Prospects of Quarkonium studies at COMPASS Experiment

Jan Matoušek
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On behalf of the COMPASS Collaboration

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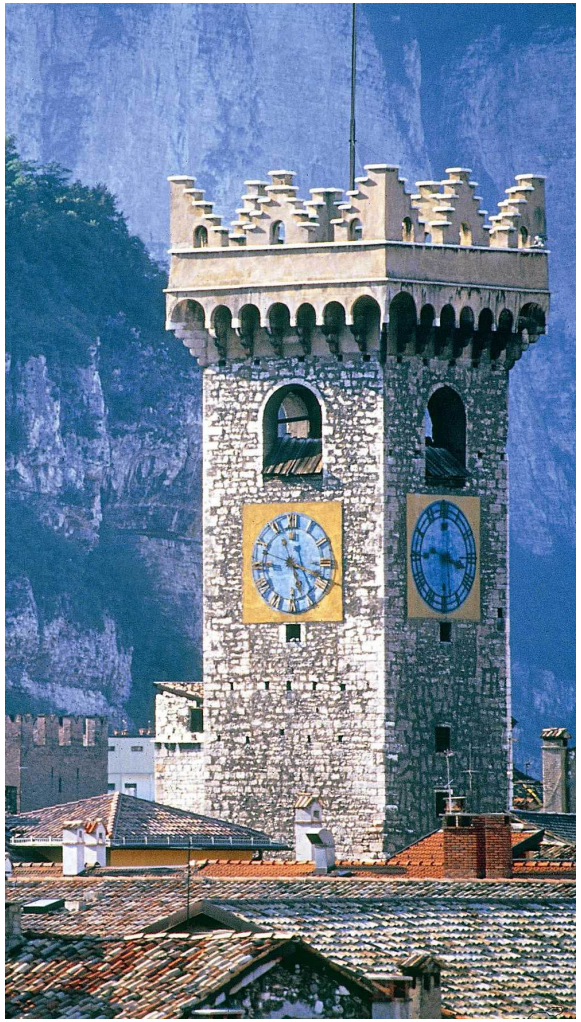
3. 3. 2016, Trento

Outline



http://www.gardalake.com/place/trento/

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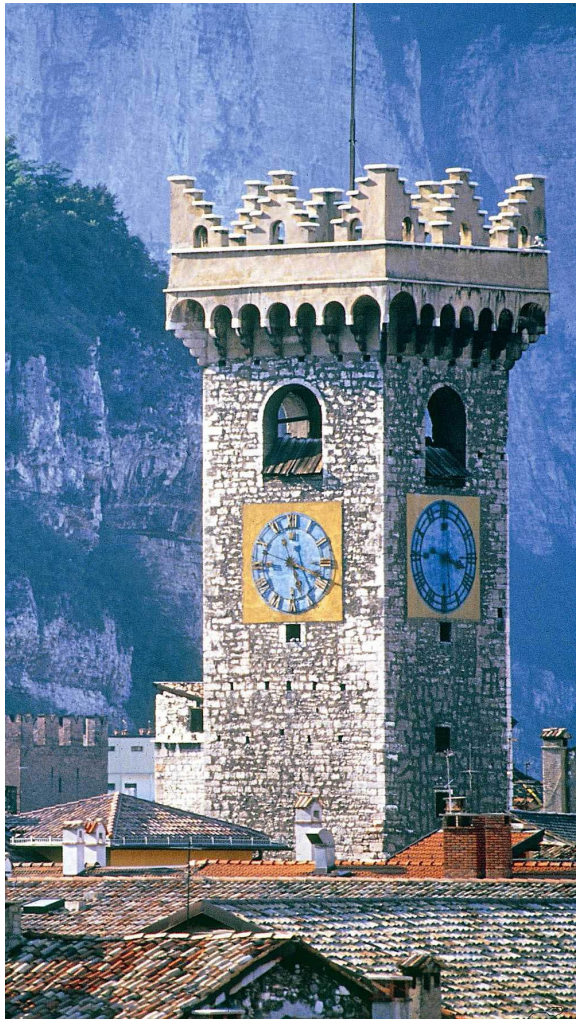

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The COMPASS Experiment: Collaboration, Apparatus

- Collaboration: 24 institutions from 13 countries ($\approx$ 220 physicists).
- Location: CERN Super Proton Synchrotron (SPS) North Area
- Secondary beams of μ or hadrons (mostly π, also K, p) at 160-200 GeV
- Fixed target.

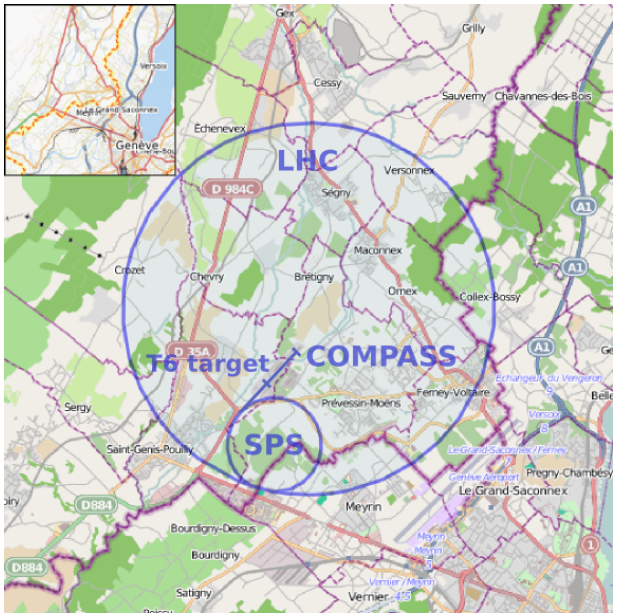

Image credit: Wikimedia Commons, https://en.wikipedia.org/wiki/File:Location_Large_Hadron_Collider.PNG

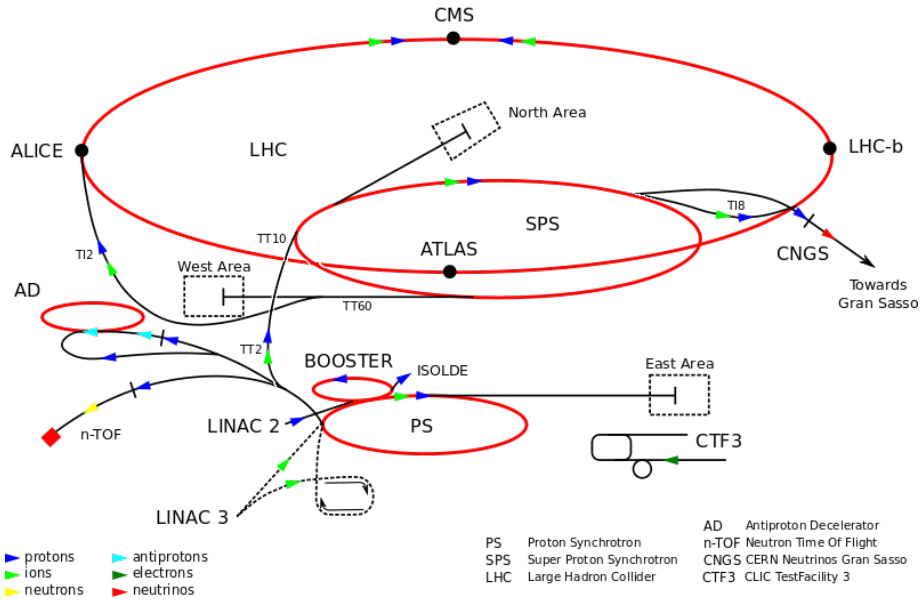

Image credit: Wikimedia Commons, https://en.wikipedia.org/wiki/File:Cern-accelerator-complex.svg

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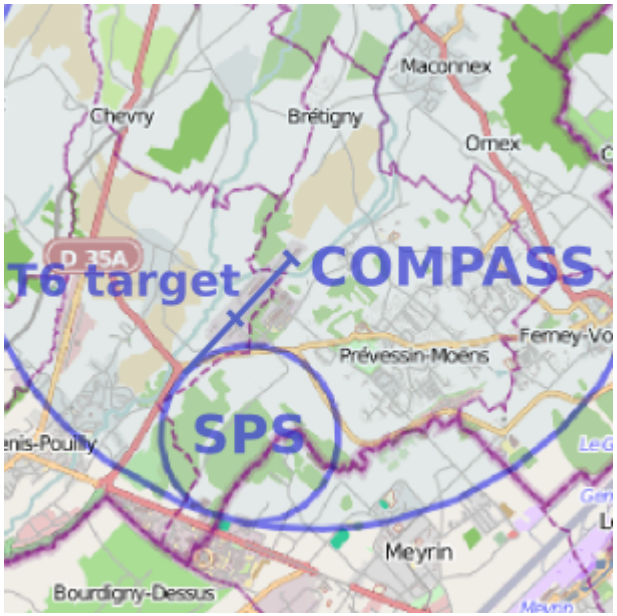

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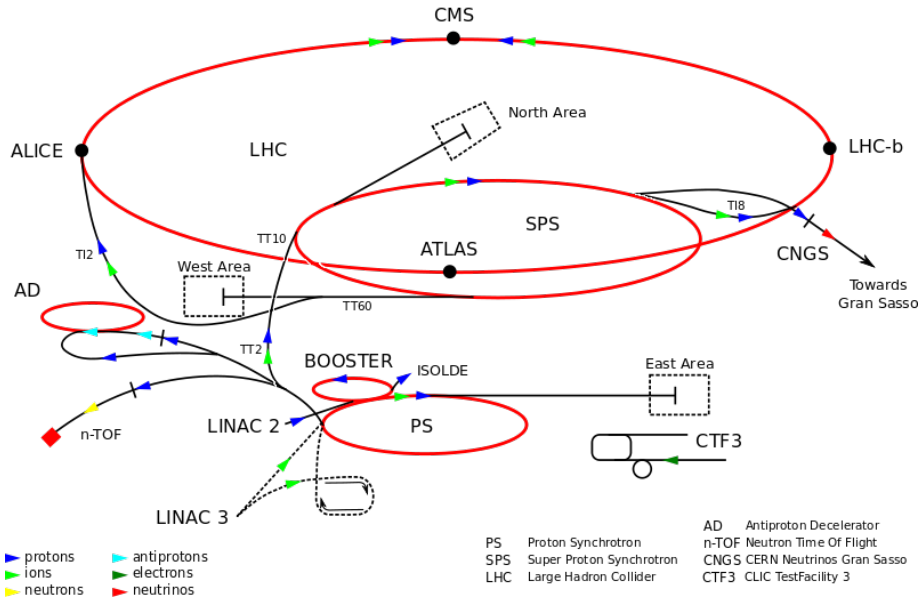

