Impact of Beam-Gas Interactions in the IP Region of the ILD

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Outline

Introduction

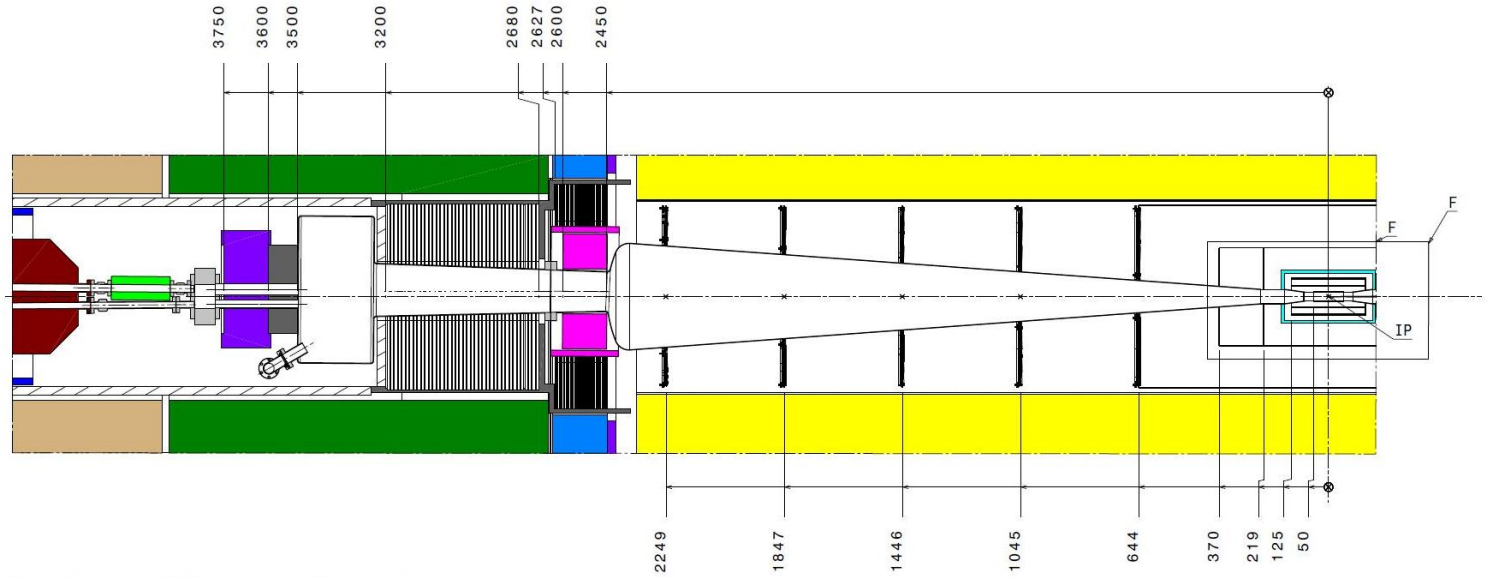
Produced Particles

Average Detector Response

Probability of single Detector Response

Conclusions

ILD Forward Region



- QD0 30cm closer to IP + additional BPM ⇒ free space required
- Option: Removing of the vacuum pump
  - → Could gain ∼30cm
  - → Change of the vacuum: roughly from 7nTorr to 150nTorr

⇒ Unknown: Change of the impact of beam-gas interaction?

Simulation of the Beam-Gas Interaction

- Relevant processes:
  - Most frequent: interaction with atomic shell
    - Bremsstrahlung ($e + X \rightarrow e + X + \gamma$)
      $\rightarrow$ Production of photons
    - coulomb scattering ($e + X \rightarrow e + X$)
      $\rightarrow$ Production of electrons
  - Largest impact: interaction with atomic nuclei (DIS)
    $\rightarrow$ Production of all kinds of hadrons
    $\rightarrow$ Mostly π-mesons and light baryons

$\Rightarrow$ Geant4 covers all of them $\Rightarrow$ use as "*event generator*"

Detector Simulation: MOKKA

- Detector model ILD_o1_v063 (∼ILD_o1_v05 ≡ DBD)
- For interactions between electron and nuclei only "*G4ElectroVDNuclearModel*" is provided

→ Used in all physics list → The standard list QGSP_BERT is used

- Option: Event and detector simulation in one step
- Difficulty: beam-gas interactions does not yield sufficient statistics
- Seperation:
  - Event generation: At high pressure to get high luminosity
  - Detector generation: Extrapolation to target pressure

Introduction

Produced Particles
- Particle Properties
- Extrapolation to low Pressure
- Final Results

Average Detector Response

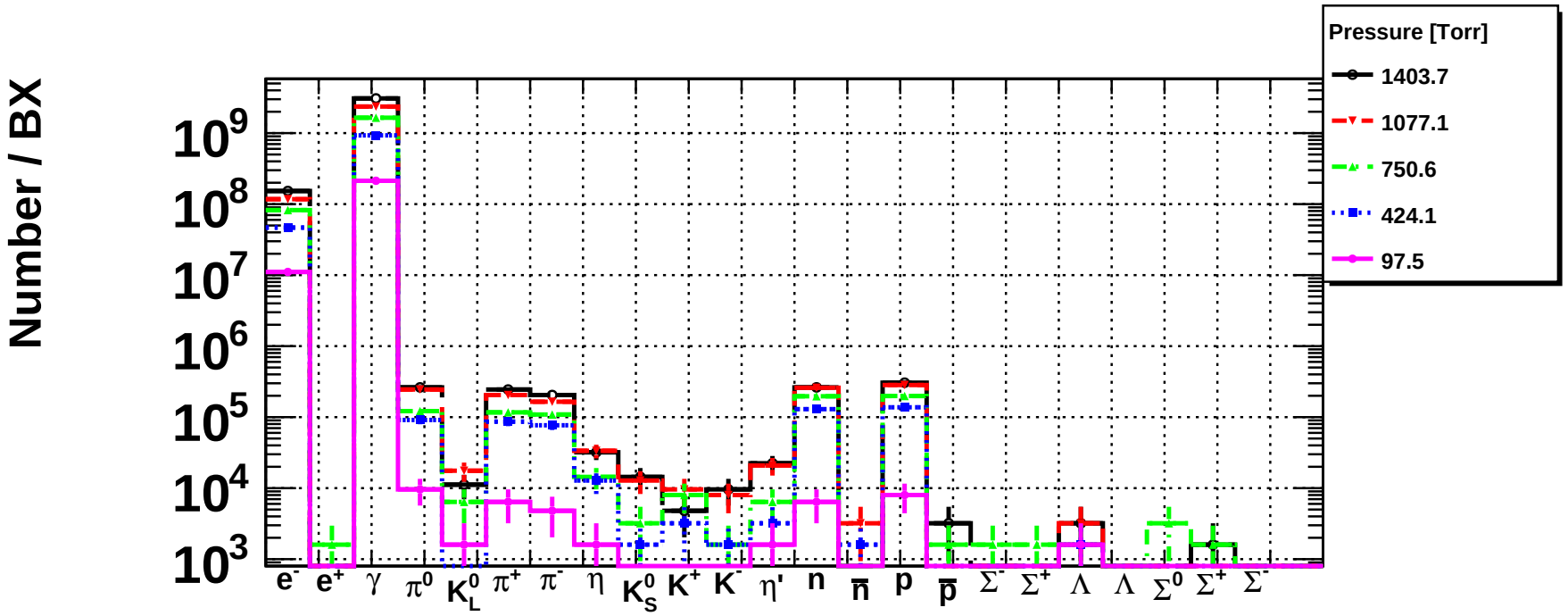
Probability of single Detector Response

Conclusions

Configuration of Event Generation

- Constant gas composition 62% H_2, 22% CO, 16% CO_2[3] added in MOKKA
- With 21 different densities:
  - → highest density value is in the order of normal air (no vacuum)
  - → lowest value is in the order of H_2
  - → equal steps in between
- The pressure is calculated via the ideal gas equation
- Simulation of 500GeV single e^- along the Beam Pipe
- $12.5 \cdot 10^6$ particles are simulated for every density
- Plots are scaled according to the bunch size ($2 \cdot 10^{10}$) (Scaling factor: $1.6 \cdot 10^3$)

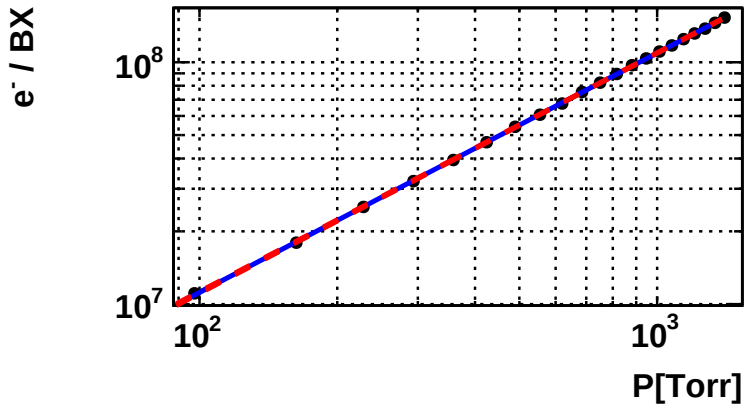
Particles Produced in Beam-Gas Interactions

