Physics with charmonia at COMPASS++/AMBER and SPD experiments

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On behalf of the SPD working group

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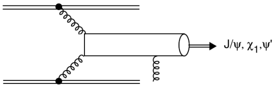
Introduction

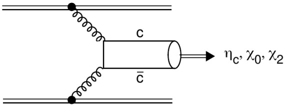
- QCD is an extremely successful theory, but our understanding of the strong interactions is incomplete without knowing how bound states are formed. Experimental determination of hadron parton structure provides an important input to this problem.
- We know much about proton PDFs, but there is a lack of experimental results for its spin-dependent structure.
- Parton structure of light mesons is badly known: in case of pion it remains highly uncertain and in case of kaon we have almost no information on it.
- The proposed SPD and COMPASS++/AMBER experiments can make a significant contributions to these areas.

J/ψ (charmonia) production as a probe of hadron structure

- Inclusive J/ψ production:
  - is sensitive to gluon and quark PDFs,
  - has large cross-section and very distinct signal in the dimuon mode,
  - is theoretically ambiguous,
  - is complicated due to the presence of feed-down contributions.



- Study and validation of J/ψ production mechanisms would be crucial to
  - **extract the gluon and quark PDF of mesons at AMBER,**
  - **interpret potential J/ψ spin asymmetries or angular modulations at SPD.**



- Complementary to the **Drell-Yan**, **prompt photons** and open charm studies.

Diagrams from
Int.J.Mod.Phys.A10:3043-3070,1995

Feed-down contributions at low energies

HERA-B, Phys.Rev.D79:012001,2009

- $\chi_{cJ} \to \gamma J/\psi$: $\approx 30\%$

Exp.	beam/ target	$\sqrt(s)$ GeV	$N_{J/\psi}$	N_{χ_c}	$R\chi_c$	$\frac{\sigma(\chi_{c1})}{\sigma(\chi_{c2})}$	$\sigma(\chi_{c1})$ (nb/n)	$\sigma(\chi_{c2})$ (nb/n)
ISR [6]	pp	$< 55 >$	658	31 ± 11	0.43 ± 0.21			
R702 [7]	pp	52.4,62.7	975		$0.15^{+0.10}_{-0.15}$			
ISR [8]	pp	62			0.47(8)			
E610 [9]	pBe	19.4,21.7	157 ± 17	11.8 ± 5.4	0.47(23)	0.24(28)	39(49)	162(81)
E705 [10]	pLi	23.8	6090 ± 90	250 ± 35	0.30(4)	0.09(29)(17)	24(48)(2)	244(83)(16)
E771 [12]	pSi	38.8	11660 ± 139	66	0.76(29)(16)	0.61(24)(4)	488(128)(56)	805(231)(92)
HERA-B [14]	pC,Ti	41.6	4420 ± 100	370 ± 74	0.32(6)(4)			
CDF [11],[13]	$p\bar{p}$	1800	$\{^{88000}_{32642 \pm 185}$	$\{^{119 \pm 14}_{1230 \pm 72}$	0.297(17)(57)	1.19(33)(14)		

- $R_{12} = \frac{\sigma(\chi_{c1}) B(\sigma(\chi_{c1}) \to \gamma J\psi)}{\sigma(\chi_{c2}) B(\sigma(\chi_{c2}) \to \gamma J\psi)} \sim 1$

	R_{12}
C	$1.06 \pm 0.21_{st} \pm 0.37_{sys}$
Ti	$0.67 \pm 0.67_{st} \pm 0.23_{sys}$
W	$0.98 \pm 0.36_{st} \pm 0.34_{sys}$
Tot	$1.02 \pm 0.17_{st} \pm 0.36_{sys}$

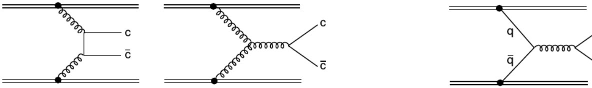
- $\psi' \to J/\psi X$: $\approx 10\%$
- In total feed-down contributions account for $\approx 40\%$ of the inclusive cross-section.

Color evaporation model

Color Evaporation Model

Color evaporation model (CEM)

- The charmonia state H production cross-section is assumed to be proportional to the one of $c\bar{c}$ pair with the mass between $2m_c$ and $2M_D$. The summation over colors and spins is implied.



