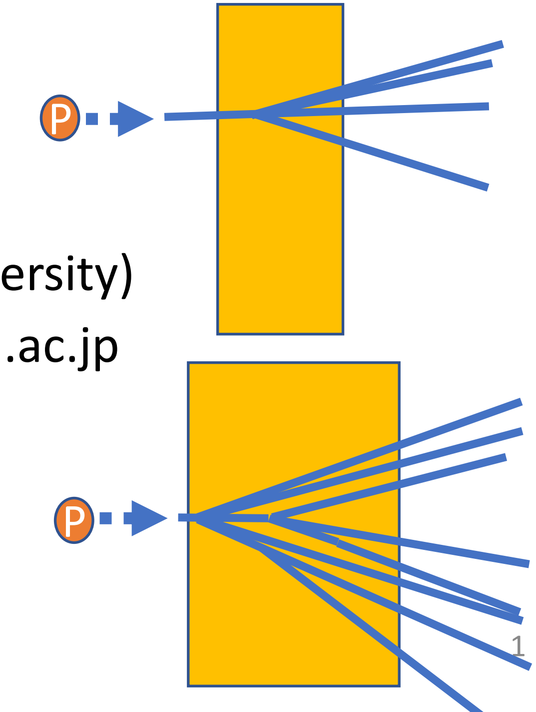
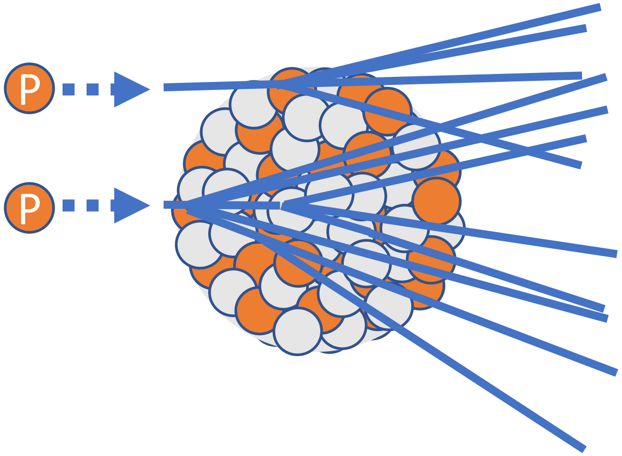
Proton interaction and Charm production study by a function of depth in nucleus.





25-26th Oct 2021

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Motivation

- I am studying DsTau(NA65) 400 GeV proton interactions and their Charm productions .
- I feel the hadron interactions are so complicated (sometimes MC generators produce different results etc.) and uncertainty related to that is our enemy or subject.

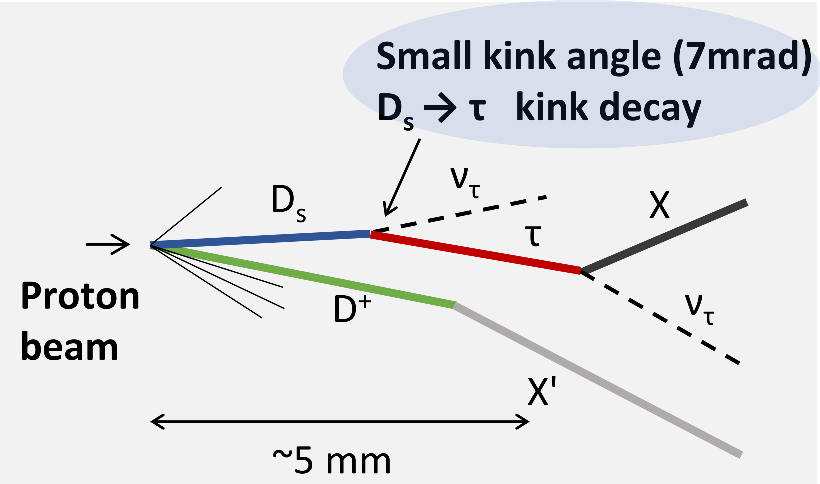
- There are nucleus A dependence on hadron interaction properties (production track multiplicity, rapidity, Charm production rate, X_F distribution .. etc.)

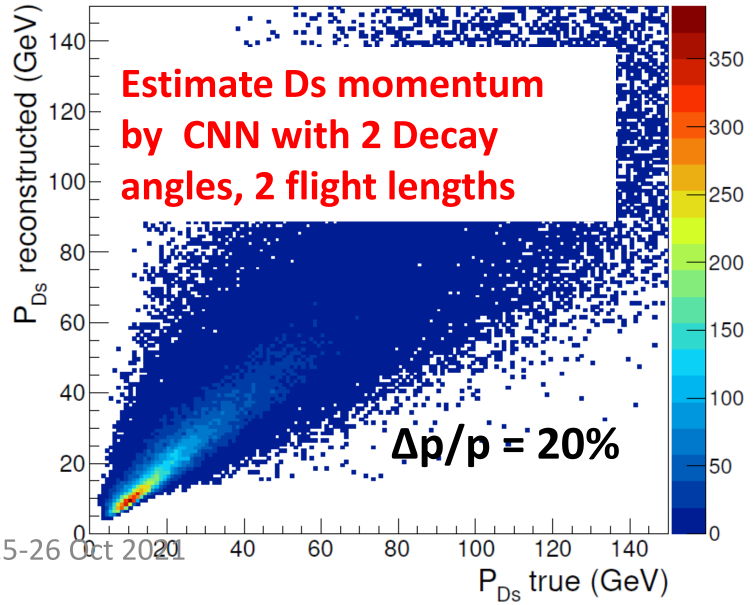
- It is nice to study /extract / understand hadron interaction, Charm production properties by simple way.

DsTau (CERN NA65)

DsTau web site
https://na65.web.cern.ch/
DsTau paper
[10.1007/JHEP01(2020)033](https://doi.org/10.1007/JHEP01(2020)033)

- **Purpose**
  - ν_τ production study
    - **By Ds differential production cross section measurement**
  - Reducing uncertainty tau neutrino flux 50% → 10%
    - Update $\nu\tau$ interaction cross section DONuT result update
    - Input nt flux for future tau neutrino experiments SHiP ν_τ etc.
  - Byproduct study
    - **Charm production: forward:、intrinsic charm exist ? Etc.**
- **The detection principle of tau neutrino production**
  - Double kinks decay + partner Charm





Estimate Ds momentum by CNN with 2 Decay angles, 2 flight lengths

Δp/p = 20%

Detector structure and multiplicity distribution

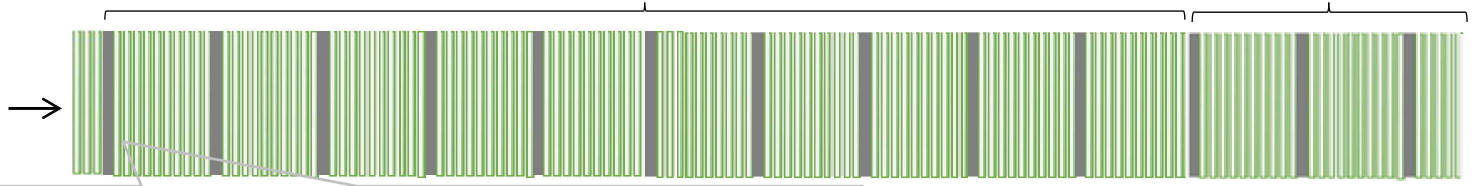
2.3×10^{8} proton x tungsten int.（4.6×10^{9} proton beam）

Pilot run 2018 and Physics run 2021~

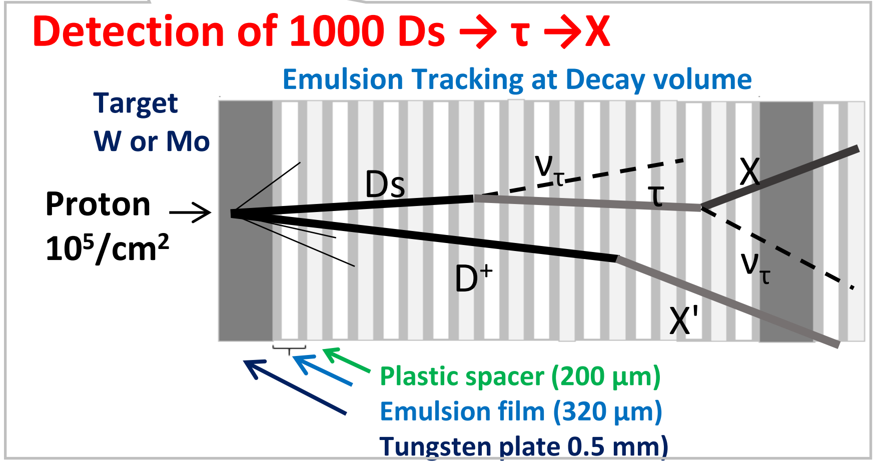
400 GeV/c Proton

10 units of target and tracking emulsion films (100 films of nuclear emulsion)

Additional two unit for down stream part momentum analyzer



Detection of 1000 Ds → τ →X



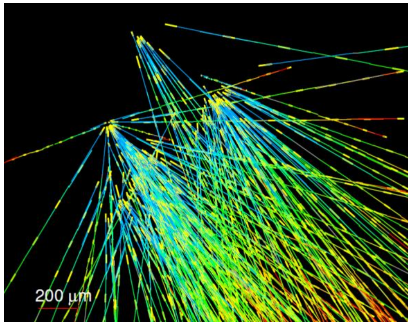
Emulsion Tracking at Decay volume

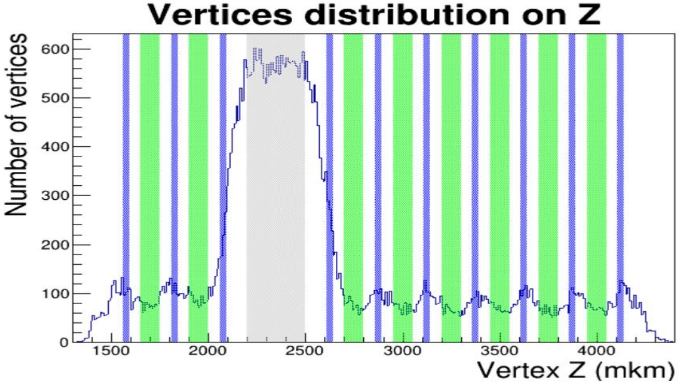
Target W or Mo

Proton 10^{5}/cm²

Plastic spacer (200 μm)
Emulsion film (320 μm)
Tungsten plate 0.5 mm)

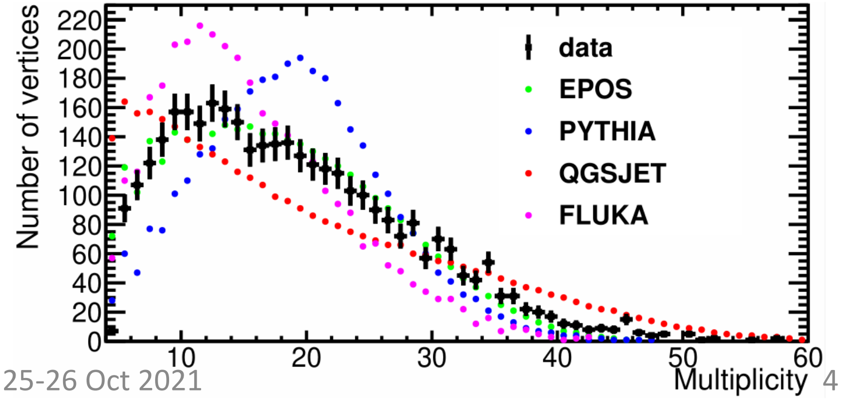
Interaction at tungsten ～500/cm²





Multiplicity distribution of tungsten interaction

(Thanks to Felix Kling for providing distributions by EPOS, PYTHIA, QGSJET)