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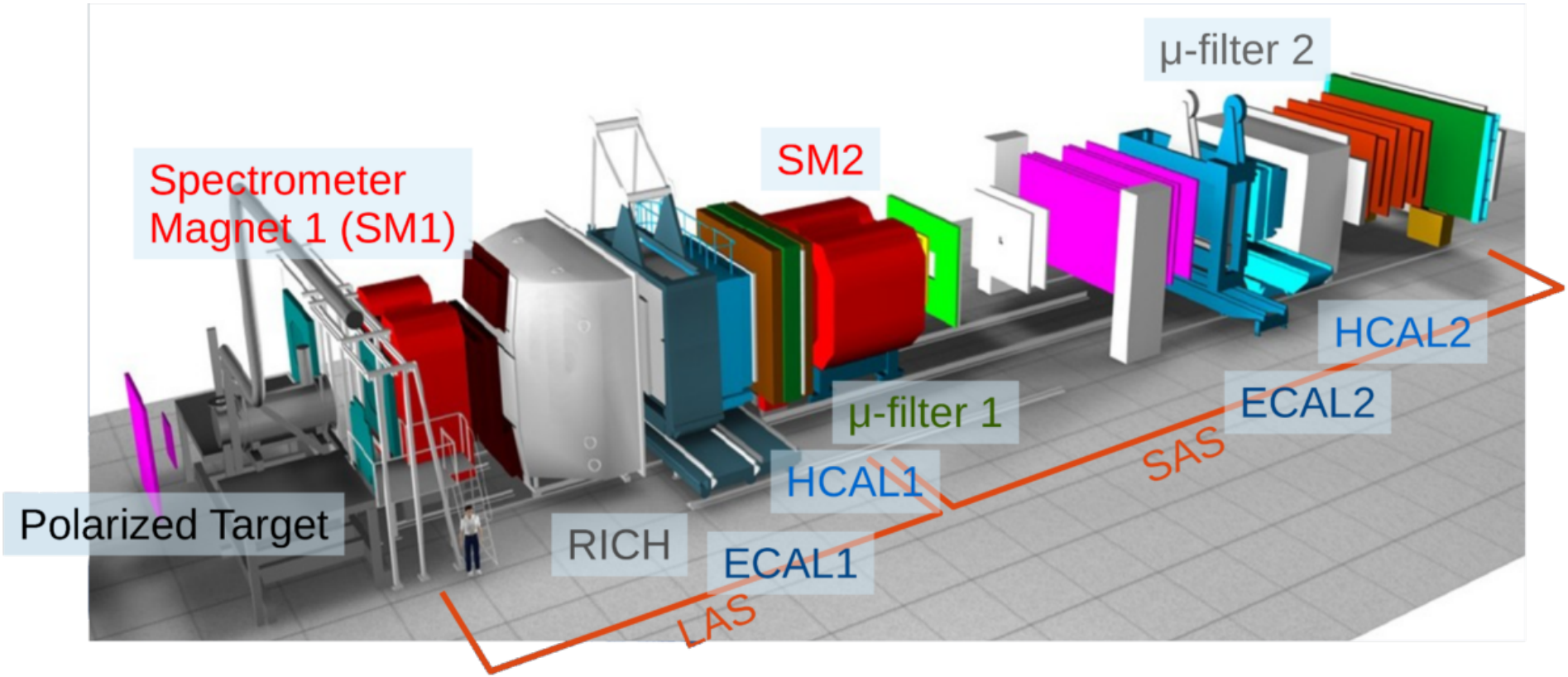


COMPASS setup for polarized μ program.

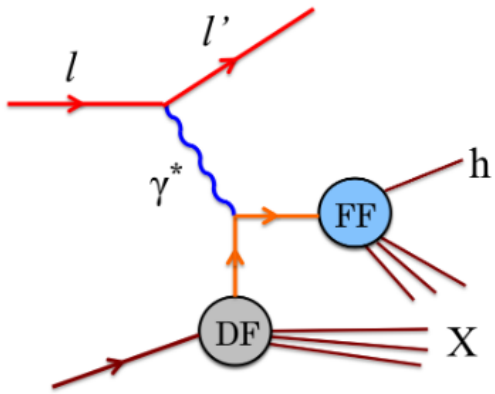
- Target (LH_2, nuclear, polarized NH_3 and ^6LiD).
- Trackers + 2 spectrometer magnets.
- RICH, calorimeters, μ filters.

The COMPASS Experiment: Physics Focus

Not a "quarkonium experiment", different focus (but it's multipurpose).

Nucleon Structure

- COMPASS I (2002–2011)
  - DIS and SIDIS on L-polarized targets
    $(\mu^+ + (\mathrm{p/d})^{\leftarrow} \to \mu^+ + \mathrm{X}\ (+\mathrm{h}))$
    $\to$ helicity distributions of quarks and gluons.
  - SIDIS on T-polarized targets
    $(\mu^+ + (\mathrm{p/d})^{\uparrow} \to \mu^+ + \mathrm{X} + \mathrm{h})$
    $\to$ Sivers and Collins effects and more.
- COMPASS II (2012–2018)
  - 2015: Drell–Yan with T-polarized p target.
  - 2016–2017: DVCS and SIDIS with LH_2 target
    (DVCS: $\mu + \mathrm{p} \to \mu + \mathrm{p} + \gamma$ to get GPDs).



(SI)DIS reaction.

Hadron Program

- Study of light meson spectrum (using a partial-wave analysis of 3π final states).
- 2012: π and K polarizability by scattering π in nuclear Coulomb field.
- And more...

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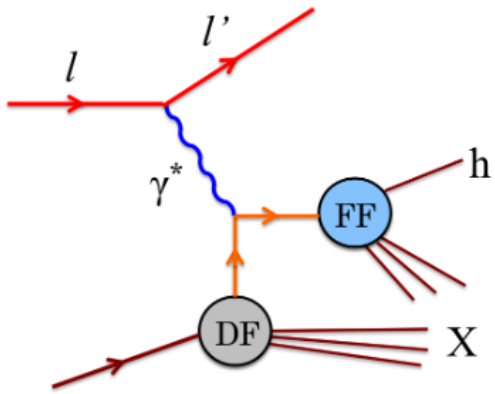

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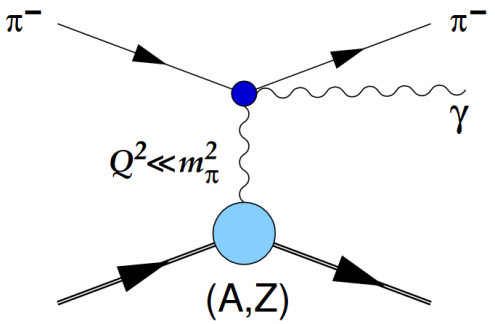
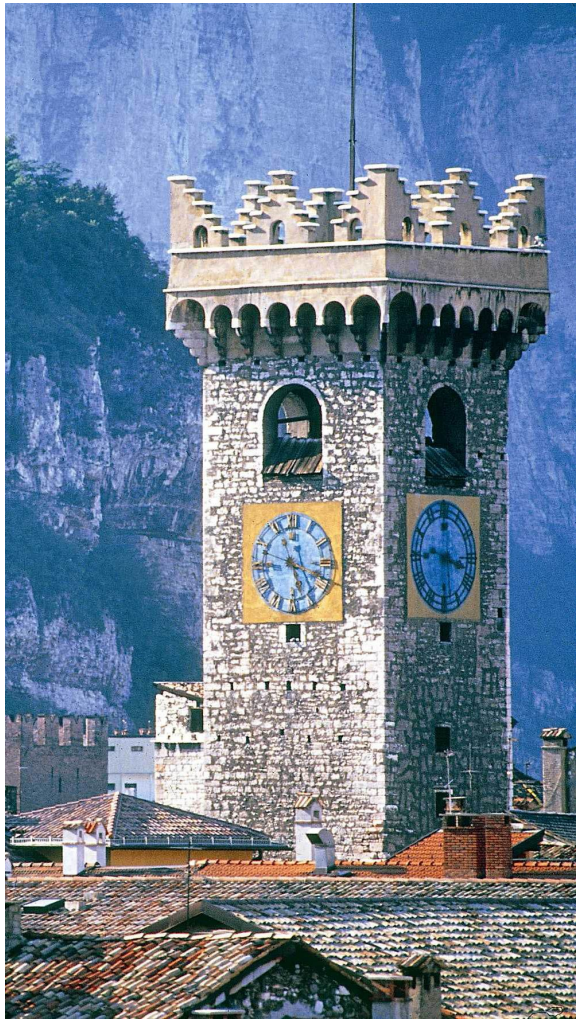


Primakoff reaction for π polarizability.

Outline



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Search for $Z_c^{\pm}(3900)$: Motivation

- An example of COMPASS versatility (also a bit quarkonium-related).
- $Z_c^{\pm}$ charmonium-like state discovered in

$$e^+ + e^- \to \pi^+ + \pi^- + J/\psi$$

at BES-III and confirmed by Belle.

