Open Charm from Run 2 p+p

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Overview

- Status of single muon analysis based on Run 2 p+p data.
- Slides from Youngil (who could not be present).
- Next step is a revised analysis note describing all steps including systematic error analysis that everyone can understand.
- Form PPG.
- Pave the way for similar analyses on subsequent data sets.

Status report of RUN2 pp single analysis

Abstract :

We report status of the RUN2 pp single analysis with an up-to-date error analysis. Invariant multiplicities for the decay μ's and the prompt μ's are nearly ready for PRELIMINARY approval. We also consider major physics issues these data can address.

Physics issues

Invariant multiplicity for the decay μ's

When RUN3 d+Au single analysis completes this summer, we can calculate R_{dAu}.

Invariant multiplicity for the prompt μ's

Yield & p_t spectra : How do the spectra compare to LO pQCD?

How big is NLO effect or higher twist effect?

Unique prompt lepton measurement at y = -1.65.

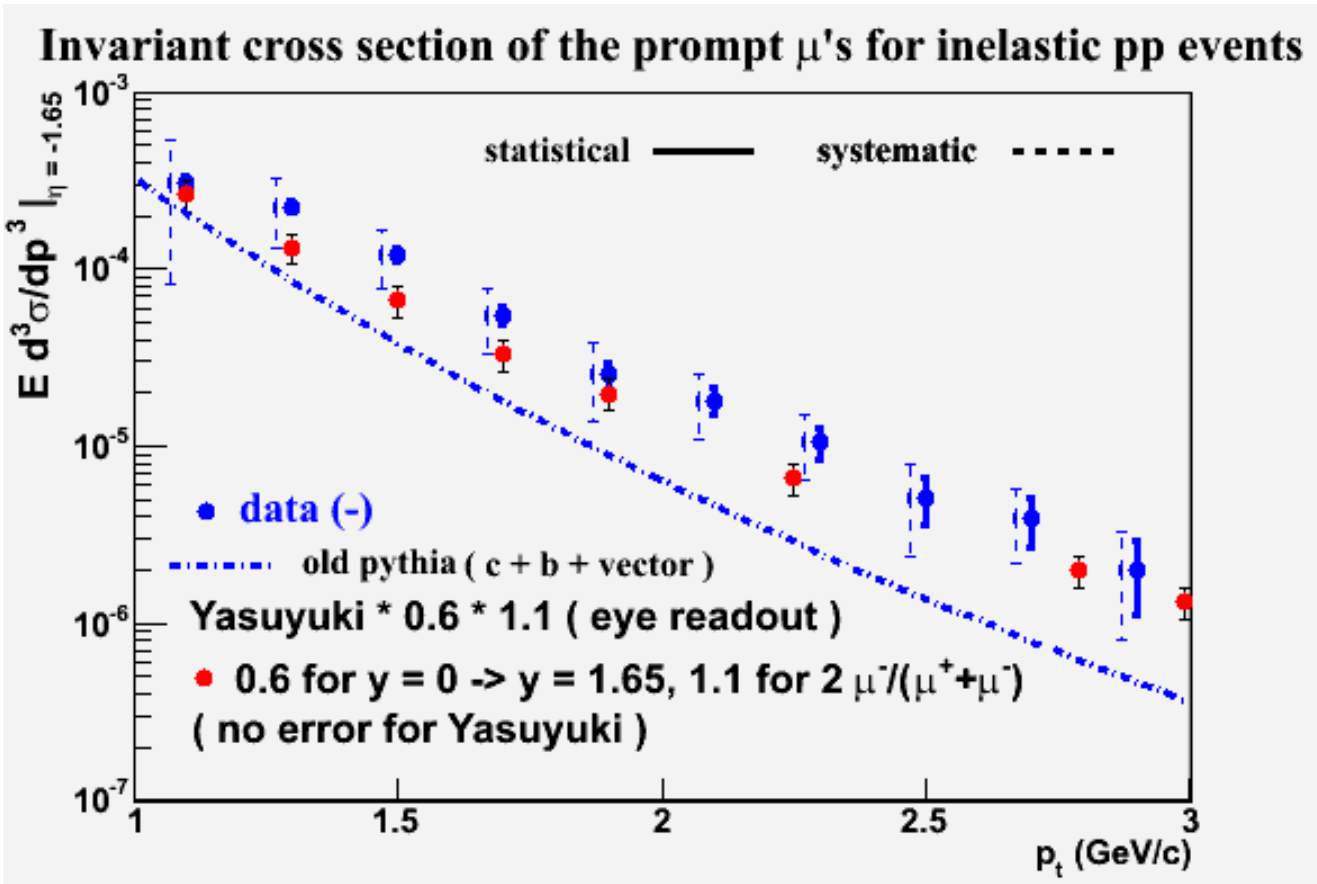
Completion of measurement at y = 0.

Data points for the prompt μ invariant multiplicity were released more than a month before data points for the PHENIX p+p and d+Au electron ones were released. Initially disagreement with the old PHENIX pythia prediction was a challenge. Two months later STAR released their data. Both data proved old PHENIX pythia parametrization was incorrect. These statements argue following two points.

1. Our report started from the strong confidence in data (even against old pythia, almighty at the time of release).
2. Our data has no bias from the PHENIX electron or the STAR electron results. STAR people still didn't know our muon results.

A comparison plot of interest (I)

Measurements by the central arm and the muon arm both exhibit excess over the old pythia parametrization.

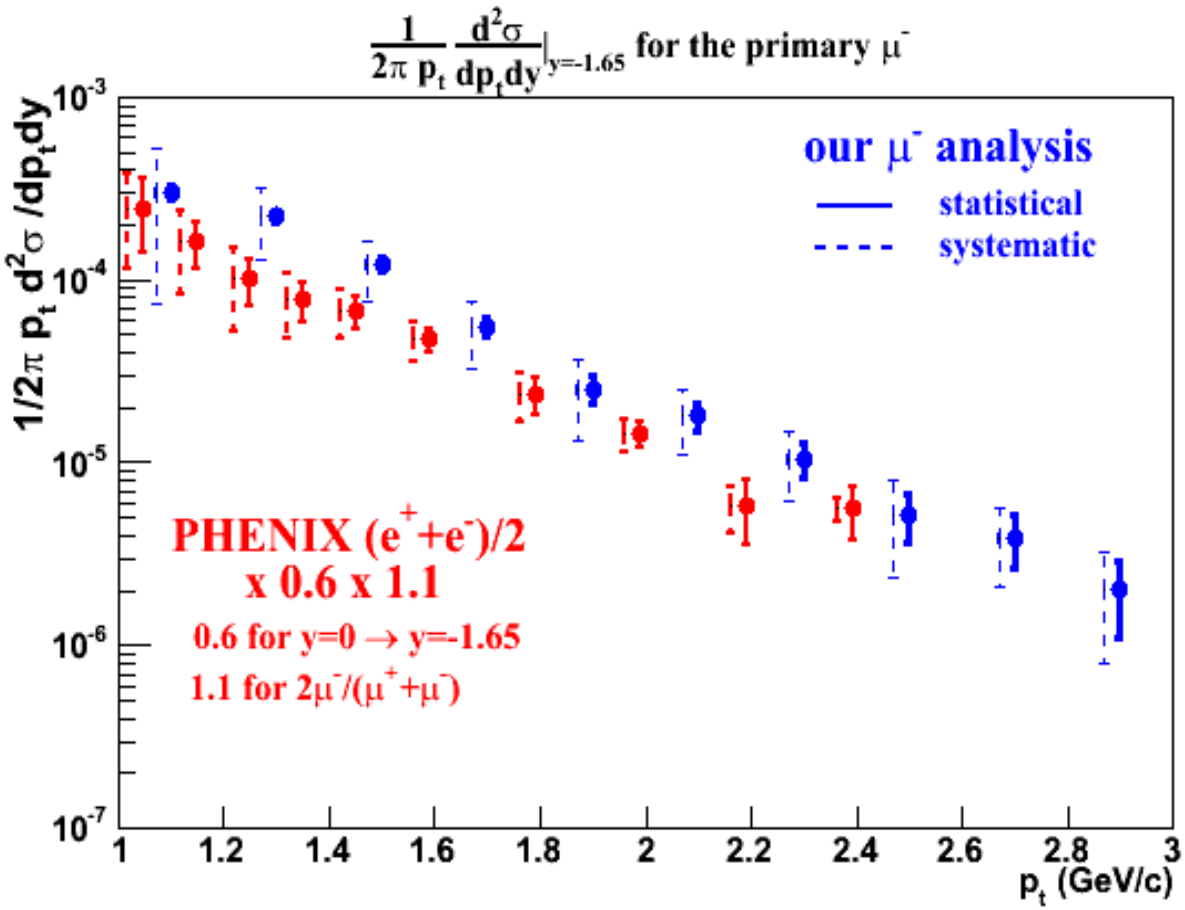


Caveat :

0.6 accounts for the difference in y (estimation from pythia). The width depends on p_t, which was ignored. Wider at low p_t and narrower at high p_t. Charge Asymmetry is also from pythia.

