RF-separated beams and “Physics Beyond Colliders”

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03.04.2017

CERN | EN ENGINEERING DEPARTMENT

Physics Beyond Colliders

EA

Agenda

- The “Physics beyond Colliders” Initiative
- Particle production and beam composition
- Enrichment of particle species in beams
- Considerations for RF-separated beams

http://pbc.web.cern.ch/

Physics Beyond Colliders – Introduction

- Extrapolary study aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders
- Projects targeting fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments
- Initiated by CERN director-general and coordinated by J. Jaeckel, M. Lamont and C. Vallee
- Kick-off workshop (September 2016) identified a number of areas of interest
- Working groups set-up to pursue studies in these areas
- PBC study remains open to further ideas for new projects

Physics Beyond Colliders – Introduction

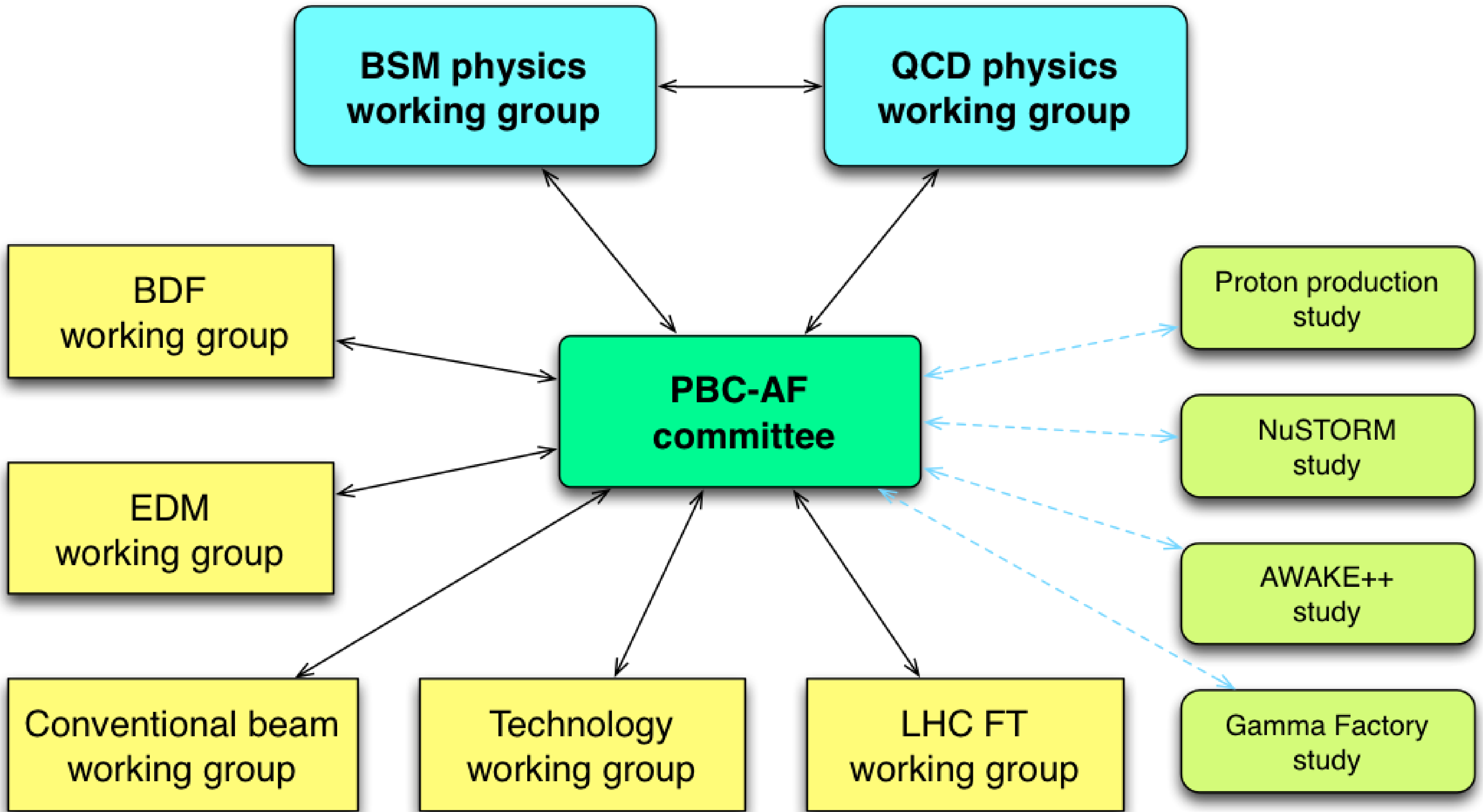
Physics Groups

- **BSM subgroup:** SHIP; NA64++; NA62++; KLEVER; IAXO; LSW; EDM
- **QCD subgroup:** *COMPASS*++; μ-e; LHC FT (gas target + crystal extraction); DIRAC++; NA60++; NA61++

Deliverables:

- Evaluation of the physics case in the worldwide context
- Possible further detector optimization
- For new projects: investigation of the uniqueness of the CERN accelerator complex for their realization

