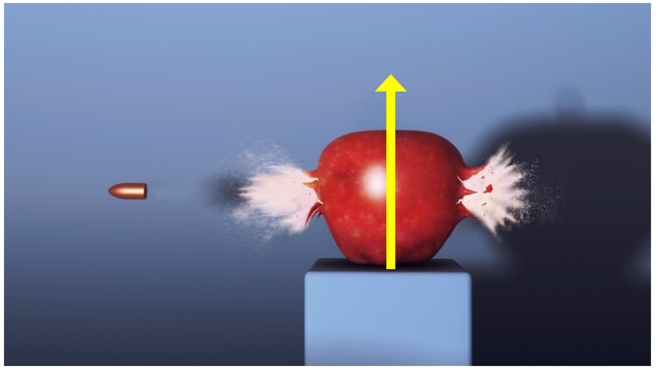
LHCspin Kick-off meeting
Ferrara – July 15-16 2019

Physics motivations for a PGT at the LHC

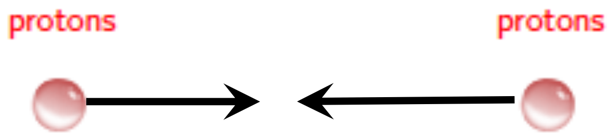


L.L. Pappalardo

(pappalardo@fe.infn.it)

