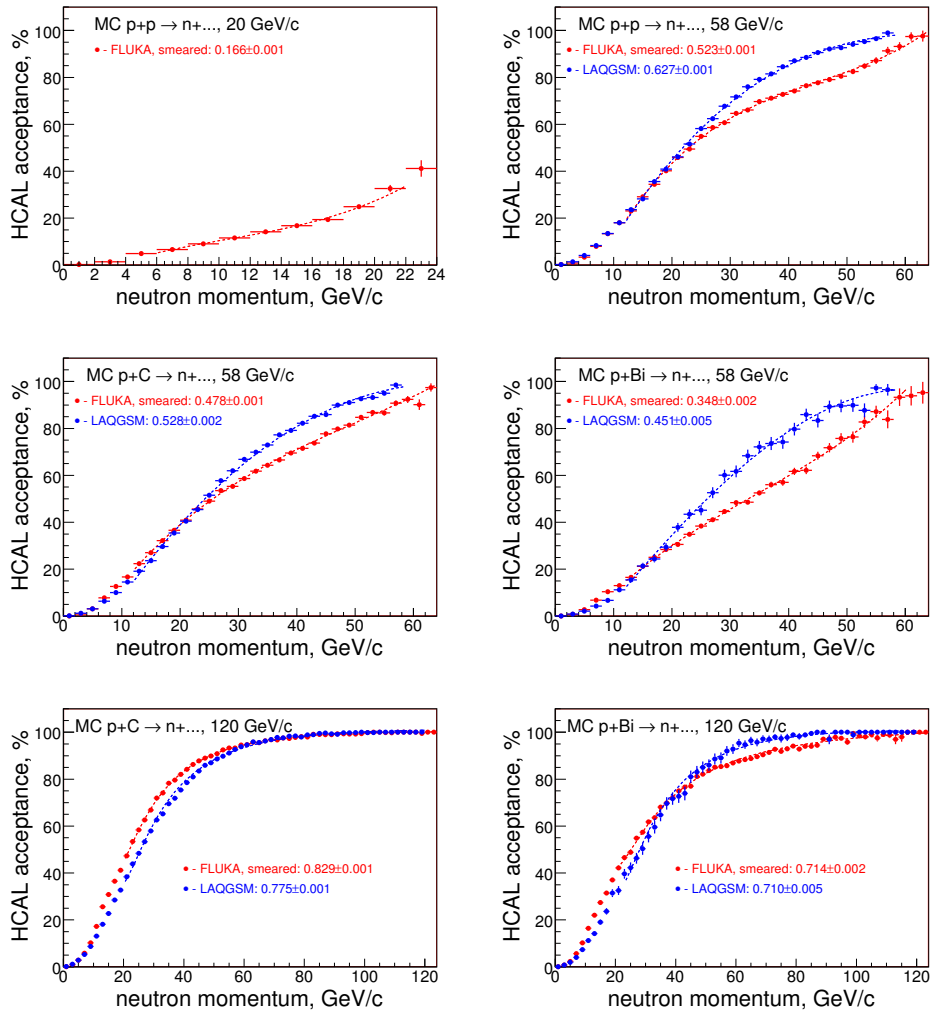
We used two models: FLUKA and LAQGSM

The decision about is neutron fall into hadron calorimeter made using the predicted position on the front face of detector (-5 cm).

Note: we do not used the hadron shower simulation info for the acceptance purpose.



Hadron calorimeter acceptance, results



HCAL acceptance as function of the smeared neutron momentum.

October plots: ..as function of the summed neutron momentum.

p_{beam}	FLUKA	LAQGSM
H_2-20	0.166±0.001	-
H_2-58	0.523±0.001	0.627±0.001
Be-58	0.492±0.004	-
C-58	0.478±0.001	0.528±0.002
Bi-58	0.348±0.002	0.451±0.005
U-58	0.349±0.002	-
H_2-84	0.680±0.001	-
Be-120	0.835±0.001	-
C-120	0.829±0.001	0.775±0.001
Bi-120	0.714±0.001	0.710±0.001

Table 7: Average HCAL acceptances.

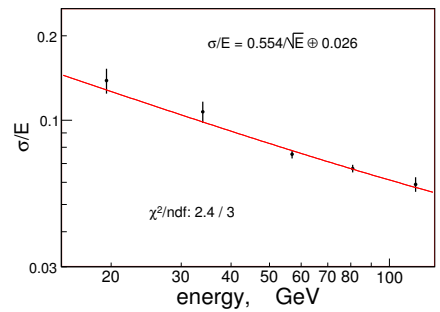
Functions (red dashed curves) were applied for data to take in account the HCAL acceptance.