NA65 DsTau

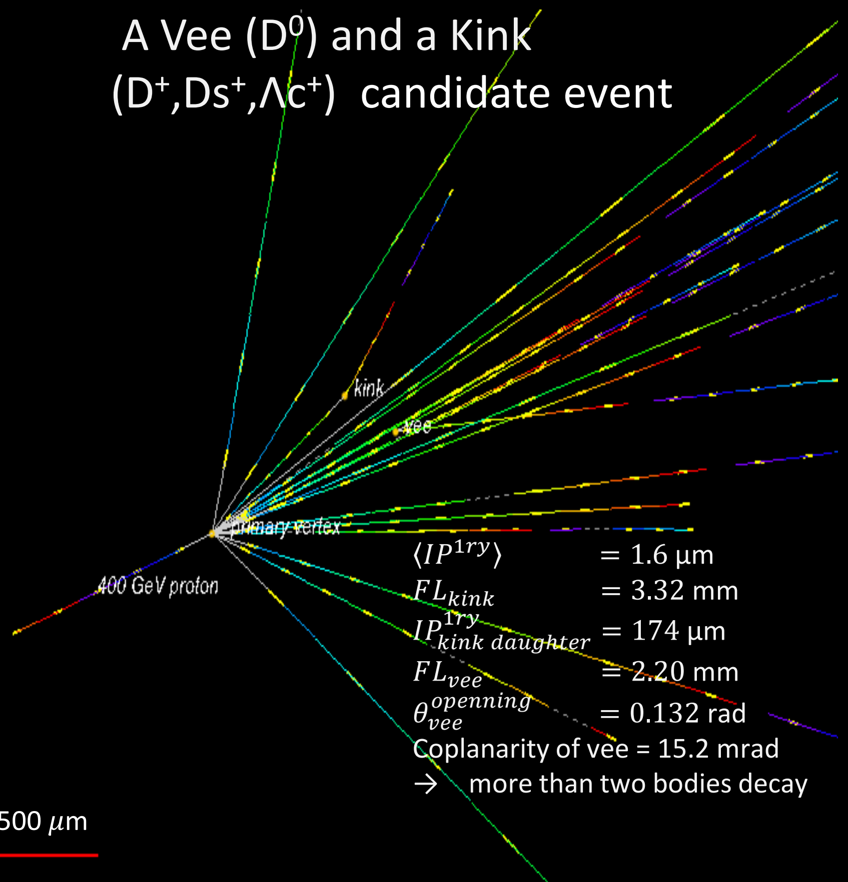
Charm decay search

- **Subsample**
- **3.4** x 10^7 **protons**
- **2.7** x 10^5 **interactions**

  （1.4 x 10^5 **interactions with tungsten）**
- **159 （115 int. at tungsten） charm pair production events detected**

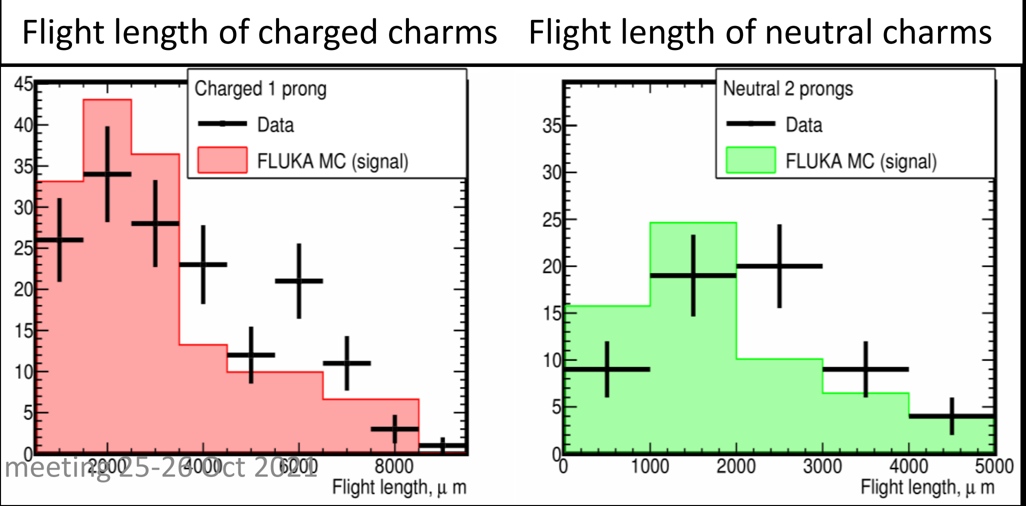
	Observed	Expected	
Vertices in tungsten	147,236	155,135	
		Signal	Background
Double decay topology	115	80.1±19.2	12.7±5.0

A Vee (D^0) and a Kink (D^+,Ds^+,Λc^+) candidate event



$\langle IP^{1ry} \rangle$ = 1.6 μm
FL_{kink} = 3.32 mm
$IP^{1ry}_{kink\ daughter}$ = 174 μm
FL_{vee} = 2.20 mm
$\theta^{openning}_{vee}$ = 0.132 rad
Coplanarity of vee = 15.2 mrad
→ more than two bodies decay

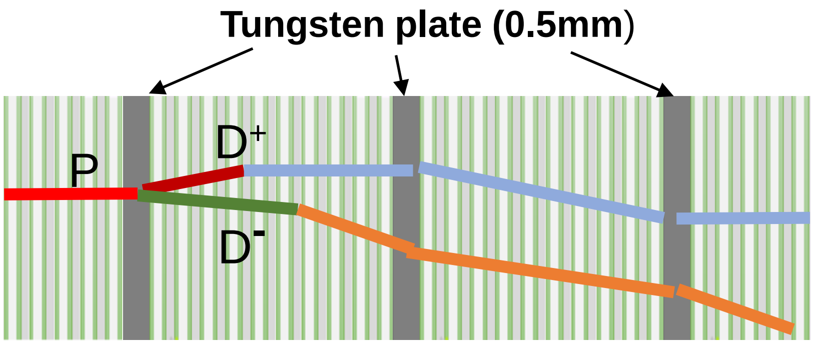
Decay volume is enough large to catch charms going forward (high energy) .
Quasi non bias charm analysis .

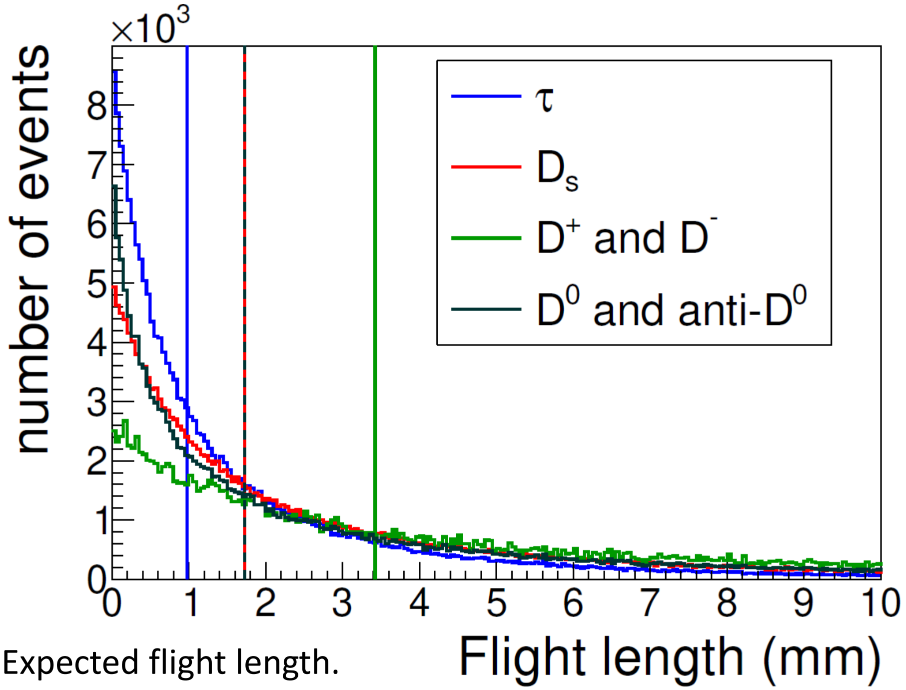

Flight length of charged charms Flight length of neutral charms

In final x1000 statistics will be available

D^+, Ds^+, Lambda_c^+ portion fit

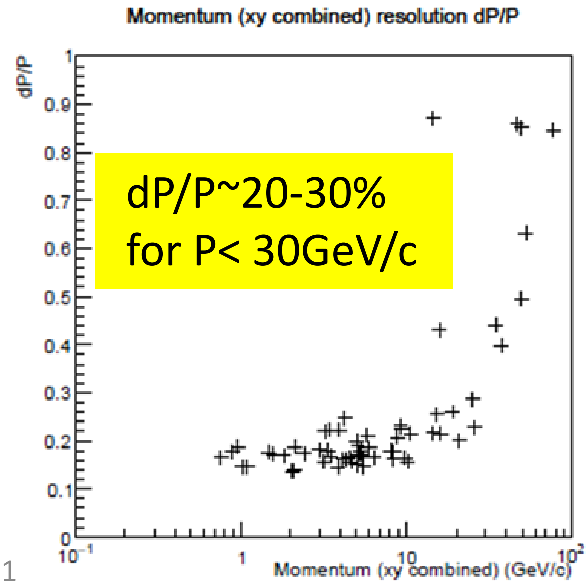
- Statistical fit of portion in charged charm is possible.
- Charm daughters momenta will be measured.
- Decay angle, flight length, daughter momentum as input for CNN and get Charm momentum .
- Distribution of proper life time ($c\tau$) will be available.





Expected flight length.
Figure.3 of JHEP01(2020)033

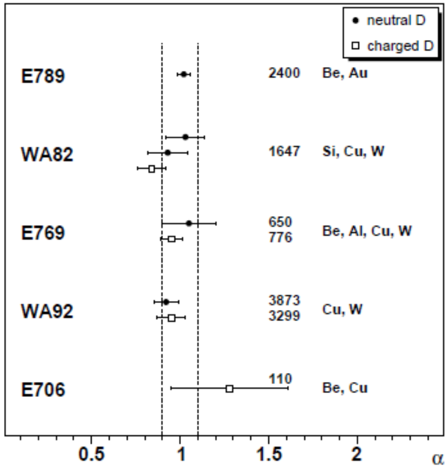
MCS scattering measurement by angle difference between tungsten plates.
1/P ~ angle difference



dP/P~20-30%
for P< 30GeV/c

Debating ..? Intrinsic Charm ?
A dependence at some Charm X_F intervals

- **SELEX** reported α of **A^{α}** dependence as **significantly less than 1**.
- There are some discussion it's **due to intrinsic charm**.
- While plenty of experiments reported **α is consistent with 1.0 @X_F~ 0** .
- DsTau can and will measure this A dependence with certain fixed intervals of X_F using about detected 10^4 - 10^5 Charms .



- X_F distribution as a function of nuclear material thickness would be interesting/ solve.

∵ α ~(2/3) indicate production at surface, α~1 indicate at anywhere in the volume.

CERN–PH–EP / 2006–013–rev
September 8, 2006

SELEX report Eur. Phys. J. C (2009) 64: 637–644

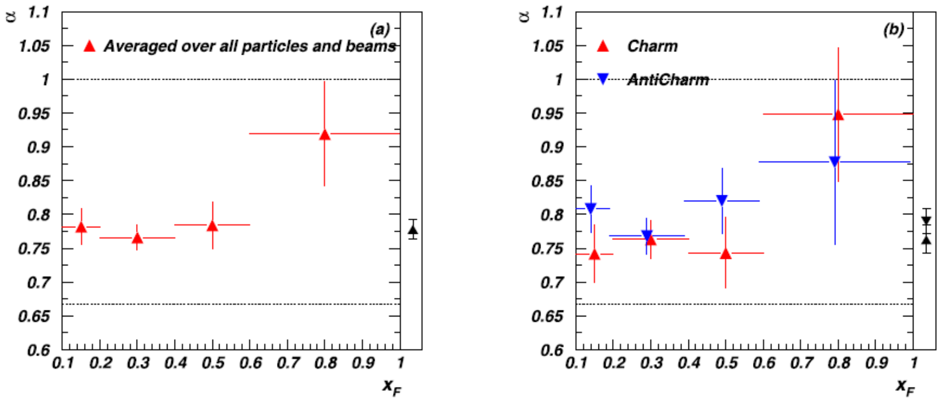


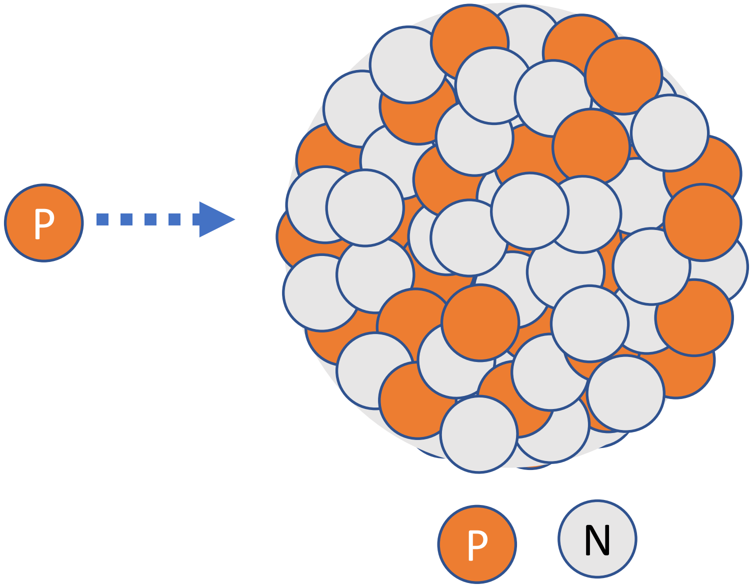
Fig. 3 Average α as function of x_F for all observed final states (**a**) and for charm and anti-charm (**b**). The data points are slightly offset to avoid overlapping of the *error bars*. Reference α values of 2/3 and 1 are shown as *dotted lines*. The points at $x_F > 1$ show the average assuming that α does not depend on x_F