Accelerator Working Group



Physics Beyond Colliders – Introduction

- ***Conventional beams subgroup***: Evaluation of NA62 beam dump, *COMPASS RF separated beam*, NA61++ beam, KLEVER beam + possible siting of NA64++, μ-e elastic experiment, NA60++, and DIRAC++ beams
- **BDF subgroup**: Completion of technical feasibility studies of a Bump Dump Facility as input to the SHiP conceptual design study (CDS)
- **EDM subgroup**: Feasibility study including preliminary costing
- **LHC Fixed Target subgroup**: Collection of various initiatives (UA9, LHC collimation team, AFTER collaboration) with the aim of a conceptual design report
- **Technology subgroup**: Evaluation of possible technological contributions of CERN to non-accelerator projects possibly hosted elsewhere

Conventional Beams – Strategy

- Large number of fixed target proposals
- Pre-proposal studies for working groups to ensure progress with their evaluation
- Focus first on projects with
  - Possible short and medium time-scale implementation
  - Limited resources
  - Most advanced and competitive (based on the available input and first feasibility analysis regarding the FT implementation)
- Additional studies based on the information provided by the collaborations and the following criteria:
  - Analysis of the physics WG
  - Sufficient details known that are required for an implementation study
  - Study can be performed within the timescale of the European Strategy update

Conventional Beams – Projects

Under consideration at present:

- NA62: Proposal to operate in beam-dump mode
- NA64++: High intensity electron, muon and hadron beams for dark particles searches
- K_LEVER: High intensity K_L beam (high flux, pencil beam, new target) for rare decays
- *COMPASS++: RF separated beams for hadron structure and spectroscopy*
- μ-e: 150 GeV muon beams for high precision measurement of hadron vacuum polarisation for g-2 of the muon
- DIRAC++: DIRAC@SPS for high statistic mesonic atoms
- NA60++: Heavy ion beams for di-muon physics
- NA61++: Higher intensity ion beam for charm studies

Conventional Beams – Structure

CONVENTIONAL BEAMS WORKING GROUP

Conveners: L.Gatignon, M.Brugger
Members: Experiments, H.Wilkens, G.Lanfranchi, T.Spadaro, EA physicists, HSE, RP, EL, CV, RF, STI

CBWG-ECN3

- K_LEVER
- NA62 Dump
- NA60
- DIRAC

CBWG-EHN2

- COMPASS (RF-separated and low energy pbar beams)
- μ-e elastic
- NA64-μ
- CEDAR

CBWG-EHN1

- NA61
- NA64 hadrons

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CBWG-ECN3

Members:
EA physicists,
RP, HSE, CV, EL,
MPE, STI, MSC, EPC,
SMB

CBWG-EHN2

Members:
EA physicists,
RP, HSE, RF, CV, EL,
STI, MSC,
EPC, CRG, SMB

CBWG-EHN1

Members:
EA physicists,
RP, HSE, CV, EL,
MSC, EPC

Conventional Beams

Successful kick-off meeting February 22nd

09:00	→ 09:15	**Introduction** **Speaker**: Lau Gatignon (CERN)	15m
09:15	→ 09:30	**NA62 Beam dump** **Speakers**: Evgueni Goudzovski (University of Birmingham) , Tommaso Spadaro (Istituto Nazionale Fisica Nucleare Frascati (IT))	15m
09:30	→ 09:45	**NA64++** **Speaker**: Paolo Crivelli (Eidgenoessische Technische Hochschule Zuerich (CH))	15m
09:45	→ 10:00	**KLEVER** **Speaker**: Matthew Moulson (Istituto Nazionale Fisica Nucleare Frascati (IT))	15m
10:00	→ 10:15	**Mu-e** **Speaker**: Clara Matteuzzi (Universita & INFN, Milano-Bicocca (IT))	15m
10:15	→ 10:30	**DIRAC++** **Speaker**: Daniel Drijard (CERN)	15m
10:30	→ 10:45	**NA60++** **Speaker**: Enrico Scomparin (Universita e INFN (IT))	15m
10:45	→ 11:00	**NA61++** **Speaker**: Antoni Aduszkiewicz (University of Warsaw (PL))	15m
11:00	→ 11:15	**COMPASS++** **Speaker**: Oleg Denisov (INFN, sezione di Torino)	15m
11:15	→ 12:00	**Discussion and Outlook** **Speakers**: Lau Gatignon (CERN) , Markus Brugger (CERN)	45m

Particle production

Atherton parameterisation (CERN 80-07):

$$\frac{d^2N}{dpd\Omega} = A\left[\frac{B}{p_0}\, e^{-Bp/p_0}\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

$$\frac{d^2N}{dpd\Omega} = A\left[\frac{(B+1)}{p_0}\left(\frac{p}{p_0}\right)^B\right]\left[\frac{2Cp^2}{2\pi}\, e^{-C(p\theta)^2}\right]$$

with primary momentum p_0 and production angle θ

Flux per solid angle [steradian], per interacting proton, and per dp [GeV/c]

	A	B	C
p	0.8	-0.6	3.5

	A	B	C
π^+	1.2	9.5	5.0
π^-	0.8	11.5	5.0
K^+	0.16	8.5	3.0
K^-	0.10	13.0	3.5
$\bar{p}$	0.06	16.0	3.0