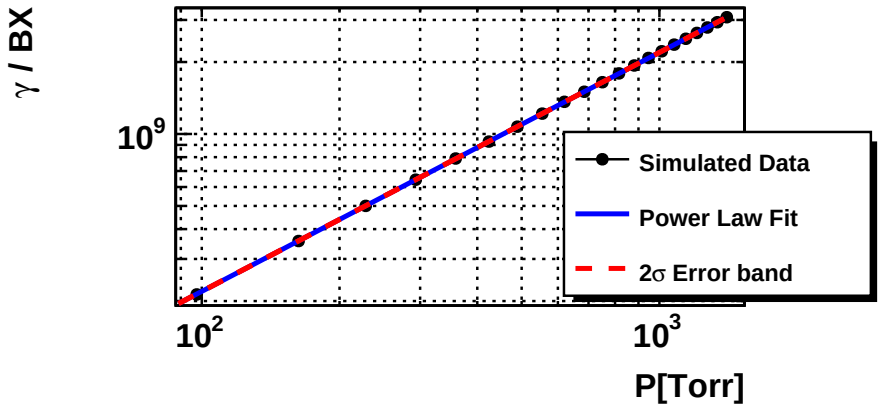


- Huge amount of e^-/γ form coulomb scattering and Bremsstrahlung
- Various hadron species from the nuclear interaction
- Group in: e^-, γ, hadrons

Fit Result: Electromagnetic Part

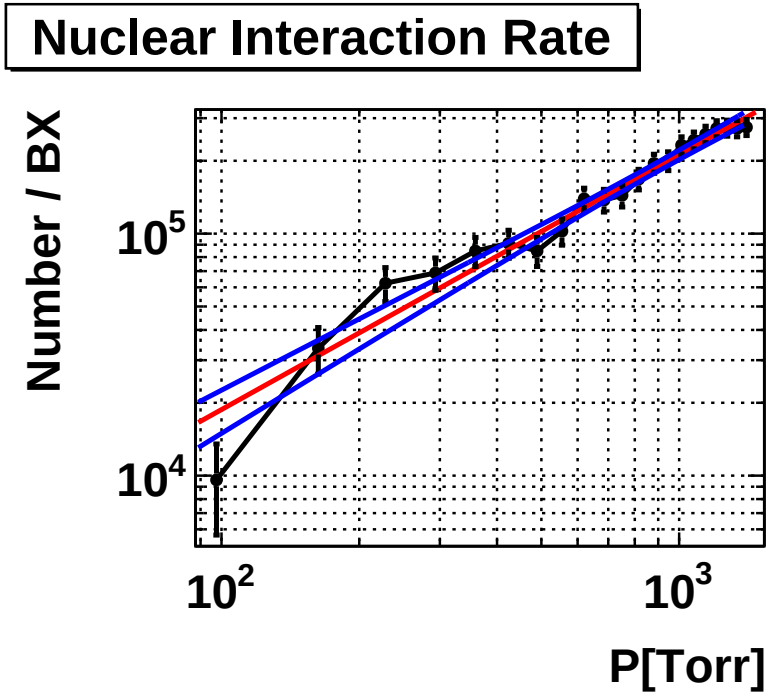
Power Law: $N(p) = C \cdot p^n$

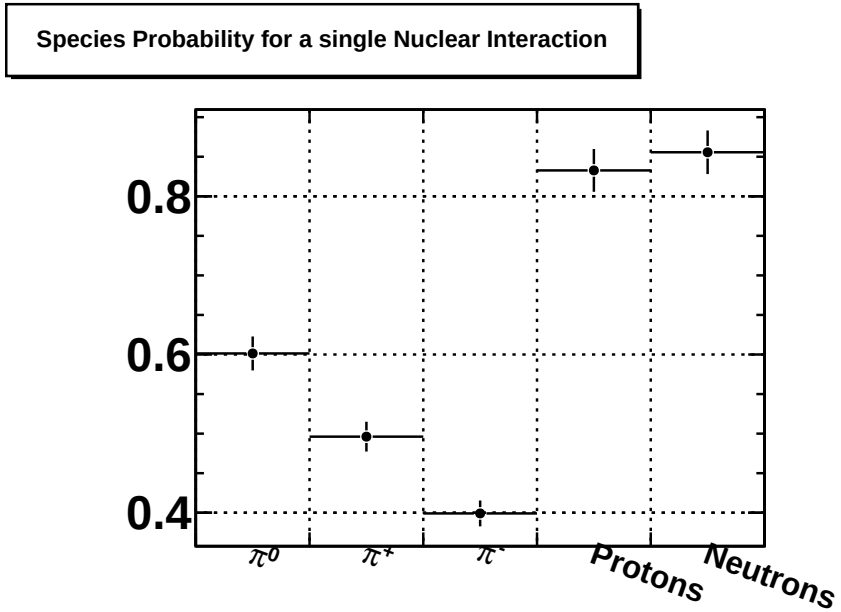




	χ^2/NDF	C	n	corr(C, n)
e^-	1	$(1.17 \pm 0.016) \cdot 10^5$	0.99 ± 0.002	-0.997
γ	1.48	$(2.2 \pm 0.0067) \cdot 10^6$	1 ± 0.00045	-0.998

Fit Result: Hadronic Part





	χ^2/NDF	C'	n	corr(C, n)
Hadronic	1.01	$(1.47 \pm 0.45) \cdot 10^2$	1.05 ± 0.045	-0.997

Final Fit Results

	C	n	corr(C,n)
e^-	$(1.17 \pm 0.016) \cdot 10^5$	0.99 ± 0.002	-1
γ	$(2.2 \pm 0.0067) \cdot 10^6$	1 ± 0.00045	-1
π^0	88 ± 27	1.05 ± 0.045	-1
π^+	73 ± 23	1.05 ± 0.045	-1
π^-	59 ± 18	1.05 ± 0.045	-1
p	$(1.22 \pm 0.38) \cdot 10^2$	1.05 ± 0.045	-1
n	$(1.26 \pm 0.39) \cdot 10^2$	1.05 ± 0.045	-1

- Within the statistical uncertainties the exponent n is totally in agreement with 1 $\rightarrow$ proportionality
- As expected the proportionality factor C depends on the particle species

Low Pressure Results

	7 nTorr	150 nTorr
e^-	$(99 \pm 5) \cdot 10^{-5}$	$(210 \pm 9.2) \cdot 10^{-4}$
γ	$(150 \pm 1.8) \cdot 10^{-4}$	$(330 \pm 3.3) \cdot 10^{-3}$
π^0	$(2.3 \pm 2.7) \cdot 10^{-7}$	$(5.8 \pm 5.9) \cdot 10^{-6}$
π^+	$(1.9 \pm 2.2) \cdot 10^{-7}$	$(4.7 \pm 4.9) \cdot 10^{-6}$
π^-	$(1.5 \pm 1.8) \cdot 10^{-7}$	$(3.8 \pm 4) \cdot 10^{-6}$
p	$(3.2 \pm 3.7) \cdot 10^{-7}$	$(8 \pm 8.2) \cdot 10^{-6}$
n	$(3.2 \pm 3.8) \cdot 10^{-7}$	$(8.2 \pm 8.4) \cdot 10^{-6}$

⇒ Determined the number of produced particles

⇒ Determine of the detector response

Introduction

Produced Particles

Average Detector Response
- Look Up Table
- Average Detector Hits
- Expected Detector Hits

Probability of single Detector Response

Conclusions

Detector Simulation

- Simulation of all events, different pressure, ...

→ Too slow/ inflexible

⇒ Parametrisation of the detector response in a look up tabel

⇒ Additional simulation:
Determine the average hits of a particle as a function of its momentum and origin

⇒ To ensure that all kinds of events are considered

Note: This can not be done by geometrical acceptance alone
⇒ Path of a particle is generally not a straight line

Simulation of the average Detector Hits

- Determine the dependence of the average hits on the particle momentum and origin
  - → Initial track is a straight line: no x,y dependence
  - → Detector is radial symmetric: no φ dependence
- At different steps along the path of beam particles:
  - → A full (180°) θ sweep was simulated in 0.2° steps
  - → The φ angle was smeared over the full range
  - → Additional smearing on the position (5mm in x,y; 10mm in z)
- Repeated for 28 different energy values
- In this simulation absolute vacuum is implemented

Look Up Table

- Sorting the particles with respect to their momentum, z momentum fraction and z position
- Calculating the average hits each interval

