Crystal experiment at CERN

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on behalf of SELDOM team

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UniGe, Genova

Outline

Fixed target experiment with bent crystals at CERN to measure EDM/MDM of charmed baryons

- Physics motivation
- Detector layout and schedule

- Beyond dipole moments:
  J/ψ photoproduction case

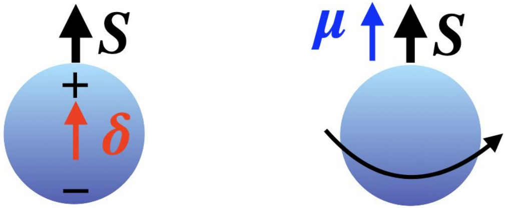
Physics Motivations

Dipole moments

$\boldsymbol{\delta}$ = Electric Dipole Moment (**EDM**)

$\boldsymbol{\mu}$ = Magnetic Dipole Moment (**MDM**)

$$\boldsymbol{\delta} = d\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar} \qquad \boldsymbol{\mu} = g\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar}$$



Hamiltonian:

$$H = -\boldsymbol{\mu}\cdot\boldsymbol{B} - \boldsymbol{\delta}\cdot\boldsymbol{E}$$

Under T, P

$$d\mu_N\boldsymbol{S}\cdot\boldsymbol{E} \xrightarrow{T,P} -d\mu_N\boldsymbol{S}\cdot\boldsymbol{E}$$

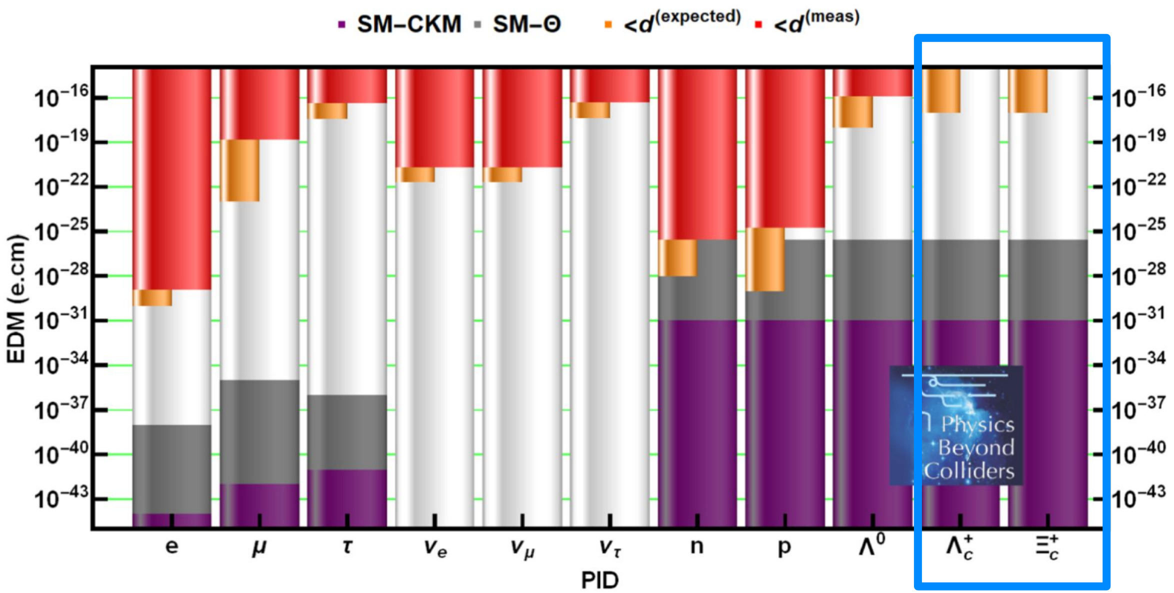
	C	P	T
$\boldsymbol{\mu}$	−	+	−
$\boldsymbol{\delta}$	−	+	−
$\boldsymbol{E}$	−	−	+
$\boldsymbol{B}$	−	+	−
$\boldsymbol{S}$	+	+	−

EDM violates T and P ⇒ via CPT, it violates CP

EDM ≠ 0 ⇒ **source of CPV beyond SM**

EDM of charm hadrons

Space for BSM discovery



J. Phys. G: Nucl. Part. Phys. **47** (2020) 010501

$$\Lambda_c^+ = [ud]c \qquad \Xi_c^+ = [us]c$$

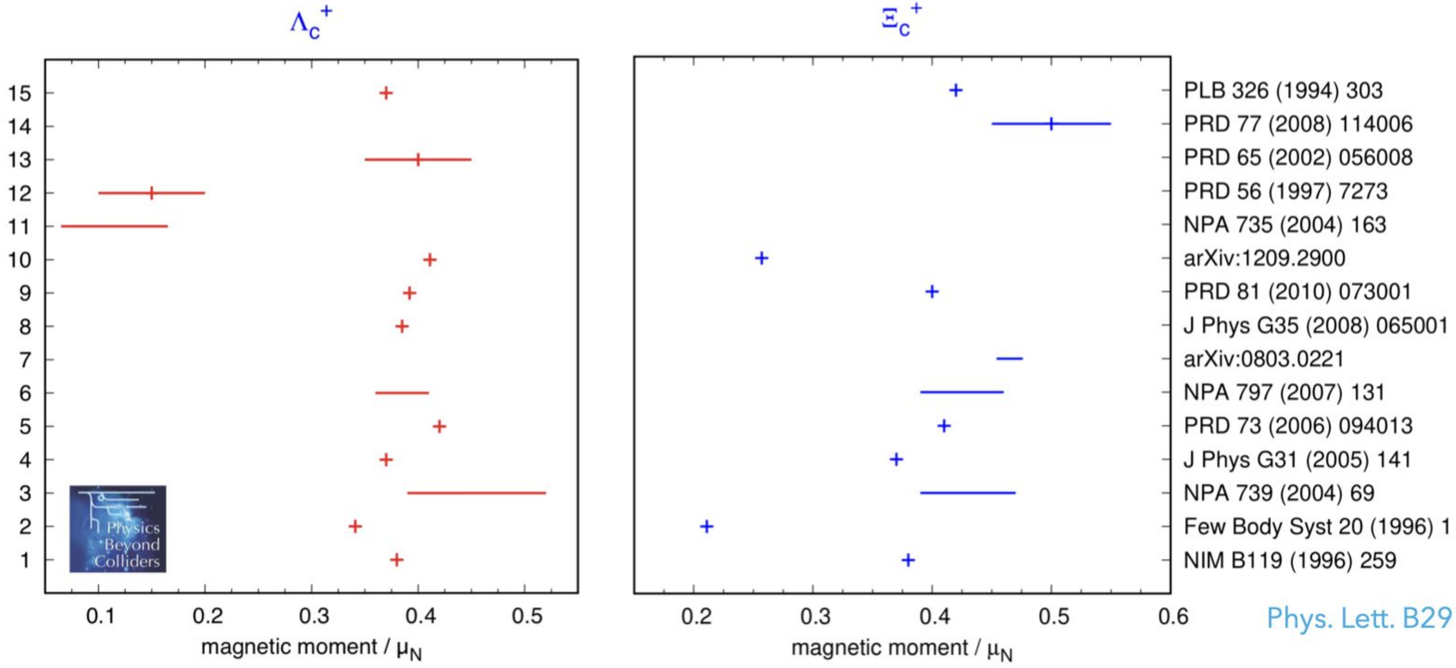
Charm baryons EDM not measured yet

- Short lifetime: $\tau \sim 10^{-13}$ s
  $c\tau \approx 100\ \mu m$
- Decay length
  $\gamma \approx 500 \quad \gamma c\tau \approx 5\ \mathrm{cm}$

EDM/MDM = measure precession in high intensity field

MDM

The measurement of the baryon MDM provides experimental anchor points for low energy models of **strong interactions**

