# Hyperons

## - a strange key to the strong interaction

24th European Conference on Few-Body Problems in Physics 2019

Guildford, UK, September 2019

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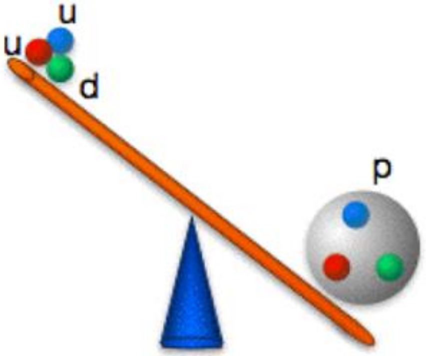
# Outline

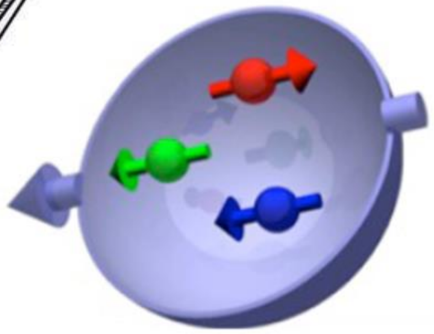
- Introduction
- Hyperon structure with BESIII
- Hyperon decays with BESIII
- Hyperon physics with PANDA

# The Nucleon

Many challenges in modern physics manifest themselves in the **nucleon:**

- Challenging to describe from first principles:
  - Its abundance
  - Its mass
  - Its spin
  - Its structure
  - Its radius

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# The Nucleon

Many challenges in modern physics manifest themselves in the **nucleon:**

- Challenging to describe from first principles:
  - Its abundance
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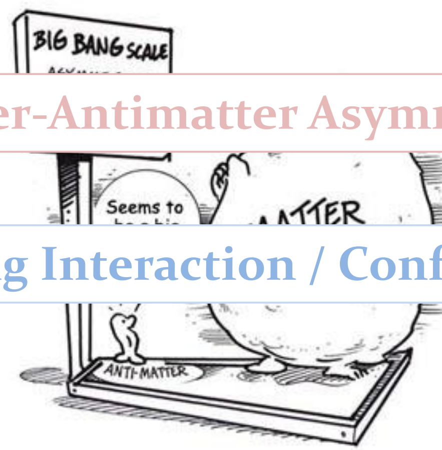
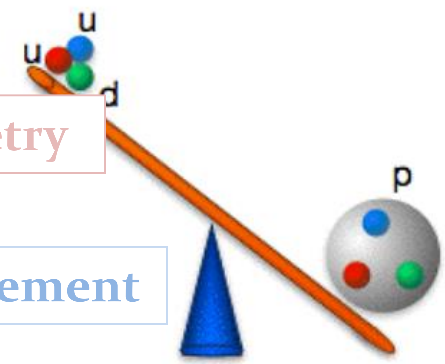
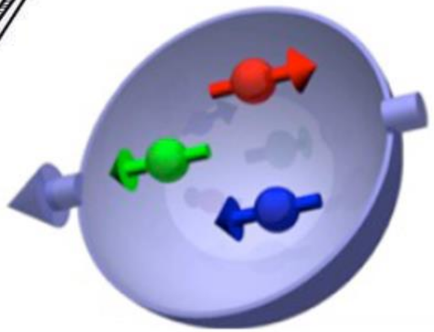
  - Its spin
  - Its structure
  - Its radius ?

Matter-Antimatter Asymmetry

Strong Interaction / Confinement



# The Nucleon

Many challenges in modern physics manifest themselves in the **nucleon:**

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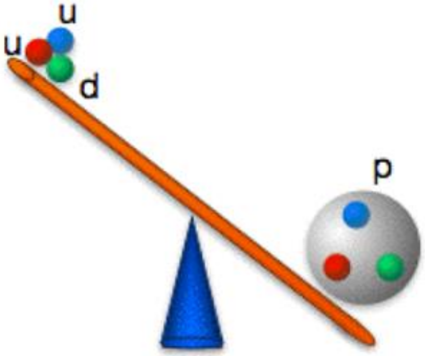
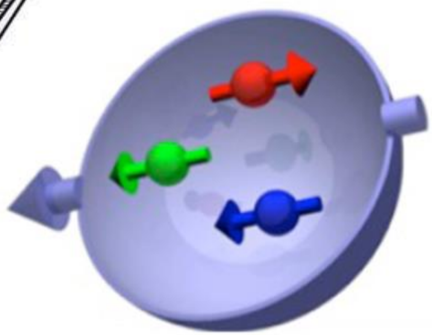
This talk

