Hadronic Interaction Studies for LHCb

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[Thanks to Silvia M., Jeroen v T.]

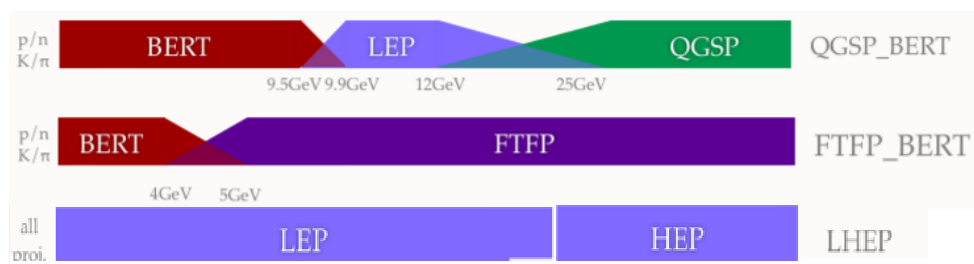
Outline

- Physics Lists (PL) in Geant4
  - What we are using, what is important to us, better alternatives?
  - Initial studies with LHCb default PL
- Extend study to different PLs
  - Cross-sections
  - Multiplicities in hadronic interactions
- How different PLs affect our detector in reality
  - Occupancies (hit multiplicities, digits, …)
  - Particularly concerned about thin layers
- Plans to extend study to more data
  - First glimpse

Physics Lists

- Set of EM PLs implementing difference precisions available
  - Matt Reid talk this morning
- Set of hadronic PLs implementing combination of models
  - Applicability varies with energy/species

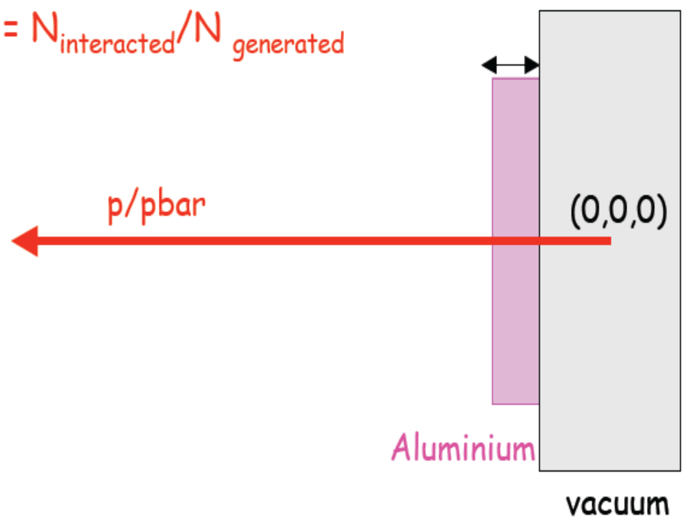
E.M. Physics:	Hadronic Physics:
EmOpt1 (Reference)	LHEP (Reference)
EmStd	QGSP_BERT
EmOpt3	FTFP_BERT
EmLHCb…	…



- Sources of bias in detector important for us, e.g. CP studies
  - Hardware: geometric/alignment, sub-detector system inefficiencies
  - Software/algorithms: momenta/position vs. magnetic field vs. acceptance
  - Interaction modelling: particle/antiparticle behaviour differs
- All need to be understood, consider whether our use of G4 models can be improved

Interaction σ studies: configuration

- Simple, standalone geometry
- G4 9.2.p03
- δ turned off

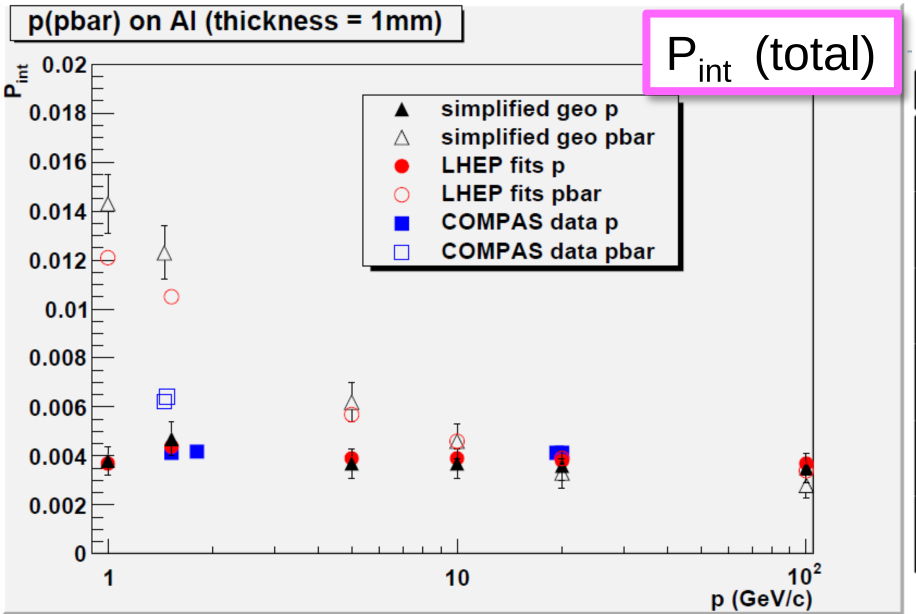


- ParticleGuns, from origin, monochromatic energies
  - $[1\ldots10^2]$ GeV
- Varying Al plate thickness
  - [1, 10, 50, 100]mm (consistency checks)
  - Studied also Si and Be targets
- Use this setup to estimate P_{int}=#interacted / #generated

- Compare with COMPAS measurements (as available) and cross-sections for LHEP fits
  - $P_{int} = \sigma\rho Nx/A$ (valid $P_{int} \ll 1$)

