New Antiproton production model and simulated rates

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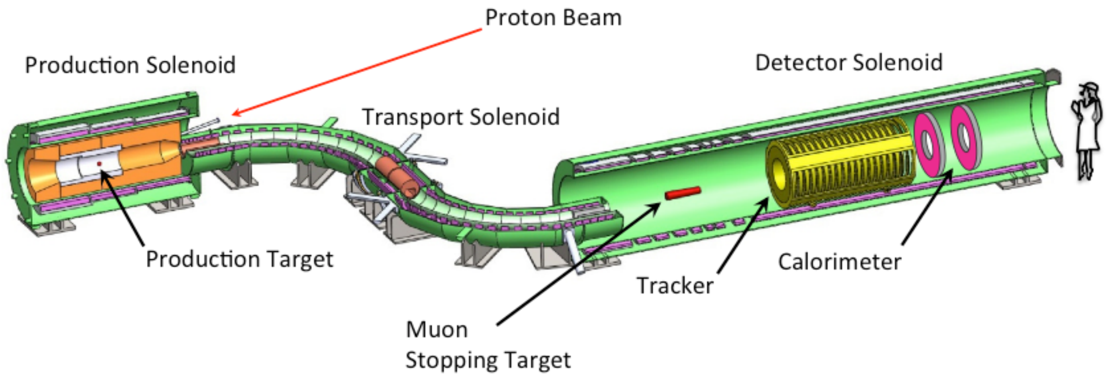
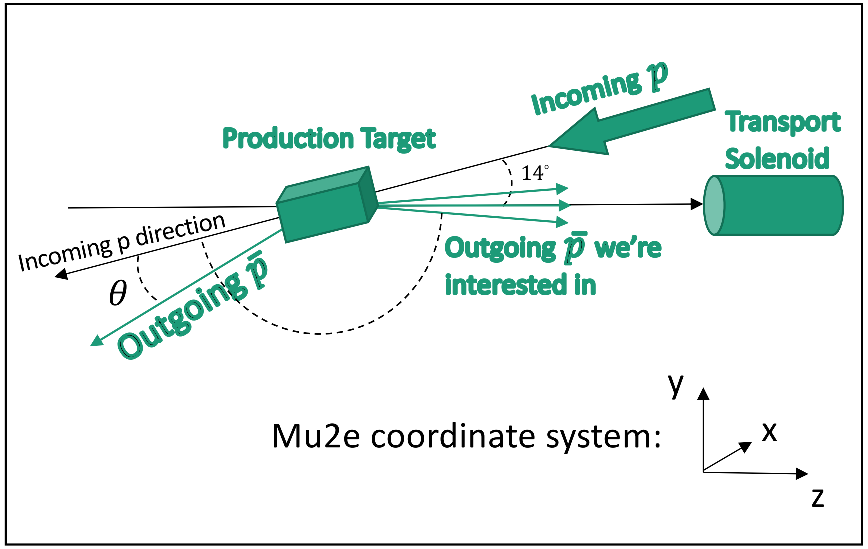
Supervised by: Robert Bernstein

Main points:

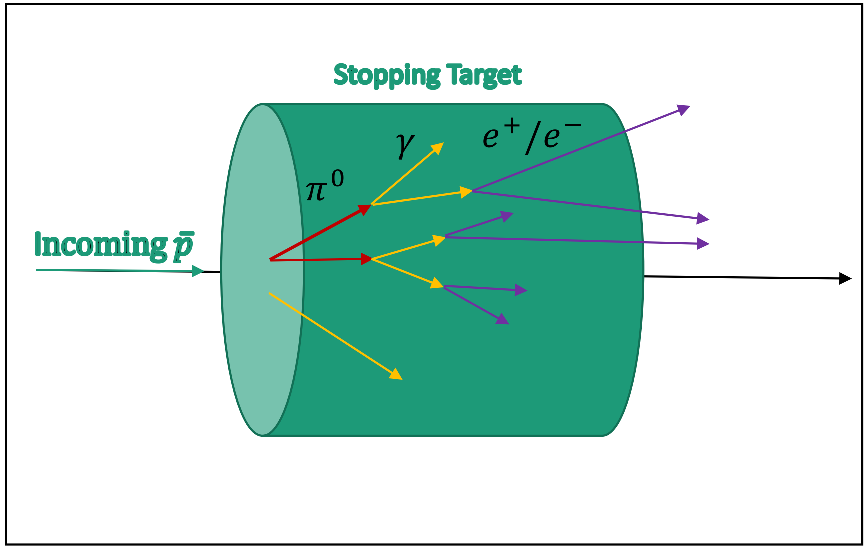
- Why this is important
- The new model: assumption and behavior in both LAB and CM frame
- Comparison with other 2 models based on parameterizations: Striganov's and Ying Wang's models
- Predictions

Why is this important? A background source!!!





Antiprotons can be produced in the production target



Antiprotons can annihilate in the stopping target and create electrons

Why is this important? Very little data and no unique model!!!

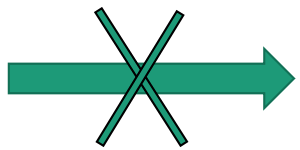
Physics is: $p + p \rightarrow (p + \bar{p}) + p + p$ Conserve charge and baryon number

But for: $p + W \rightarrow (W + \bar{p}) + X$

too complicated to be expressed in terms of QCD and people often used different parameterizations based on "Feynman x" or "p_T" . We think we need a more physical model!

Available data

- Mostly at high Energies (~ 100 GeV)
- Mostly from pp collisions
- Mostly at forward angles



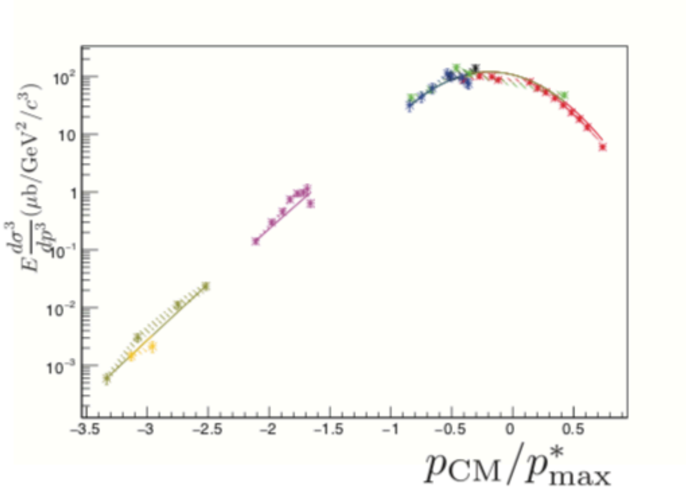
Hard to think we can extrapolate!

