Explore the Structure of Proton — Presentation of my PhD Thesis

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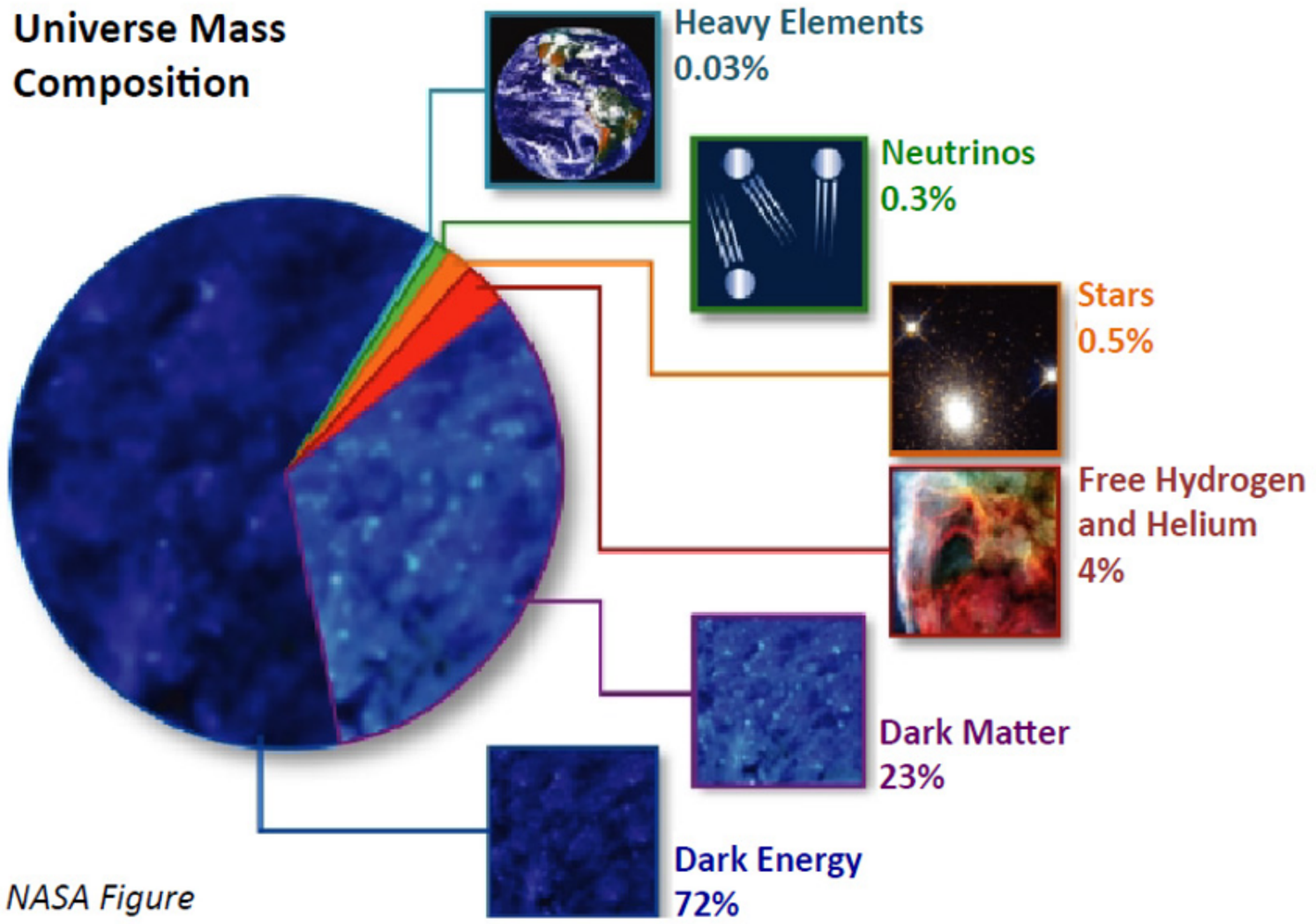
About

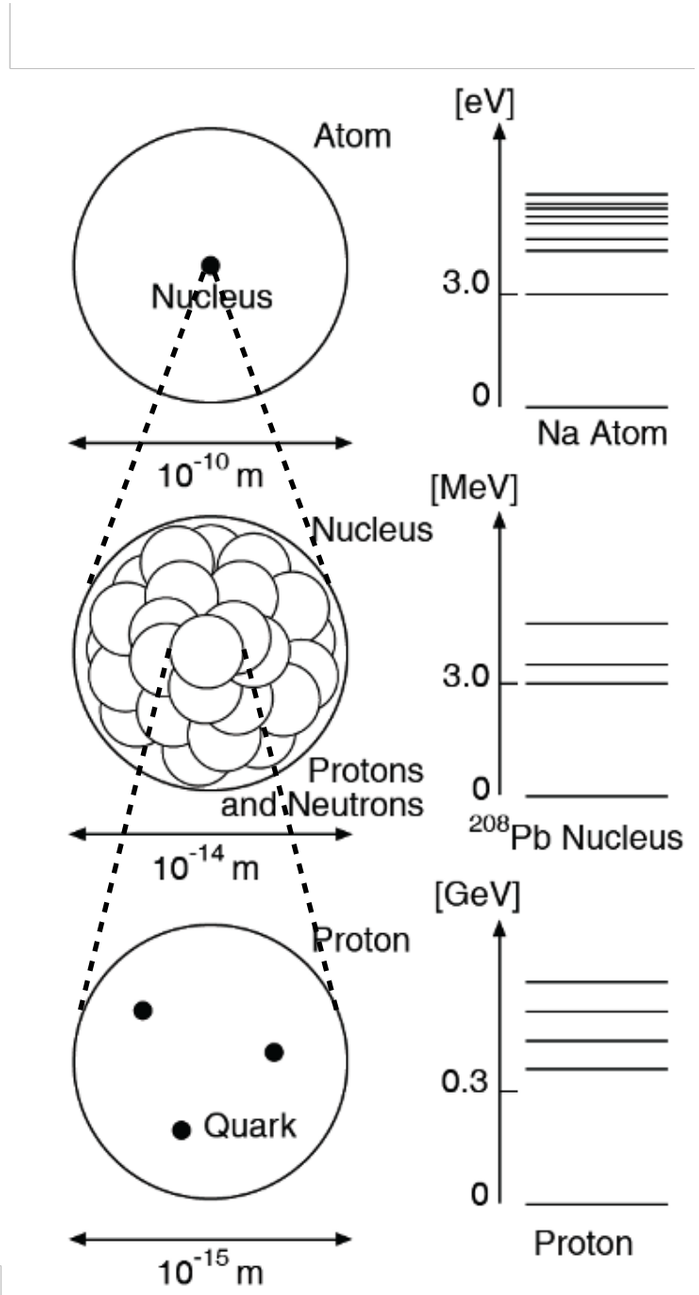
- **Education**:
  - Bachelor's Degree, 2009-2013, Department of Physics, National Kaohsiung Normal University.
  - Master's Degree, 2013-2015, Department of Physics, National Kaohsiung Normal University.
  - Doctor's Degree, 2015-2021, Department of Physics, National Kaohsiung Normal University.
- **Working experience**:
  - Institute of Physics, Academia Sinica, Taipei City, Taiwan.
  - COMPASS Collaboration at CERN, Geneva, Switzerland.
- **Publication**:
  - Yu-Hsiang Lien, "Angular Distributions of Pion-induced Drell–Yan Production", JPS Conf. Proc. 26, 031004 (2019), doi: https://doi.org/10.7566/JPSCP.26.031004
  - M. Aghasyan et al. [COMPASS Collaboration], "First Measurement of Transverse-Spin-Dependent Azimuthal Asymmetries in the Drell-Yan Process", Phys. Rev. Lett.,119(11), 112002 (2017), doi: https://doi.org/10.1103/PhysRevLett.119.112002
- **PhD thesis topic**:
  - Measurements of Unpolarized Dimuon Angular Distributions of Drell-Yan Production with 190-GeV Pion beams in the COMPASS Experiment at CERN.
    — **explore the structure of proton**.

Outline

- Partonic Structure of Proton
- COMPASS Experiment at CERN
- Data Analysis
- Extraction of Angular Coefficients
- Summary

Universe Mass Composition



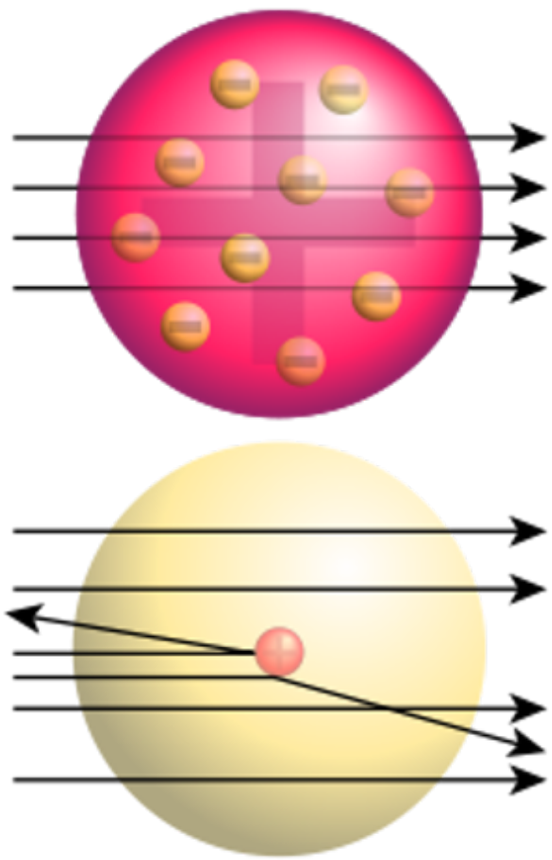


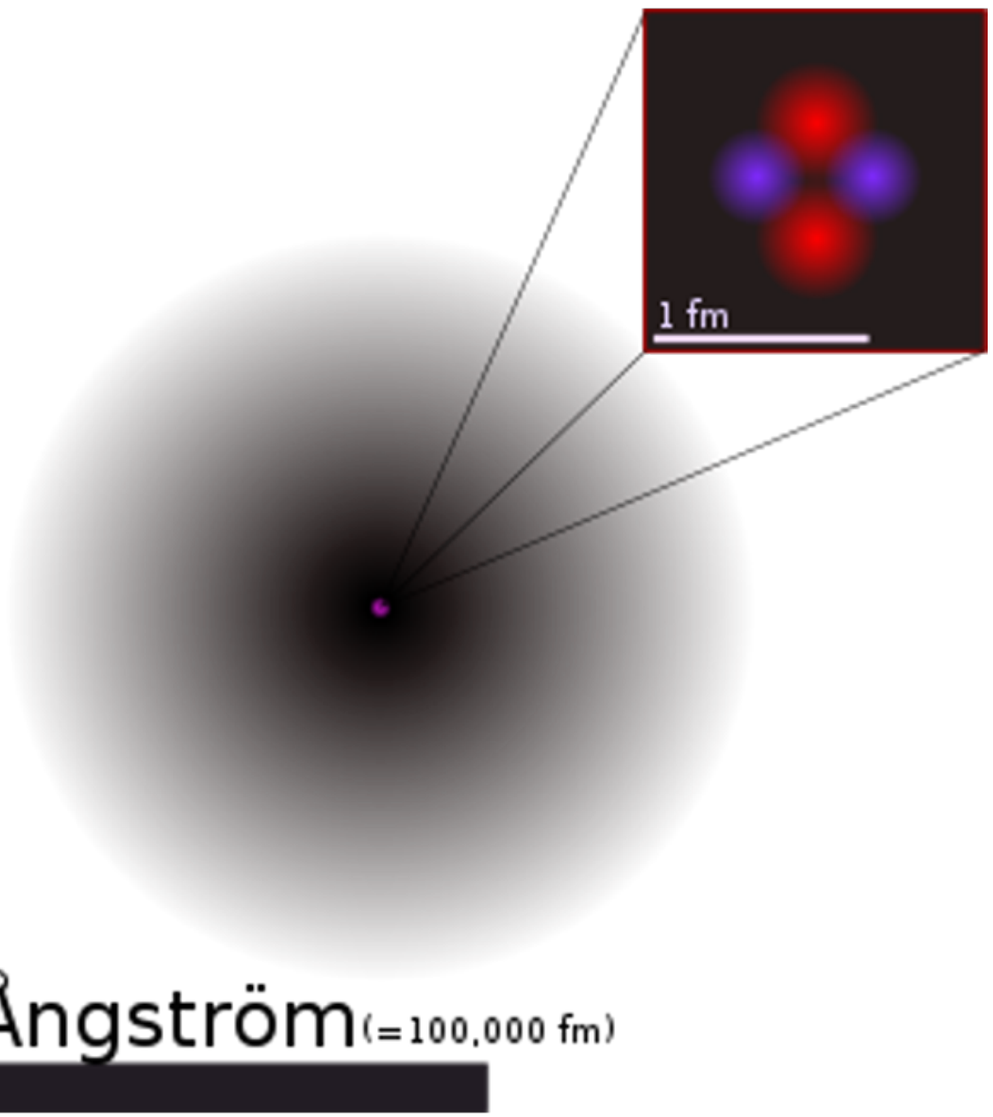
Rutherford Experiment — Nucleus Structure

Ernest Rutherford

Hans Geiger

Ernest Marsden

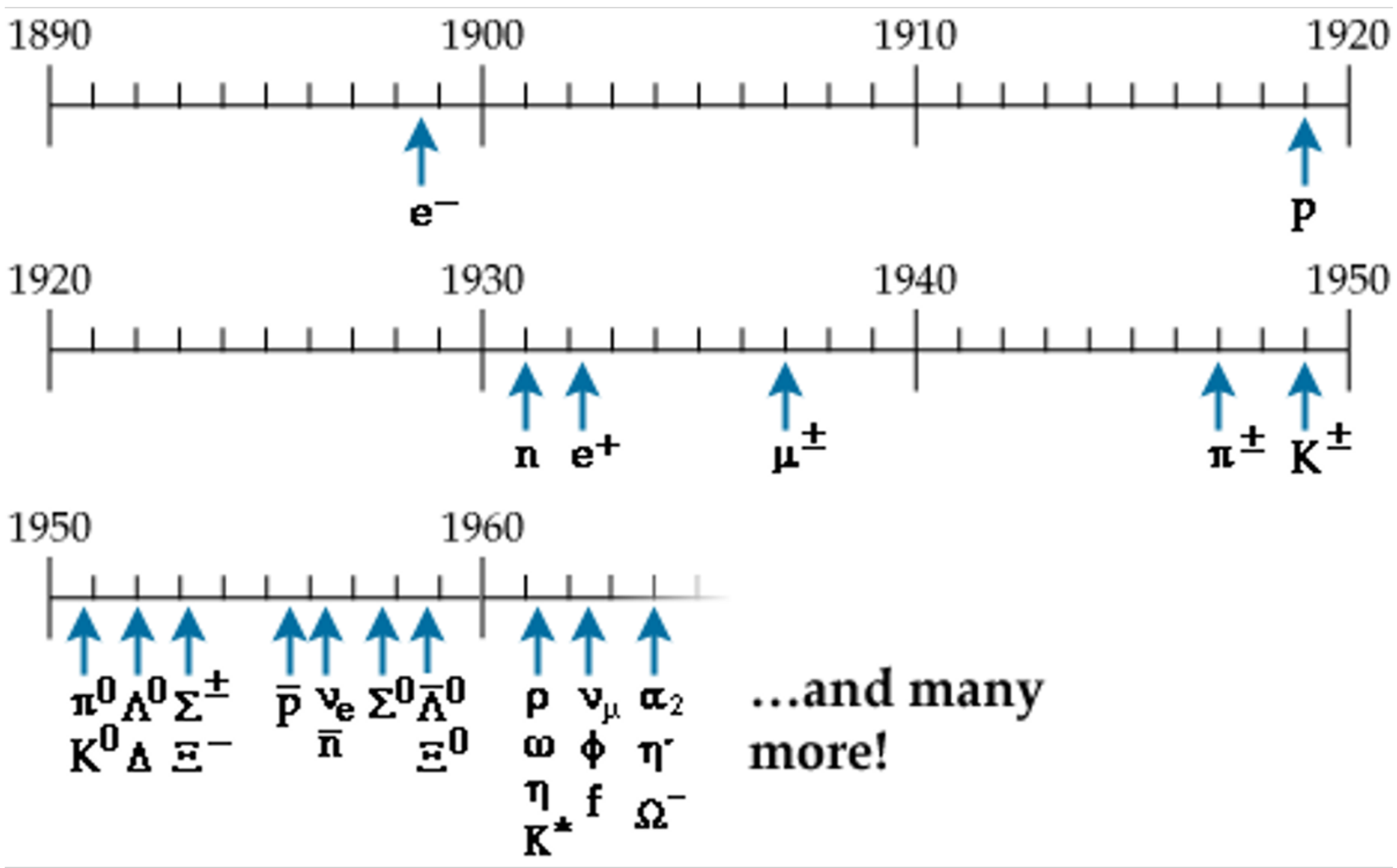




Elementary Particle Discovered

「If I could remember the names of all these particles, I'd be a botanist.」

Enrico Fermi



Quark Model — The Eightfold Way

Murray Gell-Mann
Facts

Photo from the Nobel Foundation archive.

