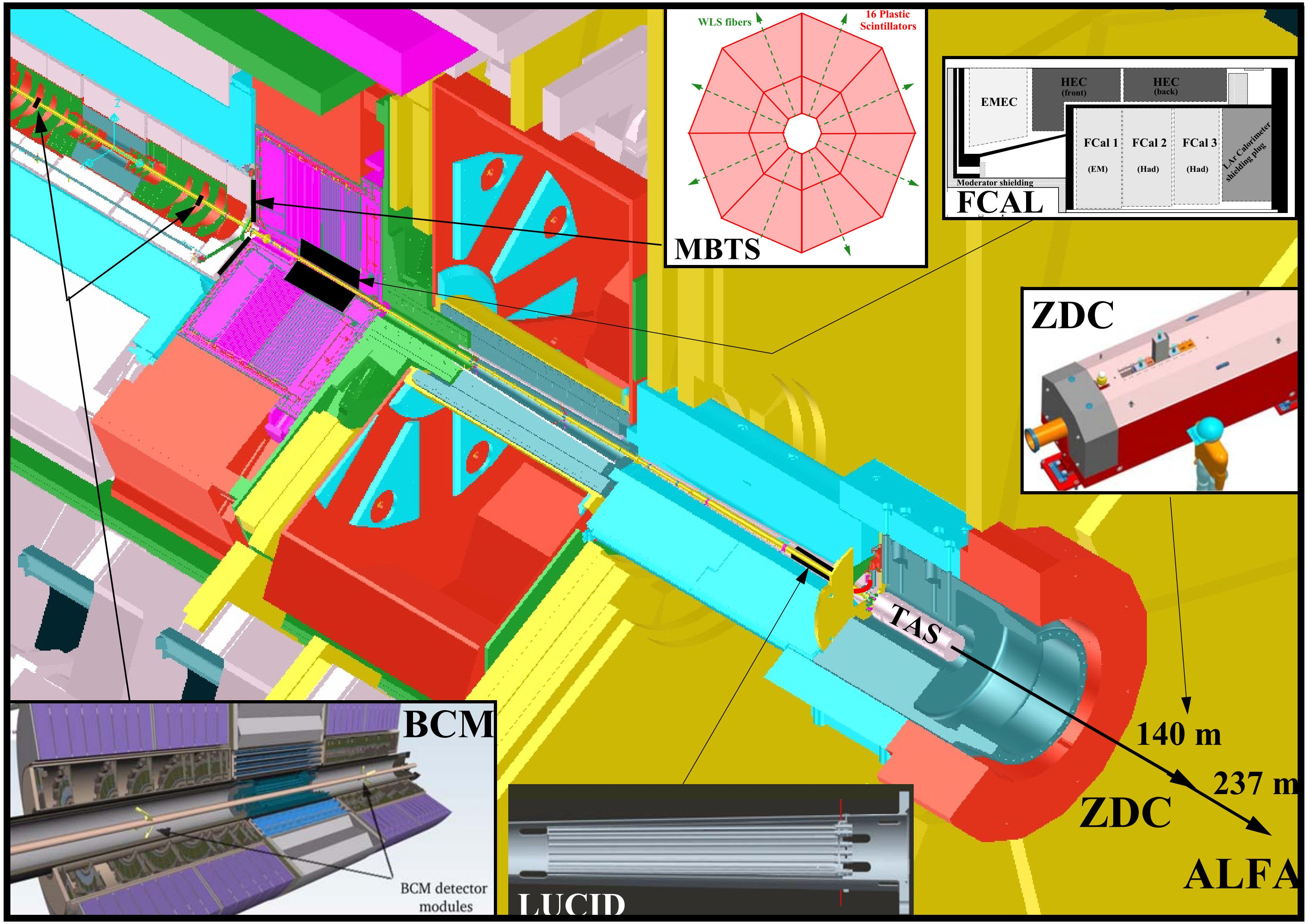
Report from the luminosity measurement taskforce



http://project-atlas-lucid.web.cern.ch/project-atlas-lucid/taskforce/main.html

The basic principle

The luminosity (L) can be calculated from the rate of all inelastic interactions (R_{in}) and the total inelastic cross section (σ_{in}) by using the simple relation:

$$L = \frac{R_{in}}{\sigma_{in}}$$

The inelastic interaction rate is given by the average number of inelastic interactions per bunch crossing (μ) and the bunch crossing rate (f_{BX}):

$$R_{in} = \mu \times f_{BX} = \mu \times \frac{\text{The Number of filled Bunch crossings}}{3564} \times 40\ \text{MHz}$$

Conclusion: To provide a luminosity the detector must estimate μ correctly from a measured rate and the inelastic cross section has to be known.

The inelastic cross section

Predicted cross section in mb from Phojet 1.12 and Pythia 6.420

14 TeV:

	Phojet	Pythia
Inelastic	83.1	79.3
Elastic	34.4	22.2
Total	117.5	101.5

	Phojet	Pythia
Non diff.	68.0 (82%)	54.7 (69%)
Double diff.	4.1 (5%)	10.3 (13%)
Single diff.	11.0 (13%)	14.3 (18%)

	Phojet	Pythia
Minimum bias	72.1	65.0

10 TeV:

	Phojet	Pythia
Inelastic	79.8	75.3
Elastic	32.0	20.8
Total	111.8	96.1

	Phojet	Pythia
Non diff.	64.9 (81%)	51.6 (68%)
Double diff.	4.0 (5%)	9.8 (13%)
Single diff.	10.8 (14%)	14.0 (19%)

	Phojet	Pythia
Minimum bias	68.9	61.3

0.9 TeV:

	Phojet	Pythia
Inelastic	54.0	52.5
Elastic	14.1	12.8
Total	68.1	65.3

	Phojet	Pythia
Non diff.	40.0 (74%)	34.4 (66%)
Double diff.	3.5 (7%)	6.4 (12%)
Single diff.	10.5 (19%)	11.7 (22%)

	Phojet	Pythia
Minimum bias	43.5	40.8

(Note: double pomeron processes were not included in PHOJET cross sections).

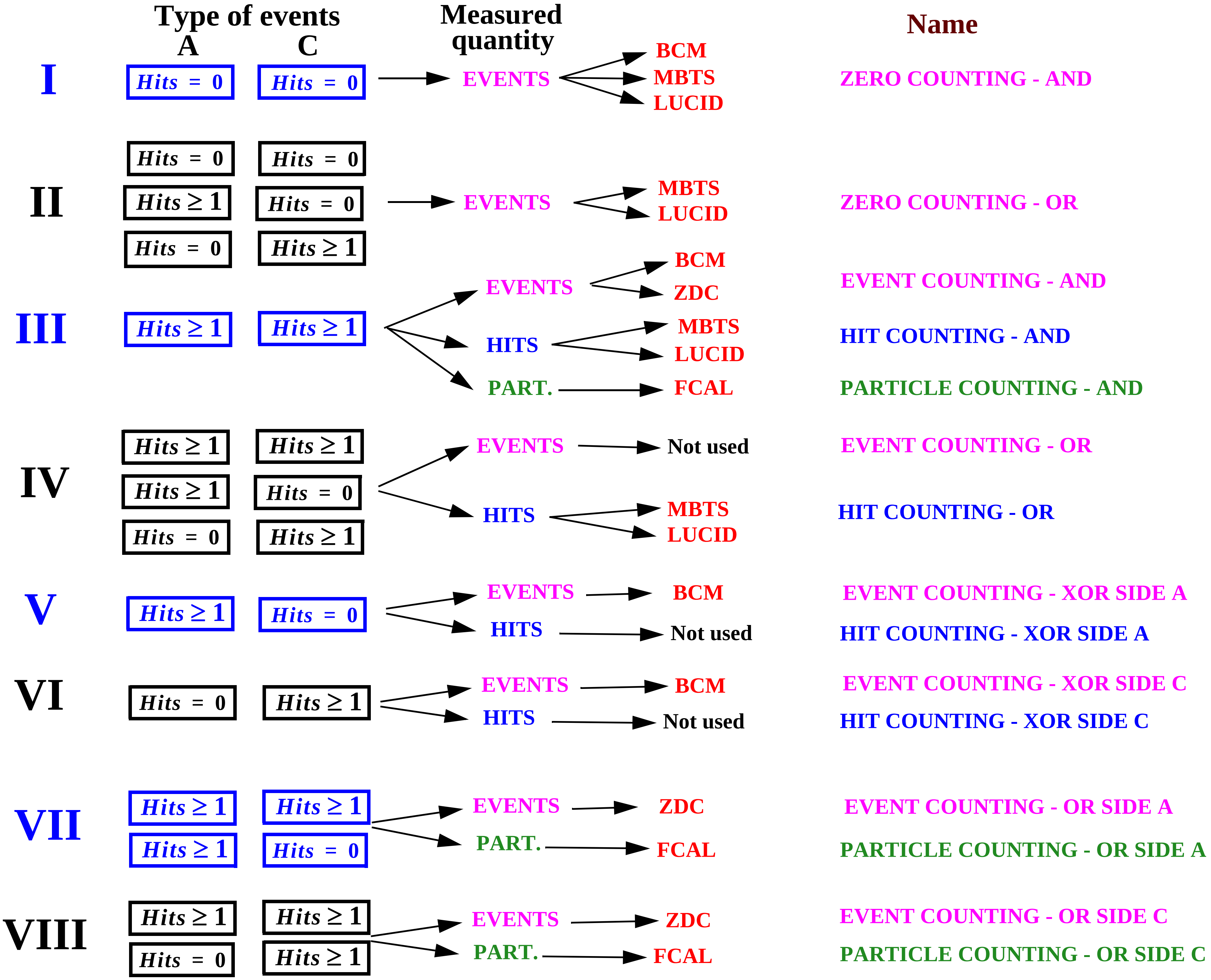
Measuring μ

The average number of interactions per bunch crossing (μ) is estimated from a rate measured by the detectors.

The measured rate that is used to estimate μ can be of three main types:

1) Event rate
2) Hit rate
3) Particle rate

The different detectors measure different quantities while requiring different combinations of signals in the two detectors. This lead to a long list of different luminosity methods.


Type of events
A
C
Measured quantity
Name
I
$Hits = 0$
$Hits = 0$
EVENTS
BCM
MBTS
LUCID
ZERO COUNTING - AND
II
$Hits = 0$
$Hits = 0$
$Hits \geq 1$
$Hits = 0$
$Hits = 0$
$Hits \geq 1$
EVENTS
MBTS
LUCID
ZERO COUNTING - OR
III
$Hits \geq 1$
$Hits \geq 1$
EVENTS
BCM
ZDC
EVENT COUNTING - AND
HITS
MBTS
LUCID
HIT COUNTING - AND
PART.
FCAL
PARTICLE COUNTING - AND
IV
$Hits \geq 1$
$Hits \geq 1$
$Hits \geq 1$
$Hits = 0$
$Hits = 0$
$Hits \geq 1$
EVENTS
Not used
EVENT COUNTING - OR
HITS
MBTS
LUCID
HIT COUNTING - OR
V
$Hits \geq 1$
$Hits = 0$
EVENTS
BCM
EVENT COUNTING - XOR SIDE A
HITS
Not used
HIT COUNTING - XOR SIDE A
VI
$Hits = 0$
$Hits \geq 1$
EVENTS
BCM
EVENT COUNTING - XOR SIDE C
HITS
Not used
HIT COUNTING - XOR SIDE C
VII
$Hits \geq 1$
$Hits \geq 1$
$Hits \geq 1$
$Hits = 0$
EVENTS
ZDC
EVENT COUNTING - OR SIDE A
PART.
FCAL
PARTICLE COUNTING - OR SIDE A
VIII
$Hits \geq 1$
$Hits \geq 1$
$Hits = 0$
$Hits \geq 1$
EVENTS
ZDC
EVENT COUNTING - OR SIDE C
PART.
FCAL
PARTICLE COUNTING - OR SIDE C

Measuring μ by particle counting

If a true number of particles is counted in the detectors without any requirement on a minimum number of particles then

$$\mu = \frac{N_{part/BX}}{N_{part/pp}} = \frac{\text{The average number of detected particles per bunch crossing}}{\text{The average number of detected particles per inelastic pp interaction}}$$

The average number of detected particles per inelastic pp interaction ($N_{part/pp}$) has to be obtained from simulations or from a reference data sample recorded at low luminosity (low μ).

Another possibility is to measure the luminosity with for example ALFA and calibrate the detector:

$$L = \frac{f_{BX}}{\sigma_{in}} \times \frac{N_{part/BX}}{N_{part/pp}}$$

$$\sigma_{in} \times N_{part/pp} = \frac{\overset{\text{ALFA}}{L}}{\underset{\text{Detector}}{N_{part/BX}}} \times \frac{1}{f_{BX}}$$

Particle counting with coincidence

In order to reduce background it is an advantage to do particle counting while requiring at least one particle in each detector. In this case μ is no longer proportional to $N_{part/BX}$.

If only events with particles in both detectors are used then the relationship between $N_{part/bx}$ and μ becomes:

$$N_{part/BX} = \mu \left[N^{Coinc}_{part/pp} + (N^{A}_{part/pp} - N^{Coinc}_{part/pp}) (1 - e^{-\mu\varepsilon^{C}}) + (N^{C}_{part/pp} - N^{Coinc}_{part/pp}) (1 - e^{-\mu\varepsilon^{A}}) \right]$$

5 parameters needed to describe the dependence on μ !

What is needed is μ as a function of $N_{part/BX}$ i.e. μ = f(Npart/BX) but the expression above cannot be inverted analytically.

Measuring μ by hit counting

Most detectors do not measure particles. If hits are measured instead without any requirement on a minimum number of hits in each detector there is no longer a linear relationship between μ and $N_{hits/BX}$:

$$N_{hits/BX} = N_{tubes}\left[1 - \left(1 - \frac{N_{hits/pp}}{N_{tubes}}\right)^{\mu}\right] \approx \mu\, N_{hits/pp} \quad \text{for } \mu << 1$$

$$\mu = \frac{\ln\left(1 - \frac{N_{hits/BX}}{N_{tubes}}\right)}{\ln\left(1 - \frac{N_{hits/pp}}{N_{tubes}}\right)} \qquad L = \frac{f_{BX}}{\sigma_{in}} \times \frac{\ln\left(1 - \frac{N_{hits/BX}}{N_{tubes}}\right)}{\ln\left(1 - \frac{N_{hits/pp}}{N_{tubes}}\right)}$$

N_{tubes} is here the number of active detector elements (30 for LUCID and 32 for MBTS) and $N_{hits/pp}$ is the average number of hits per bunch crossing when there is exactly one interaction in the events (1.2 for LUCID at 14 TeV).

Hit counting with coincidence

In order to reduce background it is an advantage to do also hit counting while requiring at least one particle in each detector.

The relationship between the number of hits and particles:

$$N_{part} = - N_{tubes} \times \ln\left(1 - \frac{N_{hits}}{N_{tubes}}\right)$$

can be used together with the relationship between μ and the number of particles

$$N_{part/BX} = 2\mu N^{A}_{part/pp}\,(1 - e^{-\mu\varepsilon^{A}}) - \mu N^{Coinc}_{part/pp}\,(1 - 2e^{-\mu\varepsilon^{A}}) \quad \text{if } N^{A}_{part/pp} = N^{C}_{part/pp} \text{ and } \varepsilon^{A} = \varepsilon^{C}$$

to obtain a relationship between N_{hits} and μ:

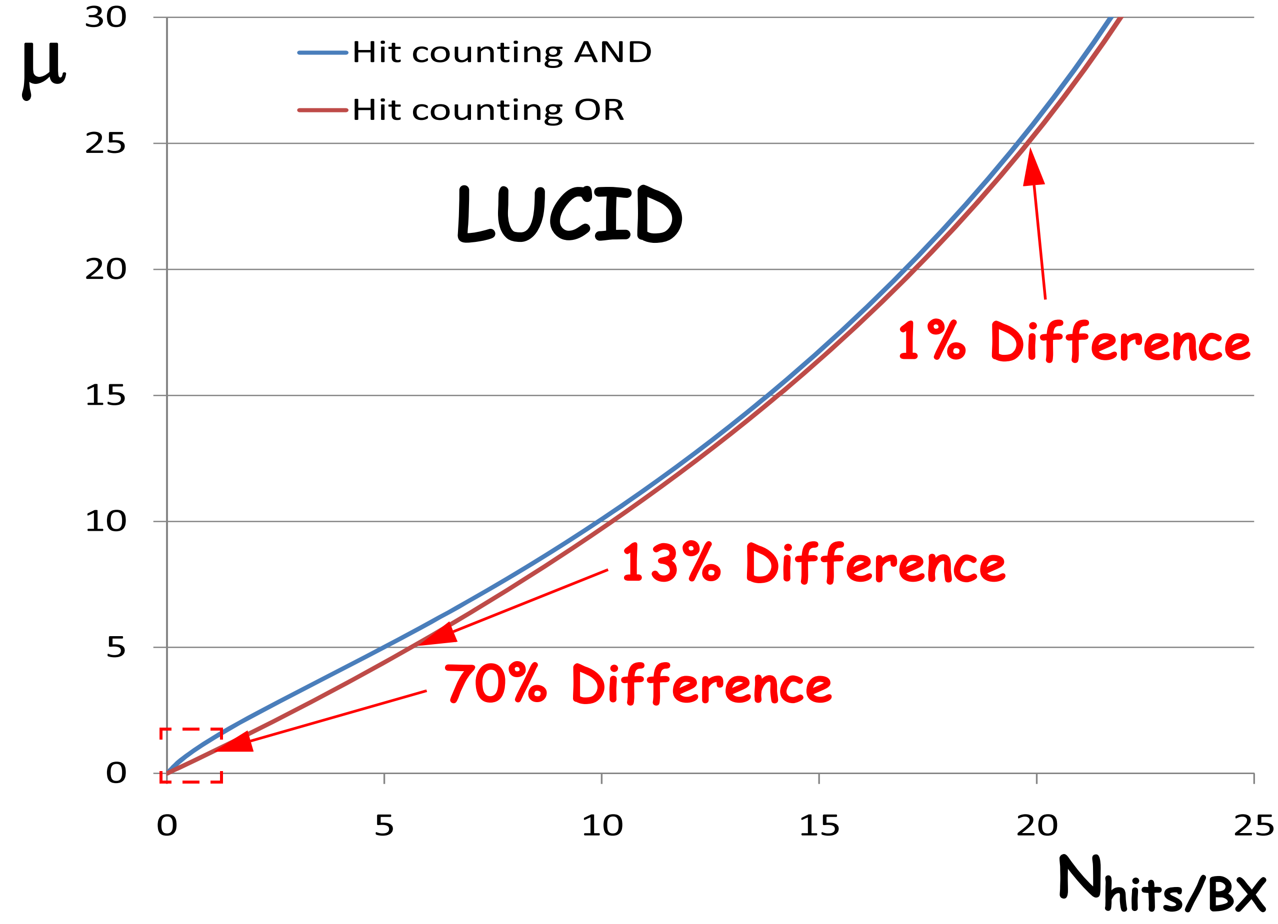
$$\boxed{N_{hits} = N_{tubes}\left[1 - e^{-(2\mu N^{A}_{part/pp}\,(1 - e^{-\mu\varepsilon^{A}}) - \mu N^{Coinc}_{part/pp}\,(1 - 2e^{-\mu\varepsilon^{A}}))/N_{tubes}}\right]}$$