Types of collisions at LHCb

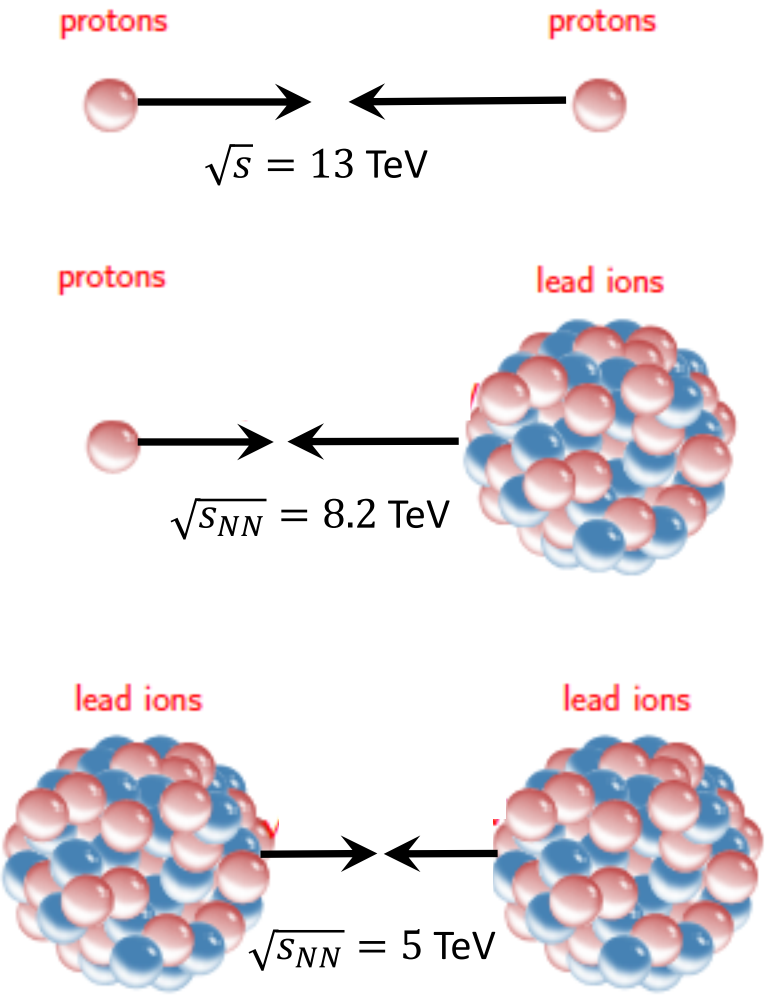
Collider mode



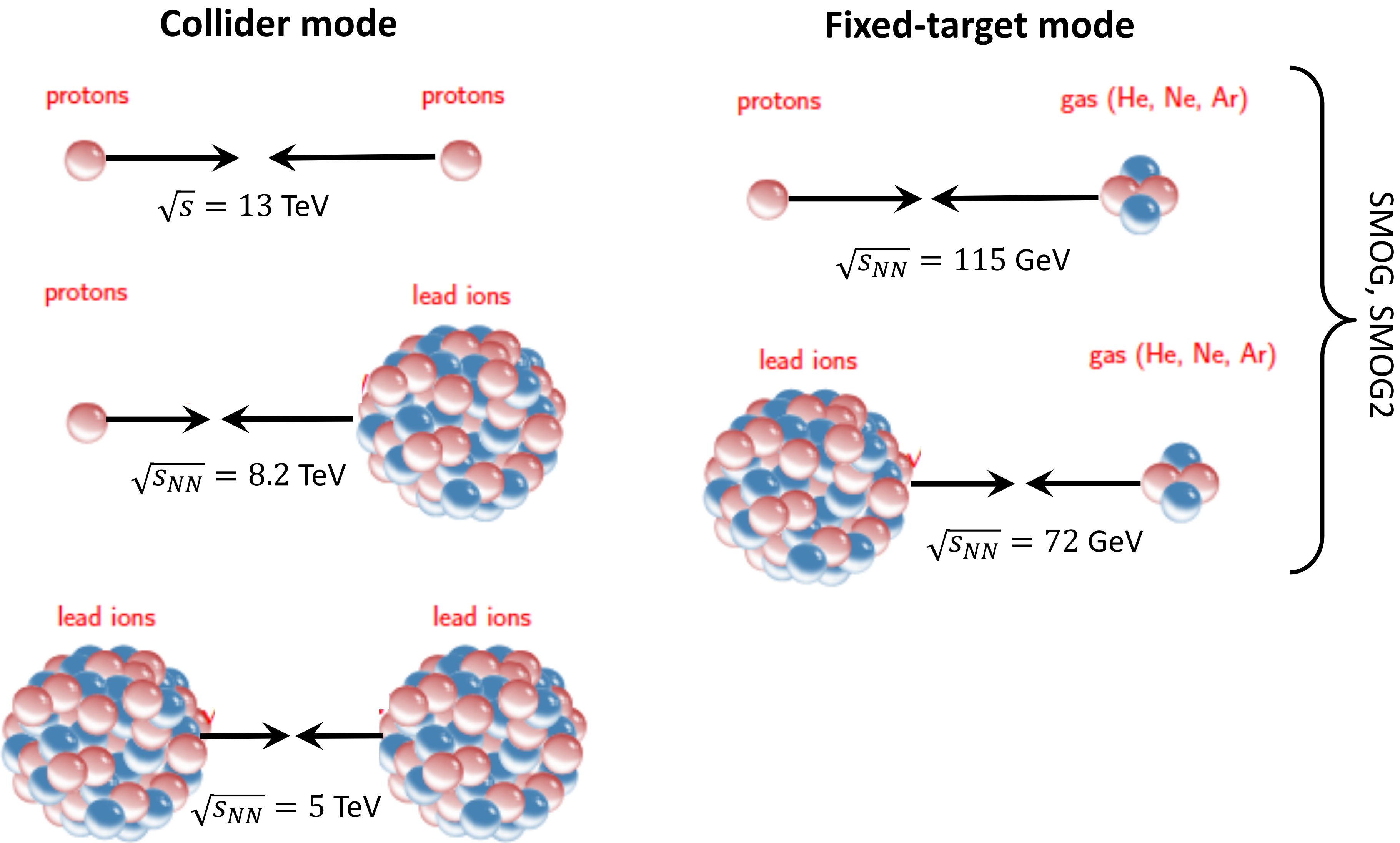
$\sqrt{s} = 13$ TeV

Types of collisions at LHCb

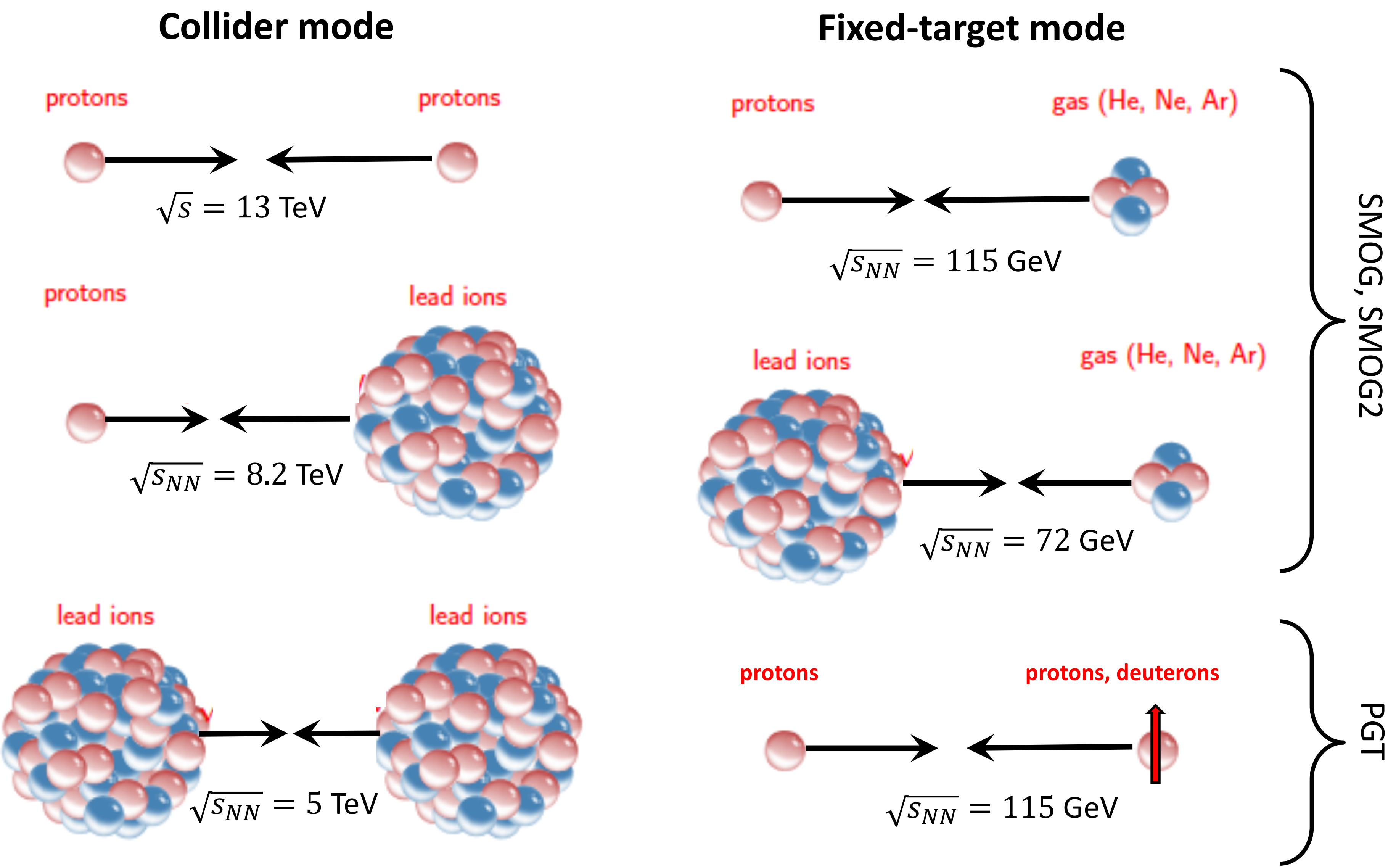
Collider mode



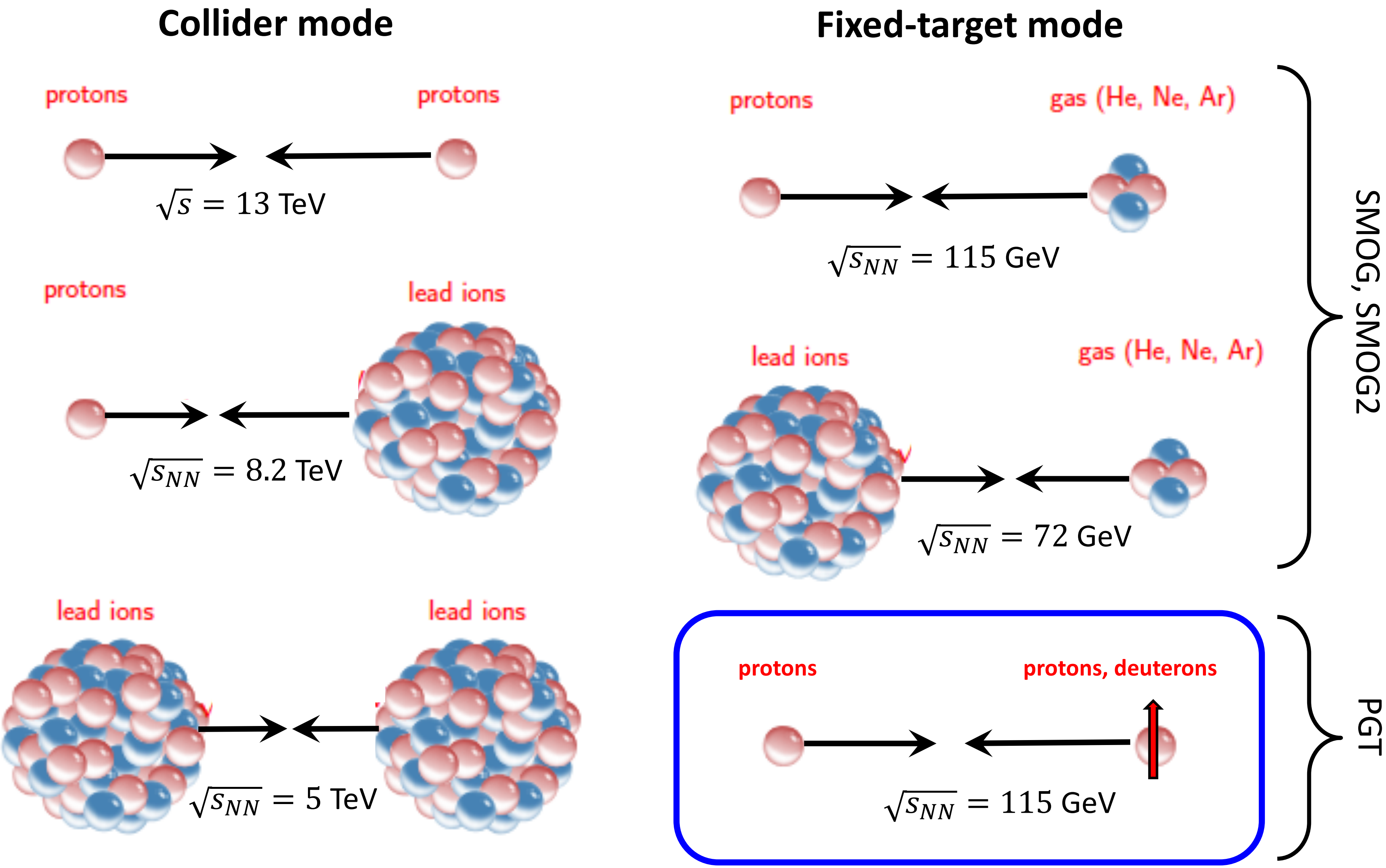
Types of collisions at LHCb



Types of collisions at LHCb

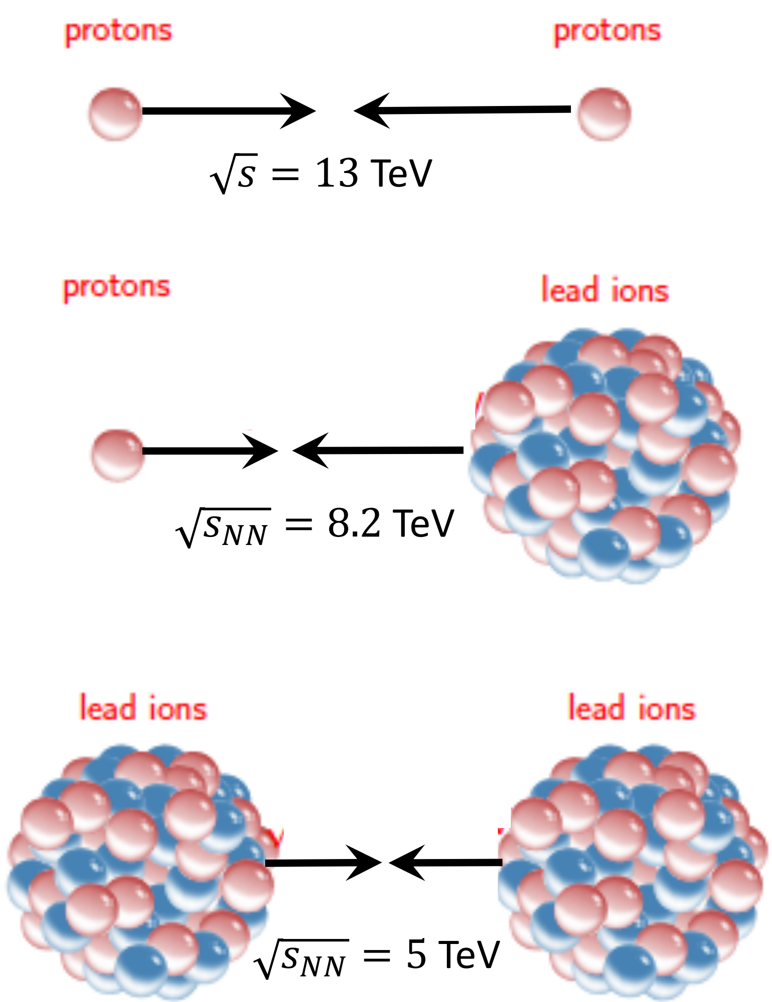


Types of collisions at LHCb

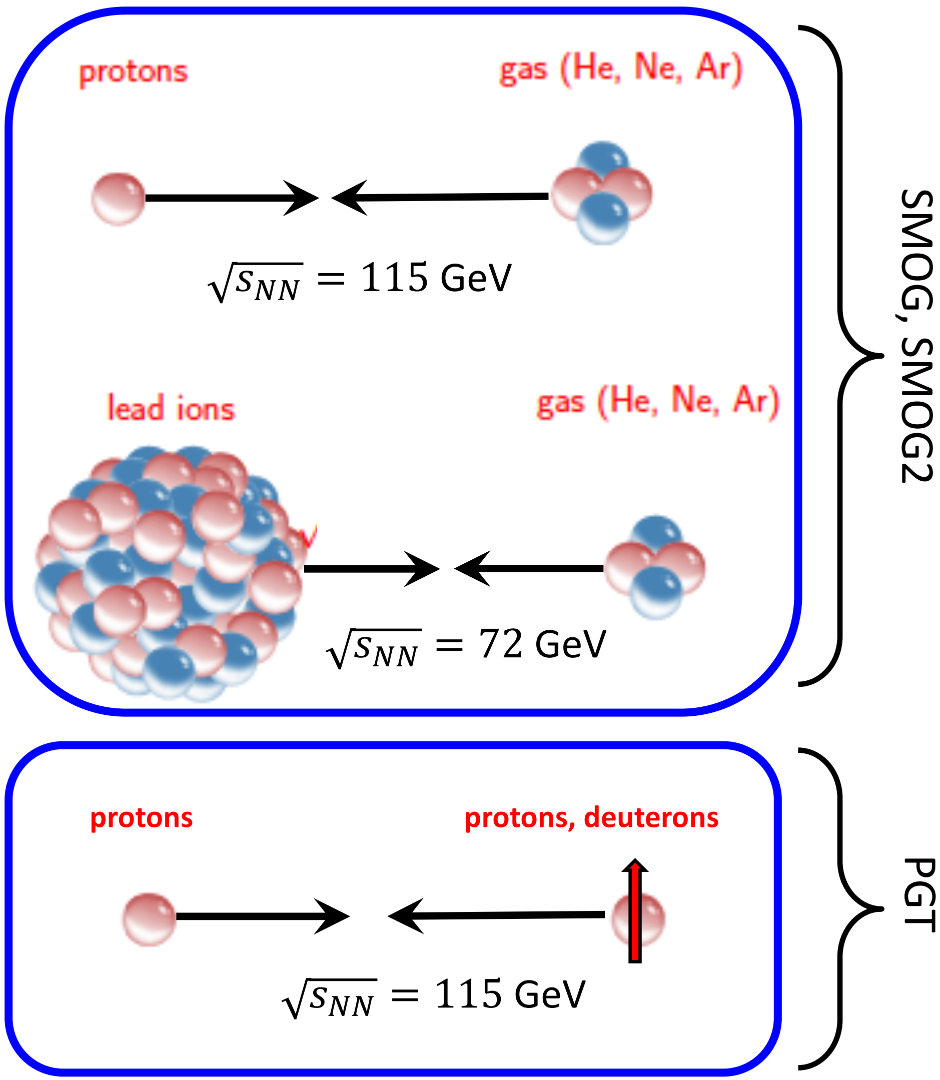


Types of collisions at LHCb

Collider mode



Fixed-target mode



Kinematic conditions for fixed-target collisions at LHC

$E_p = 7$ TeV $\Longrightarrow$ $\begin{cases} \sqrt{s_{NN}} = 115\ GeV \\ \gamma = \sqrt{s}/2m_p \approx 60 \end{cases}$ **CM strongly boosted in the lab system!**

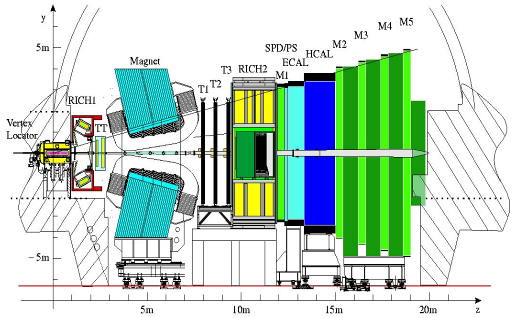
Kinematic conditions for fixed-target collisions at LHC

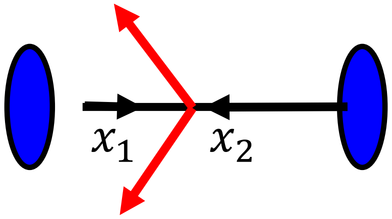
$E_p = 7$ TeV $\Rightarrow$ $\begin{cases} \sqrt{s_{NN}} = 115\ GeV \\ \gamma = \sqrt{s}/2m_p \approx 60 \end{cases}$ **CM strongly boosted in the lab system!**

$$\Delta y = y_{lab} - y_{CM} = 4.8$$

LHCb acceptance ($2 \lesssim y_{lab} \lesssim 5$) $\Rightarrow$ **CM backward rapidity region**

$$-3.0 \lesssim y_{CM} \lesssim 0$$





CM system

Kinematic conditions for fixed-target collisions at LHC

$E_p = 7$ TeV $\rightarrow$ $\begin{cases} \sqrt{s_{NN}} = 115\ GeV \\ \gamma = \sqrt{s}/2m_p \approx 60 \end{cases}$

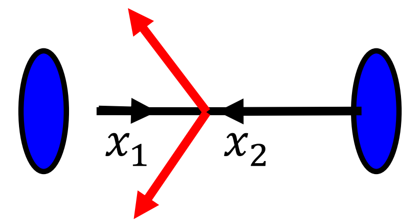
CM strongly boosted in the lab system!

$$\Delta y = y_{lab} - y_{CM} = 4.8$$

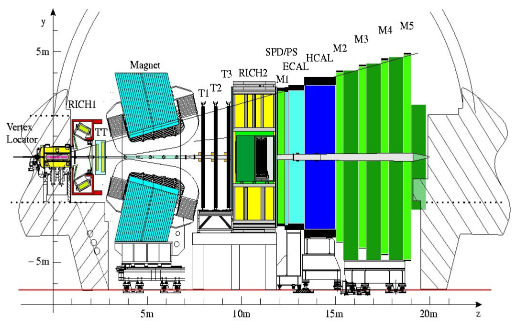
LHCb acceptance ($2 \lesssim y_{lab} \lesssim 5$) $\rightarrow$

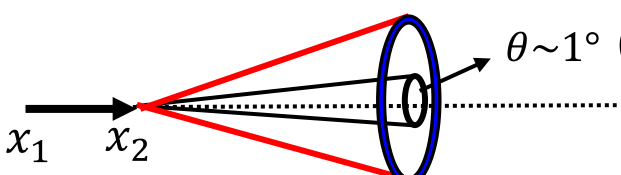
CM backward rapidity region

$$-3.0 \lesssim y_{CM} \lesssim 0$$



CM system





$\theta \sim 1°$ ($y_{CM} \approx 0$)

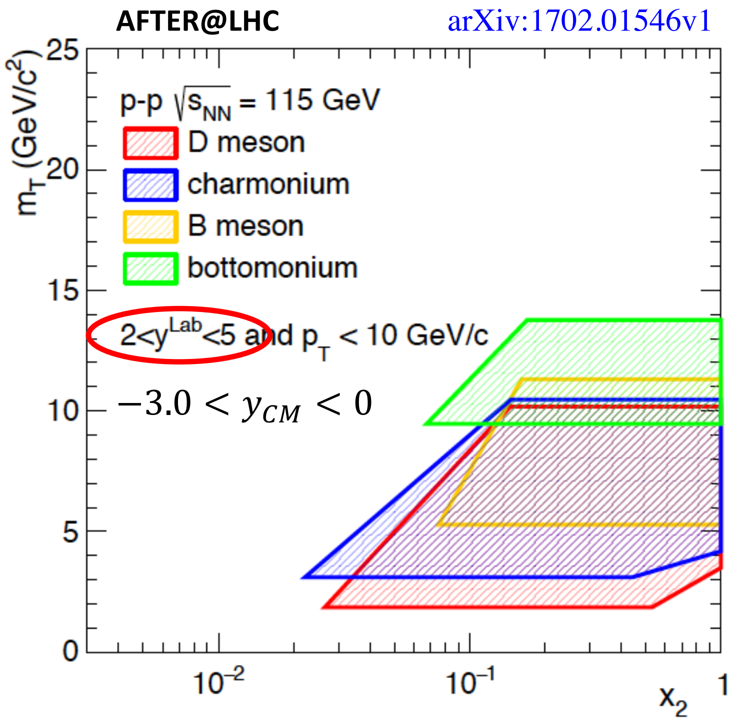
$\theta \sim 15°$ ($y_{CM} \approx -3$)

