Hadronization Studies in $e^+e^-$ annihilation at Belle

Easiest Process to study QCD

electron-positron collisions

time-like
virtual photon

hadronic jet

Hadron
Field, Feynman (1977): Fragmentation functions encode the information on how partons produced in hard-scattering processes are turned into an observed colorless hadronic bound final-state [PRD 15 (1977) 2590]

- Complementary to the study of nucleon structure (PDFs)
- Cannot be computed on the lattice
- Consequence of confinement
- Questions to be asked
  - Macroscopic effect (distribution, polarization) of microscopic properties (quantum numbers)?
  - Effect of QCD vacuum the quark is traversing
**Amsterdam notation for FFs with quark/hadron polarization**

- Theoretically many more, in particular with polarized hadrons in the final state and transverse momentum dependence

<table>
<thead>
<tr>
<th>Parton polarization → Hadron Polarization</th>
<th>Spin averaged</th>
<th>longitudinal</th>
<th>transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin averaged</td>
<td>$D_1^{h/q} (z, p_T)$</td>
<td>$G_1^{h/q} (z, p_T)$</td>
<td>$H_1^{\perp h/q} (z, p_T)$</td>
</tr>
<tr>
<td>longitudinal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse (here $\Lambda$)</td>
<td>$D_{1T}^\perp \Lambda/q (z, p_T)$</td>
<td></td>
<td>$H_1^{\perp q/\Lambda} (z, p_T)$</td>
</tr>
</tbody>
</table>

- $z$: fractional energy of the quark carried by the hadron
- $P_{h,T}$: transverse momentum of the hadron: **TMD FFs**
- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes
- Particularly important for transverse spin structure

\[
\frac{d^3\sigma}{dx_1 dx_2 dz}(pp \rightarrow \pi^+ X) \propto \tilde{q_i}(x_1, k_{q,T}) \cdot G(x_2) \times \frac{d^3\sigma}{dx_1 dx_2}(q_i q_j \rightarrow q_k q_l) \times FF_{q,k,l}(z, p_{h,T})
\]
Fragmentation Functions: Why should we bother?

- Example:
  - Hadron Spectra at the LHC confronted with current FF sets
  - Large disagreement!

Where to Study?

- $e^+e^-$ cleanest way to access FFs

- B factories
  - close in energy to SIDIS ($100 \text{ GeV}^2$ vs $2-3 \text{ GeV}^2$)
  - Large integrated lumi!, high z reach

\[ D_q^h(z, Q^2) \]

\[ e^- \rightarrow q, \bar{q} \]

\[ e^+ \rightarrow \gamma^*, q \rightarrow \text{hadronic jet}, \text{Hadron} \]
Where to Study?

- $e^+e^-$ cleanest way to access FFs
  
  $e^- \gamma^* \rightarrow q \bar{q}$
  
  $D_h^q(z, Q^2)$ hadronic jet
  
- B factories
  
  - close in energy to SIDIS (100 GeV² vs 2-3 GeV²)
  
  - Large integrated lumi!, high z reach
Belle, a typical e+e- Experiment of generation 2000

• Asym. e⁺ (3.5 GeV) e⁻ (8 GeV) collider:
  - √s = 10.58 GeV, e⁺e⁻ → Y(4S) → B anti-B
  - √s = 10.52 GeV, e⁺e⁻ → qqbar (u,d,s,c) ‘continuum’
• ideal detector for high precision measurements:
  - Azimuthally symmetric acceptance, high res. Tracking, PID: Kaon efficiency ~85%
Available data:
  ~1.8 *10⁹ events at 10.58 GeV,
  ~220 *10⁶ events at 10.52 GeV
Measuring Light Quark Fragmentation Functions
on the \( \Upsilon (4S) \) Resonance

- small B contribution \(<1\%\) in high thrust sample
- \( >75\% \) of X-section continuum under \( \Upsilon \) \((4S)\) resonance
- 89 \( fb^{-1} \) \( \Rightarrow \) 792 \( fb^{-1} \)
Baseline measurement $D(z)$ from Cross-Section for identified Pions and Kaons

$$\sigma^h(z, Q^2, p_T) \propto \sum_q e_q^2 (D_{1,q}^h(z, Q^2, p_T) + D_{1,\bar{q}}^h(z, Q^2, p_T))$$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}}$$

$N_{j,raw}(z_m)$
Baseline measurement $D(z)$ from Cross-Section for identified Pions and Kaons

\[ \sigma^h(z, Q^2, p_T) \propto \sum_q e_q^2 \left( D_{1,q}^h(z, Q^2, p_T) + D_{1,\bar{q}}^h(z, Q^2, p_T) \right) \]

\[ \frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \]

- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low $z$, correct based on MC
Baseline measurement $D(z)$ from Cross-Section for identified Pions and Kaons

\[
\sigma^h(z, Q^2, p_T) \propto \sum_q e_q^2 \left( D_{1,q}^h(z, Q^2, p_T) + D_{1,\bar{q}}^h(z, Q^2, p_T) \right)
\]

- Correct for acceptance,
- $\tau\tau$, $2\gamma$,
- Decay in flight,
- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low $z$, correct based on MC

$< 10\%$
Cross sections

\[ \frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon_{\text{joint}}^i(z) \epsilon_{\text{ISR/FSR}}^i(z) S_{zz_m}^{-1} \epsilon_{\text{imp}}^i(z_m) P_{ij}^{-1} N_{j,raw}(z_m) \]

\( i = \pi, K \)

\( \pi^\pm \) (Statistical, Systematic Uncertainties)

\( K^\pm \) (Statistical, Systematic Uncertainties)

New DSS(E,H-P) Fit

- Fit includes pp, SIDIS data and BaBar e+e-.
- From DSS:
  - Precise data at high $z$
  - Some info from scaling violations (Belle vs experiments at $M_Z$)
  - Some info on flavor due to charge weighting
- New NNLO calculations (only e+e-)
  - $\rightarrow$ Reduce theoretical uncertainty but $\chi^2$ only marginally smaller
  - K factors at 10% (down from 40% for NLO/LO (at LEP energies only ~1%))
  - Still need high $z$ resummation and target mass corrections
Perturbative QCD tests

- Time like splitting functions have singularities < 0.1 (unlike space like important for DIS)
- MLLA → test for resummation
- Observed shape consistent with QCD calculations
- Can be used to extract $\alpha_S$
Can we measure quark polarization in FFs?