- VMD model: can be produced and observed at COMPASS by

$$\mu^+ + N \to \mu^+ + Z_c^{\pm} + N \to \mu^+ + J/\psi + \pi^{\pm} + N$$

with sizeable x-section [Q.-Y. Lin, et al., Phys. Rev. D 88, 114009 (2013) http://arxiv.org/abs/1308.6345]

- Search in all COMPASS μ data (2002-2011).
- A reference process for normalization:

$$\mu^+ + N \to \mu^+ + J/\psi + N$$

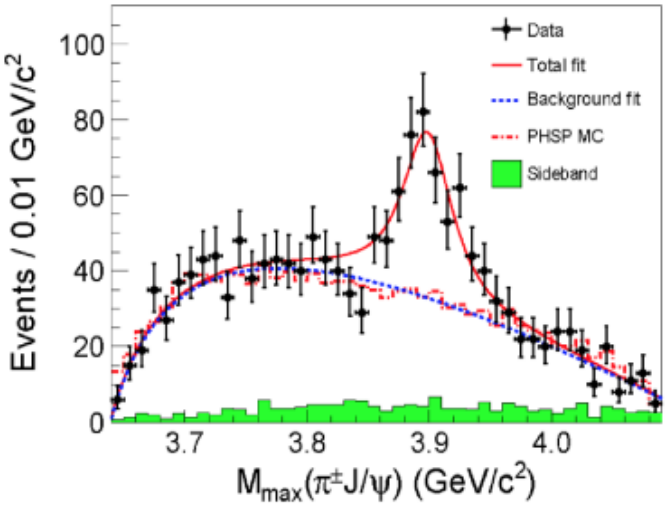
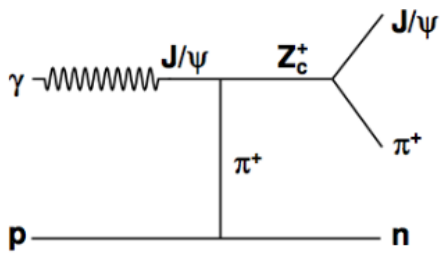


Figure: [BES-III, Phys. Rev. Lett. 110, 252001 (2013) http://arxiv.org/abs/1303.5949]



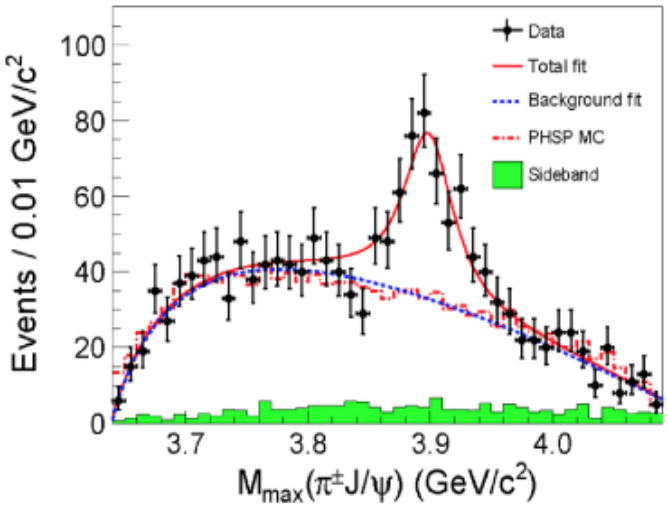
Production mech. at COMPASS

Search for $Z_c^{\pm}(3900)$: Results

- No peak in inv. mass visible, in signal region: expected bg.: 49.7 events, observed 51 events.
- 90 % conf. level: max. 15.1 signal events.
- → limit (at $\sqrt{s_{\gamma N}} = 13.8$ GeV)

$$\mathrm{BR}(Z_c^{\pm} \to J/\psi\pi) \times \frac{\sigma_{\gamma N \to Z_c^{\pm} N}}{\sigma_{\gamma N \to J/\psi N}} < 3.7 \times 10^{-3}$$

- VMD model dependent result: partial width $\Gamma_{J/\psi\pi} < 2.4$ MeV/c^2
- → if the prod. mech. proposed by Q.-Y. Lin, et al. is correct, the decay $Z_c^{\pm} \to J/\psi\pi$ cannot be the dominant one.
- Reference: [COMPASS, Phys. Lett. B 742 (2015) 330–334, http://dx.doi.org/10.1016/j.physletb.2015.01.042.]



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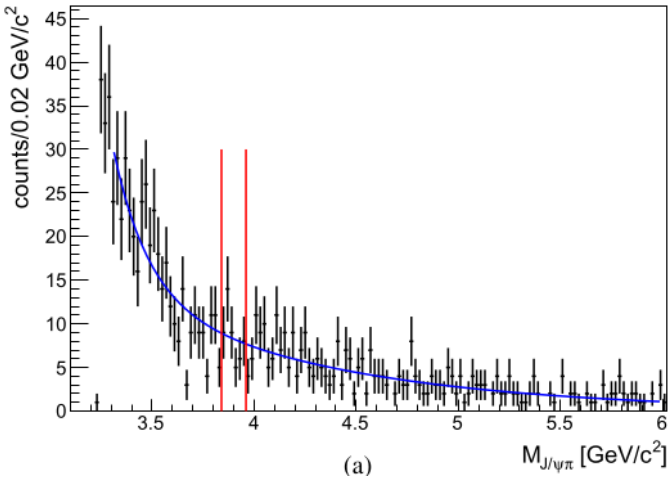
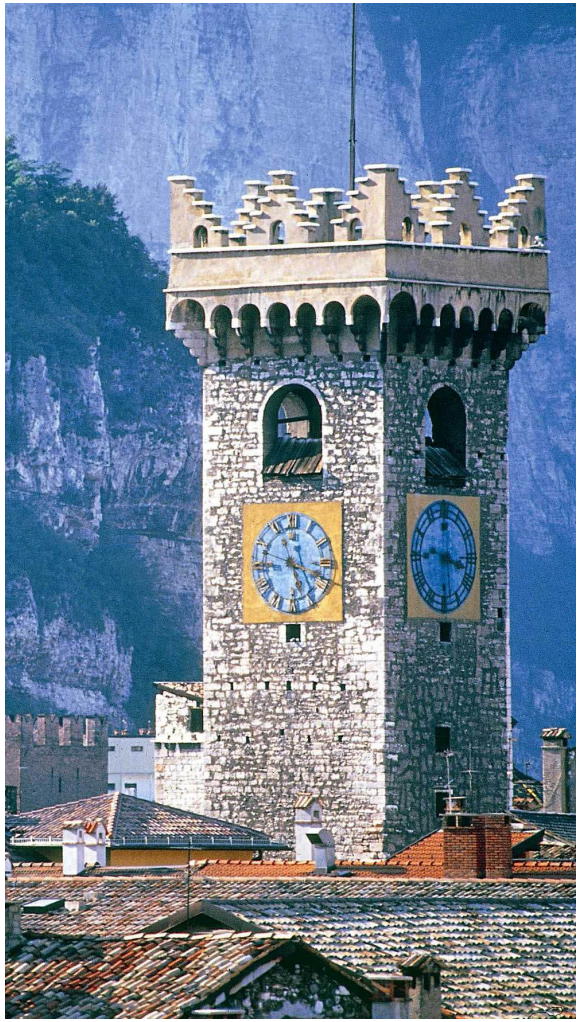


$J/\psi\ \pi^{\pm}$ invariant mass, $Z_c^{\pm}(3900)$ signal region in red.

Outline



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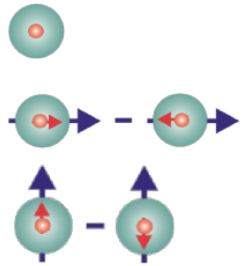
Sivers Asymmetry: Describing Nucleon Spin Structure

- Collinear picture (parton $\vec{k}_{\mathrm{T}}$ integrated over) – 3 PDFs at LO:
  - The unpolarized $f(x)$ (number density),
  - the helicity $g(x) = f_{\rightarrow}(x) - f_{\leftarrow}(x)$ and
  - the transversity $h(x) = f_{\uparrow}(x) - f_{\downarrow}(x)$.



- Beyond the collinear approx. for $|\vec{k}_{\mathrm{T}}|$ small
  - Transverse-Momentum Dependent PDFs.
  - 3 give the standard PDFs after integration over $\vec{k}_{\mathrm{T}}$.
  - contribution of the other 5 vanish after the integration.

		Parent hadron polarization		
		Unpolarized	Longitudinal	Transverse
Parton polar.	U	$f_1(x, \vec{k}_{\mathrm{T}}^2)$ (Number density)		$f_{1T}^{\perp}(x, \vec{k}_{\mathrm{T}}^2)$ (Sivers)
	L		$q_1(x, \vec{k}_{\mathrm{T}}^2)$ (Helicity)	$g_{1T}^{\perp}(x, \vec{k}_{\mathrm{T}}^2)$
	T	$h_1^{\perp}(x, \vec{k}_{\mathrm{T}}^2)$ (Boer–Mulders)	$h_{1L}^{\perp}(x, \vec{k}_{\mathrm{T}}^2)$	$h_1(x, \vec{k}_{\mathrm{T}}^2)$ (Transversity) $h_{1T}^{\perp}(x, \vec{k}_{\mathrm{T}}^2)$ (Pretzelosity)

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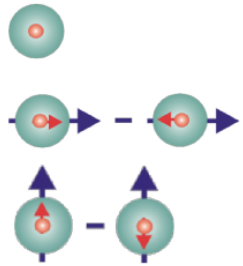

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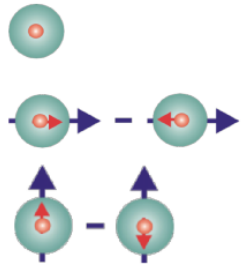

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Sivers Asymmetry: Experimental Results

- Sivers asymmetry correlates nucleon spin with parton k_{T}.
- Experimentally studied:
  - SIDIS $(\mathrm{l} + (\mathrm{p/d})^{\uparrow} \to \mathrm{l} + \mathrm{X} + \mathrm{h})$ (HERMES, COMPASS, J-Lab)
  - pp collisions (RHIC)
  - Drell–Yan process (COMPASS).
- Quark Sivers asymmetry in SIDIS experiments: $\phi_{\mathrm{Siv}} = \phi_{\mathrm{h}} - \phi_{\mathrm{S}}$ modulation of x-section.

