Stato di LHCb.

Umberto Marconi, INFN Bologna

IFAE 2010, Roma 7/4/2010.

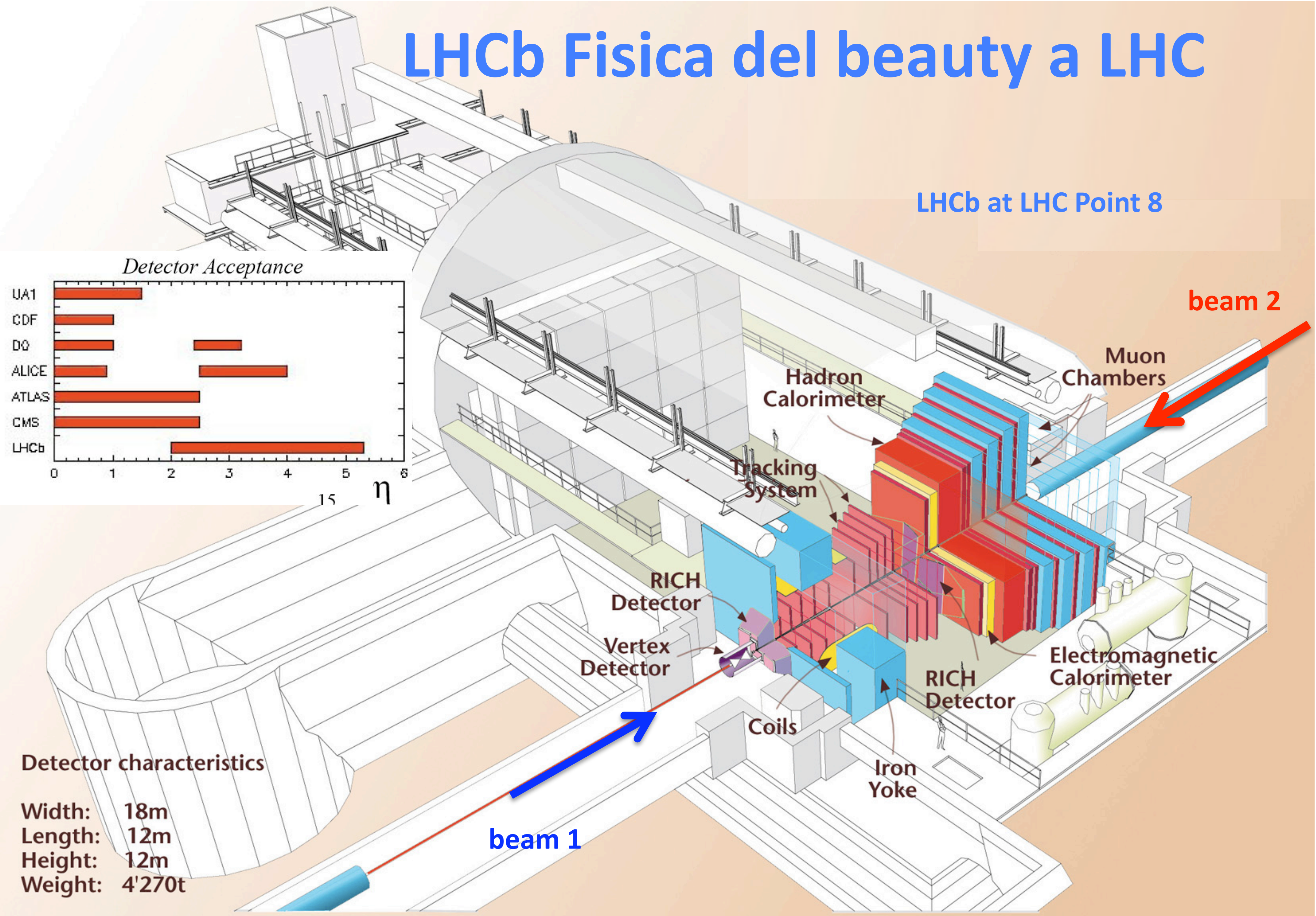
Sommario.

- L'esperimento LHCb.
- Rivelatore e trigger.
- Obiettivi del 2010-11.

Nota.

- Approfondimenti, qui a IFAE:
  - **A. Carbone**, "Commissioning di LHCb".
  - **A. Sarti**, "Risultati dal Tevatron e contributi di LHCb".
  - **M. Frosini**, "Misure di produzione di charmonio a LHCb".

LHCb Fisica del beauty a LHC

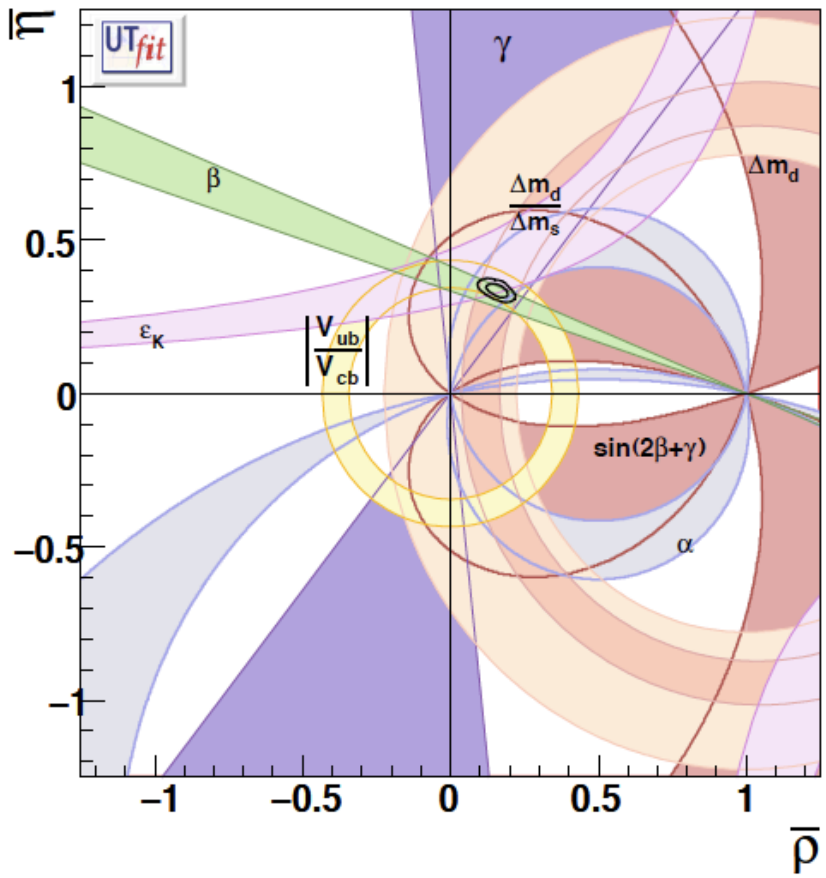


Obiettivi dell'esperimento.

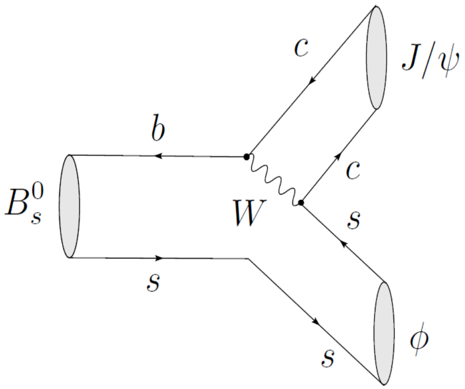
- Misure di violazione della simmetria CP e rivelazione di decadimenti rari dei mesoni costituiti da quark beauty: B_d, B_S e B_C; per misure di precisione dei parametri della matrice CKM, e verifica dei limiti di previsione del Modello Standard.
  - Il programma di fisica si estende al settore dei mesoni D.
- Le **potenzialità di LHCb** sono state valutate mediante studi di fattibilità relativi alle principali misure possibili. I risultati più significativi sono stati raccolti in un documento: LHCb key measurements, **arXiv0912.4179**
- L'esperimento LHCb è in grado di compiere alcune delle misure più importanti in programma, già con la sola statistica di un solo **anno di presa dati ideale**, corrispondente alla luminosità integrata di **2 fb^{-1} a 14 TeV**.
- LHCb richiede una luminosità istantanea di **$L=2.\times10^{32}\ cm^{-2}s^{-1}$**

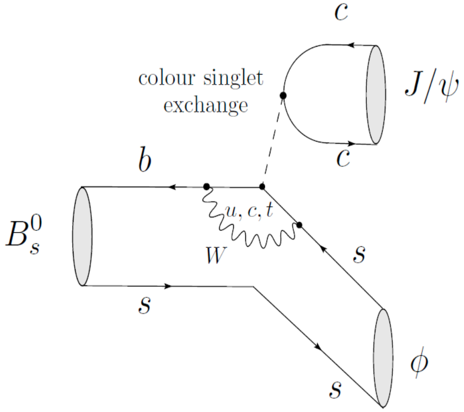
Matrice CKM.

- L'analisi del Triangolo di Unitarietà ha mostrato che la matrice **CKM è il meccanismo principale** di miscelamento del flavour ed è la ragione principale della violazione della simmetria CP.
- **Effetti di nuova fisica** (NP) al più possono costituire una **piccola correzione** a questo schema fenomenologico di riferimento/interpretazione.
- Il problema non è più quindi di verificare la validità del meccanismo CKM, quanto piuttosto di riuscire a evidenziare effetti di NP, mediante **misure indirette**, di elevata precisione.
- Effetti di NP si ritiene possano essere rivelati nei decadimenti rari (FCNC) dei mesoni B e D: qualora le ampiezze virtuali dovute a NP fossero comparabili a quelle dello SM.



Violazione di CP nel $B_s \to J/\psi(\mu\mu)\Phi(KK)$





$$A(\bar{b} \to \bar{c}c\bar{s}) = V_{cs}V_{cb}^*(A_T + P_c) + V_{us}V_{ub}^*P_u + V_{ts}V_{tb}^*P_t$$
$$= V_{cs}V_{cb}^*(A_T + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t)$$

$\sim A\lambda^2\left(1 - \frac{\lambda^2}{2}\right)$ $\qquad$ $\sim A\lambda^4(\rho + i\eta)$

Violazione di CP nel decadimento

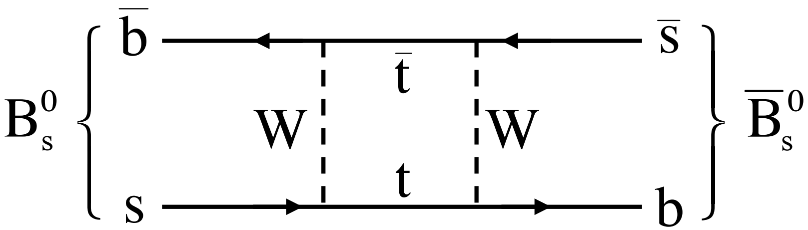
Contributi di NP possibili nel miscelamento $B_s \leftrightarrow$ anti-B_s

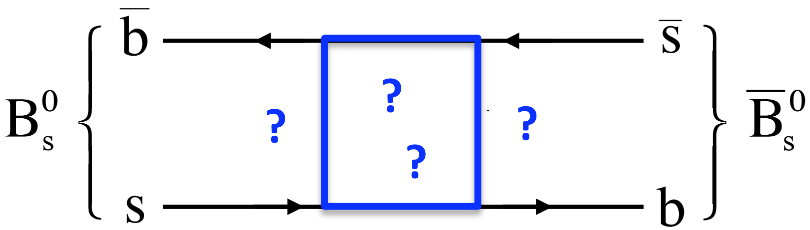
$\phi_{measured} = \phi_{SM} + \phi_{NP}$ $\quad$ $\phi_{SM} \approx -2\beta_s = 0.037 \pm 0.002$ $\quad$ $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$

$\Delta m_s^{SM} \propto |V_{ts}^2|$
$\phi_s^{SM} = 2\beta_s$

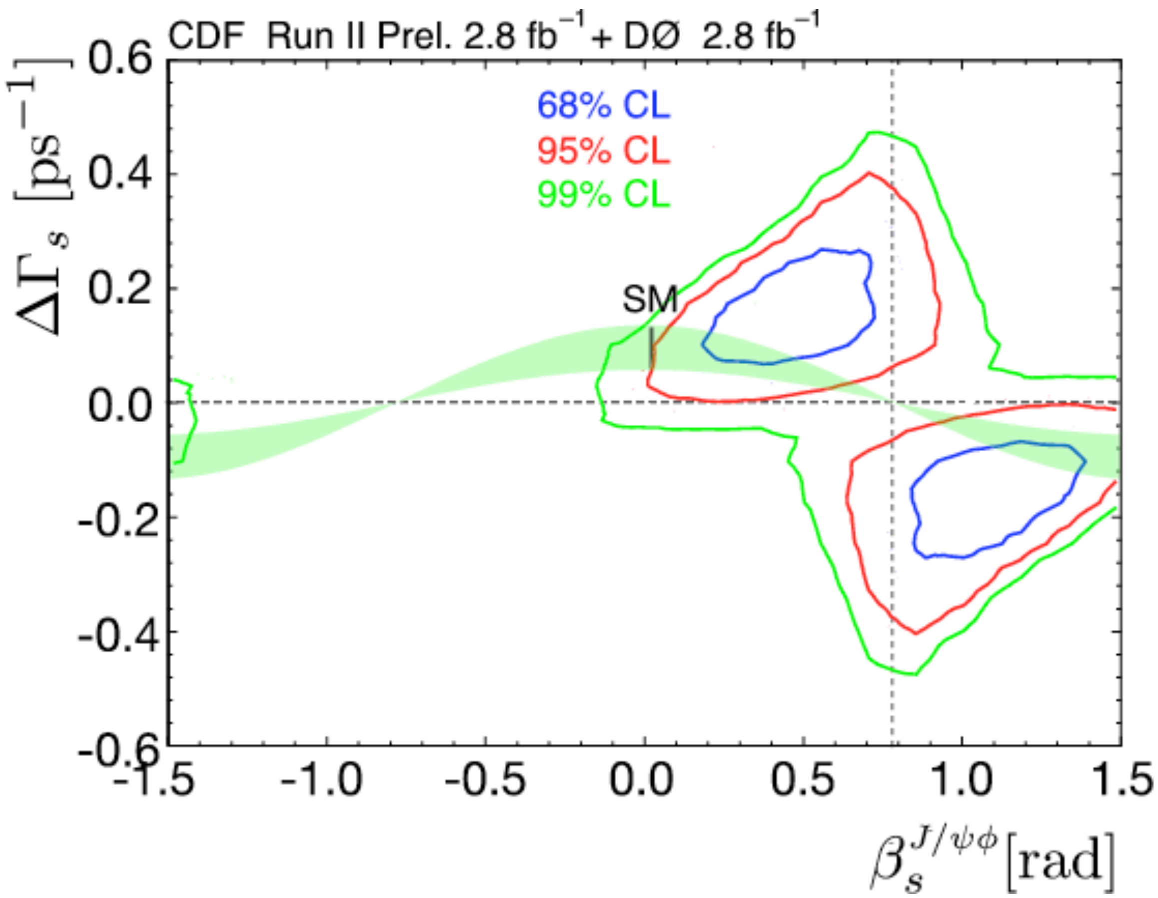
$\Delta m_s \neq \Delta m_s^{SM}$
$\phi_s^{SM} \neq \phi_s^{SM}$

New Physics





Dal Tevatron su $B_s \rightarrow J/\psi\Phi$



CDF&D0
Combined likelihood
2.1σ deviation from SM

EPS 2009
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B59/B59.pdf
http://www-cdf.fnal.gov/physics/new/bottom/090721.blessed-betas_combination2.8/

Analisi di UT

First evidence of new physics in b ↔ s transitions.

UTfit Collaboration, M. Bona et al.

PMC Physics A 2009, ***3:6***

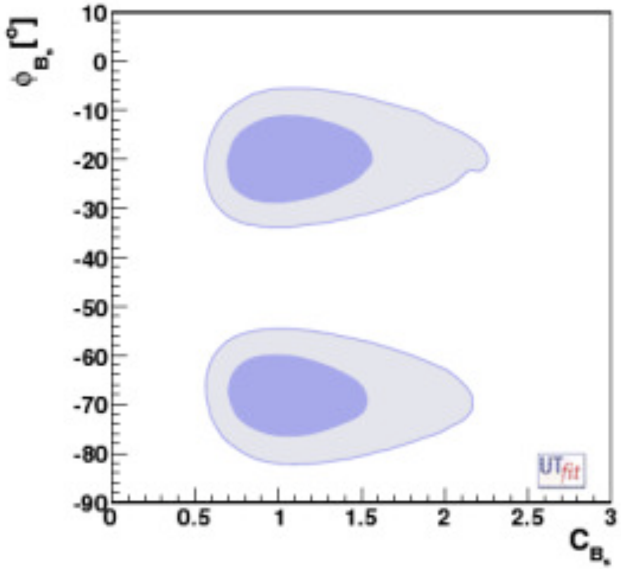
"We combine all the available experimental information on *Bs* mixing, including the very recent tagged analyses of Bs → J/Ψ ϕ by the CDF and DØ collaborations.

We find that the phase of the Bs mixing amplitude deviates more than 3σ from the Standard Model prediction.

While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result.

This is a first evidence of physics beyond the Standard Model."

