Hadronic cross sections and multiplicities in LHCb's simulation software

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LPCC Workshop

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Introduction

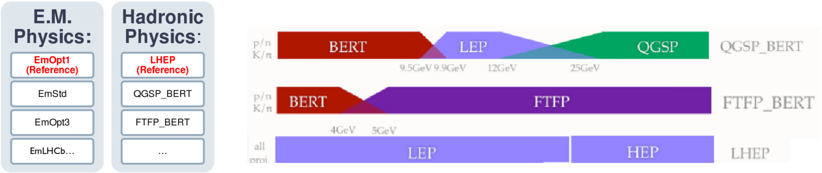
- Main focus for LHCb:
  → single particle interaction
  → part/antipart asymmetries
  → low p_t
- Unlike ATLAS and CMS: high p_T and jets
- Many of LHCb measurements are related to asymmetries and detector modelling enters in systematics
- Reliable simulation can help to lower systematics

What are important quantities to study?

- Study part/antipart cross section ratio
  → can affect detection efficiency
- Study multipicity and composition of inelastic daughters.
  → Number of particles in the detector and type can affect reconstruction

What we use, what we used and how we check it

- LHCb framework (Gauss) currently uses Geant4 v9.5p02
- validation just started for v9.6p02.
- Physics List → LHEP (used until 2012), FTFP_BERT (in use now), QGSP_BERT



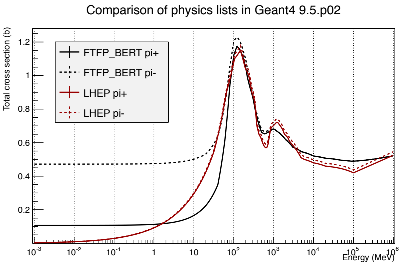
2-level checks:

- First step: checks directly on Geant4:
  → Quickly and cleanly highlight Physics List changes
- Second step study hadronic interaction using full LHCb framework:
  → technical handling of PLs/options/geometry directly by production system
  → validation not only of Geant4 but also our production system

Geant4 Examples

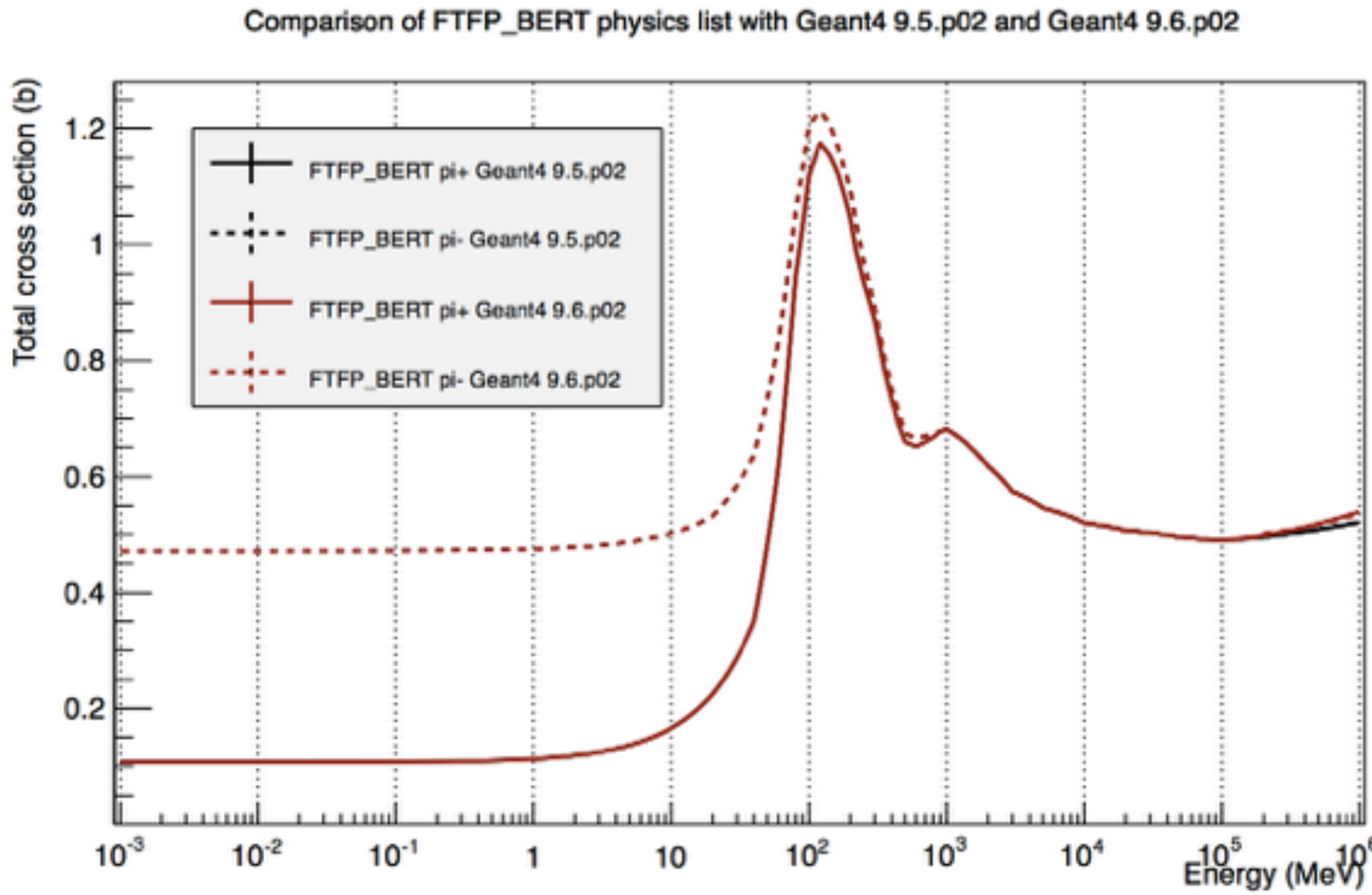
- Using standalone Geant4 examples.
  - Example code released with each version of Geant4.
  - Built in LHCb environment.
  - Doesn't rely on full LHCb simulation software.
- Hadr00 example used to test interaction cross-sections for different physics lists

J. McCarthy

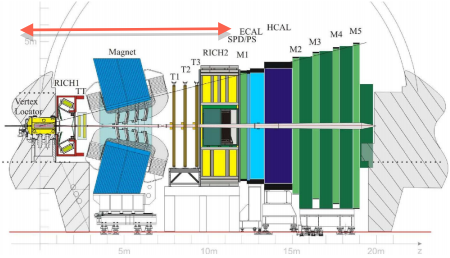


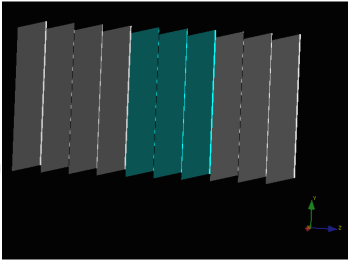
Validation

- Useful validation check for new Geant4 release.
  - Quickly highlights any changes in physics lists
- Comparing Geant4 v9.5.p02 and v9.6.p02



Using the LHCb framework





Main focus in region before RICH2. → where hadronic interaction can affect reconstruction

Interaction probability

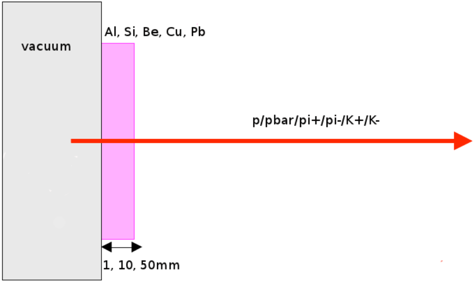
$P_{int} = N_{int}/N_{gen}$

Geant4 provides process ID:

- 111 = elastic
- 121 = inelastic

N_{gen} = 100k events

- Particle guns:
  - p, K^+, π^+, $\bar{p}$, π^-, K^-
- Materials:
  Al, Si (silicon trackers), Be (beampipe)
- Thickness: 1mm, 10mm, 50mm
  Material upstream RICH2 $\sim 0.6X_0$, so verify stable to at least 5cm Al



EM physics list is always kept the same (P. Griffith talk this morning for EM physics)

Using simplified geometry

- Particles created in a vacuum
- Particles interact in a box of uniform material
- No δ-rays simulated (to avoid counting artifacts)