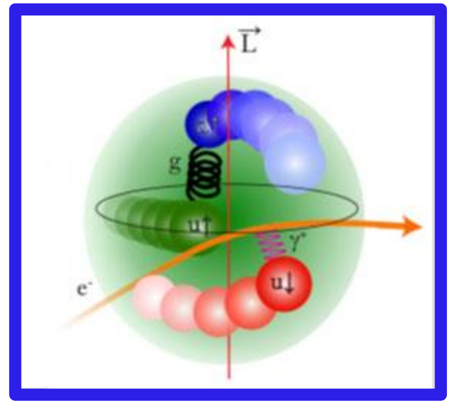



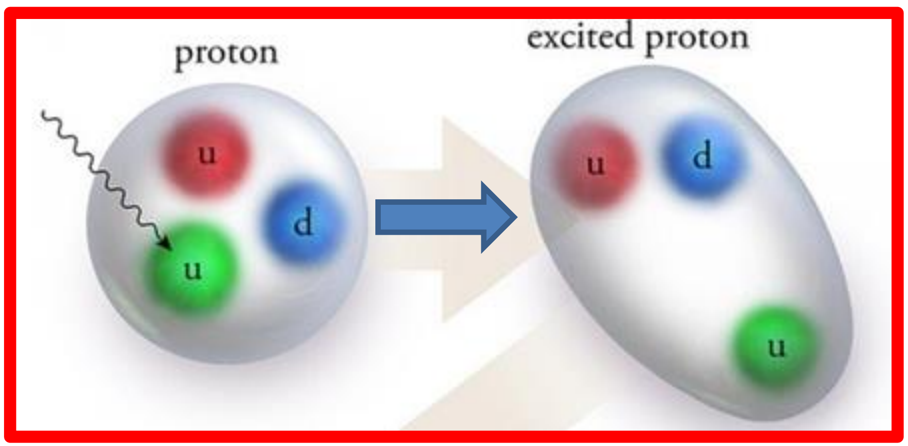



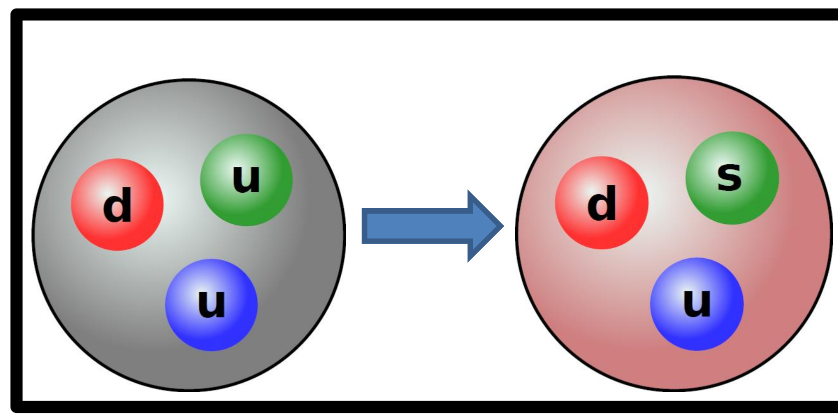
# Approaches

When you don’t understand a system, you can*

- Scatter on it
- Excite it
- Replace building blocks



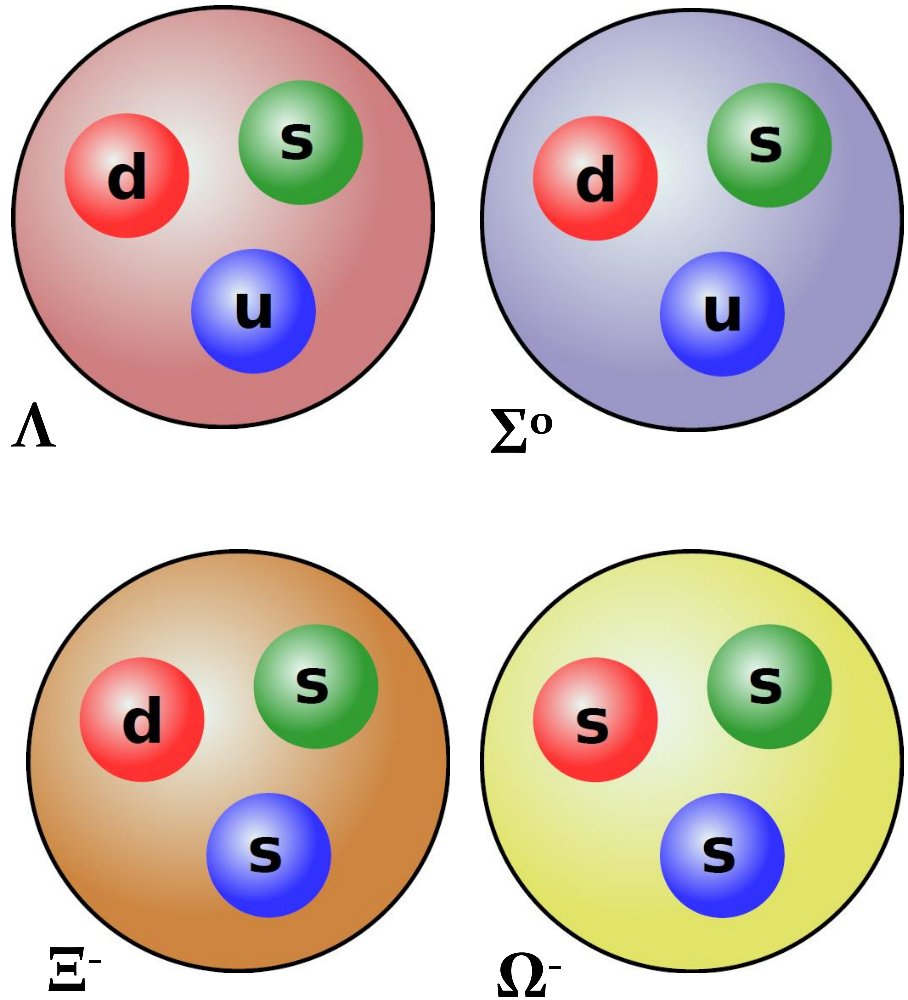



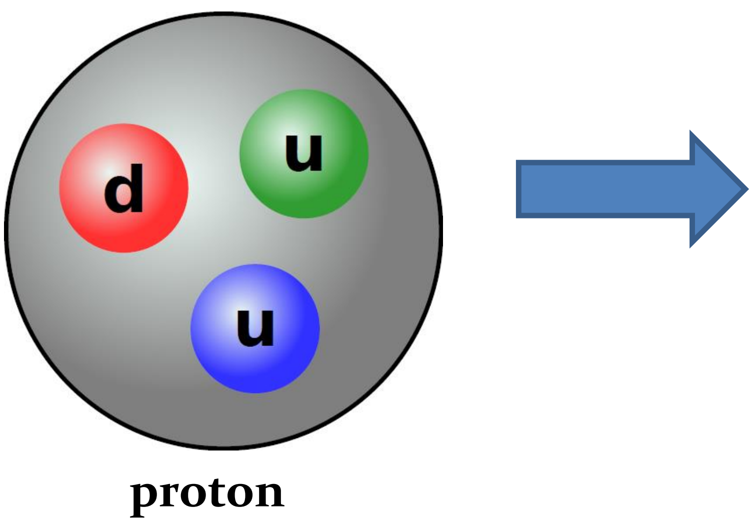




*C. Granados *et al.*, EPJA 53 (2017) 117

# Hyperons

*What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?*

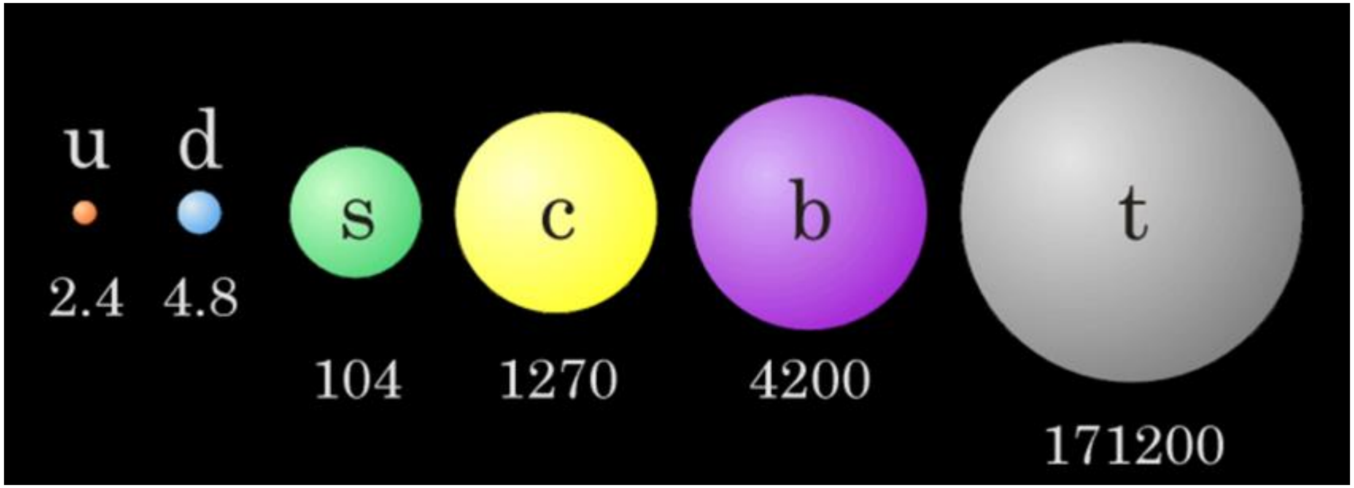


# Hyperons – key to the strong interaction

- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV: Relevant degrees of freedom?
  - **Probes QCD in the confinement domain.**

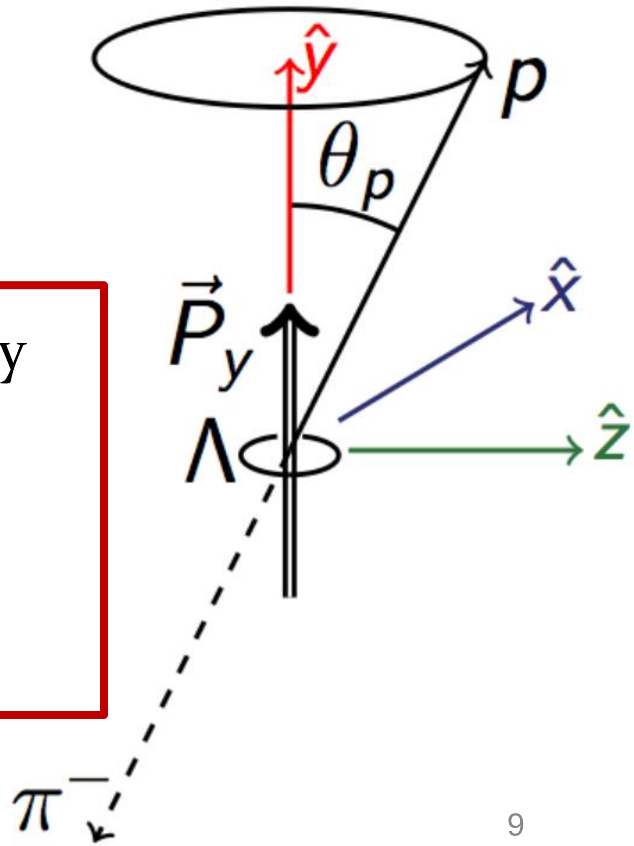
- Systems with charm
  - Scale: $m_c \approx 1300$ MeV: Quarks and gluons more relevant.
  - **Probes QCD just below pQCD.**



# Hyperons – key to the strong interaction

**Advantage of hyperons:**

Polarization experimentally accessible by the weak, parity violating decay:

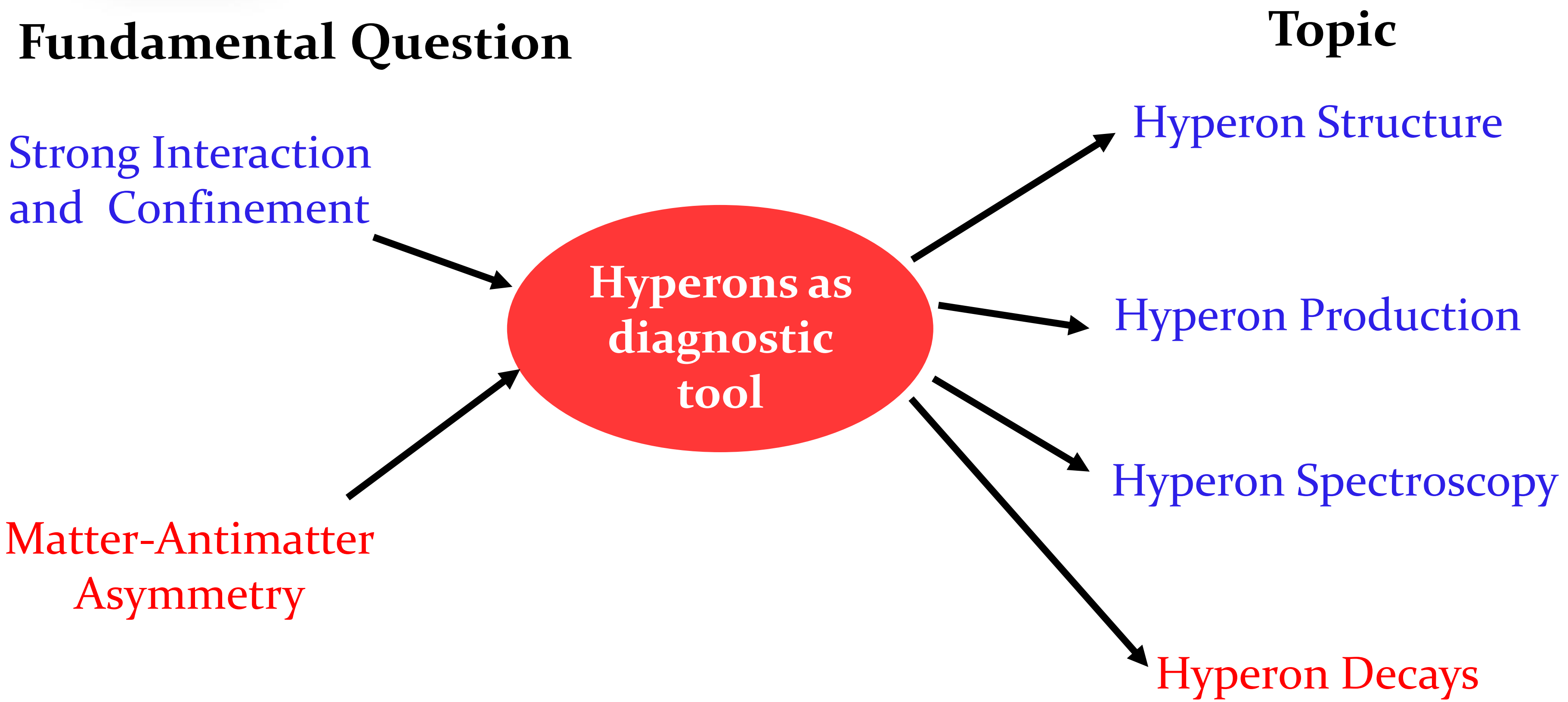



Example: Angular distribution of $\Lambda \rightarrow p\pi^-$ decay

$$I(\cos\theta_p) = N(1+\alpha_\Lambda P_\Lambda \cos\theta_p)$$

$P_\Lambda = P_\Lambda(\cos\theta_\Lambda)$ : polarisation (production)

$\alpha_\Lambda$ : asymmetry parameter (decay)


Fundamental Question
Topic
Strong Interaction and Confinement
Matter-Antimatter Asymmetry
Hyperons as diagnostic tool
Hyperon Structure
Hyperon Production
Hyperon Spectroscopy
Hyperon Decays

Part 1:

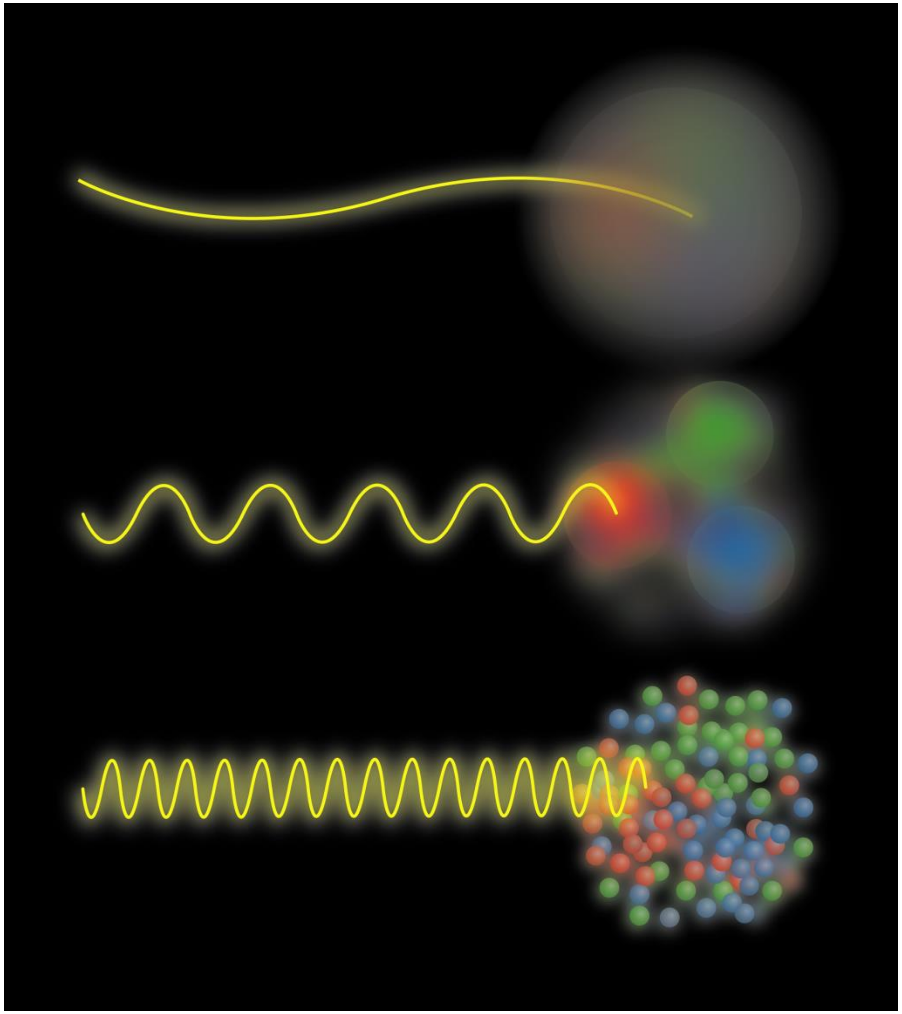
# HYPERON STRUCTURE

# Electromagnetic Form Factors

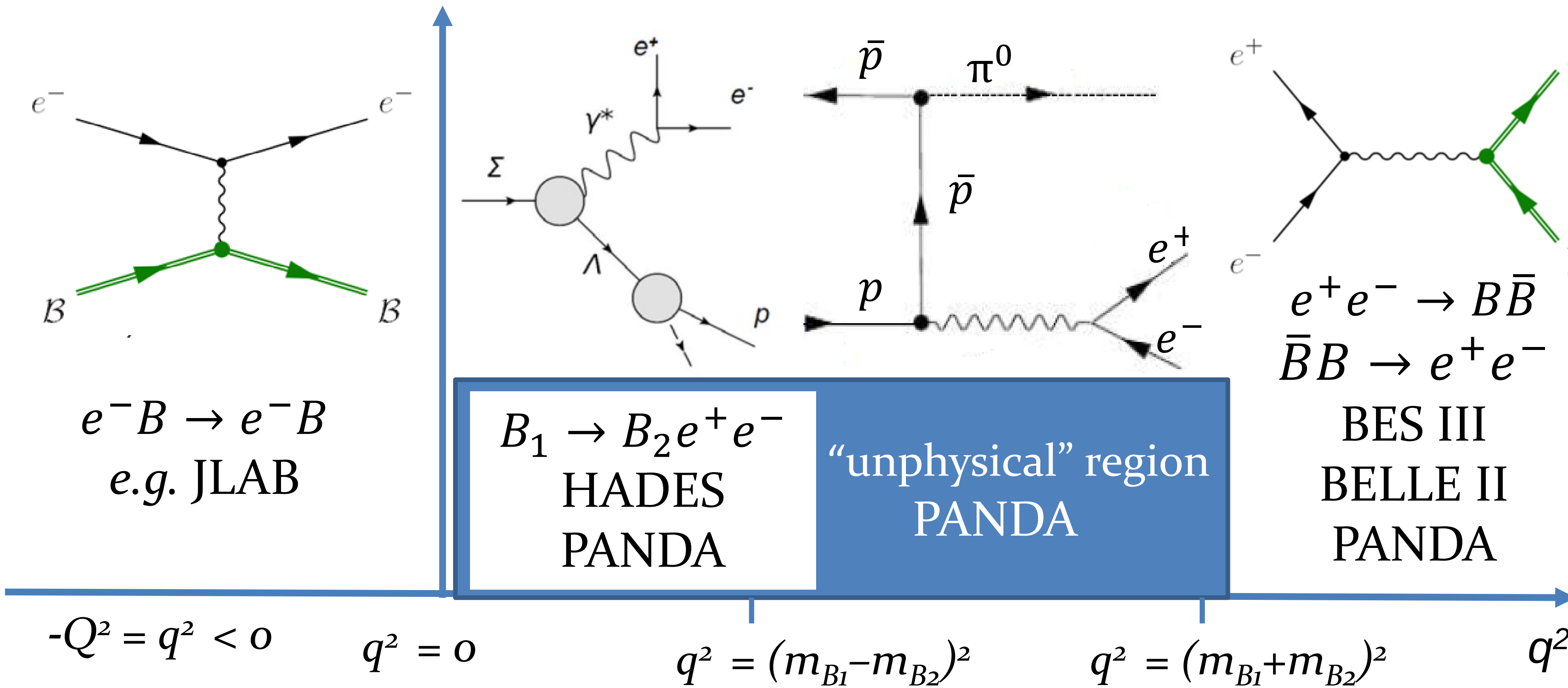
- Electromagnetic structure observable:
  - Lattice QCD, ChPT, VDM…
- Measured in interactions

  hadron – virtual photon $\gamma^*$.
- Quantify deviation from point-like case

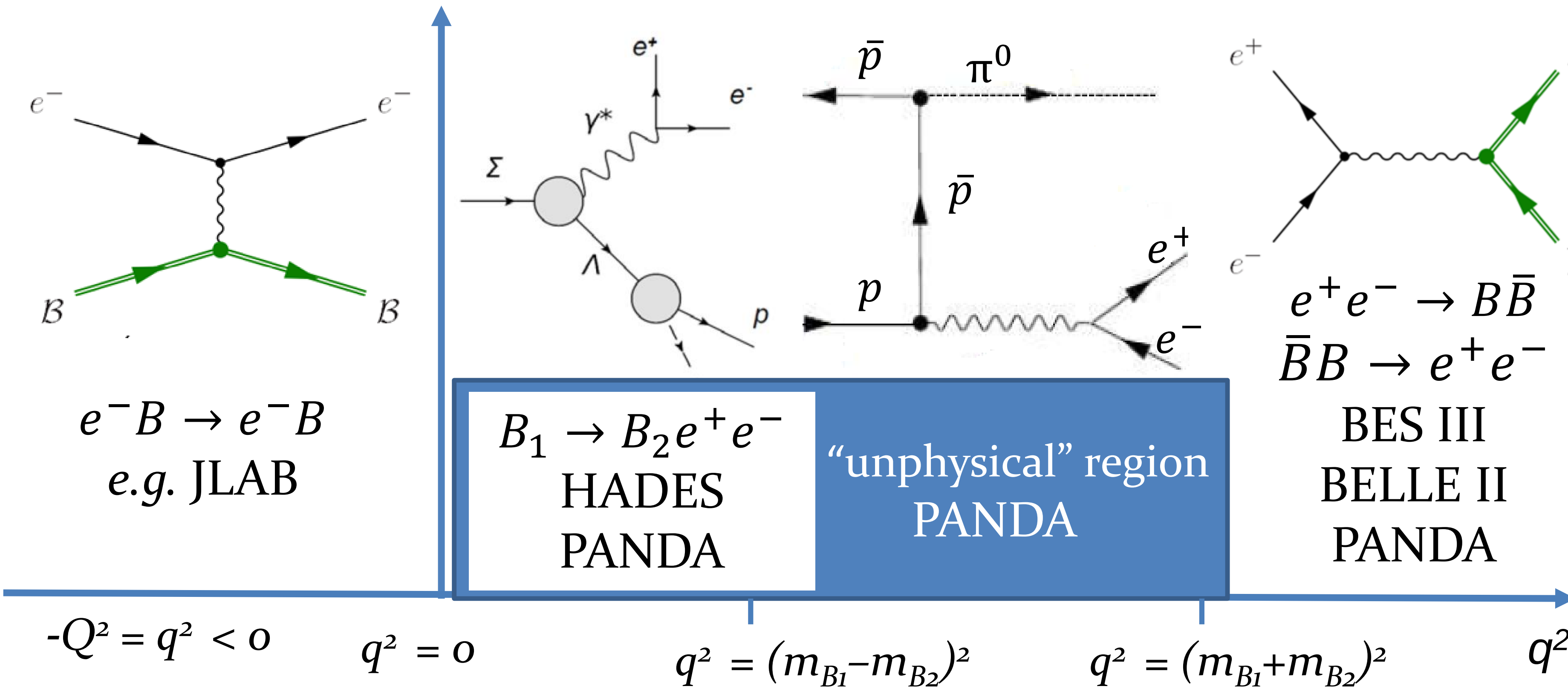
  = depend on $q^2$ of $\gamma^*$.



# Space-like *vs.* time-like FF's



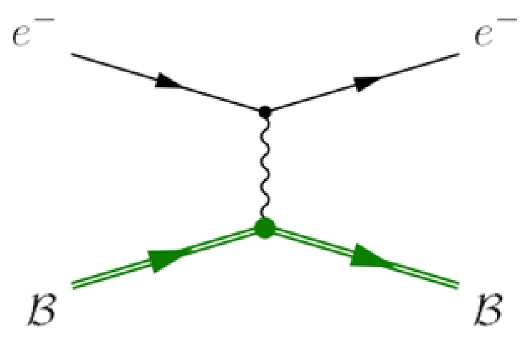
# Space-like *vs.* time-like FF's

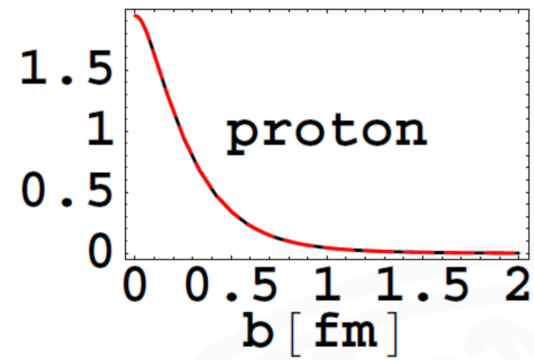


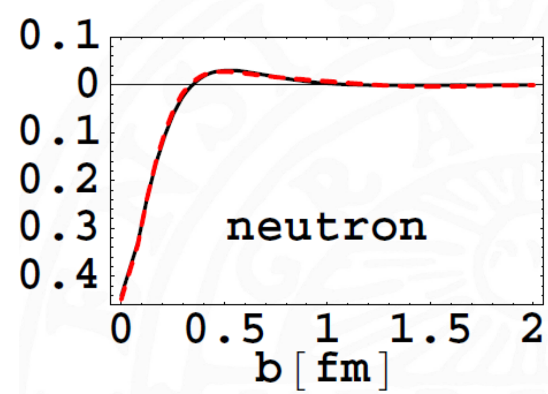

Space-like and time-like FFs related by dispersion theory

# Electromagnetic Form Factors

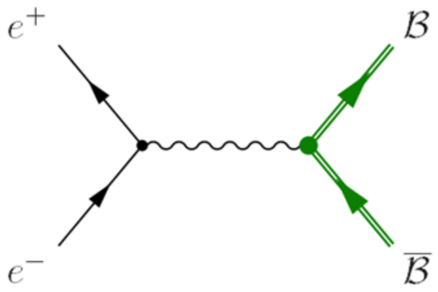
- Space-like Sachs FFs $G_E$ and $G_M$ .
  - In Breit frame:
    $G_E$ and $G_M$
    Fourier transforms of charge- and magnetization density.