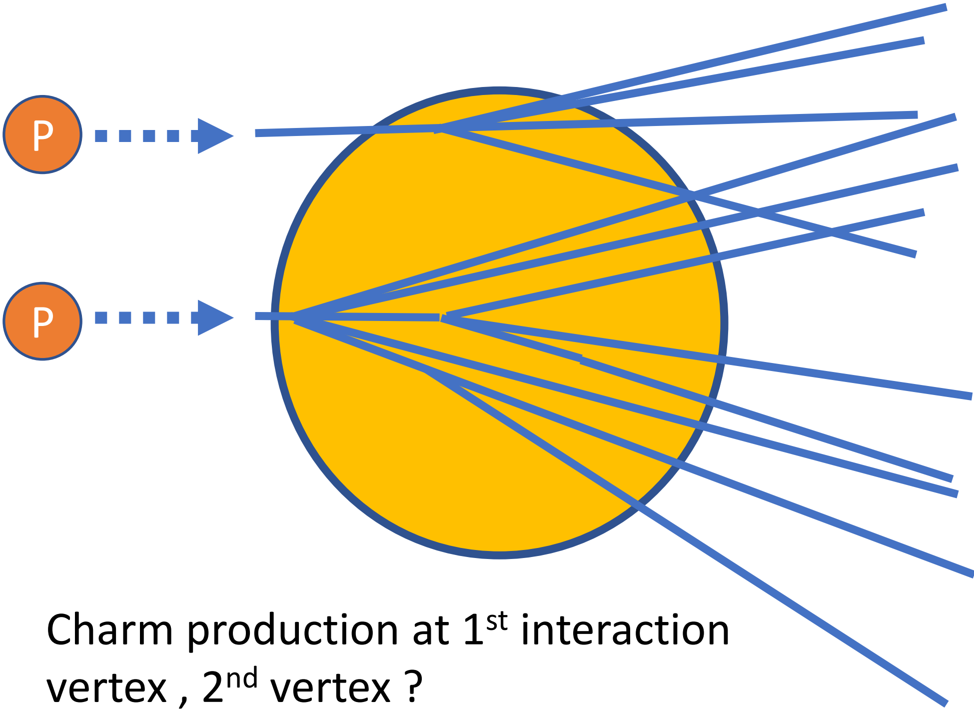
Exp.	E_{lab}[GeV] Target Phase space	Observed D mesons	α
		p-A collisions	
E789 [44]	800 Be, Au $0<x_F<0.08$, $p_T<1.1$	Be: 1360 D^0 Au: 1040 D^0	$D^0 : 1.02 \pm 0.03 \pm 0.02$
		π^--A collisions	
WA82 [52]	340 Si, Cu, W $x_F > 0.0$	Si: 102 (D^0, D^+) Cu: 528 (D^0, D^+) W: 1017 (D^0, D^+)	$D^0{+}D^+ : 0.92 \pm 0.06$ $D^0 \to K\pi : 1.03 \pm 0.11$ $D^0 \to K\pi\pi\pi : 0.93 \pm 0.11$ $D^+ \to K\pi\pi : 0.84 \pm 0.08$
E769 [126]	250 Be, Al, Cu, W $x_F > 0.0$	all targets: 650 D^0 776 D^+	$D^0{+}D^+ : 1.00 \pm 0.05 \pm 0.02$ $D^0 : 1.05 \pm 0.15 \pm 0.02$ $D^+ : 0.95 \pm 0.06 \pm 0.02$
WA92 [49]	350 Cu, W $x_F > 0.0$	Cu: W: 3245 D^0, 628 D^0 2753 D^+, 546 D^+	$D^0{+}D^+ : 0.93 \pm 0.05 \pm 0.03$ $D^0 : 0.92 \pm 0.07 \pm 0.02$ $D^+ : 0.95 \pm 0.07 \pm 0.03$
E706 [42]	515 Be, Cu $x_F>-0.2$, $1<p_T<8$	Be+Cu: 110 D^+	$D^+ : 1.28 \pm 0.33$

Table 16: Nuclear target dependence in proton and pion induced collisions. Note that D^0 and D^+ mean $D^0 + \overline{D^0}$ and $D^+ + D^-$, respectively. p_T in GeV/c.

Motivation reminder (with figure.)

- Study of inter nucleus re-interactions or fragmentation of Charm more simple way
- Pass length in the target nucleus should be a key variable of hadron interaction
- Hadron interaction, charm production analysis by pass length in the target nucleus would make things simple .





- Charm production at 1st interaction vertex , 2nd vertex ?
- Charm particle inter nuclear interaction and portion of D^0,D^+,Ds^+,Λc^+ may changed.

The Assumption applied hereafter

- Neglect size of projectile proton radius

- Nucleus is a perfect spherical object filled constant density of nucleus matter .

  Radius of a nuclei with mass number A : $r_0 A^{(1/3)}$

  $\rho(A, r) = \rho_0$ for $r \leq r_0 A^{(1/3)}$

  $= 0$ for $r > r_0 A^{(1/3)}$ $r_0 \sim 1.25\mathrm{fm}$

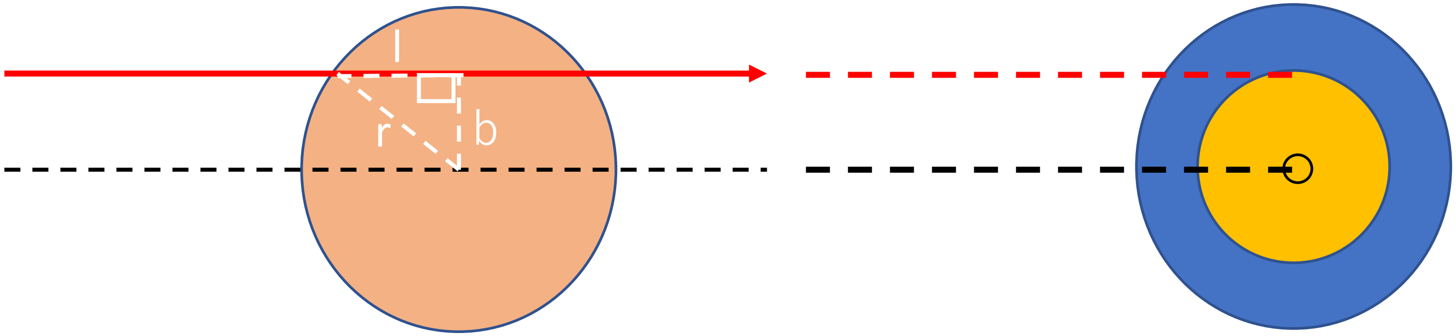
  Effect of density shoulder shape at nucleus edge
  like Woods Saxson density function could be considered as next order. (See appendix slides)

- Same reaction with a target proton and a target nucleon at high energy .

- **Same hadron interaction (Charm production) response happen if pass length in nuclear material was same . (ie. Independent on nucleus A or Z)**

- **So summarizing or studying as a function of pass length (thickness of nuclear material) would make things simpler.**

Derivation of path length distribution, dn/dL



Side view

Proton beam from right
with impact parameter b
to target nucleus whose radius r

half of path length l and r, b relation
$r^2 = l^2 + b^2$

Front view

Blue Area =Area of path length <L

$$\begin{aligned}\text{Blue Area} &= \pi r^2 - \pi b^2 \\ &= \pi(r^2 - b^2) \\ &= \pi l^2 \\ &= \pi/4\, L^2 \quad (\text{Path length } L = 2l)\end{aligned}$$

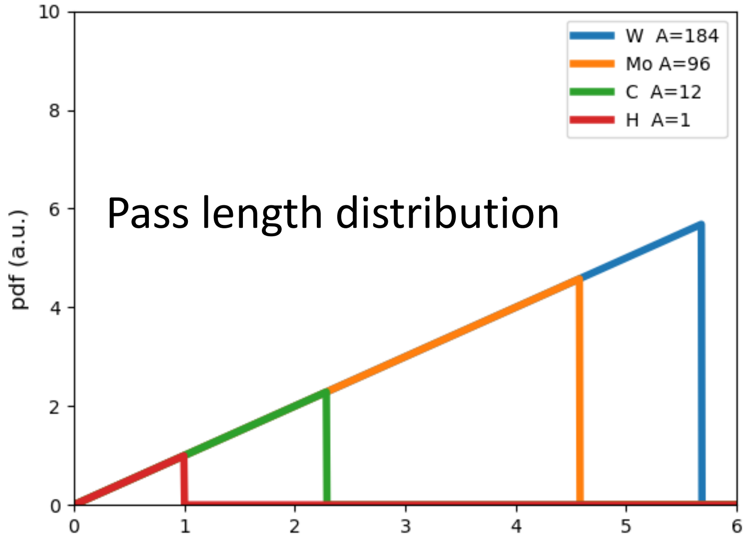
Then $dn/dL = d(\pi/4\, L^2)/dL = \pi/2\, L$

Variable change from
impact parameter(b)
to pass length (L) .

$$< A >= \int_0^R A(b) \times 2\pi b db$$

$$= \int_{2R}^0 A(L) \times -\frac{2\pi}{4} L dL = \int_0^{2R} A(L) \times \boxed{\frac{\pi}{2}} L dL$$

Study by fixed pass length



Pass length distribution

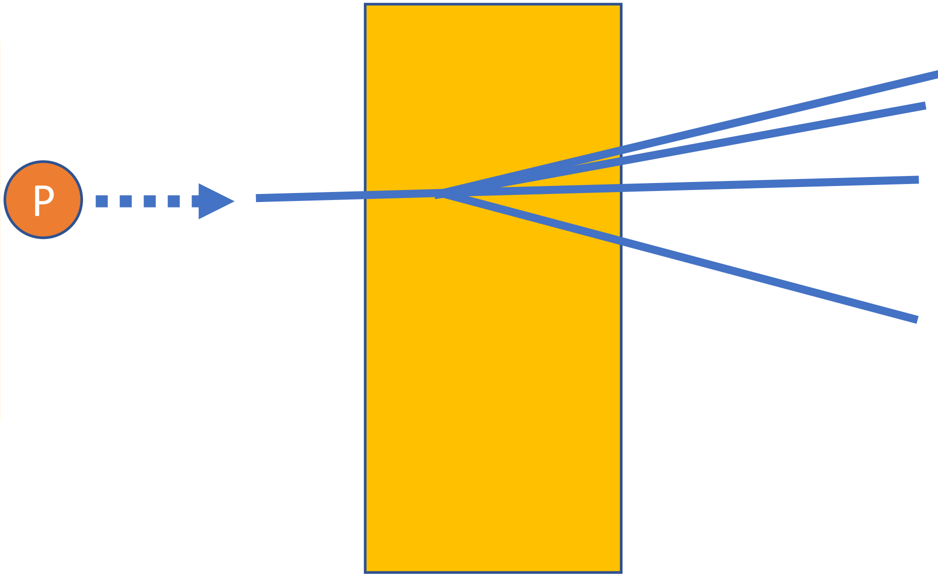
- dn/dL = cont. x L
- No nucleus dependence
  except maximum pass length.
- **TOTAL dn/dL distribution of Smaller nucleus is a PART of Larger nucleus's one ! (This is the key)**
- This makes possible to perform a fixed pass length analysis, by comparing hadron interaction properties with different A materials.

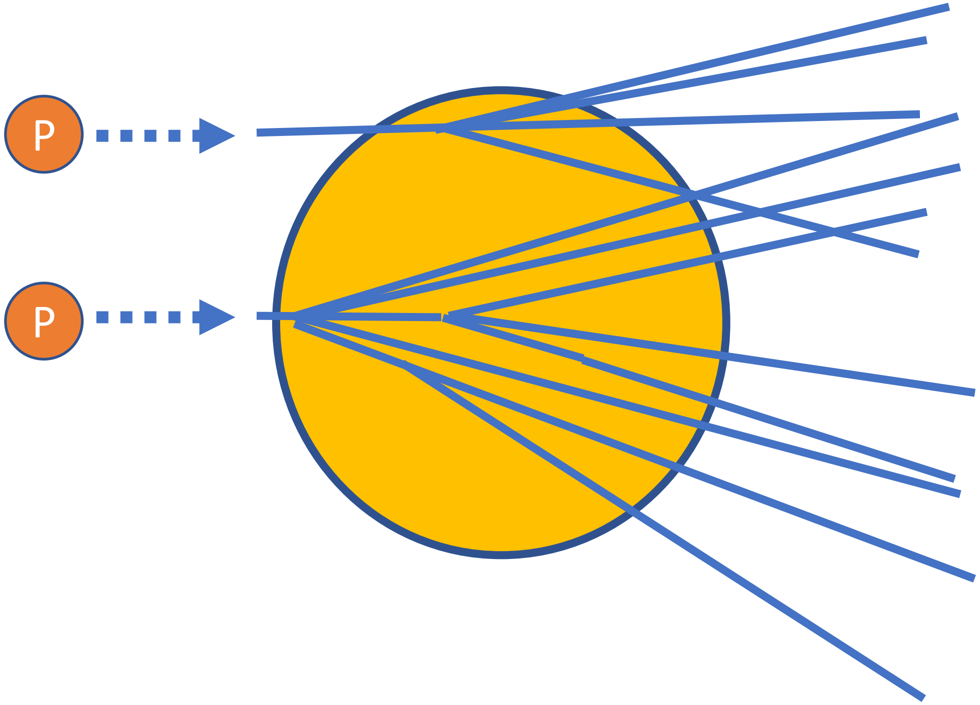
- $H(r1<r<r2,\ (x,..)\ ) = \{\ H(A2, x,..) - \sigma 1/\sigma 2\ H(A1, x, \ldots)\ \} / (1- \sigma 1/\sigma 2)$
  σi : interaction or charm production cross section for target Ai
- Histogram "H" can be a distribution on any variable(s) (x,….).
  multi-dimensional distribution possible if enough statistics available.