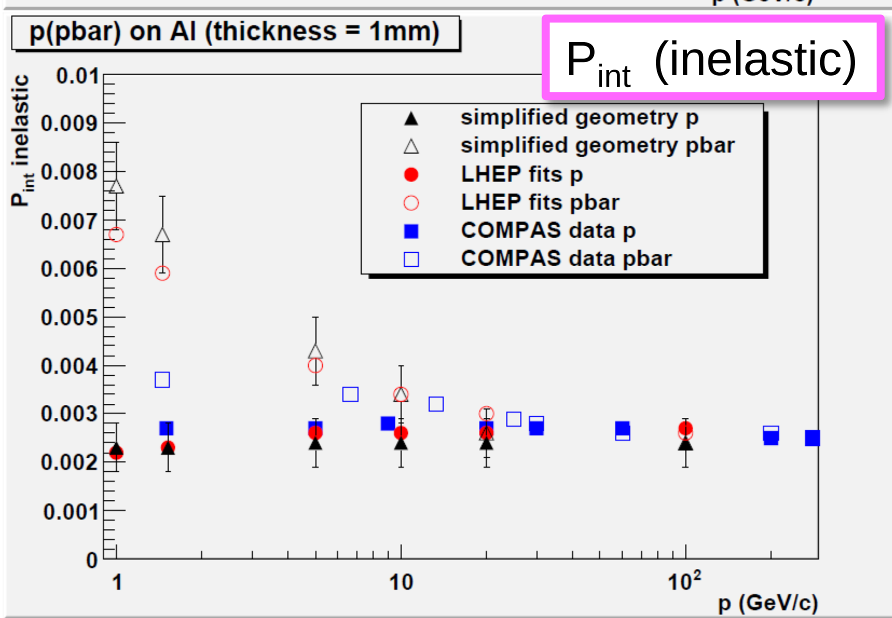
- Material upstream RICH2 ~$0.6X_0$, so verified stable to at least 5cm Al
- Work within LHCb Gauss framework, ensure technical handling of PLs/options transport directly to production system

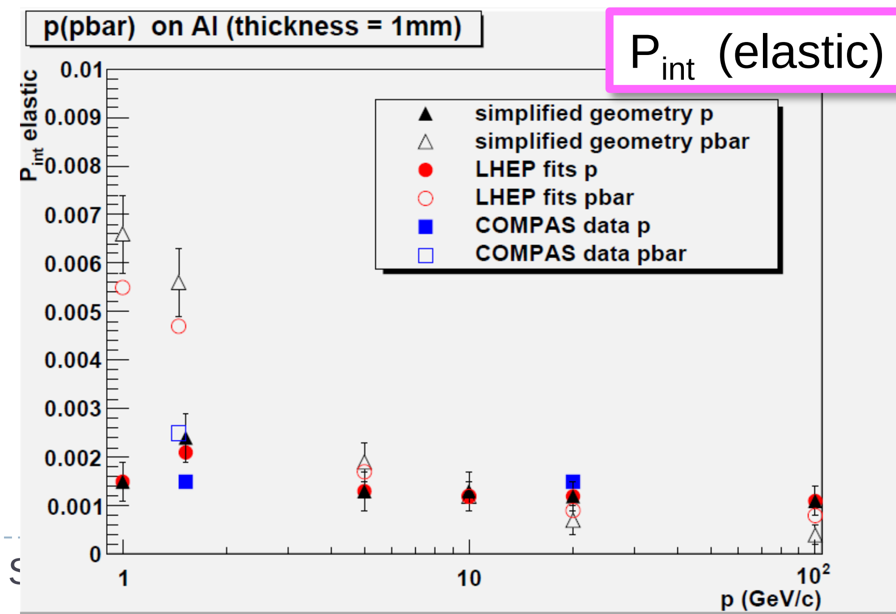
Material interaction σ, pp on 1mm Al



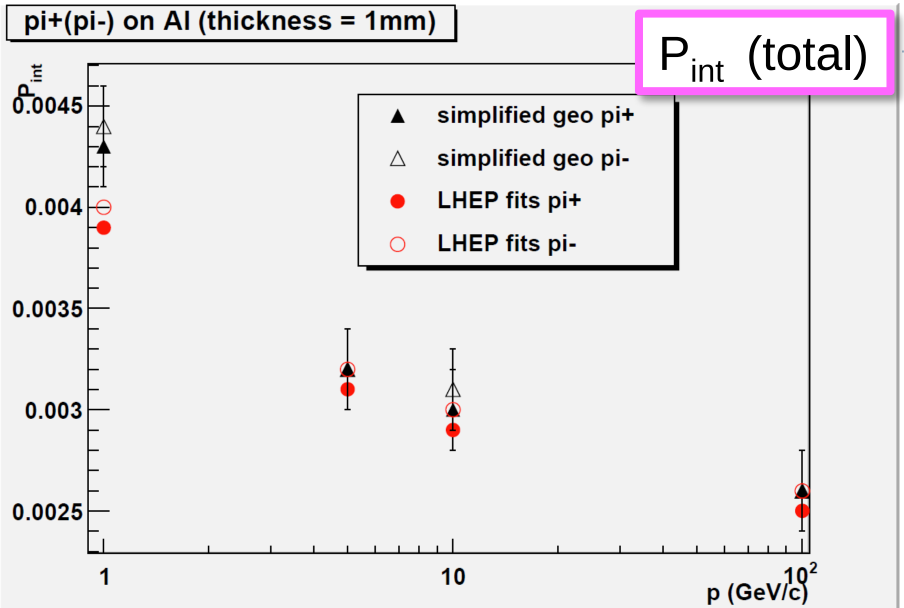
Good agreement: LHEP fits/COMPAS/simple model

Particle	p(GeV/c)	P_{int}	ratio $P_{int}(\bar{p}/p)$	PDG
p	1.	0.0038 ± 0.0006	3.76 ± 0.67	3.4-4.2
$\bar{p}$	1.	0.0143 ± 0.0012		
p	1.52	0.0047 ± 0.0007		
$\bar{p}$	1.45	0.0123 ± 0.0011		
p	5.	0.0037 ± 0.0006	1.67 ± 0.35	
$\bar{p}$	5.	0.0062 ± 0.0008		
p	10.	0.0037 ± 0.0006	1.24 ± 0.28	1.2-1.4
$\bar{p}$	10.	0.0046 ± 0.0007		
p	20.	0.0036 ± 0.0006	0.92 ± 0.23	
$\bar{p}$	20.	0.0033 ± 0.0006		
p	100.	0.0035 ± 0.0006	0.8 ± 0.24	1.0-1.1
$\bar{p}$	100.	0.0028 ± 0.0007		