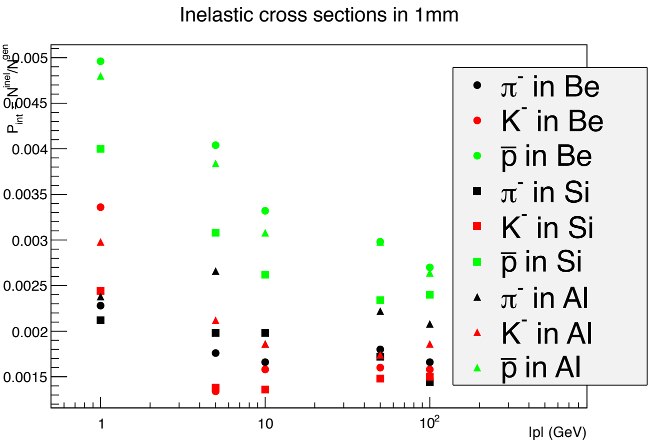
Cross section

For data comparison (valid for thin layers)

$$\sigma_{int} = P_{int} \cdot \frac{A}{\rho N_A \Delta x} \cdot 10^{-24}$$

- $\Delta x \rightarrow$ thickness
- ρ and A of material
- $10^{-24} \rightarrow$ conversion to barn

Inelastic probability of interaction (P_{int}^{inel}) (FTFP_BERT)

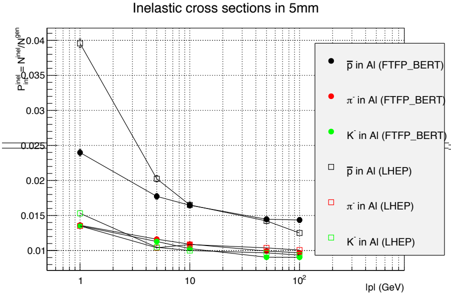


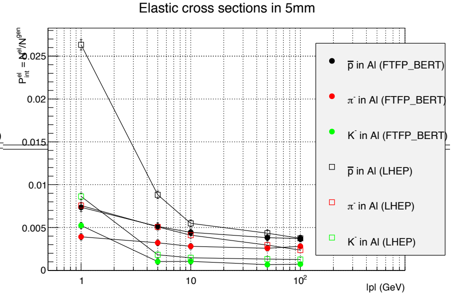
Lots of probabilities of interaction for different combinations of pguns/materials/etc...

$\rightarrow$ possibility of check against older versions

$\rightarrow$ in principle possibility to check against data

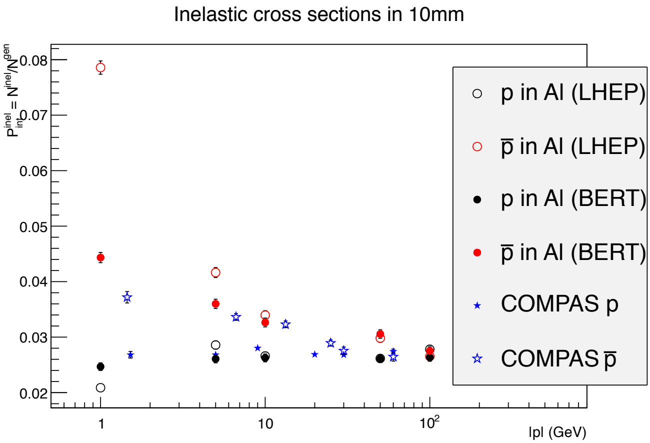
Comparison FTFP_BERT / LHEP





Antiproton at low energy is the point of biggest disagreement

Comparison with data $p/\bar{p}$ in 10mm Al

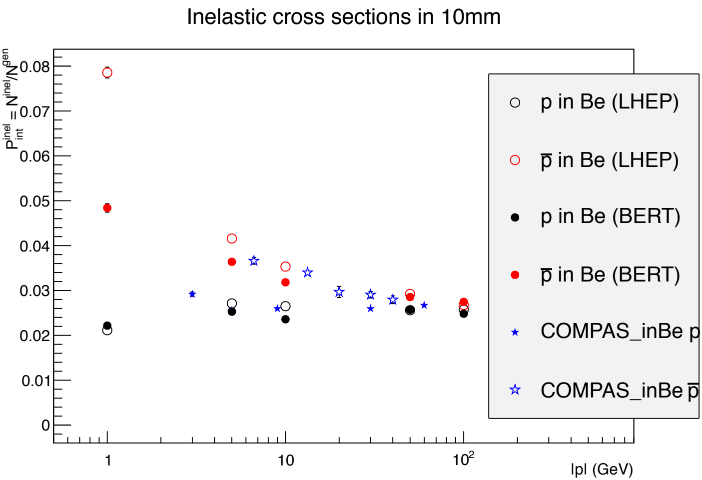


Comparing with COMPASS data (as available)

For both model good agreement with data for p

FTFP_BERT has better agreement for low energy $\bar{p}$

Comparison with data $p/\bar{p}$ in 10mm Be



Good agreement with data for *p*, FTFP_BERT slightly better

Agreement gets a little worse for smaller thicknesses

Cross sections in the PDG

In PDG cross sections of protons and neutrons parametrised as follows:

low energy

$$\sigma^{ab}_{tot} = Z^{ab} + B^{ab} log^2(s/s_M) + Y^{ab}_1 (s_M/s)^{\eta_1} - Y^{ab}_2 (s_M/s)^{\eta_2} \quad (1)$$

$$\sigma^{\bar{a}b}_{tot} = Z^{ab} + B^{ab} log^2(s/s_M) + Y^{ab}_1 (s_M/s)^{\eta_1} + Y^{ab}_2 (s_M/s)^{\eta_2} \quad (2)$$

high energy

part / antipart asymmetry

- $s_M = (m_a + m_b + M)^2$ and $B^{ab} = \lambda\pi(\frac{\hbar c}{M})^2$.
- M $= 2.15$, $\eta_1 = 0.462$, $\eta_2 = 0.551$ (universal constants)
- $\lambda = 1$ (for p, n and γ) and 1.63 (for d)
- Z^{ab}, Y^{ab}_1 and Y^{ab}_2 are characteristic of each type of collision
- For nuclei average over the number of neutrons and protons in the nucleus

Proj / Targ	Z^{ab}	Y^{ab}_1	Y^{ab}_2
$\bar{p}$,p / p	34.71	12.72	7.35
$\pi^{\pm}$ / p	19.02	9.22	1.75
$K^{\pm}$ / p	16.56	4.02	3.39
$K^{\pm}$ / n	16.49	3.44	1.82
$\bar{p}$,p / n	35.00	12.19	6.62

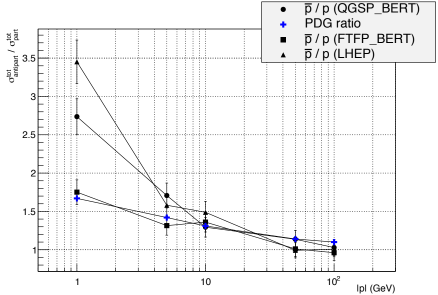
Particle-antiparticle asymmetry is contained in the last term (Y^{ab}_2).

Becomes less important at high energies → so a net asymmetry is expected found at low energies

Adding PDG to the game

Total cross section: inelastic + elastic

All ratios refer to collisions in 1mm of Al.



p [GeV]	LHEP	FTFP	PDG
1	3.48 ± 0.12	1.77 ± 0.06	1.67
5	1.62 ± 0.05	1.35 ± 0.04	1.42
10	1.48 ± 0.04	1.39 ± 0.04	1.31
50	1.03 ± 0.04	1.03 ± 0.04	1.14
100	1.01 ± 0.04	0.98 ± 0.04	1.10

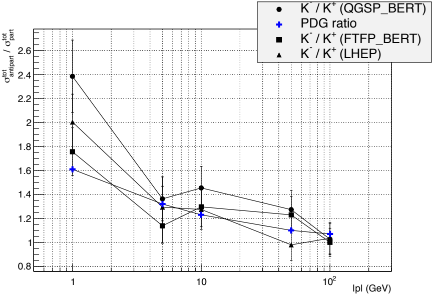
PDG agrees definitely better with FTFP at low energies

Caveat: maybe systematic due to PDG reports cross sections on p and n, not Al directly.

Adding PDG to the game

Total cross section: inelastic + elastic

All ratios refer to collisions in 1mm of Al.