- Yes! → Collins fragmentation function
- Microscopic property (spin) leave footprint in macroscopic property (hadron azimuthal distributions)
The Collins Effect in the Artru Fragmentation Model

A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

\[ \pi^+ \text{ picks up } L=1 \text{ to compensate for the pair } S=1 \text{ and is emitted to the right.} \]

String breaks and a dd-pair with spin -1 is inserted.

\[ u \quad d \quad d \quad \bar{d} \quad \pi \quad u \bar{d} \quad (favored) \]
Application Transversity $h$:

- Tensor charge $g_T = \int_{-1}^{1} dx \ h(x)\ dx$ can be computed precisely on the lattice $\Rightarrow$ Compare with first order QCD
- Important for low energy BSM physics e.g. in neutron $\beta$ decay (tensor coupling)
- Cannot Measure in Inclusive Reactions
  - Naïve picture: leptonic probe too ‘fast’ to be sensitive to transverse polarization, need quark polarimeter:
How to measure spin dependent FFs in (unpolarized) $e^+e^-$?

- Effect measured in one hemisphere averages out
Measuring transverse spin dependent di-Hadron Correlations
In unpolarized $e^+e^-\text{ Annihilation into Quarks}$
Measuring transverse spin dependent di-Hadron Correlations
In unpolarized $e^+e^-$ Annihilation into Quarks
Measuring transverse spin dependent di-Hadron Correlations
In unpolarized $e^+e^-$ Annihilation into Quarks

Spin correlation will lead to azimuthal asymmetries in hadron pair correlation measurements!

**Experimental requirements:**
- Small asymmetries $\rightarrow$ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

\[
\sigma \propto H_1^\perp (z_1) \overline{H}_1^\perp (z_2) \cos(\phi_1 + \phi_2) + C
\]
There are two methods with two or one soft scale

\( \phi_1 + \phi_2 \) method:
hadron azimuthal angles with respect to the q\( \bar{q} \) axis proxy

\( \phi_0 \) method:
hadron 1 azimuthal angle with respect to hadron 2

\[
\sigma \sim M_{12} \left( 1 + \frac{\sin^2 \theta_T}{1 + \cos^2 \theta_T} \cos(\phi_1 + \phi_2) \frac{H_1^{[1]}(z_1) \bar{H}_1^{[1]}(z_2)}{D_1^{[0]}(z_1) \bar{D}_1^{[0]}(z_2)} \right) \quad \sigma \sim M_0 \left( 1 + \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \cos(2\phi_0) \frac{H_1^{[1]}(z_1) \bar{H}_1^{[1]}(z_2)}{D_1^{[0]}(z_1) \bar{D}_1^{[0]}(z_2)} \right)
\]

\[
R_{12}^{U/L} = \frac{N(\phi_1 + \phi_2)}{\langle N_{12} \rangle}
\]

\[
R_0^{U/L} = \frac{N(2\phi_0)}{\langle N_0 \rangle}
\]

D. Boer
Use of Double Ratios

- False asymmetries due to Acceptance and QCD radiation
- Charge independent
Belle π Collins Results

Extraction of Collins FF

Kang, Prokudin, Sun, Yuan

Belle Data:

(glocal fit to Belle, Hermes, Jlab & COMPASS data)
Extracted Transversity

Belle Data:

Di-Hadron Fragmentation
First measurement of Interference Fragmentation Function

\[ a_{12} \propto H_1^* \times H_1 \]

arXiv:1104.2425
AV et. al, PRL 107, 072004(2011)
"Easy" to measure in proton-proton!

Indeed: No Evolution, Gluons do not couple to transversity!

Kinematic coverage and tests of universality

$0.06 < x < 0.35$

Still 3x (200 GeV) 15x (500 GeV) data on tape/to be taken next year → most precise determination of transversity before SoLID

One $p_T$ bin for which $p_T/\sqrt{s}$ similar $\sim x_{Bj}$

See also Phys.Rev.Lett. 115 (2015) 242501
Comparison of pp results with Theory Predictions based on SIDIS \( \rightarrow \) Test of Universality

M. Radici at Spin2016

- Theory prediction in this region driven by one COMPASS datapoint outside the Soffer bound
Helicity Dependent FFs

- Not needed for $g_1$ but
  - Needs intrinsic transverse momentum to exist in FF $\Rightarrow$ BM in the nucleon
  - Sensitive to local strong parity violating effects in the QCD vacuum
QCD Vacuum Transitions carry Chirality

Vacuum states are characterized by “winding number”
Transition amplitudes: Gluon configurations, carry net chirality
e.g. quarks: net spin momentum alignment
Similar mechanism to EW baryogenesis
QCD Vacuum Transitions carry Chirality QN

[Diagrams showing quark transitions and chirality]

Kharzeev, McLerran and Warringa, arXiv:0711.0950,
Fukushima, Kharzeev and Warringa, arXiv:0808.3382
Handedness Correlations

Thrust direction

\( \pi^- \rightarrow \text{Q=1} \rightarrow \pi^+ \)

\( L \)  \( R \)