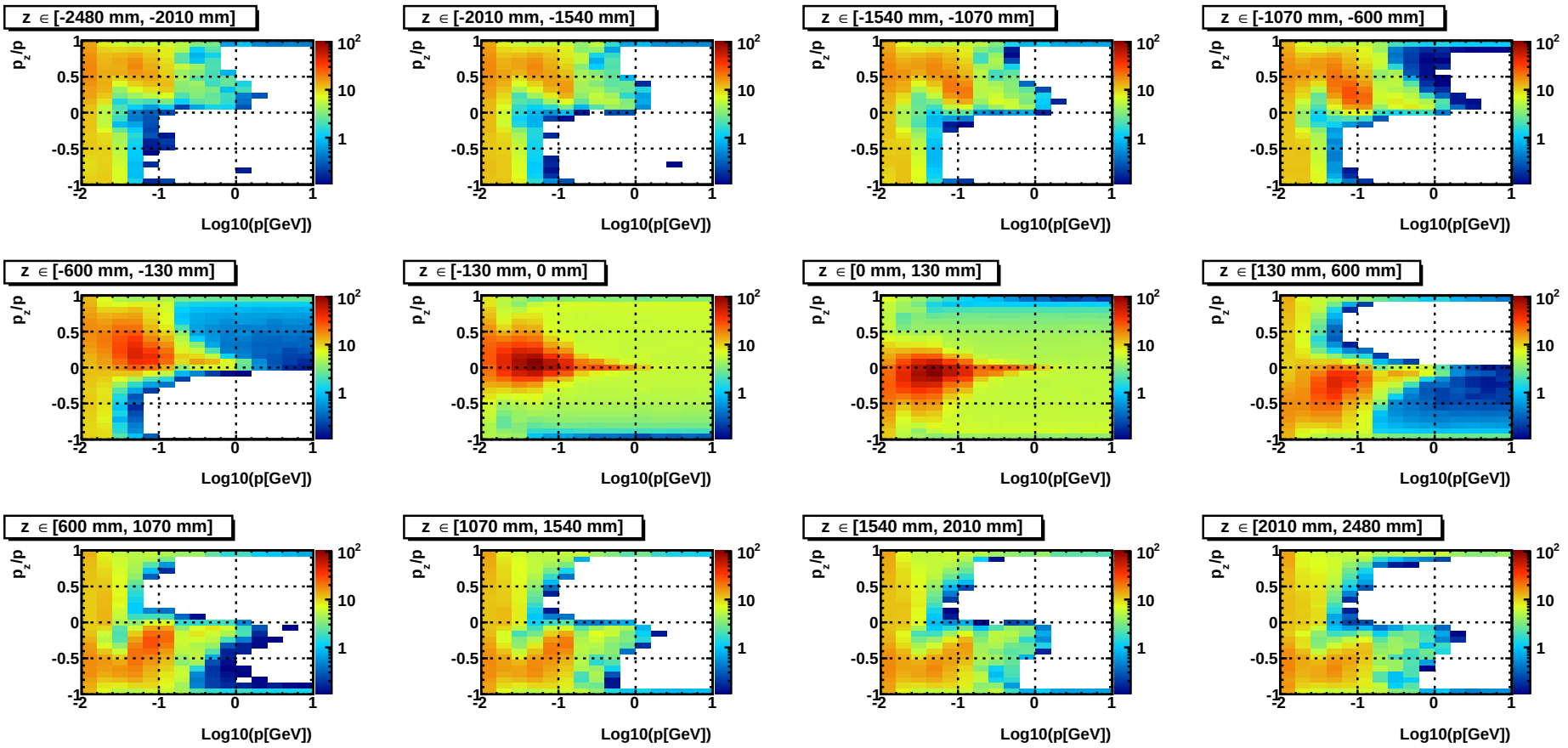
$$\langle n_{k,l,m} \rangle = \frac{1}{N\left(\Delta p^k, \Delta p_z^l, \Delta z^m\right)} \sum_i^N n_i \left(\Delta p^k, \Delta p_z^l, \Delta z^m\right) \qquad (1)$$

- Determine the interval a particle belong

⇒ Determine the average hit amount of the particle

- This is done separately for each particle type and detector part
- Hits of the complete particle cascade are treated as initial hits

Look Up Table: Example VTX Hits Electrons



Mean Tracker Hits per Particle (Excerpt)

	e^-	γ	π^0	dominated by
VTX	9.2 $\pm 8.3 \cdot 10^{-3}$	1.9 $\pm 1.5 \cdot 10^{-3}$	1.4 ± 0.16	e^-
FTD	0.36 $\pm 1.2 \cdot 10^{-3}$	6.2 $\pm 1.6 \cdot 10^{-3}$	6.6 ± 0.19	γ/π^0
TPC	0.36 $\pm 5.4 \cdot 10^{-3}$	29 $\pm 1.2 \cdot 10^{-2}$	40 ± 2.3	
SIT	$2.6 \cdot 10^{-2}$ $\pm 3.9 \cdot 10^{-4}$	1.1 $\pm 6.6 \cdot 10^{-4}$	2.5 ± 0.19	
SET	$2.9 \cdot 10^{-4}$ $\pm 5.2 \cdot 10^{-5}$	$7.4 \cdot 10^{-3}$ $\pm 8.8 \cdot 10^{-5}$	3 ± 0.32	π^0

$\Rightarrow$ Statistically significant estimate

Expected Detector Hits

Amount of detector hits:

	nTorr	Tracker	Front Calorimeter	Back Calorimeter
e^-	7	$(98 \pm 4.7) \cdot 10^{-4}$	$(160 \pm 6.4) \cdot 10^{-5}$	$(28 \pm 1.5) \cdot 10^{-6}$
	150	$(200 \pm 8.5) \cdot 10^{-3}$	$(33 \pm 1.2) \cdot 10^{-3}$	$(57 \pm 2.7) \cdot 10^{-5}$
γ	7	$(590 \pm 5.3) \cdot 10^{-3}$	$(370 \pm 2.8) \cdot 10^{-3}$	$(88 \pm 1) \cdot 10^{-4}$
	150	13 ± 0.1	$(800 \pm 5.3) \cdot 10^{-2}$	$(190 \pm 1.9) \cdot 10^{-3}$
Tot	7	$(600 \pm 5.3) \cdot 10^{-3}$	$(380 \pm 2.8) \cdot 10^{-3}$	$(88 \pm 1) \cdot 10^{-4}$
	150	13 ± 0.1	$(800 \pm 5.3) \cdot 10^{-2}$	$(190 \pm 1.9) \cdot 10^{-3}$

- On average the expected amount of hits is dominated by photons
- Order of magnitude: Estimate Tracker Hits of Photons at 7nTorr

$\rightarrow$ 10 Hits in $\approx$ 17 bunches

Note: This is only the average, for single cases it can be much larger

Introduction

Produced Particles

Average Detector Response

Probability of single Detector Response
Hit per Particle Probability Distribution

Conclusions

Hit per Particle Probability Distribution

- Determine the Probability $P(n)$ that a particle creates n hits

→ Weighting the hits per particle by the number of gas interactions

→ Normalized by the number of produced particles

→ Depending on the Momentum regime: absolute momentum, z fraction

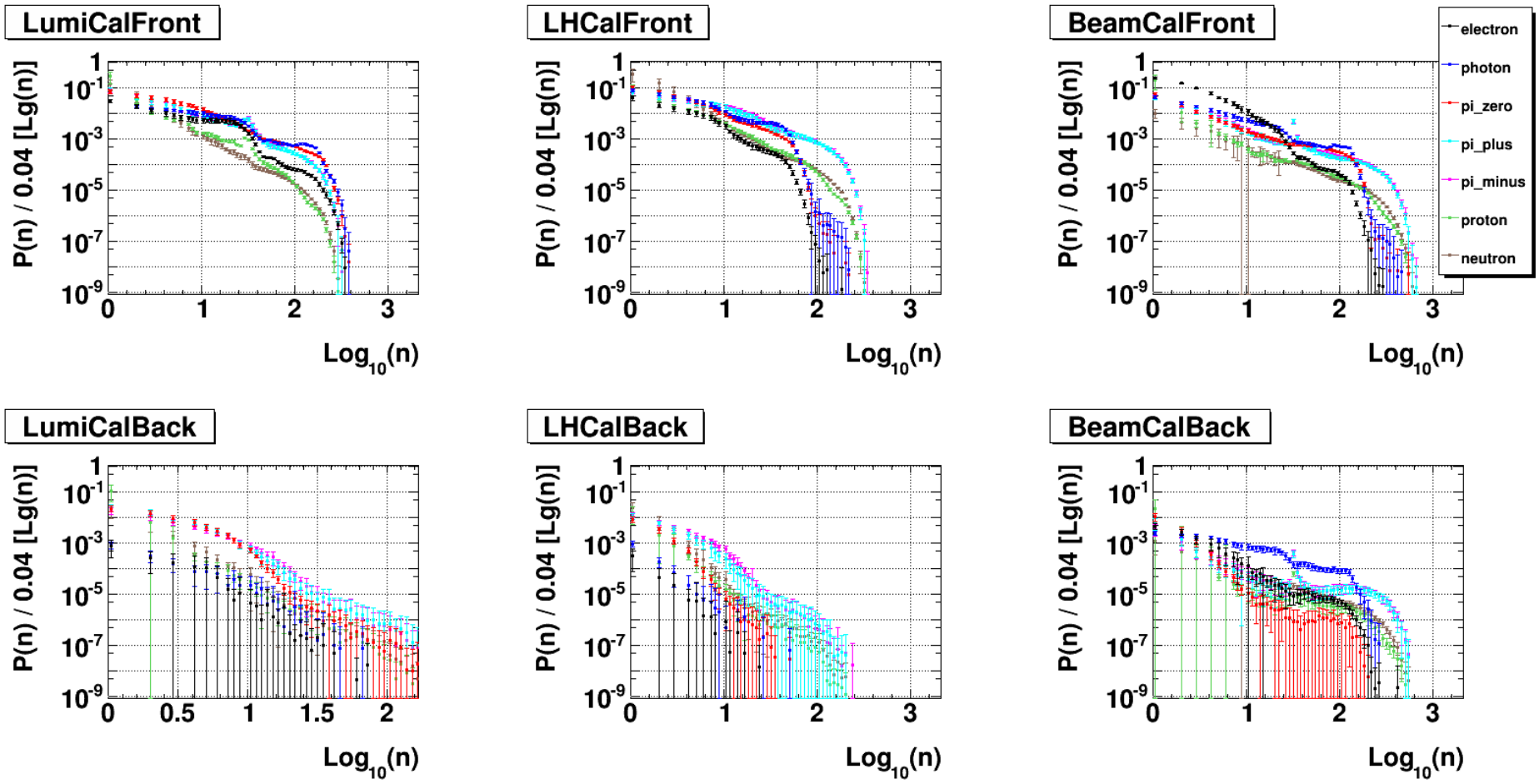
$$P(n) = \frac{1}{C} \sum_{j \in N(n)} \frac{N^{\text{scale}}(\left|\vec{p}^{j}\right|, p_z^j / \left|\vec{p}^{j}\right|)}{N^{\text{norm}}(\left|\vec{p}^{j}\right|, p_z^j / \left|\vec{p}^{j}\right|)} \tag{2}$$