- The proportionality coefficients f_H are assumed to be process independent.
- Predicts spin-averaged observables.

But

- The process-independence of f_H holds only approximately.
- Kinematic distributions for different charmnium states are not identical.

Addressed in Improved CEM (PRD98,114029 (2018)).

NRQCD

Phys.Rev.D54:2005,1996

For the process $A+B \to H+X$ in the collinear factorization:

$$\sigma_H = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1) f_{i/B}(x_2) \hat{\sigma}(ij \to H).$$

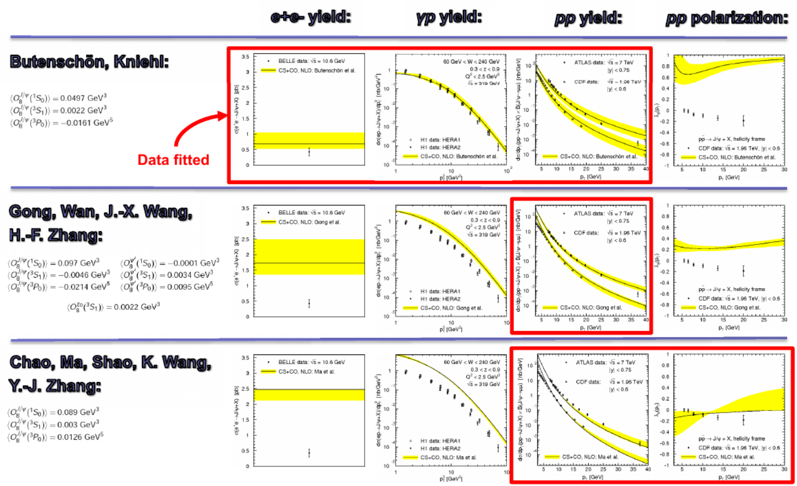
1. **Conjecture** of the cross-section factorization to short-distance ($x \approx 1/m_c$) and long-distance parts:

   $$\hat{\sigma}(ij \to H) = \sum_n C^{ij}_{Q\bar{Q}[n]} \langle O^H_n \rangle.$$

   $C^{ij}_{Q\bar{Q}[n]}$ (SDC) describe heavy quark pair production, $\langle O^H_n \rangle$ long distance matrix elements (LDME) describe its hadronization to quarkonium H and $n = {}^{2S+1}L_J^{(1,8)}$.
   Proven only for sufficiently large p_T.
2. **Hierarchy** of LDME $\langle O^H_n \rangle$ with respect to v ($v^2 \approx 0.2-0.3$ for charmonium).

Expression for cross-section is a **double** series in α_s and v. There are indications that the series is well-converged.

Slide borrowed from M. Butenschon DIS 2016 (DESY Hamburg)



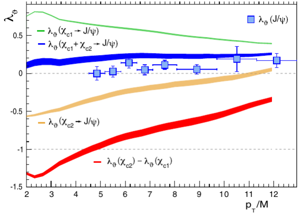
Details in Mod.Phys.Lett.A,Vol.28,No.9(2013) 1350027.

No SDML set can describe all e^+e^-, γp, pp and pp polarization data.

J/ψ polarization

- $d\sigma/d\cos\theta \propto 1 + \alpha\cos^2\theta$
  - $\alpha = 1$ – transverse
  - $\alpha = -1$ – longitudinal
- The J/ψ polarization is **sensitive to elementary J/ψ production processes** and is a **nontrivial test to the NRQCD**.
- **Polarization puzzle**: observed J/ψ are unpolarized.
- Polarization of χ_{cJ} states has not been measured yet!
- χ_{cJ} contributions might be a key to solve the polarization puzzle.

Feed-down contributions may play significant role in the polarization puzzle!