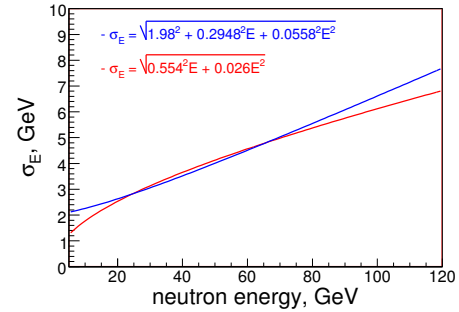
Effect of calorimeter resolution to neutron spectrum

How to take in account the hadron calorimeter resolution to neutron spectrum?

Option I: Using MC sample compare what was generated vs the simulated responses by GEANT. The electromagnetic shower simulation looks off. In 10% of cases the whole neutron energy goes to EMCAL. This behaviour is not consistent with data. We also not sure on how well the hadron shower simulation goes on. MC resolution is broader by 20% than in data.

Option II: Compare what was generated vs smeared. We have the resolution as a function of proton momentum in data. It would be good approach for neutrons too.





The hadron calorimeter energy resolution, σ/E, vs the incident proton energy (left) and how neutron energy resolution was simulated in MC (right plot - blue curve).

We see a small nonlinearity there, which can be taken in account by using a second order polynomial function:

$$\sigma = \sqrt{1.98^2 + 0.2948^2 E_{ts} + 0.0558^2 E_{ts}^2}$$

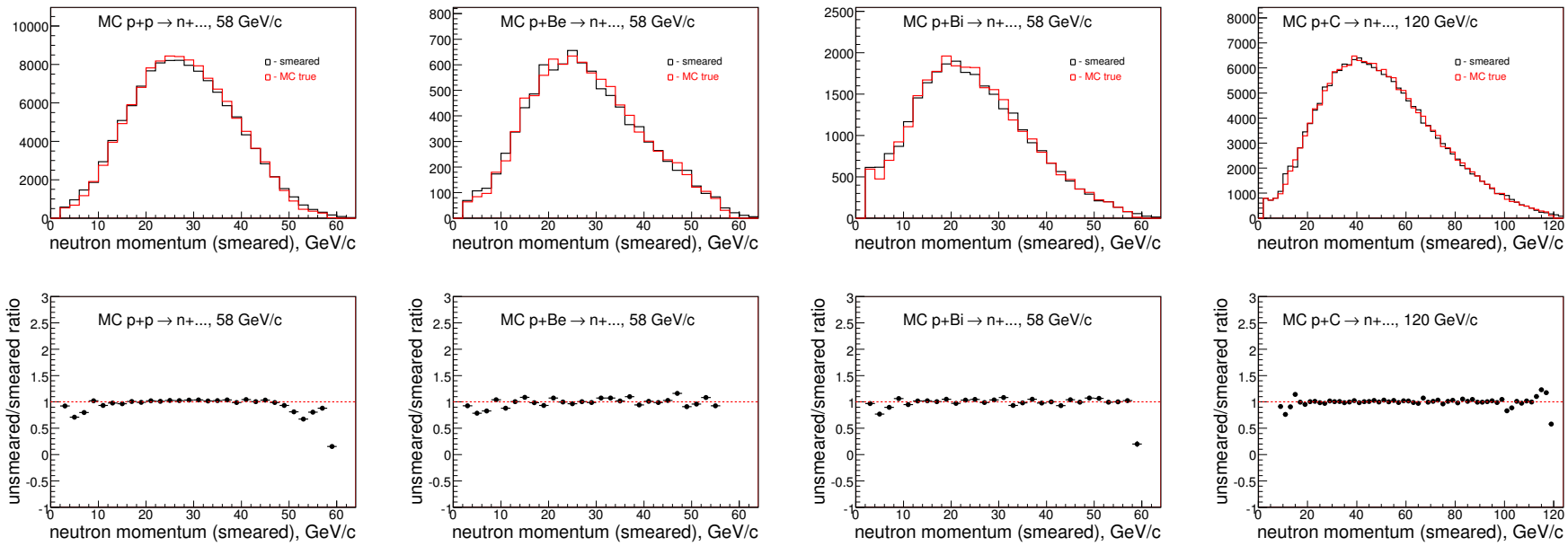
In this formula E_{ts} represents the true summed neutron momentum pointing to HCAL fiducial. The smearing value:

$$\Delta_E = \text{gRandom} \rightarrow \text{Gaus}(0, \sigma);$$

where σ is neutron resolution in GeV units for given E_{ts}.

Thus, for each MC event we have two neutron energies: E_{ts} and $E_{ts}(\pm)\Delta_E$.

Effect of calorimeter resolution, continue



Top plots: black - smeared summed spectrum as described on previous page, red - MC true summed neutron spectra.

Bottom plots: the ratio of the MC true over the smeared spectra.

Bottom plots tells that the smeared spectra pretty match similar to the true one in wide range of the neutron momentum.

Some peculiarities in the low momentum region are not important, because it is below of our threshold.