Lab system

- **In the fixed-target configuration LHCb allows to cover the Bkw CM region with reaction products at measurable forward angles.**
- **LHCb ideal detector to host a fixed target at the LHC!**

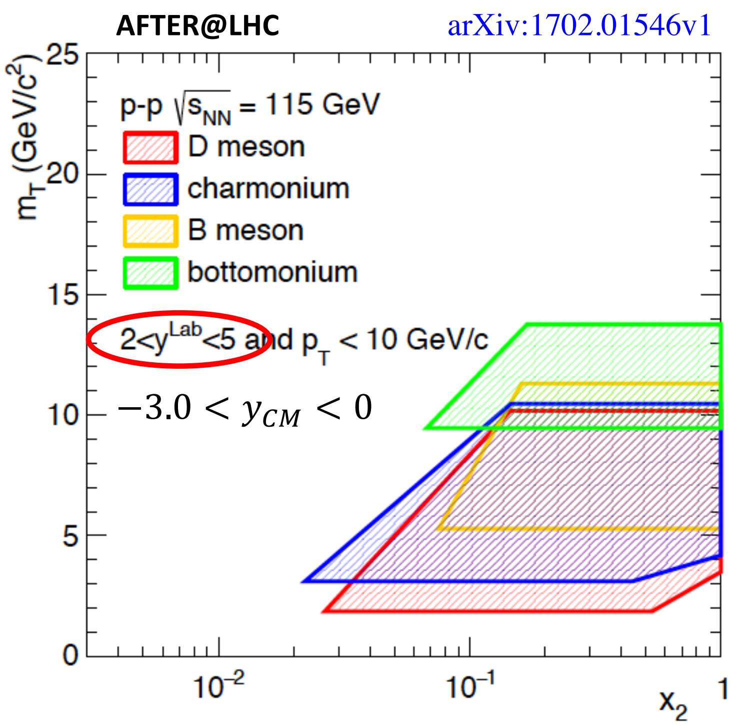
Kinematic conditions for fixed-target collisions at LHC

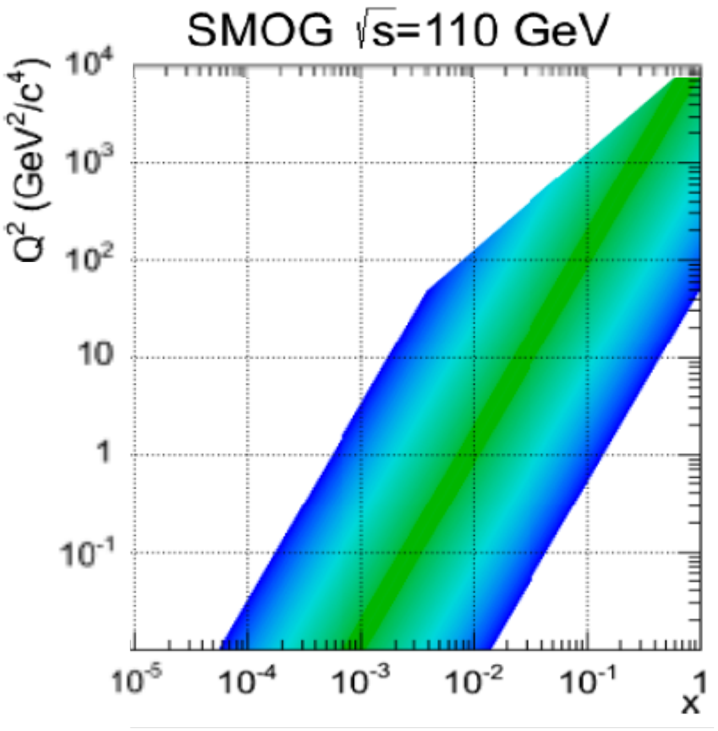
$$x_2 = \frac{m_T}{\sqrt{s}} e^{-y_{CM}} \qquad m_T = \sqrt{E^2 - p_T^2}$$



Kinematic conditions for fixed-target collisions at LHC

$$x_2 = \frac{m_T}{\sqrt{s}} e^{-y_{CM}} \qquad m_T = \sqrt{E^2 - p_T^2}$$

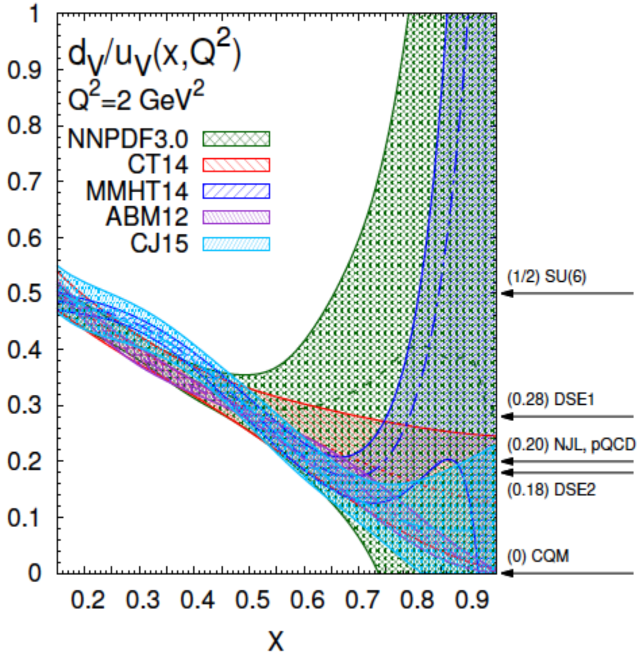




- **Sensitive to large x-Bjorken ($x_2 \rightarrow 1$) at intermediate Q^2**
- **Access to target-fragmentation region ($x_F \rightarrow -1$)**

Kinematic conditions for fixed-target collisions at LHC

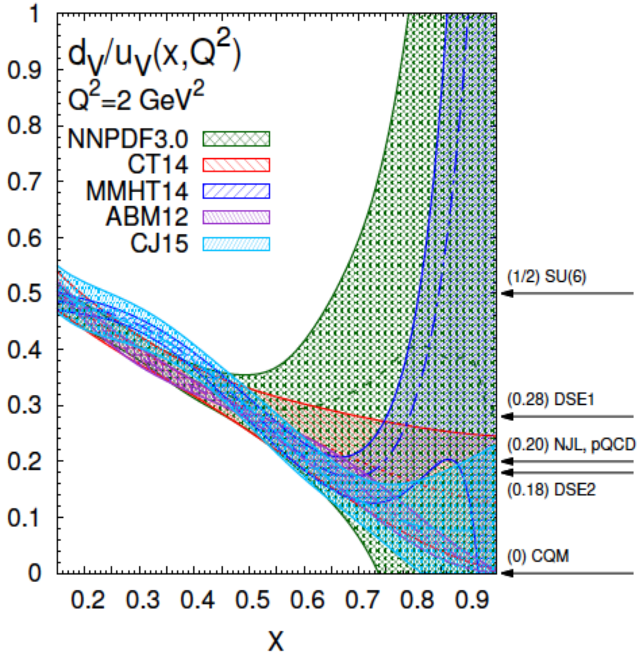
[R. D. Ball et al. Eur. Phys. J. C76 (2016) 383]

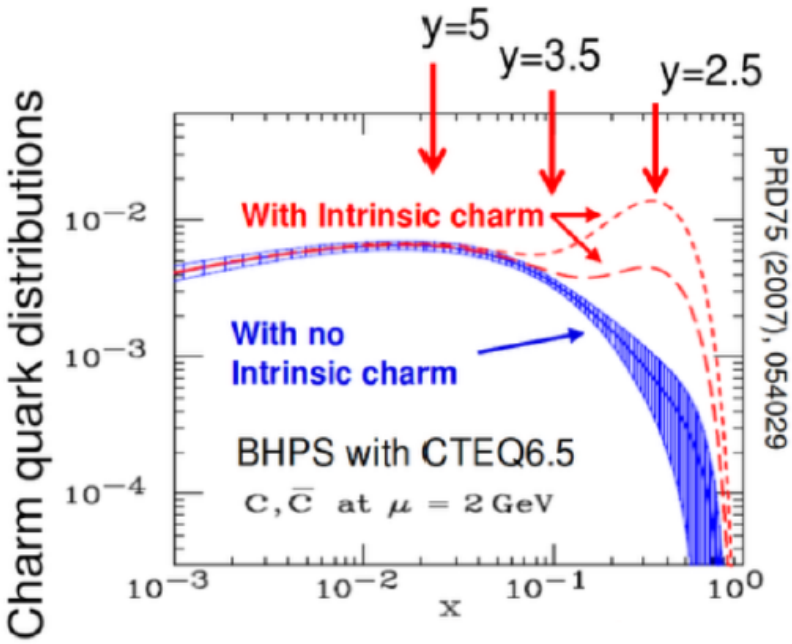


- **Sensitive to large x-Bjorken ($x_2 \to 1$)**
- **Access to target-fragmentation region ($x_F \to -1$)**

Kinematic conditions for fixed-target collisions at LHC

[R. D. Ball et al. Eur. Phys. J. C76 (2016) 383]





- ➢ **Sensitive to large x-Bjorken ($x_2 \to 1$)**
- ➢ **Access to target-fragmentation region ($x_F \to -1$)**
- ➢ **Sensitive to possible contribution of intrinsic charm**

Why a PGT at LHC?

✓ **Unique kinematic conditions**

Why a PGT at LHC?

✓ **Unique kinematic conditions**

✓ **Broad and ambitious physics program**

- study of 3D nucleon structure in a poorly explored kinematic domain
- complement SIDIS measurements of quark TMDs through Drell-Yan measurements
- first access to gluon TMDs (e.g. gluon Sivers function)
- fundamental tests of QCD (universality, factorization, etc)
- But also very interesting unpolarized physics:
  - study of cold nuclear matter effects (nPDFs, energy-loss and absorption, etc)
  - search for effects of intrinsic heavy quarks (e.g. “valence-like” charm in the proton)
  - heavy-ion physics (QGP formation, quarkonium sequential suppression)

Why a PGT at LHC?

✓ **Unique kinematic conditions**

✓ **Broad and ambitious physics program**

- study of 3D nucleon structure in a poorly explored kinematic domain
- complement SIDIS measurements of quark TMDs through Drell-Yan measurements
- first access to gluon TMDs (e.g. gluon Sivers function)
- fundamental tests of QCD (universality, factorization, etc)
- But also very interesting unpolarized physics:
  - study of cold nuclear matter effects (nPDFs, energy-loss and absorption, etc)
  - search for effects of intrinsic heavy quarks (e.g. "valence-like" charm in the proton)
  - heavy-ion physics (QGP formation, quarkonium sequential suppression)

✓ **Can run in parallel with normal collider mode (well displaced interaction region)**

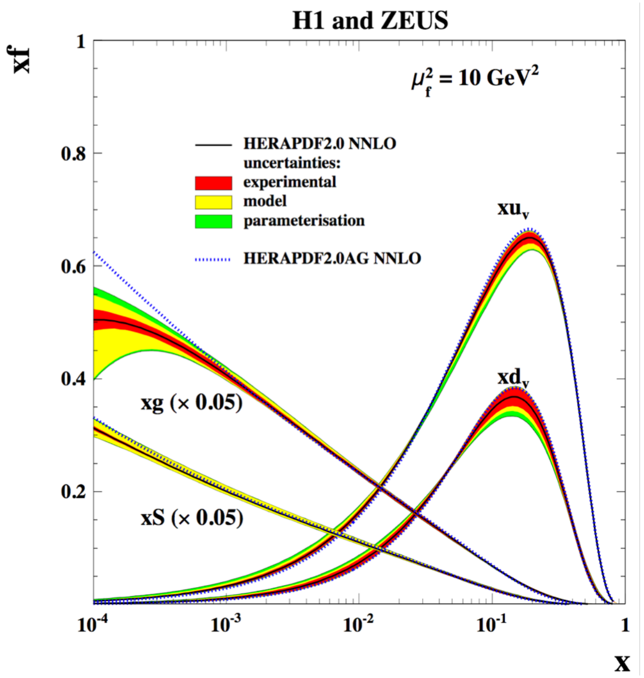
✓ **Marginal impact on LHC beam lifetime and LHCb mainstream physics program**