- Normalizing the distribution to one:

$$C \leftrightarrow \sum P(n) \equiv 1 \tag{3}$$

- The case that a particle creates no hit ($n = 0$) is included

Probability Distribution: Calorimeter Part



Background Comparison

- The total expected amount for 7nTorr is roughly 1 hit per bunch
  Mostly created by photons

⇒ For 150nTorr it increases roughly to 21 hits per bunch

⇒ TPC background from e^+e^- pairs:
5 tracks with each 200 hits per bunch

⇒ Even without pump: beam-gas interactions are a minor background

Conclusions

- The amount of produced particles can be calculated as function of the pressure
- With the Look Up Tables the average hit amount for the different particle species and detector types is determined
- The frequency for single events can be estimated
- Shown: beam-gas interactions are a minor background even with increased pressure

References

[1] **ILC Project**, T. Behnke et al., eds., *International Linear Collider Reference Design Report Volume 4: Detectors*. 2007. arXiv:0712.2356. ILC-REPORT-2007-001.

[2] International Large Detector - Letter of Intent, DESY / KEK / Fermilab, DESY 2009/87 - Fermilab PUB-09-682-E - KEK Report 2009-6, ISSN 0418-9833, ISBN 978-3-935702-42-3, http://www.ilcild.org and http://www.linearcollider.org

[3] L. KELLER, T. MARUYAMA and T. MARKIEWICZ, *Beam-gas Interactions in the Beam Delivery System*, Stanford Linear Accelerator Center, ILC-Note-2007-016

[4] http://ilcsoft.desy.de/portal/software_packages/mokka/

[5] http://geant4.cern.ch/support/proc_mod_catalog/models/hadronic/G4ElectroVDNuclearModel.html

CR-002/CR-006

- For a easy re-tuning and optimal optics after the push-pull operation

→ ILD and SiD decided to have a common L*

→ L* ILD: 4.4m → 4.1m ⇒ QD0 ∼30cm closer to IP

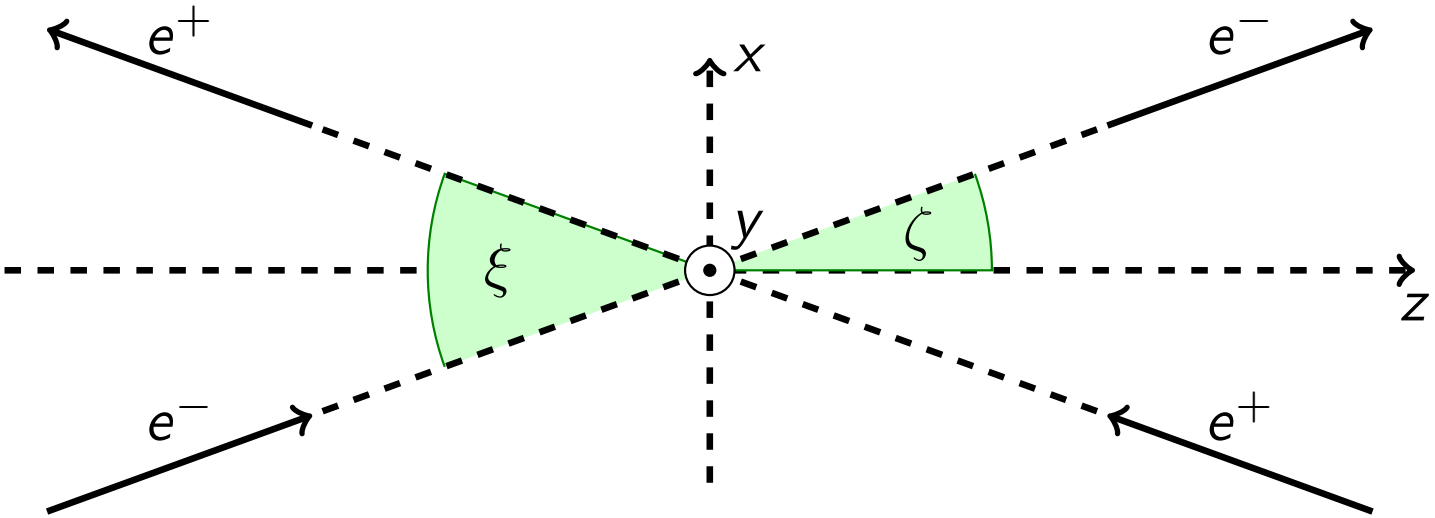
- Installation of an additional Beam Position Monitor (BPM) downstream of the IP

→ Need of ∼10cm additional space

- Need to find ∼40cm in current design of the ILD forward region

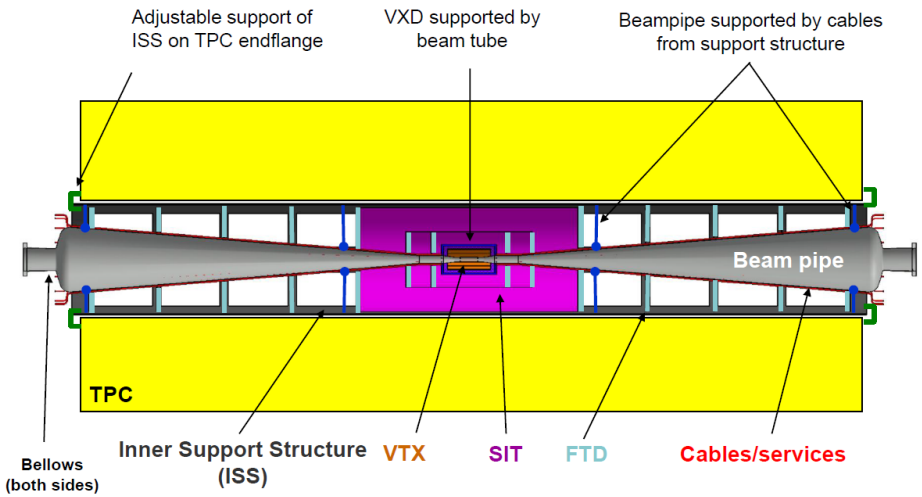
→ optimisations of all structures: regain ∼10cm

Coordinate System



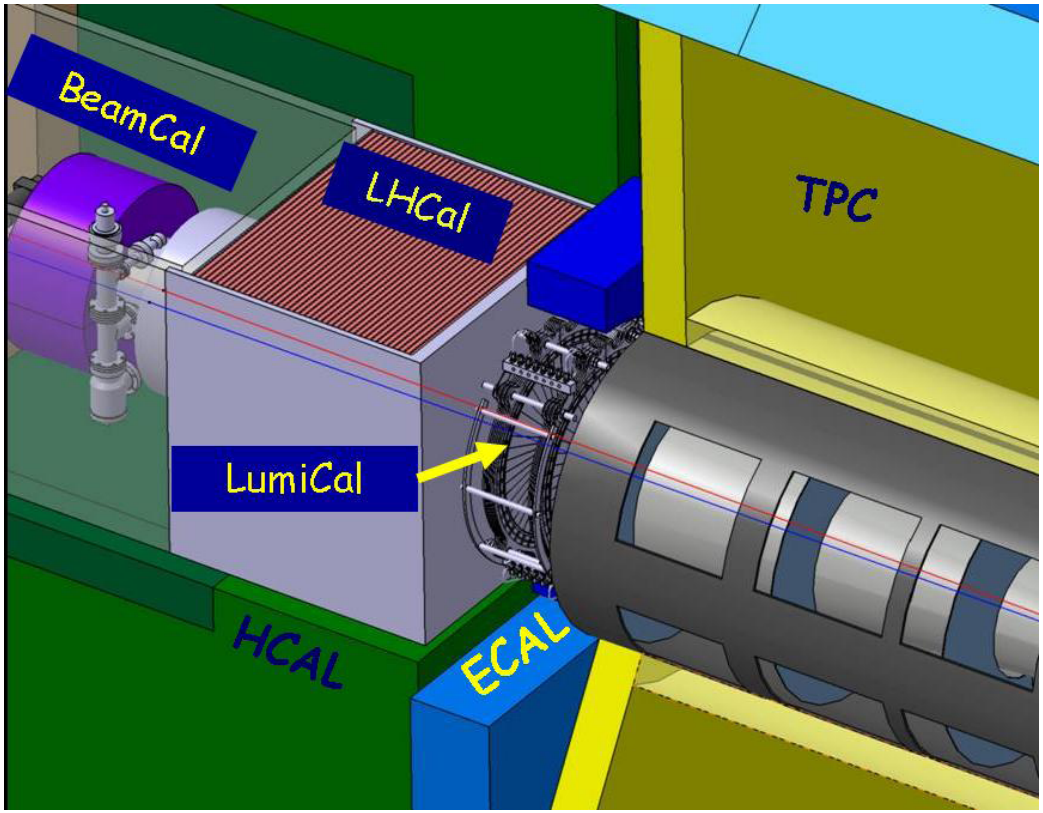
- z-axis along the beam pipe, y-axis points upwards, x-axis set for right handed system
- The origin is at the IP
- the e^- (e^+) beam is deflected by 7mrad to the z-axis, but only in th x-z-plane