Murray Gell-Mann
The Nobel Prize in Physics 1969

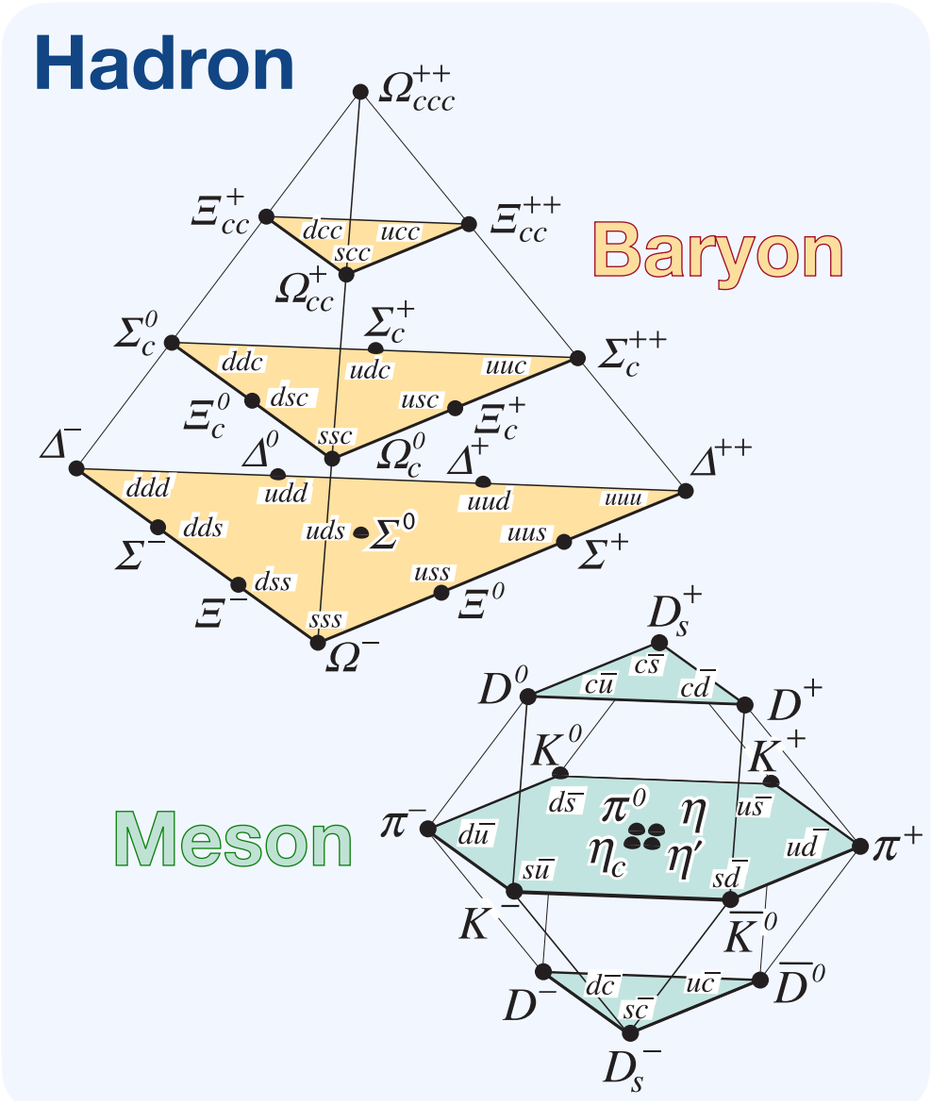
Born: 15 September 1929, New York, NY, USA

Died: 24 May 2019, Santa Fe, NM, USA

Affiliation at the time of the award: California Institute of Technology (Caltech), Pasadena, CA, USA

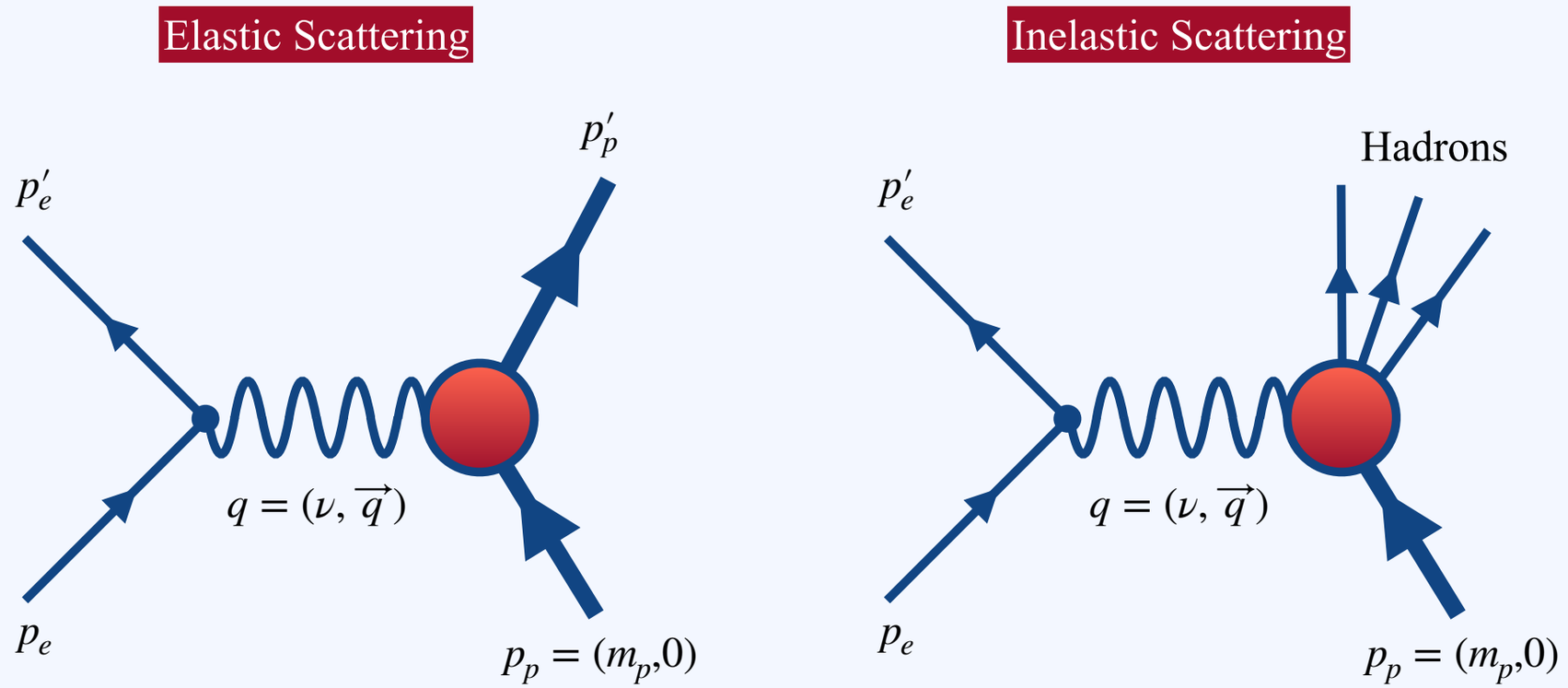
Prize motivation: "for his contributions and discoveries concerning the classification of elementary particles and their interactions."

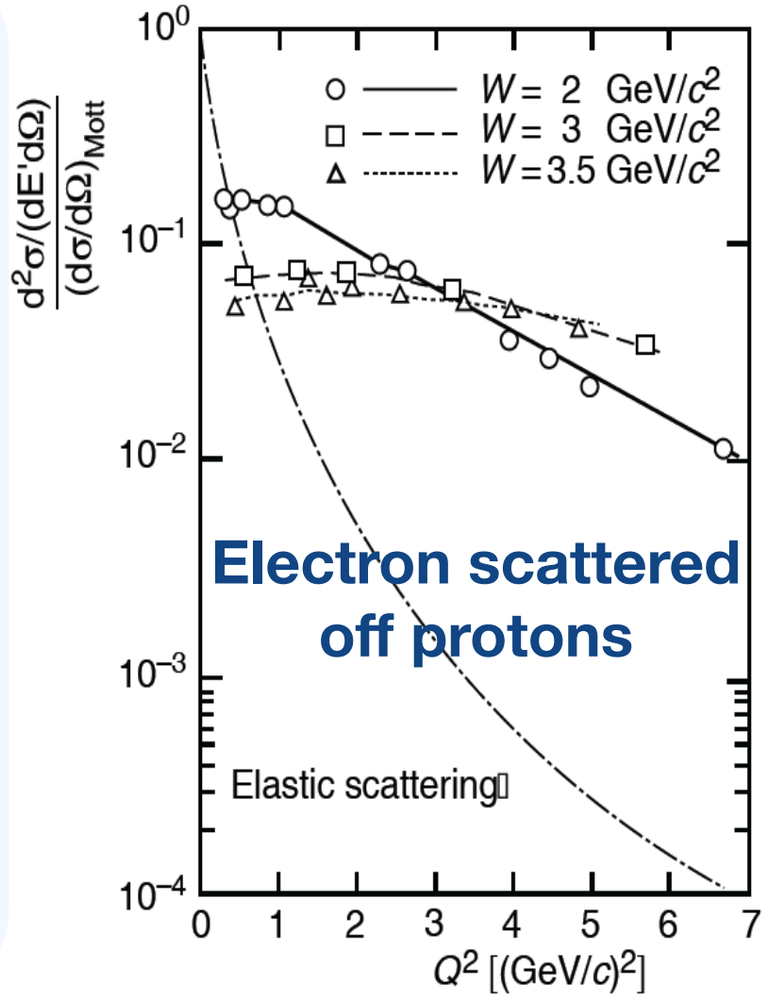
Prize share: 1/1



- The Quark Model was proposed by Murray Gell-Mann in 1964.
- Gell-Mann successfully predicted the existence of Ω^- baryon in 1964, which made of three strange quarks.

Deep Inelastic Scattering (DIS)





- In the electron scattered off protons scattering experiment, a very weak scale-dependence of cross-section is observed.
- The experimental result imply that the electron is scattered off a point-like particle inside the proton!

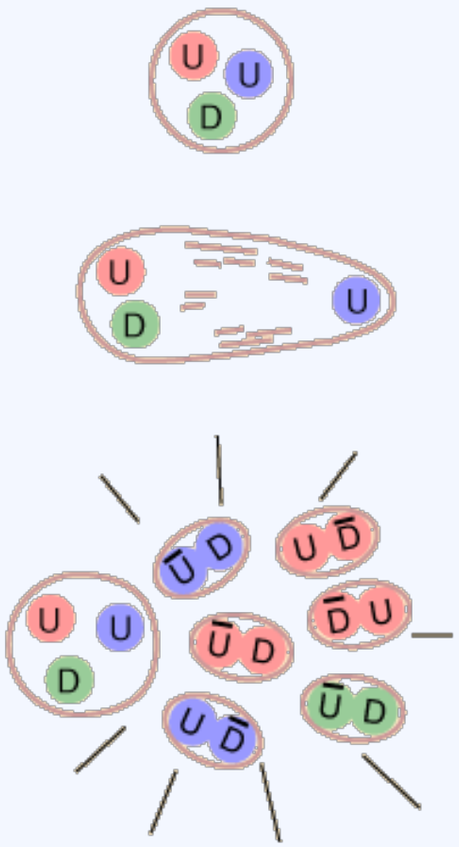
Properties of Quantum Chromodynamics

$$\mathscr{L}_{QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a = q\bar{q} + G^2 + g_s q\bar{q}G + g_s G^3 + g_s^2 G^4$$

- The Quantum Chromodynamics (QCD) describes the strong interaction.
- The QCD provide two peculiar properties: color confinement and asymptotic freedom.

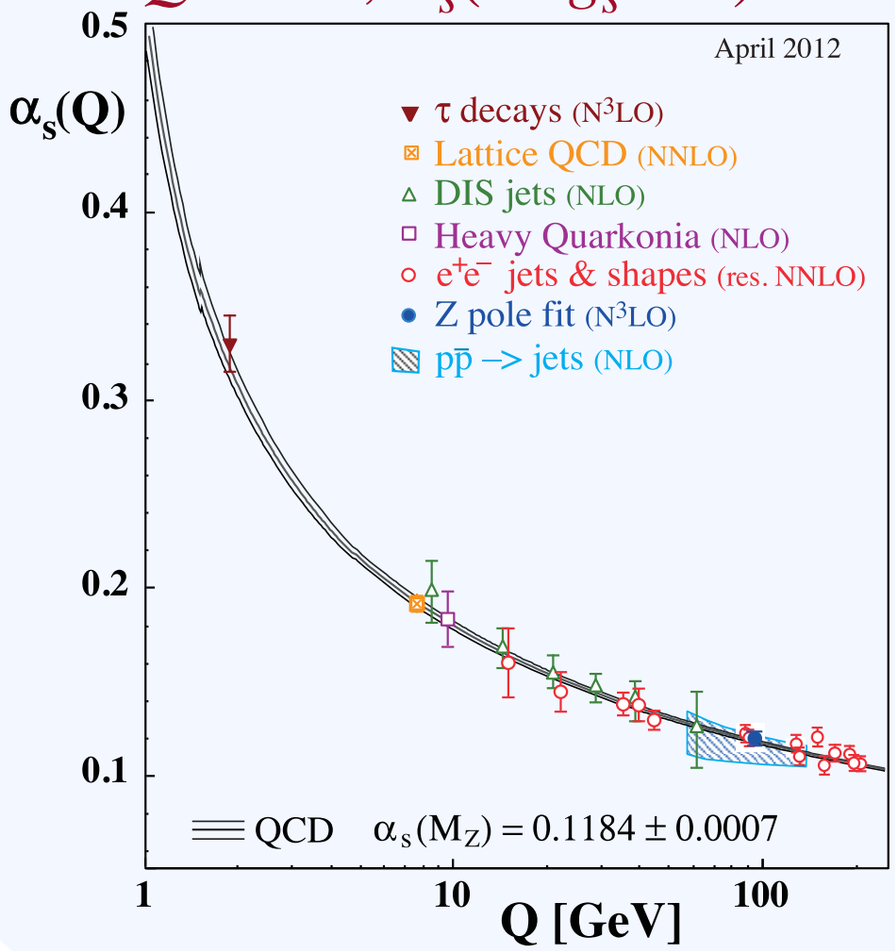
Color confinement

Color-charged particle cannot be isolated.



Asymptotic freedom

$$Q \to \infty,\ \alpha_s(= g_s^2/4\pi) \to 0$$



Parton Model (Feynman)

Richard P. Feynman

Facts

Photo from the Nobel Foundation archive.

Richard P. Feynman
The Nobel Prize in Physics 1965

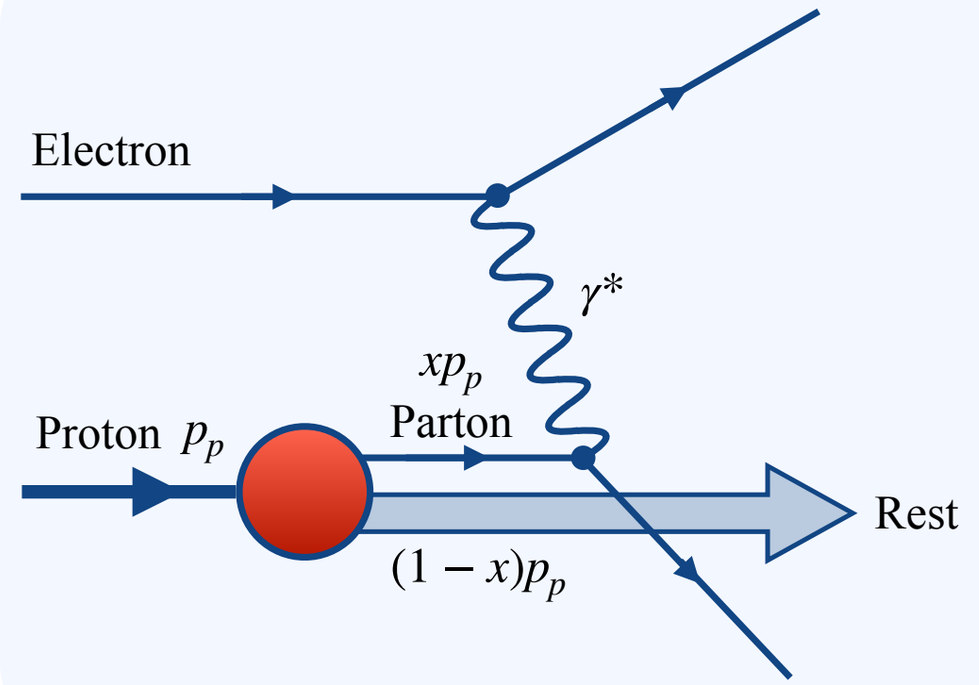
Born: 11 May 1918, New York, NY, USA

Died: 15 February 1988, Los Angeles, CA, USA

Affiliation at the time of the award: California Institute of Technology (Caltech), Pasadena, CA, USA

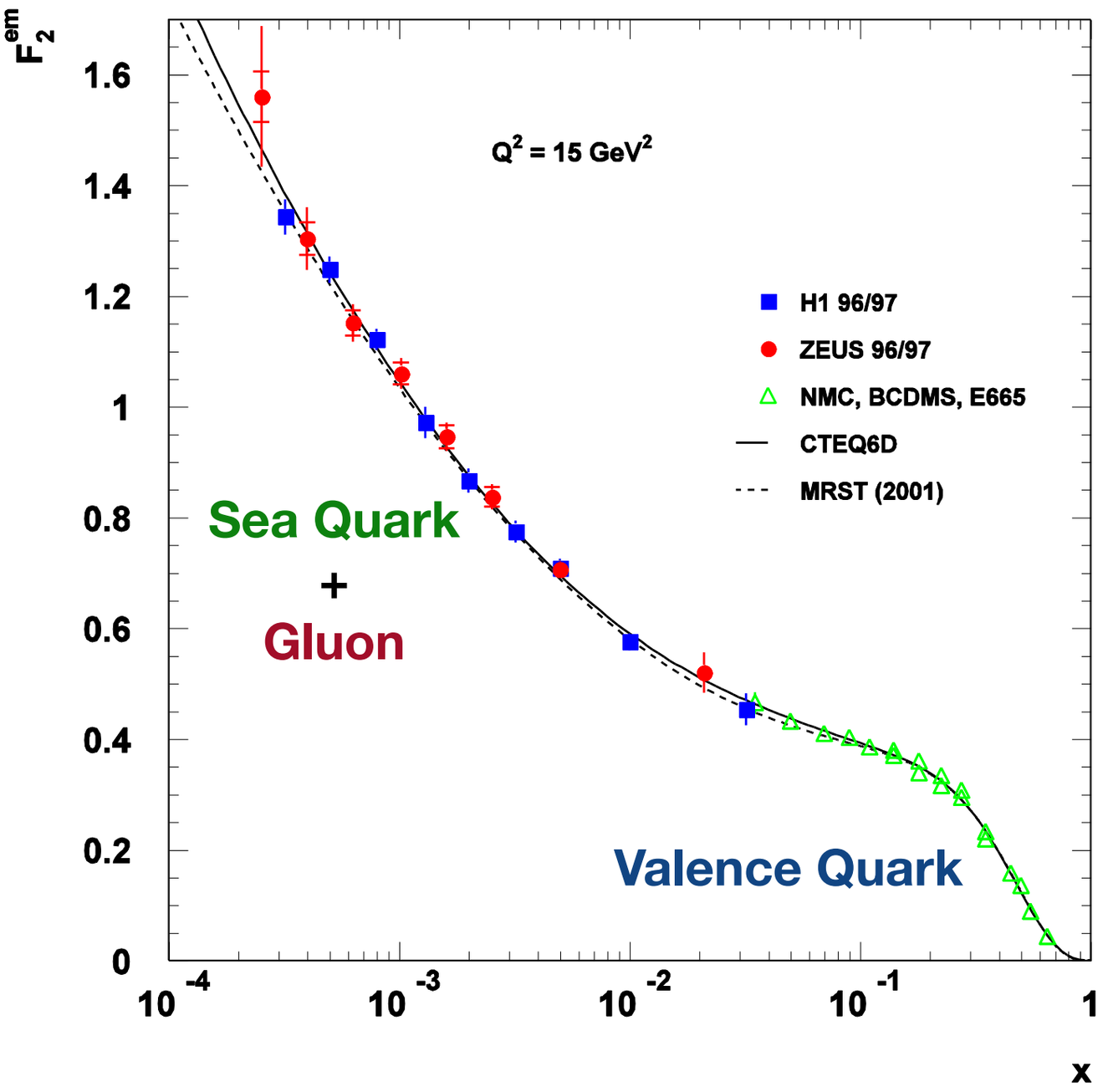
Prize motivation: "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles."

