Simulations for a forward physics experiment

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3rd workshop of EDM of unstable particles
IJCLab, Orsay

12th December '23

IR3 experiment' schedule

Run 3
2025

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

- **asked for by LHCb & approved by LHCC**
- 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), charm physics?

beyond

Phase 2:
setup to ultimate the physics measurements:
EDM/MDM measurements with full sensitivity

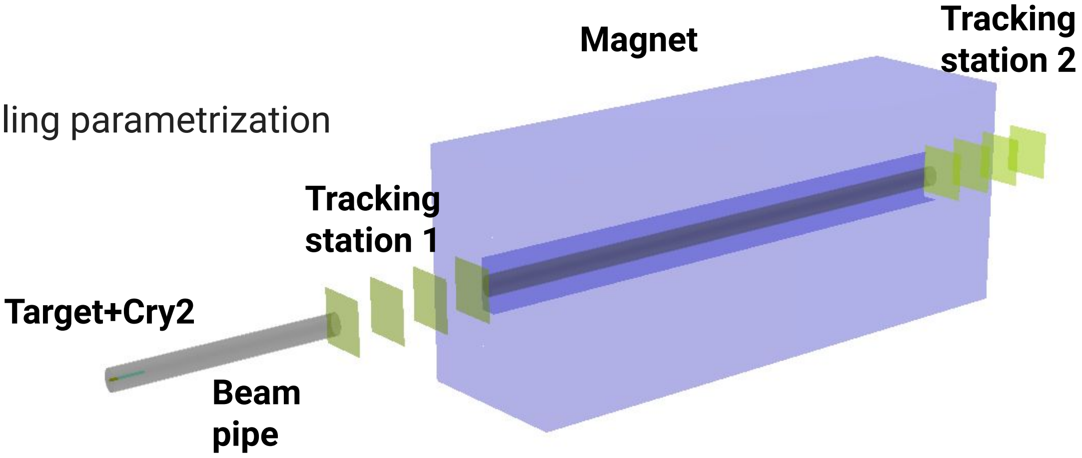
Simulation of IR3 detector

Simulation for the future experiment

- Detector geometry: DD4hep
- Generators:
  - Pythia/Argantyr model
  - Λ_c spectrum: Pythia+channeling parametrization
- Particle simulation: DDG4
  - based on Geant4
- Tracking: GenFit (by Jascha)
- Event model (PODIO) & analysis package (by Han and Tianyu)

Code repositories:

- *IR3Detector* repository: link
- *IR3_ana_tool* repository: link



On behalf of Simulation working group: J. Grabowsky, H. Miao, T. Xing, S. Cesare, S. Jaimes, P. Gandini, Z. Wang, J. Fu, N. Neri, C. Maccani, F. Martinez Vidal, M. Ferro-luzzi.

Spectrometer for IR3

Magnets

- orbit correction dipole magnets at IR3

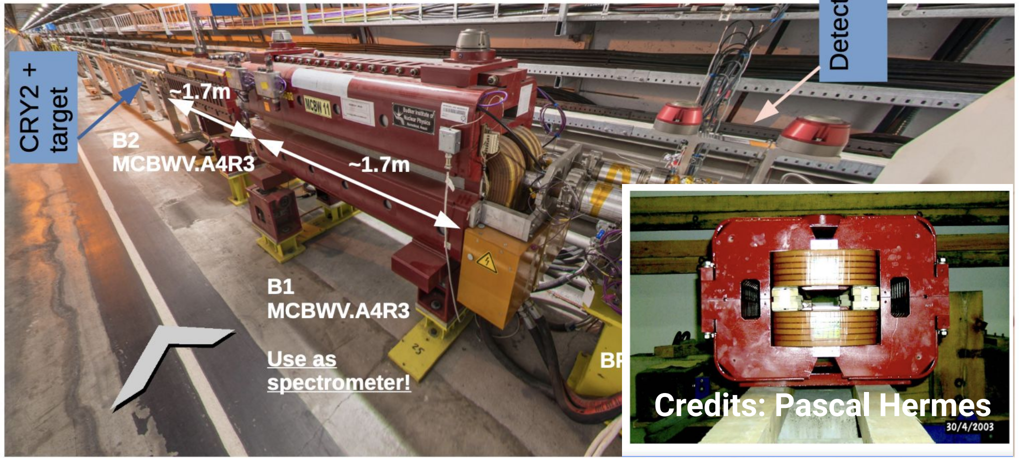
Magnet	L [m]	B [T]
MBW	3.4	1.4
MCBW	1.7	1.1

Tracking stations

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

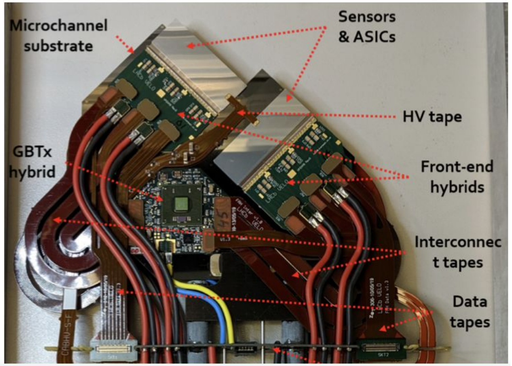
- **Roman Pots**: ALFA Roman Pots

Picture of IR3 and MCBW magnet

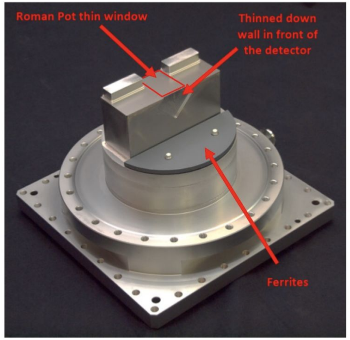


https://edms.cern.ch/panoramas/viewer?fov=90.00&id=36409858&lat=-27.06&lon=241.01

VELO module



ALFA Roman Pot



Goals of simulations

1. **Optimization of the detector design for EDM measurement**

- Magnet: **acceptance** of orbit correction dipole magnets
- Tracker stations:
    - VeloPix technology is suitable for expected **occupancy**?
    - position and lever-arm to optimize **invariant mass resolution**

2. **Background discrimination:** discrimination of Λ_c signal from combinatorial, unchanneled Lc, **peaking bkg,** ie D^+, D_s. ⇒ *covered by Jascha & Roger*

3. **Extending the physics case beyond EDM:**
    - detector optimization for photoproduction studies

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   - detector optimization for photoproduction studies

Outline of today's talk

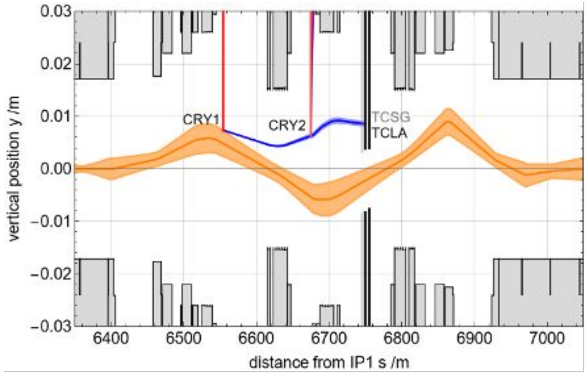
1. Geometry design
   Tracker occupancy
   Acceptance: for different detector layout