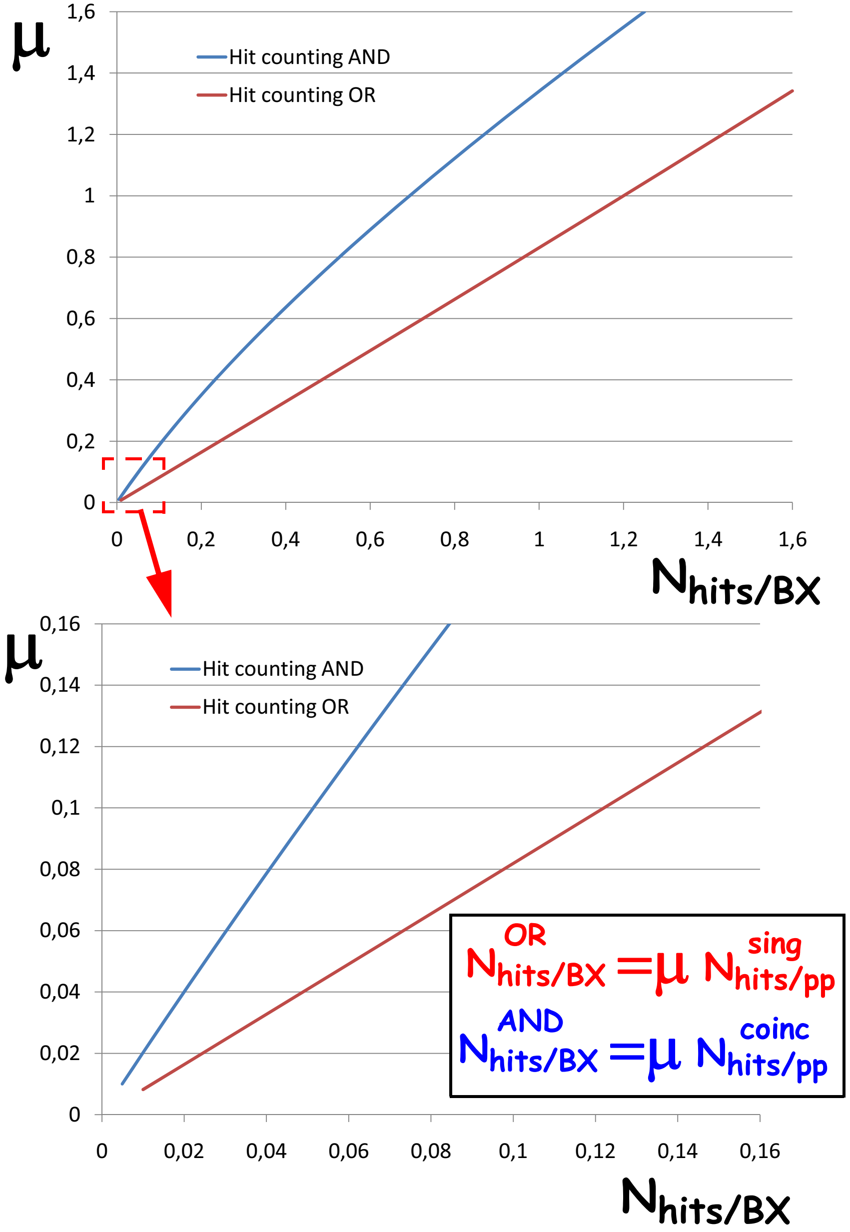
However, there is no way of analytically express μ as a function of N_{hits} in this case !

Hit counting - AND versus OR

$$N^{AND}_{hits} = N_{tubes}\left[1 - e^{-(2\mu\ N^{A}_{part/pp}\,(1 - e^{-\mu\varepsilon^{A}}) - \mu\ N^{Coinc}_{part/pp}\,(1 - 2e^{-\mu\varepsilon^{A}}))/N_{tubes}}\right]$$

$$N^{OR}_{hits/BX} = N_{tubes}\left[1 - (1 - N_{hits/pp}/N_{tubes})^{\mu}\right]$$





$$N^{OR}_{hits/BX} = \mu\ N^{sing}_{hits/pp}$$

$$N^{AND}_{hits/BX} = \mu\ N^{coinc}_{hits/pp}$$

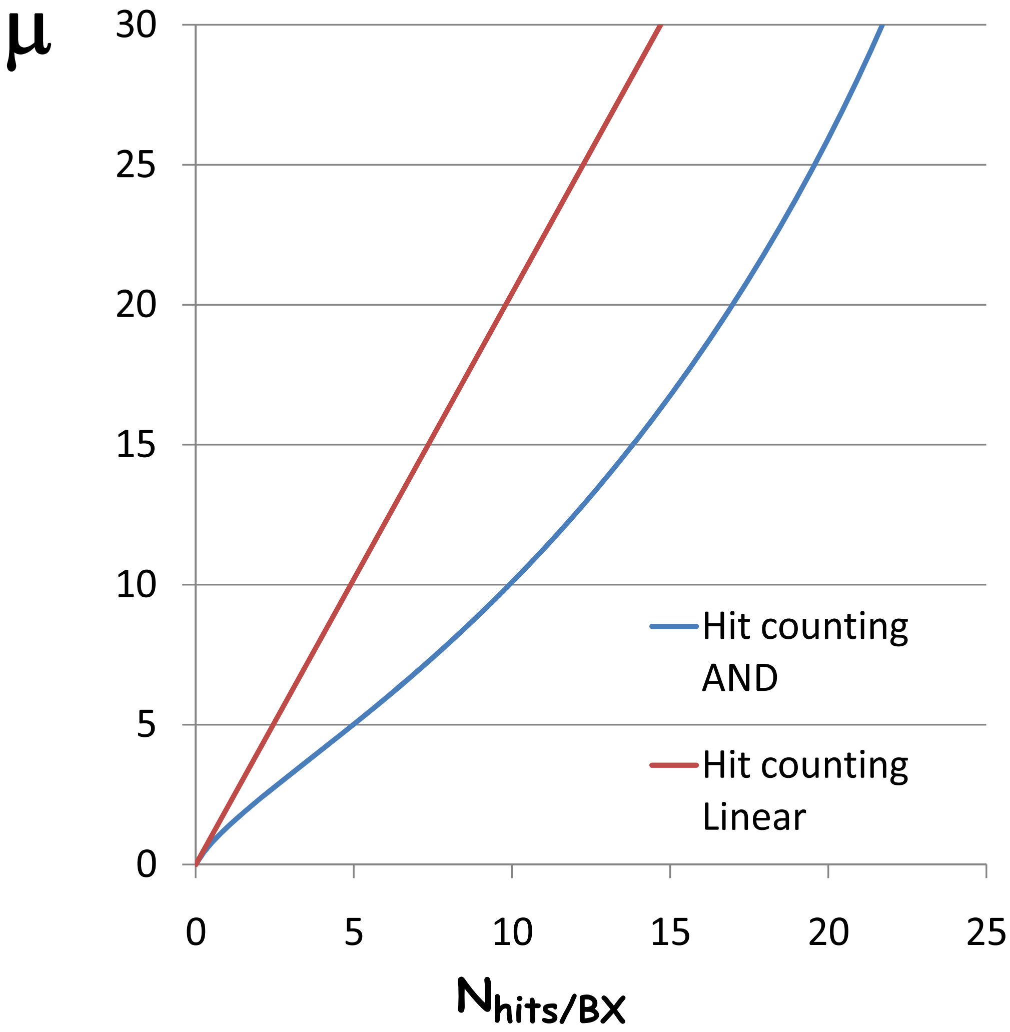
The dependence of μ on N_{hits} is only linear for small μ.

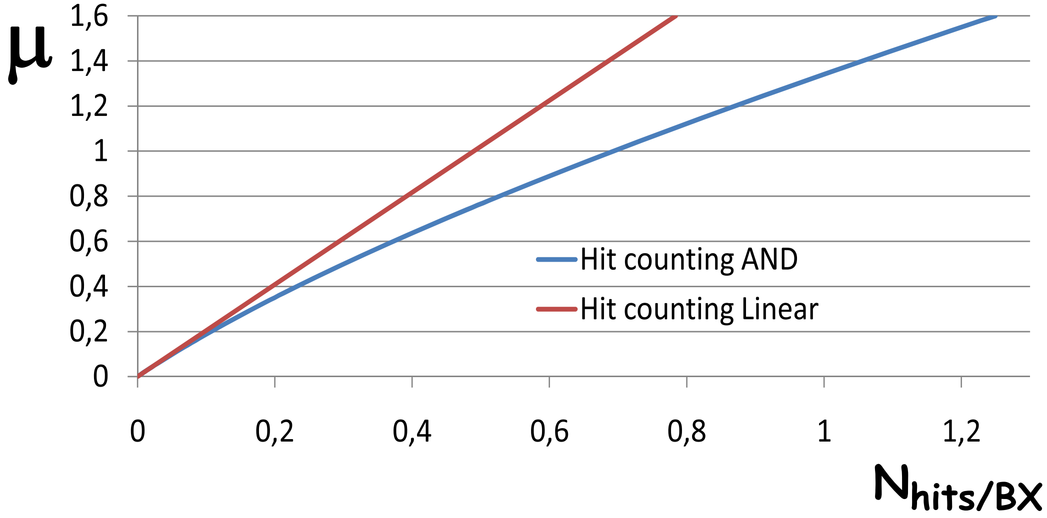
The largest difference between AND and OR is at low μ.

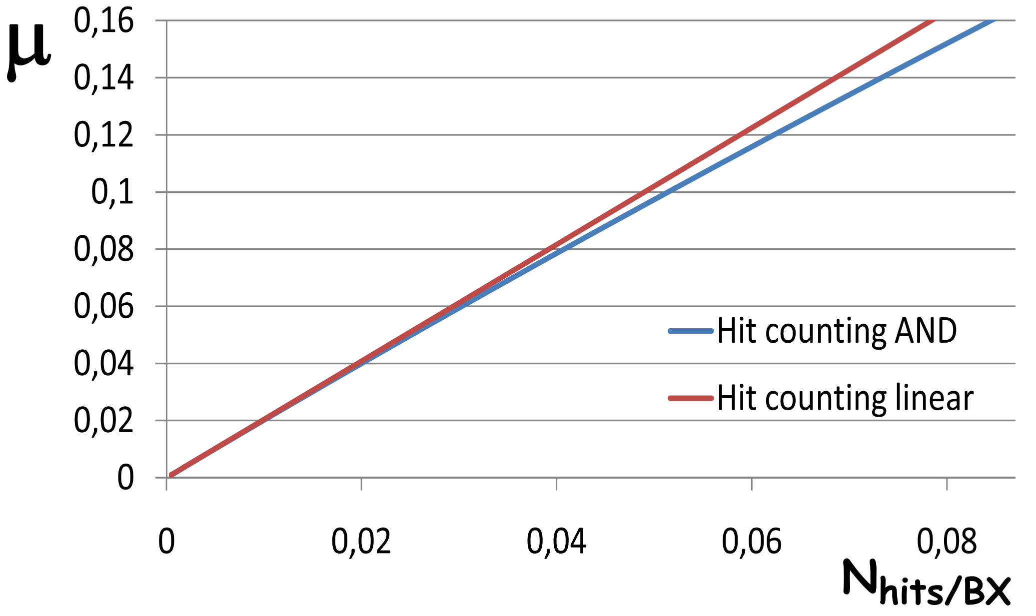
Hit counting - linear extrapolation

$$N^{AND}_{hits} = N_{tubes}\left[1 - e^{-(2\mu\ N^{A}_{part/pp}\,(1 - e^{-\mu\varepsilon^{A}}) - \mu\ N^{Coinc}_{part/pp}\,(1 - 2e^{-\mu\varepsilon^{A}}))/N_{tubes}}\right]$$

$$N^{AND}_{hits/BX} = \mu\ N^{coinc}_{hits/pp}$$







Event counting

The simplest quantity to measure is the number of events per bunch crossing.

Different requirements can be made on the signals seen in the two detectors and different system uses different requirement.

Some of these event topologies are not independent with respect to each other.

Probability(Zero-counting-AND) = 1 - Probability(Event-counting-OR)
Probability(Zero-counting-OR) = 1 - Probability(Event-counting-AND)

It is possible to calculate the probability (rate) of any event topology at any μ if three basic parameters (ε_0, ε_1 and ε_2), that describe the probability when there is one pp interaction, are known.

A problem with event counting is that at high μ the event rate tends to saturate and an increase in μ does then not give a significant increase in the event rate.

Event counting

Name	Event type		Propability for 1 pp	Probability for μ interactions
ZERO COUNTING - AND	Hits = 0	Hits = 0	$\varepsilon_0 = 1-\varepsilon_1-\varepsilon_2-\varepsilon_3$	$e^{(\varepsilon_0-1)\mu}$
EVENT COUNTING - XOR - A	Hits ≥ 1	Hits = 0	$\varepsilon_1 = \varepsilon_A - \varepsilon_{coinc}$	$e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0-1)\mu}$
EVENT COUNTING - XOR - C	Hits = 0	Hits ≥ 1	$\varepsilon_2 = \varepsilon_C - \varepsilon_{coinc}$	$e^{(\varepsilon_0+\varepsilon_2-1)\mu} - e^{(\varepsilon_0-1)\mu}$
EVENT COUNTING - AND	Hits ≥ 1	Hits ≥ 1	$\varepsilon_3 = \varepsilon_{coinc}$	$1 - e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0+\varepsilon_2-1)\mu} + e^{(\varepsilon_0-1)\mu}$
EVENT COUNTING - OR	Hits ≥ 1 Hits ≥ 1 Hits = 0	Hits ≥ 1 Hits = 0 Hits ≥ 1	$\varepsilon_{sing} = 1 - \varepsilon_0$	$1 - e^{(\varepsilon_0-1)\mu}$
ZERO COUNTING - OR	Hits = 0 Hits ≥ 1 Hits = 0	Hits = 0 Hits = 0 Hits ≥ 1	-	$e^{(\varepsilon_0+\varepsilon_1-1)\mu} + e^{(\varepsilon_0+\varepsilon_2-1)\mu} - e^{(\varepsilon_0-1)\mu}$
EVENT COUNTING - OR - A	Hits ≥ 1 Hits ≥ 1	Hits ≥ 1 Hits = 0	$\varepsilon_A = 1 - \varepsilon_0 - \varepsilon_2$	$1 - e^{(\varepsilon_0+\varepsilon_2-1)\mu}$
EVENT COUNTING - OR - C	Hits ≥ 1 Hits = 0	Hits ≥ 1 Hits ≥ 1	$\varepsilon_C = 1 - \varepsilon_0 - \varepsilon_1$	$1 - e^{(\varepsilon_0+\varepsilon_1-1)\mu}$

Event counting

Efficiencies for one pp interaction at 14 TeV

A	C		LUCID	BCM	MBTS	ZDC
Hits = 0	*Hits* = 0	ε_0	= 0.442	0.711	0	0.472
Hits ≥ 1	*Hits* = 0	ε_1	= 0.212	0.125	0.004	0.215
Hits = 0	*Hits* ≥ 1	ε_2	= 0.212	0.125	0.004	0.215
Hits ≥ 1	*Hits* ≥ 1	ε_3	= 0.135	0.040	0.992	0.098

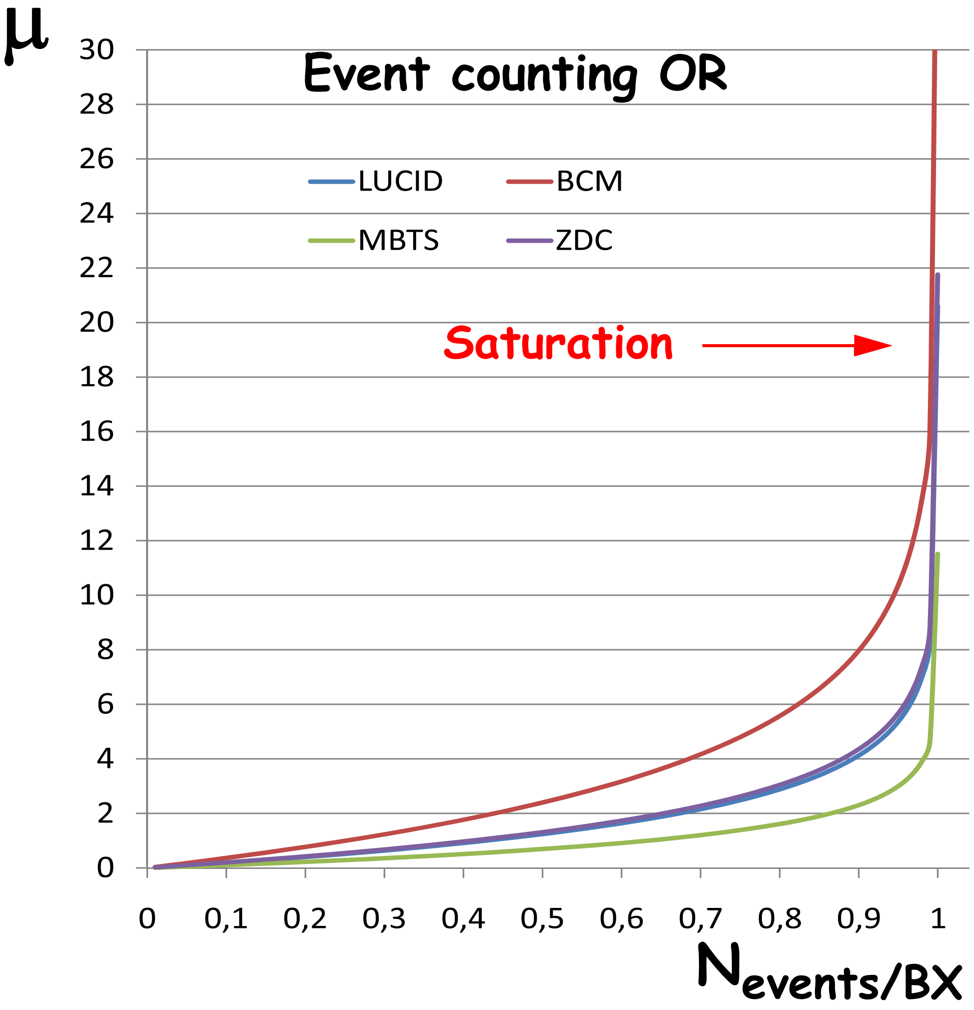
		LUCID	BCM	MBTS	ZDC
ε_{sing}	$= 1 - \varepsilon_0$	= 0.559	0.290	1.000	0.528
ε_A	$= 1 - \varepsilon_0 - \varepsilon_2$	= 0.347	0.165	0.998	0.313
ε_C	$= 1 - \varepsilon_0 - \varepsilon_1$	= 0.347	0.165	0.998	0.313
ε_{coinc}	$=1-\varepsilon_0-\varepsilon_1-\varepsilon_2$	= 0.135	0.040	0.992	0.098