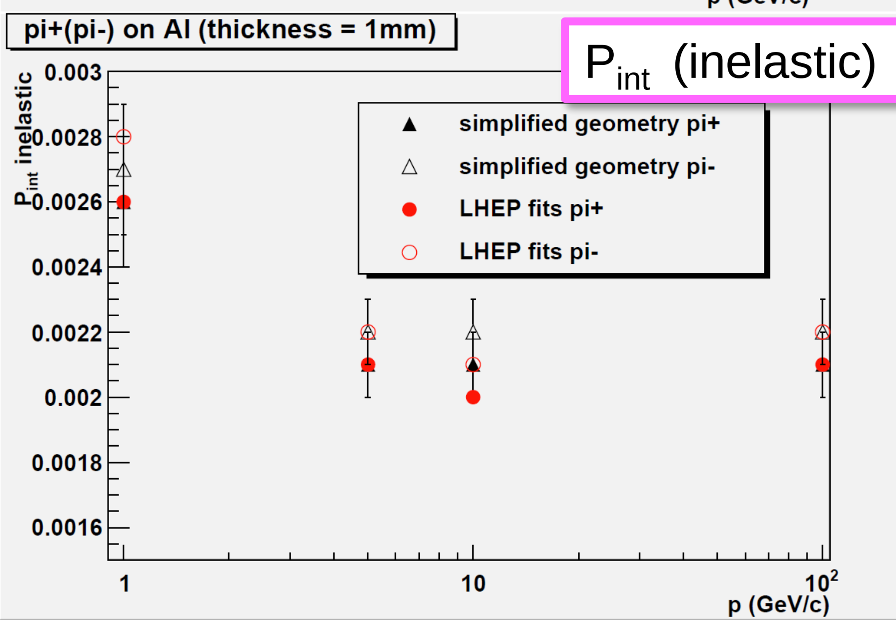


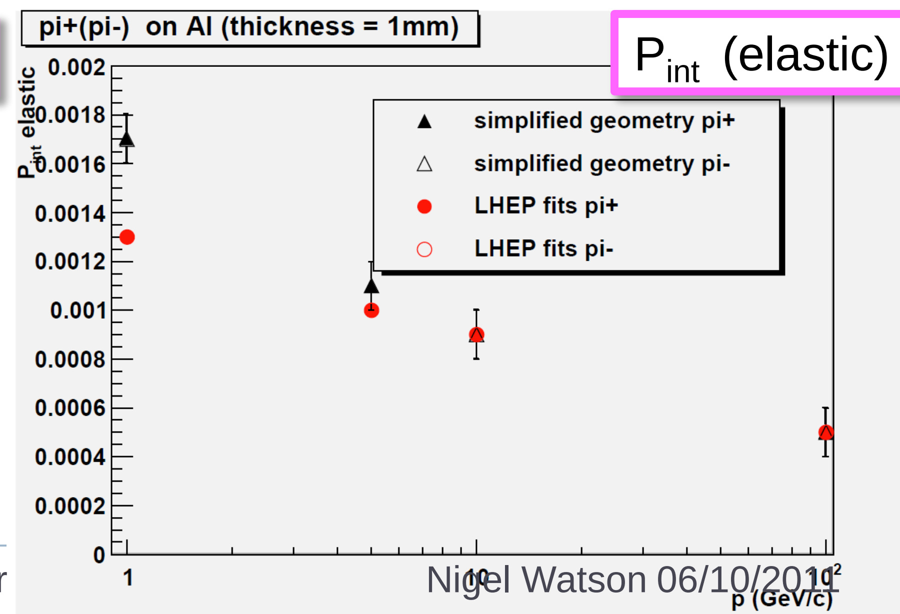
Material interaction σ, $\pi^{\pm}$ on 1mm Al



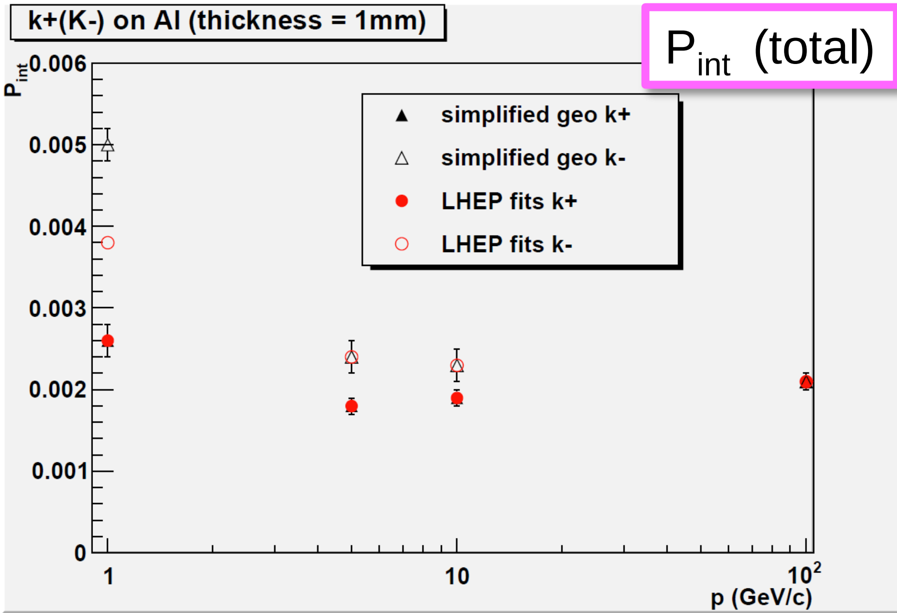
Good agreement: LHEP fits/simple model

Particle	$p(GeV/c)$	P_{int}	ratio $P_{int}(\pi^-/\pi^+)$
π^+	1.	0.0043 ± 0.0002	1.02 ± 0.07
π^-	1.	0.0044 ± 0.0002	
π^+	5.	0.0032 ± 0.0002	1.0 ± 0.09
π^-	5.	0.0032 ± 0.0002	
π^+	10.	0.0030 ± 0.0002	1.03 ± 0.10
π^-	10.	0.0031 ± 0.0002	
π^+	100.	0.0026 ± 0.0002	1.0 ± 0.11
π^-	100.	0.0026 ± 0.0002	





