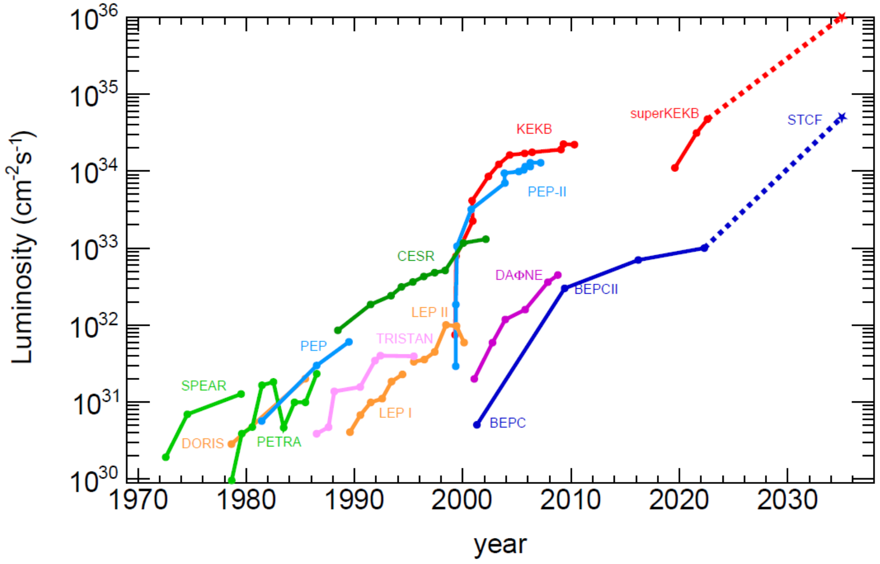
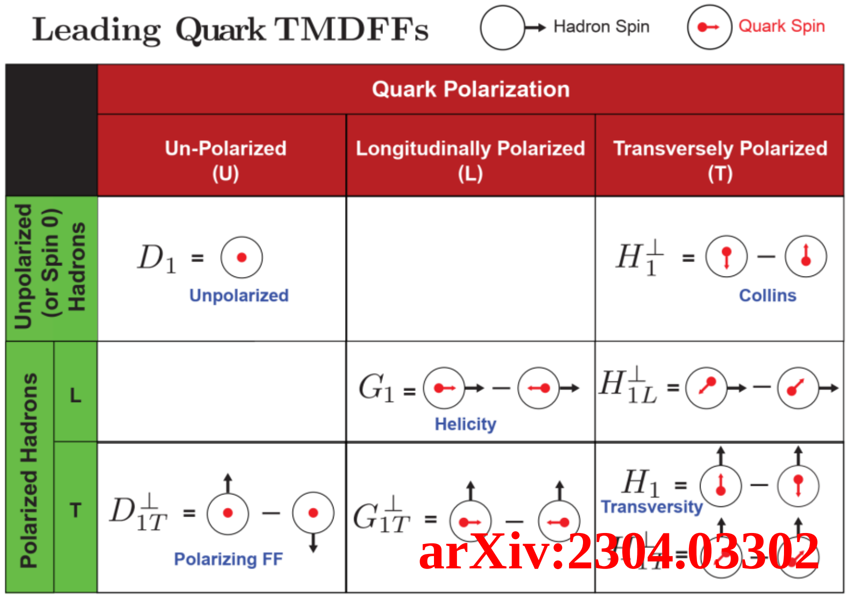
Inclusive hadron production at BESIII

鄢文标(中国科学技术大学)