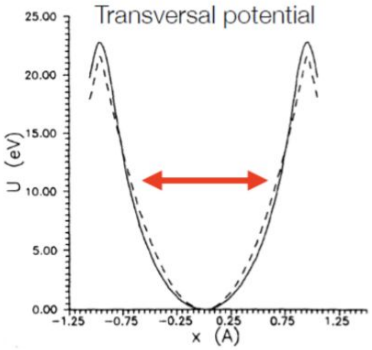


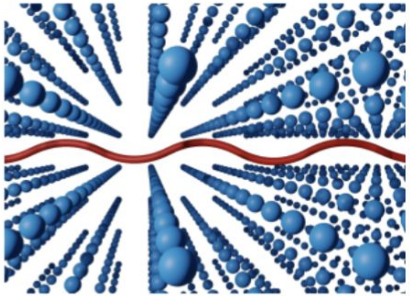
Phys. Lett. B291 (1992) 293

Channeling in bent crystals

For positive charged particles, bent crystals can be used to:

Steer particles at a given angle
(within ~μrad acceptance)

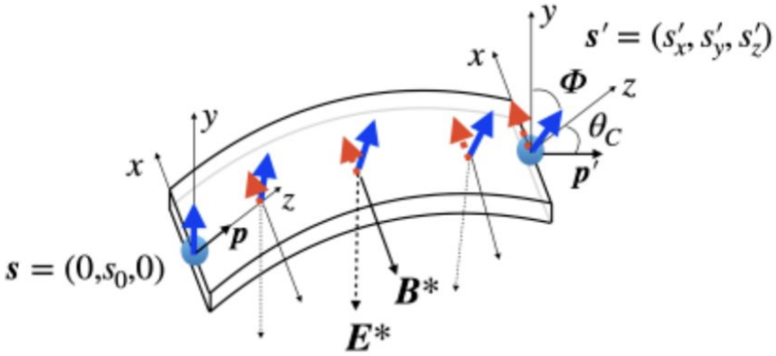




Electric field: $E \approx 1\mathrm{GV/cm}$

Effective magnetic field: $B \approx 500\,\mathrm{T}$

Induce **spin precession** in short distance

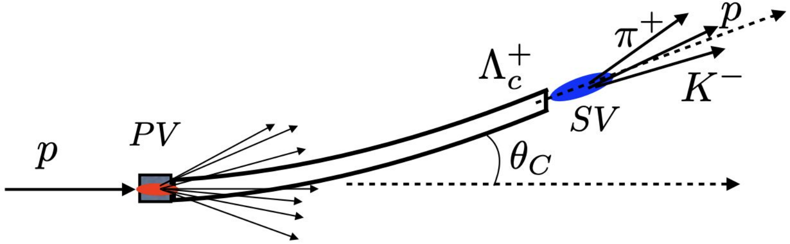


$$\Phi \approx \frac{g-2}{2}\gamma\theta_c \qquad s'_x \approx s_0\frac{d}{g-2}$$

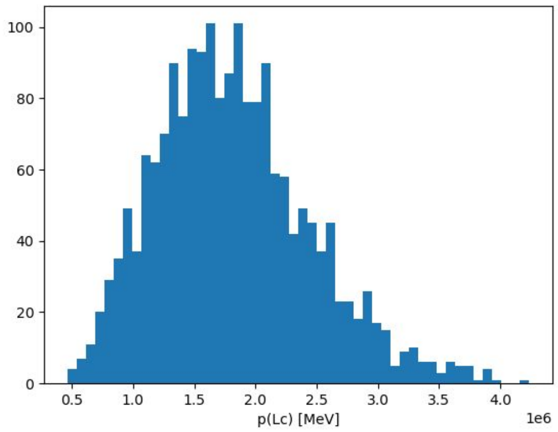
$$\gamma \approx 500 \qquad \theta_c \approx 10\,\mathrm{mrad}$$

Λ_c^+ signal topology

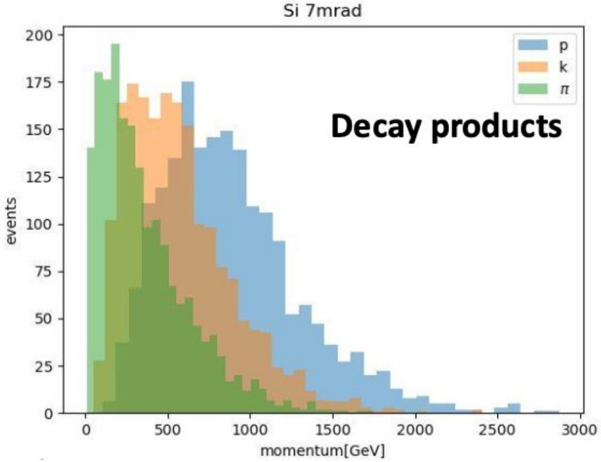
Average momentum of 1 TeV for channeled Λ_c^+ baryons for bending angle θ_C = 7 mrad



Momentum of Λ_c^+ baryons



Momentum of daughter particles



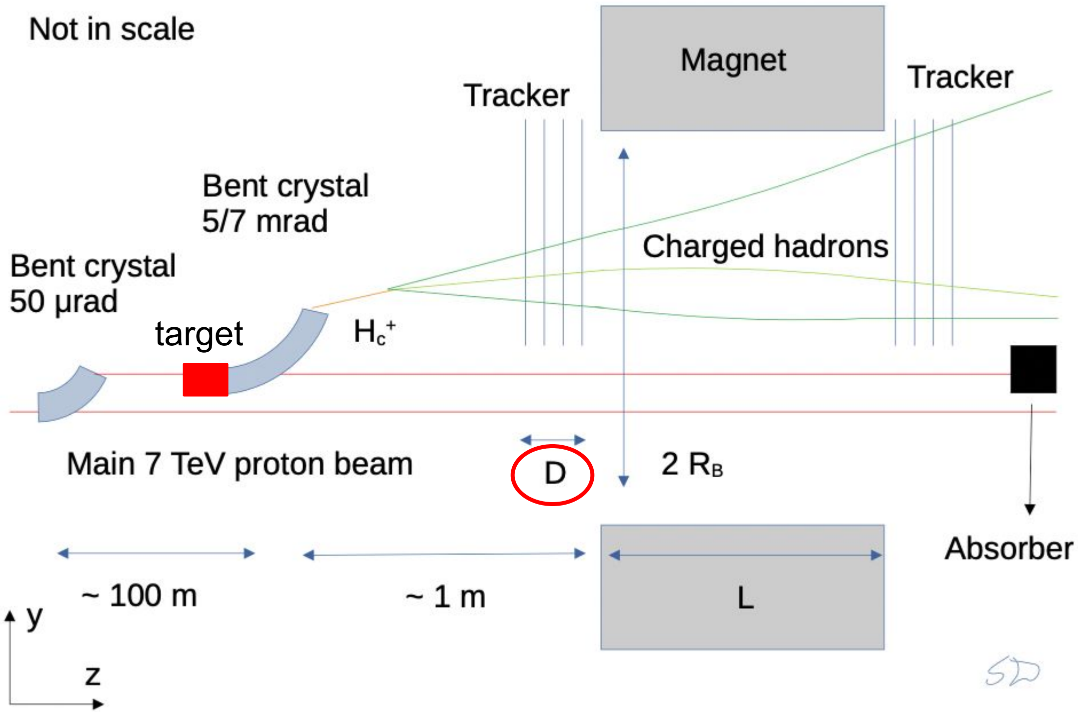
Fixed-target experiment layout

First bent crystal for secondary beam

Second bent crystal channeling charm hadrons (7 mrad of bending)

Target: W, 2cm

$\Lambda_c \rightarrow pK\pi$ is reconstructed thanks to a **spectrometer** composed by warm/permanent magnet + tracking stations