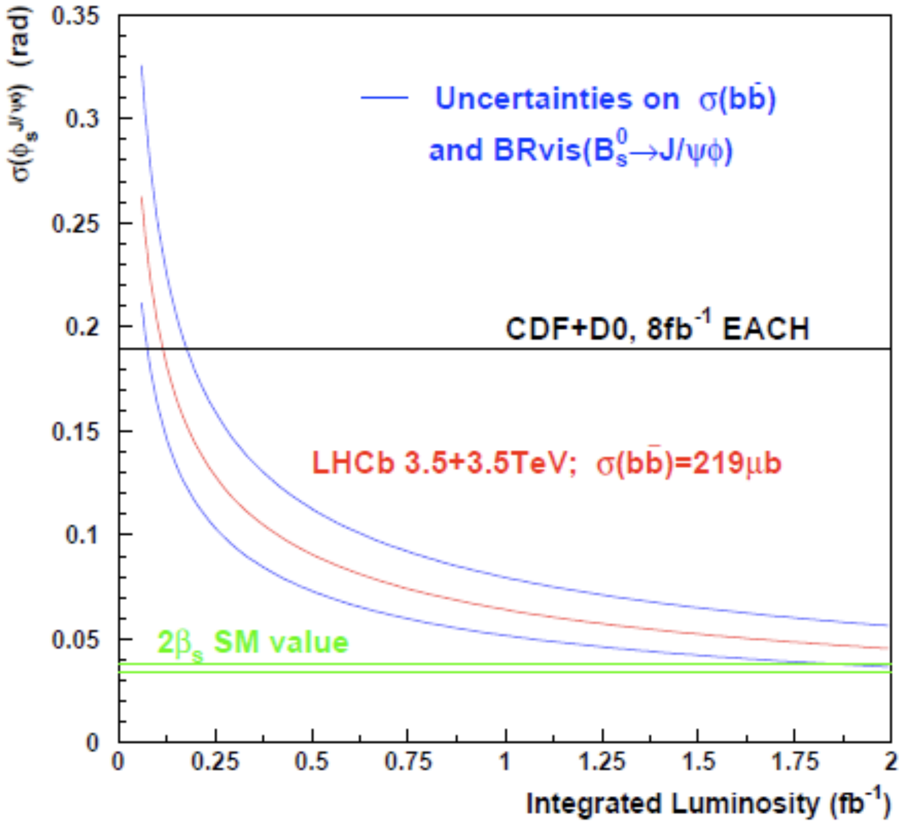
$$C_{B_S} e^{2i\phi_{B_S}} = \frac{\langle B_S | H_{eff}^{full} | \overline{B}_S \rangle}{\langle B_S | H_{eff}^{SM} | \overline{B}_S \rangle} = \frac{A_S^{SM} e^{-2i\beta_S} + A_S^{NP} e^{2i(\phi_S^{NP} - \beta_S)}}{A_S^{SM} e^{-2i\beta_S}}$$



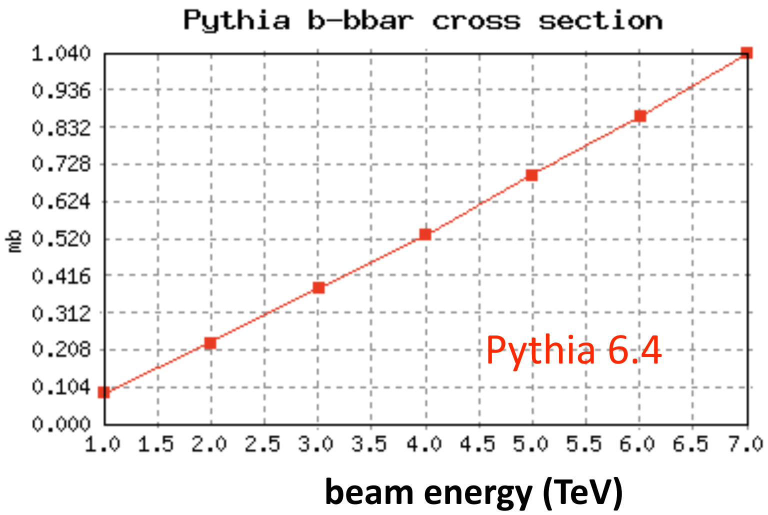
Observable	68% Prob.	95% Prob.
ϕ_{B_s} [°]	-19.9 ± 5.6	[-30.45,-9.29]
	-68.2 ± 4.9	[-78.45,-58.2]
C_{B_s}	1.07 ± 0.29	[0.62,1.93]

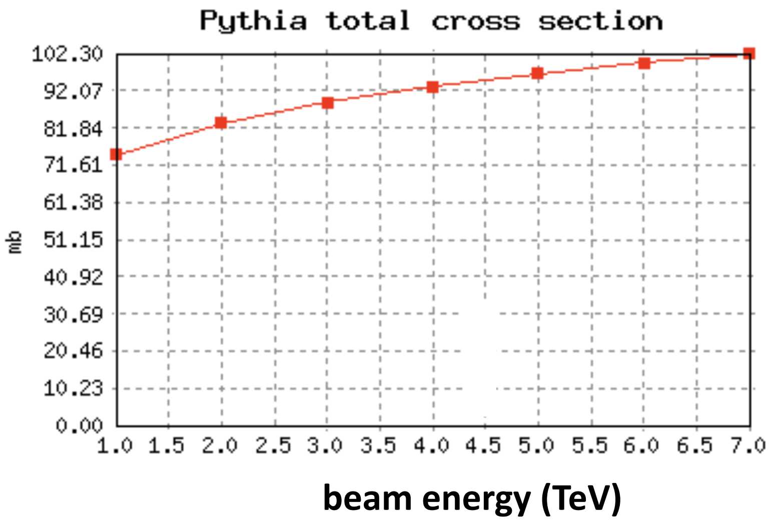
LHCb su ϕ_s

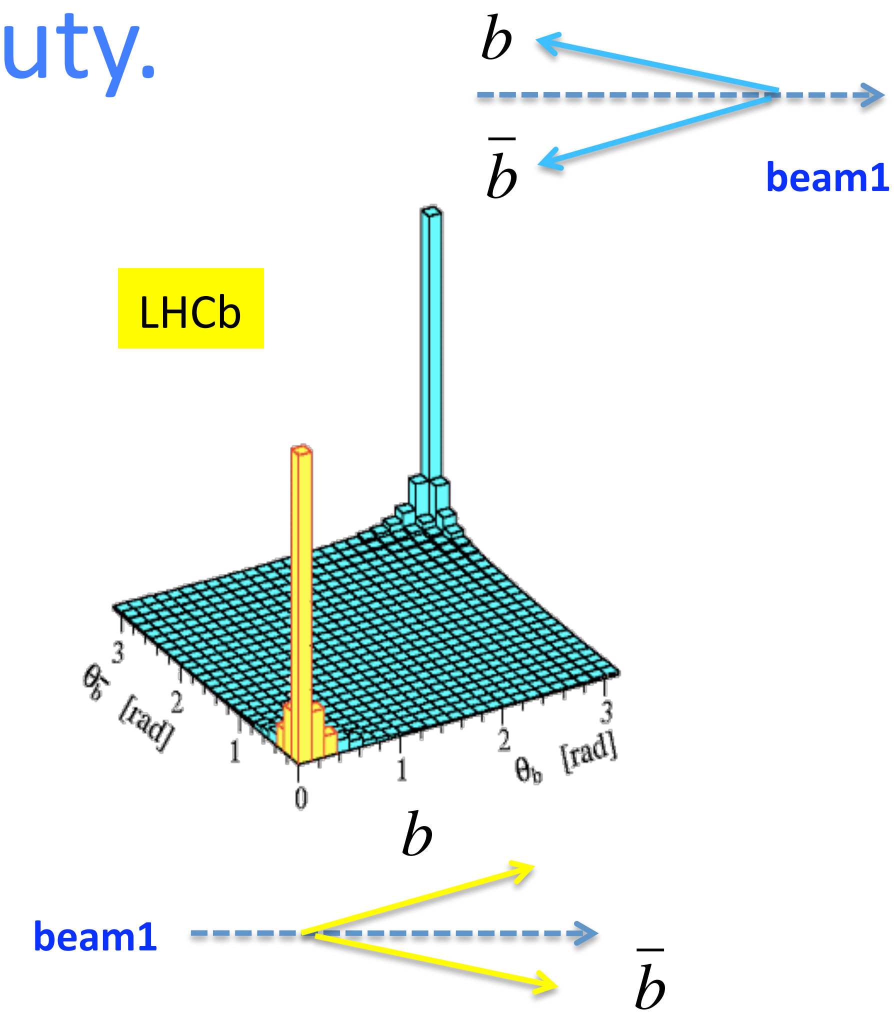
- Precisione statistica di ~0.07 rad con 1 fb^{-1}.
- Se ϕ_s fosse davvero vicina al valore misurato al Tevatron (indizio di NP) sarebbe possibile una misura a 5σ in tempi relativamente brevi.
- Sono invece necessari più di 2fb^{-1}per arrivare al valore previsto dallo SM.



Sezione d'urto di beauty.







Per convenzione: la sezione d'urto a 14 TeV è 500 μb.
A 7 TeV assumiamo sia circa la metà: 220 μb.

Pythia 6.2: 650 μb;
Pythia 6.3: 700 μb; PDF: CTEQ4L → CTEQ6L
Pythia 6.4: 1040 μb; multi-partonic interaction model.

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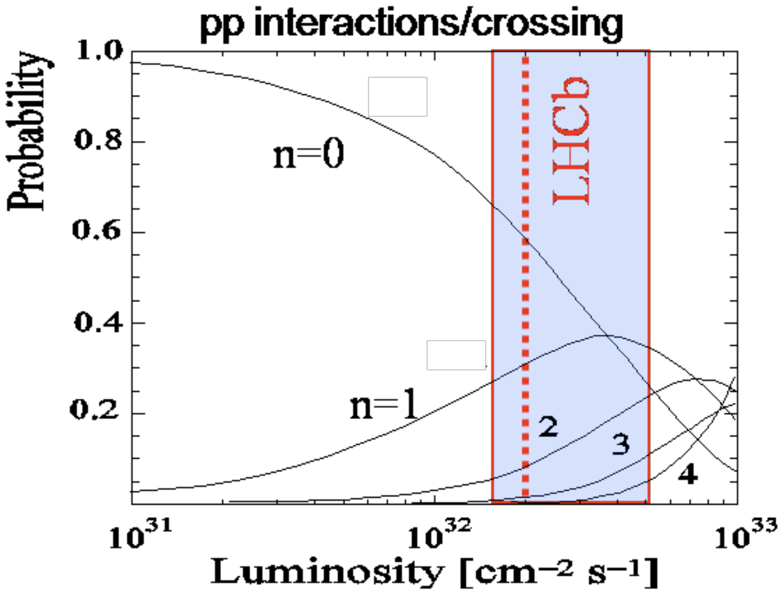
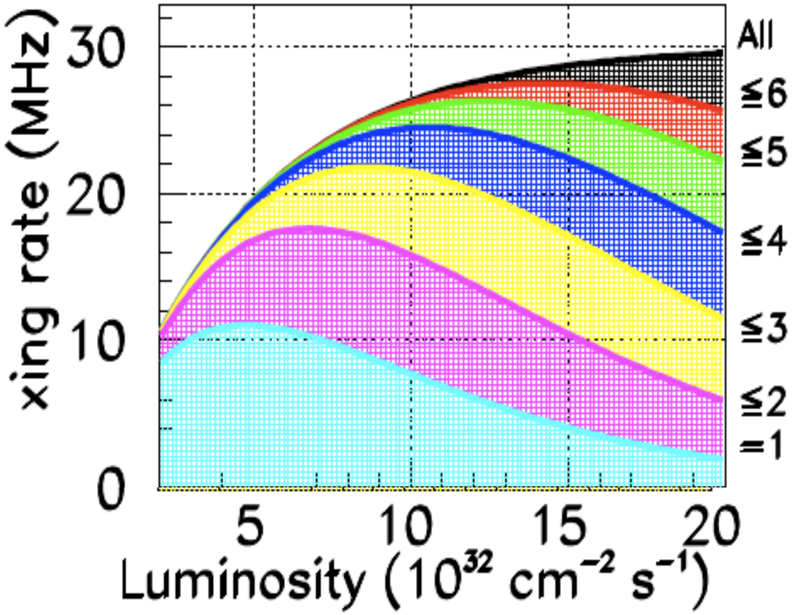
Luminosità.

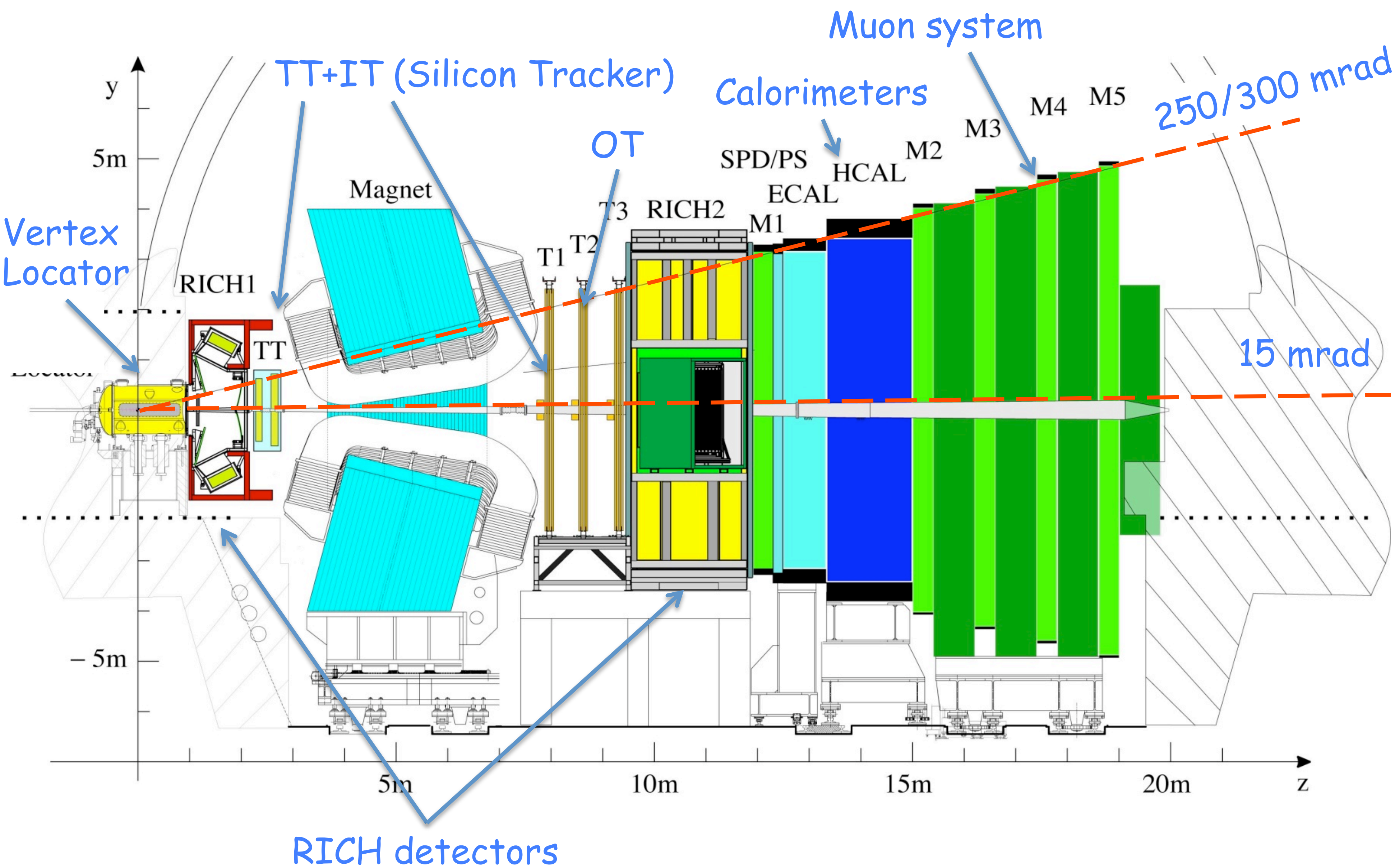




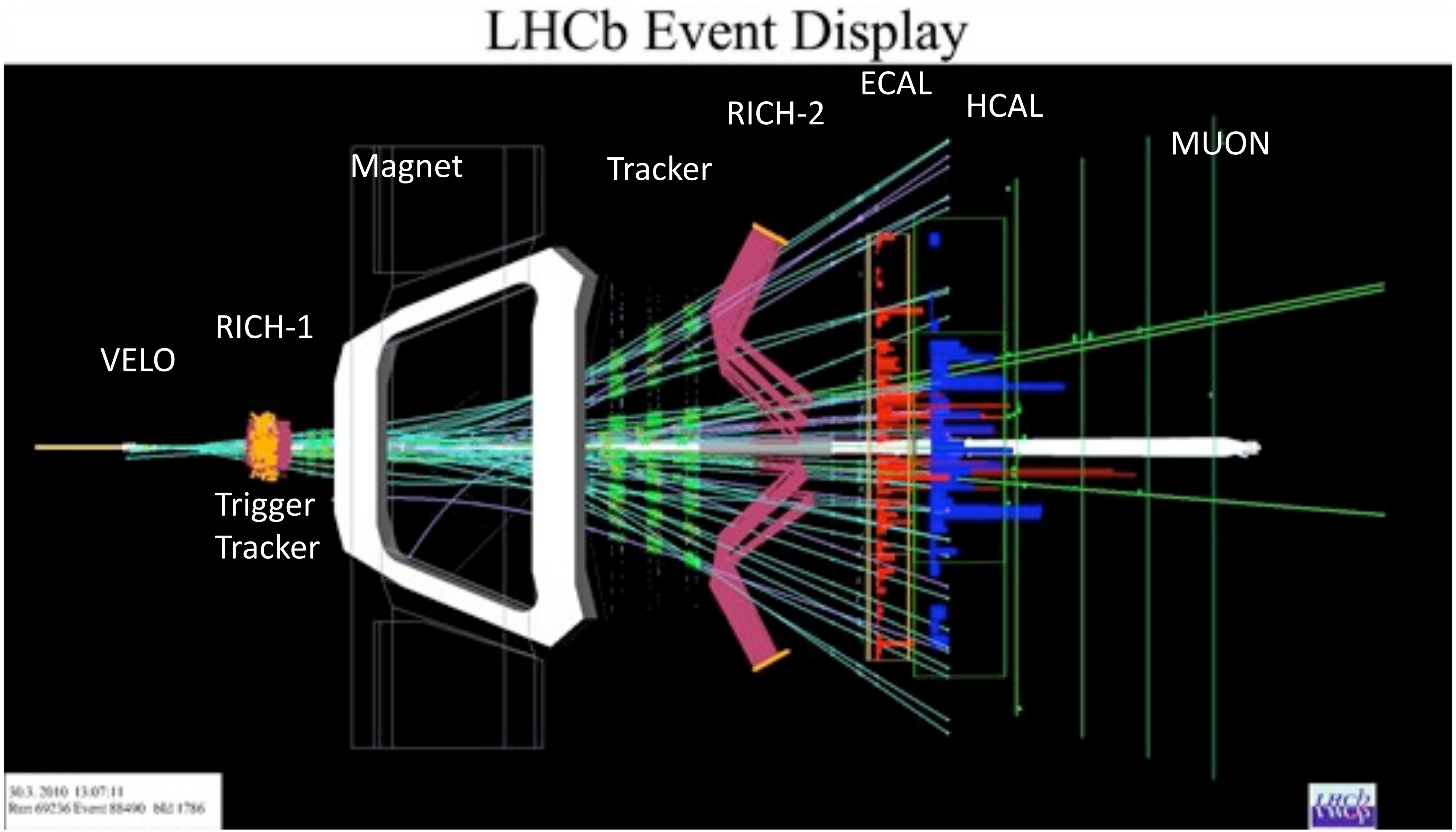
$$\mu = \frac{L \cdot \sigma_{in}}{\nu_{LHC} \cdot N_{bunch} \cdot f_{ne}} \qquad P(k) = \frac{e^{-\mu} \cdot \mu^{k}}{k!}$$

- A una luminosità fra **$1. \div 5. \times 10^{32}$ cm^{-2}s^{-1}** corrispondono interazioni p-p singole.
- L'ottica dei fasci nel punto di interazione di LHCb (P8) permette di raggiungere una luminosità fino al 50% della luminosità di LHC: fino a **$5. \times 10^{33}$cm^{-2}s^{-1}**.
- La massima frequenza di interazione con 2622 bunch collidenti su 3564 è di 30 MHz.