# Time-like form factors

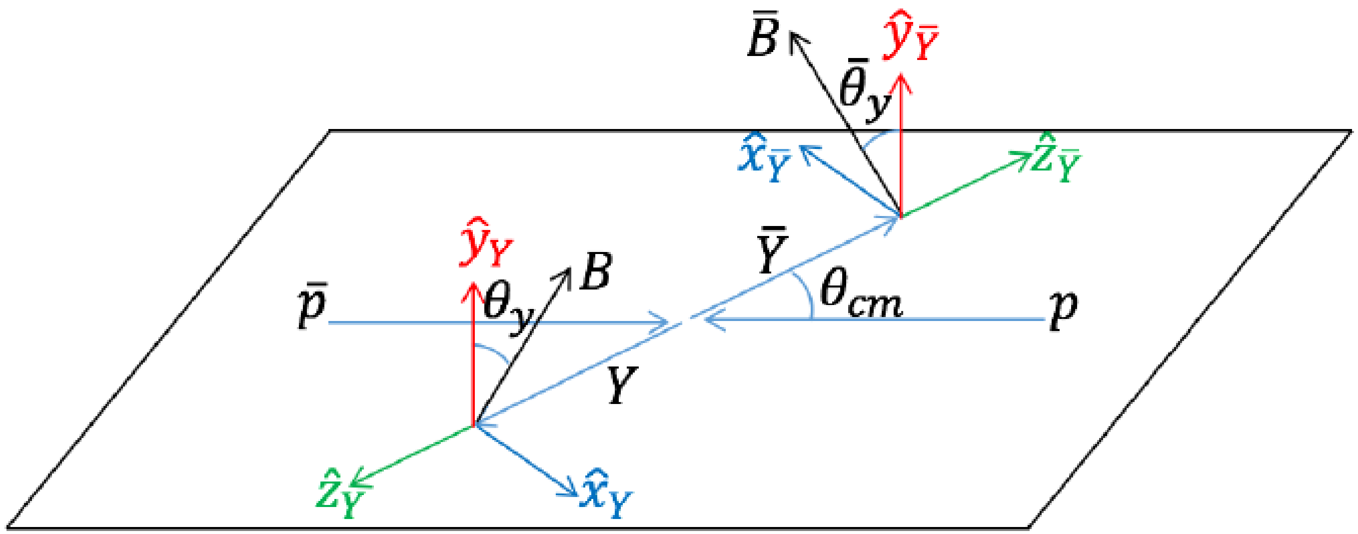



- Time-like FF's are complex:
  - $\Delta\Phi(q^2)$ : phase between $G_E$ and $G_M$ .
- Phase is **production related** and depends on $q^2$ .
  - **Constraint 1:** Phase result of interfering amplitudes (*e.g. s*- and *d* waves)
  $\rightarrow \Delta\Phi(q^2) = 0$ at threshold
  - **Constraint 2:** Analyticity requires TL FF ~ SL FF as $|q^2| \rightarrow \infty$ *,**
  $\rightarrow \Delta\Phi(q^2) \rightarrow 0$ as $|q^2| \rightarrow \infty$
- Phase $\rightarrow$ polarizes final state even for unpolarized initial state ***.

* Theor. Mat. Fiz. **15** (1973) 332.
** Phys. Rev. Lett. 31 (1973) 1153.
***Nuovo Cim. A **109** (1996) 241.

# Hyperon production in $e^+e^-$

- EM and strong interactions with unpolarized beam and target: non-zero polarization with respect to production plane.
- The produced $\bar{Y}Y$ pair is engtangled *i.e.* their spins are correlated.



# First complete measurement of Λ EMFF

Formalism for $e^+e^- \to \gamma^* \to \bar{Y}Y, Y \to BM + c.c$ :

Two complex amplitudes contribute → can parameterise in terms of

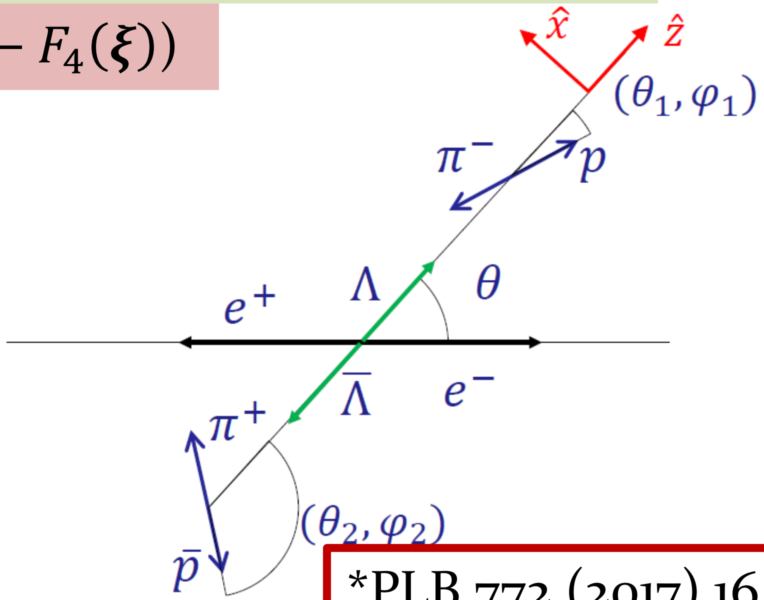
- Angular distribution parameter η
- Phase ΔΦ

**Unpolarized part** **Polarized part** **Spin correlated part**

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) - \alpha^2 \left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi)\right) + \alpha\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(F_3(\xi) - F_4(\xi)\right)$$

(assuming $\alpha = \alpha_- = -\alpha_+$)

$$\mathcal{F}_0(\xi) = 1$$
$$\mathcal{F}_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$
$$\mathcal{F}_2(\xi) = \sin\theta \cos\theta \left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right)$$
$$\mathcal{F}_3(\xi) = \sin\theta \cos\theta \sin\theta_1 \sin\phi_1$$
$$\mathcal{F}_4(\xi) = \sin\theta \cos\theta \sin\theta_2 \sin\phi_2$$
$$\mathcal{F}_5(\xi) = \cos^2\theta$$
$$\mathcal{F}_6(\xi) = \cos\theta_1 \cos\theta_2 - \sin^2\theta \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2$$



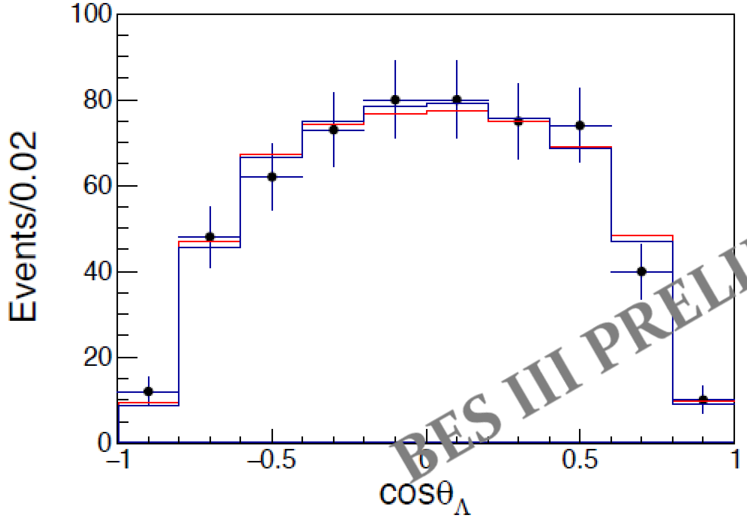

*PLB 772 (2017) 16.

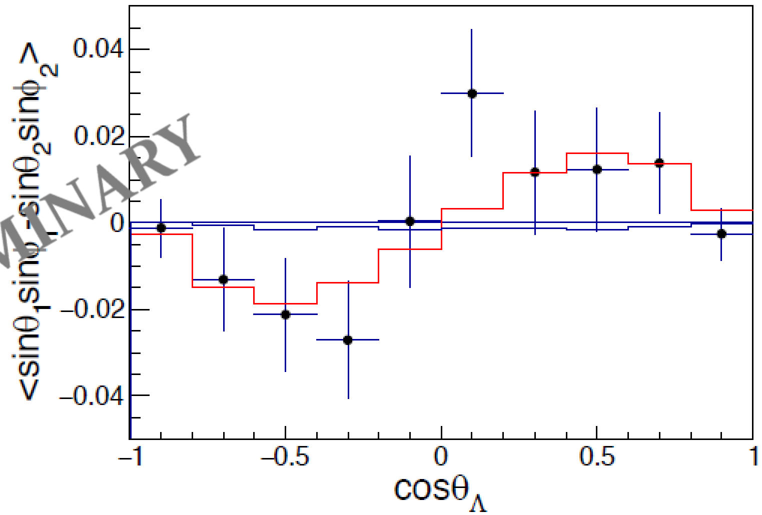
# First complete measurement of Λ EMFF

- New BESIII data at 2.396 GeV with 555 exclusive $\bar{\Lambda}\Lambda$ events in sample.
  - $R = |G_E/GM| = \mathbf{0.96 \pm 0.14 \pm 0.02}$
  - $\Delta\Phi = \mathbf{37^o \pm 12^o \pm 6^o}$
  - $\sigma = 118.7 \pm 5.3 \pm 5.1$ pb

←**BES III PRELIMINARY**
**arXiv [hep-ex]: 1903.09421**

- Most **precise** result on $R$ and $\sigma$
- **First** conclusive result on $\Delta\Phi$