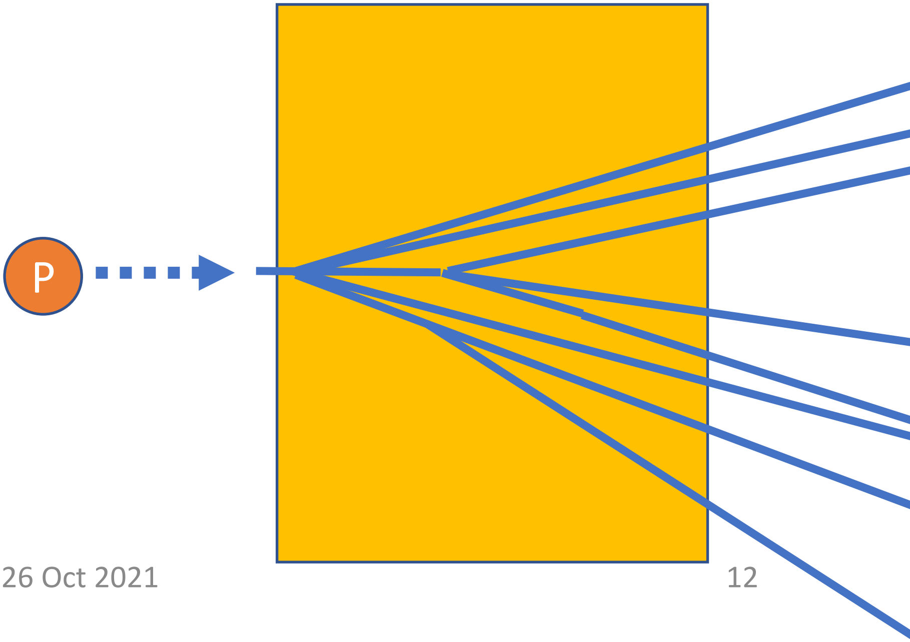
Pass length(thickness of nuclear target) fixed analysis

Interaction result by nucleus is result of mixed pass length.

It can be separate into several fixed pass length (thickness) samples .



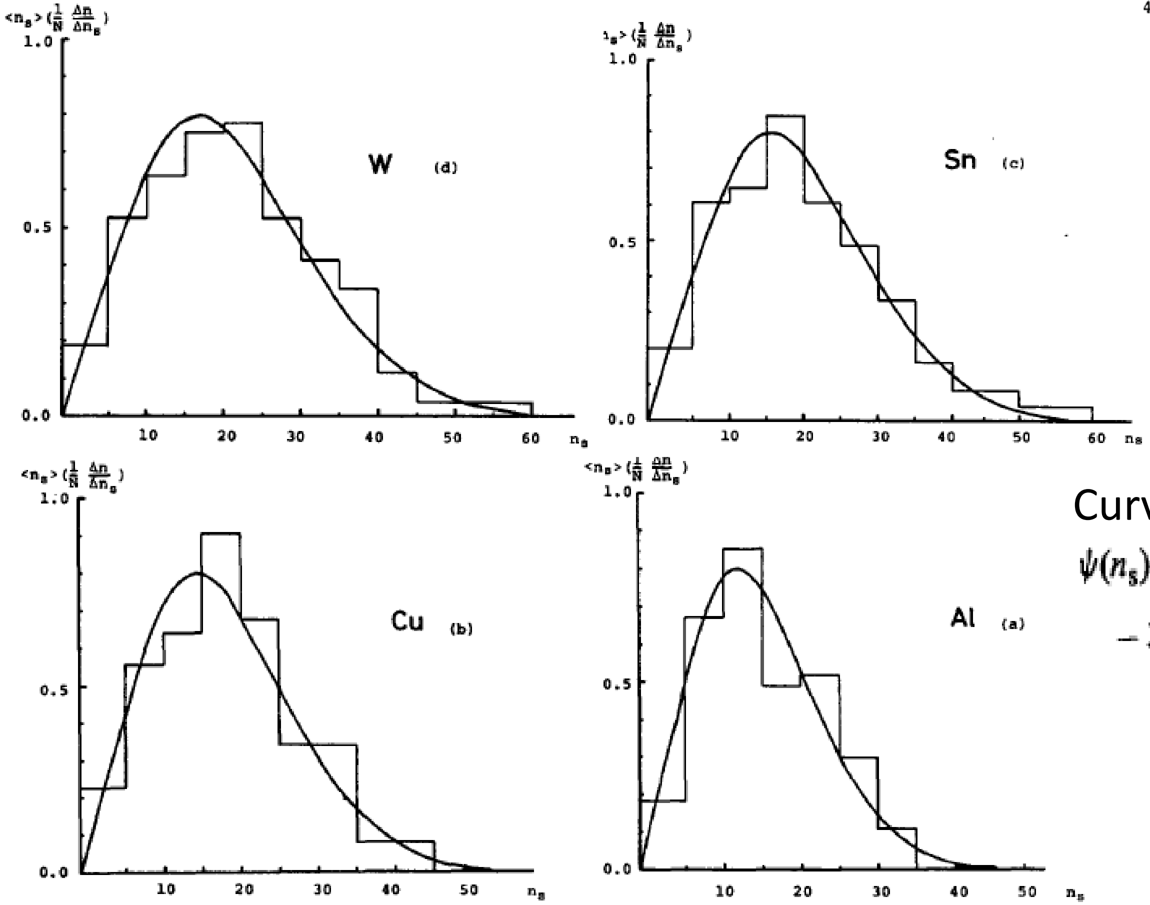


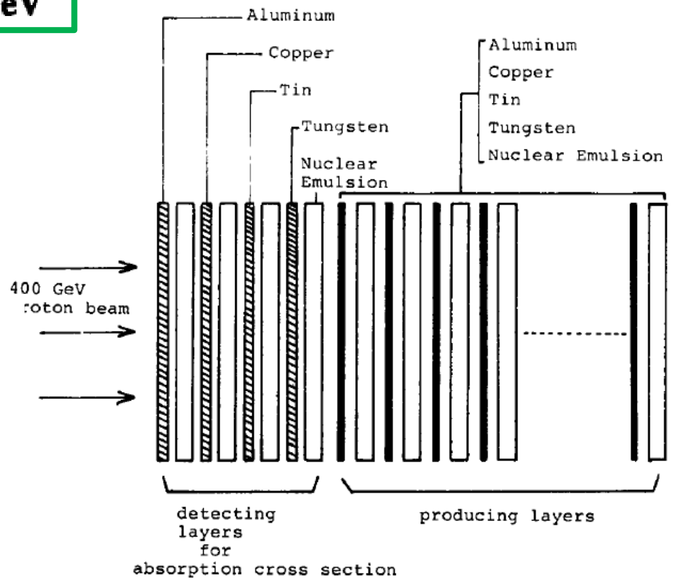


A demonstration with data from Nuclear Physics B 152 (1979) 376-389

A DEPENDENCE IN PROTON-NUCLEUS INTERACTIONS AT 400 GeV

Multiplicity distribution with several materials





chematic view of our emulsion chamber. The thicknesses of the metal plates in the ers are 500 μm for aluminum and copper, 300 μm for tin and 200 μm for tungsten; es in the producing layers are 100 μm for aluminum, copper and tin and 60 μm for

Curve is a scaling function

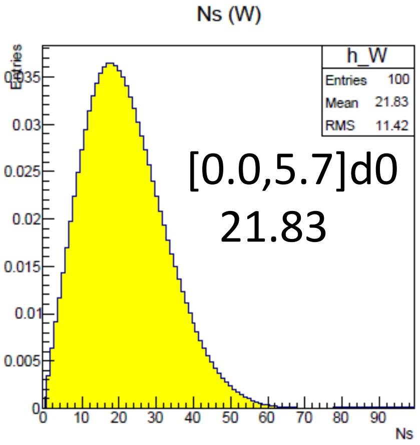
$$\psi(n_s) = \{1.895(n_s/\langle n_s\rangle) + 16.85(n_s/\langle n_s\rangle)^3 - 3.32(n_s/\langle n_s\rangle)^5 + 0.166(n_s/\langle n_s\rangle)^7\} \exp\{-3.04(n_s/\langle n_s\rangle)\} .$$

	Z	A	A^(1/3)	Sig(mb)
Al	13	27	3	438
Cu	29	64	4	856
Sn	50	119	4.9187	1376
W	74	184	5.6877	1943

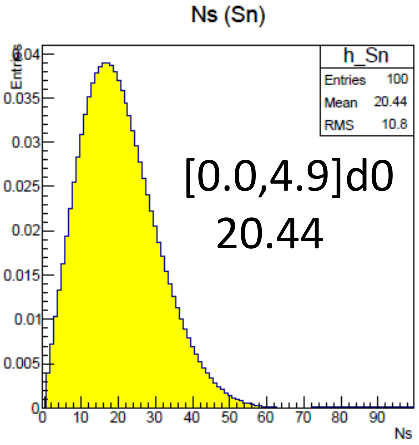
A demonstration with data from Nuclear Physics B 152 (1979) 376-389

Distribution by fixed thickness

Original distributions by the function

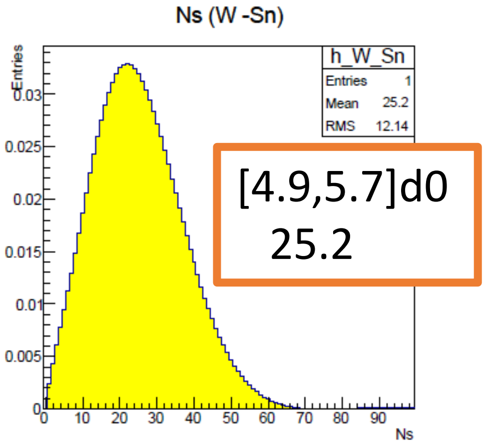

Ns (W)

[0.0,5.7]d0
21.83

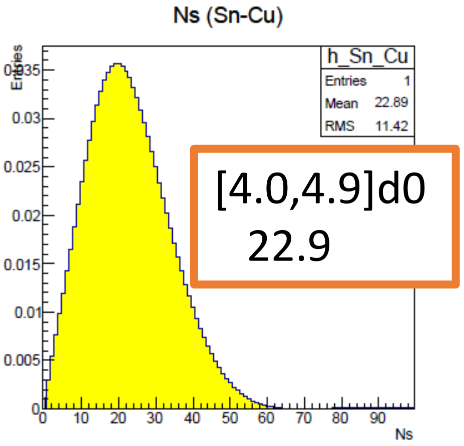

Ns (Sn)

[0.0,4.9]d0
20.44

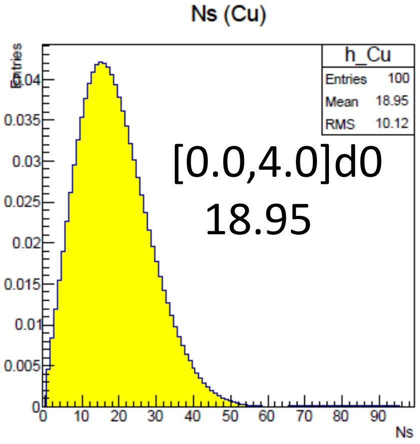
Thickness fixed distributions


Ns (W -Sn)

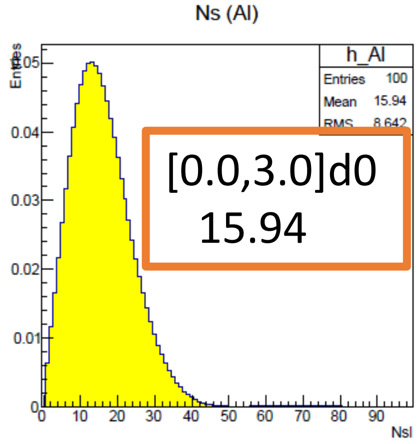
[4.9,5.7]d0
25.2


Ns (Sn-Cu)