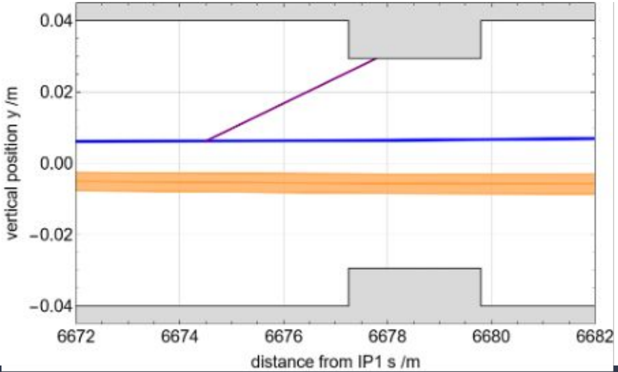
2. RICH occupancy

3. Photoproduction studies

Beam spot simulations

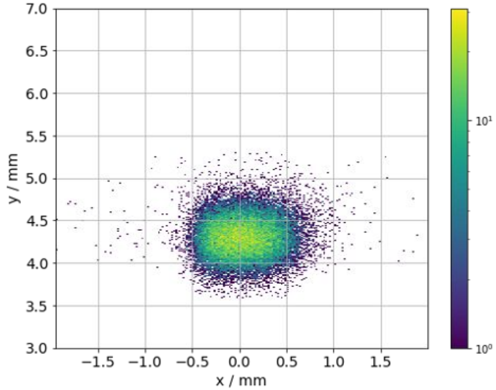
Simulations performed by Kay et al





Crystal 1 is aligned with the secondary halo (multiturn simulation – pencil beam)

A plot of the distribution at the target / crystal 2 entrance. You can see the main spot of channelled protons below. Fewer particles appear in total as some are lost in the formation of the secondary halo (forming the halo requires protons to impact the primary collimator; some are absorbed).



	peak / no. part	Mean	Sigma	3 Sigma
X	1270 ± 10	0.03 ± 0.01 mm	0.30 ± 0.01 mm	0.90 mm
Xp	1280 ± 10	0.80 ± 0.11 μrad	10.0 ± 0.1 μrad	30.0 μrad
Y	760 ± 3	4.30 ± 0.01 mm	0.21 ± 0.01 mm	0.64 mm
Yp	1130 ± 5	23.0 ± 0.1 μrad	2.91 ± 0.01 μrad	8.74 μrad

Tracker optimization: layout 1

Geometry: layout 1

Target: W, 2cm long, 8x2mm
Crystal: Si, 7cm long, 7mrad bending angle

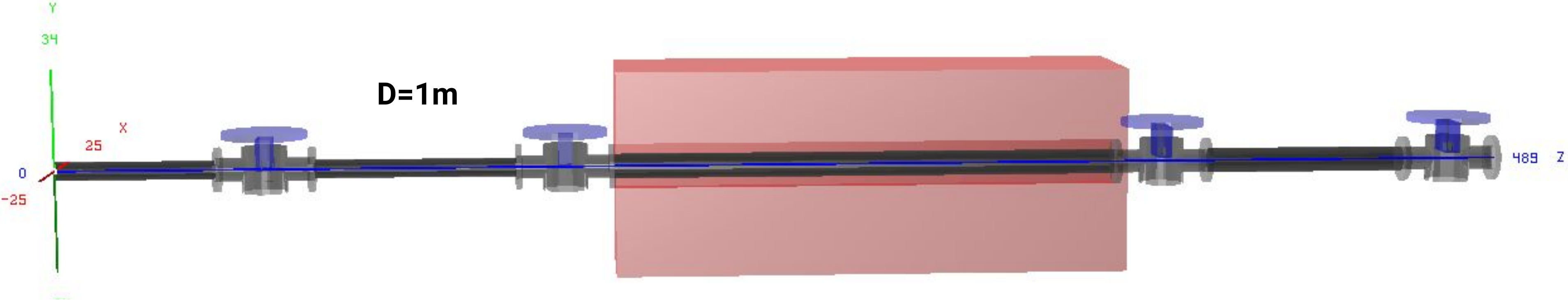
4 Roman Pots of TOTEM

- 2 trackers per RP, at distance of 2cm
- 2 Velo tiles per station, horizontal
    - y position: distance dependent
- **First tracking station: at 68 cm**
- **Lever arm: from 0.4m to 1m**

Beam pipe: Al
elliptical shape, 2.1cm x 2.9cm
→ enlarged inside/after the magnet to 2.5x5 cm

Magnet MCBW (1.1 T, 1.7m): iron box
Bore: 5.2x14cm

- constant field inside bore



Tracker occupancy

thanks to Sara Cesare for latest plots

Minimum bias events: Flux of **10^6 p/s**, on 2 cm W target

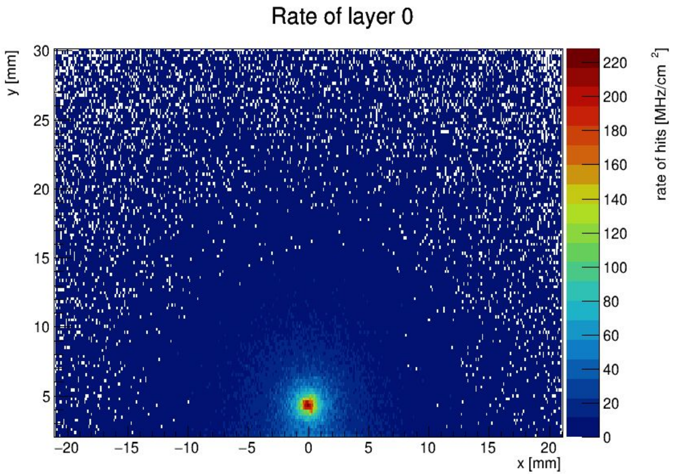
- Rate in Velo Superpixel (4x2 pixels)

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

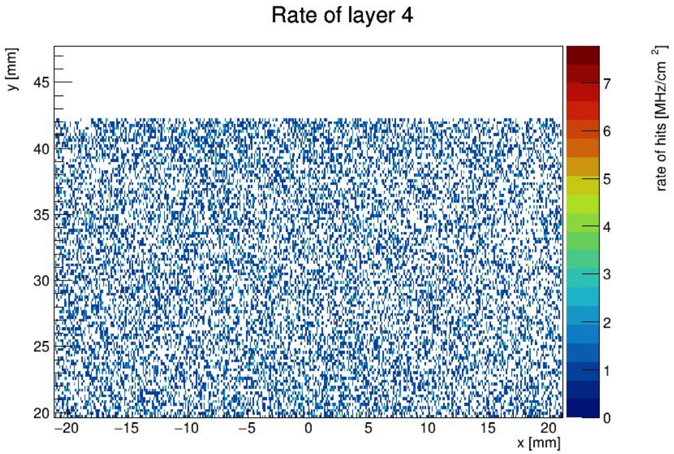
Simulation parameters:

- Production cut = 0.7mm
- No tracking cuts
- Physics list: FTFP_BERT EM

Before magnet: <250 MHz/cm^2



After magnet: <10 MHz/cm^2



Maximum pixel hit rate: 6.6KHz

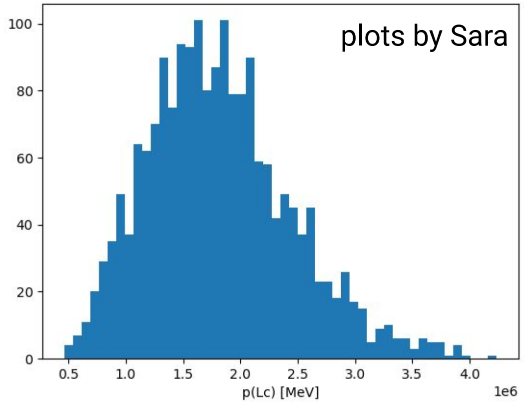
Possibility to run with flux of **10^7 p/s:**

