

Misura della luminosità al Large Hadron Collider

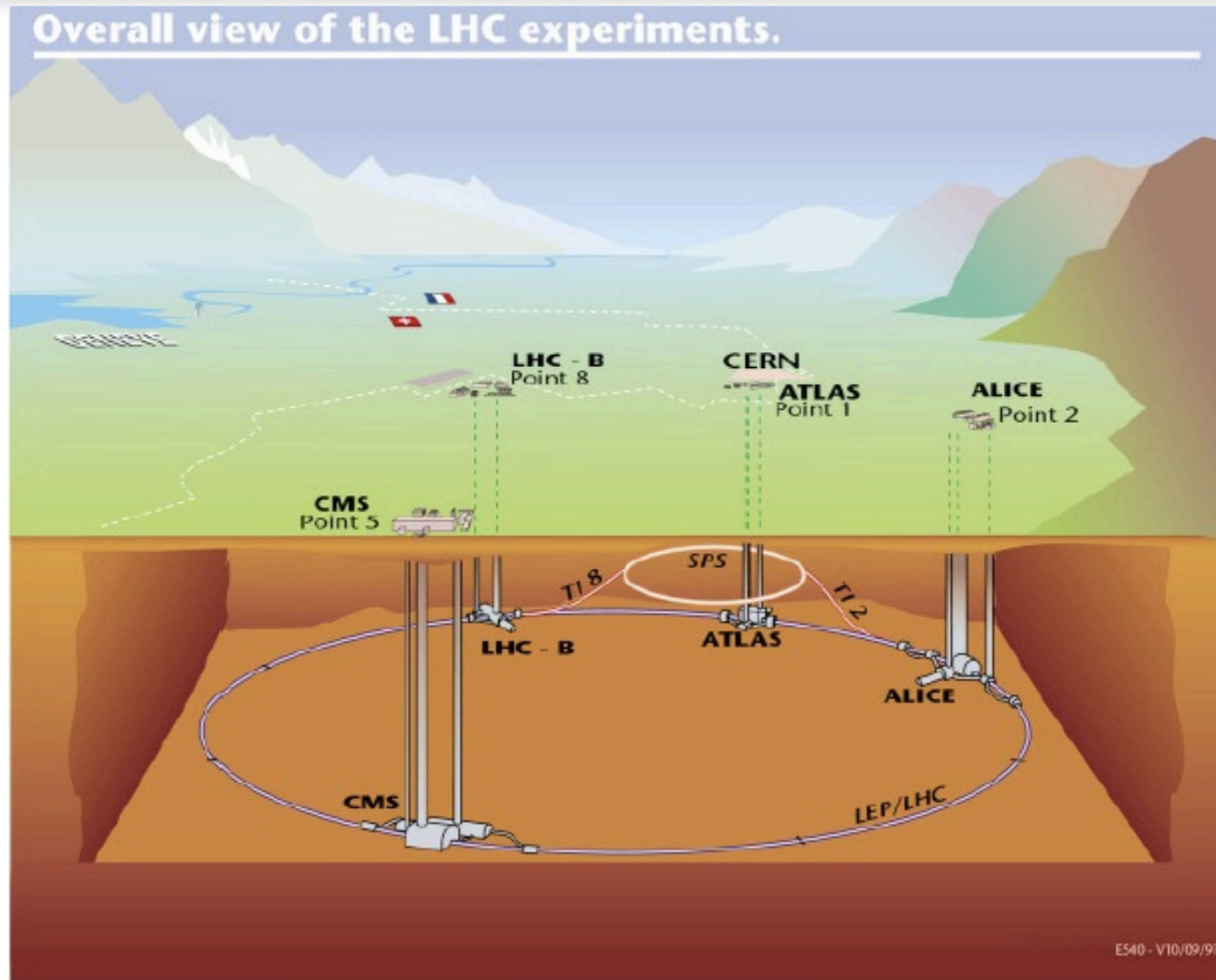
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**Università degli studi La Sapienza
24-25 Maggio 2012**

Programma

- The Large Hadron Collider
- Gli esperimenti
 - ✓ trigger
- La luminosita'
- collisioni adroniche
 - ✓ sezione d'urto, teorema ottico
 - ✓ cinematica , molteplicita' di particelle cariche in collisioni adroniche
- Misure di luminosita'
 - ✓ relativa
 - ✓ assoluta

The Large Hadron Collider



27km circumference

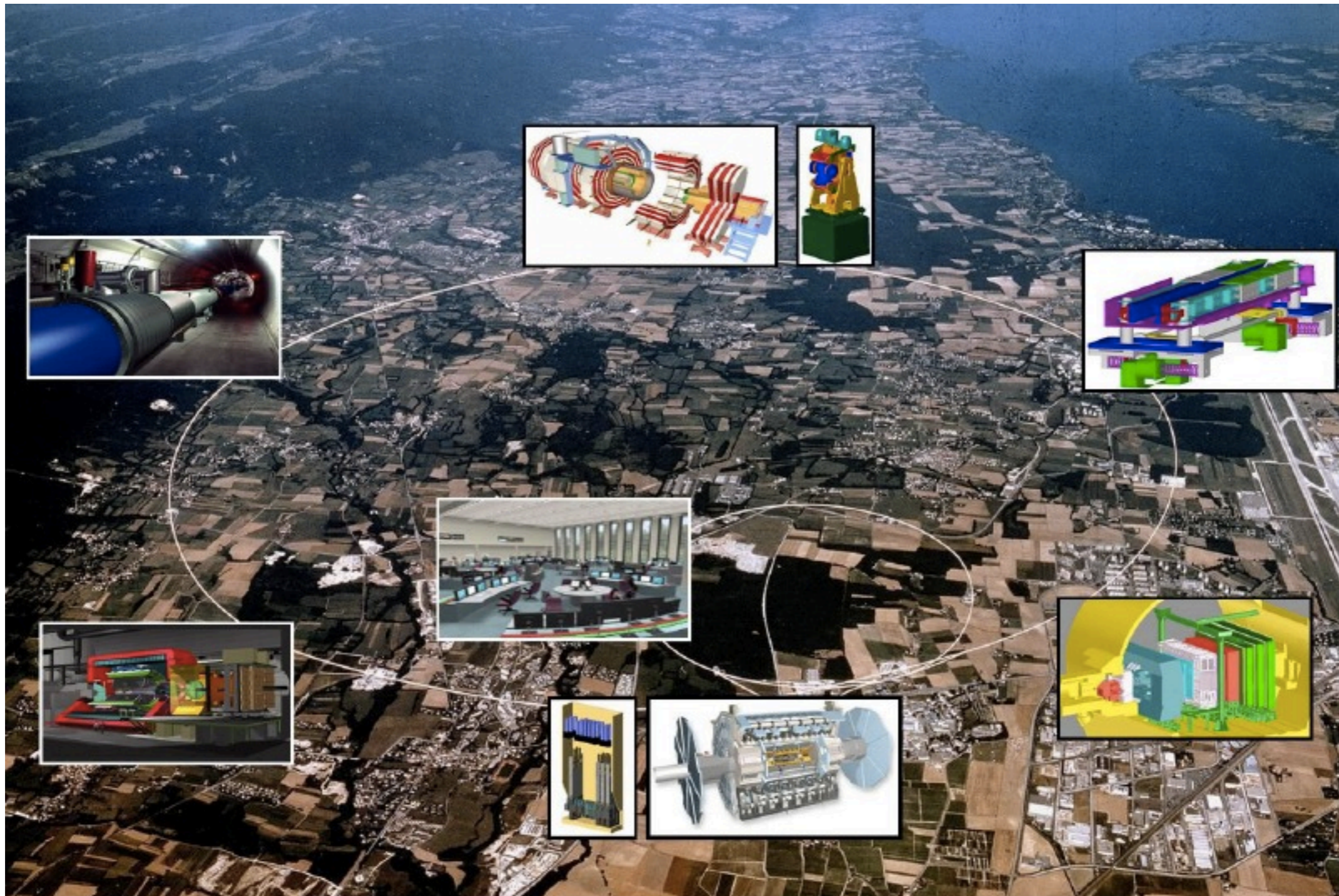
$$\sqrt{s_{pp}} = 7+7 \text{ TeV}$$

$$L_{\text{max}} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

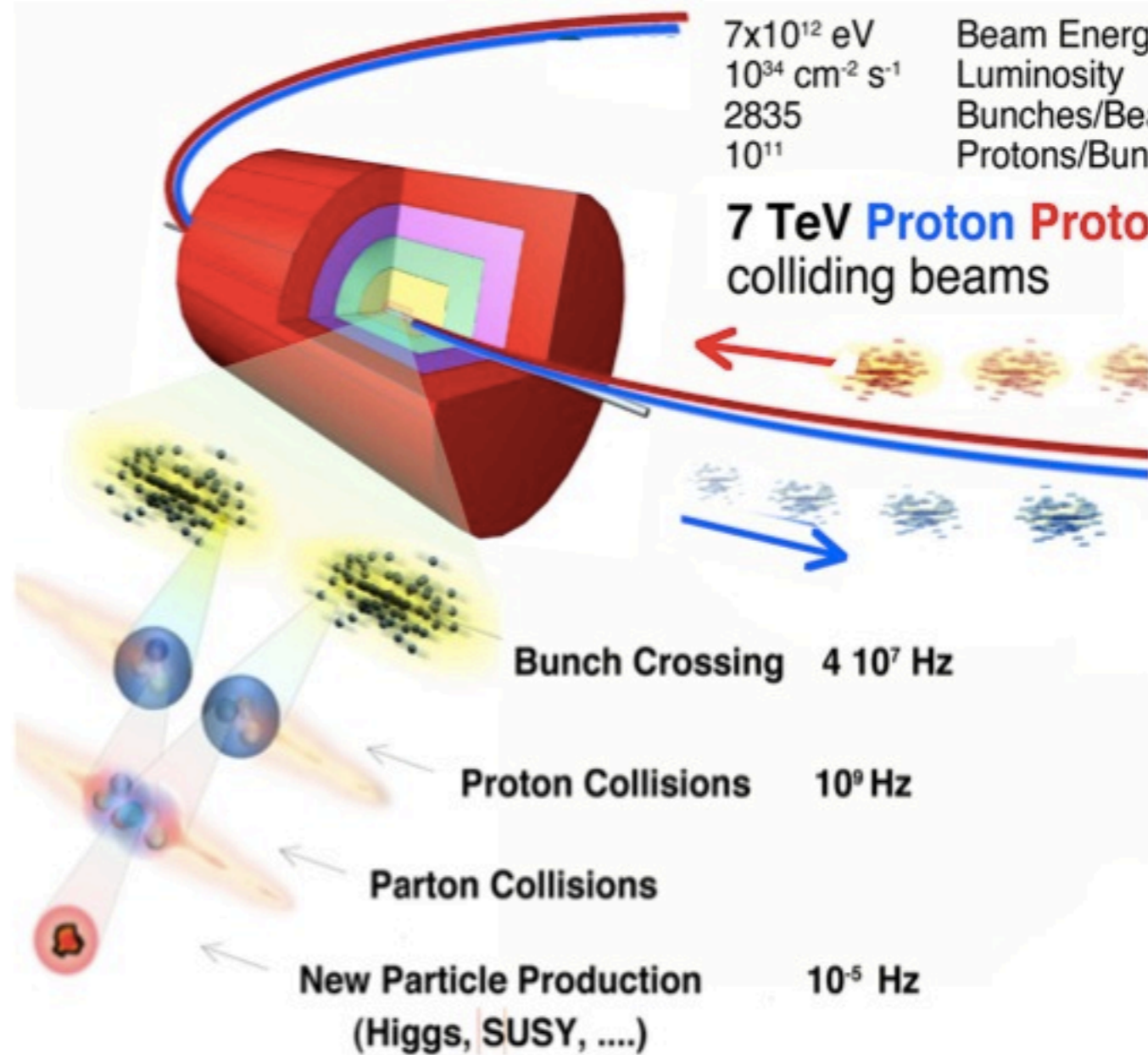
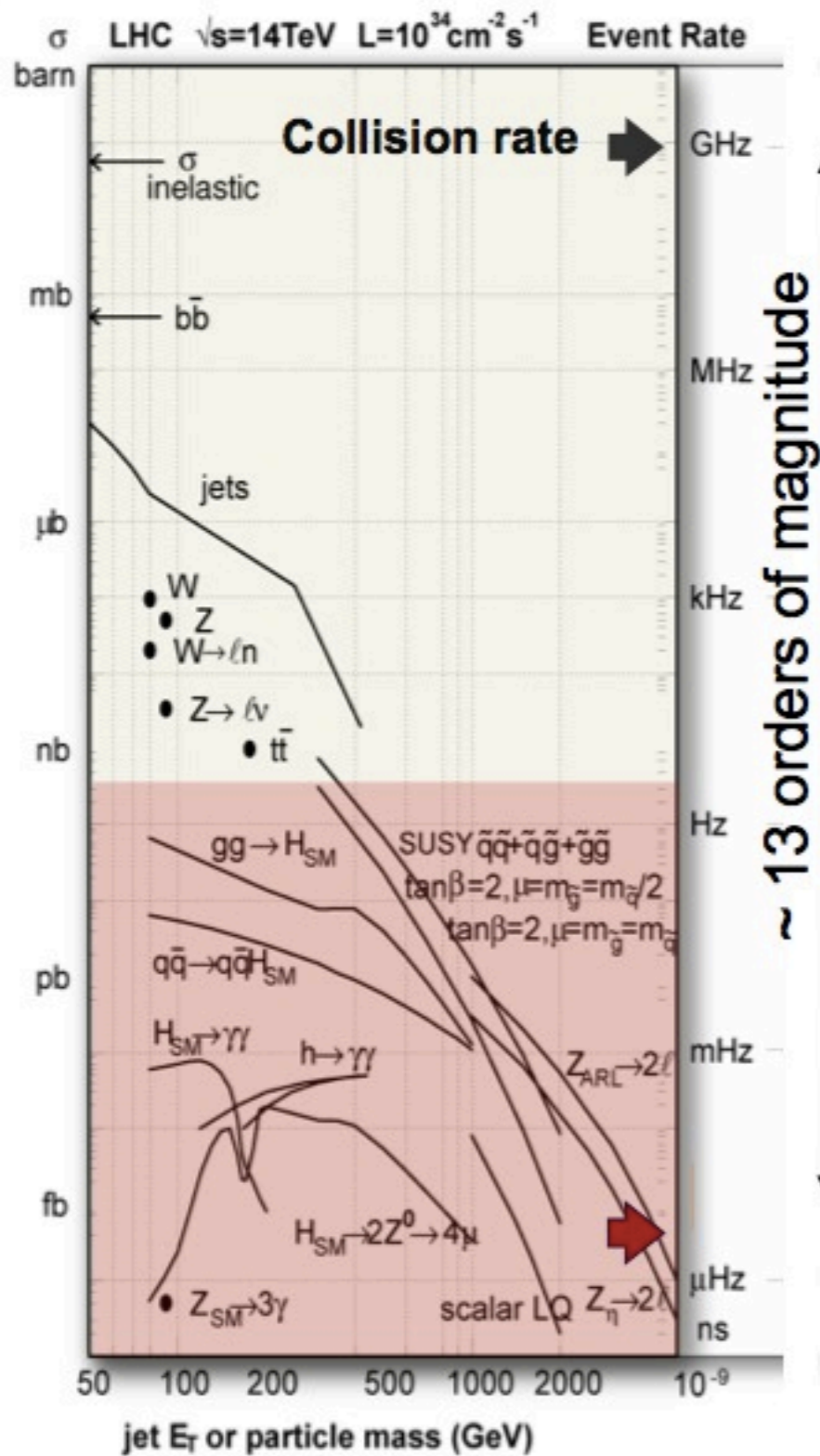
$$E_{\text{stored}} (\text{magnets}) \approx 10 \text{ GJ}$$

$$E_{\text{stored}} (\text{beam}) \approx 700 \text{ MJ}$$

The Large Hadron Collider



The Large Hadron Collider



LHC 2010-12:
 Collision Energy
 Luminosity

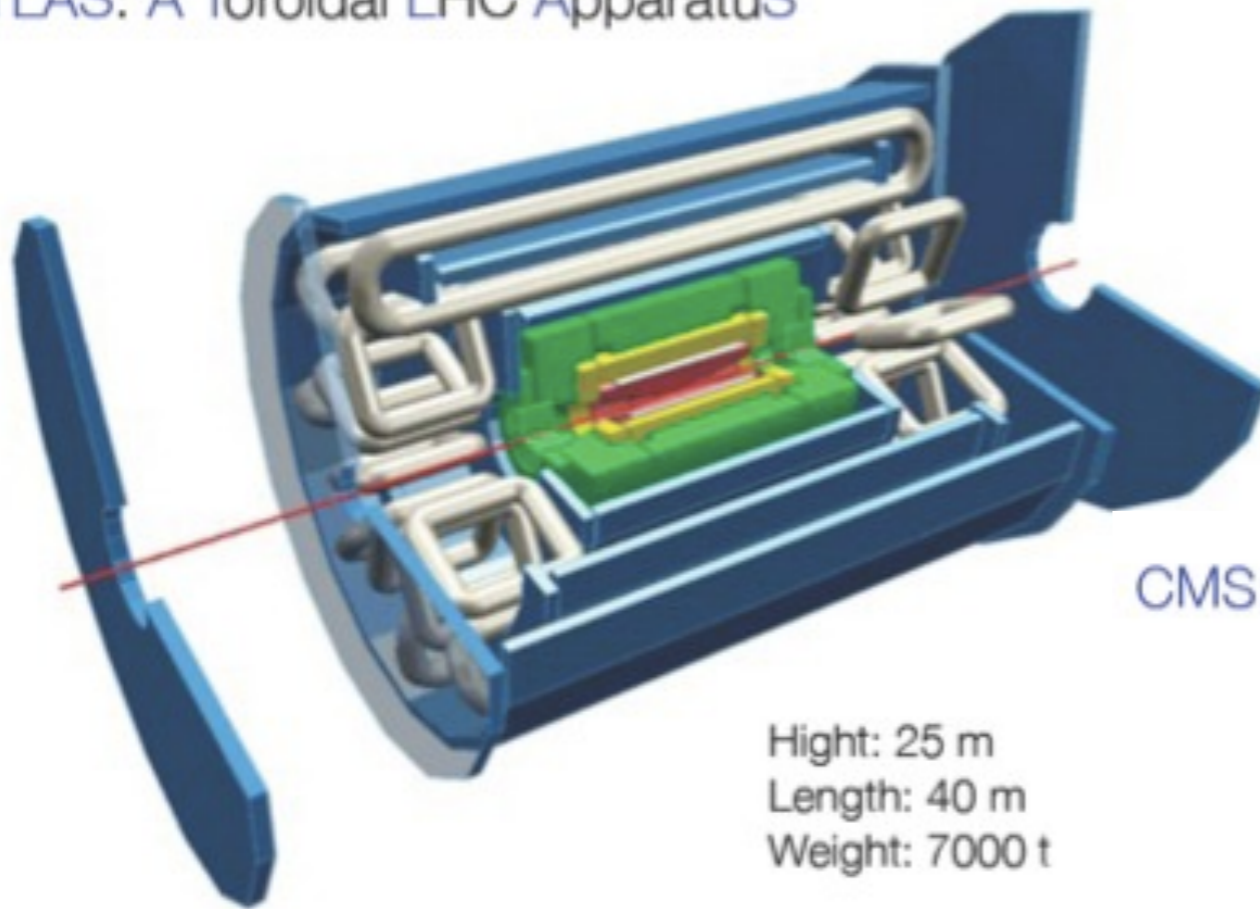
7 TeV
 10³²⁻³⁴ cm⁻²s⁻¹

confronto acceleratori

	LEP	HERA	PEP-II/KEKB	Tevatron	LHC	ILC
Particles collided	e^+e^-	ep	e^+e^-	pp	pp	e^+e^-
Date of operation	1989-2000	1992-2007	1999-2008 / 1999-now	1987-now	2009-now	TBD
Max beam energy [GeV]	104.6	30 (e) / 920 (p)	8x3.5 / 9x3.1	980	7	250
Luminosity [$10^{30} \text{ cm}^{-2} \text{ s}^{-1}$]	16 (Z) / 100	75	21083 / 12069	402	10 000	20000
Time between collisions [ns]	22000	96	4.2/8	396	25	300
Number of bunches	4	189 (e) / 180 (p)	1732 / 1585	36	2808	2625
Number of particles / bunch (10^{10})	45	3 (e) / 7(p)	5.2 (e^-) 8 (e^+) / 5.7 (e^-) 6.4(e^+)	26(p) / 9(\bar{p})	11.5	2

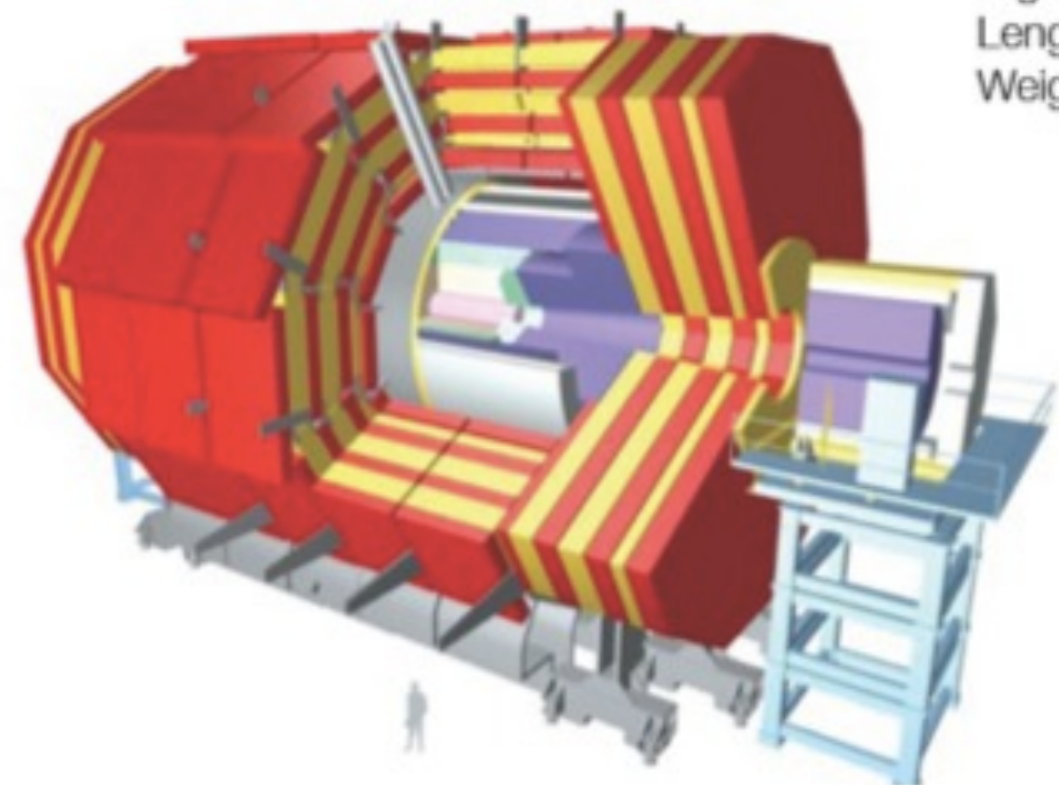
Gli esperimenti

ATLAS: A Toroidal LHC ApparatuS



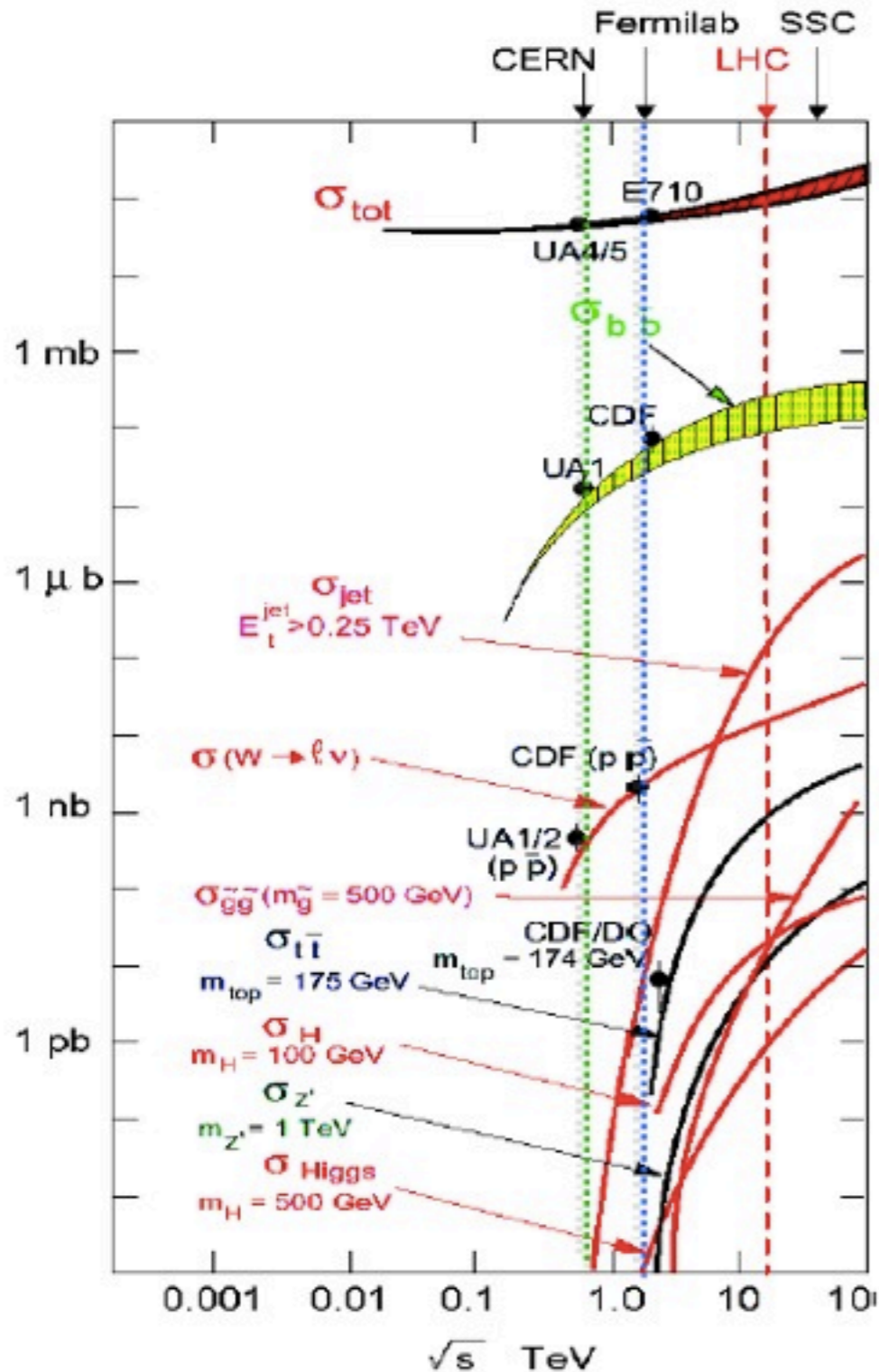
Height: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid



Height: 15 m
Length: 22 m
Weight: 12500 t

Sezioni d'urto e rates di produzione



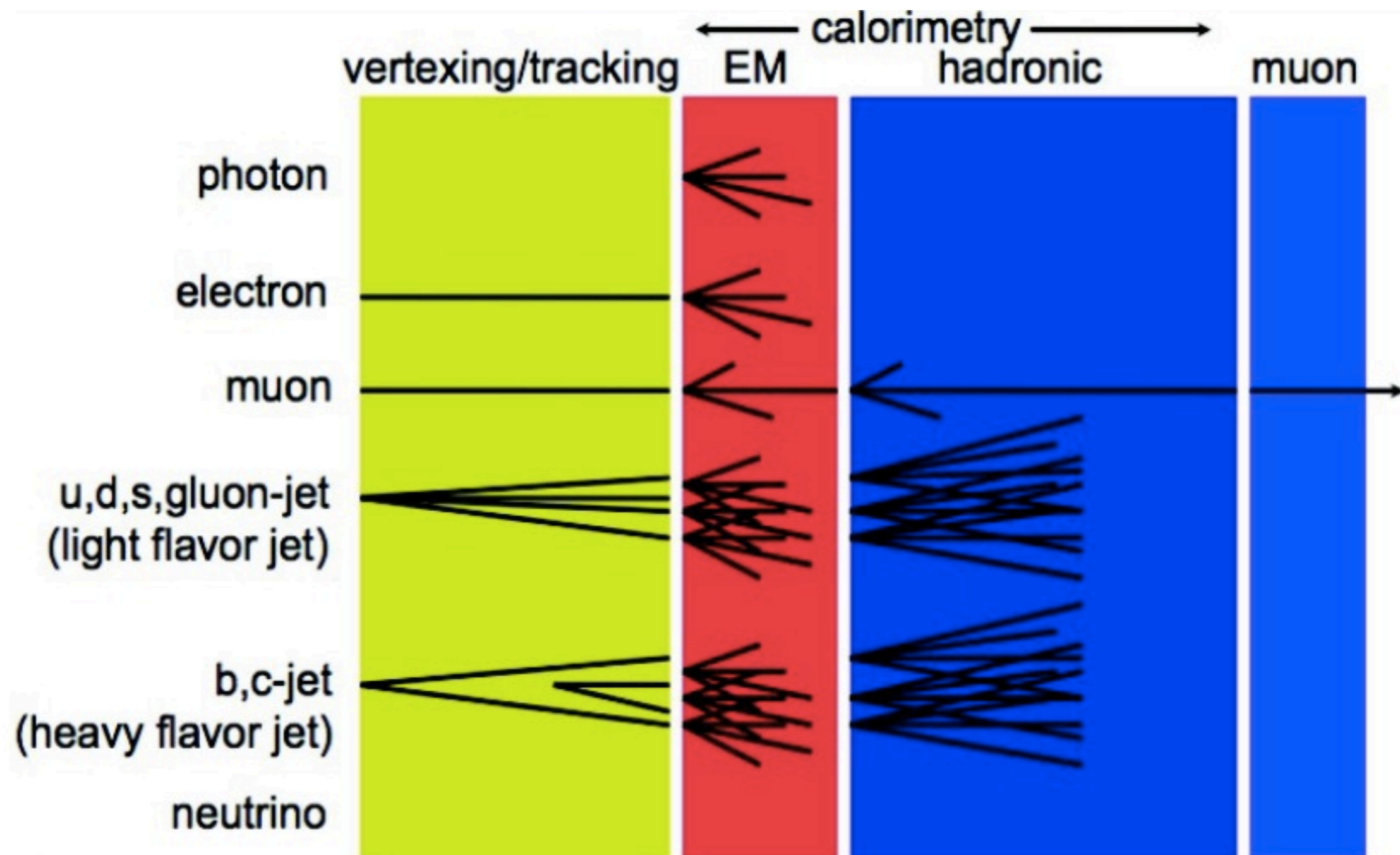
Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \rightarrow \ell\nu$	15	150
$Z \rightarrow \ell\ell$	2	20
$t\bar{t}$	1	10
$Z'(1 \text{ TeV})$	0.05	0.5
$\tilde{g}\tilde{g}(1 \text{ TeV})$	0.05	0.5
$H(120 \text{ GeV})$	0.04	0.4
$H(180 \text{ GeV})$	0.02	0.2

Conversions:

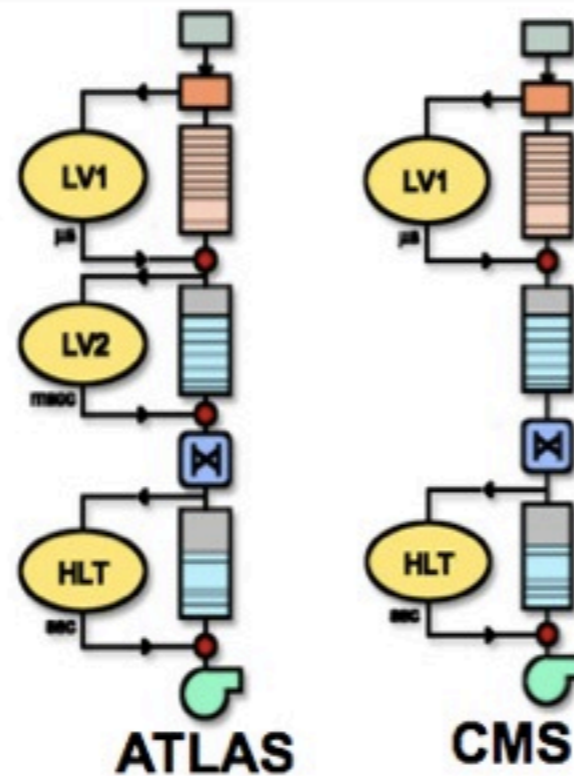
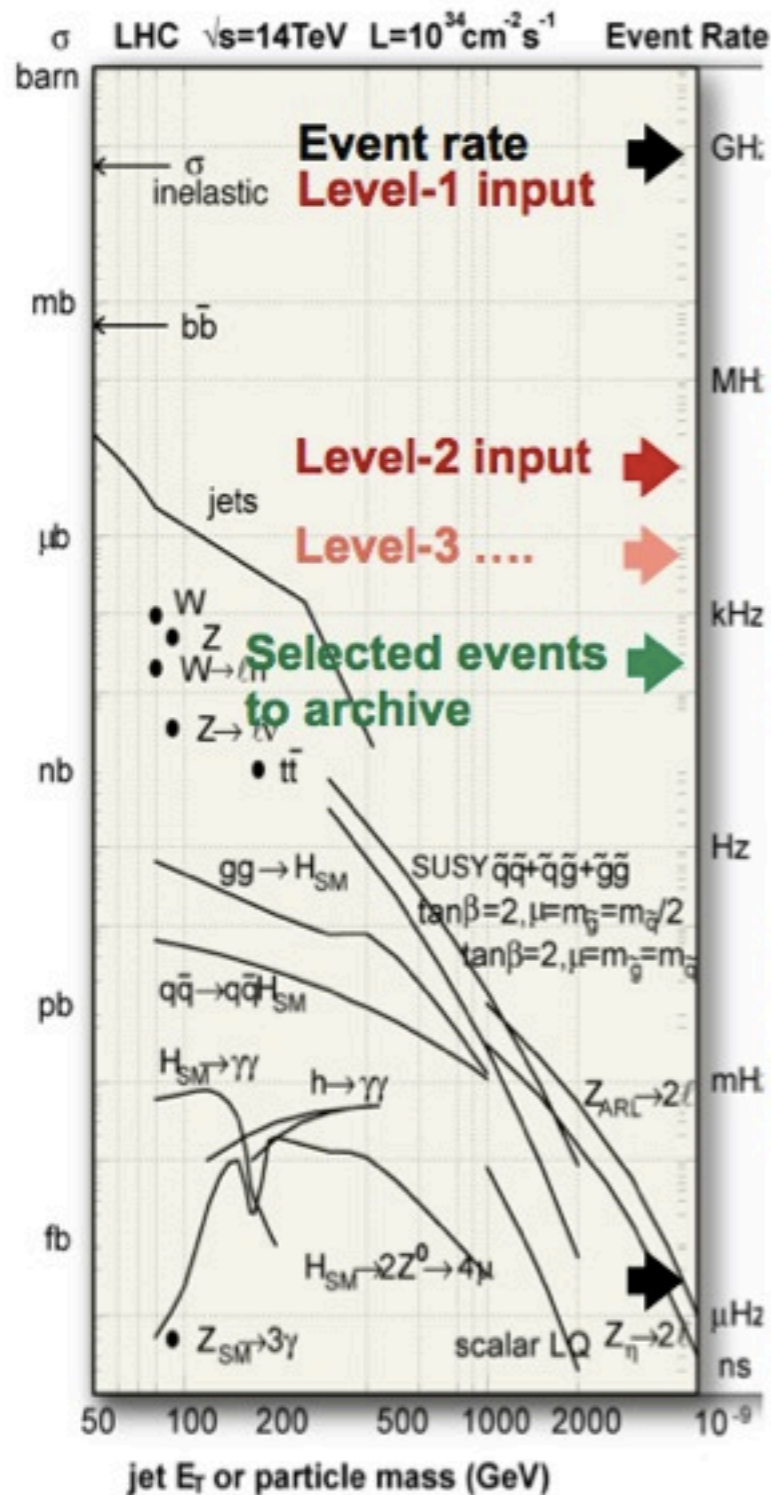
$$1 \text{ pb}^{-1} = 10^{36} \text{ cm}^{-2}$$

$$15 \text{ nb} \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1} = 150 \text{ Hz}$$

Segnatura sperimentale



Trigger



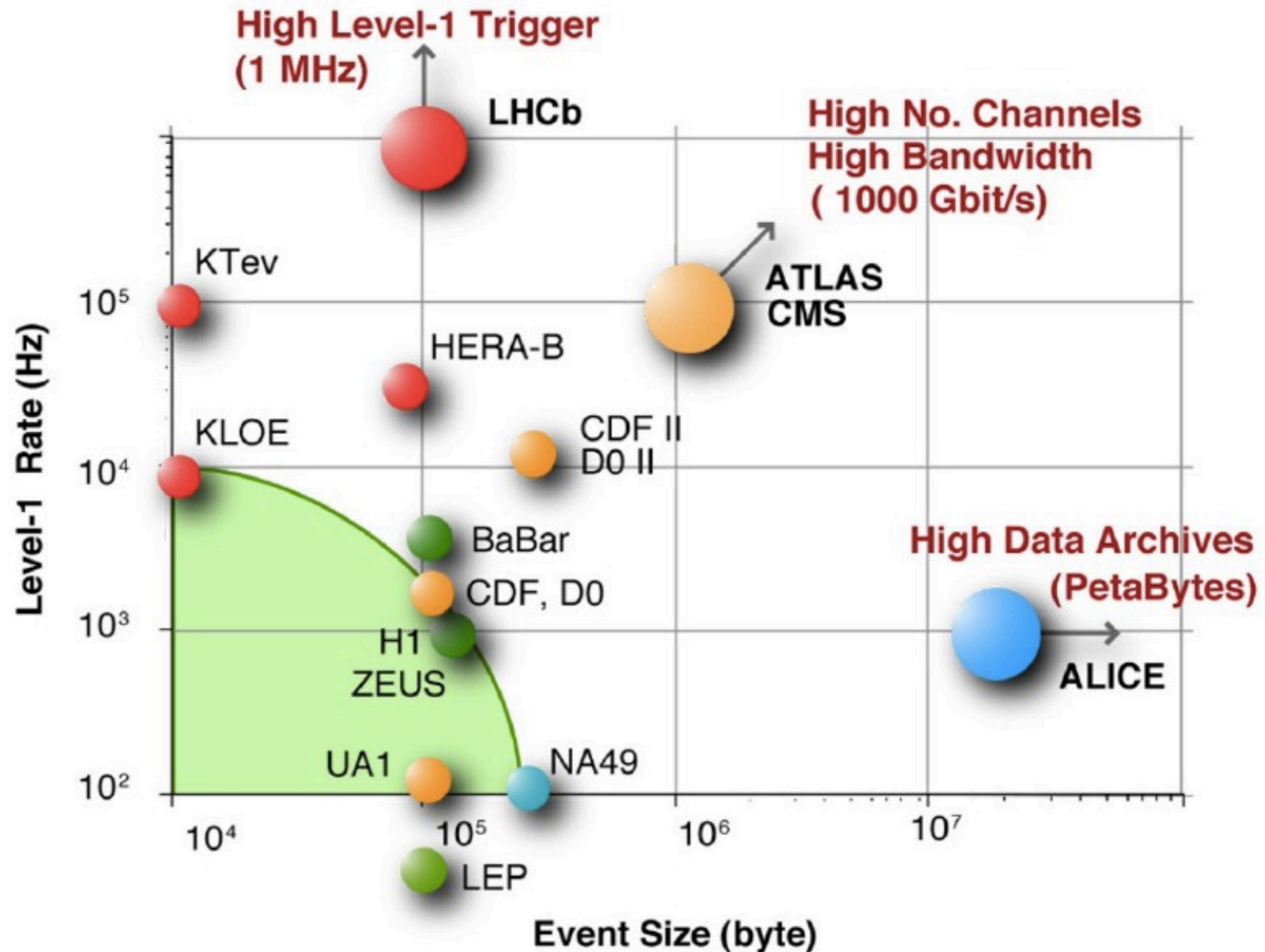
On-line requirements

Crossing rate	40 MHz
Event size	1 Mbyte
Level-1 Trigger input	40 MHz
Level-2 Trigger input	100 kHz
.....	
Mass storage rate	~300 Hz
Online rejection	99.999%

DAQ design issues

Data network bandwidth (EVB)	~ Tb/s
Computing power (HLT)	~ 10 Tflop
Computing cores	~ 10000
Local storage	~ 300 TB

Confronto trigger/Daq



Luminosita'

- sezione d'urto e' data da:

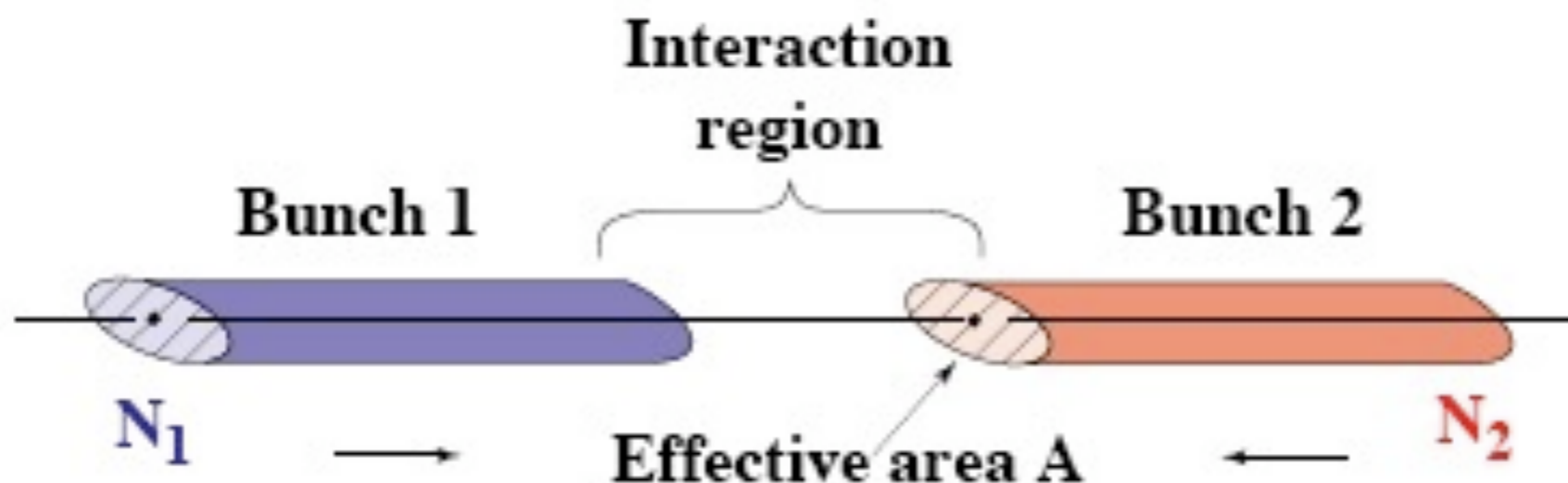
$$\sigma = \frac{\dot{N}_f}{\Phi N_b} = \frac{\dot{N}_f}{\mathcal{L}}; \quad \mathcal{L} = \Phi N_b$$

- la luminosita' istantanea \mathcal{L} ha le dimensioni del flusso $\Phi \text{ cm}^{-2} \text{ s}^{-1}$
- maggiore e' il flusso, maggiore e' la luminosita', piu' alto e' il numero di conteggi per unita' di tempo nello stato finale

$$\int \mathcal{L} dt = \mathcal{L}_{int} [\text{cm}^{-2}]$$

- la luminosita' integrata nel tempo piu' essere misurata in unita' di sezione d'urto inversa, ie barn⁻¹
- in un campione di eventi corrispondente a 10 nb^{-1} ci aspettiamo 10^9 eventi di minimum bias ($\sigma \sim 100 \text{ mb}$) e un centinaio di W ($\sigma \sim 10 \text{ nb}$)

Luminosita' di un collisore



$$\mathcal{L} = n_b \frac{N_1 N_2 f}{A_{eff}}$$

dove n_b e' il numero di pacchetti, N_1 e N_2 sono rispettivamente il numero medio di particelle in ciascun pacchetto nei due fasci, f e' la frequenza di incrocio, e A_{eff} e' la sezione trasversa

Luminosita' di un collisore

$$\begin{aligned}N_1 = N_2 &\sim 10^{10} \\n_b &= 2 \\A_{eff} &\sim (50\mu m)^2 \\f &= 11kHz \\ \Rightarrow \mathcal{L} &\sim 10^{28} cm^{-2} s^{-1}\end{aligned}$$

la corrente di un fascio di particelle e' $n_b N$. L'energia immagazzinata nel fascio e' proporzionale al numero totale di particelle. Se la corrente l'energia massima accessibile e' limitata, per massimizzare la luminosita' e' piu' conveniente mettere tutte le particelle in un unico pacchetto: la luminosita' cresce con il quadrato del numero di particelle nel pacchetto

Parametri di LHC

$$L = \frac{N_b^2 M f_{rev} \gamma_r}{4 \pi \varepsilon_n \beta^*} F \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

Number of particles per bunch	N_b	1.15 ‰ 10¹¹
Number of bunches per beam	M	2808
Revolution frequency	f_{rev}	11245 Hz
Relativistic velocity factor	γ_r	7461 (” $E = 7 \text{ TeV}$)
b-function at the collision point	β^*	55 cm
Normalised rms transverse beam emittance	ε_n	3.75 ‰ 10⁻⁴ cm
Geometric reduction factor	F	0.84

$$L = \frac{1}{4 \pi} \frac{N_b^2 M f_{rev}}{\sigma_x \sigma_y} F; (\sigma \text{ design } 16 \mu\text{m})$$