Prize share: 1/3



- The parton model was proposed by R. Feynman in 1969.
- Bjorken scaling variable x : the momentum fraction of struck parton.
- $p_{\text{parton}} = xp_{\text{proton}}$; Bjorken-x has a theoretical range: $0 < x < 1$

Partonic Structure of Proton

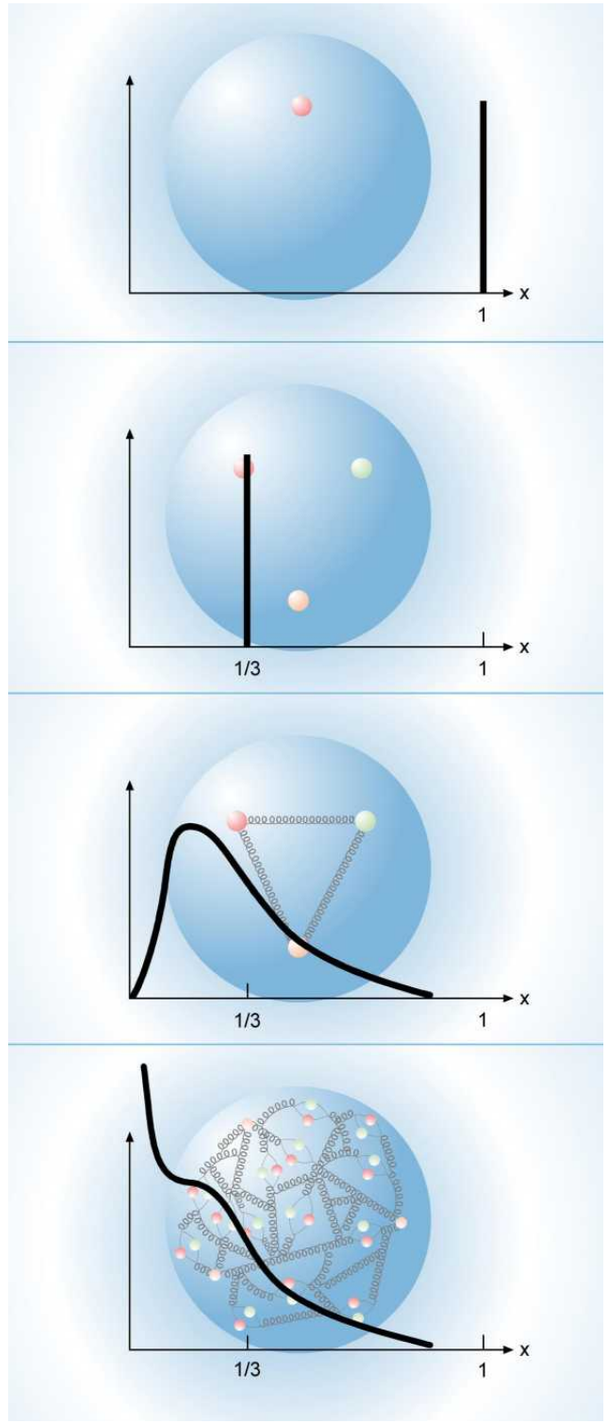


Nucleon

Valence Quark

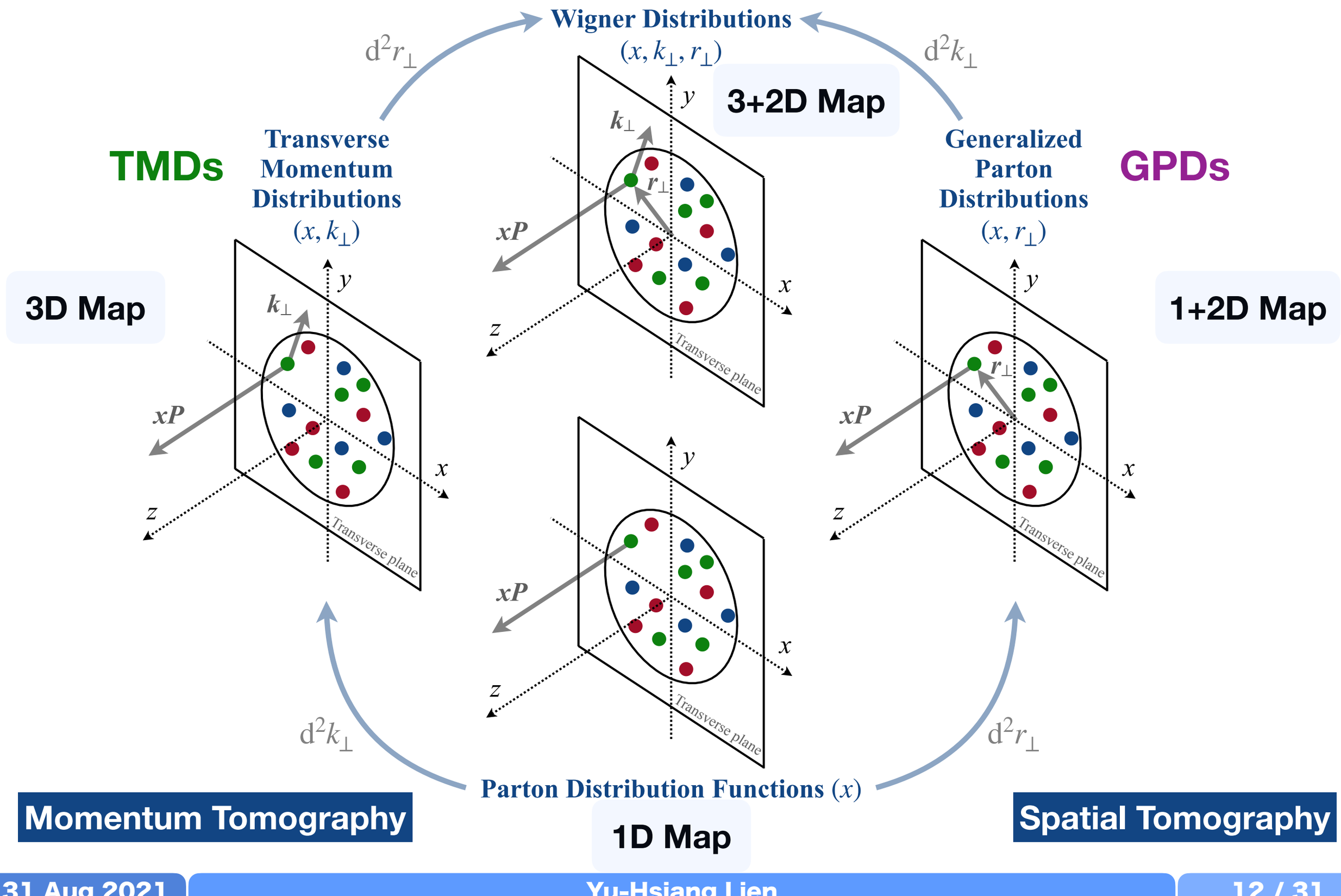
Valence Quark
+
Gluon

Valence Quark
+
Gluon
+
Sea Quark



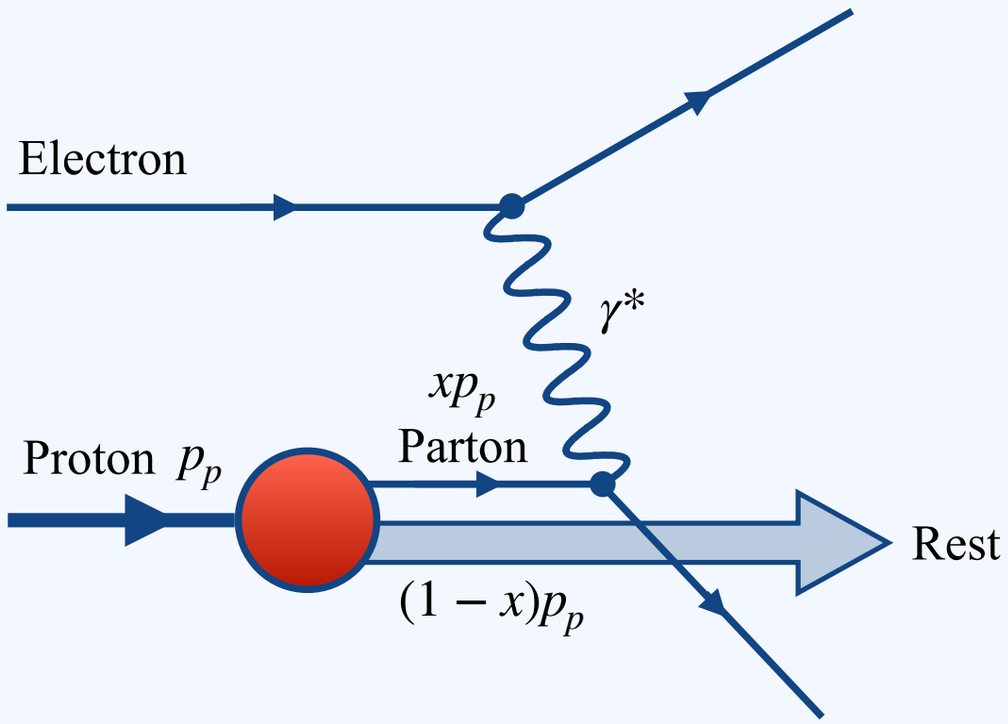
Q^2

Multi-dimensional Partonic Structures



Experimental Approach for PDFs

Deep-Inelastic Scattering

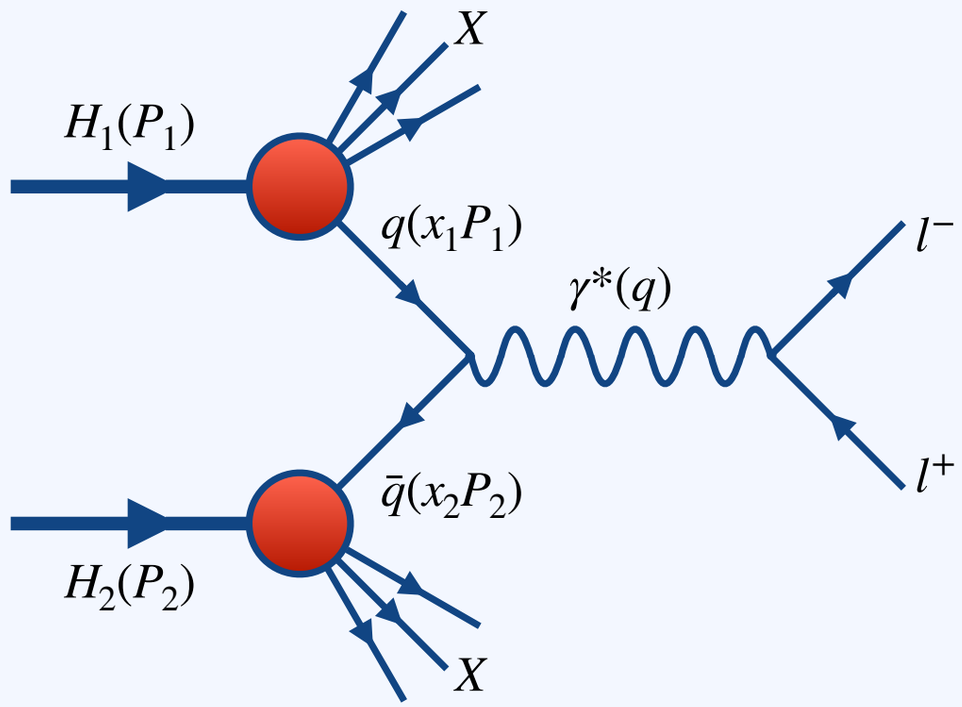


Proton PDFs ✔

Pion PDFs ✘

No rest target of pions existed in our world!

Drell-Yan Process



$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\mathrm{d}x_2} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_i e_i^2\left[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)\right]$$

Proton PDFs ✔

Pion PDFs ✔

Nice approach to probe pion structure!

Drell-Yan Practitioners with Prof. Yan

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BS, 1960, National Taiwan University. Ph.D., 1968, Harvard University. Research Associate, Stanford Linear Accelerator Center, 1968-70. Assistant Professor, Physics, Cornell University, 1970-76. Associate Professor, Physics, Cornell University, 1976-81. Professor, Physics, Cornell University, 1981-present. Visiting appointments at: Stanford Linear Accelerator Center, 1973-74. Theory Division, CERN, 1977-78. Physics Department, National Taiwan University, 1986. Institue of Physics, Academia Sinica, Taipei, Taiwan, 1991-92. National Center of Theoretical Sciences, Hsinchu, Taiwan, 1997. Alfred Sloan Fellow, 1974-78. Fellow, American Physics Society.

28 Nov. 2018 @ Academia Sinica

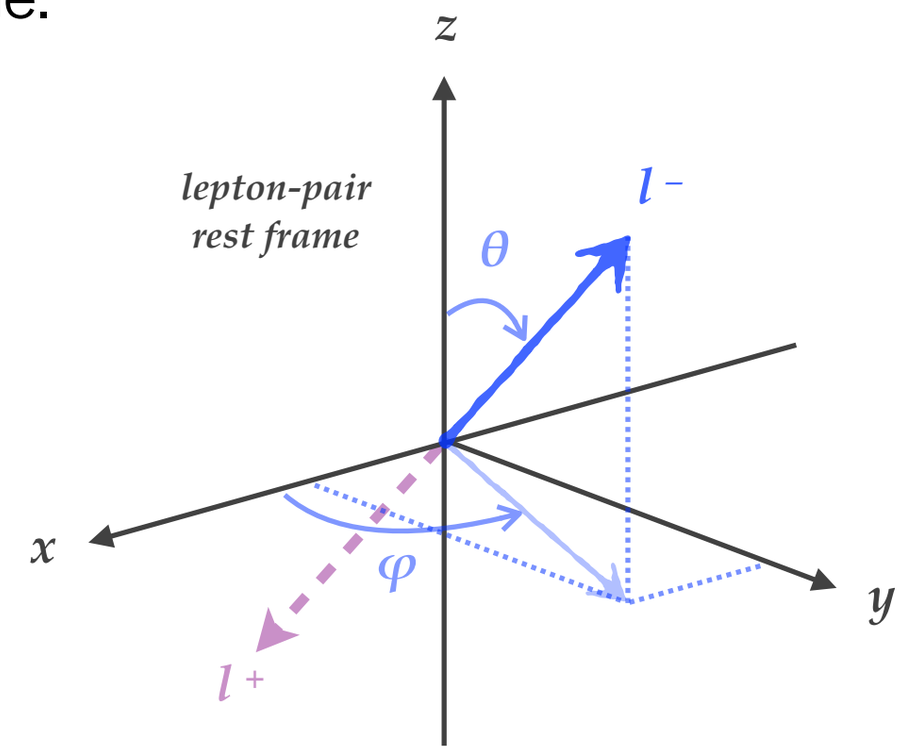
Drell–Yan Angular Distributions

- The decay angular distribution of Drell–Yan process is an important information to probe the spin and angular momentum of parton.

- The general expression for angular distribution of lepton-pair:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\varphi+\frac{\nu}{2}\sin^2\theta\cos 2\varphi\right]$$

  - where θ and φ are the polar and azimuthal angles of the lepton$^-$ in the lepton-pair rest frame.



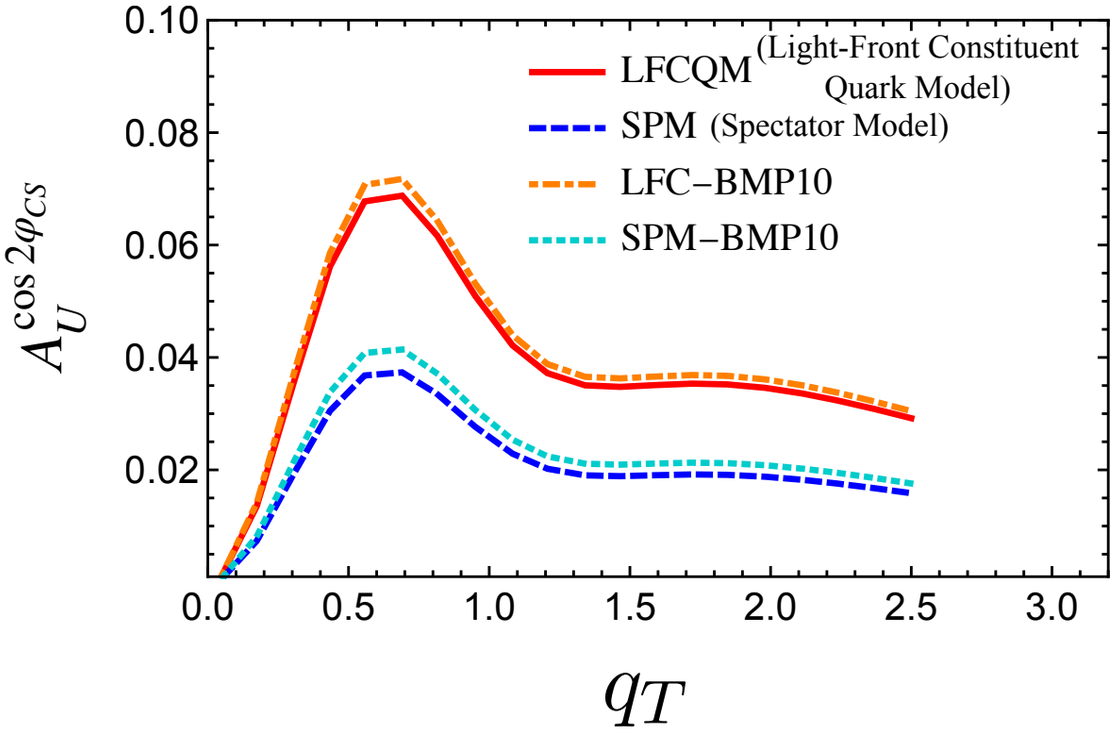
The Boer–Mulders Function

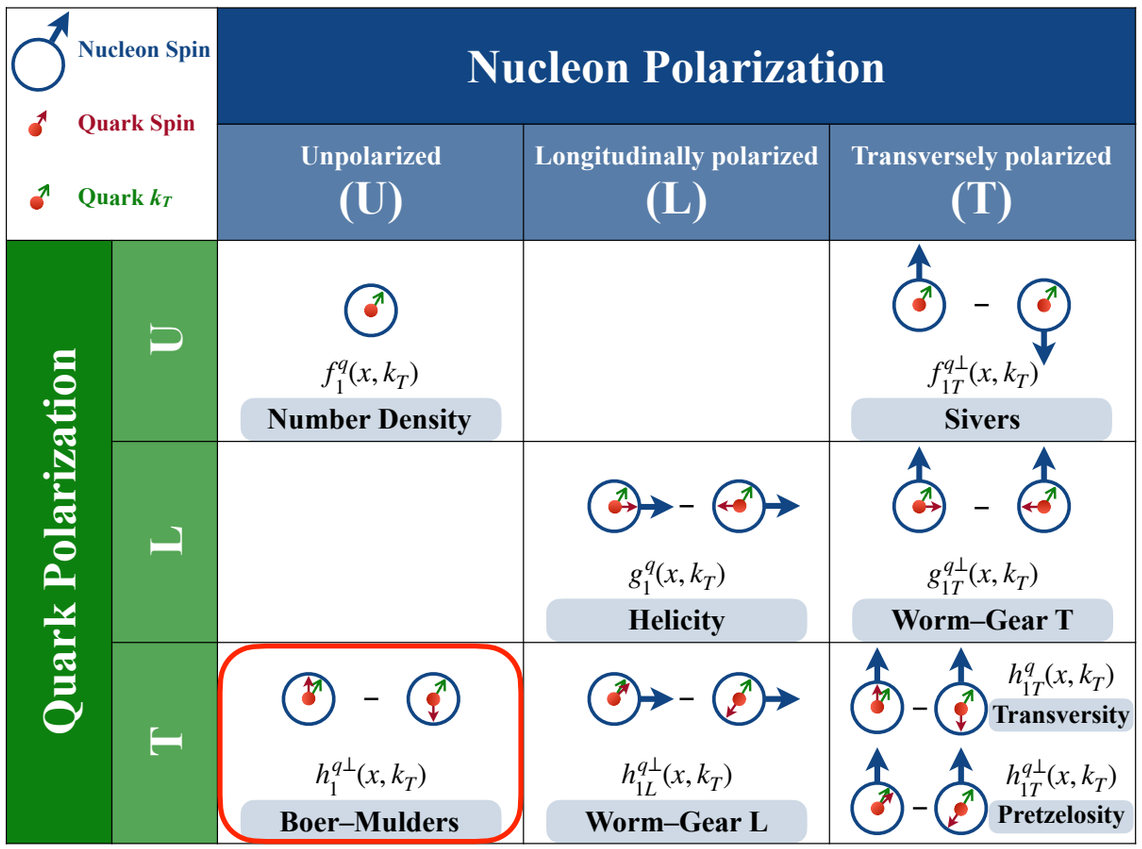
Boer, PRD 60 (1999) 014012; S. Bastami, et.al, JHEP 02 (2021) 166

- An explanation of the $\cos 2\varphi$ dependence observed in the DY process was proposed, by introducing a non-perturbative TMD **Boer–Mulders function**.