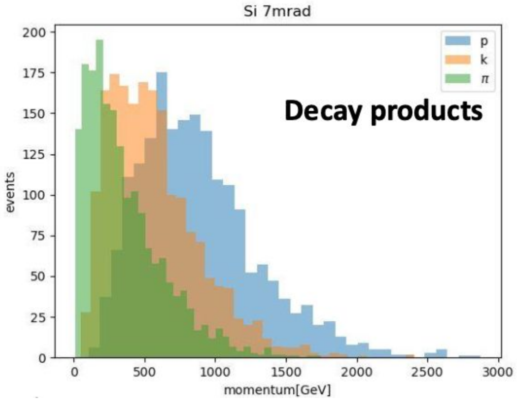
- Analog pile-up < 3MHz
- Readout logic: data transfer rate < 13MHz

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

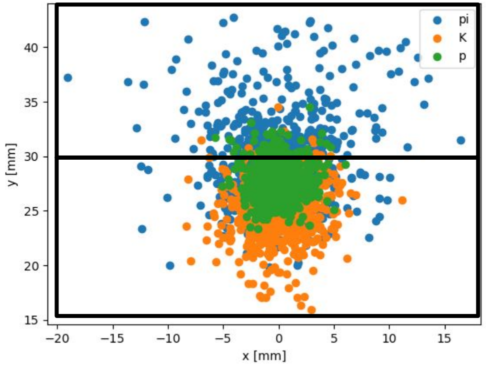
Λ_c signal

Λ_c input spectrum:
- generated using Pythia and with channeling (Biryukov's book), thanks to Fernando and Sergio
- imported in DDG4 as General Particle Source





2 Velo tiles



Hit distributions after magnet

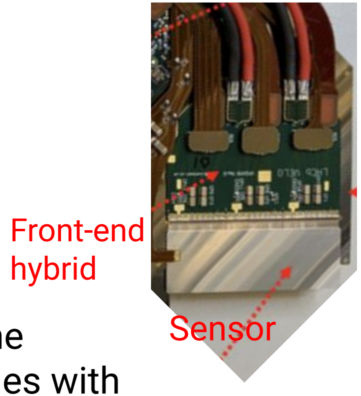
2 Velo Tiles:
VELO tile = $4.2x1.4cm^2$

Number of Velo tiles:
- 2 before magnet
- 2 or 4 after magnet (to cover forward region)

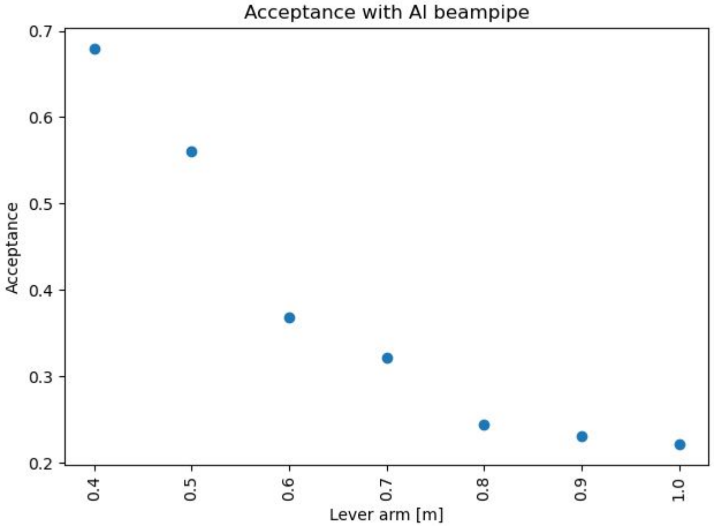
Detector acceptance

Goal: acceptance downstream the magnet using VELO tiles

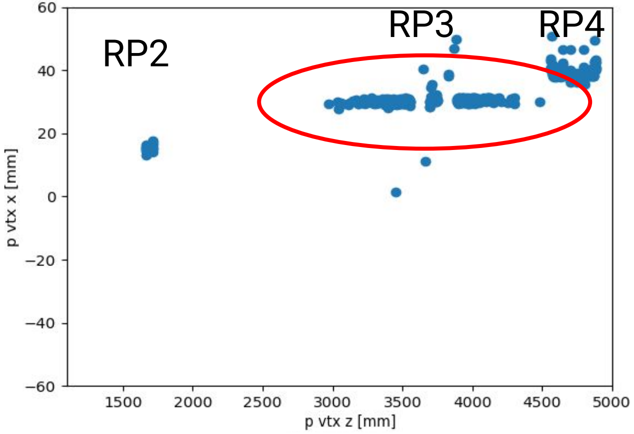
→ to read out tiles vertically inside Roman Pots: **2 horizontal Velo tiles**



As a function of **Lever arm**



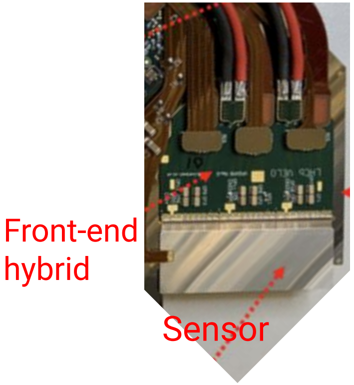
Beam pipe inside magnet reduces the acceptance → interactions of particles with beam pipe



Detector acceptance

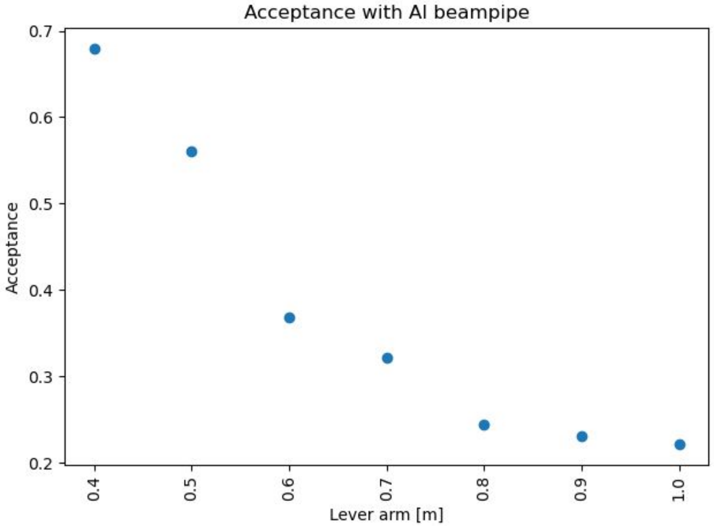
Goal: acceptance downstream the magnet using VELO tiles

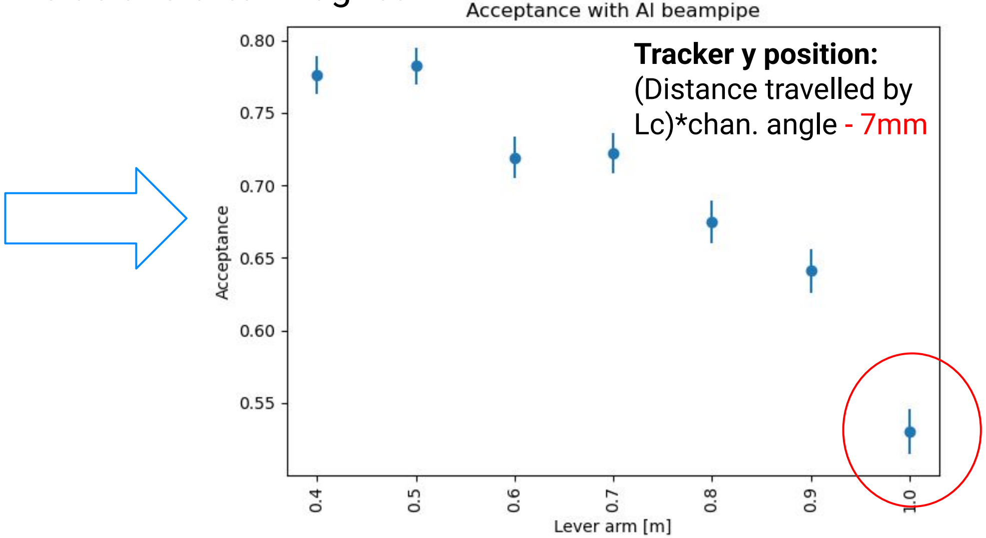
→ to read out tiles vertically inside Roman Pots: **2 horizontal Velo tiles**