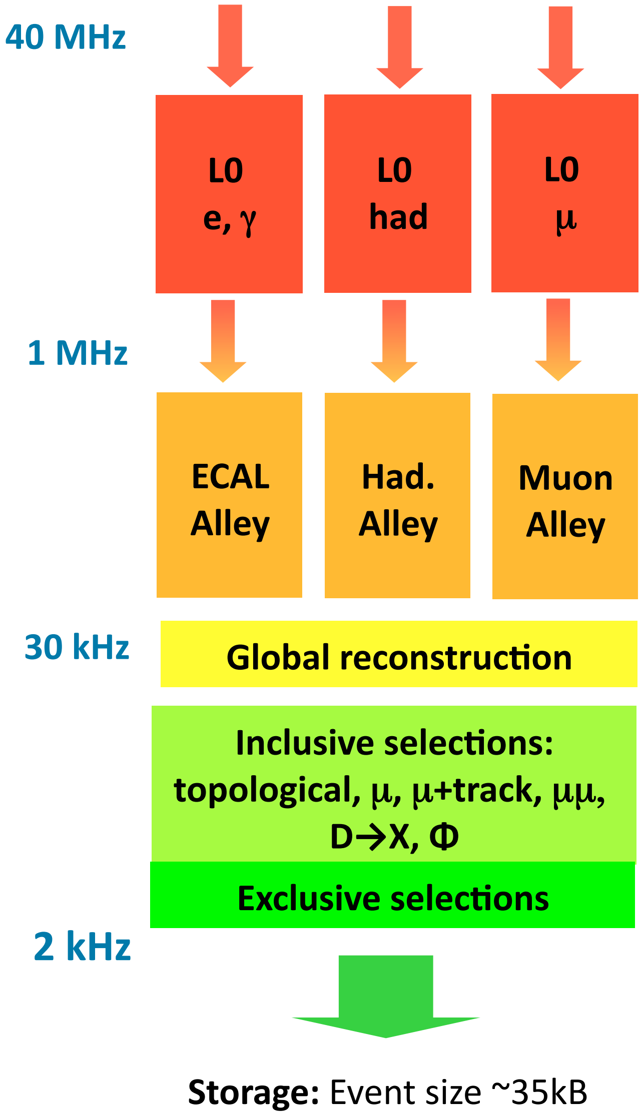
Il rivelatore.



Eventi a 7 TeV



Il Trigger.



- **Level-0 (L0)**
  Particelle di alto p_T nei calorimetri e nel rivelatore di muoni.
- **HLT-1**
  Associa segnali rivelati dal trigger L0 a tracce di elevato IP nel rivelatore di vertice.
- **HLT-2**
  Tutte le informazioni prodotte dal rivelatore sono utilizzabili.
  Selezione esclusiva di canali fondamentali.
  Selezione inclusiva.

Trigger efficiencies

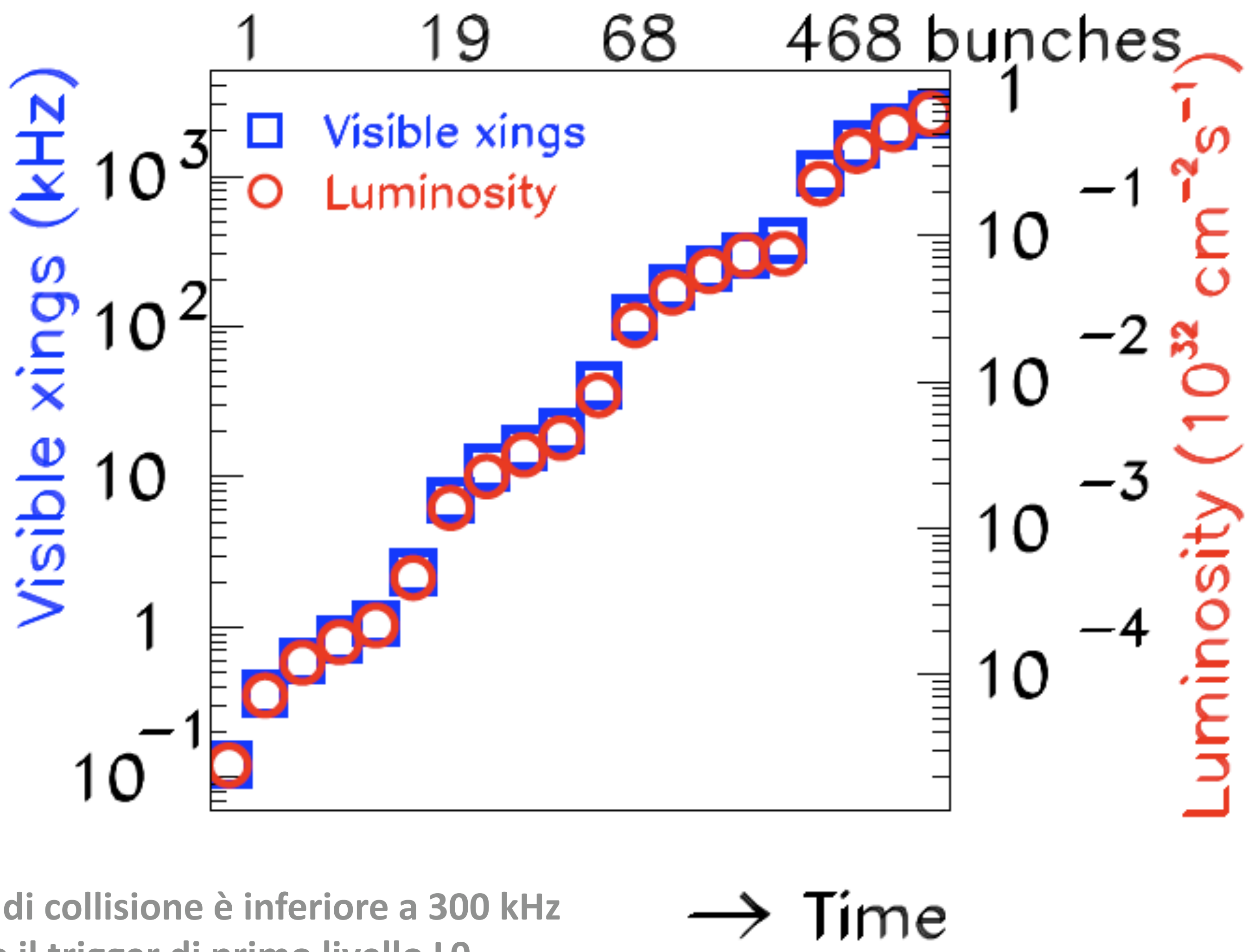
	ε(L0)	ε(HLT)	ε(total)
Hadronic	50%	80%	40%
Electromagnetic	70 %	60%	40%
Muon	90%	80%	70%

L0 Trigger Thresholds

L0 Trigger	had	μ	μμ	$e^{\pm}$	γ	π^0
p_T> (GeV/c)	3.5	1.3	Σ>1.5	2.6	2.3	4.5

Luminosità e trigger.

Luminosità di lavoro: $1.3x10^{32}$, 7×10^{10} p/bunch, 432 bunches, 50 ns, stored beam energy of 17 MJ, beta*=2-3m, 85 pb^{-1}/month.



Se la frequenza di collisione è inferiore a 300 kHz si può escludere il trigger di primo livello L0

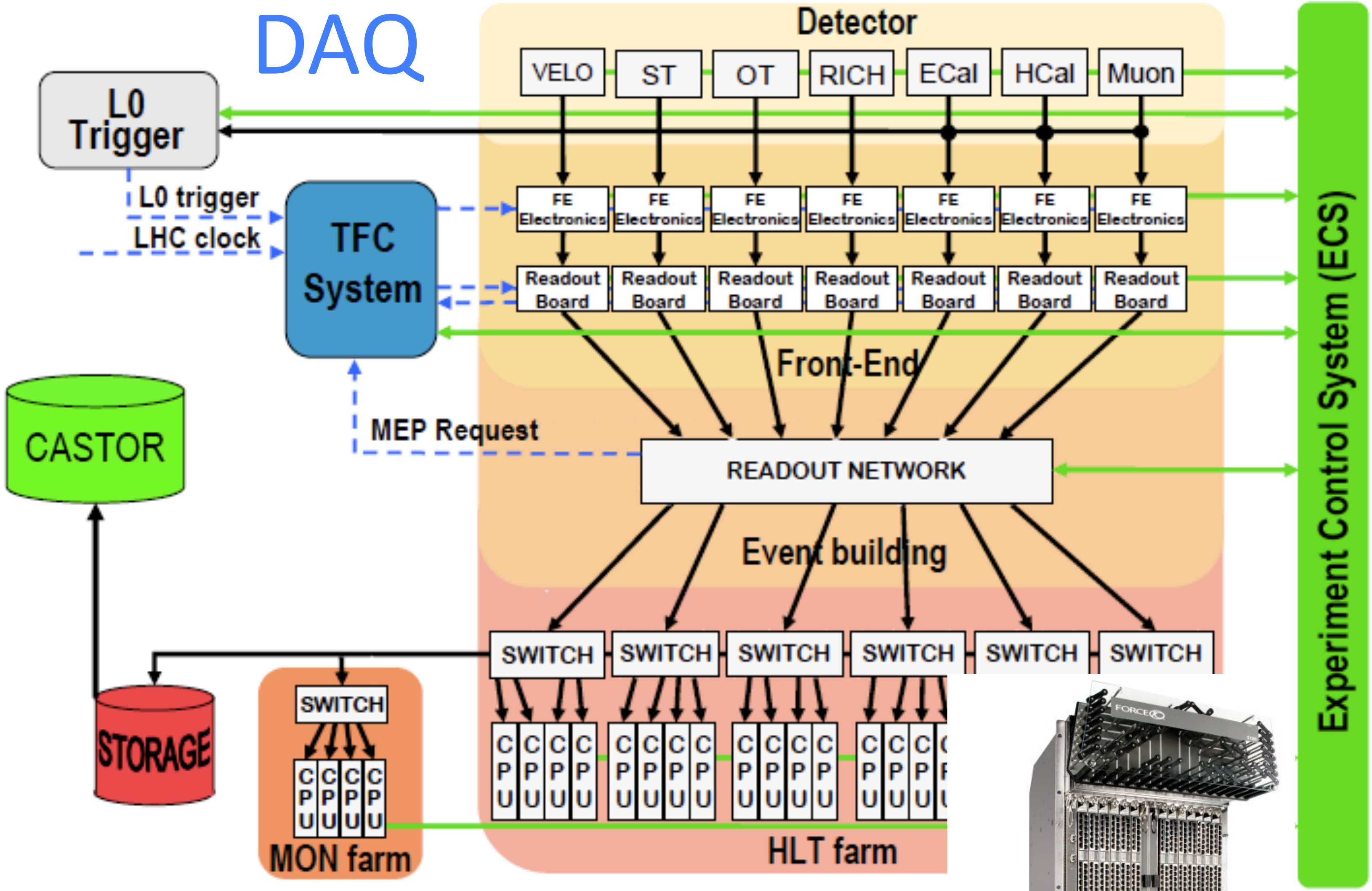
Efficienze di trigger

Channel	Eff Std	Eff L0(300kHz) Hlt1(10kHz)
B$\rightarrow$ h h	52%	88%
B$\rightarrow$ D^0 K^*	38%	89%
B$\rightarrow$ K^* $\mu\mu$	85%	-%
B$\rightarrow$ D($K_s\pi\pi$)K	36%	-%
B$\rightarrow$ Jψ ϕ	89%	-%
B$\rightarrow$ ϕ γ	59%	-%
B$\rightarrow$ $\mu\mu$	97%	98%
Prompt D^*	16%	71%

L0Channel	Std Thresholds (MeV)	Modified
L0Hadron	3840	900
L0Muon	1200	120
L0DiMuon	1480	240

Le efficienze di trigger nei canali muonici sono sostanzialmente costanti, migliorano sensibilmente nei canali adronici, è possibile acquisire eventi charm.

DAQ



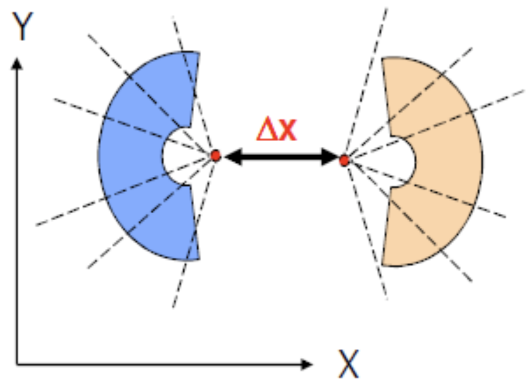
- Routed network
  - Single core router (Force10 E1200, 1260 GbE ports)
  - Routing switches in each sub-farm
  - Static routes

Stato del rivelatore.

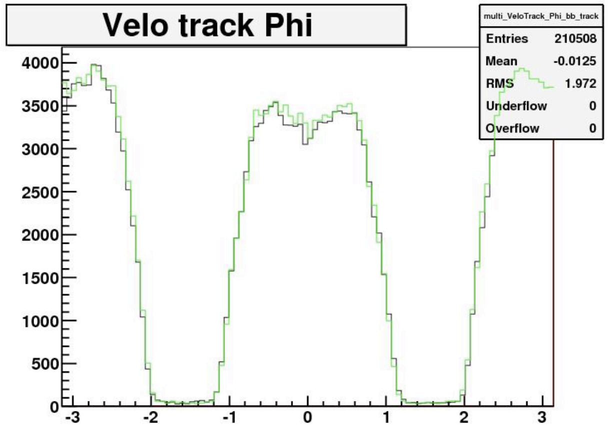
- Più del 99.5% dei canali del sistema tracciante funzionanti.
- L'allineamento del sistema tracciante non è ancora ottimale.
  - Per l'allineamento dei sotto-rivelatori LHCb ha impiegato pricipalmente i dati raccolti nel Dicembre 2009.
- Il rivelatore di vertice VELO è stato chiuso per la prima volta all'energia dei fasci di 3.5 TeV.
- La PID deve essere calibrata.

Vertici

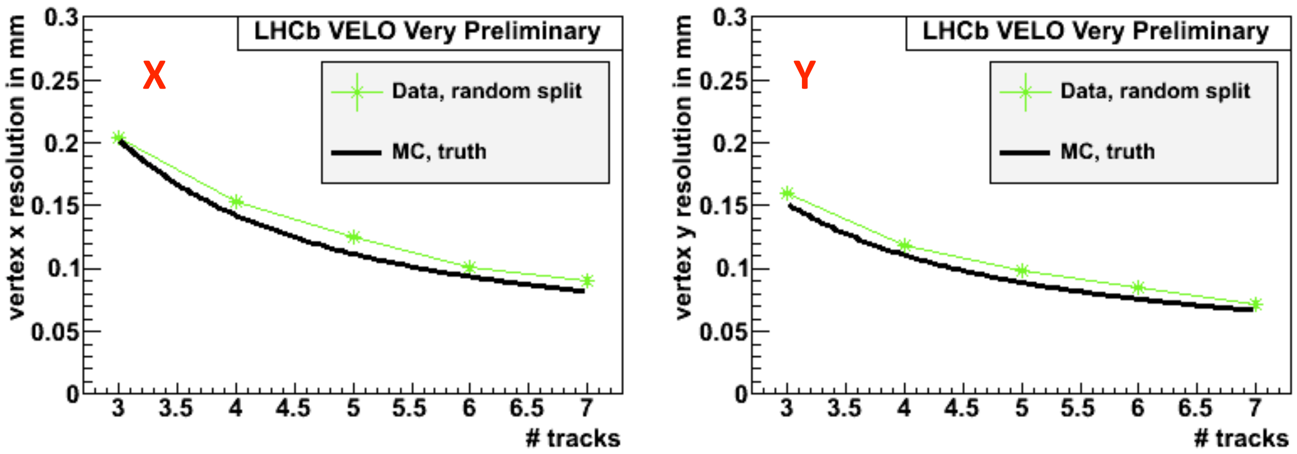
- La risoluzione è stata misurata sui dati come distanza tra i PV ricostruiti utilizzando due sottoinsiemi diversi di tracce.
- I dati 2009 sono in accordo con il MC al 10%.



Accettanza angolare con VELO a ±15mm

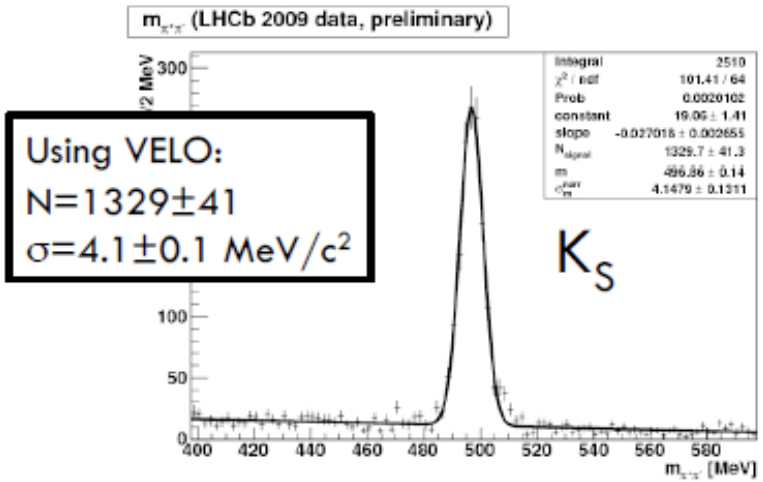


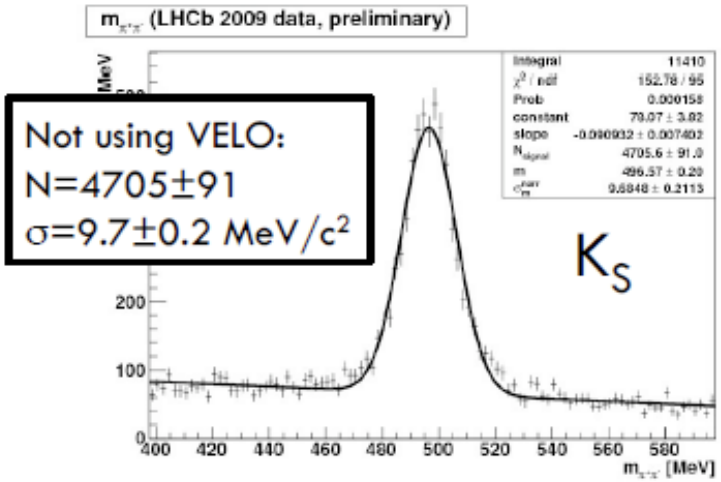
Risoluzione verso numero di tracce

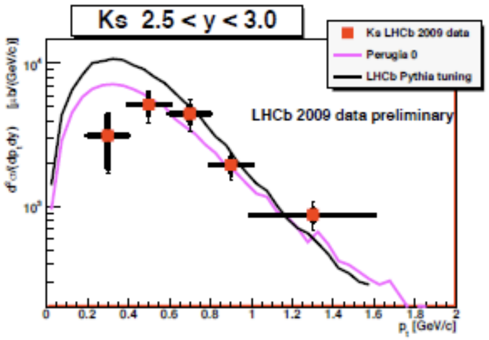


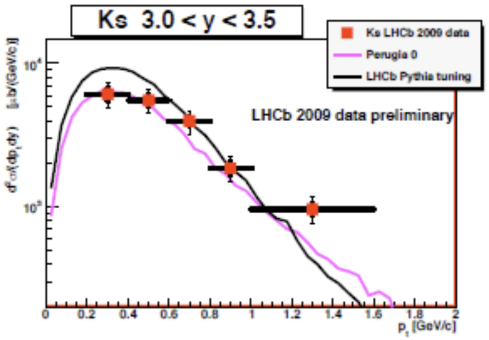
Con il VELO chiuso e dopo l'allineamento
la risoluzione si prevede migliori di un fattore 10.