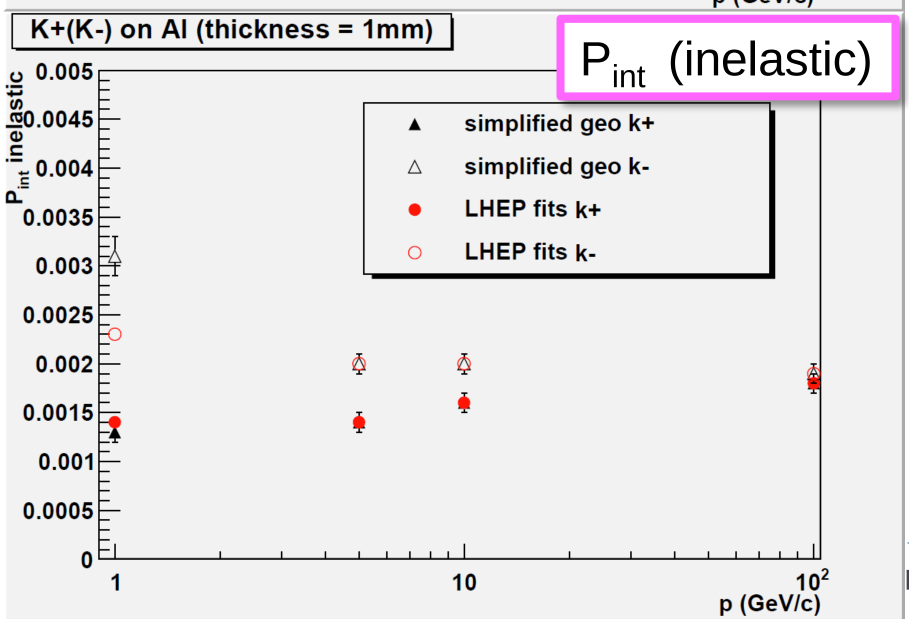
Material interaction σ, $K^{\pm}$ on 1mm Al

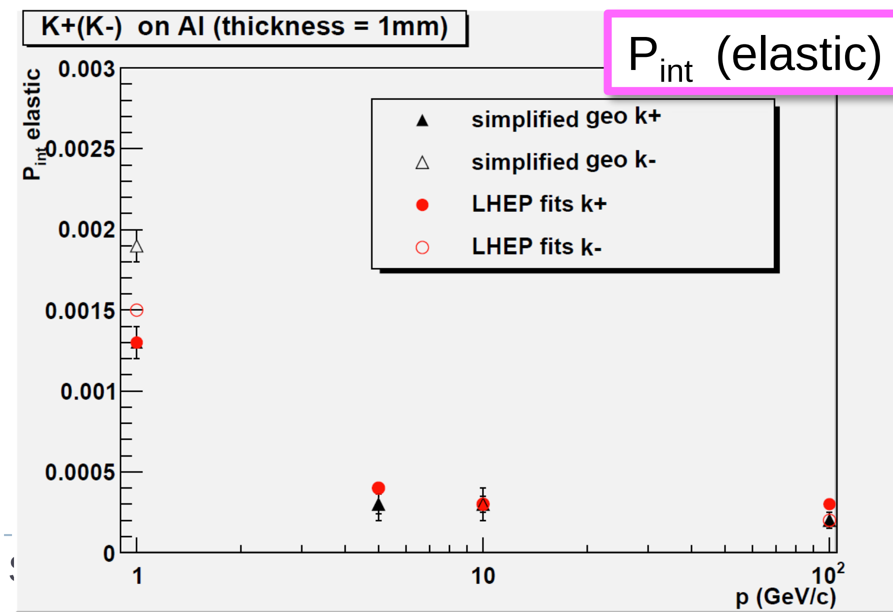


Good agreement: LHEP fits/simple model

Some differences K^- at lowest momenta

Particle	$p(GeV/c)$	P_{int}	ratio $P_{int}K^-/K^+$
k^+	1.	0.0026 ± 0.0002	1.92 ± 0.17
k^-	1.	0.0050 ± 0.0002	
k^+	5.	0.0018 ± 0.0001	1.33 ± 0.13
k^-	5.	0.0024 ± 0.0002	
k^+	10.	0.0019 ± 0.0001	1.21 ± 0.12
k^-	10.	0.0023 ± 0.0002	
k^+	100.	0.0021 ± 0.0001	1.0 ± 0.06
k^-	100.	0.0021 ± 0.0001	