As a function of **Lever arm**

⇒ Enlarge the beam pipe to 2.5x5cm inside and after magnet





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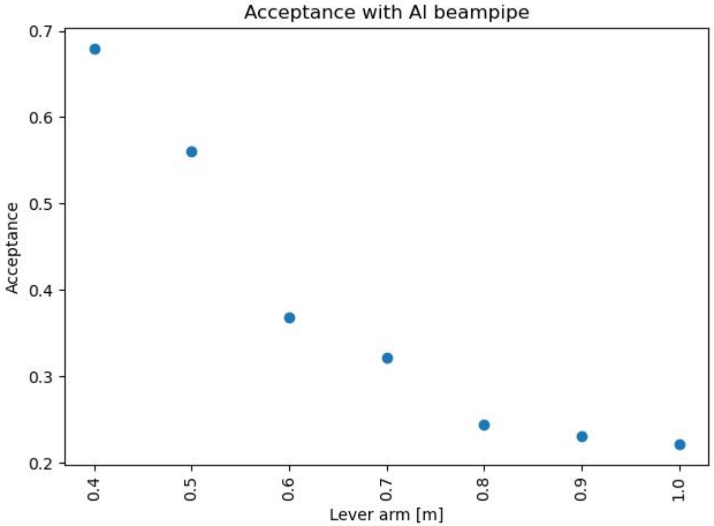

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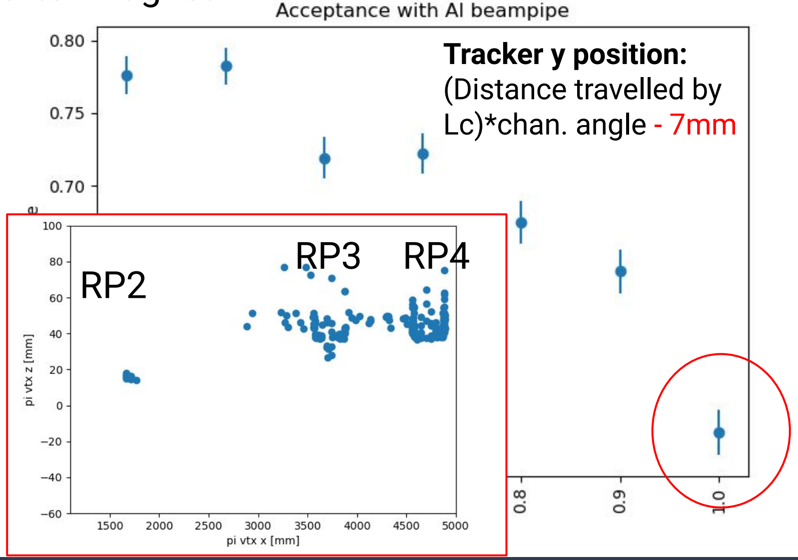
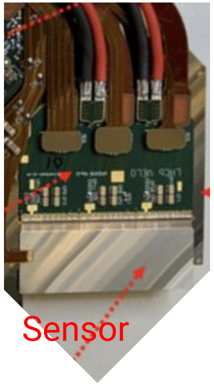
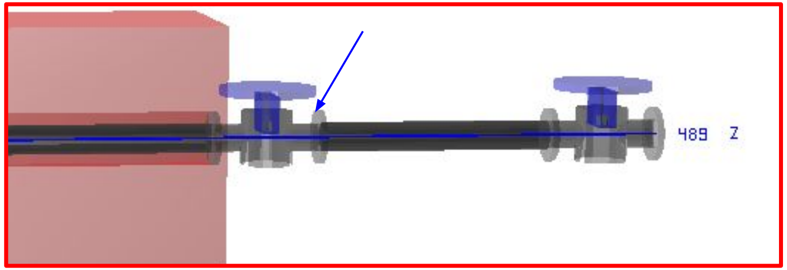




Modifying RP geometry?

Low acceptance due to interactions with beampipe and RP tube after magnet:

- RP tube radius: 4cm (nominal).
  - Enlarge it to 5cm or 6cm?
- **Beampipe radius**
  - inside magnet: **r=5cm**
  - after magnet: **r=5-6cm**



Tracker areas: 2 Velo tiles before magnet/3 Velo tiles after magnet to cover forward region

1 **Nominal**: $r_{\text{RP tube}}$ =4cm; $r_{\text{BP after magnet}}$=5cm	53%
2: $r_{\text{RP tube}}$ =4cm; $r_{\text{BP after magnet}}$=6cm	56%
3: $r_{\text{RP tube}}$ =5cm; $r_{\text{BP after magnet}}$=5cm	71%
3: $r_{\text{RP tube}}$ =5cm; $r_{\text{BP after magnet}}$=6cm	72%

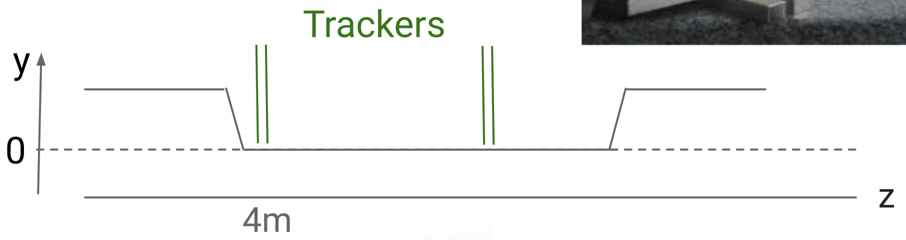
Open questions: is it feasible to enlarge the RP support?

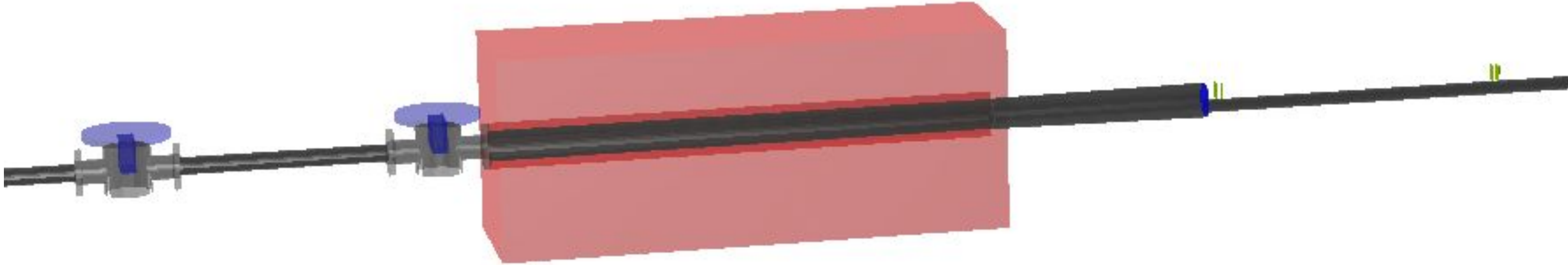
Tracker optimization: layout 2

Layout 2: Hamburg Beam pipe

Usage of Hamburg beam pipe after magnet:

- Minimum y position: y=0
  - Main beam is at -6.7mm
- Trackers to cover forward region:
  → for photoproduction studies
- Exit window of 80°





Acceptance with 4 Velo tiles, in air: 72% ⇒ Gain in acceptance: from 50% to 70%

Next:

- Need to perform optics function simulations to verify feasibility and positions

Dedicated magnet

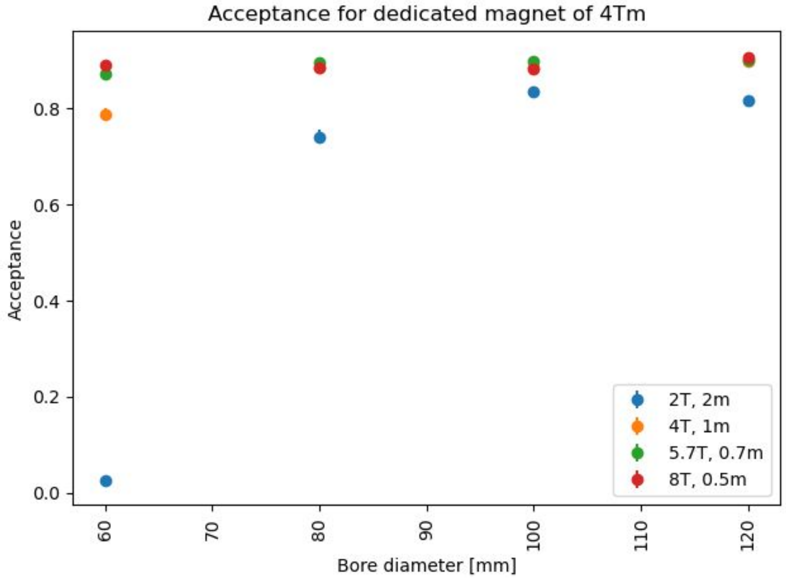
Optimization of design

Dedicated talk from Sorbi

Dedicated magnet: **B=4Tm**
Tracker geometry: Hamburg beam pipe, lever-arm L=1m

⇒ Optimization of length and bore diameter

- Bore > 6 cm, since beam pipe radius cannot be reduced below 3cm



⇒ Acceptance of **90%** for:

1. B=4T, length=1m, bore = 8 cm
2. B>4T and length<1m, bore = 6cm

⇒ increase from ~70% to 90% of acceptance with Hamburg beampipe configuration

⇒ Factor of 2 improvement in invariant mass resolution

Possible solution for Phase II

RICH detector

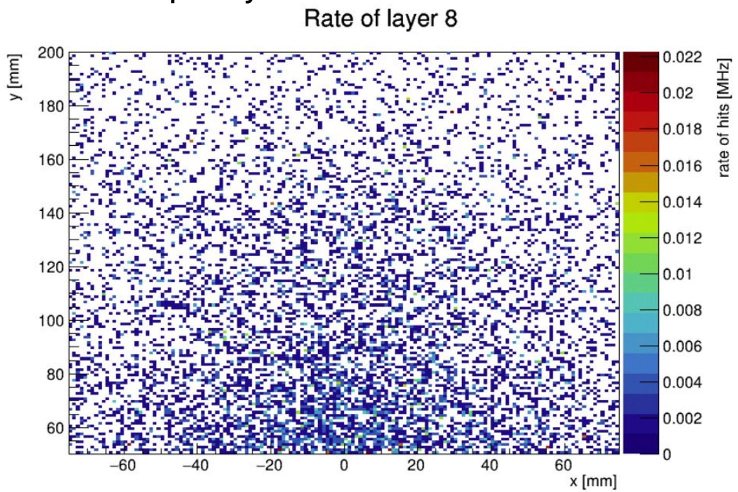
RICH detector: occupancy

Dedicated talk by R. Forty

RICH filled with He, 5m long
- N photo-electrons = 12
- SiPM:
    - submm pixel size → R&D for RICH LHCbU2: $1mm^2$
    - coverage: 11 cm of diameter, at y>8 cm

⇒ Possibility to use a longer length (10m) with $1mm^2$ pixel

1. Occupancy from mb interactions: few tracks per event (<10) impinge on SiPM



2. no background from unchanneled Lc (prob < 0.02%)

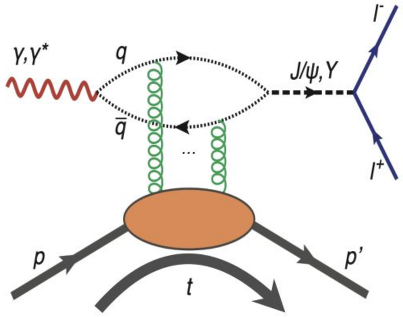
3. Since it is very close to the beam, how many charged particles from the main/deflected beam impinge on the SiPM?
→ We would need **beam dynamics simulations**:
z=6m from target, y>8cm

J/ψ photoproduction

Inclusive Vector Meson photoproduction

Motivation is to perform feasibility studies for:

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



Process characteristics:

Our experiment at IR3

- very forward production ⇒ covers a pseudorapidity range from 5 to 8
- exclusive process: only J/ψ and p ⇒ hermetic detector
- high cross-section due to high target Z ⇒ ~10 nb, to be determined with simulations
- high luminosity due to target Z ⇒ about 10^{29} cm^2s^{-1}

J/ψ photoproduction

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

2. **Detector optimization**
   a. Resolutions on angular and momentum quantities for reconstruction of m(J/ψ p)
   b. Muon optimization
   c. Trackers

3. **Acceptance**

4. **Expected yields**

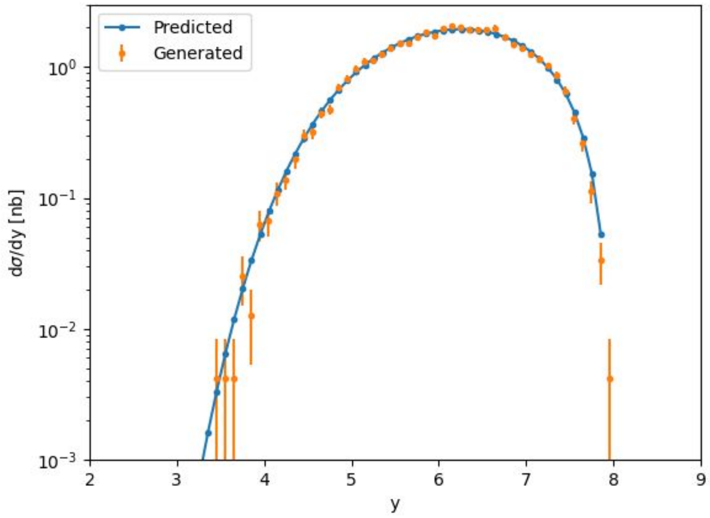
Cross-sections

Physics Letters B 805 (2020) 135447

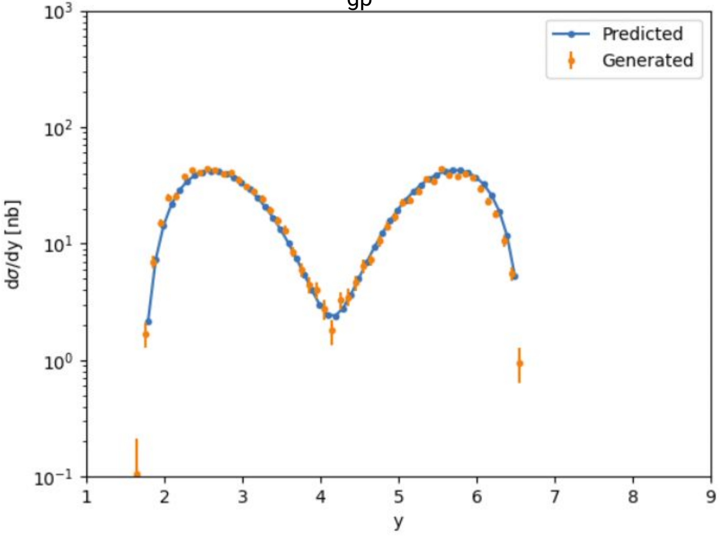
Cross-section estimate with STARLight MC link
1. pW interactions. Beam energy = 7 TeV
2. PbW interactions. Beam energy = 7 TeV x Z