✓ **Polarized gas target technology well established (10 years @ HERMES)**

Studying the 3D structure of nucleons with fixed-target collisions at LHCb

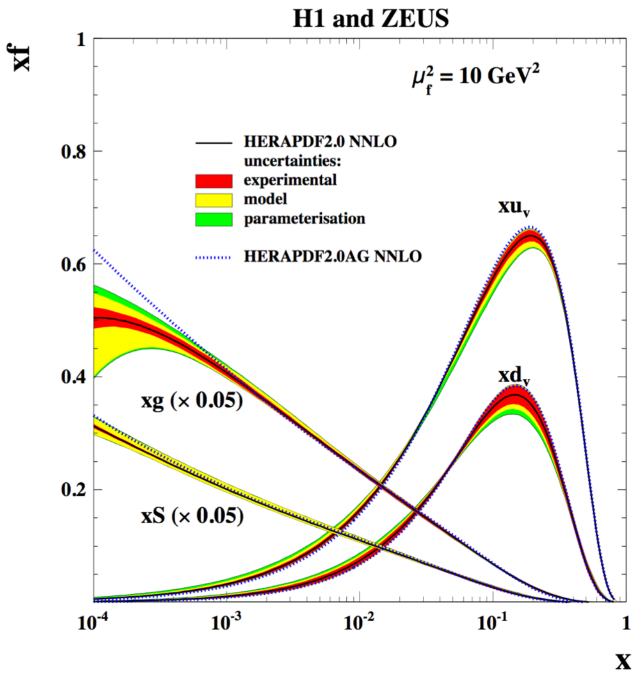
Accessing the nucleon structure

The present knowledge of the nucleon structure is dominated by **collinear (unpol.) PDFs**, measured with great precision in decades of DIS experiments

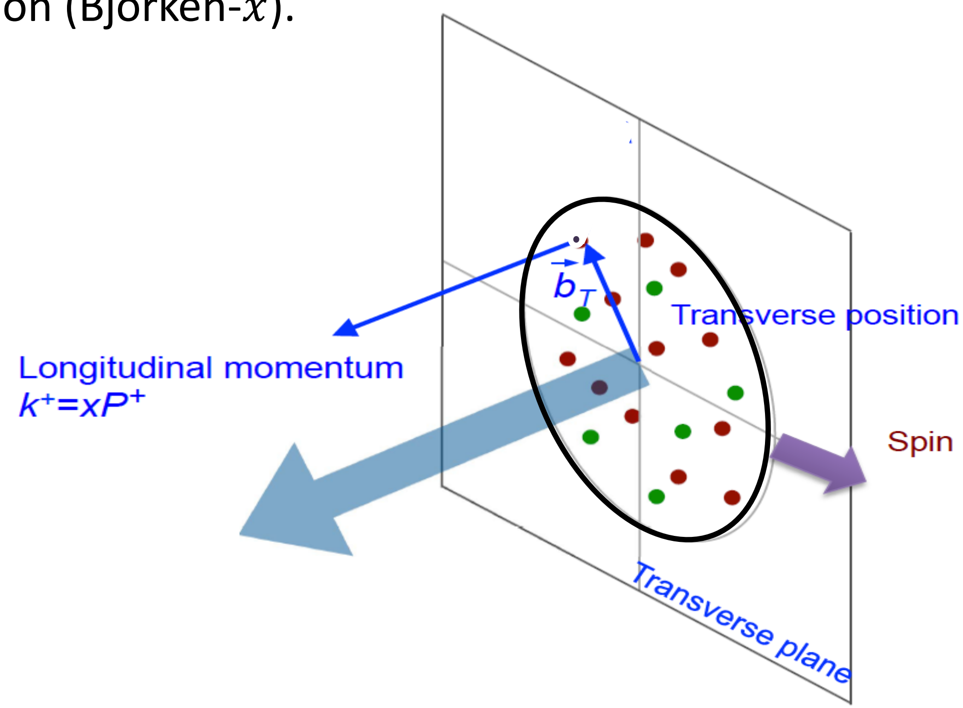


Accessing the nucleon structure

The present knowledge of the nucleon structure is dominated by **collinear (unpol.) PDFs**, measured with great precision in decades of DIS experiments

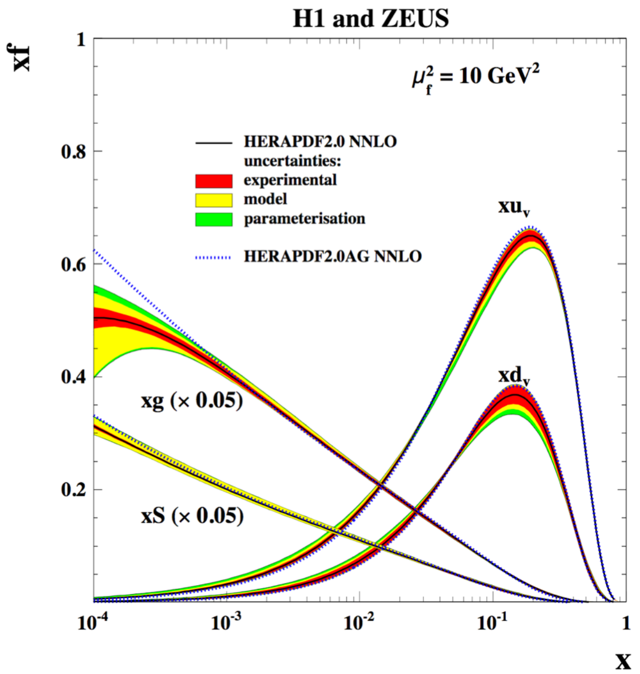


Despite the high level of accuracy, collinear PDFs provide only a 1-dim description of the nucleon structure, in terms of the parton long. momentum fraction (Bjorken-x).

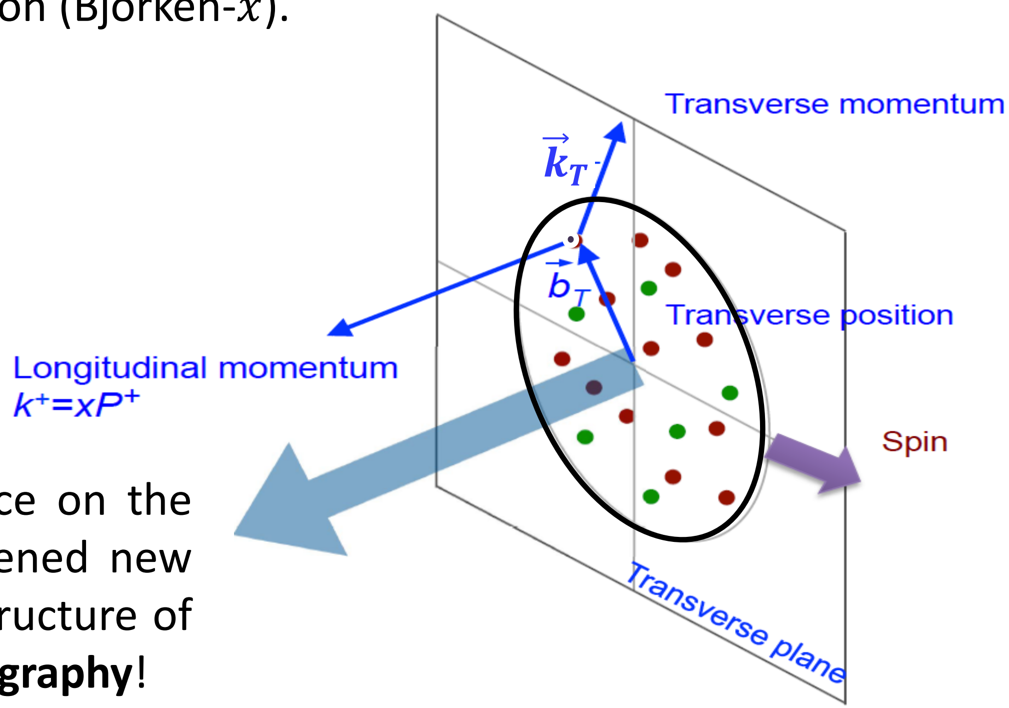


Accessing the nucleon structure

The present knowledge of the nucleon structure is dominated by **collinear (unpol.) PDFs**, measured with great precision in decades of DIS experiments



Despite the high level of accuracy, collinear PDFs provide only a 1-dim description of the nucleon structure, in terms of the parton long. momentum fraction (Bjorken-x).

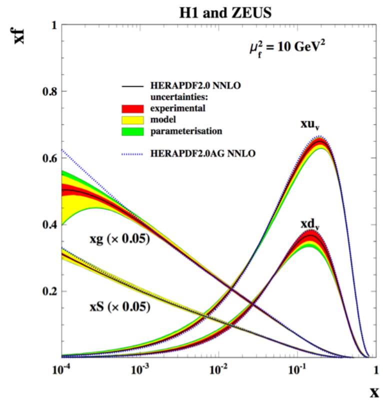


Considering also the explicit dependence on the parton transverse momenta k_T has opened new perspectives in the exploration of the structure of the nucleon! …**TMD PDFs**, **nucleon tomography**!

Mapping the nucleon structure

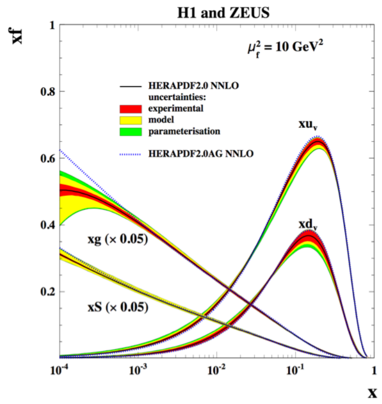
Collinear PDFs

1D

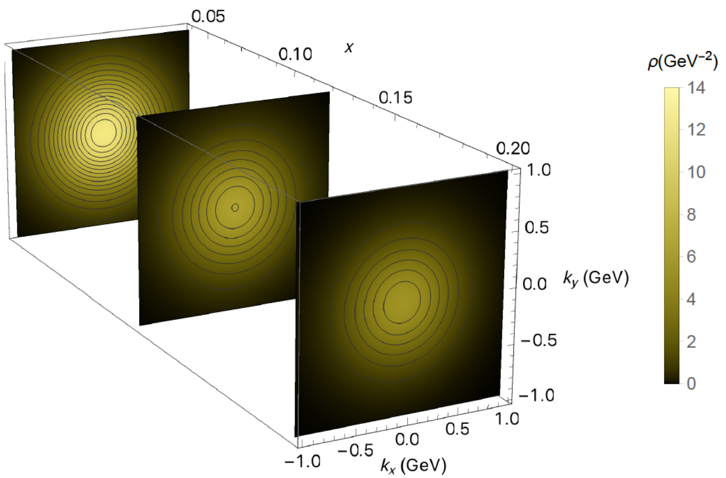


Mapping the nucleon structure

Collinear PDFs **1D**



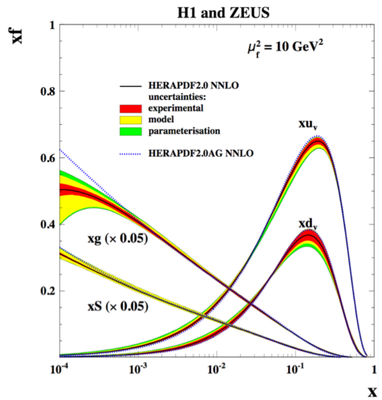
TMDs **3D**



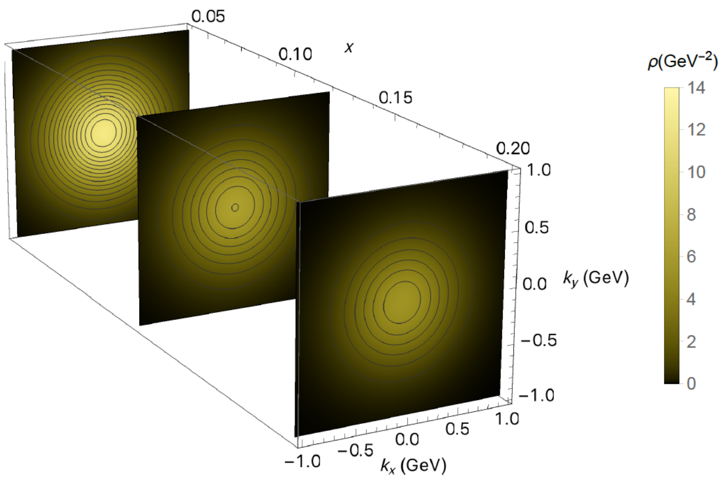
(Courtesy of A. Bacchetta)

Mapping the nucleon structure

Collinear PDFs — **1D**

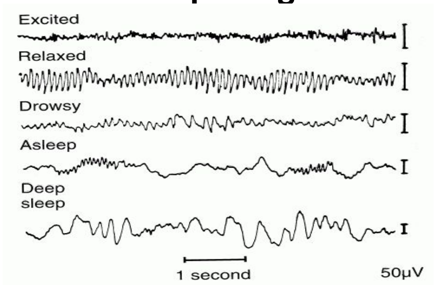


TMDs — **3D**

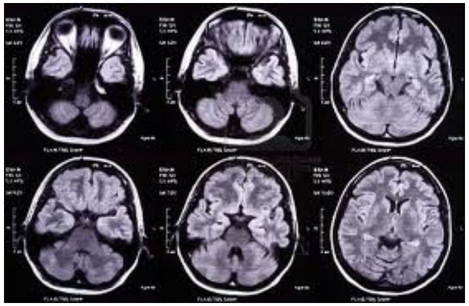


(Courtesy of A. Bacchetta)