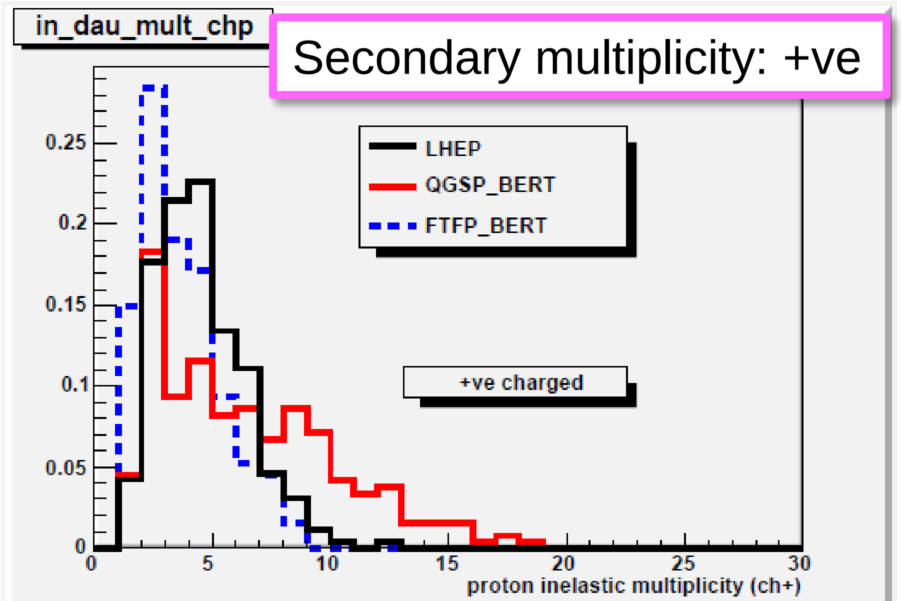


Interaction cross-section initial tests

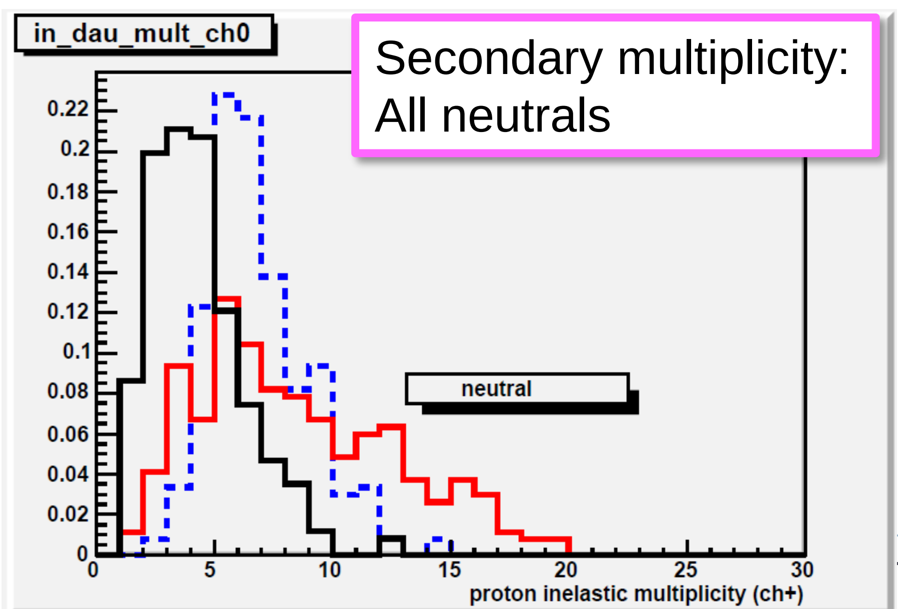
- Verified interaction cross sections simulated inside Geant4 in LHCb framework
  - p, K, pi using Al, Be, Si targets
  - Default PL LHEP
  - Compared to COMPAS database, PDG
- Results from simple configuration agree with LHEP fits
  - Technical consistency check, expected
- Extended studies to include QGSP_BERT, FTFP_BERT
  - For p, similar results all PL.
    - ~7% difference in $\sigma_{inelastic}$ at 1GeV, LHEP vs. QGSP_BERT/FTFP_BERT
  - For $\pi^{\pm}$, differences small, less than 2-3%, all P
  - For $K^{\pm}$, same cross-sections in all PL
  - Pbar cross-sections rather consistent between models?
    - e.g. p/pbar on 5cm Al

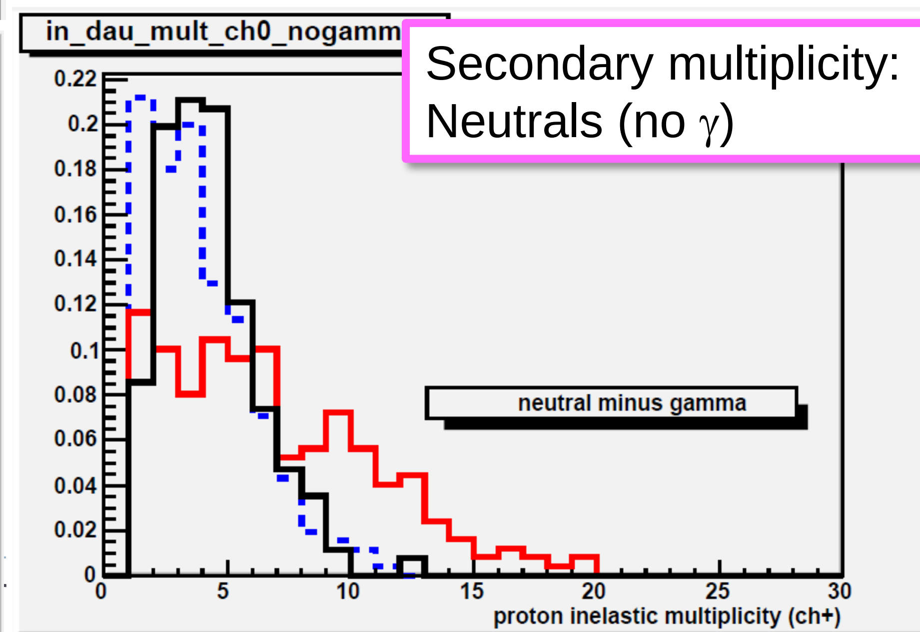
$Particle$	$p(GeV/c)$	$P_{int}(LHEP)$	$P_{int}(QGSP\_BERT)$	$P_{int}(FTFP\_BERT)$
p	1.	0.1679 ± 0.0037	0.1814 ± 0.0039	0.1814 ± 0.0039
$\bar{p}$	1.	0.4871 ± 0.0050	0.4851 ± 0.0050	0.4851 ± 0.0050
p	5.	0.1778 ± 0.0038	0.1810 ± 0.0039	0.1810 ± 0.0039
$\bar{p}$	5.	0.2548 ± 0.0044	0.2548 ± 0.0044	0.2548 ± 0.0044
p	10.	0.1746 ± 0.0037	0.1780 ± 0.0038	0.1780 ± 0.0038
$\bar{p}$	10.	0.2029 ± 0.0040	0.2029 ± 0.0040	0.2029 ± 0.0040
p	100.	0.1711 ± 0.0038	0.1745 ± 0.0038	0.1745 ± 0.0038
$\bar{p}$	100.	0.1565 ± 0.0036	0.1565 ± 0.0036	0.1565 ± 0.0036

Inelastic hadronic interaction multiplicities

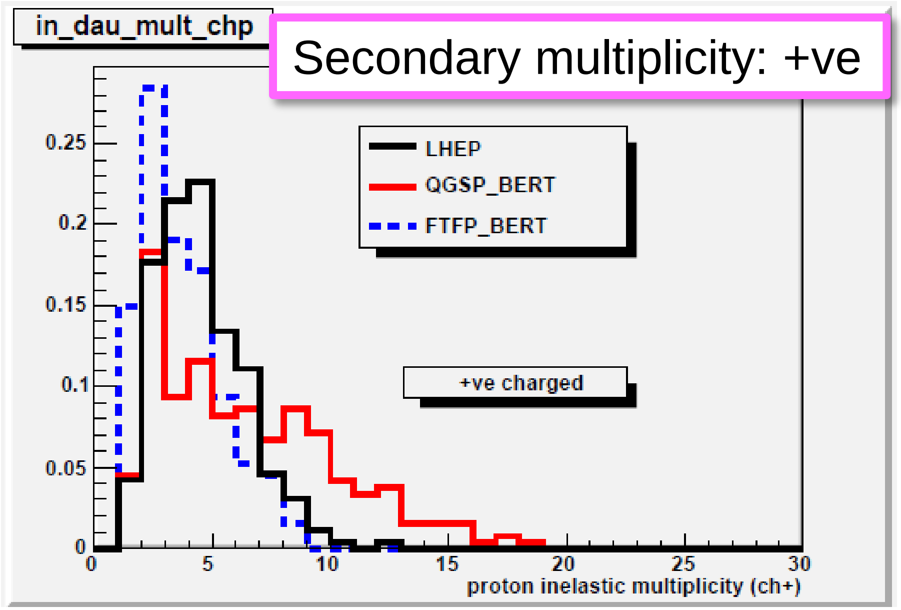


- Example: 10 GeV p on 1mm Al
- Disagreements dominated by photons
  - Particularly low E_{kin}
  - No gammas from inelastic interactions in LHEP
  - E_{kin} threshold for LHCb=1MeV
- ∴ No large consequences for observed average multiplicity in detector