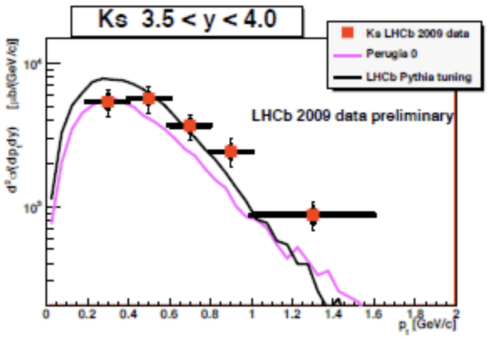
Segnale di $K_S \to \pi^+\pi^-$









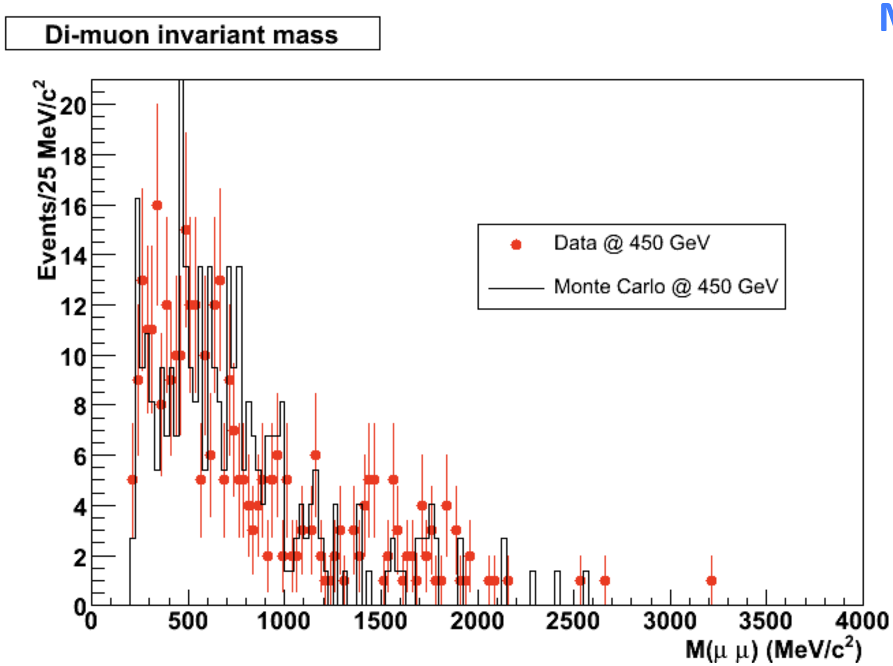


- Crosses: LHCb DATA 2009 Preliminary
- Bold error bars: statistical errors
- Thin error bars: syst. including 15% on lumi
- BLACK curve: LHCb PYTHIA tuning
- PINK curve: Perugia 0 PYTHIA tuning

Cross-sections reasonably consistent with PYTHIA predictions

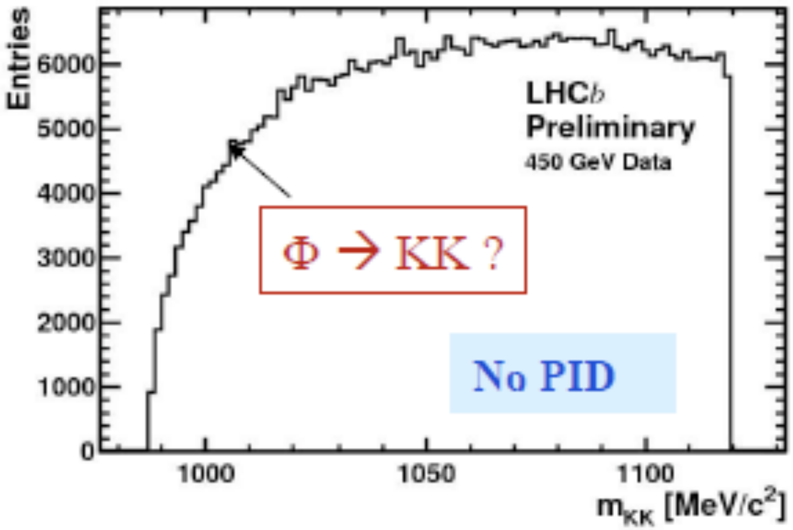
PID

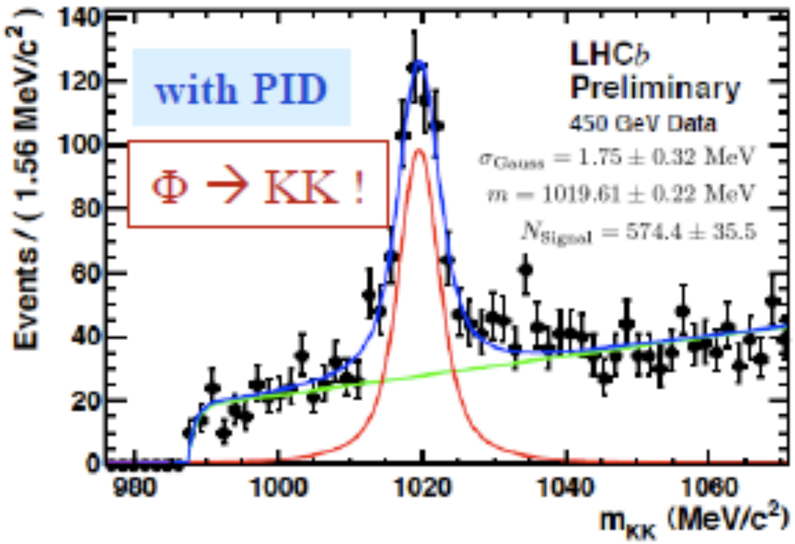
MUONI



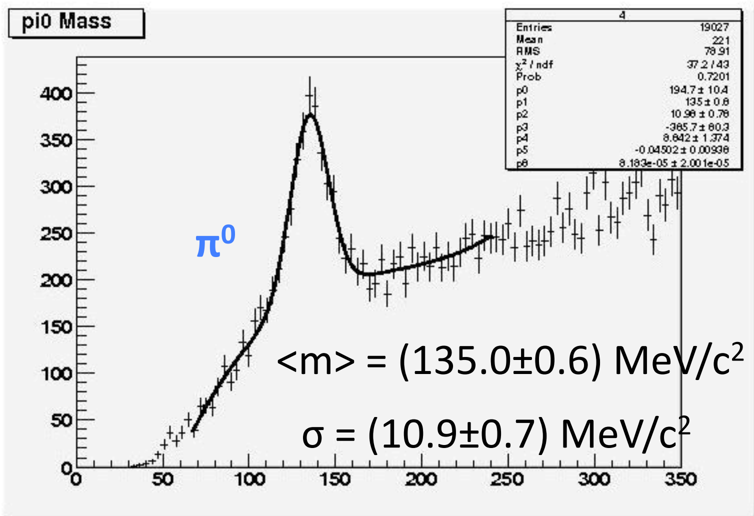
Prime misure della probabilità di errata identificazione P(μ/π) per π da K_S e Λ.
P(μ/π) =(2.3±0.4)% da MC.
Per misurare l'efficienza ε=P(μ/μ) servono segnali J/Ψ(μμ). A L=10^{30}cm^{-2}s^{-2} è previsto si abbia 1Hz di J/Ψ(μμ). Calibrazione globale all'1% con 1 ora di dati.

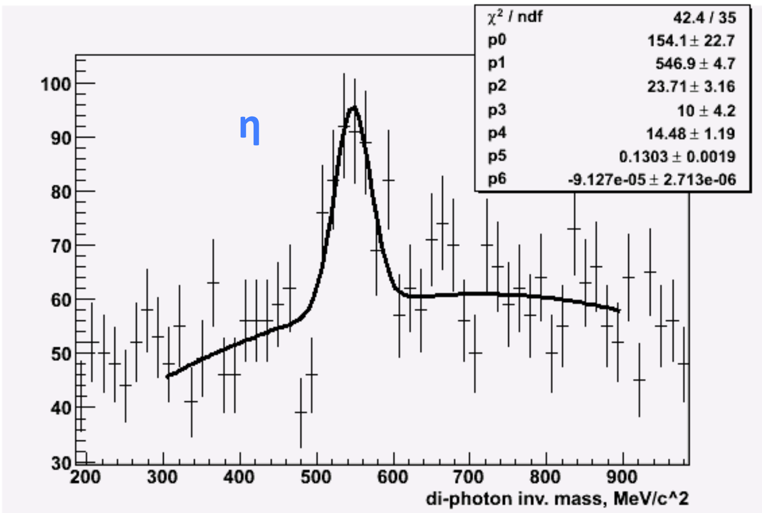
Discriminazione K/π





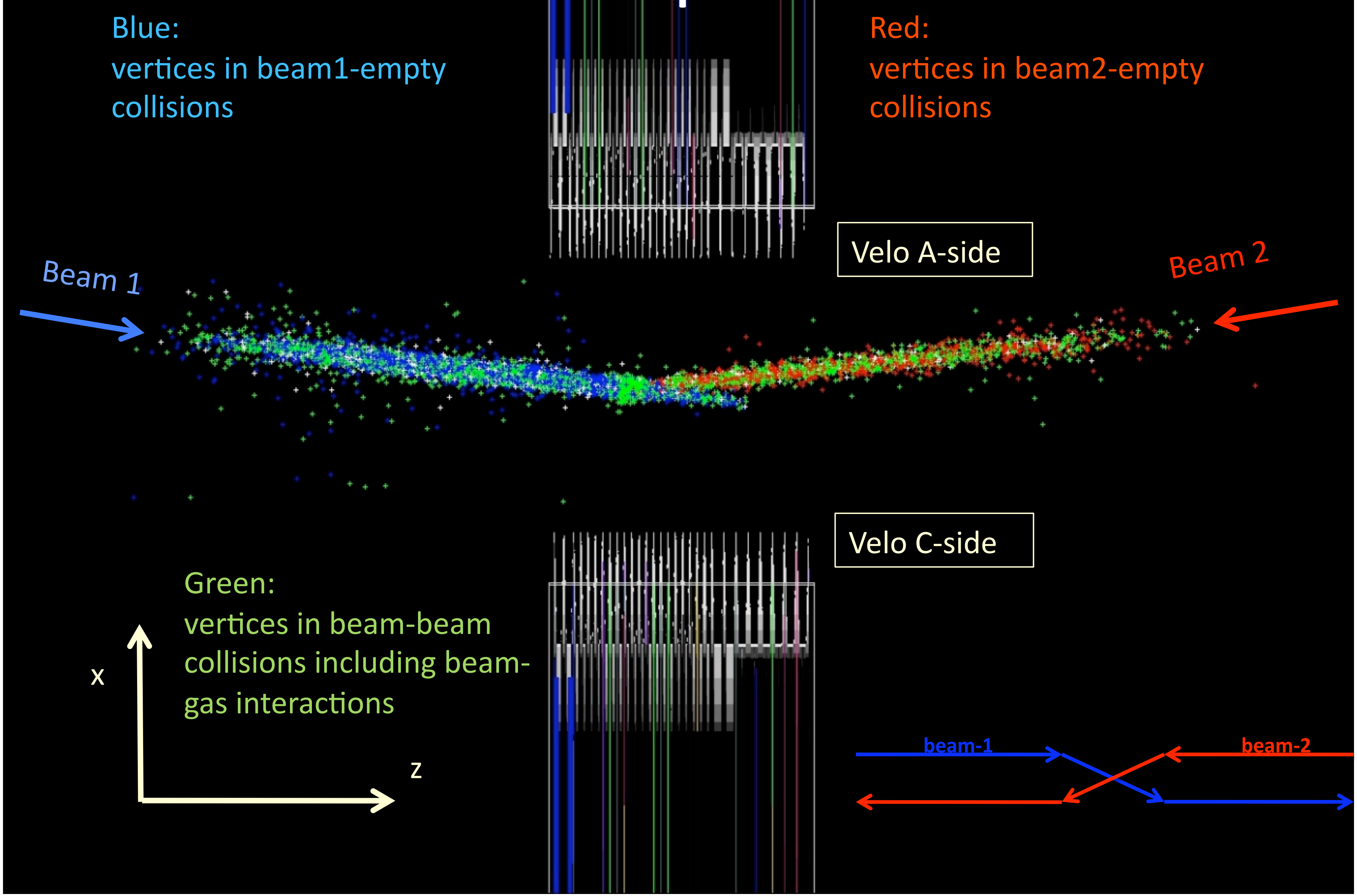
Calorimetri.





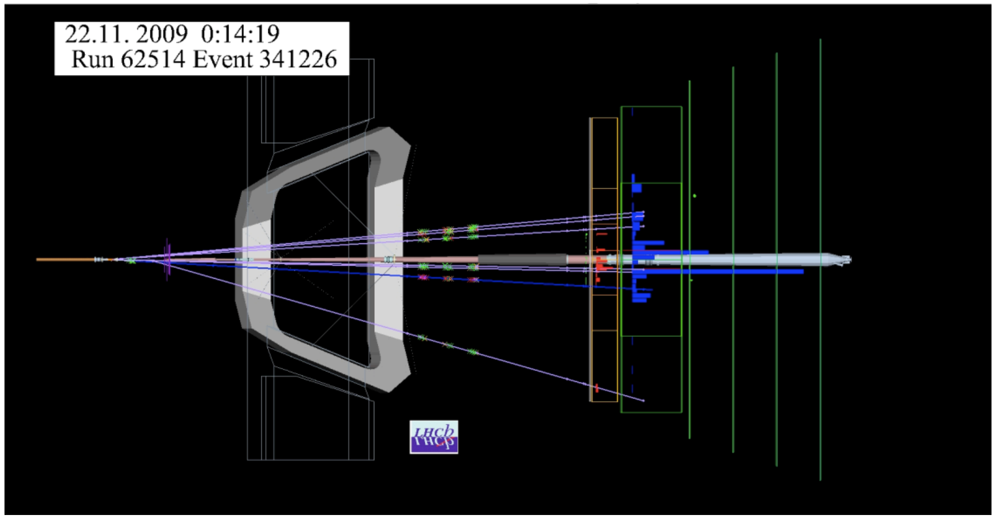
Risoluzione ottimale di ECAL non ancora raggiunta per scarsa statistica nella intercalibrazione cella-cella (7%).

Vertici primari

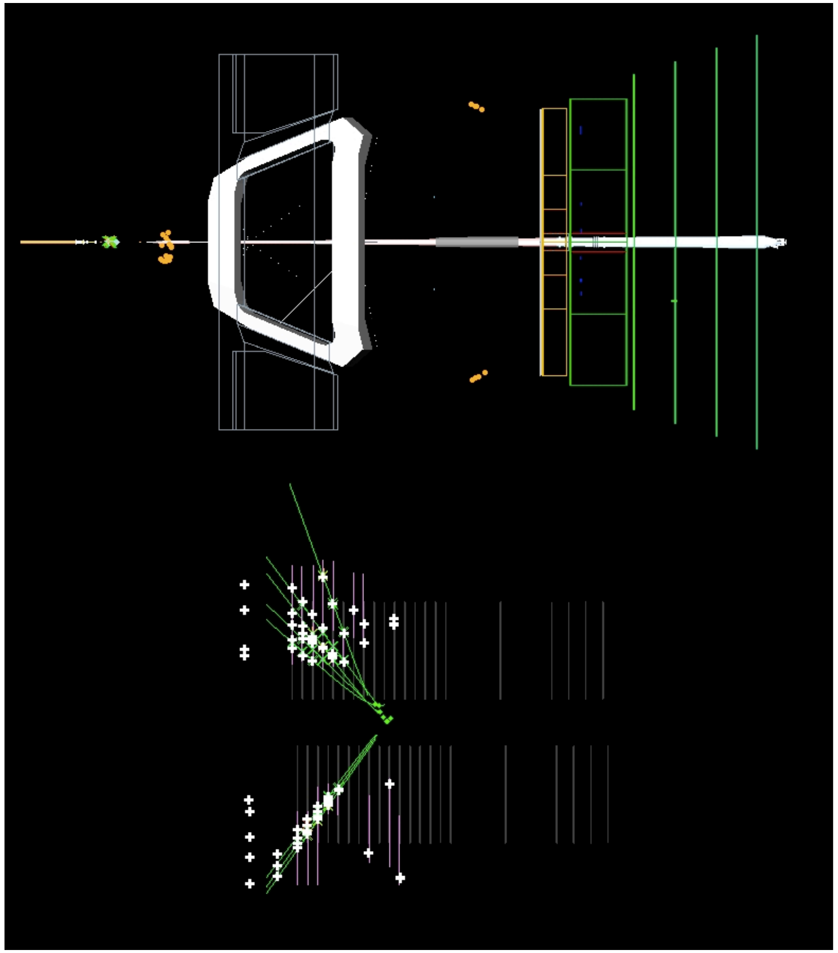


Beam-gas collisions.

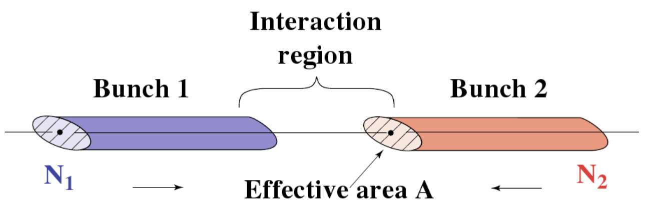
Beam1-Gas Triggered by CALO



Beam2-Gas Triggered by VELO backward silicon stations



Misura della Luminosità.