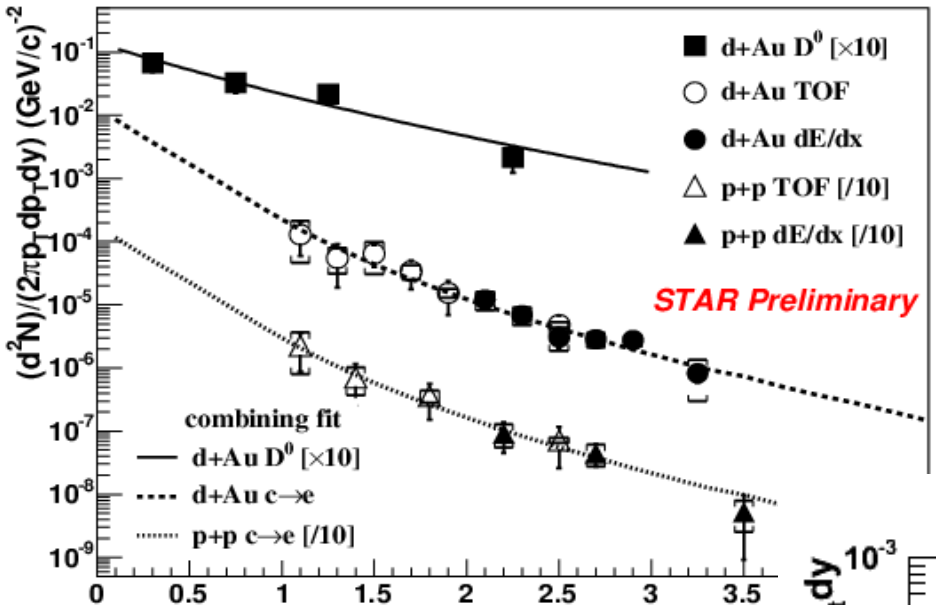
A comparison plot of interest (II)

Prompt μ^- vs PHENIX $p + p \rightarrow e + X$



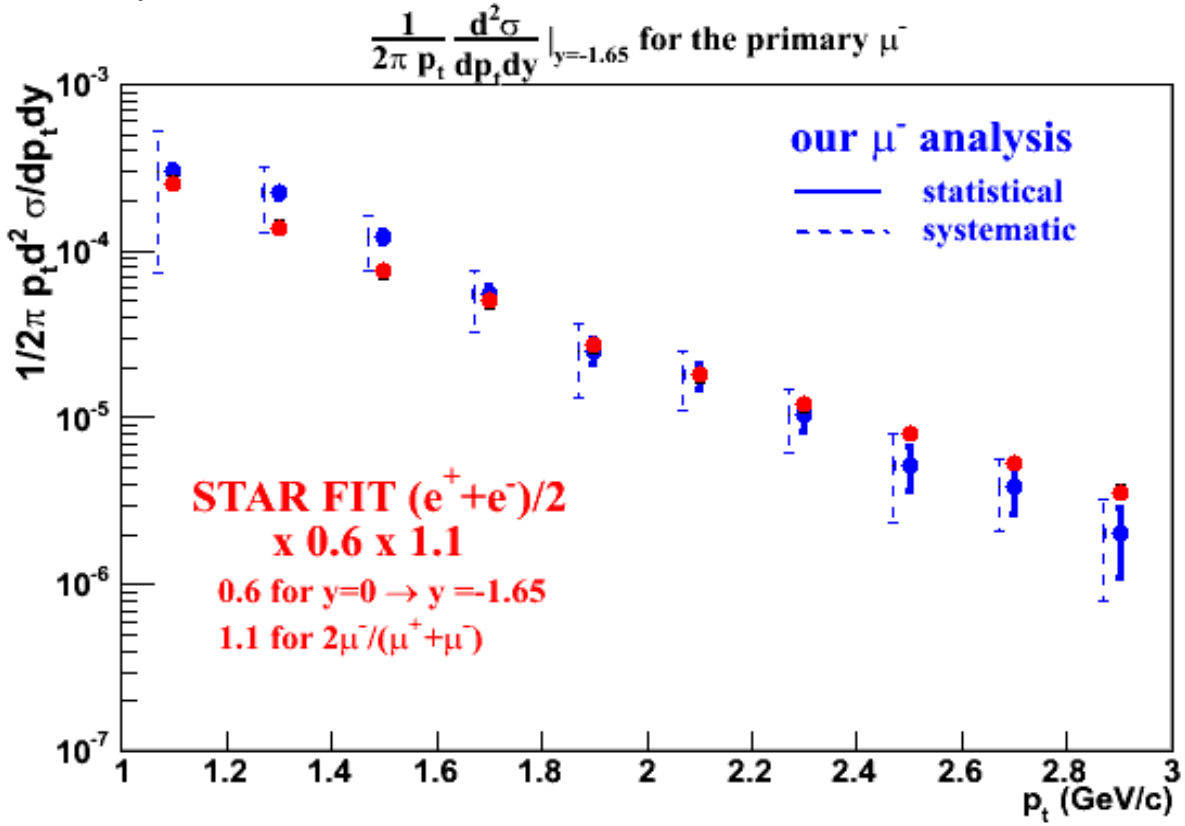
Two data are consistent within errors and the extrapolation systematics.

A comparison plot of interest (III)



We read-off fit results from the STAR Preliminary plot.

We also observe constency for this comparison.



The analysis procedure and the systematic uncertainty for the RUN2 single μ analysis

Abstract :

We describe how we proceed the RUN2 single μ analysis and estimate the systematic uncertainty in the analysis results. We try to make a simplified sketch of the procedure and the error analysis. See Note 14 for a full description (and upcoming revised, clarified PHENIX analysis note).

Equation to calculate cross section

$$\text{Invariant Multiplicity (I.M.)} = E\frac{d^3N}{dp^3}\Big|_{\eta=-1.65} = f(p_t, z_{coll})$$

(Illustrated in page 3)

$$\boxed{\text{I.M.}_{\text{primary }\mu}} = \text{I.M.}_{\text{measured}} - \text{I.M.}_{\text{decay }\mu} - \text{I.M.}_{\text{punch through}} - \text{I.M.}_{\text{ghost background}}$$

Estimated background (page 4)

$$= h(p_t, z_{coll}) = h_{fit}(p_t) \pm \delta(\text{stat})$$

Fit (page 5)

$$+\ \delta_{high}(\text{sys}) = (\text{I.M.}^{\text{max}}_{\text{primary}} - \text{I.M.}^{\text{mean}}_{\text{primary}}) \oplus \delta_{\text{single}}$$

$$-\ \delta_{low}(\text{sys}) = (\text{I.M.}^{\text{mean}}_{\text{primary}} - \text{I.M.}^{\text{min}}_{\text{primary}}) \oplus \delta_{\text{single}}$$