Some peculiarities in high momentum range are due to of kinematic boundaries for the true spectra.

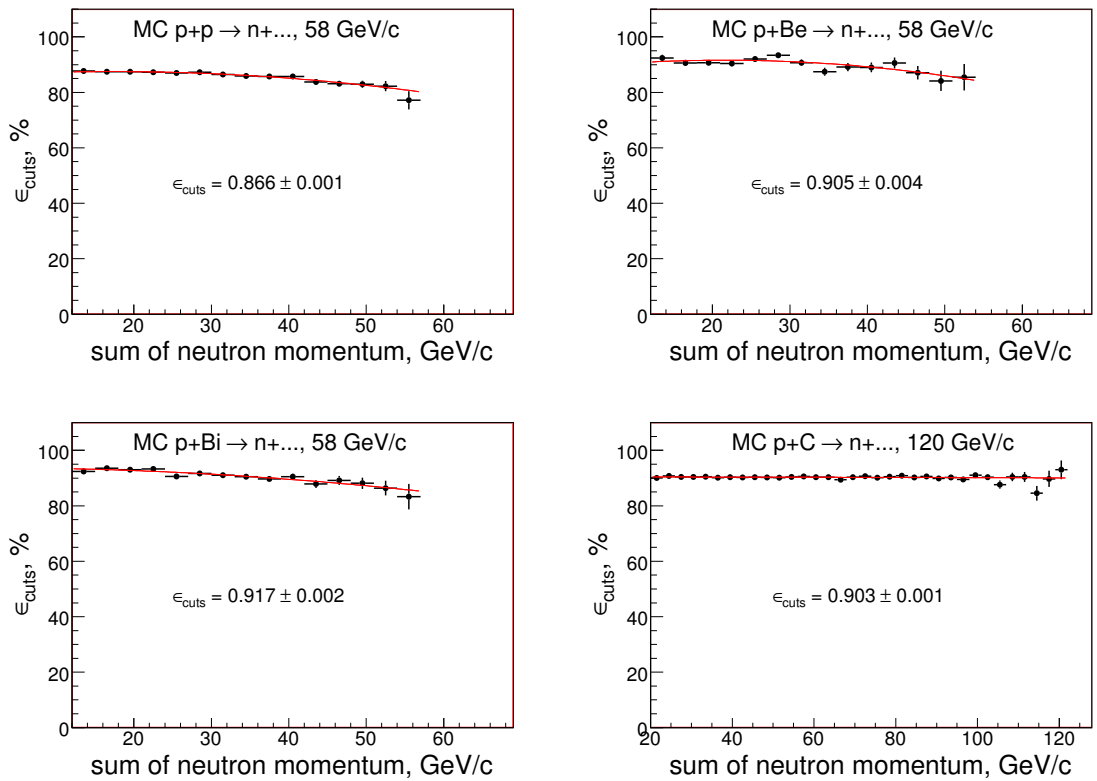
Conclusion: effect of calorimeter resolution is negligible.

Neutron selection efficiency

How to take in account some neutron losses due to of Z_{vtx} and other cuts?

p_{beam}	ϵ_{cuts}
H_2-20 GeV/c	0.801±0.004
H_2-58 GeV/c	0.866±0.001
Be-58 GeV/c	0.905±0.004
C-58 GeV/c	0.900±0.001
Bi-58 GeV/c	0.917±0.002
U-58 GeV/c	0.917±0.002
H_2-84 GeV/c	0.890±0.001
Be-120 GeV/c	0.898±0.001
C-120 GeV/c	0.903±0.001
Bi-120 GeV/c	0.916±0.001

Table 8: Monte Carlo the neutron average selection efficiency.



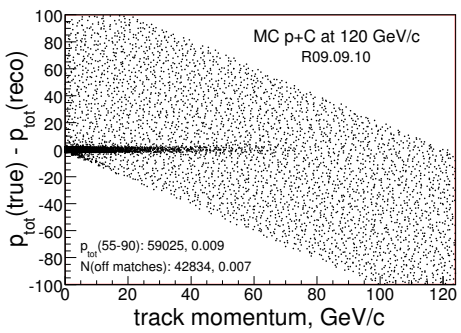
The neutron reconstruction efficiency as the function of the summed neutron momentum.

The red curves represent the second order polynomial fit, which were applied for data.

Neutron backgrounds

Background sources:

- fakes due to track misreconstruction
- combinatoric backgrounds
- contributions from K_L^o
- secondary neutrons, n_s
- photons (left-over after EMCal)



The true - reco vs the reco momentum distribution.

Upper edge line illustrates $p_{tot}(reco)$=0 case.

Bottom - $p_{tot}(true)$=0.