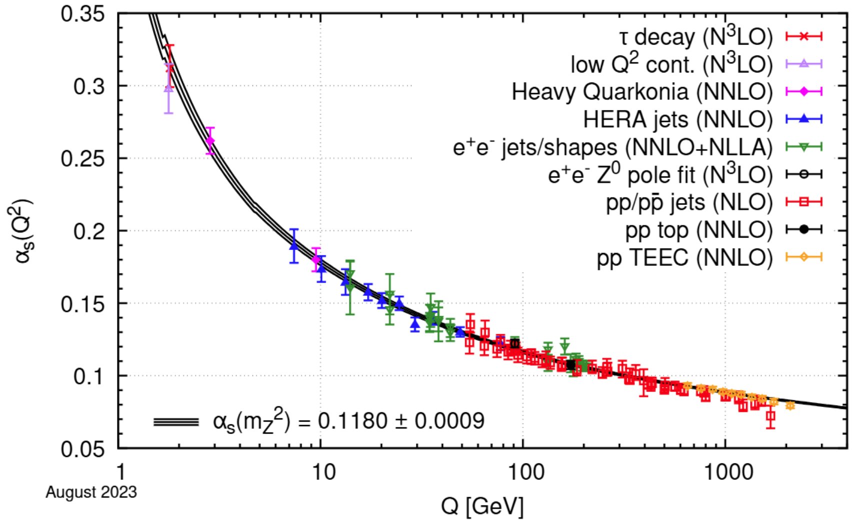


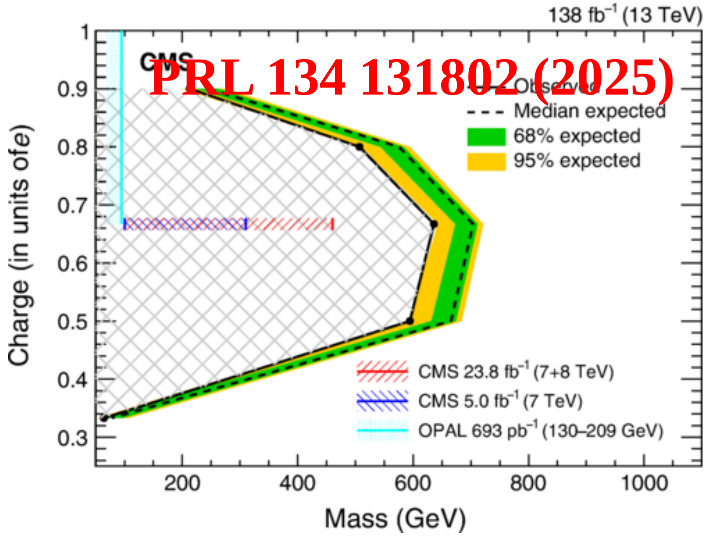


arXiv:2304.03302

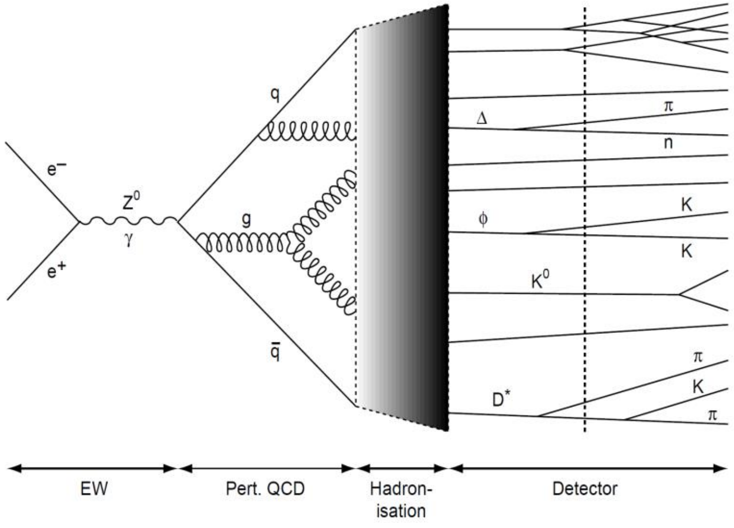
第七届全国重味物理与量子色动力学研讨会，2025.04.19，南京

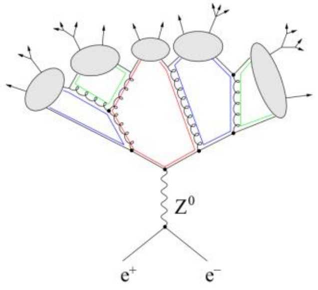
QCD: Asymptotic freedom & Confinement



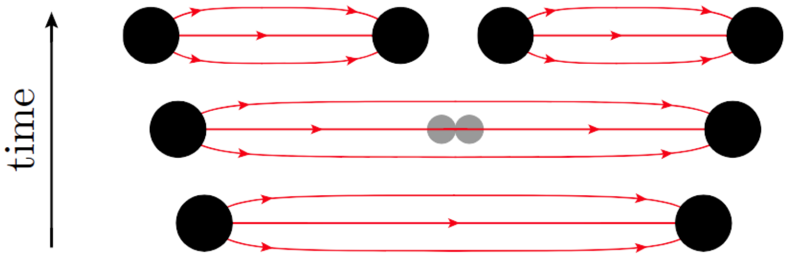


PRL 134 131802 (2025)



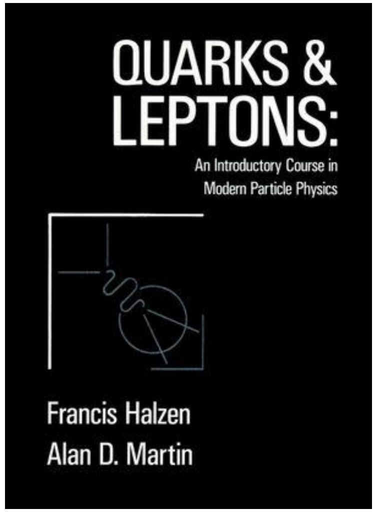


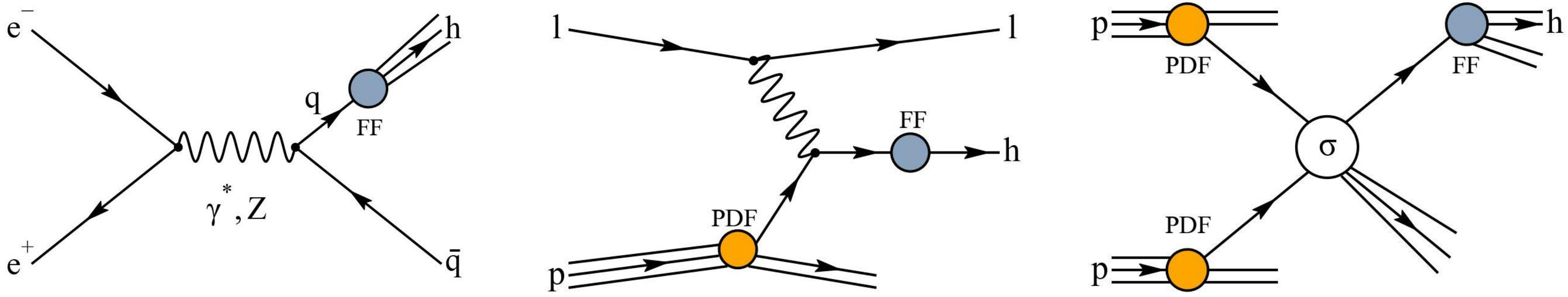
- **QCD coupling constant $\alpha_s(Q)$**
  - ✓ **High Q: asymptotic freedom, perturbative QCD**
  - ✓ **Low Q: non-perturbative QCD**
- **Confinement: partons do not exist as free particles, but are always confined in hadron**
- **Essence of confinement ? Why & how ?**
  - ✓ **Hadronization models & Fragmentation function**
  - ✓ **LPHD: Local Parton Hadron Duality hypothesis**



Fragmentation function: integrated $D_1^h(z)$

- Fragmentation function $D_q^h(z)$: probability that hadron h is found in the debris of a parton carrying a fraction z of parton's energy
- Consequence of confinement
- FF: QCD first principle (NOT YET)
  - ✓ FF evolution function: DGLAP
  - ✓ Fitting: parametrization & experimental data
  - ✓ Universality: e^+e^-, DIS, pp, $p\bar{p}$ data
- FFs contribute to virtually all processes





FFs with quark/hadron polarization

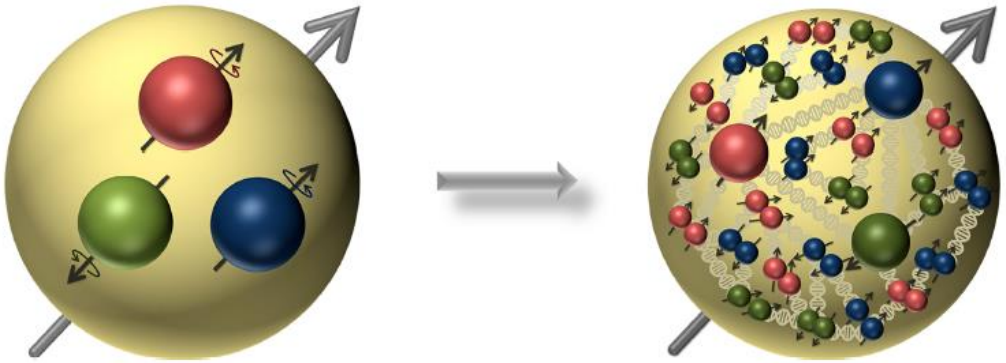
Hadron polarization	Quark polarizatiom @ PPNP 91 136 (2016)		
	Unpolarized	Longitudinally	Transversely
Unpolarized	D_1^h		$H_1^{\perp h}$
Longitudinally		G_1^h	$H_{1L}^{\perp h}$
Transversely	$D_{1T}^{\perp h}$	G_{1T}^h	H_1^h $H_{1T}^{\perp h}$

PLB396 (1993) 161

$$D_{hq^\uparrow}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2)\frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{zM_h}$$

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

FFs for EIC & EicC



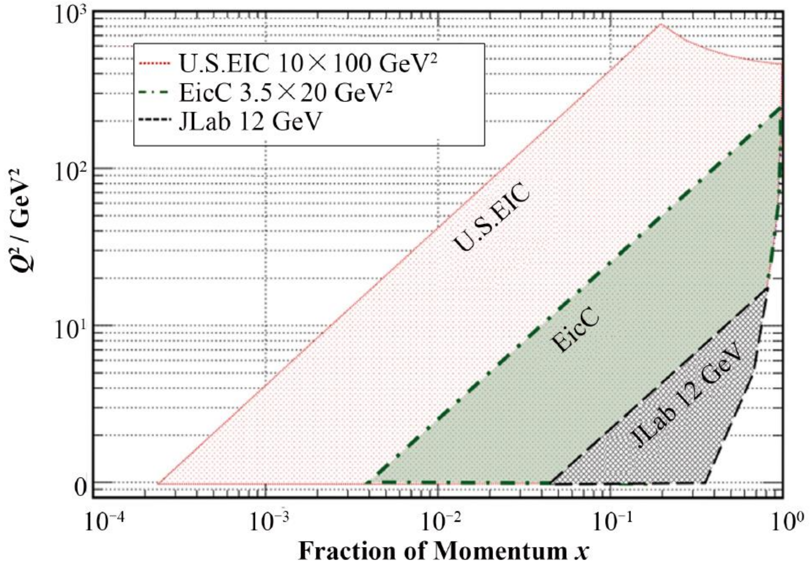
Preprints: JLAB-THY-23-3780, LA-UR-21-20798, MIT-CTP/5386