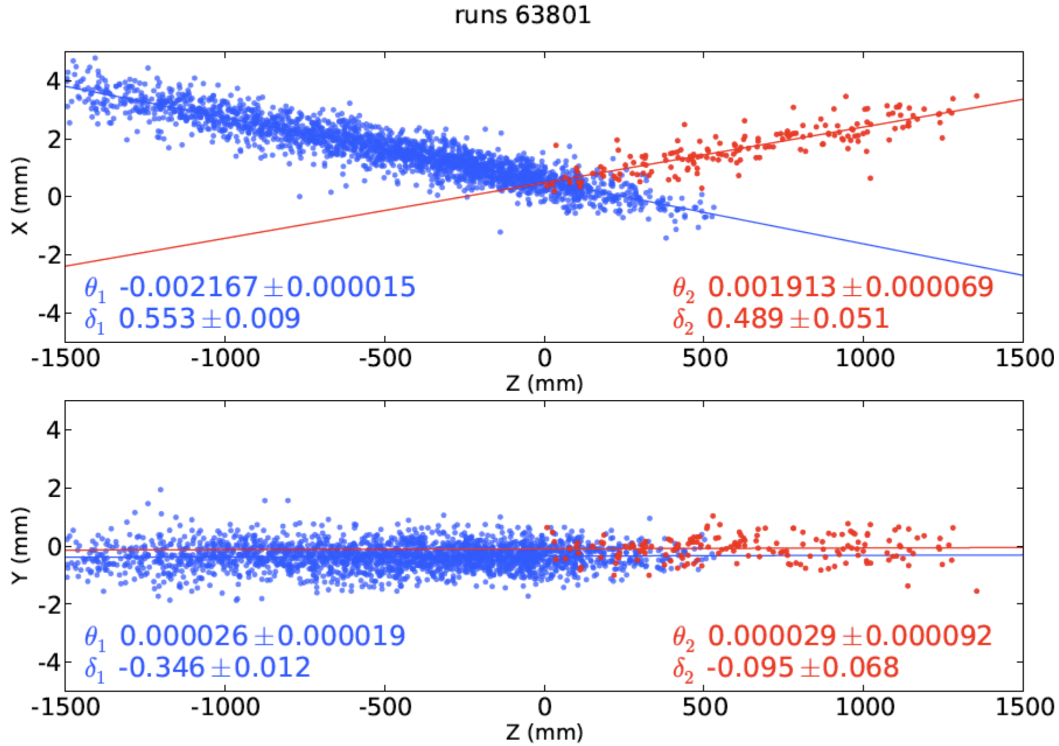


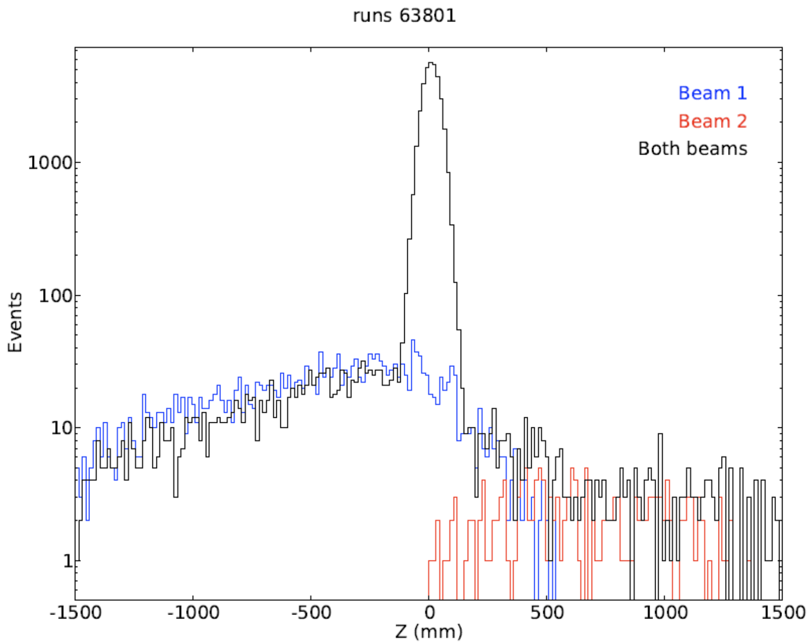
$$L = f N_1 N_2 \, 2c \cos^2(\phi/2) \int \rho_1(x,t)\rho_2(x,t) d^3x \, dt$$

bunch intensities — crossing angle — overlap integral

gaussian shapes

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



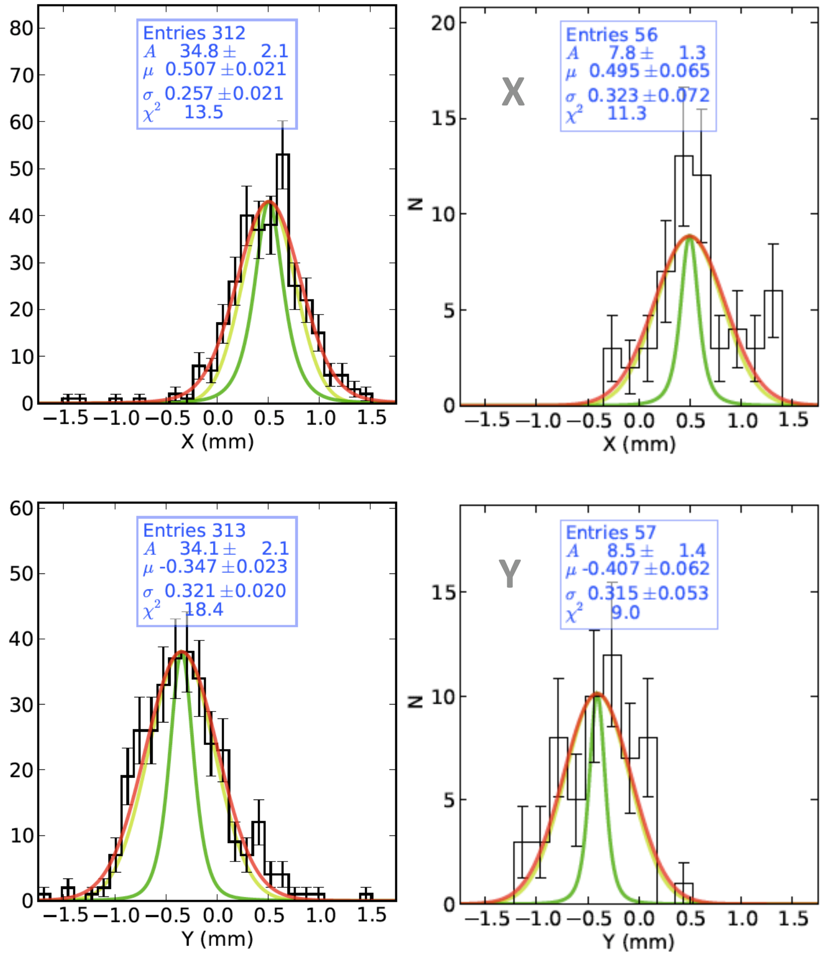


beam2-gas lower statics due to the detector asymmetry

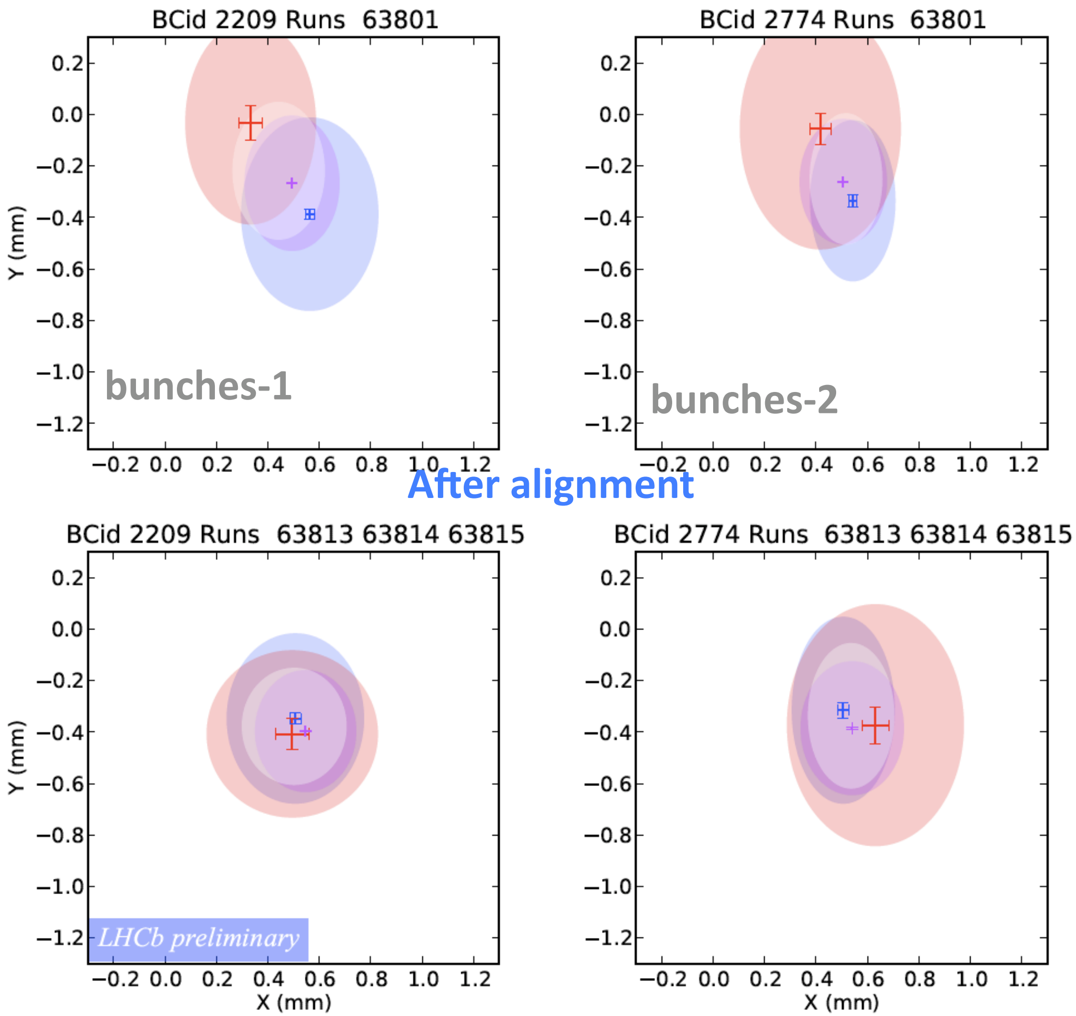
Misura della Luminosità.

Intensità di corrente dei fasci: da progetto si dovrebbe raggiungere l'1% per fascio.
Incertezza dominata da quella sulle correnti dei fasci (LHC): ±12 %.
Profilo del fascio, offset, angolo ecc. (LHCb) : ±8%

Beam-1 profile **Beam-2 profile**



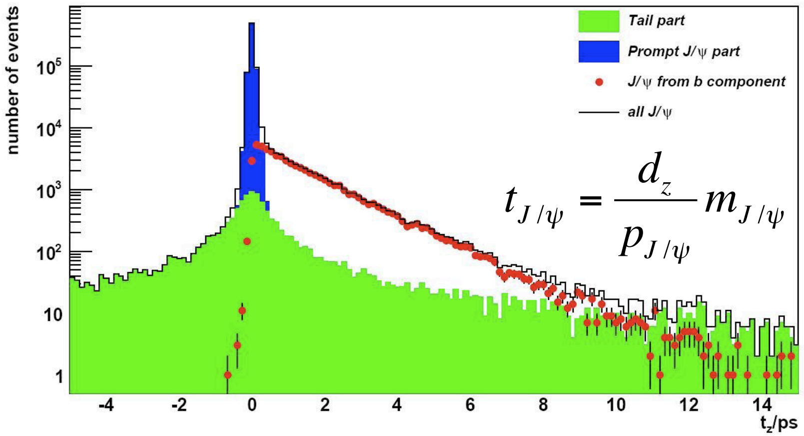
Before Van der Meer scanning



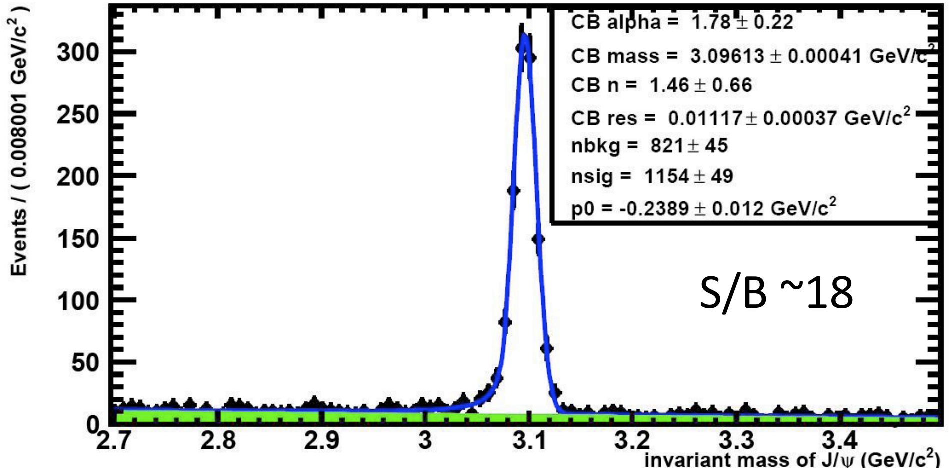
Beam profile **Unfolding** **VELO resolution**

Misura della luminosità prevista al 5%

Misura della sezione d'urto.



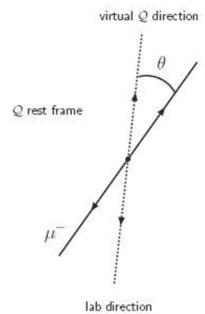
LHCbminimum bias Monte Carlo (14 TeV)



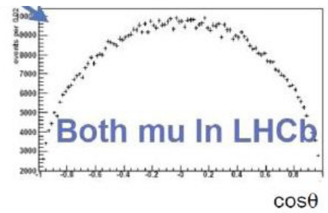
Il fit combinato della distribuzione di massa e pseudo-propertime permette di misurare il contributo relativo delle componenti J/Ψ pronta e ritardata da b→J/Ψ+X.

$$\frac{d^2N_{prompt}}{dp_T d\eta} \qquad \frac{d^2N_{b \to J/\Psi}}{dp_T d\eta}$$

A 7 TeV: 0.6M J/Ψ ricostruite per pb^{-1}.
Risoluzione in massa σ(M)~10MeV/c^2



Polarizzazione



Un sistematico importante è dovuto alla polarizzazione della J/Ψ.
La variazione dell'accettanza è stata valutata fino a 25%, se la polarizzazione è ignorata.
Pensiamo possa essere misurata, effettuando l'analisi angolare completa (in bins di η e pT).

Fisica di LHCb a 7 TeV.

10 pb^{-1} **100 pb^{-1}** **200 pb^{-1}** **500 pb^{-1}** **1 fb^{-1}**

Minimum Bias

Fisica del charm

Bs→μμ

CPV nei canali adronici.

Produzione del charmonio
Sezione d'urto di produzione di beauty

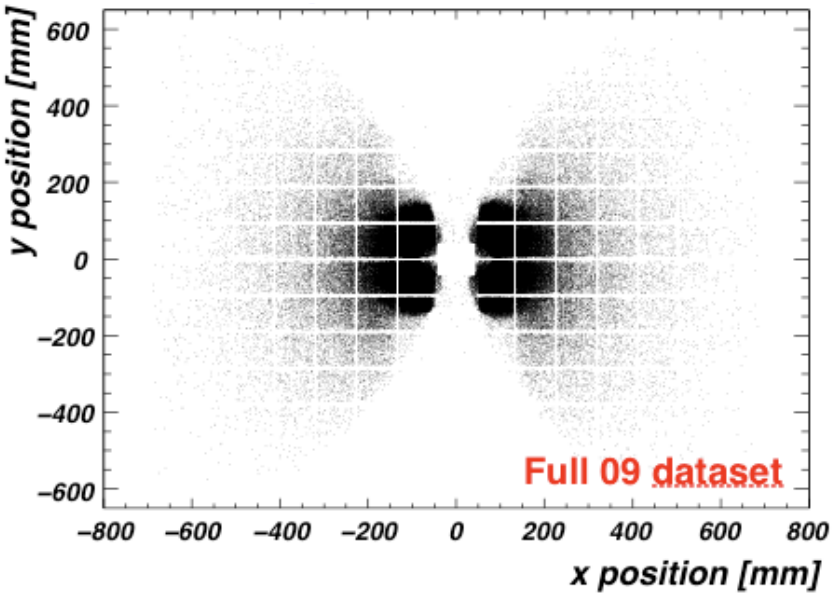
CP Violation
Bs→J/Ψ Φ

Prime misure nei canali adronici
B→hh, B→DK

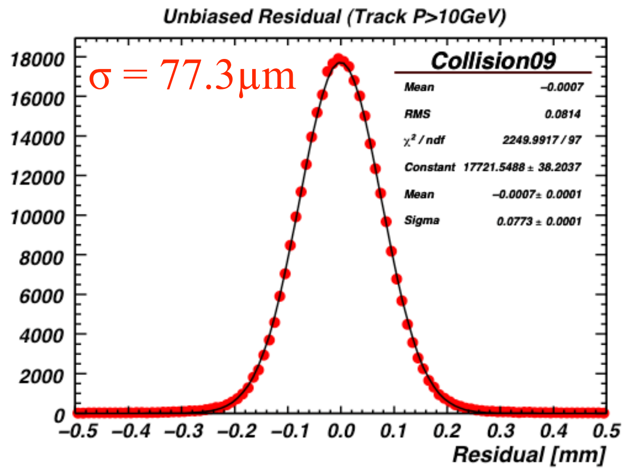
Conclusioni.

- Il ridotto valore dell'energia di collisione, benchè evidentemente costituisca una limitazione, non è costituisce un elemento critico.
- La luminosità di ~10^{32} $cm^{-2}s^{-1}$ per LHCb è pressochè ideale.
- Il rivelatore è pronto.
  - Allineamenti e PID da migliorare, calibrare.
- Il sistema di trigger potrà essere ulteriormente collaudato nel prossimo futuro per un impiego ottimale.
- Con 1/fb LHCb potrà ottenere primi risultati significativi.