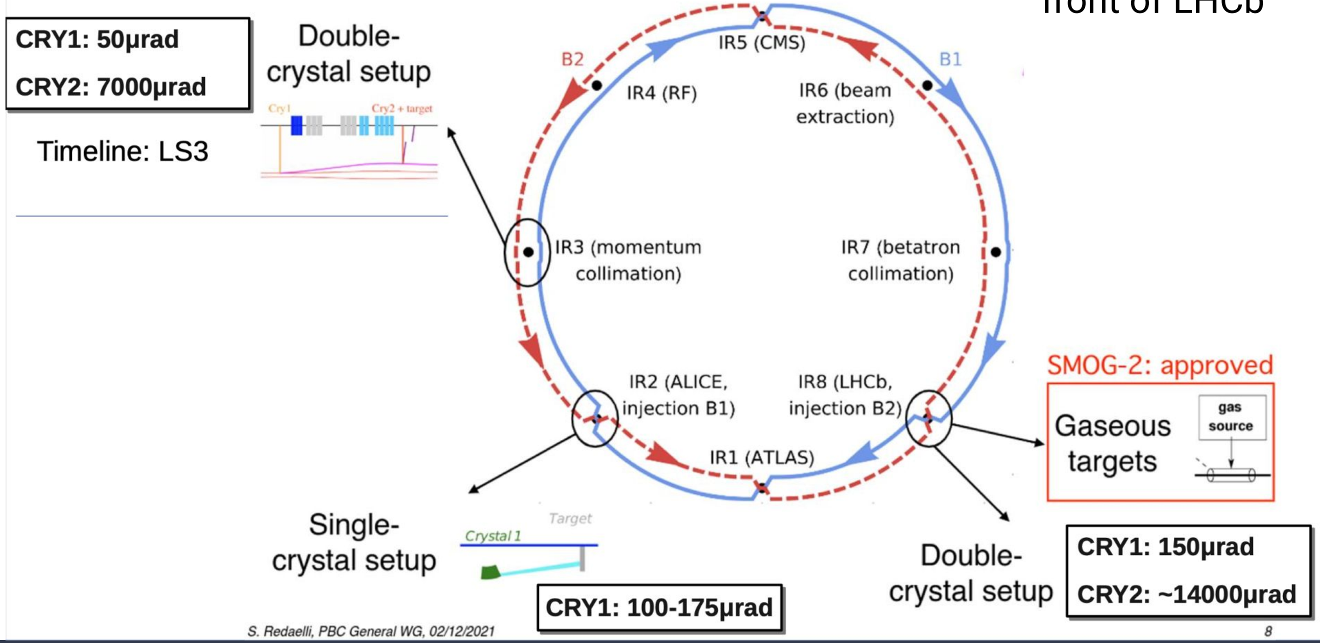
Location of double-crystal setup

IR3 scenario

build a new experiment at IR3

LHCb scenario

place the fixed-target & crystal in front of LHCb



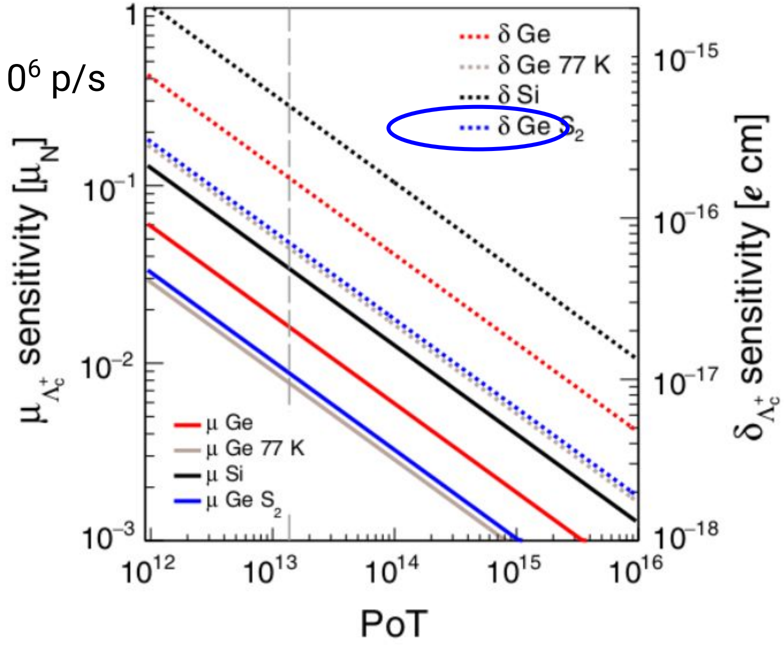
Sensitivity to EDM/MDM

2cm W target,
2 years, with a proton flux of 10^6 p/s
→ 1.37×10^{13} PoT

LHCb

EDM precision
= 2×10^{-16} e cm

MDM precision
= 4%



@IR3

EDM precision
= 7×10^{-17} e cm

MDM precision
= 2%

Dedicated experiment better than LHCb scenario by factor 2

+ higher flux ⇒ higher PoT &/or reduced data-taking time

IR3 experiment' schedule

Run 3
2025

Phase 0: "Proof-of-Principle" (PoP) experiment

- **asked for by LHCb & approved by LMC** (LHC Machine Committee)
- To measure channeling at TeV energies scale

⇒ if successful

Run 4
2029

Phase 1:
setup to perform first physics measurements:

- Charm baryons EDM/MDM with O(10^{13} PoT), τ EDM & other physics opportunities?

beyond

Phase 2:
setup to ultimate the physics measurements:

- EDM/MDM measurements with full sensitivity

MoU has been signed by CERN and contributing institutes;

Collaboration for future experiment will soon be formed & Letter of Intent is in preparation

Other physics opportunities

Proposal of studying vector-meson photoproduction:

- very forward fixed-target (Pb target) experiment with $\eta>5$ can result in high cross-sections
- complementary to existing experiments → independent measurements

⇒ Main topic of the following

Study **charm production** cross section at very small angle

- complementary kinematics with respect to SMOG2

From F. Martinez-Vidal at PBC-QCD link

Kinematic variable	> 15 mrad (~SMOG2)	Ge 293K 16 mrad 10 cm
Momentum (GeV)	< 500	>800
Transverse momentum	> 0.5	< 1
Pseudorapidity*	-4 to 0, central & backward	1 to 3.5, very forward
Momentum transfer Q	20 to 115	≈ 4
Bjorken-x	Down to ≈ $10^{-3.5}$	Down to ≈ 10^{-3}
Feyman-x	Large negative	Large positive

Detector layout

Spectrometer for IR3

Magnet

- orbit correction dipole magnets at IR3

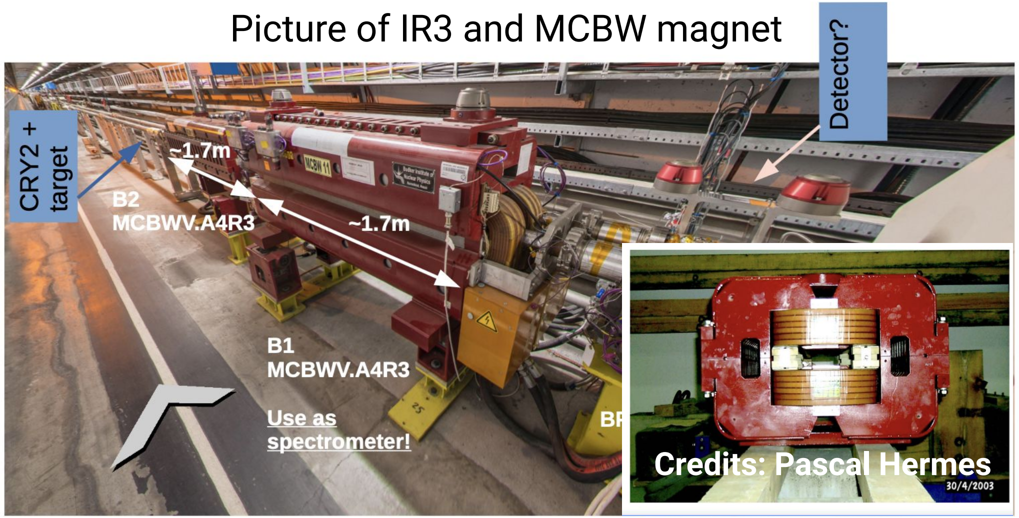
Magnet	L [m]	B [T]
MBW	3.4	1.4
MCBW	1.7	1.1