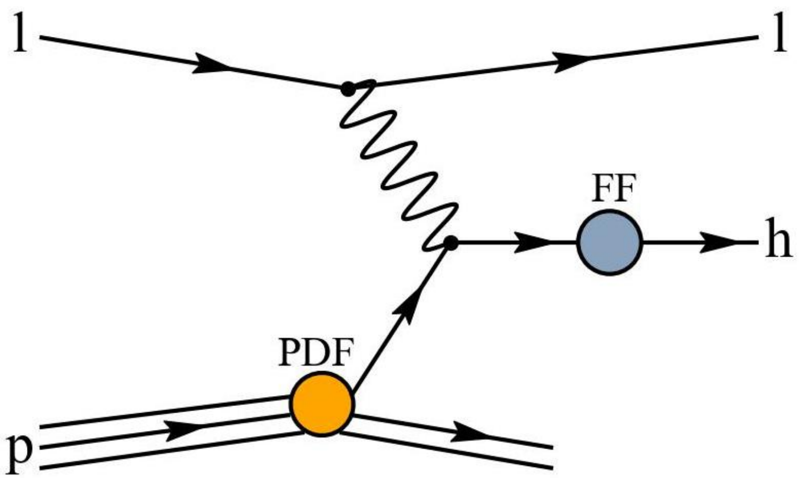
arXiv:2304.03302

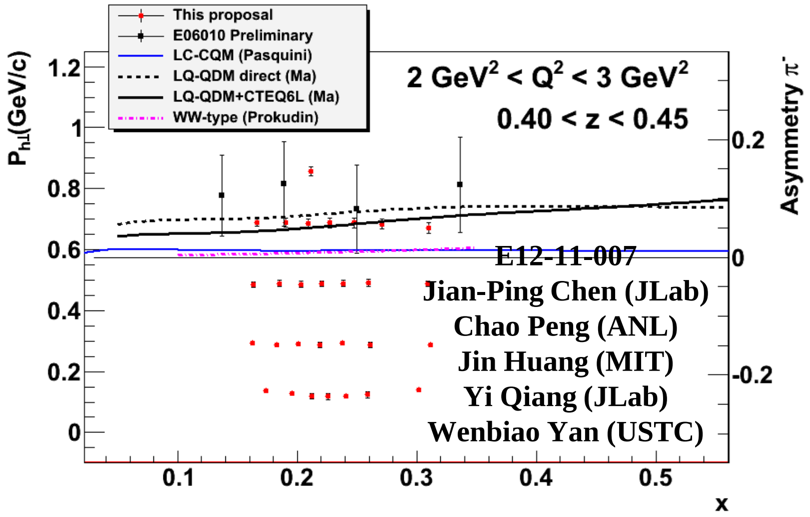
TMD Collaboration

TMD Handbook

Renaud Boussarie[1], Matthias Burkardt[2], Martha Constantinou[3], William Detmold[4], Markus Ebert[4,5], Michael Engelhardt[2], Sean Fleming[6], Leonard Gamberg[7], Xiangdong Ji[8], Zhong-Bo Kang[9], Christopher Lee[10], Keh-Fei Liu[11], Simonetta Liuti[12], Thomas Mehen[13], Andreas Metz[3], John Negele[4], Daniel Pitonyak[14], Alexei Prokudin[7,16], Jian-Wei Qiu[16,17], Abha Rajan[12,18], Marc Schlegel[2,19], Phiala Shanahan[4], Peter Schweitzer[20], Iain W. Stewart[4], Andrey Tarasov[21,22], Raju Venugopalan[18], Ivan Vitev[10], Feng Yuan[23], Yong Zhao[24,4,18]