- The Boer–Mulders function $h_1^\perp$ represents a correlation between quark's intrinsic **transverse momentum** k_T and **transverse spin** S_T (transversely polarized quark) in an unpolarized hadron.

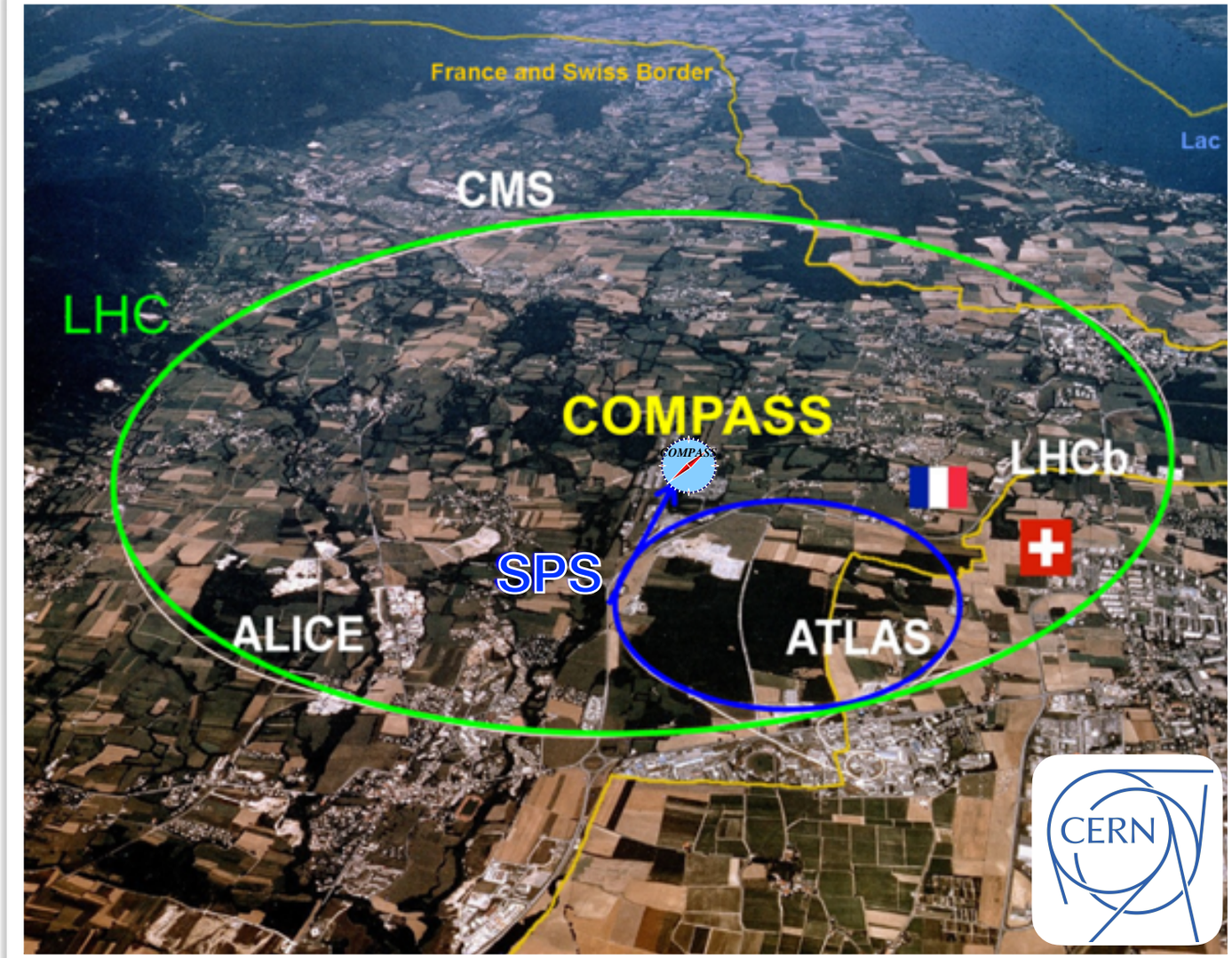
$$A_U^{\cos 2\varphi_{CS}} = \frac{\nu}{2} \propto h_1^\perp(N)\bar{h}_1^\perp(\pi)$$

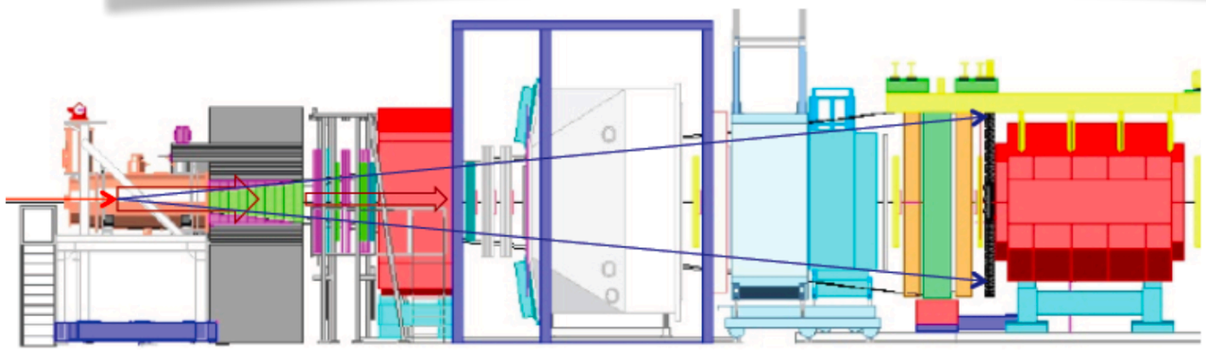




COMPASS/CERN Collaboration

Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS)

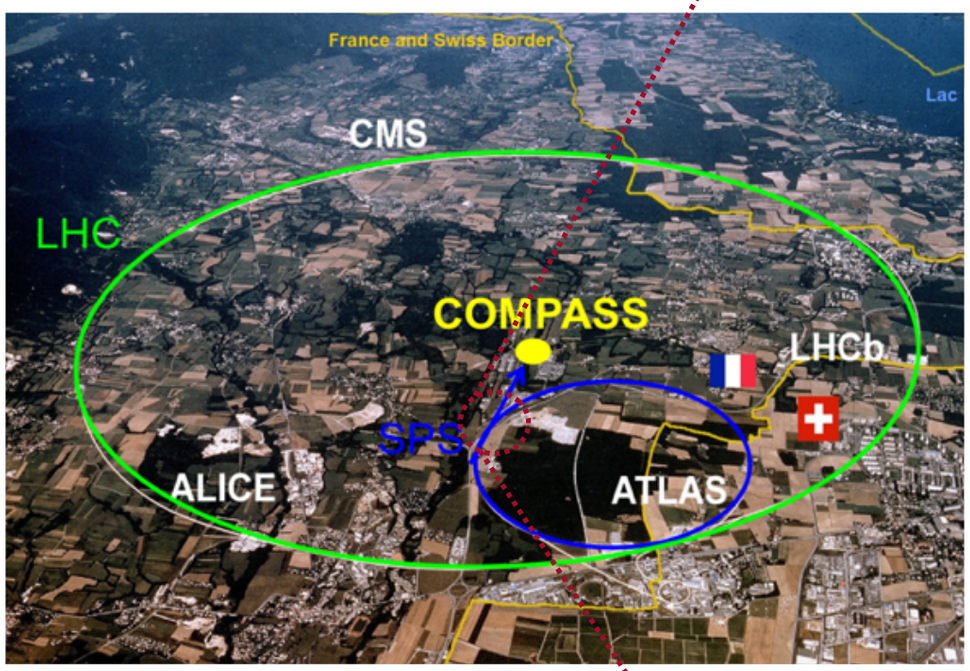




...

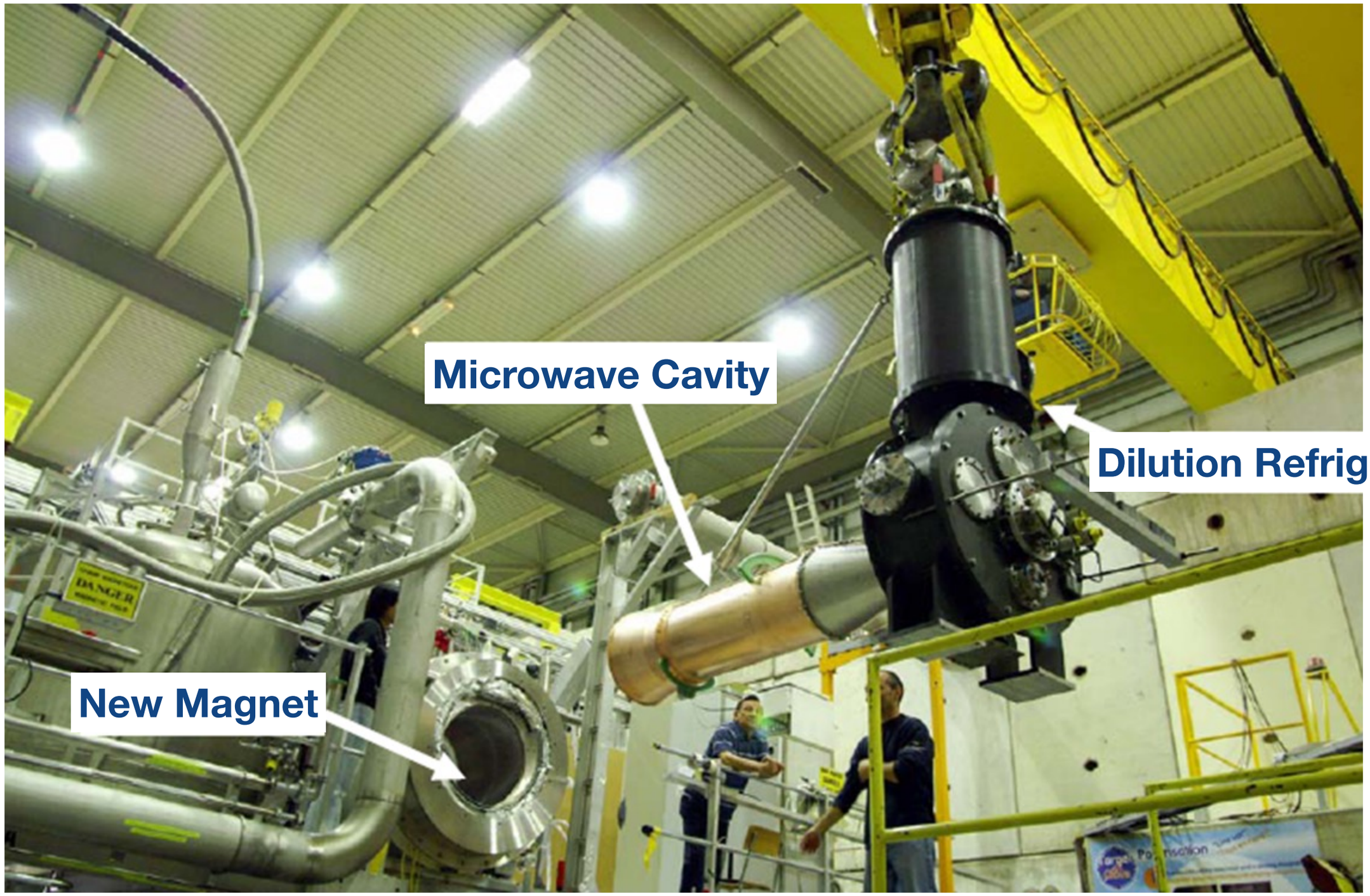
- A fixed-target experiment at SPS north area.
- 24 participating institutions from 13 countries.
- Physics programs:
  - Nucleon spin and partonic structure.
  - Hadron spectroscopy
  - TMDs + pion structure
- Taking data since 2002.
- Last run will take place in 2022.
- To be superseded by AMBER experiment.

CERN SPS M2 Beam Line

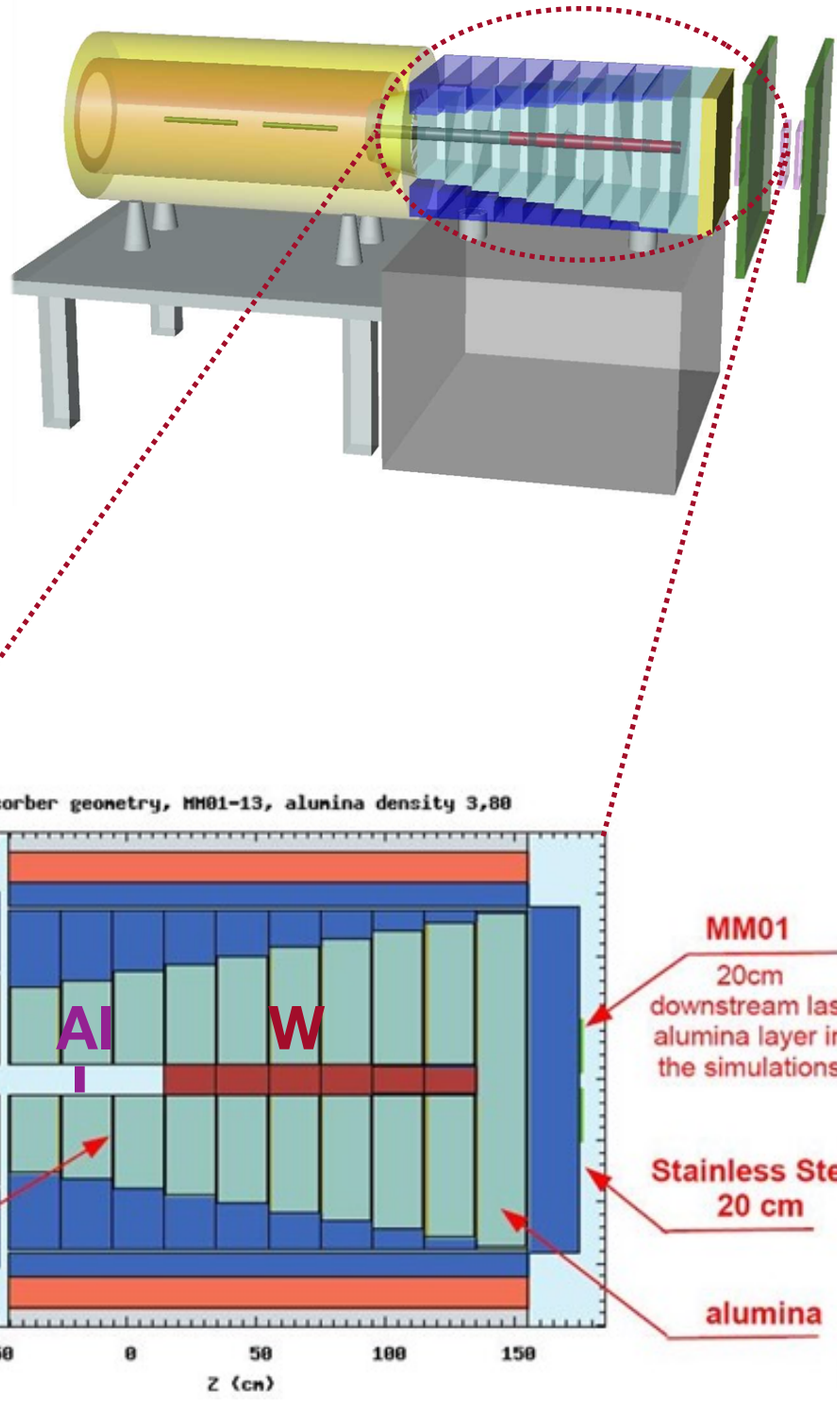


- The 190 GeV pion- beam are the secondary beam produced from the SPS proton beam hitting the nuclear target.