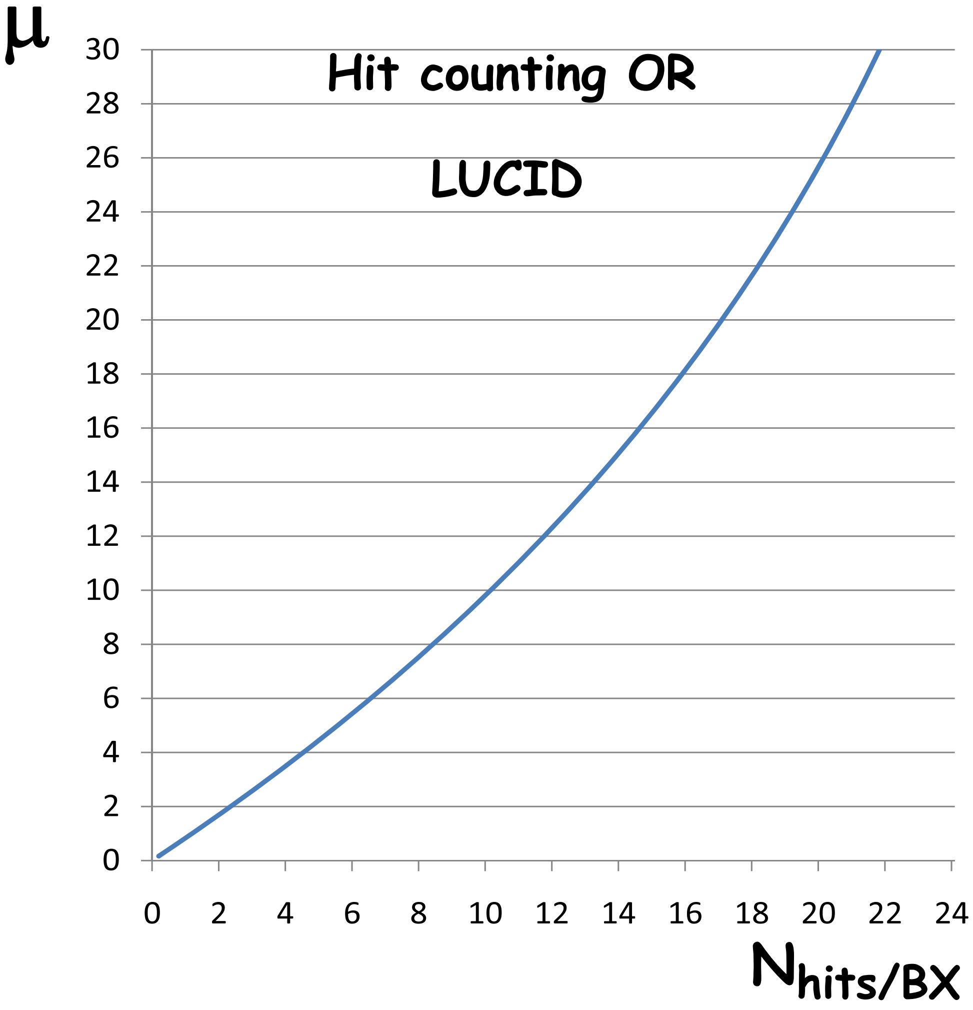
LUCID: GEANT3 + PHOJET (non-diff + diff, 16 + 16 tubes, cut = 50 p.e.)
BCM: GEANT4 + PYTHIA (non-diff + diff, 4 + 4 modules)
MBTS: GEANT4 + PYTHIA (only non-diff, 16 + 16 sectors, cut = 40 mV)
ZDC: ATL-LUM-INT-2009-002, $\varepsilon_A = \varepsilon_C = \sqrt{\varepsilon_{coinc}}$

Event versus hit counting

$N^{OR}_{events/BX} = 1 - e^{-\varepsilon_{sing}\mu}$

$N^{OR}_{hits/BX} = N_{tubes}\left[1 - \left(1 - N_{hits/pp} / N_{tubes}\right)^{\mu}\right]$





Conclusions:

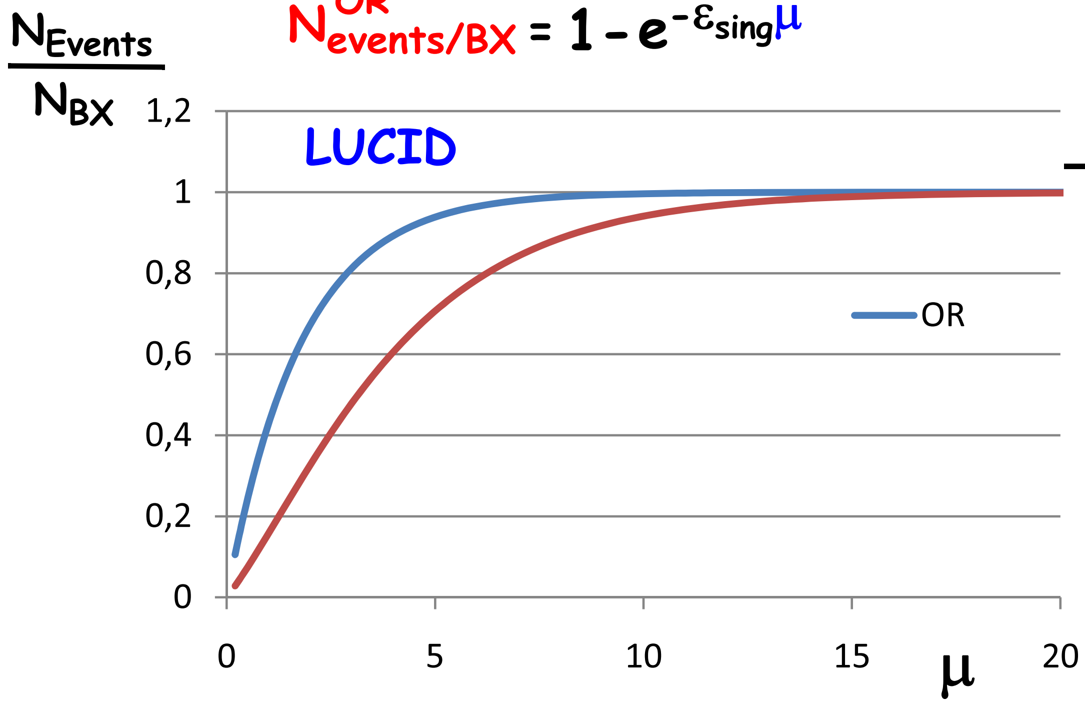
Hit counting suffers less from saturation than event counting.

A small acceptance gives less saturation (but less statistics).

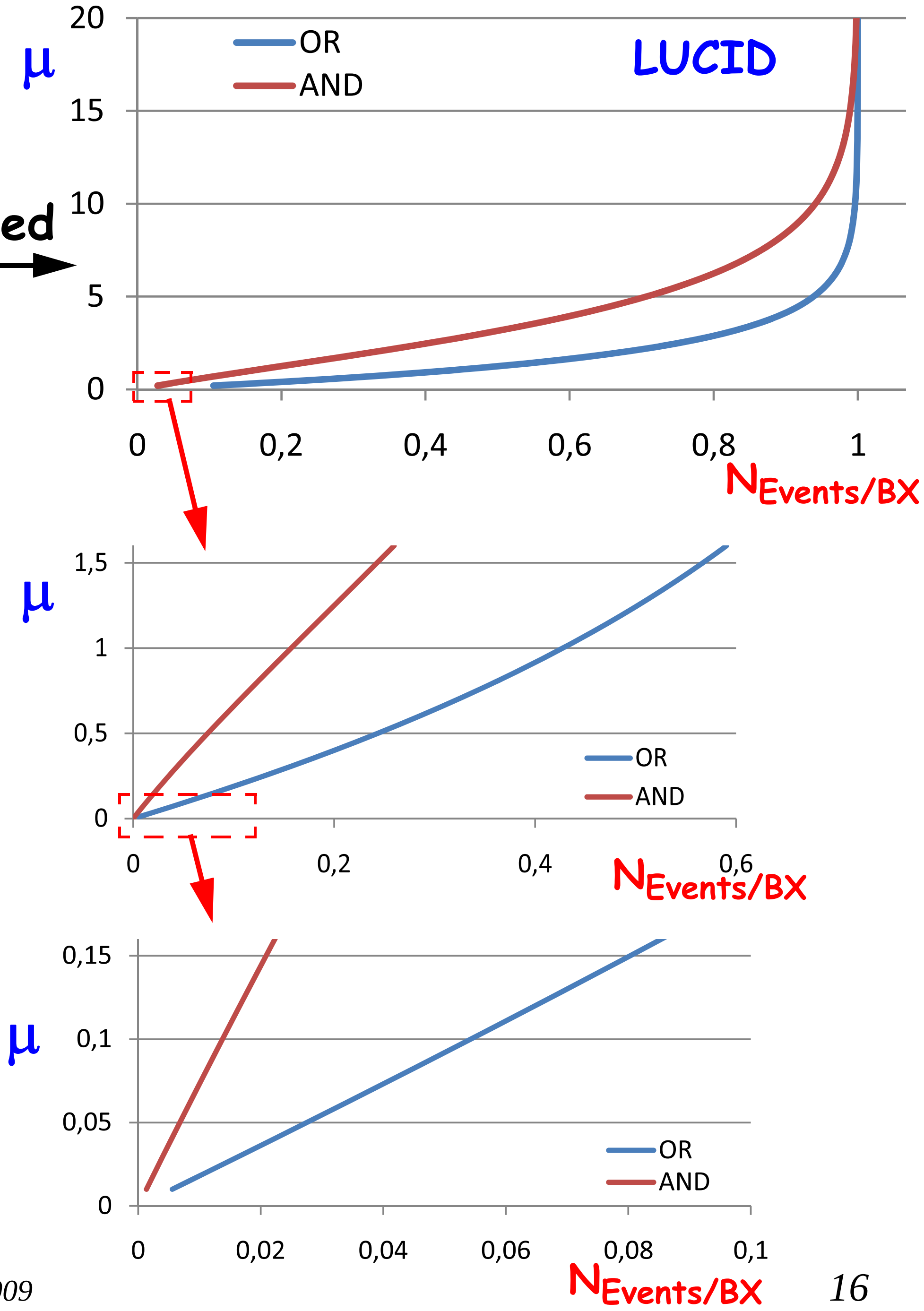
Event counting - AND versus OR

$N^{AND}_{events/BX} = 1 - e^{-\varepsilon_A \mu} - \bar{e}^{\varepsilon_C \mu} + e^{-\varepsilon_{sing} \mu}$

$N^{OR}_{events/BX} = 1 - e^{-\varepsilon_{sing} \mu}$



inverted



Conclusions:

OR counting saturates before AND counting

OR counting is described by 1 parameter

AND counting is described by 3 parameters

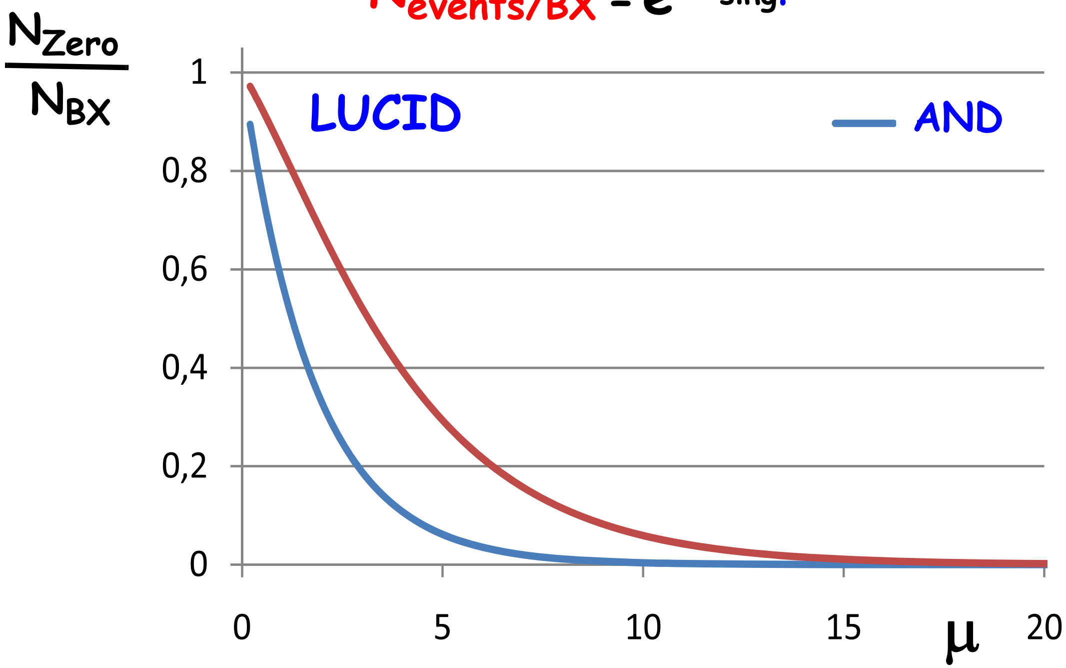
If $\mu << 1$: $N_{OR/BX} \approx \varepsilon_{Sing}\, \mu$

$N_{AND/BX} \approx \varepsilon_{Coin}\, \mu$

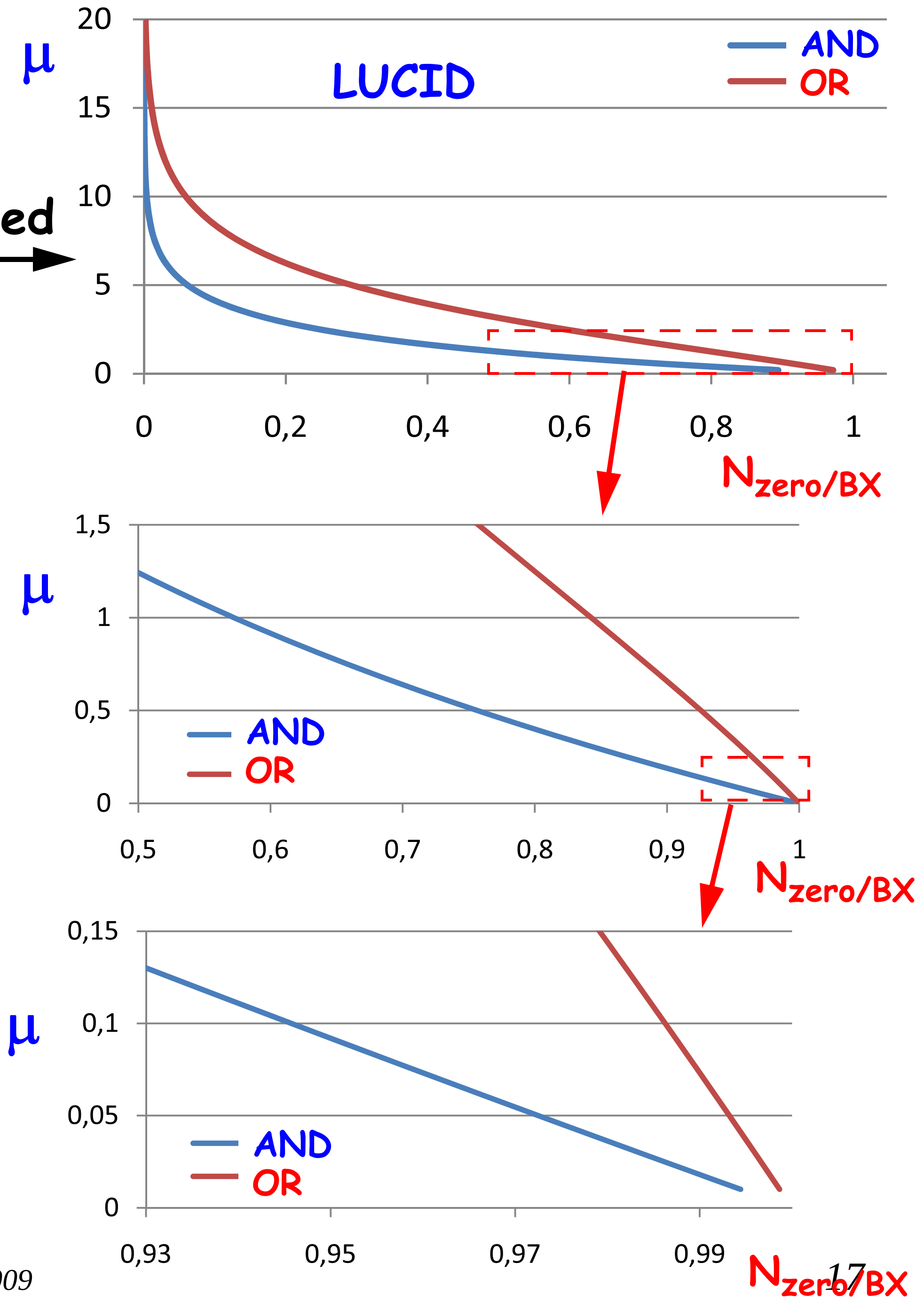
Zero counting - AND versus OR

$$N^{OR}_{zero/BX} = e^{-\varepsilon_A \mu} + e^{-\varepsilon_C \mu} - e^{-\varepsilon_{sing} \mu}$$

$$N^{AND}_{events/BX} = e^{-\varepsilon_{sing} \mu}$$



inverted



Conclusions:

AND counting saturates before OR counting

AND counting is described by 1 parameter

OR counting is described by 3 parameters

If μ << 1:

$$N_{AND/BX} \approx 1 - \varepsilon_{Sing}\, \mu$$

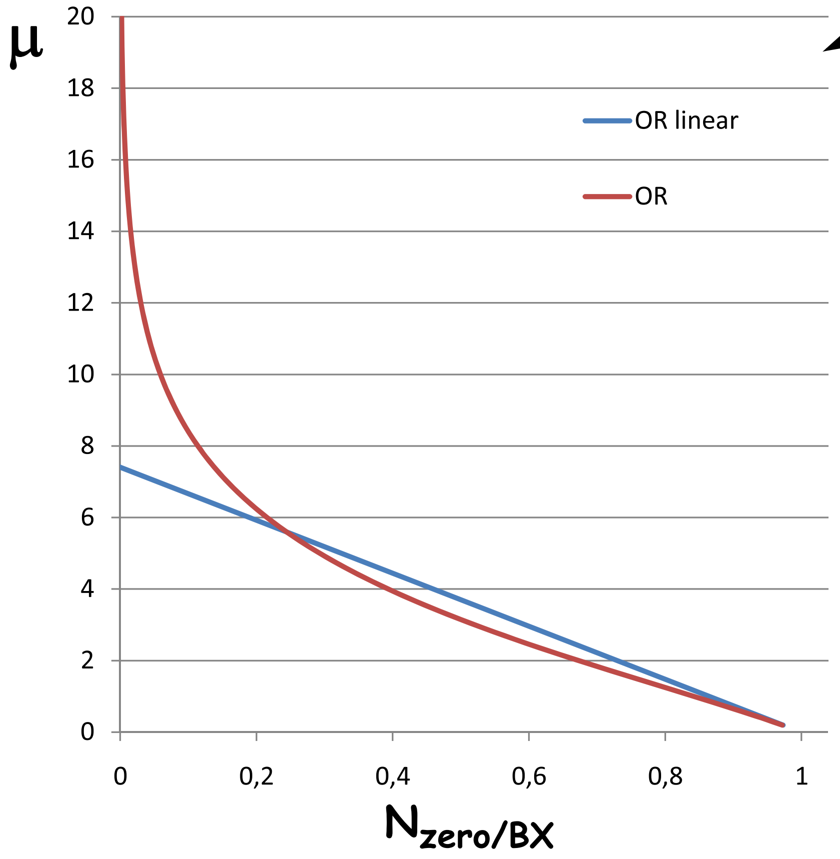
$$N_{OR/BX} \approx 1 - \varepsilon_{Coin}\, \mu$$