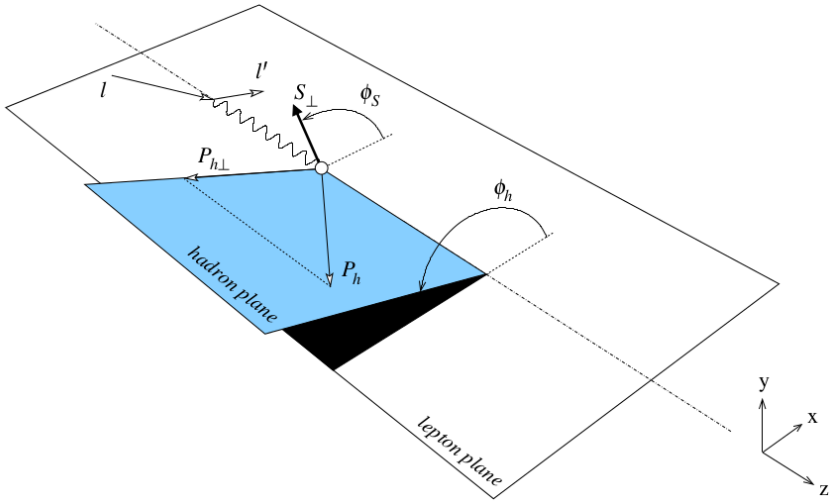

Figure: [A. Bacchetta et al., JHEP02(2007)093]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}P_{\mathrm{T}}^2\mathrm{d}\phi_{\mathrm{h}}\mathrm{d}\psi} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \ldots$$
$$+ S_{\mathrm{T}}\Big[\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}})\big(F_{\mathrm{UT,T}}^{\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}})} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}})}\big)$$
$$+ \epsilon\sin(\phi_{\mathrm{h}}+\phi_{\mathrm{S}})F_{\mathrm{UT}}^{\sin(\phi_{\mathrm{h}}+\phi_{\mathrm{S}})} + \ldots\Big] + \ldots\Big\}$$

(In experiments—asymmetries $A = \frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}$ to cancel acceptance effects)

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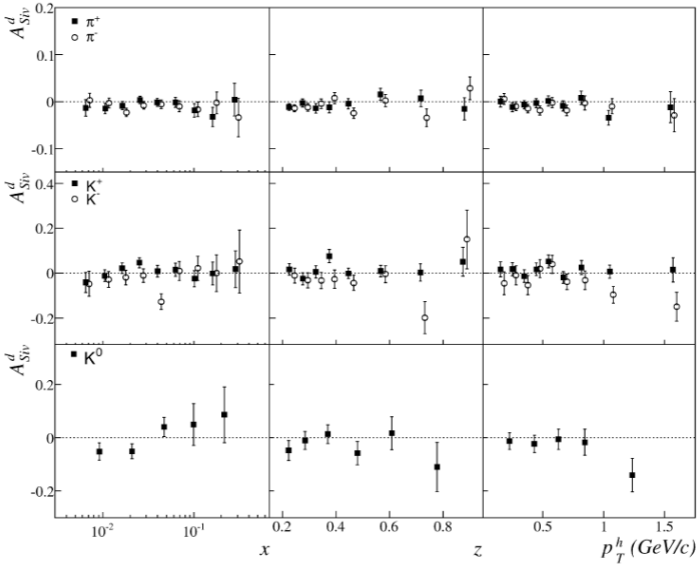
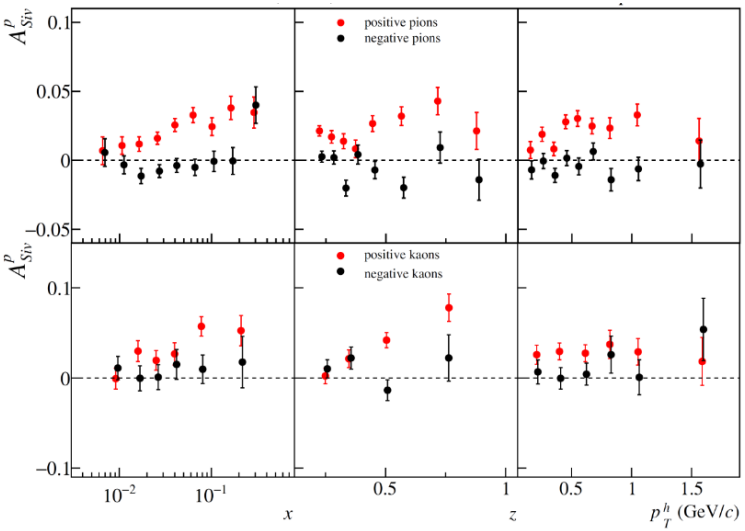
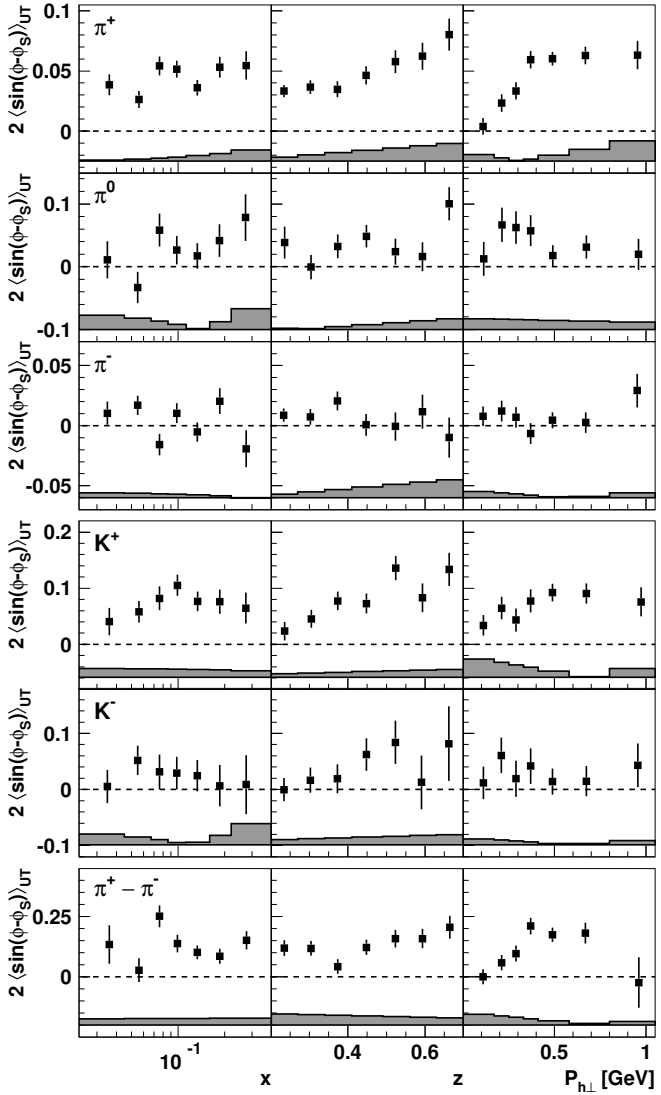


COMPASS deuteron data
[COMPASS, Phys. Lett. B 673 (2009) 127].

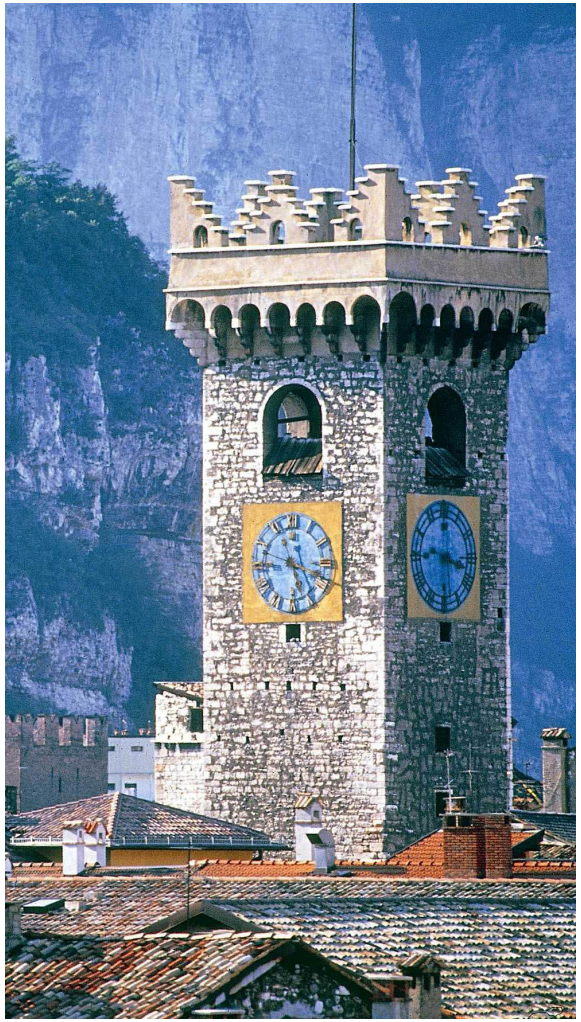


COMPASS 2007 and 2010 proton data
[COMPASS, Phys. Lett. B 744 (2015) 250].



HERMES 2002–2005 proton data
[HERMES, Phys. Rev. Lett. 103 (2009) 152002].

Outline



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Sivers asymmetry of gluons: possible hint in the search for gluon orbital angular momentum. (Sivers asymmetry correlates nucleon spin with parton k_T)

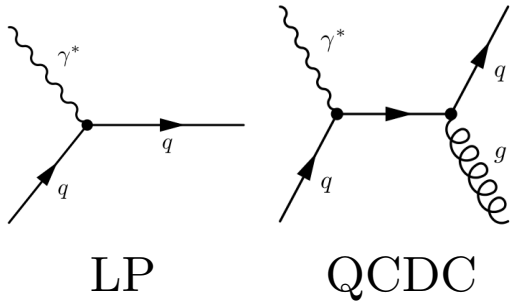
On COMPASS

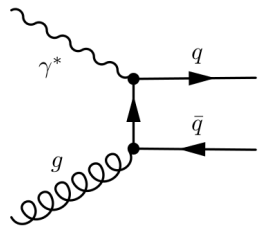
μ-nucleon scattering—single-γ exchange processes:

- Leading process (LP)
- QCD Compton process (QCDC)
- Photon-Gluon Fusion (PGF)

LP dominates ($\rightarrow$ q Sivers), how to tag the PGF?