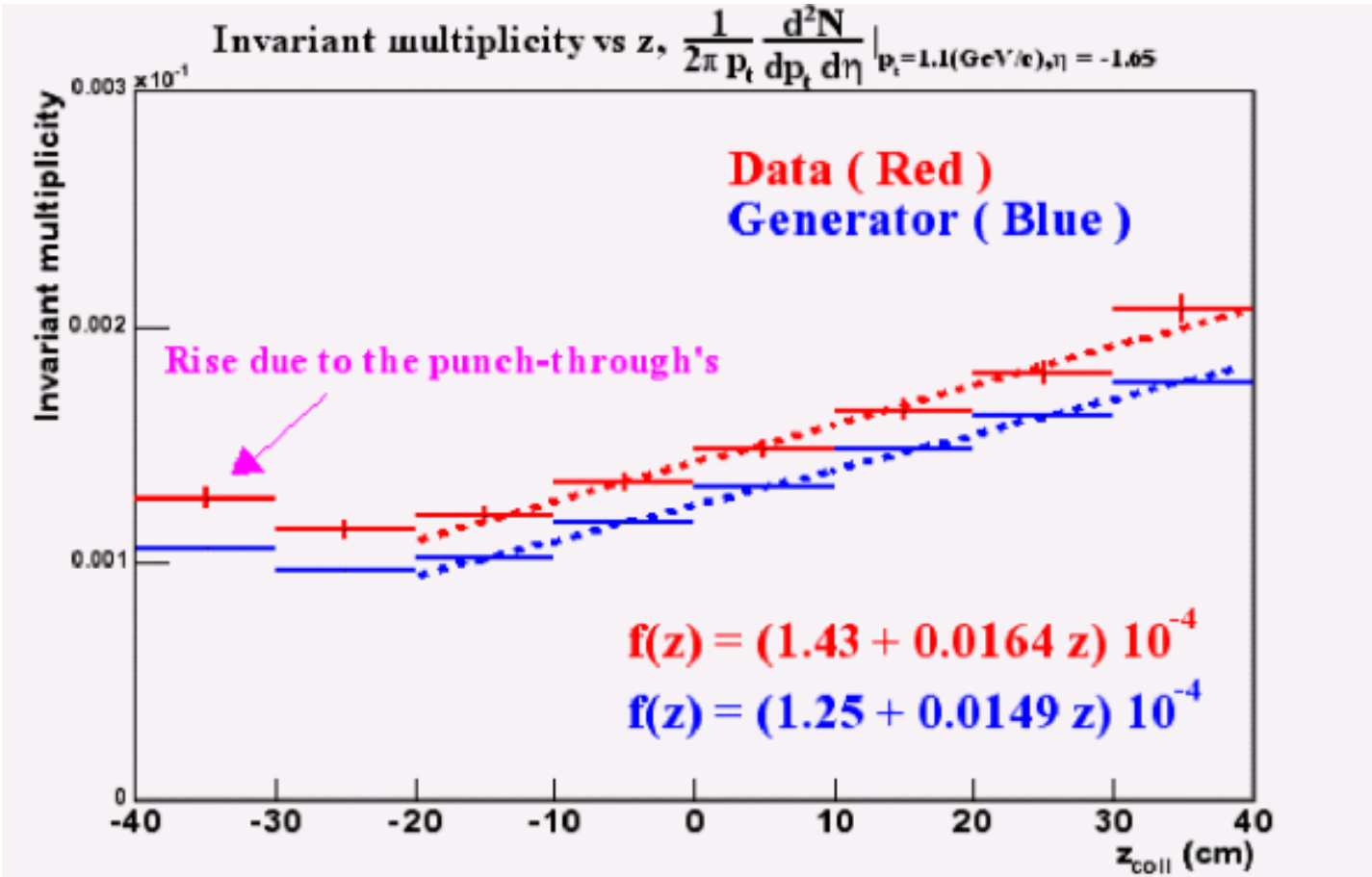
Max. & Min. variation

$$\text{I.M.}^{\text{max/mean/min}}_{\text{primary}} = \text{I.M.}_{\text{measured}} - \text{I.M.}^{\text{min/mean/max}}_{\text{decay }\mu} - \text{I.M.}^{\text{min/mean/max}}_{\text{punch_through}} - \text{I.M.}^{\text{min/mean/max}}_{\text{ghost background}}$$

$$\text{Invariant Multiplicity (I.M.)} = E\frac{d^3N}{dp^3}\Big|_{\eta=-1.65} = f(p_t, z_{coll})$$

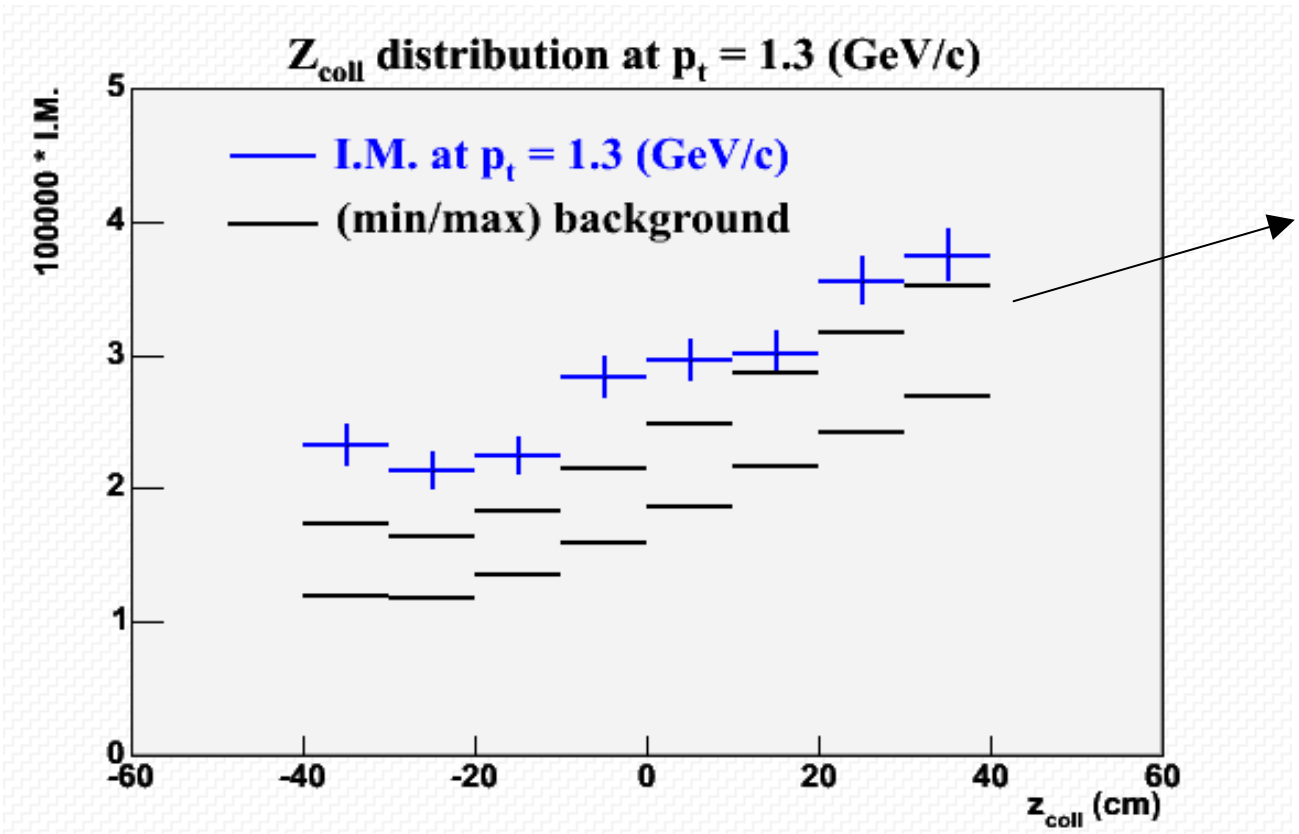
Invariant multiplicity is a function of p_t (physics) and z_{coll} (detector artifact).

Example distribution at p_t = 1.1 (GeV/c)



Estimated minimum/maximum background at p_t = 1.3 (GeV/c)

Background = Decay μ + Punch-through + Ghost background
---> Decomposition of variation is shown in pages 6, 7, and 8.

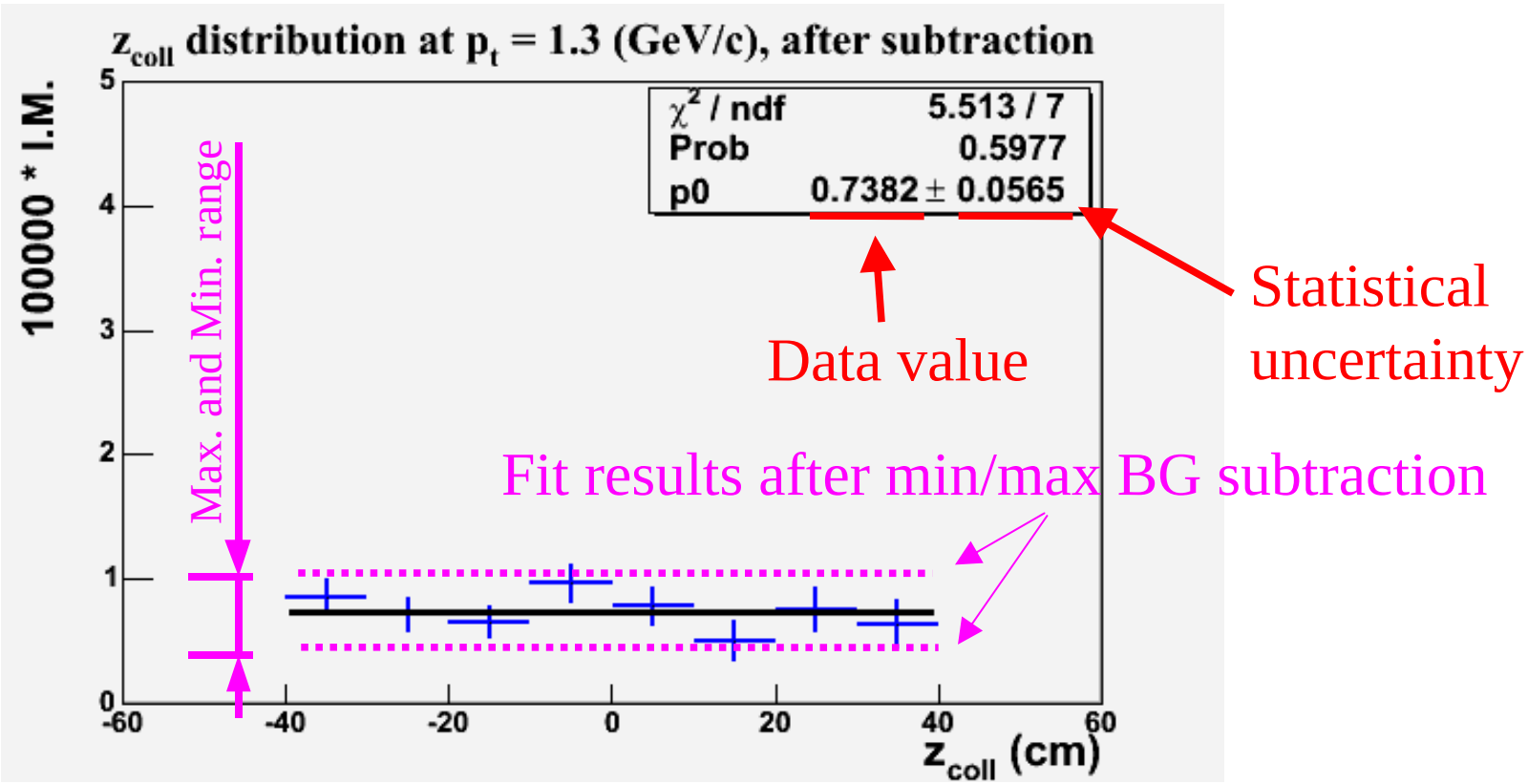


Background cocktail by Y. Kwon

Estimating maximum and minimum range of background is the real essence to estimate uncertainty.