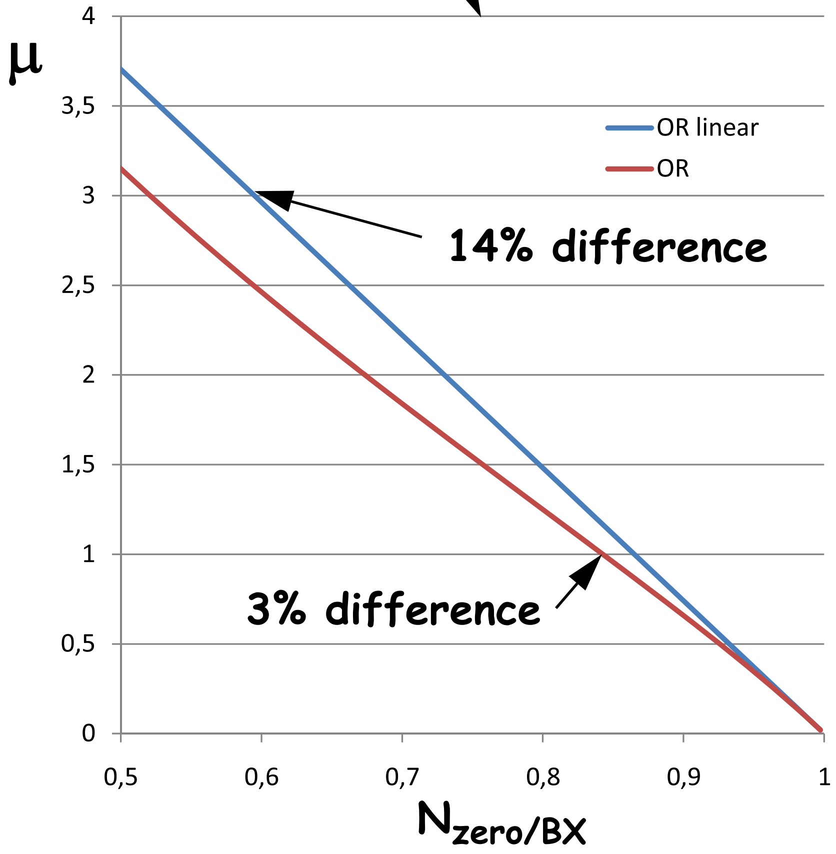
Zero counting - linear extrapolation

Compare Zero-OR counting with a linear extrapolation from the low μ limit:

$$N^{OR}_{zero/BX} = e^{-\varepsilon_A\mu} + e^{-\varepsilon_C\mu} - e^{-\varepsilon_{sing}\mu}$$

$$N^{OR}_{zero/BX} = 1 - \varepsilon_{Coin}\,\mu$$





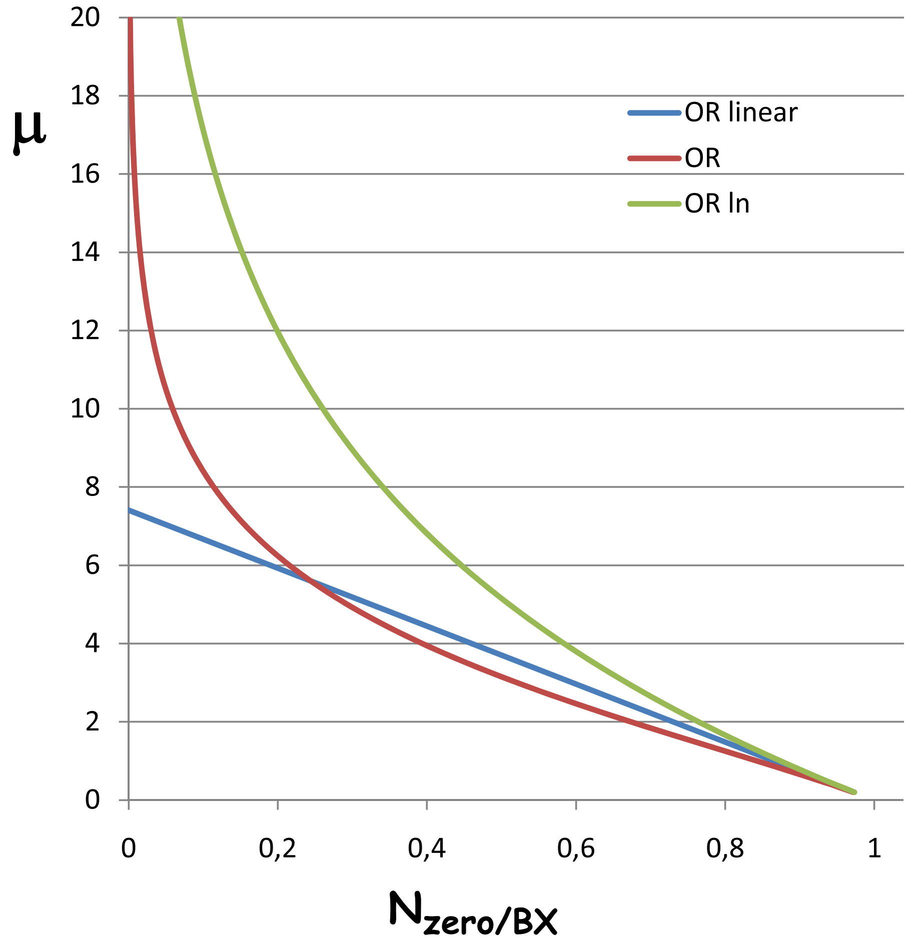
Zero counting - more extrapolation

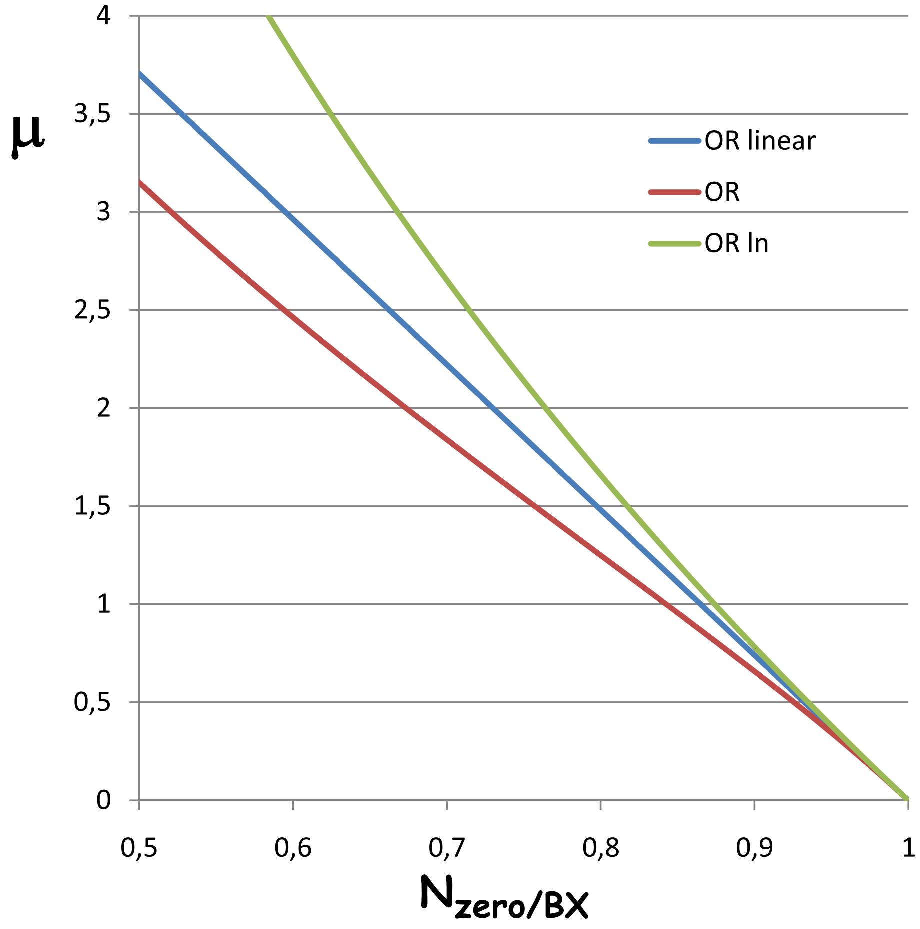
Compare Zero-OR counting with a linear extrapolation from the low μ limit and an exponential extrapolation:

$N^{OR}_{zero/BX} = e^{-\varepsilon_A\mu} + \bar{e}^{\varepsilon_C\mu} - e^{-\varepsilon_{sing}\mu}$

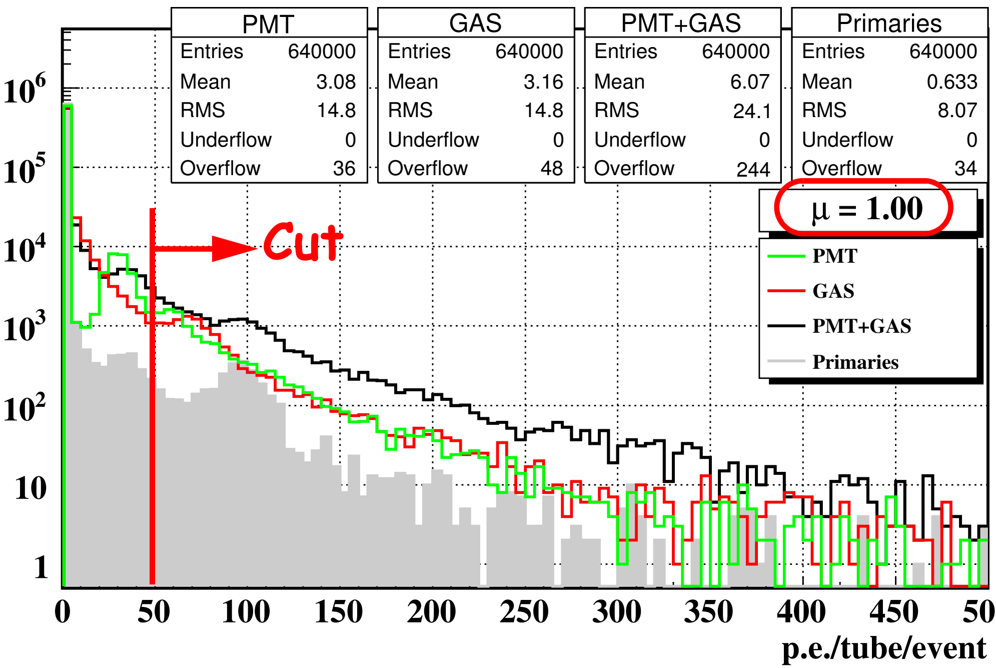
$N^{OR}_{zero/BX} = e^{-\varepsilon_{Coin}\mu}$

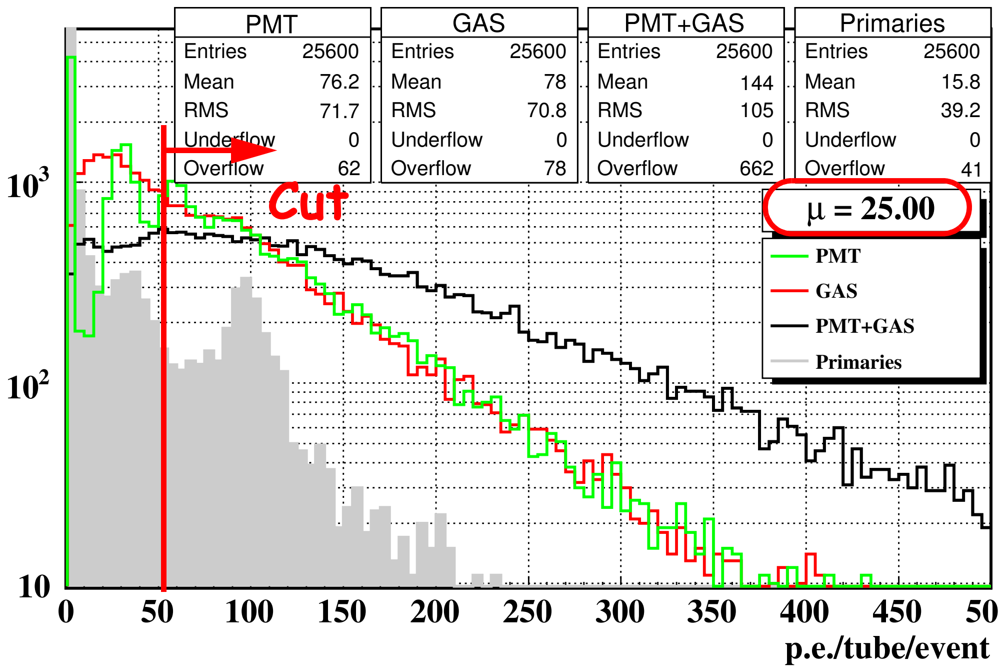
$N^{OR}_{zero/BX} = 1 - \varepsilon_{Coin}\,\mu$





Migration

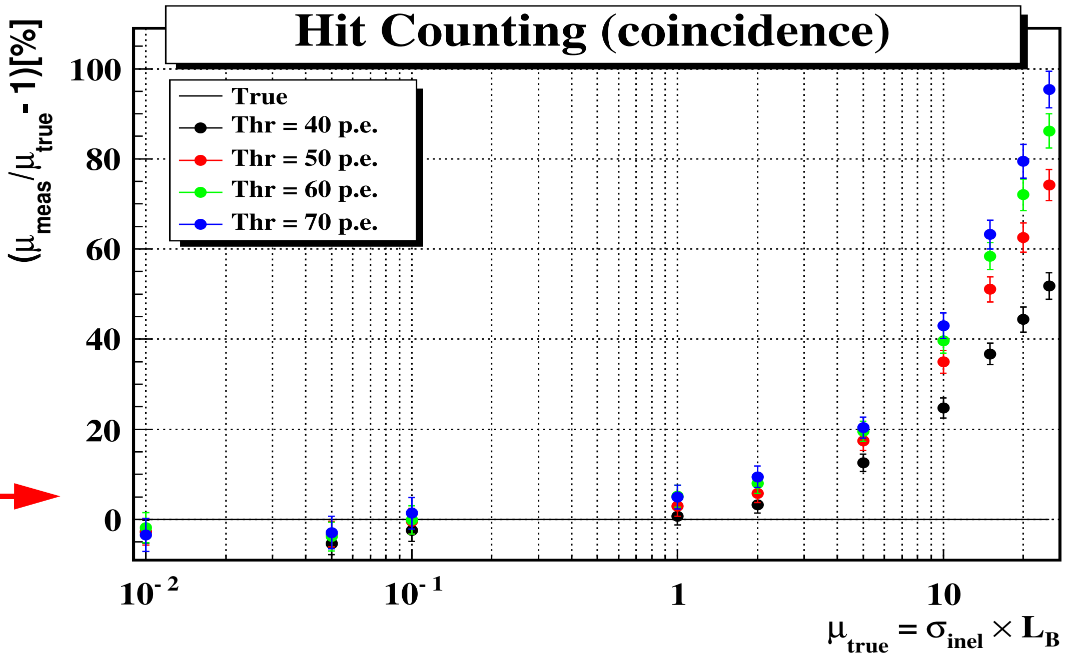




Migration:

When events are piled up at large μ, particles that give a small signal combines with other small signals to give a hit above the threshold.

The effect in LUCID is large ⟶

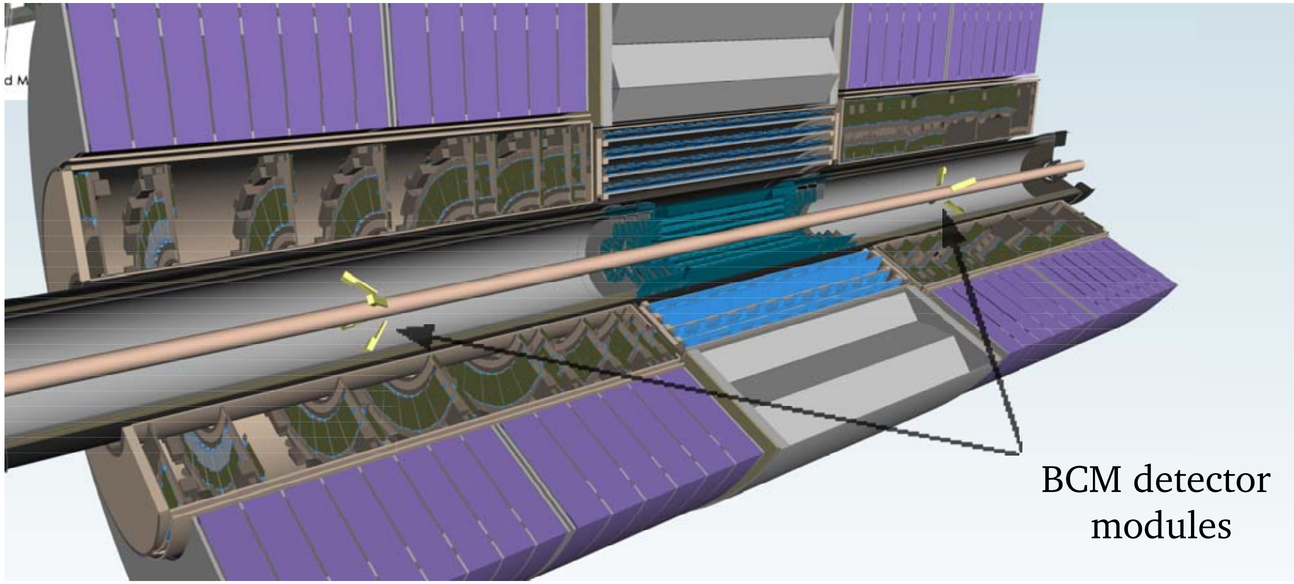


The Beam Condition Monitor

The BCM has four modules on each side.

2+2 modules are at present read out separately from the other 2+2 modules.

The detector will do event counting and not hit counting. Since the detector read-out is split in two one can make two independent measurements for each methods.