Tracking stations

- Tiles of **VELOPix**: TDR
  55x55 μm^2 pixel,
  pixel hit rate 600 MHz/cm^2, 12 μm hit resolution

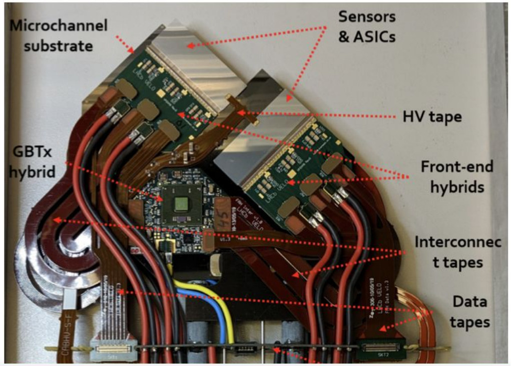
- **Roman Pots**: ALFA Roman Pots

Picture of IR3 and MCBW magnet

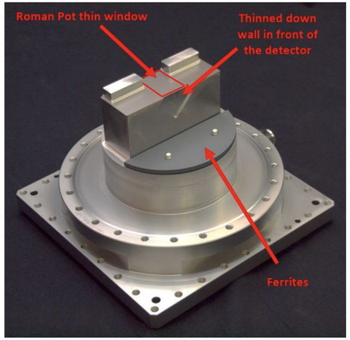


https://edms.cern.ch/panoramas/viewer?fov=90.00&id=36409858&lat=-27.06&lon=241.01

VELO module



ALFA Roman Pot



Simulations

Based on DD4hep: gitlab repository IR3Detector

Optimization of the detector design:

- Trackers technology & positions
- Magnet acceptance

Background discrimination

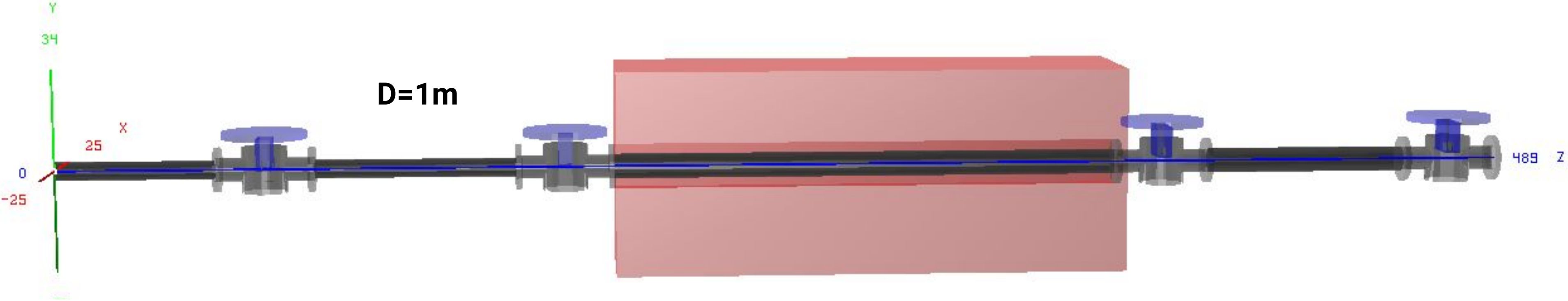
- combinatorial & unchanneled Λ_c
- peaking backgrounds from D^+ and D_s decays ⇒ proposal of a RICH detector

Results

- Proton flux of 10^6p/s (up to 10^7p/s): rate is sustainable by VeloPix chip
- Good acceptance (~50%), further increased with some design modifications
- m(Lc) resolution ~30 MeV

⇒ **Letter of Intent** under preparation

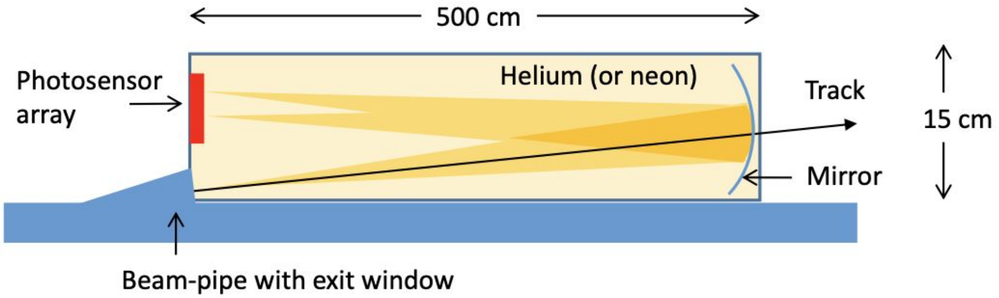
D=1m



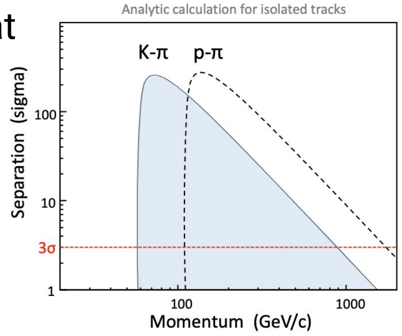
RICH Detector

Proposal by Roger Forty

Proposal of a 5m long radiator filled with He:

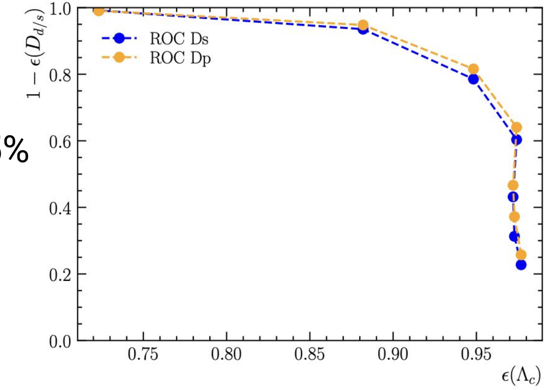


Discrimination at 3σ for p-π up to 1.7 TeV



Resolution of σ = 42 μrad per photon → sub-mm photodetector size: array of SiPM

Background discrimination
→ Lc efficiency of 90% and bkg rejection 95%



⇒ Next:
define the geometry & include into DD4hep

Project is part of ECFA DRD4

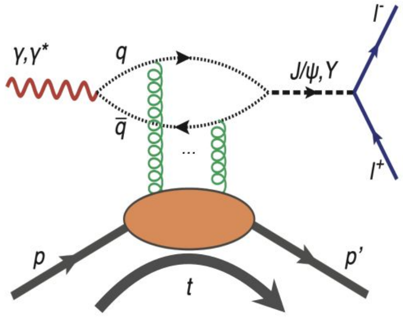
J/ψ photoproduction

Inclusive Vector Meson photoproduction

in collaboration with A. Pilloni

Motivation is to perform feasibility studies for:

- J/ψ photoproduction cross-section at threshold
  → understand role of open-charm thresholds
- search for **pentaquarks in prompt production**
  ⇒ improve upon recent GlueX results (J/ψ yield= 2270)
  [Phys. Rev. C **108**, 025201]



Process characteristics:

- very forward production
- exclusive process: only J/ψ and p
- high cross-section due to high target Z
- high luminosity due to target Z

Our experiment at IR3

⇒ covers a pseudorapidity range from 5 to 8

⇒ hermetic detector

⇒ ~10 nb, calculated with simulations

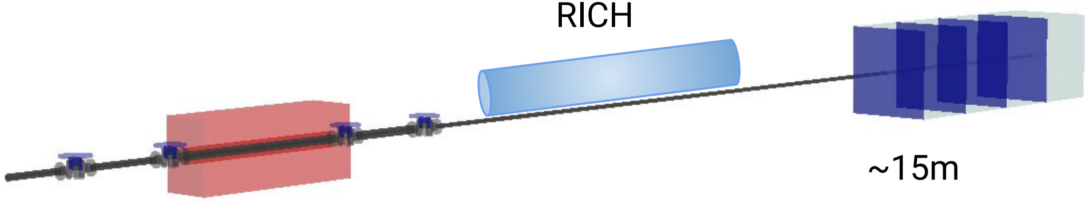
⇒ about 10^{29} cm^2s^{-1} with 10^6p/s & 2 cm W target