Subtraction, $h(p_t,z_{coll})$, $h_{fit}(p_t) \pm \delta(stat) \pm \delta(sys)$

We fit by a constant after subtracting (min./mean/max.) background from data.



We add quadratically δ_{single} to the Max. and Min. variation to get δ(sys.).

Uncertainty for the single (page 9)

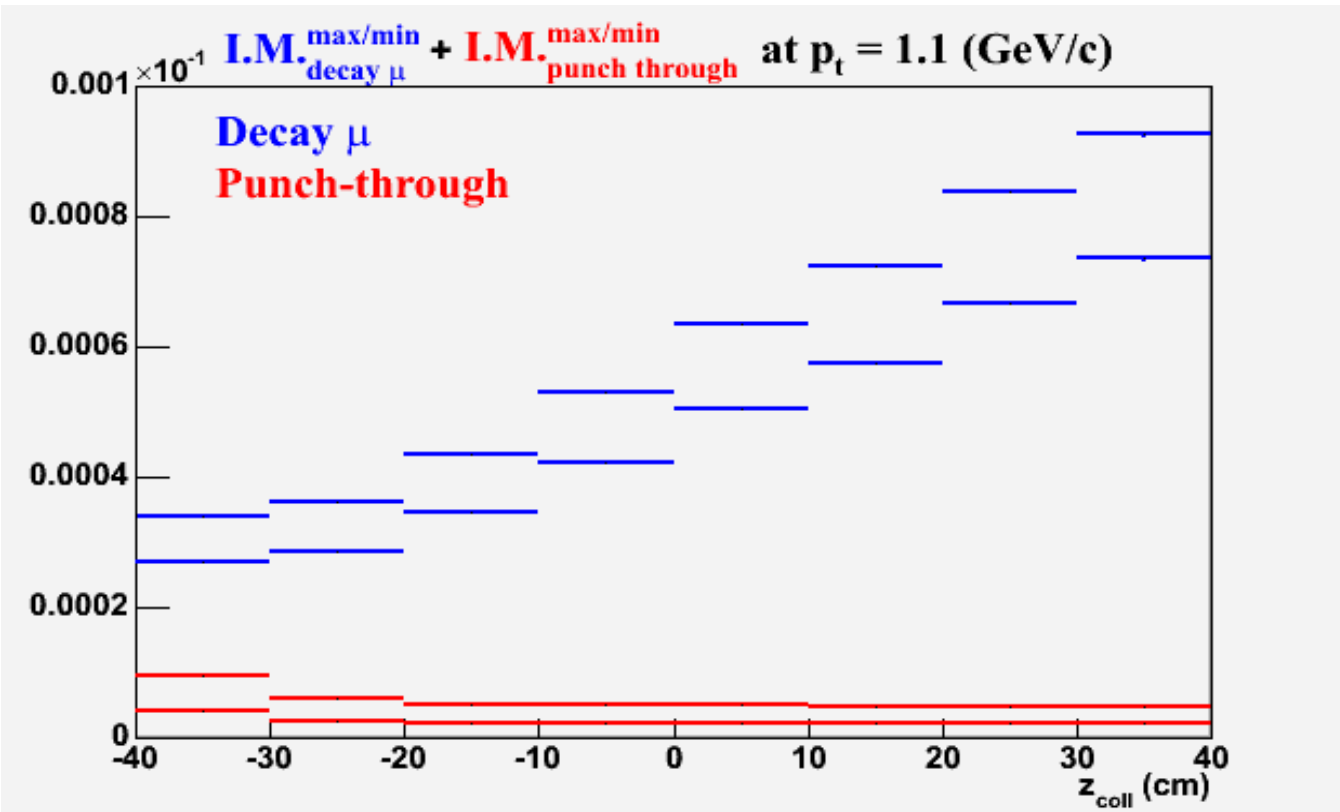
Composition of background

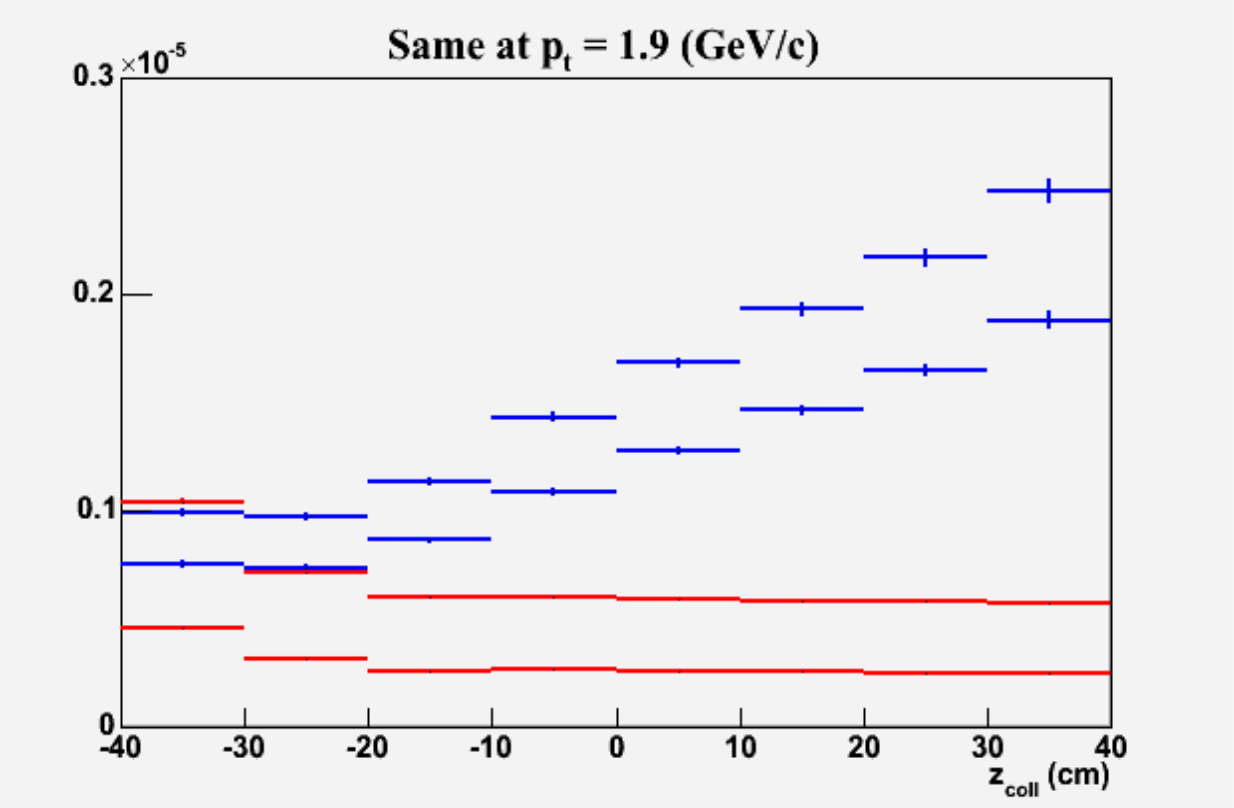
Variation of decay μ spectra

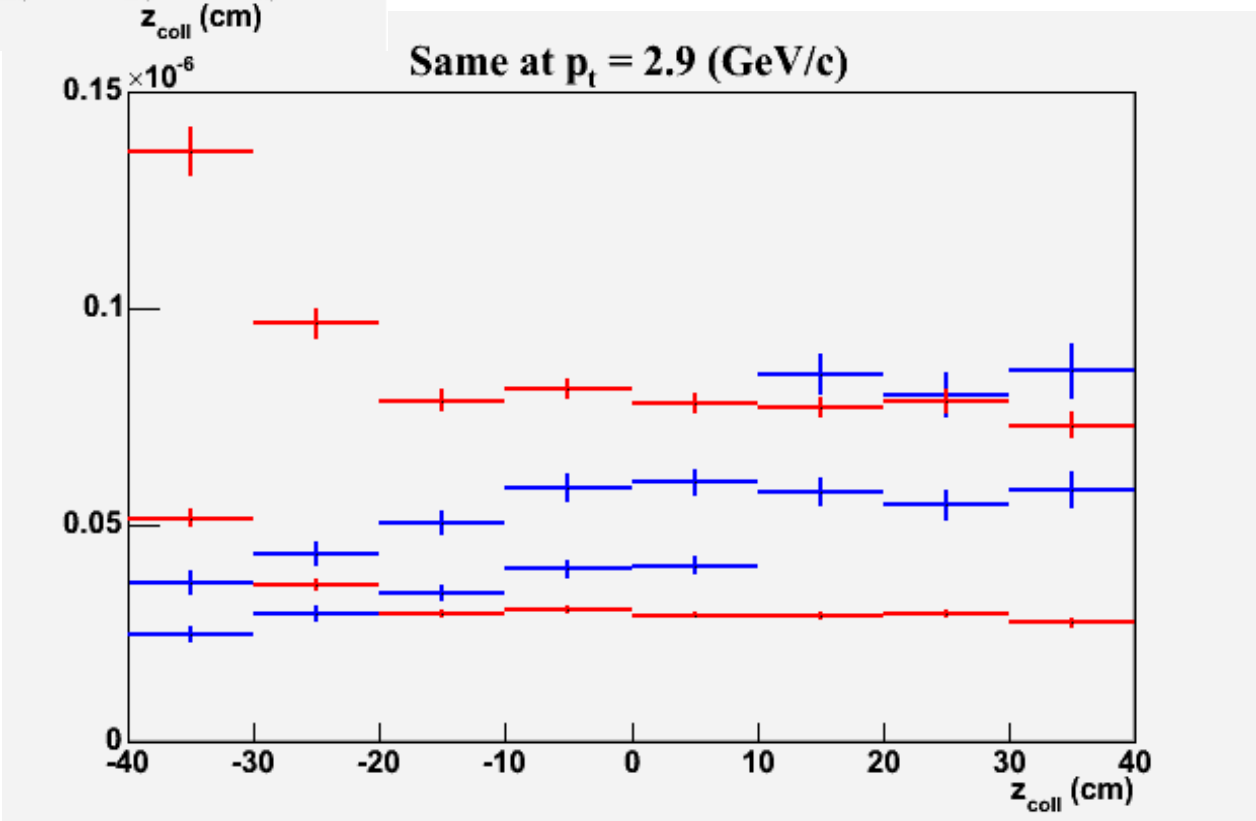
yield : 7% ⊕ 7%(p_t-1) (decay μ) + 10% (ghost background)

Variation of punch-through

Linear sum

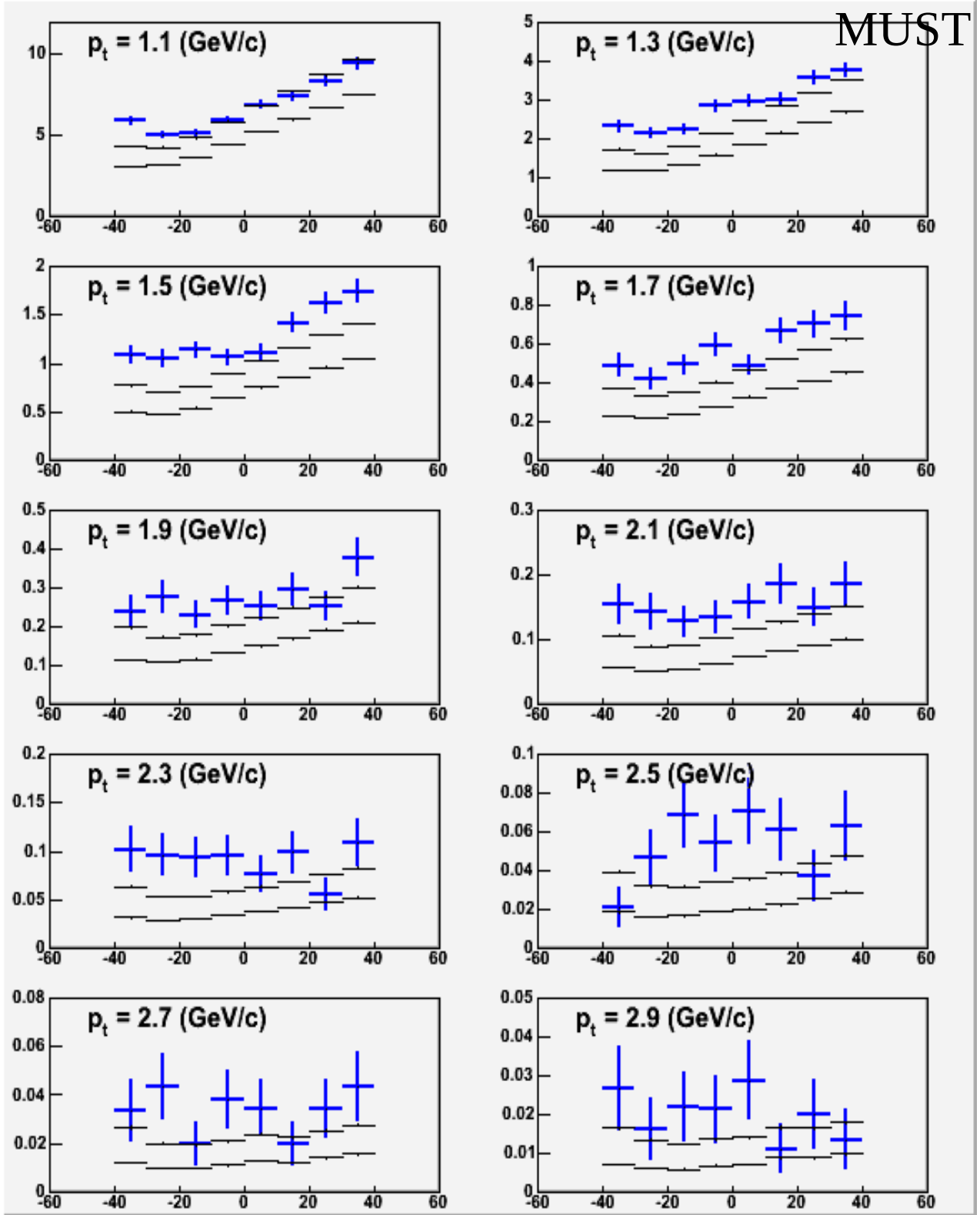



Same at p_t = 1.9 (GeV/c)
$\times 10^{-5}$
0.3
0.2
0.1
0
-40
-30
-20
-10
0
10
20
30
40
z_{coll} (cm)


Same at p_t = 2.9 (GeV/c)
$\times 10^{-6}$
0.15
0.1
0.05
0
-40
-30
-20
-10
0
10
20
30
40
z_{coll} (cm)

Data vs Background for all p_t

Black line display maximum and minimum background.



Uncertainty table, differential multiplicity for the tracks with DEPTH5