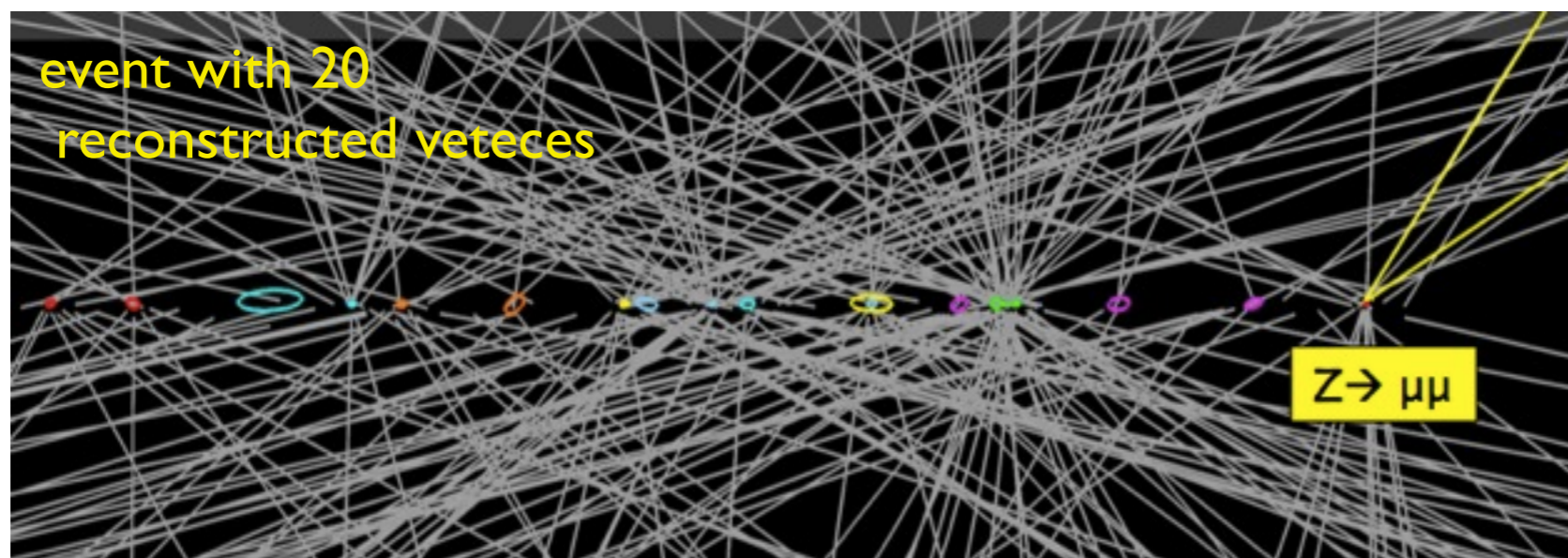
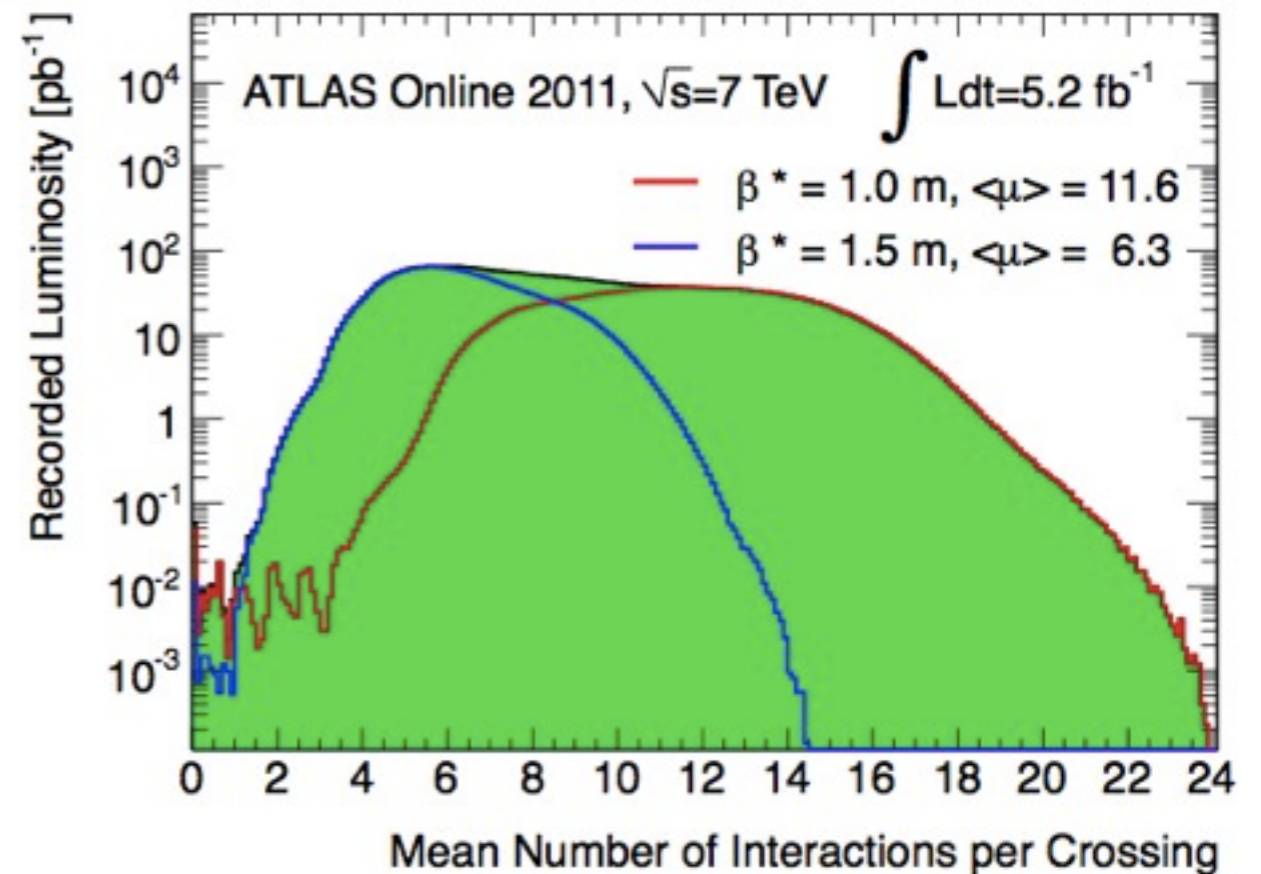
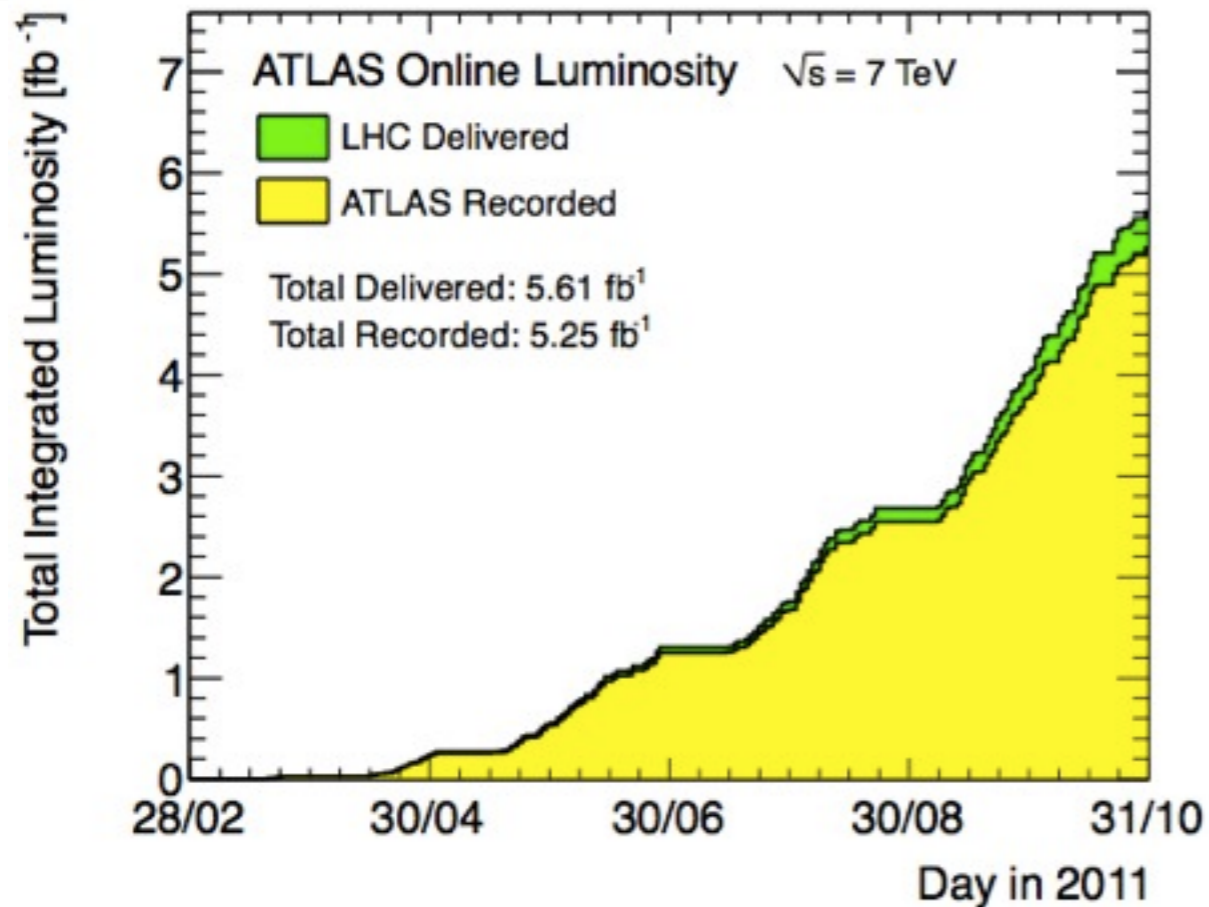
Numero di interazioni per incrocio

Ad una data luminosita' il numero di interazioni per incrocio sara':

$$\mu = \frac{\mathcal{L}}{n_b \cdot f} \cdot \sigma_{tot} =$$
$$\frac{10^{28}}{11kHz} * 50mb \sim 0.01$$

Il numero di interazioni per incrocio cresce al crescere della luminosita' ed e' inversamente proporzionale al numero di pacchetti. Ad alta luminosita' per contenere il numero di interazioni per incrocio ad un valore ragionevole (~ 20) e' necessario avere molti pacchetti

Luminosita' e pileup



Determinazione della luminosita'

- la misura della luminosita' e' di estrema rilevanza sia per gli esperimenti che per l'acceleratore:
 - ✓ misure di sezione d'urto
 - ✓ ottimizzazione della luminosita' dell'acceleratore
 - ✓ determinazione di parametri dell'acceleratore data la luminosita'
- Siamo interessati sia alla misura della luminosita' relativa che assoluta:
 - ✓ relativa: e' riferita alla luminosita' ottenuta in delle condizioni specifiche
 - ◆ permette di ottenere tutte le informazioni utili sulle condizioni del rivelatore e dell'acceleratore: andamento della luminosita' in funzione del tempo e dei parametri dell'acceleratore
 - ✓ assoluta: e' necessario ottenere una costante di calibrazione che definisca la scala di luminosita' (barn^{-1})
 - ◆ e' necessario avere una luminosita' assoluta per misurare una sezione d'urto

Misura relativa della luminosita'

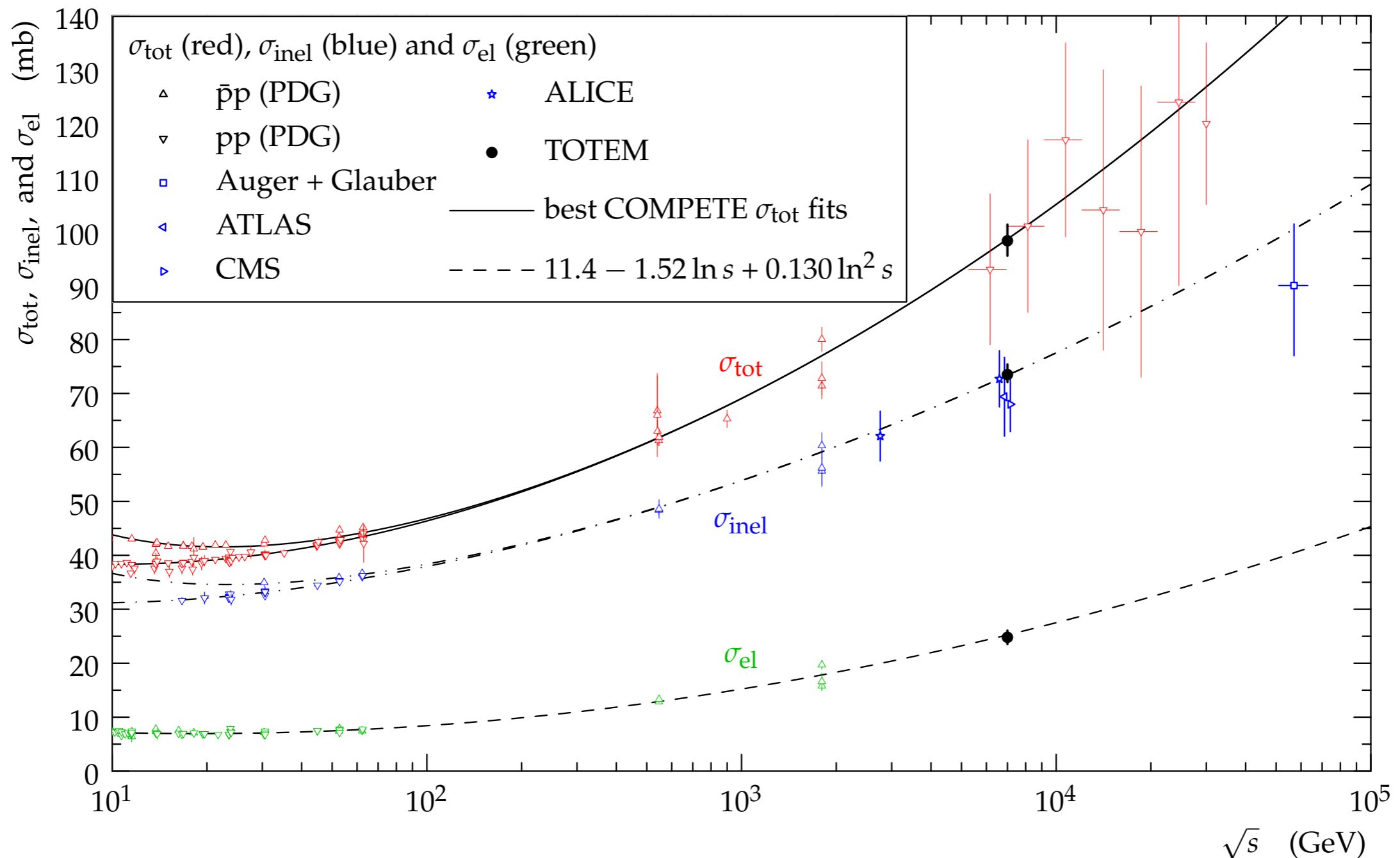
$$L = \frac{R_{inelastic}}{Acceptance \times \epsilon \times \sigma_{inelastic}}$$

- Poiche' la luminosita' e' proporzionale alla rate di collisione qualunque processo di interazione puo' essere utilizzato. Purche':
 1. sia possibile ottenere una misura robusta in breve tempo ($\sim 10s$) per un ampio intervallo di luminosita' istantanee $10^{27}-10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 2. questa misura sia molto veloce, possibilmente sensibile al singolo pacchetto $t \sim 25ns$
 3. deve poter operare per diverse condizioni dell' acceleratore (μ)
 4. la misura della luminosita' (processo e rivelatore) non sia correlata con le misure da cui si vuole estrarre la sezione d'urto
 5. avere piu' di un rivelatore che misuri la luminosita'. In particolare e' opportuno avere rivelatori che coprano regioni diverse in eta

Collisioni adroniche: σ_{tot}

$$\sigma_{\text{total}} = \sigma_{\text{elastic}} + \sigma_{\text{non-diffractive}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}}$$

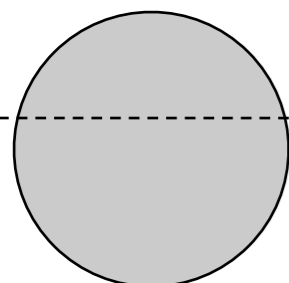
$$\sigma_{\text{total}} \sim 4\pi r_P^2 = 4\pi \cdot (1\text{fm})^2 \sim 100\text{mb}$$



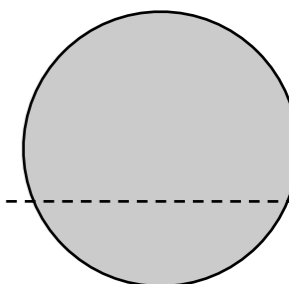
Collisioni adroniche

- **diffusione elastica:** diffusione in avanti a piccoli angoli
gli adroni rimangono intatti

$$\frac{d\sigma}{d\theta} \sim \frac{1}{\theta^4}$$

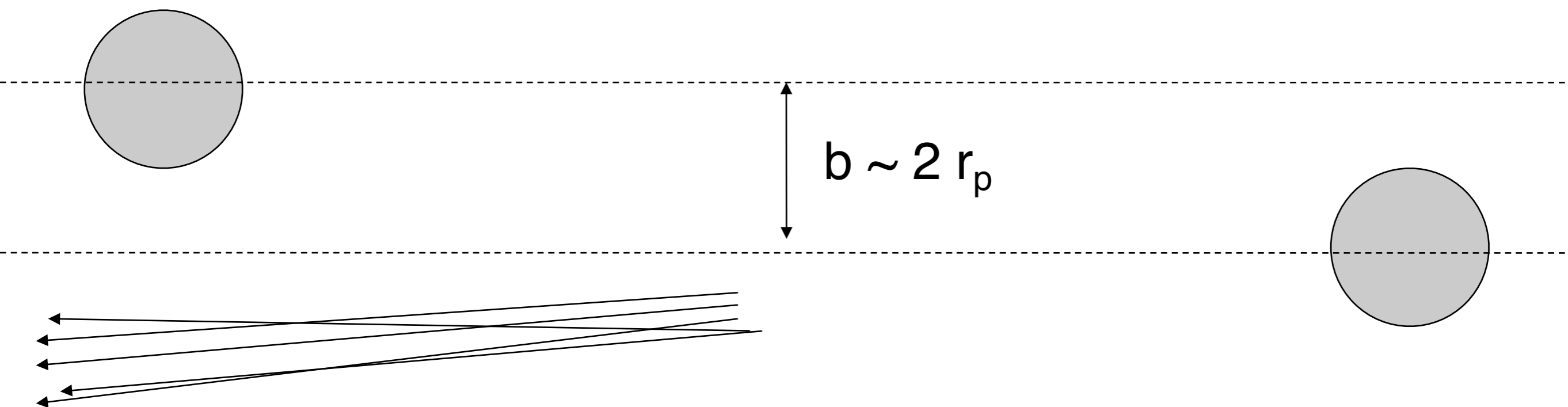


$$b \gg 2 r_p$$



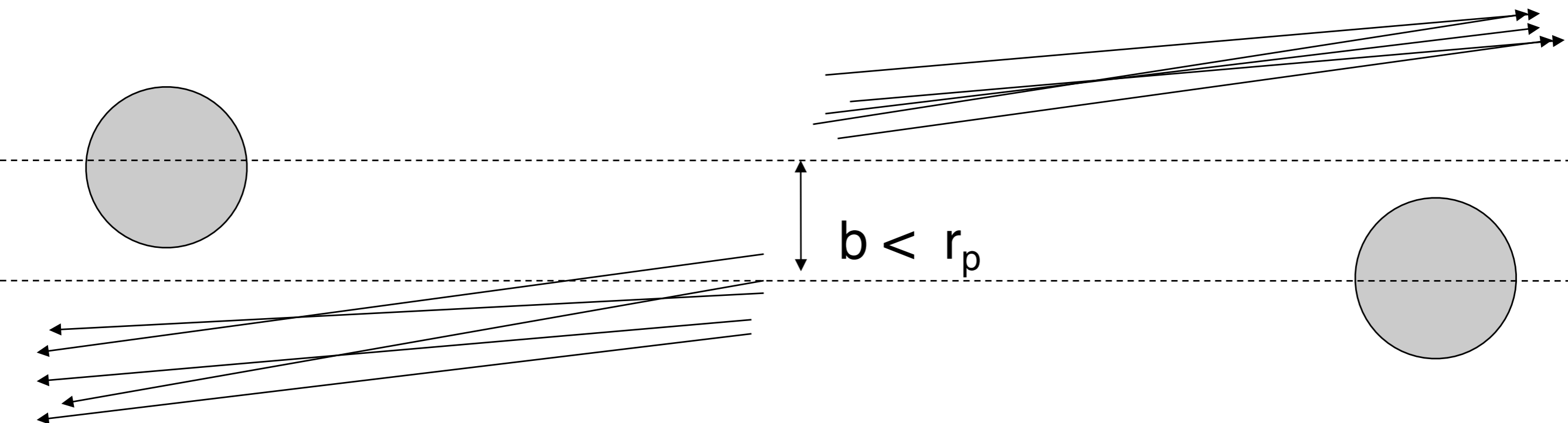
Collisioni adroniche

- **diffusione inelastica singola diffrattiva:** uno dei due adroni si dissocia in un sistema con massa invariante piccola. le particelle prodotte, in maggioranza pioni, procedono nella direzione dell'adrone iniziale



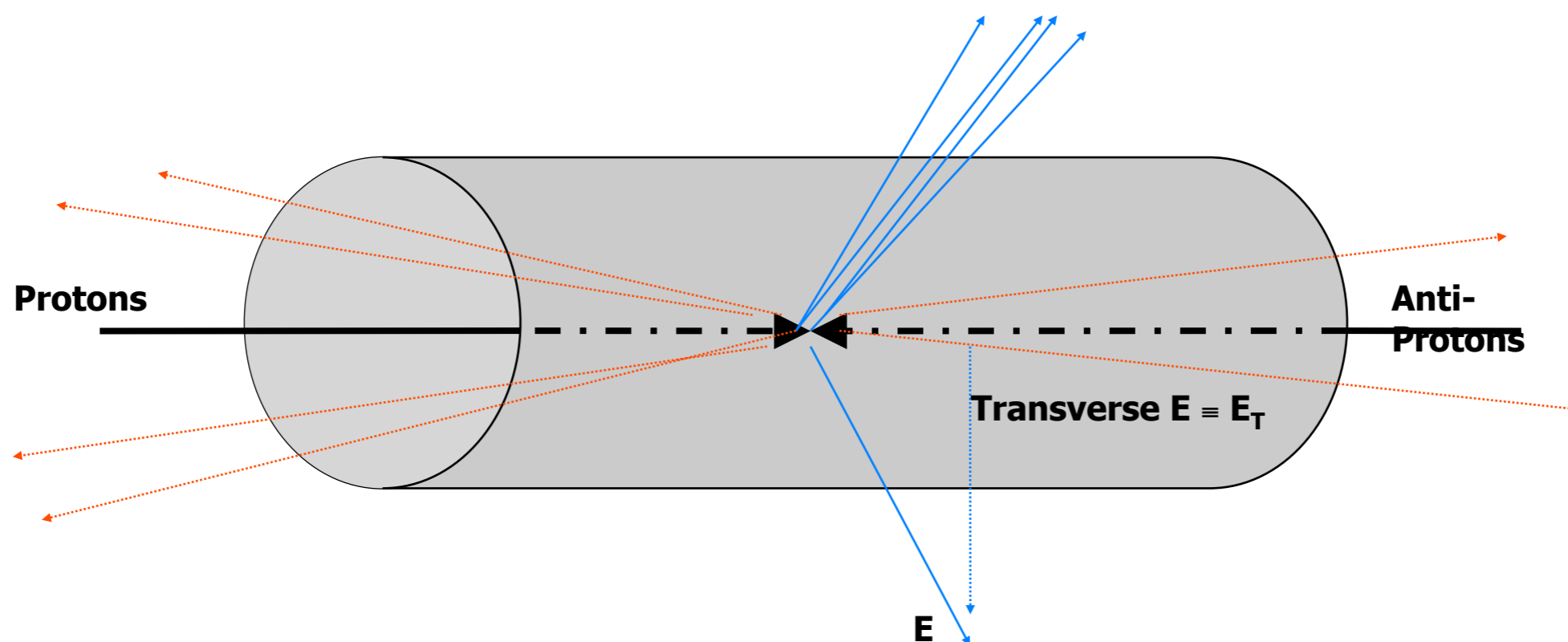
Collisioni adroniche

- **diffusione inelastica doppio diffrattiva:** entrambi gli adroni si dissociano in un sistema con massa invariante piccola. le particelle prodotte, in maggioranza pioni, procedono nella direzione dell'adrone iniziale



Collisioni adroniche

- **diffusione inelastica non-diffrattiva:** entrambi gli adroni si dissociano e i prodotti dell'interazione sono distribuiti in modo uniforme in rapidita' e hanno un impulso trasverso non trascurabile



Sezione d'urto

$$d\sigma \sim \frac{V}{v_{rel}} |\mathcal{A}_{i \rightarrow f}|^2 d\Phi_f$$

- $\frac{V}{v_{rel}}$ e' il flusso incidente
- $\mathcal{A}_{i \rightarrow f}$ e' l'ampiezza di trasizione da "i" verso "f"
- ✓ $\mathcal{A}_{i \rightarrow f}$ contiene tutta la dinamica dell'interazione $i \rightarrow f$
 - ◆ cioe' contiene la forza dell'interazione
 - ◆ la dipendenza dai 4-impulsi dello stato iniziale e finale
- $d\Phi_f$ e' lo spazio delle fasi per lo stato finale "f"
 - ✓ nota la dipendenza di $\mathcal{A}_{i \rightarrow f}$ da p_f $|\mathcal{A}_{i \rightarrow f}|^2 d\Phi_f$ determina la probabilita' di trovare lo stato finale "f" all'interno del elemento di volume dello spazio delle fasi $d\Phi_f$
- $d\sigma$ e' una probabilita' e deve essere indipendente dal sistema di riferimento!

Teorema ottico

$$H_I = I + iT;$$

$$H_I^\dagger H_I = I;$$

$$\Rightarrow (I - iT^\dagger)(I + iT) = I;$$

$$I - i(T^\dagger - T) + T^\dagger T = I;$$

$$i(T^\dagger - T) = T^\dagger T;$$

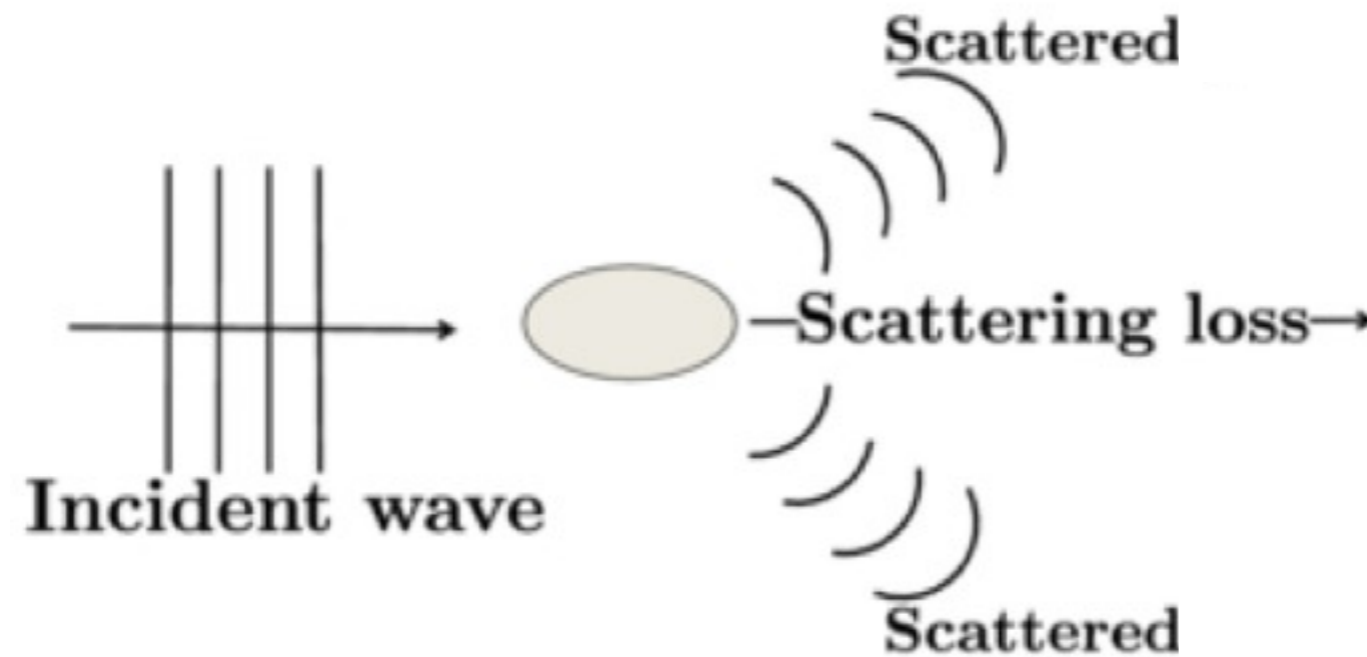
$$i \langle f, p_f | (T^\dagger - T) | i, p_i \rangle = \sum_k \langle f, p_f | T^\dagger | k, p_k \rangle \langle k, p_k | T | i, p_i \rangle;$$

$$|f, p_f \rangle = |i, p_i \rangle;$$

$$i \langle i, p_i | (T^\dagger - T) | i, p_i \rangle = \sum_k | \langle k, p_k | T | i, p_i \rangle |^2;$$

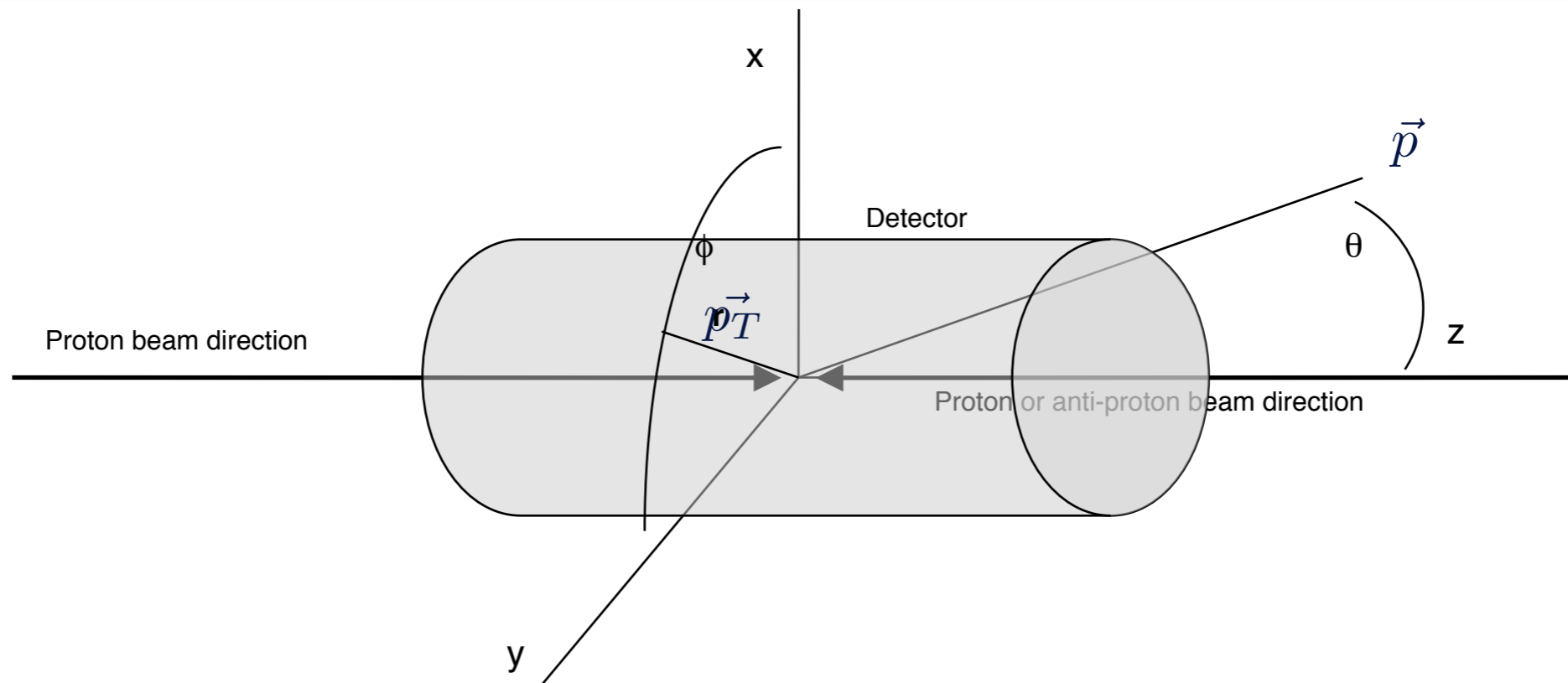
$$\frac{4\pi\hbar}{p_{cm}} \Im f_{el}(\theta = 0) = \sigma_{tot}$$

Teorema ottico



- la componente in avanti della diffusione elastica e' legata alla diffusione in tutti i canali elastici ed inelastici (sezione d'urto totale)
- il semplice fatto che una particella possa essere diffusa da un bersaglio richiede che ci sia una componente di diffusione elastica in avanti tale da interferire distruttivamente con la particella incidente e conservare la corrente totale
 - ✓ conservazione della corrente: unitarieta' della matrice di diffusione

Coordinate



$$d\Phi_{i \rightarrow f} = d\vec{x}d\vec{p} = V p^2 dp d\Omega \sim p^2 dp d\cos\theta d\phi = \pi p^2 dp d\cos\theta$$

$$\vec{p} = \vec{p}_{\parallel} + \vec{p}_T$$

$$p_T = |\vec{p}| \sin\theta$$

$$p_{\parallel} = |\vec{p}| \cos\theta$$

$$d\vec{p} = p^2 dp d\Omega = dp_{\parallel} p_T dp_T d\phi$$

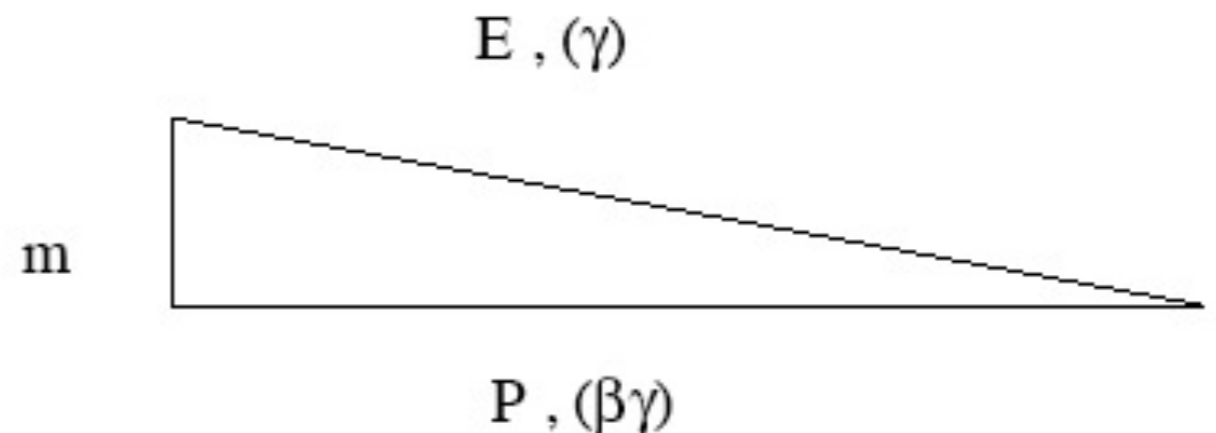
Cinematica

$$p_\mu = (E, \vec{p}); \quad p_\mu p^\mu = E^2 - |\vec{p}|^2 = m^2$$

$$\beta = \frac{v}{c} = \frac{|\vec{p}|}{E}$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} = \frac{E}{m}$$

$$\vec{p} = \vec{p}_{\parallel} + \vec{p}_T$$



- facendo un cambiamento di sistema di riferimento $\vec{x} \rightarrow \vec{x}'$ con un boost nella direzione $\vec{p}_{\parallel} / |\vec{p}_{\parallel}|$ il 4-impulso nel nuovo sistema di riferimento è dato da:

$$p'_{\parallel} = \gamma(p_{\parallel} + \beta E)$$

$$E' = \gamma(E + \beta p_{\parallel})$$

➡ lo spazio delle fasi $d\vec{p} = p^2 dp d\Omega = dp_{\parallel} p_T dp_T d\phi$ non è invariante

Spazio delle fasi (invariante)

$$d\vec{p} = p^2 dp d\Omega = dp_{\parallel} p_T dp_T d\phi$$

$$d^4 p \delta(E^2 - p^2 - m^2) = \frac{d\vec{p}}{E} = p_T dp_T d\phi dy; \quad dy = \frac{dp_{\parallel}}{E}$$

$$E^2 - p_{\parallel}^2 = p_T^2 + m^2 \equiv m_T^2$$

$$\sinh^2 y + \cosh^2 y = 1 \quad \Rightarrow \quad \sinh y = \frac{p_{\parallel}}{m_T}; \quad \cosh y = \frac{E}{m_T}; \quad \text{and} \quad \tanh y = \frac{p_{\parallel}}{E}$$

- lo spazio delle fasi ha densita' costante in y
- ➔ assumendo che p_T sia limitato dalla dinamica ($\mathcal{A}_{i \rightarrow f}$) la produzione di particelle (a piccoli y) ha una distribuzione costante in y .

$$\Rightarrow E \frac{d\sigma}{d\vec{p}} \quad \text{sezione d'urto invariante}$$

Rapidita'

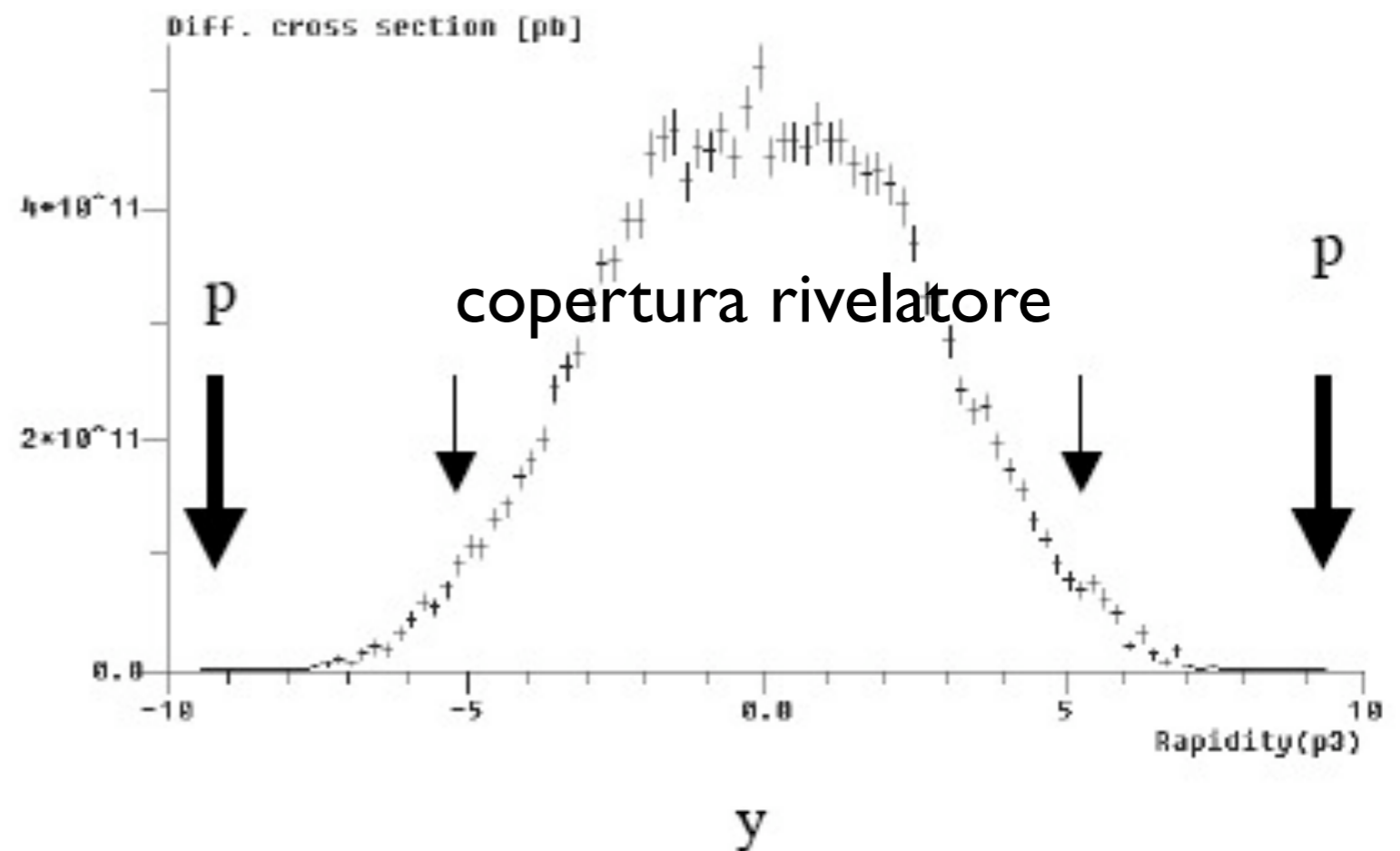
$$e^y = \sinh y + \cosh y = \frac{E + p_{\parallel}}{m_T} = \frac{E + p_{\parallel}}{E - p_{\parallel}}$$

$$y \rightarrow y_{max} \text{ for } p_T \rightarrow 0; p_{\parallel} \rightarrow p \Rightarrow y_{max} = \ln \sqrt{s/M^2}$$

$pp @ 2, 14 TeV$

$y_{max} = 7.7, 9.6$

$\sigma(\text{pb})$



Rapidita', p_T , s

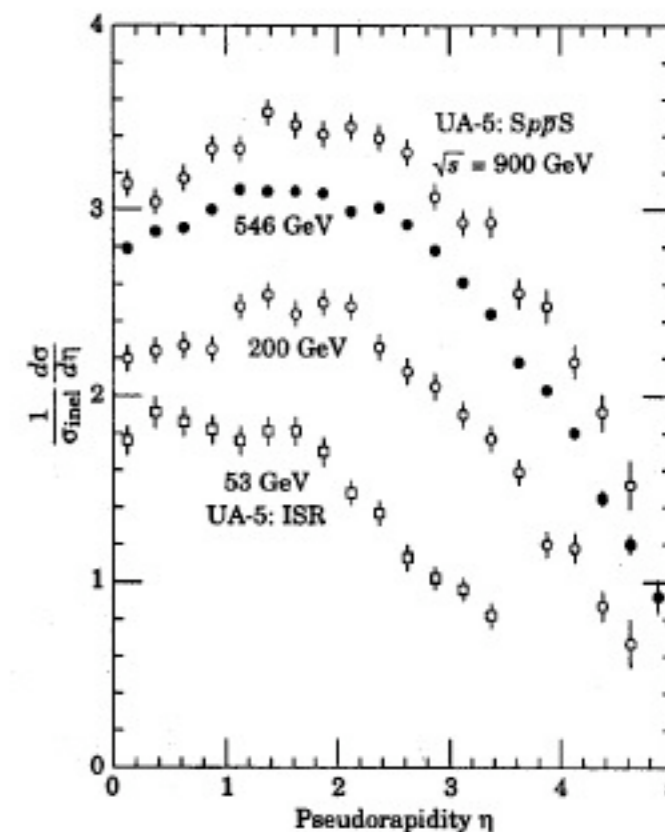
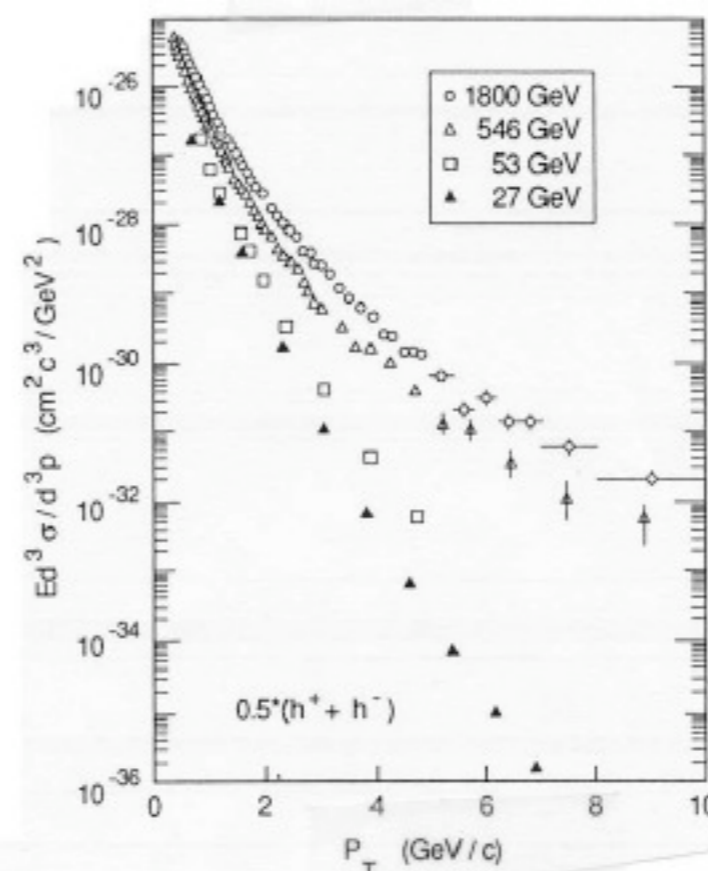
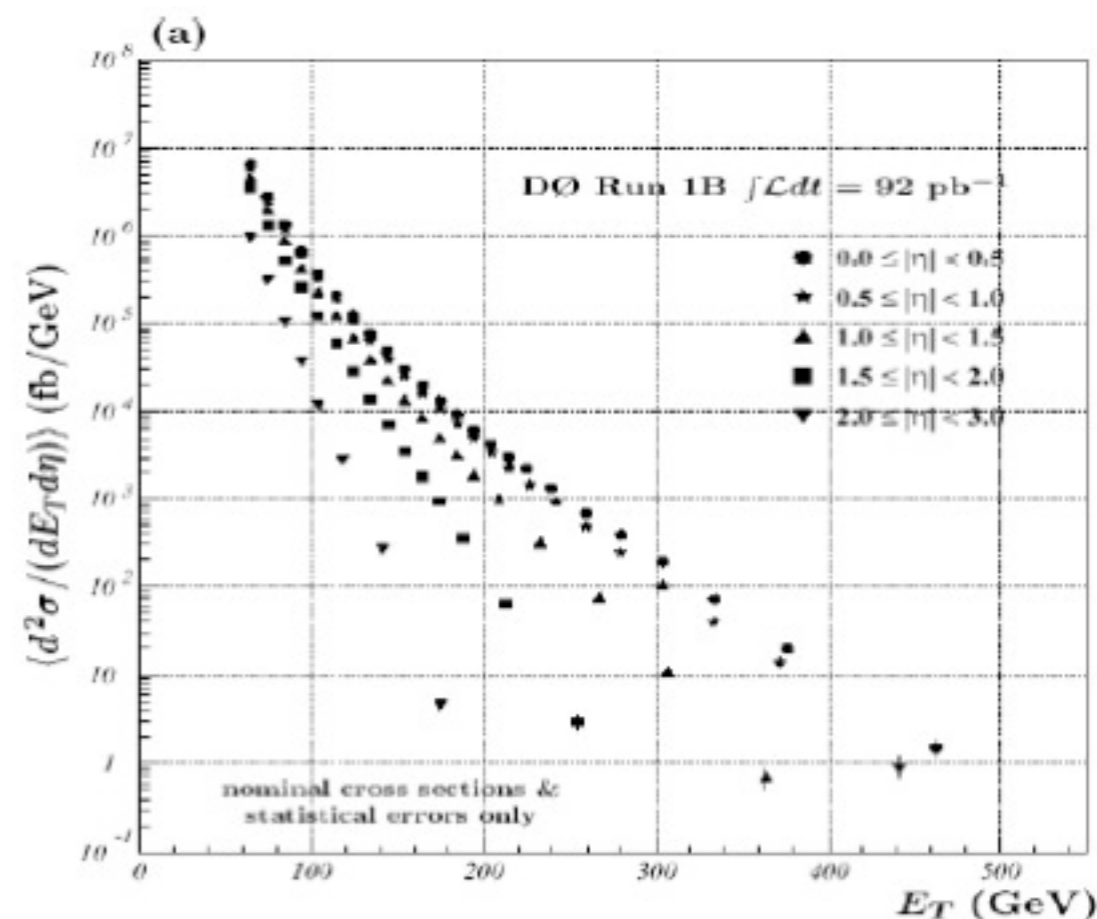
$$y_{max} = \ln \sqrt{s/M_T^2}$$

$$M_T^2 = M^2 + p_T^2$$

considerazioni puramente cinematiche (dipendenza di y da p_T e s) mostrano come la regione di rapidita' in cui la sezione d'urto rimane costante