1D **electroencephalograms**

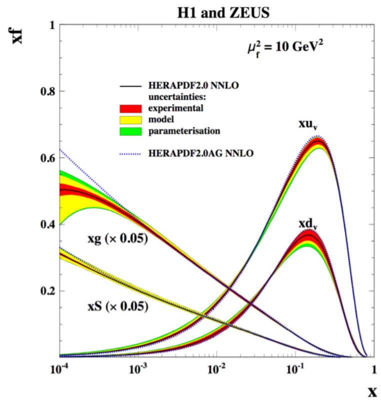


3D **NMR imaging**

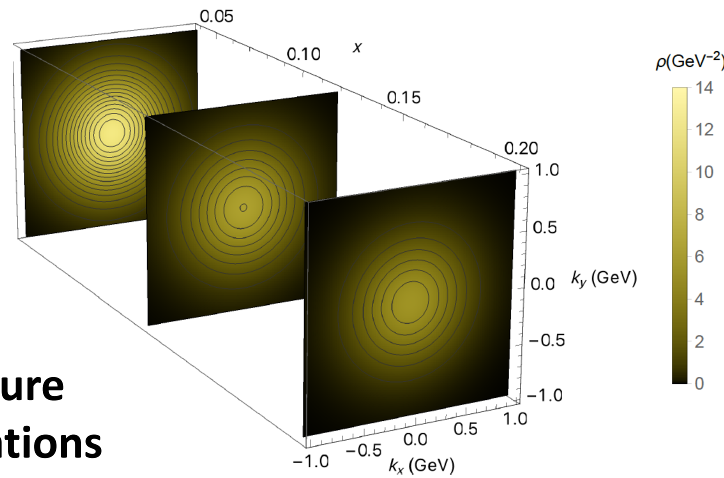


Mapping the nucleon structure …and more

Collinear PDFs — **1D**

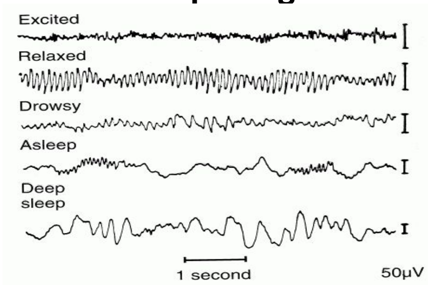


TMDs — **3D**

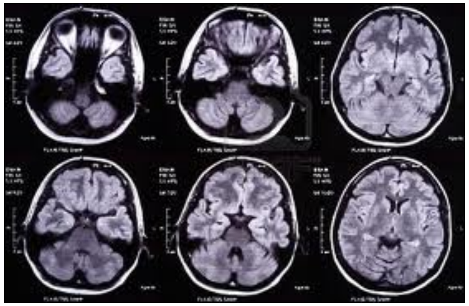


(Courtesy of A. Bacchetta)

1D **electroencephalograms**



3D **NMR imaging**



- **3D maps of nucleon structure**
- **Describe spin-orbit correlations**
- **Are sensitive to the parton OAM**
- **T-odd TMDs are process dependent (breaking of QCD universality!)**

The quark TMDs

		Quark TMDs		
		U	L	T
Hadron	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

- **8 independent TMDs at twist-2**
- **Each with a probabilistic interpretation in terms of parton densities**
- **Significant experimental progress in the last 15 years!**
- First extractions from global analyses

The quark TMDs

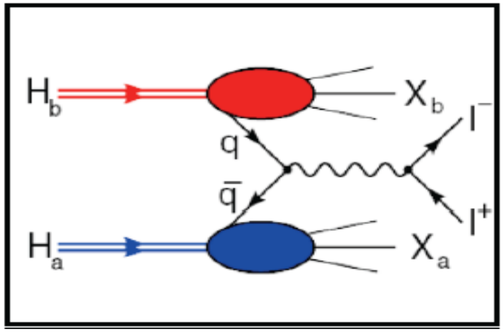
		Quark TMDs		
		U	L	T
Hadron	U	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1 $h_{1T}^{\perp}$

- **8 independent TMDs at twist-2**
- **Each with a probabilistic interpretation in terms of parton densities**
- **Significant experimental progress in the last 15 years!**
- First extractions from global analyses

- So far, main results obtained in **SIDIS** measurements (HERMES, COMPASS, JLAB)
- **Drell-Yan** in hadron-hadron collisions represents a complementary approach
- Unique kinematic region with fixed-target collisions at LHC
- Comparison of results from SIDIS and DY will allow to set stringent tests on QCD: factorization and universality

Probing the quark TMDs with a PGT at LHCb

Unpolarized Drell-Yan

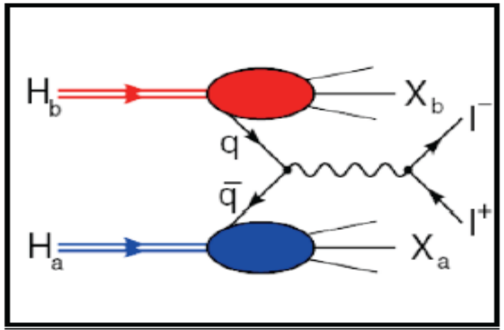


- Clean process
- LHCb has excellent reconstruction capabilities for $\mu\mu$ channel!

- Dominant process: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu\mu$

Probing the quark TMDs with a PGT at LHCb

Unpolarized Drell-Yan



- Clean process
- LHCb has excellent reconstruction capabilities for $\mu\mu$ channel!

- Dominant process: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu\mu$

- **Provides sensitivity to unpolarized and BM TMDs**

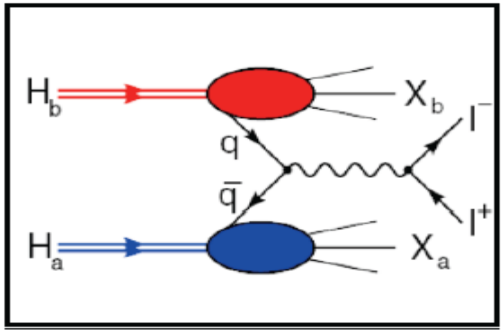
$$\sigma_{UU} \quad \propto \quad f_1 f_1 + \cos 2\phi \, h_1^{\perp} h_1^{\perp}$$

		Quark TMDs		
		U	**L**	**T**
Hadron	**U**	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Boer-Mulders funct. describes correlation between transverse spin and transverse momentum of quarks in unpol. nucleon

Probing the quark TMDs with a PGT at LHCb

Unpolarized Drell-Yan



- Clean process
- LHCb has excellent reconstruction capabilities for $\mu\mu$ channel!

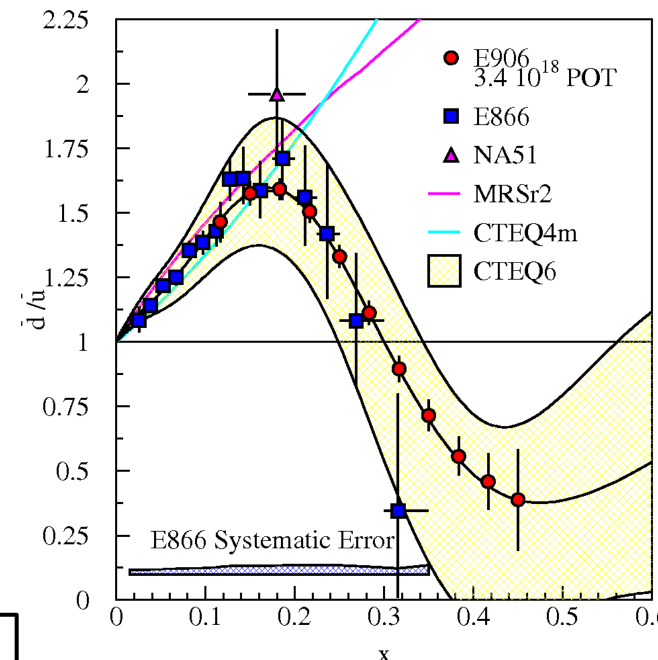
- Dominant process: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu\mu$
- **Provides sensitivity to unpolarized and BM TMDs**

$$\sigma_{UU} \propto f_1 f_1 + \cos 2\phi \, h_1^\perp h_1^\perp$$

Hadron	Quark TMDs: U	Quark TMDs: L	Quark TMDs: T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Boer-Mulders funct. describes correlation between transverse spin and transverse momentum of quarks in unpol. nucleon

- Using fixed H and D targets allows to study the **antiquark content of the nucleon!**

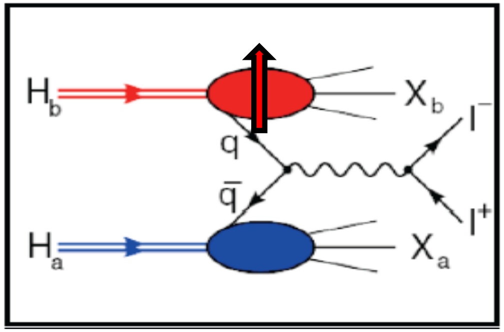


$\bar{d}(x) \neq \bar{u}(x)$!!

- hints that: $\bar{s}(x) \neq s\,(x)$
- **sea is not flavour symmetric!**
- **intrinsic sea quarks**?

Probing the quark TMDs with a PGT at LHCb

Polarized Drell-Yan

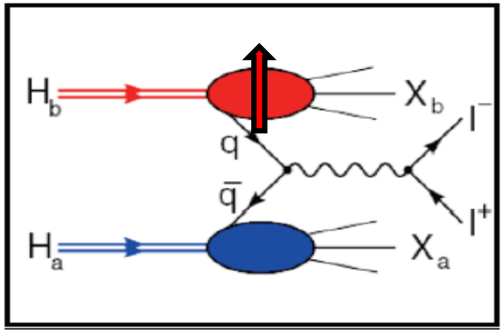


Sensitive to quark TMDs up to high $x_2^{\uparrow}$ through TSSAs

$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}}$$

Probing the quark TMDs with a PGT at LHCb

Polarized Drell-Yan



Sensitive to quark TMDs up to high $x_2^{\uparrow}$ through TSSAs

$$A_N^{DY} = \frac{1}{P} \frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}}$$

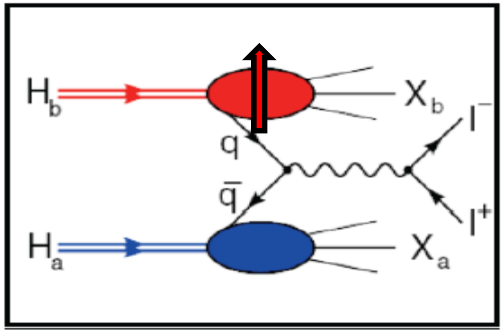
$$A_{UT}^{\sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{\sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{\sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}$$

(ϕ: azimuthal orientation of lepton pair in dilepton CM)

		Quark TMDs		
		U	L	T
Hadron	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

Probing the quark TMDs with a PGT at LHCb

Polarized Drell-Yan



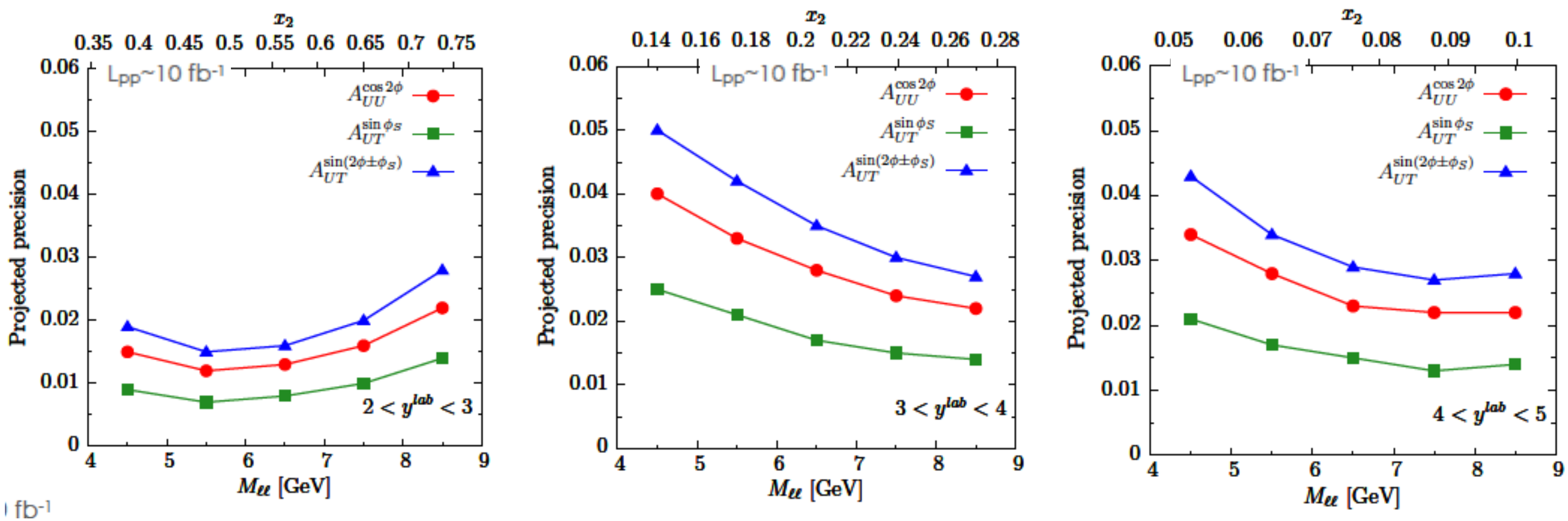
Sensitive to quark TMDs up to high $x_2^{\uparrow}$ through TSSAs

$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}}$$

$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}$$

(ϕ: azimuthal orientation of lepton pair in dilepton CM)

arXiv:1807.00603
and J.P.Lansberg, PBC CERN 2018



Probing the gluon TMDs with a PGT at LHCb

		**Gluon TMDs**		
		Unpol	Circularly pol.	Linearly pol.
Hadron	**U**	f_1^g		$h_1^{\perp g}$
	L		g_1^g	$h_{1L}^{\perp g}$
	T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g $h_{1T}^{\perp g}$

Theory framework consolidated

...but experimental access still extremely limited!