Inelastic hadronic interaction multiplicities



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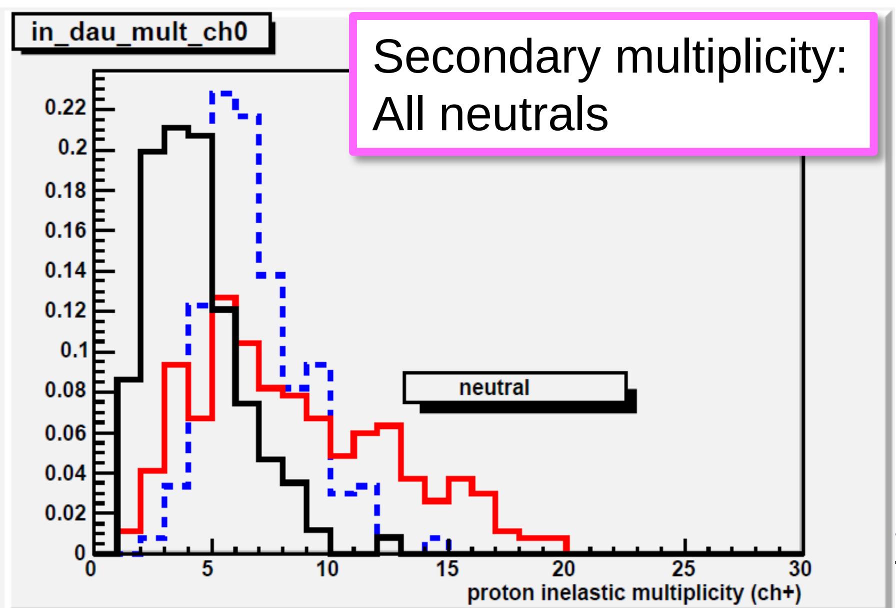
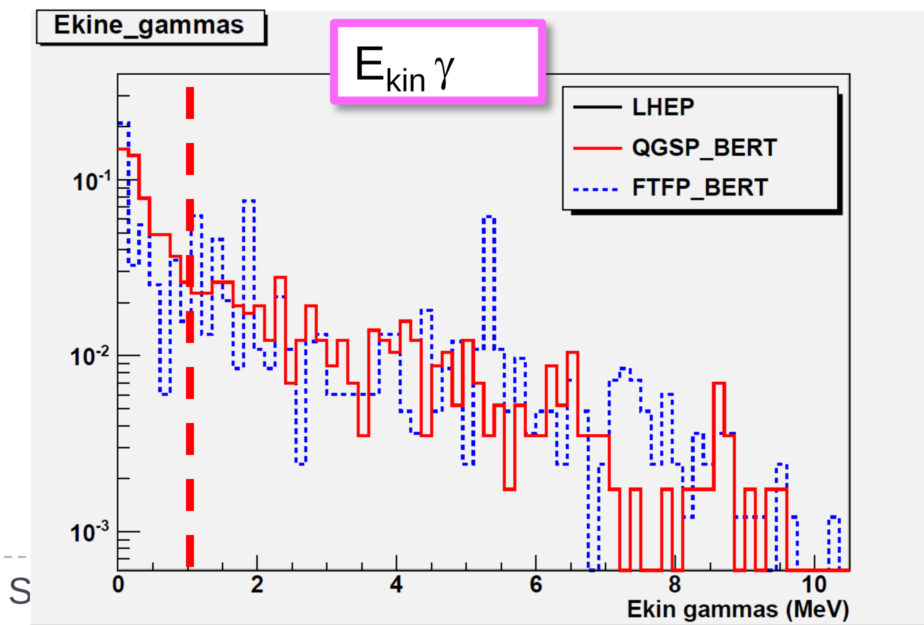
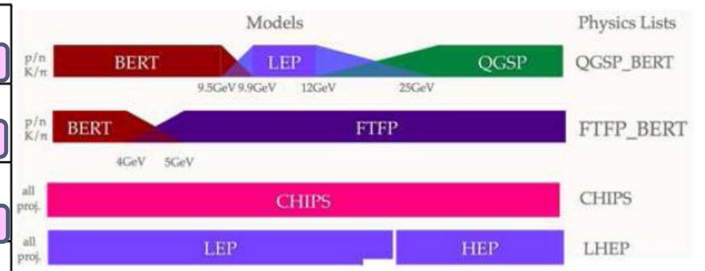




Hadronic Multiplicities: p/pbar, 1mm Al

Part.	p(GeV/c)	LHEP $<Mult>$	LHEP RMS	QGSP_BERT $<Mult>$	QGSP_BERT RMS	FTFP_BERT $<Mult>$	FTFP_BERT RMS
p	1.	10.7	4.30	8.41	2.93	8.41	2.93
$\bar{p}$	1.	11.2	4.64	11.2	4.64	11.2	4.64
p	5.	14.07	5.09	13.31	6.53	13.55	6.38
$\bar{p}$	5.	14.3	5.54	14.3	5.54	14.3	5.54
p	10.	9.19	3.74	16.72	8.35	12.2	4.36
$\bar{p}$	10.	10.22	3.81	10.22	3.81	10.22	3.81
p	13.	10.2	3.89	10.43	4.02	12.53	4.67
$\bar{p}$	13.	11.25	4.18	11.25	4.18	11.25	4.18
p	100.	16.26	8.03	21.0	10.09	19.12	8.80
$\bar{p}$	100.	17.04	7.93	17.4	7.93	17.04	7.93



- Multiplicities vary with PL, as expected with energy/model ranges
  - Identical, e.g. QGSP PLs for <4GeV, both 100% BERT
  - Up to 80% difference at 10 GeV between LHEP vs. QGSP_BERT
    - Dominated by low energy gammas below our cut-offs
- pbar multiplicities identical for all PL at all energies
  - Same model used in all PL?