Polarized NH_3 Target

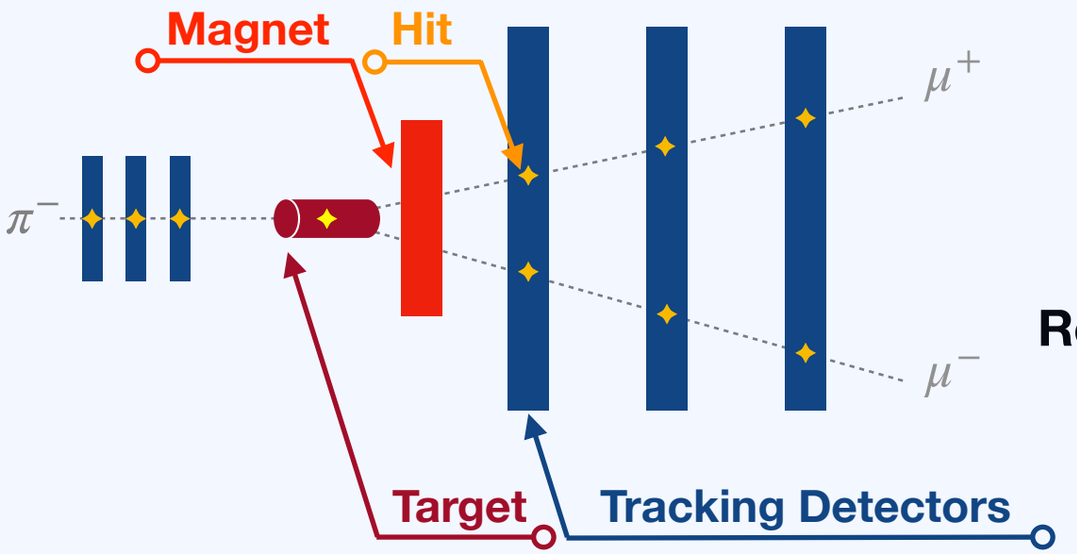


Hadron Absorber

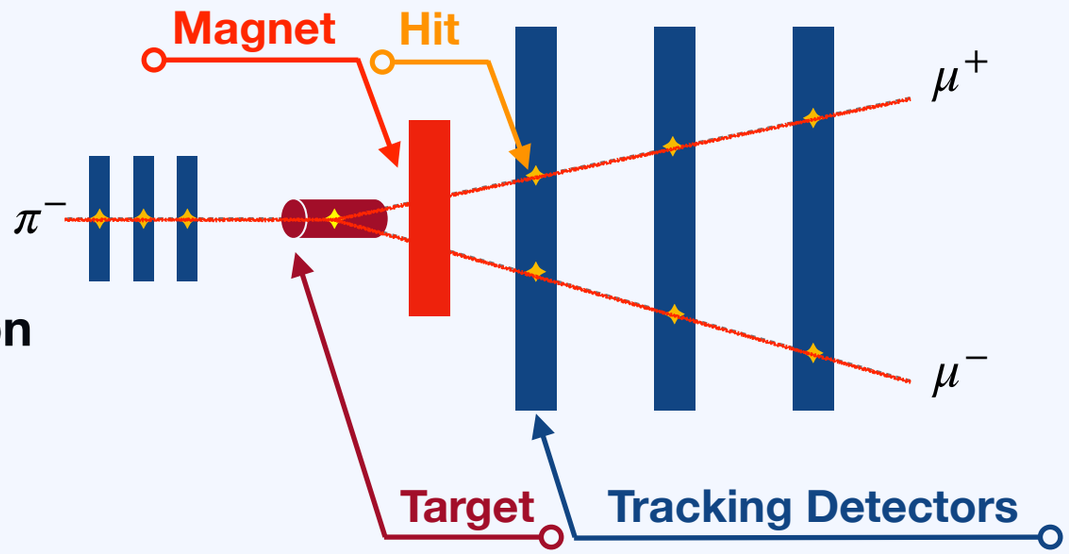


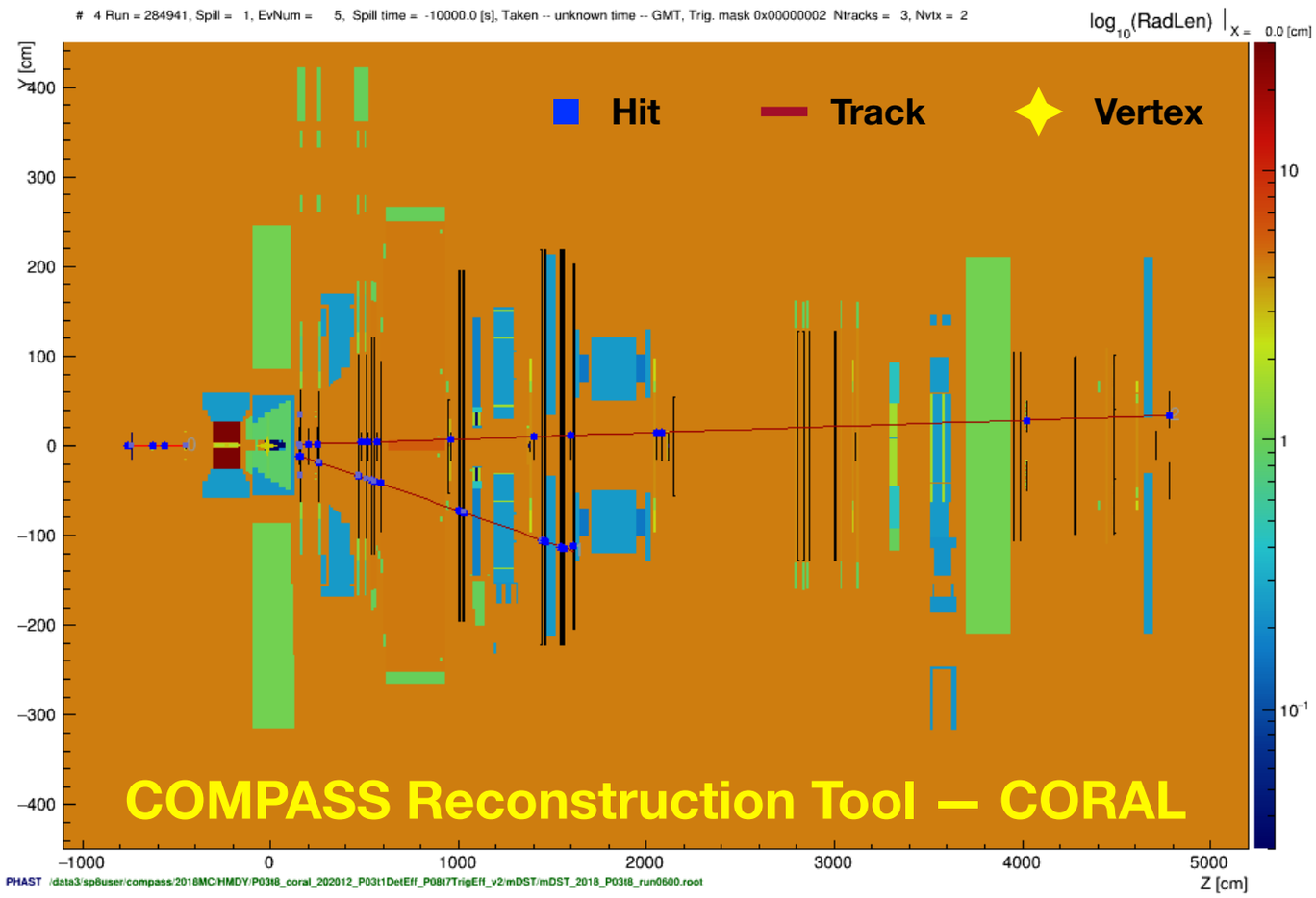
- The total length of the hadron absorber is 240 cm
- It incorporates 120 cm W beam plug and 7 cm Al target.

Tracking and Reconstruction

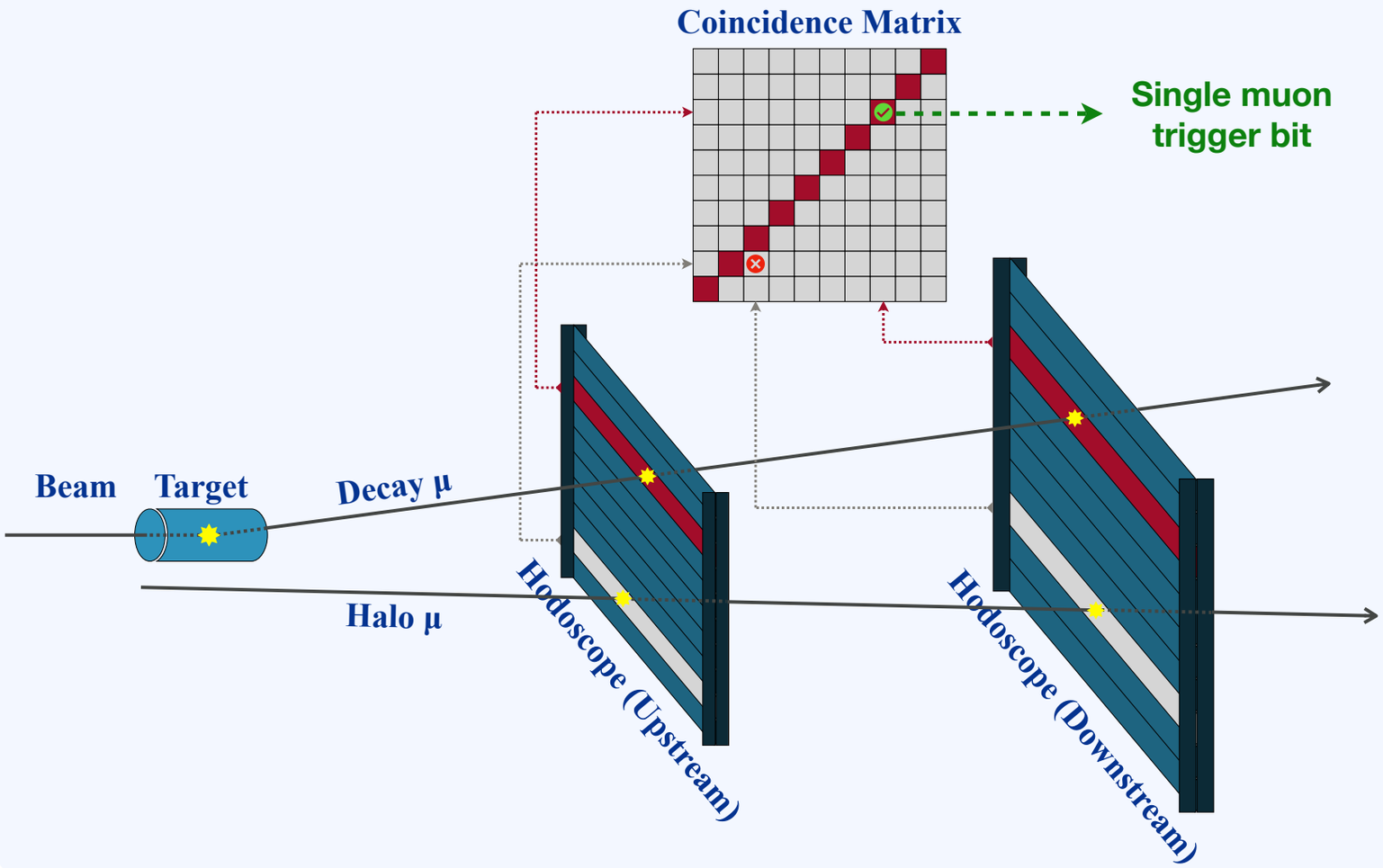


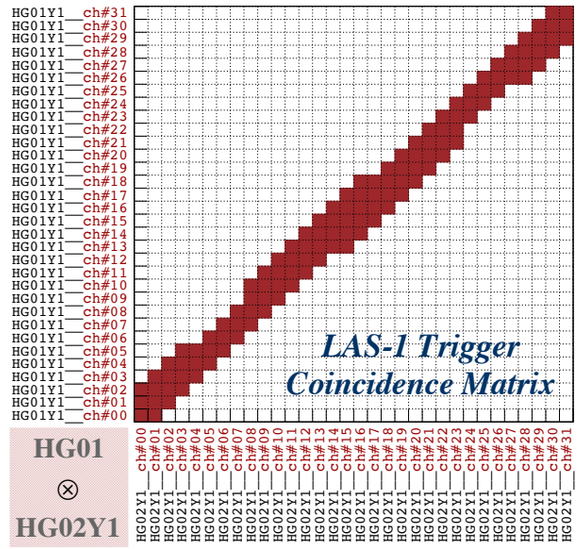
Tracking & Reconstruction

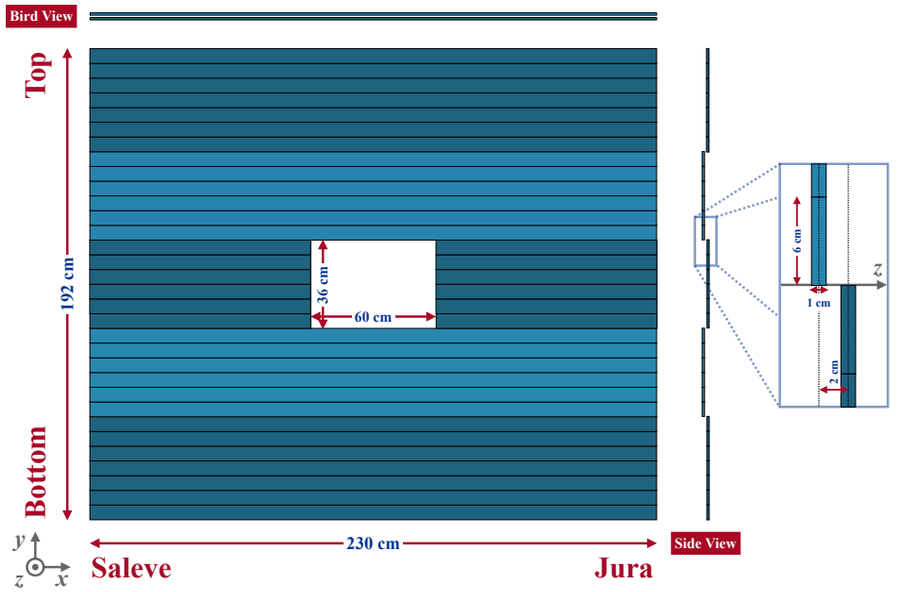




Trigger System

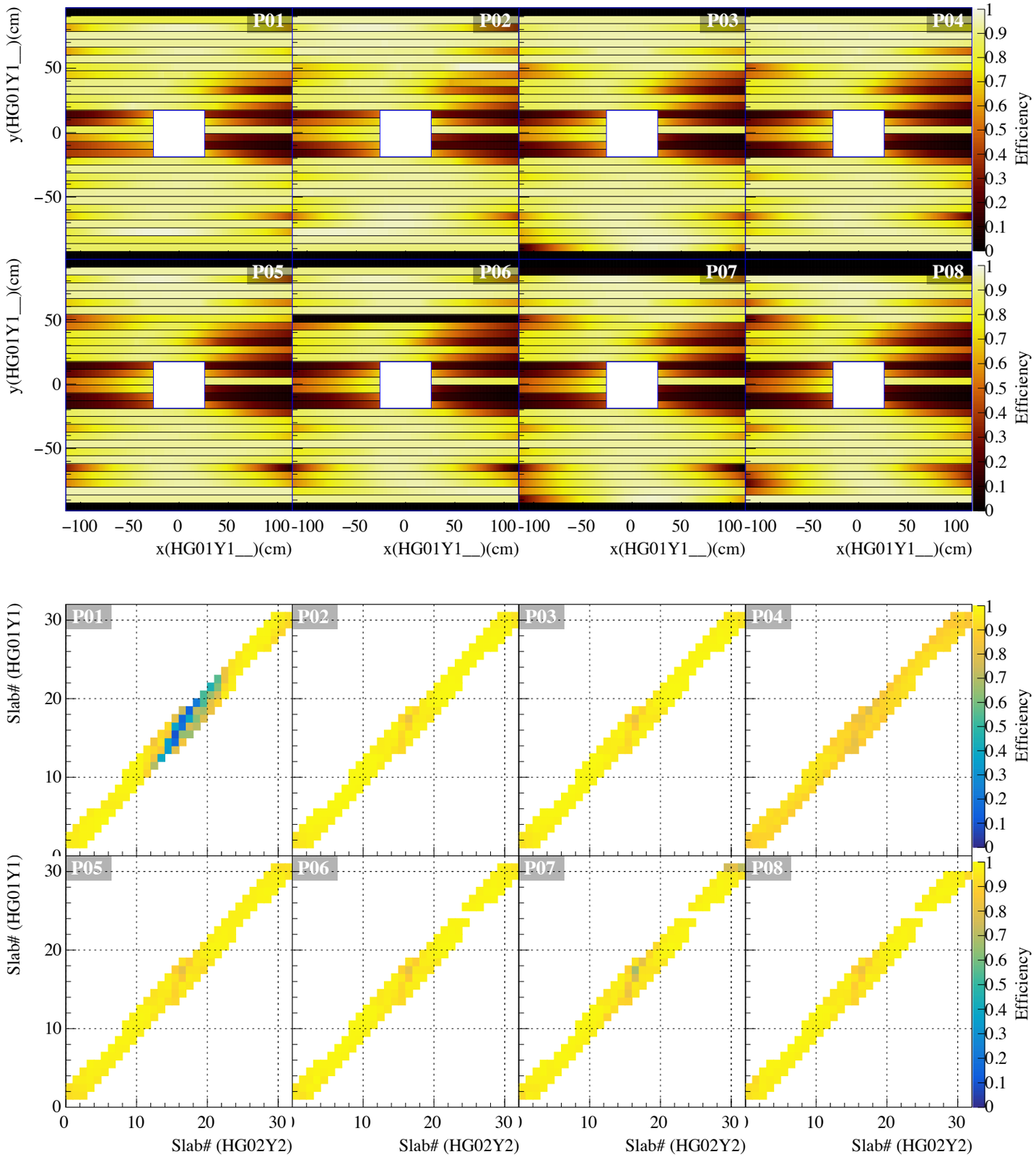






- The combination of two hodoscopes with one coincidence matrix constrain the muon to be produced from the target.
- **Large-Angle Spectrometer region** (**LAS**): 1 upstream plane + 2 downstream planes.
- **Outer trigger (OT)**: 1 upstream plane + 2 downstream planes.

Trigger Efficiencies in Period Dependence

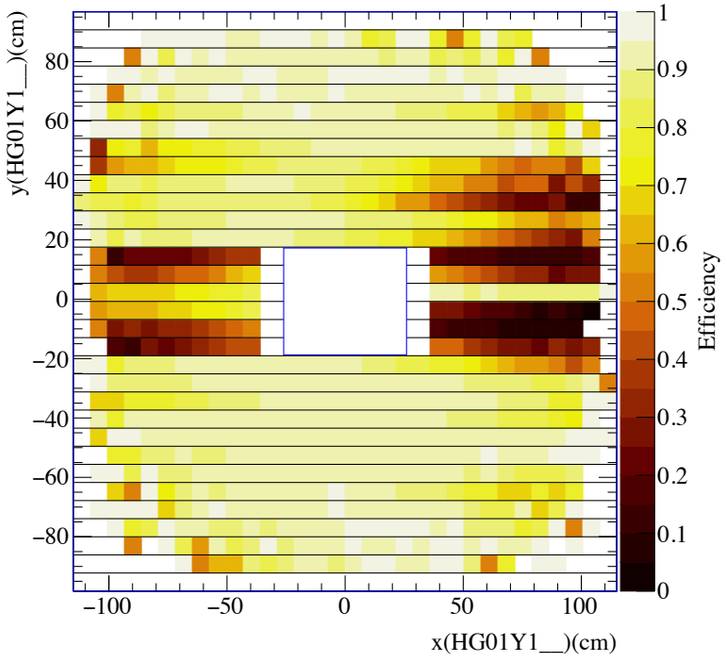


Simple, but time consuming…

- Period-by-period of hodoscopes efficiencies and trigger matrix efficiencies are successfully measured in COMPASS 2018 runs.
- The information is used in period-by-period MC simulation production.