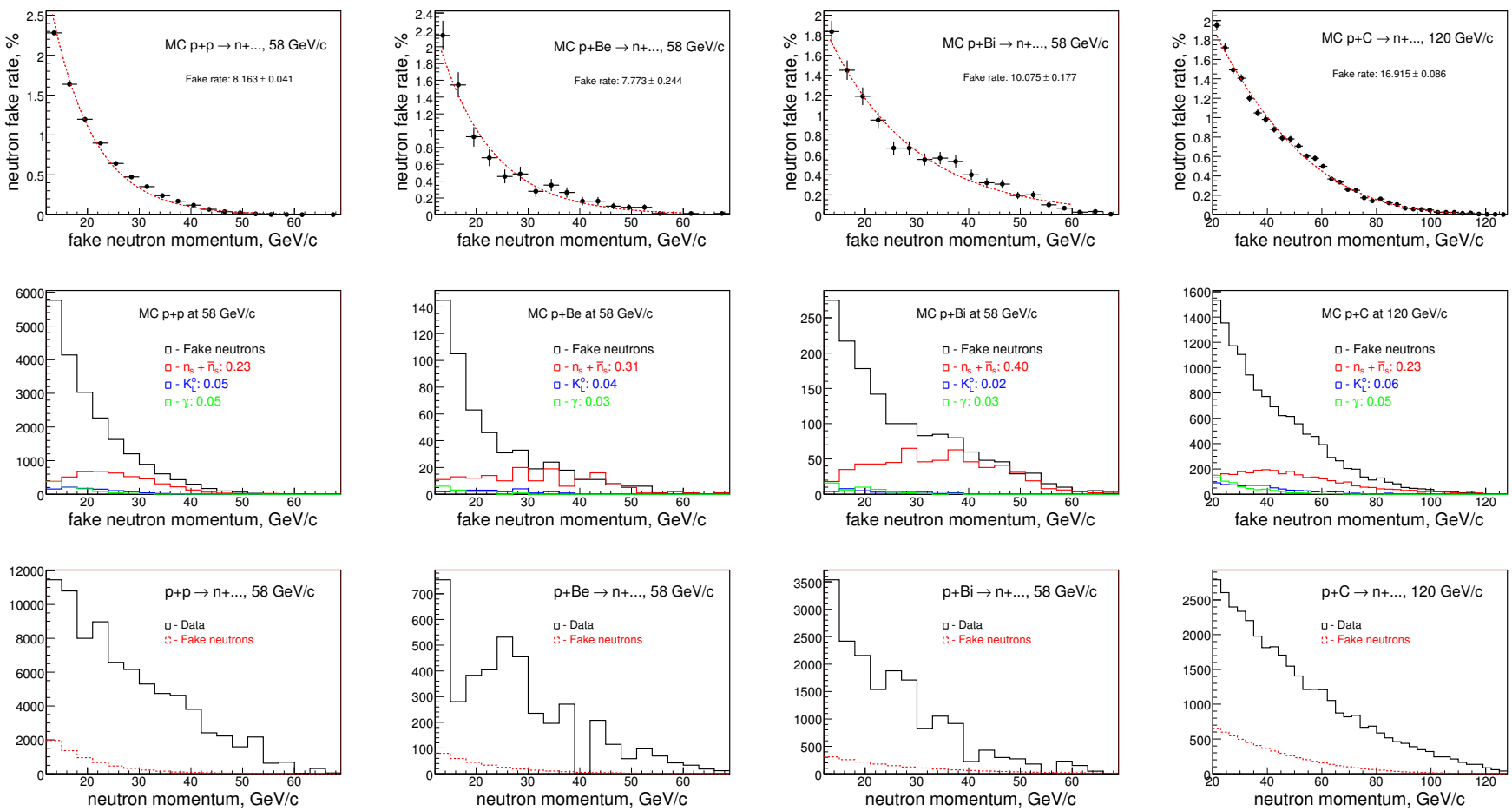
Total background calculation procedure:

- apply the neutron selection cuts in MC same way as in data
- calculate neutron momentum in MC same way as in data
- use MC sample where neutron was NOT generated
- events from the non-neutron sample, which will pass the neutron selection requirements, are fake neutrons
- calculate fake rate per single MC event using the non-neutron sample, where
  - as denominator use: events passed Z_{vtx}, Δp_T and trigger requirements;
  - as numerator use: same as above and is sufficient energy in HCAL?

Assumptions:

- tracking detectors' simulation, track and vertex reconstruction software in MC are compatible with data
- contributions from n_s, K_L, γ are about the same as in data
- HCAL simulation is more less reasonable (central value)

Fake rates and other neutrals contributions



Top: fake rates per single event. Red dashed curves - exponential for light or polynomial function for heavier nuclear target.

Middle: contributions from other neutrals in compare with the total. Thus, the tracking source is the dominant.

Bottom: illustrates the background level in data: $N_{backgr} = R_{fake} \times N_n$(data), where R_{fake} is fake rate.