		Function tested with MC data:	Function inverted:
Zero-counting-AND:	$\mu = \dfrac{\ln\left(\dfrac{N_{00}}{N_{BX}}\right)}{\varepsilon_0 - 1}$	YES	YES
Event-counting-AND:	$\dfrac{N_{AND}}{N_{BX}} = 1 - \overset{-\varepsilon_C}{\overset{\swarrow}{e^{(\varepsilon_0+\varepsilon_1-1)\mu}}} - \overset{-\varepsilon_A}{\overset{\downarrow}{e^{(\varepsilon_0+\varepsilon_2-1)\mu}}} + \overset{-\varepsilon_{sing}}{\overset{\searrow}{e^{(\varepsilon_0-1)\mu}}}$	YES	NO
Event-counting-XOR Side A:	$\dfrac{N_A}{N_{BX}} = e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0-1)\mu}$	NO	NO
Event-counting-XOR Side C:	$\dfrac{N_C}{N_{BX}} = e^{(\varepsilon_0+\varepsilon_2-1)\mu} - e^{(\varepsilon_0-1)\mu}$	NO	NO

The Beam Condition Monitor

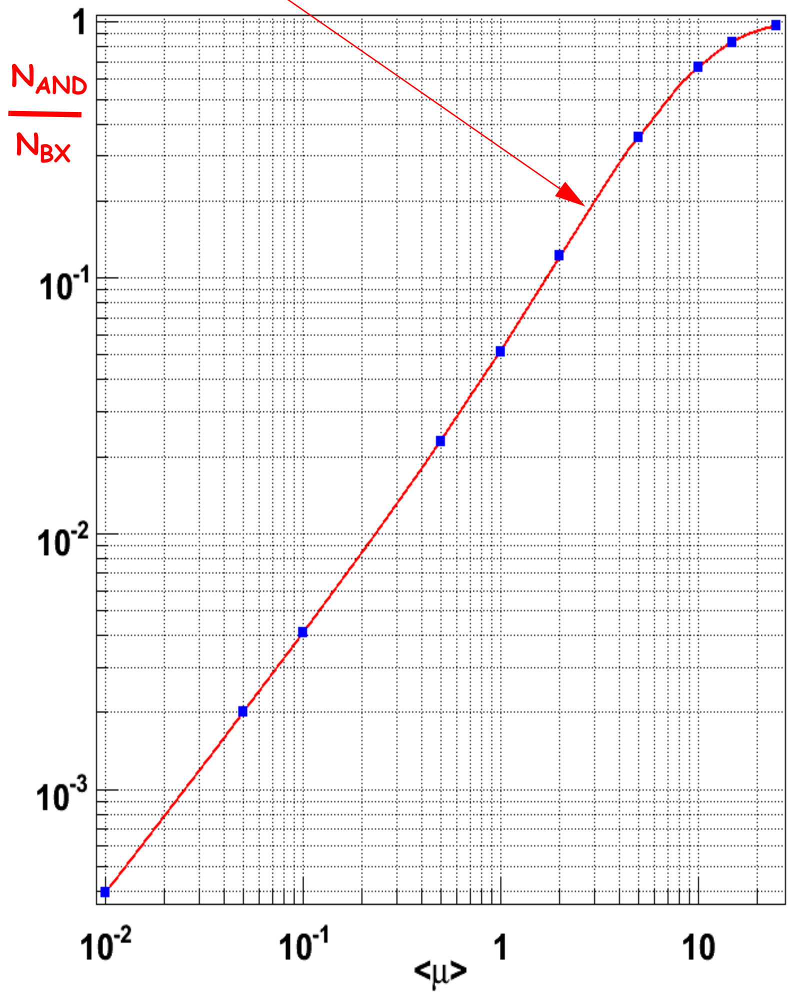
The BCM has so far only been studied with 14 TeV PYTHIA/GEANT4 events and assuming a read-out of 4 modules on each side.

Efficiency

A	C	
Hits = 0	*Hits = 0*	$\varepsilon_0 = 0.711$
Hits ≥ 1	*Hits = 0*	$\varepsilon_1 = 0.125$
Hits = 0	*Hits ≥ 1*	$\varepsilon_2 = 0.125$
Hits ≥ 1	*Hits ≥ 1*	$\varepsilon_3 = 0.040$

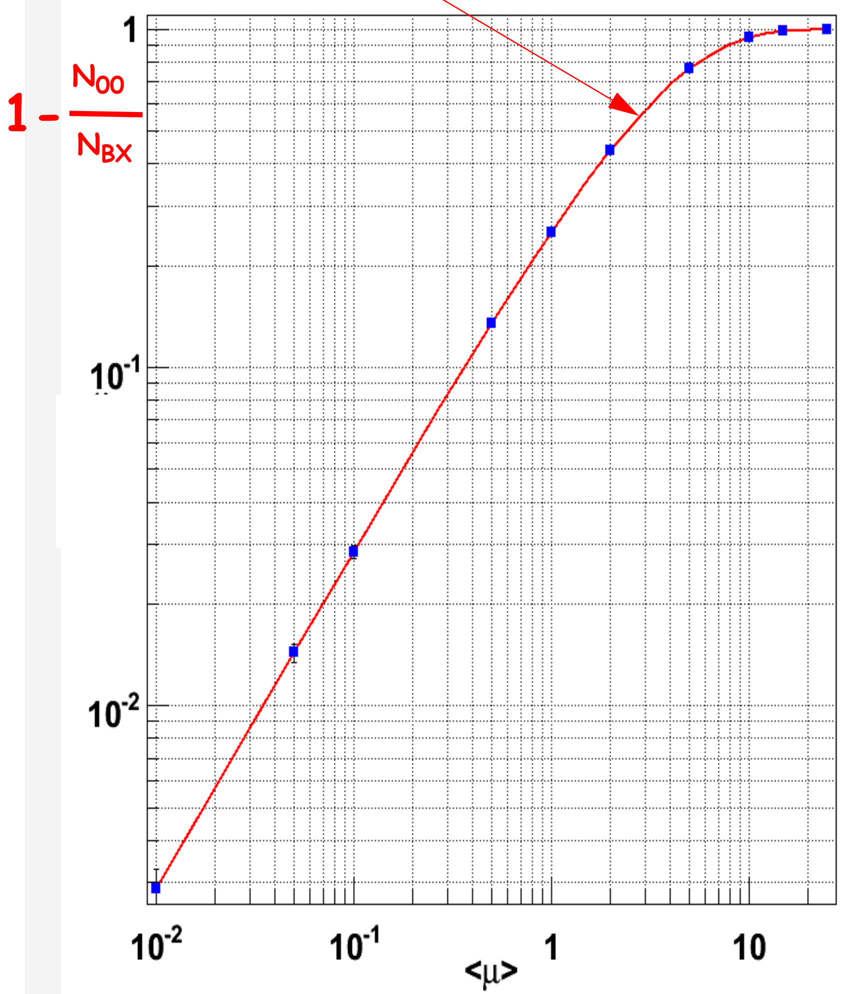
Event-counting-AND:

$$\frac{N_{AND}}{N_{BX}} = 1 - e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0+\varepsilon_2-1)\mu} + e^{(\varepsilon_0-1)\mu}$$



Zero-counting-AND:

$$1 - \frac{N_{00}}{N_{BX}} = 1 - e^{(\varepsilon_0-1)\mu}$$



The Beam Condition Monitor

What needs to be done ?

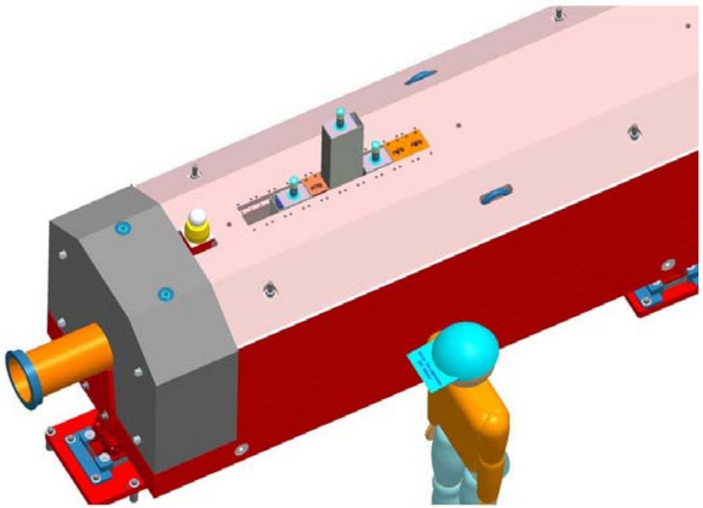
The Event-Counting-AND formula needs to be inverted.

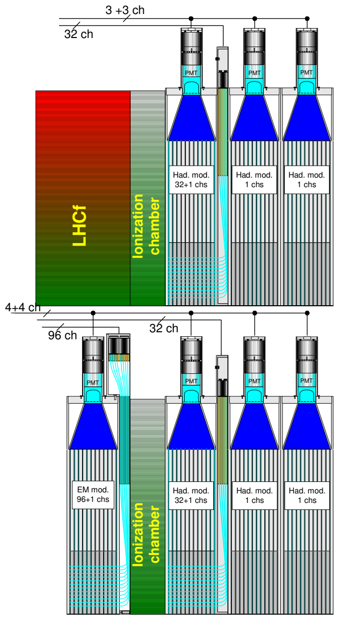
The Event-Counting-XOR formula needs to be tested with simulated events and inverted (perhaps inclusive OR would be easier ?)

The efficiencies needs to be calculated at lower energies than 14 TeV.

The Zero Degree Calorimeter

The ZDC has two calorimeters that will measure the total energy. A cut will be made on this energy and three rates will be measured:





ZDC12Rate: Inclusive single rate on Side 12

ZDC81Rate: Inclusive single rate on Side 81

ZDCcoincRate: Coincidence rate

The methods that will be used are:

Event-counting-AND:

$$\frac{N_{AND}}{N_{BX}} = 1-e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0+\varepsilon_2-1)\mu} + e^{(\varepsilon_0-1)\mu} = \frac{\text{ZDCcoincRate}}{\text{BX rate}}$$

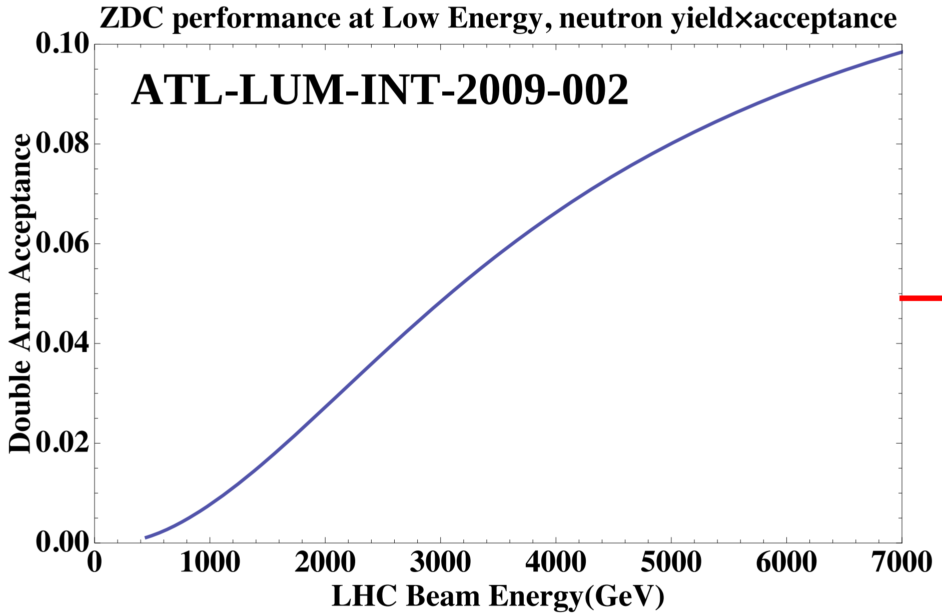
Event-counting-OR Side A:

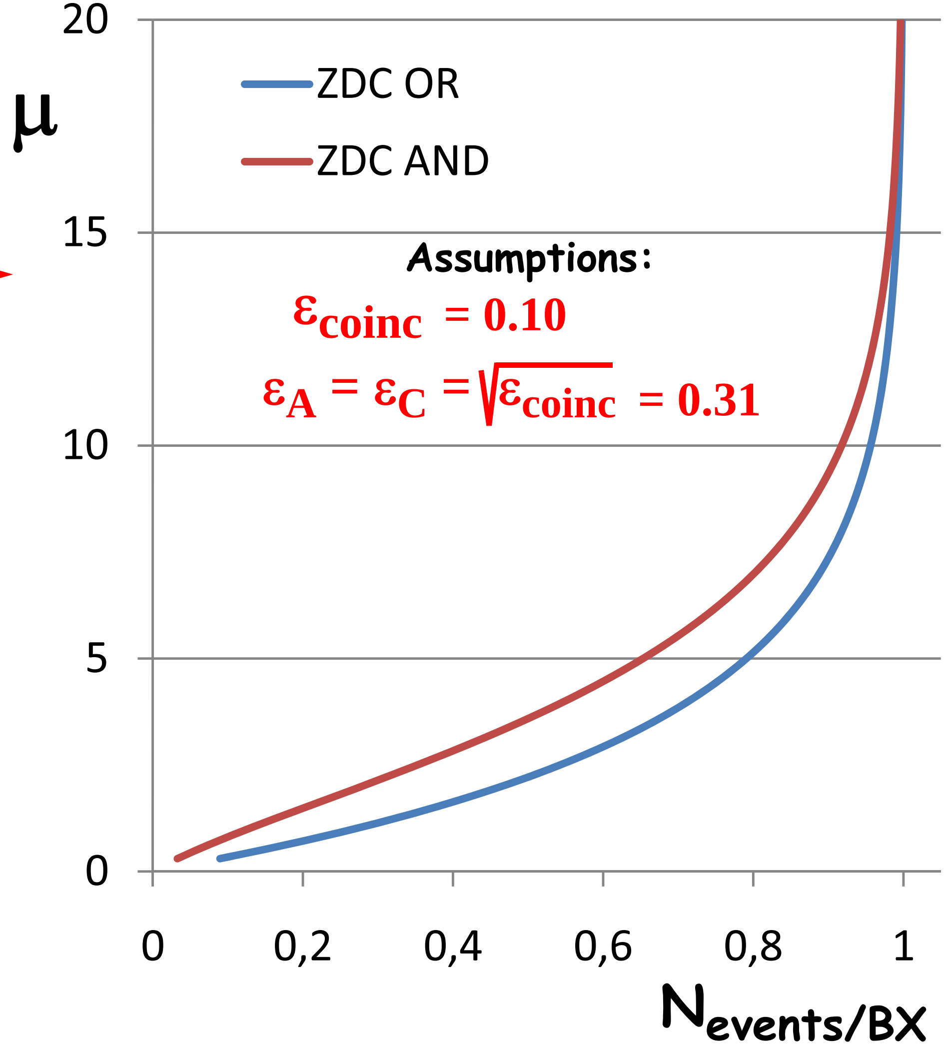
$$\frac{N_A}{N_{BX}} = 1 - e^{(\varepsilon_0+\varepsilon_2-1)\mu} = \frac{\text{ZDC12Rate}}{\text{BX rate}} \qquad \mu = \frac{\ln\left(1-\frac{\text{ZDC12Rate}}{\text{BX rate}}\right)}{\varepsilon_0+\varepsilon_2-1}$$

Event-counting-OR Side C:

$$\frac{N_C}{N_{BX}} = 1 - e^{(\varepsilon_0+\varepsilon_1-1)\mu} = \frac{\text{ZDC81Rate}}{\text{BX rate}} \qquad \mu = \frac{\ln\left(1-\frac{\text{ZDC81Rate}}{\text{BX rate}}\right)}{\varepsilon_0+\varepsilon_1-1}$$

The Zero Degree Calorimeter





Assumptions:

$\varepsilon_{coinc} = 0.10$

$\varepsilon_A = \varepsilon_C = \sqrt{\varepsilon_{coinc}} = 0.31$

What about migration ? Accidentals ?

A simulation is needed !

The Zero Degree Calorimeter

What needs to be done ?

A simulation of the detector is badly needed.

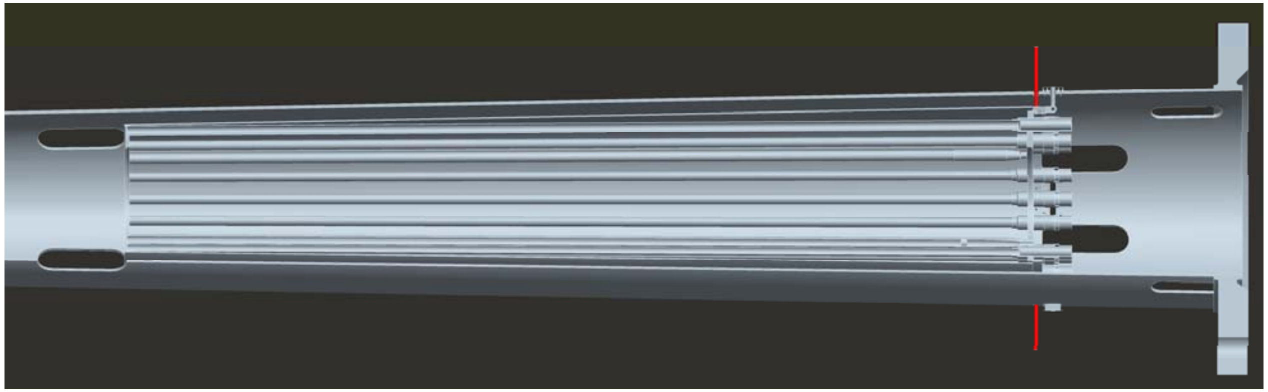
The probability functions have to be tested with simulated data.

Functions for μ = f(ZDC rate) have to be constructed at various energies.

LUCID

LUCID has 15 working Cherenkov tubes in each detector.

The signals are discriminated and provide a hit pattern that are used to do four measurements.



Zero-counting-AND, Zero-counting-OR, Hit-counting-AND, Hit-counting-OR.

Monte Carlo studies have shown that none of the probability functions describe the Monte Carlo data sufficiently well. The reason for this is migration which cannot be described in these functions.

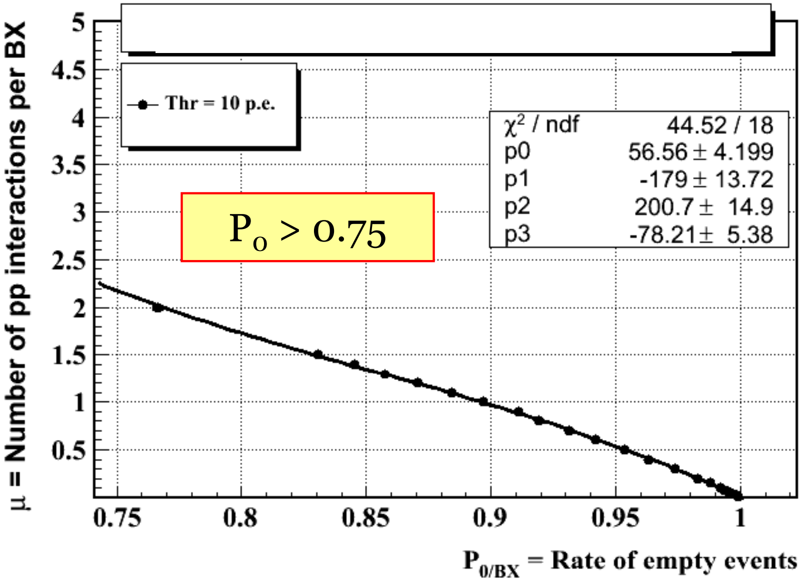
LUCID plots μ as a function of the probability (P) of events or hits and fit a polynomial function so that μ can be expressed as

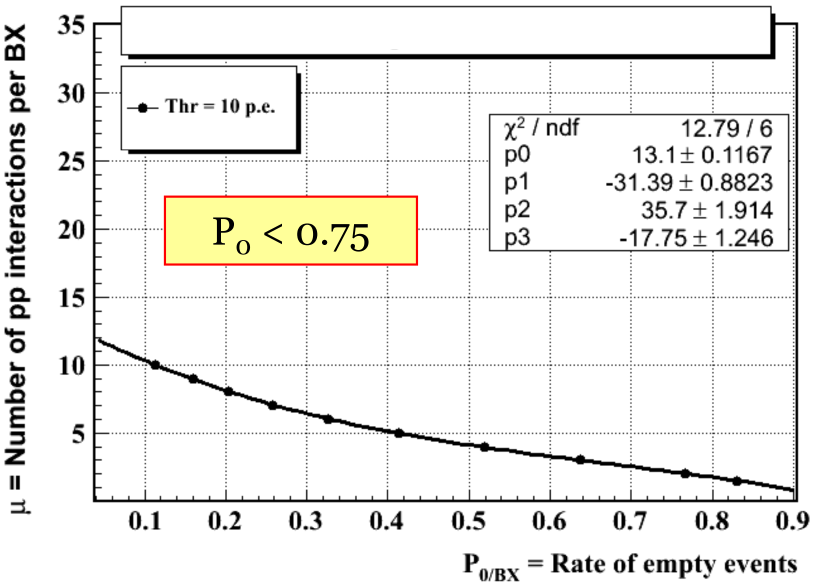
$\mu = p_0 + p_1 P + p_2 P^2 + p_3 P^3$ where $P = \frac{N_{00}}{N_{BX}}$ or $\frac{N_0}{N_{BX}}$ or $\frac{N_{hits}}{N_{BX}}$ and p_0, p_1, p_3 are constants.