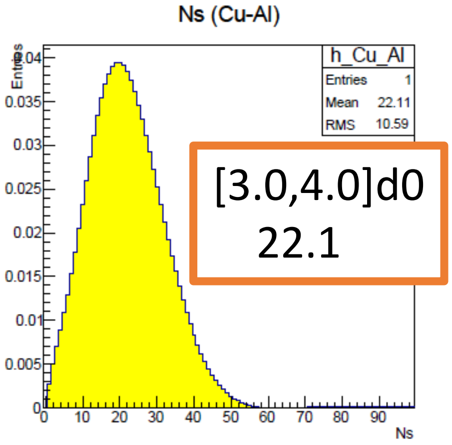
[4.0,4.9]d0
22.9


Ns (Cu)

[0.0,4.0]d0
18.95


Ns (Al)

[0.0,3.0]d0
15.94


Ns (Cu-Al)

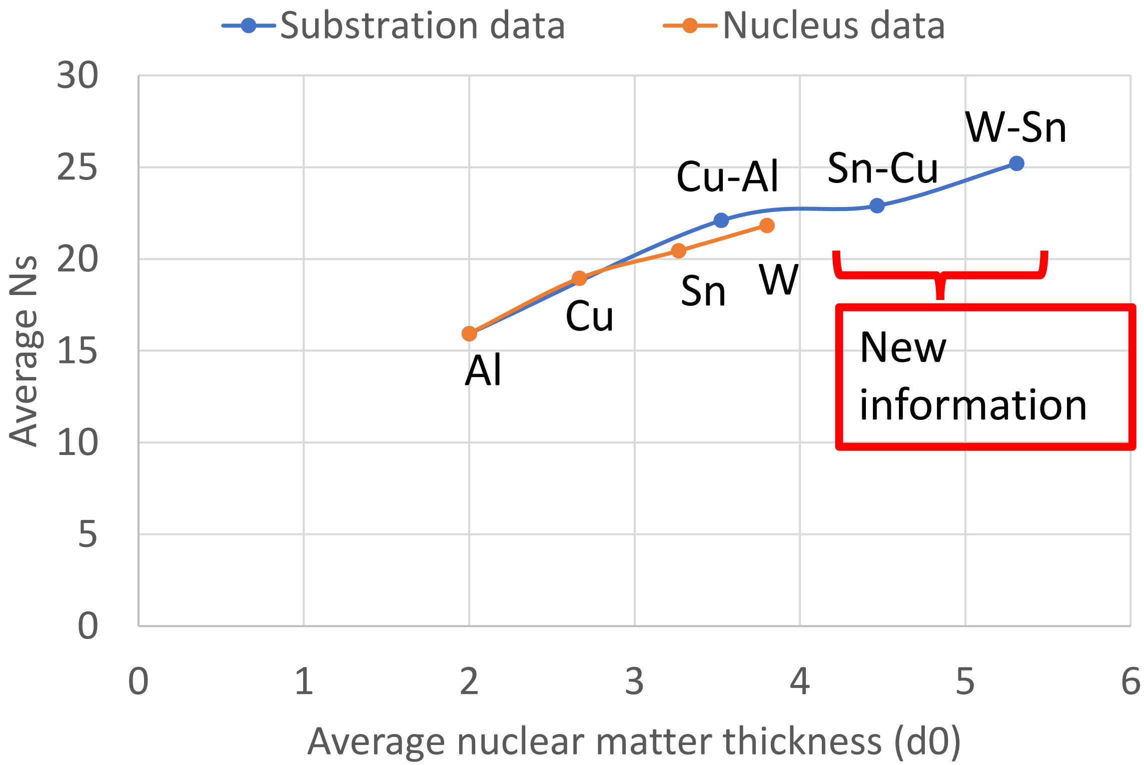
[3.0,4.0]d0
22.1

	Z	A	A^(1/3)	Sig(mb)
Al	13	27	3	438
Cu	29	64	4	856
Sn	50	119	4.9187	1376
W	74	184	5.6877	1943

A demonstration with data from Nuclear Physics B 152 (1979) 376-389

Ns as a function of target nuclear matter thickness

- 400 GeV proton injection.
- **Succeed extract more information (thickness > 4d0) from the original data.**
- It looks like NS continuously increasing with thickness of target nuclear matter thickness.



	Z	A	A^(1/3)	Sig(mb)
Al	13	27	3	438
Cu	29	64	4	856
Sn	50	119	4.9187	1376
W	74	184	5.6877	1943

DsTau case
Mass number A & Expected Radius

- By pick up target element H, C, Al, Fe, Mo, W
- By adding target material C, Al, Fe

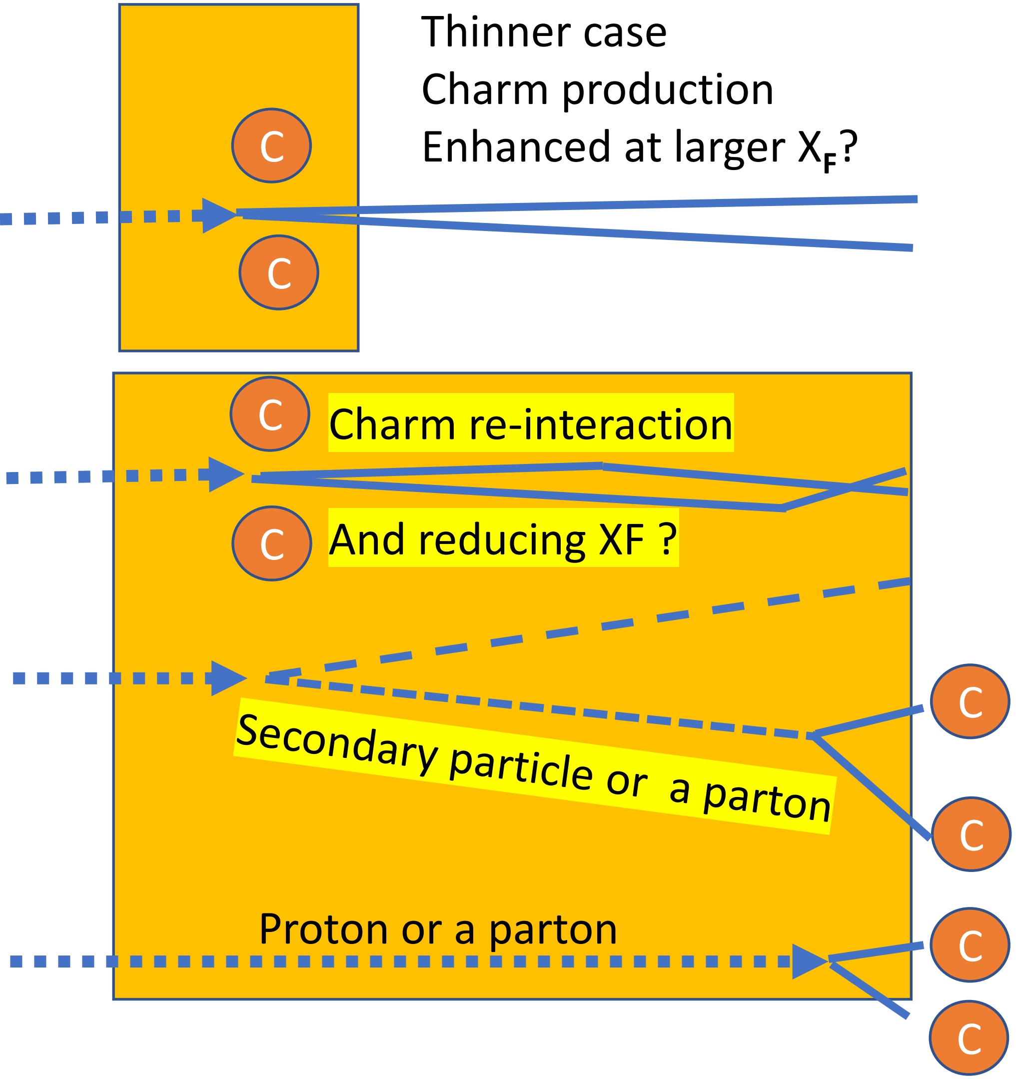
  Pass length [0-1], [1-2.3],[2.3-3],[3-3.8],[3.8-4.6],[4.6-5.7] (d0) fixed sample available.

  d0 : diameter of proton
- Elements with Green color are detector component, Target, { Composite, (Emulsion, Plastics) }.

Element	Z	A	A**(1/3)	P(W)
H	1	1	1	
C	6	12	2.289428	
O	8	16	2.519842	
Al	13	27	3	
Fe	26	56	3.825862	
Br	35	80	4.308869	
Mo	42	96	4.578857	0.64809
Ag	47	108	4.762203	
W	74	184	5.687734	
Pb	82	207	5.915482	

Sep22-Oct06 2021
Beam exposed to
Mo target .
Data Available soon !

Nuclear Material effect to be checked for charm pair production events.



Thinner case
Charm production
Enhanced at larger X_F?

Charm re-interaction

And reducing XF ?

Secondary particle or a parton

Proton or a parton

- Charms energy lower at deep production
  Charm energy (X_F , Pt) distribution.
  Charm's slope distribution.
  Forward contributions.
  Relation with track multiplicity of proton i
- How much fraction of Charms production
  by secondary particles in deeper place ?
- Charms (D0,D+,Ds+,Lambda_C+) portion
  stable as a function of depth ?
- Pair Charm particle correlation,
  Emitting angle , $\theta 12$, $\phi 12$
  X_F1, X_F2

Summary

- Pass length in nucleus would be a key for hadron interaction study.
- Thicker nuclear material(pass length) would make more (re-) interactions and make things complex.
- While typical hadron interaction study is done by target nucleus whose pass length is mixture of thin and thicker .
- Using several A target nucleus, pass length (nuclear thickness) fixed analysis is possible .

- Additional target to DsTau(NA65) , C(graphite), Al, Fe will make analysis possible with

  the pass length intervals of [0-1], [1-2.3],[2.3-3],[3-3.8],[3.8-4.6],[4.6-5.7]d0(proton diameter).

- This analysis method could be applied not only hadron interactions but also neutrino interaction (FASERν , SND@LHC, SHiPν etc.) by using several target materials if statistics are enough.

- Any comments and suggestions are well come, please send to sato@flab.phys.nagoya-u.ac.jp .

  Is the method (Useful / Useless) ? .

  What kind of analysis, variables could be useful to extract hadron interaction features

  or to reduce current uncertainty by analysis with a function of nuclear material ?

Appendix

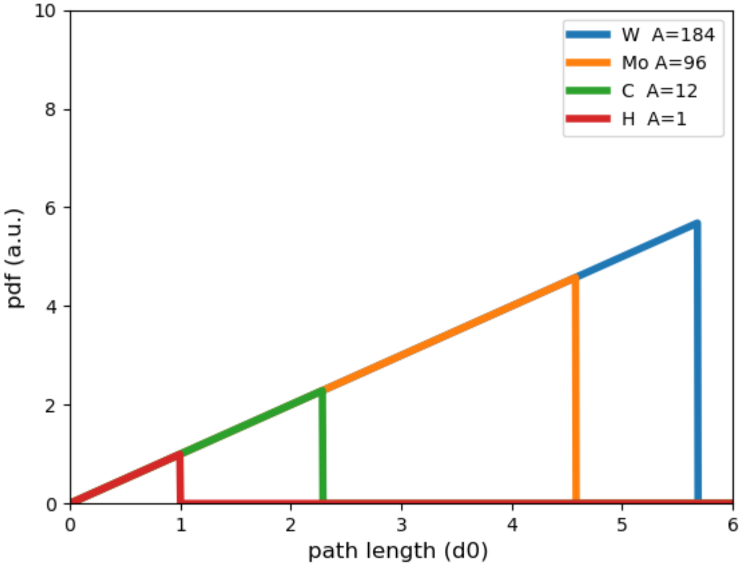
Expected interaction cross section of the model

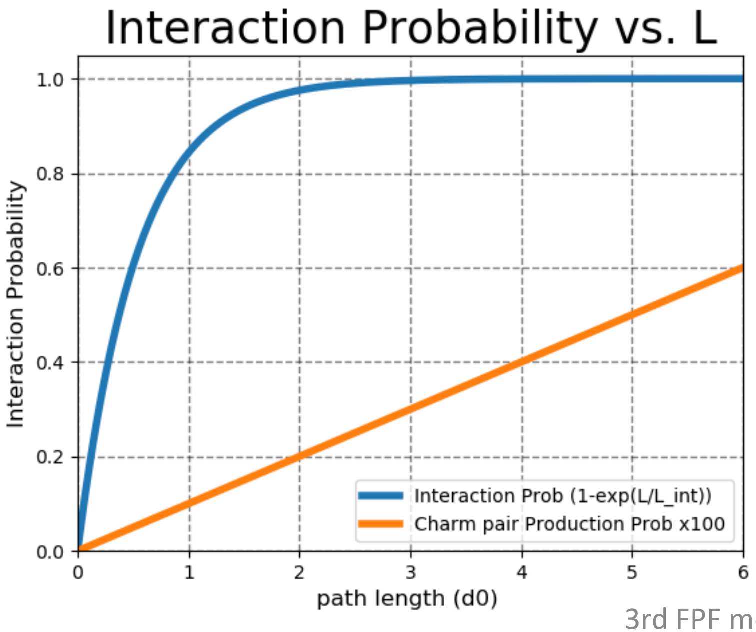
- The interaction cross section can be calculated with interaction probability function Prob(L) .
- $Sigma = \int_0^{2R} Prob(L) \times \frac{\pi}{2} L dL$
- $Prob(L) = 1. - \exp(-L/\lambda)$

λ is the mean free path of the considered process .