\( \pi^- \)  \( \pi^+ \)
Di-Hadron Asymmetries

- Di-hadron Cross Section from Boer, Jakob, Radici [PRD 67, (2003) 094003]:
  Expansion of Fragmentation Matrix $\Delta$: encoding possible correlations in fragmentation ($k$: $P_{h1} + P_{h2}$)

\[
\frac{1}{32\pi} \int dk^+ \Delta(k; P_h, R) \bigg|_{k^- = P_h^- / z, k_T} \\
= \frac{1}{4\pi} \frac{1}{4} \left\{ D_1^a(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \gamma_- - G_1^a(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \frac{\epsilon_{\mu \nu \rho \sigma} \gamma^\mu n^\nu k_T^\rho R_T^\sigma}{M_1 M_2} \gamma_5 \right. \\
+ H_1^a(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \frac{\sigma_{\mu \nu} R_T^\mu n^\nu}{M_1 + M_2} + H_1^a(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \frac{\sigma_{\mu \nu} k_T^\mu n^\nu}{M_1 + M_2} \right\}.
\]

\[
\langle \cos(2(\phi_R - \phi_\bar{R})) \rangle = \sum_{a, \bar{a}} e_a^2 \frac{3\alpha^2}{2Q^2} \frac{z^2 \bar{z}^2}{M_1 M_2 \bar{M}_1 \bar{M}_2} A(y) \frac{1}{M_1 M_2 \bar{M}_1 \bar{M}_2} G_1^a(z, M_h^2) \bar{G}_1^a(\bar{z}, M_h^2). 
\]

\[
\langle \cos(\phi_R + \phi_\bar{R} - 2\phi^l) \rangle = \sum_{a, \bar{a}} e_a^2 \frac{3\alpha^2}{Q^2} \frac{z^2 \bar{z}^2}{(M_1 + M_2)(\bar{M}_1 + \bar{M}_2)} B(y) \frac{1}{(M_1 + M_2)(\bar{M}_1 + \bar{M}_2)} H_1^a(R) \frac{1}{(M_1 + M_2)(\bar{M}_1 + \bar{M}_2)} H_1^a(\bar{R})(\bar{z}, \bar{M}_h^2). 
\]

Measure $\cos(\phi_{R1} + \phi_{R2})$, $\cos(2(\phi_{R1} - \phi_{R2}))$ Modulations!
Di-hadron Cross Section from Boer, Jakob, Radici

- $\Delta$: Fragmentation Matrix, encoding possible correlations in fragmentation
- $k$: $P_{h1} + P_{h2}$

$$\frac{1}{32\pi} \int dk^+ \Delta(k; P_h, R) \Bigg|_{k^- = P_h^- / z, k_T}$$

$$\frac{1}{4\pi} \int \frac{1}{4} \left\{ D_1^a(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \eta_- - G_1^{\perp a}(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \frac{\epsilon_{\mu \nu \rho \sigma} \gamma_\mu \gamma_\nu k_T^\rho R_T^\sigma}{M_1 M_2} \gamma_5 \right\}$$

$$+ H_1^{\perp a}(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \frac{\sigma_{\mu \nu} R_T^{\mu \nu} n_-}{M_1 + M_2} + H_1^{\perp a}(z, \xi, k_T^2, R_T^2, k_T \cdot R_T) \frac{\sigma_{\mu \nu} R_T^{\mu \nu} n_-}{M_1 + M_2} \right\} .$$

$$\langle \cos(2(\phi_R - \phi_{\bar{R}})) \rangle = \sum_{a, \bar{a}} e_a^2 \frac{3 \alpha_s^2}{2Q^2} z^2 \bar{z}^2 A(y) \frac{1}{M_1 M_2 M_{\bar{M}} M_{\bar{M}}} \frac{1}{M_1 M_2 M_{\bar{M}} M_{\bar{M}}} G_1^{\perp a}(z, M_h^2) \bar{G}_1^{\perp a}(\bar{z}, \bar{M}_h^2) .$$

$$\langle \cos(\phi_R + \phi_{\bar{R}} - 2\phi^l) \rangle = \sum_{a, \bar{a}} e_a^2 \frac{3 \alpha_s^2}{Q^2} \frac{z^2 \bar{z}^2 B(y)}{(M_1 + M_2)(\bar{M}_1 + \bar{M}_2)} H_1^{\perp a}(z, M_h^2) \bar{H}_1^{\perp a}(\bar{z}, \bar{M}_h^2) .$$

Measure $\cos(\phi_{R1} + \phi_{R2}), \cos(2(\phi_{R1} - \phi_{R2}))$ Modulations
New: Use Jet Reconstruction at Belle

- Robust vs. final state radiation
- **De-correlate axis between hemispheres**
- We use anti-kT algorithm implemented in fastjet
- Cone radius $R=1.0$
- Min energy per jet $2.75 \text{ GeV} \to$ suppress weak decays
- Only allow events with 2 jets passing energy cut (dijet events)
- Only particles that form the jet are used in the asymmetry calculation
- Thrust cut of $0.8 < T < 0.95$
Asymmetries for $\cos(2(\phi_{R1}-\phi_{R2}))$ ($G_1 \perp$) small

- No evidence of local p-odd effects yet
- Next step: partial wave analysis
Polarized Hyperon Production
(see presentation by Y. Guan at Spin2016)

- Large $\Lambda$ transverse polarization in unpolarized $pp$ collision
  \( \text{PRL36, 1113 (1976); PRL41, 607 (1978)} \)
- Caused by polarizing FF $D_{1T}^+(z, p_T^2)$?
- Polarizing FF is chiral-even, has been proposed as a test of universality.
  \( \text{PRL105, 202001 (2010)} \)
- OPAL experiment at LEP has been looking at transverse $\Lambda$ polarization, no significant signal was observed.

\[ p + p \rightarrow \Lambda^\uparrow + X \]

\[ x_F = \frac{p_L}{\text{max } p_L} [x_1 - x_2] \]

ISR data
Hyperon Production as a tool to study baryon spin structure

- Lambda polarization allows to study spin-orbit correlation of quarks inside Baryon $\rightarrow$ counterpart of the Sivers parton distribution function ($k_T$ dependence of quark distributions in transversely polarized proton)
- A non-vanishing $D_{1T}^\perp$ could help to shed light on the spin structure of the $\Lambda$, especially about the quark orbital angular momentum, a missing part of the spin puzzle of the nucleon.
- Produce Lambda with certain $p_T$
- Check Transverse Polarization depending on $p_T$ and flavor
- Analogue of the Sivers effect in the Similar Universality checks ($T$-odd but not chiral odd) allows to fix sign $q_p T$
Signal process $\Lambda \rightarrow p\pi^- (\bar{\Lambda} \rightarrow \bar{p} \pi^+ )$. Clear $\Lambda$ peak.