Sometimes the fit is done in two regions of P in order to get a good agreement between the fit and the Monte Carlo data.

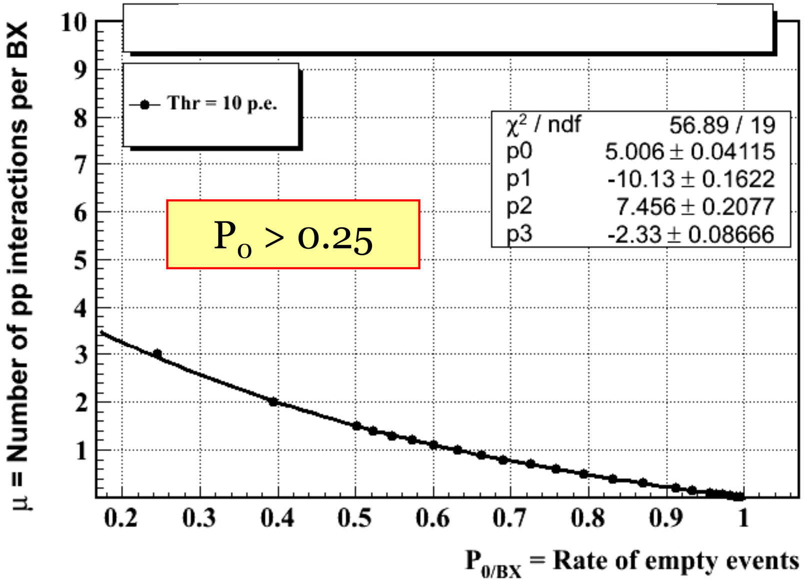
LUCID 900 GeV

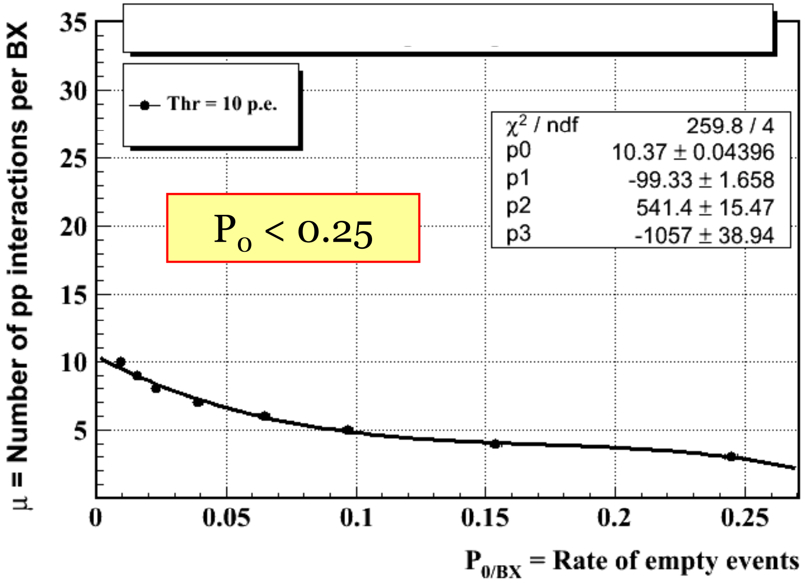
Zero counting (OR)





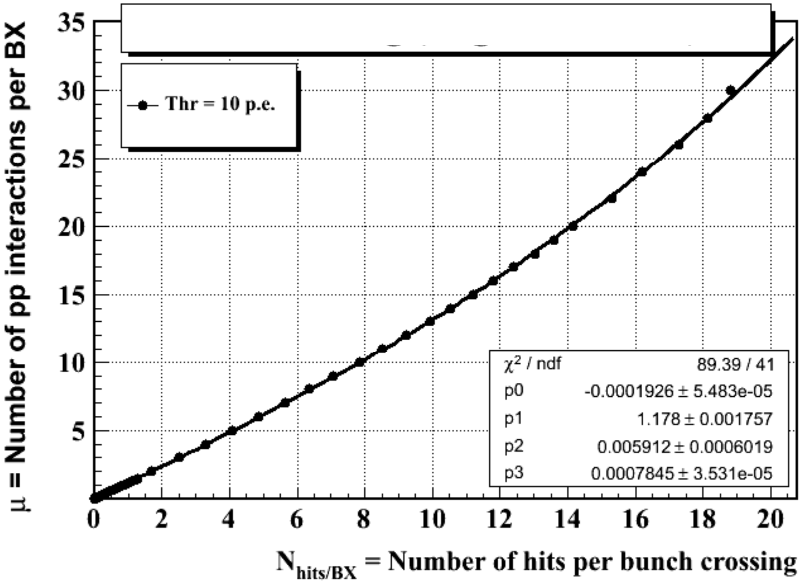
Zero counting (AND)



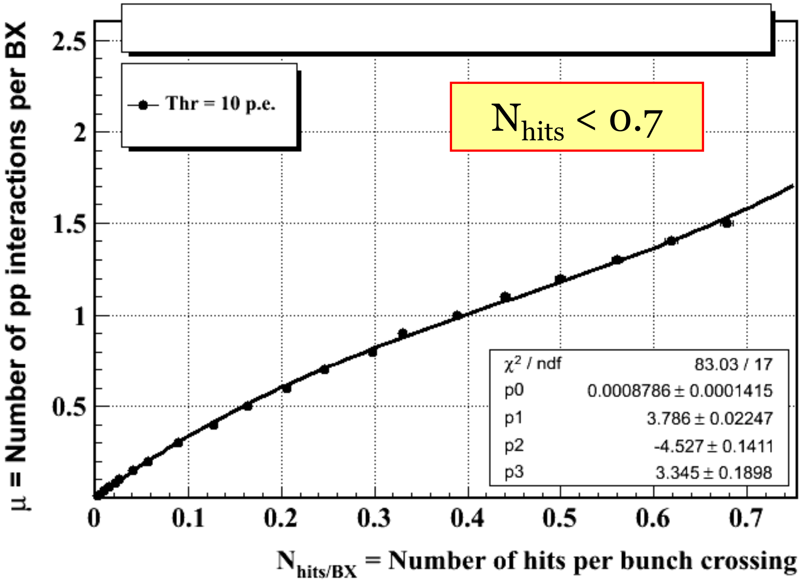


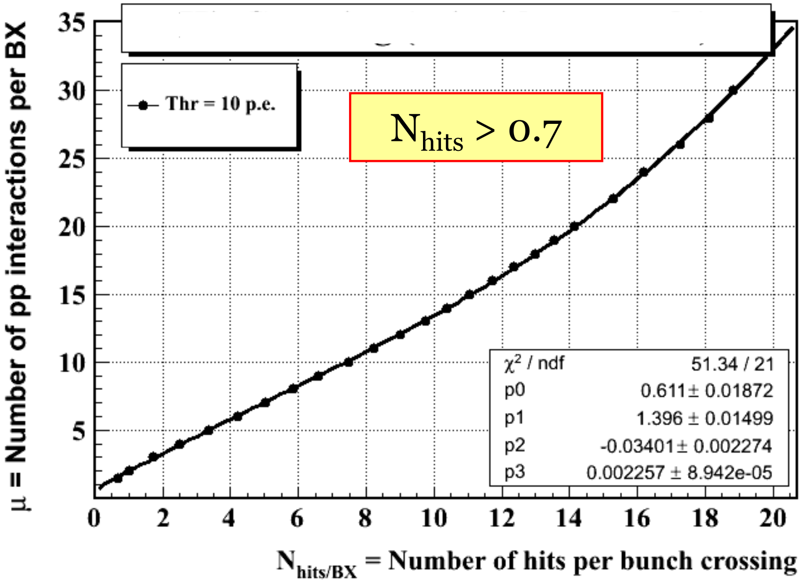
LUCID 900 GeV

Hit counting (OR)



Hit counting (AND)





Low μ approximation for LUCID at 0.9 TeV

$$N^{OR}_{zero/BX} = e^{-\varepsilon_A\mu} + e^{-\varepsilon_C\mu} - e^{-\varepsilon_{sing}\mu} = e^{-\varepsilon_{coin}\mu} = 1 - \varepsilon_{coin}\,\mu$$

$$N^{AND}_{events/BX} = e^{-\varepsilon_{sing}\mu} = 1 - \varepsilon_{sing}\,\mu$$

$$\mu = (1 - N^{OR}_{zero/BX}) / \varepsilon_{coin}$$

$$\mu = (1 - N^{AND}_{events/BX}) / \varepsilon_{sing}$$

Threshold	ε_A	ε_C	ε_{sing}	ε_{coin}
10 pe	0.269	0.273	0.463	0.0788
15 pe	0.239	0.243	0.420	0.0625
50 pe	0.104	0.107	0.199	0.0124

$$N^{AND}_{hits} = N_{tubes}\left[1 - e^{-(2\mu\, N^{A}_{part/pp}\,(1 - e^{-\mu\varepsilon^{A}}) - \mu\, N^{Coinc}_{part/pp}\,(1 - 2e^{-\mu\varepsilon^{A}}))/N_{tubes}}\right] = \mu\, N^{coinc}_{hits/pp}$$

$$N^{OR}_{hits/BX} = N_{tubes}\left[1 - (1 - N_{hits/pp} / N_{tubes})\right] = \mu\, N^{sing}_{hits/pp}$$

$$\mu = N^{AND}_{hits/BX} / N^{coinc}_{hits/pp}$$

$$\mu = N^{OR}_{hits/BX} / N^{sing}_{hits/pp}$$

Threshold	$N^{A}_{hits/pp}$	$N^{C}_{hits/pp}$	$N^{sing}_{hits/pp}$	$N^{coinc}_{hits/pp}$
10 pe	0.550	0.559	0.856	0.2530
15 pe	0.450	0.458	0.719	0.1890
50 pe	0.138	0.142	0.250	0.0299

Measured μ for LUCID at 0.9 TeV

Selection of MBTS events using pulseheight and timing cuts and requiring hits on both sides.

	Monte Carlo	Data
ε^{sing} =	0.420	24664 / 82312 = 0.2996 +–0.0016
ε^{A} =	0.239	14146 / 82312 = 0.1719 +–0.0013
ε^{C} =	0.243	12738 / 82312 = 0.1548 +–0.0013
ε^{coinc} =	0.0625	2220 / 82312 = 0.0270 +–0.0006 (2733 / 101289 = 0.0270 +–0.0006 **for loser cuts**)

	Monte Carlo	Data
$N^{coinc}_{hits/pp}$ =	0.189	6653 / 86831 = 0.0766 +–0.0009
$N^{sing}_{hits/pp}$ =	0.719	40765 / 86831 = 0.469 +–0.002

LUCID 14 TeV

Efficiency

A	C
Hits = 0	*Hits = 0*

$\varepsilon_0 = 0.442$

Hits ≥ 1	*Hits = 0*

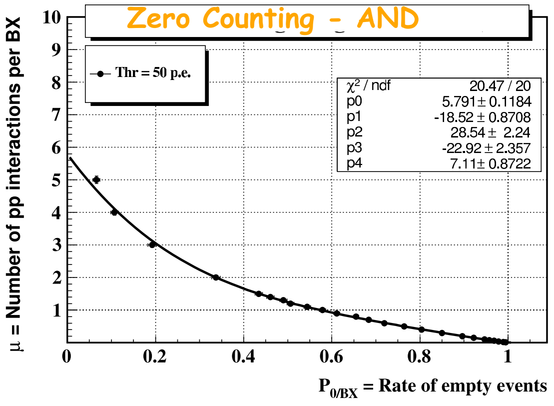
$\varepsilon_1 = 0.212$

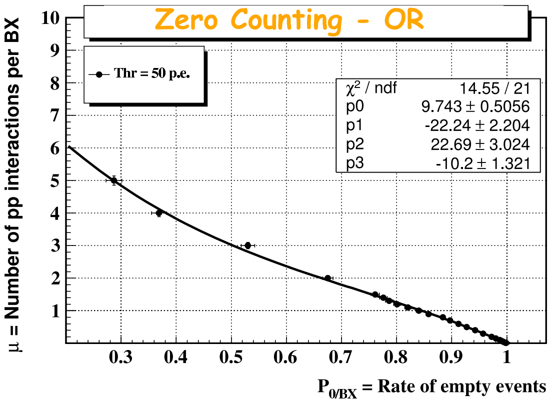
Hits = 0	*Hits ≥ 1*

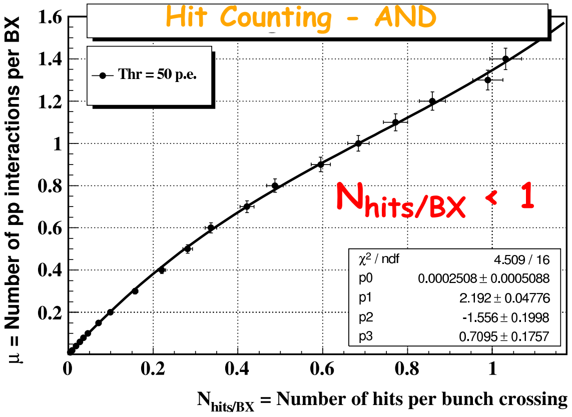
$\varepsilon_2 = 0.212$

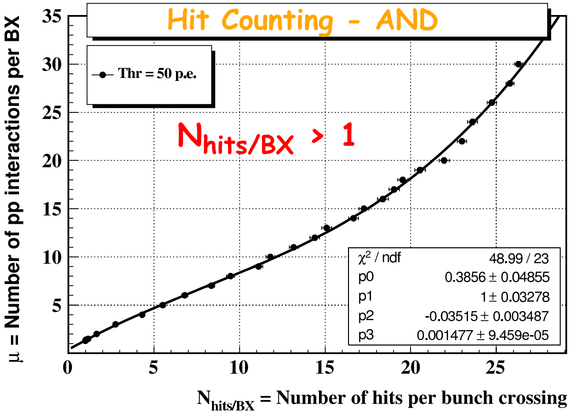
Hits ≥ 1	*Hits ≥ 1*

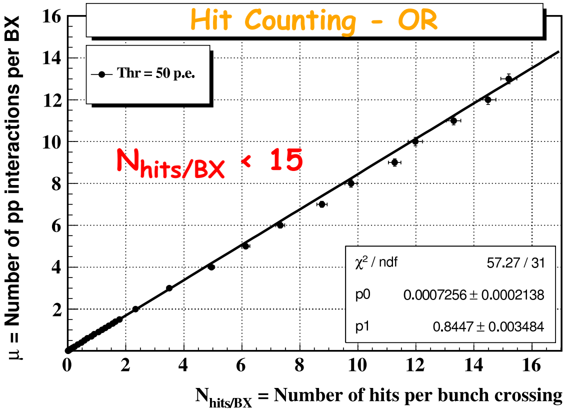
$\varepsilon_3 = 0.135$

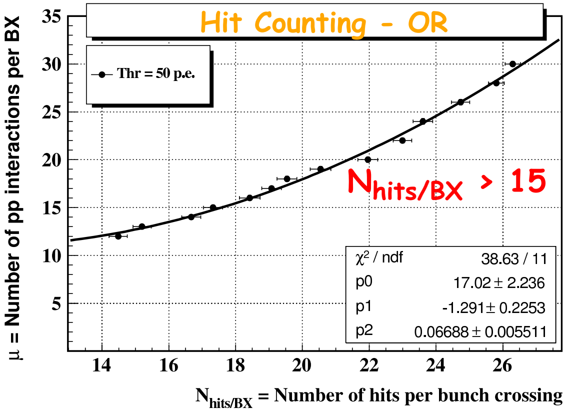












LUCID

What needs to be done ?

Fits for all possible LHC energies are needed.

Study of systematic errors.

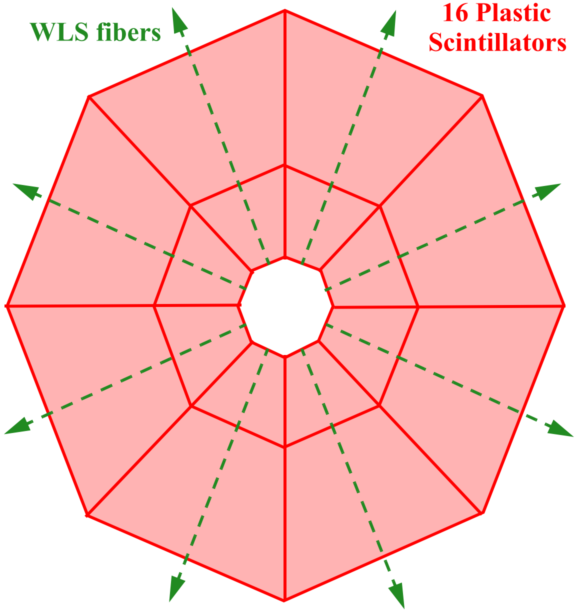
Studies using real event samples at low μ.

Studies of the detector response using real event samples.

MBTS

MBTS has 16 plastic scintillators one each side. They are arranged in two rings and read-out by WLS fibers via the TileCal electronics. The signals are discriminated and provide a hit pattern that are used to do four measurements:

Zero-counting-AND   Zero-counting-OR
Hit-counting-AND   Hit-counting-OR



The efficiency of the detector is very high for non-diff. events:

$\varepsilon_0 = 0$ $\varepsilon_1 = 0.004$ $\varepsilon_2 = 0.004$ $\varepsilon_3 = 0.992$ (14 TeV, only non-diff.)