Backgrounds, summary

Tgt-p$_{beam}$	R$_{fake}$, %	non-matches,%	$< N_{trk} >$	$< P_{trk} >$	$< F_{(n_s+K_L+\gamma)} >$
H_2-20	0.71±0.02	0.48	0.30±0.03	7.2±0.4	0.25(0.22+0.02+0.01)
H_2-58	8.16±0.04	1.41	0.73±0.01	11.8±0.1	0.33(0.23+0.05+0.05)
Be-58	7.77±0.24	1.66	0.63±0.03	12.4±0.4	0.38(0.31+0.04+0.03)
C-58	6.65±0.07	1.76	0.68±0.02	12.0±0.2	0.31(0.22+0.04+0.05)
Bi-58	10.08±0.18	1.21	0.65±0.02	11.7±0.2	0.45(0.40+0.02+0.03)
U-58	10.59±0.20	1.37	0.66±0.01	11.8±0.1	0.53(0.46+0.04+0.03)
H_2-84	11.69±0.04	1.79	1.15±0.01	12.4±0.1	0.33(0.23+0.05+0.05)
Be-120	19.22±0.14	2.50	1.51±0.01	16.36±0.04	0.39(0.29+0.06+0.04)
C-120	16.92±0.09	2.68	1.50±0.01	16.36±0.05	0.34(0.23+0.06+0.05)
Bi-120	21.76±0.19	2.21	1.53±0.01	15.85±0.04	0.46(0.38+0.05+0.03)

Table 9: Summary of Monte Carlo neutron fake rate studies. R$_{fake}$ is fake rate in $\%$, "non-matches" represents the fraction of tracks when reconstructed one is off from the true value; $< N_{trk} >$ and $< P_{trk} >$ are data based the mean value of charged track multiplicities and the mean value of track momentum pointing to front wall of RICH within ±40 cm rectangular from the center at beam line. $< F_{(n_s+K_L+\gamma)} >$ is MC predicted fraction of the neutrals in the fake rate.

Neutron sample size

Forward neutron production (sample size):

$$N_n(p_n > p_{min}) = \frac{n_n(t-in) - n_n(t-out) - n_n(backgr)}{\epsilon_{trig} \times \epsilon_{hcal} \times \epsilon_{cuts}}$$

where N_n is the resulting number of neutrons with $p_n > p_{min}$ momentum threshold,

n_n(t-in) is number of detected neutrons, target-in case;

n_n(t-out) is number of detected neutrons, target-out case;

n_n(backgr) is the estimated background (implemented as function);

ϵ_{trig} is the trigger efficiency (implemented as function);

ϵ_{hcal} is HCAL acceptance (implemented as function);

ϵ_{cuts} is neutron selection efficiency (implemented as function);