What we need

- Energy "close" to the threshold (~ 10 GeV)
- pW (proton-Tungsten) collisions
- Interest in backward events (opposite to incoming proton)

Since there's no unique model, it is important to try different ones in order to estimate a systematic uncertainty on the background prediction. This is a standard method: take a range of models and compare predictions

The new proposed model



Color Scheme:

Black	0
Red	3.5
Green	10.5
Blue	10.8
kRed+2	59
kYellow+2	97
kOrange	119

$$E^*_{max} = \frac{s-(3m_N)^2+m_p^2}{2\sqrt{s}}$$

$$p^*_{max} = \sqrt{E^2_{max} - m_p^2}$$

this scaling allows me to change energy to 8 GeV

shaded regions are correlated normalization systematic

From Robert Bernstein: Mu2e-doc-27801-v10

High p backward events are likely produced by interactions with multiple nucleons ("Fireball" model): studied at ITEP accelerator

Cumulative number (momentum, theta) : number of nucleons to be hit to produce an antiproton with that momentum at angle theta that conserves energy and momentum.

Look in the <u>center of mass,</u> calculate the invariant cross section there in terms of CM variables:

- If cumulative number =< 1: fit a single Gaussian
- If cumulative number > 1: fit an Exponential

ASSUMPTION: No privileged direction for antiprotons produced in ordinary matter QCD interaction

Boost back to the lab frame

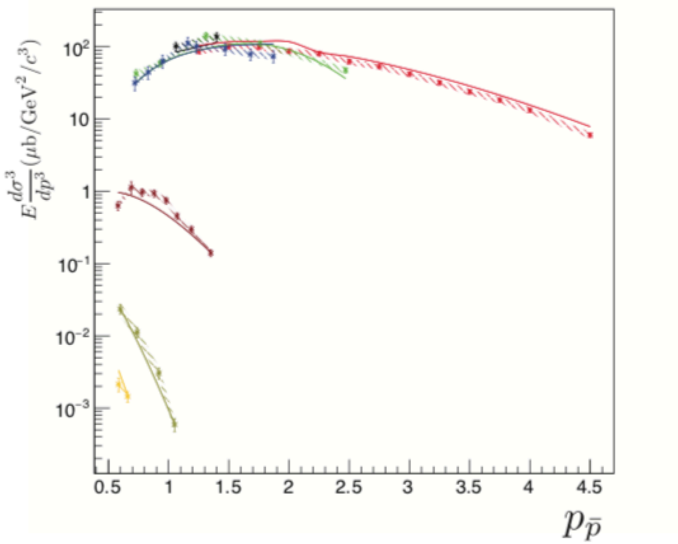
The new proposed model

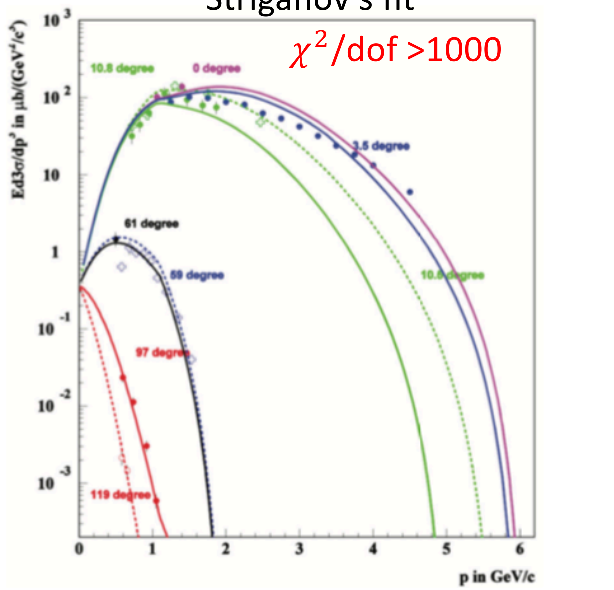
Previous model's made by Sergei Striganov (unpublished). We fitted the same data he chose so that the two models will be comparable

After cleaning up the code (with respect to mu2e-docdb 27801) what we've got is:

χ^2/dof = 88/42

Most important:
now we have a fit with a
Uncertainty Matrix





Comparison at p = 10 Gev between fits. From Robert Bernstein: Mu2e-doc-27801-v10

Behavior of the invariant Xsec

$$\frac{1}{E}\frac{d^3\sigma}{dp^3} = \begin{cases} N_G \frac{1}{\sqrt{2\pi\sigma_G^2}} e^{-\frac{|p_{cm}/p^*_{max} + O_G|^2}{2\sigma_G^2}} & \text{if cumulative number} \le 1 \\ N_E\, S_E(\theta)\, e^{-\left|\frac{K_{cm}}{E^*_{max} K_{0\,cm}} + \frac{O_E}{E^*_{max}}\right|} & \text{if cumulative number} > 1 \end{cases}$$

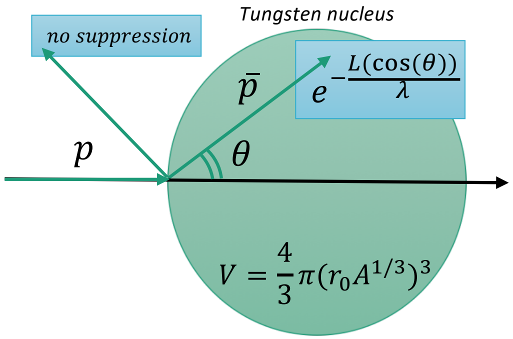
Variables:

- $p_{cm} = \begin{cases} p^{\bar{p}}_{cm} & \text{if } \cos\theta > 0 \\ -p^{\bar{p}}_{cm} & \text{if } \cos\theta < 0 \end{cases}$
- $K_{cm} = E^{\bar{p}}_{cm} - m_{\bar{p}}$

Fitted parameters: N_G, N_E, σ_G, $K_{0\,cm}$, O_G, O_E.