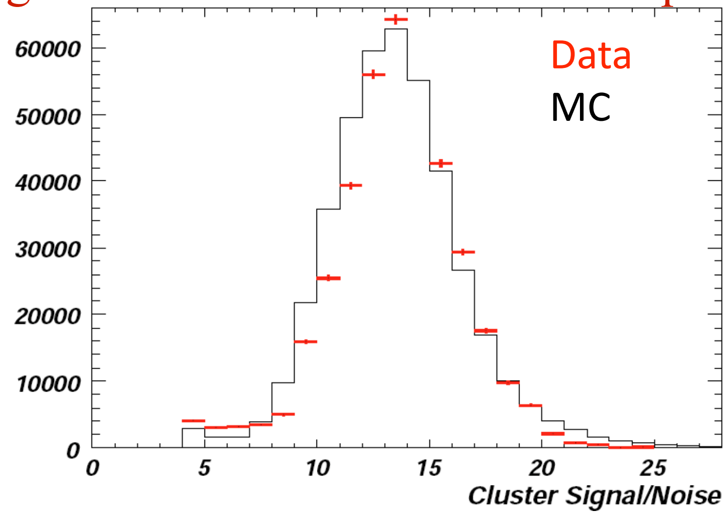
Trigger Tracker

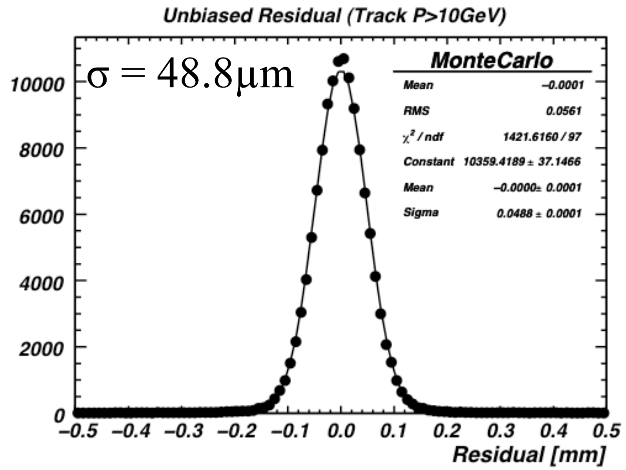


99.5 % of detector channels operational



Signal to noise ratio in line with expectations

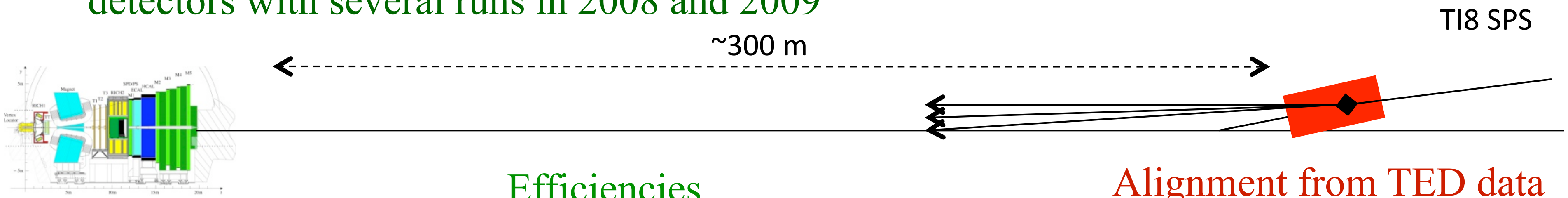


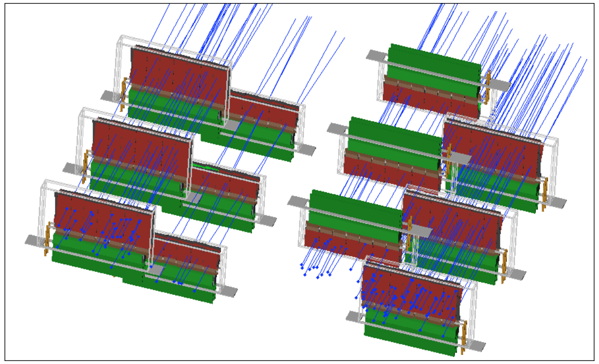


unbiased residuals still broader than in MC
→ expect further improvement with alignment

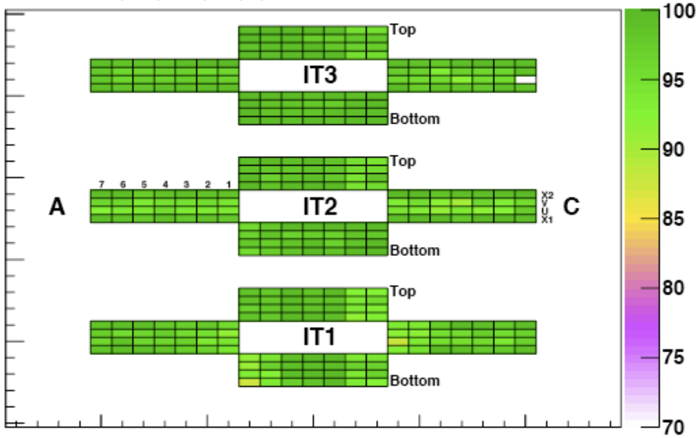
Inner Tracker.

- 2009 data → VELO open → poor overlap between VELO and IT acceptance
- TED data → VELO closed → large multiplicity, ~2/cm^2 useful for small precise detectors with several runs in 2008 and 2009

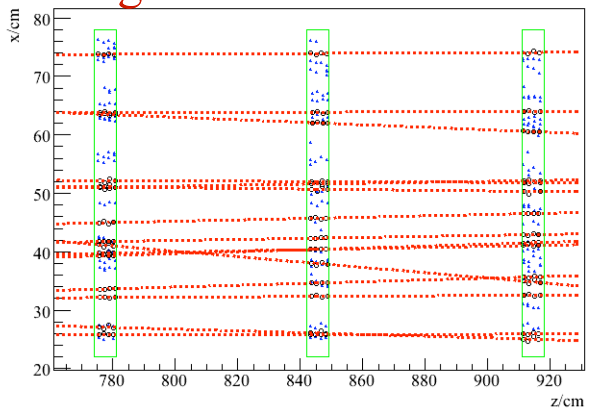


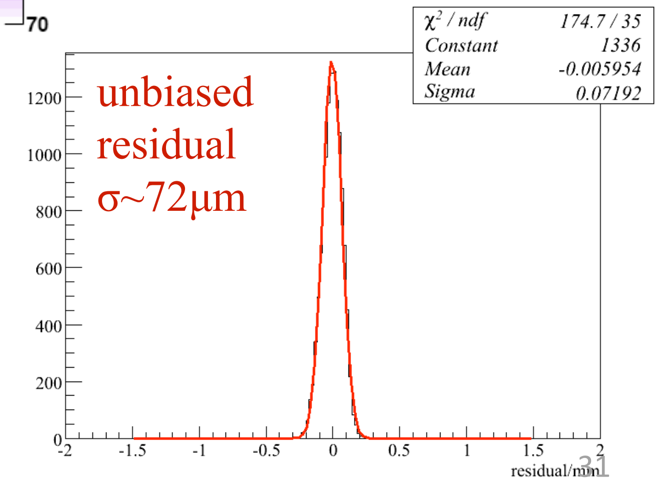


Efficiencies



Alignment from TED data

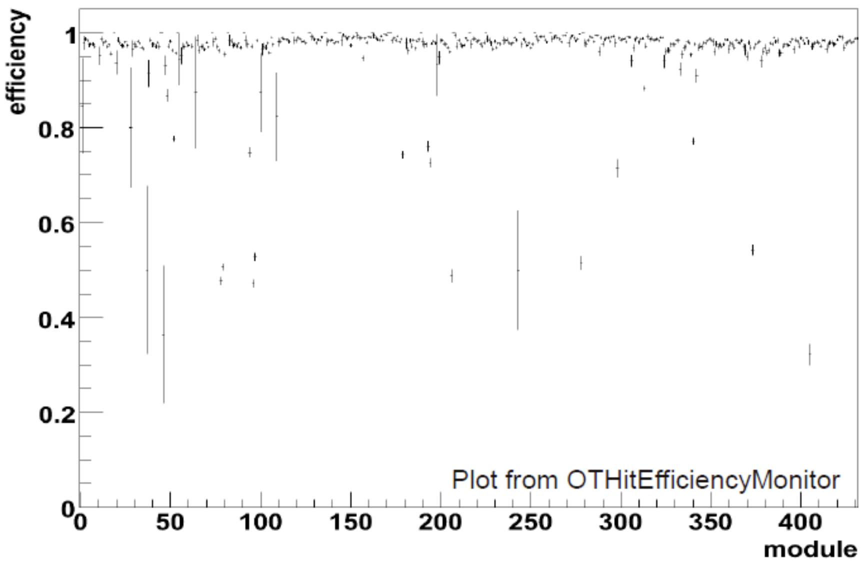




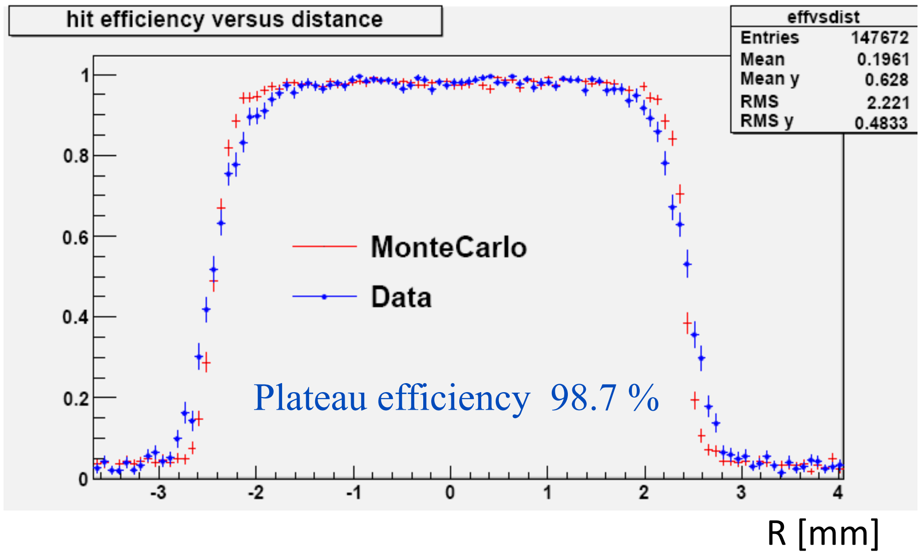
- alignment to ~15µm from TED data
- unbiased residuals from 2009 data still show room for improvement (expect ~50 µm)
- efficiencies O(98%)
- 99.5 % of detector channels working
- S/N ~ 15.5 in line with expectations

Outer Tracker

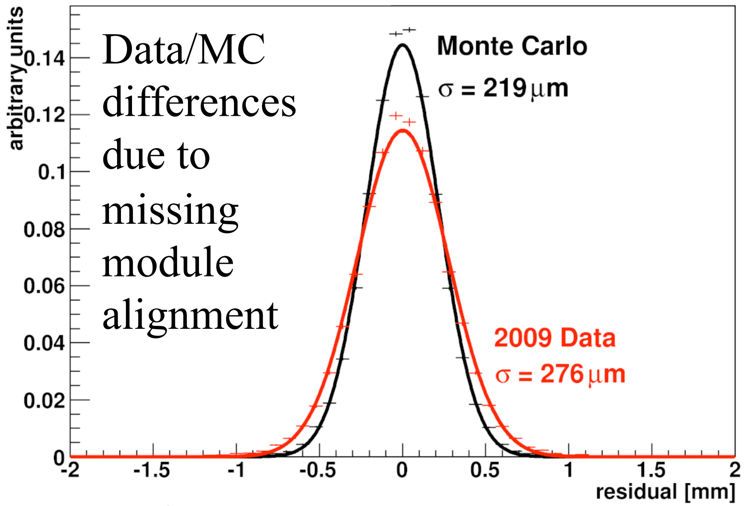
- 99.3 % of channels operational

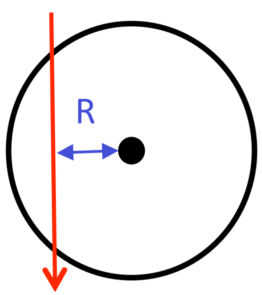


Cell efficiency profile:
Efficiency vs. distance in mono layer plane

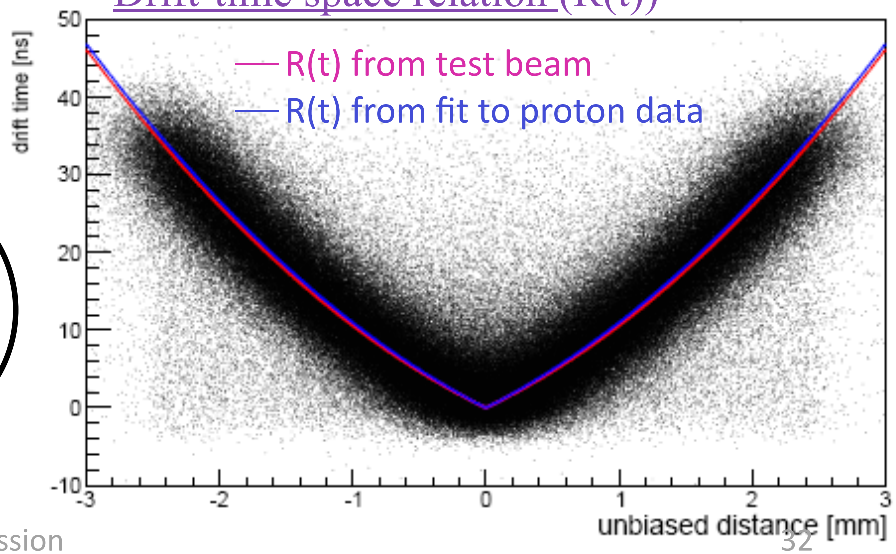


Hit residuals:

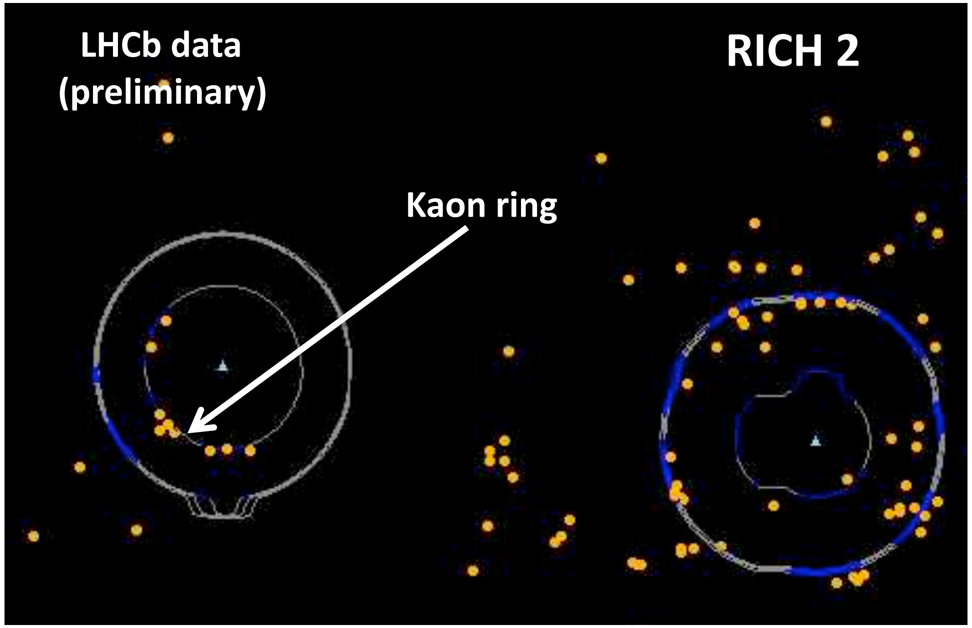




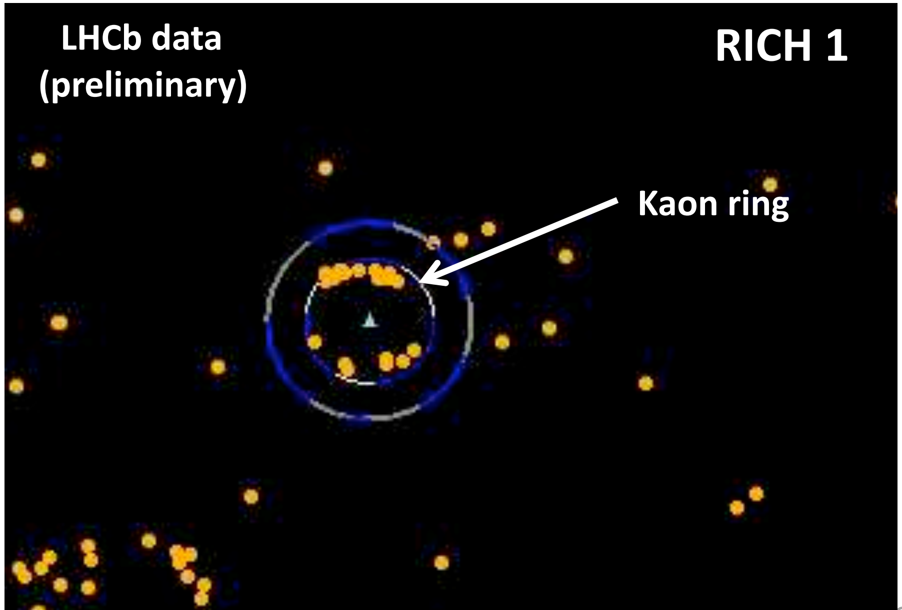
Drift-time space relation (R(t))

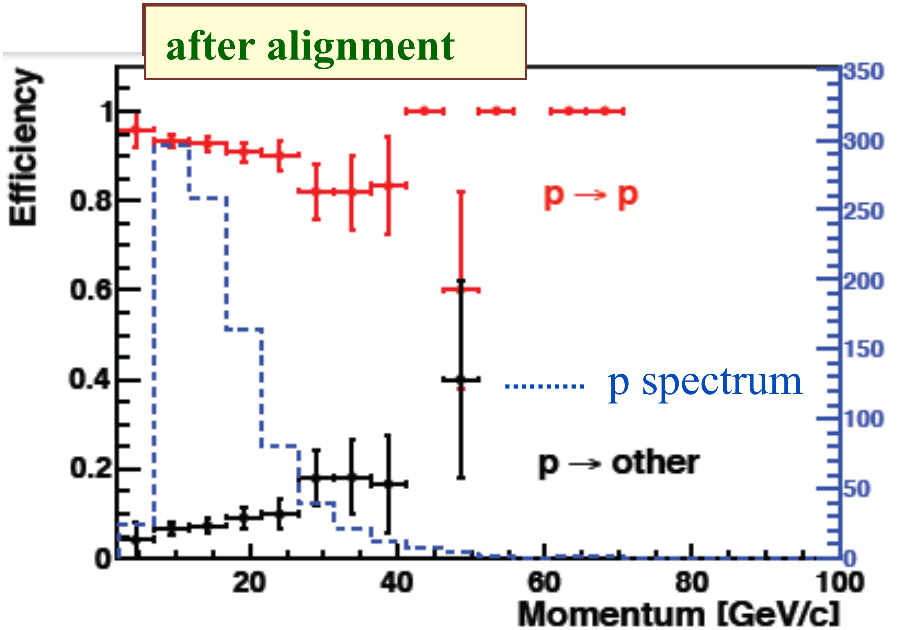


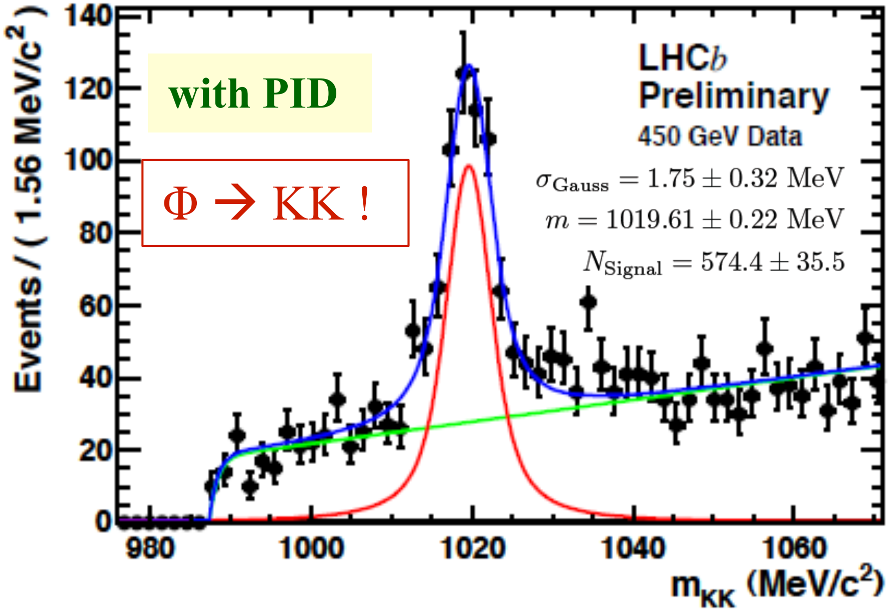
PID with RICH



➢ Orange points → photon hits
➢ Continuous lines → expected distribution for each particle hypothesis (proton below threshold)