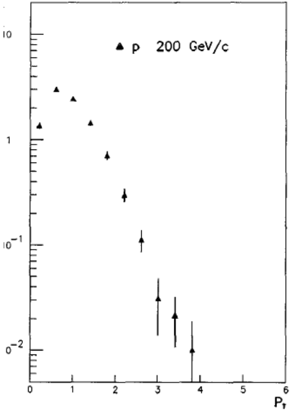


Faccioli et al, EPJC 78, 268 (2018)

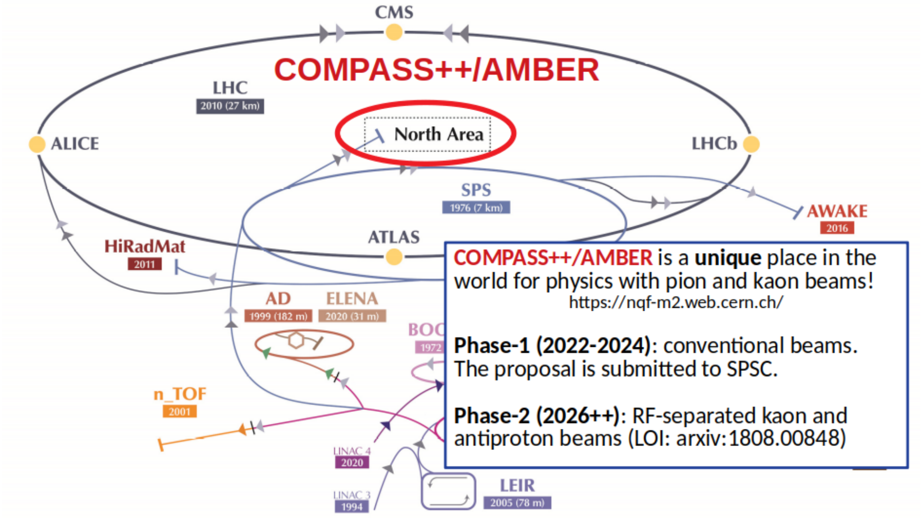
The SPD p_T range below 3-4 GeV is complicated for the analysis:

- Collinear factorization is not applicable below 4 GeV (or even higher values).
- k_T of hadrons must be taken into account.
- Parton reggeization approach (PRA, Kniehl, Vasin, Saleev, 2006) is expected to work in the SPD p_T range.
  - NRQCD fits
  - Improved CEM
- k_T-factorization approach of Baranov, Lipatov, Zotov (EPJC 75, 455 (2015), ..., PRD 100, 114021 (2019)) may be also applicable.

The J/ψ p_T distribution from NA3 at $\sqrt{s} = 19.4$ GeV



COMPASS++/AMBER

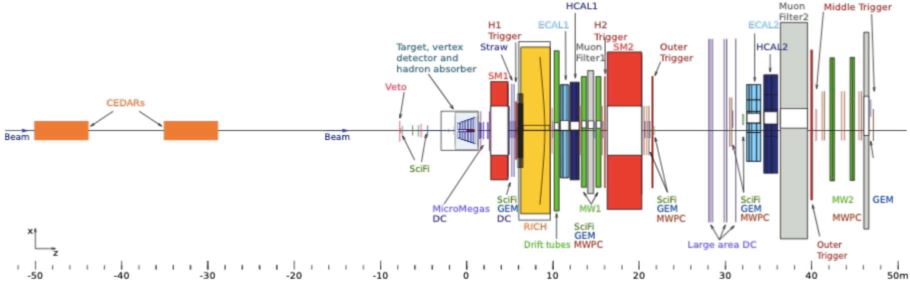


COMPASS++/AMBER is a **unique** place in the world for physics with pion and kaon beams!
https://nqf-m2.web.cern.ch/

Phase-1 (2022-2024): conventional beams. The proposal is submitted to SPSC.

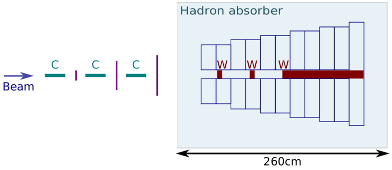
Phase-2 (2026++): RF-separated kaon and antiproton beams (LOI: arxiv:1808.00848)