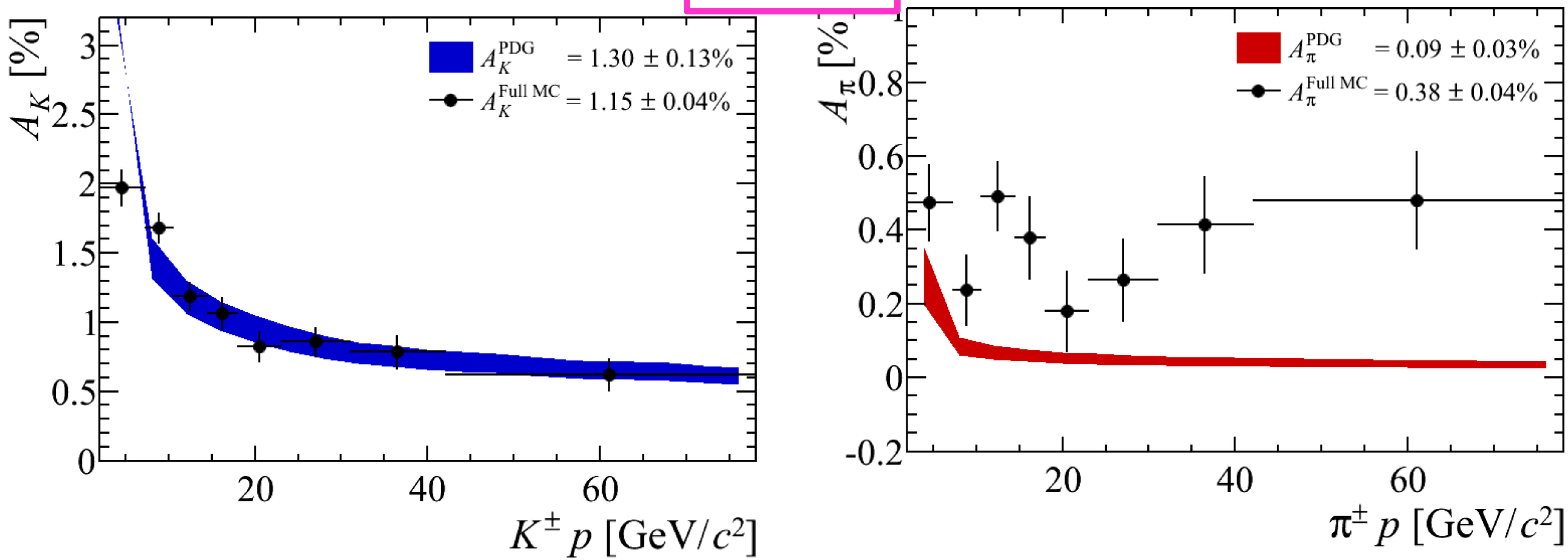


p [GeV]	LHEP	FTFP	PDG
π^-/π^+			
1	1.10 ± 0.03	0.98 ± 0.03	1.22
5	1.07 ± 0.03	1.00 ± 0.03	1.13
10	1.06 ± 0.03	0.95 ± 0.03	1.10
50	1.06 ± 0.03	0.97 ± 0.03	1.05
100	0.97 ± 0.04	1.02 ± 0.03	1.03
K^-/K^+			
1	1.98 ± 0.10	1.76 ± 0.05	1.61
5	1.37 ± 0.05	1.18 ± 0.04	1.32
10	1.44 ± 0.04	1.25 ± 0.04	1.23
50	1.13 ± 1.31	1.24 ± 0.03	1.10
100	0.99 ± 0.04	1.05 ± 0.04	1.07

Again PDG agrees definitely better with FTFP at low energies

Detection asymmetry saga

preliminary



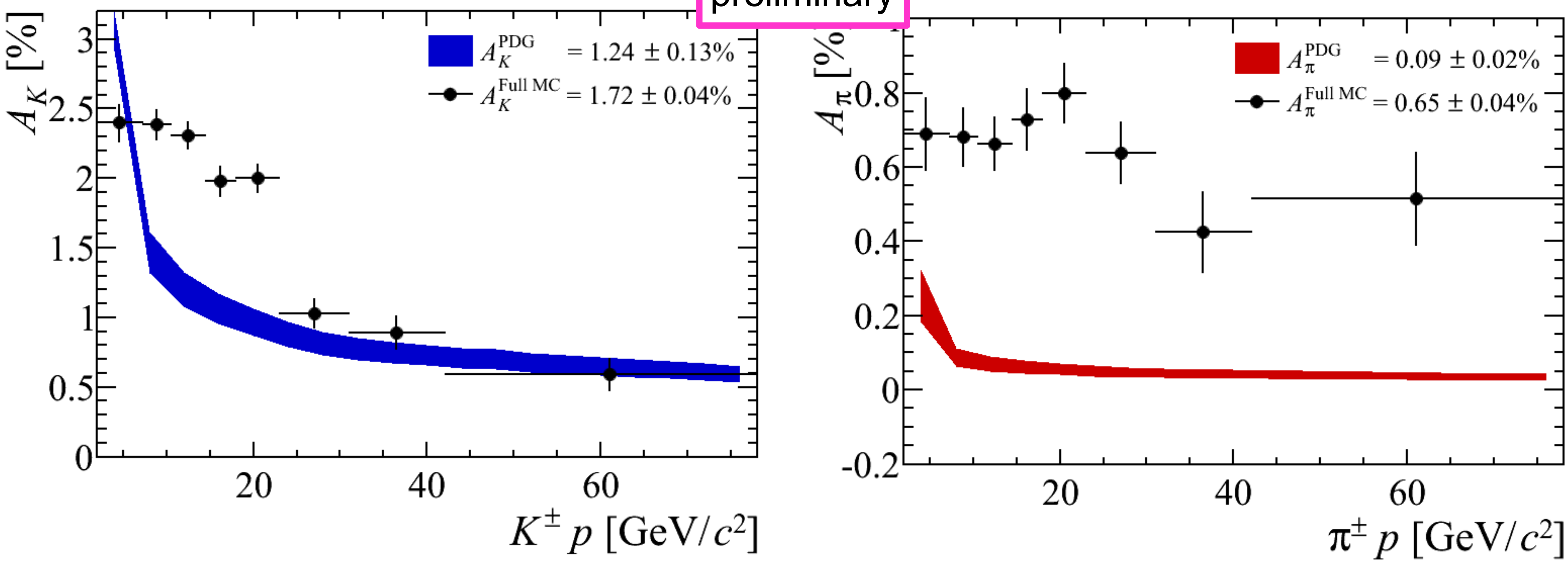
- From previous 9.4.patch02 production setup in LHCb (LHEP list)
  - Kaon asymmetry looks ok.
  - Pion asymmetry way off.

$$A = \frac{N^+_{obs} - N^-_{obs}}{N^+_{obs} + N^-_{obs}}$$

J. Van Tilburg

(LHEP G4 9.5p02) asymmetries

preliminary



- Using 9.5.patch02 setup in LHCb (LHEP list)
  - Nominally unchanged G4 physics
- Kaon asymmetry for low momentum now too high
- Pion asymmetry further off
- At one level, should not worry as we will not use this PL, but…