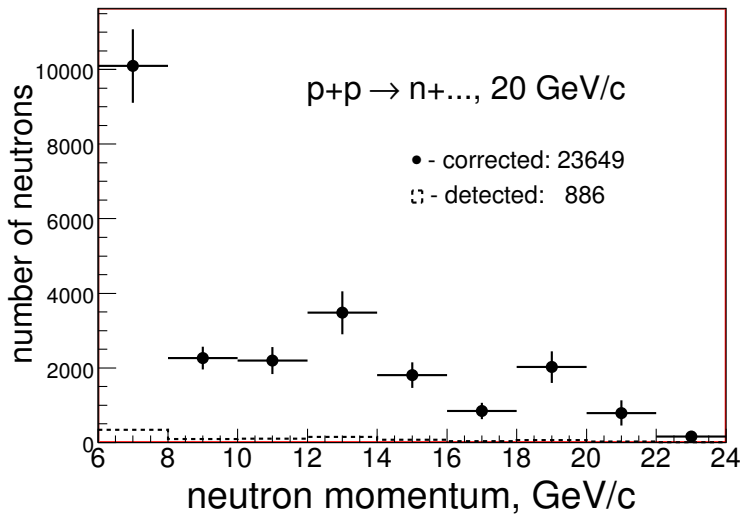
Neutron sample size, results

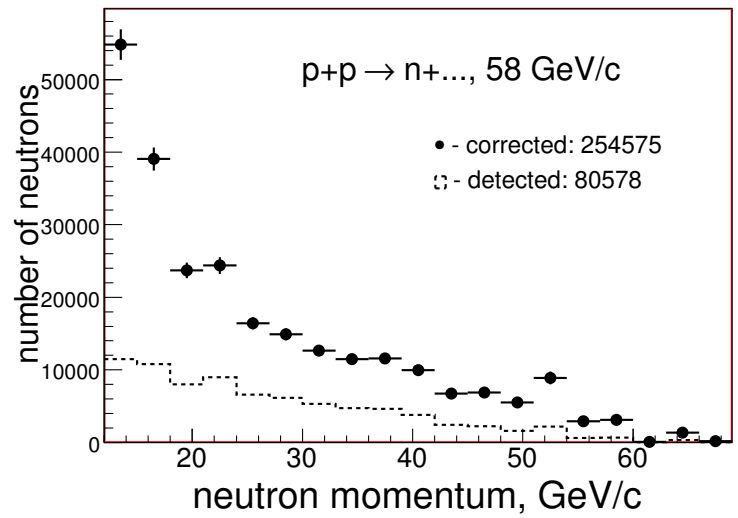
Tgt-p$_{beam}$	n_n(t-in)-n_n(t-out)	-Backgr	$\times \frac{1}{\epsilon(trig)}$	$\times \frac{1}{\epsilon(hcal)}$	$\times \frac{1}{\epsilon(n-sel)}$	N_n(results)
H_2-20	886$\pm$48	$_{-0.007}$880	$\frac{1}{0.46}$2160	$\frac{1}{0.17}$18607	$\frac{1}{0.80}$23649	23649$\pm$1292
H_2-58	80578$\pm$1154	$_{-0.08}$74121	$\frac{1}{0.71}$109633	$\frac{1}{0.52}$219883	$\frac{1}{0.87}$254575	254575$\pm$3646
Be-58	4164$\pm$247	$_{-0.08}$3856	$\frac{1}{0.82}$5025	$\frac{1}{0.49}$10344	$\frac{1}{0.91}$11475	11475$\pm$681
C-58	32589$\pm$773	$_{-0.07}$30427	$\frac{1}{0.84}$37418	$\frac{1}{0.48}$83785	$\frac{1}{0.90}$92874	92874$\pm$2204
Bi-58	17861$\pm$405	$_{-0.10}$16099	$\frac{1}{0.845}$19542	$\frac{1}{0.35}$61120	$\frac{1}{0.92}$66279	66279$\pm$1503
U-58	30864$\pm$421	$_{-0.11}$27640	$\frac{1}{0.845}$33114	$\frac{1}{0.35}$104385	$\frac{1}{0.92}$113005	113005$\pm$1541
H_2-84	161097$\pm$1517	$_{-0.12}$143496	$\frac{1}{0.73}$201994	$\frac{1}{0.68}$278596	$\frac{1}{0.89}$314452	314452$\pm$2962
Be-120	61047$\pm$199	$_{-0.19}$49436	$\frac{1}{0.885}$57567	$\frac{1}{0.84}$71233	$\frac{1}{0.90}$79377	79377$\pm$258
C-120	35568$\pm$165	$_{-0.17}$29575	$\frac{1}{0.905}$33621	$\frac{1}{0.83}$41991	$\frac{1}{0.90}$46493	46493$\pm$216
Bi-120	39825$\pm$146	$_{-0.22}$31254	$\frac{1}{0.87}$36463	$\frac{1}{0.71}$53492	$\frac{1}{0.92}$58341	58341$\pm$214

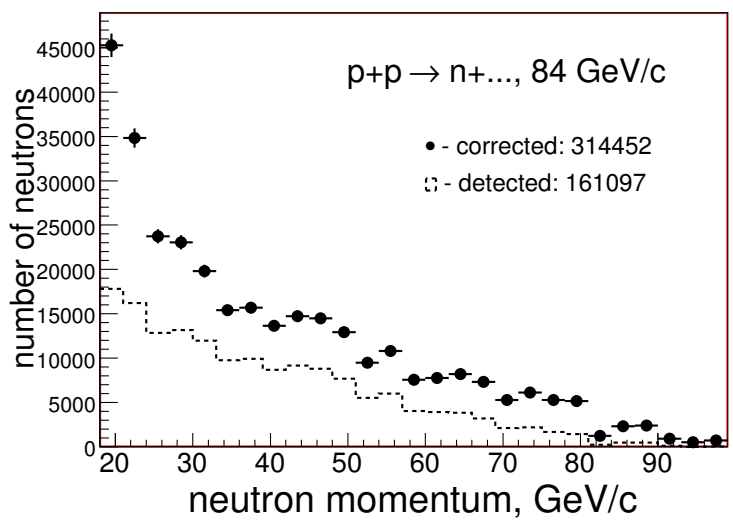
Table 10: Summary of corrections to the neutron sample size. Uncertainties are statistical.