Detect light hadron ($K^\pm, \pi^\pm$) in the opposite hemisphere $\Rightarrow$ enhance or suppress different flavors fragmenting in $\Lambda(\bar{\Lambda})$. 

Sideband subtraction will be applied.
The reference vector $\hat{n}$ is perpendicular to the $\Lambda$ production plane.

The $p_t$ is defined as the transverse momentum of $\Lambda$ relative to thrust axis in thrust frame and to hadron axis in hadron frame.

Give a polarization of $P$, the yield of the events follow:

$$\frac{1}{N} \frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta$$

where $\alpha$ is the decay parameter: $\alpha_+ = 0.642 \pm 0.013$ for $\Lambda$ and $\alpha_- = -0.71 \pm 0.08$ for $\bar{\Lambda}$ (PDG).
- Cos\(\theta\) distribution in \(\Lambda\) signal region \(\text{a)}\) is corrected by sideband subtraction \(\rightarrow \text{b)}\).
- Normalized by itself, as shown in \(\text{c)}\).
- The shape \(\text{c)}\) is divided by the corresponding shape from MC, so that we obtain the efficiency-corrected curve \(\text{d)}\).
- Or \(\text{c)}\) shape of \(\Lambda\) events is divided by that from anti-\(\Lambda\) events if we assume efficiency is independent on charge, that is \(\text{e)}\), this is called data ratios.
- We fit \(\text{d)}\) and \(\text{e)}\) to get the polarization of interest.
Fit to the $\cos \theta$ distributions with $1 + p_0 \cos \theta$.

The polarization of interest: $p_0/\alpha$.

In the data ratio, polarization is obtained via $p_0/(\alpha_+ - \alpha_-)$.

In data ratios, the slope on the $\cos \theta$ distributions are about two times larger than that in MC-corrected ratios, the $(\alpha_+ - \alpha_-)$ is also about times larger than $\alpha_+ (\alpha_-)$.

Results from MC-corrected ratio and data ratio are consistent with each other.

Nonzero polarization, magnitude rises to about $\sim 5\%$ with $z_\Lambda = 2E_\Lambda/\sqrt{s}$.  

Belle preliminary
Results in thrust frame

- Four $z$ bins and five $p_t$ bins are used: $z_{\Lambda}=[0.2,0.3,0.4,0.5,0.9]$; $p_t=[0.0,0.3,0.5,0.8,1.0,1.6]$ GeV
- Nonzero polarization was observed. Interesting shape as a function of $(z_{\Lambda}, p_t)$.
- The polarization rise with higher $p_t$ in the lowest $z_{\Lambda}$ and highest $z_{\Lambda}$ bin. But the dependence reverses around 1 GeV in the intermediate $z_{\Lambda}$ bins.
- Results are consistent between $\Lambda$ and $(\bar{\Lambda})$ and $\Lambda$ - $(\bar{\Lambda})$ data ratio.
- Error bars are statistical uncertainties and shaded areas show the systematic uncertainties.
At low $z_\Lambda$, polarization in $\Lambda + h^+$ and $\Lambda + h^-$ have opposite sign. The magnitude increases with higher $z_h$.

At large $z_\Lambda$, the differences between $\Lambda + h^+$ and $\Lambda + h^-$ reduce. Small deviations can still be seen and depend on $z_h$. 

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**Results in thrust frame**

![Graphs showing polarization](image)

- **Belle Preliminary**
- **Polarization vs. $z_{\pi}$**
- **Polarization vs. $z_{K}$**

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- **vs. $(z_\Lambda, z_h)$**

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Results in hadron frame

- Similar results with that in the thrust frame.
- Results from charge-conjugate modes are consistent with each other.
An attempt to look at the flavor tag effect of the light hadron, based on MC. (Pythia6.2)

The fractions of various quark flavors going to the Λ’s hemisphere are shown in different \([z_\Lambda z_h]\) region.

MC indicates that the tag of the quark flavors is more effective at low \(z_\Lambda\) and high \(z_h\). It explains why at low \(z_\Lambda\) and high \(z_h\), polarization in \(\Lambda + h^+\) and \(\Lambda + h^-\) have opposite sign.
Background unfolding

- Non-$\Lambda$ backgrounds are excluded out in the sideband subtraction.
- $\Sigma^*$ decays to $\Lambda$ strongly, is included in the signal.
- Feed-down from $\Sigma^0$ (22.5%), $\Lambda_c$ (20%) decays need to be understood.
- The $\Sigma^0$-enhanced ($\Sigma^0 \rightarrow \Lambda + \gamma$) (Br~100%). and $\Lambda_c$-enhanced ($\Lambda_c \rightarrow \Lambda + \pi^+$) (Br~1.07%) data sets are selected and studied.
- The measured polarization can be expressed as:

\[ P_{\text{mea.}} = (1 - \sum_i F_i) P_{\text{true}} + \sum_i F_i P_i, \]

- $F_i$ is the fraction of feed-down component $i$, estimated from MC. $P_i$ is polarization of component $i$.
- Polarization of $\Lambda$ from $\Sigma^0$ decays is found has opposite sign with that of inclusive $\Lambda$.

KEKB/Belle → SuperKEKB, Upgrade

- **Aim:** super-high luminosity \( \sim 10^{36} \text{ cm}^{-2}\text{s}^{-1} \) (\( \sim 40 \times \) KEK/Belle)

- **Upgrades of Accelerator** (Nano-beams + Higher Currents) and Detector (Vtx, PID, higher rates, modern DAQ)

- **Significant US contribution**

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http://belle2.kek.jp

Start of commissioning in 2016
SVD: 4 DSSD lyr $\rightarrow$ 2 DEPFET lyr + 4 DSSD lyr
CDC: small cell, long lever arm
ACC+TOF $\rightarrow$ TOP+A-RICH
ECL: waveform sampling (+pure CsI for end-caps)
KLM: RPC $\rightarrow$ Scintillator +MPPC(end-caps)

Technical design report:
arXiv:1011.0352
QCD studies at Belle II

- Precision study of local strong parity violation to probe the QCD vacuum
- Hadronization studies in transverse momentum-spin correlations ($\Lambda$)/Fragmentation function
- Precision studies of fragmentation functions needed for JLab12 program
  - Precision
  - Charm suppression
  - Kaon ID
Status of Belle II Installation

Sector Test of KLM
(B Kunkler from IU)
Current SuperKEKB/Belle II Schedule

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<th>CY2016</th>
<th>CY2017</th>
<th>CY2018</th>
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- **Super KEKB Construction**
- **Startup**
- **Dedicated Commissioning Detector**
- **Run w/o VTX**
- **Run with Full Belle II**

Feb 1st
Hadronization Studies in $e^+e^-$ provide a complimentary access to non-perturbative QCD

Exciting new results with respect to polarized and polarizing FFs

$k_T$ dependent FFs on the horizon

Belle II will provide ample new opportunities
Zero polarization is observed in MC, as expected.