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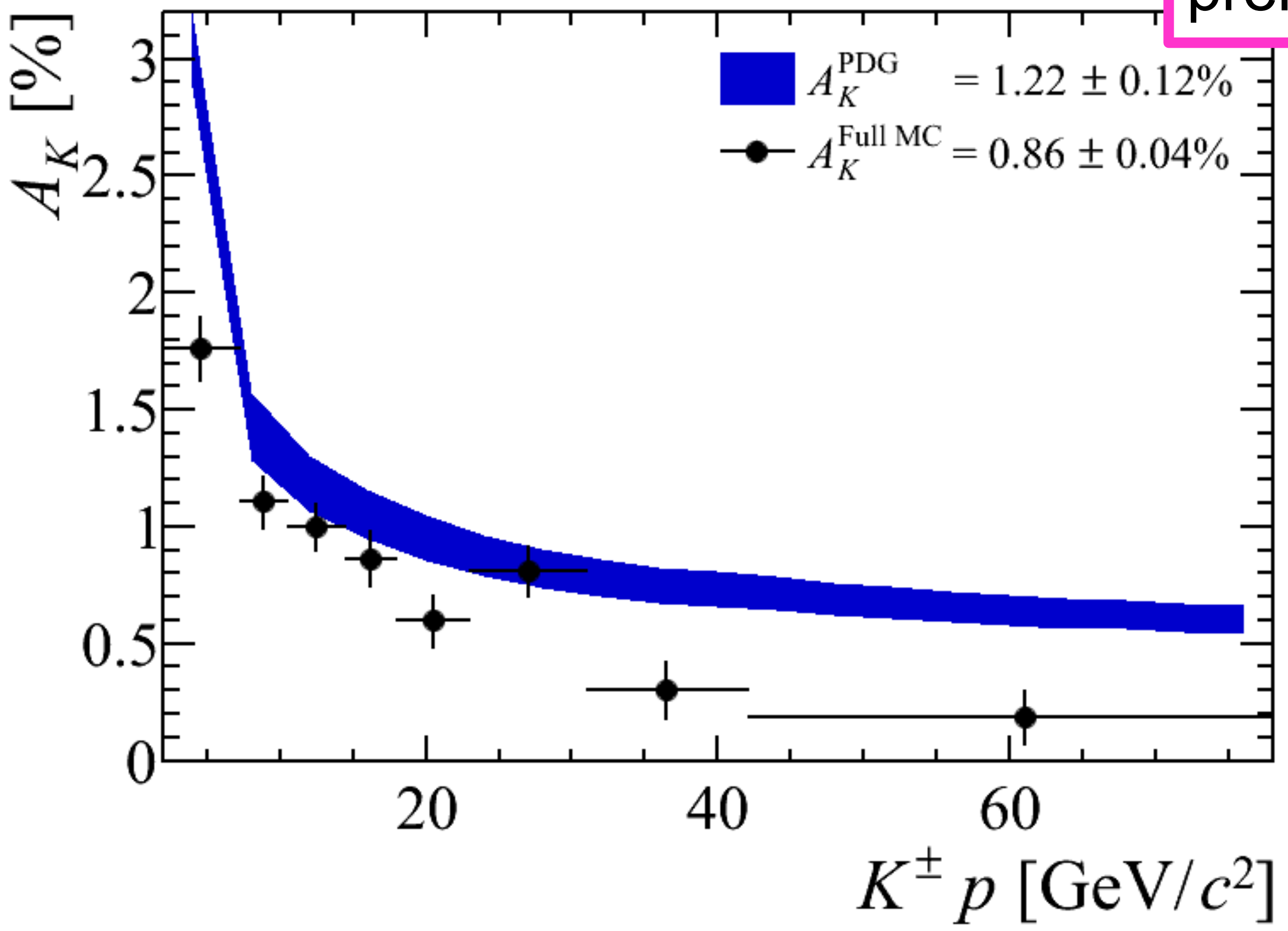
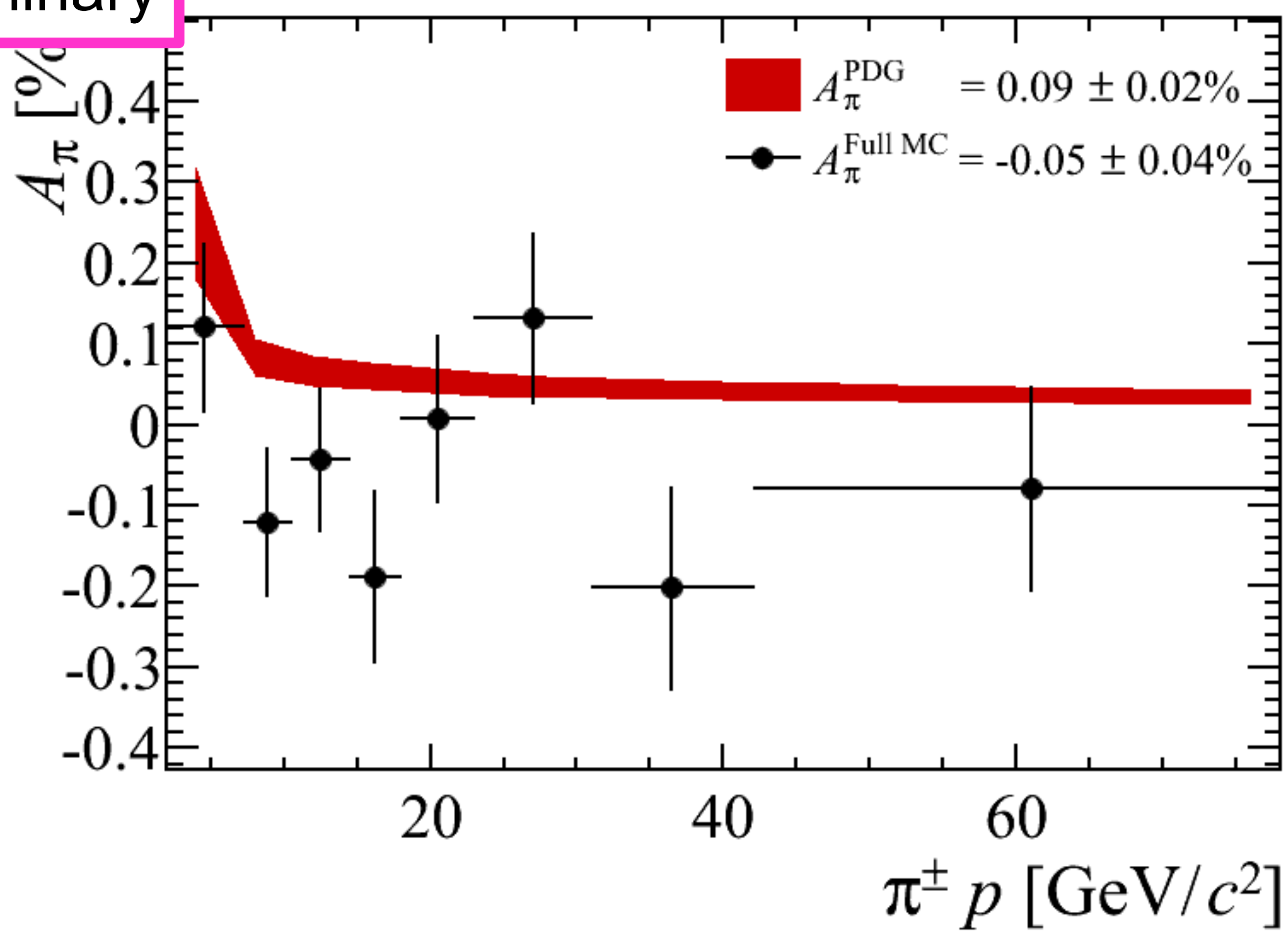
(FTFP_BERT G4 9.5p02) asymmetries

preliminary





- Using 9.5.patch02 setup in LHCb (FTFP_BERT list)
- Kaon asymmetry too low (esp. for high momentum).
- Pion asymmetry is ok now (note changed A_π scale cf. previous slide)

J. Van Tilburg

Measurement of $A_{K\pi}$ in LHCb

Measure of detection asymmetry in LHCb
$\rightarrow$ good possibility to compare with MC

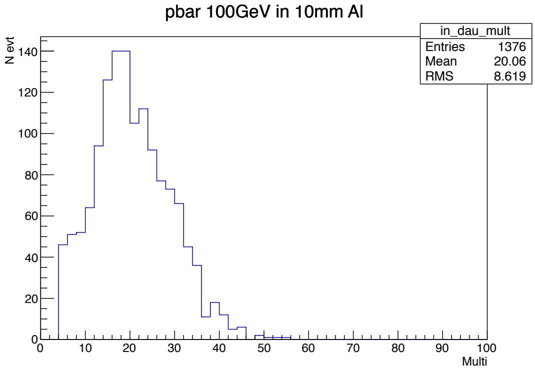
$$A_{K\pi} = \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)} \tag{3}$$

- Needed for CP violation measurements with odd number of kaons
- Measured in data using prompt charm decays
- Many possible: D have high rate (5M $D \rightarrow K_S\pi$)
- Allows to measure $A_{K\pi}$ down to $\sim 5 \times 10^{-4}$ level.
- Needs correction for PID asymmetry
- In approval just today (will be on arXiv in a few weeks).