2024 Drell-Yan setup

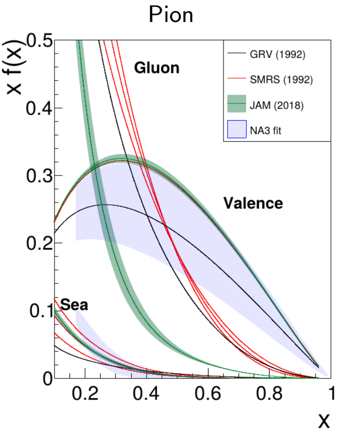


- **Phase-1**, 190 GeV beams ($\sqrt{s} = 19$ GeV):
  - positive pion (24%) and protons (74%)
  - negative pions (97%)
- **Phase-2**, 100 GeV beams:
  - negative kaons ($\approx 50\%$) and pions ($\approx 50\%$)
  - positive kaons
  - antiprotons

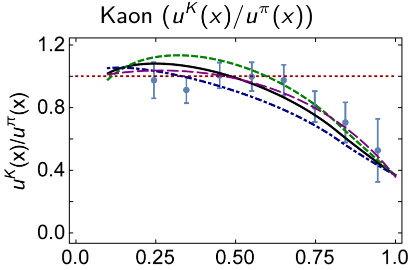
Target



Status of pion and kaon PDFs



- GRV and SMRS: DY(E615,NA10) and prompt photon measurements (WA70, NA24)
- JAM: DY + leading neutron data in DIS (ZEUS, H1)



Data: NA3 (700 kaon events)
Curves: DSE calculations for 0%, 5%, 10%, and 15% of momentum carried by gluons (PRD93,074021(2016))

Charmonium at COMPASS++/AMBER

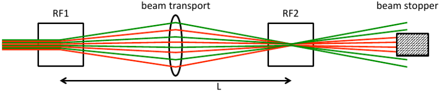
- At AMBER energies average $p_T < M_{J/\psi}$, which is complementary to LHC data. Physics is expected to be dominated by $2 \rightarrow 1$ processes.
- Unprecedented statistics to measure p_T, x_F and polarization.
- Ability to simultaneously study π^-, π^+ and proton induced reactions.
- Ability to study ψ' with large data sets (10K – 30K events per beam/target).
- Light (C) and heavy targets (W), possibility to study nuclear modifications in charmonia production.
- Unique high statistics measurements with K^+ and K^- at Phase-2.

Phase-1

Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [129, 130]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [131]	Be Fe Cu	800	p	3000000
NA50 [132]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [133]	p	450	p	301000
	d			312000
HERA-B [134]	C	920	p	152000
COMPASS 2015	110 cm NH_3	190	π^-	1000000
COMPASS 2018				1500000
This exp	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

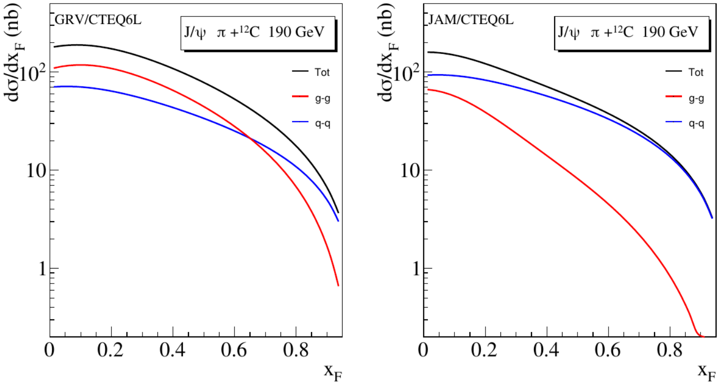
Phase-2

RF-separated beams



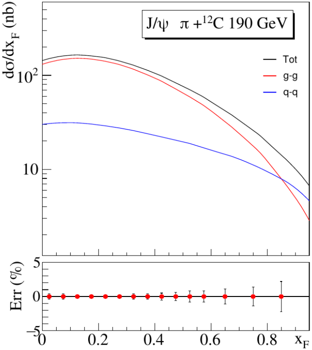
- beams types: $K^{\pm}$, $\bar{p}$ (100 GeV, C, W, NH_3 targets).
- K^-: more than **1 million** per year of data taking on a carbon target.

$d\sigma/dx_F$ for $\pi + {}^{12}C$ at 190 GeV

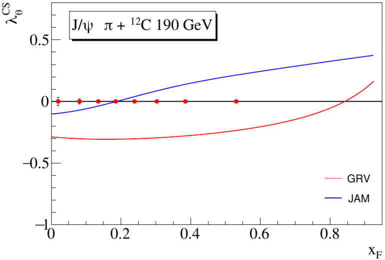


The x_F distribution of inclusive J/ψ production for LO CEM with GRV and JAM PDFs.