J/ψ photoproduction

1. **Cross-section estimates** for pW and PbW at 7 TeV beam energy

   & Resolutions on reconstructed m(J/ψ p)

2. **Detector optimization**
   a. Muon optimization
   b. Exclusive veto



3. **J/ψ acceptance**

4. **Expected yields**

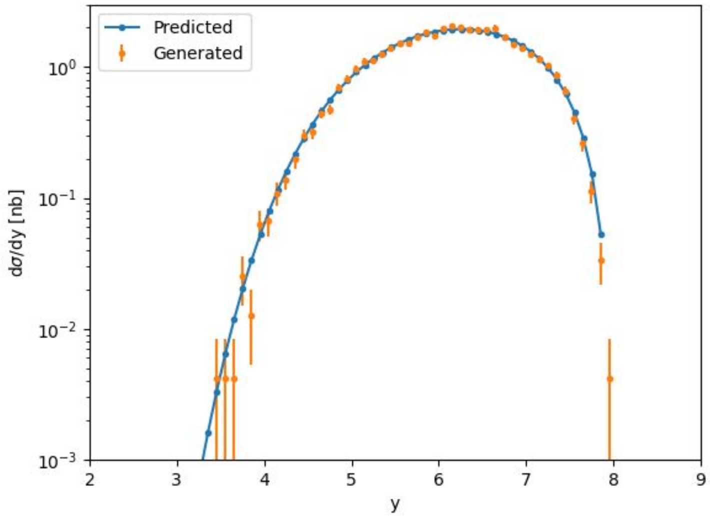
Cross-section estimates

Physics Letters B 805 (2020) 135447

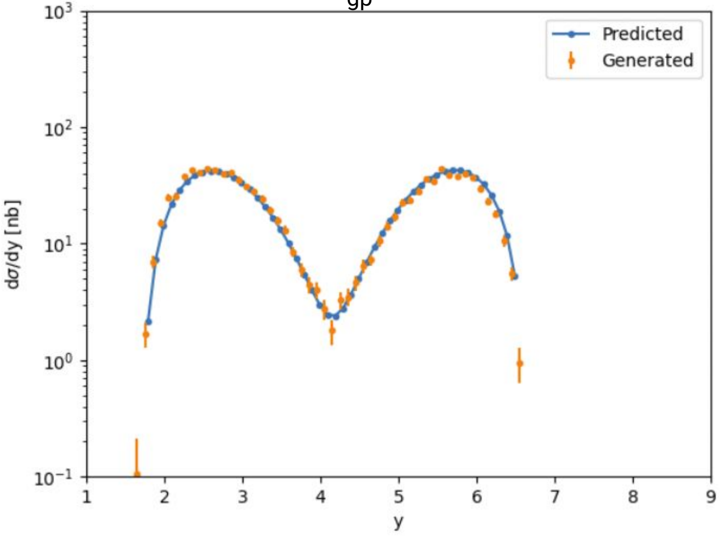
Cross-section estimate with STARLight MC link
1. pW interactions. Beam energy = 7 TeV
2. PbW interactions. Beam energy = 7 TeV x Z

⇒ Dominant process is incoherent photon-p interaction, with photon emitted by target (proportional to Z)

1. **pW: σ= 42 nb,** y in range 3<y<8 with $4.2<W_{gp}<30$ GeV



2. **PbW: σ=1.89 mub,** y in range 2<y<6.5 with $4.2<W_{gp}<50$ GeV



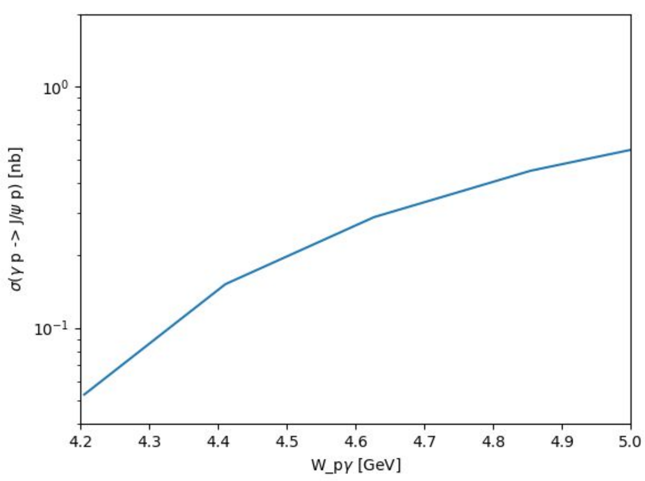
Cross-section estimates

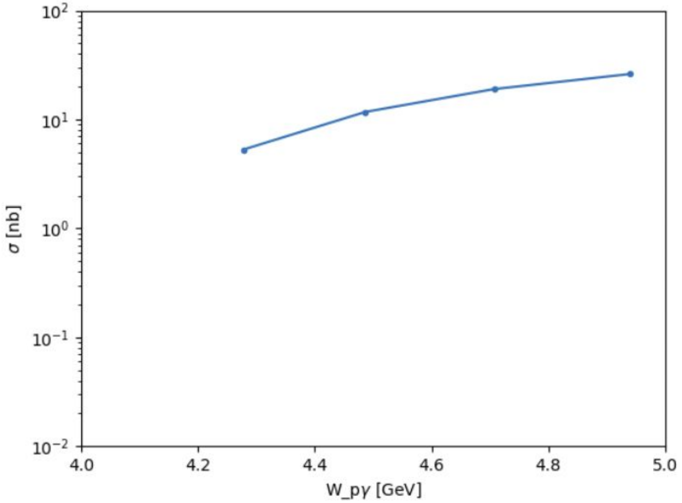
Cross-section estimate with STARLight MC link

1. pW interactions. Beam energy = 7 TeV
2. PbW interactions. Beam energy = 7 TeV x Z

Comparison with GlueX: cross-section in range 4.2<W<4.8 GeV

1. **pW: σ= 0.5 nb**
2. **PbW: σ=72 nb,** y in 2<y<6.5





Photoproduction kinematics

In order to measure the invariant mass resolution, we need to reconstruct:

- two muons → $p_{J/\psi}$ ~ 500 GeV
- deflected proton → θ_p <250 μrad

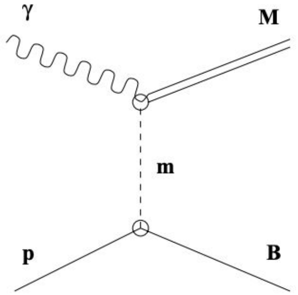
$\theta_{J/\psi p}$

$$m^2(J/\psi p) = m^2_{J/\psi} + m^2_p + 2(E_p E_{J/\psi} - |p_p||p_{J/\psi}|cos(\theta_{J/\psi p}))$$

Proton momentum measurement is not required

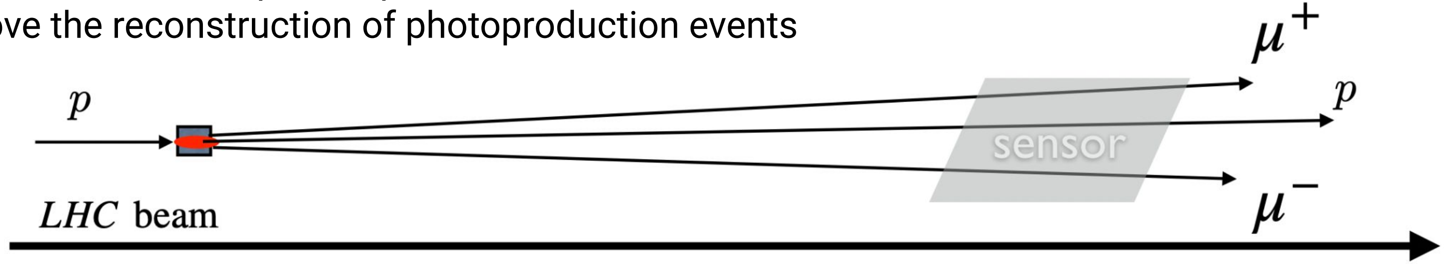
$$p_{p,fin} = p_{p,in} - p_{J/\psi}$$

(under collinear photon approximation)