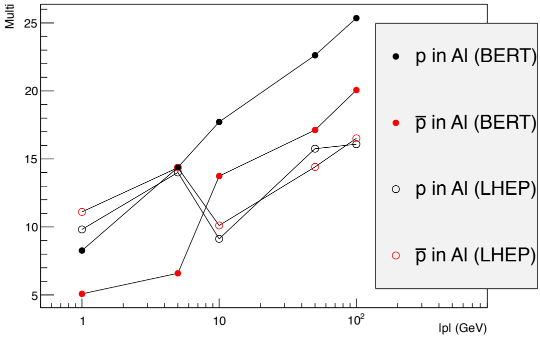
$$\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} = \frac{N(D^- \rightarrow K^+\pi^-\pi^-)}{N(D^+ \rightarrow K^-\pi^+\pi^+)} \times \frac{D^+ \rightarrow K^0_S\pi^+}{D^- \rightarrow K^0_S\pi^-} \tag{4}$$

Multiplicity and composition of daughters

- Number of particles can affect reconstruction
- Only direct inelastic daughters counted
- Using 9.5p02 + patch for K cross section ported from 9.76, provided by G5 team
- Next plots showing average multiplicities as a function of energy
- Average multiplicity is not thickness dependent (good check of method)



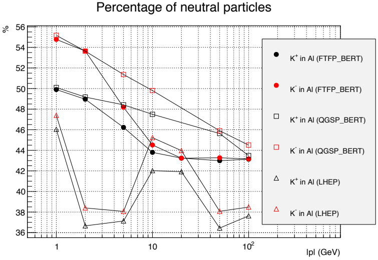
Multiplicity: LHEP and FTFP_BERT

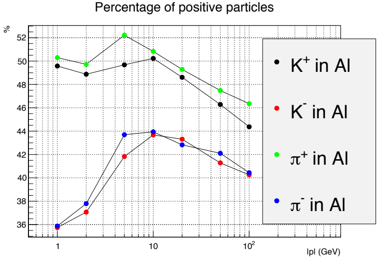


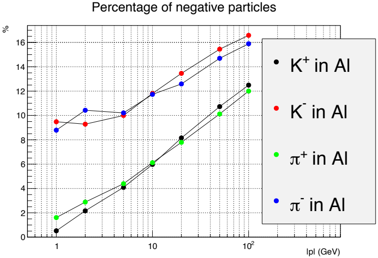
- Neutral and charged particles counted.
- Something going on with LHEP at 10GeV?
  → Maybe junction of different models? (Should be at 25 GeV)
- N.B.: In FTFP_BERT especially at low energy multiplicity produced by parti/antipart is very different
  → can this affect reconstruction efficiency?

Percentage of particle produced

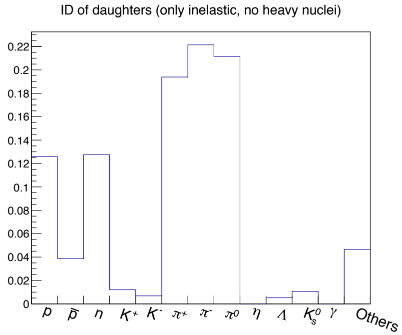
- Most of the particles are positive and neutral especially at low energy
- Negative particles produce more negatives daughters
- Hierarchy is same for all models $\rightarrow$ positive (40-50%) $<$ neutral (30-40%) $<$ negative



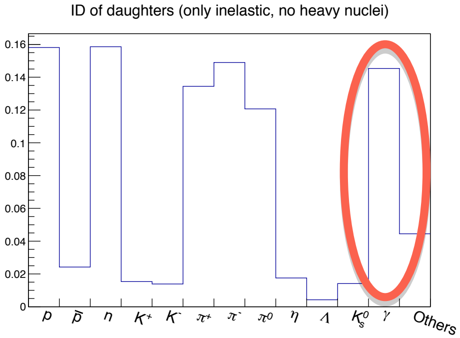




Percentage of daughter ID in 100 GeV $\bar{p}$ inelastic collisions in 5mm Al



LHEP

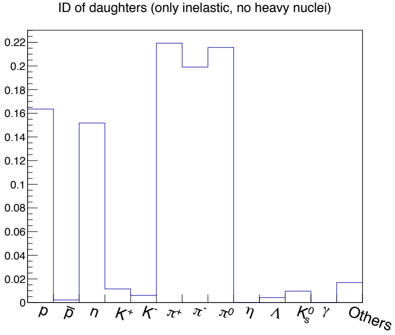


FTFP_BERT

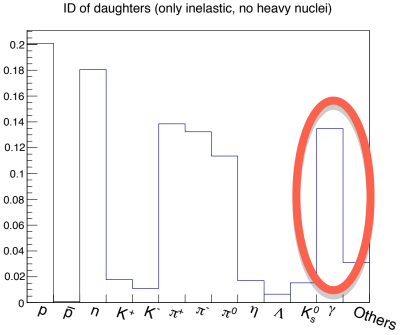
- As expected mostly $p/\bar{p}$, n and pions of the three kind
- "Others" includes mostly heavy nuclei
- γ production is biggest difference with LHEP

Composition of daughters LHEP/FTFP_BERT

Percentage of daughter ID in 100 GeV p inelastic collisions in 5mm Al



LHEP

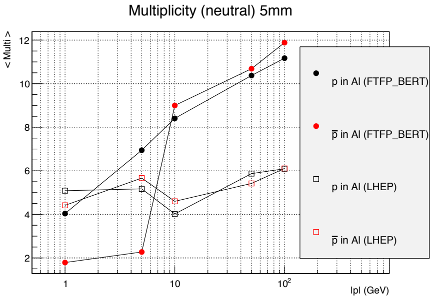


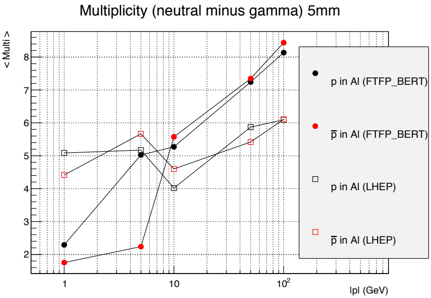
FTFP_BERT

- With FTFP_BERT 15-20% of γ are produced and this lowers mostly the percentage of pions.
- Baryon / meson ratio changes too! $n_{(p,\bar{p},n)}/n_{(\pi^+,\pi^-,\pi^0)} \sim 0.5 \rightarrow \sim 1$

A look back to multiplicity

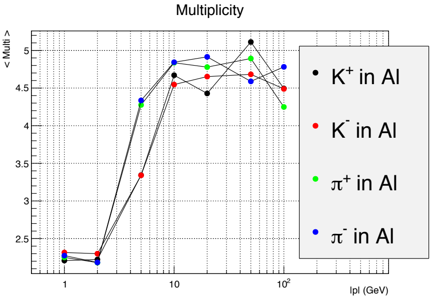
Neutral multiplicity counting and not counting gammas.





In this way mean value corresponds but energy dependence still very different.

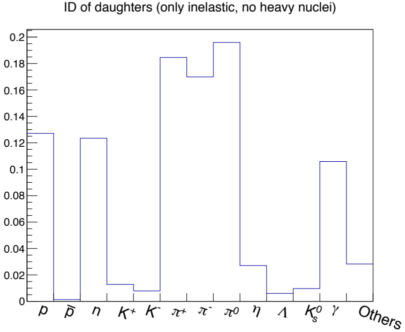
Multiplicity of γ produced



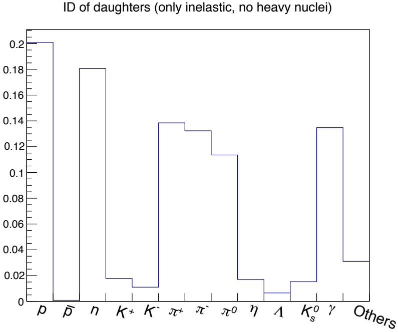
- Similar for all incoming particles
- Reaches saturation after $\sim$ 10GeV for all incoming particles.