- Heavy flavors—on COMPASS E only charm.
- P_{T} dependence: less LP on high P_{T}.



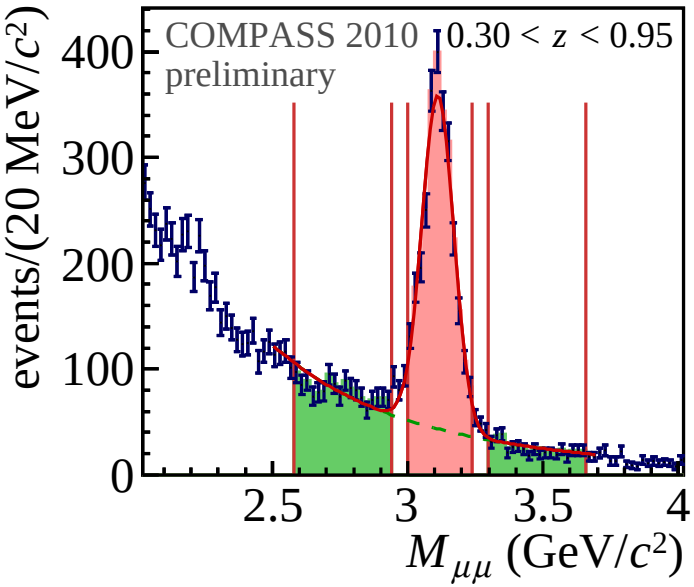


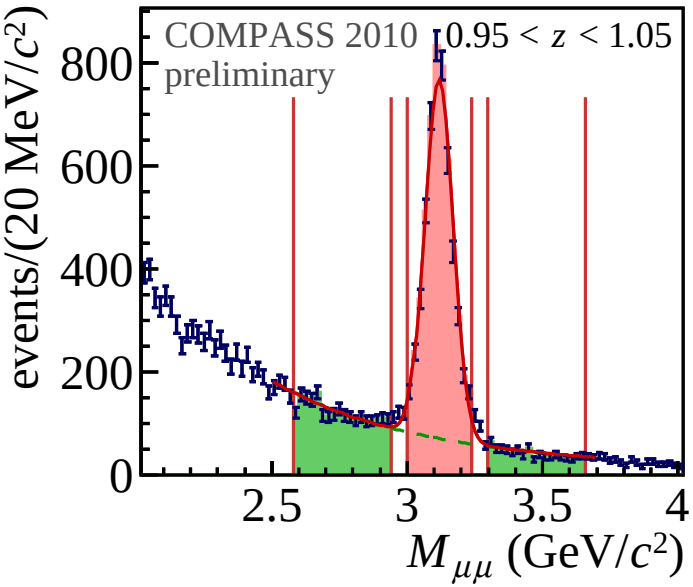
Sivers Asymmetry of Gluons: J/ψ Leptoproduction

- Use of charm quarks in the form of a J/ψ – proposed by [Godbole, Misra, Mukherjee, and Rawoot, Phys. Rev. D 85 (2012), http://arxiv.org/abs/1201.1066]:

$$\mu^+ + \mathrm{p}^\uparrow \to \mu^+ + \mathrm{J}/\psi + \mathrm{X} \to 2\mu^+ + \mu^- + \mathrm{X}$$

- the CEM model of the J/ψ production—k_T of the g is transferred to the J/ψ $\to \phi_{\mathrm{J}/\psi} = \phi_{\mathrm{g}}$.
- COMPASS 2010: Clear J/ψ signal (3.1 GeV/c^2, $\sigma \approx 55$ MeV/c^2),
- small background, but limited statistics ($\approx$ 2300 incl. and 4500 excl.).





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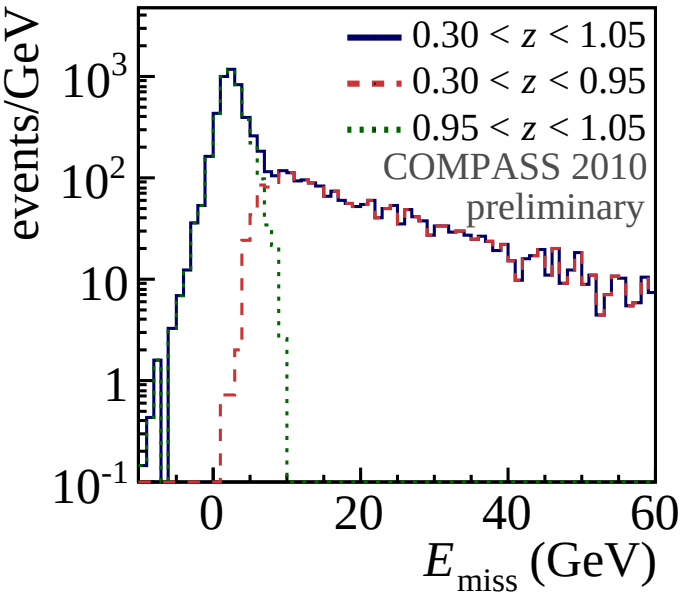
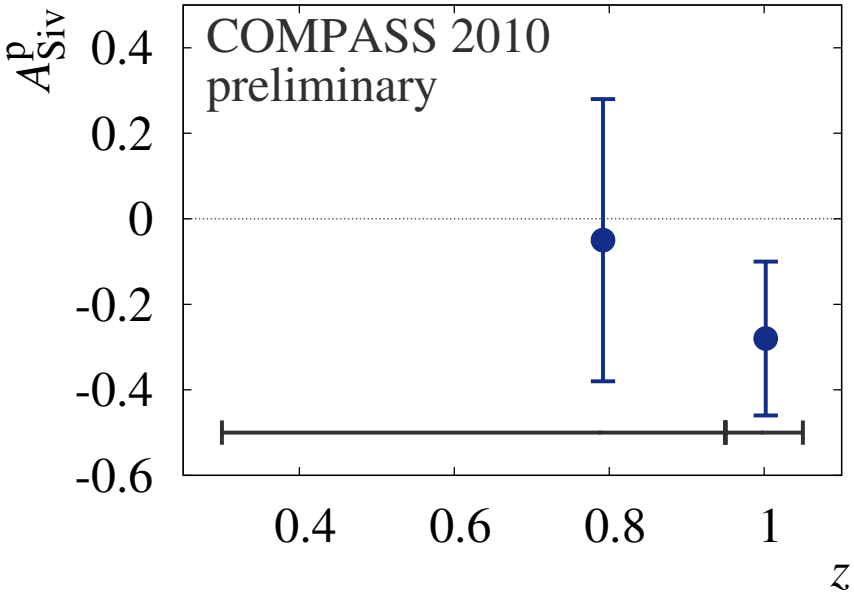


The missing energy.



The asymmetry. The black lines denote integration ranges.

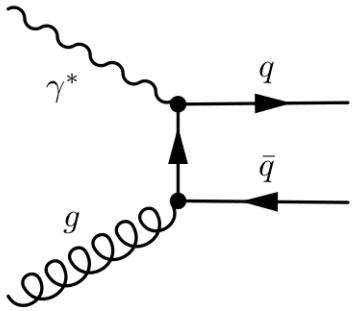
Results:

- $A^{p}_{Siv} = -0.05 \pm 0.33$ (inclusive J/ψ),
- $A^{p}_{Siv} = -0.28 \pm 0.18$ (exclusive J/ψ).
- [COMPASS, JoP Conf. Series, http://iopscience.iop.org/1742-6596/678/1/012050]
- Prospect for better statictics: max. factor of 2.

Sivers Asymmetry of Gluons: PGF Tagging by P_{T}

Reminder—problem:

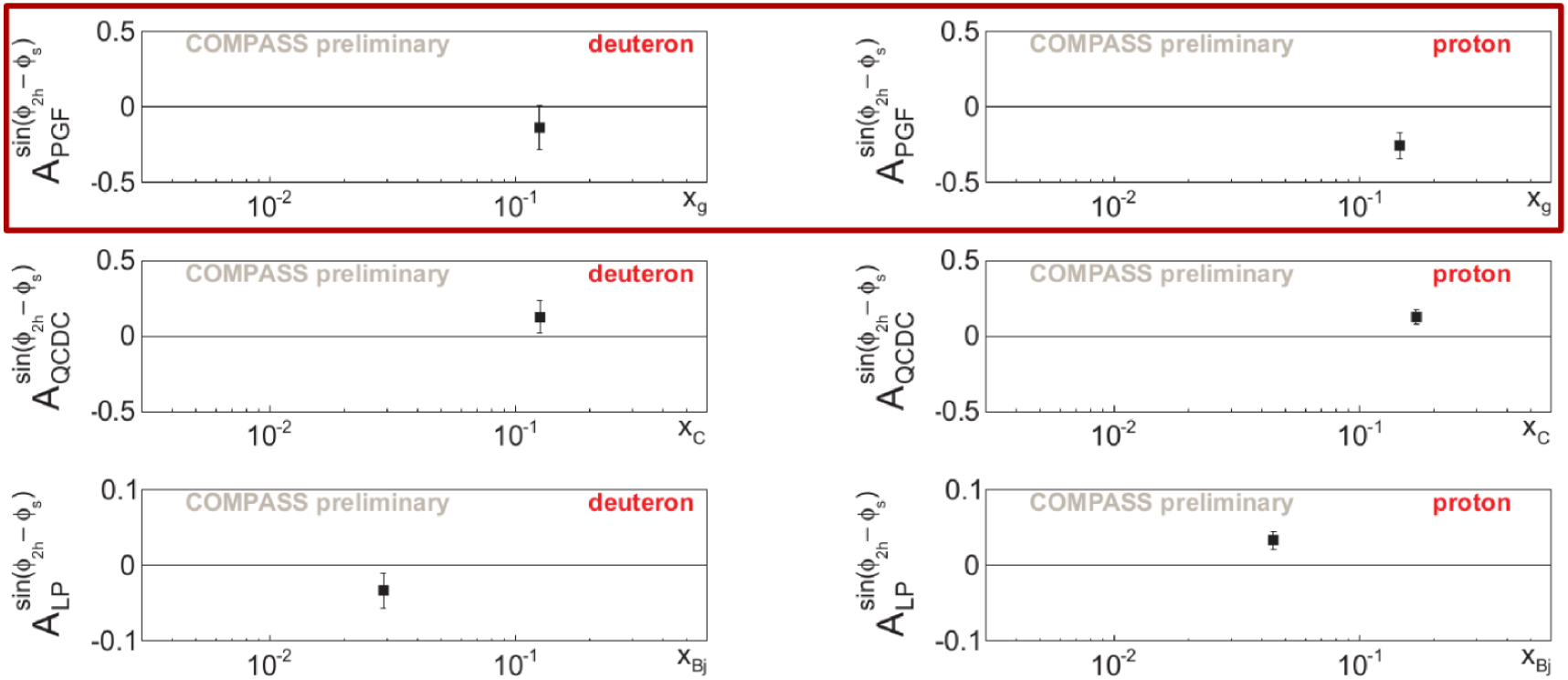
- competing processes: LP, QCDC and PGF,
- we can observe: $\mu + \mathrm{p/n} \to \mu + \mathrm{hadrons}$.