ICEM, Cheung and Vogt (PRD98,114029 (2018), private communications)



Pion: GRS
Proton: CT10
Relative statistical errors are shown.

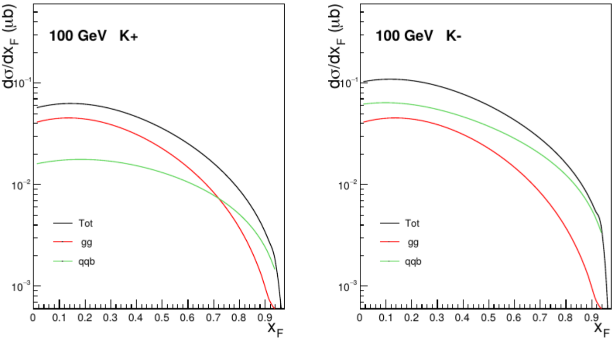


Error bars are estimated based on COMPASS 2015 data.

ICEM predictions with minimal model dependence:

- $\lambda_\theta^{CS} \approx= +0.4$ for $q\bar{q}$,
- $\lambda_\theta^{CS} \approx= -0.6$ for gg.

LO CEM (indicative)



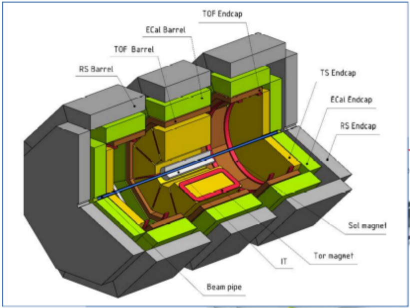
- The same program as for pions.
- Alternative way for the model validation and probing kaon $u_V^K(x)$ distribution:

$$\sigma_{J/\psi}^{K-} - \sigma_{J/\psi}^{K+} \propto \bar{u}_V^{K^-} u_V^N.$$

- Similar cancellation occurs for p and $\bar{p}$ beams.

NICA SPD

Spin **P**hysics **D**etetctor



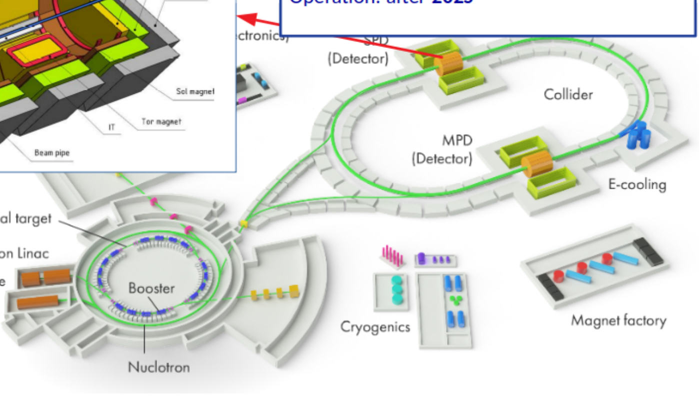
Polarized beams

p↑p↑ at $\sqrt{s}_{pp}$ **= 12 - 27 GeV, $L_{av} \approx 10^{32}$ cm^{-2}s^{-1}**

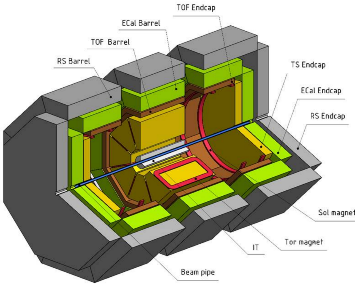
d↑d↑ at $\sqrt{s}_{NN}$ **= 4 - 13 GeV**

longitudinal and transverse polarization ~ 70%

Operation: after **2025**



Spin Physics Detector



Possible SPD set-up

Status: finalization of setup and preparation CDR.
LOI: arXiv:1408.3959

Performance relevant for charmonium physics

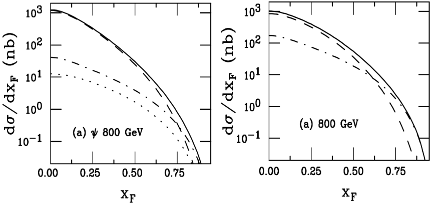
- Open spectrometer
- 4π geometry
- charged tracks momentum resolution 1-2%
- ECAL: $\sigma_E/E \sim 5\%/\sqrt{E}$
- about **20M** J/ψ events per year at $\sqrt{s} = 26$ GeV