1. For the Exponential term: forward suppression $S_E(\theta)$ in the exponential part while cumulative number > 1:

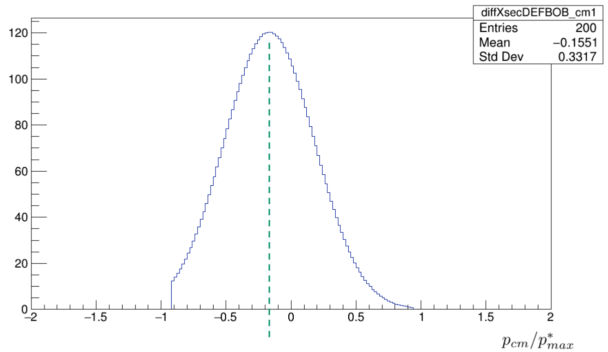
- $S_E(\theta) = \begin{cases} 1 & \text{if } \cos\theta < 0 \text{ (backward)} \\ 0 & \text{if } \cos\theta > 0 \text{ (forward)} \end{cases}$



- r_W = 6.82 fm
- ρ = 2.3e14 g cm^{-3}
- Models exists that tell us to increase the density by a factor $\sim 2^3$ inside a multinucleon state. (*)
  $\lambda_{I\,E}$ = 191.9 g cm^{-2} (from PDG) = 1.04 fm

(*) G. A. Leskin - Methods for Investigating Nuclear Matter under the Conditions Characteristic of Its Transition to Quark-Gluon Plasma February 7, 2002

2. For the Gaussian term: O_G -- an offset to the Gaussian mean – is needed in order to have a good fit. Maybe energy loss before leaving the nucleus?



Something is favoring backward-produced events here as well

Can we eliminate this parameter and apply a similar suppression ?

- 1 nucleon so:
  $\lambda_{I\,G}$ = 191.9 g cm^{-2} (from PDG) = 8.3 fm in the nucleus, but this is much more complicated – same general problem as neutrino-nucleus interactions studied for LAr!!

Behavior and first comparisons

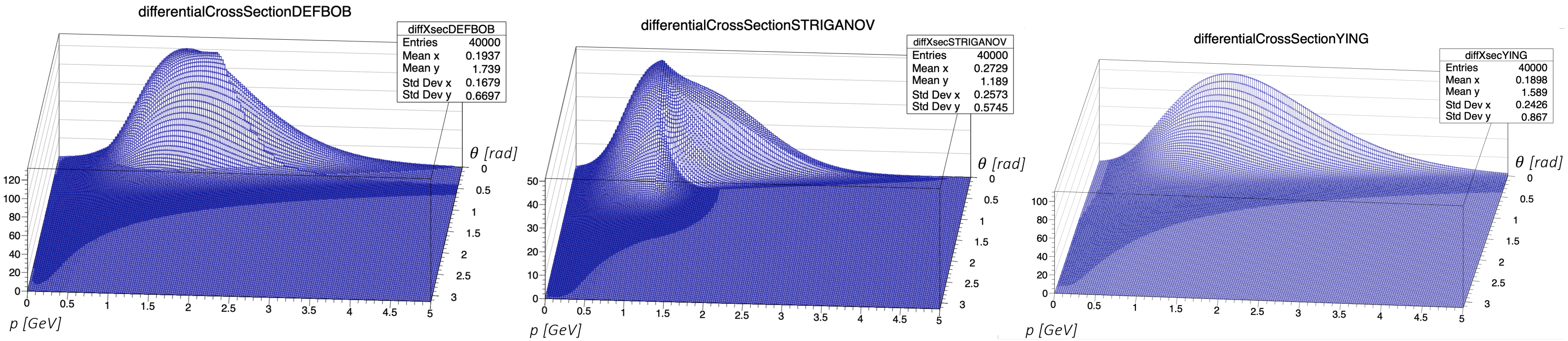
- An integration over the phase space (with p_{max} given by kinematics limits) gives us an idea:

$\int_0^{2\pi}\int_0^{\pi}\int_0^{p_{max}}\left(E\frac{d^3\sigma}{dp^3}\right)\frac{1}{E}p^2 sin(\theta)dp\, d\theta\, d\varphi \approx$ 99:

- Integrals performed with different methods, same result.
- Same for Striganov's parametrization gives us $\approx$ 30. ($\approx$ 42 for Ying Wang)
- The overall behavior is similar. Let's now look at them bin by bin for:

$\mathrm{p} \in [0,5] \qquad \theta \in [0,\pi]$.

In the LAB frame

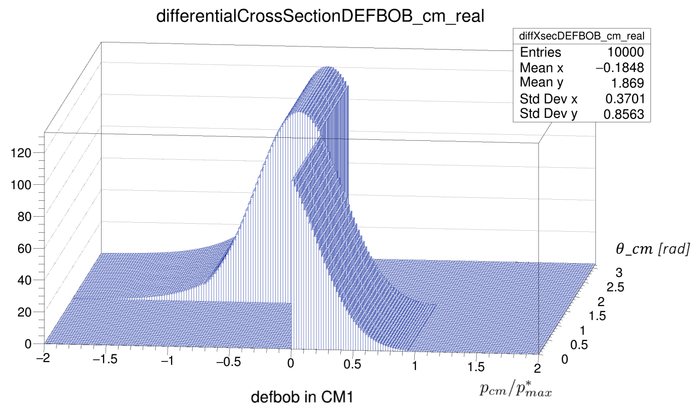


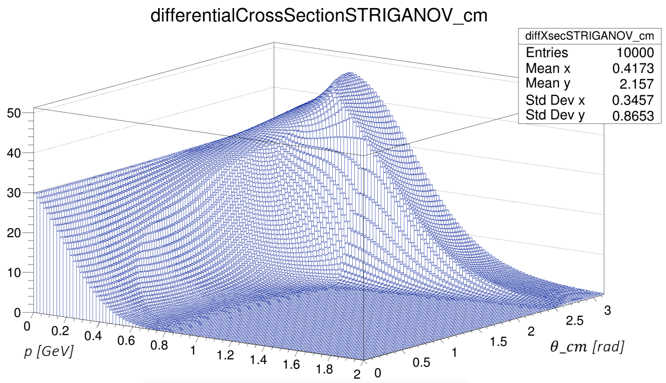
Behaviors and first comparisons

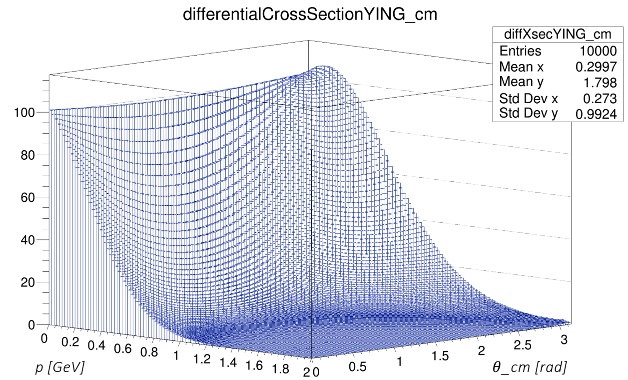
Backward preference in CM:

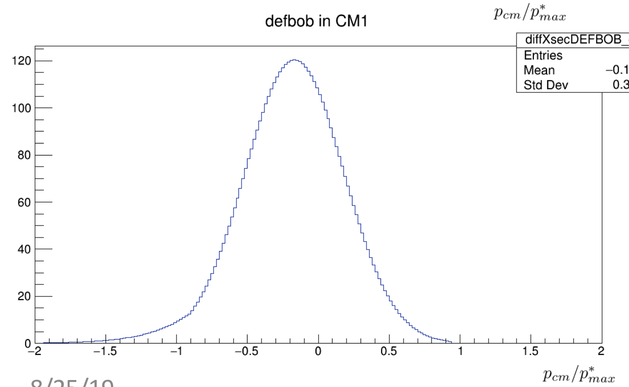
	DB	STR	YING
Percentage produced opposite to initial proton direction	83.6 %	91.5 %	69.5 %

In the CM frame

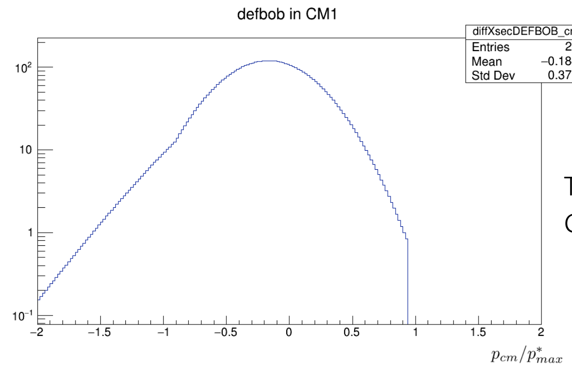








Log scale

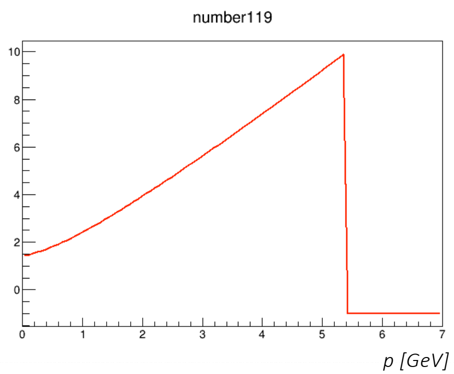


This cutoff is artificial, the Gaussian should continue

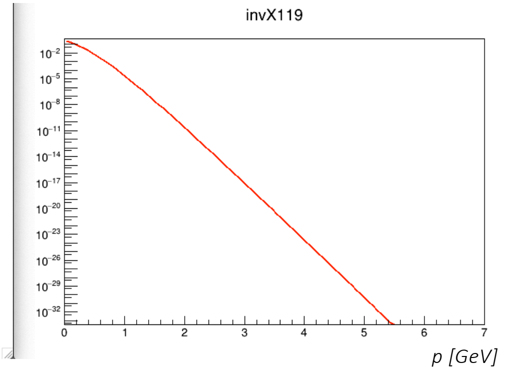
Regions of interest

1. No reason to compare them over all phase space, there are kinematic limits:

Cumulative number

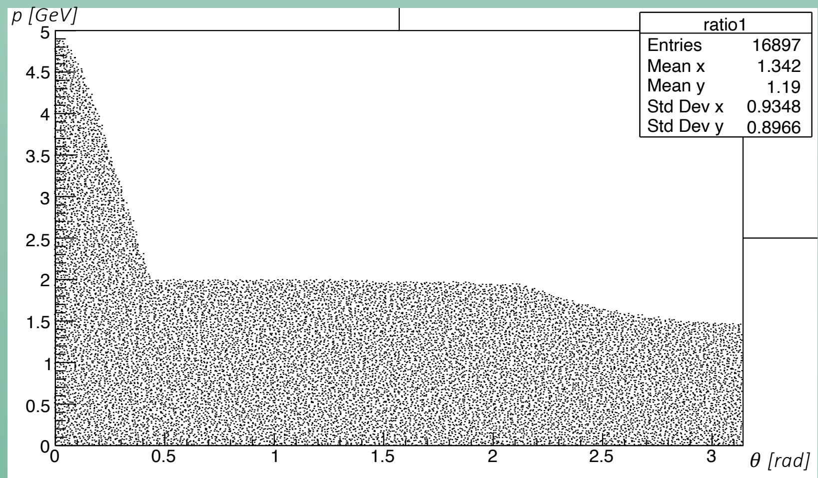


Invariant Cross Section



Example at 119 degrees

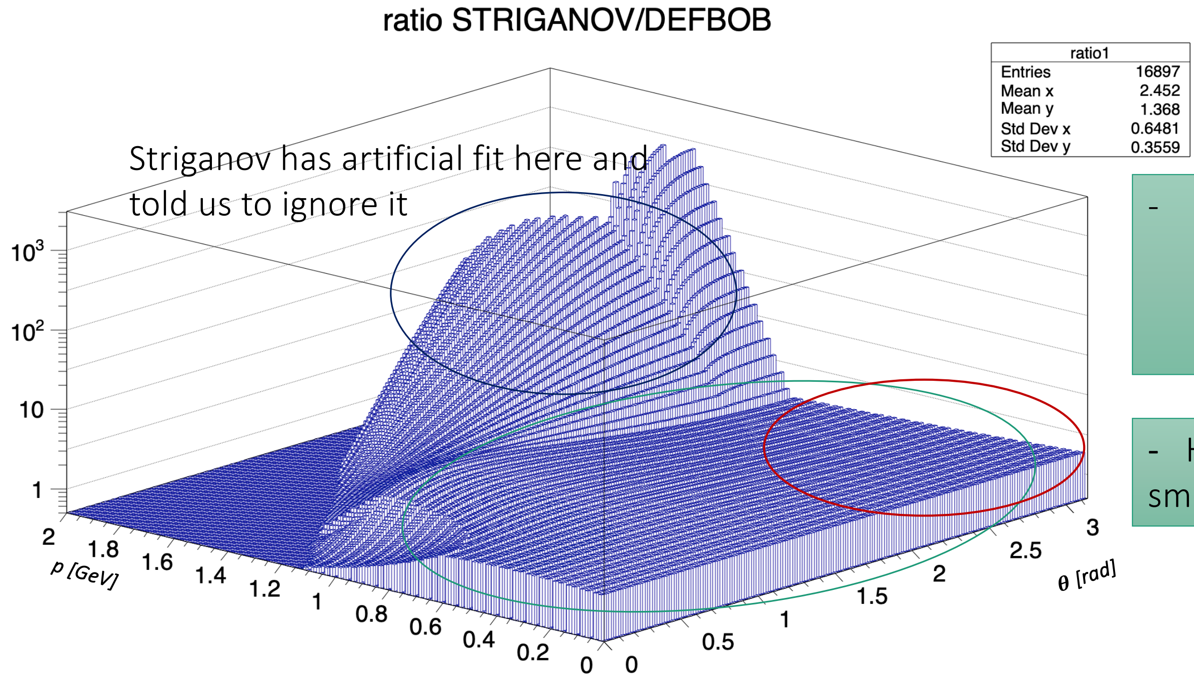
The region obtained is:



2. The probability of an antiproton making an electron $\approx 10^{-5}$
   In the entire experiment we expect 3.6 $x\ 10^{20}$ protons on target…

If: $3.6\ x\ 10^{20}\ *$ [Probability of making an antiproton] $* \ 10^{-5}$ < 1 reject the event

Quantitative bin by bin ratio

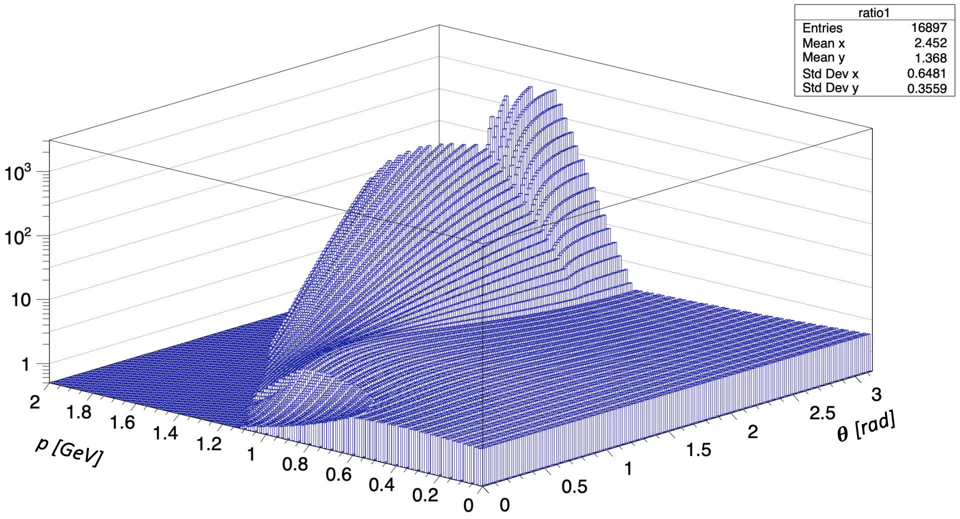


("steps" are an artifact of TH2 due to bin size 😠 not a concern)

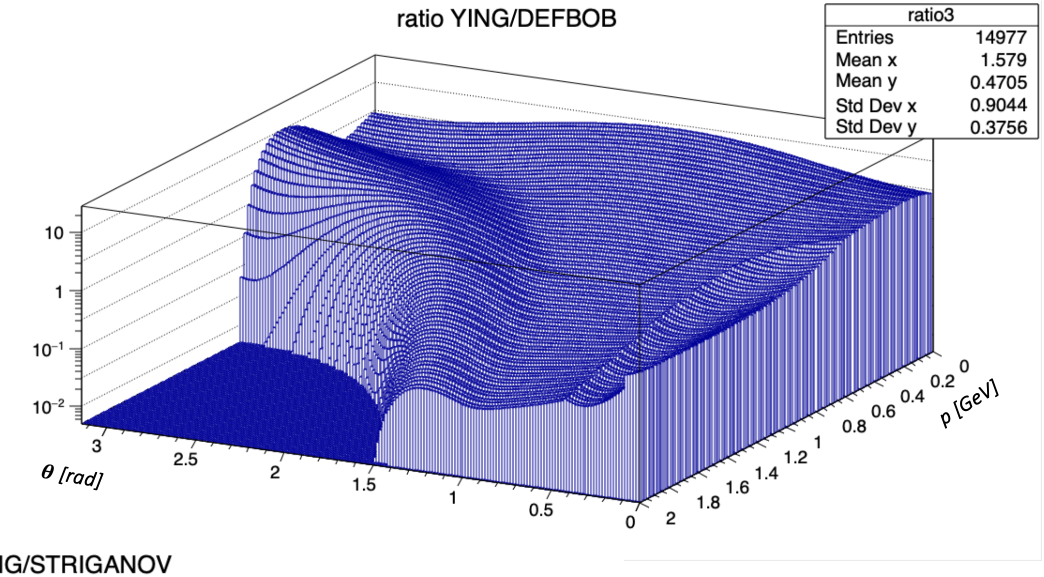
- We're mostly interested in antiprotons produced backward (towards the TS) and with p < 100 MeV (acceptance of the TS):
  ⟹ qualitatively good agreement there

- High p: different behaviors but both Xsec are very small, differences lie in the way they decrease

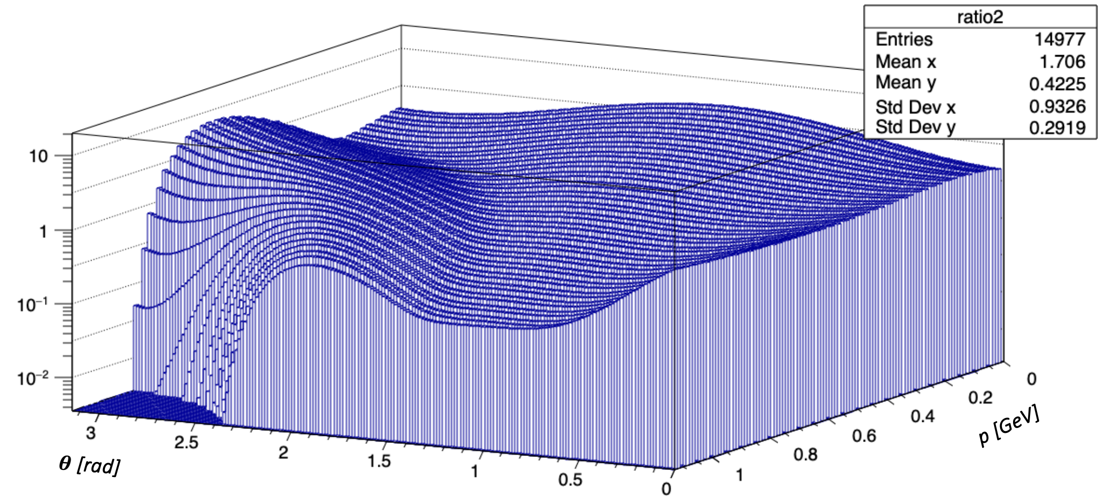
ratio STRIGANOV/DEFBOB



ratio YING/DEFBOB



ratio YING/STRIGANOV



Simulation towards the TS

Every events is required by GEANT to reach the entrance of the Transport Solenoid (at VD91*)