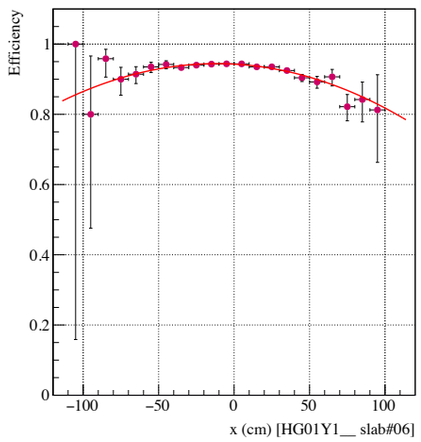
Smoothing Hodoscopes Efficiencies

Hodoscopes Efficiencies (Non-smooth)

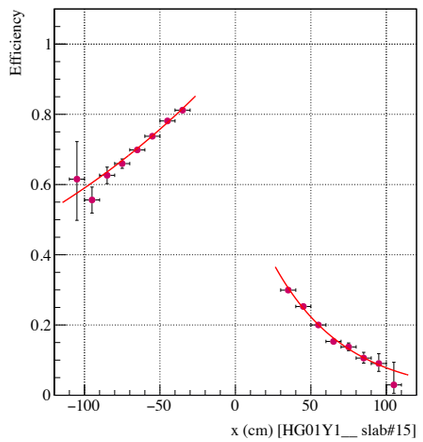


Smoothing (slab-by-slab)

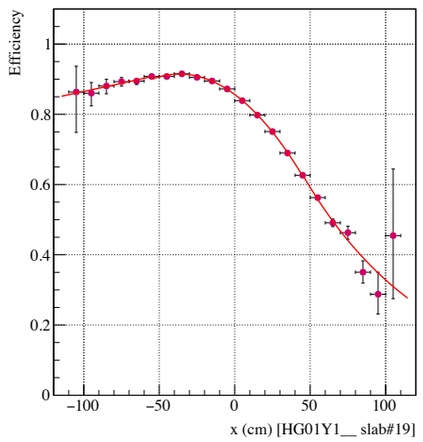
Case 1



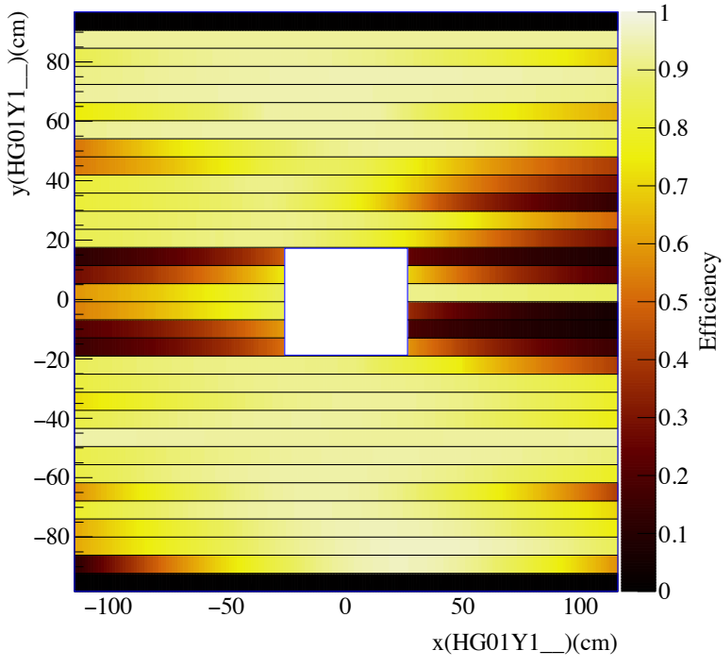
Case 2



Case 3

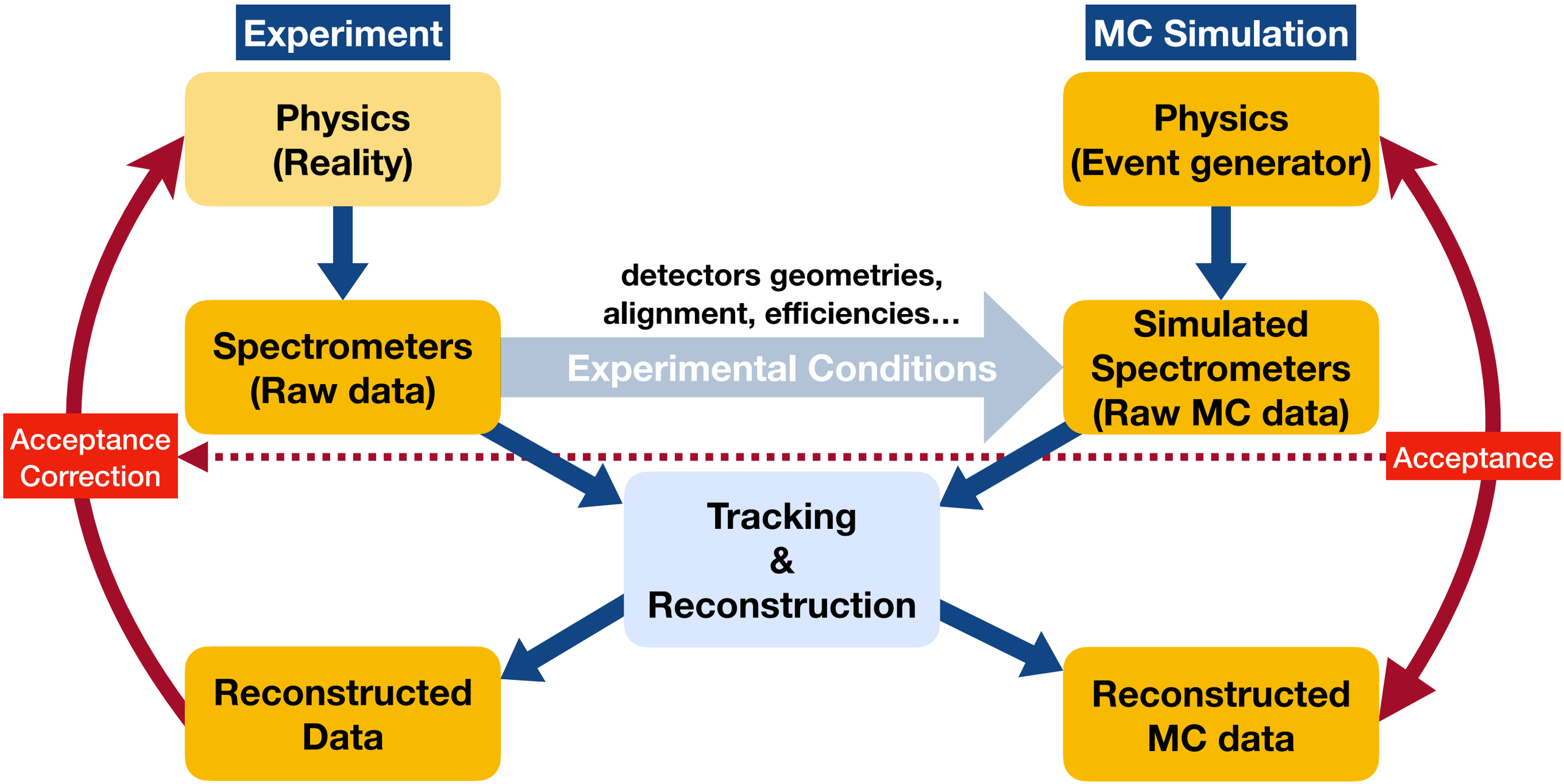


Hodoscopes Efficiencies (Smooth)



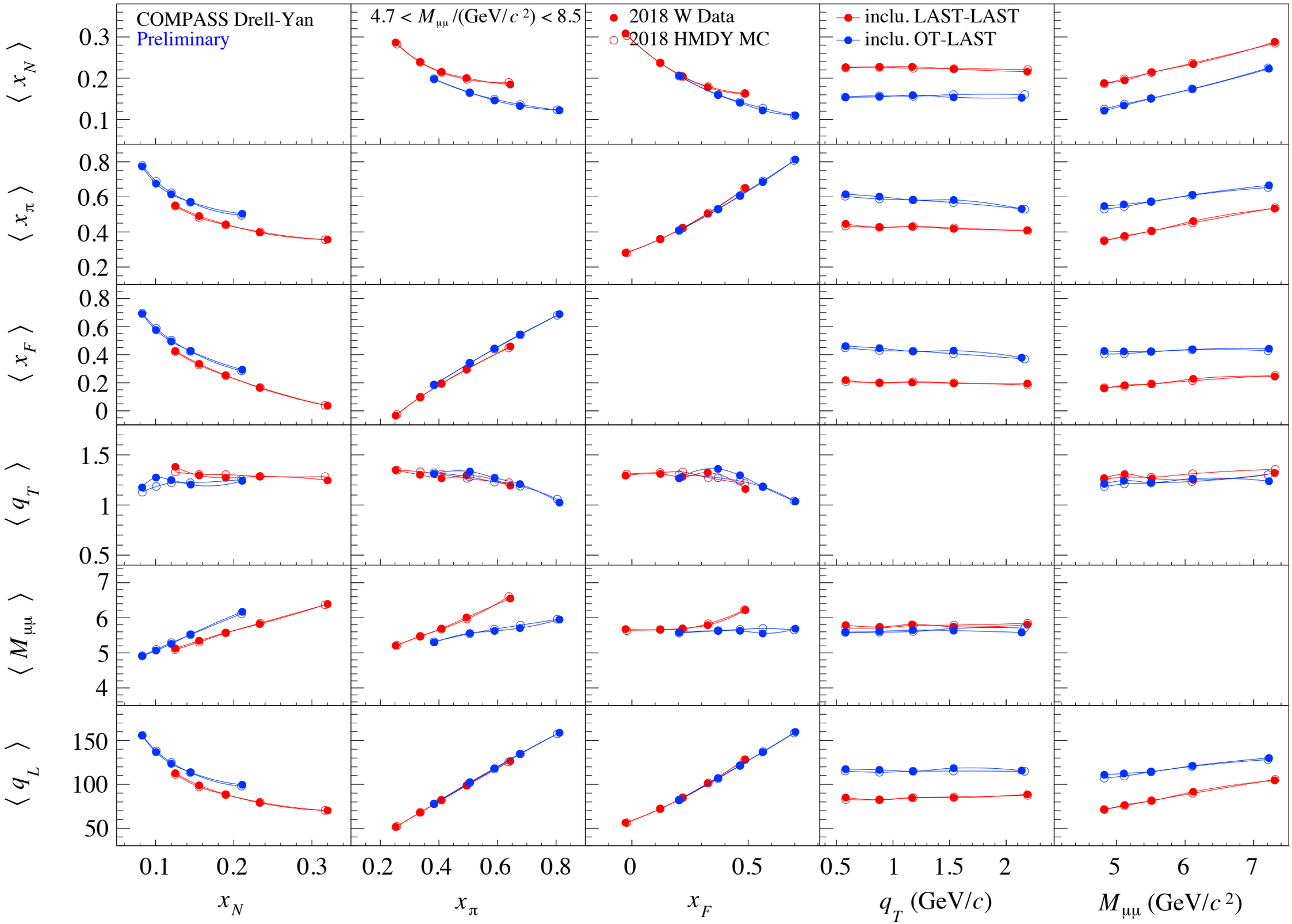
- Due to the lack of statistics, the extracted hodoscopes efficiencies are not smoothed which will cause **significant systematic effect** for the angular analysis.
  ➟ Perform a **smoothing procedure** by fitting with functions slab-by-slab.

Monte-Carlo Simulation (MC)

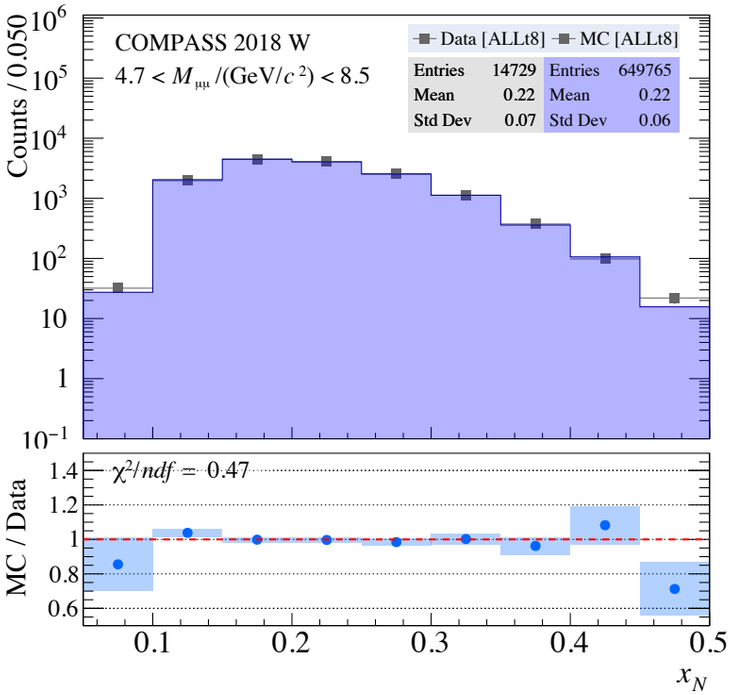


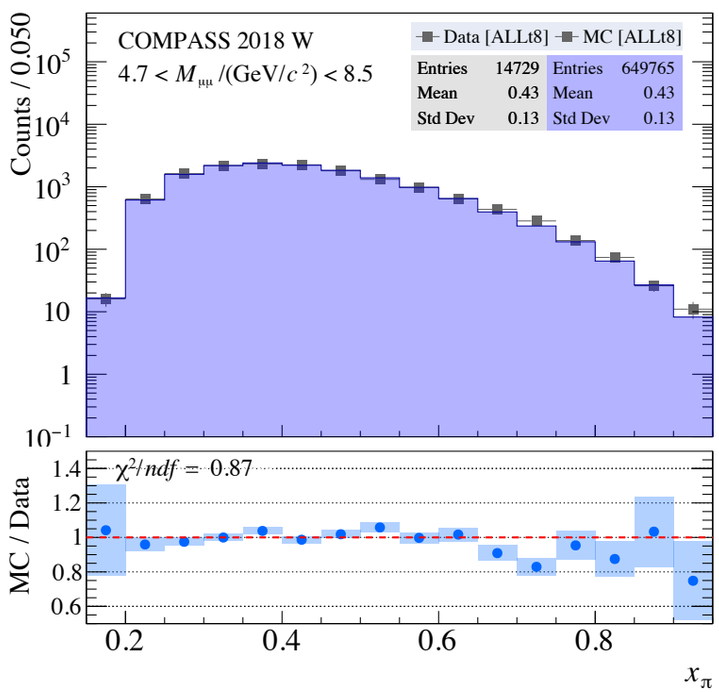
- In order to unfold the physics result, one should do the acceptance correction on reconstructed data where the acceptance is estimated from MC simulation.

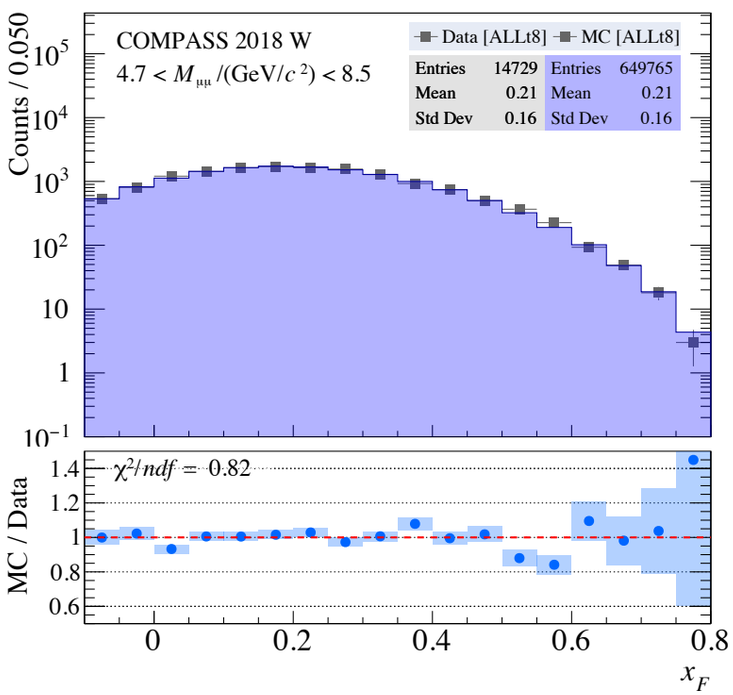
How to Verify MC Simulation?

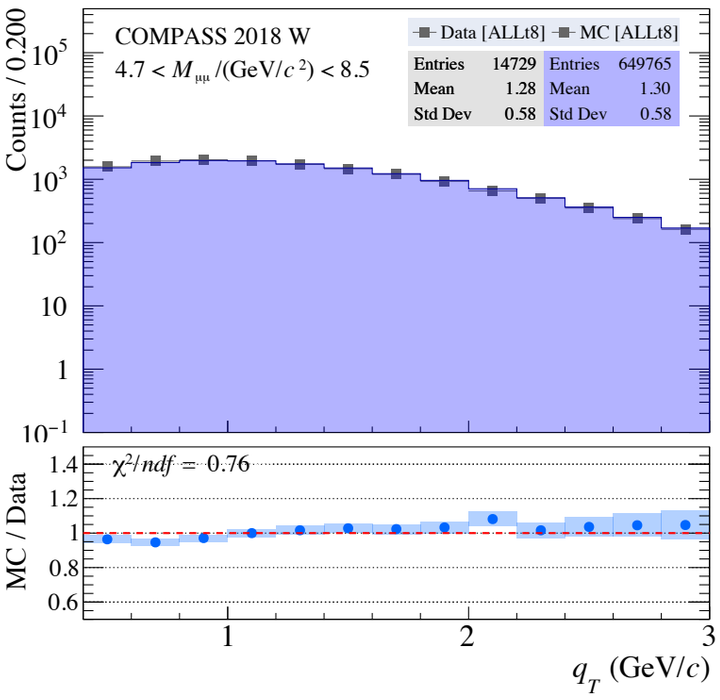


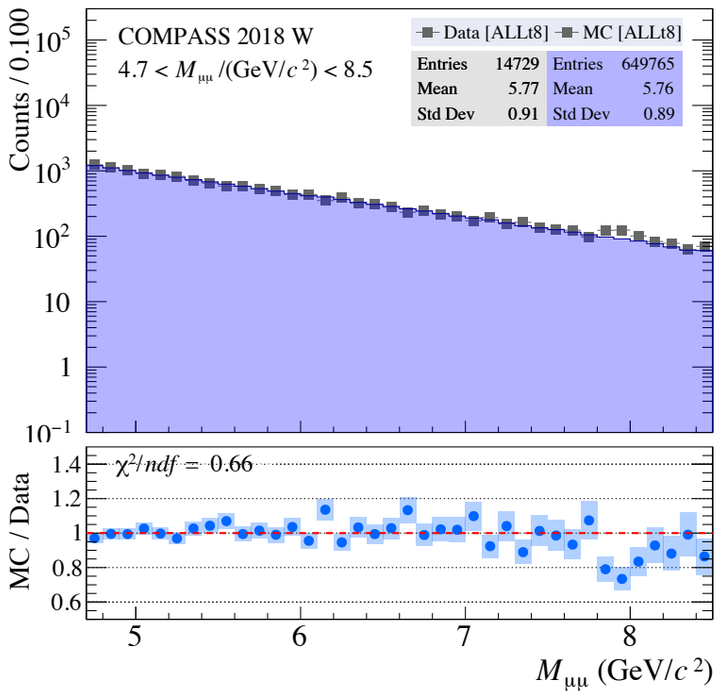
How to Verify MC Simulation?