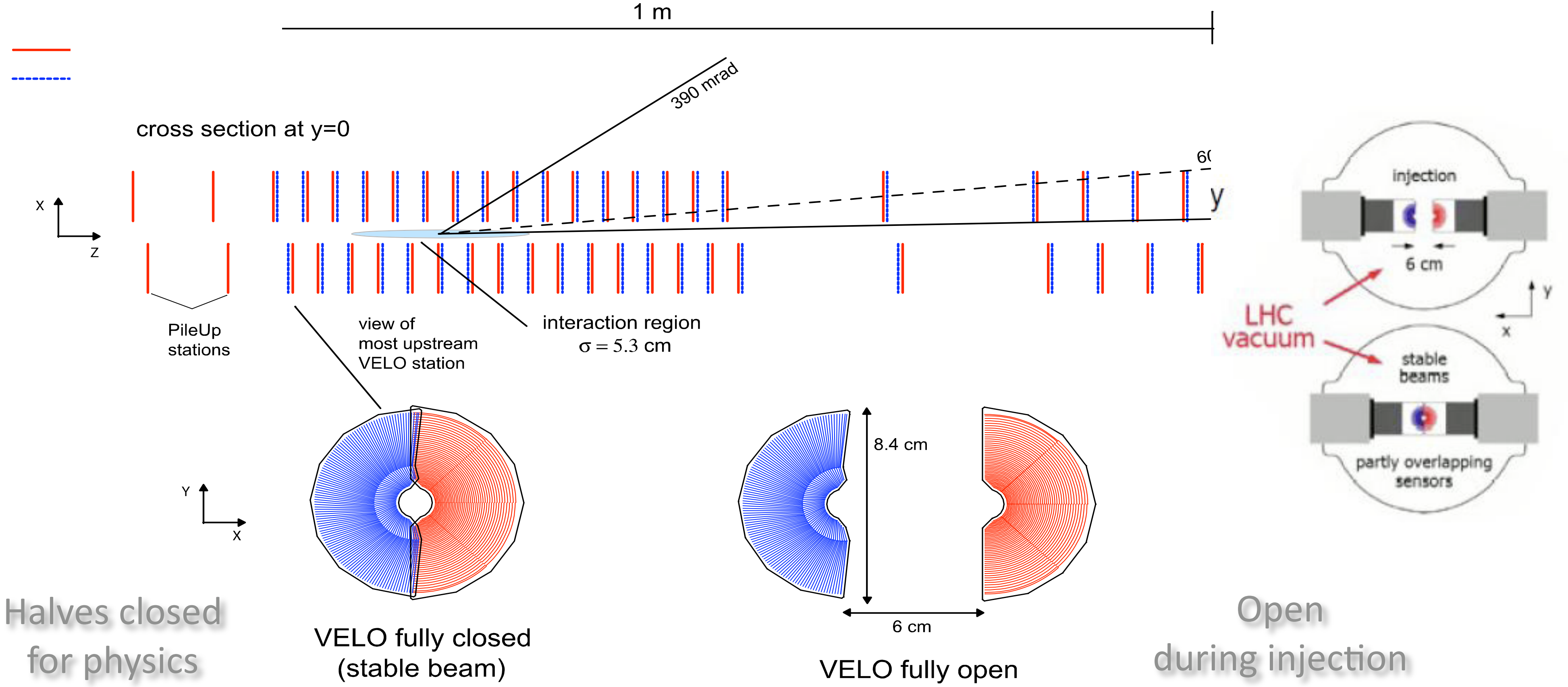






VELO: The Vertex Locator.

21 stations of silicon wafer pairs



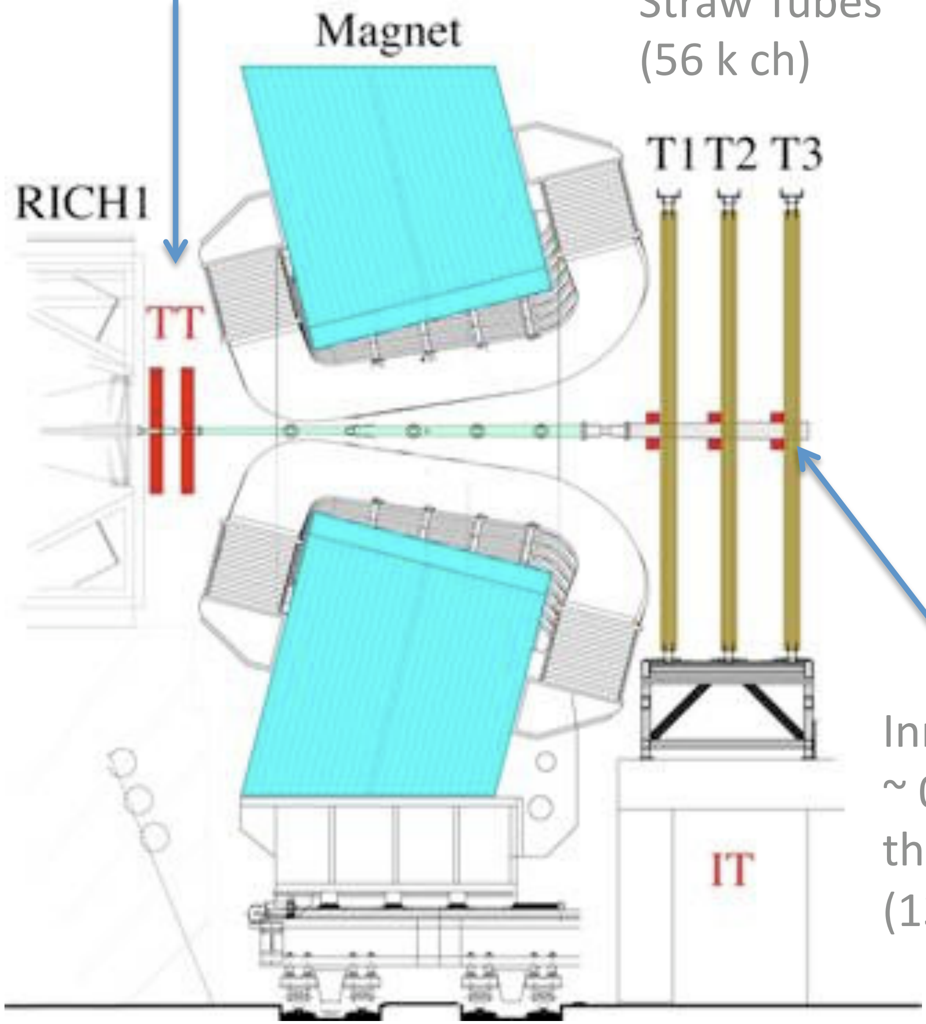
R and Φ strip readout

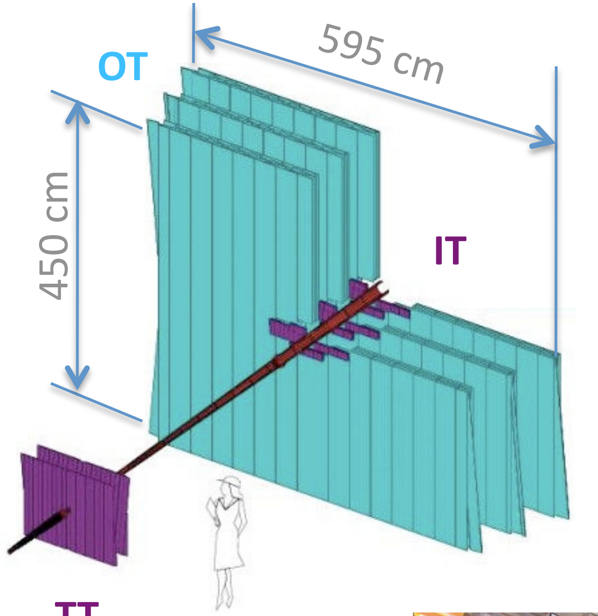
Tracking System

Similar sensors for TT and IT
micro strip 200 μm pitch

Trigger Tracker
~ 1.4×1.2 m² (144k ch)

Outer Tracker
Straw Tubes
(56 k ch)

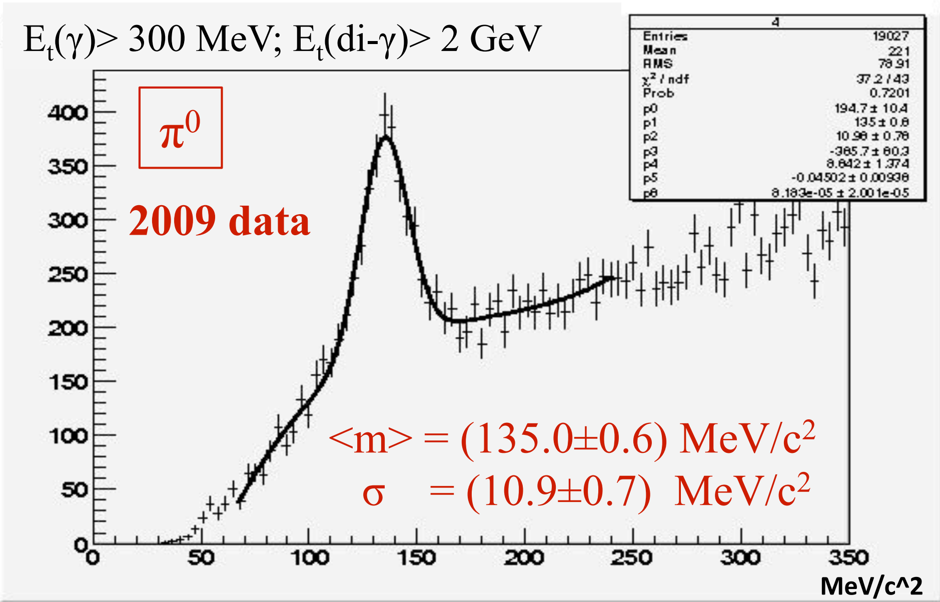


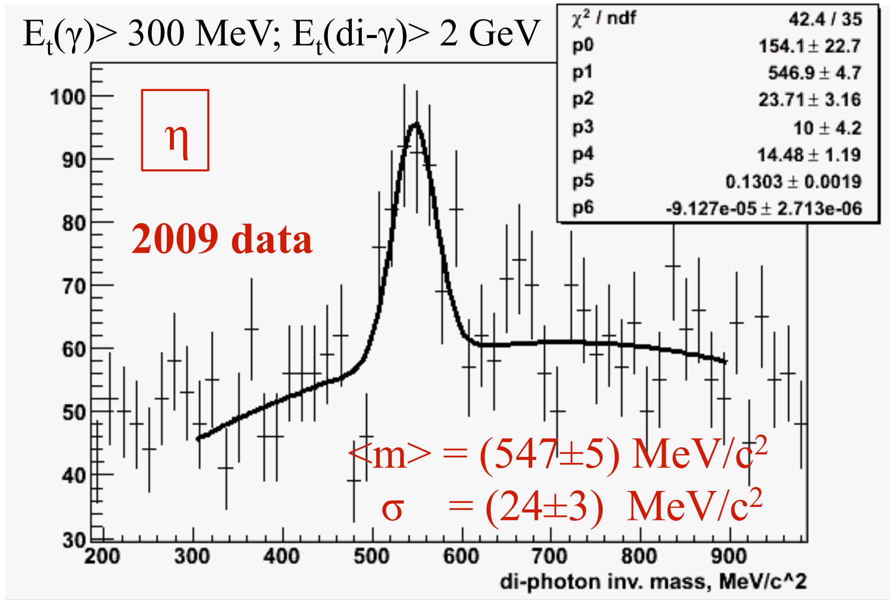


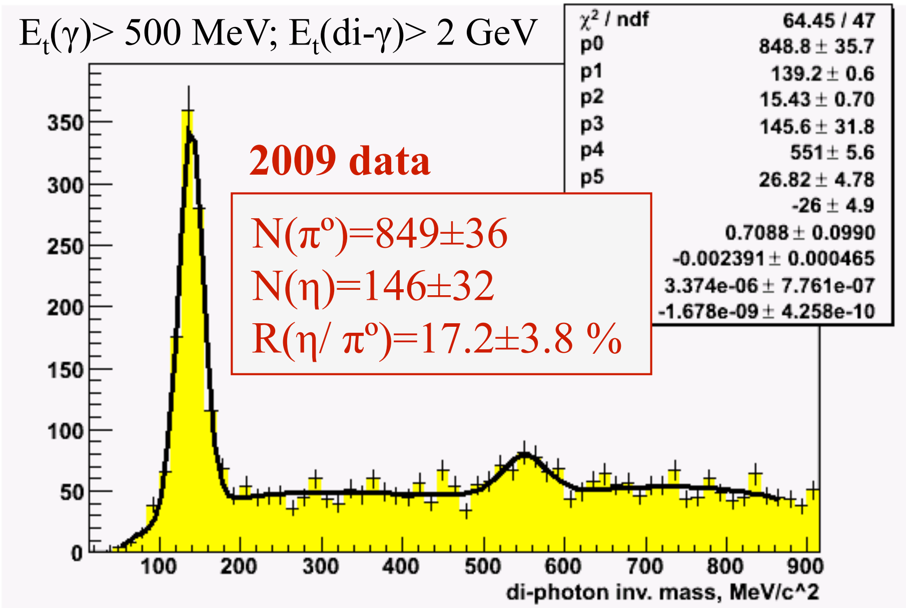
Inner Tracker
~ 0.5 m² around
the beam pipe
(130k ch)

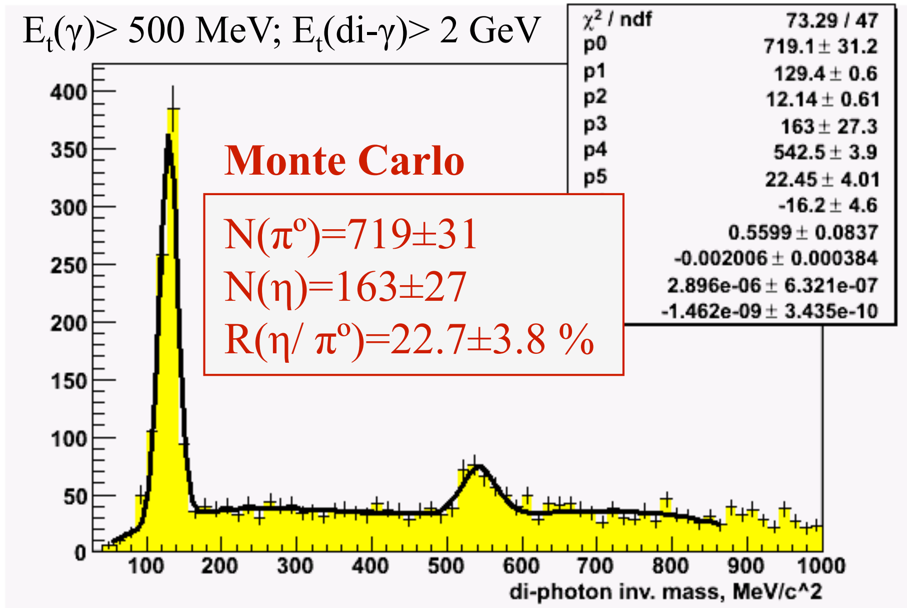
TT + 3 stations (T1,T2,T3), each with 4 detection planes (0°,+5°,-5°,0°)

Calorimeter

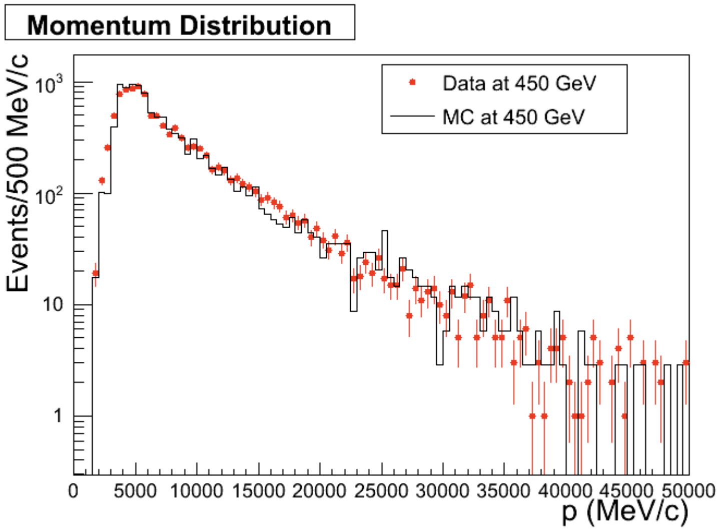




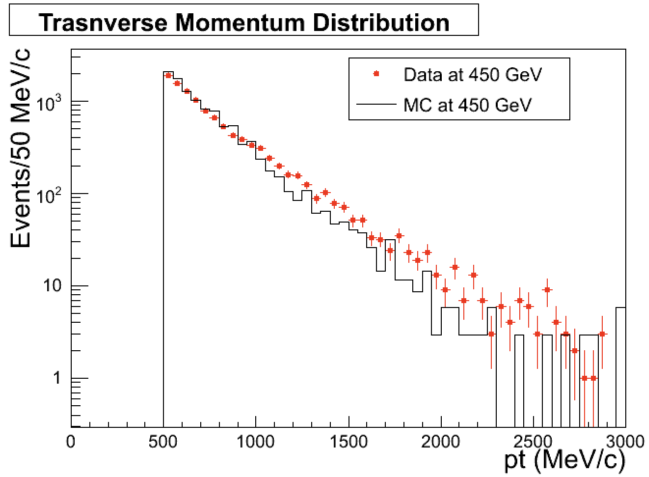




Muon ID



Momentum Distribution
Data at 450 GeV
MC at 450 GeV
Events/500 MeV/c
10^3
10^2
10
1
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
p (MeV/c)



Trasnverse Momentum Distribution
Data at 450 GeV
MC at 450 GeV
Events/50 MeV/c
10^3
10^2
10
1
0
500
1000
1500
2000
2500
3000
pt (MeV/c)

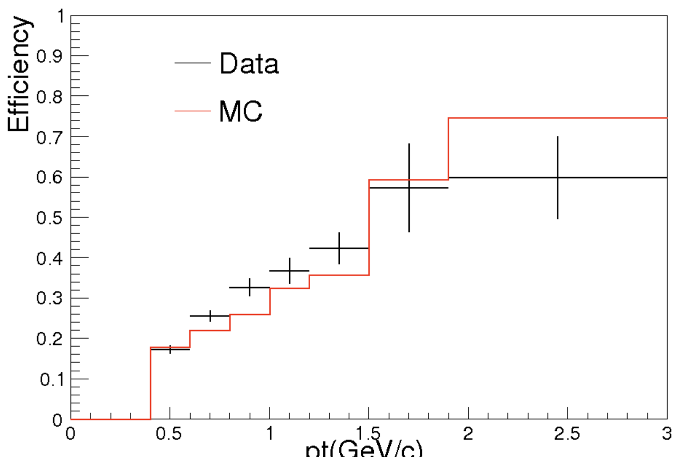
Trigger performance.