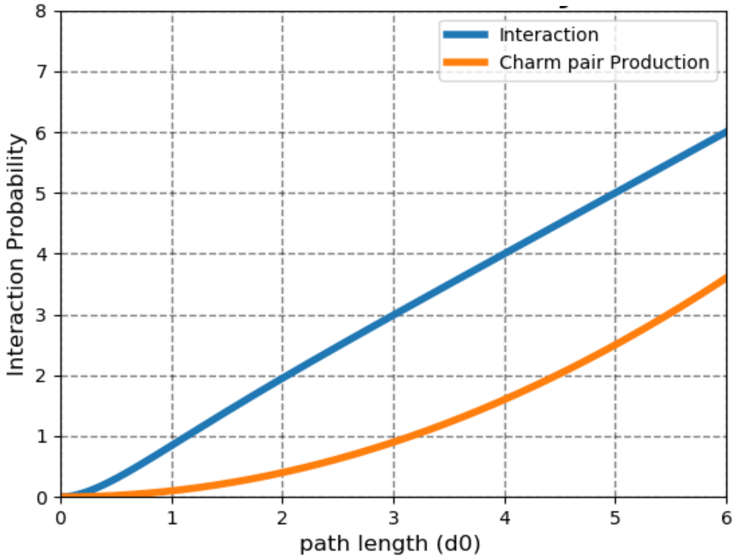
Integral can be easily done at two extreme cases

1. $\sigma(\mathrm{int}) = \pi r^{2/3} - \pi\lambda^2/2$ @$2r >> \lambda$
2. $\sigma(\mathrm{int}) = 4\pi/3\lambda\ r^3 =$ (Nucleus Volume) / λ @$2r << \lambda$





Prob(L)*dn/dL vs.L

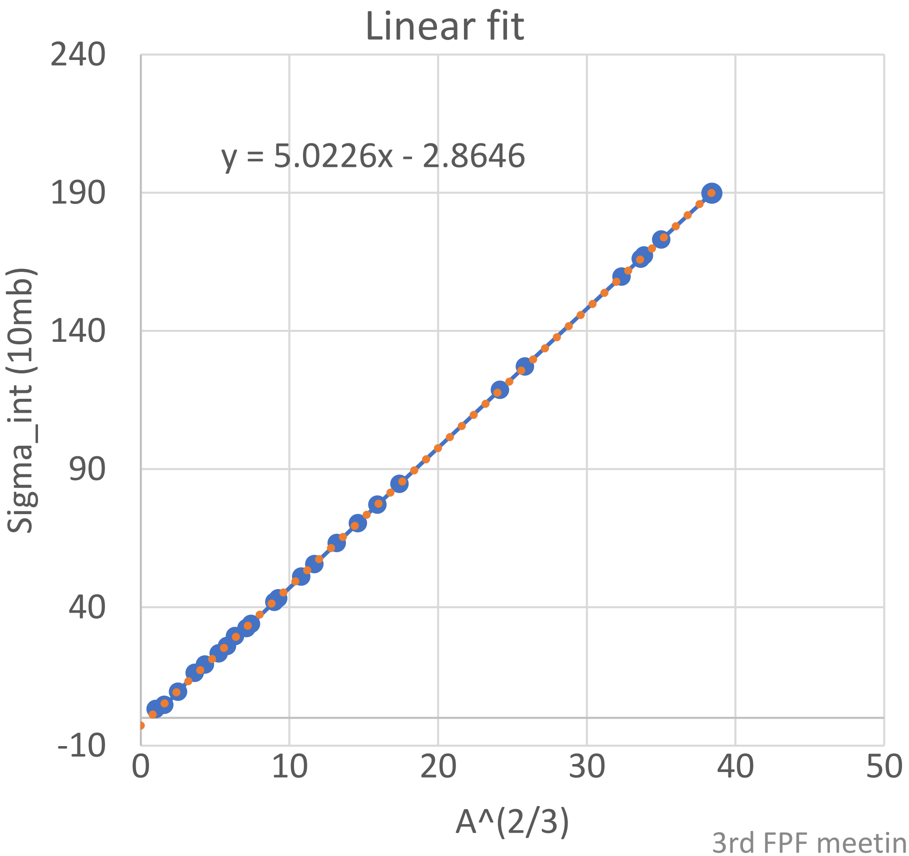


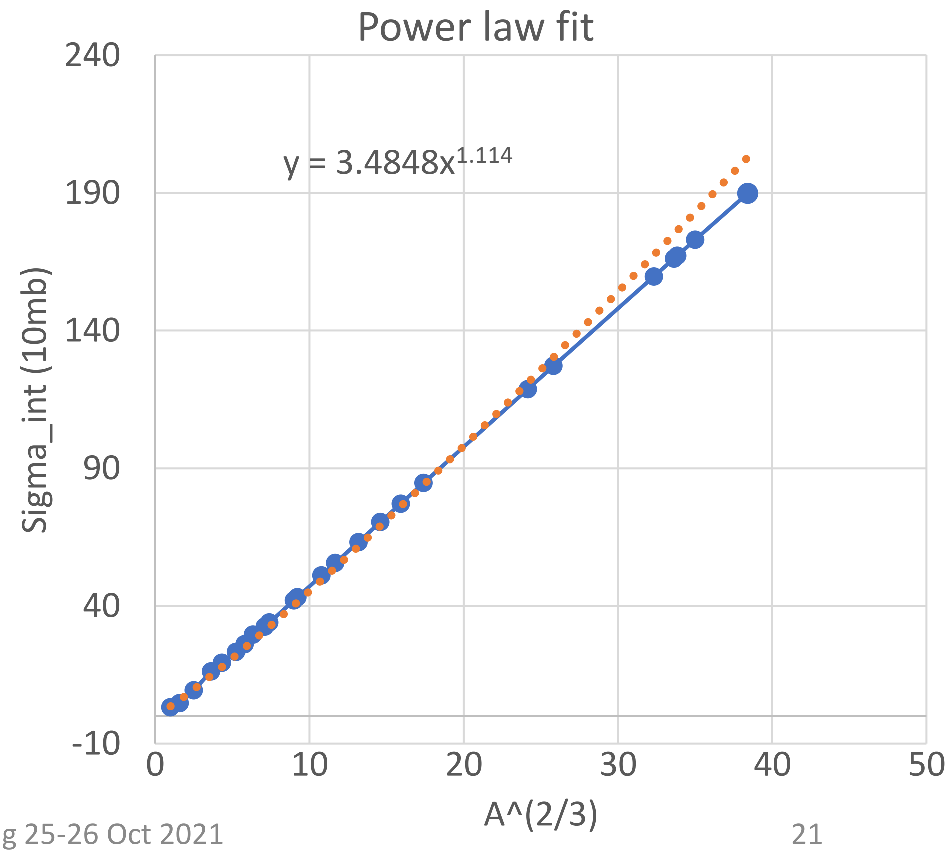
Interaction Cross section calculation with λi values in PDG (based on Glauber model calculated @200GeV/c neutrons, https://pdg.lbl.gov/2020/AtomicNuclearProperties)

Linear fit is better than Power law fit (A^{α} α=1.114*(2/3)~0.743).

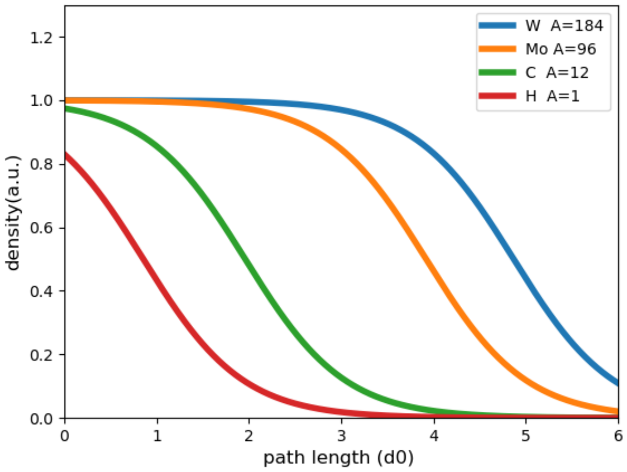
$$\sigma_{\text{int}} = 50.226\ A^{(2/3)} + 28.65\ \text{mb} = \pi\ (1.264\ \text{fm})^2 A^{(2/3)} - \pi/2\ (1.350\ \text{fm})^2$$

Interpreted as interaction mean free pass in nucleus λ= 1.350 fm





Woods Saxon density effect consideration



- $\rho(r) = \dfrac{\rho_0}{1+\exp(\frac{r-R}{a})}$

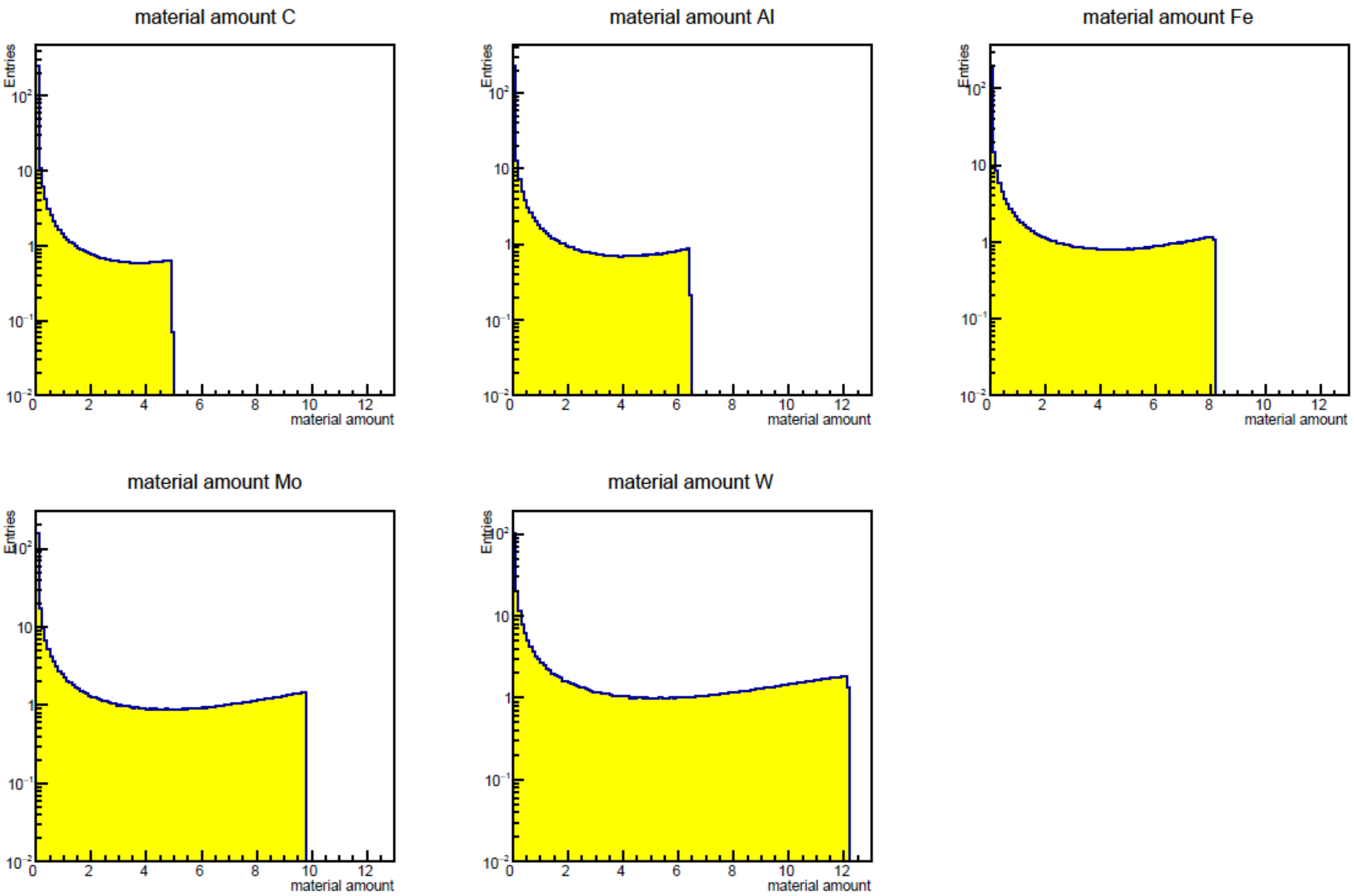
R: Woods Saxon radius of the nucleus ~1.07 $A^{(1/3)}$ fm

a ~ 0.54 fm, ρ_0~0.16fm^{-3}

- A new parameter : pass material (M) as "pass length (L) x density $\rho(r)/\rho0(r)$" instead of pass length (L) is introduced.
- Then calculating dn/dM .
- Some results in next pages

dn/dM distribution for some targets

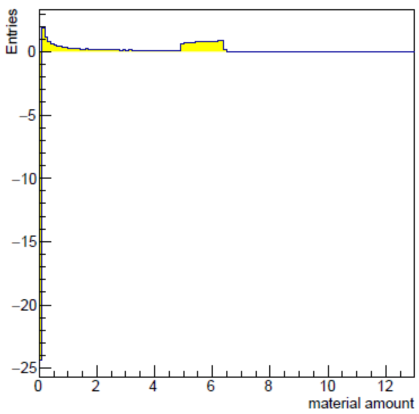
- There are large peak at M close to 0.