$p_{p,fin}$

Pixel detector intercepts the proton deflected beam to improve the reconstruction of photoproduction events



Invariant mass resolution

Track angles:
- θ_p <250 μrad
- $\theta_{J/\psi p}$ < 2.5 mrad

⇒ **Resolution**

$$\sigma_\theta \approx \sqrt{2}\sigma_s/D = 14\ \mu\text{rad}$$

with $\sigma_s = 10\mu m,\ D = 1m$

⇒ **Detector**

Pixel stations before magnet:
- Hit reso: $\sigma_s = 55\mu m/\sqrt{12} = 15\mu m$
- Multiple scattering <5 μm

Momentum:
- $<p_{J/psi}>$ ~ 500 GeV

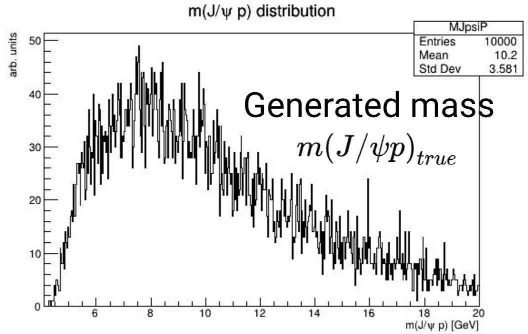
⇒

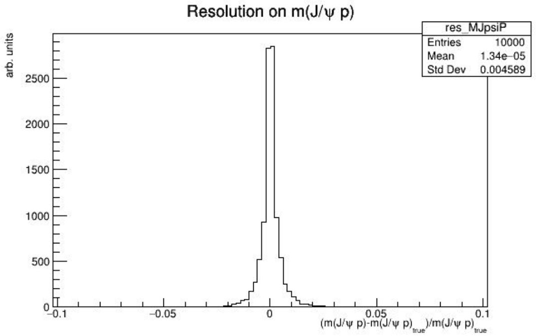
$$\sigma_p/p = \frac{2p}{0.3BLD}\sigma_s = 1.7\%$$

with $BL = 1.9$ Tm

⇒ Trackers + Muon stations

Invariant mass resolution estimated with parametric simulations (smearing mu momenta and mu, p angles)





$$\sigma_{m(J/\psi p)} = \frac{m(J/\psi p) - m(J/\psi p)_{true}}{m(J/\psi p)_{true}}$$

Resolution on P_c mass:

$$\sigma_{m(P_c)} = \sigma \cdot m(P_c) \sim 20MeV$$

Muon detector

Technologies:

- **Si strip detector:** UT sensor of 10x10 cm^2
  - pitch=180µm → σ=180/sqrt(12)= 52µm
- **MWPC: Gas mixture:** Ar:CF4:CO2 [0.6:0.1:0.3], 5mm
  - pad= 20x25mm^2
  - chamber= 48x20 cm^2 ⇒ 24 x 8 pads

⇒ angular reso of 1 mrad

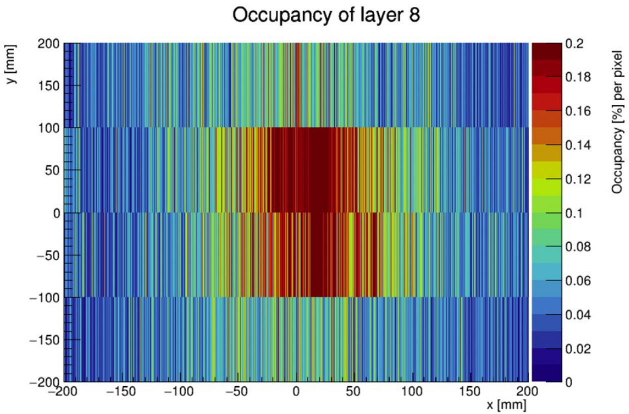
Interleaved with **iron filters,** 90 cm thick (to be optimized)

Possible design solutions investigated:

1. First station of Si strip with area of 40x20cm^2 + 3 stations of MWPC
2. 4 stations of Si, with reduced area (about 20x20 cm^2, 4/5 tracker stations per layer)

Muon stations' occupancy

Silicon strip detectors as UT
pitch: 200 mum
sensor: 10x10 cm^2



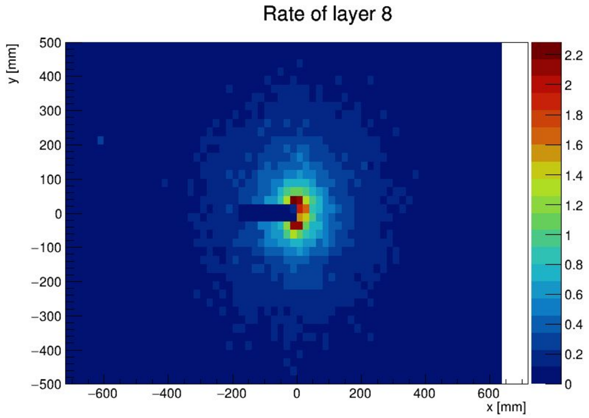
Maximum rate below limits:

- Flux=10^6 p/s ⇒ 36 kHz

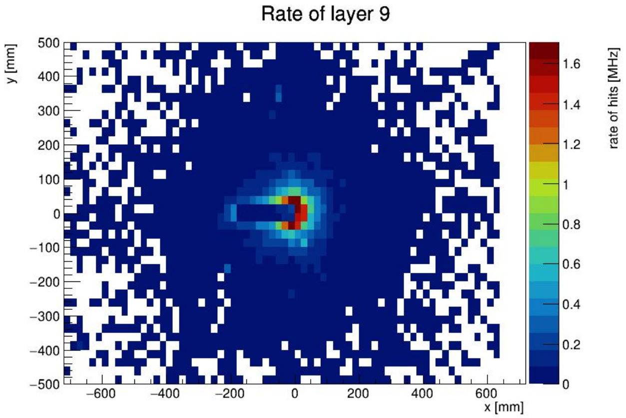
Muon Chamber MWPC
pad= 20x25mm^2
chamber= 48x20 cm^2 ⇒ 24 x 8 pads

⇒ Maximum rate < 1-2 MHz

First station



Second station



⇒ It could be used from second station on with flux 10^6 p/s

⇒ If we want to go to 10^7 p/s, we need to build full Si sensors or optimize the filter length

Veto exclusive events

Tag events which contain only 3 tracks: 1 proton and 2 muons

⇒ Necessary to build an **hermetic detector,** we are investigating:

1) Tracking stations below the beam pipe to enlarge acceptance in the forward region
2) **Scintillator** downstream at a distance of 100m, such as Hershel of LHCb [*JINST* 13 (2018) P04017]

Inelastic interactions: initial proton can interact with target and crystal after being produced

⇒ probability of having inelastic interaction with W and Si

$$P_{inel} = (1 - e^{-z_{target}/\lambda_W}) + (1 - e^{-z_{Cry}/\lambda_{Si}}) = 0.32$$
$$1 - P_{inel} = 0.68$$