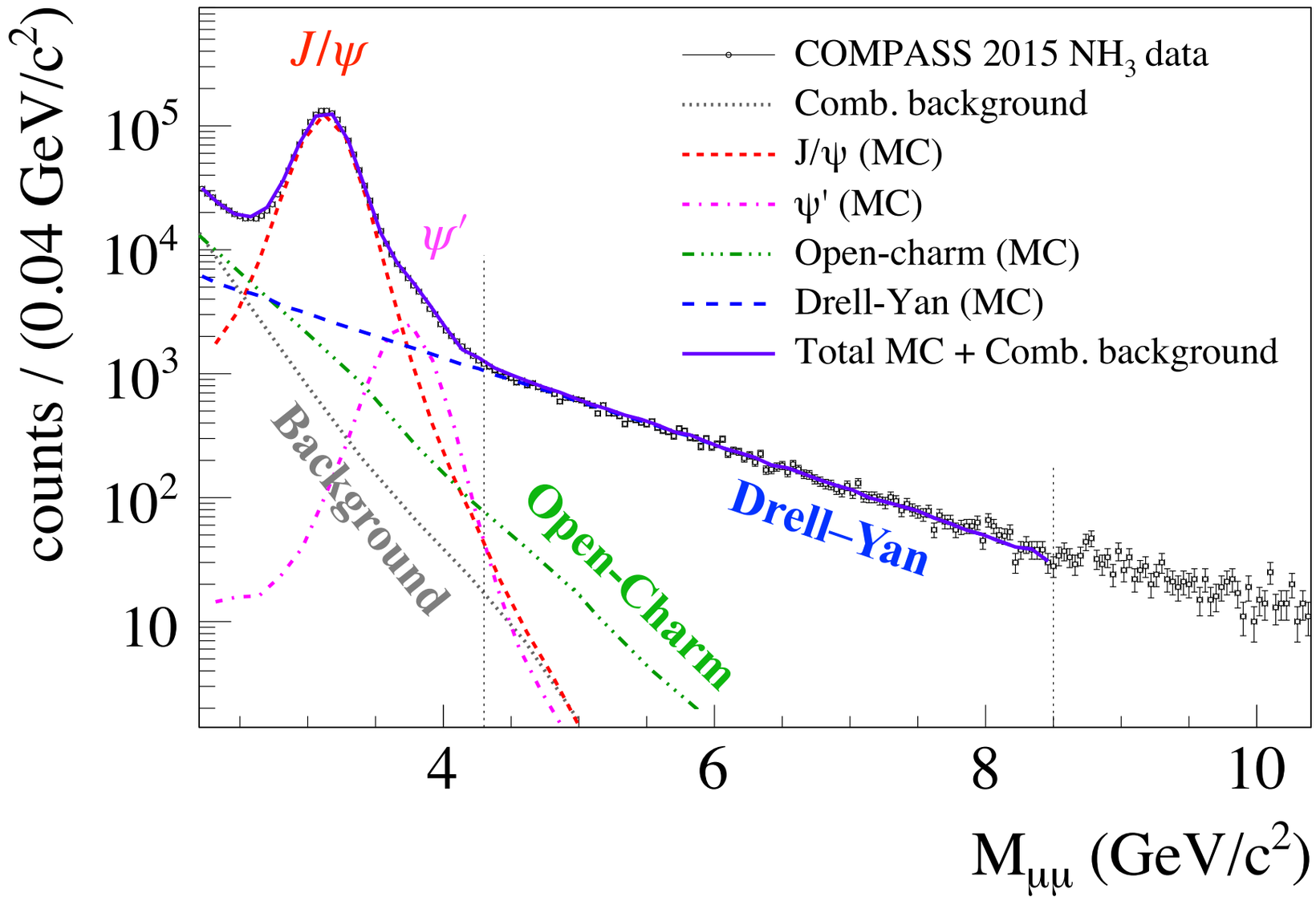






- Target: **W**
- Trigger: **LAST–LAST**
- Good Data/MC agreement in the dimuon kinematics distributions, within 20% deviation.

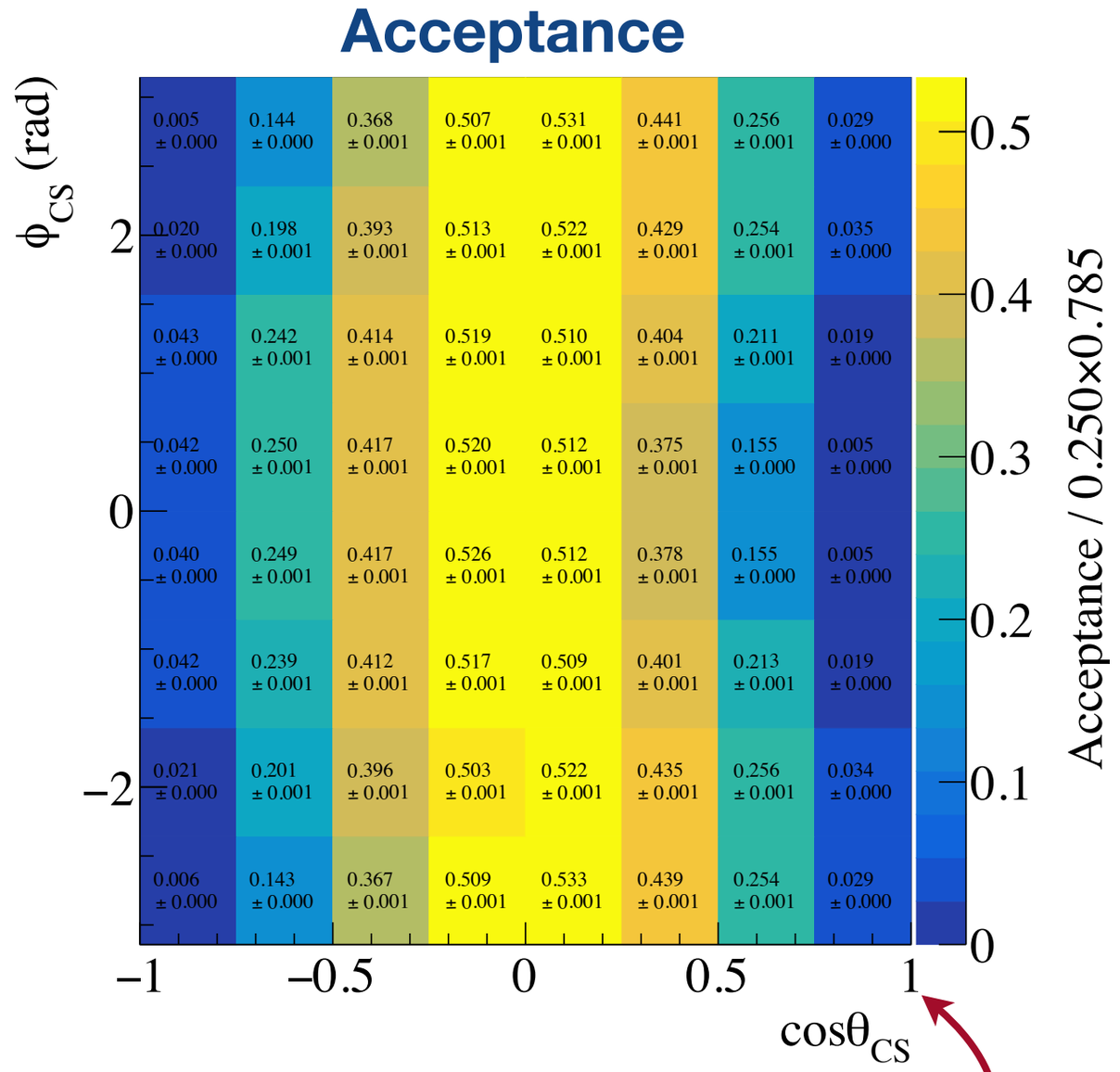
Data Analysis — Background Estimation



- Dimuons produced via **DY process** are mixed with muon pairs from **open-charm**, J/ψ, ψ' channels and **combinatorial background**.
- **96% purity of DY** in the selected mass region is concluded based on MC studies.

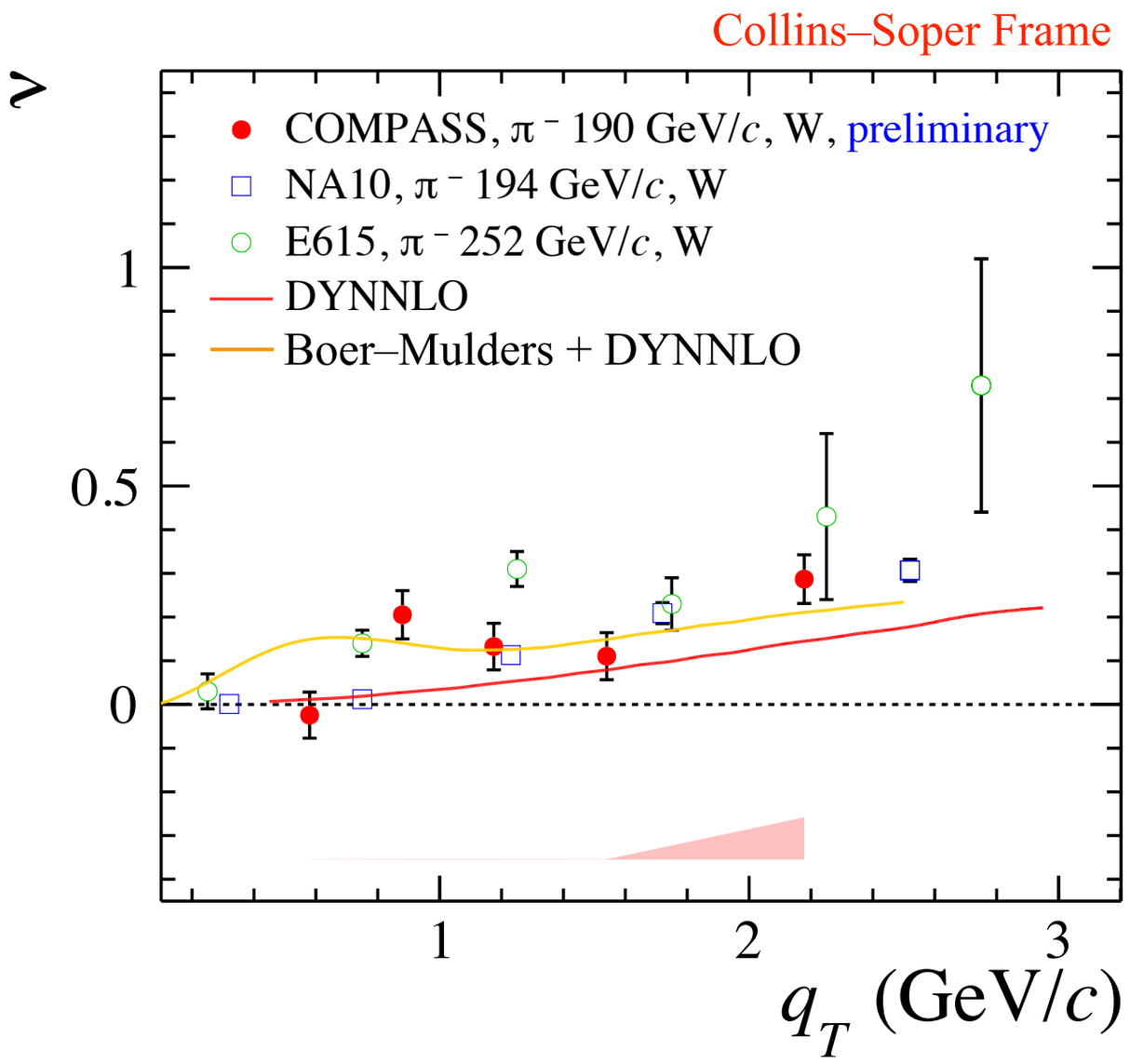
How to Extract Angular Coefficients

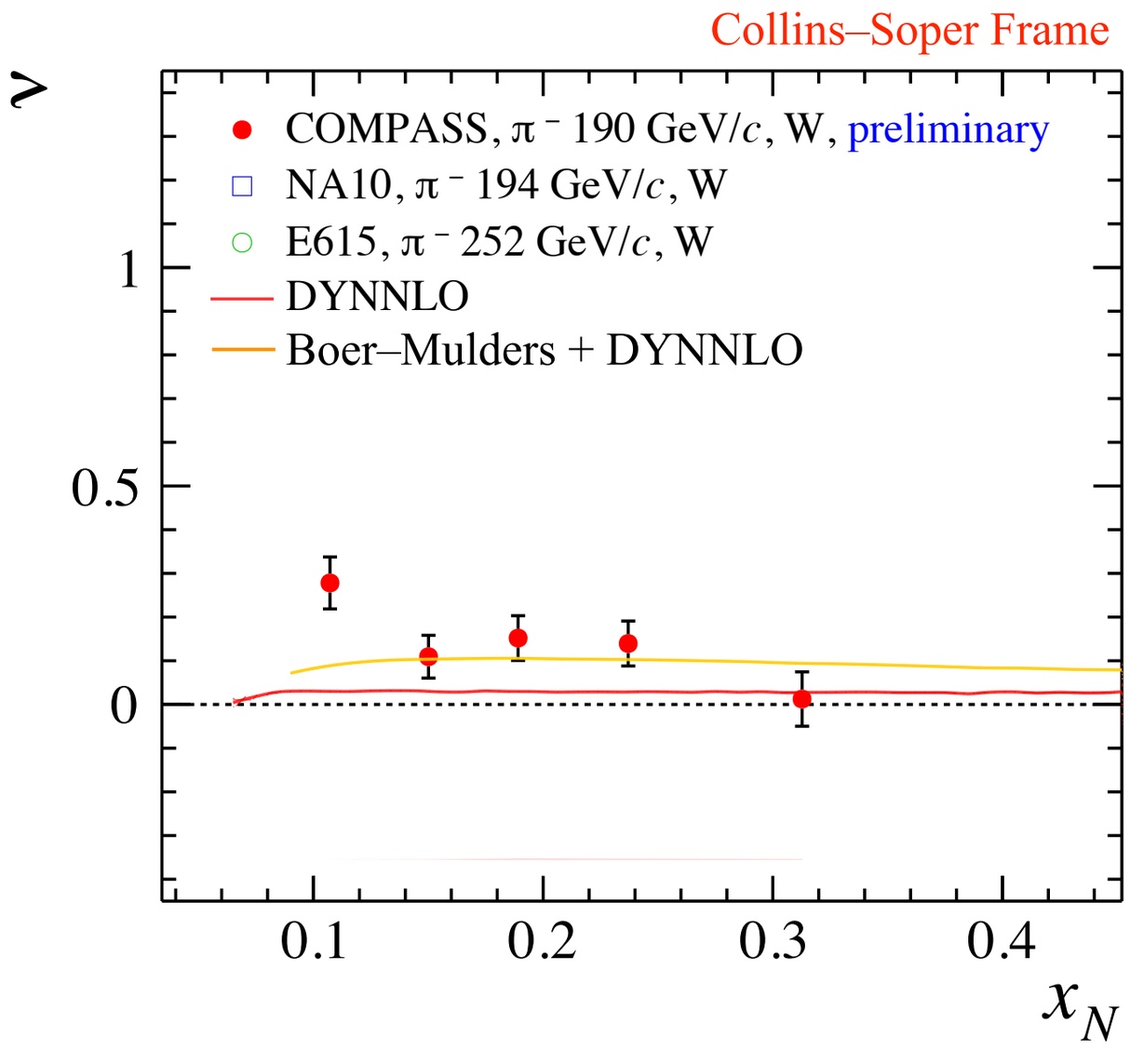
- **Histogram Binned Likelihood fit** (HBL):
  - Data filled into 2D histogram.
  - Acceptance correction $A(\cos\theta, \varphi)$ enter as a **scale factor** bin-by bin without uncertainties.
  - Likelihood Fit (assuming a Poisson probability density function for each bin)
  - Fitting function $f(\cos\theta, \varphi)$ include four free parameters, N_0, λ, μ, ν :



$$f(\cos\theta, \varphi) = N_0\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\varphi + \frac{\nu}{2}\sin^2\theta\cos 2\varphi\right) \otimes A(\cos\theta, \varphi)$$

ν Asymmetry





- The COMPASS preliminary results of DY ν asymmetry from W target is in favor of including both the perturbative QCD effect and also the non-perturbative Boer–Mulders contributions.
- The DY ν asymmetry as function of x_N is also measured by the COMPASS result which is not available in the past pion-induced DY experiments.

Summary

- Due to QCD, there are rich multi-dimensional partonic structure of hadrons.
- In COMPASS experiment, with pion beam, polarized target, hadron absorber, trigger system and MC simulation, we are able to explore the structure of proton.
- The phenomenon of transverse motion of partons was explored via Drell–Yan process by COMPASS experiment. The preliminary results of Drell–Yan angular distributions indicate the presence of TMD Boer-Mulders function.

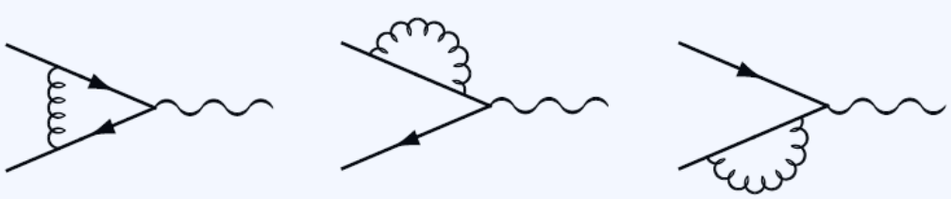
Thank you for your attention!

Back Up

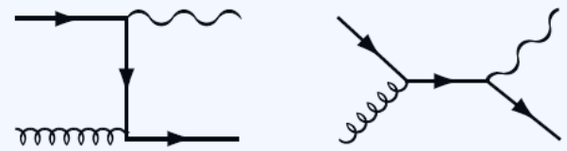
Angular Coefficients

$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta_{CS}+\mu\sin 2\theta_{CS}\cos\varphi_{CS}+\frac{\nu}{2}\sin^2\theta_{CS}\cos 2\varphi_{CS}\right]$$

- The angular coefficients λ, μ, ν are often referred to as **Unpolarized Asymmetries (UAs)**.
- [**LO**] In the naïve DY model, virtual photon is produced by the electromagnetic quark-antiquark annihilation. ($\lambda = 1, \mu = 0, \nu = 0$, because of $\vec{s}_{q,\bar{q}} = \frac{1}{2}$)
- [**NLO**] The **Lam–Tung relation** ($1 - \lambda = 2\nu$) [PRD 18(1978) 2447], valid in NLO(α_s) QCD corrections
  - ➠ **non-zero $\cos 2\varphi$ dependence**.



leading-order(α_s) annihilation diagram

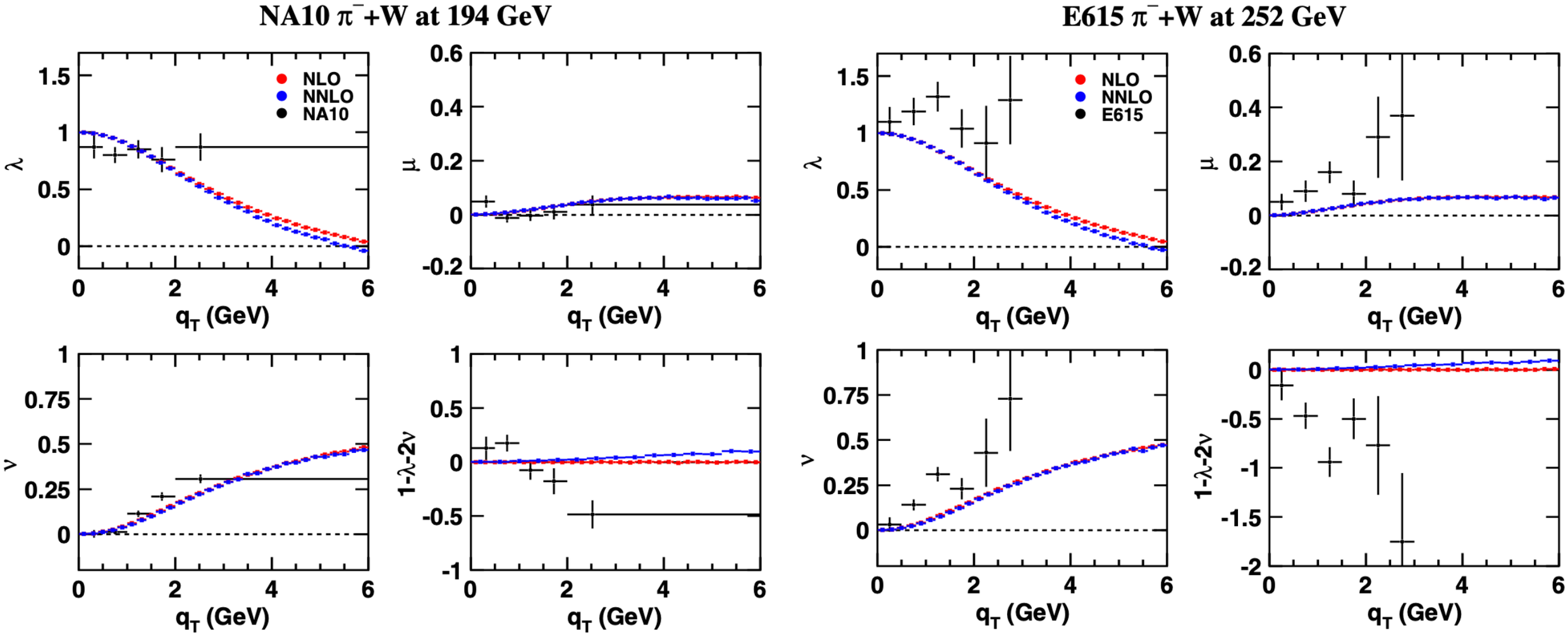


leading-order(α_s)
Compton diagram

Angular Distribution in Pion-induced Drell–Yan

NA10: ZPC 31, 513(1986); E615: PRD 39, 92(1989); W-C. Chang, et.al, PRD 99, 014032 (2019)

- The Lam–Tung relation was found to be **violated** in past **pion-induced** DY experiments.
- Significant discrepancy between **pQCD** calculations and experimentally measured ν as a function of dimuon transverse momentum q_T.