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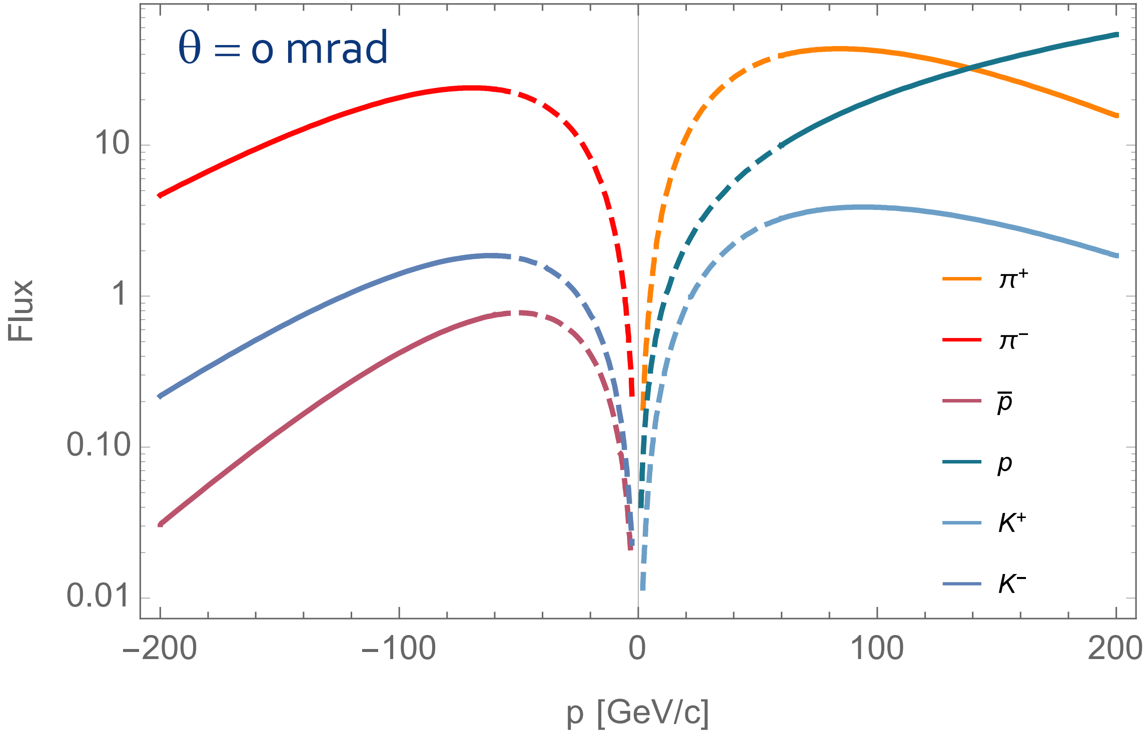
with primary momentum p_o and production angle θ

Flux per solid angle [steradian], per interacting proton, and per dp [GeV/c]



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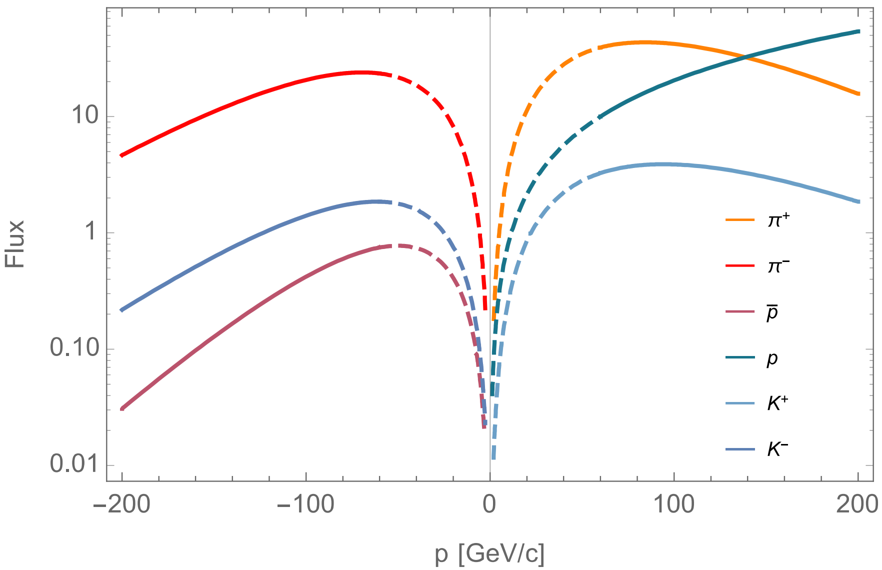
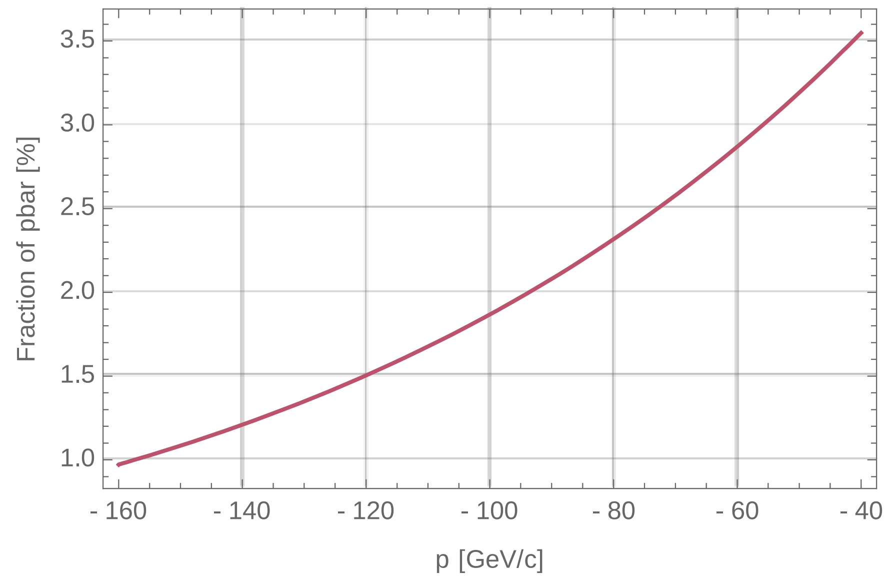
Particle production – pbar case