Physics

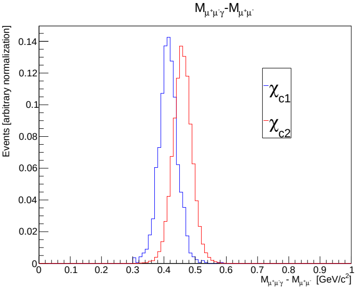
- **Unpolarized:** systematic measurements of J/ψ and ψ' p_T-, x_F-distributions and polarization. Relative χ_{c1} and χ_{c2} contributions, its dependence on kinematic variables, possibly their contribution to inclusive J/ψ polarization.
- **Polarized:** all kinds of single and double spin asymmetries including probing Sivers effect and gluon polarization.

Good acceptance for almost whole J/ψ x_F ($|x_F| < 0.85$) and p_T spectra and "transparency" for photons from χ_{cJ} decays.

NRQCD and CEM at $\sqrt{s} = 39$ GeV.

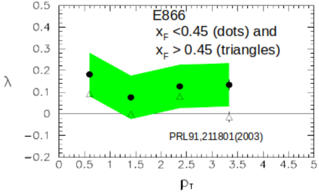


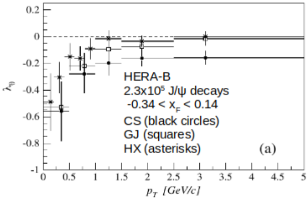
from PRC61,035203(2000)



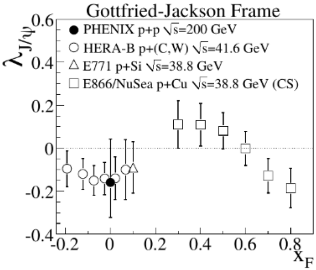
- 1% momentum resolution for muons
- $5\%/\sqrt{E}$ for photons
- the χ_{c1}/χ_{c2} fraction can be extracted as a function of kinematic variables.

J/ψ polarization at low energy pp and pN collisions

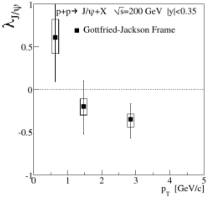




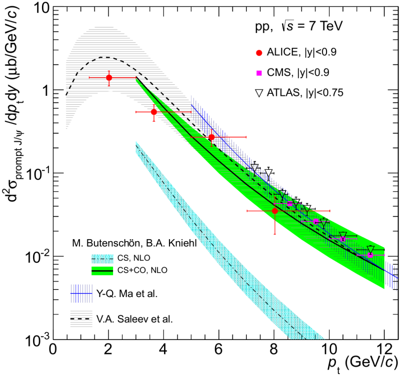
EPJC 60,517 (2009)



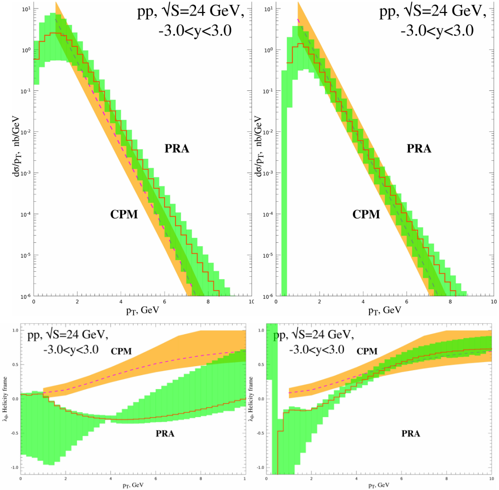
PRD82,012001(2010)



The available measurements are fragmentary and have significant uncertainties. The precise measurement of polarization in the whole allowed kinematics region would be essential for validation of theoretical models and can be expected based on SPD statistics.