Smearing effects caused by the detector acceptance and resolution are estimated using weighted-MC with nonzero polarization input.

In thrust frame correction factors are 1.0-1.3 depending on the [z,p_t].

No Correction needed for hadron frame.
**PID Corrections from Data: Significant improvements compared to previous experiments**

- Misidentification $\pi \rightarrow K$ up to 15%, $K \rightarrow \pi$ up to 20%

**Scatter plot: e, $\mu$, $\pi$, K and p tracks from 4e+05 events**

- ToF forward geometry acceptance limit
- ToF backward geometry acceptance limit

**Matrix of PID probabilities for each single bin from real data calibration - need large statistics**

$$[[P]]_{ij}^{(p_{lab}, \cos \theta_{lab})} = \begin{pmatrix}
    p(e \rightarrow e) & p(\mu \rightarrow e) & p(\pi \rightarrow e) & p(K \rightarrow e) & p(p \rightarrow e) \\
    p(e \rightarrow \mu) & p(\mu \rightarrow \mu) & p(\pi \rightarrow \mu) & p(K \rightarrow \mu) & p(p \rightarrow \mu) \\
    p(e \rightarrow \pi) & p(\mu \rightarrow \pi) & p(\pi \rightarrow \pi) & p(K \rightarrow \pi) & p(p \rightarrow \pi) \\
    p(e \rightarrow K) & p(\mu \rightarrow K) & p(\pi \rightarrow K) & p(K \rightarrow K) & p(p \rightarrow K) \\
    p(e \rightarrow p) & p(\mu \rightarrow p) & p(\pi \rightarrow p) & p(K \rightarrow p) & p(p \rightarrow p)
\end{pmatrix}$$
What we can learn by studying Hadronization

- Hadronization is the process by which colored objects (quarks/gluons) form hadrons in the final state
  - Cannot be calculated from first principles in QCD from the lattice → Measurements needed!

- Hadronization is tied to confinement → Crucial property of QCD which we are still trying to understand
  - Provide data to extract fragmentation functions parametrizing Hadronization for use in factorized expression
  - Study the formation and dynamics of short lived particles
  - Study QCD in a process complementary to looking at nucleon structure
  - Study non-perturbative QCD effects
Easiest Process to study QCD

**DIS**

\[ \text{DF} \otimes \text{FF} \]

- space-like virtual photon
- electron-electron collisions
- time-like virtual photon

**DIS**

\[ \text{FF} \otimes \text{FF} \]
• Change the reference vector $\hat{n}$ to be in the $\Lambda$ production plane. But still normal to $\vec{p}_\Lambda$.

• Combine a proton in one event and pion in the other event to form a false $\Lambda$.

• The second order term was added in the fit function $1 + p_0 \cos \theta + p_1 \cos^2 \theta$.

- Besides, uncertainties from smearing correction factors and sideband subtractions are included in systematics errors.
- Uncertainties of decay parameters are assigned as systematic errors.
QCD is hard...

- QCD has glue-glue interaction and strong coupling
  - Binding energy/constituent mass ~$10^2$ in proton, $10^{-8}$ in hydrogen atom
- Much more difficult to compute
... but significant progress in first order calculations from the lattice

- QCD has glue-glue interaction and strong coupling
  - Binding energy/constituent mass \( \sim 10^2 \) in proton, \( 10^{-8} \) in hydrogen atom
  - Much more difficult to compute

- Advances in Computational QCD (lattice)
  - Need experimental input
  - Cannot compute hadronization
“Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection - J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).”

“Experiments with spin have killed more theories than any other single physical parameter” - Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

Example: Role of spin in the particle masses of mesons:

<table>
<thead>
<tr>
<th>Mesons q̅q</th>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>pion</td>
<td>u̅d</td>
<td>+1</td>
<td>0.140</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ρ⁺</td>
<td>rho</td>
<td>u̅d</td>
<td>+1</td>
<td>0.770</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Probes to Study Polarized Proton Structure

Inclusive polarized deep inelastic scattering (DIS)

\[ \sigma_{1/2} \sim \sum_i e_i^2 q_i^+ \]

\[ \sigma_{3/2} \sim \sum_i e_i^2 q_i^- \]
Probes to Study Polarized Proton Structure

Semi-Inclusive polarized deep inelastic scattering (DIS)

Fragmentation Process:
Outgoing quark forms hadrons
The three leading order, collinear PDFs

\[ f_1^q(x) \]

unpolarized PDF
quark with momentum \( x = \frac{p_{\text{quark}}}{p_{\text{proton}}} \) in a nucleon
well known – unpolarized DIS

\[ g_1^q(x) \]

helicity PDF
quark with spin parallel to the nucleon spin in a longitudinally polarized nucleon
known – polarized DIS

\[ h_1^q(x) \]

transversity PDF
quark with spin parallel to the nucleon spin in a transversely polarized nucleon
Helicity – transversity: measurement of the nonzero angular momentum components in the protons wavefunction
Chiral odd, poorly known
Cannot be measured inclusively

\[ \rightarrow \text{Need for Quark Polarimeter!} \]
Current Status of Distribution Functions

\[ f_1 = \bullet \]

Unpolarized

\[ F_2 \propto \sum_q x e_q^2 f_q \]
Current Status of Distribution Functions

\[ f_1 = \bullet \]