COMPASS "P_{T}-weighted method"

- Monte Carlo and a neural network are used to extract asymmetries of all 3 processes from the full set of data.
- Similar methods were used to extract $\Delta g/g$ from L-polarised target data
  - high-P_{T} hadrons:
    [COMPASS, Phys. Lett. B 633 25, 2006, http://arxiv.org/abs/hep-ex/0511028],
    [COMPASS, Phys. Lett. B 718 922, 2013, http://arxiv.org/abs/1202.4064].
  - all-P_{T}, weighted (to be published: [http://arxiv.org/abs/1512.05053]).
- NN is trained on MC to assign weights events ($\approx$ prob. to be LP/QCDC/PGF).
- Best correlation with ϕ_{g}: 2 leading hadron total momentum azimuthal angle ϕ_{2h}.
- Cuts:
  - inclusive events, $Q^2 > 1\ (\mathrm{GeV}/c)^2$.
  - $P_{\mathrm{T1}} > 0.7\ \mathrm{GeV}/c$, $P_{\mathrm{T2}} > 0.4\ \mathrm{GeV}/c$

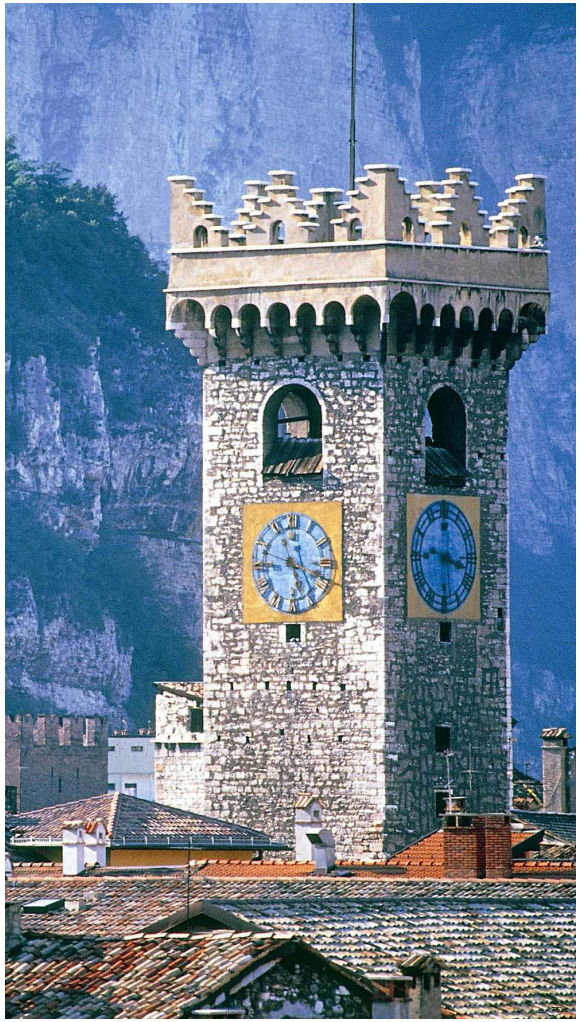
Sivers Asymmetry of Gluons: PGF Tagging by P_T



Results:

- $A_g^d = -0.14 \pm 0.15(\text{stat.}) \pm 0.06(\text{syst.})$, $A_g^p = -0.26 \pm 0.09(\text{stat.}) \pm 0.08(\text{syst.})$
- [COMPASS, JoP Conf. Series, http://iopscience.iop.org/1742-6596/678/1/012055].
- A paper is in preparation.

Outline



http://www.gardalake.com/place/trento/

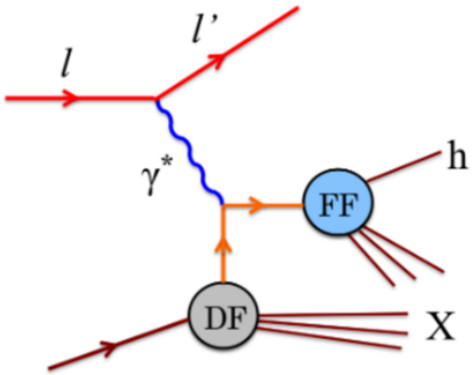
COMPASS Drell–Yan Program: Motivation

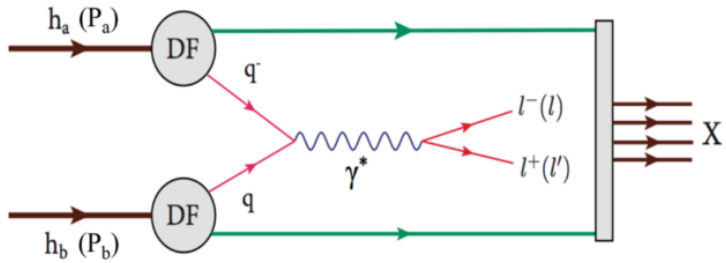
T-polarized SIDIS

- COMPASS 2002–2010.
- Many interesting results obtained.
- $A = \mathrm{DF}_{\mathrm{q,h_{targ}}} \otimes \mathrm{FF}_{\mathrm{q}\to\mathrm{h}}$.

T-polarized Drell–Yan

- COMPASS 2015 (1st ever).
- low x-section.
- $A = \mathrm{DF}_{\mathrm{q,h_{targ}}} \otimes \mathrm{DF}_{\bar{\mathrm{q}},\mathrm{h_{beam}}}$.





- Unique test of the universality of DF (Sivers function sign change).
  N.B.: STAR at RHIC, TSA in W and Z prod.: [http://arxiv.org/abs/1511.06003]
- Quarkonium-related: J/ψ and DY production on nuclear targets.

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$$\frac{d\sigma^{LO}_{SIDIS}}{dx dy dz dp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \cos 2\phi_h \left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\right.$$

$$+ S_T \left[\begin{array}{l} \sin(\phi_h - \phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right) \\ + \sin(\phi_h + \phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right) \\ + \sin(3\phi_h - \phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right) \end{array}\right]$$

$$\left. + S_T \lambda \left[\cos(\phi_h - \phi_S)\left(\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)}\right)\right]\right\}$$

$h_1^{\perp q}$ — $f_{1T}^{\perp q}$ — h_1^q — $h_{1T}^{\perp q}$ — g_{1T}^q

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{1 + \cos^2\theta + \sin^2\theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}}\right.$$

$$+ S_T \left[\begin{array}{l} \left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S} \\ + \sin^2\theta \left(\begin{array}{l} \sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ + \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array}\right) \end{array}\right]$$

$$\left.\right\}$$

$$f_{1T}^{\perp q}\big|_{DY} = -\, f_{1T}^{\perp q}\big|_{SIDIS} \qquad h_1^q\big|_{DY} = -\, h_1^q\big|_{SIDIS}$$

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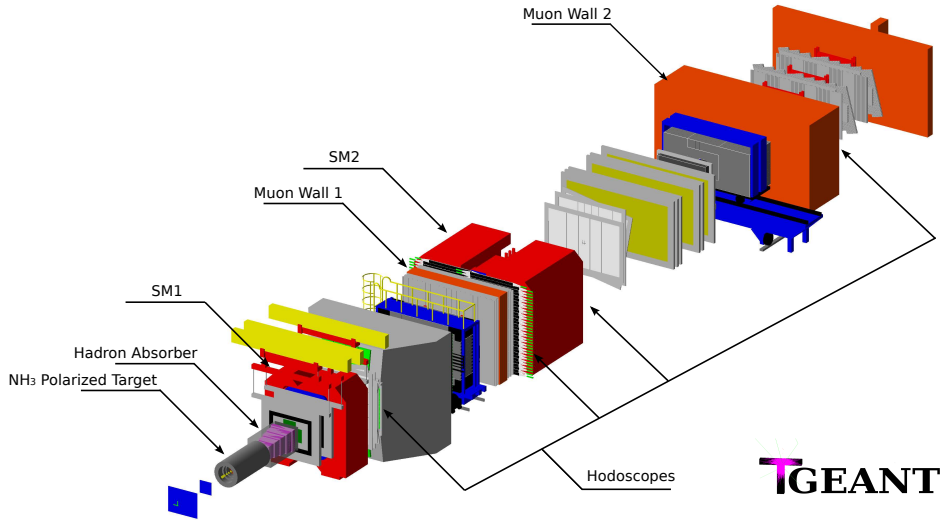
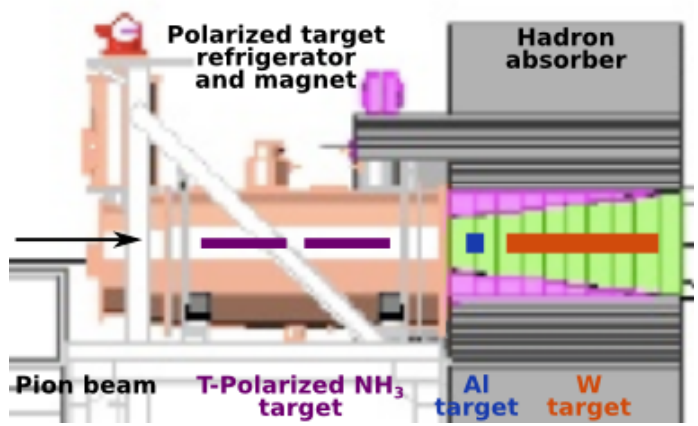


3D view of the DY Setup in COMPASS MC simulation.