Assumption: the correction factors are not correlated between each other

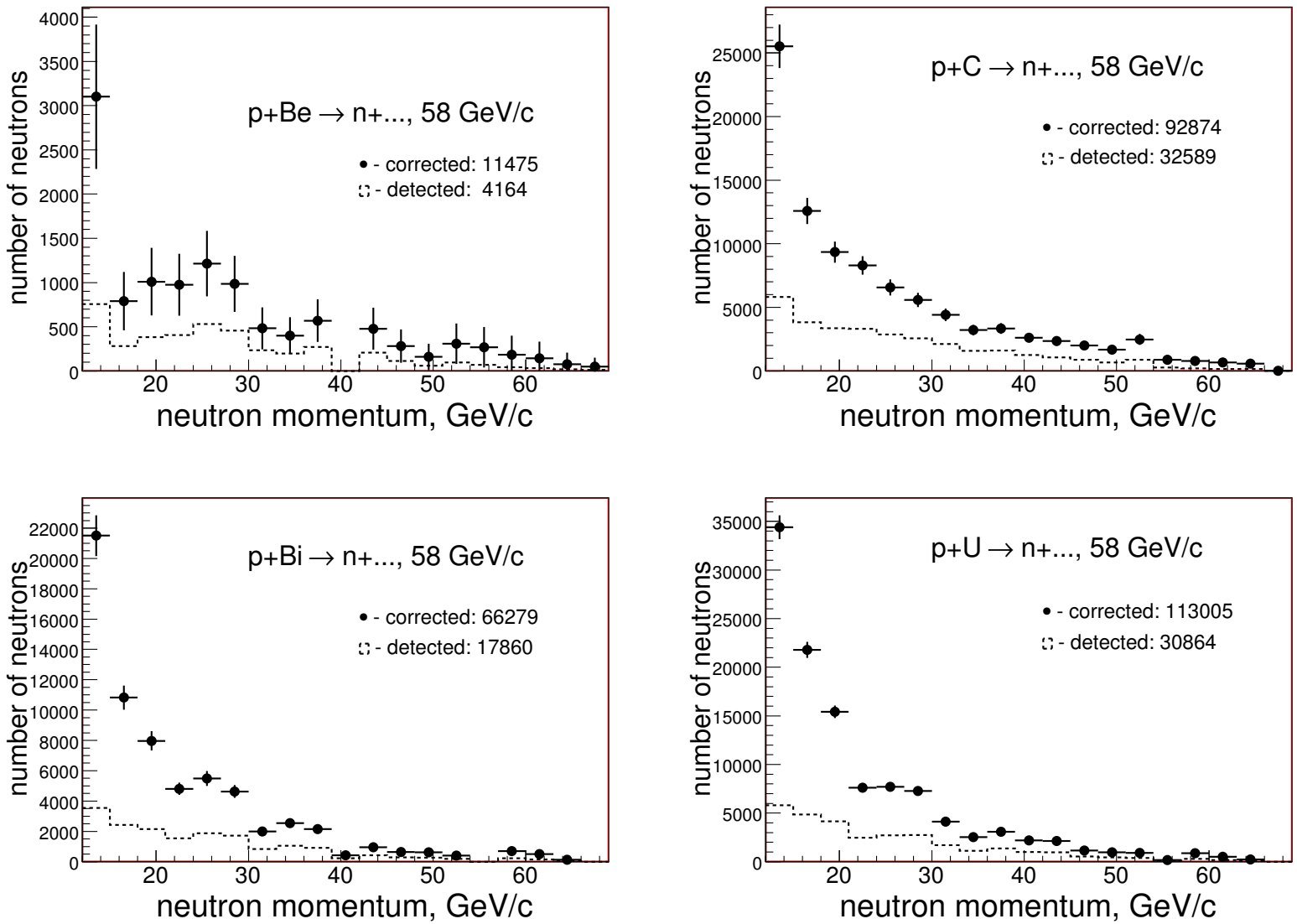
Neutron spectra from p+p interactions



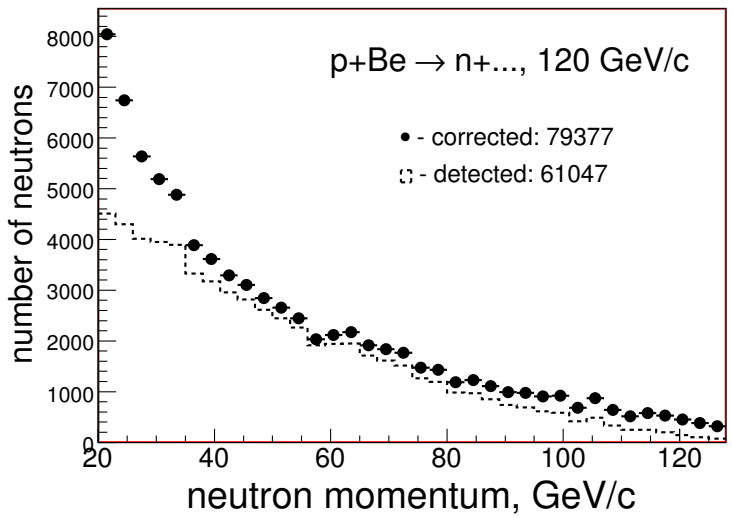


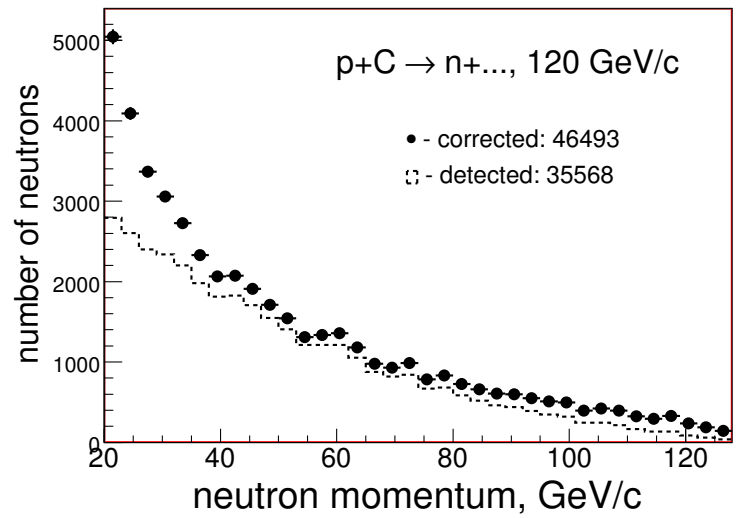


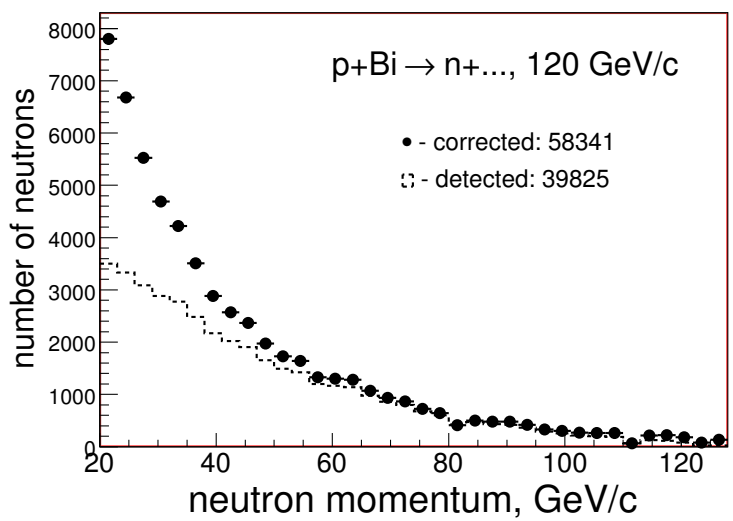
Neutron spectra from p+A interactions at 58 GeV/c



Neutron spectra from p+A interactions at 120 GeV/c







conclusions

- We presented the neutron spectra, which were corrected for the number of factors: HCAL acceptance, trigger efficiency and others. Most significant correction factor is due to of calorimeter acceptance.
- Some samples have a poor statistics: H_2 at 20 GeV and Be at 58 GeV. We might drop their for publication purpose

For next meeting:

- Systematic uncertainties
- Neutron production cross section
- Target atomic weight dependence

Back-up plots, tables

MC particles production properties at 58 GeV/c

58 GeV/c	p+p		p+C		p+Bi	
	DPMJET	LAQGSM	FLUKA	LAQGSM	FLUKA	LAQGSM