$$\frac{1}{2\pi\, p_t}\frac{d^2N}{dp_t\, d\eta} = \frac{1}{2\pi <p_t>}\frac{\Delta N_{yield}}{\Delta p_t\, \Delta \eta}\frac{1}{\epsilon}$$

$$\epsilon = \epsilon_{trigger}\ \epsilon_{acc}\ \epsilon_{rec}\ \epsilon_{user}$$

Lengthy discussion on uncertainty in note14, but straightforward.

	δ^{norm}	δ^{pt}	δ^{z}
$\varepsilon_{trigger}$	0	0	0
ε_{acc}	5%	0.7% (p_t-1)	I
ε_{rec}	9%	0	0
ε_{user}	3%	5% (p_t-1)	II
ε	11%	5% (p_t-1)	2% (I+II)

Parametrization of decay μ spectra and fit, its uncertainty

$f(p_t) = P_0/(p_t + 0.7949)^{10.59}$ for μ^+

$f(p_t) = P_0/(p_t + 0.8866)^{10.94}$ for μ^-

Obtained from central arm π,K measurement and its extrapolation to μ-arm rapidity

Variation range of fit parameter P_0 (normalization):

$P_0 \cdot (1 \pm 0.07)$, statistical

Description of p_t spectra : Good.

Uncertainty of parametrization (dominated by Gaussian extrapolation)

5% (p_t -1)

Why?

Parametrization works well when pt = 1 (GeV/c).

Parametrization is consistent to data within statistics up to pt = 2(GeV/c).