Composition of daughters QGSP_BERT/FTFP_BERT

Percentage of daughter ID in 100 GeV p inelastic collisions in 5mm Al



QGSP_BERT

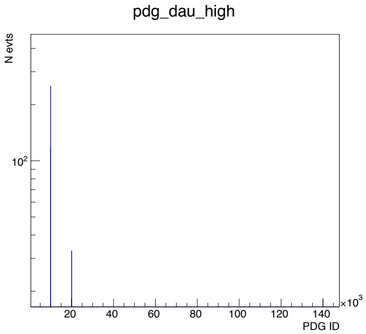


FTFP_BERT

- γ still abundantly produced.
- Baryon / meson ratio goes back to LHEP. $n_{(p,\bar{p},n)}/n_{(\pi^+,\pi^-,\pi^0)} \sim 0.4$

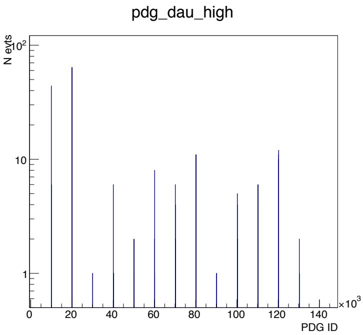
Composition of heavy particles

Daughter ID in 10GeV p inelastic collisions in 1 mm Al (only heavy nuclei)



(LHEP)

Only alpha, deuteron and triton

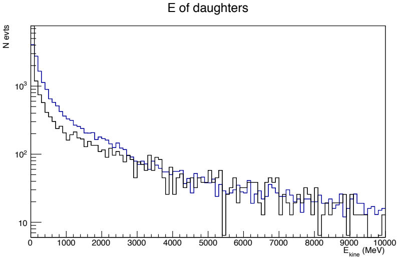


(FTFP_BERT)

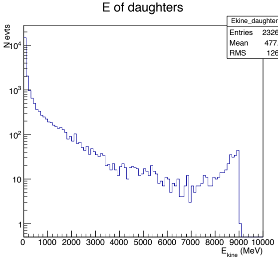
Much wider variety produced in FTFP_BERT

Kinetic energy of daughters

Distribution of kinetic energy of daughters (both neutral and charged), excluding heavy nuclei



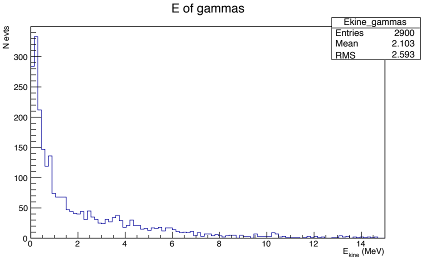
50GeV *p* in 1mm Al.
LHEP (blue), FTFP_BERT (black)



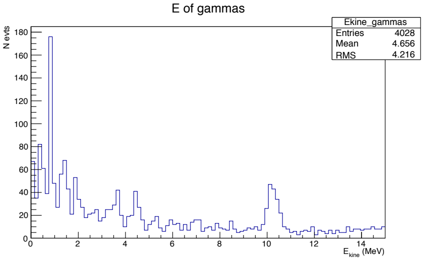
p 10GeV in 10mm Al
Peak and cutoff at high energy in FTFP_BERT??
Seems not present in LHEP

Kinetic energy of gammas

Distribution of kinetic energy of γ produced in inelastic p collision in 1mm Al (using FTFP_BERT).



(1 GeV incoming p)



(100 GeV incoming p)

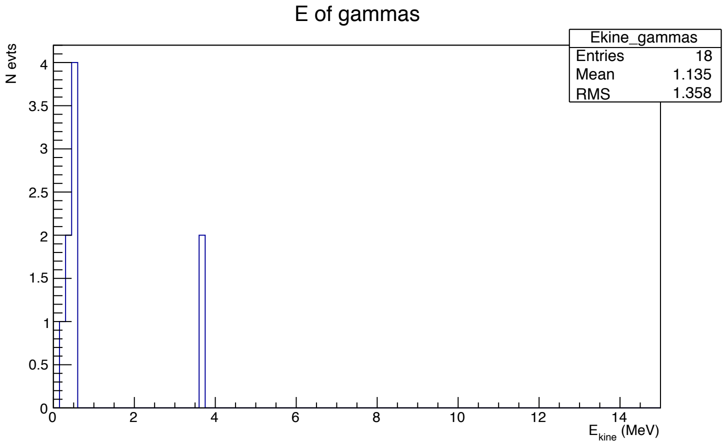
Conclusions

- Current LHCb production uses FTFP_BERT with CHIPS cross-sections in Geant4 9.5p02
- Just started testing Geant4 9.6p02
- FTFP_BERT seems to perform generally well (cross section-wise)
  → Pion/proton asymmetries improved but kaon asymmetries can still be improved
- We qualitatively see smoother behaviour in FTFP_BERT multiplicities
  → comparison with data would be interesting
- More data required for reliable comparison
  → we'll use more data for the next validation
  → paper measuring kaon detection asymmetry in LHCb coming soon

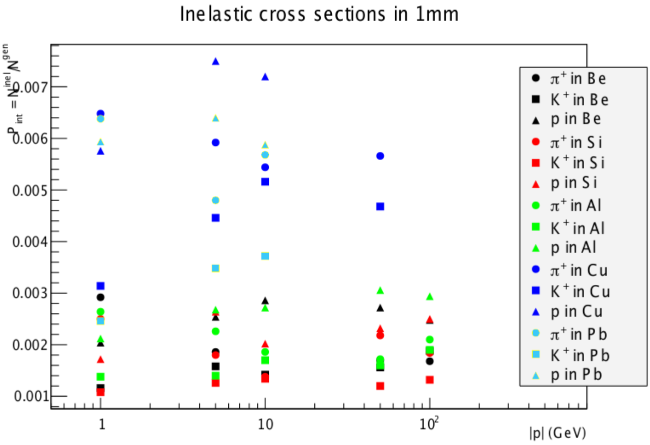
Back-up slides

Kinetic Energy of γ daughters

10 GeV p collisions in Be with FTFP_BERT.



Inelastic probability of interaction (P_{int}^{inel}) (LHEP)



Lots of probabilities of interaction for different combinations of pguns/materials/etc...

$\rightarrow$ possibility of check against older versions

$\rightarrow$ in principle possibility to check against data

Cross sections for particles (LHEP)

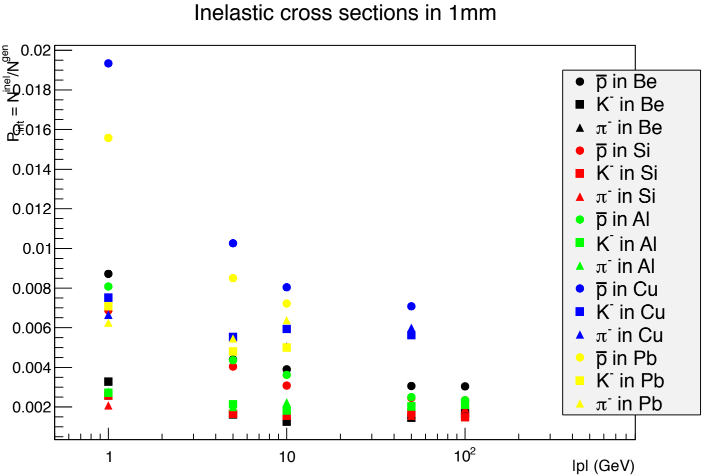
PGun in Material	N^{inel}/N^{gen} (10^{-3})	σ_{inel} (mb)	N^{el}/N^{gen} (10^{-3})	σ_{el} (mb)
		PGun energy = 10GeV		
		Thickness = 1mm		
π^+ in Al	1.86 ± 0.19	309 ± 32	0.78 ± 0.12	129 ± 21
K^+ in Al	1.70 ± 0.18	282 ± 31	0.20 ± 0.06	33 ± 10
p in Al	2.72 ± 0.23	451 ± 39	1.08 ± 0.15	179 ± 24
		Thickness = 10mm		
π^+ in Al	21.32 ± 0.65	354 ± 11	8.28 ± 0.41	137 ± 7
K^+ in Al	16.42 ± 0.57	272 ± 9	3.00 ± 0.24	50 ± 4
p in Al	26.60 ± 0.72	441 ± 12	12.52 ± 0.50	208 ± 8
		PGun energy = 50GeV		
		Thickness = 1mm		
π^+ in Al	1.72 ± 0.19	285 ± 31	0.78 ± 0.12	129 ± 21
K^+ in Al	1.60 ± 0.18	265 ± 30	0.16 ± 0.06	27 ± 9
p in Al	3.06 ± 0.25	508 ± 41	0.96 ± 0.14	159 ± 23
		Thickness = 10mm		
π^+ in Al	20.68 ± 0.64	343 ± 11	6.04 ± 0.35	100 ± 6
K^+ in Al	17.14 ± 0.58	284 ± 10	2.76 ± 0.23	46 ± 4
p in Al	26.16 ± 0.71	434 ± 12	10.98 ± 0.47	182 ± 8

Cross sections for antiparticles (LHEP)