Detector Setup: Tracker



- VTX (Vertex Detector):
  6 cylindrical layers of Si pixel sensors
- FTD (Forward Tracking Detector):
  System of Si strip and pixel discs around the beam pipe
- TPC (Time Projection Chamber):
  Around the entire inner beam pipe
- SIT (Silicon Internal Tracker): 2 layers of Silicon strip detectors
- SET (Silicon External Tracker): Barrel part around the TPC

Detector Setup: Calorimeter



- LumiCal:
  → Measurement for the luminosity
- LHCal:
  → Low angle hadrond calorimeter
- BeamCal:
  → Measurement of beam parameter
  → Luminosity estimate

The other calorimeter and the myon detector has been removed

Strategy Overview

1. Calculation of the pressure depended number of beam-gas interactions at high pressure values
   → Extrapolation to lower pressures

2. Average detector hits of initial produced particles
   → Together with the amount of interactions, the calculation of the average detector hits for different pressure

3. Probability for a single number of hits
   → Determine the frequency of single hit amounts

1. Pressure Dependence of Interactions

- According to a previous study[3], the pressure is set to $\mathcal{O}$(nTorr) to reduce the background from beam-gas interactions
- Increasing the statistics but saving computation time
- Calculation of the pressure dependence at high pressure values
- Extrapolating the number of interaction the the lower pressure

2. Average Detector Hits

- Secondary interactions at higher pressure:

→ With the residual gas it has to be removed (suppressed in lower pressures)

→ Within a detector part it has to be taken into account

- At higher pressure, particles can be absorbed by the gas

⇒ Additional simulation:
Determine the average hits of a particle as a function of its momentum and origin

Note: This can not be done by geometrical acceptance alone
⇒ Path of a particle is generally not a straight line

3. Hit per Particle Probability

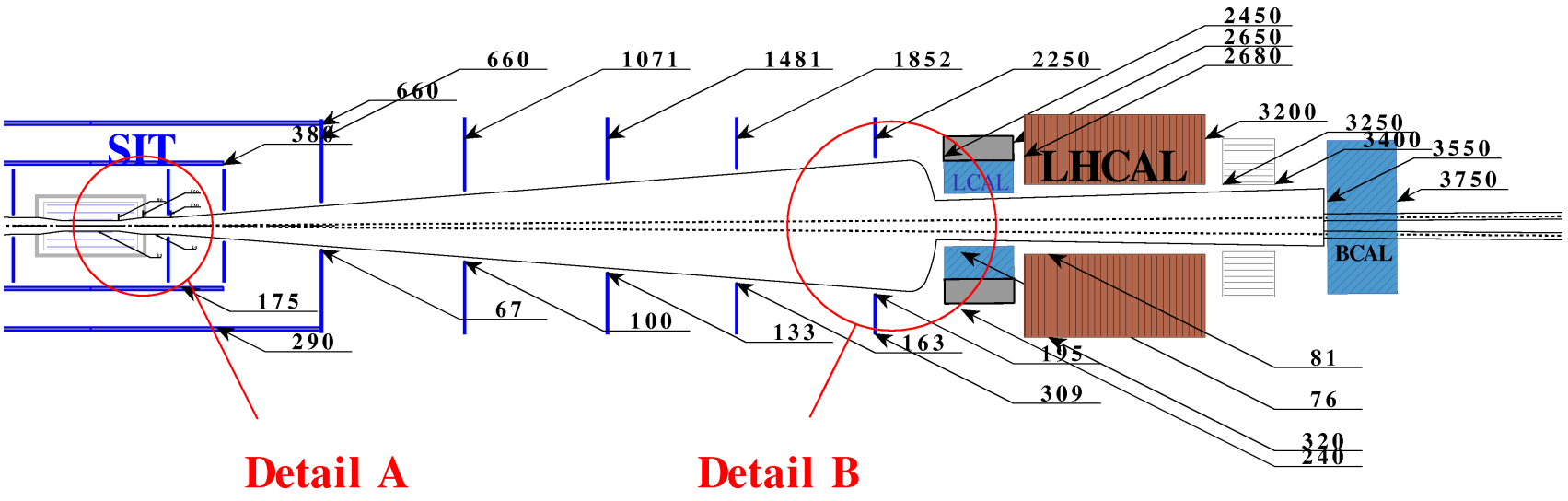
- Deviation from the average

→ Determine the Probability distribution for any hit per particle

- Weighting the hit per particle distribution by the momentum distribution of the produced particles

⇒ Frequency for any hit amount

Beam Pipe Schematic



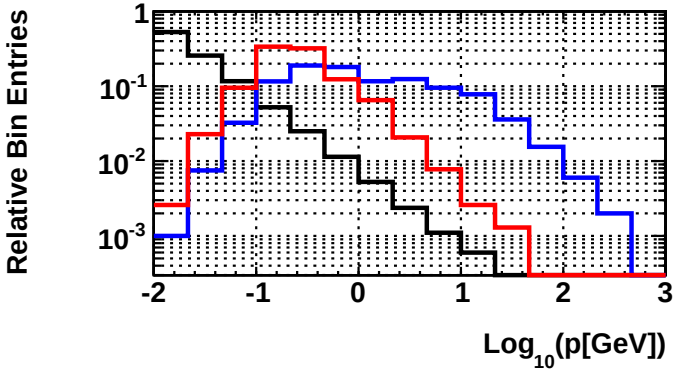
→ Shoot in positive z-direction

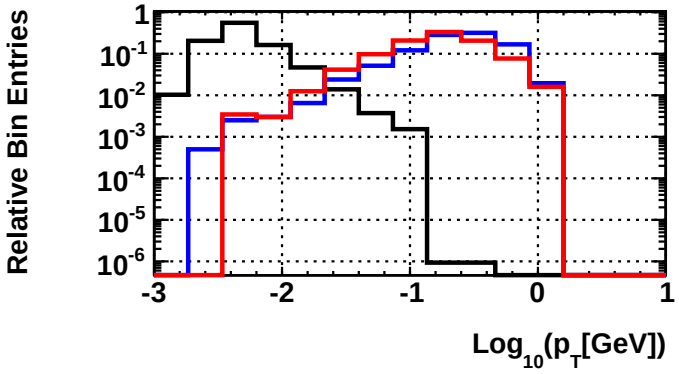
→ 7mrad crossing angle to the z-axis is done by MOKKA

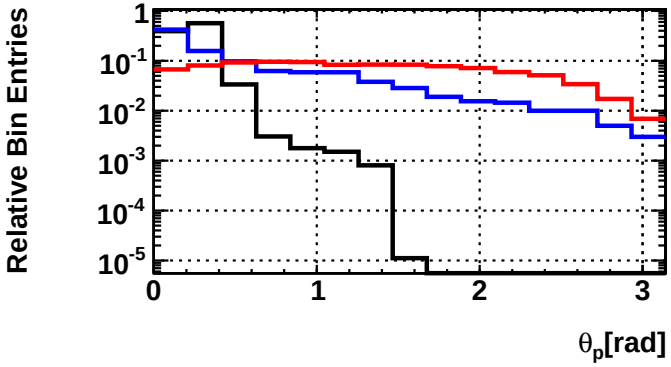
→ To cross the IP: Start position at (-15.743mm, 0, -2249mm)