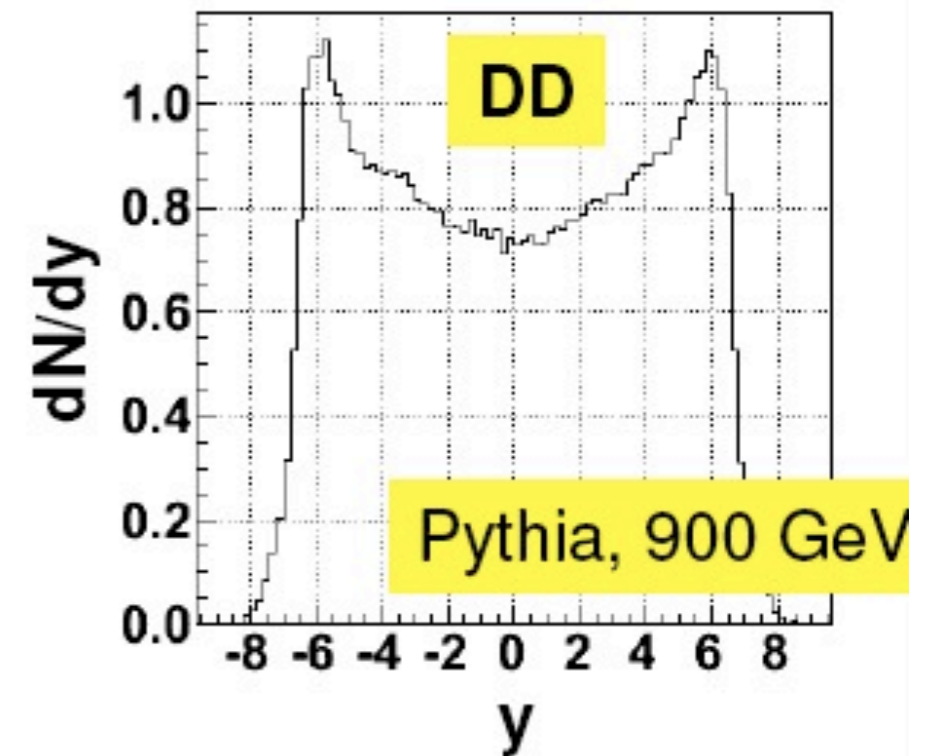
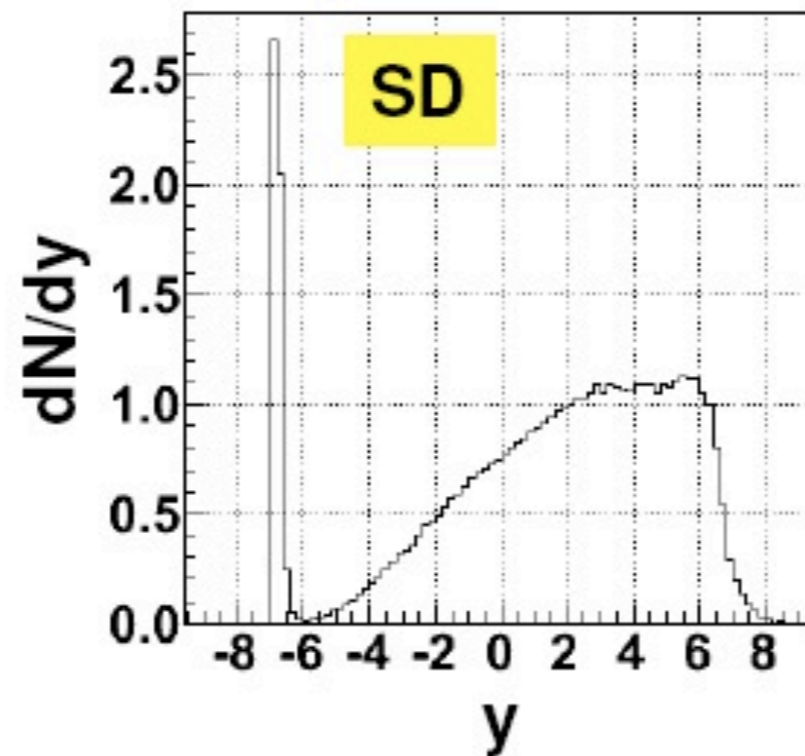
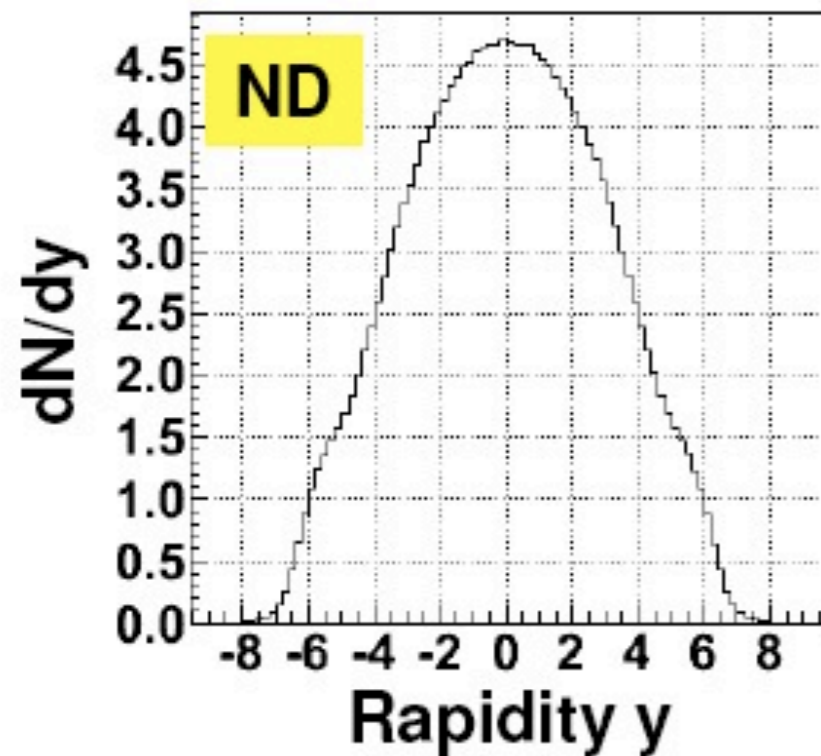
- si restringe al crescere di p_T
- si estende al crescere di s

questa dipendenza e' in entrambi in casi logaritmica



sezione d'urto adronica (rapidita')

$$\sigma_{\text{total}} = \sigma_{\text{elastic}} + \sigma_{\text{non-diffractive}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}}$$



Pseudo-rapidita' e rapidita'

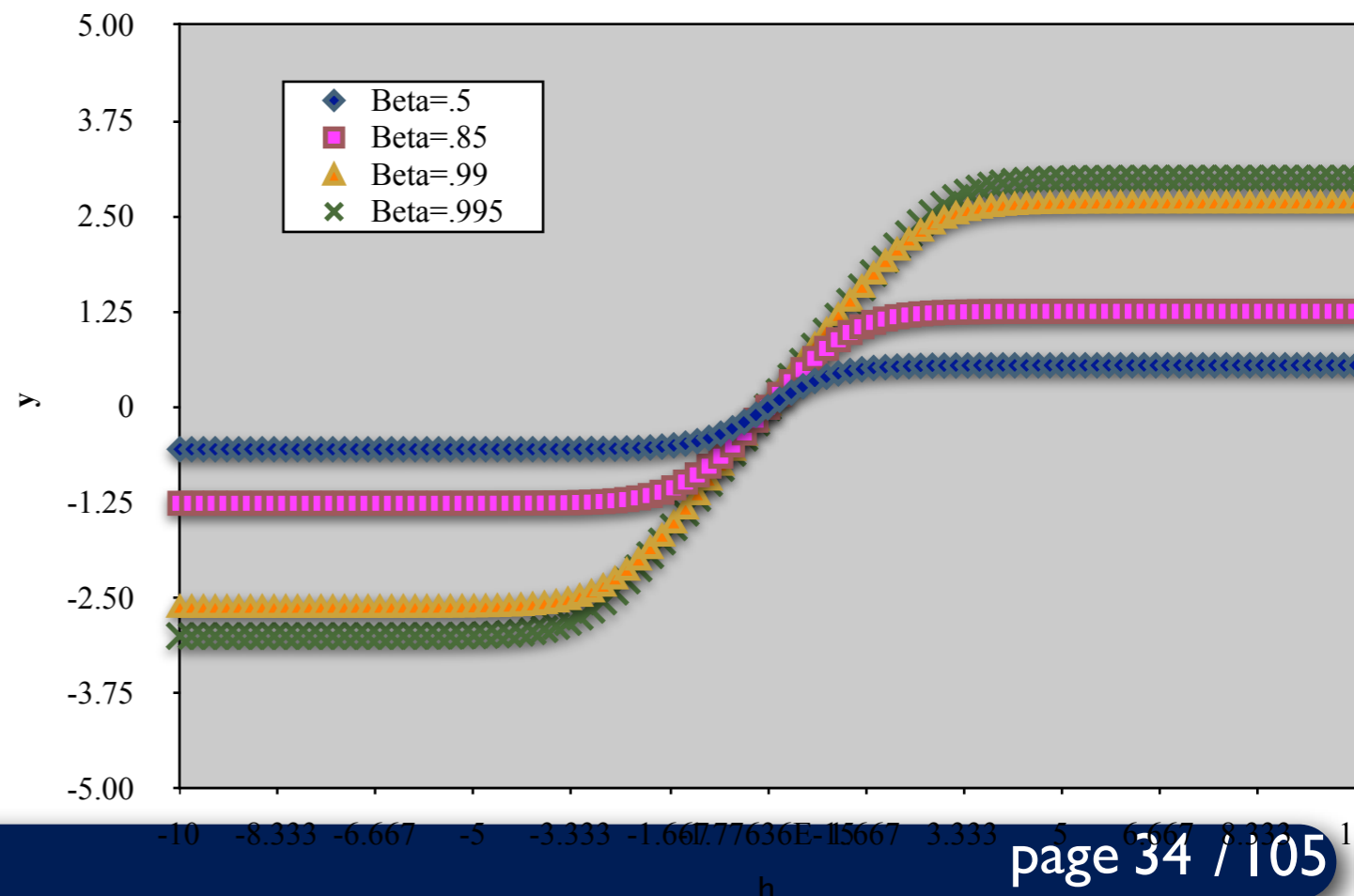
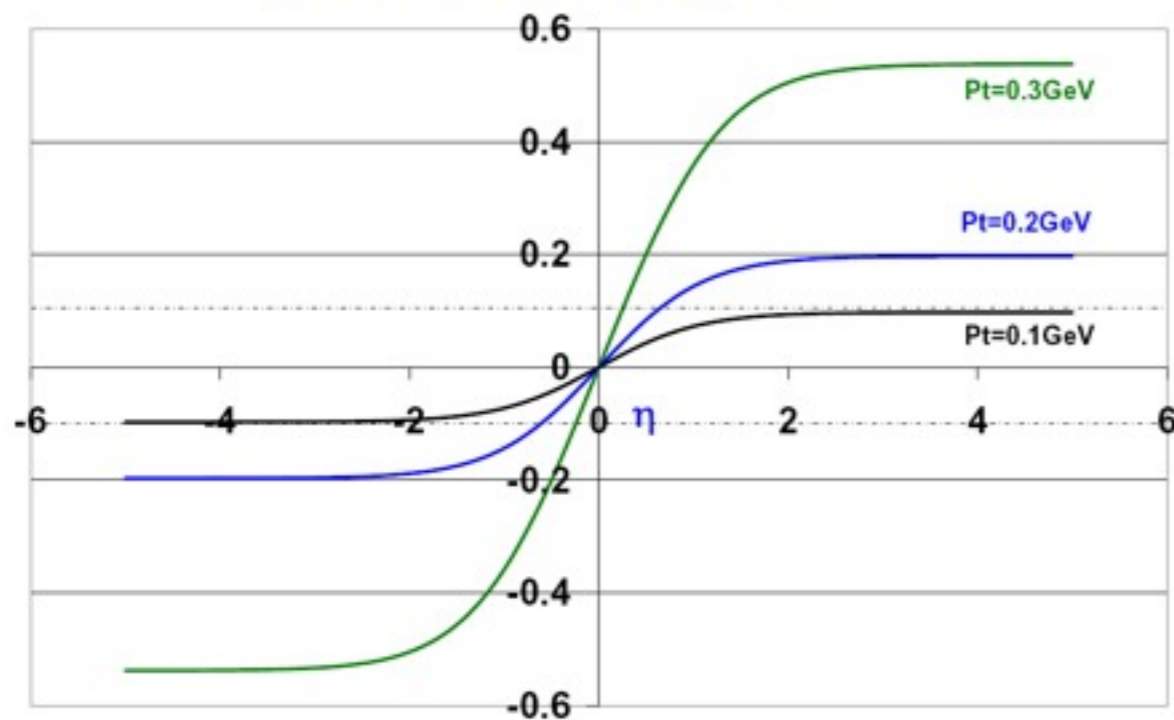
$$e^y = \sinh y + \cosh y = \frac{E + p_{\parallel}}{E - p_{\parallel}} = \frac{1 + p_{\parallel}/E}{1 - p_{\parallel}/E} = \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta}$$

$$\eta = \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta} = -\ln \left(\tan \frac{\theta}{2} \right)$$

$$\lim_{m \rightarrow 0} y(m) = \eta \quad |\eta| \geq |y|$$

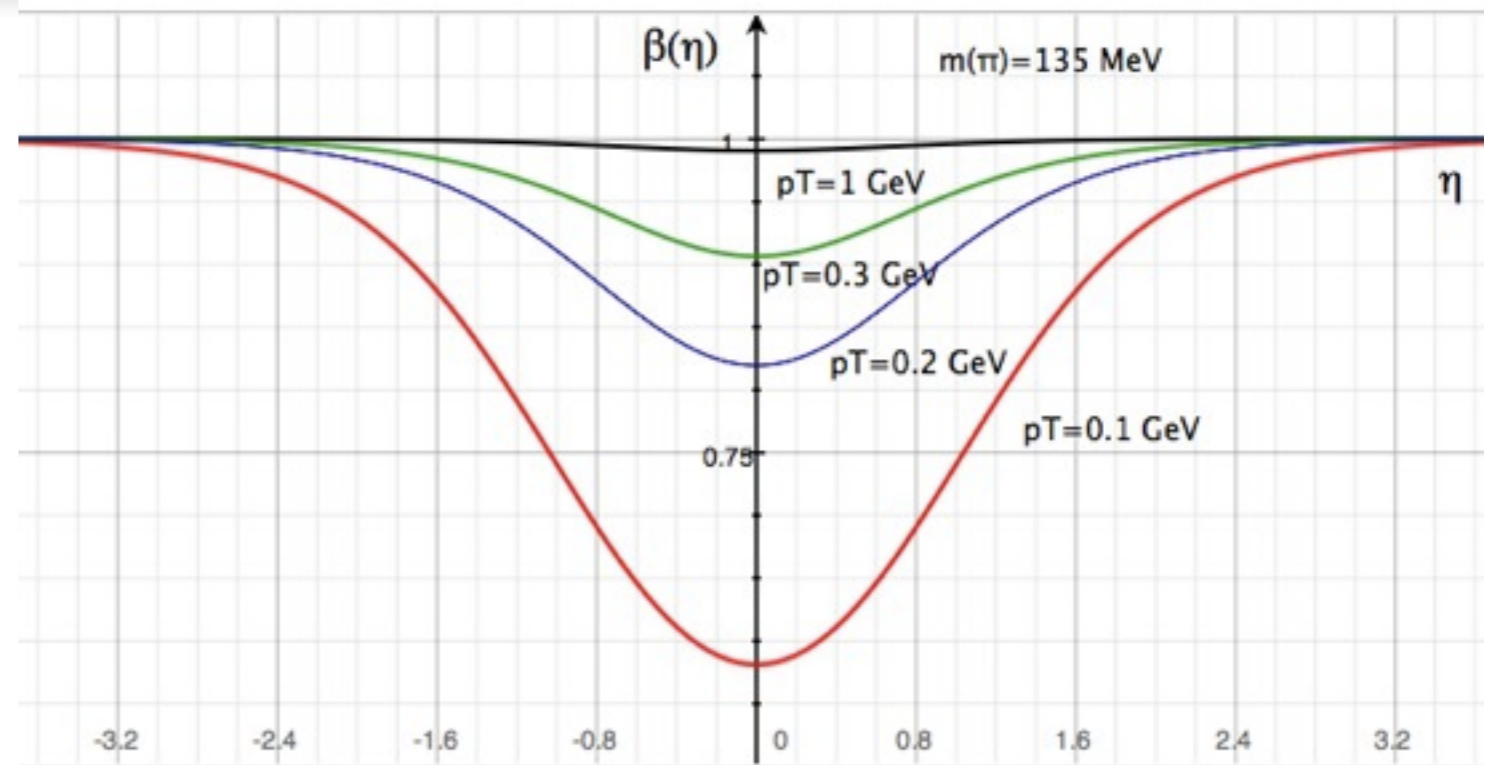
processi costanti in rapidita' non sono costati in pseudo-rapidita' (almeno per masse non trascurabili)

η - y v detector position (η) for π 's



pseudo-rapidita'

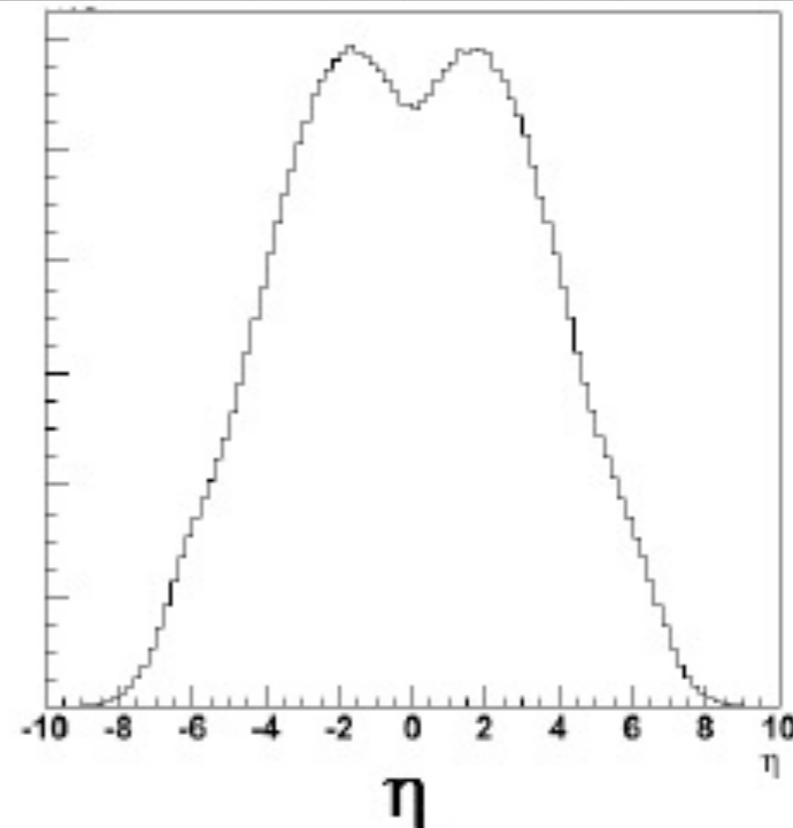
$$\frac{\sigma}{d\eta} = \frac{d\sigma}{dy} \frac{dy}{d\eta} = k\beta(\eta)$$



per particelle di bassa energia, la funzione di trasformazione ha un minimo pronunciato.

Questo implica che la distribuzione di particelle in funzione di eta non e' piu' piatta!

$$\frac{dN_{ch}}{d\eta}$$



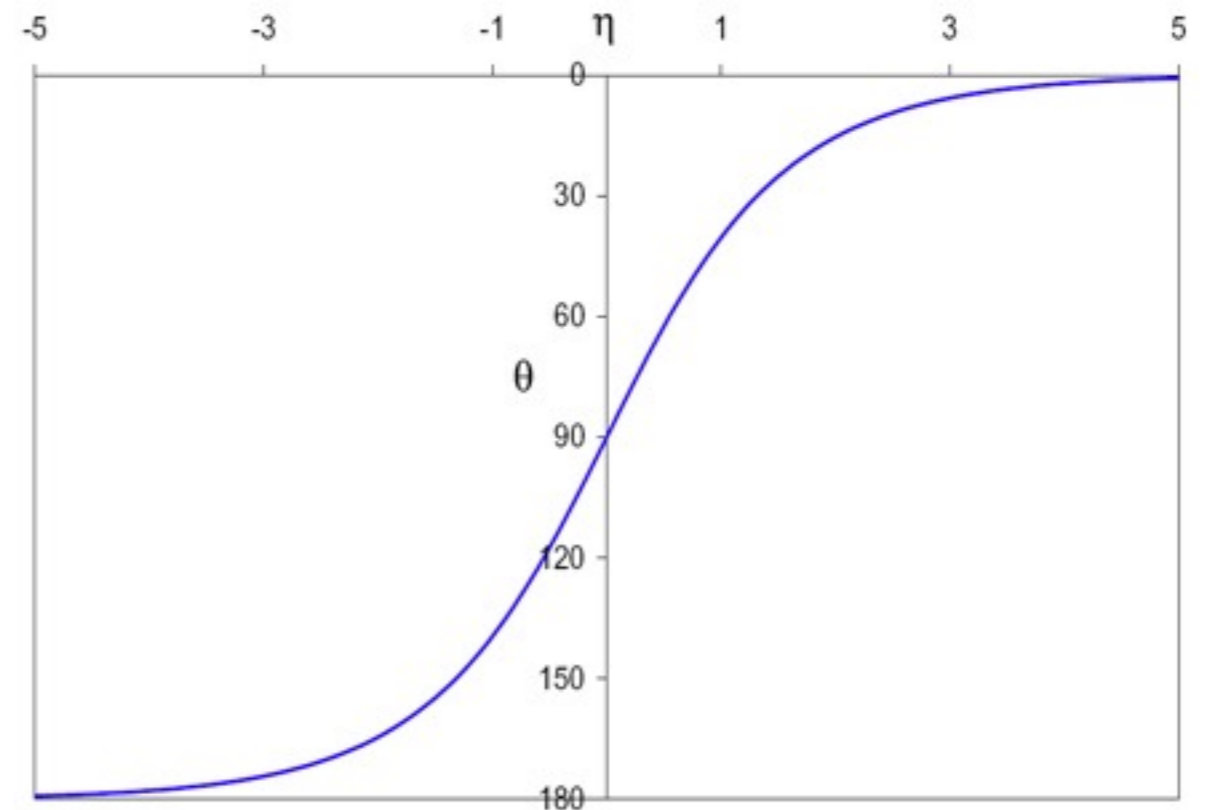
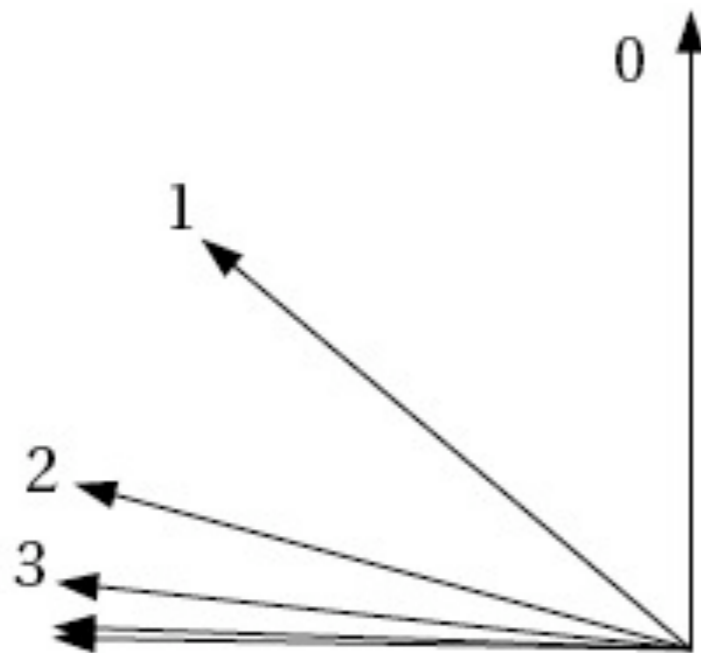
pseudo-rapidita'

la pseudo-rapidita' e' funzione solo di theta e non della massa della particella (ie e' uguale per tutte le particelle)

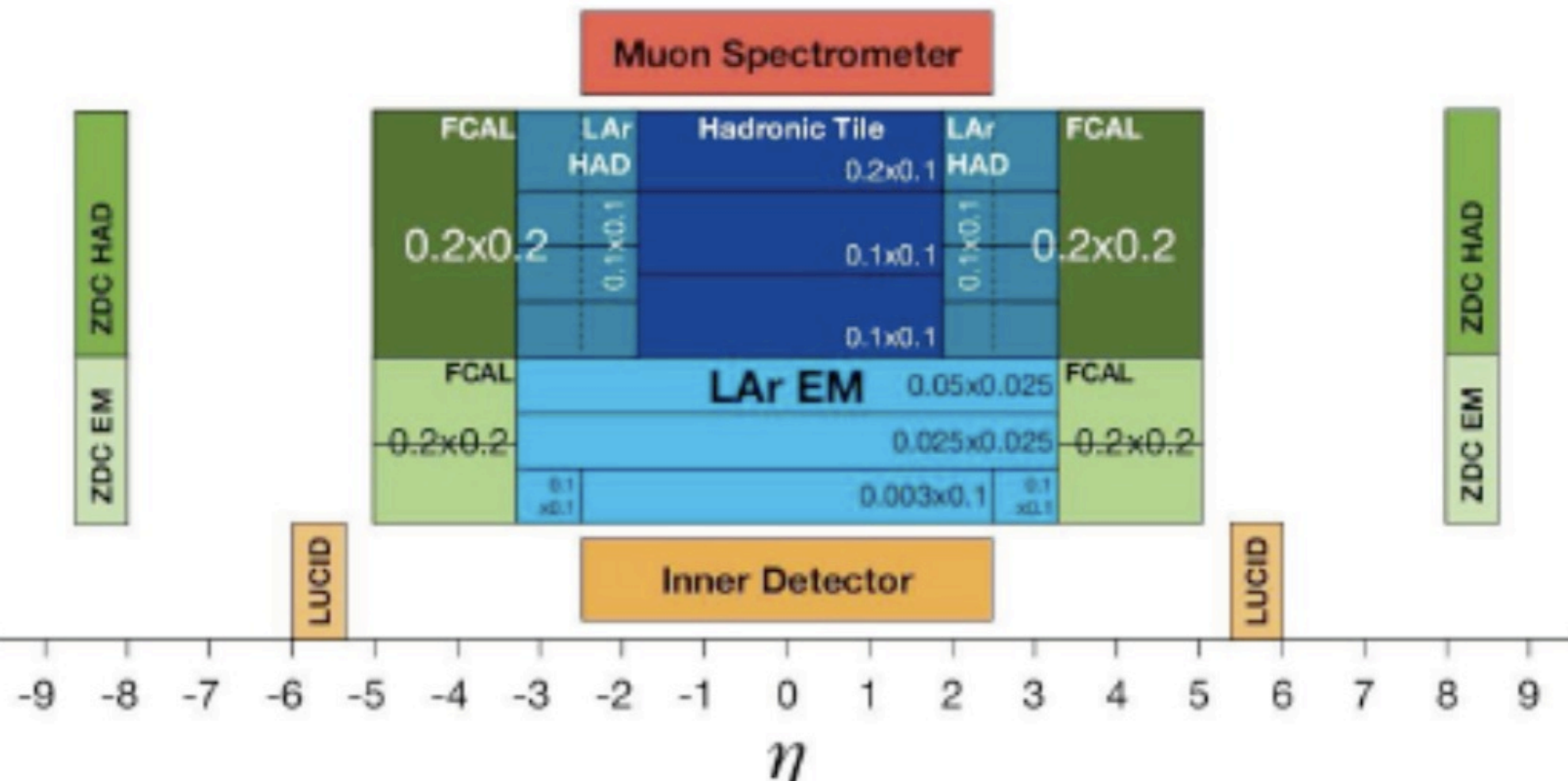
per impulsi $O(10M)$ la differenza tra y e $\eta < 10\%$

η e' la variable usata per concepire un rivelatore di particelle

η	θ
0	90°
± 1	$\pm 40^\circ$
± 2	$\pm 15^\circ$
± 3	$\pm 6^\circ$
± 4	$\pm 2^\circ$
± 5	$\pm 1^\circ$



Rivelatore



Feynman scaling

$$W = 2\sqrt{s}$$

$$\int f_i(p_T, x_F) d^2 p_T = f_i(x_F) \int g(p_T) d^2 p_T = f_i(x_F)$$

$$\langle N \rangle = \int f_i(p_T, x_F) \frac{d^3 p}{E} = \int f_i(x_F) \frac{dp_z}{\sqrt{W^2 x^2 + m_T^2}}$$

$$\langle N \rangle = \int_{-1}^1 f_i(x_F) \frac{dx_F}{\sqrt{x_F^2 + \frac{m_T^2}{W^2}}}$$

$$2 \int_0^1 f_i(x_F) \frac{dx_F}{\sqrt{x_F^2 + \frac{m_T^2}{W^2}}} < 2 \int_0^1 B \frac{dx_F}{\sqrt{x_F^2 + \frac{m_T^2}{W^2}}} = 2B \ln \left(x_F + \sqrt{x_F^2 + \frac{m_T^2}{W^2}} \right)_0^1$$

$$= 2B \ln \left(x_F + \sqrt{x_F^2 + \frac{m_T^2}{W^2}} \right) - 2B \ln \frac{m_T}{W}$$

$$\Rightarrow \langle N \rangle \propto \ln W \propto \ln \sqrt{s}$$

Ricapitolazione

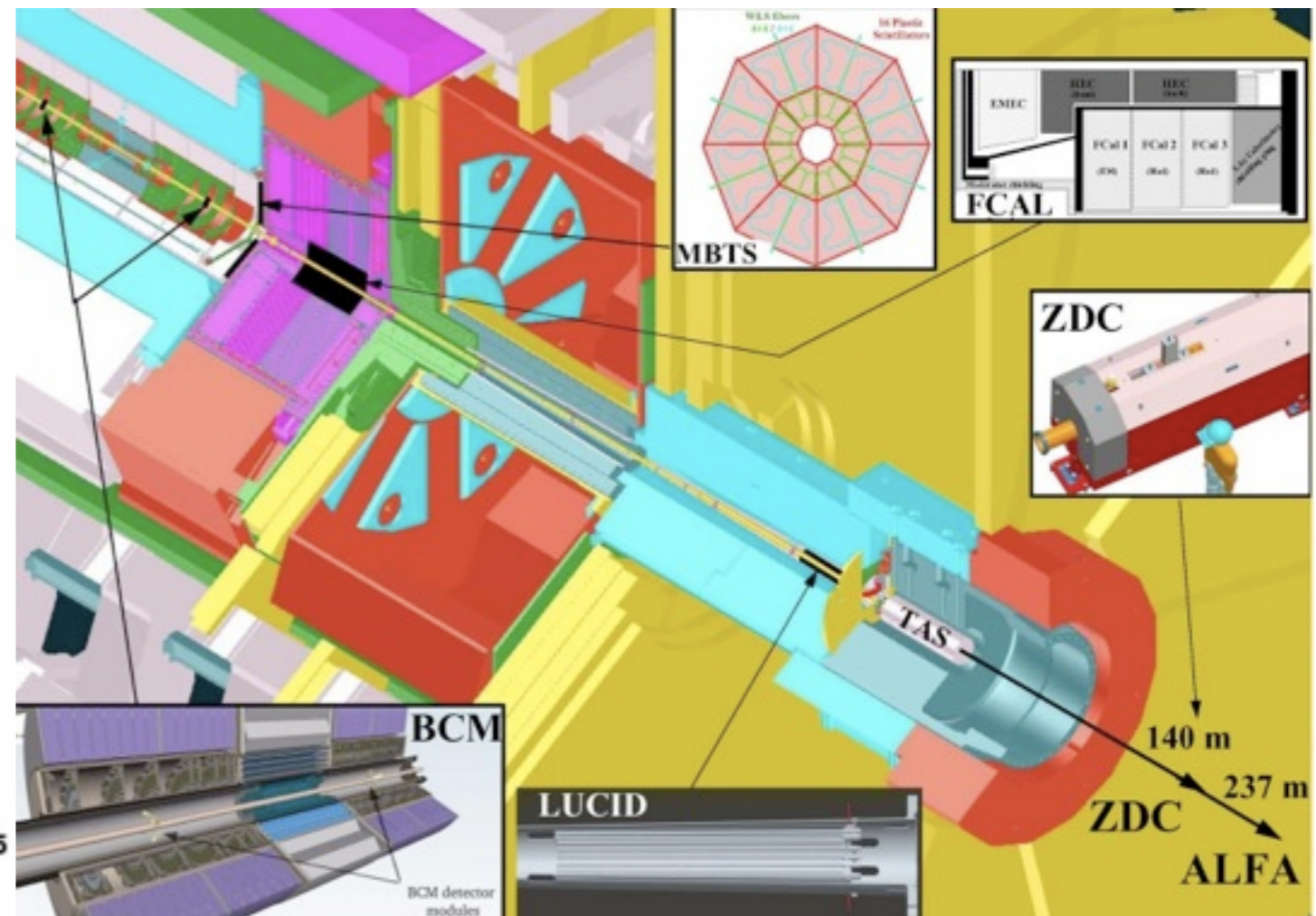
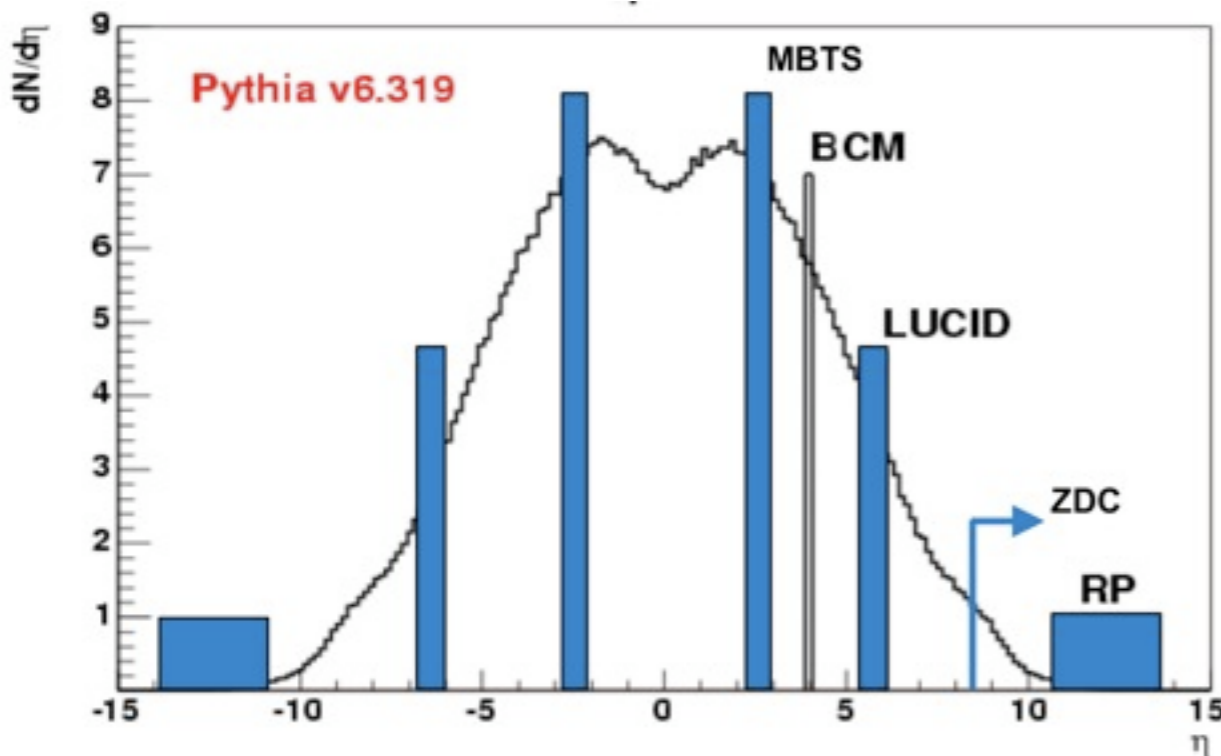
- la generalizzazione invariante dello spazio delle fasi richiede l'introduzione della rapidità y
- lo spazio delle fasi è uniforme in y
- se p_T è limitato dalla dinamica a piccoli y la distribuzione di particelle è costante
- $y_{max} = \ln \sqrt{s/M^2}$
- $\langle N \rangle \propto \ln \sqrt{s}$
- per energie sufficientemente più grandi della massa in gioco la rapidità tende alla pseudo-rapidità η (che è una variabile angolare)
- η è la variabile rispetto alla quale vengono concepiti i rivelatori in esperimenti ai collisori adronici

Rivelatori utilizzati per la luminosita'

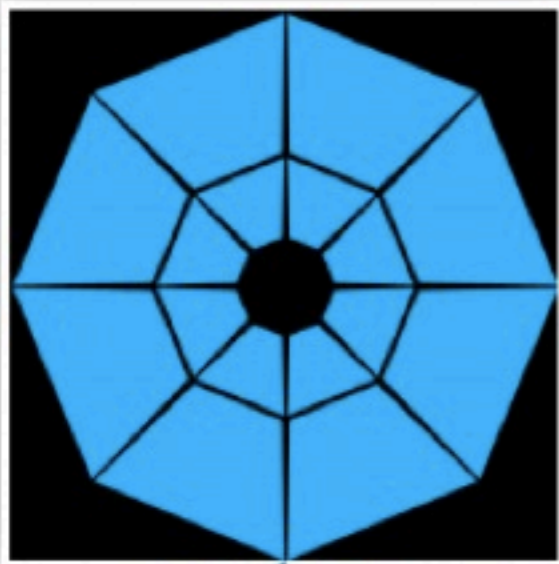
- normalmente self triggering
- insensibili al tempo morto dell'esperimento

Forward detectors

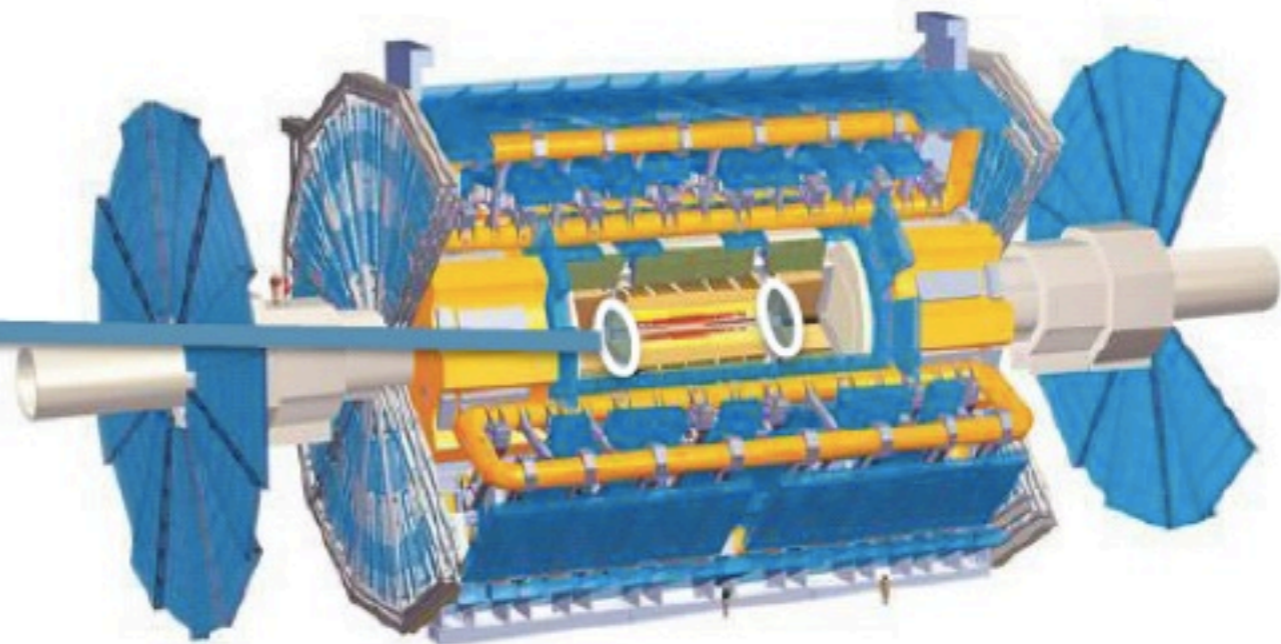
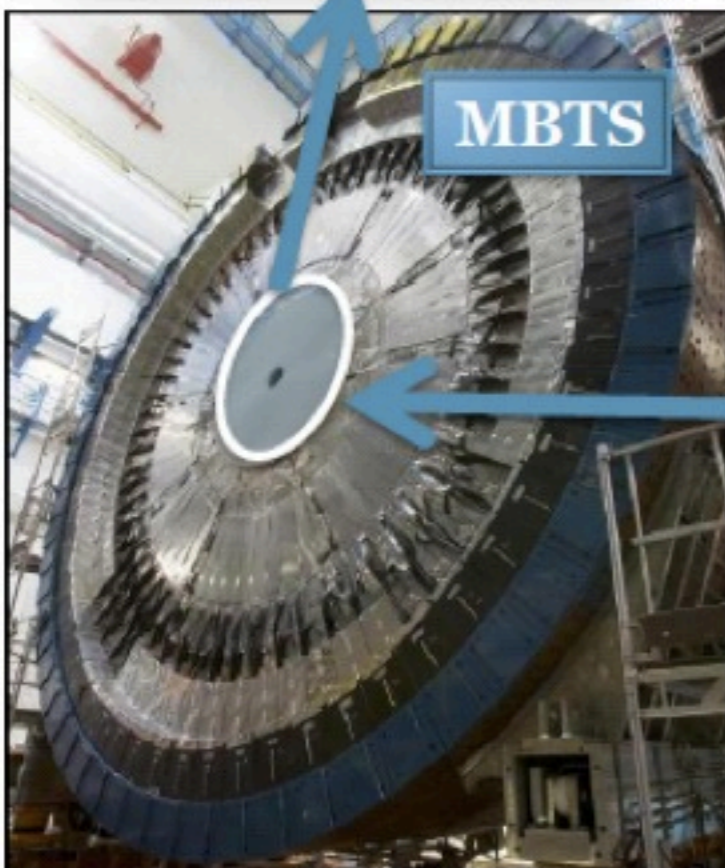
• MBTS	2.1	<	$ \eta $	<	3.8
• LUCID	5.6	<	$ \eta $	<	5.9
• ZDC			$ \eta $	>	8.3
• ALFA	10.6	<	$ \eta $	<	13.5