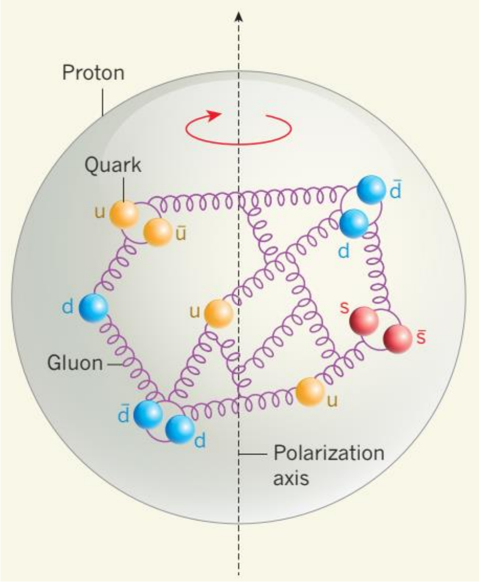


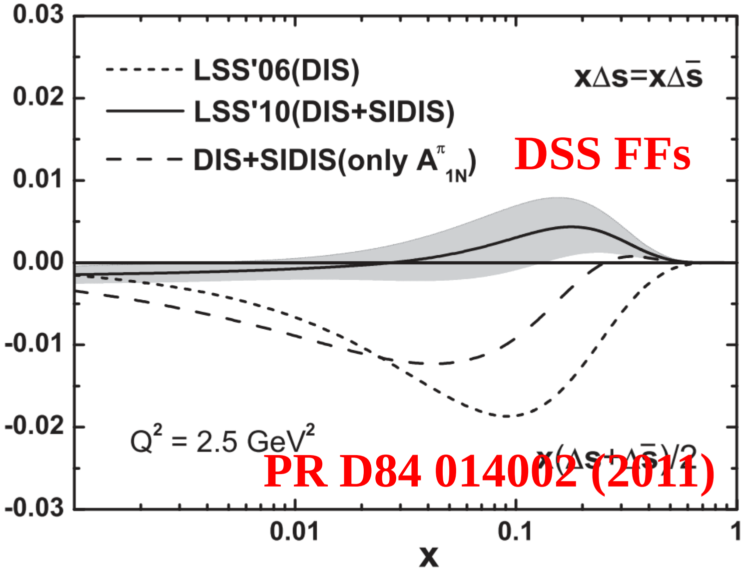


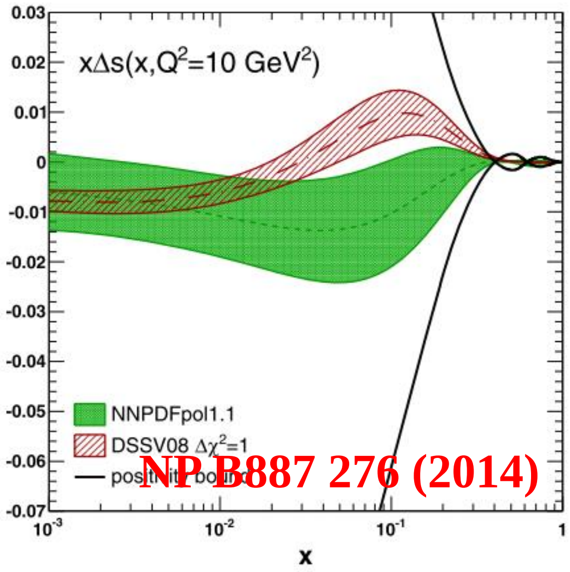


Precise knowledge of FFs will be crucial

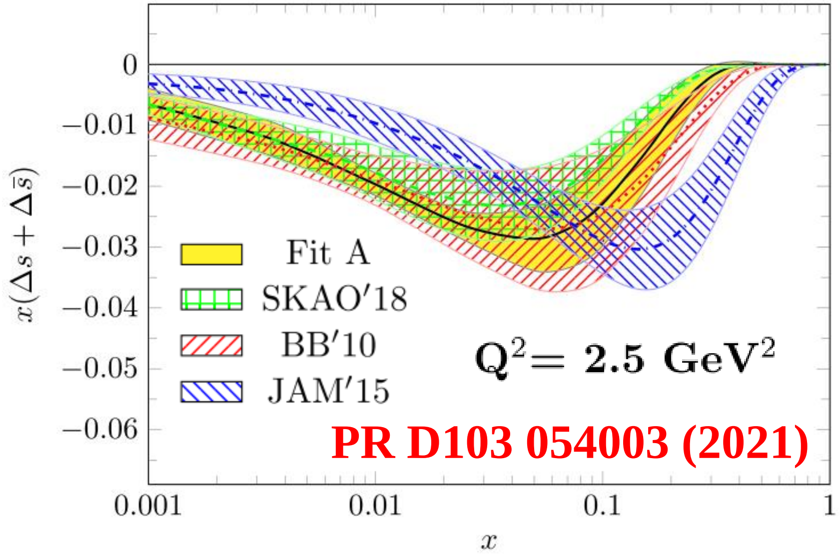
Strange quark polarization puzzle



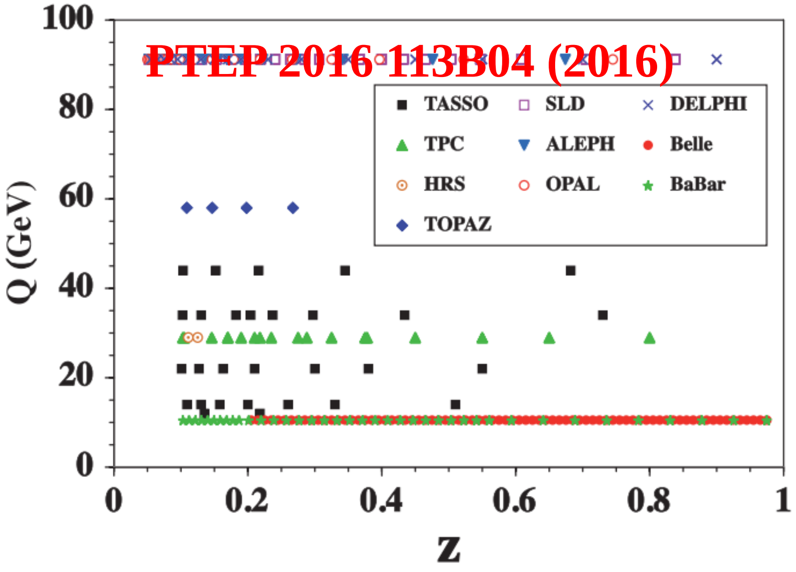




- Strange quark density function: $\Delta s(x)+\Delta\bar{s}(x)$
  - ✓ Inclusive DIS: only proton PDF
    - a. negative for all values of x
  - ✓ Semi-inclusive DIS: proton PDF & kaon FF
    - a. DSS FFs: positive for most of measured x
    - b. NNPDF FF: negative
    - c. JAM FFs: negative
- Reliable FFs knowledge ? Need more efforts



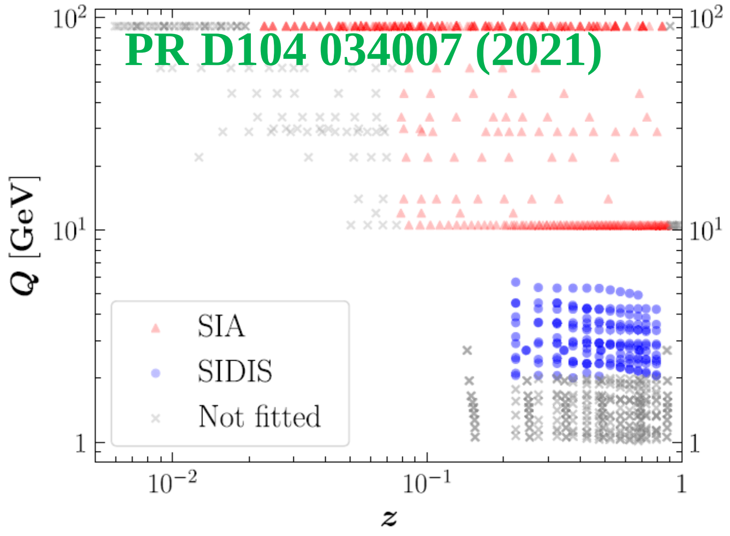
Used data set @ unpolarized FFs fitting



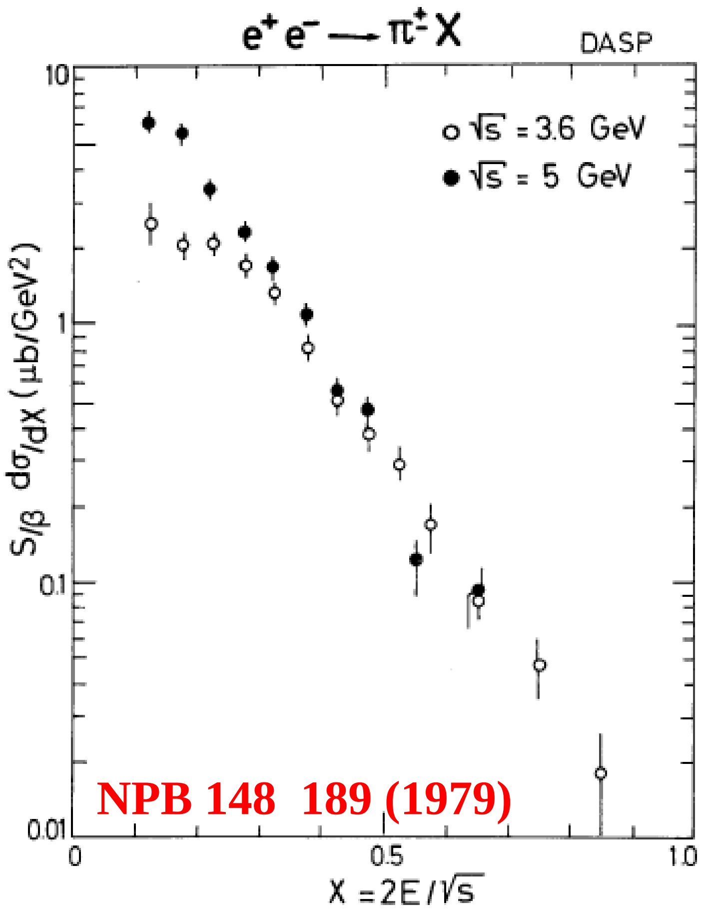
PPNP 91 136 (2016)