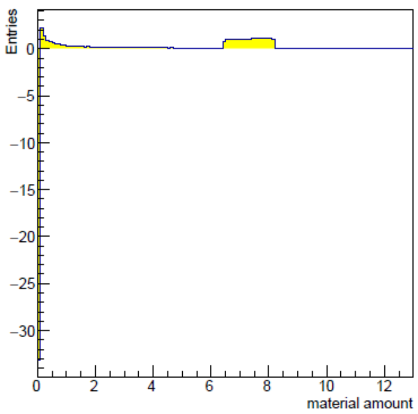


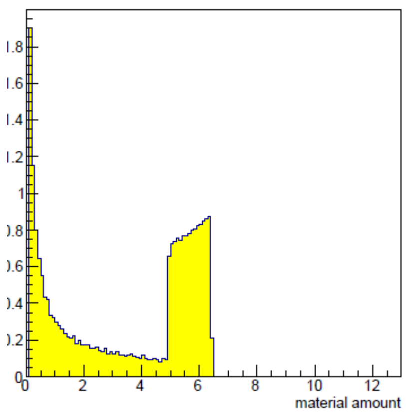
Substruction of smaller nucleus distribution

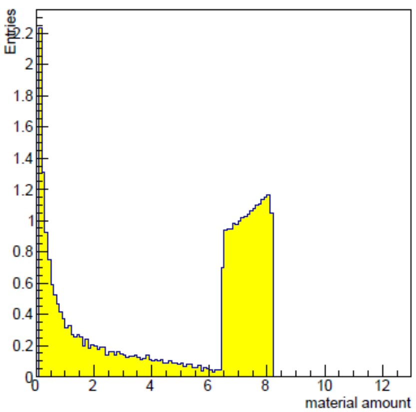
- Large negative spike at M ~0 .   ie. Smaller nucleus have much thin density pass.
- Negative spike at only <0.1 ρ_0 (fm) and it would be too amount of material to interact. It would be neglectable.
- Expected shape (ie. limited M interval) at large M end.
- Woods Saxon effect remain at small M (<4) part especially small nucleus.

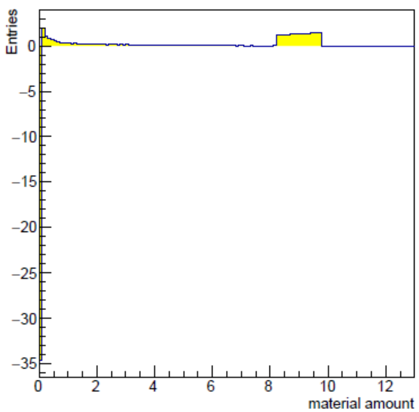
Histogram without negative spike

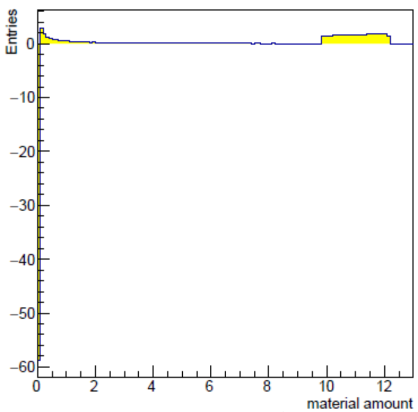

material amount Al-C

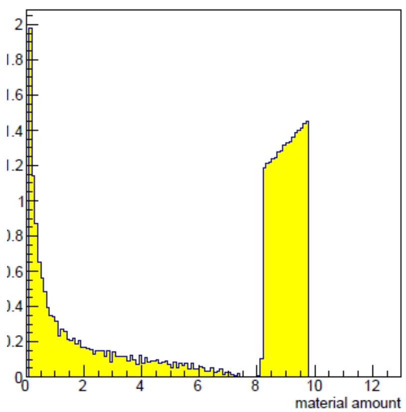

material amount Fe-Al

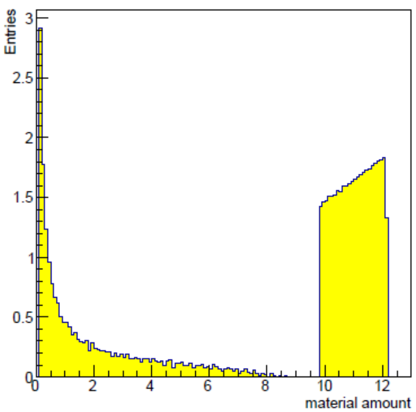

material amount Al-C


material amount Fe-Al


material amount Mo-Fe


material amount W-Mo


material amount Mo-Fe


material amount W-Mo

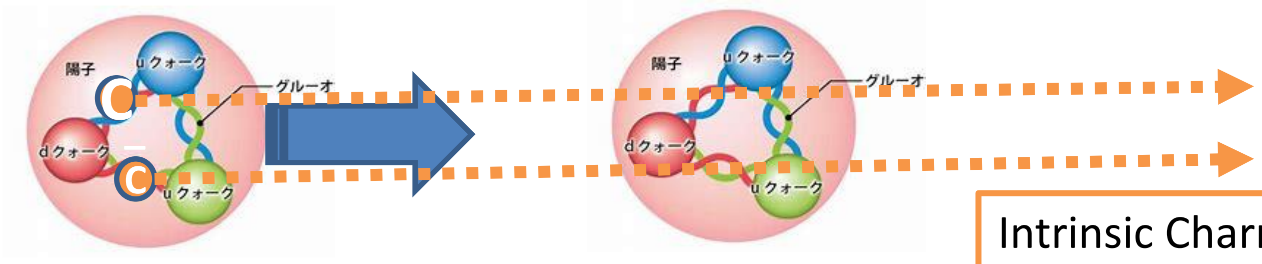
Back up

Intrinsic (valence quark like) charm ??

Two case could be considered and both cases can be analyzed in DsTau.

1）Intrinsic Charm in beam proton.

The Charm became forward going high energy .



Beam proton

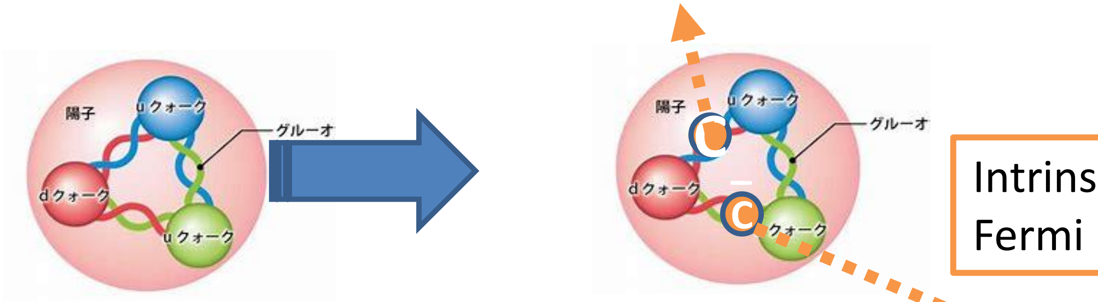
Target proton

Intrinsic Charms
Carry significant part of
beam proton’s momentum

2）Intrinsic Charm in target nucleon.

It would be a soft Charmed hadron.

Could it be captured in the target nucleus (ie. Charmed Hyper Nucleus) ?



Intrinsic Charms in Soft production
Fermi momentum + α ??

Beam proton

Target proton

Schedule
Physics run(NA65) in 2021 -2022

2016 test beam exposure

- Test for detector structure

2017 test beam exposure

- Improvement of detector structure
- Improvement beam exposure scheme

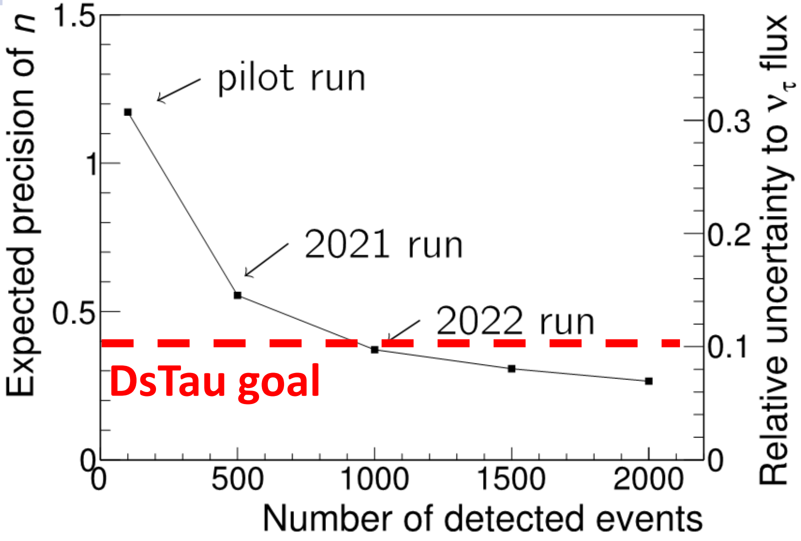
2018 Pilot run

- **1/10 accumulation events scale**
- **ν_τ flux∼30% uncertainty**
- **DONUT update ν_τ cross section**

2021-2022 Physics run

- **1000 detected $D_s \to \tau \to X\ \nu_\tau$**
- **ν_τ flux uncertainty∼10%**

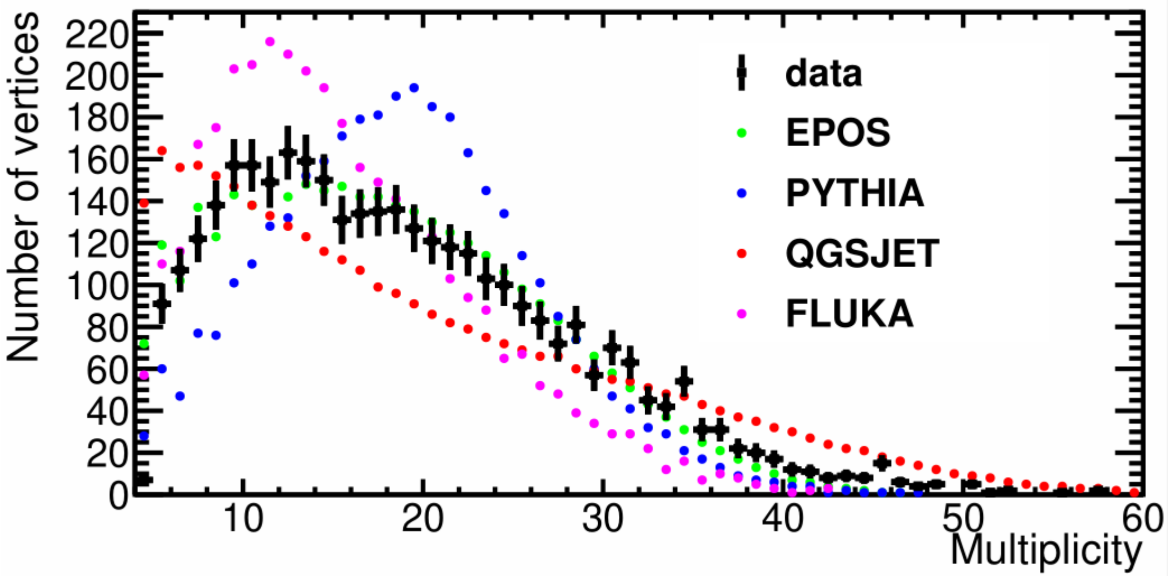
	detector modules	Nuclear emulsion(m^2)
Pilot run 2018	30 (=1)	49
Physics run 2021	**150 (x5)**	**246→ 100**
Physics run 2022	**190 (x6.3)**	**312→ 458**

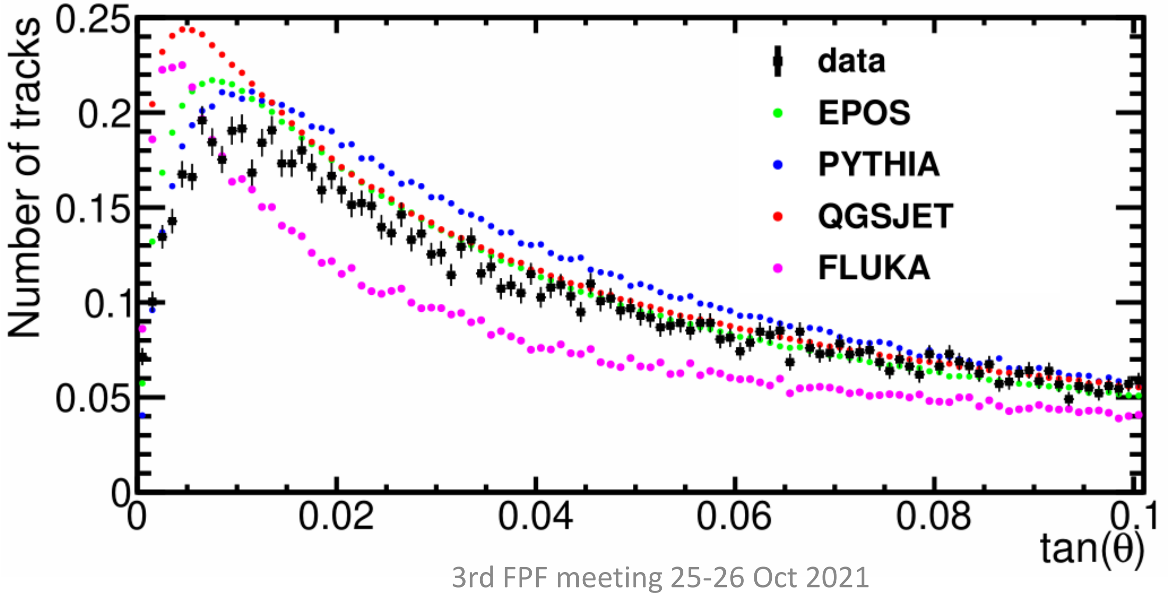


- 2021 Sep22 to Oct06 beam exposure done
- Smaller size than original schedule due to COVID19.