Unpolarized

\[ g_1 = \bullet \longrightarrow \bullet \longrightarrow \bullet \]

Longitudinally Polarized

\[ F_2 \propto \sum_q x e^2_q f^q_1 \]

\[ g_1 \propto \sum_q e^2_q g^q_1 \]
Current Status of Distribution Functions

Unpolarized

Longitudinally Polarized

Transversely Polarized

\[ f_1 = \begin{array}{c}
\bullet
\end{array} \]

\[ g_1 = \begin{array}{c}
\rightarrow -
\end{array} \]

\[ h_1 = \begin{array}{c}
\bullet -
\end{array} \]

\[ F_2 \propto \sum_q x e_q^2 f_q^1 \]

\[ g_1 \propto \sum_q e_q^2 g_q^1 \]

\[ h_1 \propto \sum_q e_q^2 h_q^1 (x) * H_1^q \]

Chiral odd - cannot be measured inclusively
Current Status of Distribution Functions

Unpolarized

Unpolarized

Longitudinally Polarized

Transversely Polarized

\[ F_2 \propto \sum_q x e_q^2 f_1^q \]

\[ g_1 \propto \sum_q e_q^2 g_1^q \]

Anselmino et al
Comparison between 0.2 and 0.5 TeV: Consistent and no Sign of Evolution

Indeed: No Evolution, Gluons do not couple to transversity!
Measurements of Fragmentation Functions in e+e- at Belle

- KEK-B: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - \( \sqrt{s} = 10.58 \) GeV, e^+e^-\( \rightarrow \) Y(4S)\( \rightarrow \) B \( \bar{B} \)
  - \( \sqrt{s} = 10.52 \) GeV, e^+e^-\( \rightarrow \) qqbar (u,d,s,c) ‘continuum’
- ideal detector for high precision measurements:
  - tracking acceptance \( \theta \) [17°;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - \( \sim 1.8 \times 10^9 \) events at 10.58 GeV,
  - \( \sim 220 \times 10^6 \) events at 10.52 GeV
Measurements of Fragmentation Functions in $e^+e^-$ at Belle

- KEK-B: asymmetric $e^+$ (3.5 GeV) $e^-$ (8 GeV) collider:
  - $\sqrt{s} = 10.58$ GeV, $e^+e^- \rightarrow Y(4S) \rightarrow B \bar{B}$
  - $\sqrt{s} = 10.52$ GeV, $e^+e^- \rightarrow q\bar{q} (u,d,s,c)$ ‘continuum’
- Ideal detector for high precision measurements:
  - Tracking acceptance $\theta [17^\circ;150^\circ]$: Azimuthally symmetric
  - Particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - $\sim 1.8 \times 10^9$ events at 10.58 GeV,
  - $\sim 220 \times 10^6$ events at 10.52 GeV
Where to Study?

- $e^+e^-$ cleanest way to access FFs
- B factories
  - close in energy to SIDIS (100 GeV$^2$ vs 2-3 GeV$^2$)
  - Large integrated lumi!, high z reach
Measurements of Fragmentation Functions in e⁺e⁻ at Belle

- Asym. e⁺ (3.5/3.1 GeV) e⁻ (8/9 GeV) collider:
  - $\sqrt{s} = 10.58$ GeV, e⁺e⁻ → Y(4S) → B anti-B
  - $\sqrt{s} = 10.52$ GeV, e⁺e⁻ → qqbar (u,d,s,c) ‘continuum’
- Ideal detector for high precision measurements:
  - Azimuthally symmetric acceptance, high res. Tracking, PID
- Available data:
  - ~1.8 *10⁹ events at 10.58 GeV,
  - ~220 *10⁶ events at 10.52 GeV
Cross-Section for identified Pions and Kaons

- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low $z$, correct based on MC

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon_{\text{joint}}^{i}(z) \epsilon_{\text{ISR/FSR}}^{i}(z) S^{i-1}_{zzm} \epsilon_{\text{impu}}^{i}(z_m) P_{ij}^{-1} N_{j,\text{raw}}(z_m)$$

- Correct for acceptance, $\tau\tau$, $2\gamma$,
- decay in flight,

< 10%
PID Corrections from Data

- **Misidentification**
  - $\pi \rightarrow K$ up to 15%
  - $K \rightarrow \pi$ up to 20%

**Fill matrix of PID probabilities for each single bin from real data calibration** - need large statistics

- $(p_{lab}, \cos \theta_{lab})$

- **ToF forward geometry acceptance limit**

- **ToF backward geometry acceptance limit**

- **Examples**
  - $D^*$
  - $D^0$
  - $K^-$
  - $\pi^+_{\text{slow}}$
  - $\pi^+_{\text{fast}}$

- **Scatter plot**
  - $e$, $\mu$, $\pi$, $K$ and $p$ tracks from $4 \times 10^5$ events
Cross sections

\[ \frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \varepsilon_{joint}^i(z) \varepsilon_{ISR/FSR}^i(z) S_{zzm}^{-1} \varepsilon_{imp}^i(z_m) P_{ij}^{-1} N_{j,raw}(z_m) \]

\[ i = \pi, K \]

New DSS(E,H-P) Fit

- Good agreement, however, there seems to be a trend away from the fit for the Belle data at high z
- Babar low z data needs resummation
- From DSS:
  - Precise data at high z
  - Some info from scaling violations (Belle vs experiments at $M_Z$)
  - Some info on flavor due to charge weighting
Data set

- Data sets: $\sim 792 \text{ fb}^{-1}$ at or near $\sqrt{s} \sim 10.58 \text{ GeV}$

- Thrust $> 0.8$ to select back-to-back event topology and suppress $B$ decays to less than 1%.
- Signal process $\Lambda \to p\pi^- (\bar{\Lambda} \to \bar{p} \pi^+ )$. Clear $\Lambda$ peak.
- By considering light hadron ($K^\pm, \pi^\pm$) in the opposite hemisphere, we can emphasize or suppress one kind of flavor which contributes to $\Lambda(\bar{\Lambda})$.