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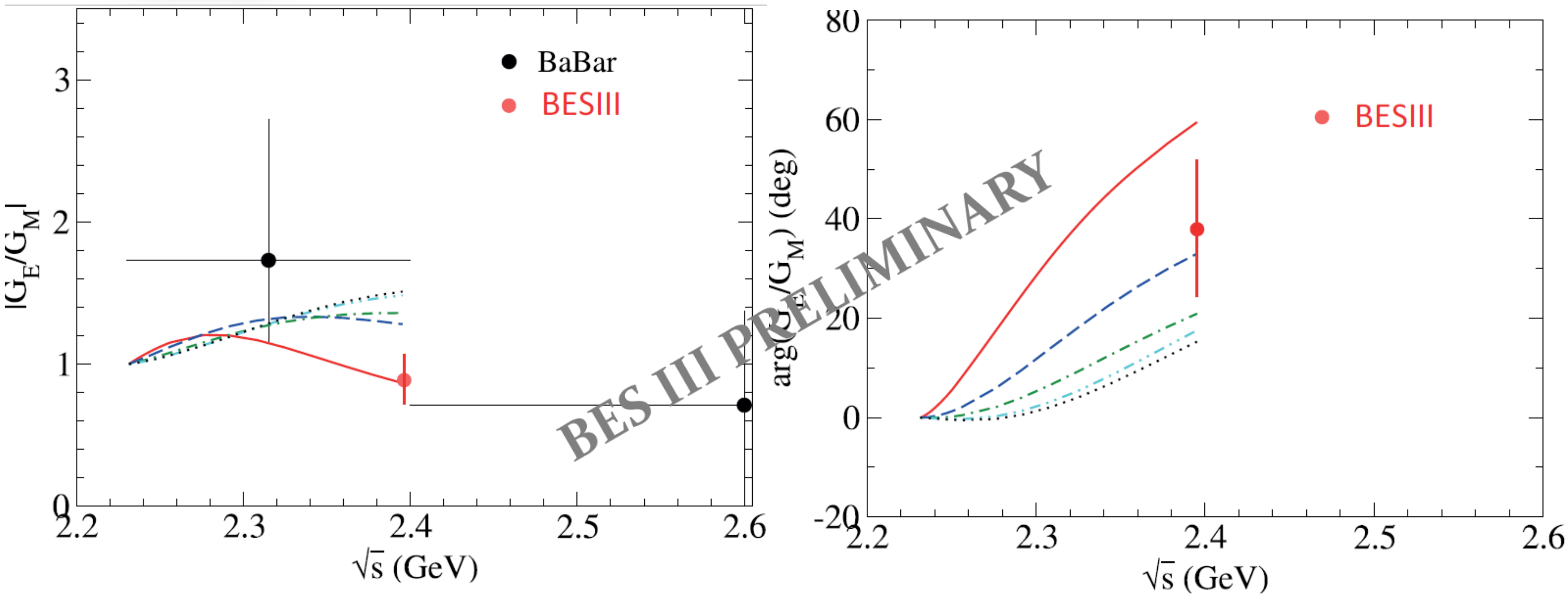
# First complete measurement of Λ EMFF




Model predictions by Haidenbauer and Meissner.*

Lines represent different $\bar{\Lambda}\Lambda$ potentials.

Model fitted to $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ data from PS185**

*Phys. Lett. B 761(2016) 456
** Phys. Rept. 368 (2002) 119-316

# First complete measurement of Λ EMFF

Lessons learned:

- Framework for phase measurements: can be applied to other hyperons and at other energies.

- Phase non-zero: at what scale does it approach zero?

    - Alternative way to test analyticity (TL FF ~ SL FF as $|q^2| \to \infty$ )

Part 2

# HYPERON DECAYS

# Matter-antimatter asymmetry

More matter than anti-matter in the Universe –why?

- As much matter/baryons as anti-matter/anti-baryons, should have been created in the Big Bang.

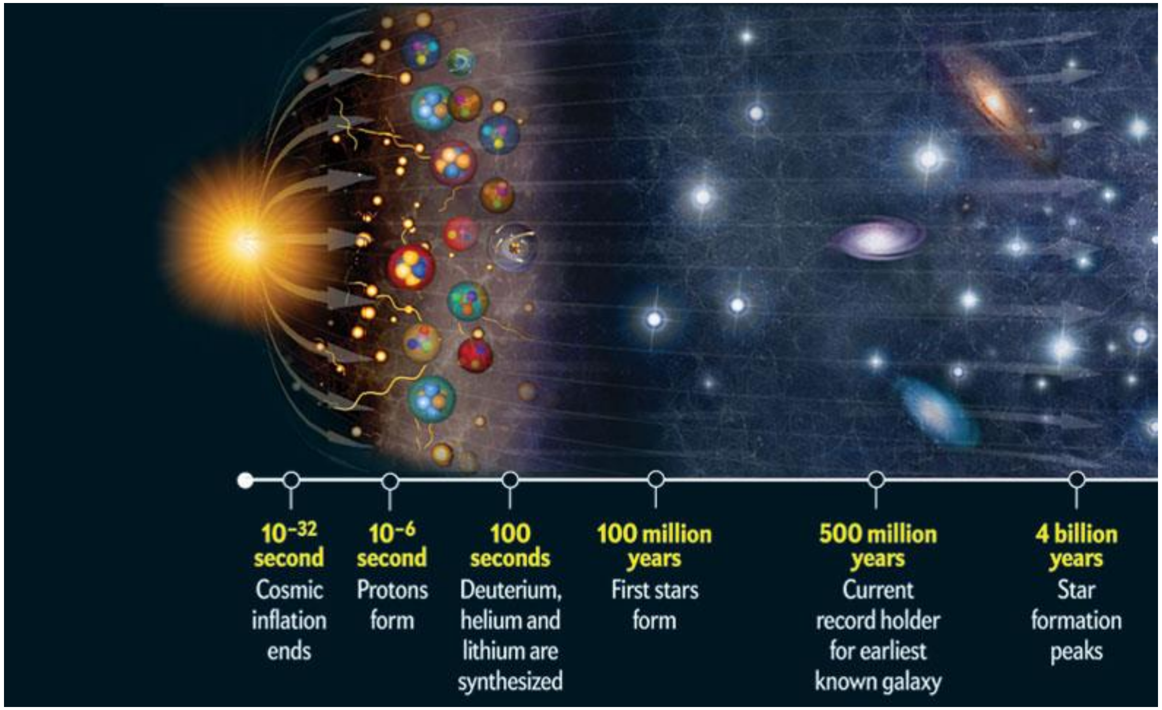
- Where did the anti-baryons go (*"Baryogenesis"*)?


Picture from Virginia Tech

# Matter-antimatter asymmetry

The Sakharov criteria:

- There must be processes that do not conserve baryon number.
- There must be processes that violate C- and CP symmetry.
- These processes must have occurred outside thermal equilibrium.

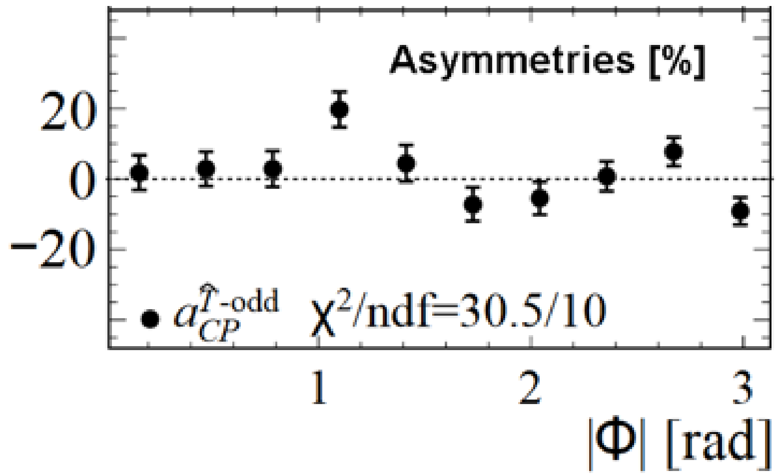



*A. D. Sakharov,. J. Exp. Theor. Phys. Lett.* **5**: 24–27.

# CP violation

- Allowed within SM through Cabibbo-Kobayashi-Maskawa (CKM) mechanism.
- **Mesons:** Observed in decays of strange, charmed and bottom mesons.
- **Baryons:** Observed in $\Lambda_b$ decays by LHCb

Observed and SM predicted amount too small to explain matter-antimatter asymmetry!




*Nature Phys.* **13**, p. 391–396 (2017)

Baryogenesis requires physics beyond the Standard Model!

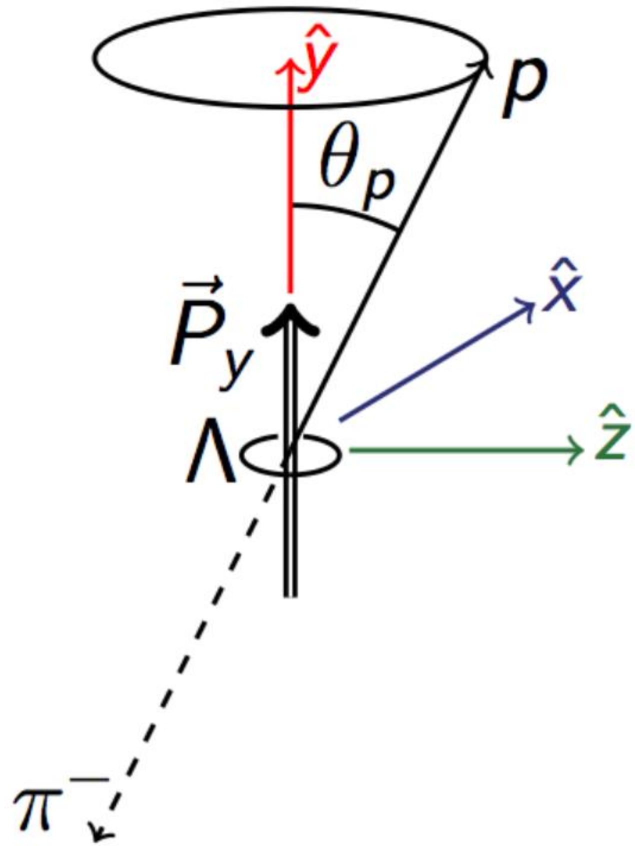
# Weak two-body decays

- Parity violating and parity conserving decay amplitudes.
  → interference quantified by decay parameters α, β, γ
  → α accessible in decay
  → β, γ accessible in sequential decays

- CP symmetry:
  $\alpha_{-}(\Lambda) = -\alpha_{+}(\overline{\Lambda})$
  $\beta = -\overline{\beta}$ etc.