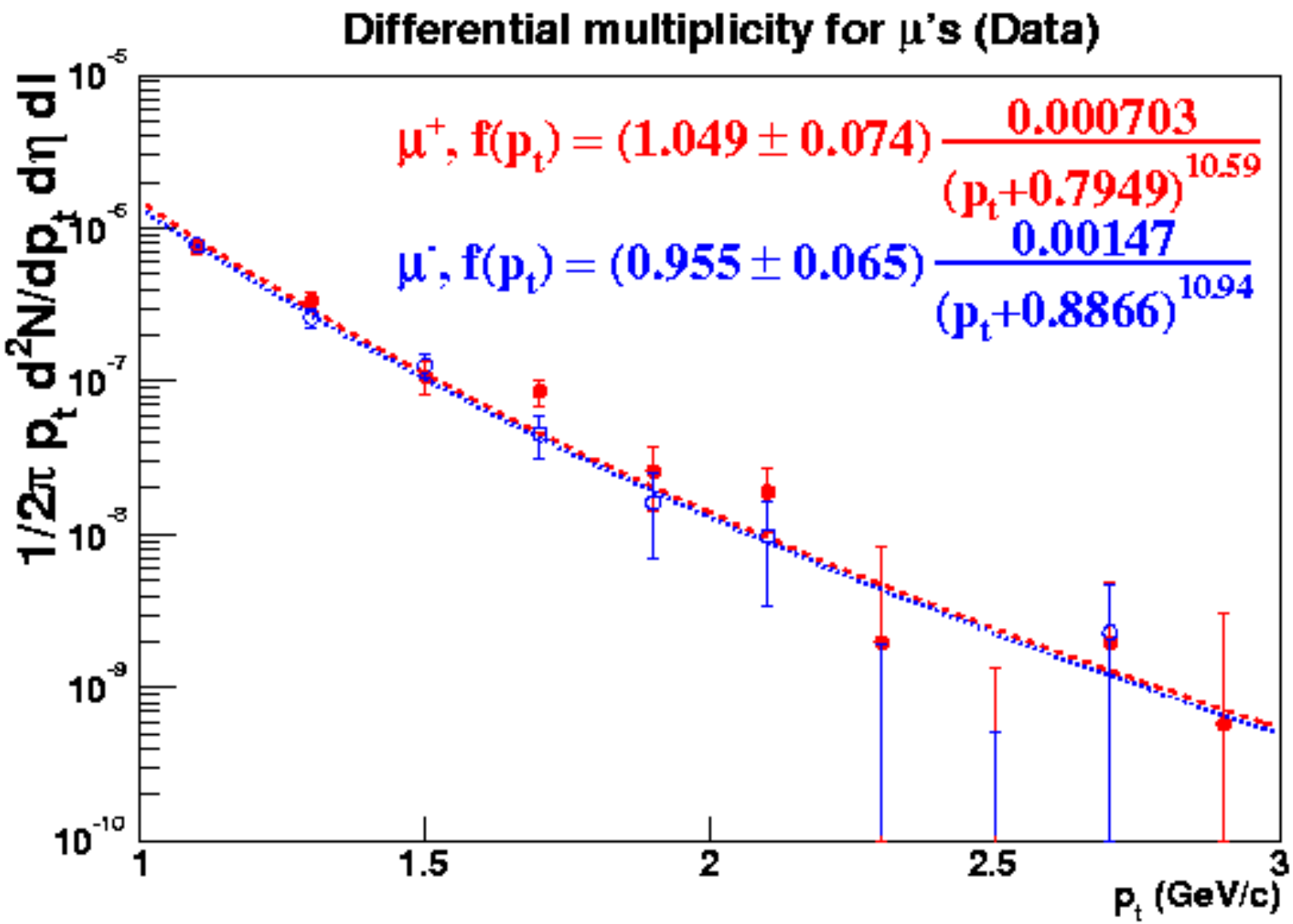


FIG. 12: Extracted *l*-differential invariant multiplicities of the *decay muons* produced within one cm of the collision point, Data vs fit parameterization of the simplified generator (scaled by ±5%).

Background simulation for the primary μ analysis and its uncertainty

We estimate and subtract background from signal.

Decay μ

Parametrization based on C.A. measurement scaled to fit data

uncertainty : $7\% \oplus 7\% (1-p_t)$

(statistical) (systematical)

efficiency + parametrization

$5\% (1\text{-pt}) \oplus 5\% (1\text{-pt})$

Punch-through

Correction factor to the simplified extrapolation

$\approx 1.3(1<pt<2)/1.1(2<pt<3)$,

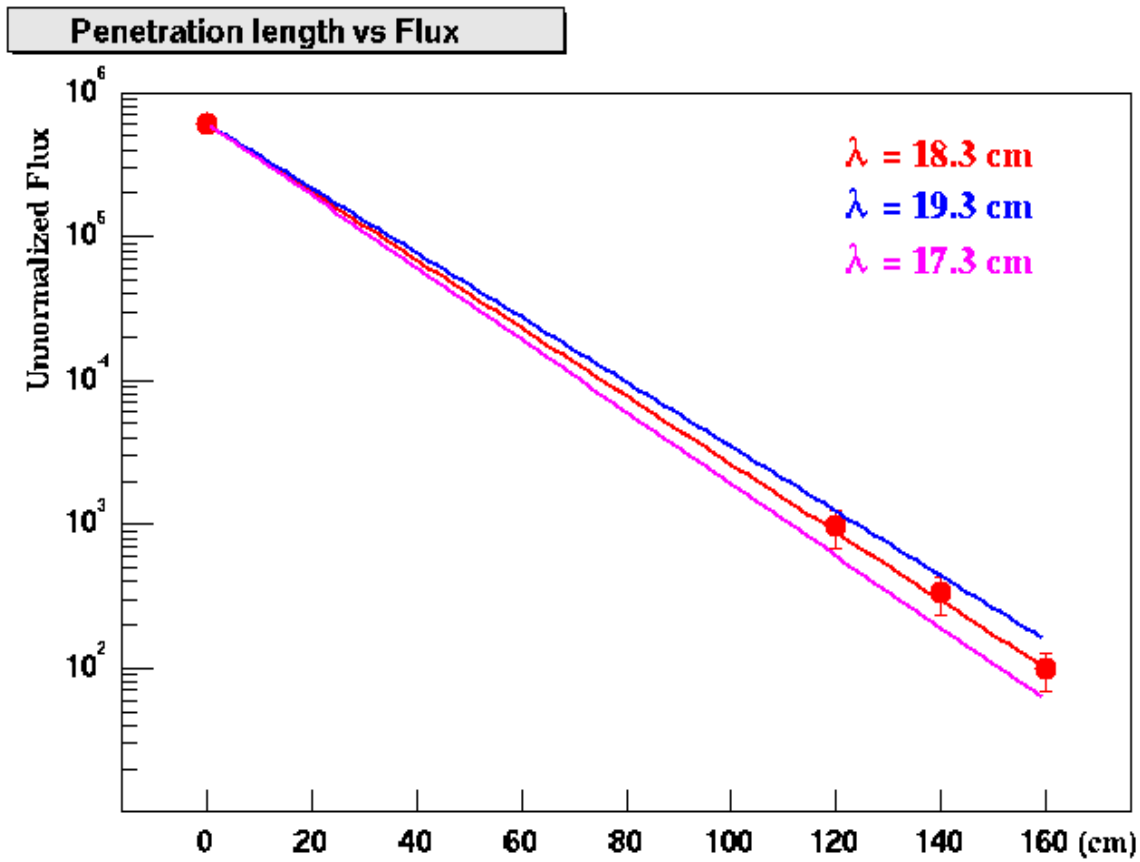
Uncertainty $\delta \approx 0.4(1<pt<2)/0.35(1<pt<2)$

Background

up to 10%, proportional to decay μ

Punch-through, simplified model

We set up a simplified model to estimate punch-through's. The model use measured DEPTH4 hadrons (also used in Rcp analysis) and extrapolate them to DEPTH5.
This data-driven approach reduce uncertainty.



What's the correction factor to the simplified model and reasonable variations to account for the uncertainty?

Measurement uncertainty (hadron flux at DEPTH4) : $\delta^{norm} = 0.23$

Also, this simplified model has generic uncertainty. We tested the simplified model against PISA simulations with different hadron interaction packages (FLUKA, GHEISHA). Average correction factor is about 1.3 and uncertainty is tabulated here. Substancial variation depending on p_t and particles are seen.

Model uncertainty only

When we add measurement uncertainty 0.23...