θ = 0 mrad

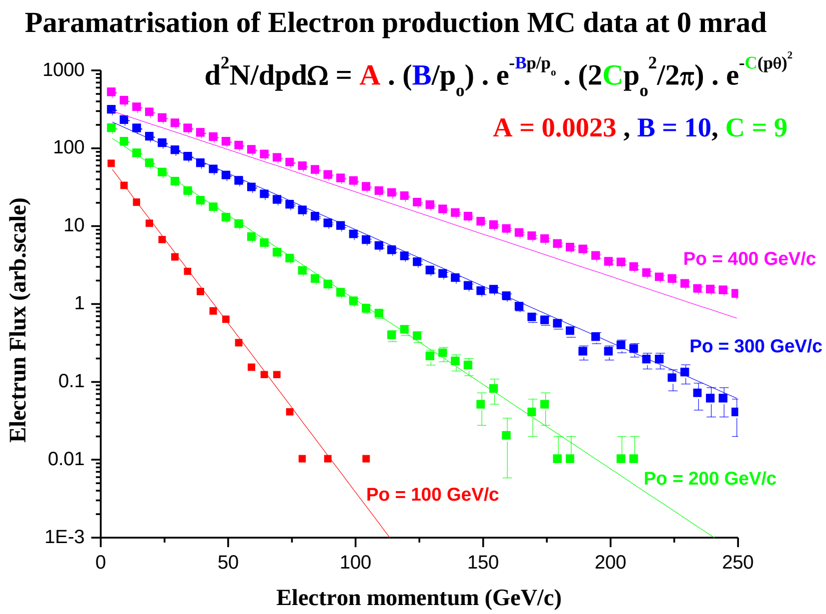




Best case for flux: about 50 GeV/c

- 0.77 pbar / interacting proton / steradian / GeV
- 3.2% of the total negative hadron flux
- Warning: many electrons at low energies!

Electron production



Monte Carlo for e^- production:

- Process $\pi^o = (\pi^+ + \pi^-)/2$, $\pi^o \rightarrow \gamma\gamma$
- $x=E_e/E_\gamma$ with $f(x)=x^2+(1-x)^2+2x(1-x)/3$

Extrapolation from West Area experience:

- e^- about 8% of beam at -120 GeV/c (θ = 0 mrad)

Possible reduction:

- Thin Pb sheet
- Drawback: affects parallelism at CEDARs

M2:

Momentum [GeV/c]	e^- fraction [%]
50	30
100	8
200	0.7

Beam composition

Example: p = -100 GeV/c (Kaons and electrons at similar fractions)

Particle type	Fraction at T6	Fraction at COMPASS
pbar	1.7 %	2.1 %
K^-	5.8 %	1.6 %
π^-	84.5 %	86.3 %
e^-	8.0 %	10.0 %

- Present M2 hadron beam: ≤ 2 10^6 pbar due to 10^8 / 10 s spill limit on total beam flux for RP
- Drell-Yan configuration: < 10^7 pbar (for 5 10^8 total flux)

Enrichment of particle species – I

Differential absorption:

- Beam through filter

- Enrichment = single particle attenuation a_i over total beam attenuation

$$a'_i = \frac{a_i\, e^{-L/\lambda_i}}{\sum_i a_i\, e^{-L/\lambda_i}}$$

Example: +300 GeV/c beam filtered with 3m polyethylene

- Initial flux 5 10^8 particles

Particles	% initial beam	% filtered beam	Flux
Protons	92.5	73.4	7.9 10^6
Pions	5.8	19.1	2.1 10^6
Kaons	1.7	7.5	8 10^5

- Drawbacks:
  - Small suppression factor for unwanted particles
  - Big losses with low efficiency

