Motivation for fixed-target experiments at the LHC (AFTER@LHC) (with emphasis on gas targets)

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Part I

Assets, Kinematics, Possible Implementations and Luminosities
The fixed-target mode with TeV beams: why and what for?
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The fixed-target mode with TeV beams: why and what for?

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- accessing the high $x$ frontier
- achieving high luminosities,
- varying the atomic mass of the target almost at will,
- polarising the target.

$|x_F| \equiv \frac{|p_z|}{p_{z\text{ max}}} \to 1$
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All this can be realised at CERN in a parasitic mode with the most energetic beams ever!

Nota: all (past) colliders with $E_p \geq 100$ GeV have had a fixed-target program (Tevatron, HERA, SPS, RHIC)
Fixed-target collisions at the LHC: main kinematical features

- **Energy range**: 7 TeV proton beam on a fixed target
- **c.m.s. energy**: Rapidity shift:
  - Boost:
    - 7 TeV proton beam on a fixed target

Such beams allow, for the first time, for systematic studies of W boson, bottomonia, p\_T spectra, associated production, ... in the fixed-target mode.

**Effect of boost**: particularly relevant for high energy beams.

With the reduced rates, their acceptance for physics grows and nearly covers half of the backward region for most probes.

Allows for backward physics up to high x target (uncharted for proton-nucleus; most relevant for p-p with large x).
## Fixed-target collisions at the LHC: main kinematical features

### Energy range

- **7 TeV proton beam on a fixed target**
  - **c.m.s. energy:** $\sqrt{s} = \sqrt{2m_N E_p} \approx 115$ GeV
  - **Boost:** $\gamma = \sqrt{s / (2m_N)} \approx 60$

- **Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$

- **2.76 TeV Pb beam on a fixed target**
  - **c.m.s. energy:** $\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72$ GeV
  - **Boost:** $\gamma \approx 40$

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- With the reduced $\sqrt{s}$, their acceptance for physics grows and nearly covers half of the backward region for most probes
  
  $[-1 < x_F < 0]$ 

- Allows for backward physics up to high $x_{target} (\equiv x_2)$
  
  [uncharted for proton-nucleus; most relevant for p-p$^\uparrow$ with large $x^\uparrow$]
Internal gas targets

SMOG(-like) system

SMOG: System for Measuring Overlap with Gas

Designed for precise luminosity determination

Noble gas directly injected in the VELO

3 $p(\text{He}, \text{Ne}, \text{Ar}), \text{Pb}(\text{Ne}, \text{Ar})$ tested: completely parasitic [up to one week, so far]

3 New pressure monitor to be installed

3 Could be coupled to ALICE: ideal demonstrator

7 No specific pumping system: limits the injected gas [pressure and duration]

7 No possibility to use polarised gases

7 Gas flows in the beam pipe; pressure profile not optimised

7 Kr and Xe may be only at the end of a run

---

2 $\text{invariant mass (MeV/c)}$

2 $\mu + \mu^2$

2900 3000 3100 3200 3300 3400 3500

2 entries / 16 MeV/c

LHCb preliminary 2015 $p\text{Ne}$ data

---

Injection of gas in an open-end storage cell

Used e.g. at DESY for one fitted zero fitted years

3 Dedicated pumping system [turbo-molecular pumps]

3 Pressure in the cell significantly higher [diameter $B$ / two fitted cm in the closed position]

3 Polarised $\text{H}$ and $\text{D}$ can be injected ballistically with high polarisation

3 Polarised / three fitted $\text{He}$ or unpolarised heavy gas ($\text{Kr}, \text{Xe}$) can also be injected

7 Not compatible with an injection inside ALICE; only upstream

7 May need complementary vertexing capabilities

---

Part III simulations show in $\hat{O}$

Set-up coupled to a LHCb-like detector

With $a \, p \, p \, A \, \text{PbA}$ storage cell
### SMOG(-like) system
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[+ turbo-molecular pumps] |
| ✓ p(He, Ne, Ar), Pb(He, Ar) tested: completely parasitic  
[+ up to one week, so far] | ✓ Pressure in the cell significantly higher  
[+ diameter ≤ 2cm in the closed position] |
| ✓ New pressure monitoring to be installed | ✓ Polarised H and D can be injected ballistically with high polarisation |
| ✓ Could be coupled to ALICE: ideal demonstrator | ✓ Polarised $^3$He or unpolarised heavy gas (Kr, Xe) can also be injected |
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![ invariant mass (MeV/c) vs. entries / 16 MeV/c ]

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The simulations showed in Part III are based on this set-up coupled to a LHCb-like detector

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Part II

Physics Motivation
High-\(x\) frontier

Advance our understanding of the high-\(x\) gluon, antiquark and heavy-quark content in the nucleon & nucleus
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- Very large PDF uncertainties for \(x \gtrsim 0.5\).