Experiment	Process	$\mathcal{L}[pb^{-1}]$	$Q^2[GeV^2]$	Final states
TPC [288–291]	e^+e^-	140	29	$\pi^\pm, K^\pm, p/\bar{p}$
TASSO [292–294]	e^+e^-	34	34,44	$\pi^\pm, K^\pm, p/\bar{p}, K^0_S, \Lambda/\bar{\Lambda}$
[295–298]				
SLD [299,300]	e^+e^-	20	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
ALEPH [301,302]	e^+e^-	800	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
DELPHI [303–306]	e^+e^-	800	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
OPAL [307–310]	e^+e^-	800	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
H1 [311–313]	$e+p$	500	$27.5(e)+920(p)$	$h^\pm, K^S_0$
ZEUS [314–316]	$e+p$	500	$27.5(e)+920(p)$	$h^\pm$
BELLE [317,318]	e^+e^-	10^6	Near 10.58	$\pi^\pm, K^\pm, p/\bar{p}$
BaBar [319,320]	e^+e^-	$557 \cdot 10^3$	Near 10.58	$\pi^\pm, K^\pm, \eta, p/\bar{p}$
HERMES [321,322]	$e+p(d)$	272 (p) 329 (d)	27.6 fixed target	$\pi^{\pm,0}, K^\pm$
COMPASS [323]	$\mu+p(d)$	775	160 GeV fixed target	$h^\pm$
PHENIX		16×10^{-3}	62.4	
[324–326]	pp	2.5	200	$\pi^{\pm,0}, \eta$
[327–329]		128	510	
STAR				
[330–332]	pp	8	200	$\pi^{0,\pm}, \eta, p/\bar{p}, K^0_S, \Lambda/\bar{\Lambda}$
[333–335]				
ALICE [336]	pp	6×10^{-3}	7×10^3	π^0, η
TOPAZ [337]	e^+e^-	278	52–61.4	$\pi^\pm, K^\pm, K^0_S,$
CDF [338,339]	$p+\bar{p}$	n/a	630 (1800)	$h^\pm, K^0_S\Lambda^0$

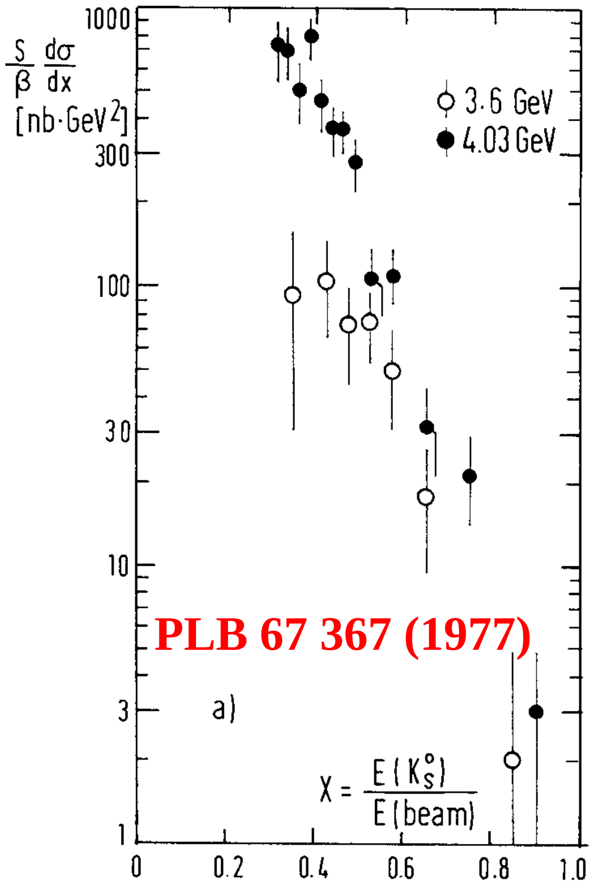
- Updated **HKNS FFs** @ 2016
  - ✓ only e^+e^- ($\sqrt{s}$ > 10 GeV) data sets
- **MAPFF1.0 FFs** @ 2021
  - ✓ e^+e^- ($\sqrt{s}$ > 10 GeV) and SIDIS data sets
- Data set at $\sqrt{s}$ < 10 GeV e^+e^- collision ?



Inclusive π & K data of e^+e^- at low energy

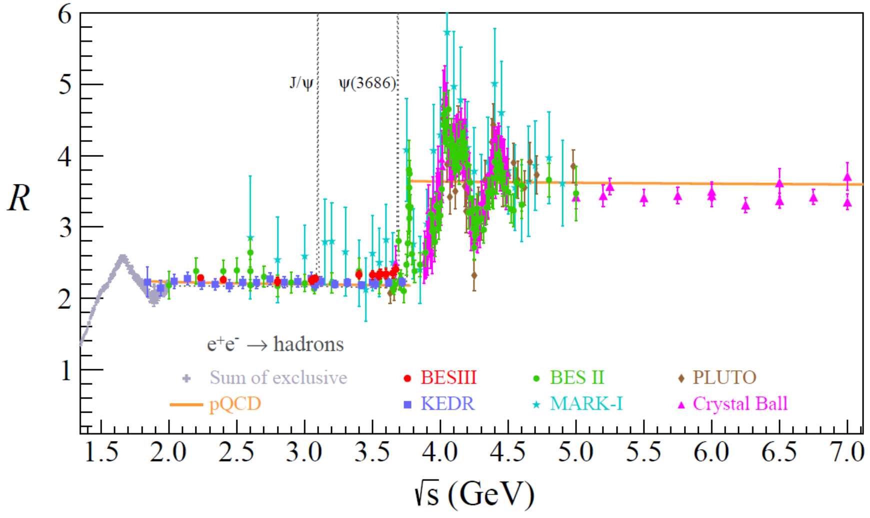


NPB 148 189 (1979)



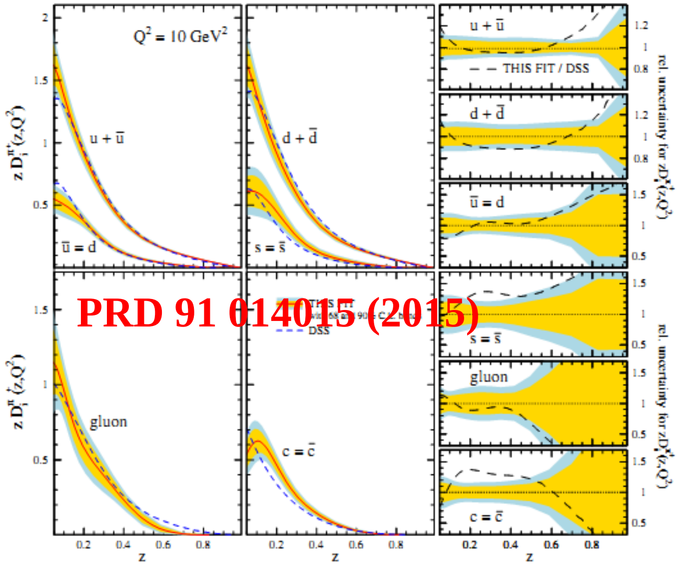
PLB 67 367 (1977)