Number of simulated protons	Initial proton momentum	Pbar momentum generation	Pbar theta generation
1.3e8	Peaked around 8.89 GeV/c	Flat in CM	Flat in CM

Generate unweighted distributions → Weight them with different cross section models → Normalize to the number of simulated protons

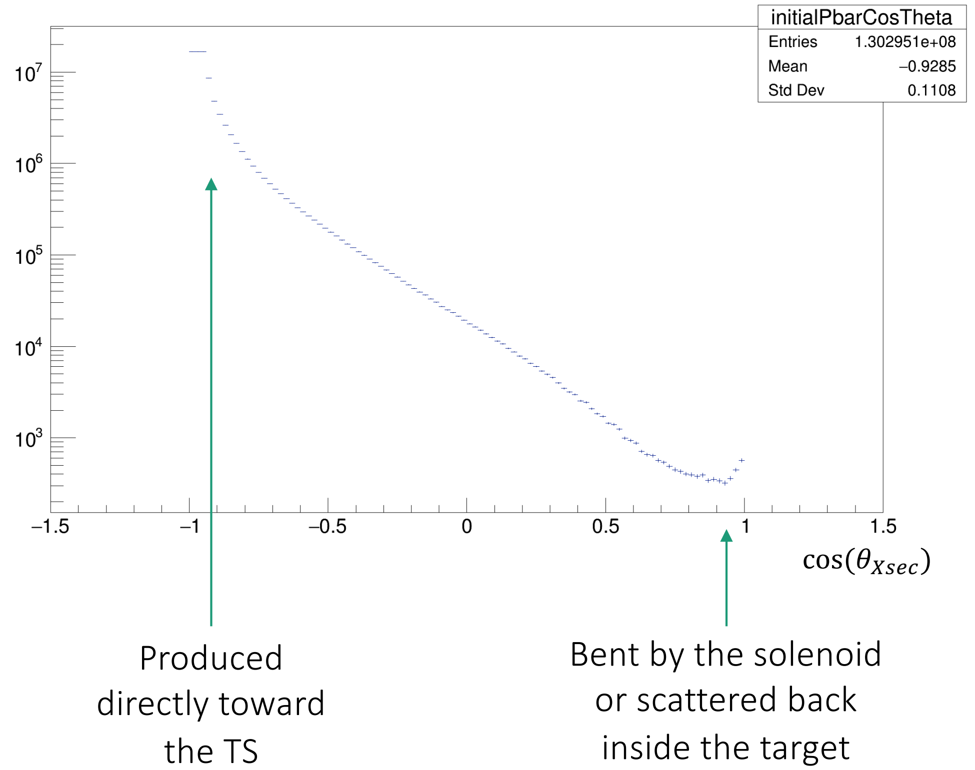
*Really VD92 with no material between VD91 and 92, 1mm downstream

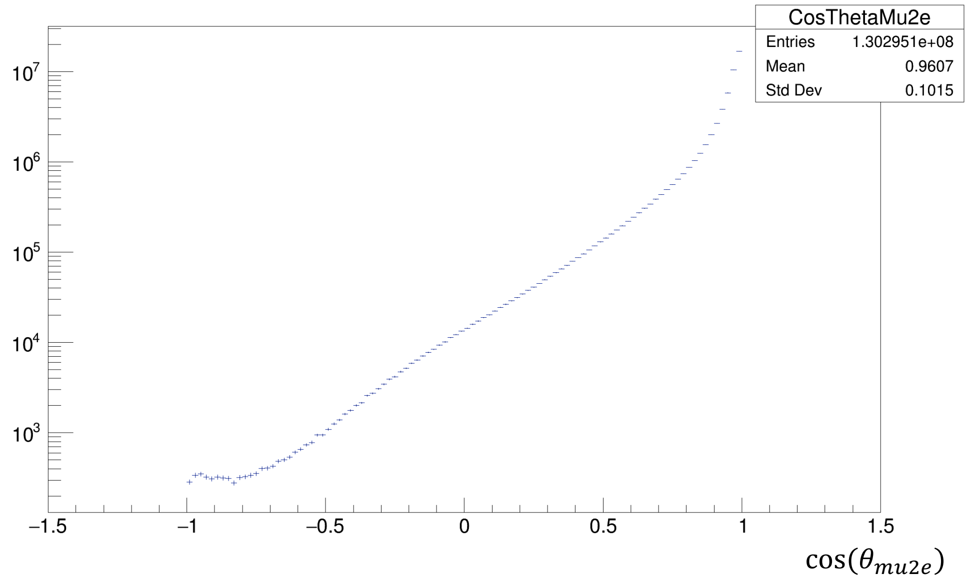
Simulation towards the TS

- θ_{Xsec}: with respect to the initial proton direction
- θ_{mu2e}: with respect to the z axis in the mu2e frame

Contributions in the unweighted $\cos(\theta)$ distributions:

- Magnetic field
- Scattering
- Target's 14° is included





Systematic and statistical uncertainties:

Weighted sum (over different p) in each cos(θ) bin: $$Y = \sum_{i=0}^{entries} \alpha_i$$

- Statistical errors come from the usual Poisson distribution: → Managed and added correctly by Sumw2()

- Systematic errors come from the uncertainties on the fit parameters: → Different weights in each bin are correlated:

  Correct form is in the backup slides and hard to implement

  → $$\hat{\sigma}_Y = \sum_i \sigma_{\alpha_i}$$ with $$\sigma^2_{\alpha_i} = \sum_{p',q'} \frac{\partial \alpha_i}{\partial k_{p'}} \frac{\partial \alpha_i}{\partial k_{q'}} cov_{k_{p'}, k_{q'}}$$

  $\hat{\sigma}_Y$: It won't give the correct result. Considering every fluctuation in the same direction ends with an overestimation.