  [could be crucial to characterise possible BSM discoveries]
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- Relevance of nuclear PDF to understand the initial state of heavy-ion collisions

Best to take data at large $x$ and small scale, than at large scale: advantage of low $E$; provided HT are under control
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- Relevance of nuclear PDF to understand the initial state of heavy-ion collisions
- Search and study rare proton fluctuations

where one gluon carries most of the proton momentum

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Gas target and AFTER@LHC
3D mapping of the parton momentum

Advance our understanding of the dynamics and spin of gluons and quarks inside (un)polarised nucleons
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Advance our understanding of the dynamics and spin of gluons and quarks inside (un)polarised nucleons

- Possible missing contribution to the proton spin: Orbital Angular Momentum $\mathcal{L}_{g,q}$:

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q$$

[First hint by COMPASS that $\mathcal{L}_g \neq 0$]
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- Test of the QCD factorisation framework

[beyond the DY $A_N$ sign change]
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- Test of the QCD factorisation framework [beyond the DY $A_N$ sign change]

- Determination of the linearly polarised gluons in unpolarised protons
  [once measured, allows for spin physics without polarised proton, e.g. at the LHC]
Heavy-ion collisions towards large rapidities
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- A complete set of heavy-flavour studies between SPS and RHIC energies
  [needed to calibrate the quarkonium thermometer ($J/\psi, \psi', \chi_c, \Upsilon, D, J/\psi \leftrightarrow b + \text{pairs}$)]
Heavy-ion collisions from one colliding nucleus rest frame

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- Test the factorisation of cold nuclear effects from $p + A$ to $A + B$ collisions
Part III

A selection of projected performances

What is not covered by lack of time

- Azimuthal anisotropies
- Photon related observables
- $W$ boson
- Antiproton and related $x$-section measurements for astroparticle MC tuning
- C-even quarkonia

[Heavy-Ion, Spin]
[High-$x$, Spin, Heavy-Ion]
[High-$x$, Spin]
[High-$x$]
[High-$x$, Spin, Heavy-Ion]
Drell-Yan simulation

Unique acceptance (with a LHCb-like detector) compared to existing DY pA data used for nuclear PDF/fitted&E/seven.fitted/two.fitted@Fermilab).

Same acceptance for pp collisions

Extremely large yields up to x/two.fitted/one.fitted\[plot made for pXe with a Hermes-like target\]

Combinatorial background well under control

combinatorial background easily subtracted using the large like-sign yields

le/f_t over charm and beauty interesting on their own [although accessible by other means]

one could re/fine with mixing event techniques [needed for PbAsystems]

No existing measurements at RHIC (per 0.10)

2x0

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 M (GeV) (per 0.50)

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> 1.2 GeV/c, L = 100 pb µ T < 5, p lab µ µ = 115 GeV, 2 < Y s

Drell-Yan, pXe @ FNAL-E866

FNAL-E772

AFTER @ LHC sim

L = 100 pb

= 115 GeV

p + Xe, < 3 µ µ

2 < Y

s

> 1.2 GeV/c

µ T

p

M

4

4.5

5

5.5

6

6.5

7

7.5

8

Counts per 100 MeV/c

2

10

3

10

4

10

5

10

6

10

7

10

8

F

x

0.65

−0.6

−0.55

−0.5

−0.45

−0.4

−0.35

−0.3

−0.25

−0.2

−0.15

−0.1

−0.05

−0

0

DY signal

ccbar

bbbar

sum - MB bkg

-1
**Drell-Yan simulation**

- Unique acceptance (with a LHCb-like detector) compared to existing DY $pA$ data used for nuclear PDF fit (E866 & E772 @ Fermilab).