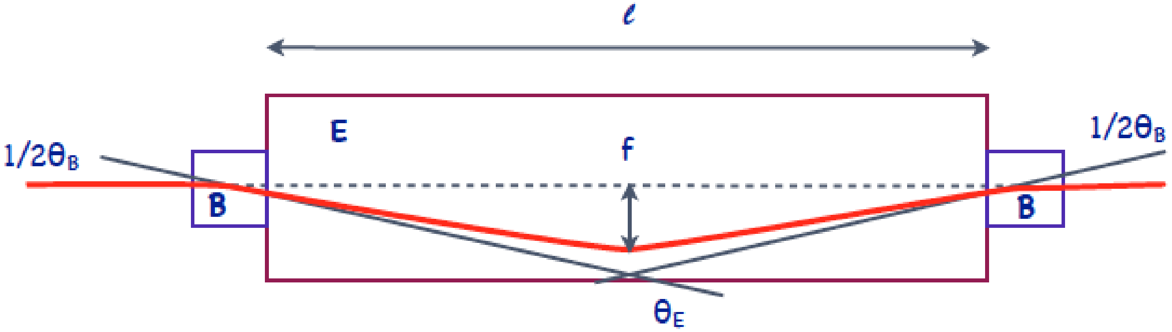
Enrichment of particle species – II

Electrostatic separation:

- Beam traverses electric field coupled to magnetic fields at the ends

$$\frac{\mathrm{d}^2 x}{\mathrm{d}s^2} = 0$$

$$\frac{\mathrm{d}^2 y}{\mathrm{d}s^2} = \frac{e}{p}\left(\frac{E}{v} - B\right)$$



- Separation for particle species 1 and species 2

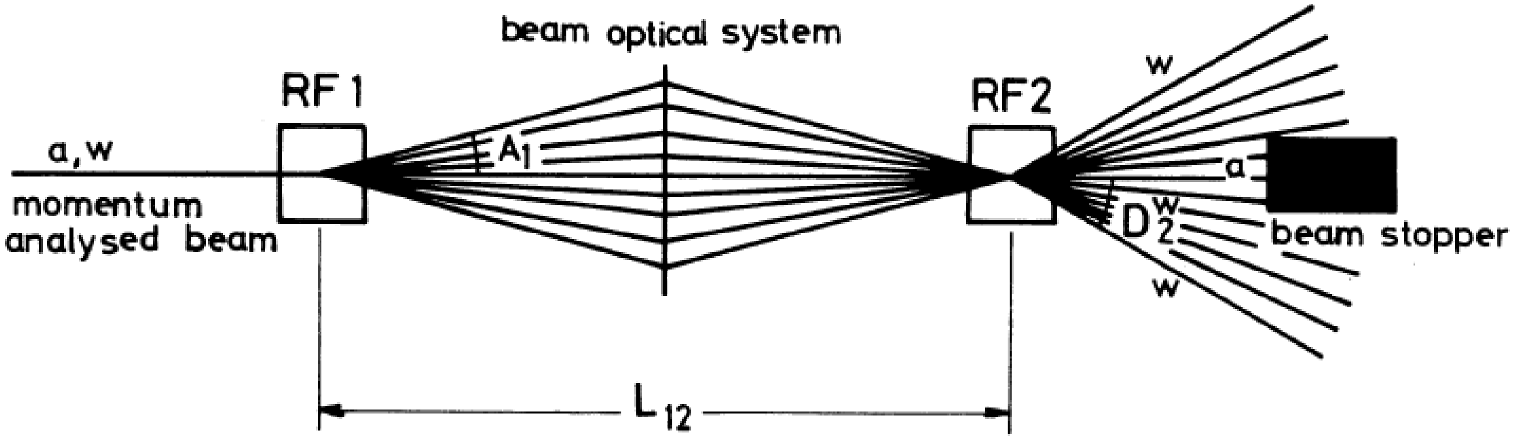
$$\Delta y = \frac{E\,c^2}{2\,p^3}\left(\frac{l^2}{2} + l\,L\right)\cdot\left(m_1^2 - m_2^2\right)$$

- Unwanted particles dumped on collimators
- Drawbacks:
  - Separation only for very low momenta
  - Chromatic aberrations

RF-separated beams

Note: Preliminary considerations, guided by initial studies for P326 and CKM studies by J.Doornbos/TRIUMF

Panofsky-Schnell-System with two cavities (CERN 68-29):



- Particle species have same momenta but different velocities
- Time-dependent transverse kick by RF cavities in dipole mode
- RF1 kick compensated or amplified by RF2
- Selection of particle species by selection of phase difference

  $\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$

How to choose phases?

$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$

For large momenta: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p^2}$

For $K^{\pm}$ beams: $\Delta\Phi_{\pi p} = 360^o$ and Φ_{RF2} such that both π and p go straight i.e. dumped

$\Delta\Phi_{pK} = 94^o$, i.e. a good fraction of K outside the dump, depending on phase at 1st cavity