- Clean CP observable defined by *e.g.*:

$$A = \frac{\alpha_{-} + \alpha_{+}}{\alpha_{-} - \alpha_{+}}$$



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# Measurement of Λ decay parameter

Formalism for $e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$ *
(same as before but **without** assuming $\alpha = \alpha_- = -\alpha_+$)

**Unpolarized part** **Polarized part** **Spin correlated part**

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) + \alpha_-\alpha_+(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\, F_2(\xi) + \eta F_6(\xi))$$
$$+ \sqrt{1-\eta^2}\sin(\Delta\Phi)(\alpha_- F_3(\xi) + \alpha_+ F_4(\xi))$$

$$\mathcal{T}_0(\xi) = 1$$
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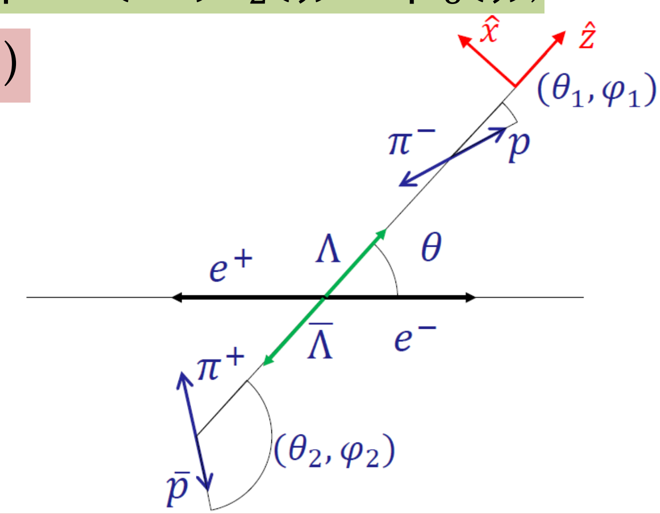
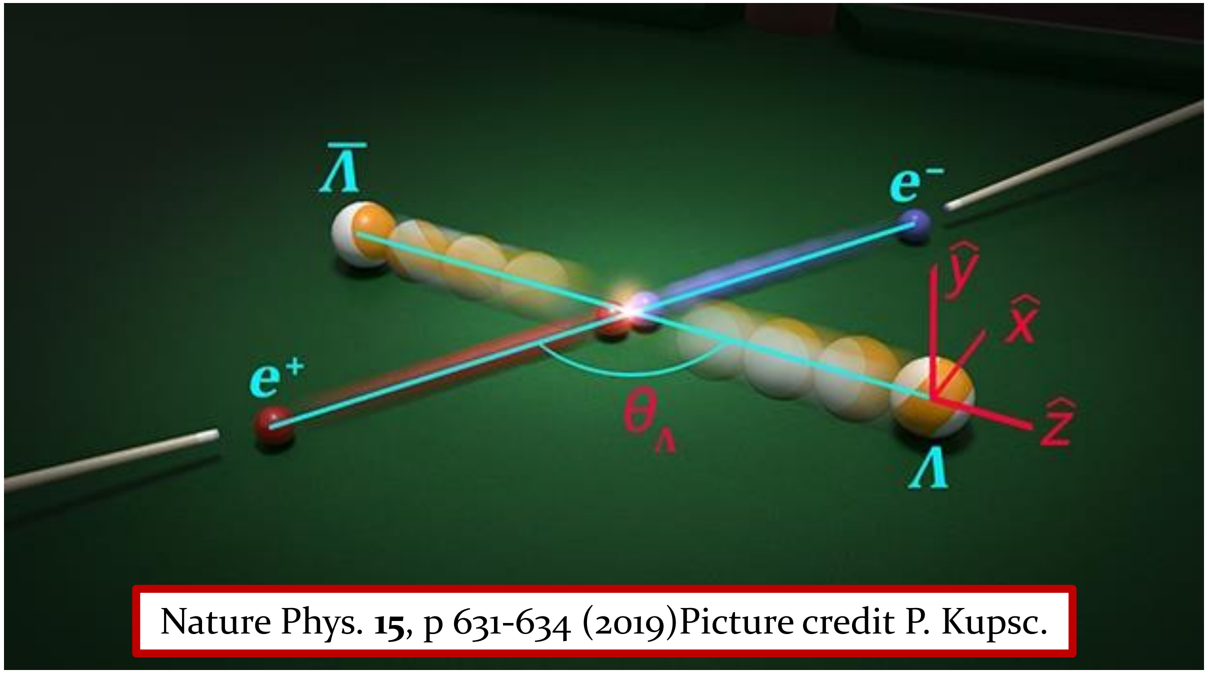



*G. Fäldt & A. Kupsc, PLB 772 (2017) 16.

# Measurement of Λ decay parameter

- New BESIII measurement using > 400 000 events of $e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$ .
- New formalism
  - Model independent
  - Takes full process (production and decay) into account.
  - Maximizes information → larger precision for a given sample size




Nature Phys. **15**, p 631-634 (2019)Picture credit P. Kupsc.

# Measurement of Λ decay parameter

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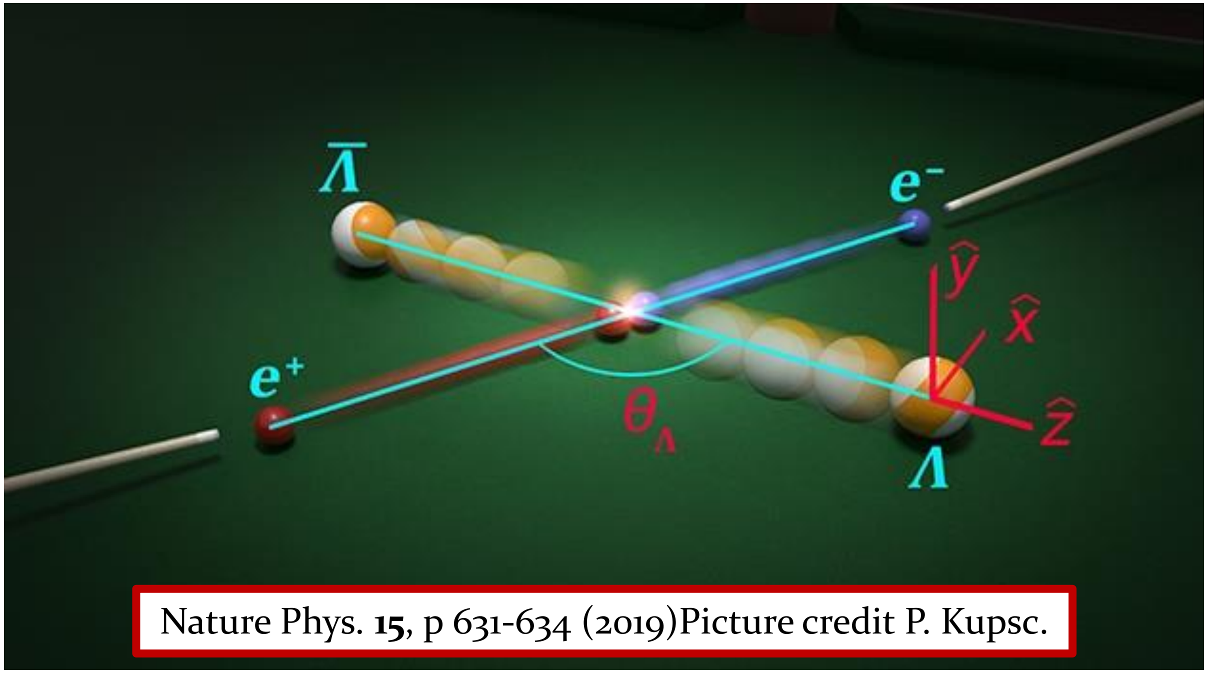
- Decay asymmetries $\alpha_-$, $\alpha_0$ and $\alpha_+$ measured.
- Value of $\alpha_-$ : 17 $\pm$ 3% > PDG value.
- Most precise CP test so far for Λ decay:

$$\frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = -0.006 \pm 0.012 \pm 0.007$$




Nature Phys. **15**, p 631-634 (2019)Picture credit P. Kupsc.

BESIII

# Measurement of Λ decay parameter

Lessons learned:

- Non-zero polarization gives access to decay parameters.
- Full process gives more precise and accurate results.
- PDG values not written in stone.

## Λ DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings. Some early results have been omitted.

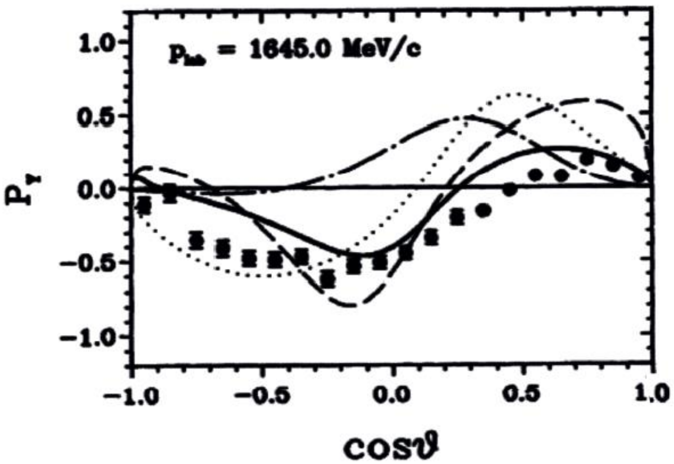
### $\alpha_-$ FOR $\Lambda \to p\pi^-$

| *VALUE* | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **0.750±0.009±0.004** | 420k | ABLIKIM | 18AG | BES3 | $J/\psi$ to $\Lambda\overline{\Lambda}$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 0.584±0.046 | 8500 | ASTBURY | 75 | SPEC | |
| 0.649±0.023 | 10325 | CLELAND | 72 | OSPK | |
| 0.67 ±0.06 | 3520 | DAUBER | 69 | HBC | From $\Xi$ decay |
| 0.645±0.017 | 10130 | OVERSETH | 67 | OSPK | $\Lambda$ from $\pi^- p$ |
| 0.62 ±0.07 | 1156 | CRONIN | 63 | CNTR | $\Lambda$ from $\pi^- p$ |

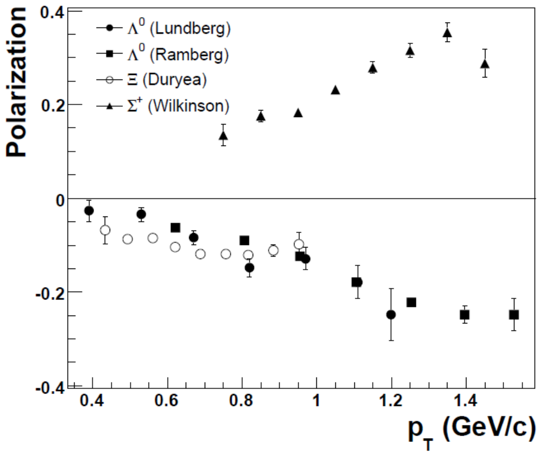
2019 update of PDG

# Consequences

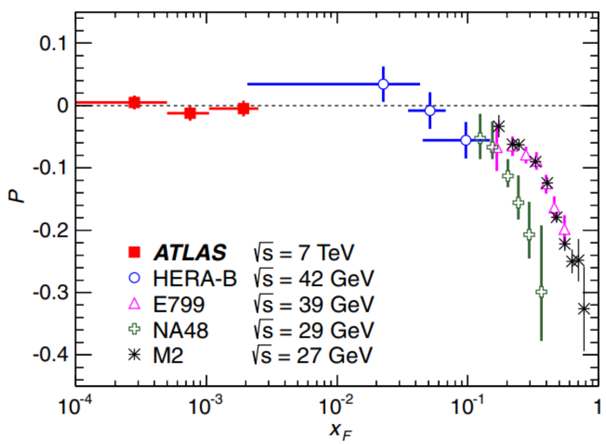
E. Klempt *et al.*,
Phys. Rept. **368** p. 119 (2002)