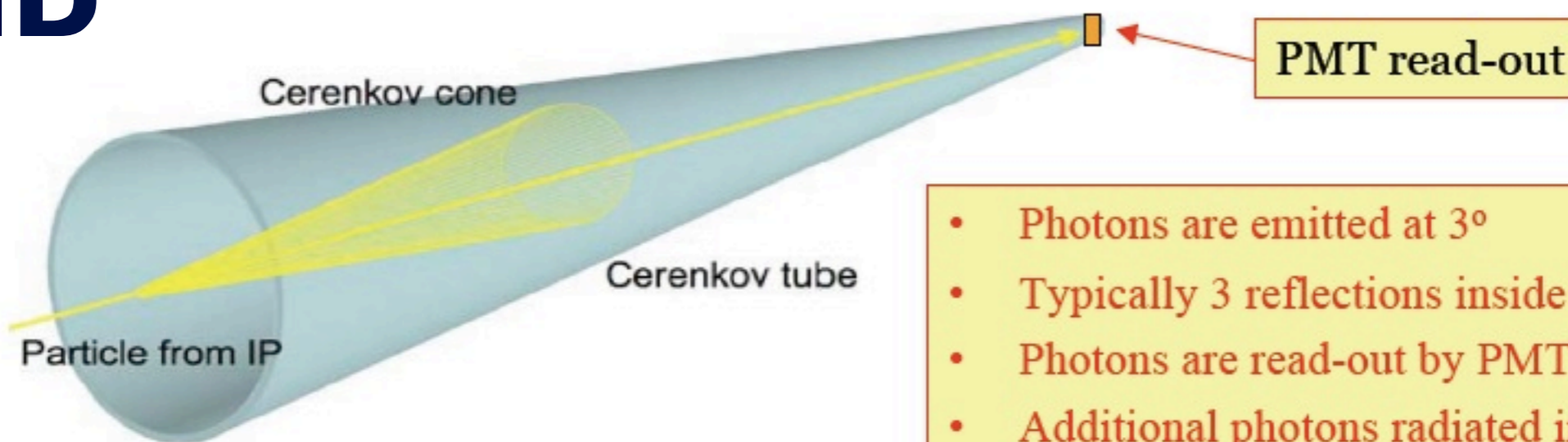
MBTS



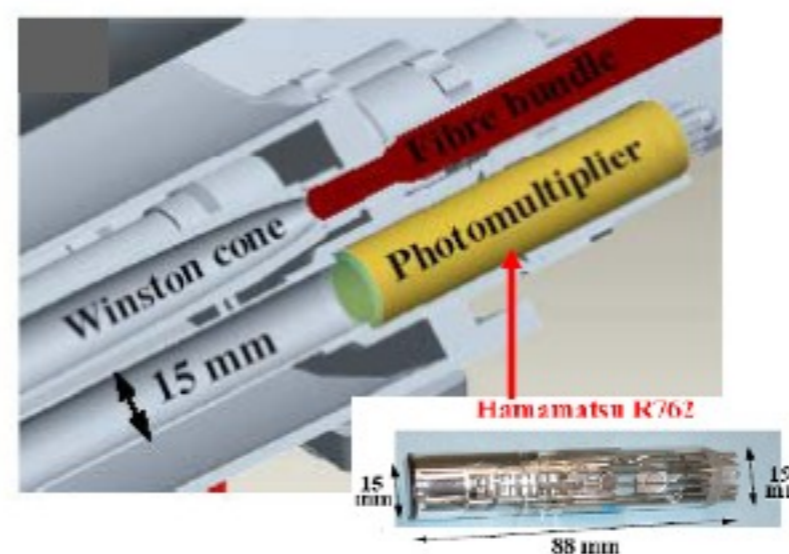
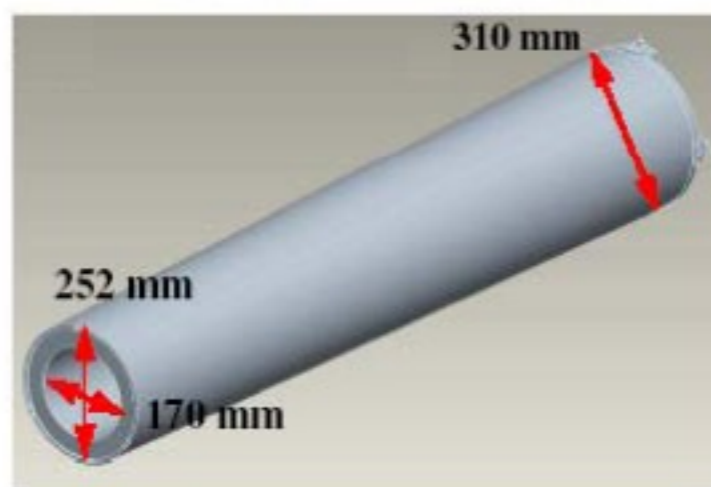
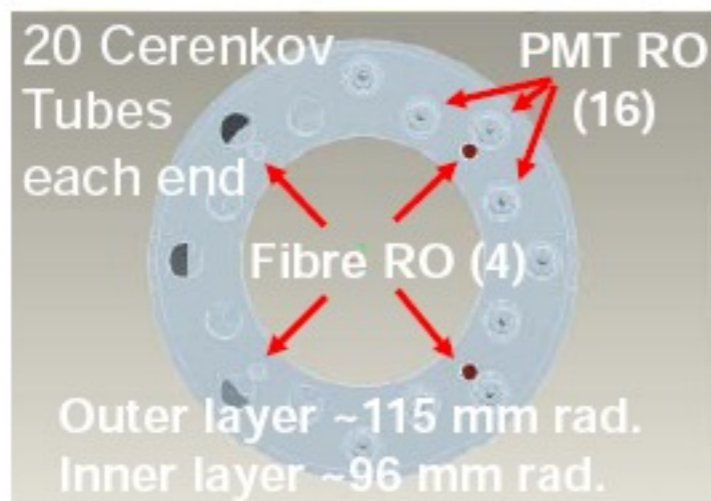
- **Segmented into 16 counters on each side.**
- Plastic scintillator planes connected to photomultiplier tubes via wavelength shifting fiber.
- Highly efficient trigger on charged particles.
- Generally trigger on the **Inclusive Or** of both sides.
- **MBTS is the primary Minimum Bias trigger.**
 - $2.1 < |\eta| < 3.8$



LUCID

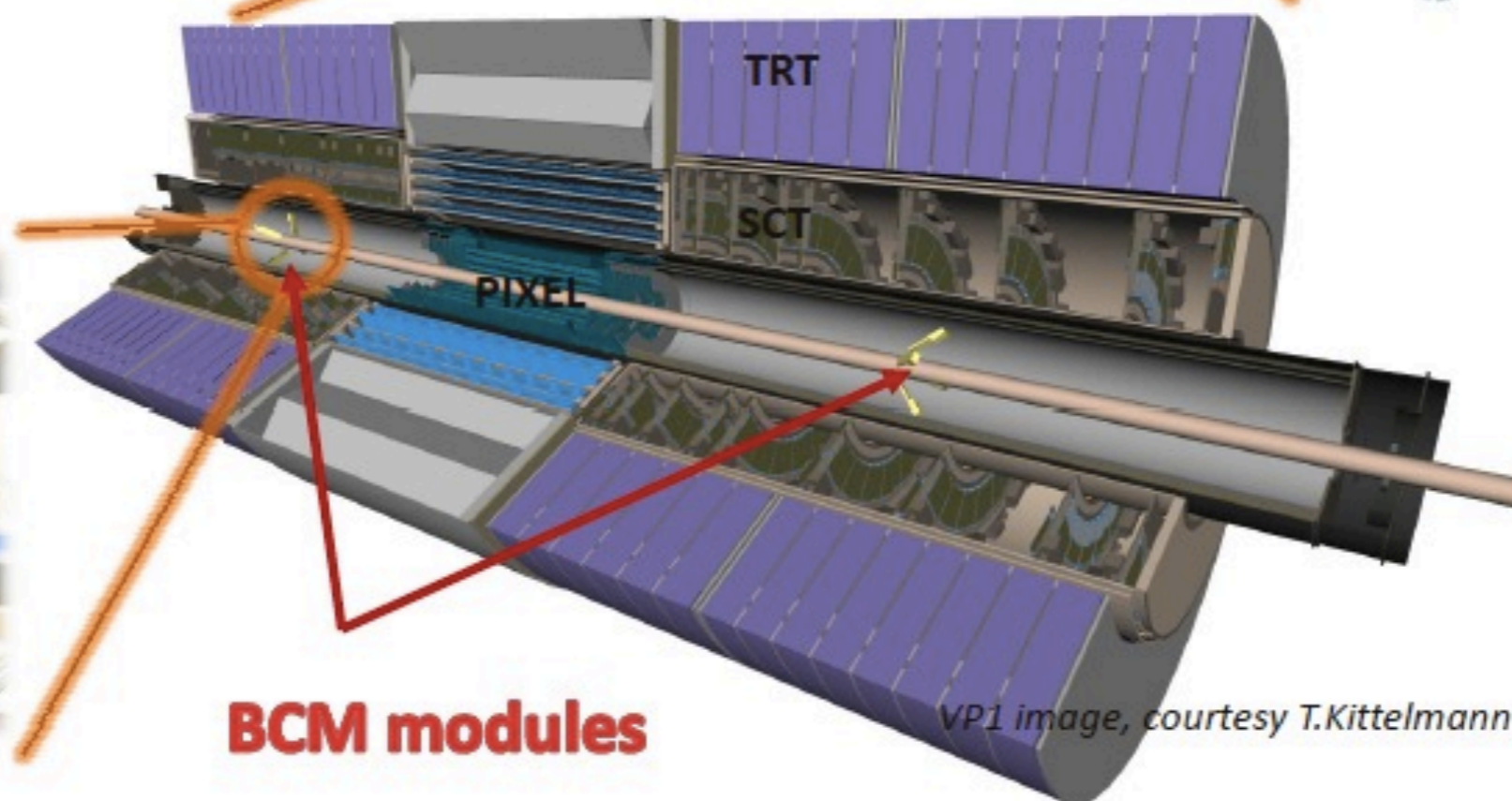
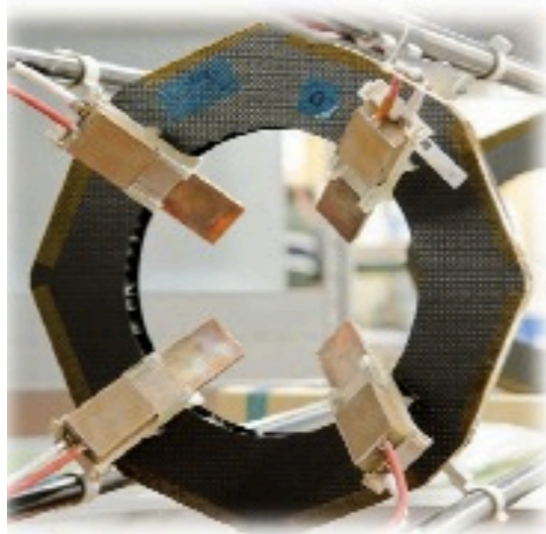
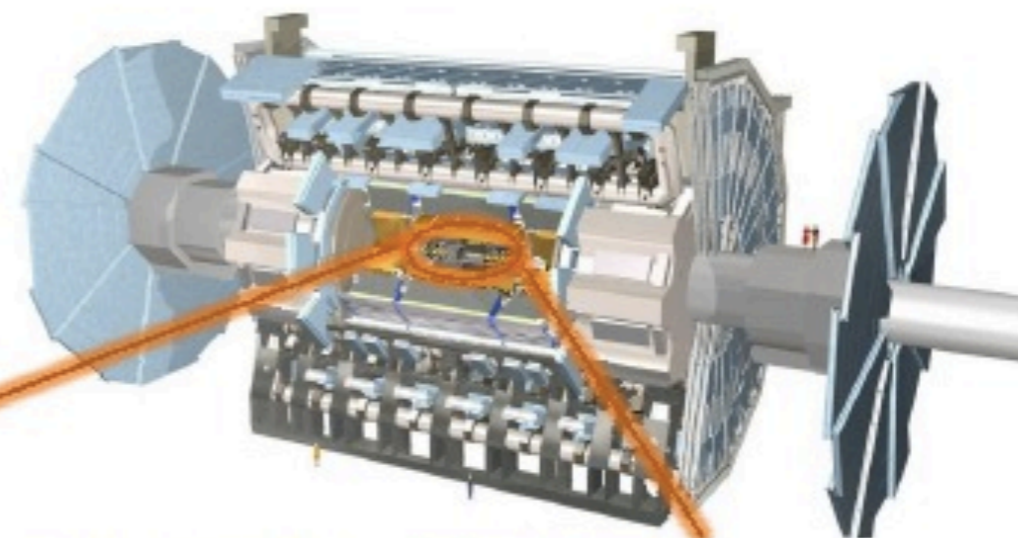


- Photons are emitted at 3°
- Typically 3 reflections inside the tubes
- Photons are read-out by PMT
- Additional photons radiated inside PMT



BCM

- » 4 detector modules on each side of the detector
- » mounted on PIXEL support structure
 - » modules at $z \approx \pm 1.8\text{m}$
 - » $r=5.5\text{ cm}$ ($\eta \approx 4.2$)
 - » 45° angle with respect to the beam pipe



Misura relativa della luminosita'

$$R_{inelastic} = \sum_{bunch} \mu_{bunch} \cdot \frac{f_{rel}}{n_b}$$

la grandezza sconosciuta e' μ in generale e' diversa da pacchetto a pacchetto.

In realta' quello che misuriamo e' la rate media ovvero μ medio. μ e' distribuito secondo una distribuzione di Poisson.

In pratica si misura una grandezza "O" funzione di $\mu \Rightarrow O(\mu) \quad O \propto \mu$

1. per esempio la rate di eventi visti da un rivelatore e' proporzionale a μ

2. la rate di oggetti (hits, tracce) e' proporzionale a μ

Per ottenere una misura accurata e' importante poter fare la misura per ciascun pacchetto, infatti nel caso in cui la relazione tra O e μ non e' lineare non sara' vero che la rate media totale e' uguale alla somma delle rate medie di ciascun pacchetto

Luminosity

this is the quantity to be measured as a function of time (min). It incorporates all the experimental effect associated to the measuring technique and detector

$$\mathcal{L} = \frac{R_{inel}}{\sigma_{inel}} = \frac{\mu n_b f_r}{\sigma_{inel}} = \frac{\epsilon \mu n_b f_r}{\epsilon \sigma_{inel}} = \frac{\mu^{vis}(\epsilon, \mu) n_b f_r}{\sigma_{vis}}$$

acts as a calibration constant, determined in specific experimental runs, measured by other experiments, or input from theory.

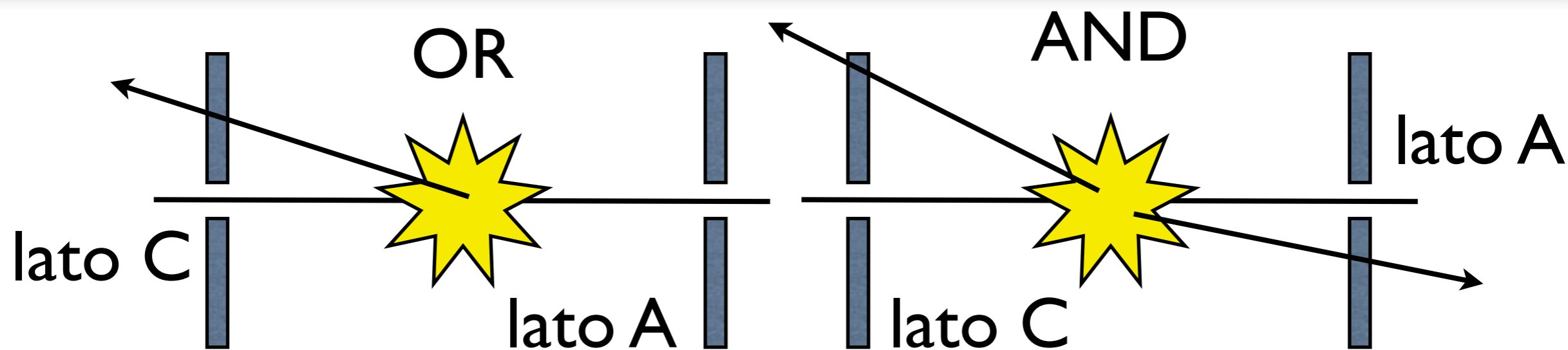
The physics process used to monitor the luminosity at LHC is the inelastic pp cross section (~ 70 mb @ 7TeV)

Techniques to measure μ

The idea is to define an observable that strongly depends on μ . The ideal case would be a linear dependence.

- **Event counting:**
 - ✓ measure the fraction of BC where a detector registered at least an event satisfying certain criteria
- **Hit counting:**
 - ✓ counting the number of hits per BC
- **Particle counting:**
 - ✓ determine the number of particles per BC from observables that reflect the particle flux (eg: total current drawn by a liquid-argon module)

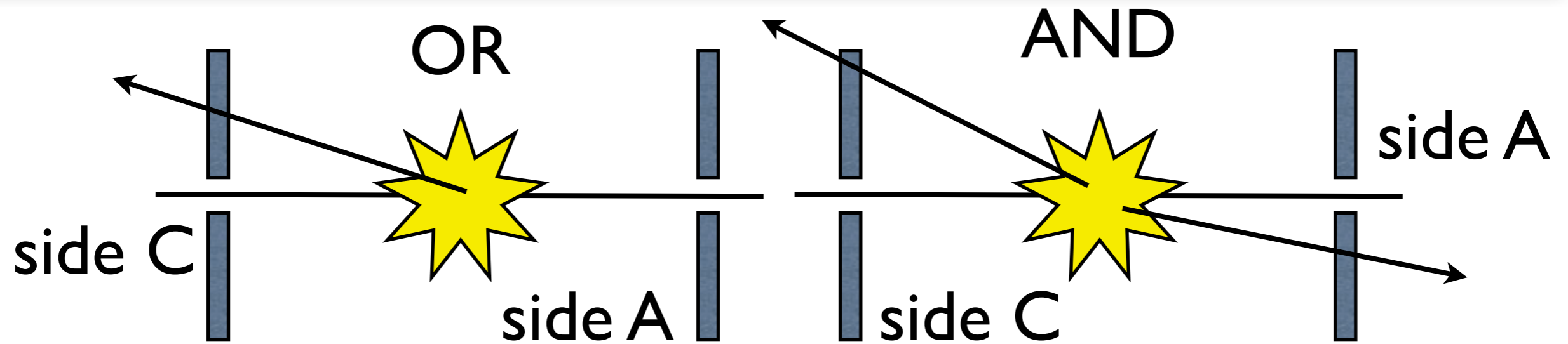
Conteggio eventi



contiamo gli eventi che lasciano un segnale sopra una certa soglia (hit) in un dato rivelatore (da almeno un lato OR, da entrambi i lati AND). Le efficienze riportate sotto sono per singola interazione ie $\mu = 1$ (esatto)

A	C		LUCID	BCM	MBTS	ZDC		LUCID	BCM	MBTS	ZDC
$Hits = 0$	$Hits = 0$	ϵ_0	= 0.442	0.711	0	0.472	$\epsilon_{sing} = 1 - \epsilon_0$	= 0.559	0.290	1.000	0.528
$Hits \geq 1$	$Hits = 0$	ϵ_1	= 0.212	0.125	0.004	0.215	$\epsilon_A = 1 - \epsilon_0 - \epsilon_2$	= 0.347	0.165	0.998	0.313
$Hits = 0$	$Hits \geq 1$	ϵ_2	= 0.212	0.125	0.004	0.215	$\epsilon_C = 1 - \epsilon_0 - \epsilon_1$	= 0.347	0.165	0.998	0.313
$Hits \geq 1$	$Hits \geq 1$	ϵ_3	= 0.135	0.040	0.992	0.098	$\epsilon_{coinc} = 1 - \epsilon_0 - \epsilon_1 - \epsilon_2$	= 0.135	0.040	0.992	0.098

Event counting



$$\begin{aligned}
 P_{Event_OR}(\mu) &= N_{OR}/N_{BC} \\
 &= 1 - P_0(\mu) \\
 &= 1 - e^{-\mu}
 \end{aligned}$$

$$\mu = -\ln\left(1 - \frac{N_{OR}}{N_{BC}}\right)$$

$$\begin{aligned}
 P_{Event_AND}(\mu) &= N_{AND}/N_{BC} \\
 &= 1 - P_0^{Zero_OR}(\mu) \\
 &= 1 - (e^{-\mu\epsilon^A} + e^{-\mu\epsilon^C} - e^{-\mu\epsilon^{OR}})
 \end{aligned}$$

that's not invertible

Conteggio eventi

Problema: vogliamo conoscere la probabilita' di osservare n eventi per incrocio sapendo che il numero di interazioni per incrocio e' μ ed e' distribuito secondo una distribuzione di Poisson.

E' molto piu' semplice ragionare in termini di eventi "vuoti = senza interazione". Alla fine del calcolo usiamo l'unitarieta' della probabilita':

$$P(\text{interazione}) = 1 - P(\text{non interazione})$$

Conteggio eventi vuoti

I - probability of having 0 interactions;

II - probability of having n interactions with 0 hits in both modules.

Term I is the Poissonian probability of having zero interactions:

$$I = P_{\mu}(0) = \frac{e^{-\mu} \mu^0}{0!} = e^{-\mu} \quad (10)$$

Given the probability to detect an interaction in single side mode (ϵ^{Sing} , see Table 4), term II is the combined probability of not detecting the n interactions occurring in a bunch:

$$II = (1 - \epsilon^{Sing})^n \quad (11)$$

Term II is convoluted with a Poissonian distribution of average μ (the sum starts from $n = 1$ to exclude term I):

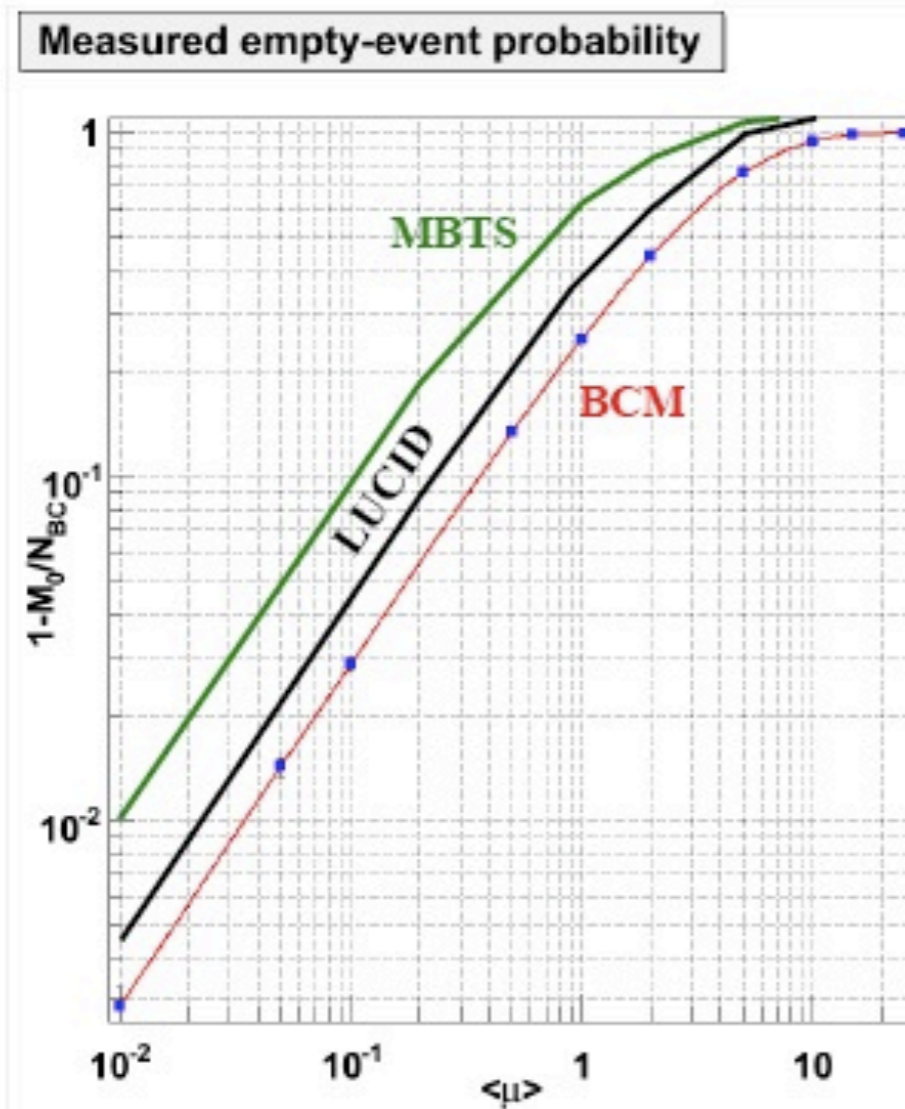
$$\sum_{n=1}^{\infty} (1 - \epsilon^{Sing})^n \frac{e^{-\mu} \mu^n}{n!} = \sum_{n=0}^{\infty} (1 - \epsilon^{Sing})^n \frac{e^{-\mu} \mu^n}{n!} - e^{-\mu} = e^{-\epsilon^{Sing} \mu} - e^{-\mu} \quad (12)$$

The probability of observing an empty event is the sum of Equations 10 and 12:

$$N_{0/BX} = e^{-\mu} + e^{-\epsilon^{Sing} \mu} - e^{-\mu} = e^{-\epsilon^{Sing} \mu} \quad (13)$$

Conteggio eventi vuoti OR

$$\begin{array}{cc} \text{A} & \text{C} \\ \boxed{\text{Hits} = 0} & \boxed{\text{Hits} = 0} \end{array}$$



The probability to have a bunch crossing with an average number of interactions that is $\langle \mu \rangle$ is

$$P_{\langle \mu \rangle > 0} = e^{-(P_{10} - 1)\langle \mu \rangle} = \frac{M_0}{N_{BC}}$$

$$\langle \mu \rangle = \frac{\ln\left(\frac{M_0}{N_{BC}}\right)}{P_{10} - 1}$$

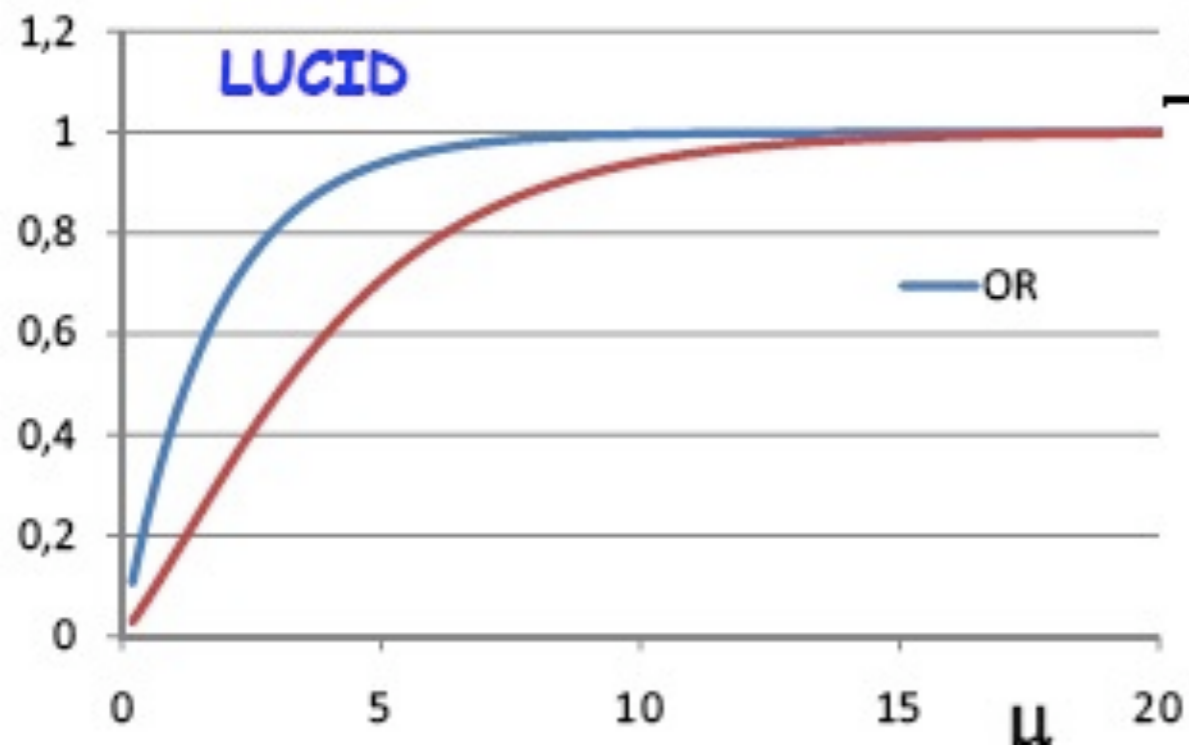
where M_0 is the number of detected empty events

N_{BC} is the number of bunch crossings

P_{10} is the probability to measure an empty event when there is exactly one pp interaction

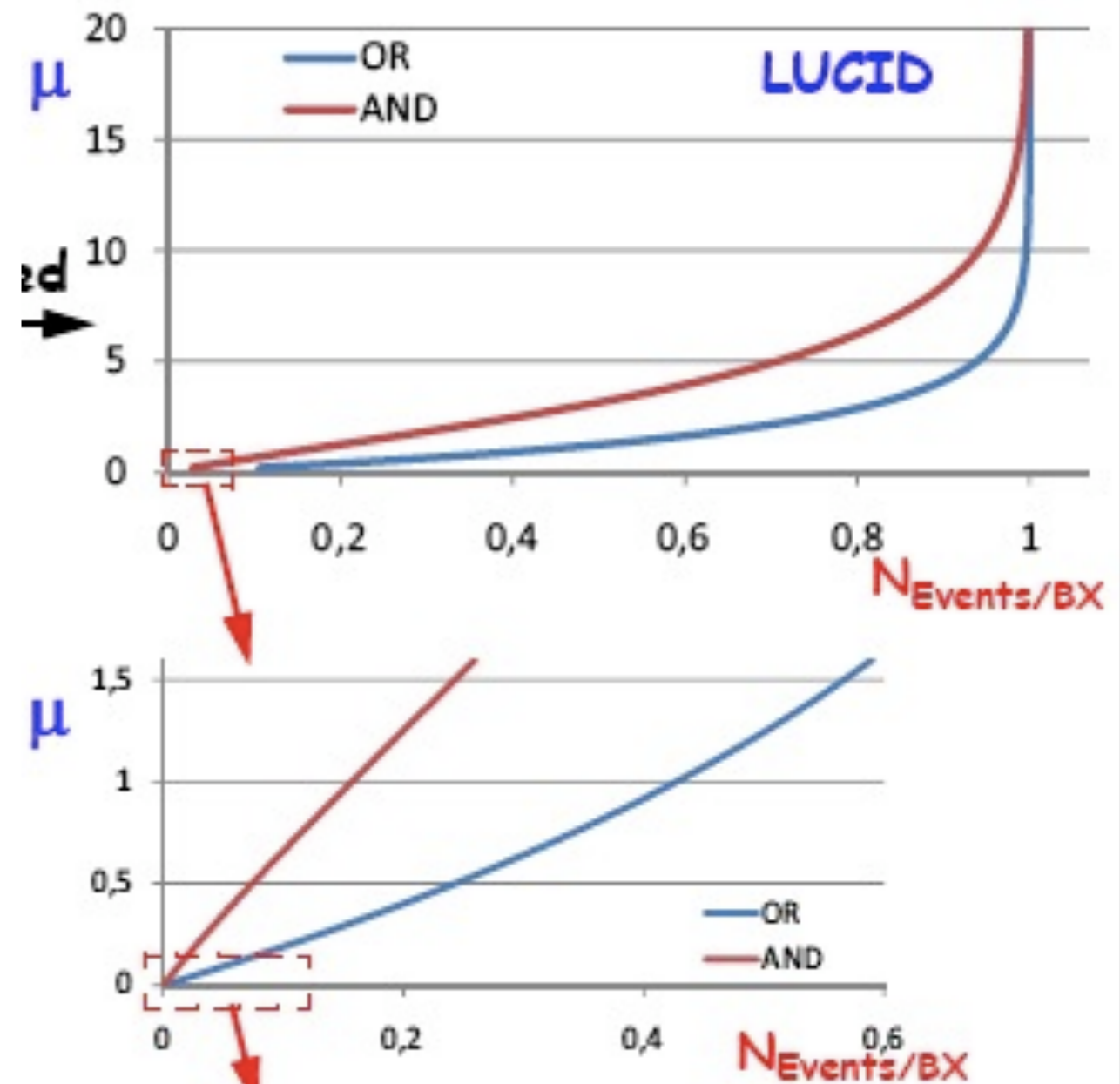
$$P_{10} = 0.711 \text{ (BCM)} = 0.442 \text{ (LUCID)} = 0 \text{ (MBTS)}$$

Conteggio eventi vuoti



Osservazioni:

1. maggiore e' l'efficienza prima inizia la saturazione
2. OR satura prima dell' AND



Conteggio di eventi

C Event Counting AND

The fraction of detected events in the AND mode (F_{ext}^{AND}) can be written as

$$F_{ext}^{AND} = 1 - F_0^{OR} \tag{17}$$

Based on reference [17], the fraction of events with no hits in side A or C (F_0^{OR}) is the sum of:

- I - probability of having 0 interactions;
- II - probability of having n interactions with at least one detected in side A, together with any number not detected in both modules;
- III - probability of having n interactions with at least one detected in side C, together with any number not detected in both modules.
- IV - probability of having n interactions with 0 hits in both modules.

The calculations are performed under the same assumptions done in the previous section (efficiencies are not time-dependent and no migration effect). Assuming that interactions are Poissonian, Term I can be written as:

$$I = P_\mu(0) = \frac{e^{-\mu} \mu^0}{0!} = e^{-\mu} \tag{18}$$

To perform the calculations, *exclusive* detection efficiencies (e_1, e_2, e_3 and e_0) are defined in Table 11.

e_1	probability of detecting an interaction in A, but not in C
e_2	probability of detecting an interaction in C, but not in A
e_3	probability of detecting an interaction in both modules
e_0	probability of detecting no interactions ($=1 - e_1 - e_2 - e_3$)

Table 11: Exclusive detection efficiencies

Exclusive efficiencies are related to the *inclusive* ones defined in Table 3 by:

$$\begin{aligned} e_1 &= e^A - e^{AND} \\ e_2 &= e^C - e^{AND} \\ e_3 &= e^{AND} \\ e_0 &= 1 - e^A - e^C + e^{AND} \end{aligned} \tag{19}$$

Term II (III) consists of all permutations of k interactions detected in module A (C) and $n - k$ interactions not detected in any module:

$$II_n = \sum_{k=1}^n e_1^k e_0^{n-k} \binom{n}{k} = (e_1 + e_0)^n - e_0^n \tag{20}$$

$$III_n = \sum_{k=1}^n e_2^k e_0^{n-k} \binom{n}{k} = (e_2 + e_0)^n - e_0^n \tag{21}$$

Term IV is the probability of having an event with n interactions which are not detected neither by any module nor by both modules together:

$$IV_n = e_0^n \tag{22}$$

Terms II, III and IV are convoluted with a Poissonian distribution with a average μ (the sum starts from $n = 1$ to avoid double counting of Term I):

$$II = \sum_{n=1}^{\infty} \frac{e^{-\mu} \mu^n}{n!} II_n = \sum_{n=1}^{\infty} \frac{e^{-\mu} \mu^n}{n!} [(e_1 + e_0)^n - e_0^n] = e^{-\mu} [e^{\mu(e_1+e_0)} - e^{\mu e_0}] \tag{23}$$

$$III = \sum_{n=1}^{\infty} \frac{e^{-\mu} \mu^n}{n!} III_n = \sum_{n=1}^{\infty} \frac{e^{-\mu} \mu^n}{n!} [(e_2 + e_0)^n - e_0^n] = e^{-\mu} [e^{\mu(e_2+e_0)} - e^{\mu e_0}] \tag{24}$$

$$IV = \sum_{n=1}^{\infty} \frac{e^{-\mu} \mu^n}{n!} IV_n = \sum_{n=1}^{\infty} \frac{e^{-\mu} \mu^n}{n!} e_0^n = e^{-\mu} (e^{\mu e_0} - 1) \tag{25}$$

The total probability of observing an empty event is the sum of Equations 18, 23, 24 and 25:

$$F_0^{OR} = I + II + III + IV = e^{-\mu(1-e_0-e_1)} + e^{-\mu(1-e_0-e_2)} - e^{-\mu(1-e_0)} \tag{26}$$

Given the relations in Table 11, Equation 26 can be written as:

$$F_0^{OR} = e^{-\mu e^A} + e^{-\mu e^C} - e^{-\mu(e^A + e^C - e^{AND})} \tag{27}$$

Eventually, the fraction of detected events is

$$F_{ext}^{AND} = 1 - F_0^{OR} = 1 - e^{-\mu e^A} - e^{-\mu e^C} + e^{-\mu(e^A + e^C - e^{AND})} \tag{28}$$

When $\mu \ll 1$, this equation simplifies to:

$$\mu \xrightarrow{\mu \ll 1} \frac{F_{ext}^{AND}}{e^{AND}} \tag{29}$$

Conteggio di hits

D Hit Counting OR

In the OR mode, the average number of pp collisions per event (μ) is the ratio between the average number of particles per event (N_{part}^{OR}) and those per pp collision (n_{part}^{OR})

$$\mu = \frac{N_{part}^{OR}}{n_{part}^{OR}} \quad (30)$$

LUCID does not count particles, it only count hits. The way particles are distributed among the tubes depends on the type of interaction: non-diffractive, single- and double-diffractive. Assuming that particles are spread uniformly over the detector⁸, the number of detected particles per tube is N_{part}/N_{tubes} where $N_{tubes} = 32$. Assuming that particles in a tube are distributed according to a Poissonian, the number of hits in a event (N_{hits}) can be written as the number of tubes times the probability to have at least one particle in a tube (namely a hit):

$$N_{hits} = N_{tubes} \left[1 - e^{-\frac{N_{part}}{N_{tubes}}} \right] \quad (31)$$

Equation 31 can be inverted to turn the number of hits into particles:

$$N_{part} = -N_{tubes} \ln \left(1 - \frac{N_{hits}}{N_{tubes}} \right) \quad (32)$$

Since the logarithm goes to infinity when $N_{hits} = N_{tubes}$, N_{part} is constrained to be smaller than 200. By taking larger upper limits, the results presented in this note do not considerably change.

The numerator in Equation 30 (N_{part}^{OR}) is the average of the number of particles per event ($N_{part,i}^{OR}$) over N_{BX} events with an unknown μ :

$$N_{part}^{OR} = \frac{\sum_{i=1}^{N_{BX}} N_{part,i}^{OR}}{N_{BX}} = -\frac{N_{tubes}}{N_{BX}} \sum_{i=1}^{N_{BX}} \ln \left(1 - \frac{N_{hits,i}^{OR}}{N_{tubes}} \right) \quad (33)$$

The denominator in Equation 30 (n_{part}^{OR}) is the average of the number of particles per collision ($n_{part,j}^{OR}$) over N_{pp} collisions:

$$n_{part}^{OR} = \frac{\sum_{j=1}^{N_{pp}} n_{part,j}^{OR}}{N_{pp}} = -\frac{N_{tubes}}{N_{pp}} \sum_{j=1}^{N_{pp}} \ln \left(1 - \frac{n_{hits,j}^{OR}}{N_{tubes}} \right) \xrightarrow{n_{hits,j}^{OR} \ll N_{tubes}} n_{hits}^{OR} \quad (34)$$

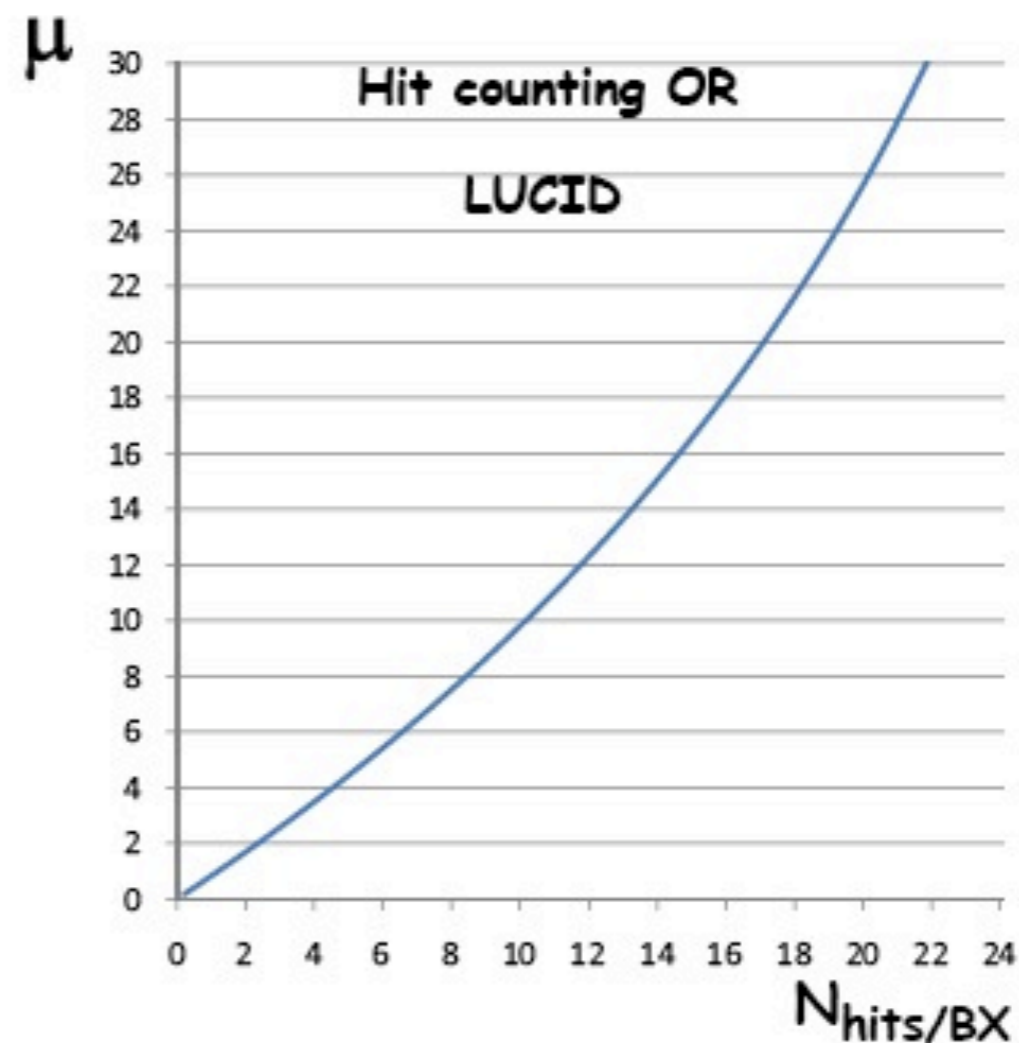
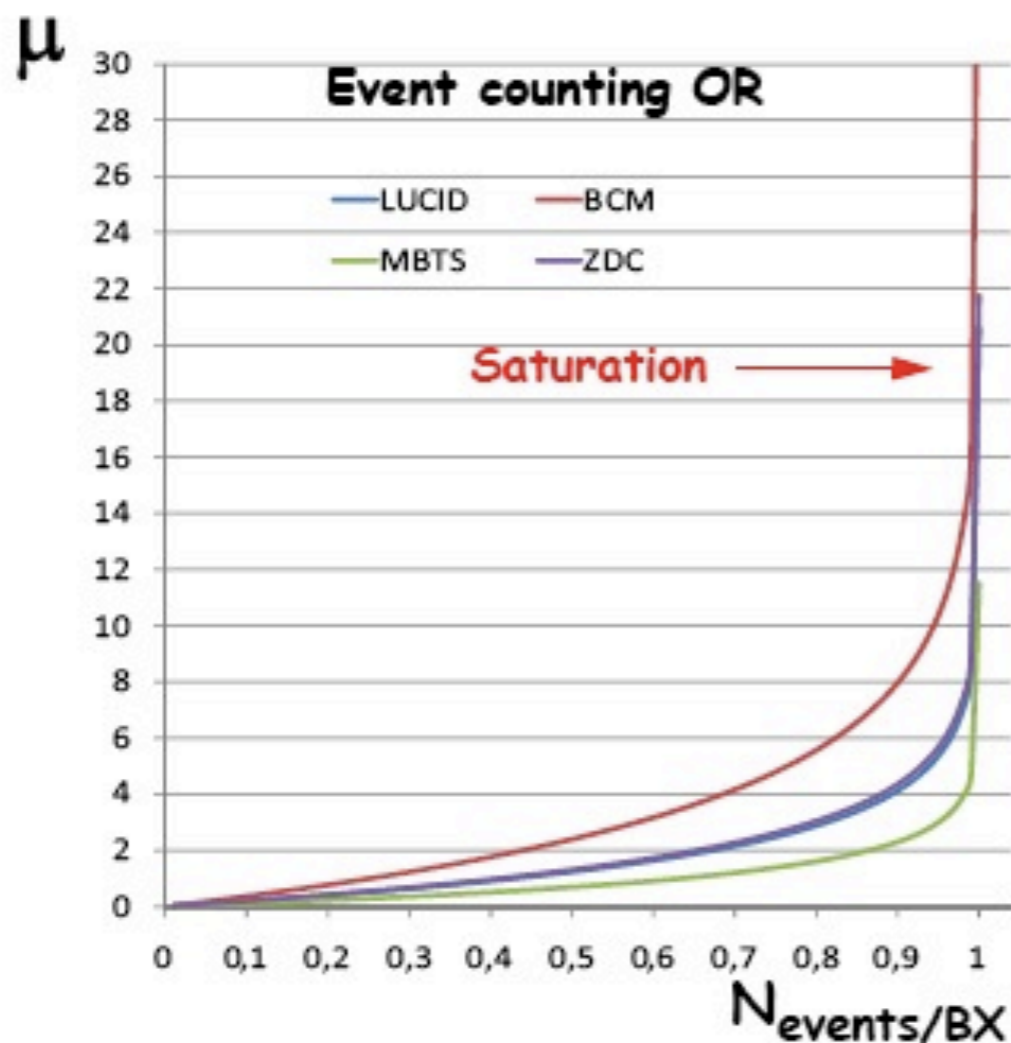
By using Equation 33 and Equation 34, Equation 30 becomes:

$$\mu = \frac{N_{tubes}}{n_{hits}^{OR}} \cdot \frac{\sum_{i=1}^{N_{BX}} \ln \left(1 - \frac{N_{hits,i}^{OR}}{N_{tubes}} \right)}{N_{BX}} \xrightarrow{\mu \ll 1} \frac{N_{part}^{OR}}{n_{hits}^{OR}} \quad (35)$$

Confronto conteggio hit - eventi

$$N_{\text{events/BX}}^{\text{OR}} = 1 - e^{-\epsilon_{\text{sing}} \mu}$$

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



Osservazioni: il conteggio di hit e' affetto meno dagli effetti di saturazione. Un'accettanza minore ritarda la saturazione (ma c'e' meno statistica a disposizione)

Misura dell'efficienza

- Simuazione Monte Carlo della fisica e del rivelatore in esame

✓ Le incertezze del modello MC si propagano nella misura in 3 effetti:

- ◆ calcolo della sezione d'urto visibile

$$\sigma_{\text{vis}} = \epsilon_{\text{ND}} \sigma_{\text{ND}} + \epsilon_{\text{SD}} \sigma_{\text{SD}} + \epsilon_{\text{DD}} \sigma_{\text{DD}}$$

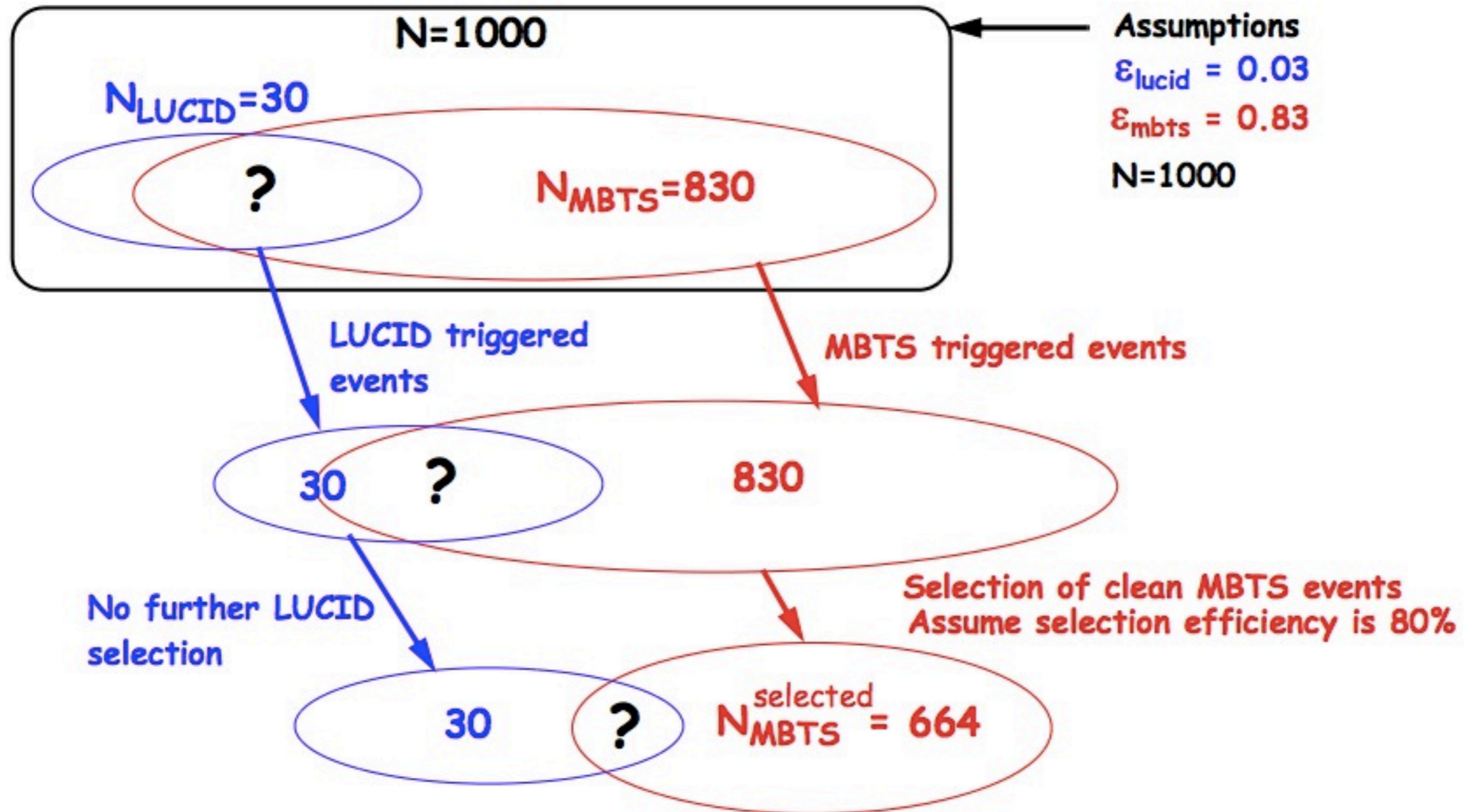
- ◆ determinazione efficienza di trigger
- ◆ determinazione accettazione del rivelatore

- Confrontando le efficienze di due o piu' rivelatori tra loro. Nota l'efficienza di un rivelatore (e la correlazione) si determina l'efficienza del secondo rivelatore.