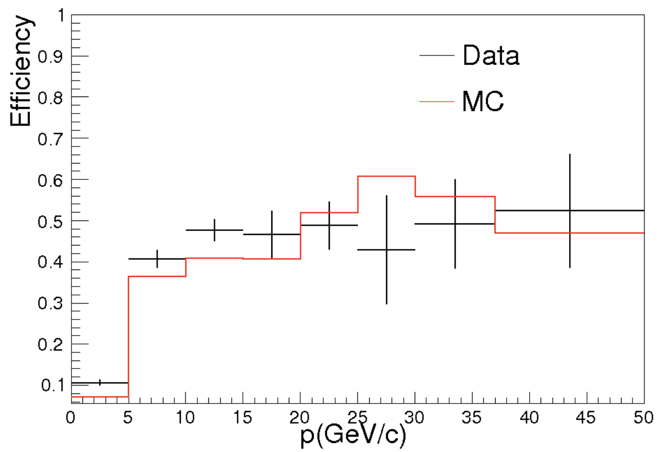
Offline selection of events with at least one **muon**.

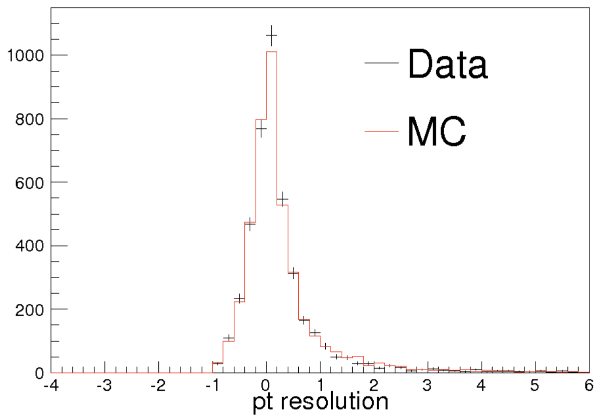
p_T > 500 MeV/c, above the L0Muon threshold.

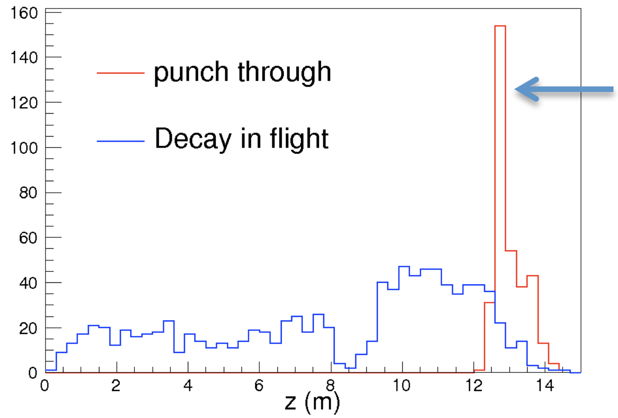
Count the number of events passing the L0Muon trigger emulator.

Muons seen at 450 GeV are all decay-in-flight muons or puchthrough muons.





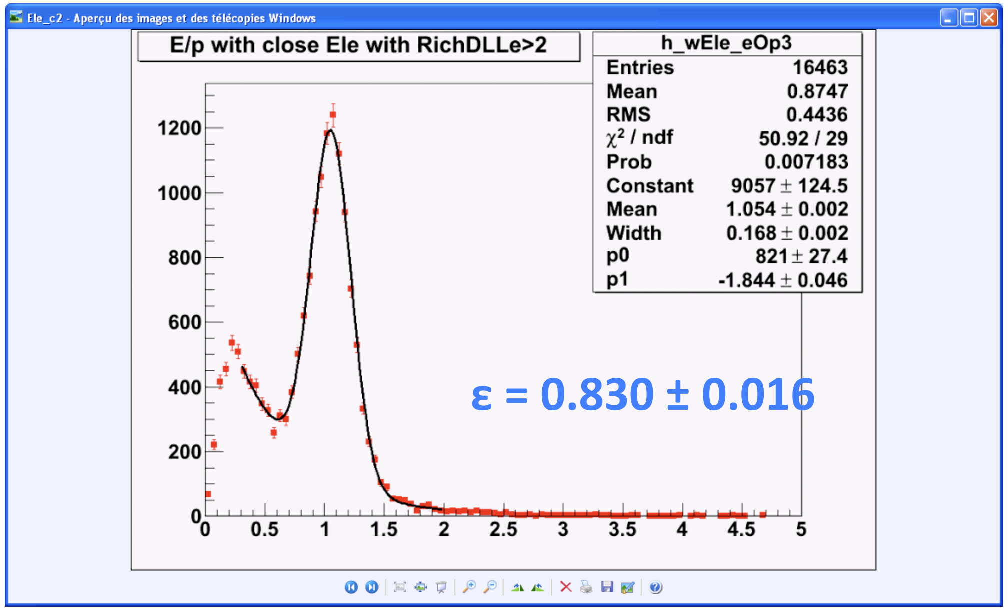


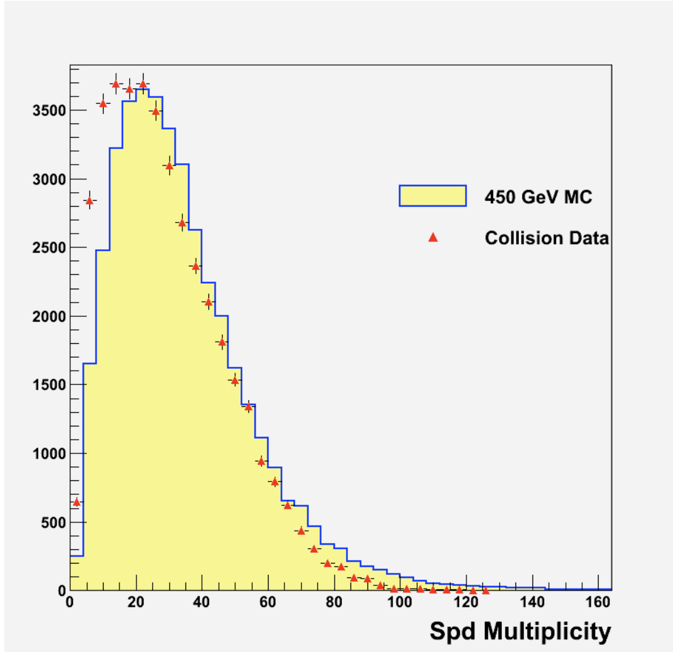


Calorimeter Region

Trigger perfomance. (II)

Select electron tracks using RICH and count the number of these electrons seen in L0 Electron trigger line.





On Muon triggered events:

– ε(pp interaction) = (99.6 ± 1.5) %

On **Monte Carlo**:

– Muon triggered events: ε = (95.5 ± 1.1) %

– **For events with one hit in SPD: ε = (83.8 ± 0.2) %**

– For events with at least one generated particle in the LHCb acceptance: ε = (81.3 ± 0.2) %

– For events with at least one VELO track: ε = (87.7 ± 0.2) %

All these numbers increase when we add ECAL energy sum to HCAL in the hadron trigger, which is what will be done in 2010.

LHC scenarios

- 2010-2011: LHC energy limited to 3.5 TeV/beam
  - In 2010 much MD gradually increasing currents, can hope for ~100 pb-1
  - Technical stop around Xmas, ~1-2 months
  - Run through 2011 with a monthly cycle (3 days stop, 2 days MD, physics)
- 2012:
  - Shut-down for consolidation (splices, remaining safety valves, etc.)
- 2013-14:
  - From then on operate with a two year cycle (~18 months run - ~6 mo stop)
  - Start at 6.5 TeV per beam increase then to 7 TeV
  - Intensity limited to 30% (collimators)
- LCHb expects to run with nominal Lumi, could hope for 1÷ 2 fb^{-1} per year.
- We aim for collecting 5-10 fb-1 by 2016.

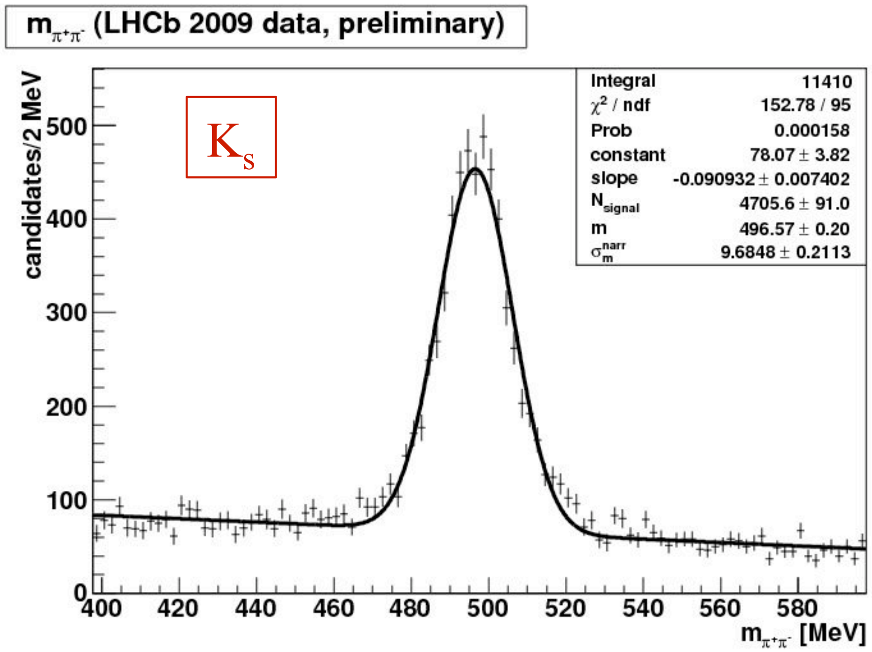
β_s con i primi dati.

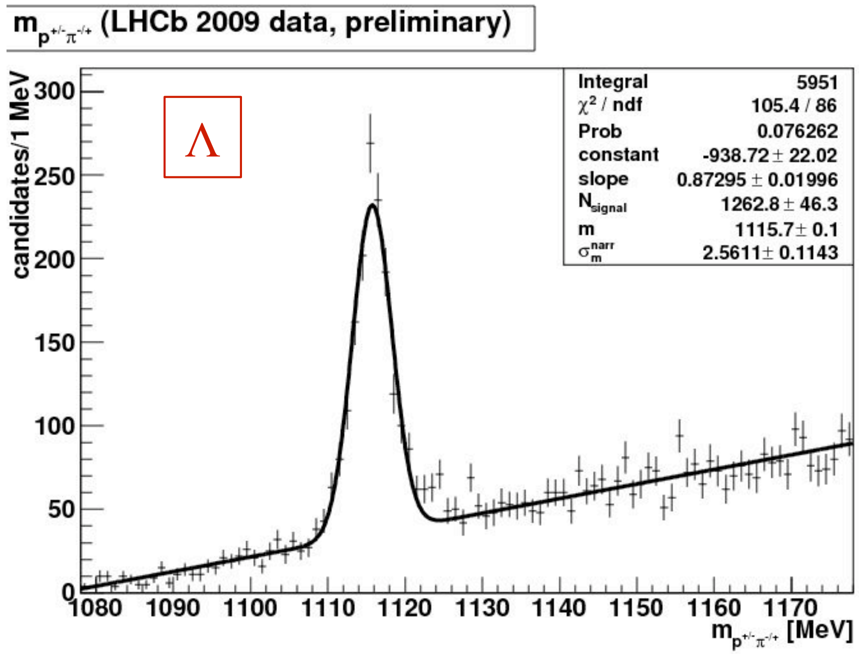
ALTAS: CERN-OPEN-2008-020
CMS: PHYSICS TDR 2006
LHCb: CERN-LHCb-2009-025
CERN-LHCb-2009-021

	LHCb	LHCb ($\sqrt{s}$ = 7 TeV)	ATLAS	CMS
Integrated luminosity	**2 fb^{-1}**	**0.3 fb^{-1}**	**0.15 fb^{-1}** [a]	**10 fb^{-1}**
$B_s \to J/\psi\phi$ signal events	117k	8k	1.14k [a]	110k
bb background/signal ratio	0.5		~ 5.5 [a]	0.33
B_s mass resolution	16 MeV/c^2		61 MeV/c^2 [a]	14 MeV/c^2 [b]
Proper-time resolution	38 fs		152 fs [a]	78 fs [c]
Flavour tagging εD^2	6.2%		4.6% [c]	–
$\sigma_{stat}(2\beta_s)$	**0.030**	**0.12**		

Reconstructed K_s and Λ masses

Tracking without VELO



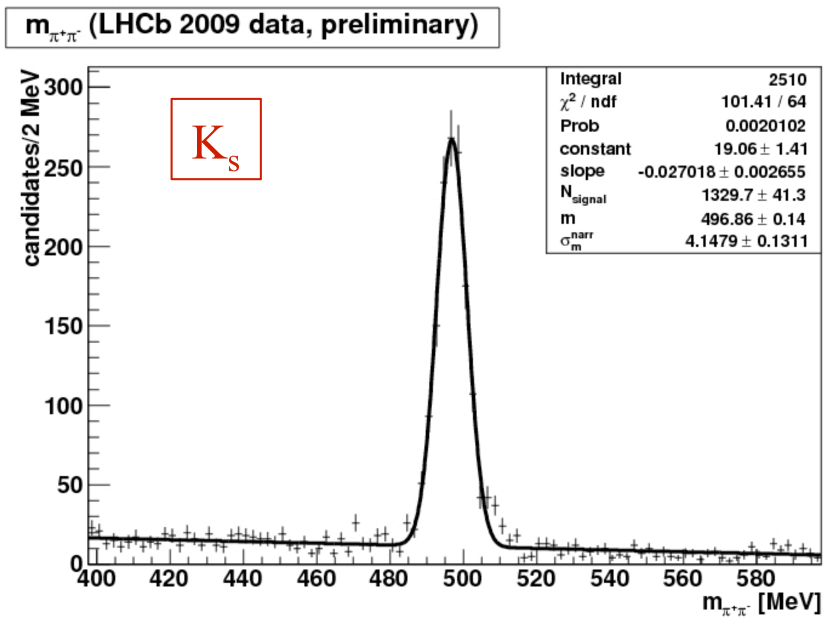


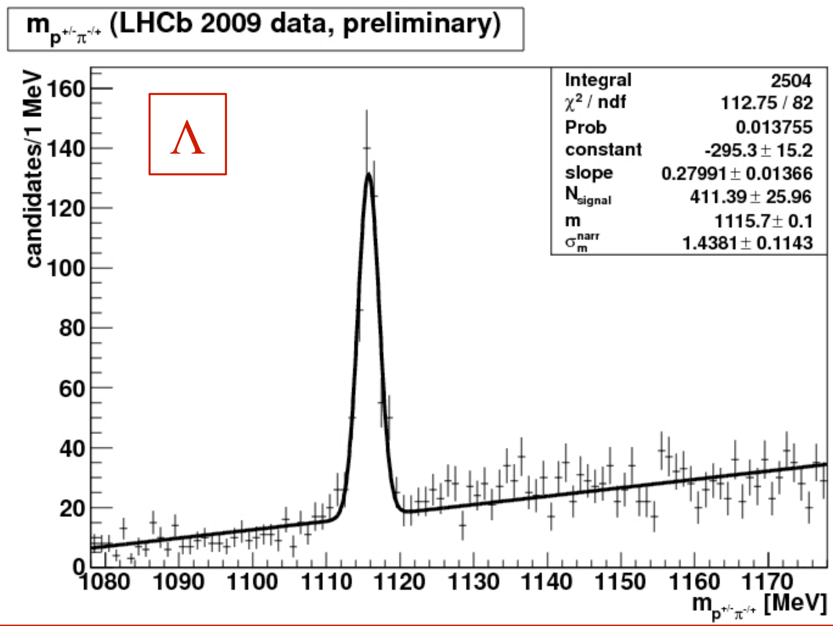
$m = (496.6 \pm 0.2_{stat.})$ MeV/c^2
$\sigma = (9.7 \pm 0.2_{stat})$ MeV/c^2
PDG: 497.61(2) MeV/c^2

$m = (1115.7 \pm 0.1_{stat.})$ MeV/c^2
$\sigma = (2.6 \pm 0.1_{stat})$ MeV/c^2
PDG: 1115.683(6) MeV/c^2

Reconstructed K_s and Λ masses

Using full tracking power, including VELO
→ resolutions improve by ~ factor 2





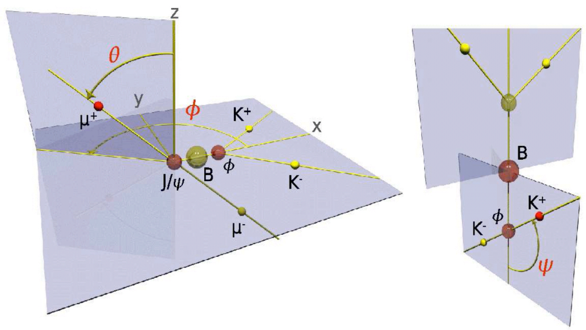
- ✓ overall improvement of tracking after first alignment with B-field OFF data
- ✓ ultimate performance of MC not yet achieved
- ➢ improvements expected with:
  - → new alignment procedure with magnet ON data (on the way…)
  - → VELO closed
  - → more data with B-field OFF

Tasso di decadimento di $B_s \rightarrow J/\psi\phi$

$$\frac{d\Gamma\left(B_s(t)\rightarrow J/\psi\ \phi\right)}{dt} \propto \sum_{k=1}^{6} h_k(t) g_k(\vartheta,\psi,\varphi)$$

8 parametri:
Φ, Γ_s, $\Delta\Gamma_s$, Δm_s, $R_\perp$, R_0, δ_1, δ_2

k	$h(t)$	$g_{J/\psi\phi}(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\mathrm{Re}\{A_0^*(t)A_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
5	$\mathrm{Im}\{A_\parallel^*(t)A_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
6	$\mathrm{Im}\{A_0^*(t)A_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$



$$|A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right]$$

$$\mathrm{Re}\{A_0^*(t)A_\parallel(t)\} = |A_0(0)||A_\parallel(0)|e^{-\Gamma_s t}\cos(\delta_2-\delta_1)\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right]$$

$$\mathrm{Im}\{A_\parallel^*(t)A_\perp(t)\} = |A_\parallel(0)||A_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_1\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\delta_1\cos(\Delta m_s t) - \cos\delta_1\cos\Phi\sin(\Delta m_s t)\right]$$

$$\mathrm{Im}\{A_0^*(t)A_\perp(t)\} = |A_0(0)||A_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_2\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\delta_2\cos(\Delta m_s t) - \cos\delta_2\cos\Phi\sin(\Delta m_s t)\right]$$

$$\delta_1 = \arg(A_\parallel^* A_\perp) = \delta_\perp - \delta_\parallel$$

$$\delta_2 = \arg(A_0^* A_\perp) = \delta_\perp - \delta_0$$

$$R_\perp = \frac{|A_\perp(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2}$$

$$R_0 = \frac{|A_0(0)|^2}{|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2}$$