Particles	δ^{pt} ($1 < p_t < 2$)	δ^{pt} ($2 < p_t < 3$)
$\pi+$	0.49 (0.43)	0.28 (0.16)
$\pi-$	0.39 (0.32)	0.51 (0.45)
K+	0.39 (0.31)	0.28 (0.16)
K-	0.39 (0.31)	0.33 (0.23)

Ghost Background

Reconstructed decay-in-tracking-volume

From the simulation study for $\pi^{\pm}$,

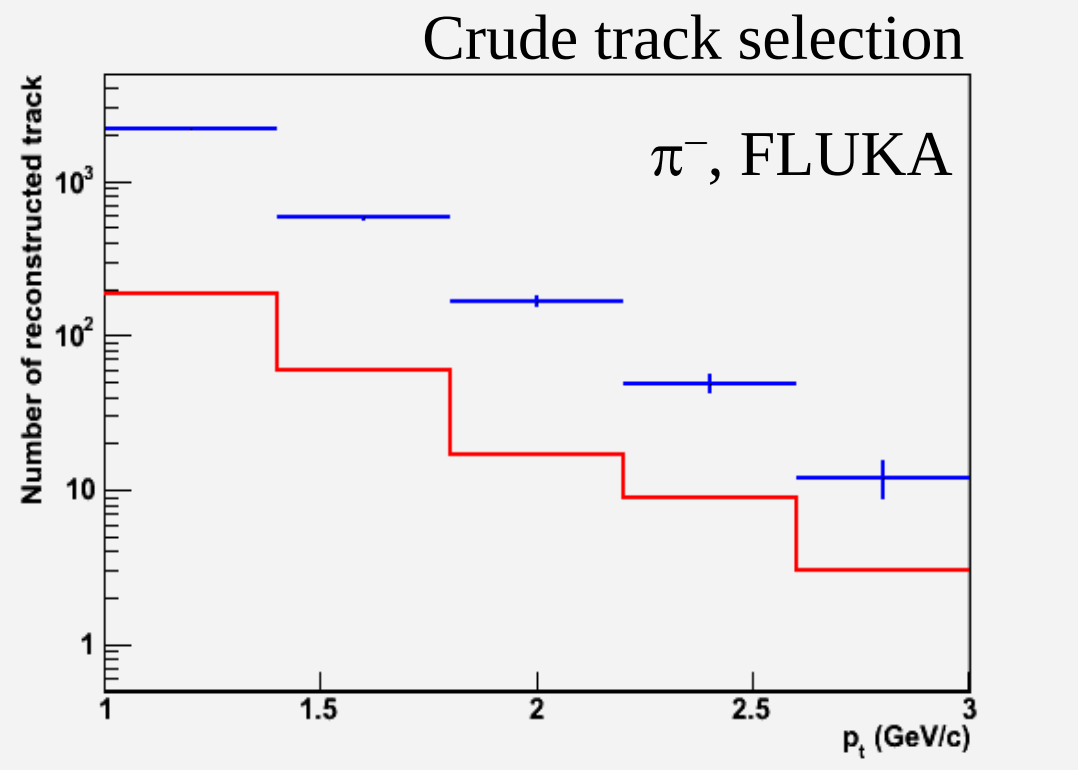
5 % D.E. (p_t = 1 GeV/c)

7 % D.E. (p_t = 2 GeV/c)

12 % D.E. (p_t = 3 GeV/c)

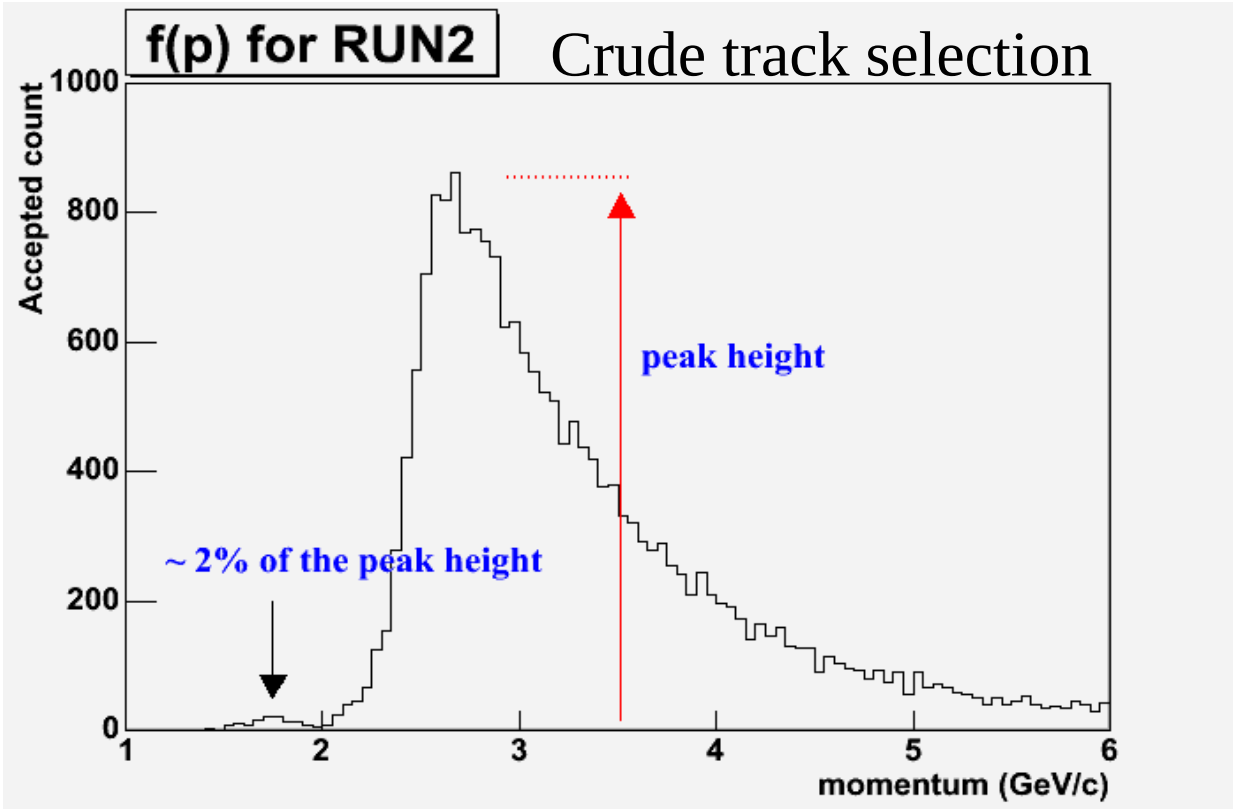
Random association

2 % (D.E. + P.T.) (small & ignored)



Reconstructed decay-in-tracking-volume can reach up to 24% when p_t = 3(GeV/c). However a large number of tracks are also reconstructed as with DEPTH3, and our Punch-Through subtraction procedure suppress this background by about factor of 2. Tighter selection, usage of K^-,or GHEISHA as hadron package will reduce the estimated background even further. Long simulation will help the issue.

Random association
RUN3 study suggests background level underneath peak will be 2% level.



Presented error in the invariant multiplicity for minimum bias events.

1. We simulate z-dependent background in three way,

   Background(maximum) :

   Decay(maximum)+PunchThrough(maximum)+Ghost Background(maximum)

   Background(mean)

   Decay(mean)+PunchThrough(mean)+Ghost Background(mean)

   Background(minimum)

   Decay(minimum)+PunchThrough(minimum)+Ghost Background(minimum)

2. We subtract background from signal and fit by a constant over z.

   Statistical error for mean is taken as statistical error.

   Differences between $case_{max} - case_{mean}$ and between $case_{mean} - case_{min}$ becomes err_{high} and err_{low}.

3. We add systematic uncertainty for the singles and get the final systematic uncertainty

$$\varepsilon_{high} = err_{high} \oplus \varepsilon_{single}, \quad \varepsilon_{low} = err_{low} \oplus \varepsilon_{single}$$

Further detail on background cocktail

STEP I : source of z-vertex dependence from decay μ

Extrapolation of the central arm invariant multiplicity predicts triple differential cross section for μ in $-1.8 < \eta < -1.5$ (note dN/dl, and l is distance from the collision point)

$$1/2\pi p_t \, d^3N^{decay}/dp_t d\eta dl|_{\eta=-1.65} = 0.00147/(p_t+0.8866)^{10.94}$$

and this converts to

$$f(z,p_t) = 1/2\pi p_t \, d^3N^{decay}/dp_t d\eta dz$$

after we multiply dl/dz = 1.06.

STEP II : line fit of the measured distribution

When -20 (cm) < z < 40 (cm) and geometry simplifies,

$$n(z,p_t) \equiv 1/2\pi p_t \, d^3N^{measured}/dp_t d\eta dz = C_{eff} \, f(z,p_t) \, (z - z_{eff}) + b(p_t)$$

where $b(p_t) = 1/2\pi p_t \, d^3N^{primary}/dp_t d\eta$ (primary=punch-through+prompt μ)

, $z_{eff} = 40$ (cm) + $\lambda_{\pi,K} \approx 60$ (cm), C_{eff} (arbitrary normalization factor)

STEP III : How do we determine normalization constant C_{eff}?

$$n(z,p_t) \equiv 1/2\pi p_t \, d^3N^{measured}/dp_t d\eta dz = C_{eff} \, f(z,p_t) \, (z - z_{eff}) + b(p_t)$$

Forced to match 10 slopes (decay μ invariant multiplicities) of data
see Page 11, $C_{eff} = 0.955 *(1\pm 7\%)$

STEP IV : How do we deal with the uncertainty in $C_{eff} \, f(z,p_t)$?