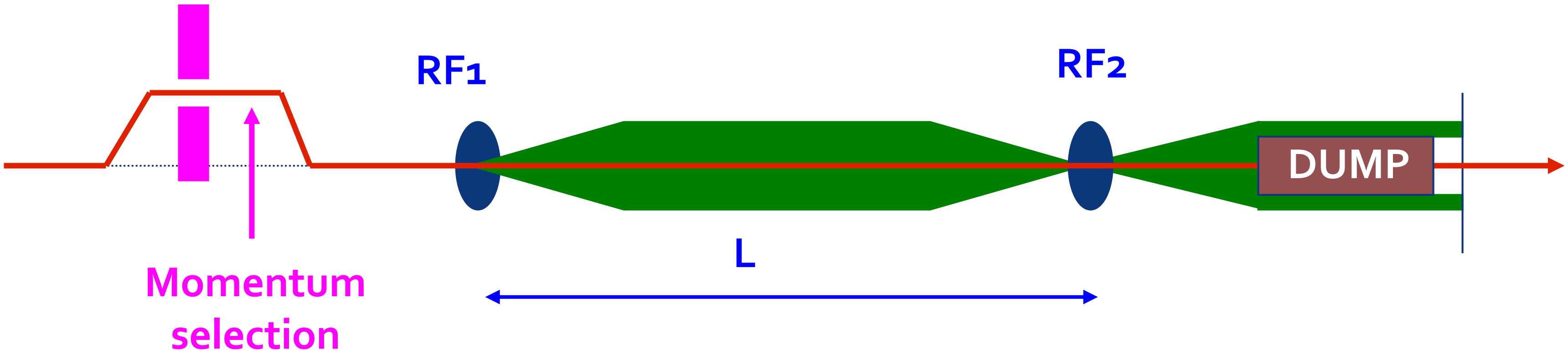
For pbar beams: $\Delta\Phi_{\pi p} = 180^o$ and then $\Delta\Phi_{pe} = 184^o$, $\Delta\Phi_{pK} = 133^o$ with phase of RF2 such that pions go straight, antiprotons get reasonable deflection, electrons are dumped effectively and K reduced

Note: pbar may arrive at any phase w.r.t. the RF signal $\rightarrow$ **Losses!**

Example

$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$

For large momenta: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p}^2$



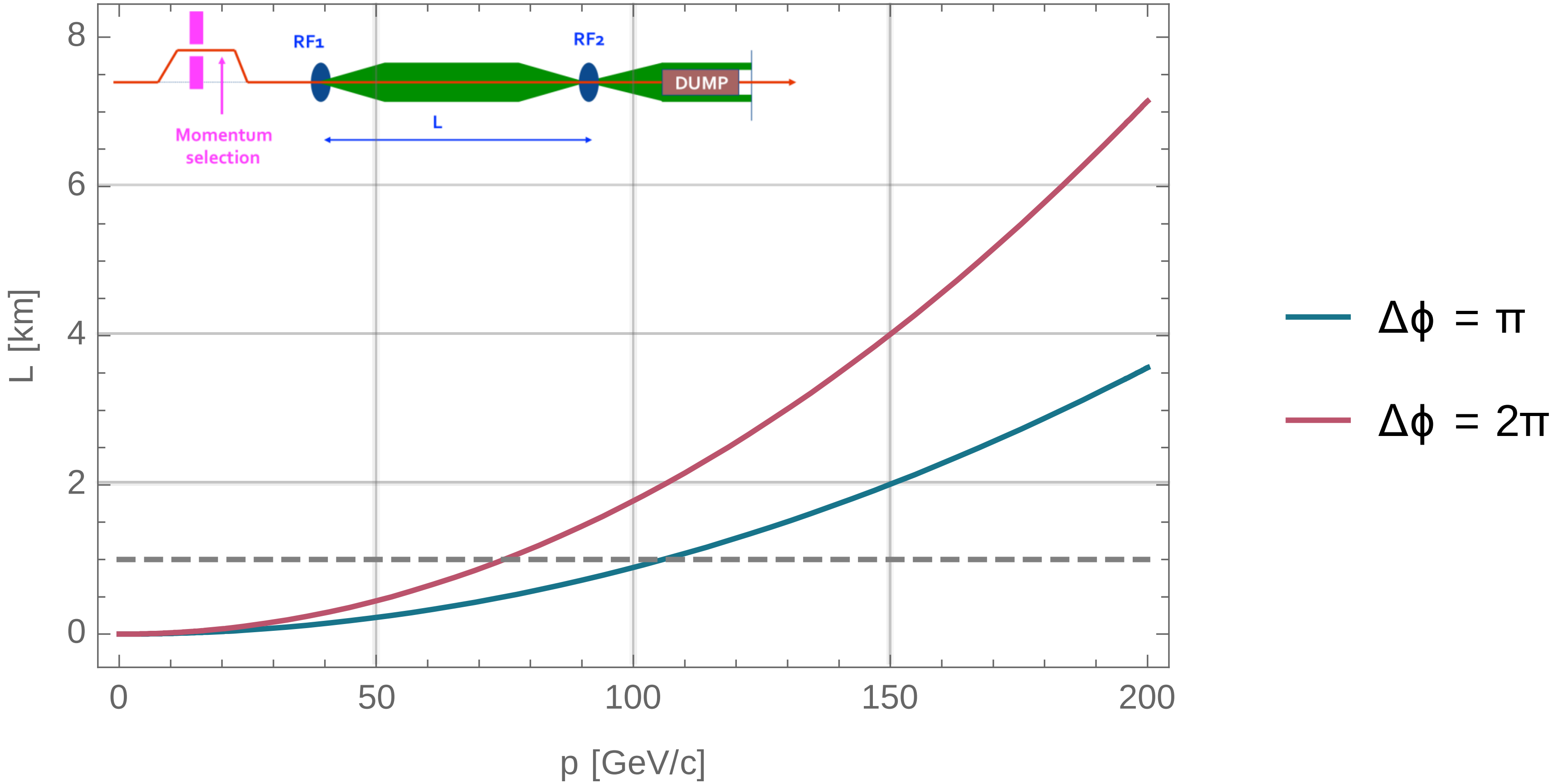
Use input from CKM studies

- Kick: 15 MeV/c
- f = 3.9 GHz
- dp/p = 2%
- $\Delta\phi_{\pi p} = \pi$ (pbar selection) / $\Delta\phi_{\pi p} = 2\pi$ (K selection)