⇒ Crossing the IP(z = 0) at $x = (-0.107 \pm 0.003)mm$

Particle Momentum and Angle Distribution







electron
pi_zero
neutron

- Hadrons have a much wider angular spectrum and larger p_T

$\Rightarrow$ Larger geometrical acceptance for hadrons

Pressure Dependence

- Approximation of produced particle amount by a power law fit

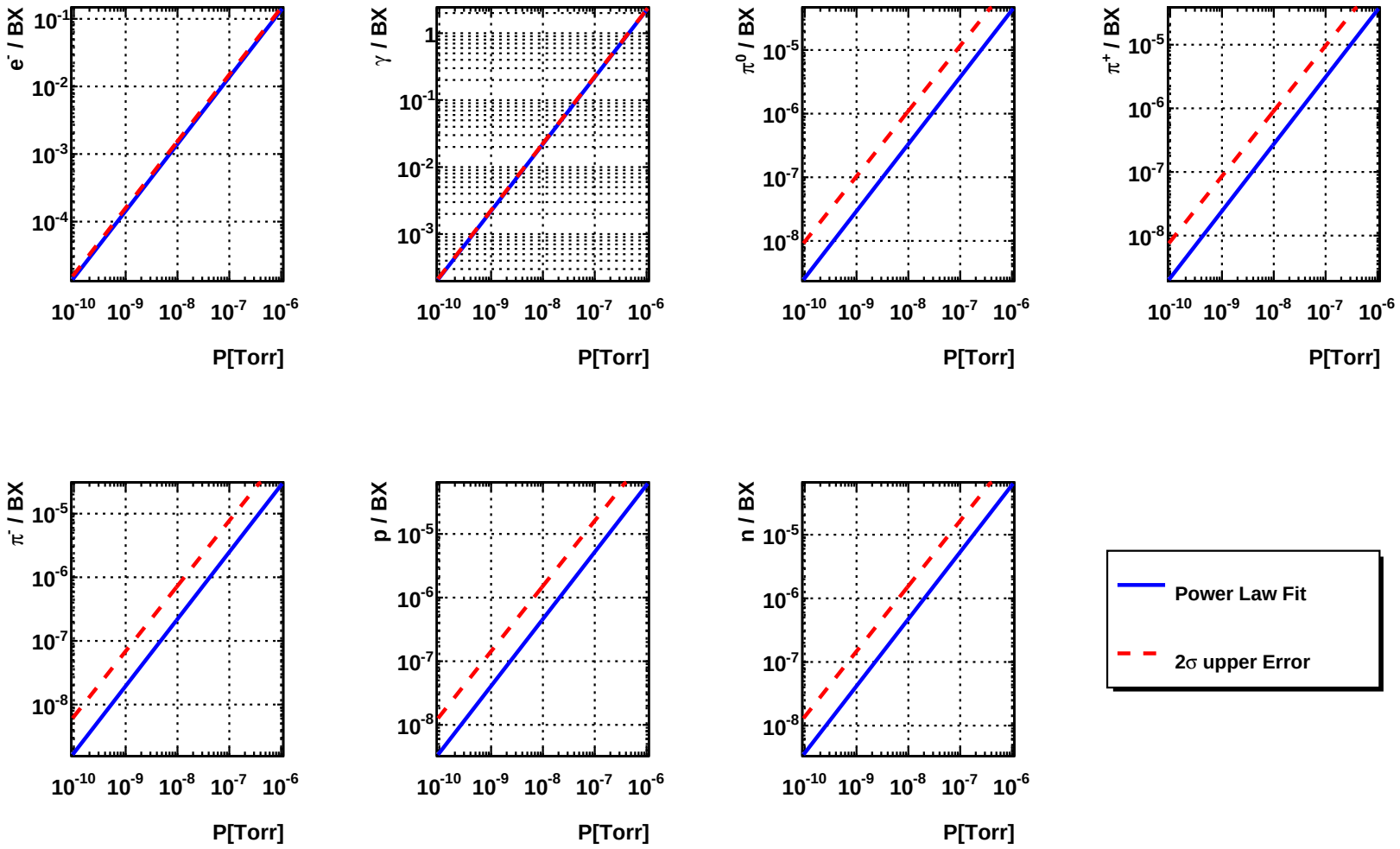
$$N(p) = C \cdot p^n \tag{4}$$

- It is expected to be linear ($n = 1$):
  Improve of the fit n is set as free parameter

- Improvement of the hadronic part:
  - → Count all interactions with at least 1 hadron
  - → Scaling the results by a global scaling factor S to obtain individual results

$$N(p) = C \cdot p^n = S \cdot C' \cdot p^n \tag{5}$$

Low Pressure Results



Total Average Hits

- Creating an average hit value for each pressure sample:

$$\langle n(p) \rangle = \frac{1}{N(p)} \sum_{j}^{N} \left\langle n_{k,l,m} \left(\Delta p^k, \Delta p_z^l, \Delta z^m \right) \right\rangle \tag{6}$$

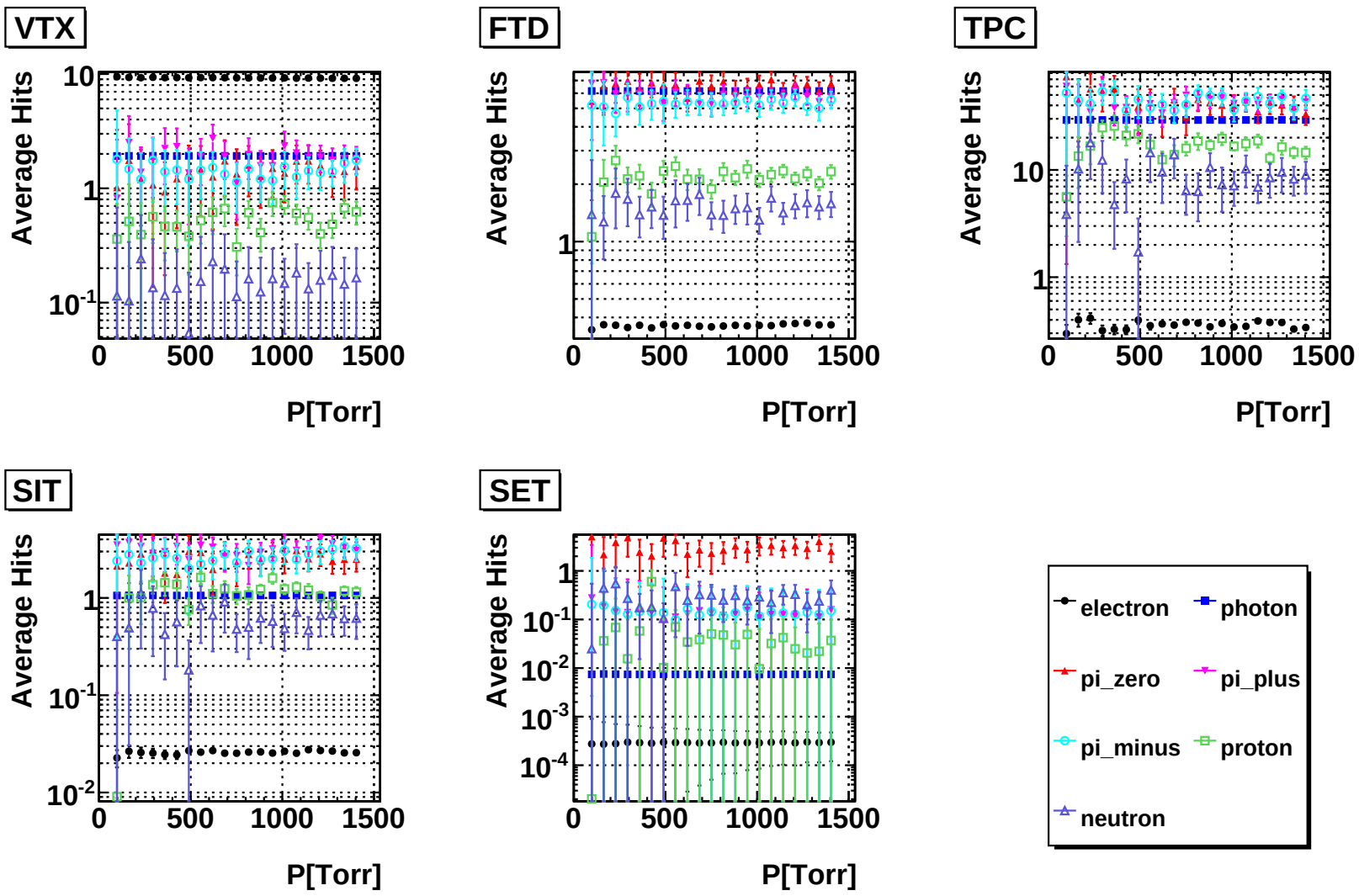
- For each pressure sample the same hit per particle value is expected