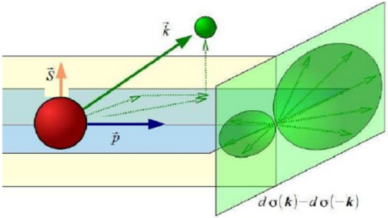


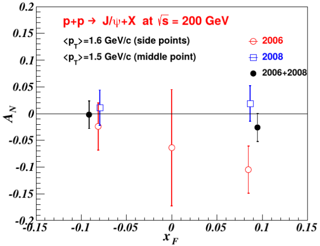
Alice Collaboration (JHEP1211(2012)065)



CPM is NLO CPM calculations by B.A. Kniehl and M. Butenschoen, **PRA** is LO Parton Reggeization Approache by M.Nefedov, V. Saleev and A. Karpishkov (Nefedov et al at Quarkonia as tools 2020).

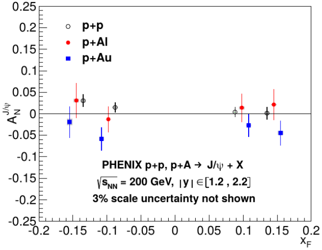
Probing gluon Sivers function in TSSA





PRD82, 112008 (2010)

- TSSA were measured by PHENIX to be small (consistent with zero) in a narrow x_F interval,
- **With the high statistics a precise measurement by SPD can be expected in wide x_F range.**



PRD98, 012006 (2018)

Perceiving the Emergence of Hadron Mass through AMBER@CERN

kick-off meeting of the initiative took place 11/12/2019, very good attendance

Joint CERN TH department and AMBER event, web site will be open by the end of the week

The goal of the workshop, location etc.

- Overview
- Timetable
- Committee
- Registration
- Participant List
- Submit abstract
- Book of Abstracts
- Venue
  - How to get to CERN
  - Visa information
  - Accomodation
  - Transportation
  - Network access
  - Visit CERN

Local Organizers

EHM-AMBER-2020-03...

+41 75 411 9025

The origin of the bulk of visible mass in the Universe is still unknown. Contrasting to the massiveness of the proton, the pion appears as unnaturally light, although both are of composite nature. This dichotomy forms a key part of the conundrum of "Emergence of Hadron Mass". The mechanism responsible for the generation of mass is the dynamical breaking of the scale invariance in Quantum Chromodynamics; and measurements of parton distribution functions (PDFs) are sensitive to this effect and its corollaries.

PDFs can be experimentally accessed via deep inelastic scattering, by pion and kaon-induced Drell-Yan interactions, charmonium production at moderate energies and hadro-production of direct photons. Remarkable theoretical progress has been achieved during the last decade. The resulting predictions require confrontation with accurate experimental data, like those that would become available at the AMBER experiment, very recently proposed at CERN. The prospects opened by the AMBER proposal provide now the opportunity for reviewing the present theoretical understanding of the Emergence of Hadron Mass, in order to harden and extend the list of experimental observables accessible at AMBER.

This Theory Initiative will join theorists from high-energy nuclear and particle physics, in a dialogue with the experimentalists, addressing the origin of hadron masses. The workshop is meant to start a collaborative effort between the experimentalists proposing this new measurement campaign, the phenomenologists doing global data analyses for parton distributions, and hadron-structure theorists.

Starts 30 Mar 2020, 09:00
Ends 3 Apr 2020, 18:00
Europe/Zurich

CERN
4/2-037 - TH meeting room

Craig Roberts
Oleg Denisov
Jan Friedrich
Wolf-Dieter Nowak
Catarina Quintans

Booking form Amber @CERN.docx
Booking form Amber @CERN.pdf

- Charmonium production is a powerful probe of hadron structure, but its applicability is **limited** by our understanding of its production process.
- There is rich physics with charmonia production in the two proposed complimentary experiments, NICA SPD and COMPASS++/AMBER, with **unprecedented statistics** at their energies.
- COMPASS++/AMBER is **a unique place** in the world to study pion and kaon parton structure.
- SPD can be expected to
  - systematically and precisely measure production properties of J/ψ, ψ', χ_{cJ} providing an input for validation of theoretical approaches to charmonia production;
  - probe proton spin-dependent structure by measuring spin asymmetries in the inclusive J/ψ production.

Thank you!