Hadronic Multiplicities: protons, 5cm Al

- Same observations on pbar with thicker targets

		LHEP		QGSP_BERT		FTFP_BERT	
Particle	*p(GeV/c)*	< *Mult* >	RMS	< *Mult* >	RMS	< *Mult* >	RMS
p	1.	10.66	4.17	8.27	3.12	8.27	3.12
$\bar{p}$	1.	11.19	4.55	11.19	4.35	11.19	4.55
p	5.	14.20	5.34	13.97	6.80	13.38	6.68
$\bar{p}$	5.	14.74	5.89	14.74	5.89	14.74	5.89
p	10.	9.51	3.61	17.08	8.31	12.54	4.10
$\bar{p}$	10.	10.21	3.76	10.21	3.76	10.21	3.76
p	100.	16.45	7.83	20.19	9.81	19.67	8.45
$\bar{p}$	100.	16.29	7.58	16.67	7.58	16.67	7.58

Hadronic Multiplicities: $\pi^{\pm}$, $K^{\pm}$, 1mm Al

Particle	$p(GeV/c)$	LHEP $<Mult>$	LHEP RMS	QGSP_BERT $<Mult>$	QGSP_BERT RMS	FTFP_BERT $<Mult>$	FTFP_BERT RMS
π^+	1.	9.84	4.06	10.13	4.44	10.13	4.44
π^-	1.	9.40	3.82	10.05	4.39	10.5	4.39
π^+	5.	14.94	5.72	16.62	7.30	11.88	4.16
π^-	5.	13.92	5.56	16.43	7.41	12.03	4.4
π^+	10.	10.02	3.88	11.0	5.59	12.22	3.7
π^-	10.	10.16	4.01	10.96	5.74	12.25	3.72
π^+	13.	11.47	4.90	11.64	5.06	12.79	4.15
π^-	13.	11.47	4.47	10.94	4.55	12.73	4.29
π^+	100.	17.24	8.75	18.94	8.42	17.75	7.58
π^-	100.	16.98	7.58	18.63	8.46	17.83	7.44

Particle	$p(GeV/c)$	LHEP $<Mult>$	LHEP RMS	QGSP_BERT $<Mult>$	QGSP_BERT RMS	FTFP_BERT $<Mult>$	FTFP_BERT RMS
k^+	1.	9.6	3.66	8.905	3.36	8.905	3.36
k^-	1.	11.77	6.45	12.46	5.85	12.46	5.85
k^+	5.	14.59	6.12	15.12	6.72	12.53	5.63
k^-	5.	13.81	5.47	16.87	7.17	13.91	6.16
k^+	10.	9.76	3.76	17.6	8.67	11.37	3.27
k^-	10.	9.91	3.97	18.73	8.21	12.15	3.53
k^+	13.	10.51	4.21	10.59	4.35	11.94	3.40
k^-	13.	11.15	4.55	11.02	4.93	12.47	3.59
k^+	100.	16.78	8.07	17.29	8.40	18.07	7.17
k^-	100.	16.39	7.34	17.36	8.29	18.55	6.98

- Similar conclusions to proton case (models, ranges, not anti-particles)

Summary

- Interaction cross-sections studied standalone model, using LHCb framework
- Generally good agreement, some significant model differences
  - e.g. in multiplicity, but we are less sensitive in given Ekine
  - or not, in case of pbar
- Areas of particular interest to us: thin layers

- Near-term future plans
- Test the new PL QGSP_BERT_CHIPS with GEANT4 v9.4.px
  - Improved K cross sections
  - Improved inelastic models and cross sections, anti-nucleons and hyperons
  - Re-evaluate hadronic PLs with our production versions (see Gloria talk Fri.)
  - Decision to adopting new PLs by end of 2011

- Study interaction lengths using data
  - Use partially reconstructed decays, daughter is reconstructed in VELO
  - The momentum can be deduced from constraints

Hadronic interaction studies – int. length

Jeroen van Tilburg

- Absorption of hadrons give large uncertainty on reconstruction efficiency
  - Distance up to RICH2: 20% of λ_I
  - Uncertainty on material budget 10%
  - → (1-e-0.2)*0.1=1.8% uncertainty per track
  - Main systematic limitation for cross section and BR measurements
- Need to improve knowledge on the absorption length (i.e. material budget)

First step:

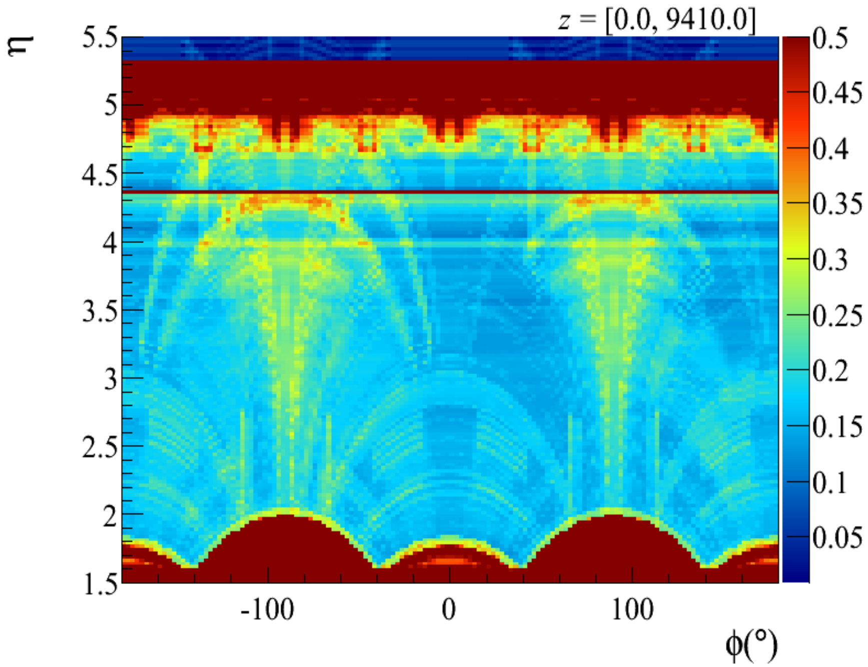
- Made plots of material in terms of λ_I
- Assumed hadronic interaction length for high-p neutrons (PDG).
  - Simple formula used (from Material class)
  - Absorption depends on p, particle type and difference particle – anti-particle