Example

$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$

For large momenta: $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2\mathbf{p}^2$



Example

$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$

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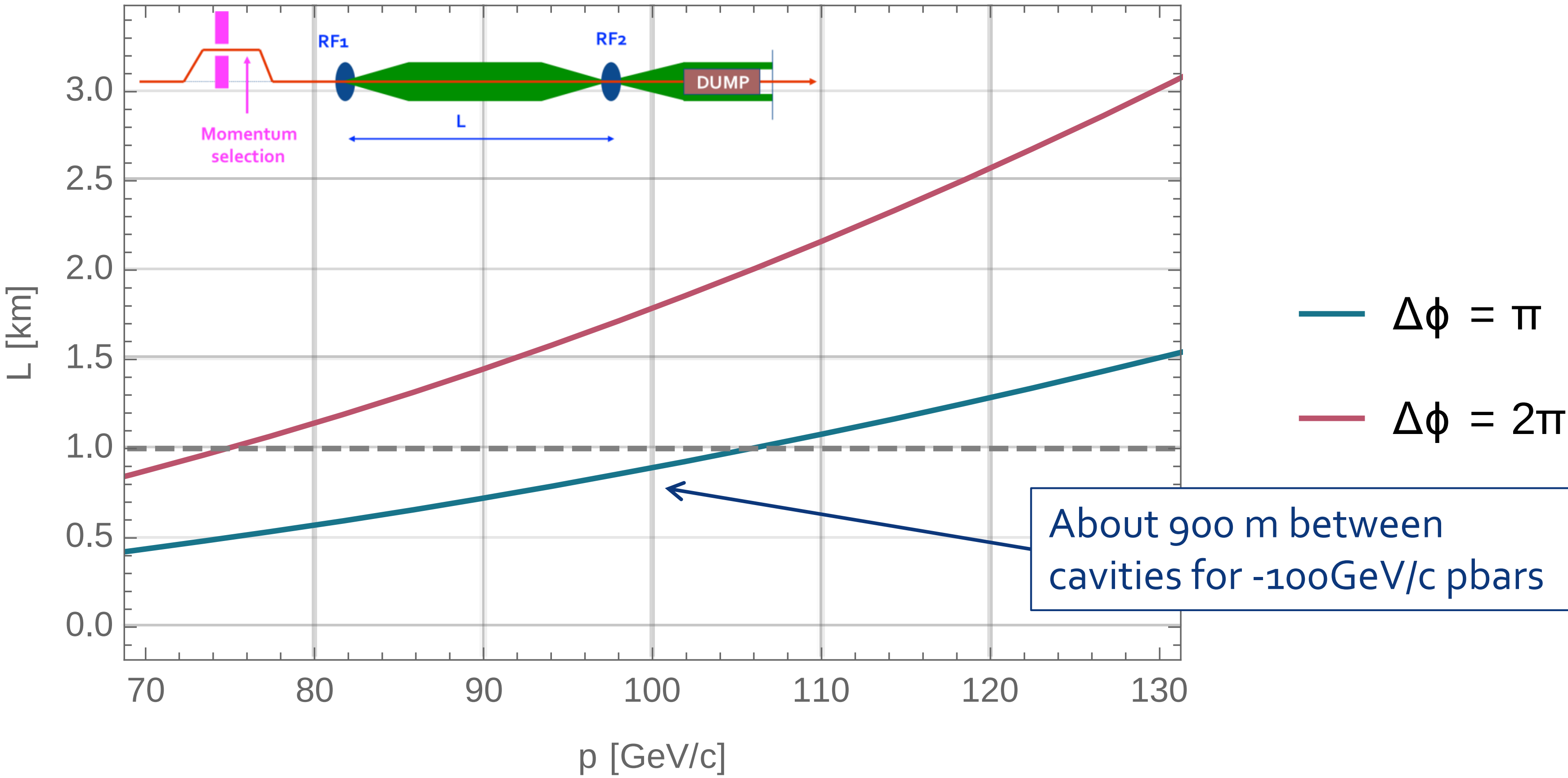
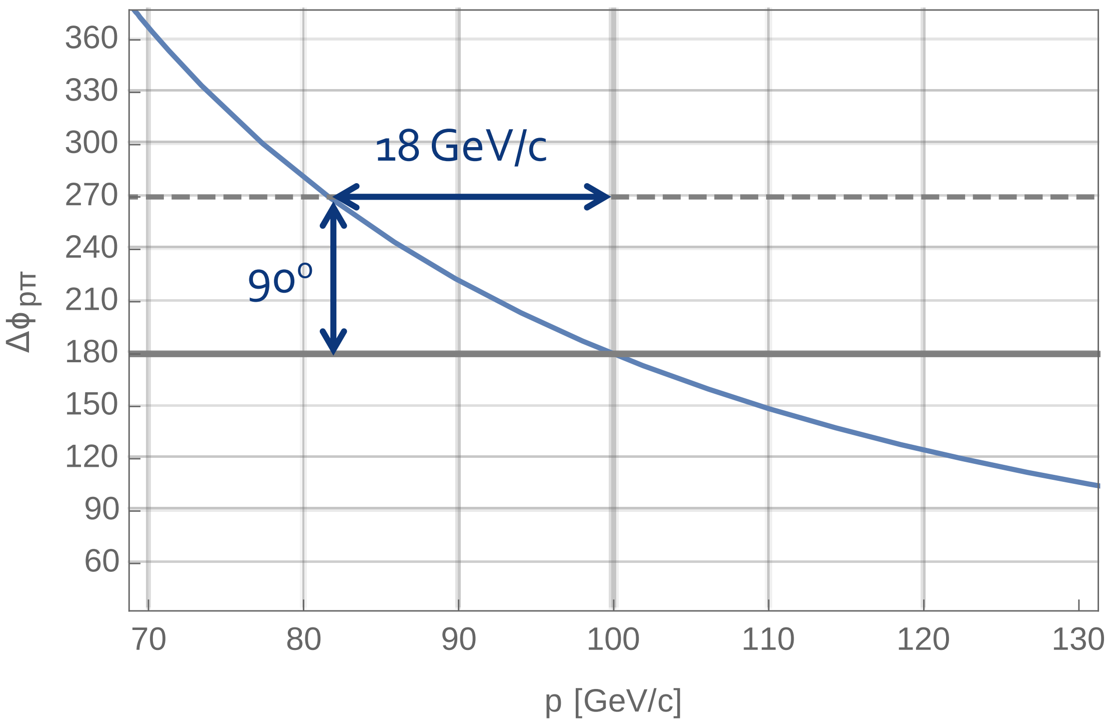