✓ necessario quando un rivelatore seleziona gli eventi a livello di trigger e un'altro viene usato per determinare la luminosita'

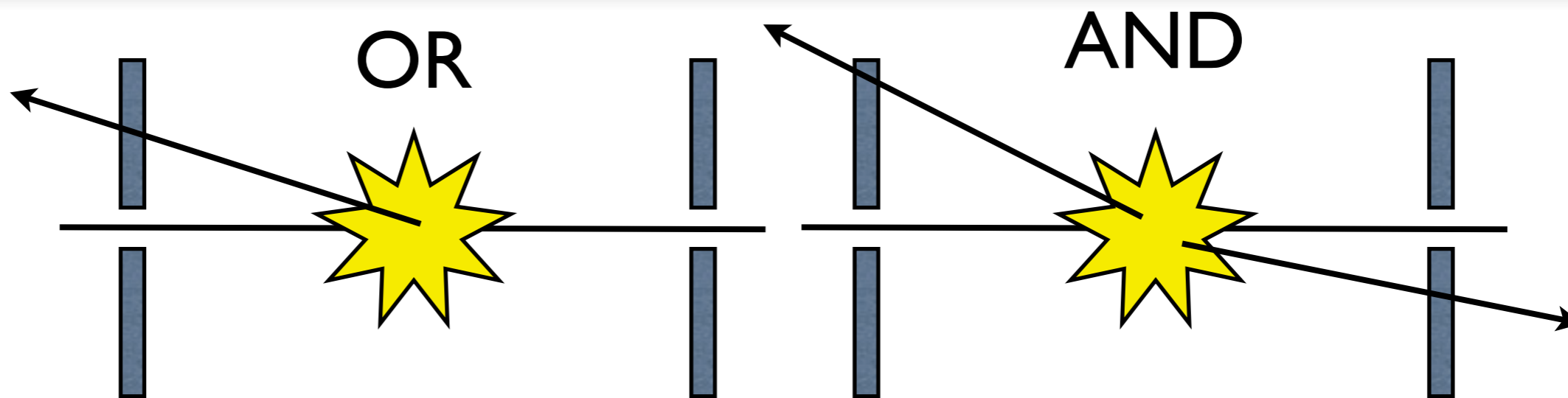
- Per determinare l'efficienza di trigger e' indispensabile avere un campione di eventi selezionati senza imporre una condizione di trigger: "zero bias"

Misura dell'efficienza



$$\epsilon_{lucid} = \frac{N_{LUCID}}{N_{MBTS}^{selected}} \epsilon_{mbts}^{trig} \epsilon_{mbts}^{selection} = 30 / 664 \times 0.83 \times 0.8 = 0.03$$

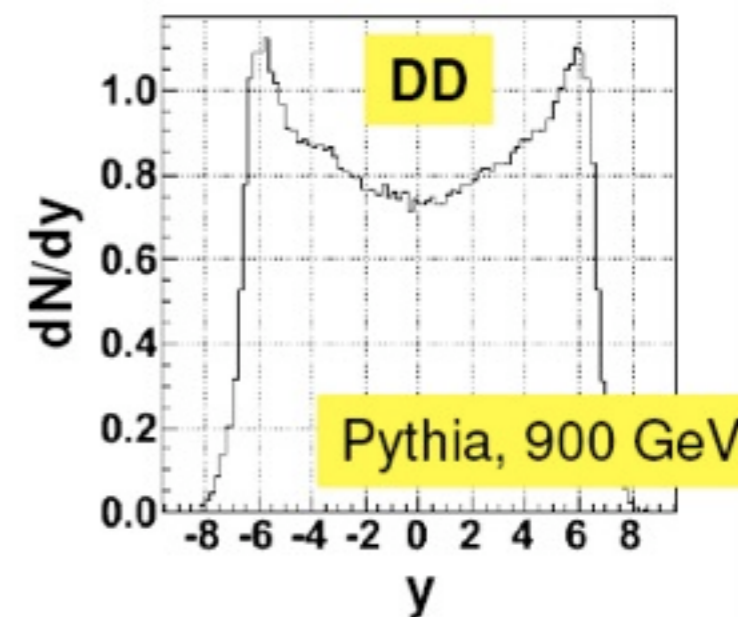
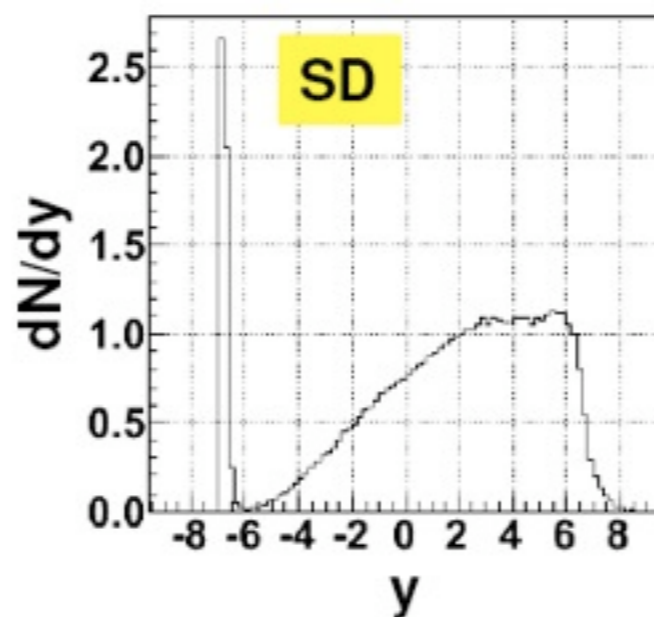
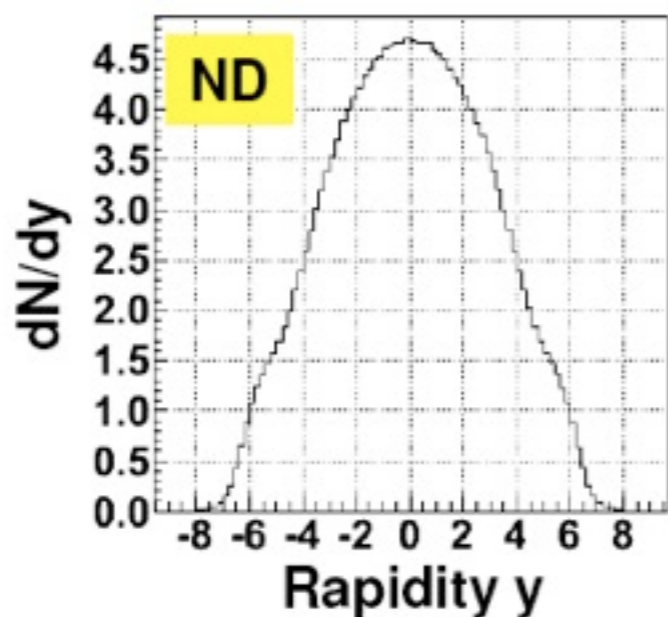
Trigger (bias)



35mb (66%)

12mb (22%)

6.5mb (12%)



efficienza di trigger	OR	100%	75%	90%	Tot	93%
	AND	98%	35%	50%		75%

Efficienza di trigger

- l'efficienza di trigger viene studiata utilizzando un campione di eventi selezionato con un trigger complementare: ovvero un trigger che selezioni parte degli eventi selezionati dal trigger di cui vogliamo conoscere l'efficienza

- campioni dipendenti:

$$\epsilon_{item1} = \frac{n_{item1}}{N},$$

$$\epsilon_{item2} = \frac{n_{item2}}{N},$$

$$\epsilon_{item1|item2} = \frac{n_{item1\&item2}}{n_{item2}},$$

$$\epsilon_{item2|item1} = \frac{n_{item1\&item2}}{n_{item1}},$$

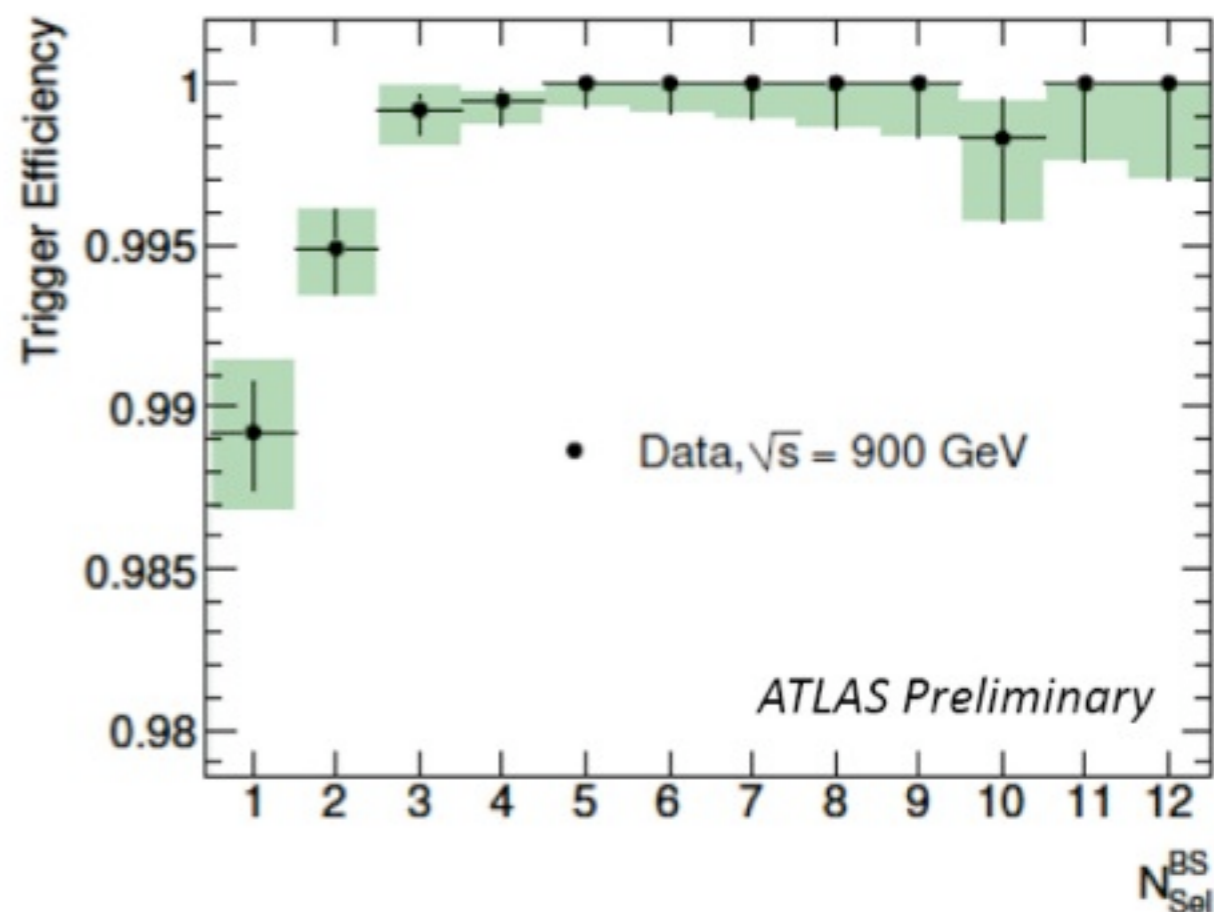
$$\epsilon_{item1} = \epsilon_{item1|item2} \cdot \frac{\epsilon_{item2}}{\epsilon_{item2|item1}}$$

- campioni indipendenti:

$$\epsilon_{item1} = \frac{n_{item1}}{N},$$

$$\epsilon_{item2} = \frac{n_{item2}}{N},$$

$$\epsilon_{item1} = \frac{n_{item1}}{n_{item2}} \cdot \epsilon_{item2}$$

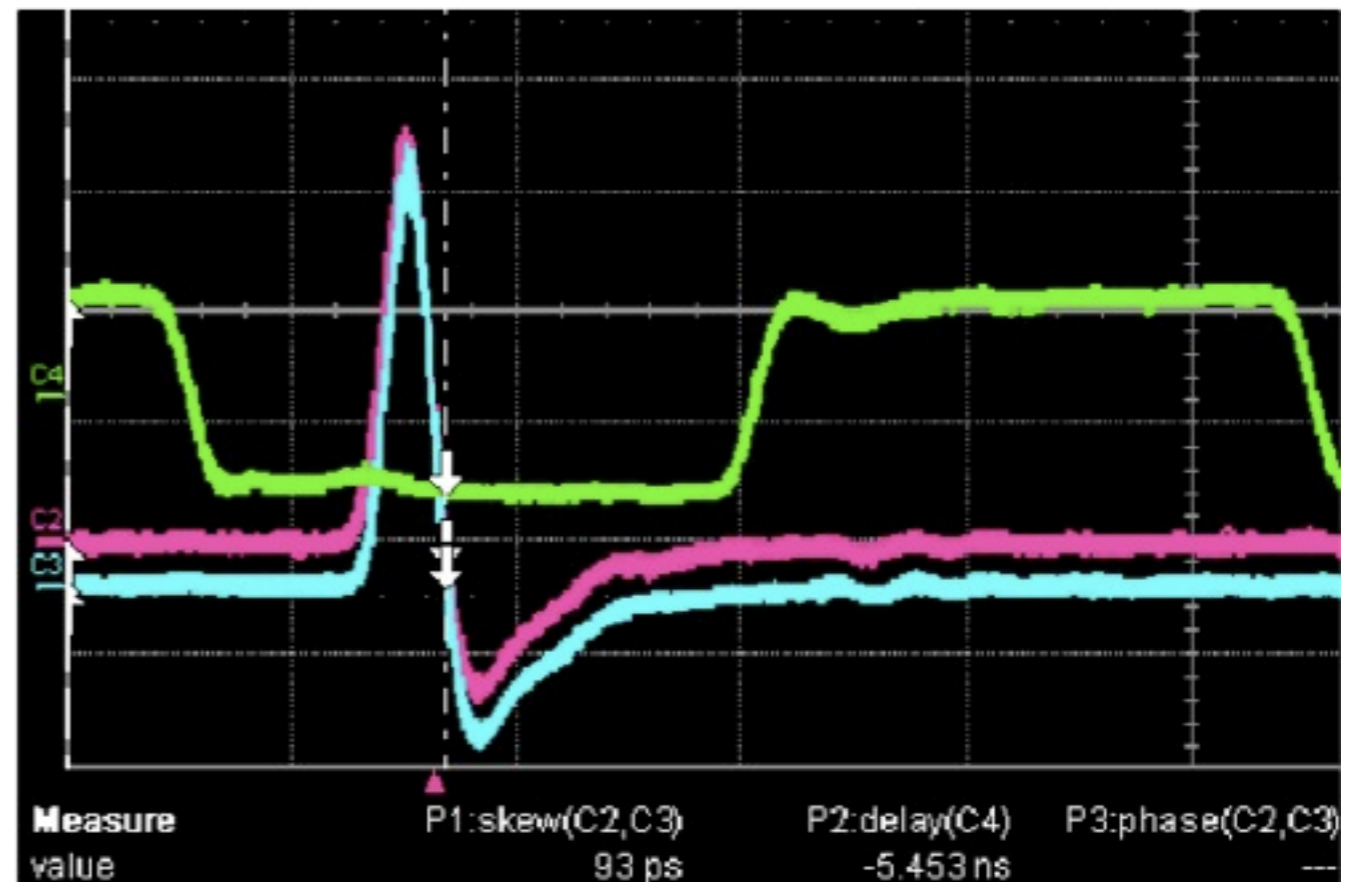
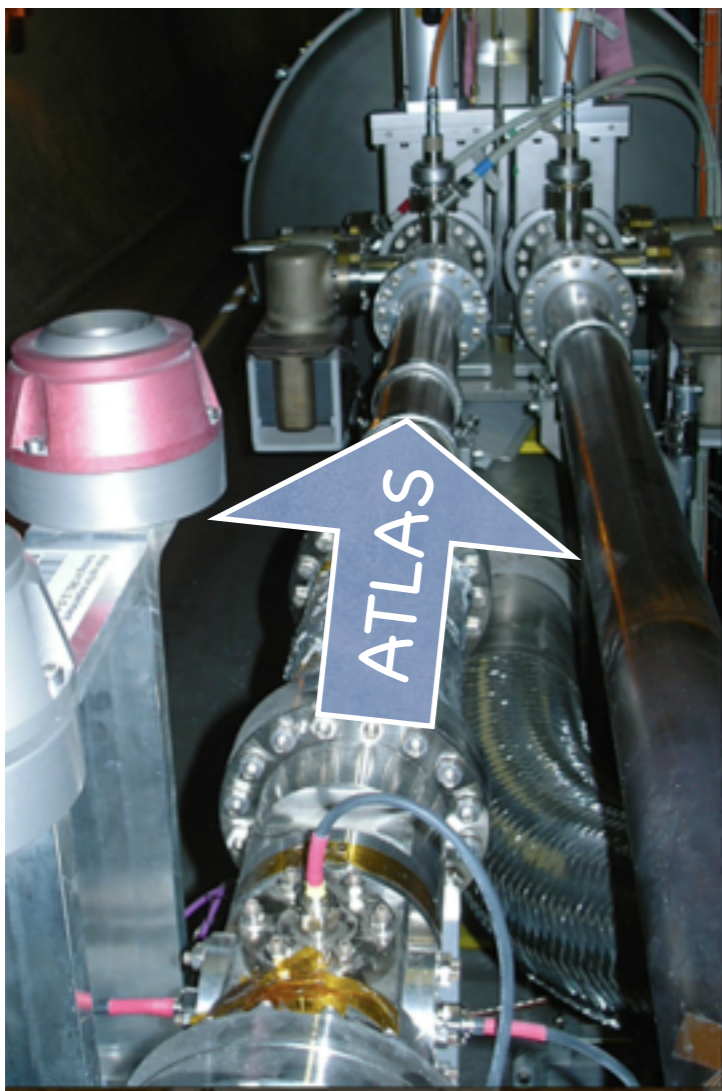


Misura della luminosita' in ATLAS

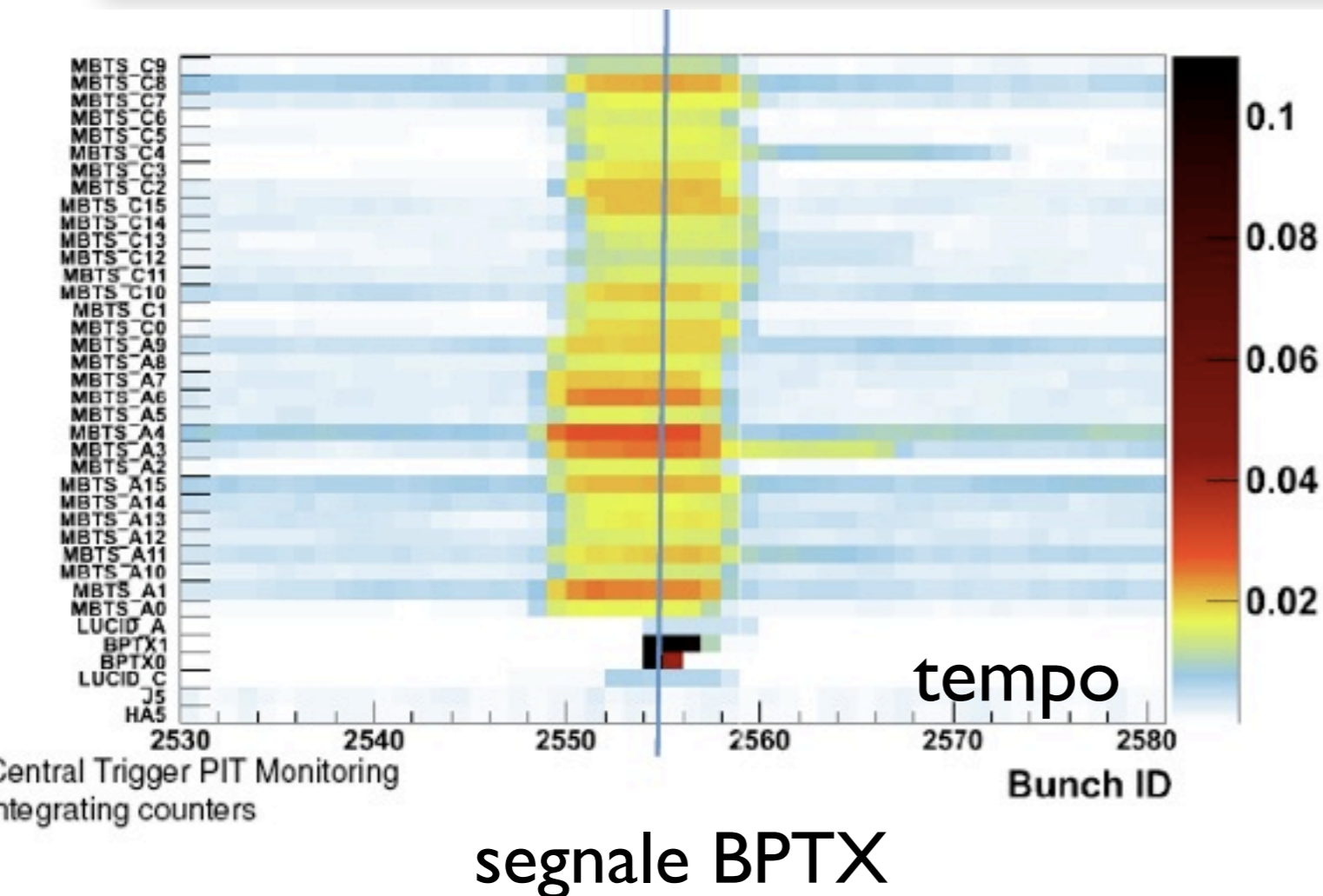
- steps:
 - ✓ osservazione passaggio di protoni
 - ✓ primi eventi da collisione
 - ✓ messa in tempo esperimento
 - ✓ raccolta di eventi di collisione - rimozione fondo
 - ✓ determinazione efficienza rivelatore con la simulazione
 - ✓ determinazione luminosita'
 - ✓ confronto tra rivelatori diversi

Passaggio di protoni

- Beam pickups are electric pads sensitive to the passage of the the bunches and are installed (175m) on both sides of ATLAS



Messa in tempo del trigger



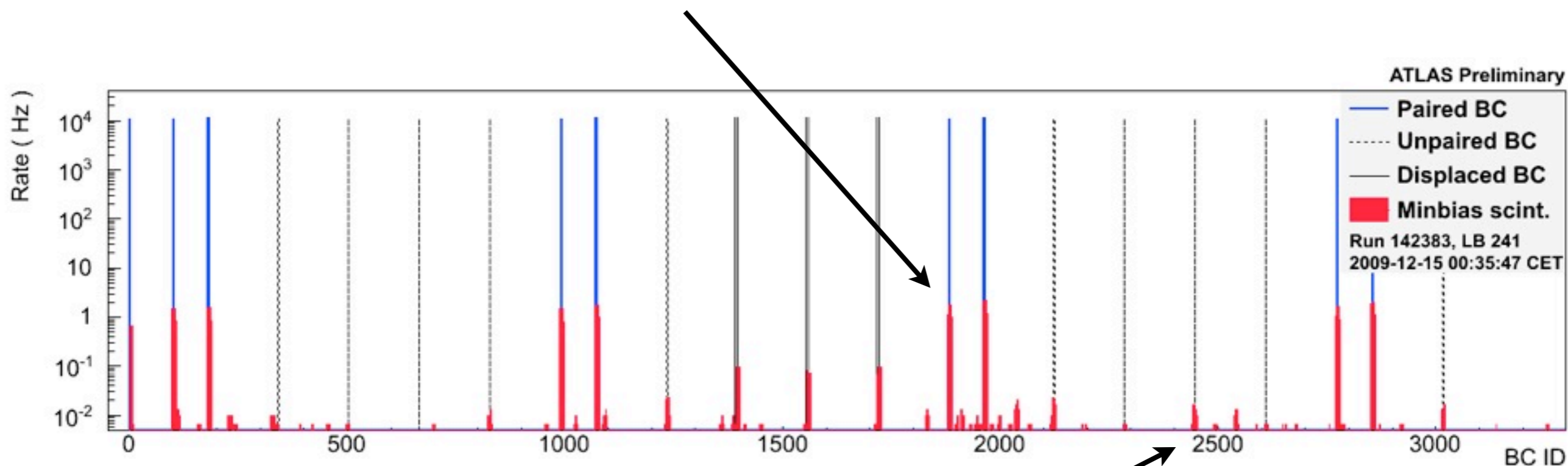
MBTS reminder:

- Late add-on of 2x16 scintillator paddles installed in front of LAr cryostat, on both sides
- For use during initial running
- $2.1 < \eta < 3.8$

Sono collisioni?

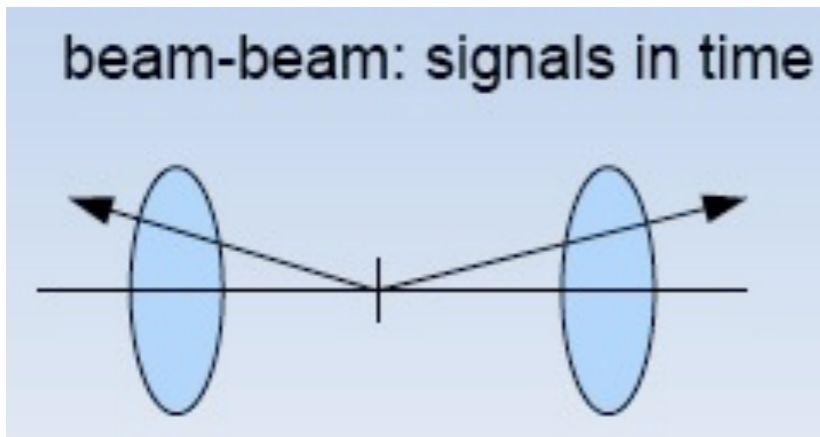
LHC e' stato riempito con 16x16 pacchetti, 8 dei quali si incrociano nel punto di interazione di ATLAS. Ci aspettiamo che la rate di eventi per i pacchetti accoppiati sia molto piu' alta che per pacchetti non accoppiati: il segnale e' dominato da collisioni

MBTS_I_I_Col: contribution from colliding bunches ~ 1 Hz

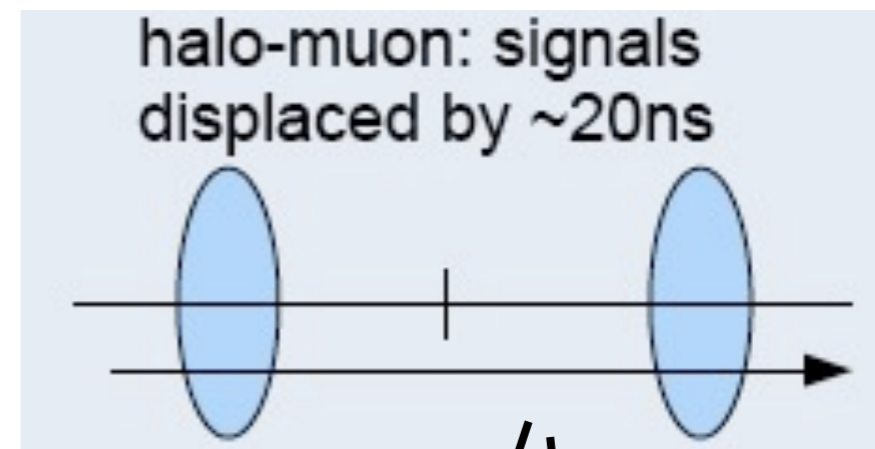


MBTS_I_I: contribution from halo $\sim 10^{-2}$ Hz

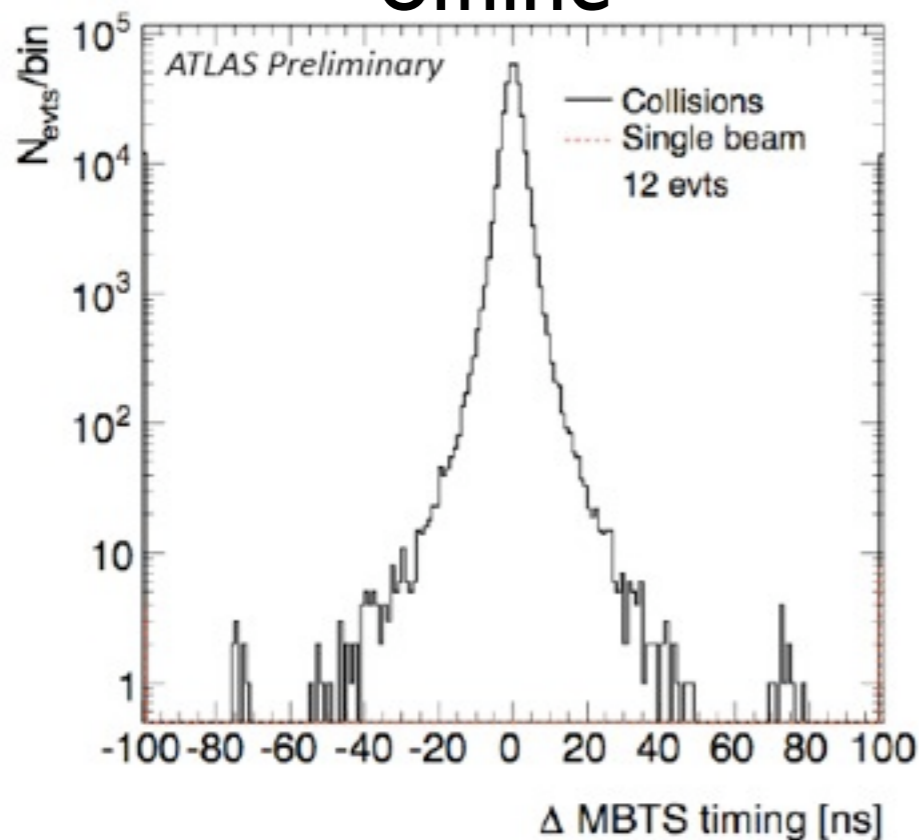
Fondo dal fascio



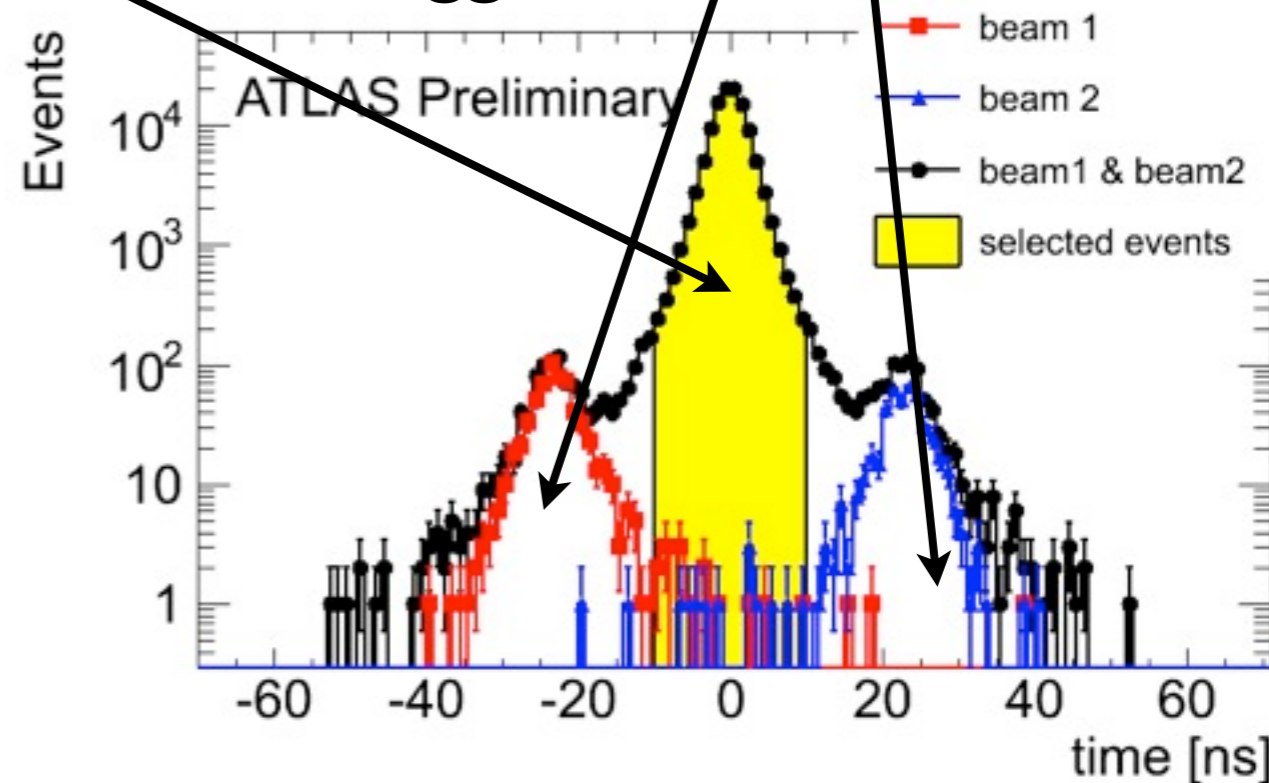
$dz \sim 7m$
 $dt \sim 20ns$



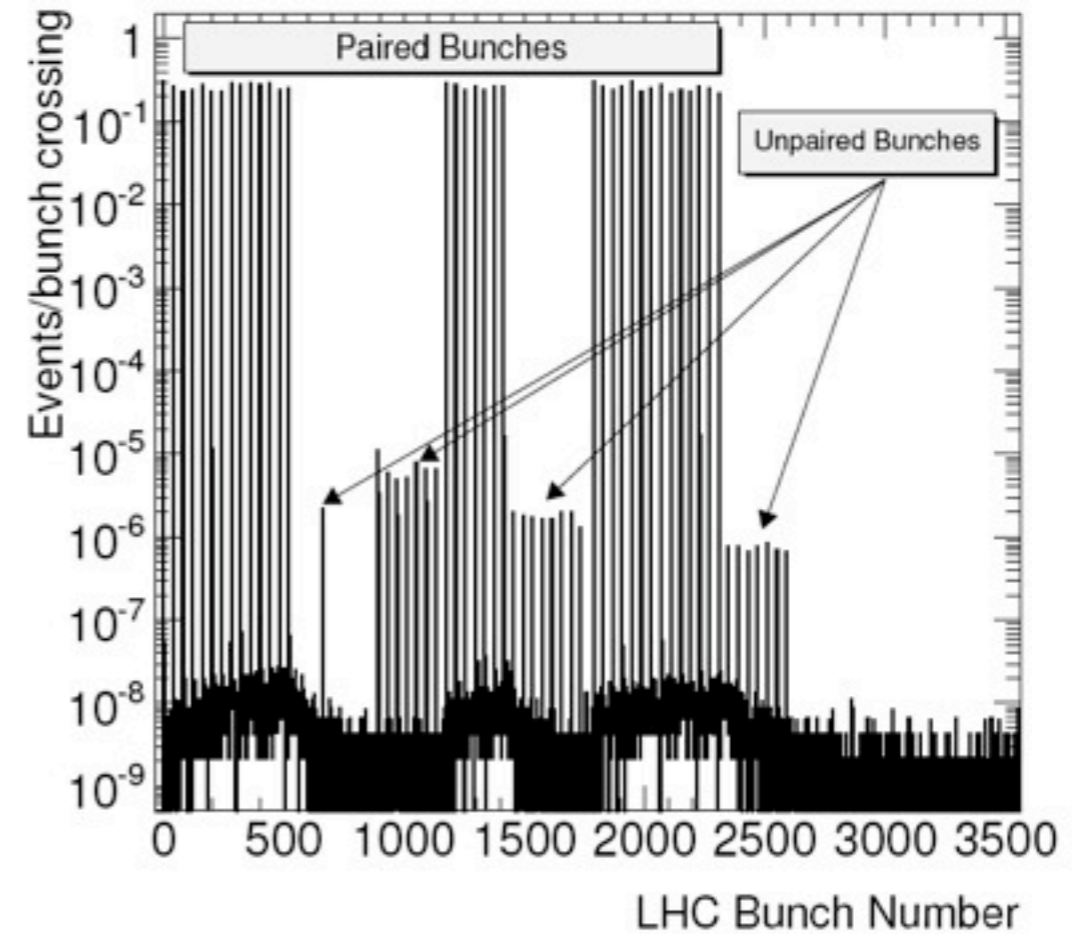
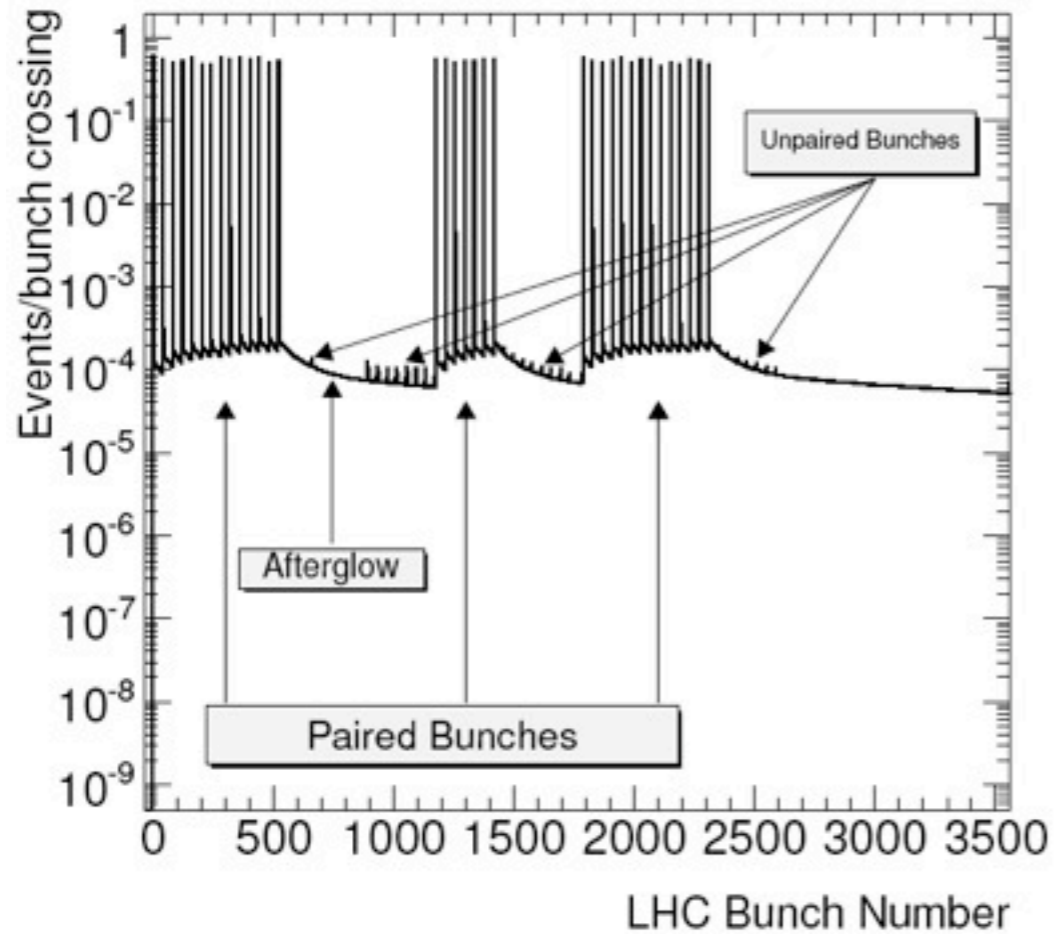
dopo la selezione
offline