$\text{PRL105,202001 (2010)}$
Measuring transverse spin dependent di-Hadron Correlations
In unpolarized $e^+e^-$ Annihilation into Quarks

Interference effect in $e^+e^-$ quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

**Experimental requirements:**
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

$$A \propto H_1^\perp(z_1, m_1)\overline{H}_1^\perp(z_2, m_2)\cos(\phi_1 + \phi_2)$$
First measurement of Interference Fragmentation Function

\[ a_{12} \propto H_1^< \cdot H_1^< \]
COMPASS 2004 Setup

- **two stages spectrometer**
  - Large Angle Spectrometer (SM1), Small Angle Spectrometer (SM2)
- **MuonWall**
- **E/HCAL**
- **RICH**
- **Polarised Target**

2002-2004: 6LiD (Deuteron)
- Dilution factor $f = 0.38$
- Polarization $P_T = 50\%$

2005 NH3 (proton)
- 3 target cells with opposite polarization, 90% polarization, 16% dilution

- **High energy beam**
- **Large angular acceptance**
- **Broad kinematical range**

\[ \sigma^\uparrow - \sigma^\downarrow \left( \phi_S - \phi_R \right) = A_{UT} \sin(\phi_S - \phi_R) \]

\[ A_{UT} \propto h_1 \cdot H^< \]
Measurement at Belle leads to first point by point extraction of Transversity

Future Plans at Star/Belle:
Better sensitivity to d transversity From $\pi^0/\pi^+/-$ combinations
Increase x range

Is Soffer Bound violated?
$h(x) < |f(x) + g(x)|/2$

$A_{UT} \propto h_1 \cdot H_1$

M. Radici at FF workshop, RIKEN, 11/2012
Predictions for STAR

$x^2 h_1^a(x)$

$Q^2 = 10 \text{ GeV}^2$

$x$ region covered by STAR

M. Radici at
Good Agreement in Backwards Region

- Gluons under control?
Mismatch at low pT and high $\eta$

- Theory prediction in this region driven by one Compass datapoint outside the Soffer bound
STAR data prefers “more reasonable” transversity
Tensor Charge

- Still a lot to do to get experimental precision to lattice/model predictions
- STAR data will provide higher precision and $Q^2$ leverage
- JLAB12 will give high precision at high $x$
- Belle II will provide comparable precision for fragmentation function measurements
Summary and Outlook

- Precision measurements of the proton’s spin structure important step to ab-initio solutions to QCD
- Combining p-p scattering, SIDIS and e+e- data allows to extract protons transversity
- Belle and Belle II data will provide further inside into hadronization, confinement and the structure of the QCD vacuum
Backup
Improve Charm Discrimination with SVD&PXD

Impact parameter resolution $d_0$

**Belle**

$\sigma [\mu m]$

$p\beta \sin(\theta)^{3/2} [GeV/c]$

$p\beta \sin(\theta)^{3/2} [GeV/c]$
PID improvement with iTOP

- Compare with ~85% efficiency for Belle

![Kaon efficiency, 1-bar graph](image)

- Only iTOP, no dE/dx
- 2 GeV/2
- 3 GeV/2
- 4 GeV/2

![Pion fake rate, 1-bar graph](image)
Comparison of prediction based on fit to SIDIS and e+e- IFF data & STAR IFF asymmetry data in p-p
• Ueberleitung? Need for charm discrimination etc
Summary
Transversity from di-Hadron SSA

\[ d\sigma_{UT} = 2|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|R_C|}{M_C} |S_{BT}| \sin (\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a) h_1^b(x_b) \frac{d\Delta\sigma_{ab\rightarrow c\bar{c}d}}{dt} H_{1,ot}(\bar{z}_c, M_C^2) \]

**Unpolarized quark distribution**
Known from DIS

**Transversity**
to be extracted

**Hard scattering cross section**
from pQCD

**IFF + Di-hadron FF**
measured in e+e at Belle-
Collins Extraction of Transversity: model dependence from Transverse Momentum Dependences!

\[
A_{UT}^{\text{Collins}} = \sum_{q} e_q^2 \int d\phi_S d\phi_h d^2 k_{\perp} h(x, k_{\perp}) \frac{d(\Delta \sigma)}{d\gamma} H_{1,q}(z, p_{\perp}) \sin(\phi_S + \phi + \phi_{q}^h) \sin(\phi_S + \phi_h)
\]

\[
\sum_{q} e_q^2 \int d\phi_S d\phi_h d^2 k_{\perp} q(x, k_{\perp}) \frac{d(\Delta \sigma)}{d\gamma} D_{q}^{h}(z, p_{\perp})
\]

\( k_{\perp} \) transverse quark momentum in nucleon
\( p_{\perp} \) transverse hadron momentum in fragmentation

The transverse momentum dependencies are still unknown
Need \( p_T \) dependent FFs from Belle to extract transversity and test TMD framework

Unpolarized Fragmentation Functions

- Precise knowledge of upol. FFs necessary for virtually all SIDIS measurements

Lack of data at high z, lower CMS

- $\pi^0$, $\eta$ fragmentation function under way
- In particular important at RHIC

Submitted to PRL
arXiv:1301.6183
Handedness Correlations

- Handedness Correlations expected to be zero in factorized approach
- Non-zero asymmetries predicted in factorized approach for azimuthal asymmetries sensitive to $G_{1}^{\perp}$
- Several suggestions how interactions with QCD vacuum can lead to non-zero asymmetries
- SLD: Upper bound from 90k hadronic Z events: 7%

![Diagram of particle interactions](image)

Handedness: $\frac{(k_+ \times k_-) \cdot \hat{t}}{|k_+||k_-|} > 0 \implies L/R$

Jet handedness: $\frac{N_R - N_L}{N_R + N_L}$

C: $\frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$
Belle II Detector at SuperKEKB (L x 40)
and IU contributions to Barrel Particle ID

- Barrel PID instrumental for fragmentation function measurements

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

RPC Front End Electronics, Concentrator boards for barrel and endcap scintillator layers

Particle Identification
Time-of-Propagation counter (barrel)
Active HV Divider board for MCP-PMT
Validation of FPGA code of iTOP

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Vertex Detector
2 layers DEPFET + 4 layers DSSD
Vertex resolution improved by order of magnitude:
Separate charm/uds