Note: gluons with non-zero p_T inside an unpolarized hadron can be linearly polarized!

Probing the gluon TMDs with a PGT at LHCb

Hadron	Gluon TMDs: Unpol	Gluon TMDs: Circularly pol.	Gluon TMDs: Linearly pol.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g $h_{1T}^{\perp g}$

Theory framework consolidated

…but experimental access still extremely limited!

Note: gluons with non-zero p_T inside an unpolarized hadron can be linearly polarized!

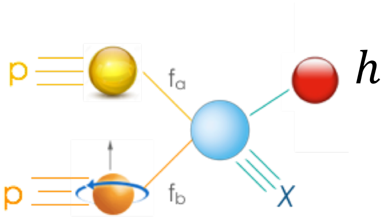
Gluon Sivers function:

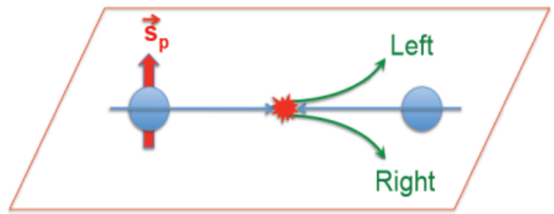
- sheds light on spin-orbit correlations of gluons inside the proton
- sensitive to gluon orbital angular momentum!
- first hints by RHIC and COMPASS, but still basically unknown!

Probing the gluon TMDs with a PGT at LHCb

Main observables in pol. hadron collisions: **Single Transverse Spin Asymmetries (TSSAs)**

Polarized inclusive hard scattering



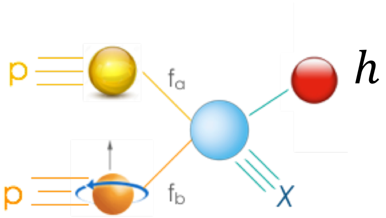


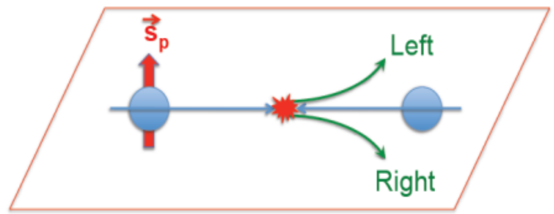
$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}}$$

Probing the gluon TMDs with a PGT at LHCb

Main observables in pol. hadron collisions: **Single Transverse Spin Asymmetries (TSSAs)**

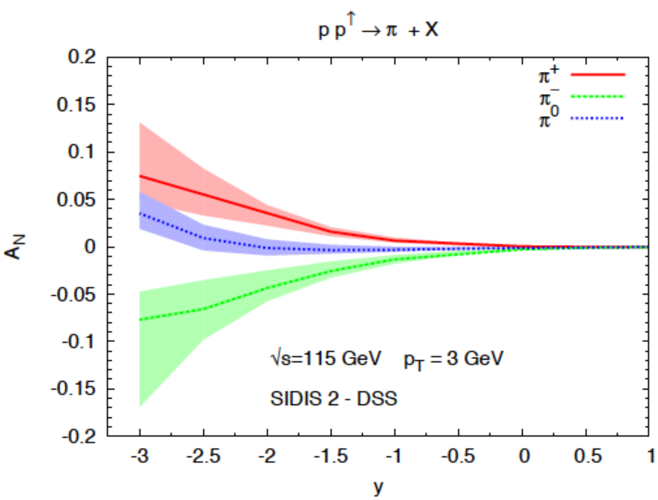
Polarized inclusive hard scattering



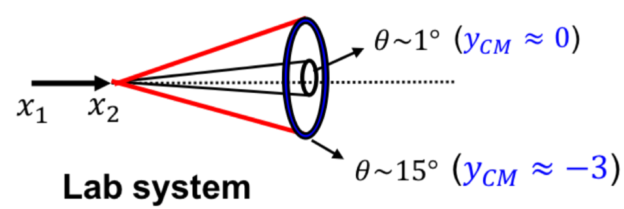


$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}}$$

Anselmino et al. arXiv:1504.03791v2)



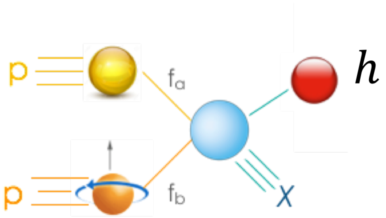
- **Asymmetries above 10 %! Big signature!!**
- The effect increases with more negative CM rapidity
- Nicely matches the LHCb acceptance with fixed target at LHC

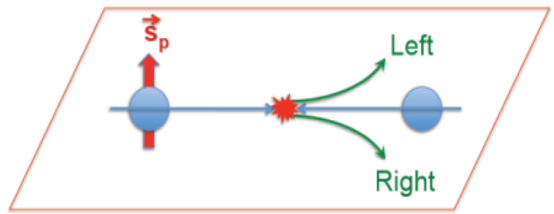


Probing the gluon TMDs with a PGT at LHCb

Main observables in pol. hadron collisions: **Single Transverse Spin Asymmetries (TSSAs)**

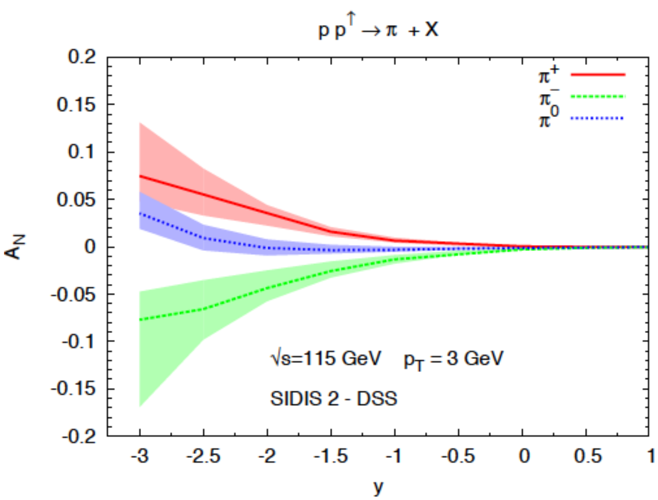
Polarized inclusive hard scattering



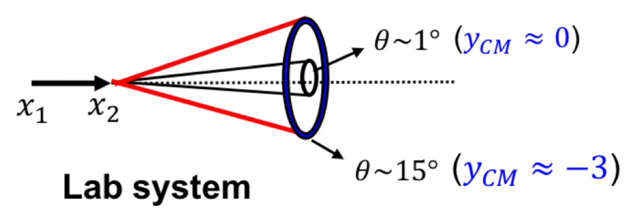


$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}}$$

Anselmino et al. arXiv:1504.03791v2)



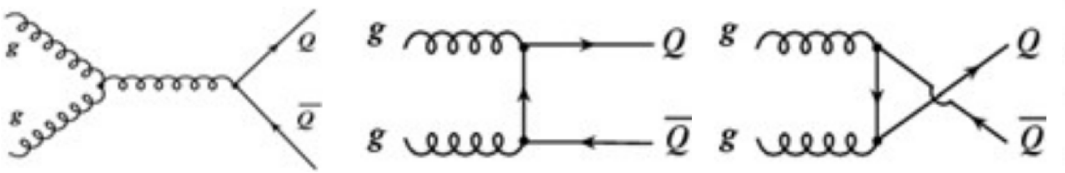
- **Asymmetries above 10 %! Big signature!!**
- The effect increases with more negative CM rapidity
- Nicely matches the LHCb acceptance with fixed target at LHC



- Inclusive pion production provides mainly sensitivity to the quark PDFs.
- **The most efficient way to get sensitivity to the gluon PDFs is through heavy-flavour observables.**

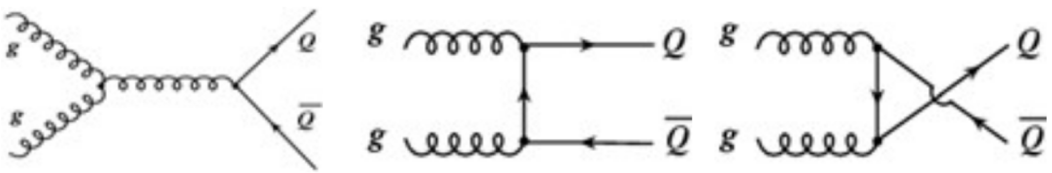
Probing the gluon TMDs with a PGT at LHCb

In high-energy hadron collisions heavy quarks dominantly produced through gg interactions:

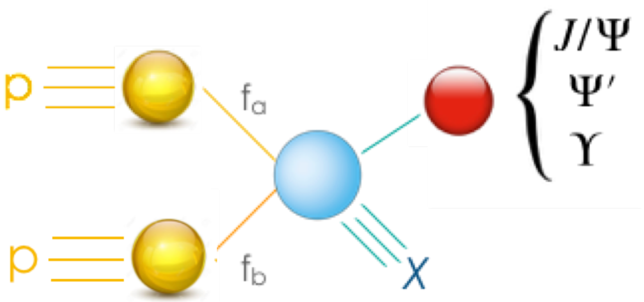


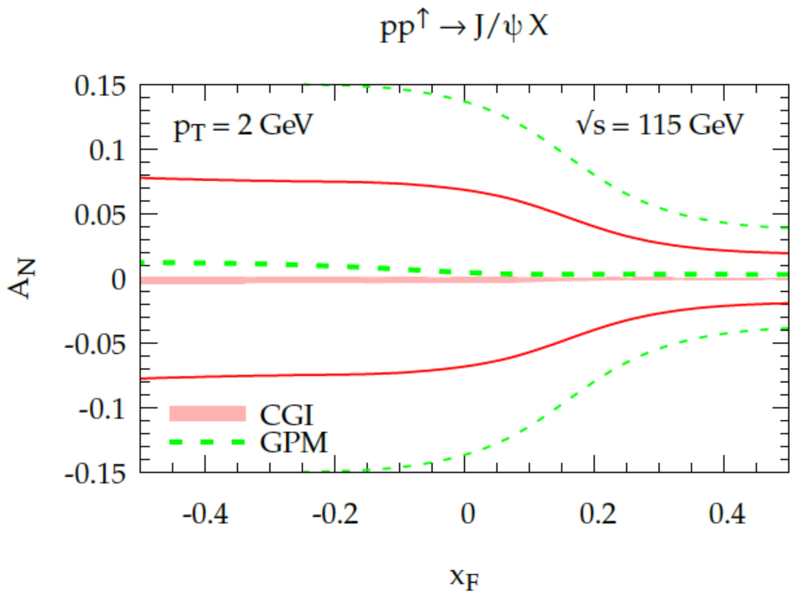
Probing the gluon TMDs with a PGT at LHCb

In high-energy hadron collisions heavy quarks dominantly produced through gg interactions:



Inclusive quarkonia production in pp interaction turns out to be an ideal **gluon-sensitive observable!**





Phys. Rev. D 99, 036013 (2019)

Probing the gluon TMDs with a PGT at LHCb

The measured TSSAs can be related to the convolution of the gluon Sivers function for the target proton and the unpolarized gluon pdf for the beam proton:

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg \to QQg}\right] \sin\phi_S + \cdots$$

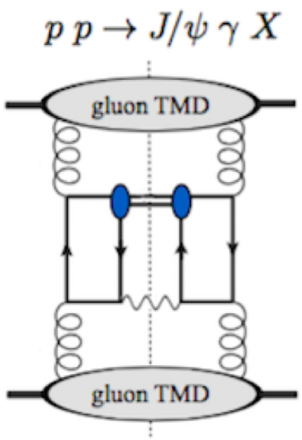
Probing the gluon TMDs with a PGT at LHCb

The measured TSSAs can be related to the convolution of the gluon Sivers function for the target proton and the unpolarized gluon pdf for the beam proton:

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg\to Q Q g}\right] \sin\phi_S + \cdots$$

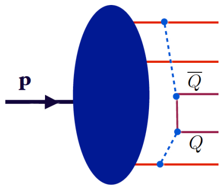
Caveat: TMD factorization requires $p_T(Q) \ll M_Q$. At LHC one can look at **back-to-back production of quarkonia and isolated photon or associate quarkonia production**, where only the relative p_T has to be small:

$$\mathrm{pp} \to \mathrm{J}/\psi + \gamma + \mathrm{X} \qquad \mathrm{pp} \to \Upsilon + \gamma + \mathrm{X} \qquad \mathrm{pp} \to \mathrm{J}/\psi + \mathrm{J}/\psi + \mathrm{X}$$



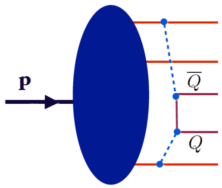
More physics reach with unpolarized FT reactions

- **Intrinsic heavy-quark** **[S.J. Brodsky et al.,** Adv.High Energy Phys. 2015 (2015) 231547]
  - 5-quark Fock state of the proton may contribute at high x!
  - **charm PDFs** at large x could be larger than obtained from conventional fits



More physics reach with unpolarized FT reactions

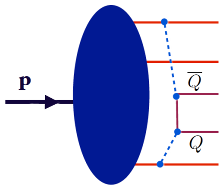
- **Intrinsic heavy-quark** **[S.J. Brodsky et al.,** Adv.High Energy Phys. 2015 (2015) 231547]
  - 5-quark Fock state of the proton may contribute at high x!
  - **charm PDFs** at large x could be larger than obtained from conventional fits



- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x**)
  - studies of parton energy-loss and absorption phenomena in the cold medium

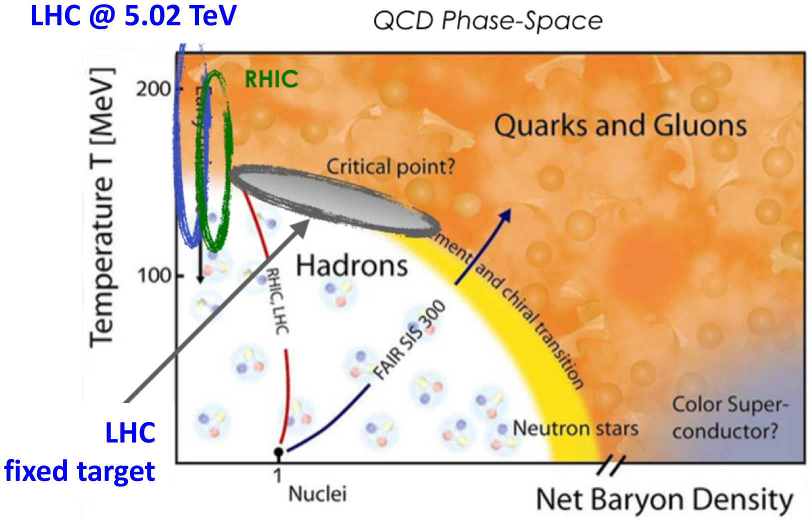
More physics reach with unpolarized FT reactions

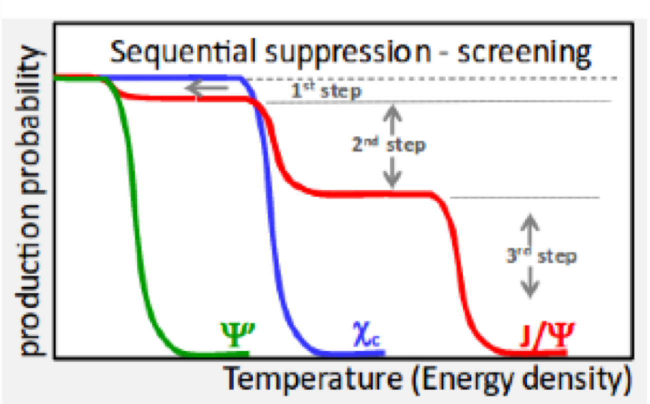
- **Intrinsic heavy-quark** **[S.J. Brodsky et al.,** Adv.High Energy Phys. 2015 (2015) 231547]
  - 5-quark Fock state of the proton may contribute at high x!
  - **charm PDFs** at large x could be larger than obtained from conventional fits



- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x**)
  - studies of parton energy-loss and absorption phenomena in the cold medium

- **PbA collisions at $\sqrt{s_{NN}} \approx 72$ GeV** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - Study of **QGP formation** (search for predicted **sequential quarkonium suppression**)





$c\bar{c}$ states: J/ψ, χ_c, ψ',...
Different binding energy, different dissociation temp.

Main reactions or interest (…an incomplete wishlist)

- $pp \rightarrow \mu^+\mu^- + X \quad (pp \rightarrow e^+e^- + X)$
- $pd \rightarrow \mu^+\mu^- + X \quad (pd \rightarrow e^+e^- + X)$

☛ **unpolarized TMDs of valence and sea quarks and momentum distrib. of sea quarks**

Main reactions or interest (…an incomplete wishlist)

- $pp \rightarrow \mu^+\mu^- + X \quad (pp \rightarrow e^+e^- + X)$
- $pd \rightarrow \mu^+\mu^- + X \quad (pd \rightarrow e^+e^- + X)$

☛ **unpolarized TMDs of valence and sea quarks and momentum distrib. of sea quarks**

- $pp^\uparrow \rightarrow \mu^+\mu^- + X \quad (pp^\uparrow \rightarrow e^+e^- + X)$
- $pd^\uparrow \rightarrow \mu^+\mu^- + X \quad (pd^\uparrow \rightarrow e^+e^- + X)$

☛ **TMDs of valence and sea quarks**

Main reactions or interest (…an incomplete wishlist)

- $pp \rightarrow \mu^+\mu^- + X \quad (pp \rightarrow e^+e^- + X)$
- $pd \rightarrow \mu^+\mu^- + X \quad (pd \rightarrow e^+e^- + X)$

☛ **unpolarized TMDs of valence and sea quarks and momentum distrib. of sea quarks**

- $pp^\uparrow \rightarrow \mu^+\mu^- + X \quad (pp^\uparrow \rightarrow e^+e^- + X)$
- $pd^\uparrow \rightarrow \mu^+\mu^- + X \quad (pd^\uparrow \rightarrow e^+e^- + X)$

☛ **TMDs of valence and sea quarks**

- $pp^{(\uparrow)} \rightarrow \eta_c + X \quad (pp^{(\uparrow)} \rightarrow \chi_{c,b} + X)$
- $pp^{(\uparrow)} \rightarrow J/\psi + X$
- $pp^{(\uparrow)} \rightarrow \Upsilon + X$
- $pp^{(\uparrow)} \rightarrow J/\psi + J/\psi + X$
- $pp^{(\uparrow)} \rightarrow J/\psi + \gamma + X$
- $pp^{(\uparrow)} \rightarrow \Upsilon + \gamma + X$

☛ **Pol and unpol gluon PDFs**

Main reactions or interest (…an incomplete wishlist)

- $pp \rightarrow \mu^+\mu^- + X \quad (pp \rightarrow e^+e^- + X)$
- $pd \rightarrow \mu^+\mu^- + X \quad (pd \rightarrow e^+e^- + X)$

☛ **unpolarized TMDs of valence and sea quarks and momentum distrib. of sea quarks**

- $pp^{\uparrow} \rightarrow \mu^+\mu^- + X \quad (pp^{\uparrow} \rightarrow e^+e^- + X)$
- $pd^{\uparrow} \rightarrow \mu^+\mu^- + X \quad (pd^{\uparrow} \rightarrow e^+e^- + X)$

☛ **TMDs of valence and sea quarks**

- $pp^{(\uparrow)} \rightarrow \eta_c + X \quad (pp^{(\uparrow)} \rightarrow \chi_{c,b} + X)$
- $pp^{(\uparrow)} \rightarrow J/\psi + X$
- $pp^{(\uparrow)} \rightarrow \Upsilon + X$
- $pp^{(\uparrow)} \rightarrow J/\psi + J/\psi + X$
- $pp^{(\uparrow)} \rightarrow J/\psi + \gamma + X$
- $pp^{(\uparrow)} \rightarrow \Upsilon + \gamma + X$

☛ **Pol and unpol gluon PDFs**

- pA, PbA $(A = He, Ne, Ar, Kr, \ldots)$

☛ **Nuclear matter effects, QGP, etc**

Projected luminosity for the PGT (Run4)

PGT

- $I_0 = 6.5 \cdot 10^{16} s^{-1}$
- C_{tot} = 13.90 l/s
- θ= 7.02 $\cdot 10^{13}$/cm^2

Projected luminosity for the PGT (Run4)

PGT

- $I_0 = 6.5 \cdot 10^{16} s^{-1}$
- C_{tot} = 13.90 l/s
- **θ= 7.02 $\cdot 10^{13}$/cm^2**

Beam

- $2.2 \cdot 10^{11}$ p/bunch
- 2760 bunches
- $I_{beam} = 6.8 \cdot 10^{18}\ p/s$

Projected luminosity for the PGT (Run4)

PGT

- $I_0 = 6.5 \cdot 10^{16} s^{-1}$
- C_{tot} = 13.90 l/s
- θ= 7.02 $\cdot 10^{13}/cm^2$

Beam

- $2.2 \cdot 10^{11}$ p/bunch
- 2760 bunches
- $I_{beam} = 6.8 \cdot 10^{18}\ p/s$

- $L_{pH}(T_{cell} = 300\ K) = 4.8 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $L_{pH}(T_{cell} = 100\ K) = 8.3 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Projected luminosity for the PGT (Run4)

PGT

- $I_0 = 6.5 \cdot 10^{16} s^{-1}$
- C_{tot} = 13.90 l/s
- θ = 7.02 $\cdot 10^{13}$/cm^2

Beam

- $2.2 \cdot 10^{11}$ p/bunch
- 2760 bunches
- $I_{beam} = 6.8 \cdot 10^{18}\ p/s$

Result:

- $L_{pH}(T_{cell} = 300\ K) = 4.8 \cdot 10^{32}\ \mathrm{cm^{-2}s^{-1}}$
- $L_{pH}(T_{cell} = 100\ K) = 8.3 \cdot 10^{32}\ \mathrm{cm^{-2}s^{-1}}$

- Instantaneous luminosity for PGT in Run4 $\sim \times$ 20-40 higher than for SMOG2 in Run3
- But significant distance from VELO (→ additional tracker is mandatory)

Conclusions

- A polarized fixed target at LHCb will open the way to a broad and ambitious physics program at unique kinematic conditions.

Conclusions

- A polarized fixed target at LHCb will open the way to a broad and ambitious physics program at unique kinematic conditions.
- Novel approaches and reactions will be exploited for studies of the 3D nucleon structure in terms of transvserse-momentum-dependent PDF.

Conclusions

- A polarized fixed target at LHCb will open the way to a broad and ambitious physics program at unique kinematic conditions.
- Novel approaches and reactions will be exploited for studies of the 3D nucleon structure in terms of transvserse-momentum-dependent PDF.
- First insights into the yet unknown gluon TMDs (such as the gluon Sivers funcions) will be possible thanks to the excellent capabilities of LHCb in reconstructing quarkonia states and heavy mesons.

Conclusions

- A polarized fixed target at LHCb will open the way to a broad and ambitious physics program at unique kinematic conditions.
- Novel approaches and reactions will be exploited for studies of the 3D nucleon structure in terms of transvserse-momentum-dependent PDF.
- First insights into the yet unknown gluon TMDs (such as the gluon Sivers funcions) will be possible thanks to the excellent capabilities of LHCb in reconstructing quarkonia states and heavy mesons.
- Comparison of quarks and gluons TMDs results with analogous results from SIDIS experiments or from a future EIC will shed light on the process-dependence (breaking of QCD universality) of T-odd TMDs (find more details in backup slides).

Conclusions

- A polarized fixed target at LHCb will open the way to a broad and ambitious physics program at unique kinematic conditions.
- Novel approaches and reactions will be exploited for studies of the 3D nucleon structure in terms of transvserse-momentum-dependent PDF.
- First insights into the yet unknown gluon TMDs (such as the gluon Sivers funcions) will be possible thanks to the excellent capabilities of LHCb in reconstructing quarkonia states and heavy mesons.
- Comparison of quarks and gluons TMDs results with analogous results from SIDIS experiments or from a future EIC will shed light on the process-dependence (breaking of QCD universality) of T-odd TMDs (find more details in backup slides).
- Cutting-edge unpolarized physics will also be at reach (cold nuclear matter effects, intrinsic charm, QGP studies, etc.) by injecting unpolarized nuclear targets.