- Transversely polarized p (NH_3) target + Al and W targets.
- Low x-section → high beam flux needed ($\approx 10^9$ π^-/spill of 10 s).
- Hadron absorber—μ filter, ensures reasonable detector occupancies.
- Large acceptance, mostly in valence region ($x > 0.1$).

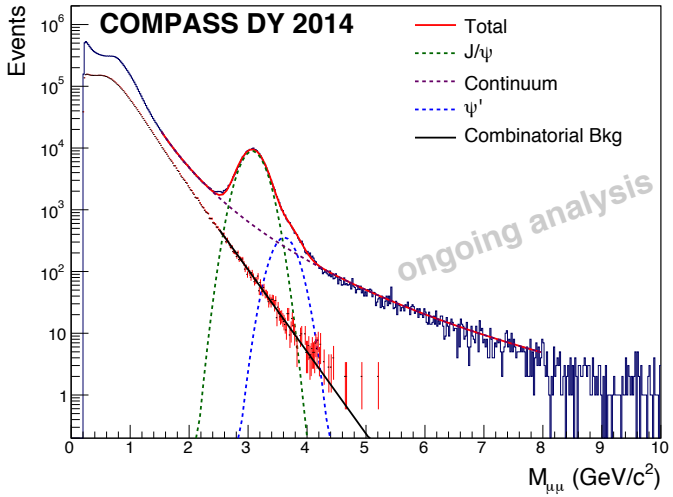


The target region.

COMPASS Drell–Yan Program: Prospects

2014 Pilot Drell–Yan run

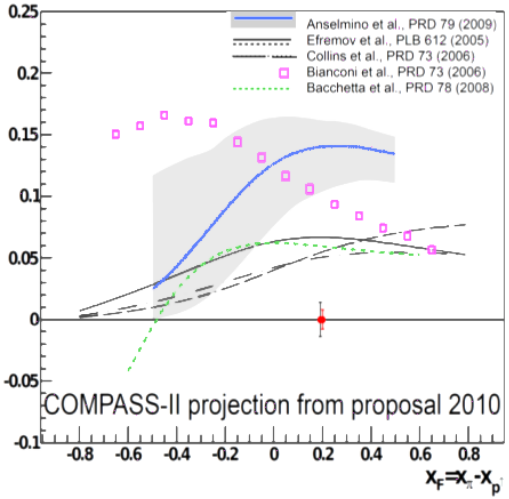
- No target polarization, lower beam intensity.
- $\approx$ 10 days of good data (ongoing analysis).
- $\approx$ 7000 DY events with $M_{\mu\mu} > 4$ GeV/c^2
- Confirmed our expectations
  (Z_{vtx} and $M_{\mu\mu}$ resolution, acceptance etc.)



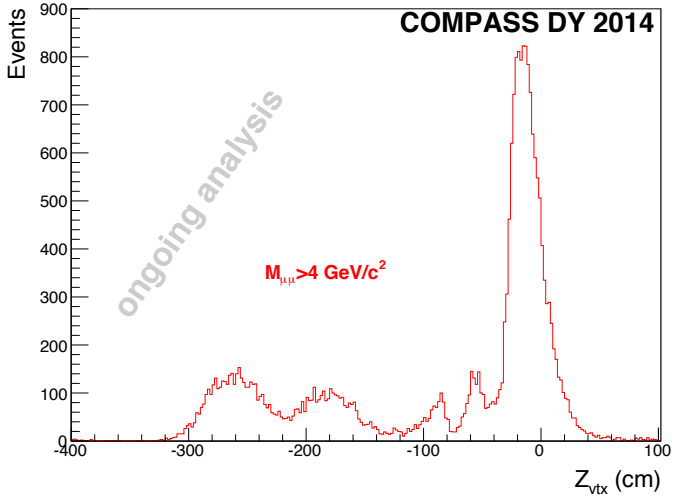
Dimuon inv. mass,
$M_{\mathrm{J}/\psi} = 3.072$ GeV/c^2,
$\sigma_{\mathrm{J}/\psi} = 0.20$ GeV/c^2

2015 Drell–Yan run

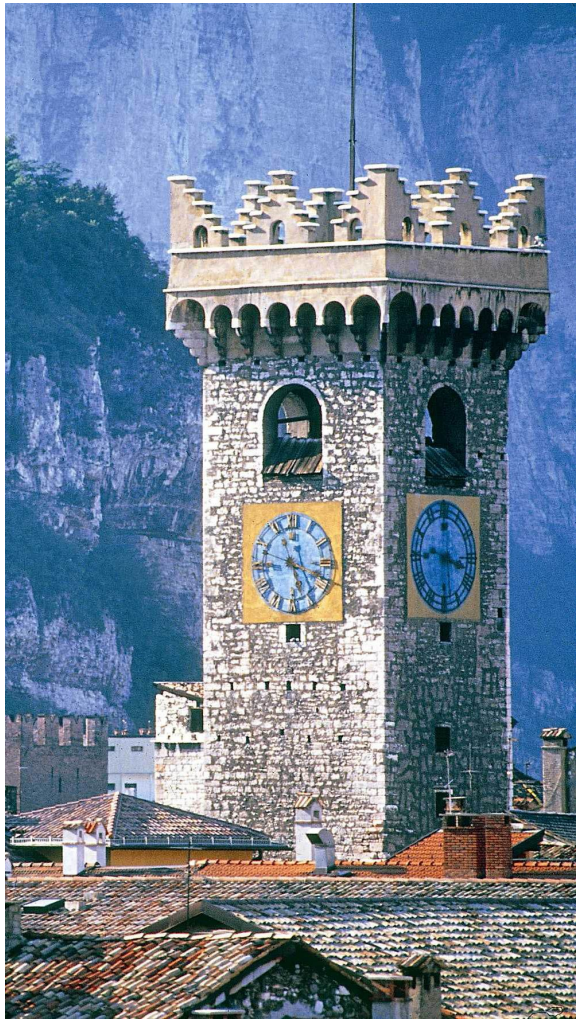
- full DY setup, 140 days.



Several models compared with projected stat. uncert. for 280 days (2 years) of data taking and for $M_{\mu\mu} > 4$ GeV/c^2 on the Sivers asym. (0.014).



Outline



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Conclusions

- COMPASS focuses on
  - nucleon spin structure studies,
  - meson spectroscopy
  - and more...
- COMPASS I phase (2002–2011): many interesting results. Mentioned here:
  - Sivers asymmetry of quarks.
  - Sivers asymmetry of gluons.
  - Upper limit on $Z_c^{\pm}$ photoproduction.
    (not main program—versatility of COMPASS!)
- COMPASS II phase:
  - Drell–Yan 2015 (may continue in 2018),
  - DVCS and SIDIS 2016–2017.
- Multipurpose experiment—prospects of interesting quarkonium results too (especially from DY run).
- COMPASS is collecting ideas for possible program after LS2 (2020+)

Thank you for your attention!

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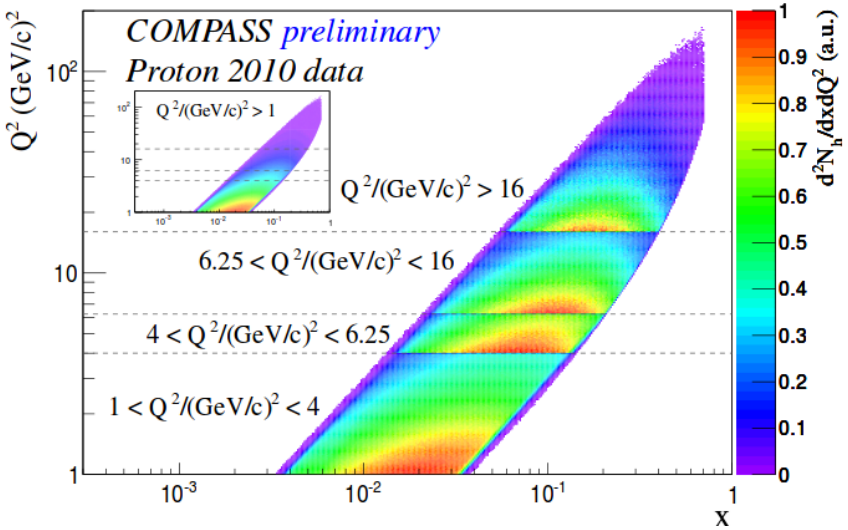
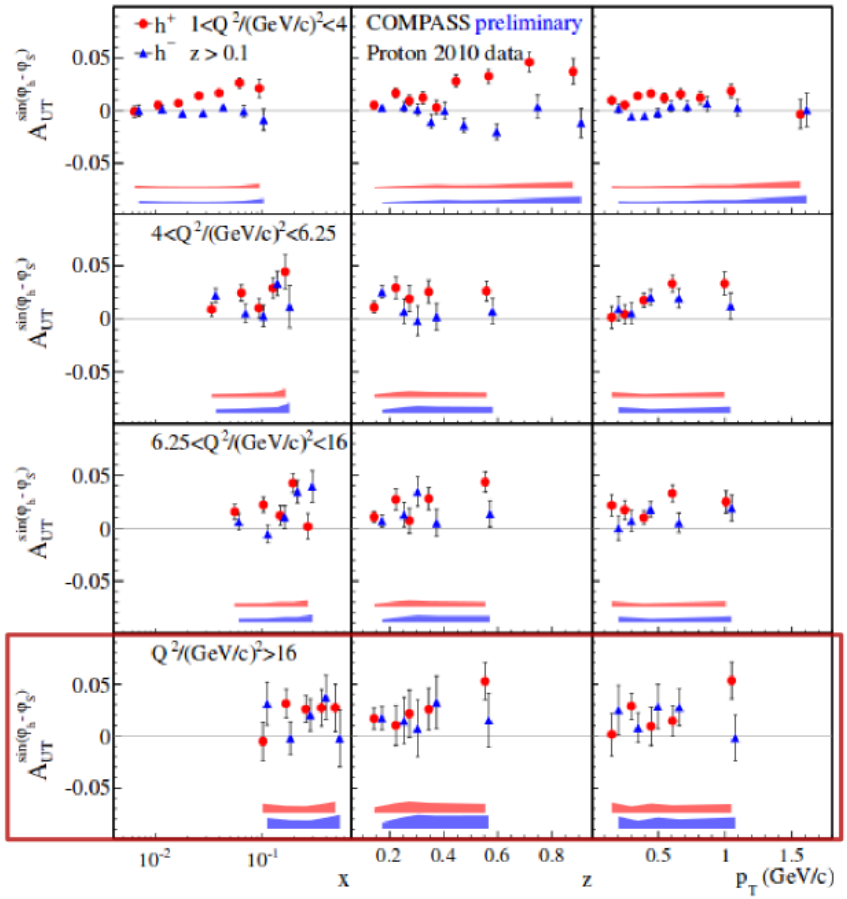
Backups: Sivers from SIDIS in DY Range