K. Heller
Colloque de Physique C**6** (1990) 163



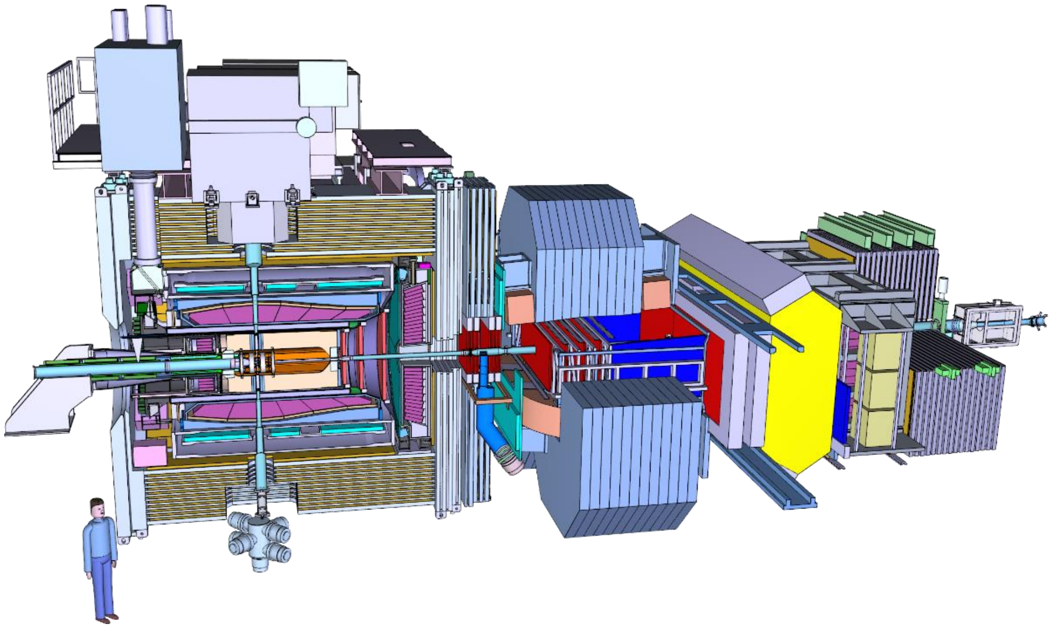

ATLAS
Phys. Rev. D **91**, 032004 (2015)




Most polarisation measurements actually measured $\alpha P$ and calculated $P$ with old PDG value of $\alpha$

→ Need to be re-scaled to updated value!

Part 3



# HYPERON PHYSICS 2.0 WITH PANDA @ FAIR

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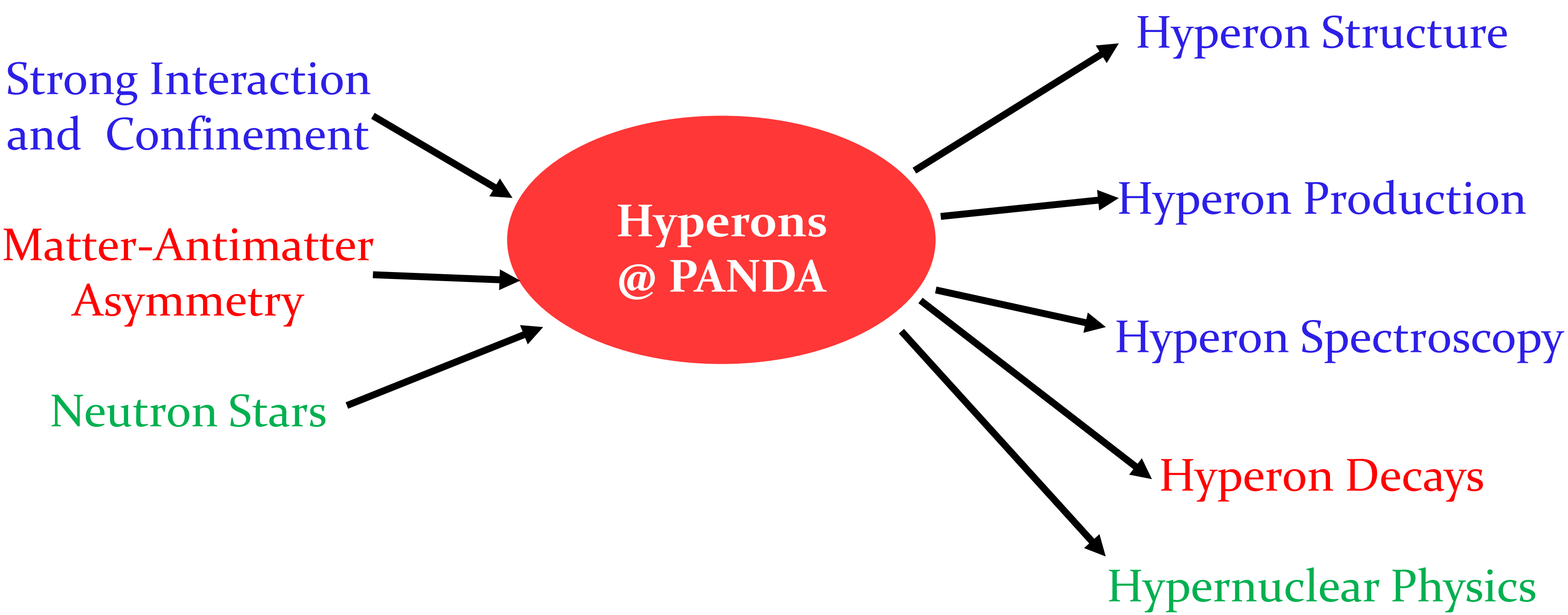
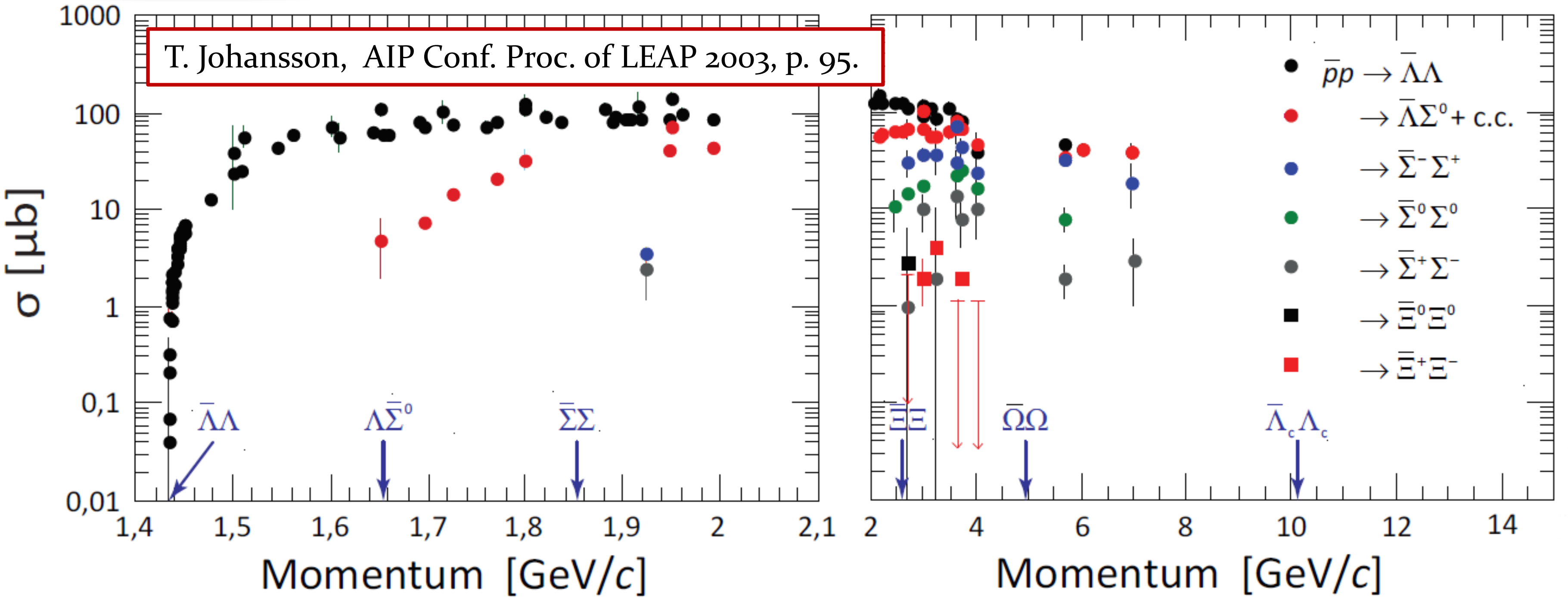
# HYPERON TOPICS IN PANDA

**Fundamental Question** | **Topic**




panda

# Advantages of PANDA




- Measured cross sections of ground-state hyperons in $\bar{p}p \rightarrow \bar{Y}Y$ 1-100 μb*.
- Excited hyperon cross sections should to be similar to those of ground-states**.

**→ Large expected production rates!**

* E. Klempt *et al.*, Phys. Rept. 368 (2002) 119-316
**V. Flaminio *et al.*, CERN-HERA 84-01

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# Advantages of PANDA

Near $4\pi$ detectors → exclusive measurements:

- Large reconstruction efficiency
- Small bias

Antihyperon – hyperon pair production:

- Two-body processes

  → well-defined kinematics

- Symmetric particle-antiparticle final state

  → controllable systematics.

p̄anda

# Hyperon production prospects with PANDA

New simulation studies of single- and double-strange hyperons*:

- Exclusive measurements of
  - $\bar{p}p \to \bar{\Lambda}\Lambda, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$.*
  - $\bar{p}p \to \bar{\Sigma}^0\Lambda, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \bar{\Lambda} \to \bar{p}\pi^+$. **
  - $\bar{p}p \to \bar{\Xi}^+\Xi^-, \Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$.*
  - $\bar{p}p \to \bar{\Xi}^+\Lambda K^- + c.c., \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+, \Lambda \to p\pi^-$. ***
- Ideal pattern recognition.
- Background using Dual Parton Model.