π^+	2.71	1.81	2.05	2.84	1.97	5.35
π^-	2.00	1.28	1.82	2.50	1.89	5.81
K^+	0.21	0.15	0.16	0.25	0.16	0.48
K^-	0.11	0.10	0.09	0.15	0.09	0.20
p	1.59	1.41	1.65	2.86	3.10	11.01
n	0.68	0.52	1.49	2.61	3.20	32.27
Total (charged)	6.62	4.75	5.77	8.60	7.21	22.85

Table 11: The particles multiplicity production from p+p, p+C and p+Bi interactions at 58 GeV/c using Fluka and LAQGSM generators. The multiplicities are calculated per single interaction.

MC particles production properties at 120 GeV/c

120 GeV/c	p+p		p+C		p+Bi	
	DPMJET	LAQGSM	FLUKA	LAQGSM	FLUKA	LAQGSM
π^+	-	2.36	2.56	3.87	2.53	7.72
π^-	-	1.82	2.33	3.53	2.46	8.24
K^+	-	0.25	0.21	0.41	0.22	0.79
K^-	-	0.18	0.13	0.28	0.14	0.39
p	-	1.39	1.67	2.97	2.92	11.88
n	-	0.54	1.53	2.74	3.16	33.69
Total (charged)	-	6.00	6.90	11.06	8.27	29.02

Table 12: The particles multiplicity production from p+p, p+C and p+Bi interactions at 120 GeV/c using Fluka and LAQGSM generators. The multiplicities are calculated per single interaction.