  But is easy, fast and gives us a good enough estimate!

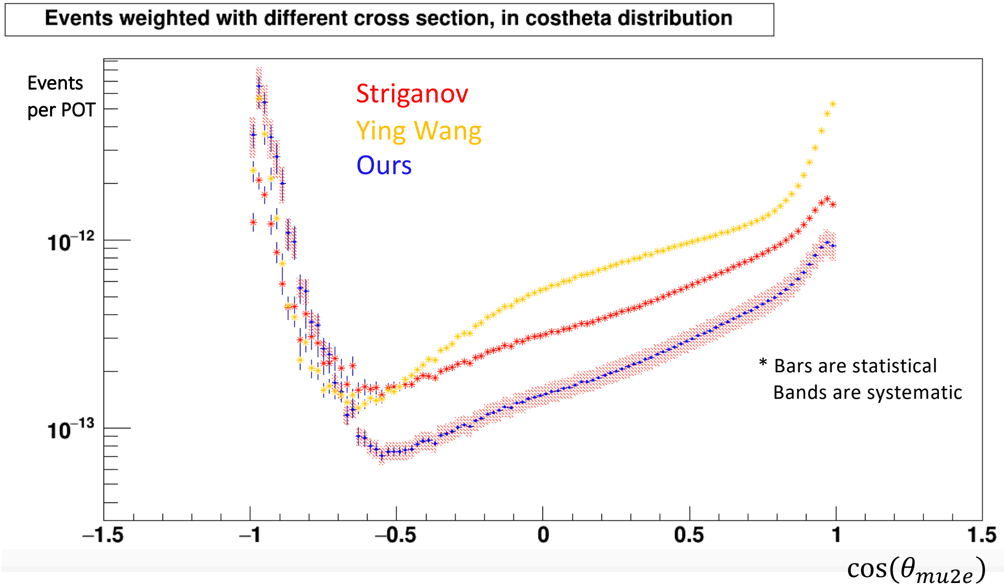
  ~ 10%

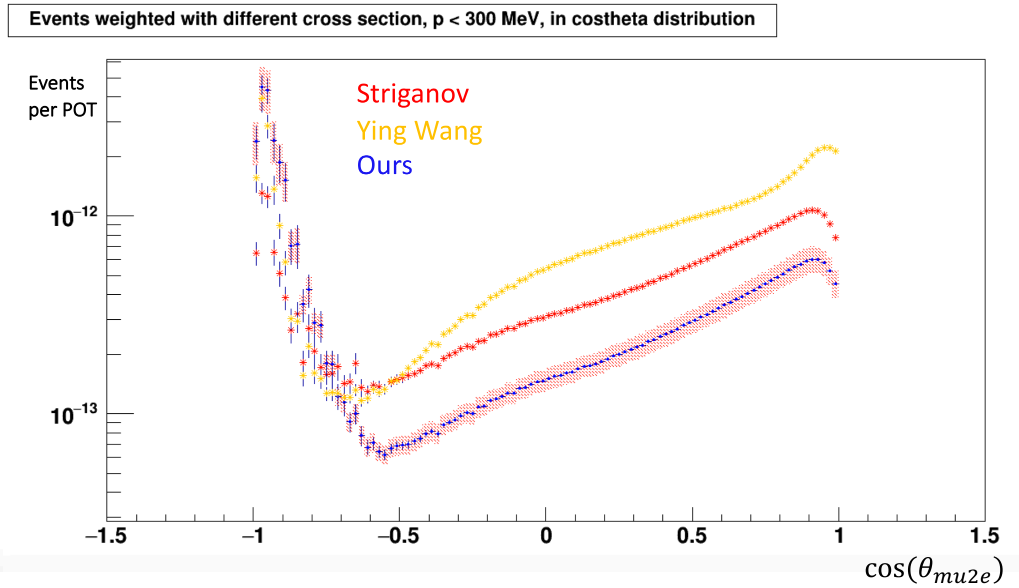
  $\frac{\partial \alpha_i}{\partial k}$: From the general expression of the Xsec

  cov: From the fit

Rates per Proton on Target (POT)

Number of interacting protons
in Mu2e = 0.78 x 3.6e20
(From docdb 21872)





Conclusions and recap

- We now have a model to predict the antiproton background
- It has a reasonable physical basis in the CM → Possible extensions
- If everything is correct the predicted rate are smaller than the previous one
- Uncertainties tell us that:
  - the model is distinguishable from the others
  - Mu2e needs absorbers strategically located inside the TS to reduce the antiprotons
  - This study will give us reliable estimates and the associated uncertainties that we need to design these absorbers
- Next step will be to propagate them inside the TS…

-Many thanks to Robert Bernstein for plots and continuous help

Thanks for the attention

-Many thanks to Giorgio Bellettini for the great opportunity

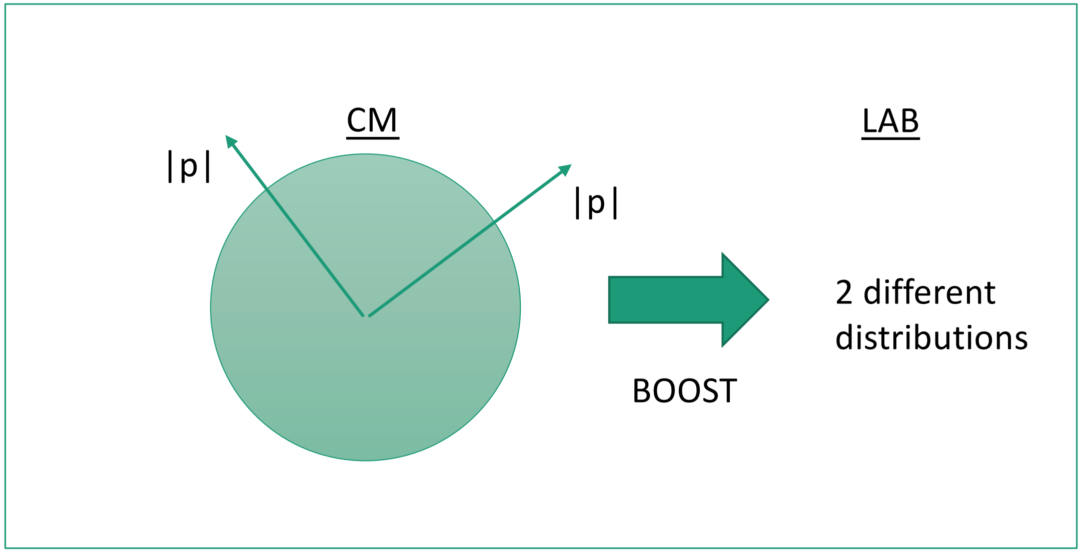
Backup Slides

Gaussian Model in CM:

```
if (trivectorMomentum.CosTheta() < 0.) {centerOfMassMomentum = -centerOfMassMomentum;}

cmAdj = TMath::Abs(centerOfMassMomentum/pStarMax + currentValue[2]);
```

This fits the data with a better chi2 than any other choice -> there must be something behind it



1st interpretation: include the Fermi motion (random motion):

…should average to zero

2nd interpretation: a fraction of the initial energy is lost in the nucleus before leaving it.