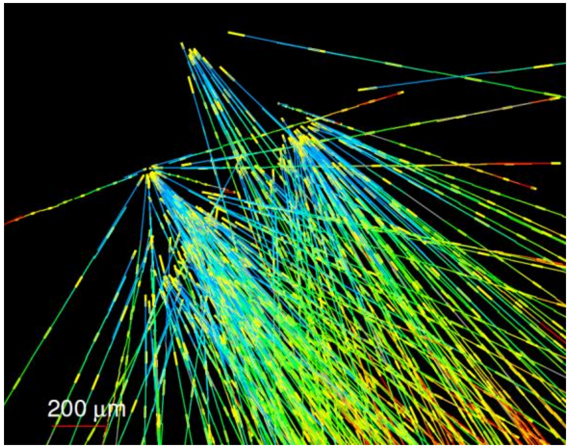
$$\frac{d^2\sigma}{dx_F\,dp_T^2} \propto \underbrace{(1-|x_F|)^{\boxed{n}}}_{\text{longitudinal dependence}}\ \underbrace{\exp(-bp_T^2)}_{\text{transverse dependence}}$$

Multiplicity and slope distribution comparison with MC Generators

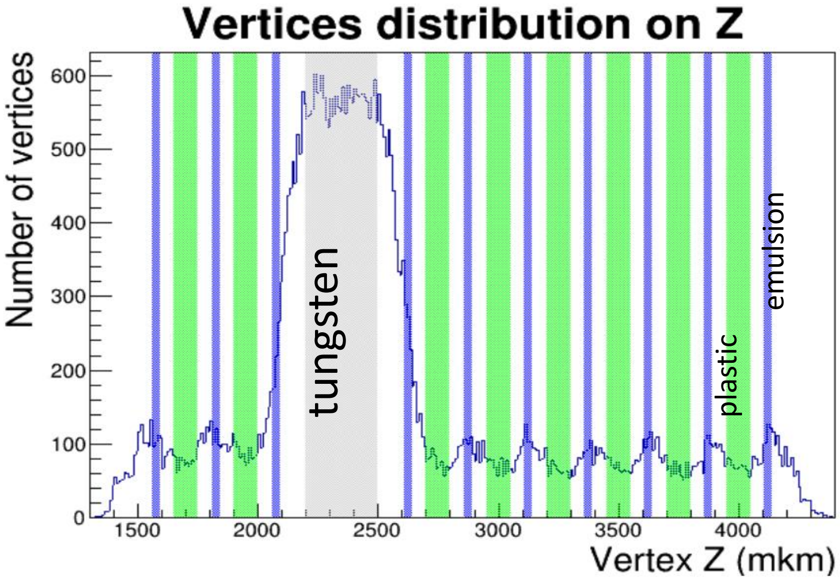


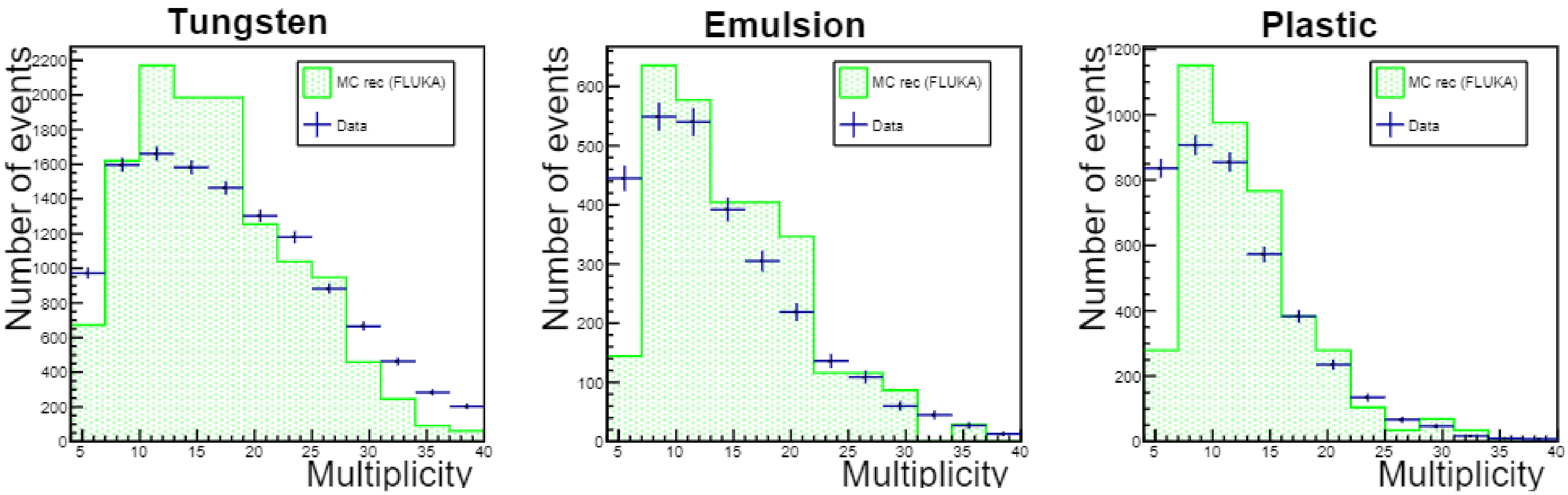


Proton-target nucleus interaction



Interaction density par a tungsten plate
~500/cm

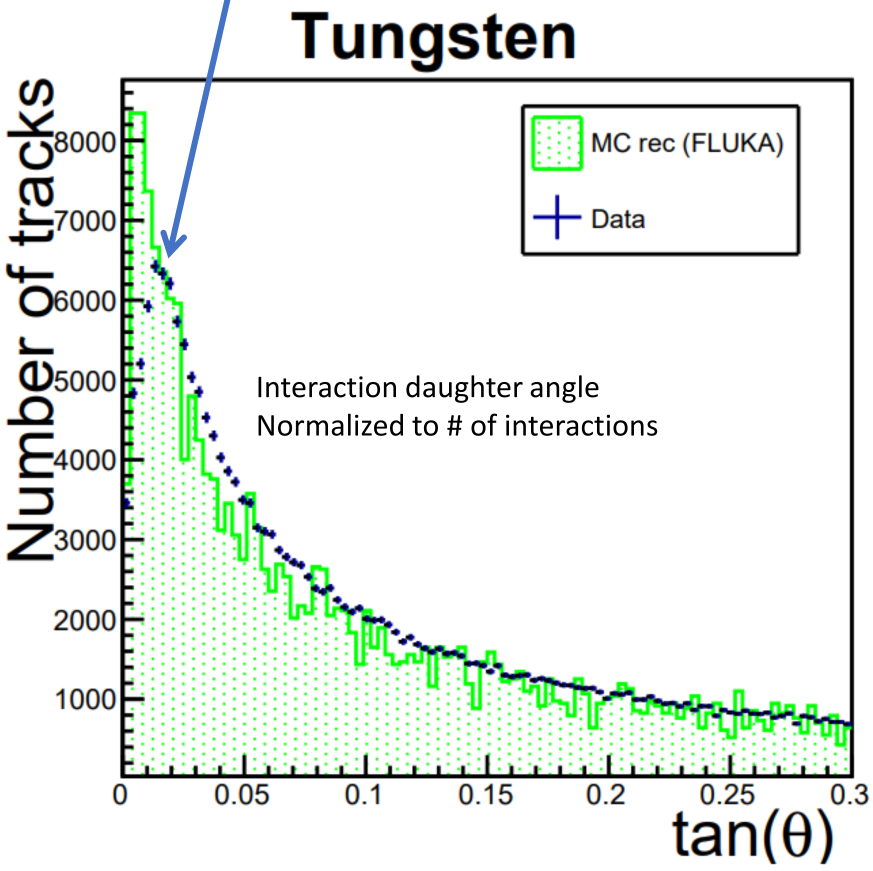




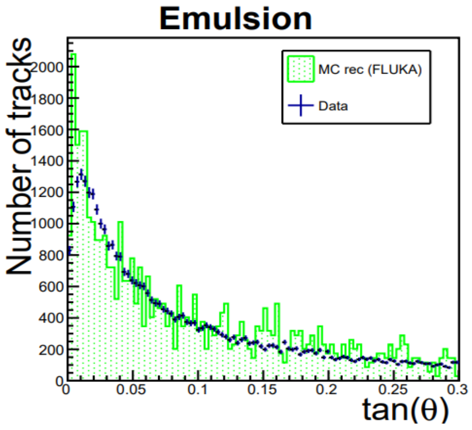
Multiplicity distribution of several materials

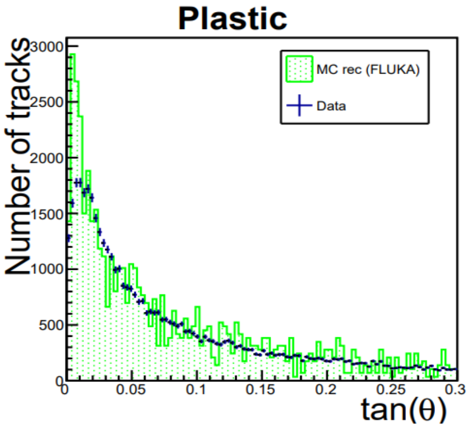
Angular distributions of proton interaction

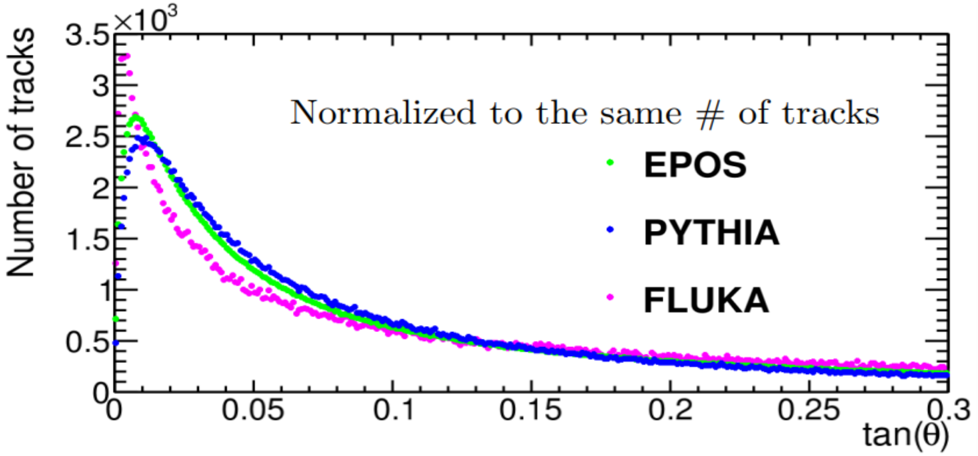
- General distribution agrees with the FLUKA prediction.
- A deficit of forward angle (<20 mrad or $\eta > 4.6$) is observed.
- Comparisons between other generators are ongoing.



Interaction daughter angle
Normalized to # of interactions







Normalized to the same # of tracks

Demonstration with interaction multiplicity (data)

- (tungsten $-\sigma_c/\sigma_w$ (0.146)polystyrene) / ($1-\sigma_c/\sigma_w$) distribution
- Distribution at material thickness between d0(C) to d0(W)