Conclusions

- A polarized fixed target at LHCb will open the way to a broad and ambitious physics program at unique kinematic conditions.
- Novel approaches and reactions will be exploited for studies of the 3D nucleon structure in terms of transvserse-momentum-dependent PDF.
- First insights into the yet unknown gluon TMDs (such as the gluon Sivers funcions) will be possible thanks to the excellent capabilities of LHCb in reconstructing quarkonia states and heavy mesons.
- Comparison of quarks and gluons TMDs results with analogous results from SIDIS experiments or from a future EIC will shed light on the process-dependence (breaking of QCD universality) of T-odd TMDs (find more details in backup slides).
- Cutting-edge unpolarized physics will also be at reach (cold nuclear matter effects, intrinsic charm, QGP studies, etc.) by injecting unpolarized nuclear targets.

If approved, this project will bring for the first time spin physics to the LHC, and LHCb will become the first experiment simultaneously running in collider and fixed-target mode with polarized targets, opening a whole new range of explorations.

Backup

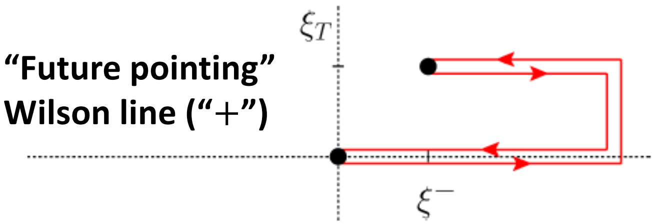
Probing the gluon PDFs

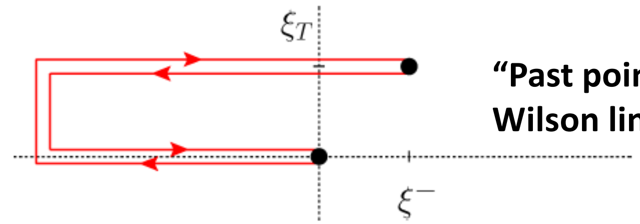
As for quark TMDs, also the gluon TMD phenomenology is enriched by the **process dependence** originating from ISI/FSI and encoded in the **gauge links**.

The gluon correlator depends on two path-dependent gauge links [D. Boer: arXiv:1611.06089]

$$\Gamma^{\mu\nu\,[\mathcal{U},\mathcal{U}']}(x,\boldsymbol{k}_T) \equiv \int \frac{d(\xi\cdot P)\,d^2\xi_T}{(P\cdot n)^2(2\pi)^3}\, e^{i(xP+k_T)\cdot\xi}\langle P|\mathrm{Tr}_c\left[F^{n\nu}(0)\,\mathcal{U}_{[0,\xi]}\,F^{n\mu}(\xi)\,\mathcal{U}'_{[\xi,0]}\right]|P\rangle$$

"Future pointing" Wilson line ("+")





"Past pointing" Wilson line ("−")

Both f_1^g and $h_1^{\perp g}$ are process dependent! Each of them can be of two types:

[+ +] = [− −] Weizsacker-Williams (WW) [+ −] = [− +] DiPole (DP)

- **can differ in magnitude and width (!)**
- **can be probed by different processes**

Probing the gluon PDFs

[D. Boer: arXiv:1611.06089]

	DIS	DY	SIDIS	$pA \to \gamma\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$f_1^{g\,[+,+]}$ (WW)	×	×	×	×	√	√	√
$f_1^{g\,[+,-]}$ (DP)	√	√	√	√	×	×	×

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp\,g\,[+,+]}$ (WW)	√	×	√	√	√
$h_1^{\perp\,g\,[+,-]}$ (DP)	×	√	×	×	×

Can be measured at the EIC

Can be measured at the LHC (and in particular at LHCb with SMOG2)

Process dependence of the GSF

Two independent gluon Sivers functions can be defined from the different combinations of Wilson lines in the gluon correlator:

$f_{1T}^{\perp g[+,+]}$ **"f-type"** → antisymmetric colour structures

$f_{1T}^{\perp g[+,-]}$ **"d-type"** → symmetric colour structures

Can differ in magnitude and width (!)

Can be probed by different processes:

[D. Boer: arXiv:1611.06089, D. Boer et al. HEPJ 08 2016 001]

	DY	SIDIS	$p^\uparrow A \to h\,X$	$p^\uparrow A \to \gamma^{(*)}\,\text{jet}\,X$	$p^\uparrow p \to \gamma\,\gamma\,X$ $p^\uparrow p \to J/\psi\,\gamma\,X$ $p^\uparrow p \to J/\psi\,J/\psi\,X$	$e\,p^\uparrow \to e'\,Q\,\overline{Q}\,X$ $e\,p^\uparrow \to e'\,j_1\,j_2\,X$
$f_{1T}^{\perp\,g\,[+,+]}$ (WW)	×	×	×	×	√ (LHCb with a PGT)	√ (EIC)
$f_{1T}^{\perp\,g\,[+,-]}$ (DP)	√	√	√ (LHCb with a PGT)	√ (LHCb with a PGT)	×	×

Can be measured at the EIC — Can be measured at the LHCb with a PGT

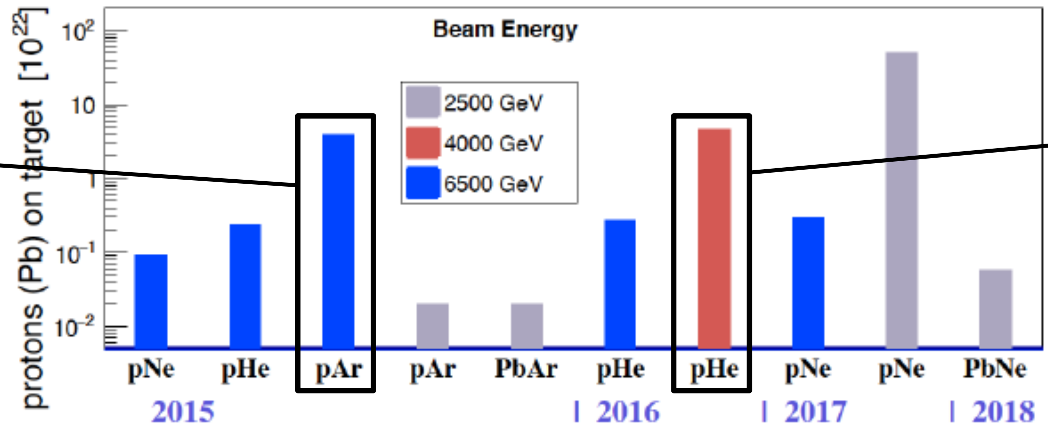
$$[+,+] \longleftrightarrow \quad f_{1T}^{\perp\,g[e\,p^\uparrow\to e'\,Q\bar{Q}\,X]}(x,p_T^2) = -f_{1T}^{\perp\,g[p^\uparrow\,p\to\gamma\,\gamma\,X]}(x,p_T^2) \quad \longleftrightarrow [-,-]$$

Same sign-change relation expected for the other T-odd gTMDs h_1^g and $h_{1T}^{\perp g}$!

How well can we reconstruct quarkonia and heavy mesons at LHCb in fixed-target mode?

LHCb recently reported the first measurement of J/ψ **and** D^0 **production** in fixed-target configuration using **p-He** and **p-Ar** collisions with SMOG

$\sqrt{s_{NN}} = 110$ GeV

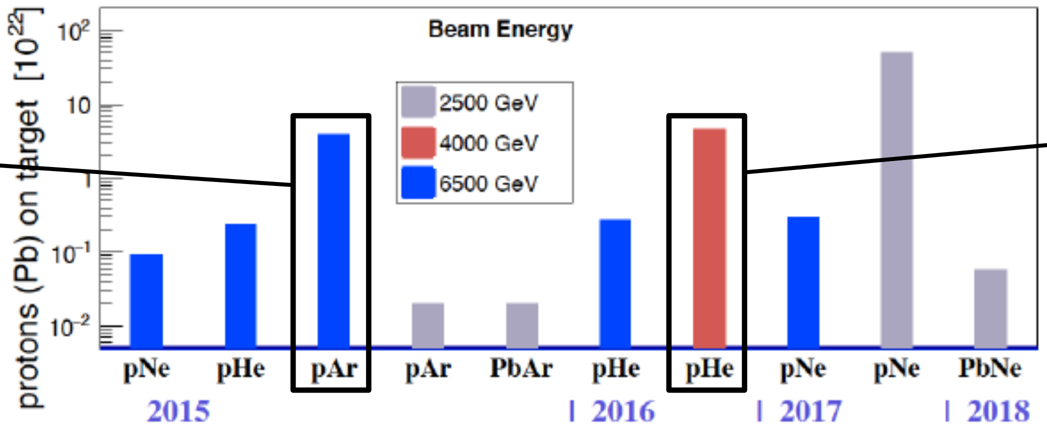


$\sqrt{s_{NN}} = 87$ GeV

How well can we reconstruct quarkonia and heavy mesons at LHCb in fixed-target mode?

LHCb recently reported the first measurement of J/ψ **and** D^0 **production** in fixed-target configuration using **p-He** and **p-Ar** collisions with SMOG

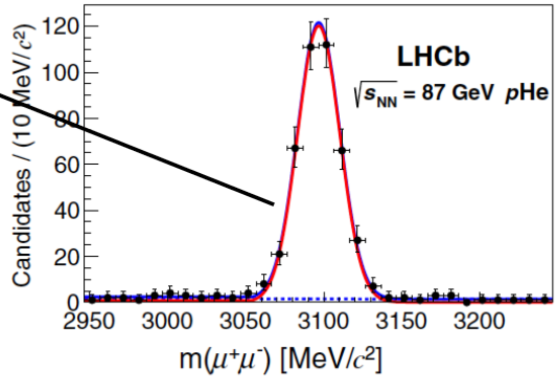
$\sqrt{s_{NN}} = 110$ GeV



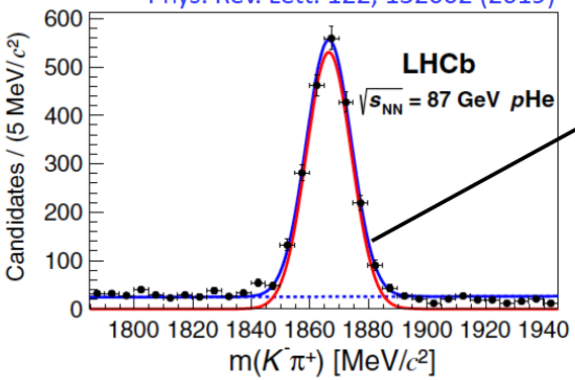
$\sqrt{s_{NN}} = 87$ GeV

- **Prompt J/ψ and D^0 signal yields** are obtained in an unbinned ML fit of the invariant mass distributions using $J/\psi \to \mu^+\mu^-$ and $D^0 \to K\pi$

Sig: CB
Bkg: exp



Phys. Rev. Lett. 122, 132002 (2019)



Sig: 2 Gauss
Bkg: exp

SMOG2 projected performances for LHC Run3

	SMOG published result pHe@87 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim 45\ \text{pb}^{-1}$
syst. error on J/ψ x-sec.	7%	2 - 3 %
J/ψ yield	400	15M
D^0 yield	2000	150M
Λ_c^+ yield	20	1.5M
$\psi(2S)$ yield	negl.	150k
$\Upsilon(1S)$ yield	negl.	7k
Low-mass Drell-Yan yield	negl.	9k

Assumptions (for **p-Ar collisions):**

- Simultaneous beam-gas and beam-beam data taking for 1/3 of total beam time
- Use of all beam bunches for fixed-target physics
- Beam intensity $\sim 3\times10^{18}$ protons/s
- **Inst. Lumi:** $L \sim 2 \cdot 10^{31}\ cm^{-2}s^{-1}$
- Global reconstruction efficiency 10% lower for SMOG2

Expected performance for the PGT

- The LHC beam runs through the target cell and experiences an **Areal density**: $\theta = ½\, \rho_0\, L$
- **Volume density**: $\rho_0 = I_0/(2C_1 + C_2)$ where: $C = 3.81\sqrt{\frac{T(K)}{M}}\frac{D^3}{L+1.33D}\left(\frac{l}{s}\right)$

$I_0 = 6.5 \cdot 10^{16} s^{-1}$ C_{tot} = 13.90 l/s ρ_0 = 4.68 $\cdot 10^{12}$/cm^3 ⟹ **θ= 7.02 $\cdot 10^{13}$/cm^2**

$$\begin{cases} N_{p/bunch} = 2.2 \cdot 10^{11} \\ N_{bunch} = 2760 \\ f_{rev} = 11245\ Hz \end{cases} \Longrightarrow \boldsymbol{I_{beam} = 6.8 \cdot 10^{18}\ s^{-1}}$$

$$\boldsymbol{L(T_{cell} = 300\ K) = I_{beam} \cdot \theta = 4.8 \cdot 10^{32}\ \mathrm{cm^{-2}s^{-1}}}$$

$$\boldsymbol{L(T_{cell} = 100\ K) = \sqrt{3} \times L(T_{cell} = 300K) = 8.3 \cdot 10^{32}\ \mathrm{cm^{-2}s^{-1}}}$$

- ➢ The pressure in the LHC beam pipe outside the target region would be $\sim 10^{-7}$mbar, one order of magnitude lower than the maximum pressure allowed by LHC
- ➢ Parallel operation will cause marginal reduction of beam half-life!