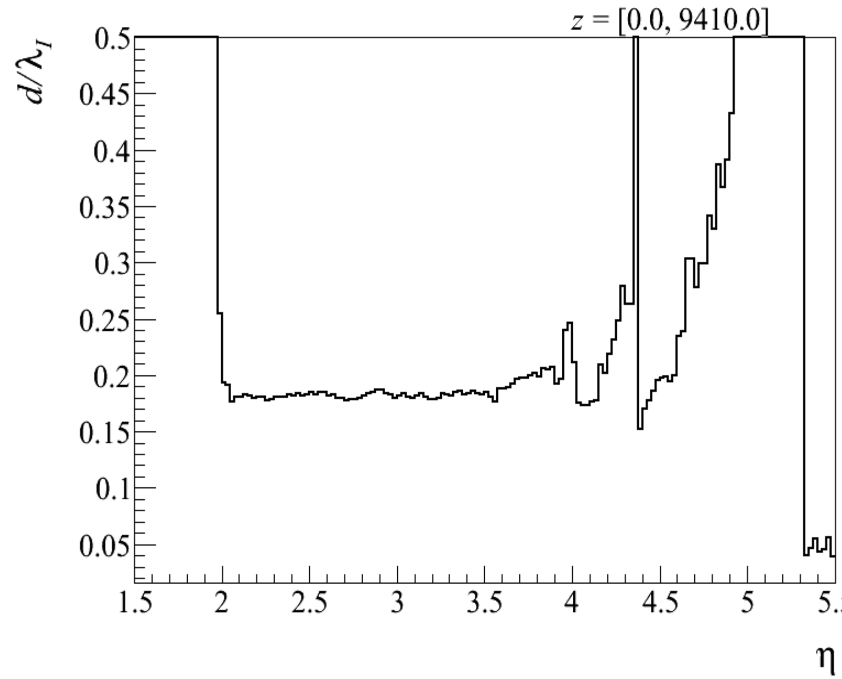
$$\lambda_I = \frac{k\sqrt[3]{N}}{\rho}$$

Second step:

- Count MCParticles with hadronic interaction in MC simulation
  - Vertices for kaons and pions: hadronic interactions, decays and delta rays

Material scan in λ_I (1^{st} step – MC only)





- Peak at η = 4.38 comes from the 25 mrad conical beam pipe inside RICH1
- Between 2<η<4.8 the material amounts to 20% of an absorption length

- Competition between decays and hadronic interactions (esp. low p)
- Work in progress (for those hungry for data/MC comparisons)

Backup

Hadronic σ, p/pbar on 1mm Al

$Particle$	$p(GeV/c)$	$P_{int}^{inel}(LHEP)$	$P_{int}^{inel}(QGSP\_BERT)$	$P_{int}^{inel}(FTFP\_BERT)$
p	1.	0.0022 ± 0.0001	0.0024 ± 0.0001	0.0024 ± 0.0001
$\bar{p}$	1.	0.0078 ± 0.0003	0.0078 ± 0.0003	0.0078 ± 0.0003
p	5.	0.0026 ± 0.0002	0.0027 ± 0.0002	0.0027 ± 0.0002
$\bar{p}$	5.	0.0042 ± 0.0002	0.0042 ± 0.0002	0.0042 ± 0.0002
p	10.	0.0026 ± 0.0002	0.0027 ± 0.0002	0.0027 ± 0.0002
$\bar{p}$	10.	0.0035 ± 0.0002	0.0035 ± 0.0002	0.0035 ± 0.0002
p	13.	0.0026 ± 0.0002	0.0027 ± 0.0002	0.0027 ± 0.0002
$\bar{p}$	13.	0.0033 ± 0.0002	0.0033 ± 0.0002	0.0033 ± 0.0002
p	100.	0.0026 ± 0.0002	0.0027 ± 0.0002	0.0027 ± 0.0002
$\bar{p}$	100.	0.0026 ± 0.0002	0.0026 ± 0.0002	0.0026 ± 0.0002

$\pi^{\pm}$ hadronic σ on 1mm Al

$Particle$	$p(GeV/c)$	$P_{int}^{inel}(LHEP)$	$P_{int}^{inel}(QGSP\_BERT)$	$P_{int}^{inel}(FTFP\_BERT)$
π^+	1.	0.0026 ± 0.0002	0.0027 ± 0.0002	0.0027 ± 0.0002
π^-	1.	0.0027 ± 0.0002	0.0027 ± 0.0002	0.0027 ± 0.0002
π^+	5.	0.0021 ± 0.0001	0.0022 ± 0.0001	0.0022 ± 0.0001
π^-	5.	0.0022 ± 0.0001	0.0022 ± 0.0001	0.0022 ± 0.0001
π^+	10.	0.0021 ± 0.0001	0.0022 ± 0.0001	0.0022 ± 0.0001
π^-	10.	0.0022 ± 0.0001	0.0022 ± 0.0001	0.0022 ± 0.0001
π^+	13.	0.0021 ± 0.0001	0.0022 ± 0.0001	0.0022 ± 0.0001
π^-	13.	0.0022 ± 0.0001	0.0022 ± 0.0001	0.0022 ± 0.0001
π^+	100.	0.0021 ± 0.0001	0.0021 ± 0.0001	0.0021 ± 0.0001
π^-	100.	0.0022 ± 0.0001	0.0021 ± 0.0001	0.0021 ± 0.0001

Inelastic cross-sections, very similar for all PL studied

$K^{\pm}$ cross-sections, on 1mm Al

$Particle$	$p(GeV/c)$	P_{int}^{tot}	P_{int}^{el}	P_{int}^{inel}
K^+	1.	0.0026 ± 0.0002	0.0013 ± 0.0001	0.0013 ± 0.0001
K^-	1.	0.0050 ± 0.0002	0.0019 ± 0.0001	0.0031 ± 0.0002
K^+	5.	0.0018 ± 0.0001	0.0003 ± 0.0001	0.0014 ± 0.0001
K^-	5.	0.0024 ± 0.0002	0.0003 ± 0.0001	0.0020 ± 0.0001
K^+	10.	0.0019 ± 0.0001	0.00028 ± 0.00005	0.0016 ± 0.0001
K^-	10.	0.0023 ± 0.0002	0.00028 ± 0.00005	0.0020 ± 0.0001
K^+	13.	0.0019 ± 0.0001	0.00028 ± 0.00005	0.0016 ± 0.0001
K^-	13.	0.0023 ± 0.0002	0.00026 ± 0.00005	0.0020 ± 0.0001
K^+	100.	0.0021 ± 0.0001	0.00023 ± 0.00005	0.0018 ± 0.0001
K^-	100.	0.0021 ± 0.0001	0.00021 ± 0.00005	0.0019 ± 0.0001

Same cross-sections for all PL studied