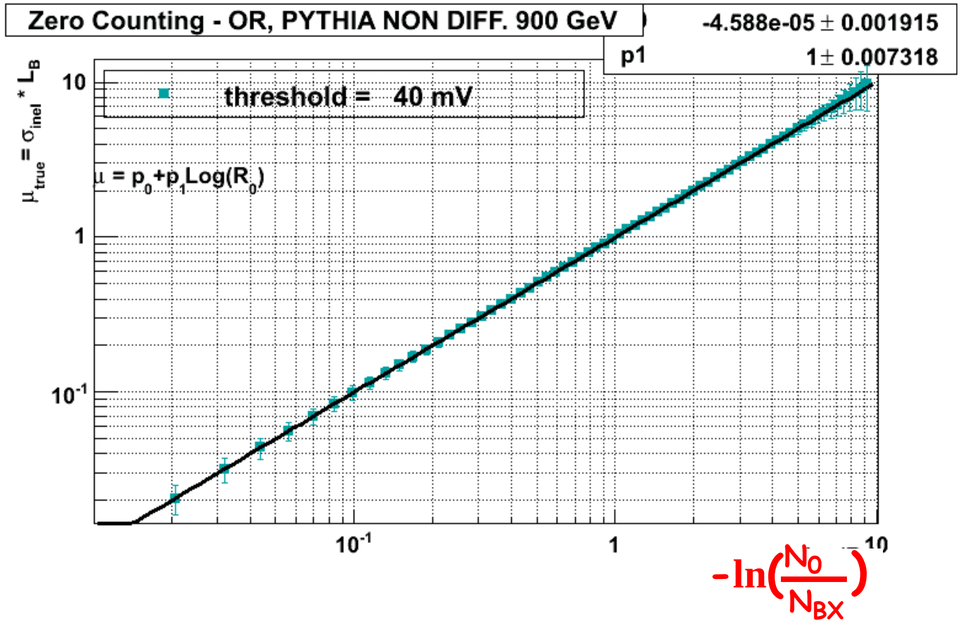
For the two zero-counting-methods, MBTS uses the following function that is fitted to the event probability (P):

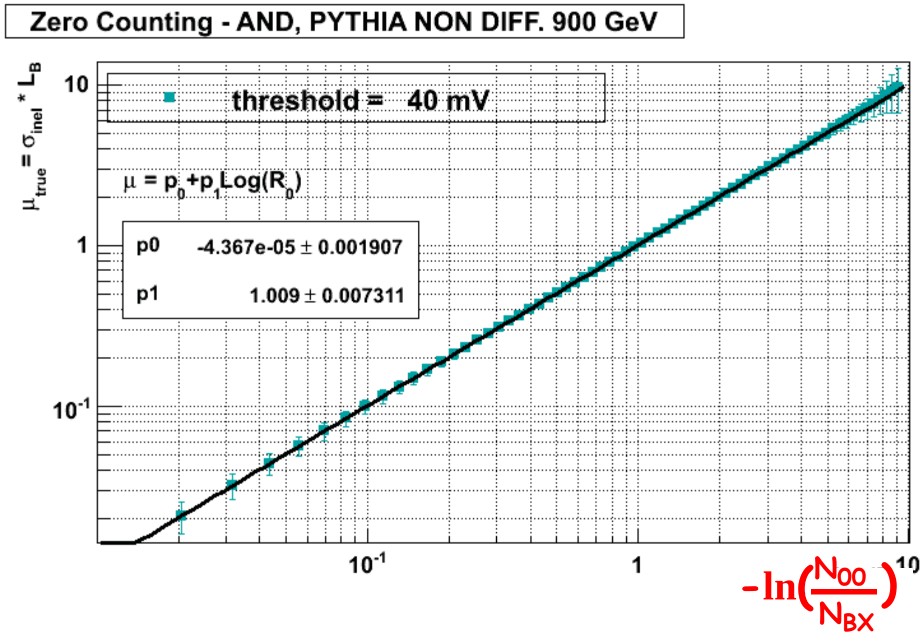
$$\mu = -p_0 - p_1 \ln(P) \quad \text{where } P = \frac{N_{00}}{N_{BX}} \text{ or } \frac{N_0}{N_{BX}} \quad \text{and } p_0,\ p_1 \text{ are constants}$$

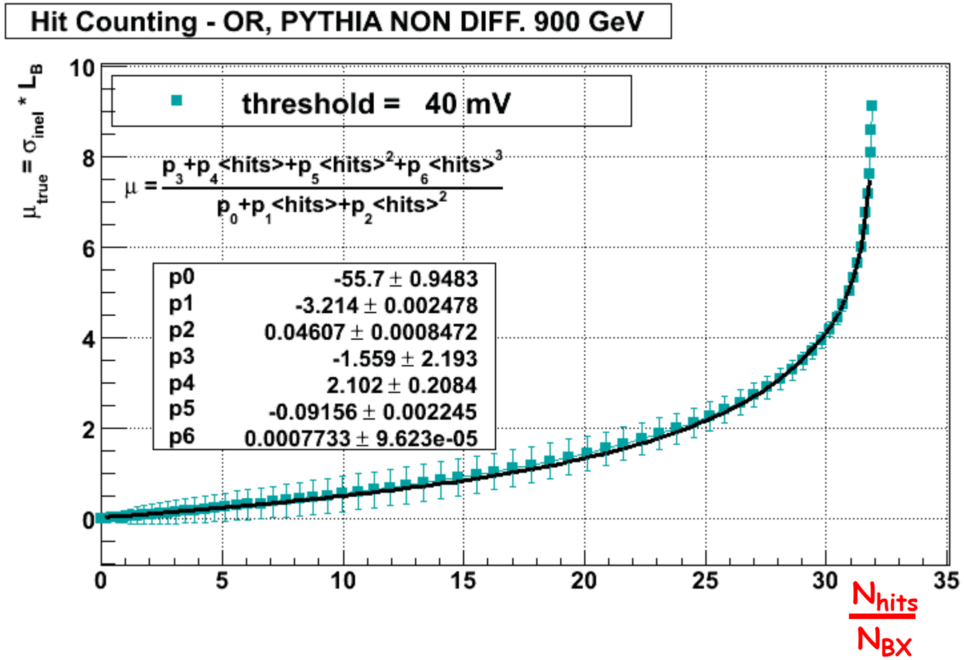
For hit counting, MBTS plot μ as a function of the hit probability (P) and fit a ratio of two polynomial functions so that μ can be expressed as

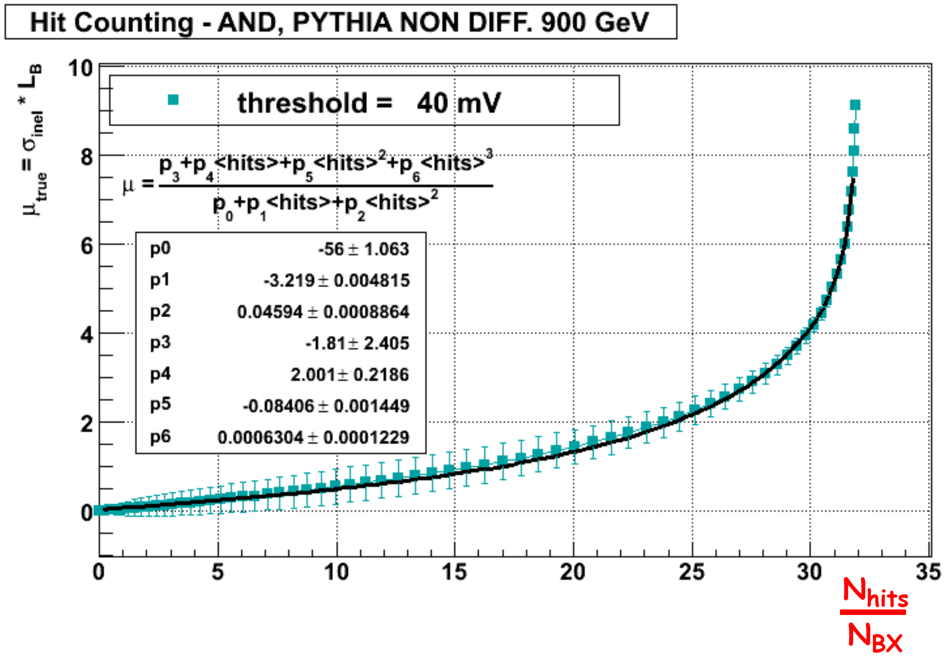
$$\mu = \frac{p_3 + p_4 P + p_5 P^2 + p_6 P^3}{p_0 + p_1 P + p_2 P^2} \quad \text{where } P = \frac{N_{hits}}{N_{BX}} \quad \text{and } p_0, \ldots\ldots, p_6 \text{ are constants}$$

MBTS 900 GeV - Only non-diff.

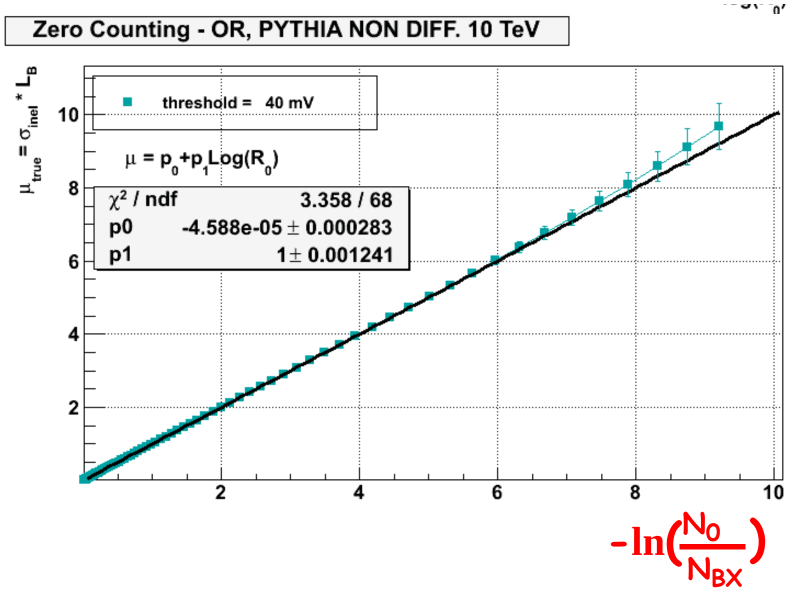


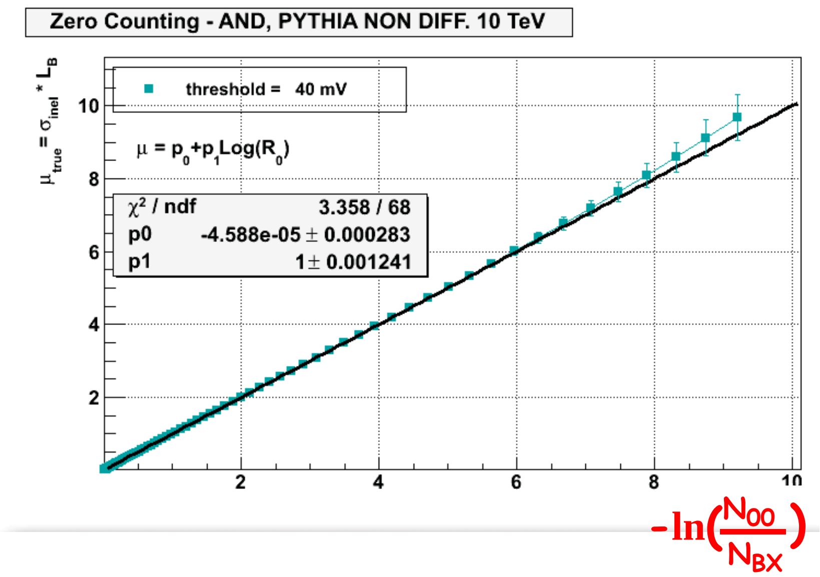


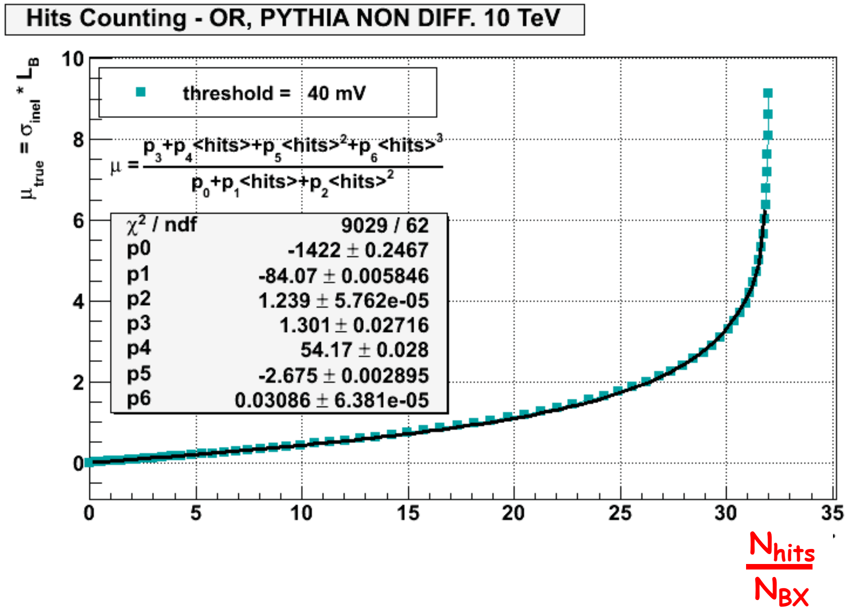


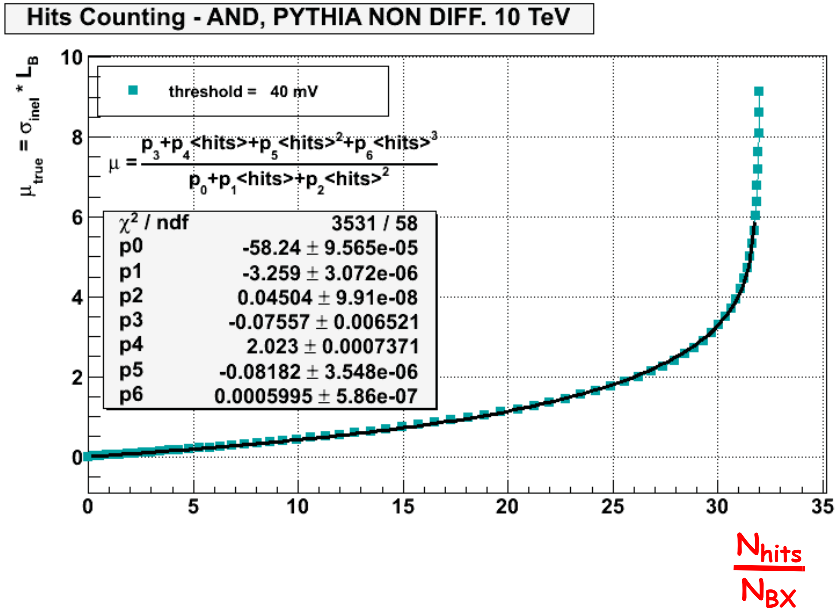


MBTS 10 TeV - Only non-diff.


Zero Counting - OR, PYTHIA NON DIFF. 10 TeV


Zero Counting - AND, PYTHIA NON DIFF. 10 TeV


Hits Counting - OR, PYTHIA NON DIFF. 10 TeV


Hits Counting - AND, PYTHIA NON DIFF. 10 TeV

MBTS

What needs to be done ?

Monte Carlo samples with a mixture including diffractive events have to be used.

Fits for all possible LHC energies are needed.

Studies of the detector response using real event samples.

Studies where only a few of the 32 segments are used.

Correct for pulses that are longer than the bunch separation time.

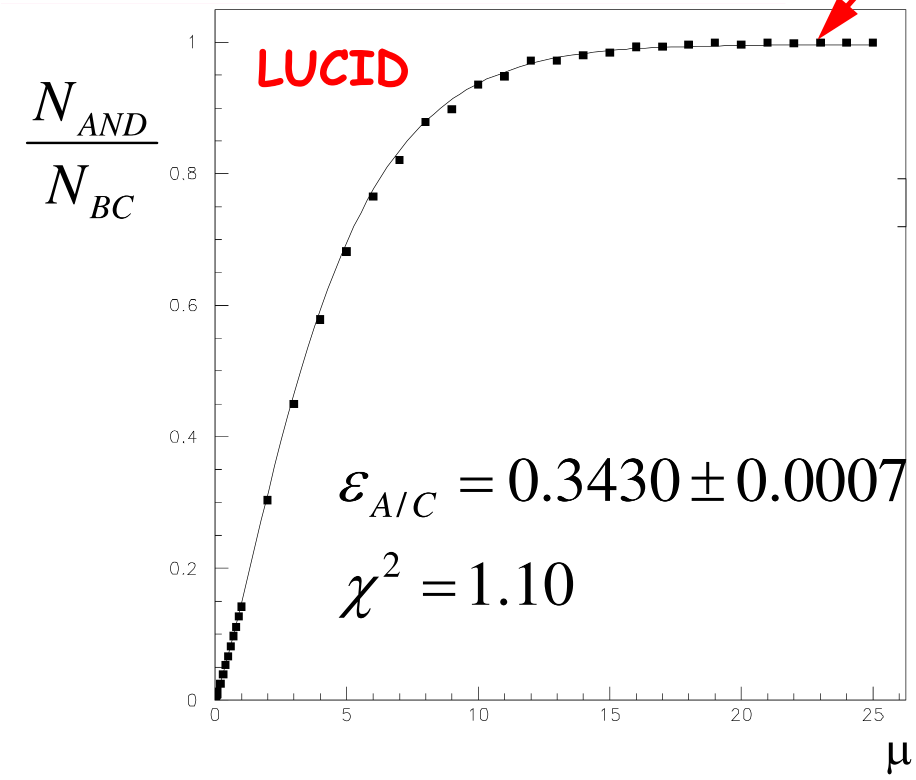
Beam separation scans

For Event-Counting-AND
the probability function is ⟶ $N_{AND/BX} = 1 - e^{-\varepsilon^A\mu} - e^{-\varepsilon^C\mu} + e^{-(\varepsilon^A+\varepsilon^C-\varepsilon^{Coin})\mu}$

Assume that $\varepsilon^A=\varepsilon^C$ and that $\varepsilon^{coin}=\varepsilon^A\times\varepsilon^C$