⇒ Cross check for systematic uncertainties

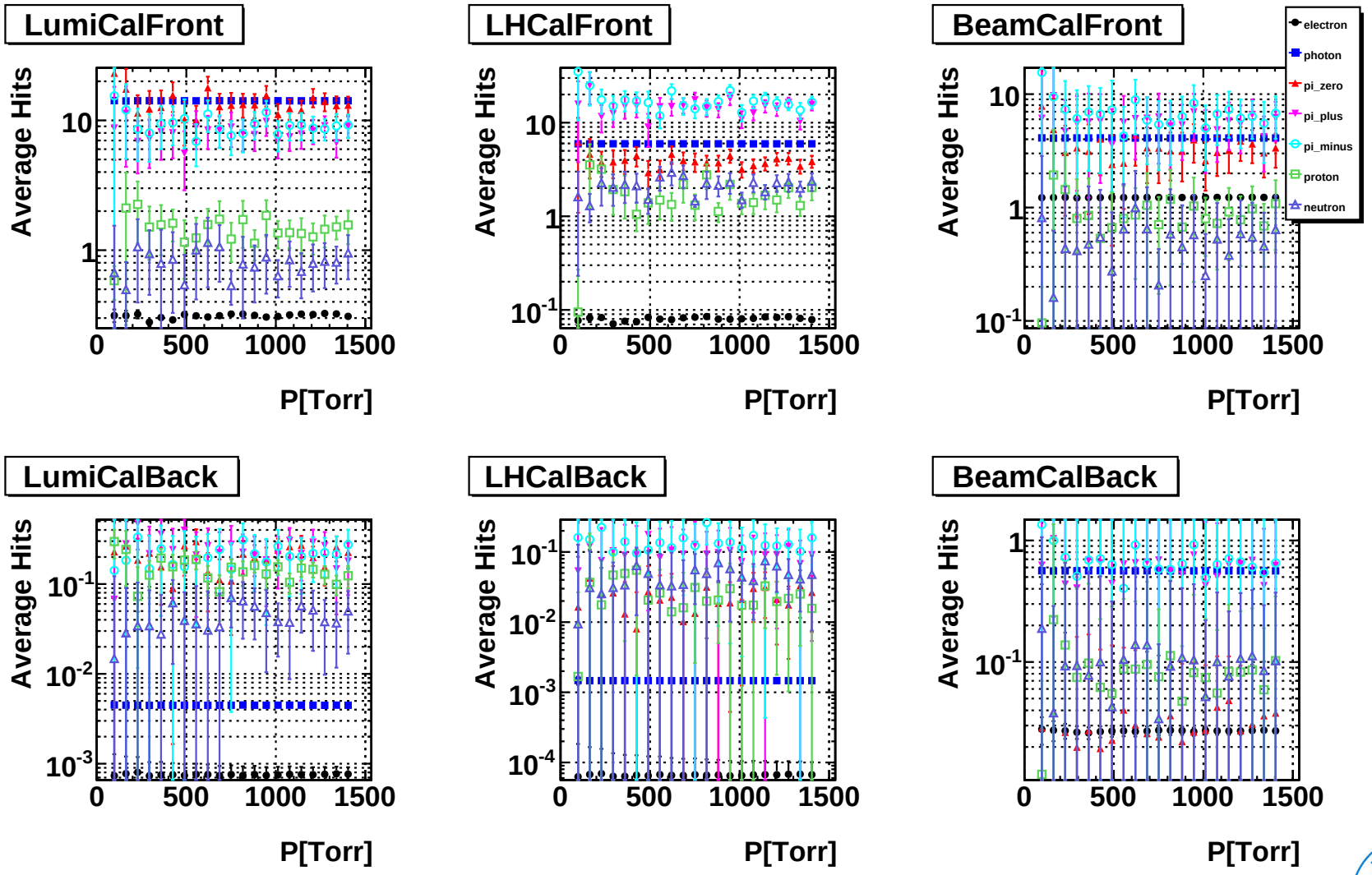
- Fit of a constant an the average hit value:

⇒ Determine a global mean of the average hit

Total Average Tracker Hits



Total Average Calorimeter Hits



Mean Tracker Hits per Particle

	π^+	π^-	p	n
VTX	1.8 ± 0.15	1.4 ± 0.12	0.53 $\pm 3.4 \cdot 10^{-2}$	0.14 $\pm 3.1 \cdot 10^{-2}$
FTD	5.7 ± 0.16	5.3 ± 0.16	2.2 $\pm 5 \cdot 10^{-2}$	1.5 $\pm 6.1 \cdot 10^{-2}$
TPC	42 ± 1.9	44 ± 2.1	16 ± 0.54	7.1 ± 0.7
SIT	3.1 ± 0.2	2.8 ± 0.2	0.79 $\pm 3.5 \cdot 10^{-2}$	0.53 $\pm 5.9 \cdot 10^{-2}$
SET	0.13 $\pm 6.9 \cdot 10^{-2}$	0.14 $\pm 7.3 \cdot 10^{-2}$	$7.6 \cdot 10^{-4}$ $\pm 2.6 \cdot 10^{-3}$	0.25 $\pm 4.1 \cdot 10^{-2}$

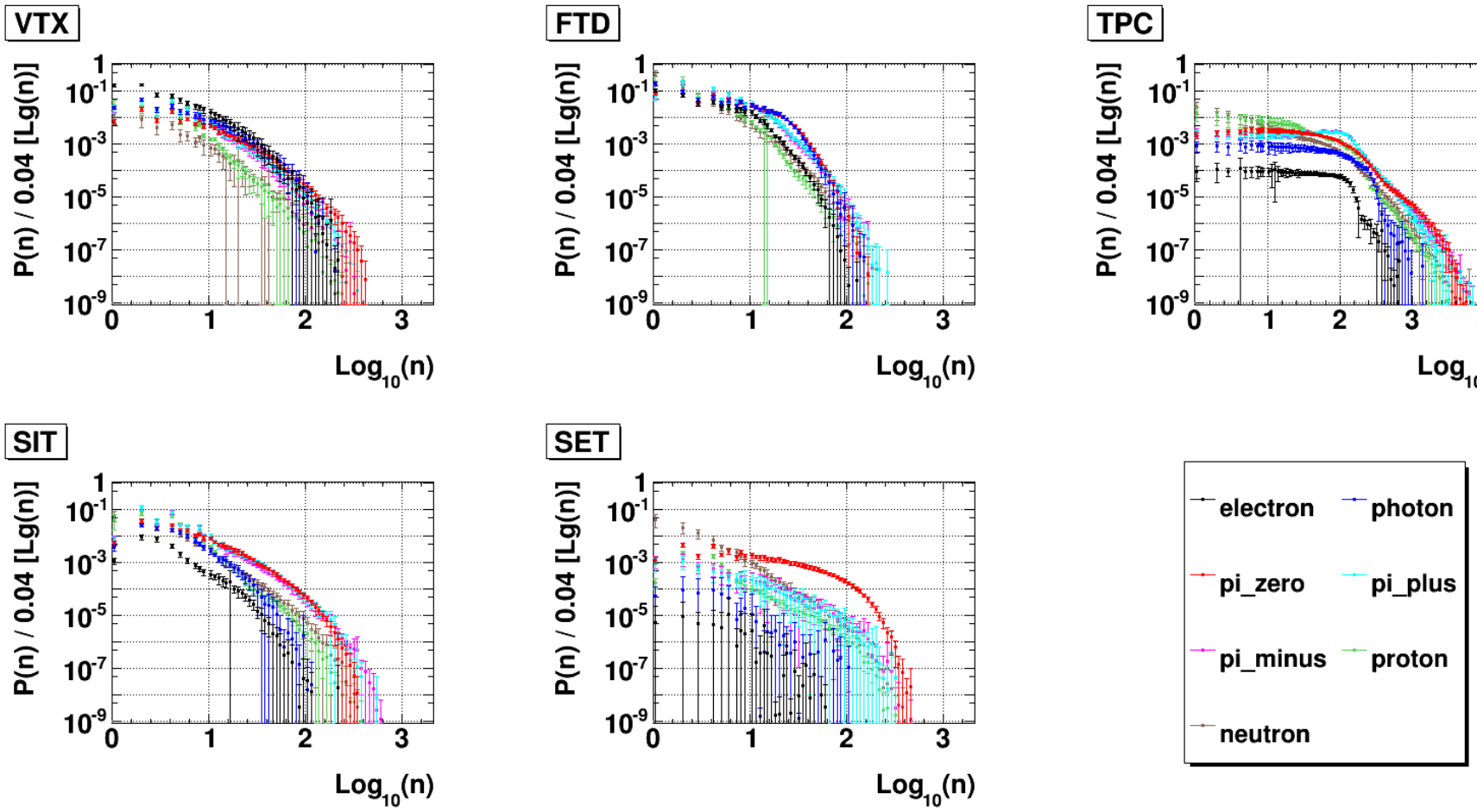
Mean Calorimeter Hits per Particle

	e^-	γ	π^0
LumiCalFront	0.31 $\pm 2.8 \cdot 10^{-3}$	14 $\pm 7.4 \cdot 10^{-3}$	13 ± 0.64
LumiCalBack	$7.6 \cdot 10^{-4}$ $\pm 4.4 \cdot 10^{-5}$	$4.5 \cdot 10^{-3}$ $\pm 3.2 \cdot 10^{-5}$	0.19 $\pm 1.9 \cdot 10^{-2}$
LHCalFront	$8.1 \cdot 10^{-2}$ $\pm 7.9 \cdot 10^{-4}$	5.9 $\pm 2.2 \cdot 10^{-3}$	3.8 ± 0.17
LHCalBack	$6.6 \cdot 10^{-5}$ $\pm 1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$ $\pm 1.5 \cdot 10^{-5}$	$2.1 \cdot 10^{-2}$ $\pm 4.8 \cdot 10^{-3}$
BeamCalFront	1.2 $\pm 1.6 \cdot 10^{-3}$	4.1 $\pm 3.9 \cdot 10^{-3}$	3.3 ± 0.34
BeamCalBack	$2.7 \cdot 10^{-2}$ $\pm 5 \cdot 10^{-4}$	0.56 $\pm 1.5 \cdot 10^{-3}$	$3.2 \cdot 10^{-2}$ $\pm 1.8 \cdot 10^{-2}$

Mean Calorimeter Hits per Particle

	π^+	π^-	p	n
LumiCalFront	8 ± 0.48	8.9 ± 0.54	1.2 $\pm 8.6 \cdot 10^{-2}$	0.72 $\pm 7.2 \cdot 10^{-2}$
LumiCalBack	0.24 $\pm 3.1 \cdot 10^{-2}$	0.22 $\pm 3.3 \cdot 10^{-2}$	0.14 $\pm 8.1 \cdot 10^{-3}$	$4.5 \cdot 10^{-2}$ $\pm 8 \cdot 10^{-3}$
LHCalFront	14 ± 0.6	16 ± 0.69	1.1 $\pm 8.8 \cdot 10^{-2}$	1.8 $\pm 9.9 \cdot 10^{-2}$
LHCalBack	$9.4 \cdot 10^{-2}$ $\pm 2.4 \cdot 10^{-2}$	0.14 $\pm 2.9 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$ $\pm 5.6 \cdot 10^{-3}$	$4.8 \cdot 10^{-2}$ $\pm 8.6 \cdot 10^{-3}$
BeamCalFront	5.5 ± 0.68	6.3 ± 0.78	0.36 $\pm 8 \cdot 10^{-2}$	0.37 ± 0.12
BeamCalBack	0.58 ± 0.26	0.63 ± 0.29	$4.9 \cdot 10^{-2}$ $\pm 3.4 \cdot 10^{-2}$	$7.1 \cdot 10^{-2}$ $\pm 5.6 \cdot 10^{-2}$