- **Charged π @ DASP**
  - ✓ **about 46 years ago**
  - ✓ **stat. uncertainty: 18%**
- **K_S^0 @ PLUTO**
  - ✓ **about 48 years ago**
  - ✓ **stat. uncertainty: 18-41%**
- **Precision data ? TMD FFs ?**

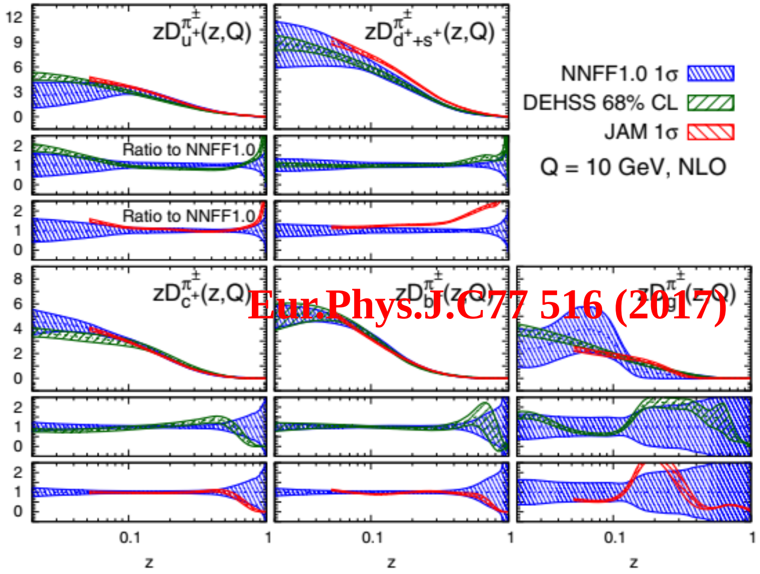


BESIII R scan data ⇒ Precision measurement ?

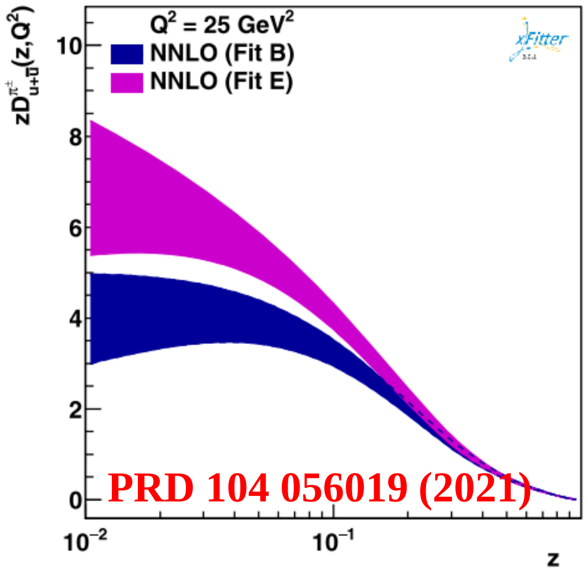
Pion FF: Best known FF



PRD 91 014035 (2015)

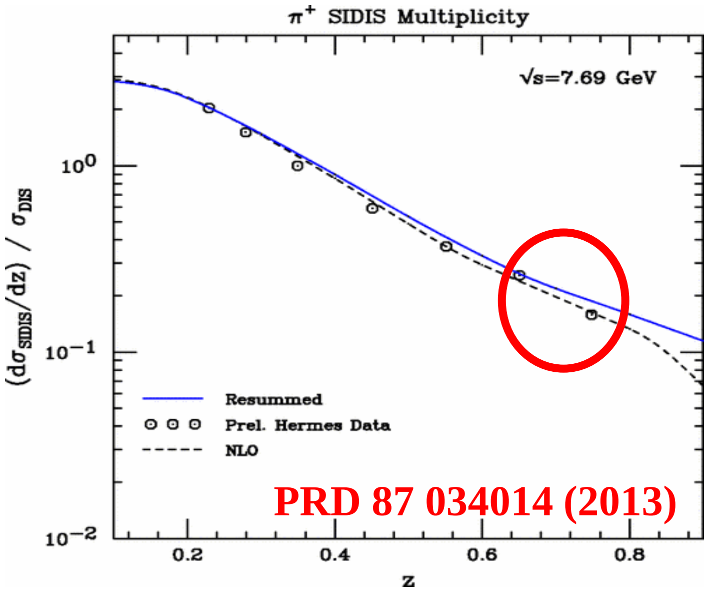


Eur.Phys.J.C77 516 (2017)



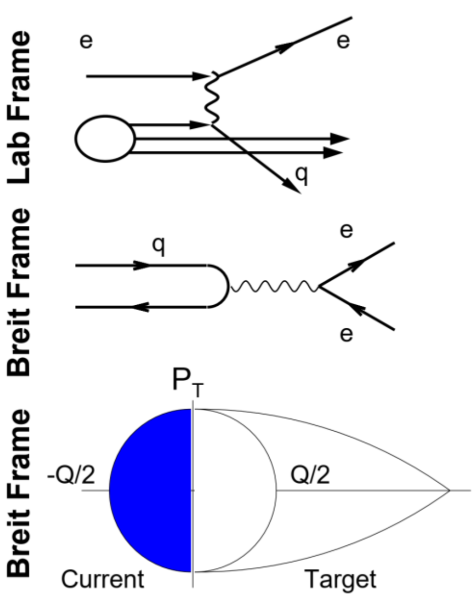
PRD 104 056019 (2021)

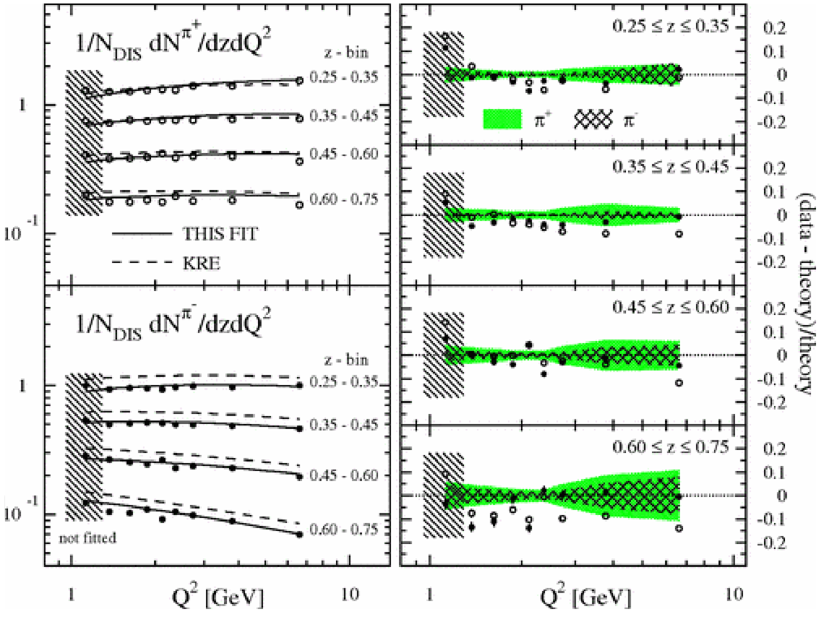
- For z≥0.8, uncertainty rapidly increase because of the lack of experimental data
- Xfitter: data at $\sqrt{s}$ > 10 GeV e^+e^-
  - ✓ Low $\sqrt{s}$ e^+e^- data ?
- Large z re-summation
  - ✓ High z data ?