PGun in Material	N^{inel}/N^{gen} (10^{-3})	σ_{inel} (mb)	N^{el}/N^{gen} (10^{-3})	σ_{el} (mb)
PGun energy = 1GeV				
Thickness = 1mm				
π^- in Al	2.78 ± 0.24	461 ± 39	1.56 ± 0.18	259 ± 29
K^- in Al	2.72 ± 0.23	451 ± 39	1.68 ± 0.18	279 ± 30
$\bar{p}$ in Al	8.08 ± 0.40	1341 ± 66	5.34 ± 0.33	886 ± 54
Thickness = 10mm				
π^- in Al	27.74 ± 0.73	460 ± 12	15.16 ± 0.55	252 ± 9
K^- in Al	29.24 ± 0.75	485 ± 13	18.28 ± 0.60	303 ± 10
$\bar{p}$ in Al	78.58 ± 1.20	1304 ± 20	50.02 ± 0.97	830 ± 16
PGun energy = 5GeV				
Thickness = 1mm				
π^- in Al	2.00 ± 0.20	332 ± 33	1.04 ± 0.14	173 ± 24
K^- in Al	2.14 ± 0.21	355 ± 34	0.34 ± 0.08	56 ± 14
$\bar{p}$ in Al	4.36 ± 0.29	723 ± 49	1.82 ± 0.19	302 ± 32
Thickness = 10mm				
π^- in Al	22.08 ± 0.66	366 ± 11	10.44 ± 0.45	173 ± 8
K^- in Al	21.10 ± 0.64	350 ± 11	3.76 ± 0.27	62 ± 5
$\bar{p}$ in Al	41.64 ± 0.89	691 ± 15	17.34 ± 0.58	288 ± 10

PGun in Material	N^{inel}/N^{gen} (10^{-3})	σ_{inel} (mb)	N^{el}/N^{gen} (10^{-3})	σ_{el} (mb)
PGun energy = 10GeV				
Thickness = 1mm				
π^- in Al	2.24 ± 0.21	372 ± 35	0.94 ± 0.14	156 ± 23
K^- in Al	1.82 ± 0.19	302 ± 32	0.40 ± 0.09	66 ± 15
$\bar{p}$ in Al	3.62 ± 0.27	601 ± 45	1.20 ± 0.15	199 ± 26
Thickness = 10mm				
π^- in Al	22.68 ± 0.67	376 ± 11	8.24 ± 0.40	137 ± 7
K^- in Al	18.50 ± 0.60	307 ± 10	2.92 ± 0.24	48 ± 4
$\bar{p}$ in Al	33.96 ± 0.81	564 ± 13	10.92 ± 0.46	181 ± 8
PGun energy = 50GeV				
Thickness = 1mm				
π^- in Al	2.02 ± 0.20	335 ± 33	0.78 ± 0.12	129 ± 21
K^- in Al	2.04 ± 0.20	339 ± 33	0.20 ± 0.06	33 ± 10
$\bar{p}$ in Al	2.50 ± 0.22	415 ± 37	0.92 ± 0.14	153 ± 22
Thickness = 10mm				
π^- in Al	22.24 ± 0.66	369 ± 11	5.84 ± 0.34	97 ± 6
K^- in Al	19.68 ± 0.62	327 ± 10	2.66 ± 0.23	44 ± 4
$\bar{p}$ in Al	29.82 ± 0.76	495 ± 13	8.76 ± 0.42	145 ± 7

Inelastic probability of interaction for antiparticles (LHEP)



Multiplicities for particles

PGun in Material	$< Mult >$	RMS
PGun energy = 1GeV		
Thickness = 1mm		
$\bar{p}$ in Al	10.96	4.37
K^- in Al	11.63	6.29
π^- in Al	8.95	4.40
Thickness = 10mm		
$\bar{p}$ in Al	11.11	4.62
K^- in Al	11.19	6.31
π^- in Al	8.68	3.62
PGun energy = 5GeV		
Thickness = 1mm		
$\bar{p}$ in Al	14.42	5.77
K^- in Al	14.04	6.10
π^- in Al	14.14	6.18
Thickness = 10mm		
$\bar{p}$ in Al	14.36	5.94
K^- in Al	13.86	5.57
π^- in Al	13.83	5.80

PGun in Material	$< Mult >$	RMS
PGun energy = 10GeV		
Thickness = 1mm		
$\bar{p}$ in Al	9.71	3.94
K^- in Al	10.04	3.85
π^- in Al	9.40	4.14
Thickness = 10mm		
$\bar{p}$ in Al	10.11	3.87
K^- in Al	9.86	4.05
π^- in Al	9.85	4.10
PGun energy = 50GeV		
Thickness = 1mm		
$\bar{p}$ in Al	14.08	5.86
K^- in Al	14.69	6.37
π^- in Al	15.77	9.23
Thickness = 10mm		
$\bar{p}$ in Al	14.41	6.80
K^- in Al	15.12	7.05
π^- in Al	16.32	7.89

Cross sections for particles (FTFP_BERT)

PGun in Material	N^{inel}/N^{gen} (10^{-3})	σ_{inel} (mb)	N^{el}/N^{gen} (10^{-3})	σ_{el} (mb)
	PGun energy = 1GeV			
	Thickness = 1mm			
π^+ in Al	2.60 ± 0.23	431 ± 38	0.84 ± 0.13	139 ± 21
K^+ in Al	2.28 ± 0.21	378 ± 35	0.70 ± 0.12	116 ± 20
p in Al	2.28 ± 0.21	378 ± 35	0.70 ± 0.12	116 ± 20
	Thickness = 10mm			
π^+ in Al	29.08 ± 0.75	483 ± 12	7.92 ± 0.40	131 ± 7
K^+ in Al	24.68 ± 0.69	410 ± 12	7.94 ± 0.40	132 ± 7
p in Al	24.68 ± 0.69	410 ± 12	7.94 ± 0.40	132 ± 7
	PGun energy = 5GeV			
	Thickness = 1mm			
π^+ in Al	2.40 ± 0.22	398 ± 36	0.76 ± 0.12	126 ± 20
K^+ in Al	2.72 ± 0.23	451 ± 39	0.48 ± 0.10	80 ± 16
p in Al	2.72 ± 0.23	451 ± 39	0.48 ± 0.10	80 ± 16
	Thickness = 10mm			
π^+ in Al	22.28 ± 0.66	370 ± 11	7.24 ± 0.38	120 ± 6
K^+ in Al	26.08 ± 0.71	433 ± 12	7.18 ± 0.38	119 ± 6
p in Al	26.08 ± 0.71	433 ± 12	7.18 ± 0.38	119 ± 6

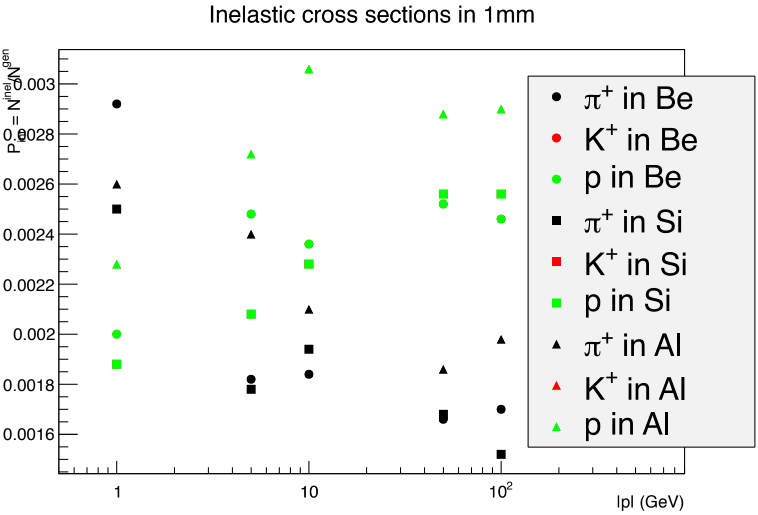
PGun in Material	N^{inel}/N^{gen} (10^{-3})	σ_{inel} (mb)	N^{el}/N^{gen} (10^{-3})	σ_{el} (mb)
PGun energy = 10GeV				
Thickness = 1mm				
π^+ in Al	2.10 ± 0.20	348 ± 34	0.84 ± 0.13	139 ± 21
K^+ in Al	3.06 ± 0.25	508 ± 41	0.76 ± 0.12	126 ± 20
p in Al	3.06 ± 0.25	508 ± 41	0.76 ± 0.12	126 ± 20
Thickness = 10mm				
π^+ in Al	21.24 ± 0.64	352 ± 11	5.68 ± 0.34	94 ± 6
K^+ in Al	26.26 ± 0.72	436 ± 12	6.74 ± 0.37	112 ± 6
p in Al	26.26 ± 0.72	436 ± 12	6.74 ± 0.37	112 ± 6
PGun energy = 50GeV				
Thickness = 1mm				
π^+ in Al	1.86 ± 0.19	309 ± 32	0.70 ± 0.12	116 ± 20
K^+ in Al	2.88 ± 0.24	478 ± 40	0.68 ± 0.12	113 ± 19
p in Al	2.88 ± 0.24	478 ± 40	0.68 ± 0.12	113 ± 19
Thickness = 10mm				
π^+ in Al	20.78 ± 0.64	345 ± 11	5.14 ± 0.32	85 ± 5
K^+ in Al	26.12 ± 0.71	433 ± 12	6.78 ± 0.37	113 ± 6
p in Al	26.12 ± 0.71	433 ± 12	6.78 ± 0.37	113 ± 6