⇒ this factor needs to be multiplied by the acceptance efficiency

Simulations

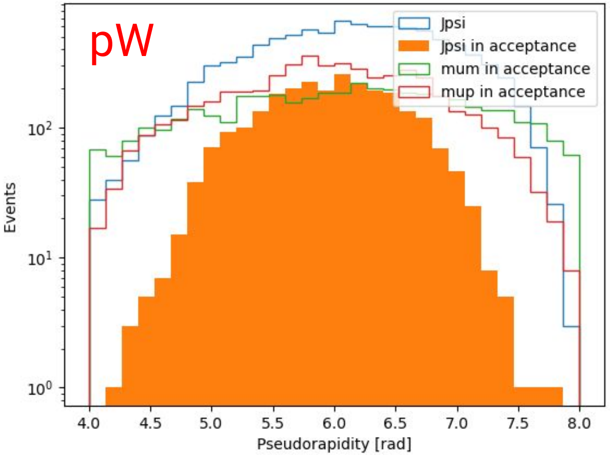
Events: 10000 J/ψ events in DD4hep
Stations geometry:

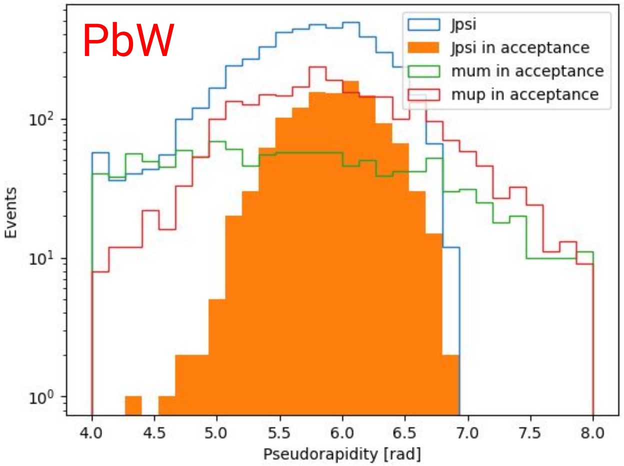
- **Position:** first station at z=15m
- **Outside beam pipe**:
  - 2 beampipes at about 20 cm
  - radius reduced to 2.5 cm

Muon stations

Pseudorapidity coverage:

Very forward acceptance: 4.5<y<7



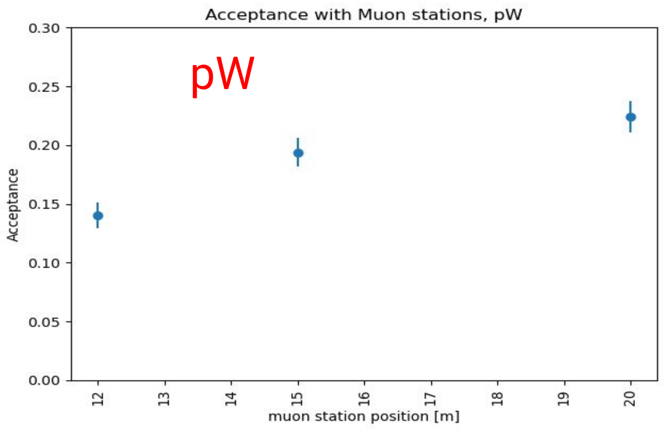


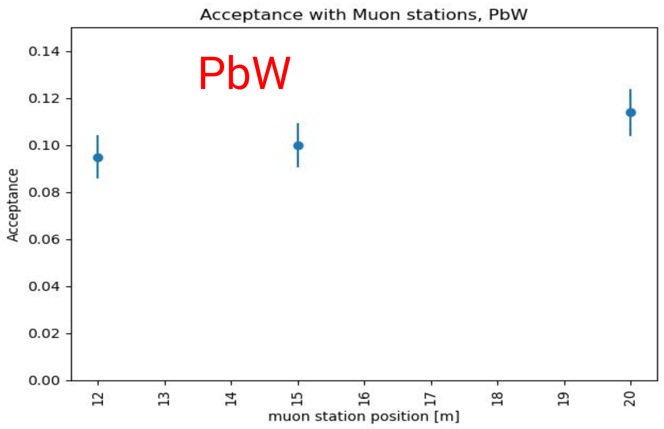
Acceptance

Scenario 1: 1st plane of Si strip ($40x20cm^2$) + MWPC ($1m^2$)

- **Position:** first station at z=12-20m

Acceptance = number of J/ψ reconstructed using tracker stations before magnet and muon stations (at least 6 hits out of 8)





⇒ **Position of 15m** is acceptable:

- pW: 20%
- PbW: 10% ⇒ ~½ pW

⇒ Investigating if it is possible to increase the acceptance:

- by reducing beam pipe radius and/or moving beam pipe down

First estimates of yields

$* \quad \rho = 19.3\ g/cm^3$
$N_A = 6.02 \cdot 10^{23}$
$l = 2\ cm$
$M = 184 g\ /mol$

Luminosity:

$$\mathcal{L} = \theta_{target} \cdot \Phi = 1.26 \cdot 10^{29}\, cm^{-2}\, s^{-1}$$

$$\theta_{target} = \frac{N_A \rho l}{M} \; * \quad \text{and} \quad \Phi = 10^6 p/s$$

Expected data-taking time:

- proton run (/year): 6.85×10^6 s
- Pb run (~1 week): 6×10^5 s

Integrated L:

$\int \mathcal{L} = 0.89\ pb^{-1}$

$\int \mathcal{L} = 0.076\ pb^{-1}$

Estimated yield	**σ [nb]**	**Flux**	**Int L [pb^{-1}]**	**ε**	**Yield x ε**
pW, J/ψ	42	10^6 p/s	0.89	0.136	5'000/year
PbW, J/ψ	1890	10^6 p/s	0.076	0.075	10’800/week
pW, J/ψ W<4.8GeV	0.5	**10^7 p/s**	8.9	0.136	600/year
PbW, J/ψ W<4.8GeV	72	10^6 p/s	0.076	0.075	400/week 800/year

Results:

- High yields of J/ψ for σ measurement
- Yields limited by acceptance → optimization is ongoing
- Pentaquark search with 10^7 protons/s in pW and 10^6p/s in PbW: ~2800 events in 2 years

Conclusions

First fixed-target experiment with bent crystals at LHC to measure EMDM of charm baryons

- Main physics program is on EMDM of charmed baryons and τ lepton
- Phase-0 already approved by LMC and planned for 2025

Extending the physics case to J/ψ photoproduction:

- J/ψ cross-section measurements in wide W range and pentaquark search, with p and Pb beams
  - P_c search would be more promising if detector acceptance can be increased → under investigation
  - good invariant mass resolution, ~20 MeV, can be achieved
- Paper in collaboration with A. Pilloni is under preparation

Thank you for the attention!

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- L. Burmistrov, G. Calderini, Yu Ivanov, L. Massacrier, P. Robbe, W. Scandale, A. Stocchi, *Measurement of short living baryon magnetic moment using bent crystals at SPS and LHC*, CERN-SPSC-2016-030 ; SPSC-EOI-012.

For Leptons:

- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, J. Ruiz Vidal, *Novel method for the direct measurement of the τ lepton dipole moments,* Phys. Rev. Lett. 123, 011801 (2019)
- A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, J. High Energ. Phys. (2019) 2019: 156.