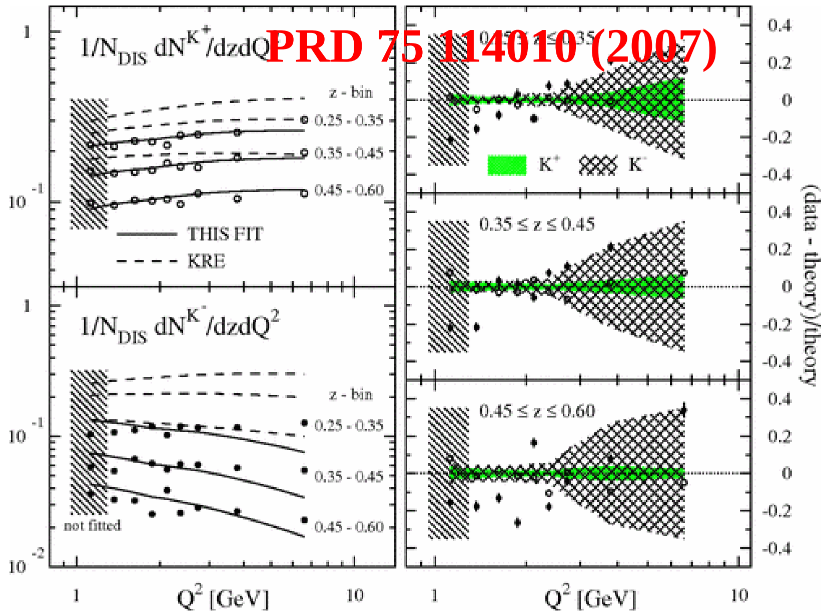


PRD 87 034014 (2013)

Pion FFs



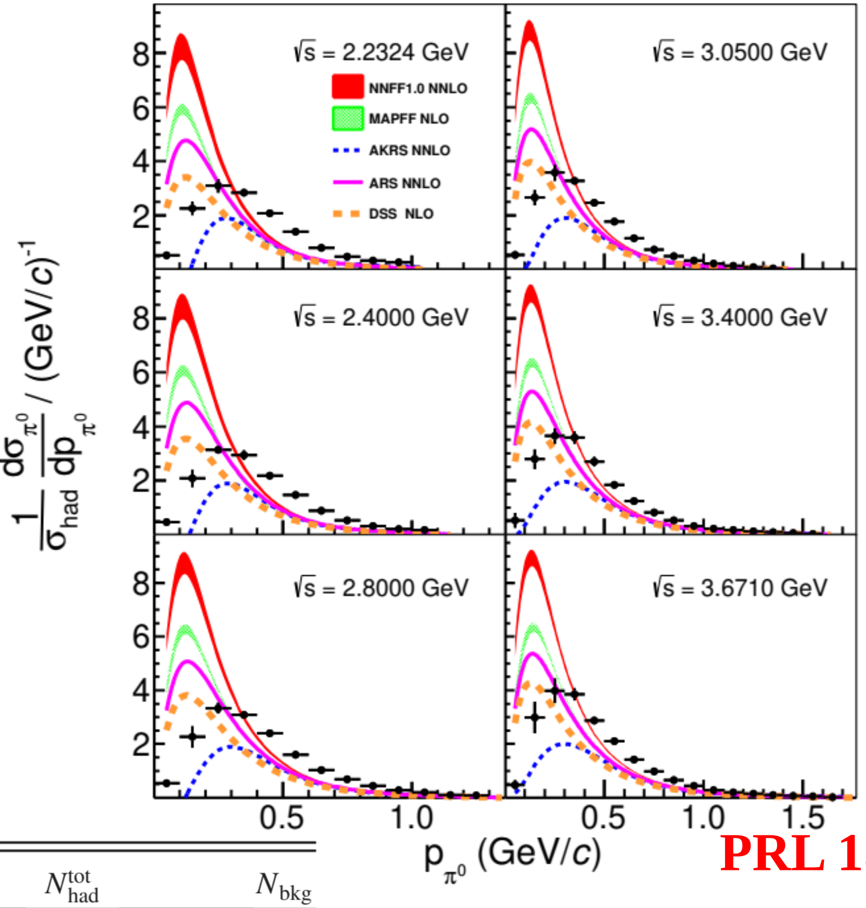


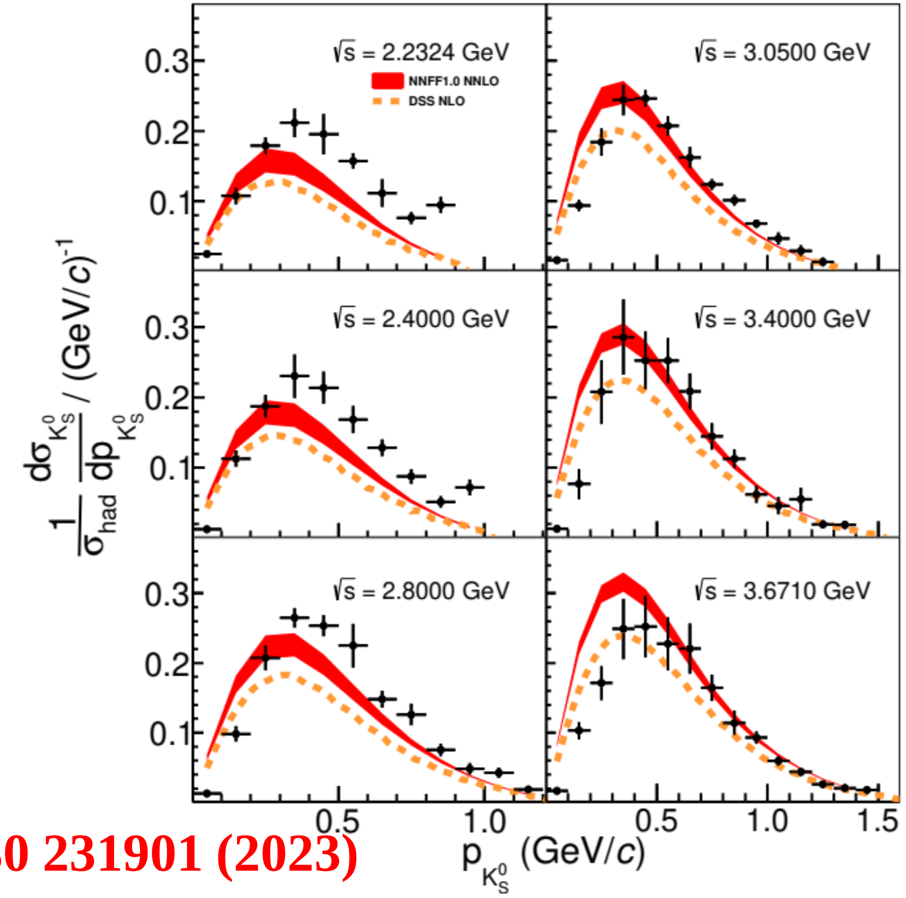


PRD 75 114010 (2007)