Cross sections for antiparticles (FTFP_BERT)

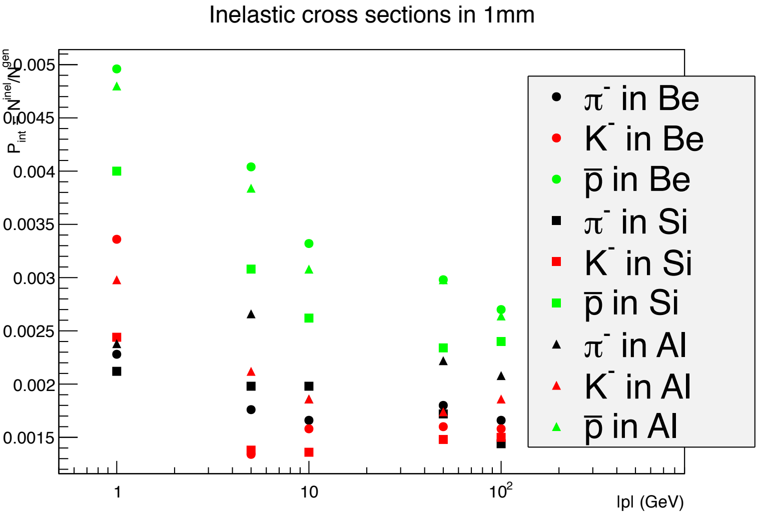
PGun in Material	N^{inel}/N^{gen} (10^{-3})	σ_{inel} (mb)	N^{el}/N^{gen} (10^{-3})	σ_{el} (mb)
PGun energy = 1GeV				
Thickness = 1mm				
π^- in Al	2.38 ± 0.22	395 ± 36	0.92 ± 0.14	153 ± 22
K^- in Al	2.98 ± 0.24	494 ± 40	1.14 ± 0.15	189 ± 25
$\bar{p}$ in Al	4.80 ± 0.31	796 ± 51	1.64 ± 0.18	272 ± 30
Thickness = 10mm				
π^- in Al	27.06 ± 0.73	449 ± 12	8.20 ± 0.40	136 ± 7
K^- in Al	29.90 ± 0.76	496 ± 13	10.60 ± 0.46	176 ± 8
$\bar{p}$ in Al	44.34 ± 0.92	736 ± 15	13.36 ± 0.51	222 ± 9
PGun energy = 5GeV				
Thickness = 1mm				
π^- in Al	2.66 ± 0.23	441 ± 38	0.66 ± 0.11	110 ± 19
K^- in Al	2.12 ± 0.21	352 ± 34	0.12 ± 0.05	20 ± 8
$\bar{p}$ in Al	3.84 ± 0.28	637 ± 46	1.12 ± 0.15	186 ± 25
Thickness = 10mm				
π^- in Al	22.78 ± 0.67	378 ± 11	6.76 ± 0.37	112 ± 6
K^- in Al	19.86 ± 0.62	330 ± 10	2.24 ± 0.21	37 ± 4
$\bar{p}$ in Al	36.00 ± 0.83	597 ± 14	9.92 ± 0.44	165 ± 7

PGun in Material	N^{inel}/N^{gen} (10^{-3})	σ_{inel} (mb)	N^{el}/N^{gen} (10^{-3})	σ_{el} (mb)
PGun energy = 10GeV				
Thickness = 1mm				
π^- in Al	1.86 ± 0.19	309 ± 32	0.52 ± 0.10	86 ± 17
K^- in Al	1.86 ± 0.19	309 ± 32	0.18 ± 0.06	30 ± 10
$\bar{p}$ in Al	3.08 ± 0.25	511 ± 41	1.06 ± 0.15	176 ± 24
Thickness = 10mm				
π^- in Al	20.02 ± 0.63	332 ± 10	5.94 ± 0.34	99 ± 6
K^- in Al	20.32 ± 0.63	337 ± 10	1.94 ± 0.20	32 ± 3
$\bar{p}$ in Al	32.64 ± 0.79	542 ± 13	9.60 ± 0.44	159 ± 7
PGun energy = 50GeV				
Thickness = 1mm				
π^- in Al	2.22 ± 0.21	368 ± 35	0.60 ± 0.11	100 ± 18
K^- in Al	1.74 ± 0.19	289 ± 31	0.06 ± 0.03	10 ± 6
$\bar{p}$ in Al	2.98 ± 0.24	494 ± 40	0.84 ± 0.13	139 ± 21
Thickness = 10mm				
π^- in Al	20.02 ± 0.63	332 ± 10	5.50 ± 0.33	91 ± 5
K^- in Al	18.78 ± 0.61	312 ± 10	1.66 ± 0.18	28 ± 3
$\bar{p}$ in Al	30.56 ± 0.77	507 ± 13	7.60 ± 0.39	126 ± 6

Inelastic probablility of interaction for particles (FTFP_BERT)



Inelastic probablility of interaction for antiparticles (FTFP_BERT)



Multiplicities for particles (FTFP_BERT)

PGun in Material	$< Mult >$	RMS
PGun energy = 1GeV		
Thickness = 1mm		
π^+ in Al	10.43	4.39
K^+ in Al	8.11	2.85
p in Al	8.11	2.85
Thickness = 10mm		
π^+ in Al	10.19	4.26
K^+ in Al	8.27	3.05
p in Al	8.27	3.05
PGun energy = 5GeV		
Thickness = 1mm		
π^+ in Al	16.36	5.28
K^+ in Al	14.85	7.39
p in Al	14.85	7.39
Thickness = 10mm		
π^+ in Al	16.55	6.13
K^+ in Al	14.38	6.84
p in Al	14.38	6.84

PGun in Material	$< Mult >$	RMS
PGun energy = 10GeV		
Thickness = 1mm		
π^+ in Al	17.10	4.74
K^+ in Al	18.68	7.15
p in Al	18.68	7.15
Thickness = 10mm		
π^+ in Al	18.39	6.18
K^+ in Al	17.72	6.52
p in Al	17.72	6.52
PGun energy = 50GeV		
Thickness = 1mm		
π^+ in Al	22.80	5.85
K^+ in Al	22.24	8.49
p in Al	22.24	8.49
Thickness = 10mm		
π^+ in Al	22.88	7.52
K^+ in Al	22.62	8.56
p in Al	22.62	8.56

Multiplicities for antiparticles (FTFP_BERT)

PGun in Material	$< Mult >$	RMS
PGun energy = 1GeV		
Thickness = 1mm		
π^- in Al	10.14	4.60
K^- in Al	11.26	4.02
$\bar{p}$ in Al	4.85	1.58
Thickness = 10mm		
π^- in Al	10.43	4.36
K^- in Al	10.57	4.16
$\bar{p}$ in Al	5.08	1.53
PGun energy = 5GeV		
Thickness = 1mm		
π^- in Al	15.95	6.37
K^- in Al	16.39	6.24
$\bar{p}$ in Al	6.15	2.02
Thickness = 10mm		
π^- in Al	16.93	6.37
K^- in Al	16.20	6.43
$\bar{p}$ in Al	6.59	2.16

PGun in Material	$< Mult >$	RMS
PGun energy = 10GeV		
Thickness = 1mm		
π^- in Al	17.71	6.35
K^- in Al	17.68	5.36
$\bar{p}$ in Al	12.95	5.67
Thickness = 10mm		
π^- in Al	18.10	5.92
K^- in Al	18.19	5.92
$\bar{p}$ in Al	13.74	6.32
PGun energy = 50GeV		
Thickness = 1mm		
π^- in Al	23.61	7.79
K^- in Al	23.31	6.95
$\bar{p}$ in Al	16.38	6.48
Thickness = 10mm		
π^- in Al	22.69	7.52
K^- in Al	23.24	7.55
$\bar{p}$ in Al	17.13	7.67