The shift in energy is reasonable assuming minimum ionizing at nuclear density to within a factor of 2

$$Y = \sum_{i=0}^{entries} \alpha_i$$

with

$$\sigma^2_{\alpha_i} = \sum_{p\prime,q\prime} \frac{\partial \alpha_i}{\partial k_{p\prime}} \frac{\partial \alpha_i}{\partial k_{q\prime}} cov_{k_{p\prime}k_{q\prime}}$$

I can try now to estimate

$$\sigma^2_Y = \sum_{p,q} \frac{\partial Y}{\partial k_p} \frac{\partial Y}{\partial k_q} cov_{k_p k_q} = \sum_{p,q} \frac{\partial \sum_i \alpha_i}{\partial k_p} \frac{\partial \sum_j \alpha_j}{\partial k_q} cov_{k_p k_q} =$$

$$= \sum_{p,q} \sum_{i=j} \frac{\partial \alpha_i}{\partial k_p} \frac{\partial \alpha_j}{\partial k_q} cov_{k_p k_q} + \sum_{p,q} \sum_{i \neq j} \frac{\partial \alpha_i}{\partial k_p} \frac{\partial \alpha_j}{\partial k_q} cov_{k_p k_q}$$

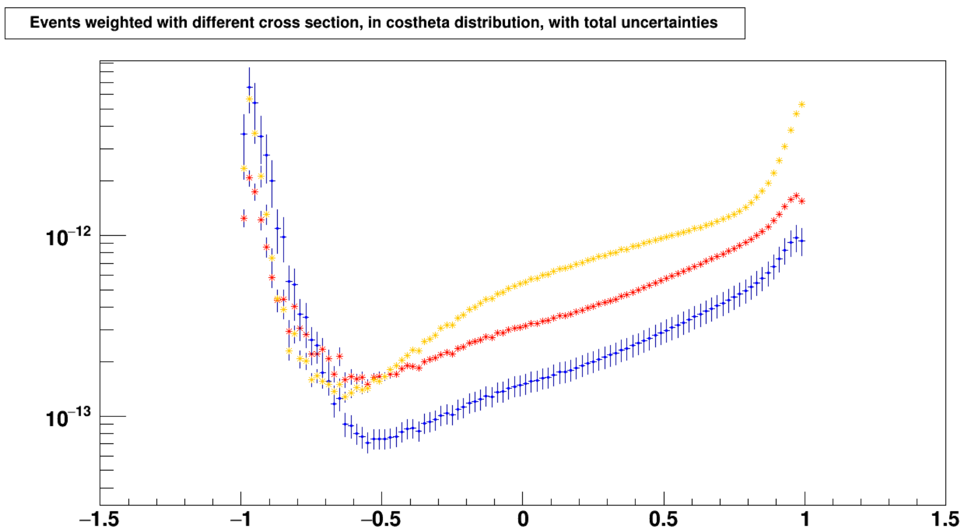
with

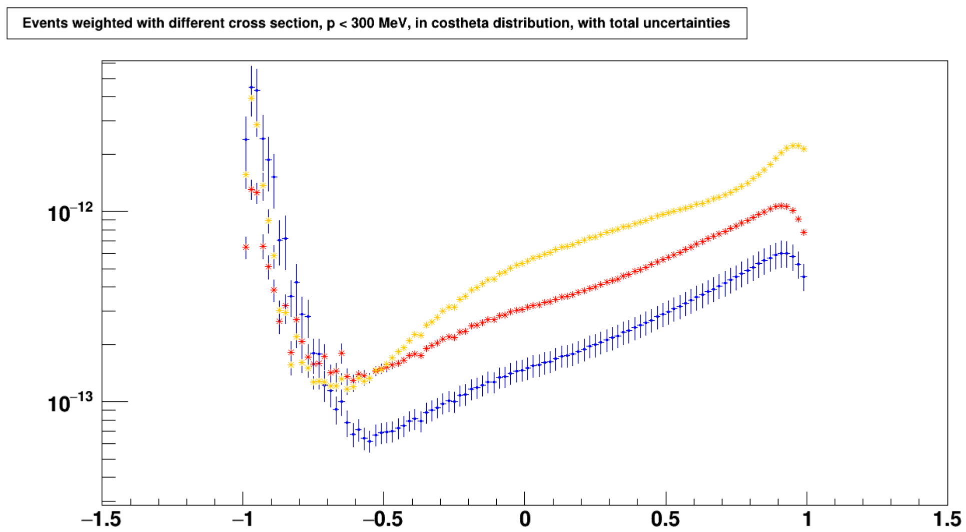
$$\hat{\sigma}_Y = \sum_i \sigma_{\alpha_i}$$

$$\hat{\sigma}^2_Y = (\sum_i \sigma_{\alpha_i})^2 =$$

$$= \left(\sum_i \sqrt{\sum_{p\prime,q\prime} \frac{\partial \alpha_i}{\partial k_{p\prime}} \frac{\partial \alpha_i}{\partial k_{q\prime}} cov_{k_{p\prime}k_{q\prime}}} \right)^2 =$$

$$= \sum_{p,q} \sum_{i=j} \frac{\partial \alpha_i}{\partial k_p} \frac{\partial \alpha_j}{\partial k_q} cov_{k_p k_q} + \sum_{i \neq j} \sqrt{\sum_{p\prime,q\prime} \frac{\partial \alpha_i}{\partial k_{p\prime}} \frac{\partial \alpha_i}{\partial k_{q\prime}} cov_{k_{p\prime}k_{q\prime}}} \sqrt{\sum_{p\prime,q\prime} \frac{\partial \alpha_j}{\partial k_{p\prime}} \frac{\partial \alpha_j}{\partial k_{q\prime}} cov_{k_{p\prime}k_{q\prime}}}$$





- Statistical and systematic errors are comparable in the left region

- Systematic errors dominate in the right region