⇒ 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



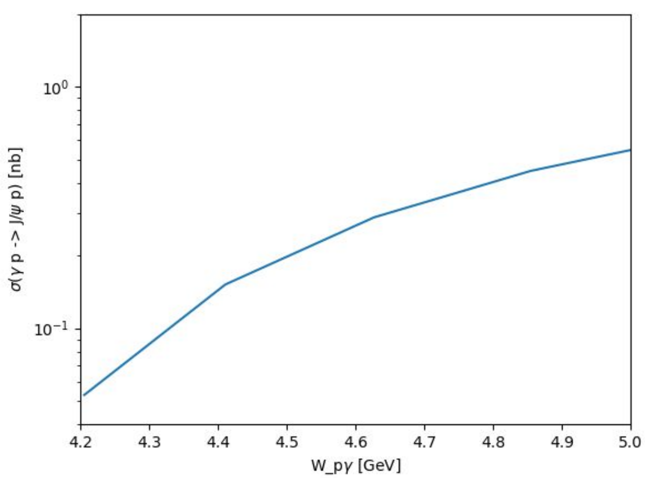
Cross-sections

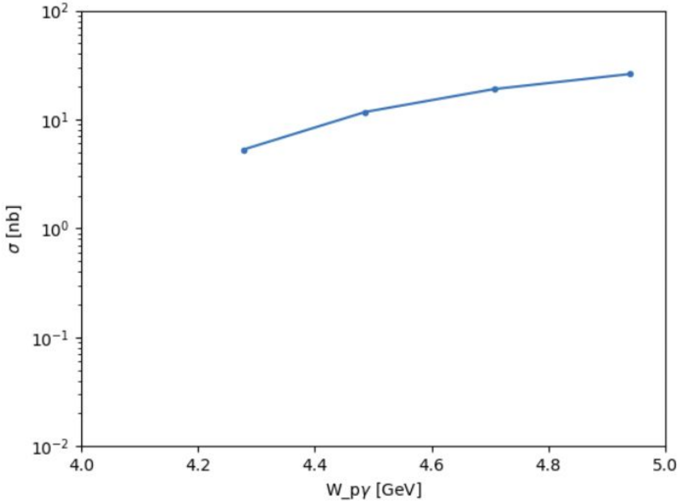
Cross-section estimate with STARLight MC link

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=36 nb,** y in range 2<y<6.5





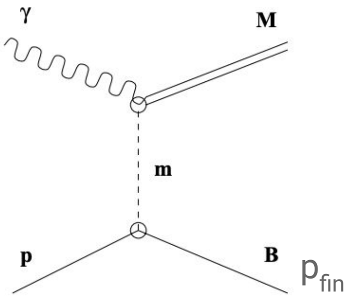
Photoproduction kinematics

Invariant mass resolution depends on the angle between the Jpsi and the scattered proton

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

Conservation of 4-momentum, neglecting E_γ:

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



⇒ the invariant mass depends on $p_{J/\psi}$, the deflection angle of proton and $cos(\theta_{J/\psi p})$

What is the resolution on these quantities?

Resolutions

see talk by N. Neri

Resolution | **Detector**

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

⇒ $\sigma_\theta \sim 10\mu rad$

$\sigma < 10\mu rad \cdot D(=2m) = 20\mu m$

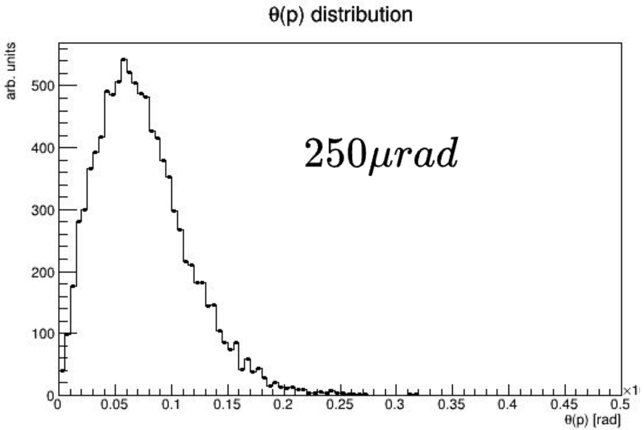
⇒ Pixel stations before magnet:
- Hit reso:
  $\sigma = 55\mu m/\sqrt{12} = 15\mu m$
- Multiple scattering <5 μm

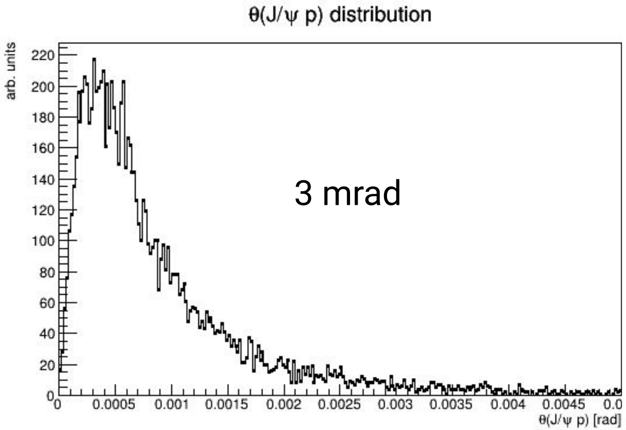
Momenta:
- $\langle p_{J/psi}\rangle$ ~ 500 GeV

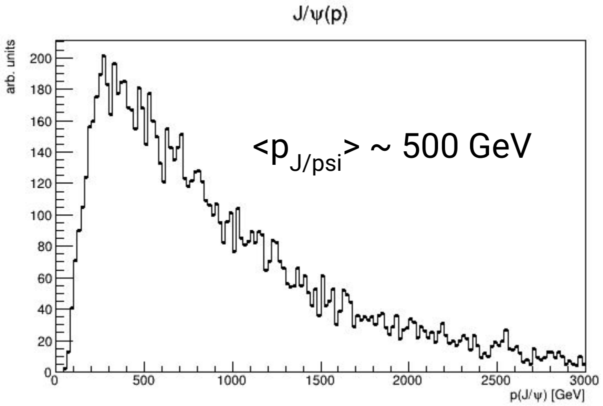
⇒ $\sigma_p/p = \frac{2p}{0.3BLD}\sigma_s$

⇒ Trackers + Muon stations

$= 1.7\% \ \sigma_s = 10\mu m, \ D = 1m$







Resolutions

talk by N. Neri

Angles:
- θ_p <250 µrad
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Resolution

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Detector

⇒ Pixel stations before magnet:
- Hit reso:
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- Multiple scattering <5 µm