About 900 m between cavities for -100GeV/c pbars

Example

- Phase shift depends on square momentum: Separation only over very limited momentum range for one particle species
- Dispersion: $\Delta\Phi_{final} = \Delta\Phi_{initial}\,(1 - 2\,\Delta p/p)$
- Limits $\Delta p/p$ to about 1 %



Coherence length of cavity

Another example: $f = 3.9$ GHz

- RF wavelength $\lambda = c/f = 3\ 10^{10}\ \text{cm s}^{-1} / 3.9\ 10^{9}\ \text{s}^{-1} = 7.5$ cm
- Coherence length (“phase is sufficiently preserved”, $\Delta\phi \approx \pi/10$)

$$L_{coh} \approx \lambda \cdot (\pi/10) / (2\pi) \approx 4 \text{ mm}$$

$\longrightarrow$ Beam spot has to remain within $\pm$1.5 mm throughout the cavity

- p_t-kick 15 MeV/c (see CKM system), i.e. 0.15 mrad at 100 GeV
- Beam divergence must be smaller than this in the bending plane
- Non-bending plane: sufficiently small divergence, e.g. $\pm$ 0.5 mrad
- Conclusion: RF system limits transverse emittance

Acceptance values

Note: rough estimate, based on extrapolation from J.Doornbos

	CKM K^+ beam	pbar beam
Beam momentum [GeV/c]	60	100
Momentum spread [%]	±2	±1
Angular emittance H, V [mrad]	±3.5, ±2.5	±3.5, ±2.5
Solid angle [μsterad]	10-12 π	10-12 π
% wanted particles lost on stopper	37	20

Estimation by Lau: As the pbar kick is more favorable than for K^+, assume that 80% of p bar pass beyond the beam stopper

→ Acceptance 10π μsterad, 2 GeV/c

Summary of exercise for p = -100 GeV/c

- Atherton parameterisation: 0.42 pbar / int.proton / GeV / steradian
- Solid angle $\pi \cdot 10^{-5}$
- Assume target efficiency of 40% and 10^{13} ppp on target
- Assume 80% wanted particles pass dump
- Assume 2% momentum bite

Particle flux: $0.4 \cdot 10^{13} \cdot 0.42 \cdot \pi \cdot 10^{-5} \cdot 2 \cdot 0.8$ pbar = **$8\ 10^7$ pbar/pulse**

- Note: e^- and π are well filtered, but K^+ only partly
- For RP limit of 10^8 on total flux, max antiproton flux limited by purity (probably about 50%), hence **$5\ 10^7$ pbar per pulse**
- K^+ flux: reduced by factor 1.6 / 2.1 ~0.75 (see before)

Summary

http://pbc.web.cern.ch/

RF-separated beams

- Increase the beam content of wanted particles
- Reduce the required overall beam intensity (less radiation)

Complex and detailed study needed in the framework of "Physics Beyond Colliders" – Conventional Beams WG

- Examples: refine principle (3 cavity design?), optics, technology survey (RF, CRG, …), radiation protection, expected purity, muon backgrounds, beam instrumentation / particle ID, integration in existing tunnel, etc.
- Work will be organised within the CBWG – EHN2 subgroup

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Thank you!