Probability Distribution: Tracker Part



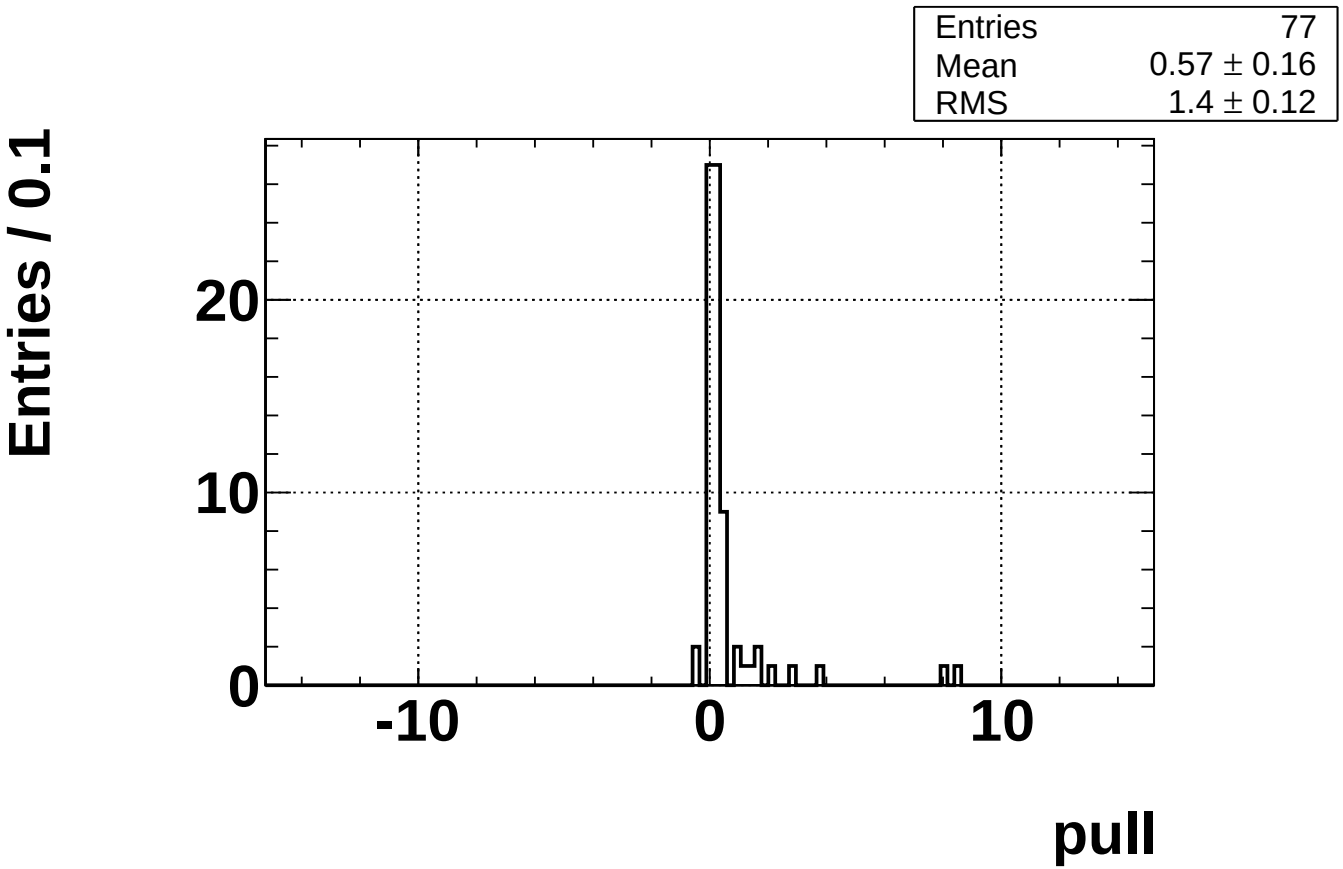
Mean Value of the Distribution

- Obtaining the average hit via the mean value of the distribution
- Average hit of a particle $\equiv$ mean value probability distribution
- Consistency check: Pull Distribution

$$\text{pull} := \frac{< x > -\mu}{\Delta x} \tag{7}$$

$< x >$: Mean value of the distribution;
Δx: Deviation of the mean value;
μ: Previous average hit

Pull Distribution



- Expected Mean: 0 → Miscalculation of the distribution tails
- Expected RMS: 1 → Large deviations from low statistic distributions

Event Probability

- Determine the Probability that a particle creates between X and Y hits
- Integrating the Probability distribution:

$$P\left(X \leq n \leq Y\right) = \int_X^Y P(n)\mathrm{dn} = \sum_{n=X}^{Y} P_n \tag{8}$$

- All probabilities are calculated separately for particle types and detector parts

Note: Probabilities of hits in multi-detector parts are omitted

Probability of Particle Hits Intervals

Hits	e^-	π^0	π^+	n
VTX [1, 10]	0.63 $\pm 3.6 \cdot 10^{-2}$	$9.3 \cdot 10^{-2}$ $\pm 5.1 \cdot 10^{-3}$	0.18 $\pm 2 \cdot 10^{-2}$	$4 \cdot 10^{-2}$ $\pm 9.7 \cdot 10^{-3}$
[11, 100]	0.12 $\pm 1.3 \cdot 10^{-2}$	$4.8 \cdot 10^{-2}$ $\pm 2.3 \cdot 10^{-3}$	$4.7 \cdot 10^{-2}$ $\pm 4.1 \cdot 10^{-3}$	$4.8 \cdot 10^{-3}$ $\pm 1.1 \cdot 10^{-3}$
FTD [1, 10]	0.37 $\pm 2.3 \cdot 10^{-2}$	0.47 $\pm 2.4 \cdot 10^{-2}$	0.69 $\pm 6.2 \cdot 10^{-2}$	0.66 ± 0.21
[11, 100]	$6.2 \cdot 10^{-2}$ $\pm 4.6 \cdot 10^{-3}$	0.28 $\pm 9.3 \cdot 10^{-3}$	0.19 $\pm 1.4 \cdot 10^{-2}$	$3 \cdot 10^{-2}$ $\pm 3 \cdot 10^{-3}$
TPC [1, 10]	$9.7 \cdot 10^{-4}$ $\pm 2.3 \cdot 10^{-4}$	$3.1 \cdot 10^{-2}$ $\pm 2.1 \cdot 10^{-3}$	$2.2 \cdot 10^{-2}$ $\pm 2 \cdot 10^{-3}$	$9.6 \cdot 10^{-2}$ $\pm 1.6 \cdot 10^{-2}$
[11, 100]	$6.6 \cdot 10^{-3}$ $\pm 3.1 \cdot 10^{-4}$	0.19 $\pm 4 \cdot 10^{-3}$	0.24 $\pm 6.5 \cdot 10^{-3}$	0.12 $\pm 4.1 \cdot 10^{-3}$

Frequency of Particle Hits Intervals per BX

150nTorr	e^-	π^0	π^+	n
VTX $[1,10]$	0.013	$5.4 \cdot 10^{-7}$	$8.8 \cdot 10^{-7}$	$3.3 \cdot 10^{-7}$
$[11,100]$	$2.4 \cdot 10^{-3}$	$2.8 \cdot 10^{-7}$	$2.2 \cdot 10^{-7}$	$3.9 \cdot 10^{-8}$
FTD $[1,10]$	$7.5 \cdot 10^{-3}$	$2.7 \cdot 10^{-6}$	$3.3 \cdot 10^{-6}$	$5.4 \cdot 10^{-6}$
$[11,100]$	$1.3 \cdot 10^{-3}$	$1.6 \cdot 10^{-6}$	$9 \cdot 10^{-7}$	$2.5 \cdot 10^{-7}$
TPC $[1,10]$	$2 \cdot 10^{-5}$	$1.8 \cdot 10^{-7}$	$1 \cdot 10^{-7}$	$7.9 \cdot 10^{-7}$
$[11,100]$	$1.4 \cdot 10^{-4}$	$1.1 \cdot 10^{-6}$	$1.1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$

- Order of magnitude: $[1,10]$ VTX hits of electrons

$\rightarrow$ Once every 77 bunches

- Average amount: 0.2 VTX e^- hits per bunch
- Average hits: 9.2 VTX per produced e^-

$\Rightarrow$ Consistent with 0.013 events per bunch with hits between $[1,10]$

Summary

- The pressure dependence had been calculated and it is in very good agreement with the linear expectation
- With the Look Up Tables it is possible to determine the average hit amount
- The total expected amount for 1nTorr is roughly 1 hit every 7 bunches Mostly created by photons
- Hit per particle probability distribution had been calculated to obtain the frequency for single events and to estimate the deviation from the average