Momenta:
- $\langle p_{J/psi}\rangle \sim 500$ GeV

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

⇒ Trackers + Muon stations

$= 1.7\% \;\; \sigma_s = 10\mu m, \; D = 1m$

Resolution on invariant mass:

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

Dominant term:

$$\Delta cos\theta_{J/\psi p} = \frac{1}{2m} p_{J/\psi} p_p sin\theta_{J/\psi p} \sigma_{\theta_{J/\psi p}} \sim 15MeV$$

⇒ To be checked with full reconstruction

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

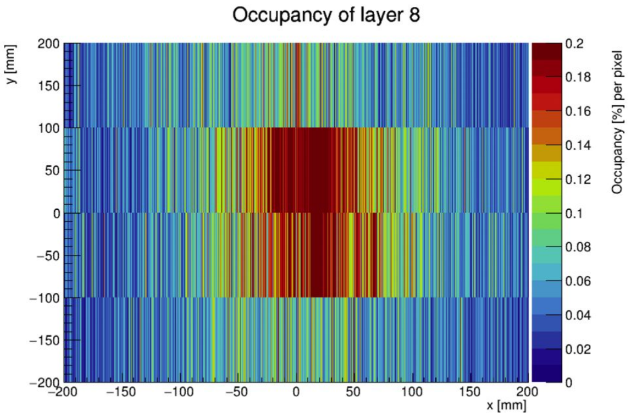
Interleaved with **iron filters,** 90 cm thick (to be optimized)

Possible design solutions:

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 UT stations per layer)
3. 4 stations of MWPC

Muon occupancy

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



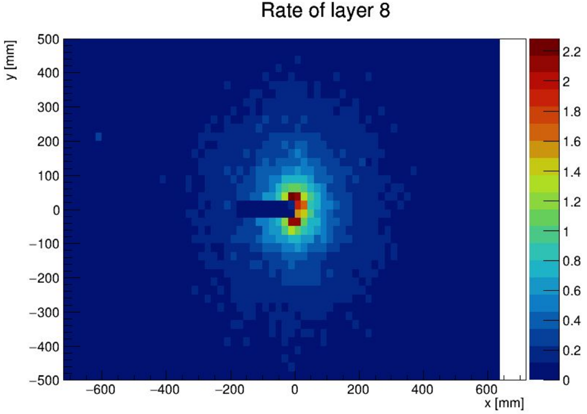
Maximum rate below limits:

- Flux=10^6 p/s ⇒ 36 kHz

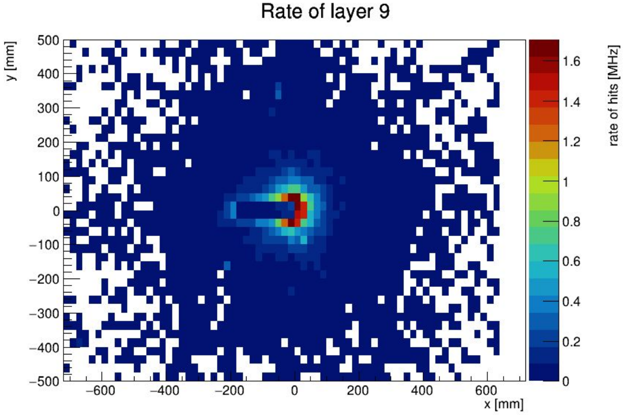
Muon Chamber MWPC
pad= 20x25mm^2
chamber= 48x20 cm^2 ⇒ 24 x 8 pads

⇒ 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:**

- Tracking stations below the beam pipe to enlarge acceptance in the forward region?
- **Scintillator** downstream at a distance of 100m, such as Hershel

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

Possible solution to overcome this problem:

- dedicated run with thinner W target and no crystal

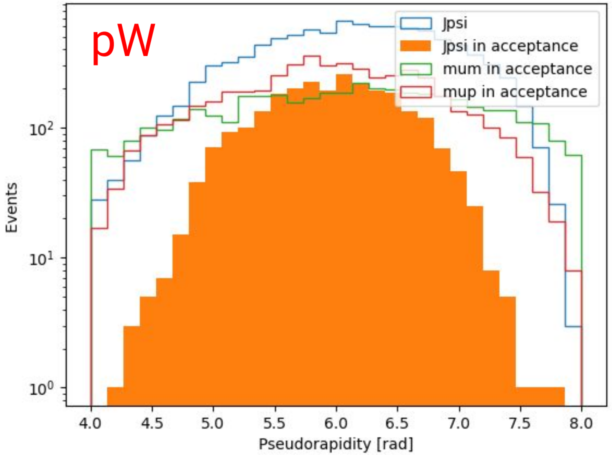
Simulations

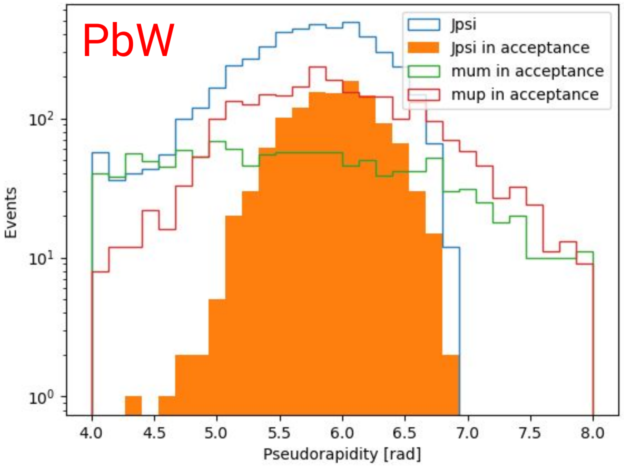
Events: 10000 J/ψ events in DD4hep
Stations geometry:

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

Pseudorapidity coverage:

Very forward acceptance: 4.5<y<7



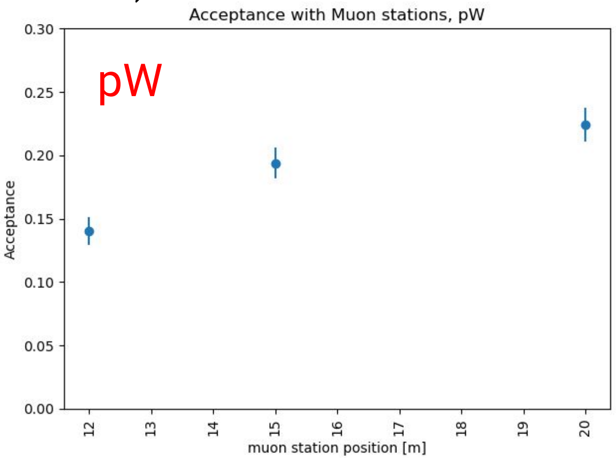


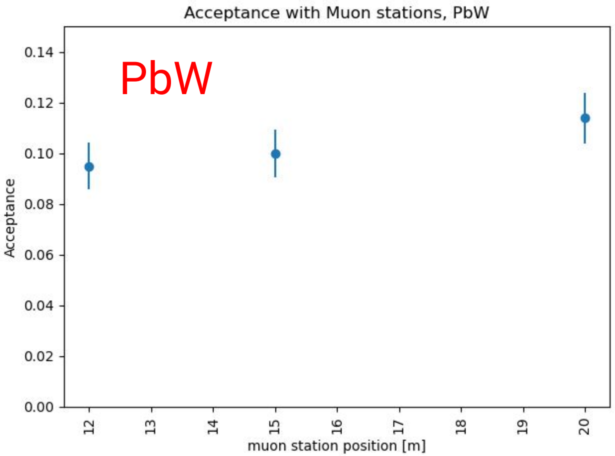
Acceptance

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

→ Reconstruction with tracker downstream magnet: acceptance drops to ~1%

- Enlarge active area and/or place trackers below main beam

→ To consider the multiplicative factor of 68% due to inelastic interactions

Expected yield

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

Luminosity:

$$\mathcal{L} = \theta_{target} \cdot \Phi = 1.26 \cdot 10^{29}\, cm^{-2}\, s^{-1}$$
$$\theta_{target} = \frac{N_A \rho l}{M} \ \star$$