* W. Ikegami-Andersson (FAIRNESS 2019)
** G. Perez Andrade (Master thesis, Uppsala 2019)
*** J. Puetz, (NSTAR 2019)

| $p_{beam}$ (GeV/c) | Reaction | σ (μb) | ε (%) | Rate @ $10^{31}$ $cm^{-2}s^{-1}$ | S/B | Events /day |
|---|---|---|---|---|---|---|
| 1.64 | $\bar{p}p \to \bar{\Lambda}\Lambda$ | 64.0 | 16.0 | 44 $s^{-1}$ | 114 | $3.8 \cdot 10^6$ |
| 1.77 | $\bar{p}p \to \bar{\Sigma}^0\Lambda$ | 10.9 | 5.3 | 2.4 $s^{-1}$ | >11 (90% C.L) | 207 000 |
| 6.0 | $\bar{p}p \to \bar{\Sigma}^0\Lambda$ | 20 | 6.1 | 5.0 $s^{-1}$ | 21 | 432 000 |
| 4.6 | $\bar{p}p \to \bar{\Xi}^+\Xi^-$ | ~1 | 8.2 | 0.3 $s^{-1}$ | 274 | 26000 |
| 7.0 | $\bar{p}p \to \bar{\Xi}^+\Xi^-$ | ~0.3 | 7.9 | 0.1 $s^{-1}$ | 65 | 8600 |
| 4.6 | $\bar{p}p \to \bar{\Xi}^+\Lambda K^-$ | ~1 | 5.4 | 0.2 $s^{-1}$ | 30 | 18000 |

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# Hyperon production prospects with PANDA

New simulation studies of single- and double-strange hyperons*:

- Exclusive measurements of
  - $\bar{p}p \rightarrow \bar{\Lambda}\Lambda, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.*
  - $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda, \Lambda \rightarrow p\pi^-, \bar{\Sigma}^0 \rightarrow \bar{\Lambda}\gamma, \bar{\Lambda} \rightarrow \bar{p}\pi^+$. **
  - $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-, \Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^-, \bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.*
  - $\bar{p}p \rightarrow \bar{\Xi}^+\Lambda K^- + c.c., \bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+, \bar{\Lambda} \rightarrow \bar{p}\pi^+, \Lambda \rightarrow p\pi^-$. ***
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- Background using Dual Parton Model

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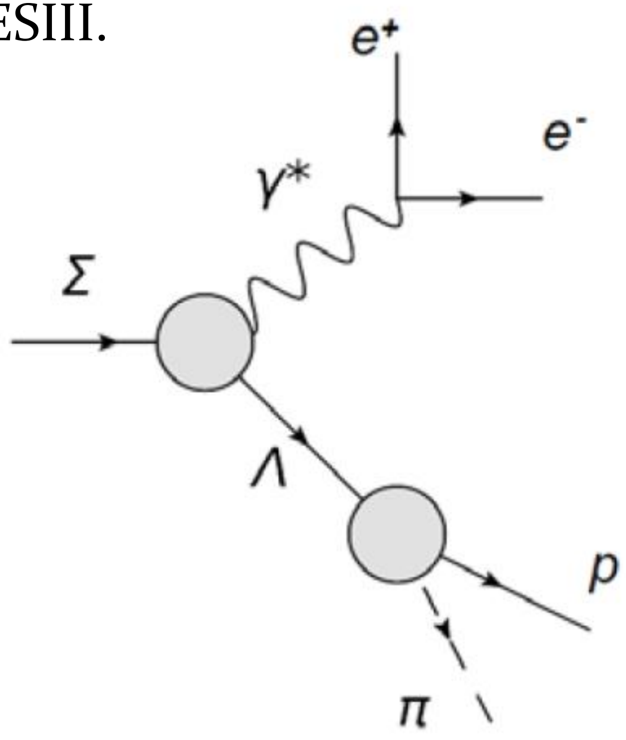
| 6.0 | | | | | | 432 000 |
| 4.6 | | | | | | 26000 |
| 7.0 | | | | | | 8600 |
| 4.6 | $\bar{p}p \rightarrow \bar{\Xi}^+\Lambda K^-$ | ~1 | 5.4 | 0.2 $s^{-1}$ | 30 | 18000 |

PANDA will be a **hyperon factory** already at Day One!

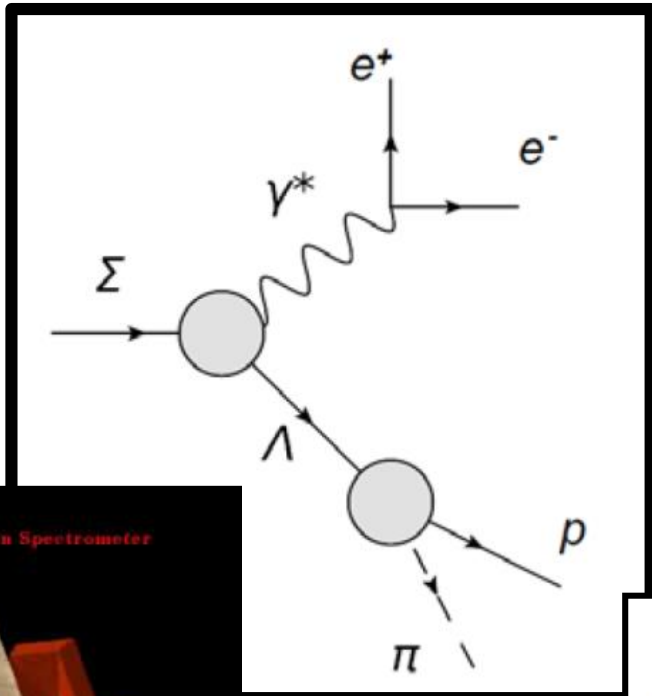
With full luminosity, the rate will be ~20 times larger!

# Hyperon structure @ PANDA

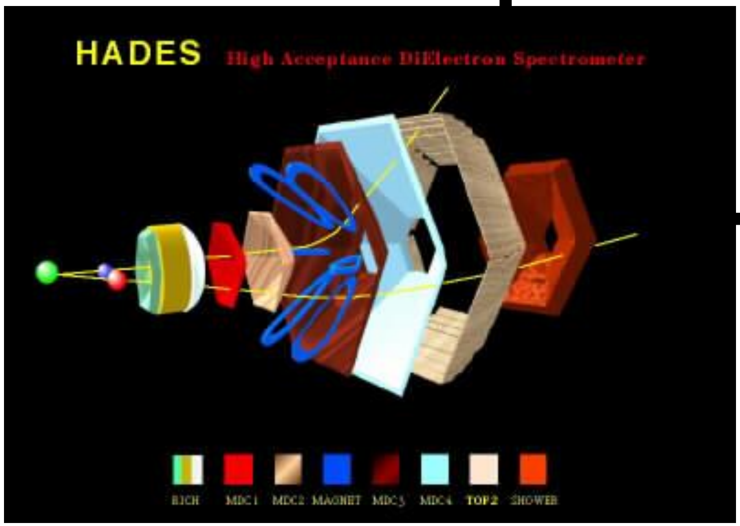
- Transition form factors accessible from Dalitz decays
  - Complemenary kinematic region w.r.t. BESIII.
- Possible in case of *e.g.* $\Sigma^0$ and $\Lambda(1520)$
- **Challenge:** Small predicted BR's ($10^{-3}$ - $10^{-6}$)
- **Good news:** Large hyperon production cross sections.

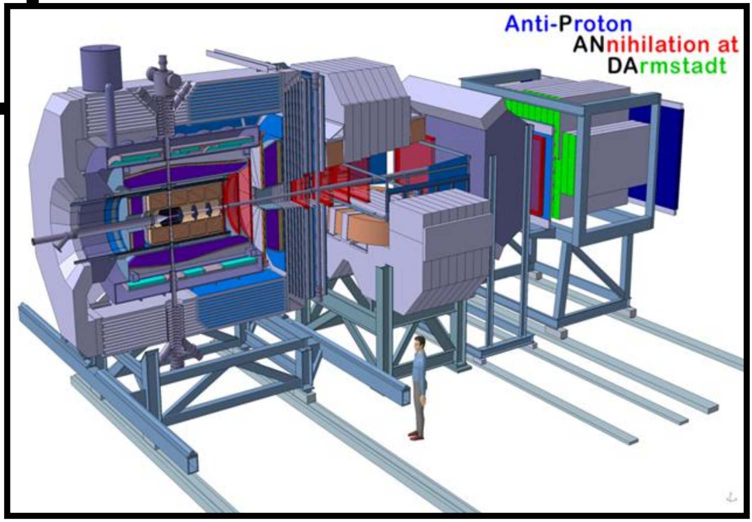


# Hyperon Structure at PANDA




Possible already during Phase 0 with HADES +PANDA FTS!



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# Summary

- Hyperons is a powerful diagnostic tool to study
  - The strong interaction in the confinement domain.
  - The matter-antimatter asymmetry of the Universe.
- New measurements from BESIII
  - Complete measurement of Λ EM form factors.
  - Most precise test of CP symmetry in Λ decays.
  - > 40 year old PDG value updated.
- Future at PANDA
  - "Hyperon factory" already at Day One.
  - Broad and unique hyperon programme.

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# Thanks for your attention!

Knut and Alice Wallenberg Foundation

# "Old" PDG

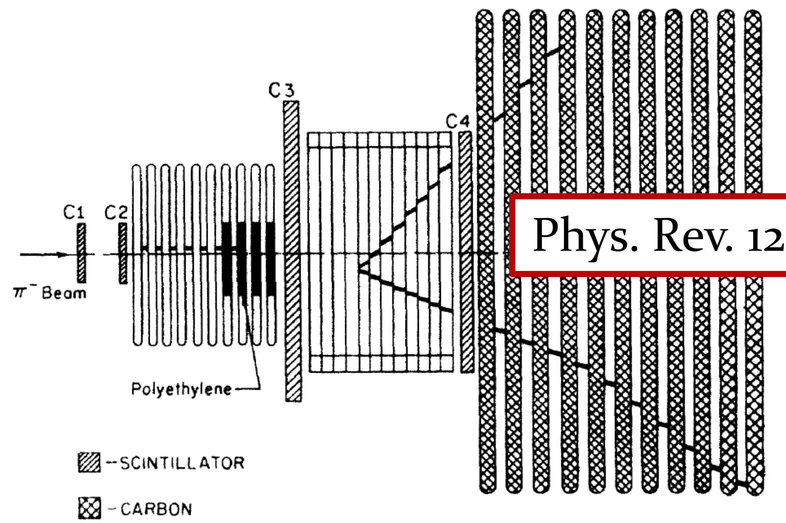


FIG. 1. Schematic diagram showing arrangement of apparatus. An example of an event has been sketched in.

Phys. Rev. 129, 1795 (1967)

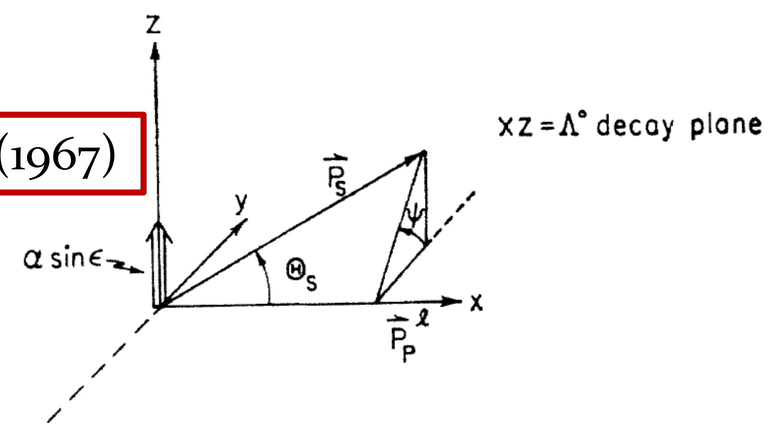


FIG. 8. Angles involved in analysis of polarization of decay protons from unpolarized $\Lambda^0$ particles.