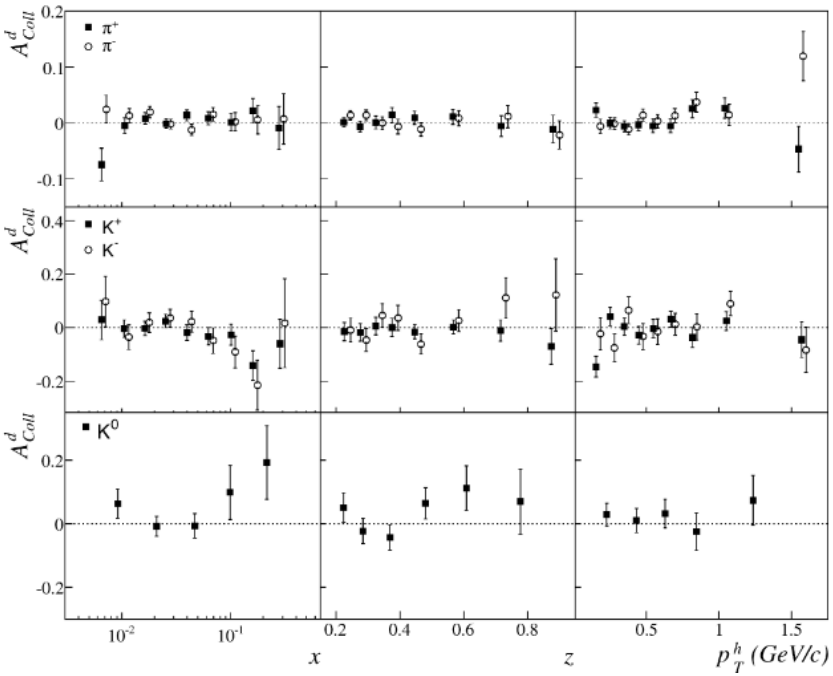
The SIDIS x and Q^2 range was divided into several bins.



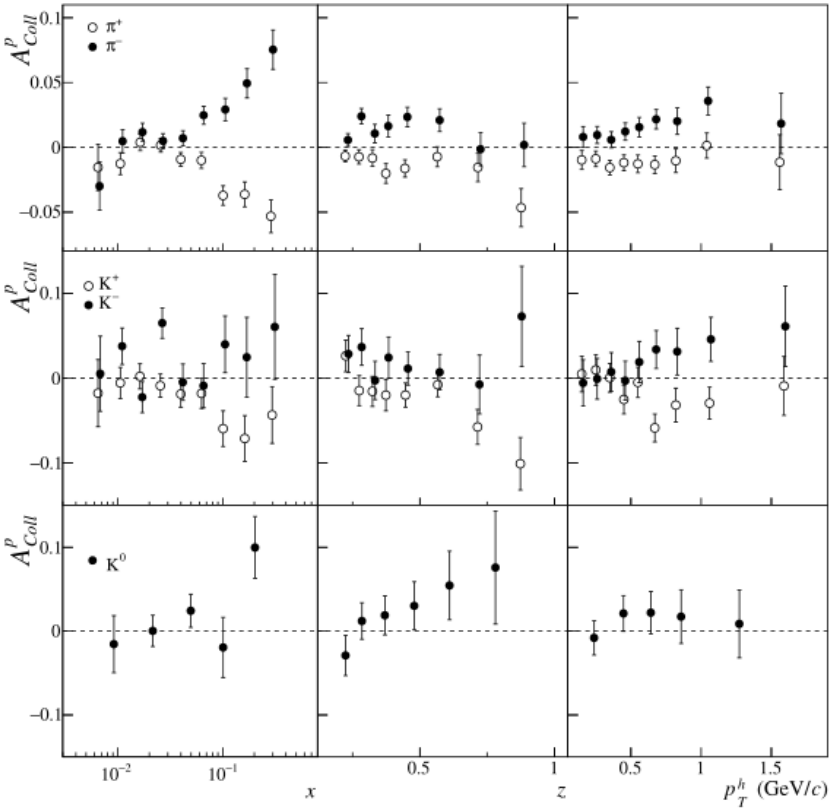
The Sivers asymmetry from 2010 data in the bins (http://arxiv.org/abs/1411.1568). The kinematic range compatible with our DY acceptance is highlighted.

Sivers asymmetry in compatible range measured and nonzero.
Just the DY-part of the riddle is missing...

Backups: Collins Asymmetry

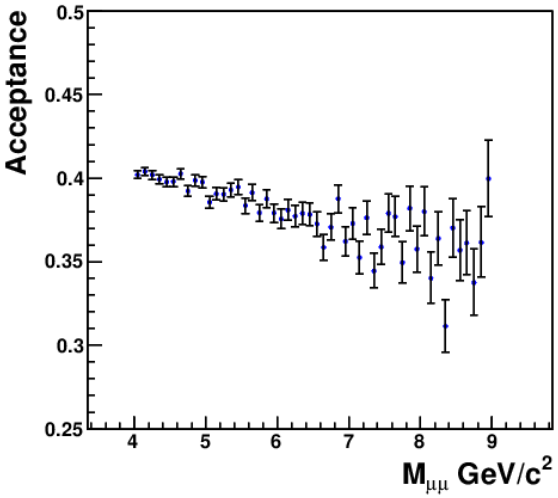


COMPASS deuteron data
[COMPASS, Phys. Lett. B 673 (2009) 127].

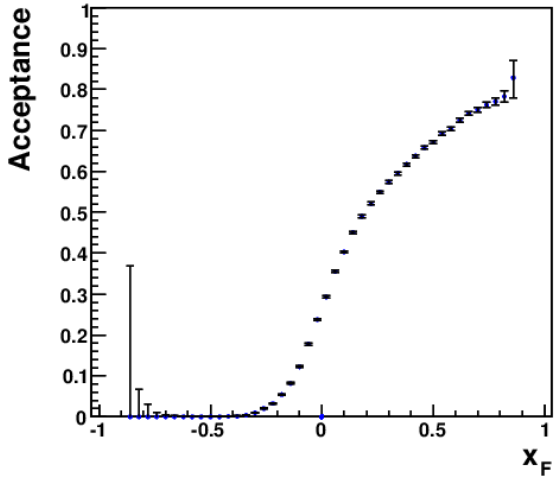


COMPASS 2007 and 2010 proton data
[COMPASS, Phys. Lett. B 744 (2015) 250].

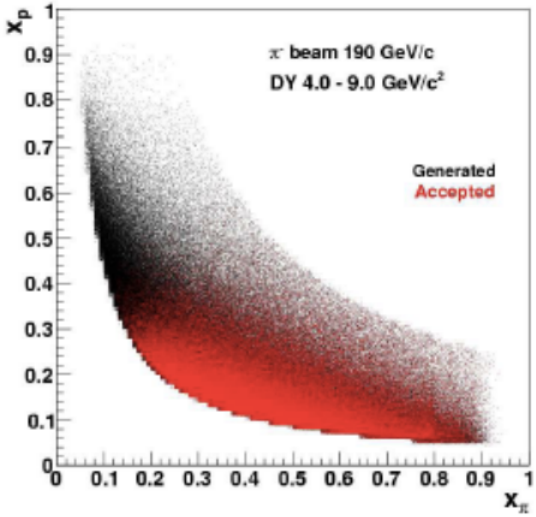
Backups: Drell–Yan Acceptance



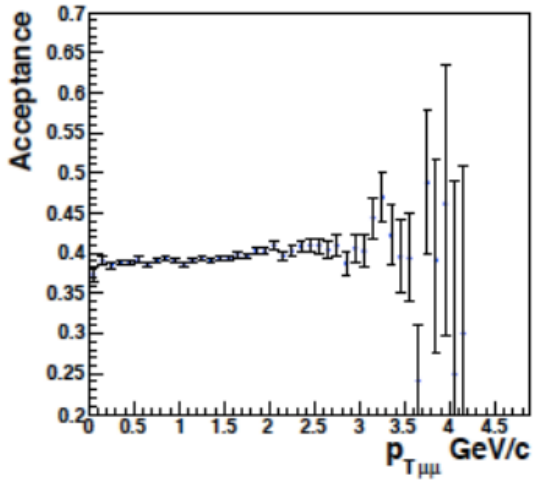
Acceptance in $M_{\mu\mu}$ [S. Platchkov (COMPASS), Hep Chile, 2016]



Acceptance in x_F [COMPASS II Proposal]



Acceptance in x_1, x_2 [S. Platchkov (COMPASS), Hep Chile, 2016]



Acceptance in p_T [S. Platchkov (COMPASS), Hep Chile, 2016]