![Graph showing Drell-Yan simulation results](image-url)
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![Drell-Yan simulation plot]

**J.P. Lansberg (IPNO, Paris-Sud U.)
Gas target and AFTER@LHC**

March 1, 2017
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- No existing measurements at RHIC

![Drell-Yan simulation plot](image)

J.P. Lansberg (IPNO, Paris-Sud U.)
Drell-Yan performances for spin analyses

DY pair production on a transversely polarised target is the aim of several experiments (COMPASS, E/one.fitted/zero.fitted/three.fitted/nine.fitted, STAR, E/one.fitted/zero.fitted/three.fitted/nine.fitted)

Check the sign change in $A_N^{DYvsSIDIS}$: hot topic in spin physics!

With a highly polarised gas target, from an exploration phase to a consolidation phase

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Relevant parameters for existing and proposed polarized DY experiments.

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J.P. Lansberg (IPNO, Paris-Sud U.)

Gas target and AFTER@LHC
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March 1, 2017
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- New constraints on quark nPDF with DY in $pA$ collisions
Drell-Yan performances for nuclear matter analysis

- New constraints on quark nPDF with DY in $pA$ collisions
- Stat. uncertainties smaller than nPDF: discrimating power

[only 1 bin out of 5 shown; global syst. : $pp$ vs $pA$ lumi.]
Open heavy flavour: charm
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> [total x-section]

< [see below]
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- Looking at $D \to K\pi$ gives direct access to charm – anticharm asymmetries

![Graph showing D0 yield per year](image)

- Same yields for $D^0$
- $10 \text{ fb}^{-1}$ of $pp$ collisions at $\sqrt{s}=115$ GeV
- $<\epsilon> = 10\%$; $\text{Br}_{K\pi}=3.93\%$

$LHCb$ preliminary

$N_{D^0} = 6451 \pm 90$

$\sigma \sim 8$ MeV/$c^2$
Open charm projections

Longstanding debate in the QCD community: perturbative vs. non-perturbative origin

Relevant for cosmic neutrinos

[Not well constrained by lack of inputs]

Yield relative uncertainty due to $c(x)$

$P_{T,D0} (GeV)$

10 fb$^{-1}$ of pp collisions at $\sqrt{s}=115$ GeV

Syst.: 5%, $\epsilon > 10%; 2<y_D<3, Br_{K\pi}=3.93\%$

Coloured curves: yield uncert. from IC central $c(x)$ with scale uncert.

AFTER at LHC projected uncertainty

Differences in $A_{D/zero.fitted}$ and $A_{D/zero.fitted}\bar{N}$ gives access to $C$-odd correlators

[No other facility can measured this]

Precision at the percent level

$[GeV/c]$ $T_p$ $p_0$ $1$ $2$ $3$ $4$ $5$ $6$ $0$

$D$ $N$ $A$ $0.1$ $-0.05$ $-0$ $0.05$ $0.1$ $0.15$ $0.2$

Stat. unc. projection

$q$ [PRD 72 (2005)]

$g$ [JHEP 09 (2016)]

$g$ [pos. bound]

$= 10 fb$ $pp L = 115 GeV$

$P_{eff. pol.}$

SIDIS$^1$

As for $AA$ collisions, nuclear modification factors vs $P_{T,y,centrality}$ as well as azimuthal anisotropies ($v/two.fitted$) can be of course measured

[Not time to cover them]

J.P. Lansberg (IPNO, Paris-Sud U.)

Gas target and AFTER@LHC

March 1, 2017
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Yield relative uncertainty due to $c(x)$

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$= 10 \, \text{fb}^{-1}$
$p+p = 2.25$, CMS

$= 0.03 \pm 0.6$
$P_{\text{eff. pol.}}$

SIDIS$_1$ [GeV/c]

$T_p0$

$1 \, 2 \, 3 \, 4 \, 5 \, 6 \, 0$

$D \, N \, A$

$0.1 \, -0.05 \, -0 \, 0.05 \, 0.1 \, 0.15 \, 0.2$

---

As for $AA$ collisions, nuclear modification factors vs $p_T$, $y$, centrality as well as azimuthal anisotropies ($v_2/\text{fitted}$) can of course be measured [not time to cover them]
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Quarkonium Projections

Our aim is to measure a complete set of heavy-flavours to use them as tools [gluon luminometers (TMDs, PDFs, nPDFs), QGP effects]
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- In PbA collisions, one can repeat the celebrated $\Upsilon(nS)$ CMS analysis in a new energy domain

J.P. Lansberg (IPNO, Paris-Sud U.)
Gas target and AFTER@LHC
A\n\forall quarkonia (J ∼ ψ, ψ^œ, χ^c, Υ^nS, χ^b & η^c) can be measured