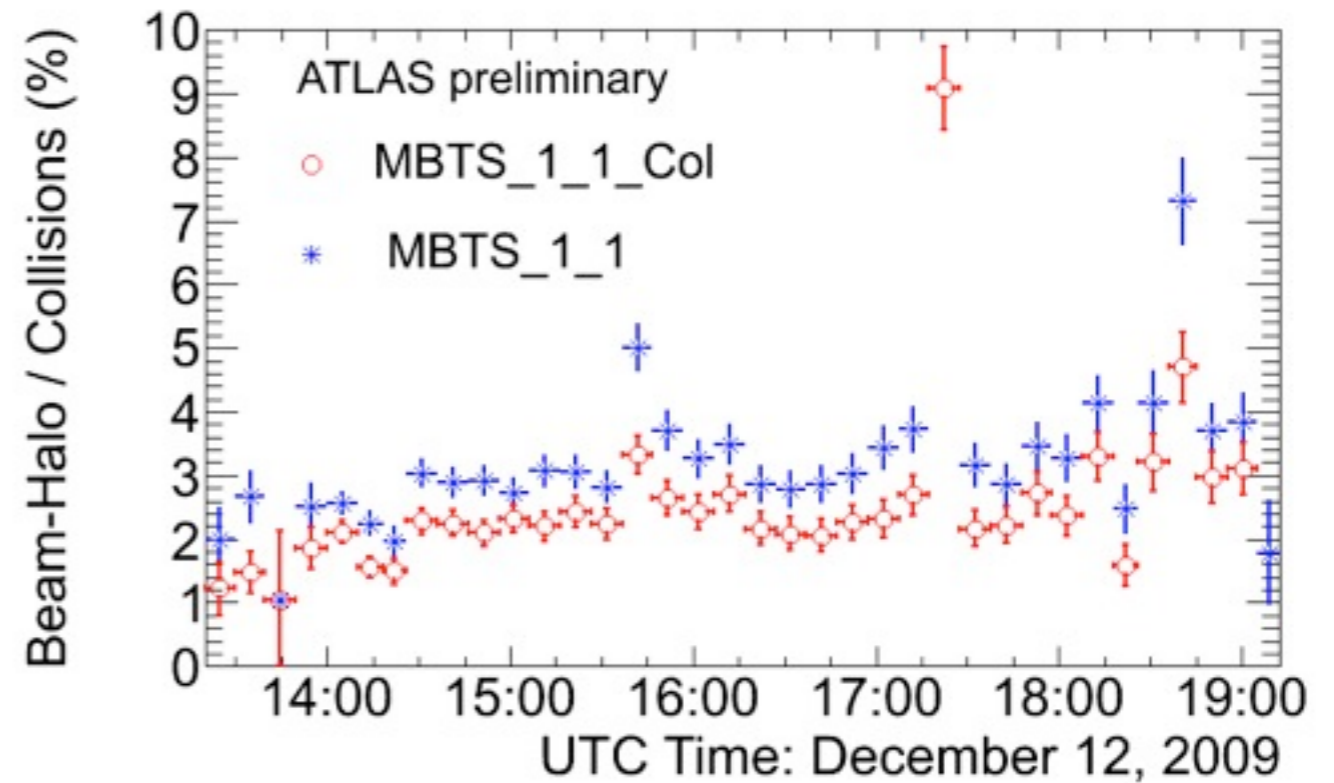
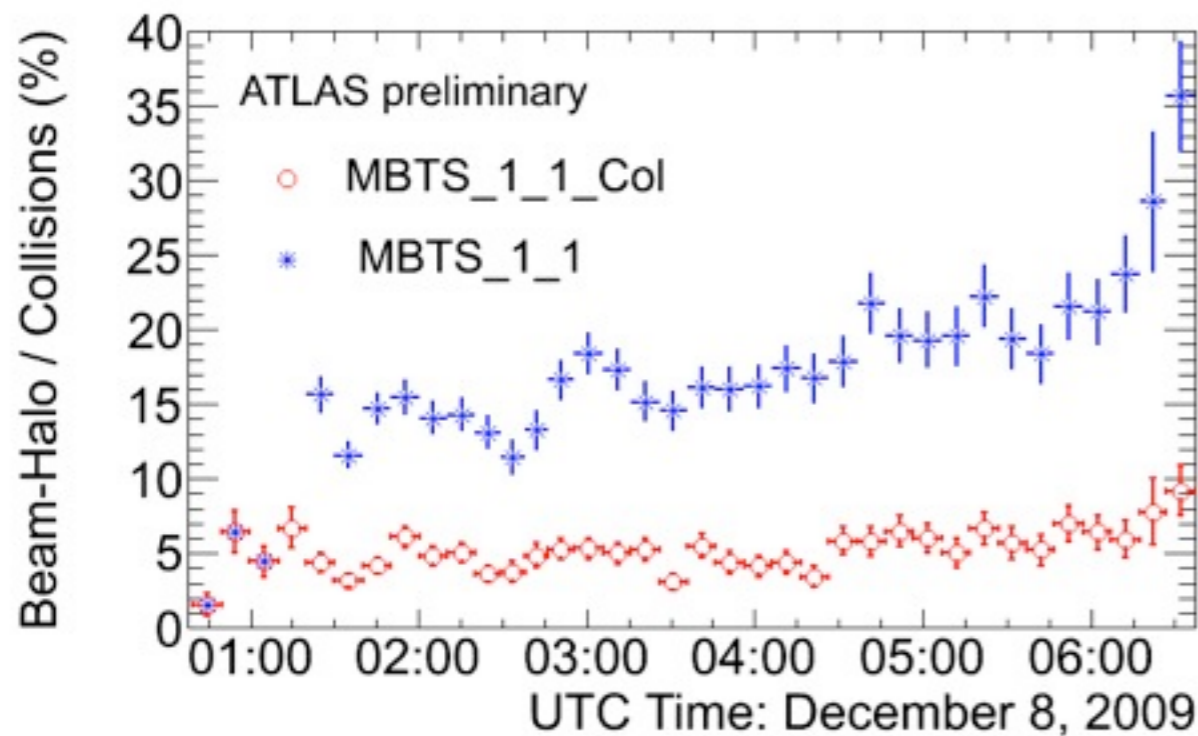
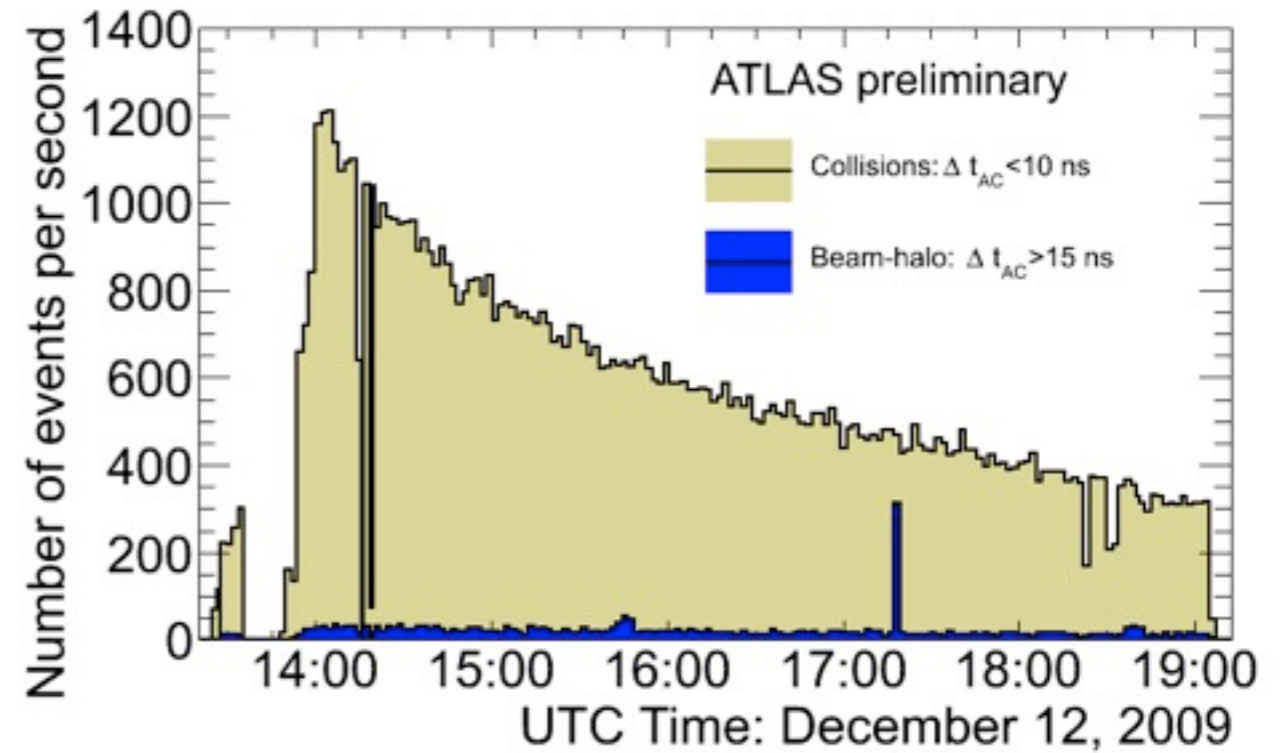
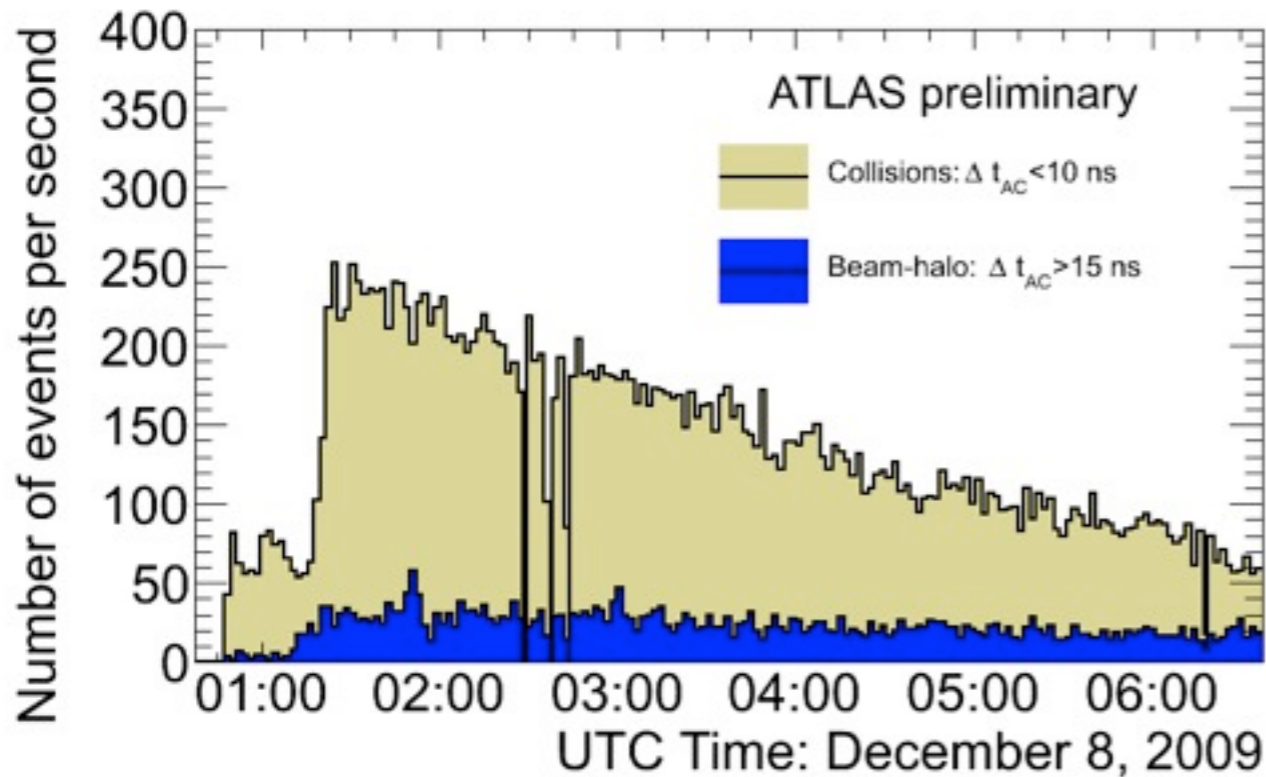
dopo la selezione
di trigger



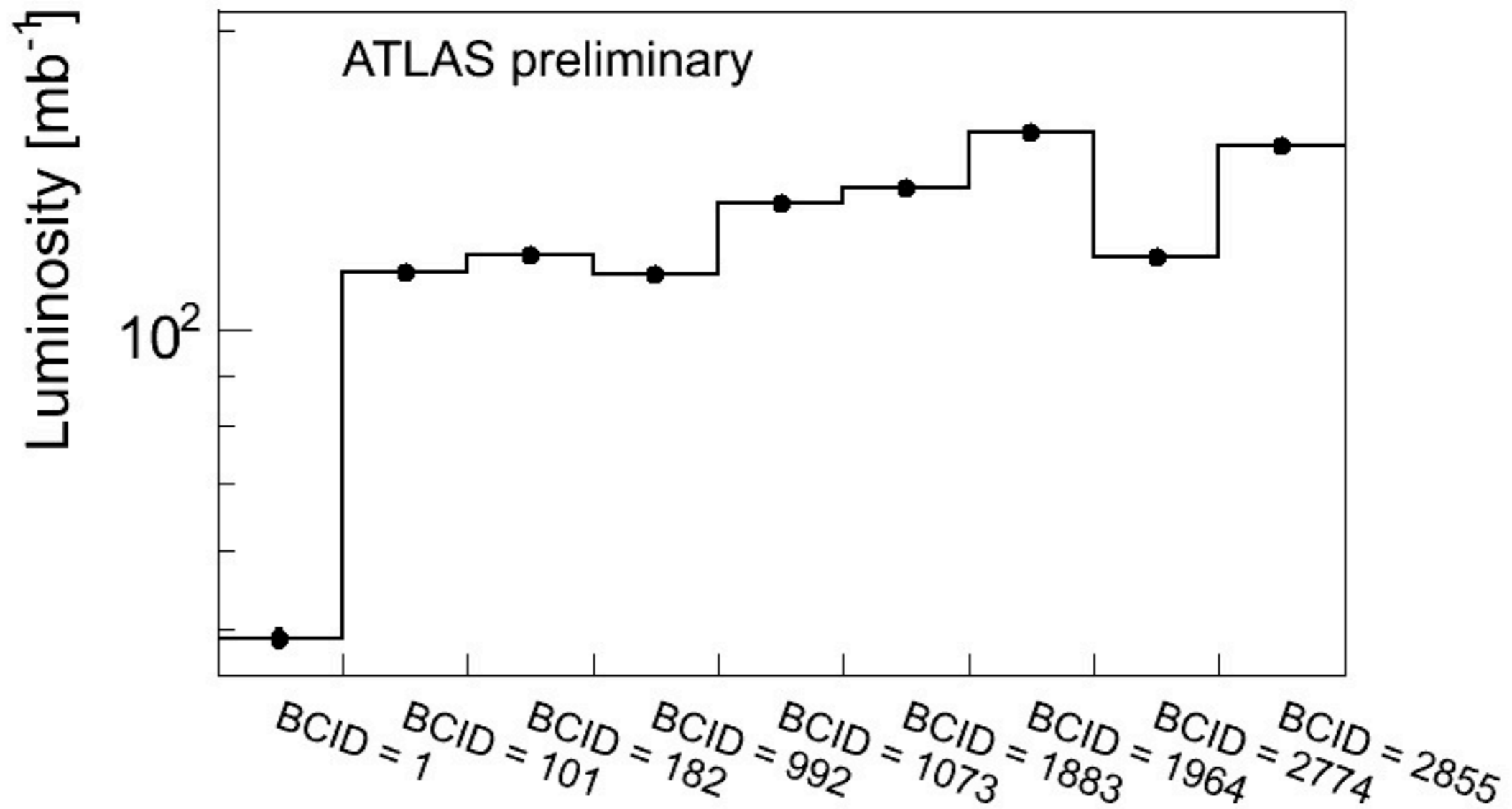
Fondo del fascio



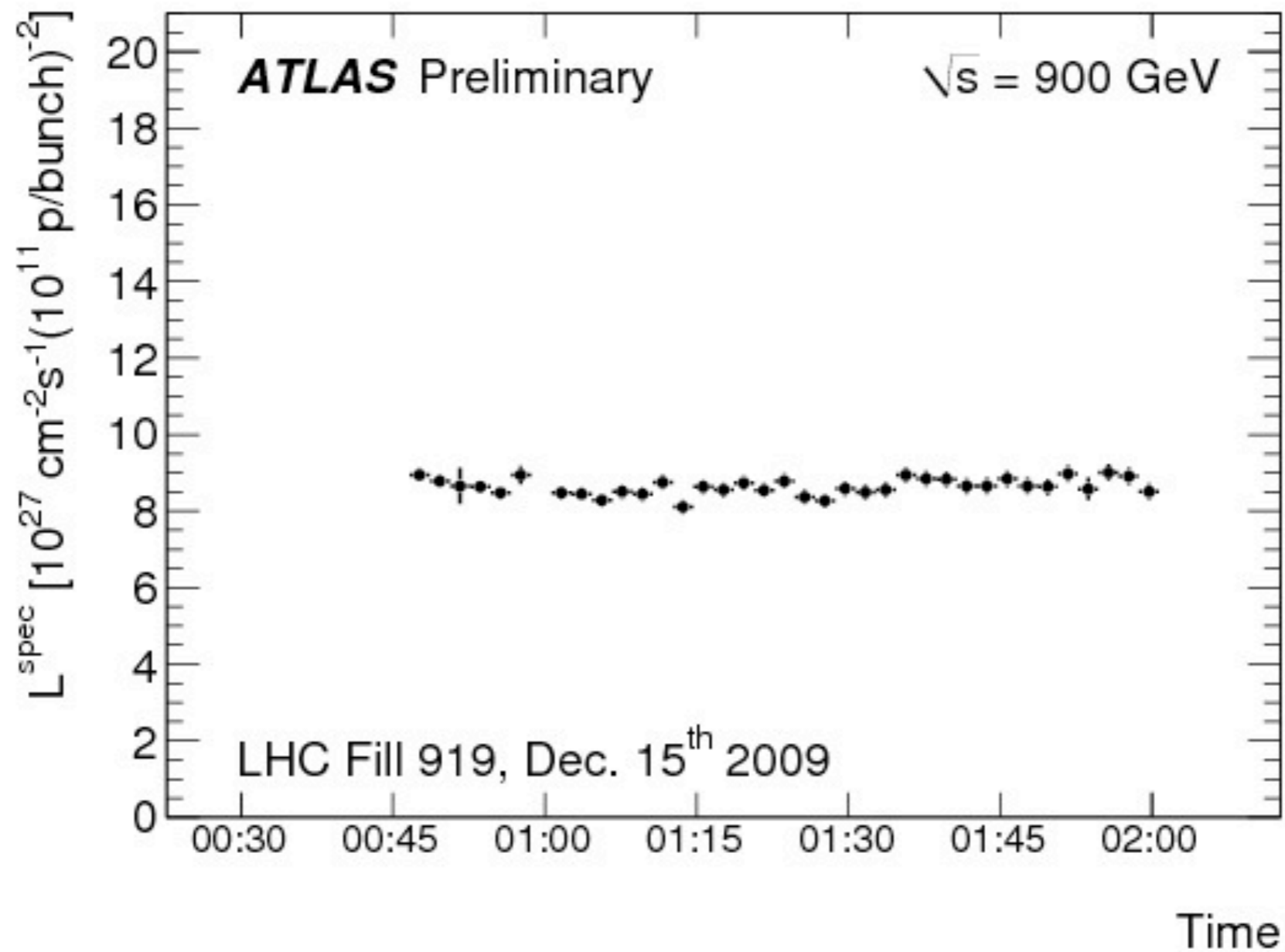
Eventi di collisione e di fondo



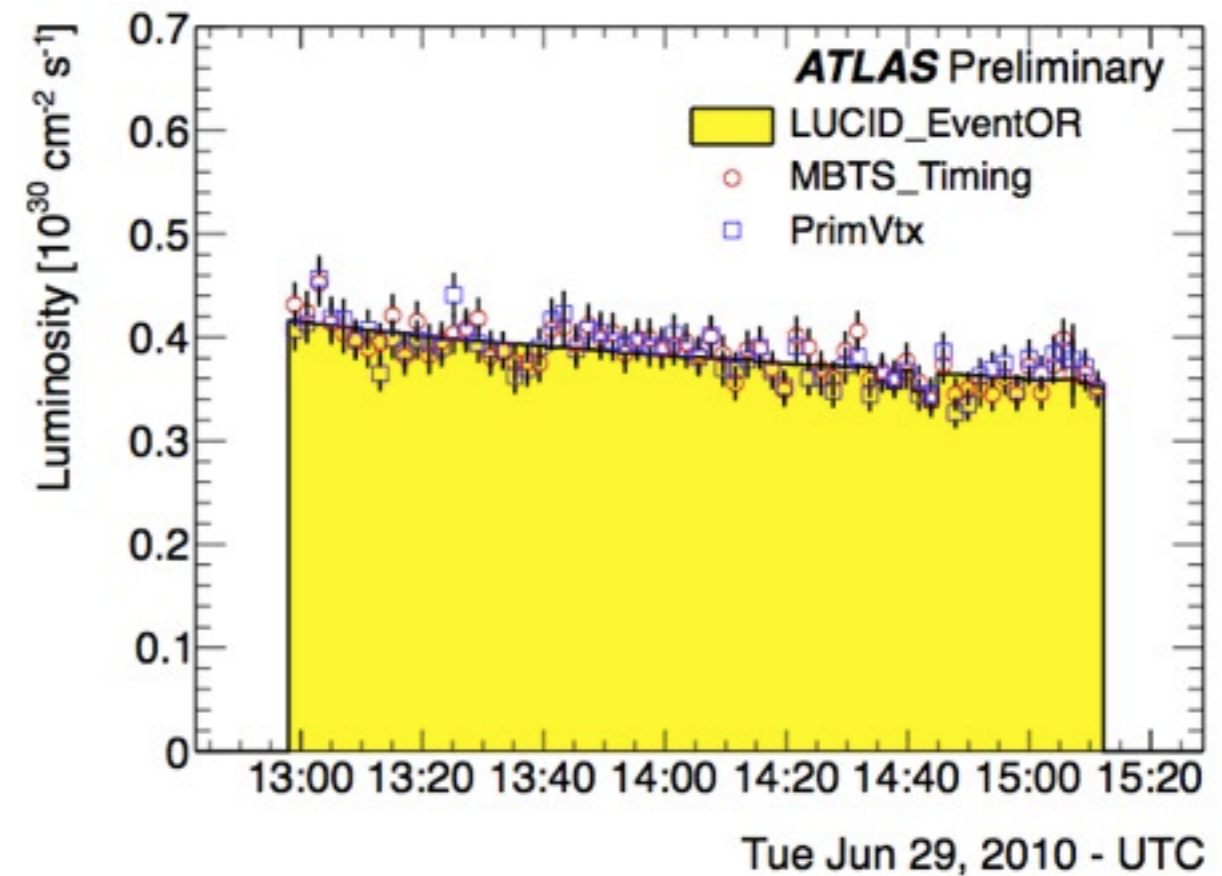
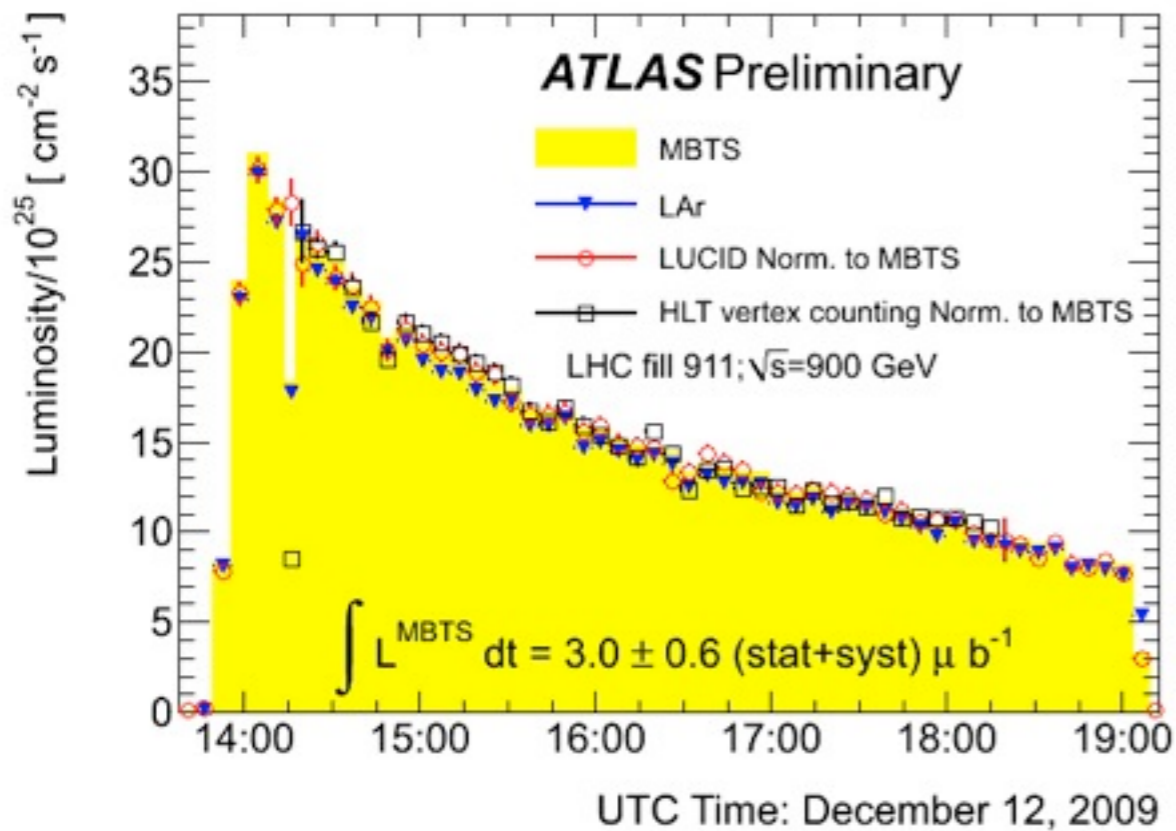
Luminosita' per pacchetto



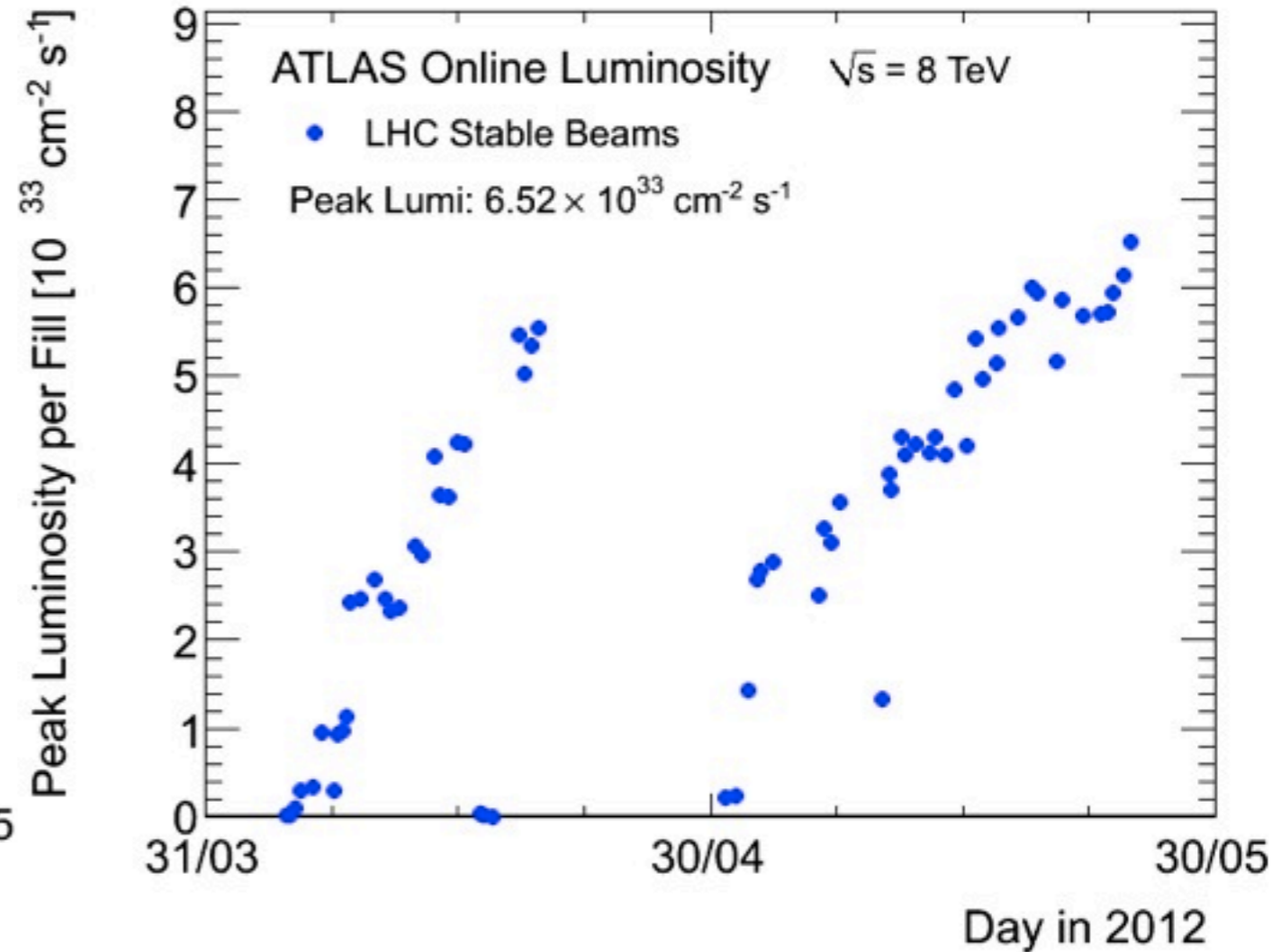
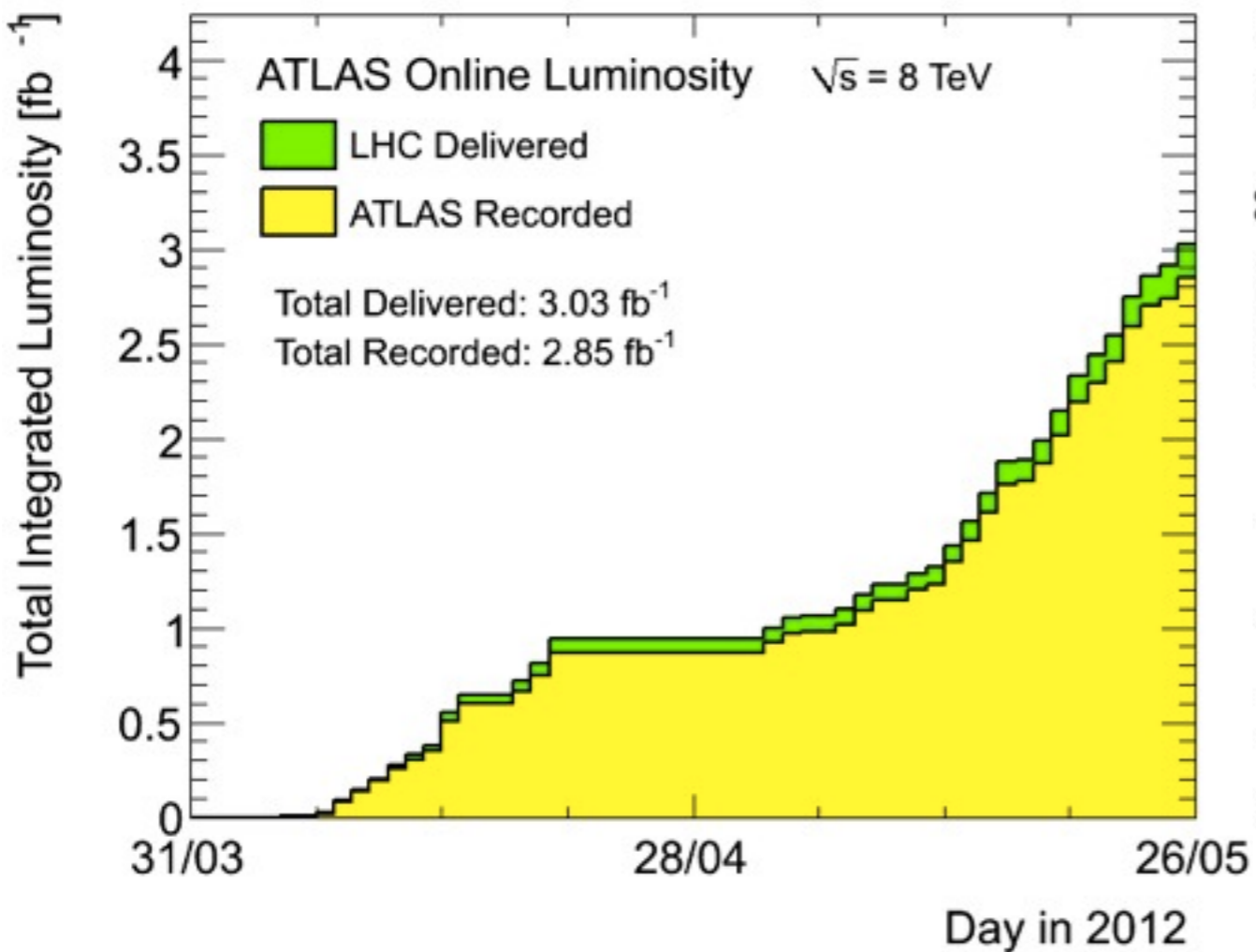
Luminosita' specifica



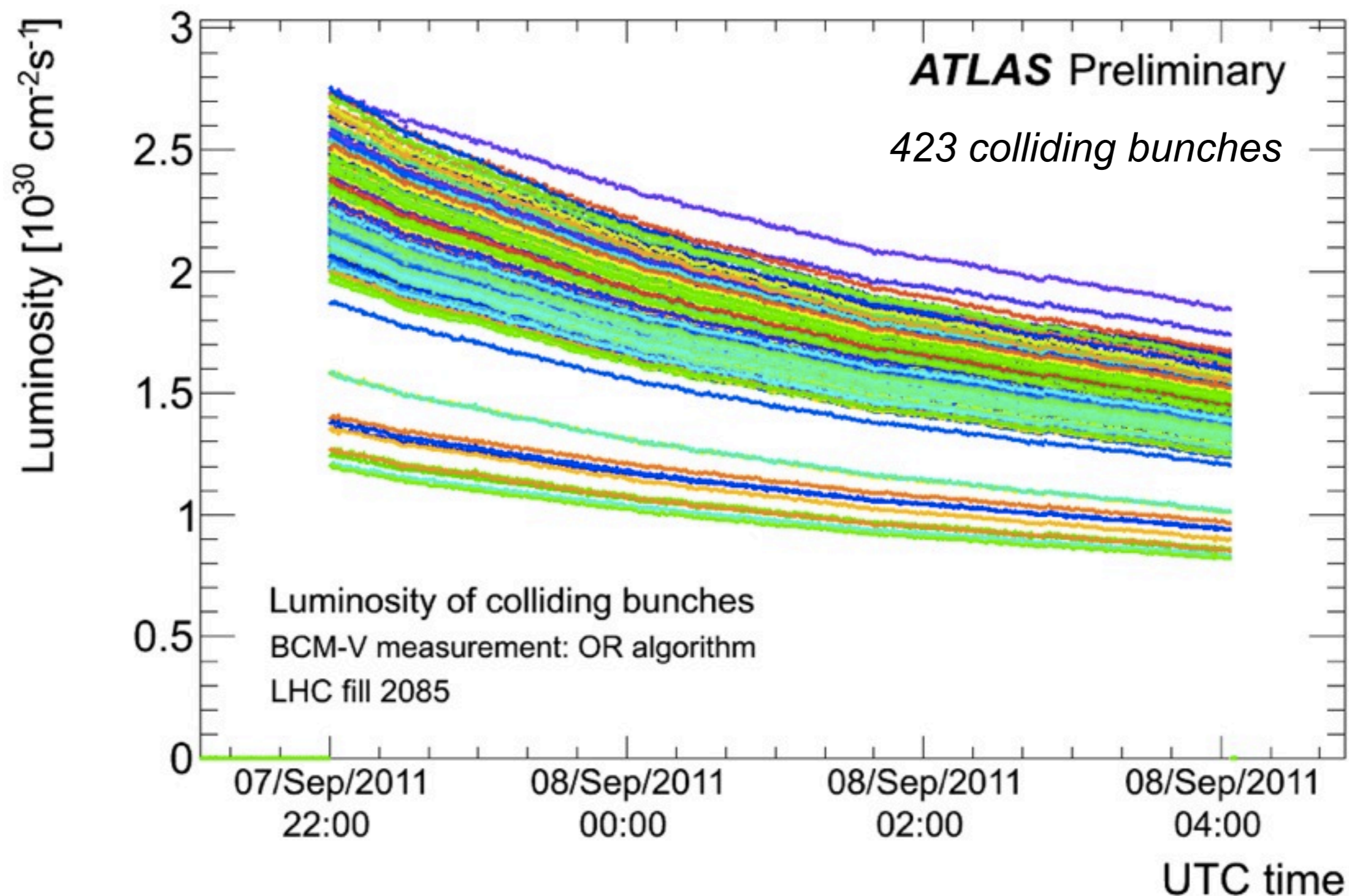
Confronto tra rivelatori diversi



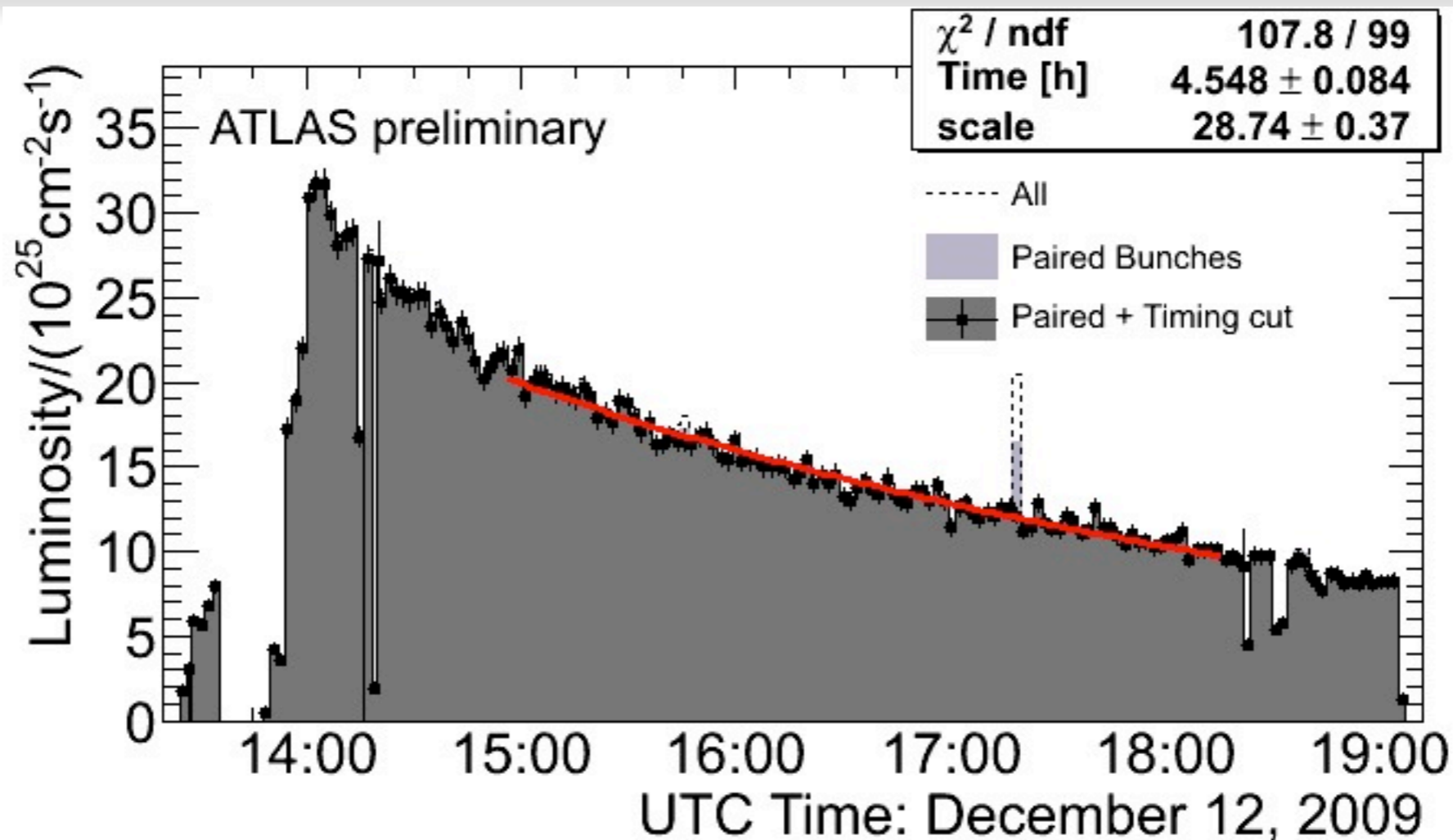
Prestazioni attuali di LHC



Luminosita' bunch-by-bunch



Costante di tempo della luminosita'



$$\mathcal{L}(t) \sim e^{-\frac{t}{\tau}}$$

Un decadimento di tipo esponenziale e' in generale una buona approssimazione. L'ipotesi e' che la probabilita' di deterioramento della luminosita' e' costante nel tempo. Contributi dominanti al deterioramento provengono dal decadimento dell'intensita' del fascio, aumento della sezione trasversa

Ricapitolazione

- La luminosita' dipende dall'intesita' dei fasci dalla frequenza di interazione e dalla sezione trasversa dei fasci
- Luminosita' relativa e' fondamentale per conoscere le prestazioni dell'acceleratore
- la luminosita' e' proporzionale alla rate di eventi. Qualunque processo con una rate di alcuni hertz e' sufficiente per valutare la luminosita' relativa
- difficolta' stima dell'efficienza
- saturazione

Luminosita' assoluta

- Le misure di luminosita' relativa descritte fin ora sono affette da una grande incertezza sulla scala assoluta dovuta alla simulazione monte carlo necessaria a valuta l'efficienza e la la sezione d'urto totale
- Ci sono 2(3) metodi per ottenere la normalizzazione assoluta in modo
 - ✓ Teorema ottico
 - ✓ metodo di Van der Meer

Applicazione teorema ottico

$$\begin{aligned}\sigma_{el} &= \frac{\pi \hbar^2}{p^2} |f(\theta)|^2 = \frac{\pi \hbar^2}{p^2} [(\Re f(\theta))^2 + (\Im f(\theta))]^2 \\ \sigma_{tot} &= \frac{4\pi \hbar}{p} \Im(f(\theta = 0)) \\ \frac{\sigma_{tot}^2}{\sigma_{el}} &= \frac{1}{4\pi} \left[1 + \frac{(\Re(f(\theta = 0)))^2}{(\Im(f(\theta = 0)))^2} \right] \leftarrow \text{from theory 1-2\%}\end{aligned}$$

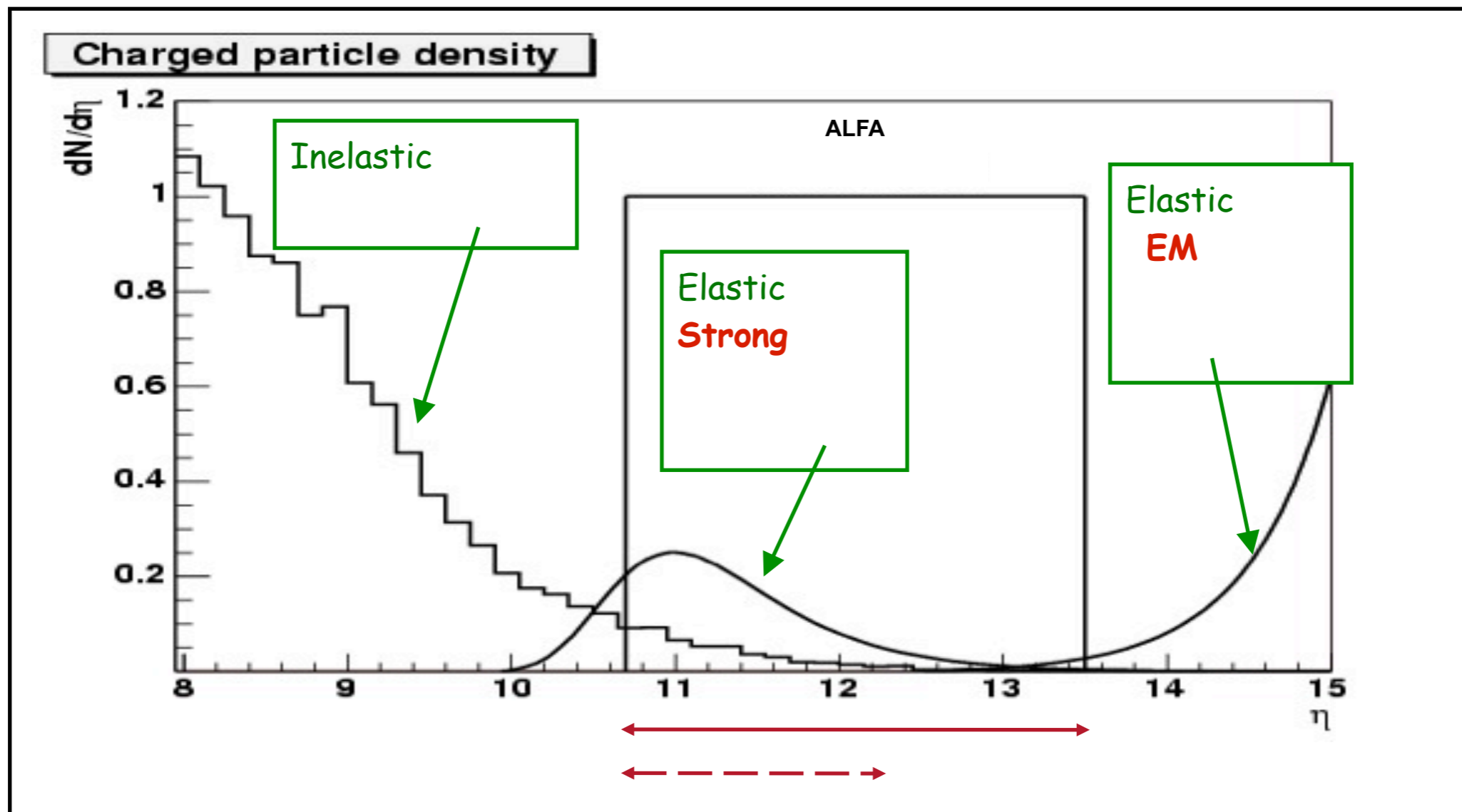
Se possiamo misurare la sezione d'urto elastica nel limite di angolo zero, possiamo fare una misura indipendente della sezione d'urto totale e quindi estrarre la luminosita'. Il rapporto della parte immaginaria e reale di f deve essere calcolato (LHC $\sim 0.1 \pm 0.02$)

Molteplicita di particelle vs theta

diffusione elettromagnetica

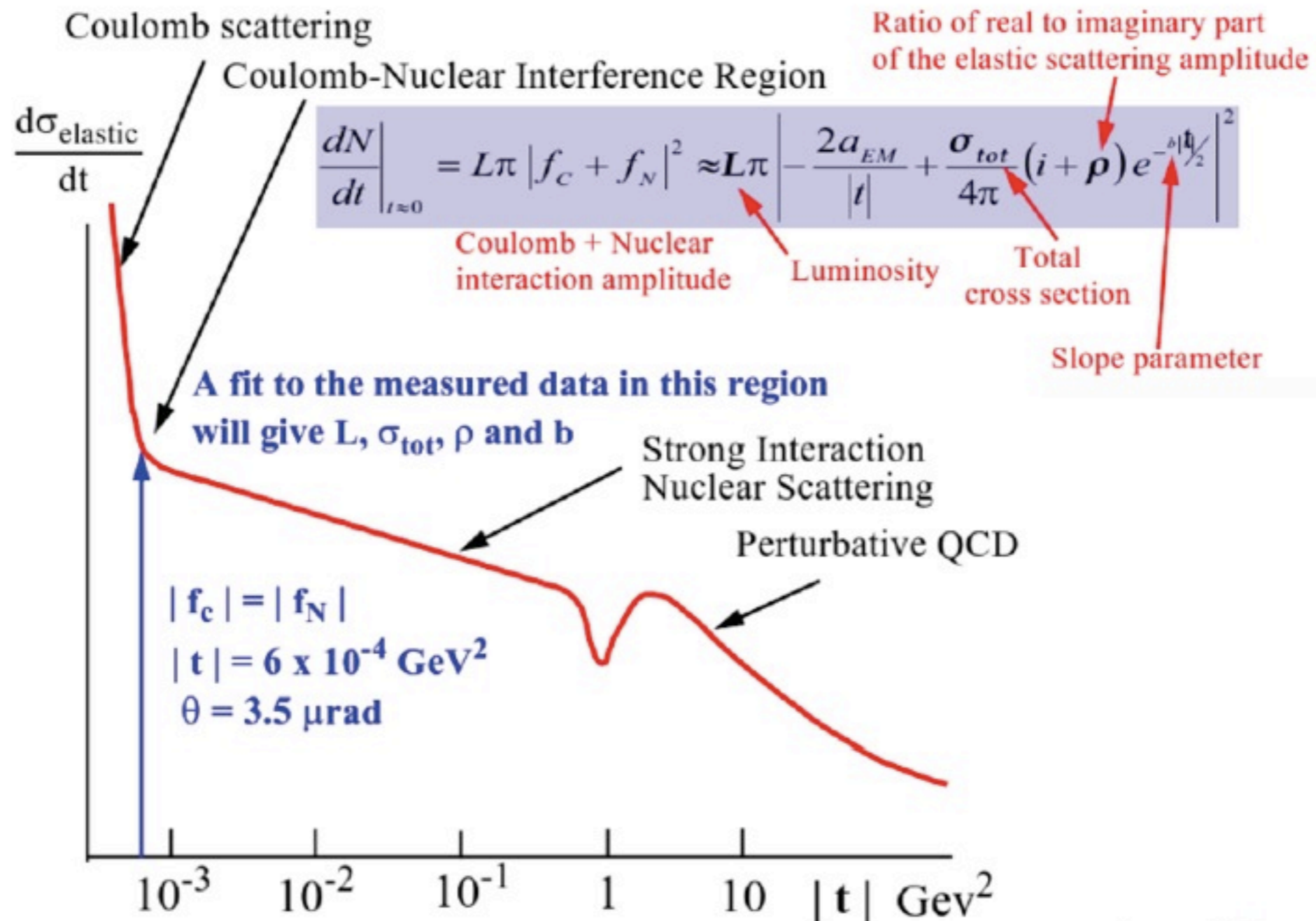
$$t \ll 1 \quad t \sim (p\theta)^2$$

$$\frac{dN}{dt} = L\pi |F_C + F_N|^2 = L \left(\frac{4\pi\alpha^2 (\hbar c)^2}{|t|^2} - \frac{\alpha\rho\sigma_{tot} e^{-B|t|/2}}{|t|} + \frac{\sigma_{tot}^2 (1+\rho^2) e^{-B|t|}}{16\pi (\hbar c)^2} \right)$$