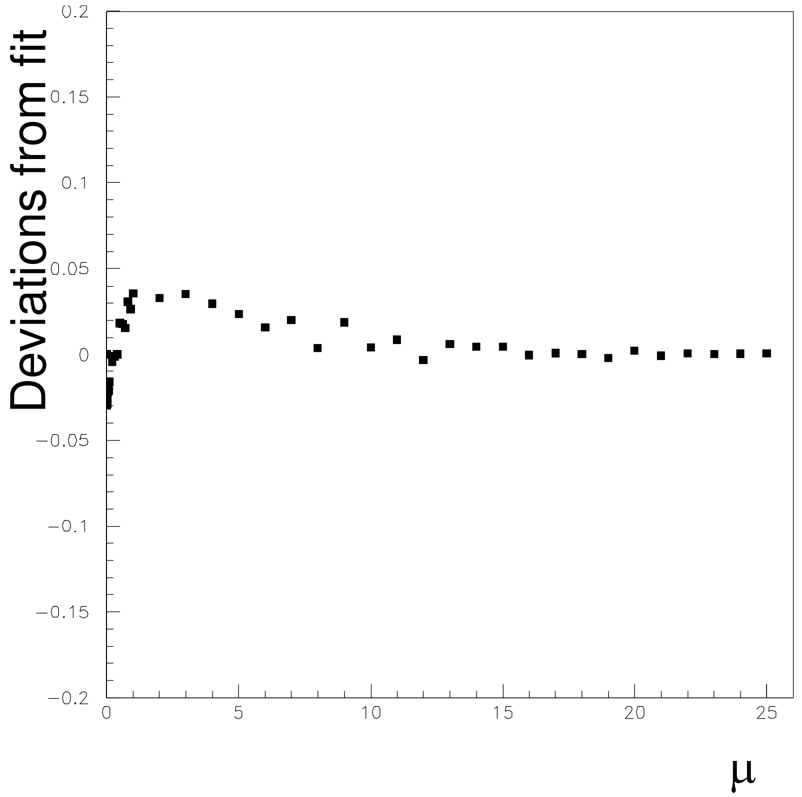
$$\boxed{N_{AND/BX} = 1-2e^{-\varepsilon^A\mu} + e^{-(2\varepsilon^A-\varepsilon^A\varepsilon^A)\mu}}$$

Fit



$\varepsilon_{A/C} = 0.3430 \pm 0.0007$

$\chi^2 = 1.10$



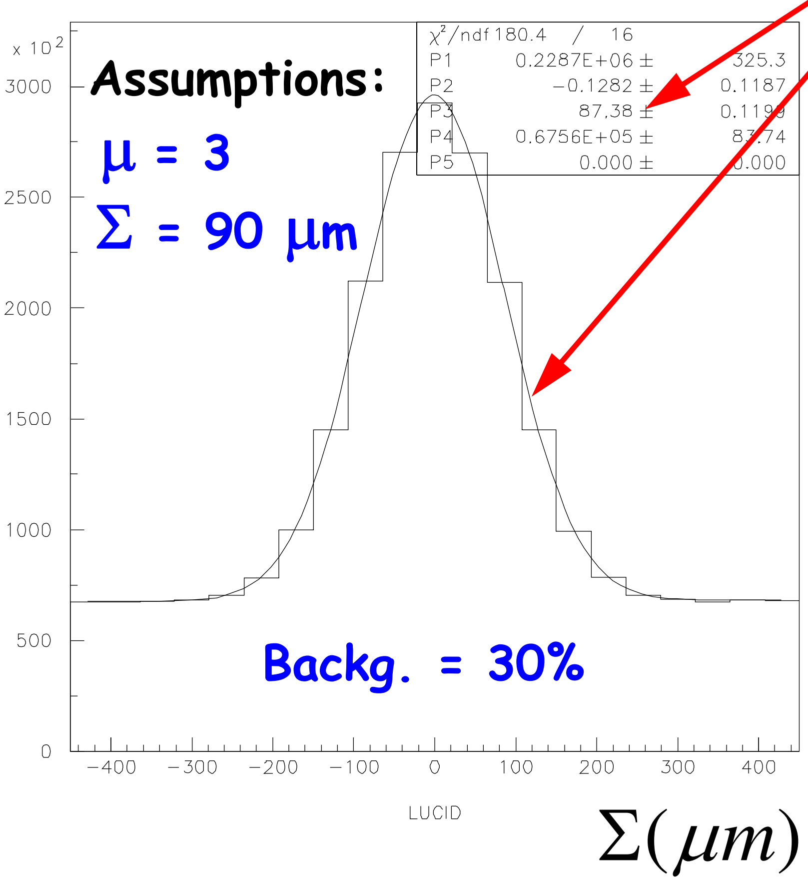
The fit works surprisingly well !

Beam separation scans

A separation scan done at $\mu>1$ will be distorted by the non-linear behaviour of the rate measurement.

A Gaussian fit gives Σ = 87.4 μm

Beam separation scan with LUCID



Assumptions:

μ = 3

Σ = 90 μm

Backg. = 30%

A fit with $N_{AND/BX} = 1\text{-}2e^{-\varepsilon^A\mu} + e^{-(2\varepsilon^A-\varepsilon^A\varepsilon^A)\mu}$ gives:

	True	Measured	Difference
μ:	3	3.2	8%
Σ:	90 μm	90.8 μm	0.9%
ε^A:	0.343	0.321	7%

The fit works better at higher μ where the distortions are larger !

A second fit with $N_{OR/BX} = 1\text{-}\ e^{-\varepsilon^{sing}\mu}$ to Event-Counting-OR events give ε^{sing} .

Final remarks

All detectors have done a lot of progress towards the goal of having realistic luminosity algorithms.

But we are not there yet !

Due to a lack of manpower the progress is slow (and LHC running does not help).

We will have a lot of work to do also in 2010 !

LIST OF METHODS

Zero-counting-AND

Zero-counting-AND events are events with no signals in both detectors:

A $\boxed{Hits\ =\ 0}$ **C** $\boxed{Hits\ =\ 0}$

The probability to have a zero-AND event is

$$N_{00/BX} = e^{(\varepsilon_0-1)\mu} = e^{-\varepsilon^{sing}\mu} = \frac{N_{00}}{N_{BX}} = \frac{\text{Number of measured zero-AND events}}{\text{Number of bunch crossings}}$$

This function can easily be inverted so that μ can be obtained from the measured events:

$$\mu = \frac{\ln\left(\frac{N_{00}}{N_{BX}}\right)}{\varepsilon_0-1} = \frac{\ln\left(\frac{N_{00}}{N_{BX}}\right)}{-\varepsilon^{sing}}$$

where only one parameter (ε_0) has to be determined from Monte Carlo

The instantaneous luminosity is the obtained from

$$L = \frac{R_{in}}{\sigma_{in}} = \frac{f_{BX}}{\sigma_{in}} \times \frac{\ln\left(\frac{N_{00}}{N_{BX}}\right)}{\varepsilon_0-1}$$

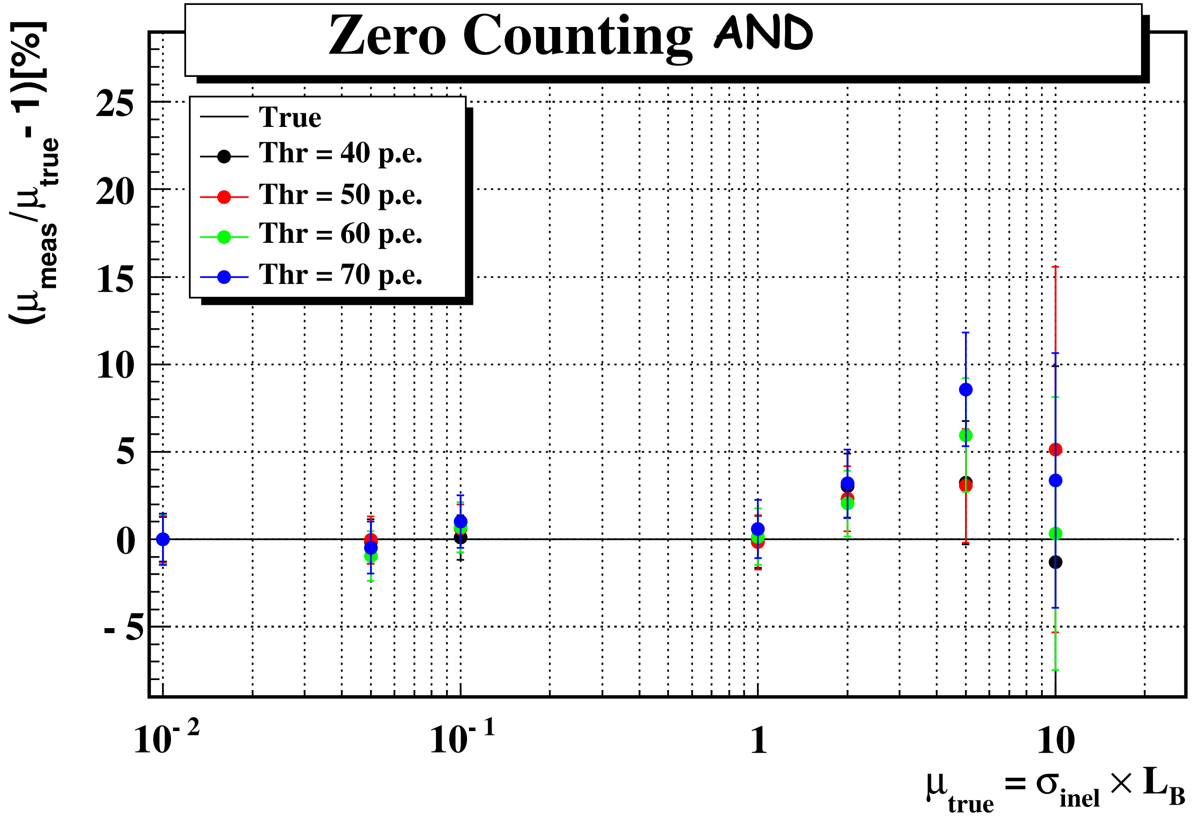
where σ_{in} = 79-83 mb at 14 TeV

ε_0 = 0.442 (LUCID) = 0.711 (BCM) = 0 (MBTS) all at 14 TeV

Zero-counting-AND

Even if one can find a simple expression of μ as a function of the number of measured empty events, this does not mean that this expression gives a perfect estimation of μ.

LUCID:



The reason for the error in the μ-determination above is migration i.e. the effect of particles with a low pulseheight (below the discriminator threshold) that add up at large μ and produce a total signal above threshold.

Event-counting-OR

A	C
Hits ≥ 1	*Hits* ≥ 1
Hits ≥ 1	*Hits* = 0
Hits = 0	*Hits* ≥ 1

Event-counting-OR events are events with a signal in at least one detector:

Probability(Zero-counting-AND) = 1 - Probability(Event-counting-OR)

The probability to have an event-counting-OR event is

$$N_{OR/BX} = 1 - e^{(\varepsilon_0 - 1)\mu} = 1 - e^{-\varepsilon^{sing}\mu} = \frac{N_{OR}}{N_{BX}} = \frac{\text{Number of measured event-counting-OR events}}{\text{Number of bunch crossings}}$$

$$N_{OR/BX} \approx \varepsilon_{Sing}\,\mu \quad \text{if } \mu \ll 1$$

This function can easily be inverted so that μ can be obtained from the measured events:

$$\mu = \frac{\ln(1 - \frac{N_{OR}}{N_{BX}})}{\varepsilon_0 - 1} = \frac{\ln(1 - \frac{N_{OR}}{N_{BX}})}{-\varepsilon^{sing}}$$

where only one parameter (ε_0) has to be determined from Monte Carlo

The instantaneous luminosity is the obtained from

$$L = \frac{R_{in}}{\sigma_{in}} = \frac{f_{BX}}{\sigma_{in}} \times \frac{\ln(1 - \frac{N_{OR}}{N_{BX}})}{\varepsilon_0 - 1}$$

where σ_{in} = 79-83 mb at 14 TeV

ε_0 = 0.442 (LUCID) = 0.711 (BCM) = 0 (MBTS) at 14 TeV

Zero-counting-OR

Zero-counting-OR events are events with no signals in one or two detectors:

A	C
Hits = 0	*Hits* = 0
Hits ≥ 1	*Hits* = 0
Hits = 0	*Hits* ≥ 1

The probability to have a zero-AND event is given by

$$N_{0/BX} = \frac{N_0}{N_{BX}} = \frac{\text{Number of measured zero-OR events}}{\text{Number of bunch crossings}}$$

$$N_{0/BX} = e^{(\varepsilon_0+\varepsilon_1-1)\mu} + e^{(\varepsilon_0+\varepsilon_2-1)\mu} - e^{(\varepsilon_0-1)\mu} = e^{-\varepsilon^A\mu} + e^{-\varepsilon^C\mu} - e^{-(\varepsilon^A+\varepsilon^C-\varepsilon^{Coin})\mu} = \frac{N_0}{N_{BX}}$$

$$N_{0/BX} = 2e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0-1)\mu} = 2e^{-\varepsilon^A\mu} - e^{-(2\varepsilon^A-\varepsilon^{Coin})\mu} = \frac{N_0}{N_{BX}} \quad \text{if } \varepsilon_1 = \varepsilon_2 \text{ and } \varepsilon^A = \varepsilon^C$$

This function cannot be inverted analytically and it depends on two parameters (ε_0 and ε_1).

Event-counting-AND

A $\boxed{Hits \geq 1}$ **C** $\boxed{Hits \geq 1}$

Event-counting-AND events are events with a signals in both detectors:

Probability(Zero-counting-OR) = 1 - Probability(Event-counting-AND)

The probability to have an event-counting-AND event is given by

$$N_{AND/BX} = \frac{N_{AND}}{N_{BX}} = \frac{\text{Number of measured event-counting-AND events}}{\text{Number of bunch crossings}}$$

ε^{Sing}

$$N_{AND/BX} = 1 - e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0+\varepsilon_2-1)\mu} + e^{(\varepsilon_0-1)\mu} = 1 - e^{-\varepsilon^A\mu} - e^{-\varepsilon^C\mu} + e^{-(\varepsilon^A+\varepsilon^C-\varepsilon^{Coin})\mu}$$

$$N_{AND/BX} = 1 - 2e^{(\varepsilon_0+\varepsilon_1-1)\mu} + e^{(\varepsilon_0-1)\mu} = 1 - 2e^{-\varepsilon^A\mu} + e^{-(2\varepsilon^A-\varepsilon^{Coin})\mu} \quad \text{if } \varepsilon_1 = \varepsilon_2 \text{ and } \varepsilon^A = \varepsilon^C$$

This function cannot be inverted analytically and it depends on two parameters (ε_0 and ε_1).

$$N_{AND/BX} = \varepsilon^{Coin}\mu \quad \text{if } \mu << 1$$

Event-counting-XOR

Event-counting-XOR events are events with signals in only one detector:

A		C
$\boxed{Hits \geq 1}$		$\boxed{Hits = 0}$
	or	
$\boxed{Hits = 0}$		$\boxed{Hits \geq 1}$

The probability to have an event-counting-XOR event on side A is given by

$$N_{A/BX} = \frac{N_A}{N_{BX}} = \frac{\text{Number of measured event-counting-XOR-side A events}}{\text{Number of bunch crossings}}$$

$$N_{A/BX} = e^{(\varepsilon_0+\varepsilon_1-1)\mu} - e^{(\varepsilon_0-1)\mu}$$

and for side C one gets

$$N_{C/BX} = e^{(\varepsilon_0+\varepsilon_2-1)\mu} - e^{(\varepsilon_0-1)\mu}$$

These functions cannot be inverted analytically and they depends on two parameters.

Hit-counting-OR

Hit-counting-OR is a method which uses the hits in any detector:

A	C
$Hits \geq 1$	$Hits \geq 1$
$Hits \geq 1$	$Hits = 0$
$Hits = 0$	$Hits \geq 1$

If the detectors counted the true number of particles then

$$\mu = \frac{N_{part/BX}}{N_{part/pp}} = \frac{\text{The average number of detected particles per bunch crossing}}{\text{The average number of detected particles per inelastic pp interaction}}$$

Instead the detectors count hits and at large μ there will be several particles in each detector element. The number of particles can, however, be estimated from the number of hits:

$$N_{part} = - N_{tubes} \times \ln\left(1 - \frac{N_{hits}}{N_{tubes}}\right)$$

where N_{tubes} is the number of detector elements i.e. tubes in the case of LUCID and scintillator segments in the case of MBTS.

and so

$$\mu = \frac{\ln\left(1 - \frac{N_{hits/BX}}{N_{tubes}}\right)}{\ln\left(1 - \frac{N_{hits/pp}}{N_{tubes}}\right)}$$

Hit-counting-AND

A

$Hits \geq 1$

C

$Hits \geq 1$

Hit-counting-AND is a method which uses the hits under the condition that both sides have hits:

The average number of particles in a bunch crossing can be estimated in this mode from the expected number of hits for one inelastic pp interaction and the efficiencies. Assuming that the detector response on side A and side C are identical one gets

$$N_{part/BX} = 2\mu\, N^{A}_{part/pp}\,(1 - e^{-\mu\varepsilon^{A}}) - \mu\, N^{Coinc}_{part/pp}\,(1 - 2e^{-\mu\varepsilon^{A}}) \qquad \text{if} \quad N^{A}_{part/pp} = N^{C}_{part/pp} \quad \text{and} \quad \varepsilon^{A} = \varepsilon^{C}$$

where N_{part} is obtained from N_{hits} by

$$N_{part} = - N_{tubes} \times \ln\left(1 - \frac{N_{hits}}{N_{tubes}}\right)$$

$$N_{hits/BX} = N_{tubes}\left[\ 1 - e^{-(2\mu N^{A}_{part/pp}(1 - e^{-\mu\varepsilon^{A}}) - \mu N^{Coinc}_{part/pp}(1 - 2e^{-\mu\varepsilon^{A}}))/N_{tubes}}\right]$$

What is needed is μ expressed as N_{hits} but the function above cannot be inverted analytically.

$$N_{hits/BX} = N_{tubes}\left[\ 1 - e^{-\mu(N^{Coinc}_{part/pp} - 2N^{A}_{part/pp})/N_{tubes}}\right] \qquad \text{for large } \mu$$

$$N_{hits/BX} = \mu N^{Coinc}_{part/pp} \qquad \text{for small } \mu$$

Statistics at low μ

Zero-AND

$\boxed{Hits = 0}$ $\boxed{Hits = 0}$

Event-OR

$\boxed{Hits \geq 1}$ $\boxed{Hits \geq 1}$

$\boxed{Hits \geq 1}$ $\boxed{Hits = 0}$

$\boxed{Hits = 0}$ $\boxed{Hits \geq 1}$

Compare the methods zero-counting-AND with event-counting-OR:

Zero-counting-AND: $e^{(\varepsilon_0-1)\mu} = \frac{N_{00}}{N_{BX}}$ Event-counting-OR: $1 - e^{(\varepsilon_0-1)\mu} = \frac{N_{OR}}{N_{BX}}$

Conclusion: $N_{00} = N_{BX} - N_{OR}$ where N_{BX} is a constant and so both methods have the same statistical uncertainty.

Event-AND

$\boxed{Hits \geq 1}$ $\boxed{Hits \geq 1}$

Event-OR

$\boxed{Hits \geq 1}$ $\boxed{Hits \geq 1}$

$\boxed{Hits \geq 1}$ $\boxed{Hits = 0}$

$\boxed{Hits = 0}$ $\boxed{Hits \geq 1}$

Compare the methods event-counting-AND with event-counting-OR:

Conclusion: $N_{OR} > N_{AND}$

Compare the methods event-counting-OR with hit-counting-OR:

$$N_{OR/BX} = 1 - e^{(\varepsilon_0-1)\mu} \approx \mu(1-\varepsilon_0) = 0.56\mu \text{ for } \mu << 1 \text{ and } 14 \text{ TeV}$$

$$N_{hits/BX} = N_{tubes}\left[1 - \left(1 - \frac{N_{hits/pp}}{N_{tubes}}\right)^{\mu}\right] \approx \mu N_{hits/pp} = 1.20\mu \text{ for } \mu << 1 \text{ and } 14 \text{ TeV}$$

Conclusion: $N_{hits} = 2N_{OR}$