- RPC test stand at IU to test electronics: E. Zarndt, S. Arnold

$90k + $700k Grant
From DOE US Belle II project
+~$100k from NSF for prototyping
Belle II Status
Outlook over Next 5 Years

**Analysis:**
- **Be dataset:** existing dataset
  - Extraction of Di-hadron FF from Belle with \( \pi-K \) final states
  - Di-hadron correlations at Belle to test TMD framework and probe local parity violating effects
  - Current Student Hairong Li: \( \pi^0/\eta \) unpolarized and Collins FF dataset:
    - Explore charm rejection for \( \pi^+/\pi^- \) IFF
  - Transverse spin physics at SoLID, di-hadron correlations at CLAS

**Instrumentation:**
- Participation in detector upgrades (experience with GEM detector and building RPCs ),
- Investigating Transversely polarized target option at CLAS
- Readout electronics. Currently PI on ~$90k grant, MoU for ~$700k dependent on US-Congress
Long Term Outlook

- **Fragmentation Extraction at Belle II**
  - Transverse spin dependent FFs with Kaons in final state
  - $p_T$ dependent FFs
  - Reduce systematic effects by removing charm
- **EIC?**
Summary

- Breakthrough Measurements of Proton Structure underway: How does QCD work inside the Nucleon?
- Di-hadron Correlations best way to access transversity in p+p, SIDIS
- Needed to describe spin structure of the proton, derive tensor charge
- Corresponding Fragmentation Functions measured at Belle

Outlook
- **CLAS, SoLID @JLab:** Transversity measurements on helium3, proton, high x, p_T dependence, wide kinematic range
- Di-hadron correlations of π-K to access higher twist distribution functions
- TMD x-sections
- **Belle II:** Continuation of FF measurements with improved Kaon ID and vertex reconstruction
- Test TMD framework
- Probe QCD vacuum polarization
- Precision measurements at Belle (II) **crucial** for success of Jlab program
atom $\sim 10^{-8}$ cm

nucleus $\sim 10^{-12}$ cm

electron $< 10^{-16}$ cm

proton (neutron) $\sim 10^{-13}$ cm

quark $< 10^{-16}$ cm
Di-Hadron correlations allow model independent extraction of transversity

- Ab-initio contact to the tensor charge
- Transverse momentum is integrated
  - Collinear factorization
    - No assumption about $k_t$ in evolution
    - Evolution known, collinear scheme can be used
    - Universal function: directly applicable to semi-inclusive DIS and pp
      - No ambiguity due to Sudakov suppression
- SIDIS experiment show that the effect is large
- Interest in transverse spin physics in the theoretical community is growing rapidly

In p+p:
- No jet reconstruction necessary, better systematics: “Easier” measurement
- No $u$-quark dominance
COMPASS 2004 Setup

- High energy beam
- Large angular acceptance
- Broad kinematical range

2002-2004: 6LiD (Deuteron) dilution factor \( f = 0.38 \) polarization \( PT = 50\% \)

>2005 NH3 (proton)

3 target cells with opposite polarization, 90\% polarization, 16\% dilution

\[
A_{UT} \propto h_1 \cdot H^<
\]

\[
\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} (\phi_S - \phi_R) = A_{UT} \sin(\phi_S - \phi_R)
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Future Plans at Star/Belle:
Better sensitivity to d transversity
From $\pi^0/\pi^+/-$ combinations
Increase x range

Is Soffer Bound violated?
$h(x)<|f(x)+g(x)|/2$

$A_{UT} \propto h_1 \cdot H^{< 1}$

M. Radici at FF workshop, RIKEN, 11/2012
Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

- QCD successful in describing high energy reactions, Asymptotic freedom, Nobel 2004
- **BUT** No consistent description of hadronic sector
  - No consistent description of fundamental bound state of the theory
  - QCD binding energy: most of the visible mass in the universe
  - Spin is fundamental Quantum Number: What role does it play? Use transverse spin as precision probe.
Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

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  - QCD binding energy: most of the visible energy in the universe
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- **Compare to QED:**
  - Bound state: QED: atom
  - Stringent tests of QED from study of spin structure of hydrogen
    - Lamb shift (Nobel prize 1955)
  - Atomic physics, QCD?
QCD Factorization Theorem needed to Access Nucleon Structure

(semi) Inclusive polarized deep inelastic scattering (DIS)

F time sigma times FF

Describes probability to find a quark In the nucleon with a specific polarization state

polarized pp scattering

Hard x section

Hard Scattering Process
The proton as a QCD “laboratory”

Proton—simplest stable bound state in QCD!

QED & Atoms
- Fraunhofer lines
- Bohr Model
- Schroedinger eqn.
- Lamb shift
- QED
- hydrogen structure ab initio!
- complex atoms & molecules

QCD & Hadrons
- Proton magnetic moment
- Quark Structure
- QCD generally accepted
- HERA

fundamental theory
observation & models
precision measurements
application

1814  1913  1926  1947  1948  120  2020

precision measurements & more powerful theoretical tools
application?
Transversity:

Why is \( T \) so hard to measure?

- Naïve picture: leptonic probe too ‘fast’ to be sensitive to transverse polarization
Mechanisms for SSA

Collins Fragmentation

$H_1^+ = \begin{array}{c}
\uparrow \\
\downarrow \\
\end{array}$

fragmentation of transversely polarized quarks into unpolarized hadrons

Orbital momentum generated in string breaking and pair creation produces left-right asymmetry from transversely polarized quark fragmentation (Artru-93)

- L/R SSA generated in fragmentation
- Unfavored SSA with opposite sign
- No effect in target fragmentation

$u \quad d \quad \bar{d} \quad \pi \quad u\bar{d}$ (favored)
$g_T$: zeroth moment of transversity\[ \Gamma = \sigma_{\mu\nu} \]

A state-of-the-art calculation (PNDME)

Extrapolate to the physical limit

\[
g_T(a, m_\pi, L) = c_1 + c_2 m_\pi^2 + c_3 a + c_4 e^{-m_\pi L}
\]

First extrapolation to the physical limit of a nucleon matrix element!