[Sofar, only J ∼ ψ by PHENIX with large uncertainties]

Also access on polarised neutron (/three.fitted) at the percent level!
Quarkonium Projections 2

- $A_N$ for all quarkonia ($J/\psi$, $\psi'$, $\chi_c$, $\Upsilon(nS)$, $\chi_b$ & $\eta_c$) can be measured
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![Graph showing $A_N$ vs. $x_F$ for $J/\psi$ and $\Upsilon$ with statistical uncertainties and projections.](image)
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- Completely new perspectives to study the gluon Sivers effect  
  [and beyond $\to L_g$]
A N for all quarkonia \((J/\psi, \psi', \chi_c, \Upsilon(nS), \chi_b & \eta_c)\) can be measured

[So far, only \(J/\psi\) by PHENIX with large uncertainties]

Also access on polarised neutron \((^3\text{He}^\uparrow)\) at the per cent level!

Completely new perspectives to study the gluon Sivers effect \([and beyond → \mathcal{L}_g]\)

Di-\(J/\psi\) allow one to study the \(k_T\) dependence of the gluon Sivers function for the very first time!
Part IV

Next steps
Next steps

- **2 ways towards fixed-target collisions with the LHC beams**
Next steps

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  - A slow extraction with a bent crystal with dense targets
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  - Similar luminosities; Better polarisation performances with a gas target; Different timeline, but likely complementary

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- Obviously, all this is also doable with a beamline in the long run, which probably adds up the possibility of secondary beams [TeV $\nu$ & $K$, $\pi$ and charm/beauty beams]
Part V

Backup slides
Further quarkonium projections

Hint from $\Upsilon$ data at RHIC

Strongly limited in terms of statistics

A quest for the gluon EMC effect with $J/\psi$ and $\phi$,

Strong $J/\psi$ signal in AuAu collisions

High statistics

Quarkonium production in $pA$ and $AA$ collisions

[production/suppression mechanisms]

J.P. Lansberg (IPNO, Paris-Sud U.)

Gas target and AFTER@LHC

March 1, 2017
Further quarkonium projections

- Large-$x$ gluon nPDF: unknown
- Gluon EMC effect: unknown

Hint from $\Upsilon$ data at RHIC

Strongly limited in terms of statistics

A quest for the gluon antishadowing with $J/\psi$ or $\chi_c$ statistical uncertainties are not even visible

A quest for the gluon EMC effect for bottom (onium)
Further quarkonium projections

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Further quarkonium projections

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- Gluon EMC effect: unknown
- Hint from \(\Upsilon\) data at RHIC
- Strongly limited in terms of statistics after 10 years of RHIC:
Further quarkonium projections

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- Hint from \( \Upsilon \) data at RHIC
- Strongly limited in terms of statistics after 10 years of RHIC:
- Quest for the gluon antishadowing with \( J/\psi \)

The statistical uncertainties are not even visible.

J.P. Lansberg (IPNO, Paris-Sud U.)

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March 1, 2017
Further quarkonium projections

- Large-\(x\) gluon nPDF: unknown
- Gluon EMC effect: unknown
- Hint from \(Y\) data at RHIC
- Strongly limited in terms of statistics after 10 years of RHIC:
- Quest for the gluon antishadowing with \(J/\psi\)
- Quest for the gluon EMC effect for bottom(onium)

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- One could access \(\eta_c\) production in \(pA\) collisions for the first time
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  - Quest for the gluon EMC effect for bottom(onium)
- One could access \( \eta_c \) production in \( pA \) collisions for the first time
- High stat. \( \rightarrow \) quarkonium polarization in \( pA \) and AA collisions

UPC in the fixed target mode and $J/\psi$ production

JPL, L. Massacrier, L. Szymanowski, J. Wagner
UPC in the fixed target mode and $J/\psi$ production

- $\gamma_p^{\text{beam}}_{\text{lab}} \approx 7450 \ (E_p = 7000 \text{ GeV})$
- $\gamma_{\text{lab}}^{\text{Pb \ beam}} \approx 2940 \ (E_{\text{Pb}} = 2760 \text{ GeV})$
- $E_{\gamma}^{\text{max}} \approx \gamma_{\text{lab}}^{\text{beam}} \times 30 \text{ MeV} \ (1/(R_{\text{Pb}} + R_p) \approx 30 \text{ MeV})$
UPC in the fixed target mode and $J/\psi$ production