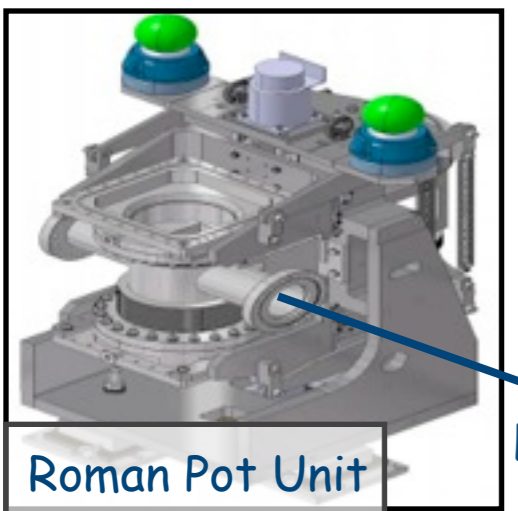
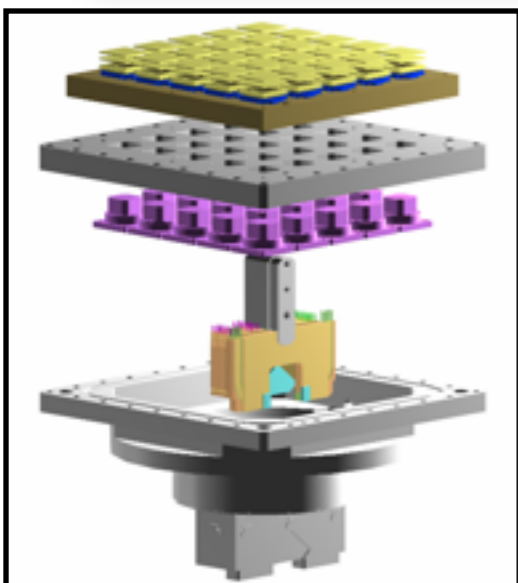
Elastic scattering: EM interference

- Measure at very low t the elastic scattering \Rightarrow sensitive to Coulomb amplitude (ALFA)



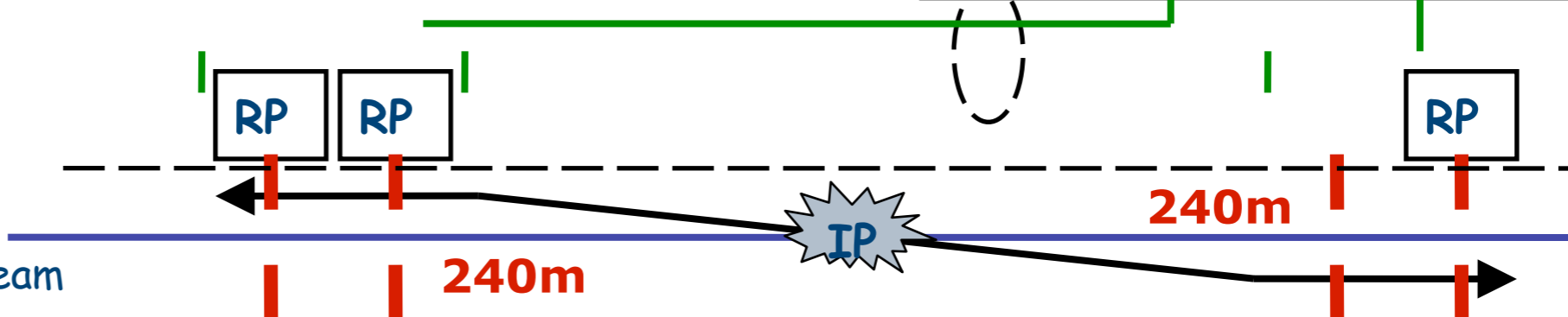
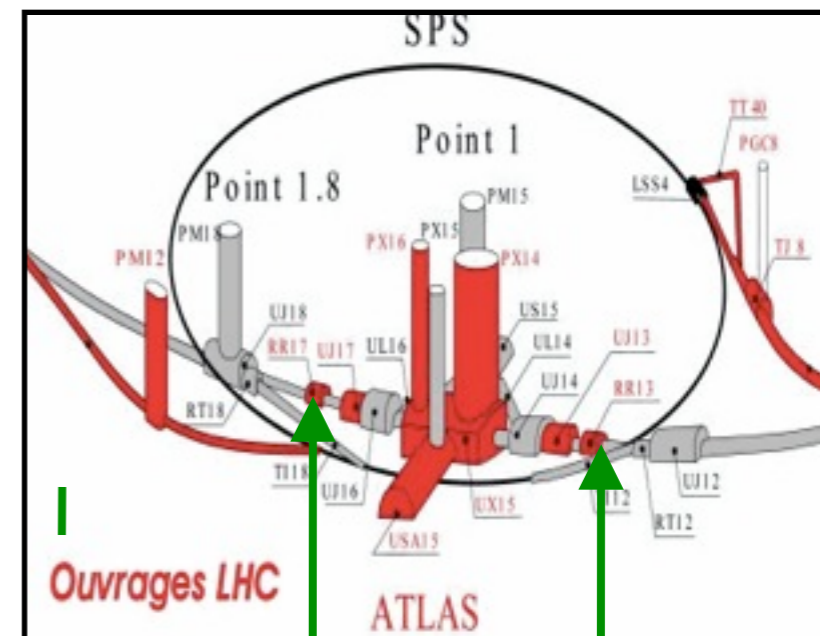
Rivelatore: roman pot

Concetto: tracciatore di fibre scintillanti estremamente vicino al fascio



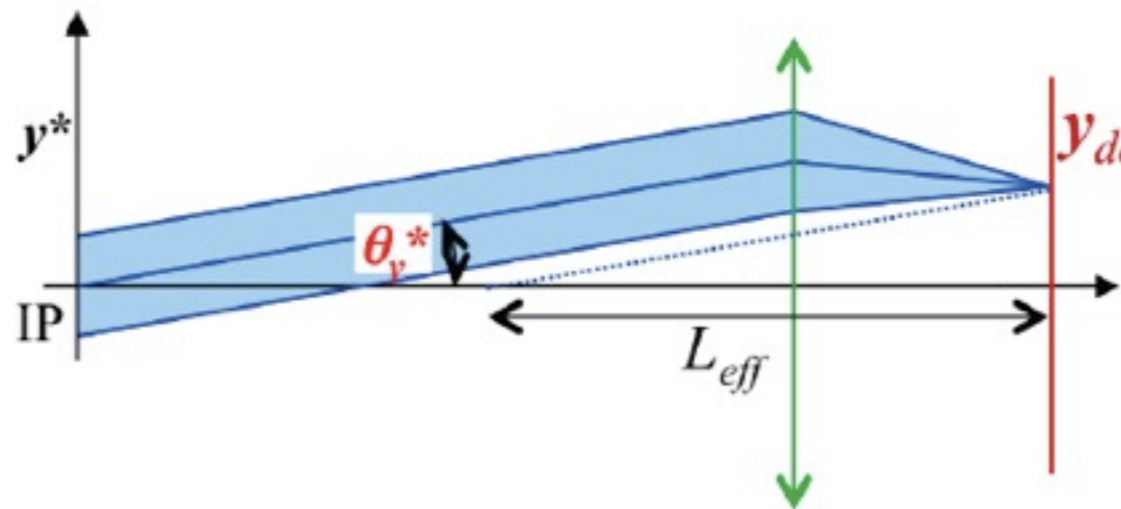
LHC Beam

Roman Pot Unit



Elastic scattering

- Very demanding beam conditions ($\theta \sim 3-6 \mu\text{rad}$):
 - ✓ Tiny angular divergence $\sigma^* = \sqrt{\epsilon} / \beta^* \ll \theta_{scat.}$
 - ◆ very small emittances: $\epsilon \sim 1 \mu\text{m}$
 - ◆ large β^* : 90m, 1540m(TOTEM), 2600m(ALFA)
 - ✓ parallel-to-point focussing \Rightarrow same angle same place in the detector



- ✓ zero crossing angle \Rightarrow 156 bunches \Rightarrow low L ($10^{29} \text{cm}^{-2} \text{s}^{-1}$)
- Detector able to approach the beam within 1-1.5 mm (10-12 σ)
 - ✓ extremely precise detectors: Si (TOTEM), Sci-fibers (ALFA)
 - ✓ compact electronics, very good alignment

Elastic scattering: precision

- Optical theorem + total rate
 - ✓ Estimated TOTEM systematics on absolute L : 2-4 % (@ $\beta^*=1540\text{m}$)
 - ◆ extrapolation to $t = 0$: 5-6% @ $\beta^*=90\text{m}$, <1% @ $\beta^*=1540\text{m}$
 - ◆ total inelastic rate <1%
 - ◆ $\rho \sim 1\text{-}2\%$
- Optical theorem + Coulomb interference (2013-2014):
 - ✓ Main challenge are the beam requirements to go at very small t :
 - ◆ will it be possible to reduce the emittance as low as required?
 - ◆ will the optical properties of the beam known at the required precision?
 - ◆ will the beam-halo allow to approach the beam so close

Absolute L: from beam parameters

normalized transverse beam density $\int \rho(x, y) dx dy = 1$

$$\mathcal{L} = n_b f_r I_1 I_2 \int \hat{\rho}_1(x, y) \hat{\rho}_2(x, y) dx dy$$

bunch current
measured by LHC

beam transverse
overlap integral

In the hypothesis of beam densities uncorrelated in x, y

$$\mathcal{L} = n_b \cdot f_r \cdot N_1 \cdot N_2 \cdot I_x(\rho_1(x) \cdot \rho_2(x)) \cdot I_y(\rho_1(y) \cdot \rho_2(y))$$

$$I_x(\rho_1(x) \cdot \rho_2(x)) = \int \rho_1(x) \cdot \rho_2(x) dx$$

we need to measure the overlap integrals in x and y

Luminosity & vdM scan method

$$\mathcal{L} = n_b f_r I_1 I_2 \int \hat{\rho}_1(x, y) \hat{\rho}_2(x, y) dx dy = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y} = \frac{\epsilon \mu n_b f_r}{\epsilon \sigma_{inel}} = \frac{\mu^{vis}(\epsilon, \mu) n_b f_r}{\sigma_{vis}}$$

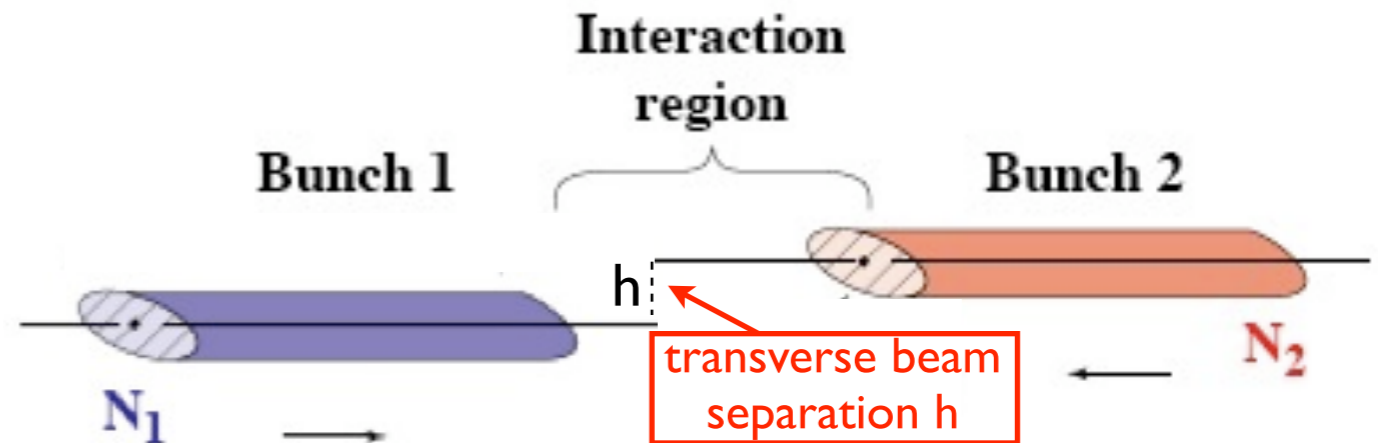
number of bunches
LHC frequency

beams overlap integral

visible interactions

visible cross section
(calibration constant)

- measure the rate as a function of h
 $R(h) = A \cdot I_x(\rho_1(x) \cdot \rho_2(x-h))$
 to estimate the overlap integral



experimental data are well described by a Double Gaussian

$$I_x(\rho_1(x) \cdot \rho_2(x)) = \frac{1}{\sqrt{2\pi \tilde{\Sigma}_x}} = \left[\frac{f_a}{\sigma_a} + \frac{1-f_a}{\sigma_b} \right]$$

fraction of core gaussian (blue arrow to f_a)
 core sigma (green arrow to σ_a)
 tail sigma (red arrow to σ_b)

Fasci con profilo gaussiano

Nel caso in cui la densita' di particelle dei fasci sia rappresentata da una Gaussiana:

$$G(x, \sigma, \mu) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

possiamo calcolare esplicitamente l'integrale di convoluzione ottenendo:

$$I_x(G_1(x, \sigma_1, \mu_1 = 0) \cdot G_2(x, \sigma_2, \mu_2 = 0)) = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{\sqrt{\sigma_1^2 + \sigma_2^2}} = \frac{1}{\sqrt{2\pi\Sigma_x}}$$

da cui si ricava l'espressione generale della luminosita':

$$\mathcal{L} = n_b \cdot f_r \cdot \frac{N_1 \cdot N_2}{2\pi \cdot \Sigma_x \cdot \Sigma_y}$$

notare che $\Sigma_{x(y)}$ e' la sigma di convoluzione e non la sigma del fascio. Nel caso di fasci uguali $\Sigma_{x(y)} = \sqrt{2}\sigma_{x(y)}$ da cui:

$$\mathcal{L} = n_b f_f \frac{N_1 N_2}{4\pi \sigma_x \sigma_y}$$

Metodo di van der Meer

Il metodo proposto da Van der Meer (1968 - ISR) per misurare la luminosita' assoluta consiste nel misurare direttamente l'integrale di convoluzione. Poiche' la rate di interazione e' proporzionale alla luminosita', lo sara' anche l'integrale di convoluzione. Nel caso in cui i due fasci non siano in asse ma i loro centri siano separati di una distanza h , avremo:

$$R(h) = A \cdot I_x(\rho_1(x) \cdot \rho_2(x-h))$$

dove $R(h)$ e' la rate di interazione quando i fasci sono separati di h , ed A e' una costante di proporzionalita' sconosciuta.

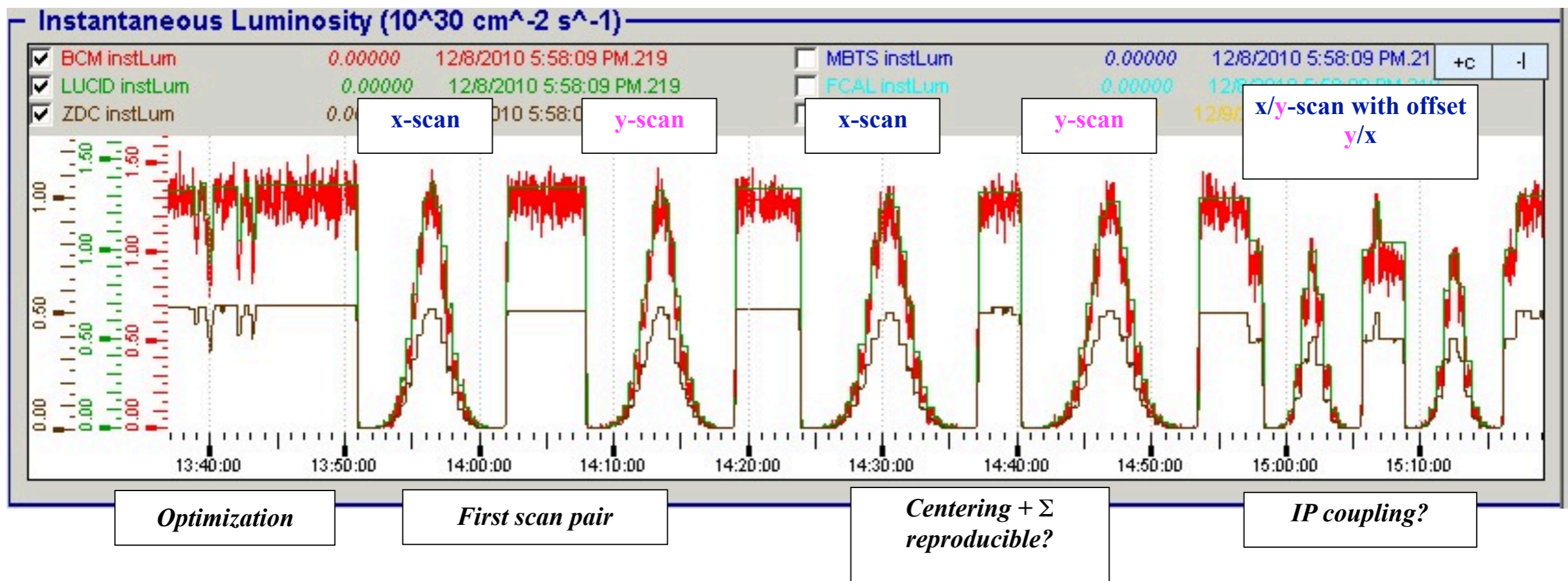
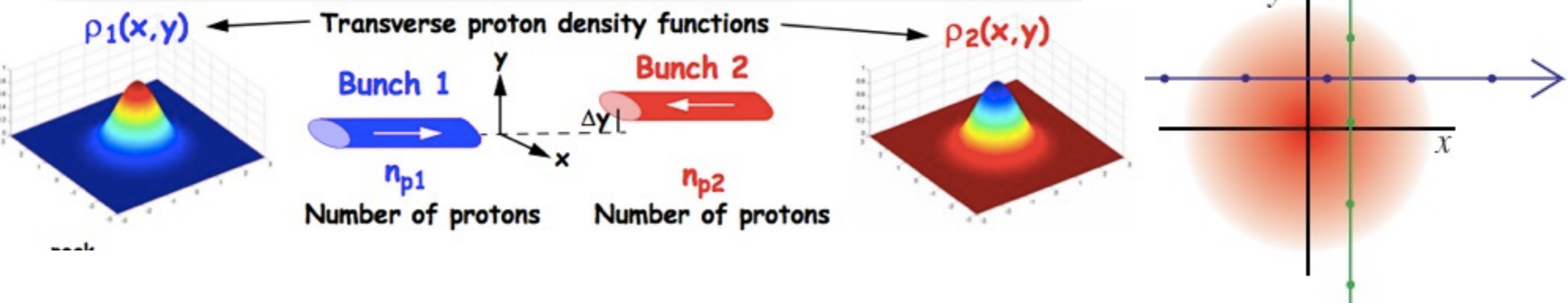
$$\int_{-\infty}^{\infty} R(h)dh = A \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} \rho_1(x)\rho_2(x-h)dx \right] dh =$$

$$A \int_{-\infty}^{\infty} \rho_1(x) \left[\int_{-\infty}^{\infty} \rho_2(x-h)dh \right] dx = A \int_{-\infty}^{\infty} \rho_1(x)dx = A$$

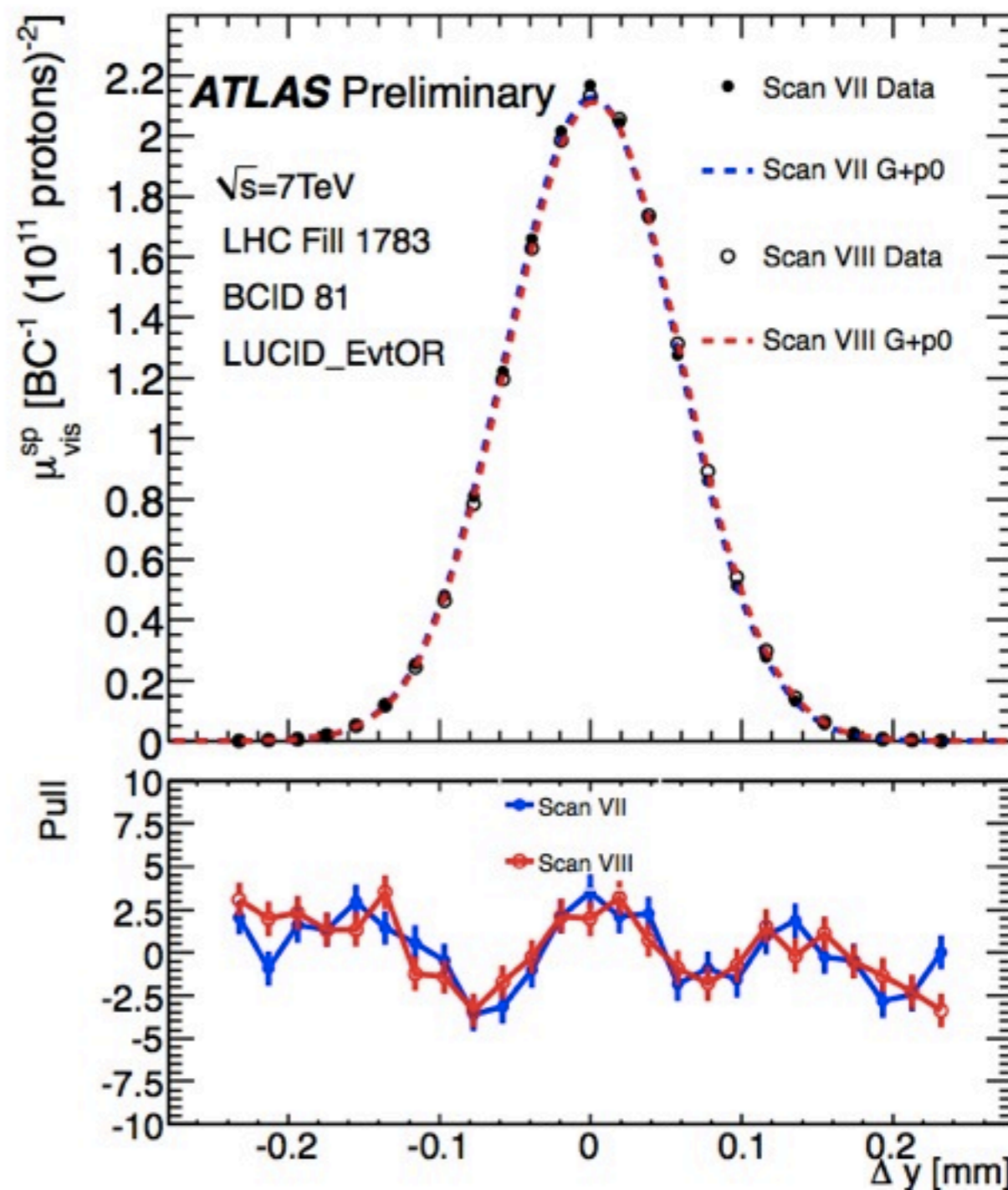
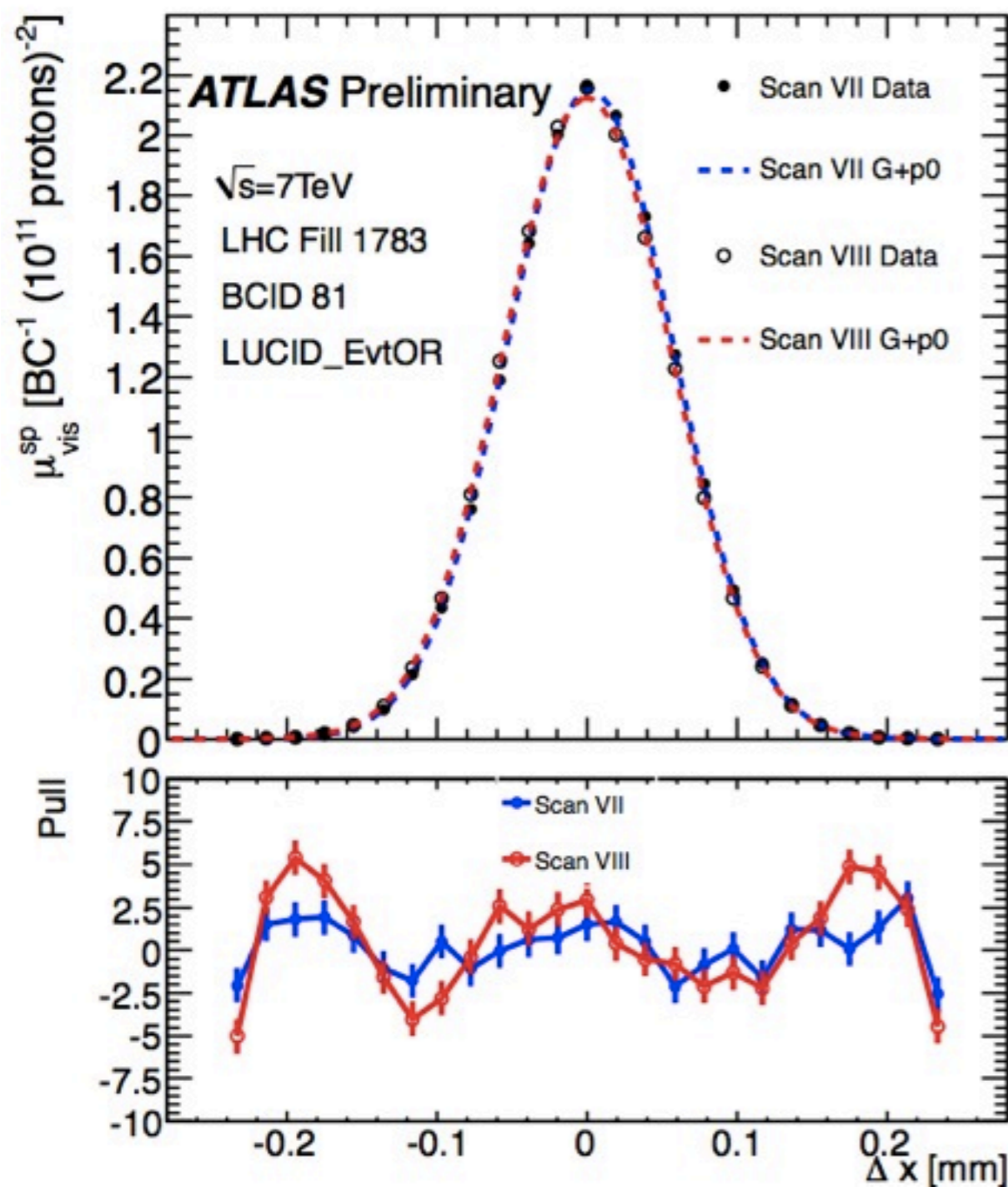
da cui otteniamo che l'integrale di convoluzione e' dato da:

$$I_x(\rho_1(x) \cdot \rho_2(x)) = \frac{R(0)}{\int R(h)dh}$$

Metodo di van der Meer



Metodo di van der Meer



Sezione d'urto visibile

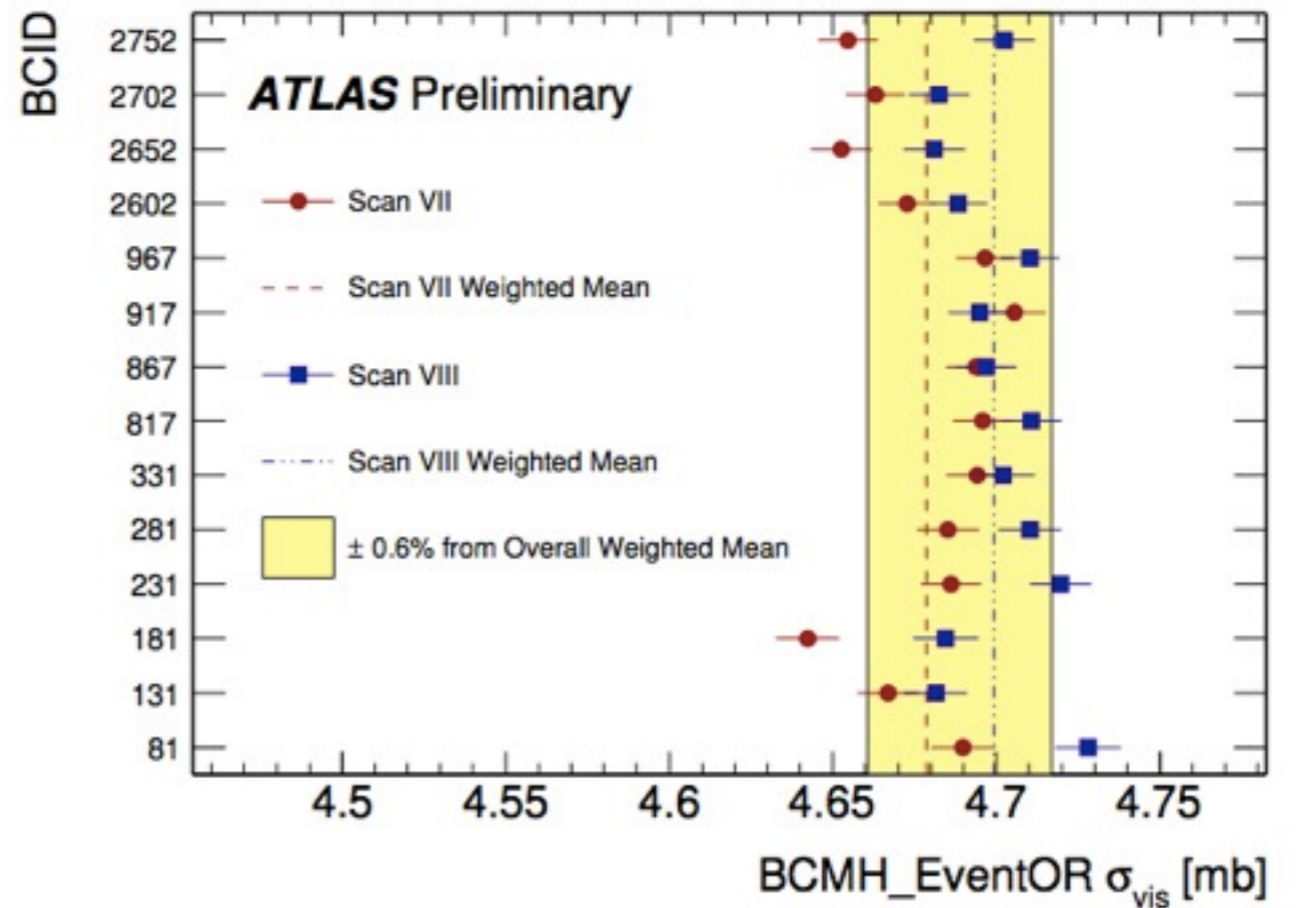
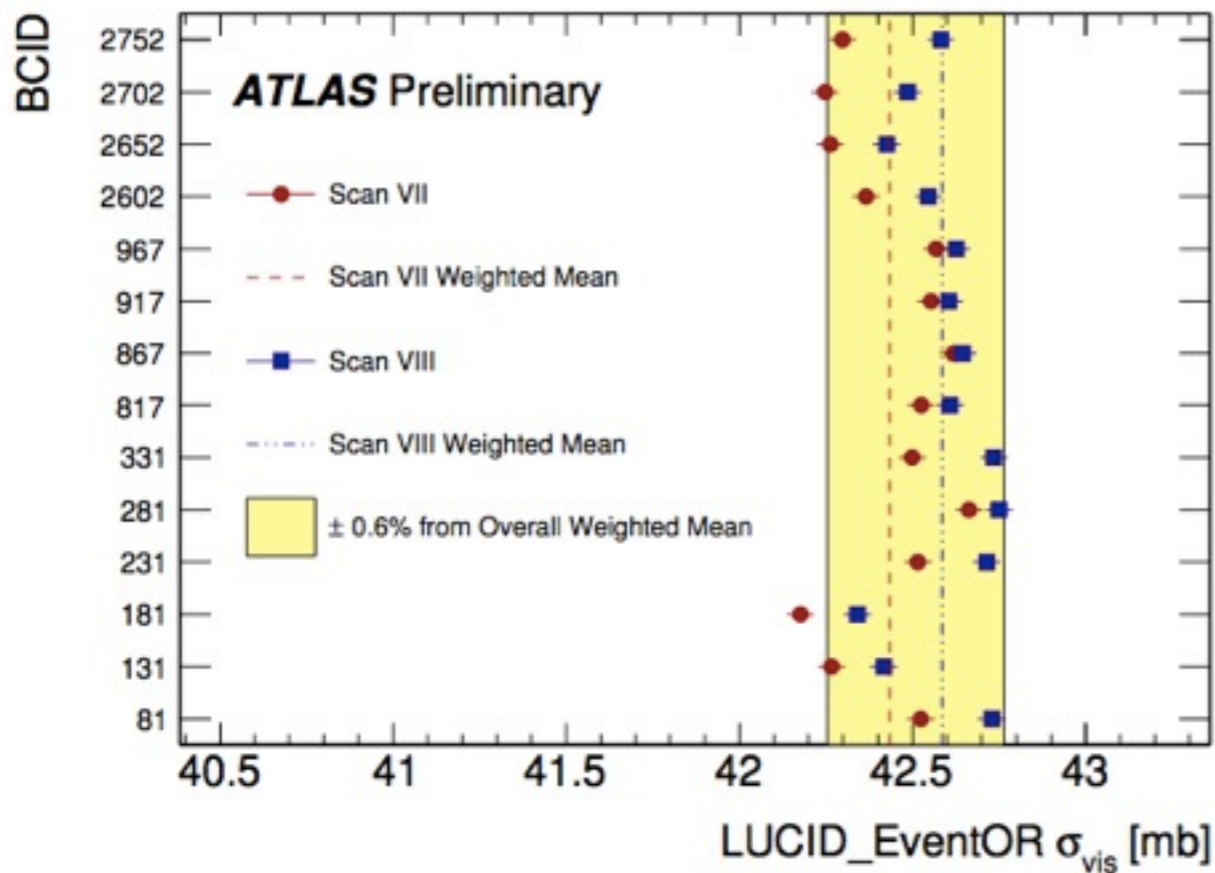
$$\mathcal{L} = n_b f_r I_1 I_2 \int \hat{\rho}_1(x, y) \hat{\rho}_2(x, y) dx dy = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y} = \frac{\epsilon \mu n_b f_r}{\epsilon \sigma_{inel}} = \frac{\mu^{vis}(\epsilon, \mu) n_b f_r}{\sigma_{vis}}$$

number of bunches
LHC frequency

beams overlap integral

visible interactions

visible cross section
(calibration constant)

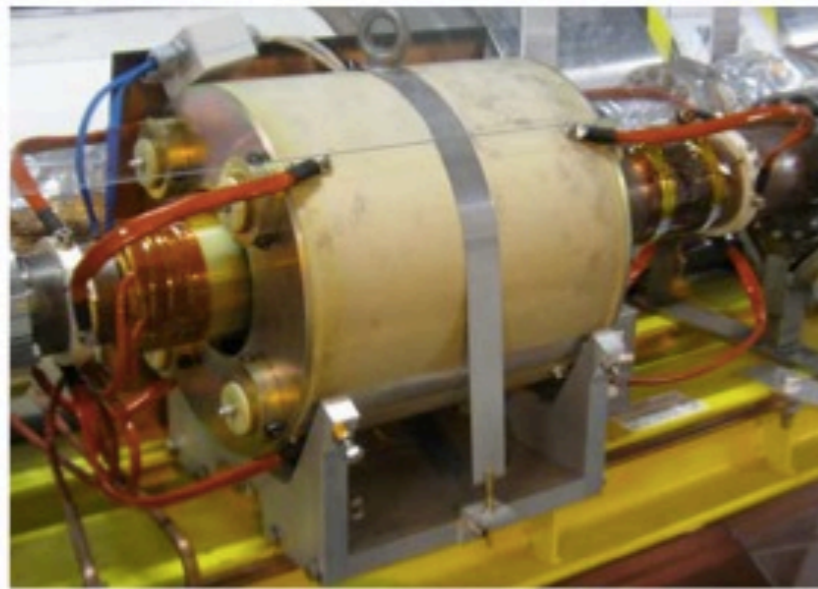


Incertezze sistematiche

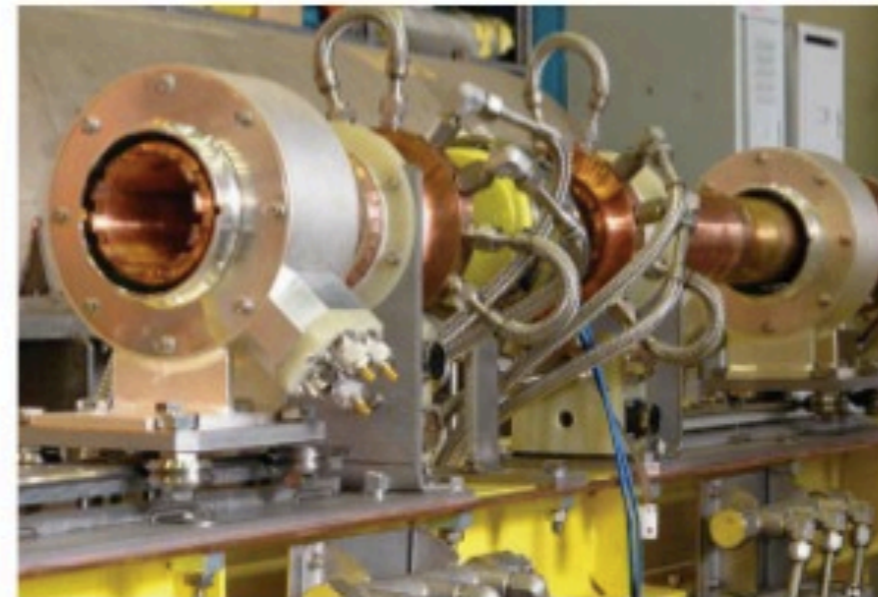
- intensita' dei fasci
- calibrazione scala assoluta delle lunghezze
- decentramento dei fasci
- scelta della funzione di fit della rate in funzione della separazione
- crescita della sezione trasversa dei fasci nel tempo
- fondo di eventi non da collisioni protone-protone
- dipendenza residua della rate dal numero di interazione per crossing



Current measurements



DCCT: DC Current Transformer
Measures the total current



FBCT: Fast Beam Current Transformer
Measures the fraction of the current in each bunch.

Number of protons in bunch j \rightarrow $n_{pj} = (\alpha N^{DCCT} - N_{baseline} - N_{ghostcharge}) \frac{N_j^{FBCT}}{\sum_j N_j^{FBCT}}$
 Calibrated scale factor \rightarrow

Syst. error on $n_{p1}n_{p2}$: 2.7% ⊕ <0.1% ⊕ negligible ⊕ 1.6% = 3.1%

Total calibration error = Error scan ⊕ Error current = 1.3% ⊕ 3.1% = 3.4%

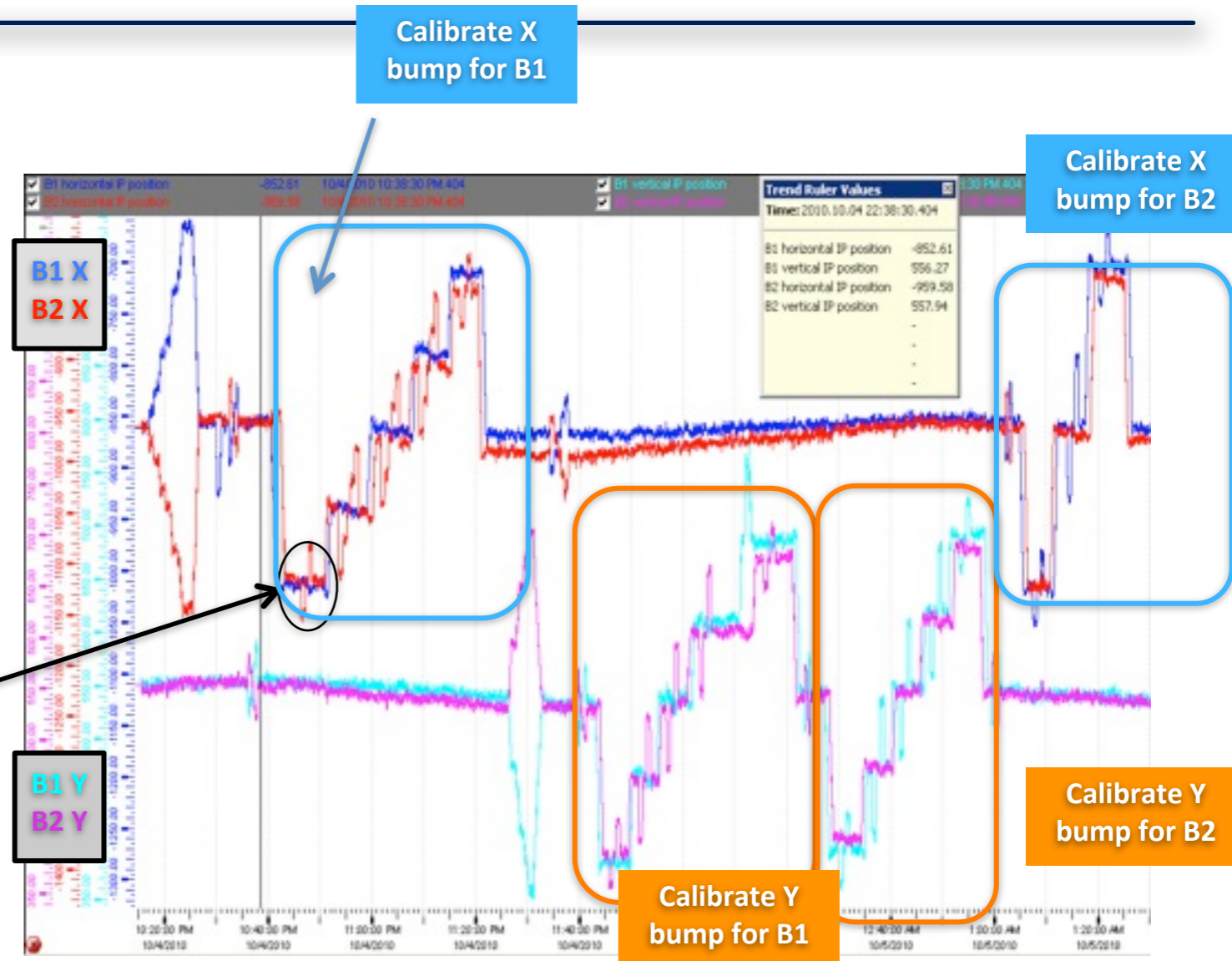
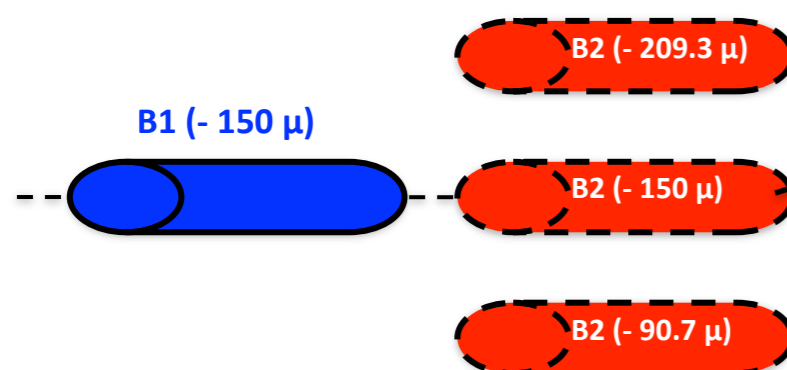
Calibrazione scala delle lunghezze

➤ Example, B1 X, bump step -150 μm :

μm :

- ✓ Move B1X to $x_1 = -150 \mu\text{m}$
- ✓ Move B2X to $x_2 = -150 \mu\text{m}$
- ✓ Scan B2X around x_1 by ± 0.5 (or ± 1.0)

$\sigma_{b,nom}$ (= 59.3 μm)



➤ For every scan step for beam 1 and beam 2,

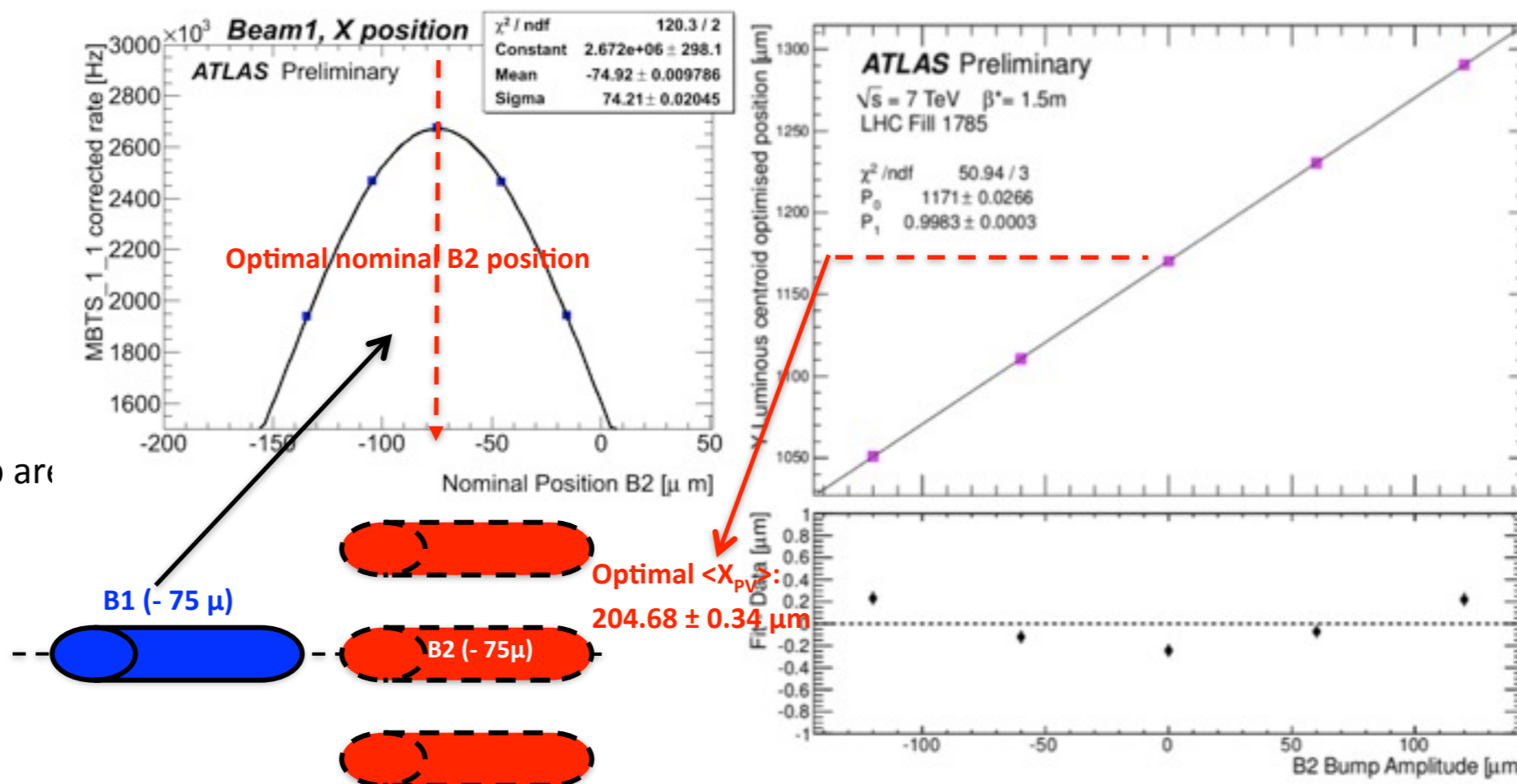
- ✓ the beam spot centre (x, y) is measured averaging over the primary interaction vertices as determined by the ATLAS inner tracker
- ✓ the rate is measured using the Minimum Bias Trigger Scintillator (MBTS)

Calibrazione scala delle lunghezze

➤ For every step in X (Y) for beam 1 (beam 2) a mini scan is performed using beam 2 (beam 1)

- ✓ The online rate from MBTSeventAND is used
- ✓ With a Gaussian fit, the optimal position using the VdM scan is extracted. This corresponds to the two beams being right on top to each others.