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Photoproduction:

- **Exclusive vector meson photoproduction in fixed-target collisions at the LHC, V. P. Gonçalves, M. M. Jaime,** Eur. Phys. J. C (2018) 78:693, https://doi.org/10.1140/epjc/s10052-018-6185-2

- **Photoproduction of pentaquark states at the LHC, V. P. Gonçalves, M. M. Jaime,** Physics Letters B Volume 805, 10 June 2020, 135447

Backup slides

A bit of history

2016

MDM proposal: using bent crystals at SPS and LHC, *by Stocchi et al*
CERN-SPSC-2016-030

Initial EDM proposal: Measurement of charm baryon EDMMs from spin precession in bent crystal **using LHCb detector**
Eur. Phys. J. C 77, 181 (2017)

2017

Charm baryon MDM with bent crystals at LHCb *by Fomin etal*
JHEP**1708**(2017)120

Dec 2017

Update: Proposal for 2 experimental scenarios: **LHCb vs dedicated experiment**
Eur. Phys. J. C 77, 828 (2017)

2018

Test of bent crystal prototypes at SPS H8

2019

Feasibility studies of fixed-target layouts at different LHC points *by Mirarchi et al*
EPJC 80, 929 (2020)

2020

Double bent crystal setup proof-of-principle at CERN SPS *by Scandale et al.*
Nucl. Instrum. Meth. A 1015 165747 (2021)

2021

Progress towards the first measurement of charm baryon dipole moments *by Aiola et al*
Phys. Rev. D 103, 072003 (2021)

Tracker's occupancy

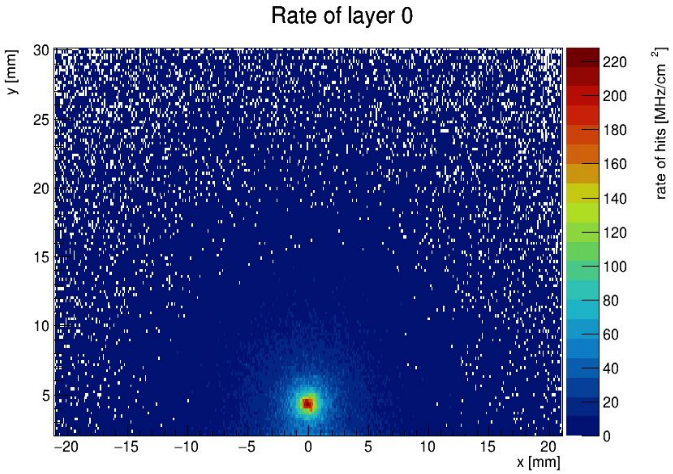
thanks to Sara Cesare
for latest plots

Flux of **10^6 p/s** (minimum bias events), on 2 cm W target

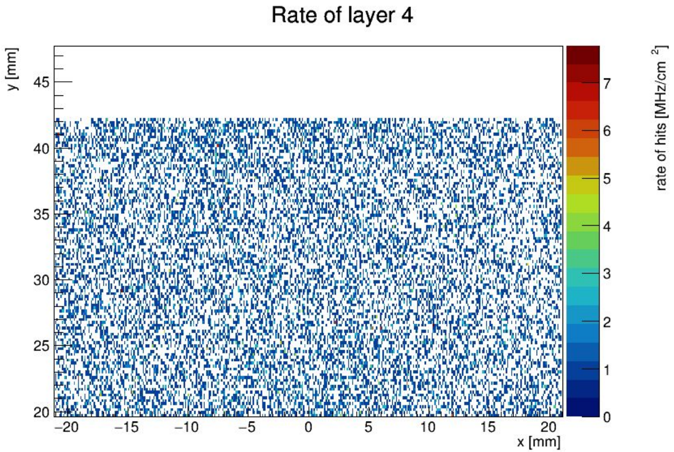
Velo Superpixel = 4x2 pixels

$$\text{Rate} = N_{\text{hits}}/cm^2/s$$

Before magnet: <250 MHz/cm^2



After magnet: <10 MHz/cm^2

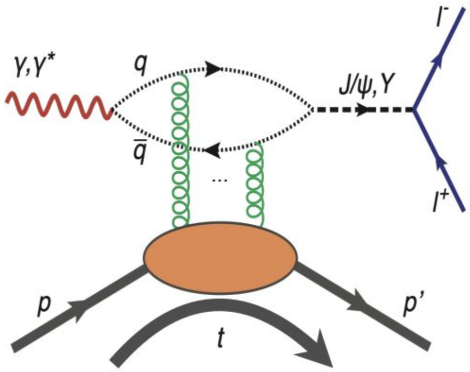


Maximum Fluence before magnet in the region of beam spot:
~2.2 x 10^{15} 1 MeV neq/cm^2

⇒ for cooling system design

⇒ within VeloPix/TimePix3 allowed maximum rate (600 MHz/cm^2)

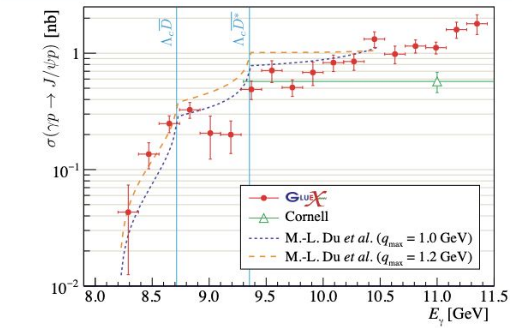
Inclusive Vector Meson photoproduction

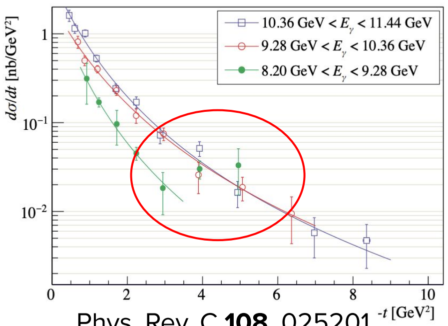


Models based on **perturbative QCD** and **gluon exchange** predict a smooth dependence to E

→ to access Gluonic (generalized) parton distributions (**GPD**) of proton to have insights into nature of proton mass

- Recent results from GlueX with 2270 J/ψ





Phys. Rev. C **108**, 025201

⇒ Our fixed-target experiment at LHC can reach high luminosity due to target density + very forward acceptance

Feasibility studies for:

- Jpsi and psi(2S) photoproduction cross-section & search for pentaquarks

J/ψ & ψ(2S) cross-section measurement

J/ψ/ψ(2S) cross-section measurement in range complementary to GlueX, HERA & SLAC

- **HERA**: Eur. Phys. J. C 24, 345–360 (2002)
    - J/ψ cross-section: 20 < W < 150 GeV
    - ψ(2S) cross-section: 307 events in 40<W<150GeV
- **SLAC**: PRL 35, 483 (1975)
    - J/ψ cross-section: 13< E_γ < 21 GeV, 5<W<6.5 GeV
    - 1200 J/psi

Luminosity:

$$\mathcal{L} = \theta_{target} \cdot \Phi \qquad \theta_{target} = \frac{N_A \rho l}{M}$$

$$\rho = 19.3\ g/cm^3$$
$$N_A = 6.02 \cdot 10^{23}$$
$$l = 2\ cm$$
$$M = 184 g\ /mol$$

Expected yield without acceptance

- F=10^6 p/s, ∫L = 0.89 pb^{-1} per year

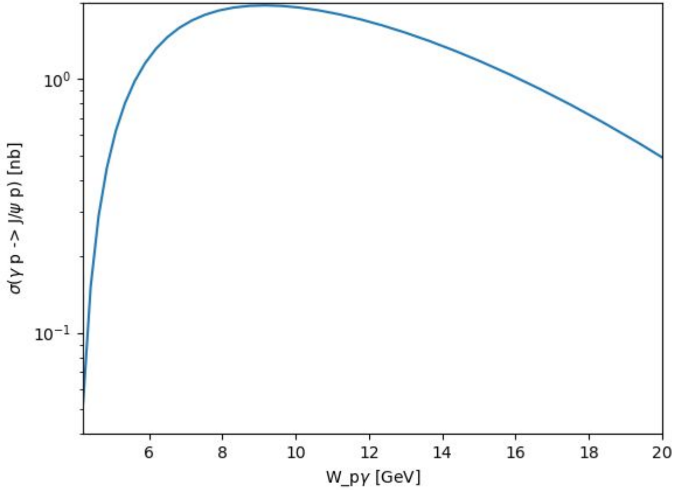
	σ [nb]	**Yield/year**
J/ψ	42	37'000
ψ(2S)	0.76	670

Cross-sections

Cross-section estimates with STARLight MC link
1. pW interactions. Beam energy = 7TeV
2. PbW interactions. Beam energy = 7TeV x Z

⇒ Dominant process is incoherent photon-p interaction, with photon emitted by target

1. **pW: σ= 42 nb,** y in range 3<y<8
Center-of-mass energy: 4.2<W<30 GeV



2. **PbW: σ=1.89 mub,** y in range 2<y<6.5