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- $\gamma^{\text{Pb beam}}_{\text{lab}} \approx 2940$ ($E_{\text{Pb}} = 2760$ GeV)
- $E^\text{max}_\gamma \approx \gamma^\text{beam}_{\text{lab}} \times 30$ MeV ($1/(R_{\text{Pb}} + R_p) \approx 30$ MeV)
- $\sqrt{s_{\gamma p}} = \sqrt{2m_pE_\gamma}$ up to 20 GeV
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- $\sqrt{s_{\gamma p}} = \sqrt{2m_pE_{\gamma}} \text{ up to } 20 \text{ GeV}$
- $\mathcal{L}_{\text{PbH}} \dagger \approx 0.1 \text{ pb}^{-1}; \mathcal{L}_{\text{PH}} \dagger \approx 10 \text{ fb}^{-1}$
- $A_{N}^{\gamma p \rightarrow J/\psi p} \propto \sqrt{t_0 - t \text{Im}(E_{g}^*\mathcal{H}_{g})} \rightarrow \text{access to the GPD } E_{g} \text{ and the gluon OAM}$
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$$A_N^{\gamma p^+ \rightarrow J/\psi p} \propto \sqrt{t_0 - \text{Im}(\mathcal{E}_g^* \mathcal{H}_g)} \rightarrow \text{access to the GPD } E_g \text{ and the gluon OAM}$$

In the LHCb acceptance (muon cuts):

- $\sigma[pb^{1-\gamma} (\text{Pb}) J/\psi (p) \times \text{Br}(J/\psi \rightarrow \mu\mu)]$ via 1-photon exchanges : 16 nb
- $\sigma[pp^{1-\gamma} (p) J/\psi (p) \times \text{Br}(J/\psi \rightarrow \mu\mu)]$ via 1-photon exchanges : 34 pb
UPC in the fixed target mode and $J/\psi$ production

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- $A_{N}^{\gamma p \rightarrow J/\psi} \propto \sqrt{t_0 - t \text{Im}(\mathcal{E}^* \mathcal{H}^\gamma)} \rightarrow$ access to the GPD $E_\gamma$ and the gluon OAM

In the LHCb acceptance (muon cuts):

- $\sigma[\text{Pb}p \stackrel{1-\gamma}{\rightarrow} (\text{Pb}) J/\psi (p) \times \text{Br}(J/\psi \rightarrow \mu\mu)]$ via 1-photon exchanges : 16nb
- $\sigma[pp \stackrel{1-\gamma}{\rightarrow} (p) J/\psi (p) \times \text{Br}(J/\psi \rightarrow \mu\mu)]$ via 1-photon exchanges : 34pb
- 1600 dimuon events with the Pb beam [which we know for sure to be the $\gamma$ emitter]
- 340 000 dimuon events with the $p$ beam [each $p$ can emit; possible $\mathcal{O}^\perp$ contributions]
Heavy-Ion Physics


- **Lepton-pair production in ultraperipheral collisions at AFTER@LHC**

Further readings

Spin physics


Further readings

**Hadron structure**

- **Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC).**

- **Next-To-Leading Order Differential Cross-Sections for Jpsi, psi(2S) and Upsilon Production in Proton-Proton Collisions at a Fixed-Target Experiment using the LHC Beams (AFTER@LHC)**

- **$\eta_c$ production in photon-induced interactions at a fixed target experiment at LHC as a probe of the odderon**

- **A review of the intrinsic heavy quark content of the nucleon**

- **Hadronic production of $\Xi_{cc}$ at a fixed-target experiment at the LHC**
Further readings

Feasibility study and technical ideas


Simulations with Pythia 8.185

the LHCb detector is NOT simulated but LHCb reconstruction parameters are introduced in the fast simulation (resolution, analysis cuts, efficiencies,…)

Requirements:
- Momentum resolution: $\Delta p/p = 0.5\%$
- Muon identification efficiency: $98\%$

Cuts at the single muon level
- $2 < \eta_\mu < 5$
- $p_{T\mu} > 0.7$ GeV

Muon misidentification:
- If $\pi$ and $K$ decay before the calorimeters (12m), they are rejected by the tracking
- otherwise a misidentification probability is applied following: F. Achilli et al, arXiv:1306.0249