✓ $\langle X_{pV} \rangle$ and $\langle Y_{pV} \rangle$ at the optimal overlap are extracted by interpolation



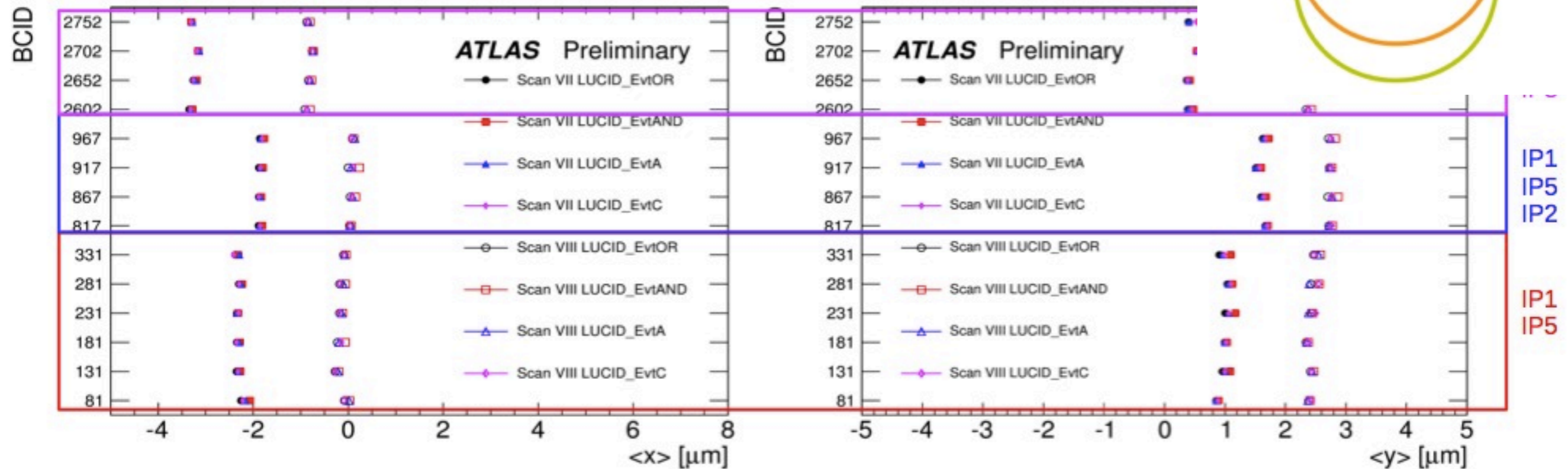
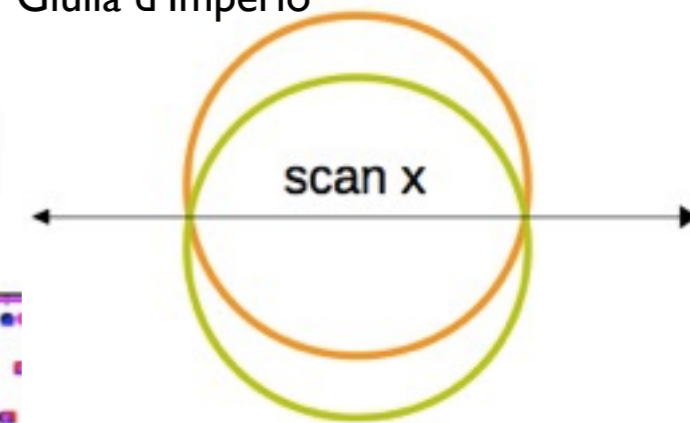
$$L_X = 0.999 \pm 0.001$$

$$L_Y = 0.998 \pm 0.001$$

✓ Systematics

- ✓ no correction of the scale applied, residual from 1 included into the systematics
- ✓ geometry inner detector, needs to be quantified
- ✓ undetected beam motion = 0.3%

Beam Recentering

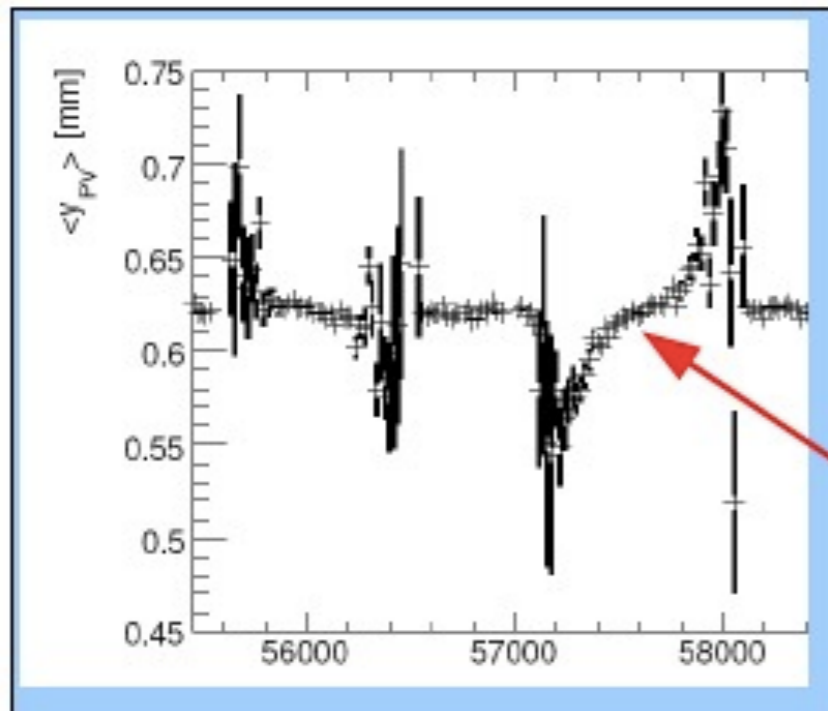
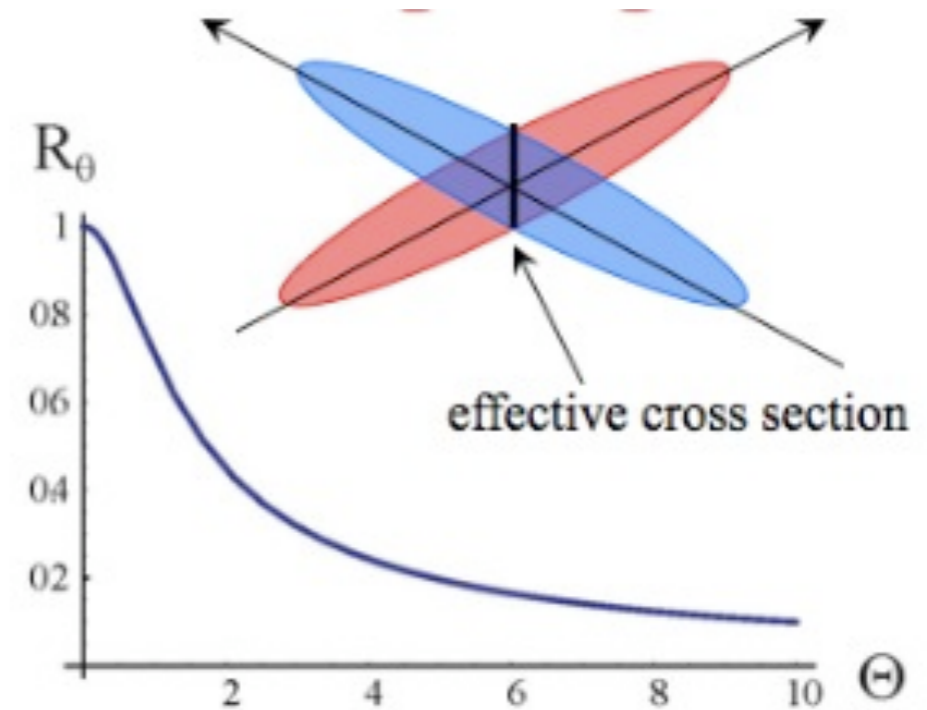
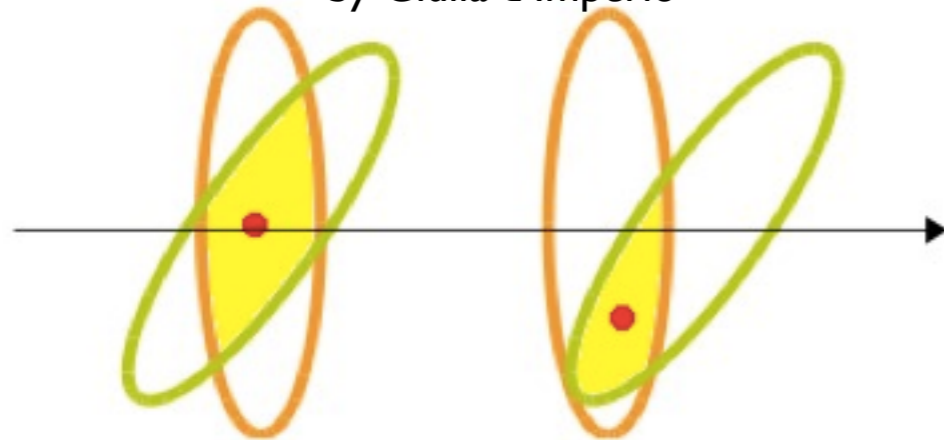


- Observe up to 2 micron non-reproducibility in fitted peak position
 - NB. Beams not recentered between scans
 - Observed effect larger at larger β^* ; should scale as $\sqrt{\beta^*}$
 - Affects estimate of μ_{vis} at peak, impact on σ_{vis} is 0.1%
- Visible systematic difference depending on cross-talk with other IPs

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Crossing Angle and x-y correlation

by Giulia d'Imperio

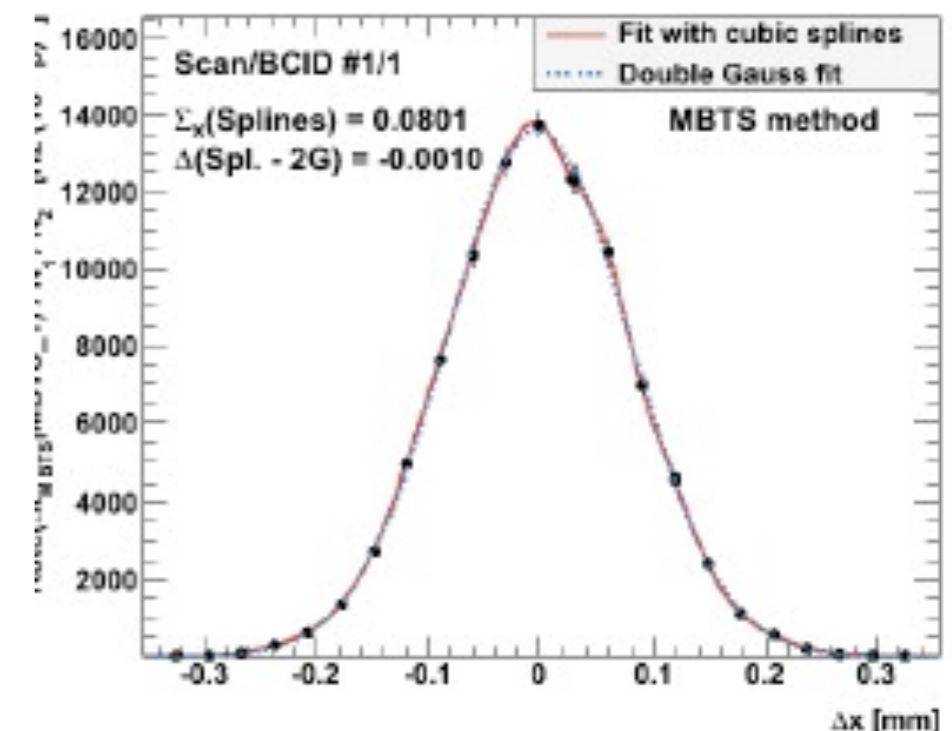
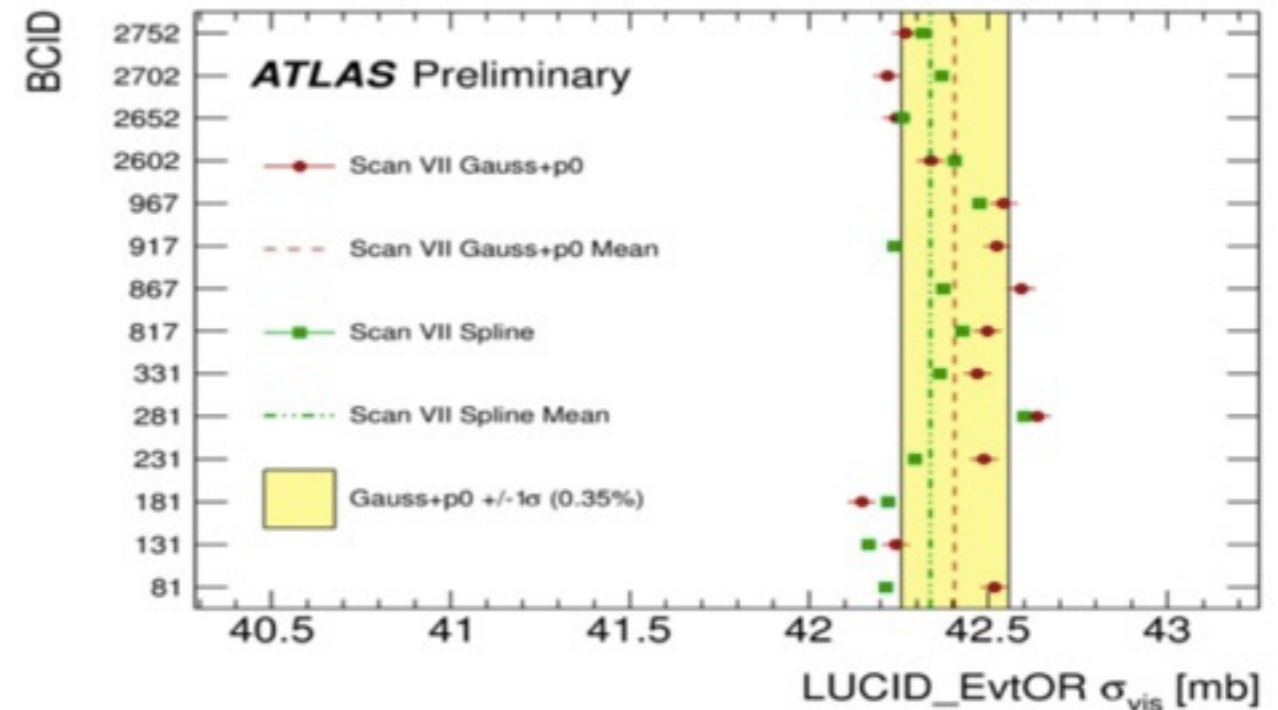


movement of luminous region during a scan will allow to extract the correlation factor between the horizontal and vertical single beam profiles.

Parametrizzazione di F di overlap

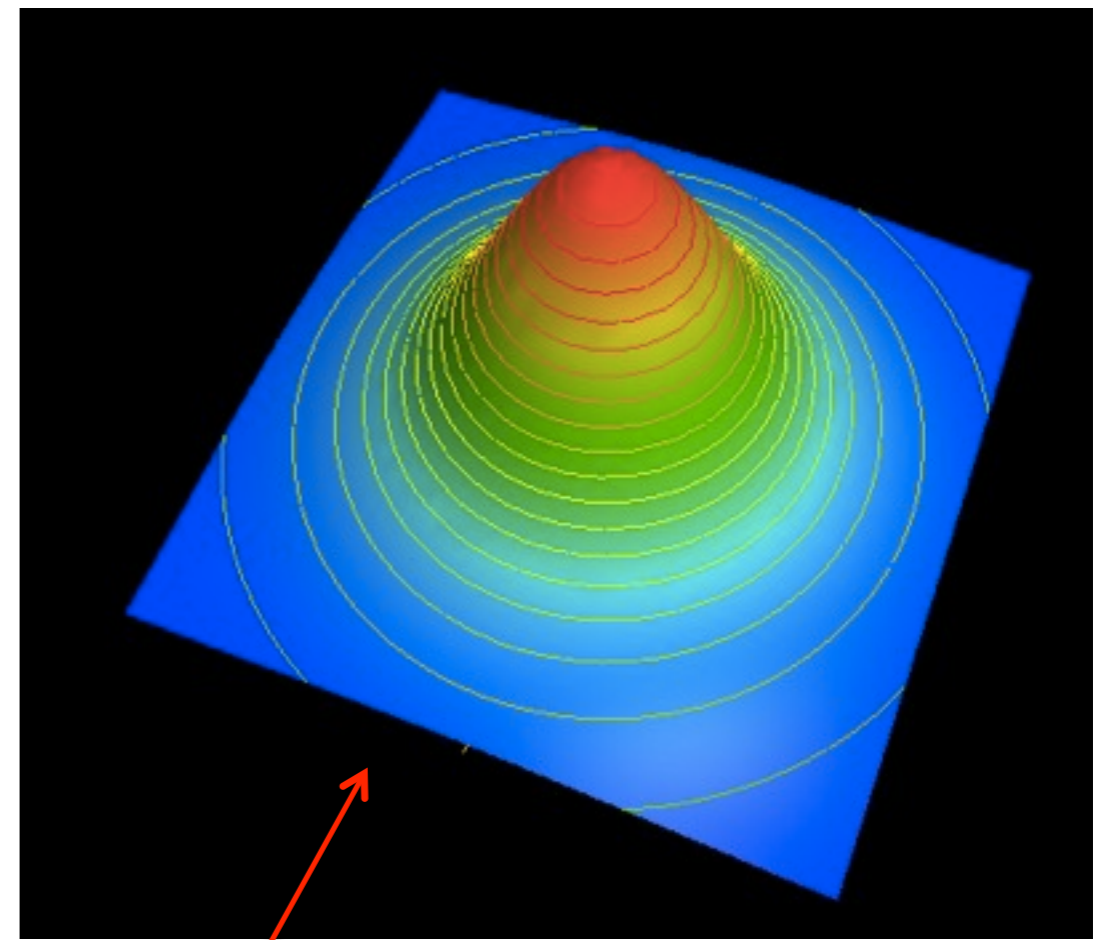
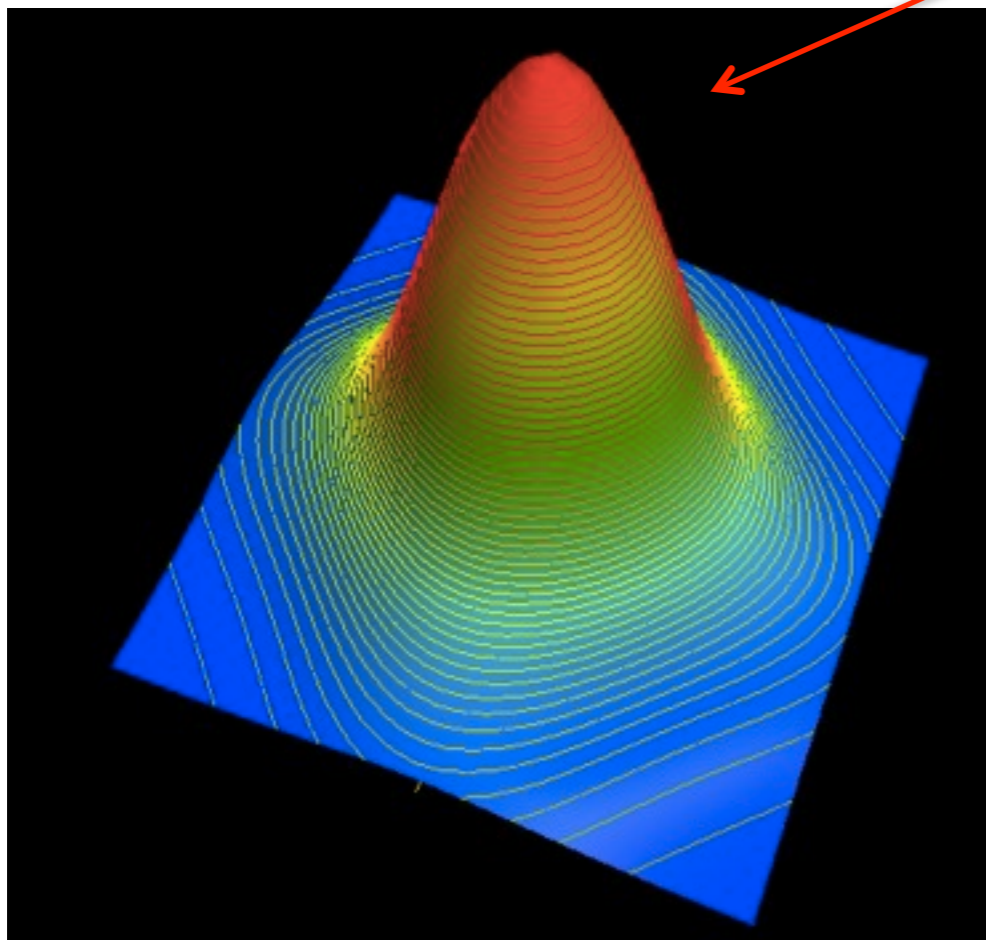
- Refit data with alternative models
 - Cubic spline
 - Gauss+p0 fit to background subtracted data
 - p0 included in Σ & $\mu_{\text{vis}}(0)$
 - Gauss+p0 fit to uncorrected data
 - p0 as background
- Largest deviation in means for any one algorithm/scan assigned as fit model systematic (0.3%)

REMINDER: σ_{vis} should be identical for all BCIDs



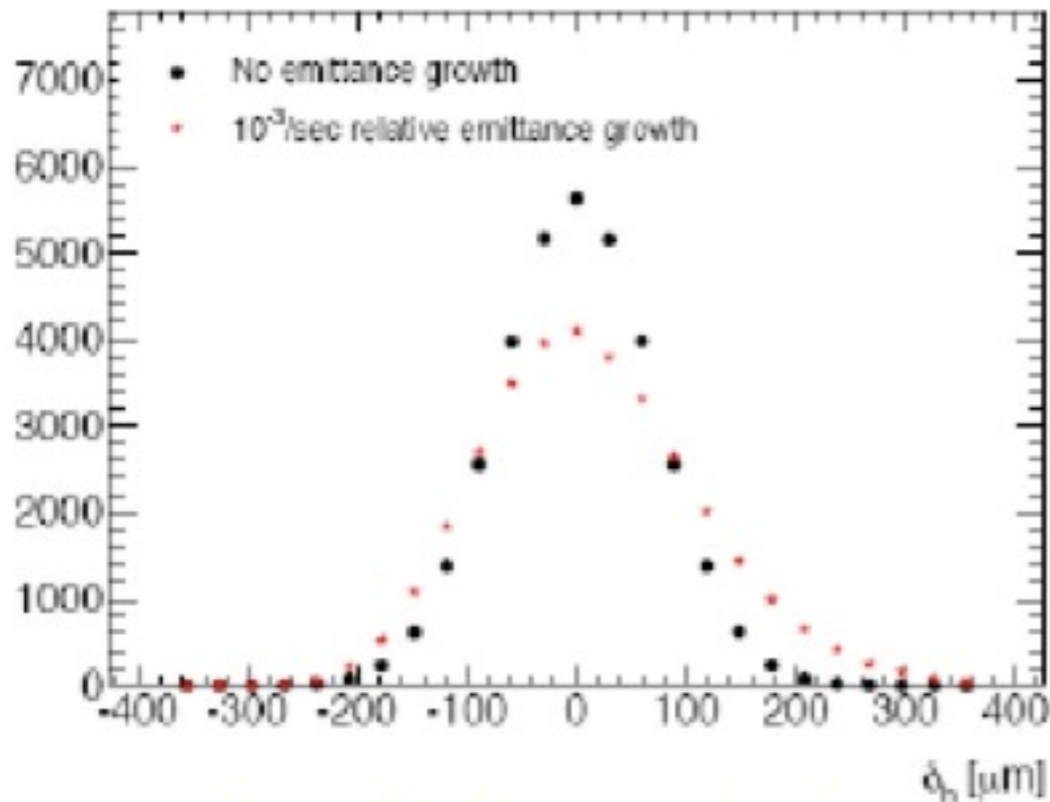
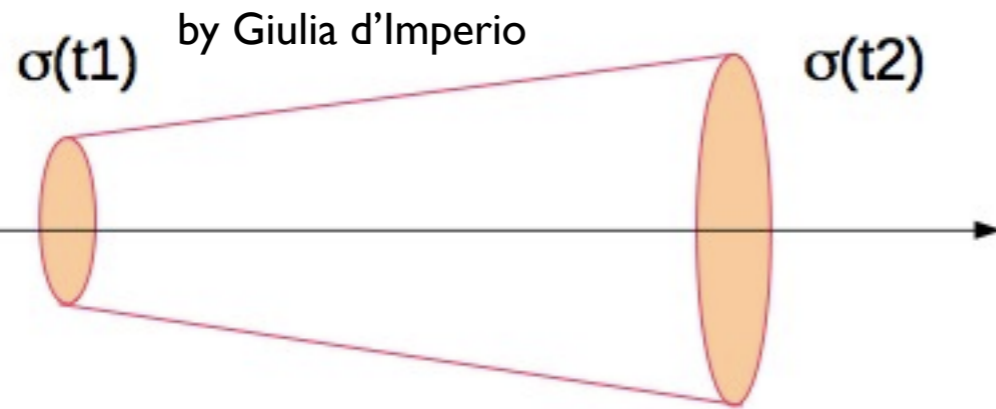
Parametrizzazione di F di overlap

$$z = \frac{1}{4} \left(\left(\exp(-(x^2)) + \frac{1}{0.5} \exp\left(-\left(\frac{x}{0.5}\right)^2\right) \right) \left(\exp(-(y^2)) + \frac{1}{0.5} \exp\left(-\left(\frac{y}{0.5}\right)^2\right) \right) \right)$$

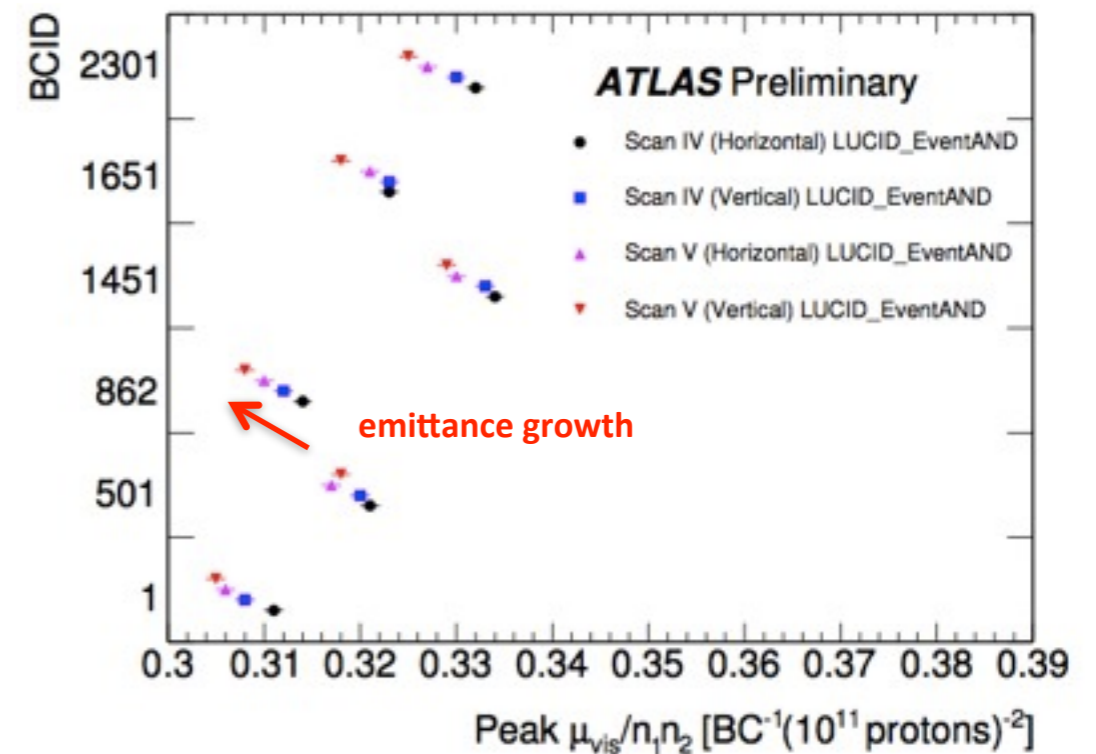
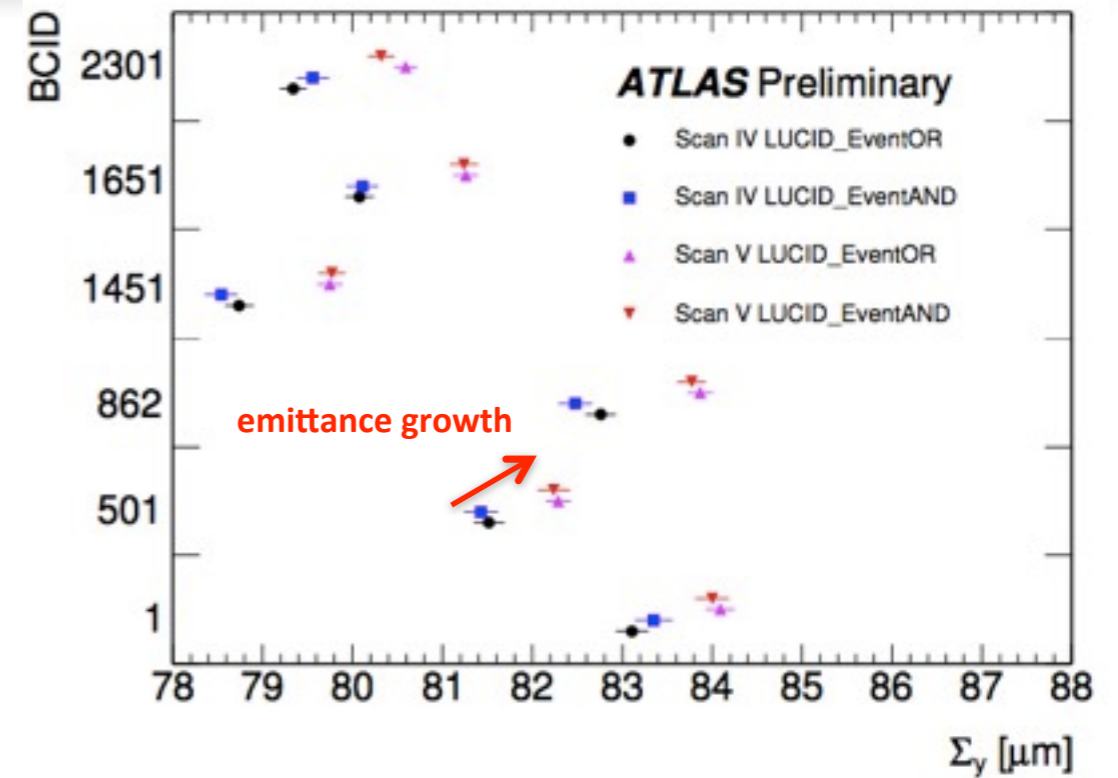


$$z = \frac{1}{2} \left(\exp(-(x^2+y^2)) + \frac{1}{0.5} \exp\left(-\frac{(x^2+y^2)}{0.5^2}\right) \right)$$

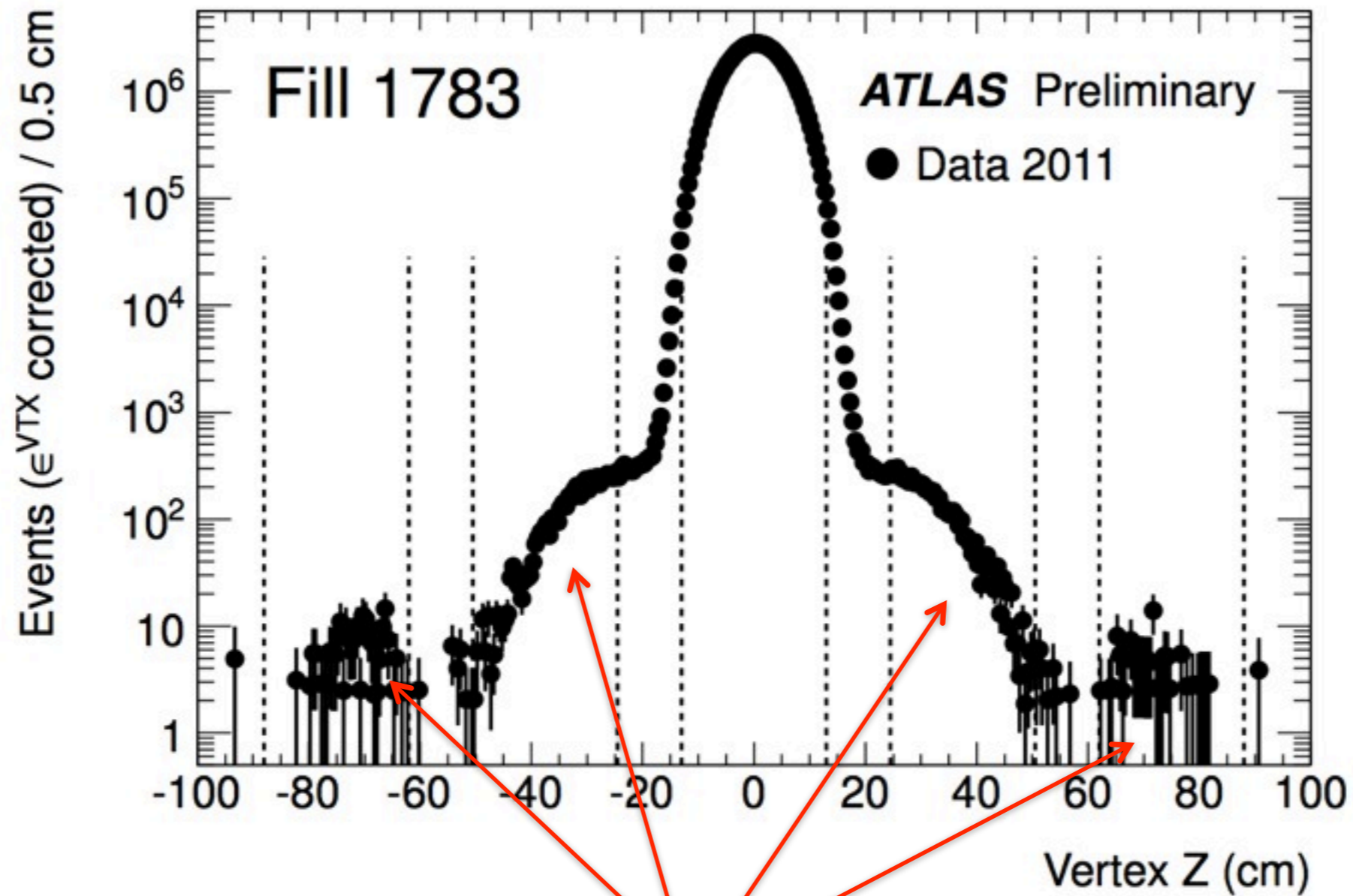
Emittance growth



effect of a large relative emittance growth rate of $10^{-3}/\text{s}$



Satellite bunches



Satellite bunches

7TeV vdM ATLAS Uncertainties

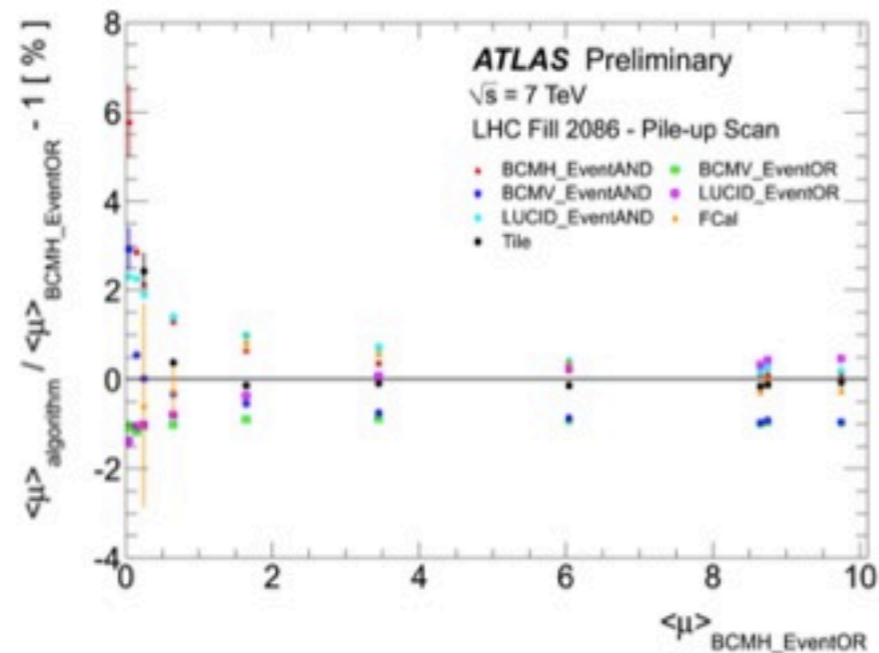
	ATLAS-CONF-2011-117 (Aug 2011 2/fb)	2011 5/fb projected	2012 projected	Comment
Beam centering	0.1	0.1	Measured in scan	Fill dependent
Beam jitter	0.3	0.3		
Non-reproducibility	0.4	0.8	Measured in scan	Fill dependent
Bunch consistency	0.4	0.5	Measured in scan	Fill dependent
Fit model	0.8	0.3	Measured in scan	Fill dependent
Bkgd subtraction		0.3	Measured in scan	Fill dependent
Reference L_{sp}		0.3	Measured in scan	Fill dependent
Dynamic beta		0.8		Collisions at IP1 only
Non-linear correlations	0.5	0.5	Measured in scan	Fill dependent
μ -dependence in scan	0.5	0.5	Measured in scan ~2011?	
Length scale calibration	0.3	0.3		Depends on β^*
Inner det. Length scale	0.3	0.3		
BCM H/V consistency	0.7	0.7	?	
Total vdM uncertainty	1.5	1.75	~2011?	Without beam current

Full 2011 7TeV Uncertainty Table

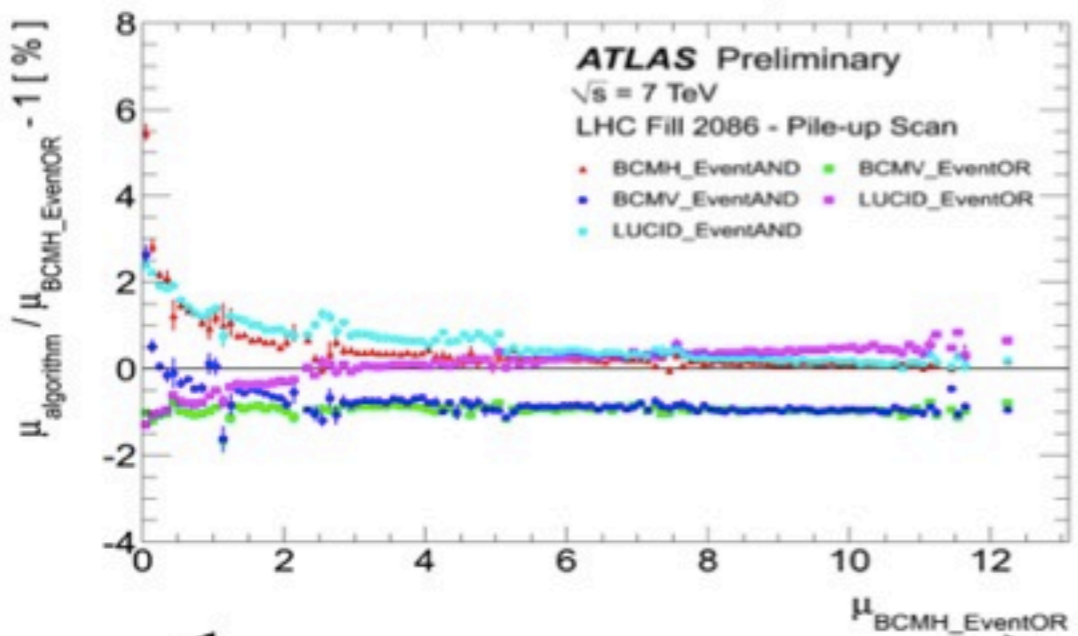
	ATLAS-CONF-2011-117 (2/fb Aug 2011)	5/fb projected	2012 projection	Comment
DCCT	2.73	0.23		
FBCT	1.30	0.20		
Ghost charge	0.18	0.18		
Total BCP	3.0	0.35	~2011?	Thanks to BCNWG!
Total vdM	1.5	1.75	~2011?	
Total σ_{vis} uncertainty	3.4	1.8	~2011?	
Long term stability	1.0	1.0	~2011	Detector aging in 2012?
μ -dependence in physics running	1.0	1.0	~2011	Larger μ range for 2012
Afterglow subtraction	0.2	0.2		
Total monitoring	1.4	1.4	~2011	Unchanged from summer despite more data & higher μ values
Total 2011 7TeV pp	3.7	2.3	~2011?	

Dipendenza da μ

Scan in Single Physics Fill



Notation: $\langle \mu \rangle$ is average μ
 for an algorithm over all bunches



Beams
Separated

Beams
Centered

- LHC Fill 2086 beams separated at IP1 then recentered
 - Effectively samples wide range of μ
 - Peak $\mu \sim 12$
 - FCal calibrated to BCM in this fill
 - Observe residual non-linearity
- Comparison between BCM, LUCID & Tile suggests consistency across physics μ range (2-12) of 1%
- AND algorithms diverge at $\mu < 2$
 - Imperfect background subtraction in the region it becomes important
 - Subject of investigation, plot likely to change in this region

22

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Luminosity from W/Z counting

- Leptonic decays of vector bosons provide a very clean signature
 - ✓ good high- p_T lepton reconstruction
 - ✓ low background
 - ✓ robust against pile-up
 - ✓ relative good event statistics:

$$\sigma(W \Rightarrow l\nu) \sim 10 \text{ nb}; \quad \epsilon \sim 30\%$$

$$L \sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \Rightarrow 4 \text{ pb}^{-1} / \text{day} \Rightarrow 12 \text{ k events} / (\text{day} * \text{channel})$$

- robust theory predictions for production cross section:

$$\mathcal{L} = \frac{N_{cand} - N_{bkgd}}{\epsilon \sigma}$$

Luminosity from W/Z counting

	precision 2010	precision in 2012	comment
$\sigma_{\text{th}}(\mu_R, \mu_F)$	<1%	<1%	scale uncertainty at NNLO
PDF-> σ_{th}	4-5%	3-4%	LHC data
reco. efficiency	7-8%	3%	with Z data
Acceptance(PDF)	3%	2%	LHC data
Total	8-10%	4-5% ?	dominated PDF

Sommario

- definito in modo rigoroso la luminosita' come funzione delle caratteristiche del fascio e dell'integrale di convoluzione dei fasci
- discusso misure di luminosita' relative e metodi di conteggio
 - ✓ conteggio di eventi e conteggio di hit
- discusso i metodi di misura della luminosita' assoluta
 - ✓ teorema ottico e diffusione elettromagnetica
 - ✓ misura diretta dell'itegrale di convoluzione col metodo di Van der Meer

Ricapitolazione

- la misura della luminosita' assoluta e' basata su 2 metodi:
 - ✓ teorema ottico e scattering elettromagnetico, elimino il problema della stima della sezione d'urto totale
 - ✓ metodo di Van der Meer basato sulla misura esplicita' dell'itegrale di convoluzione dei due fasci
- Terzo metodo:
 - ✓ Misura di una sezione d'urto ben nota teoricamente e misurabile con ottima precisione per normalizzare la scala assoluta:
 - ◆ $W \rightarrow \nu$ $Z \rightarrow ll$

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 - ✓ <http://totem.web.cern.ch/Totem/>
 - ✓ <http://atlas-project-lumi-fphys.web.cern.ch/atlas-project-lumi-fphys/ALFA/default.html>
- LHC lumi days
 - ✓ <http://indico.cern.ch/conferenceDisplay.py?confId=162948>
 - ✓ <http://indico.cern.ch/conferenceDisplay.py?confId=109784>