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	0.073	0.075	10’350/week
pW, J/ψ W<4.8GeV	0.5	**10^7 p/s**	8.9	0.136	1700/year
PbW, J/ψ W<4.8GeV	72	10^6 p/s	0.073	0.075	400/week

Promising yields:

- sum different data taking runs to collect high yields
- Pentaquark search with 10^7 p/s

Conclusions

Optimization of detector design:

- Trackers: Velo pixel technology is suitable for PoP and future experiment
- Acceptance:
  - Best configuration: usage of hamburg beam pipe ⇒ **acceptance of 70%**
  - For future: with a dedicated magnet we could reach 90%

Photoproduction:

- Extending the physics case to cover forward production can enrich our project
- Requirements:
  - place trackers in front of the beam
  - build muon stations
- Yield estimates for P_c yield are promising compared to other experiments and good invariant mass resolution
- **Next: finalize reconstruction of J/ψ and p**

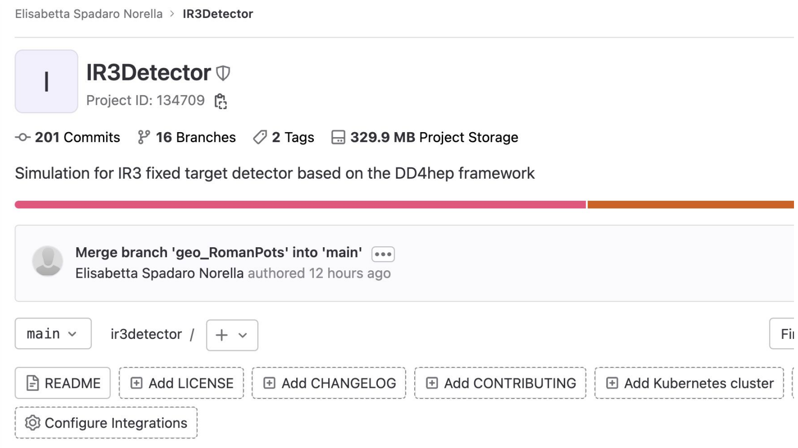
Thank you for the attention!

Backup slides

Code repositories

IR3Detector repository: link
- Geometry implementation
  - xml files
  - factories for subdetectors
- Simulation based on DDG4
  - python file

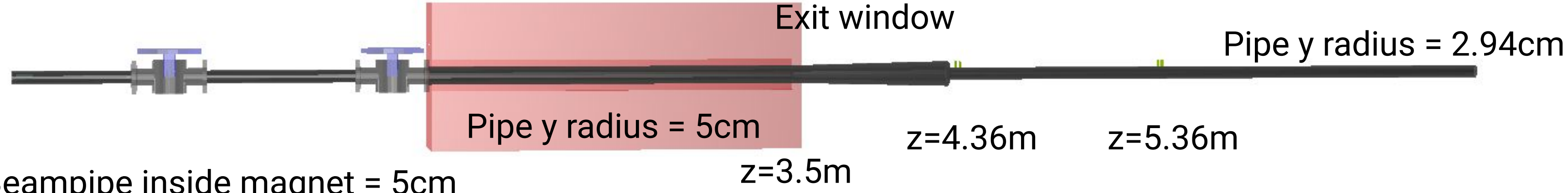
⇒ developer: myself, implementation and testing



IR3_ana_tool repository: link
- Event model (PODIO)
- Modules for data analysis
  - Occupancy
  - Reconstruction
  - Digitization

⇒ developers: Han, Tianyu from UCAS and Jascha from Bonn

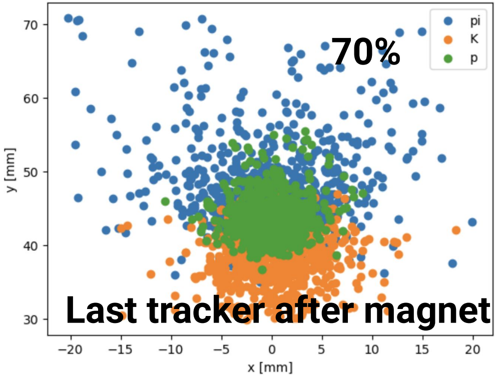
Exit window geometry



Beampipe inside magnet = 5cm
Different configurations are tested:

- Exit window from 70-90 degrees, thickness: 1-3 mm

Exit window 80 degrees:



Acceptance	Pipe radius 2.94cm	Pipe radius 2.5cm
70°, 1mm	72+/-1%	81+/-1%
80°, 1mm	70+/-1%	76+/-1%
90°, 1mm	74+/-1%	77+/-1%
80°, 2mm	**70+/-1%**	**77+/-1%**
80°, 3mm	69+/-1%	76+/-1%

Preliminary: Charm hadron yield

Decays: $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^-K^+\pi^+$, $\Lambda_c^+ \rightarrow pK^-\pi^+$

Flux on target 10^6 p/s, crystal length 7 cm, target thickness 2 cm, MCBW magnet with RB= 2.5 cm

Best configuration: Ge crystal, 5 mrad

D^+ most abundant:
- thousands of events with flux of 10^6 p/s (or 10000 with 10^7 p/s) in few days

D_s and Λ_c^+: resolvable with reso < 50 MeV
- thousand of events in ~2 months

We can do it!
- First measurement of EDM of Λ_c^+
- study of the very forward region

Si crystal

5 mrad bending

	D^+	D_s^+	Λ_c^+
1 day	109	16	8
1 month	3275	479	248

7mrad bending

	D^+	D_s^+	Λ_c^+
1 day	1.6	0.2	0.1
1 month	48	7	4

Ge crystal

5 mrad bending

	D^+	D_s^+	Λ_c^+
1 day	616	94	21
1 month	18481	2807	645

7mrad bending

	D^+	D_s^+	Λ_c^+
1 day	78	11	4
1 month	2334	342	114

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:

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

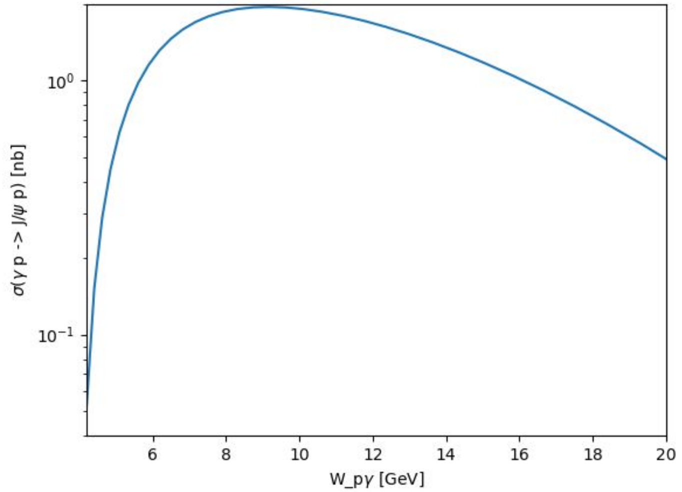
	σ [nb]	**Yield/year**
J/ψ	42	37'000
ψ(2S)	0.76	670

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