We simulate ±7% limit in C_{eff} . We also add ±7% (p_t-1) to account for the p_t dependent uncertainty. The formular used to estimate upper and lower limit in decay μ within the background simulation is $(1\pm 7\%) \otimes (1\pm 7\% \, (p_t-1)) \otimes C_{eff} \, f(z,p_t)$ where $C_{eff} \, f(z,p_t)$ is the average decay background.

Further detail on z_{eff} estimation

The effective location source of hard decay μ disappears, z_{eff} , is given as $z_{eff} = 40\ (cm) + \lambda_{\pi,K} \cos\theta_{eff}$. Key uncertainty arises from $\lambda_{\pi,K}$ corresponding to the effective depth particle propagate in the absorber.

STEP I : how to determine λ

We determine λ from the hadrons used in the R_{cp} analysis and the simple absorption model. Invariant multiplicity of the R_{cp} hadrons

$$1/2\pi p_t\, d^2 h_{\pi Kp} /dp_t dy$$
$$= 1/2\pi p_t\, d^2 N_{\pi Kp} /dp_t dy \cdot \underbrace{\exp(-L_4/\lambda_i)\cdot (1-\exp(-(L_5-L_4)/\lambda_i))}_{\text{Suppression factor}}$$

$L_{4,5}$: absorber thickness up to DEPTH 4,5. λ_i : absorption length

$\lambda_{\pi,K}$ determined from the hadrons is close to the effective depth according to the PISA simulation (better than 1 cm). Major source of observed hadrons are

1) pure punch-through (no hadron interaction),

and

2) leading hadrons. 1) and 2) are also major sources of "hard decay μ's".

STEP II : $1/2\pi p_t\, d^2 h_{\pi Kp} /dp_t dy$? Measurements for + & - charged.

$1/2\pi p_t\, d^2 h^+/dp_t dy = C_+/(p_t+0.306)^{5.25786}$,

$C_+ = 0.106 \pm 0.024 \pm 0.011$

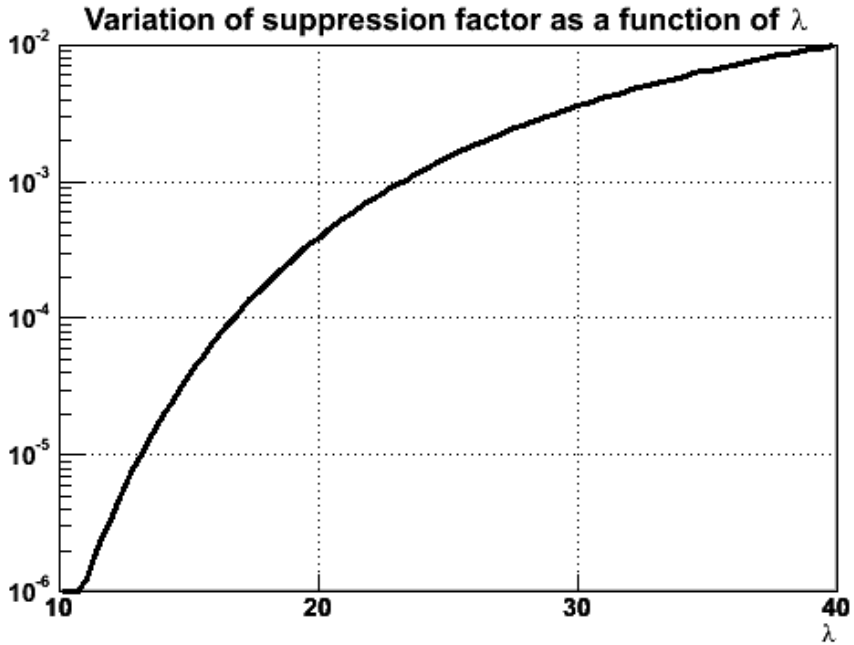
$1/2\pi p_t\, d^2 h^-/dp_t dy = C_-/(p_t+0.306)^{5.25786}$,

$C_- = 0.0352 \pm 0.008 \pm 0.0075$

STEP III : how sensitive is the hadron yield to the change of λ?

λ	Suppression factor
23(cm)	0.00039·2.4
20(cm)	0.00039
17(cm)	0.00039/3.4

3(cm) change yields of decay μ by 5%.



STEP IV : how do we deal with multiple particle species?

For each p_t, we need to determine 6 λ's (for π^+,π^-,K^+,K^-,p, and pbar) while there are only two measurements. Some facts of note are ...

1. To 1st order, all particles have similar λ.

   (naively cross section for X+ Fe is dominated by Fe nucleus

2. $\lambda(K^+) > \lambda(K^-) \approx \lambda(\pi^+) = \lambda(\pi^-)$, $\lambda(\pi) \geq \lambda(p) \geq \lambda(pbar)$

   Used for z_{eff}

$\sigma(K^+ + p) \approx 17.5$ mb, $\sigma(K^- + p) \approx 30$ mb, $\sigma(\pi^{\pm}+p) \approx 30$ mb,

$\sigma(p+p) \approx 45$ mb, $\sigma(pbar+p) \approx 60$ mb from PDG booklet

We make simplification based on these facts and the charge asymmetry observed in data. Subsequently we can determine λ assuming hadron spectra extrapolated from central arm was produced at collision point.

$$\lambda_{long} = \lambda_{K+} = 27.9 + 3.7\cdot(p_t - 1)\ (cm)$$
$$\lambda_{short} = \lambda_{\pi+} = \lambda_{\pi-} = \lambda_{K-} = \lambda_p = \lambda_{pbar} = 18.45 + 2.2\cdot(p_t - 1)\ (cm)$$

STEP V : Errors in λ and z_{eff}?

For the given λ's,

$$h^-_{\pi+pbar} \approx 0.8\ h^-_{measured},$$
$$h^-_{K-} \approx 0.2\ h^-_{measured}$$

Upper limit

If $\lambda_\pi = \lambda_\pi + 3(cm)$, $h^-_{\pi+pbar} = 2.4\ h^-_{measured}$ (impossible!)

Lower limit

If $\lambda_\pi = \lambda_\pi - 3(cm)$, then $h^-_{\pi+pbar} = 0.24\ h^-_{measured}$, and

this must be matched by $\lambda_{K-} = \lambda_{K-} + 4.5(cm)$ ($h^-_{K-} = 0.69\ h^-_{measured}$).

This results in $\Delta\lambda = 7.5$ (cm) between $\lambda_{\pi-}$ and λ_{K-} which is an extreme. Considering $N_{\mu-}$(from π-)/$N_{\mu-}$ (from K-) ≈ 1(0.9 in fact), change in amount of decay μ cased by these changes almost cancel.

Systematic uncertainty in line fit (caused by δ^z)

Parametrization of line :

$$y = a \cdot (z - z_{eff}) + b, \text{ where } z_{eff} \approx -60 \text{ (cm)}.$$

Decay μ yields (D.E.) : $a \cdot (z_{max} - z_{eff})$

Primary tracks yields (P.T.) : b

For measurement (y_{min}, y_{max}) at $(z_{min}=-40\text{cm}, z_{max}=40\text{cm})$,

$$a = (y_{max} - y_{min})/(z_{max} - z_{min}), \quad b = -a \cdot (z_{min} - z_{eff}) + y_{min}$$

Taking maximal z-dependent uncertainty δ^z, $y_{max}' = (1+\delta^z) \cdot y_{max}$

$$\delta a = a\, \delta^z\, (1 + P.T./D.E.)\, (z_{max} - z_{eff})/(z_{max} - z_{min})$$

$$\approx 1.25 \cdot a \cdot \delta^z \cdot (1 + P.T./D.E.)$$

$$\delta b \approx -0.25 \cdot b \cdot \delta^z \cdot (1 + D.E./P.T.)$$

p_t (GeV/c)	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9
P.T./D.E.(+)	0.29	0.55	0.75	1.1	1.4	2.2	2.2	2.6	2.0	9.5
P.T./D.E.(-)	0.16	0.24	0.34	0.48	0.71	0.63	0.95	1.2	1.8	1.3

$\delta a/a$: 3% ~ 5% ~ 10%

$\delta b/b$ (uncertainty in slope) : 3% ~ 1% ~ 0.5%

Systematic uncertainty in line fit (caused by δz_{eff})

$\delta b = a\ \delta z_{eff}$ = D.E. $\Delta z_{eff}/80 \approx 1.5\%$ D.E.

db/b = 1.5% /(P.T./D.E.) < 9% maximum at p_t = 1.1 (GeV/c)

These uncertainties are much smaller than the uncertainty we use finally.

Antiprotons?

Discussion for the negatively charged particles

pbar/π^- (generated) $\approx$ 0.25,

σ(pbar) > $\sigma(\pi^-)$

pbar/π^- (DEPTH4) < 0.25,

Using extrapolation factor based on π^- for pbar doesn't make much difference (< 10 % of the whole punch-through)