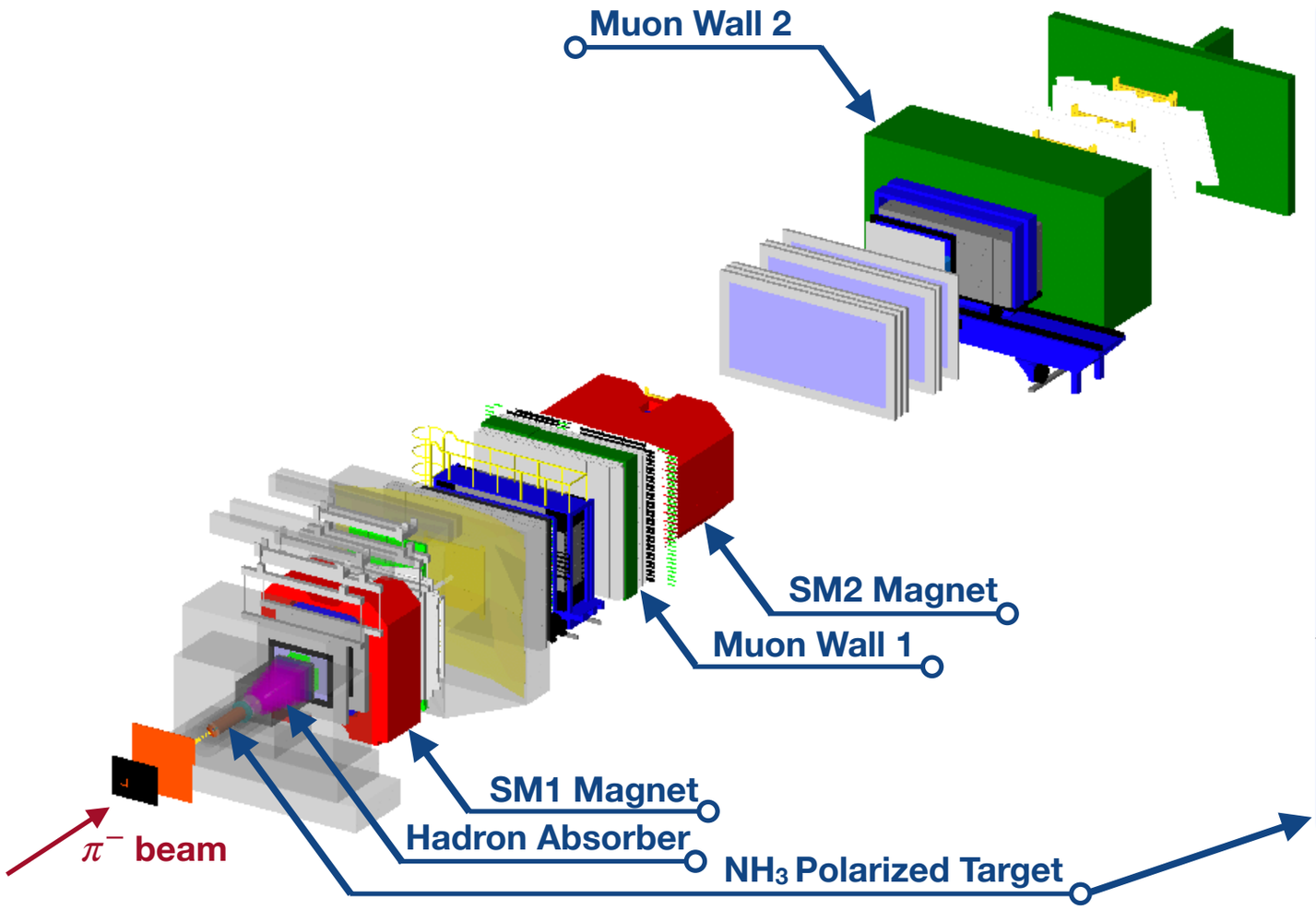


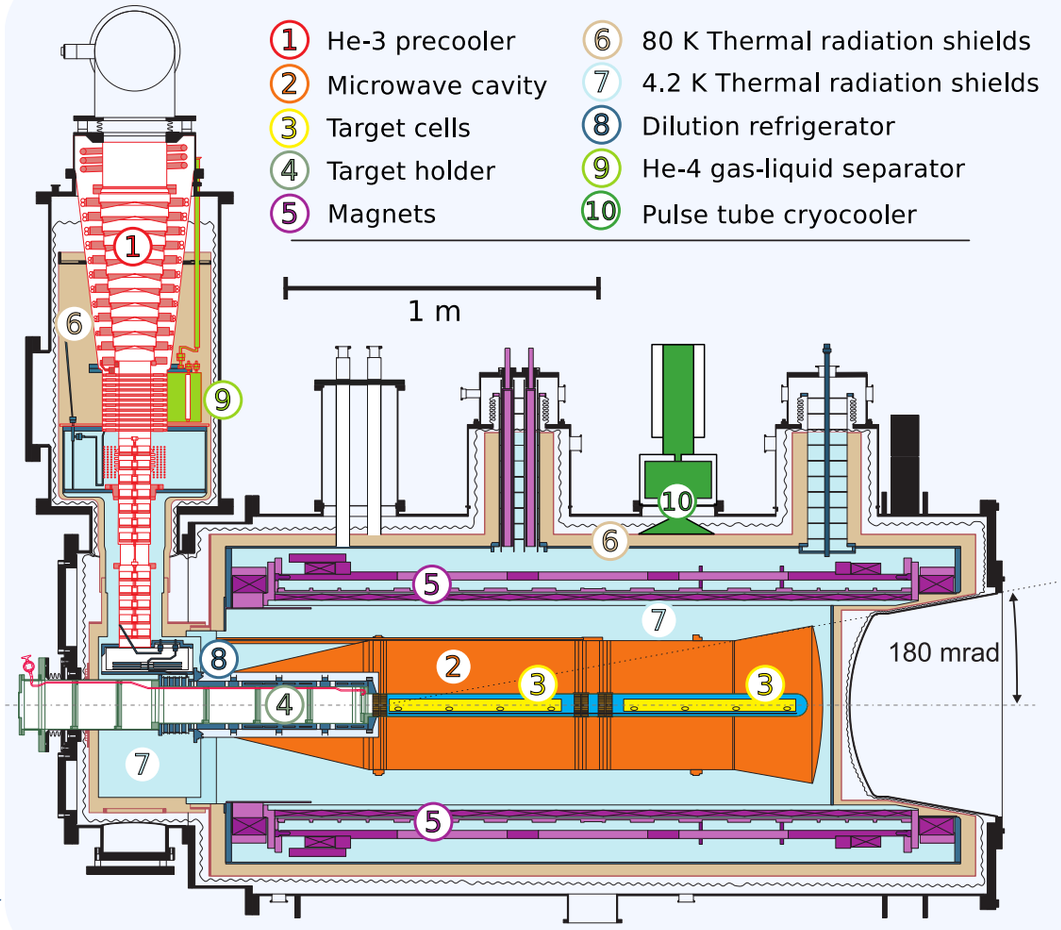
Transverse-Momentum Dependent PDFs

Nucleon Spin / Quark Spin / Quark k_T	Nucleon Polarization: Unpolarized (U)	Nucleon Polarization: Longitudinally polarized (L)	Nucleon Polarization: Transversely polarized (T)
Quark Polarization: U	$f_1^q(x, k_T)$ **Number Density**		$f_{1T}^{q\perp}(x, k_T)$ **Sivers**
Quark Polarization: L		$g_1^q(x, k_T)$ **Helicity**	$g_{1T}^{q\perp}(x, k_T)$ **Worm–Gear T**
Quark Polarization: T	$h_1^{q\perp}(x, k_T)$ **Boer–Mulders**	$h_{1L}^{q\perp}(x, k_T)$ **Worm–Gear L**	$h_{1T}^q(x, k_T)$ **Transversity**; $h_{1T}^{q\perp}(x, k_T)$ **Pretzelosity**

- The TMD PDFs are sorted according to the nucleon polarization and individual polarization of partons.

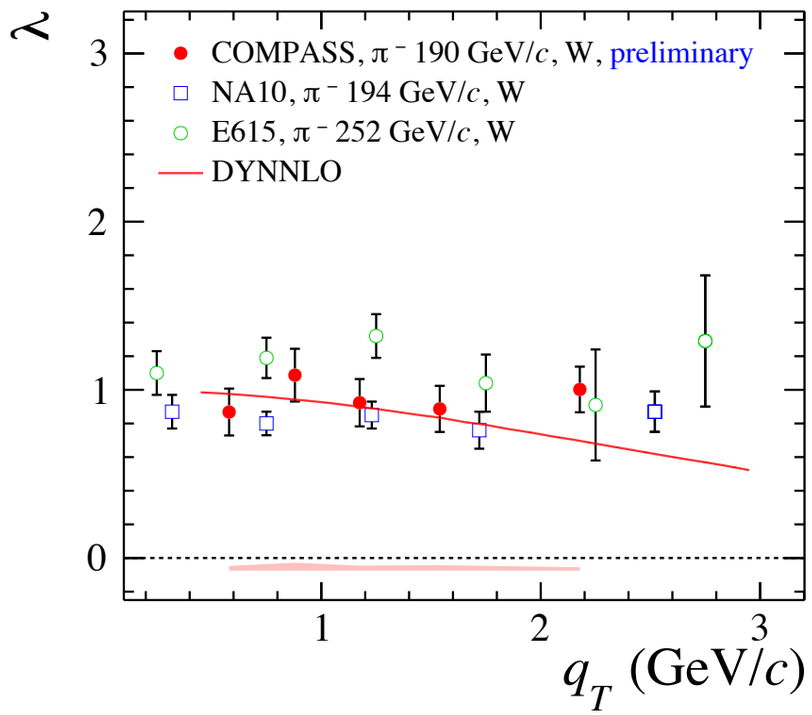
Drell-Yan Program in COMPASS

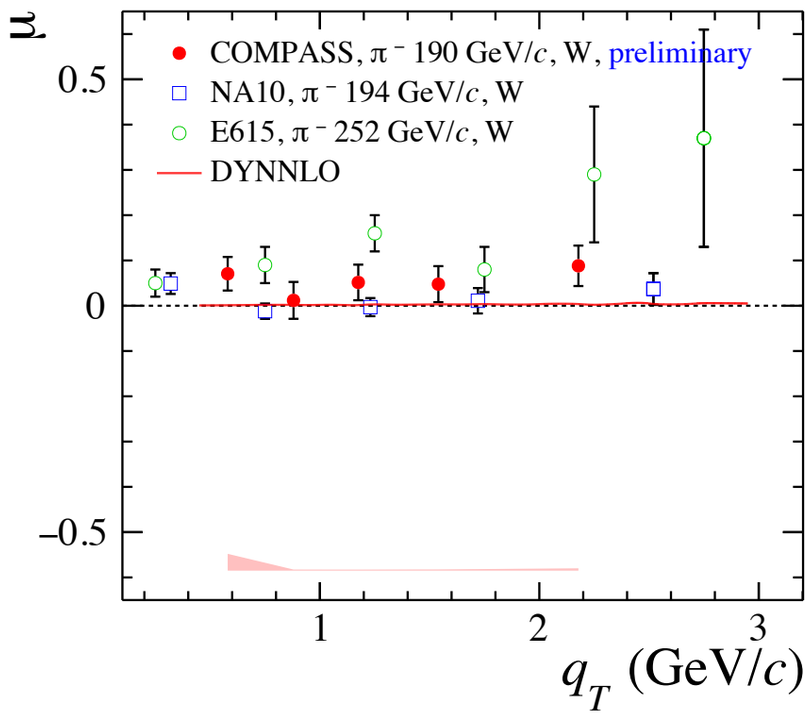


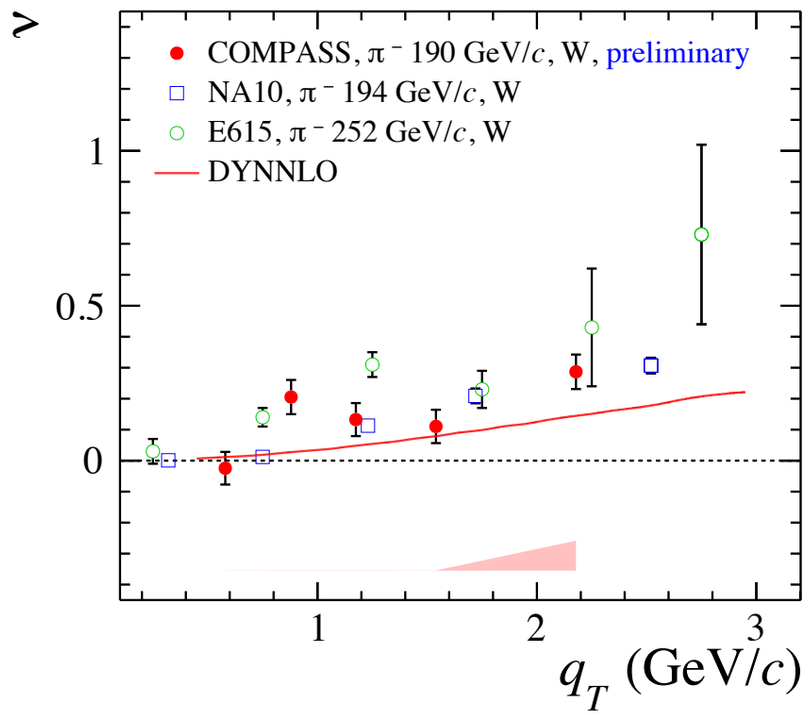


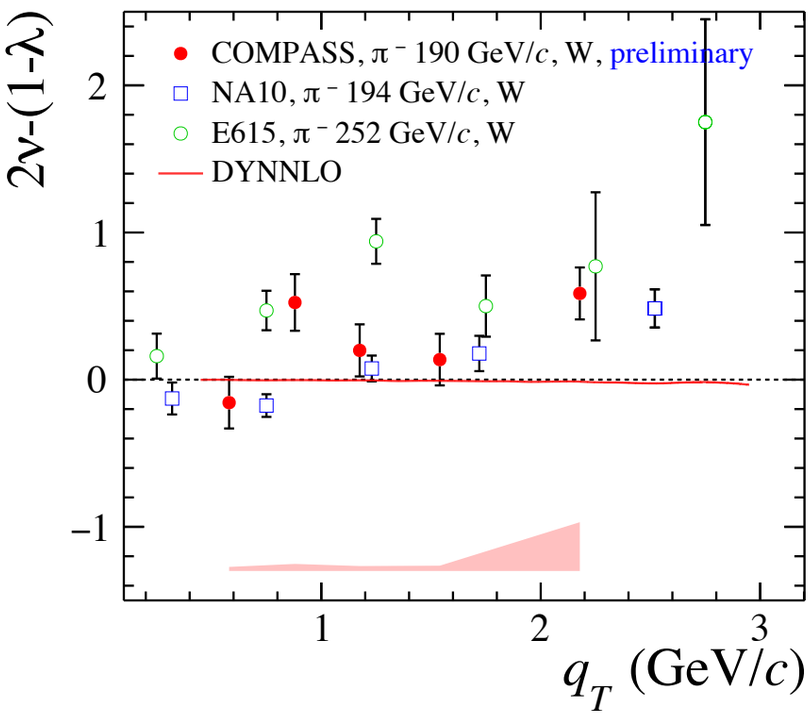
- First ever polarized DY measurements were performed by COMPASS in 2015 and 2018.
- π^- beam at **190 GeV/c** with average beam intensity **7×10^7 s^{-1}** from **CERN SPS M2 beam line**.
- **Transversely polarized NH_3 target cells** (55+55 cm) + **Al target** (7 cm) + **W beam plug** (120 cm)

Compare with Old Experiments









Collins–Soper Frame

Experiment	**COMPASS**	**COMPASS**	**NA10**	**E615**
Interaction	$\pi^- + NH_3$	$\pi^- + W$	$\pi^- + W$	$\pi^- + W$
Beam Energy	190 GeV/c	190 GeV/c	194 GeV/c	252 GeV/c
$\langle\lambda\rangle$	0.89 ± 0.06	0.89 ± 0.06	0.83 ± 0.04	1.17 ± 0.06
$\langle\mu\rangle$	-0.03 ± 0.02	-0.06 ± 0.02	0.008 ± 0.010	0.09 ± 0.02
$\langle\nu\rangle$	0.24 ± 0.02	0.14 ± 0.02	0.091 ± 0.009	0.169 ± 0.019
$\langle 2\nu - (1-\lambda)\rangle$	0.39 ± 0.07	0.21 ± 0.08	0.01 ± 0.04	0.51 ± 0.07
x_1 range	$0.2 \rightarrow 0.9$	$0.2 \rightarrow 0.9$	$0.2 \rightarrow 1.0$	$0.2 \rightarrow 1.0$
x_2 range	$0.05 \rightarrow 0.5$	$0.05 \rightarrow 0.5$	$0.1 \rightarrow 0.4$	$0.04 \rightarrow 0.38$

Estimation of Systematic Uncertainties

Included in the final systematic uncertainties

- Compatibility of the results obtained from different periods.
- Compatibility of the results obtained from different target cells.
- Compatibility of the results obtained from different trigger priority.

No systematic effect observed

- Systematic of different q_T cut.
- Systematic of different x_F cut.
- Systematic of different θ_{μ^-} cut.
- Systematic of different bin size of two-dimensional angular histogram.
- Systematic of different dead zone cut.
- Impact of different MC-generator settings.