- **DIS @ Breit frame**
  - ✓ **Incoming quark scatters off photon and returns along same axis**
- **Current region of Breit frame is analogous to e^+e^-**
  - ✓ **Born level: DIS Q = e^+e^- $\sqrt{s}$**
- **DSS FFs: HERMES ep pion data at 10% level**
- **e^+e^- data at low energy $\sqrt{s}$**
  - ✓ **FFs packages could describe e^+e^- data at ?% level**

$e^+e^- \to \pi^0/K_S^0 + X$ @ BESIII



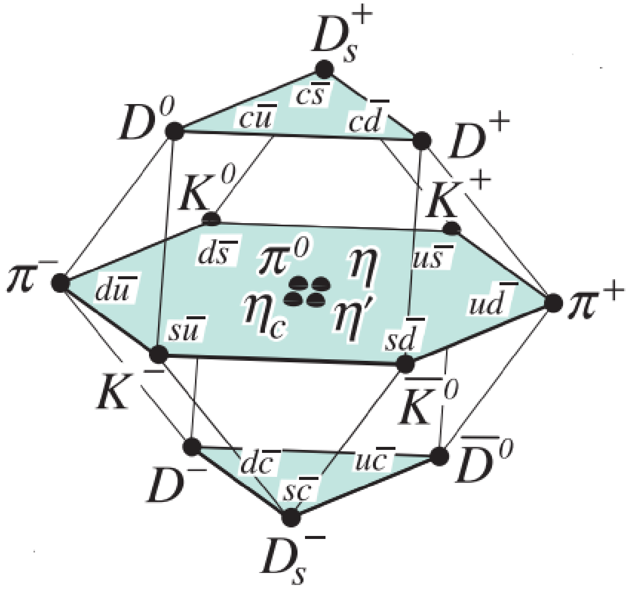


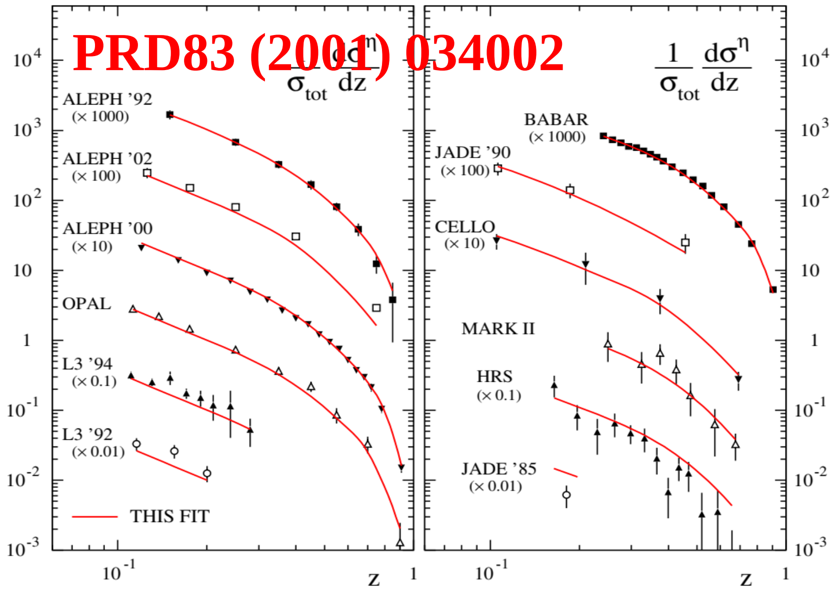
PRL 130 231901 (2023)

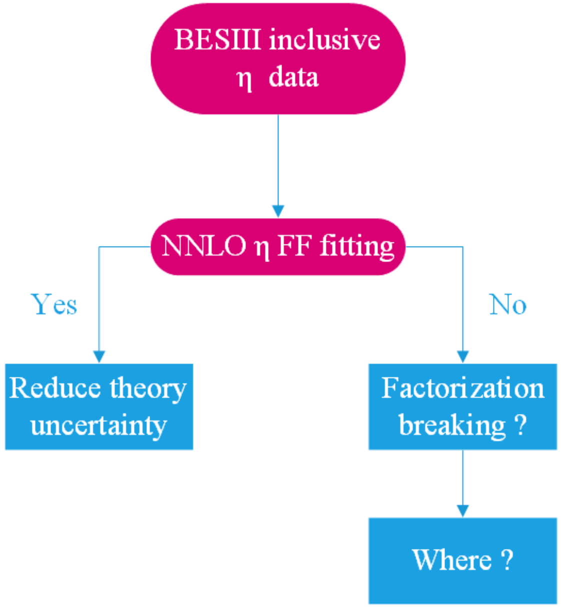
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	N_{had}^{tot}	N_{bkg}
2.2324	2.645	83227	2041
2.4000	3.415	96627	2331
2.8000	3.753	83802	2075
3.0500	14.89	283822	7719
3.4000	1.733	32202	843
3.6710	4.628	75253	6461

- **Dominated uncertainty: MC generator**
- **inclusive π^0 production: surprise**
- **inclusive K_S^0 production: not so bad**

η FF

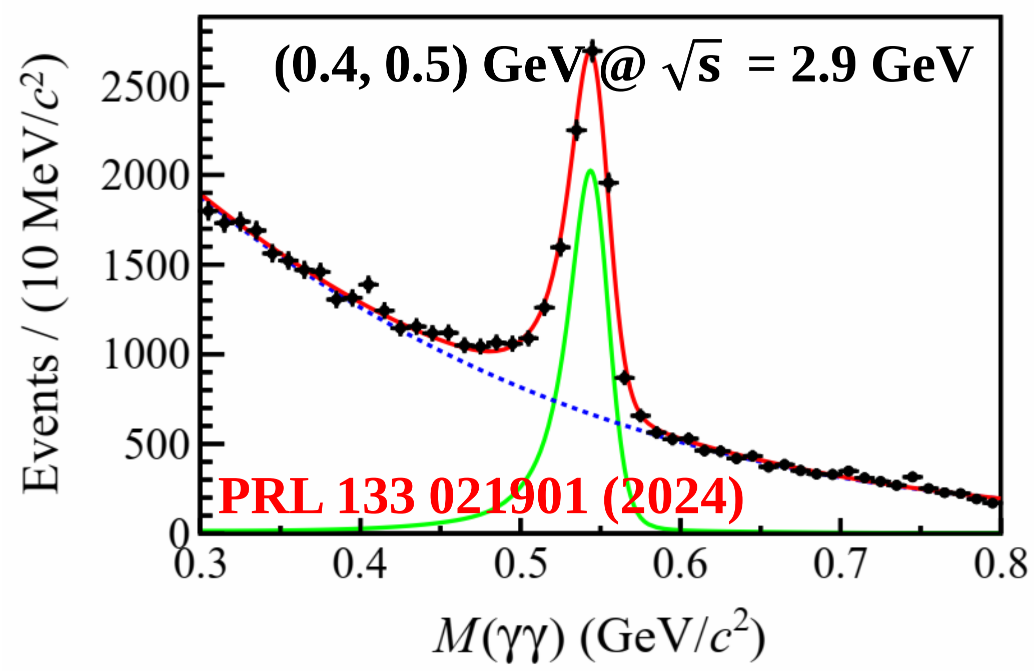


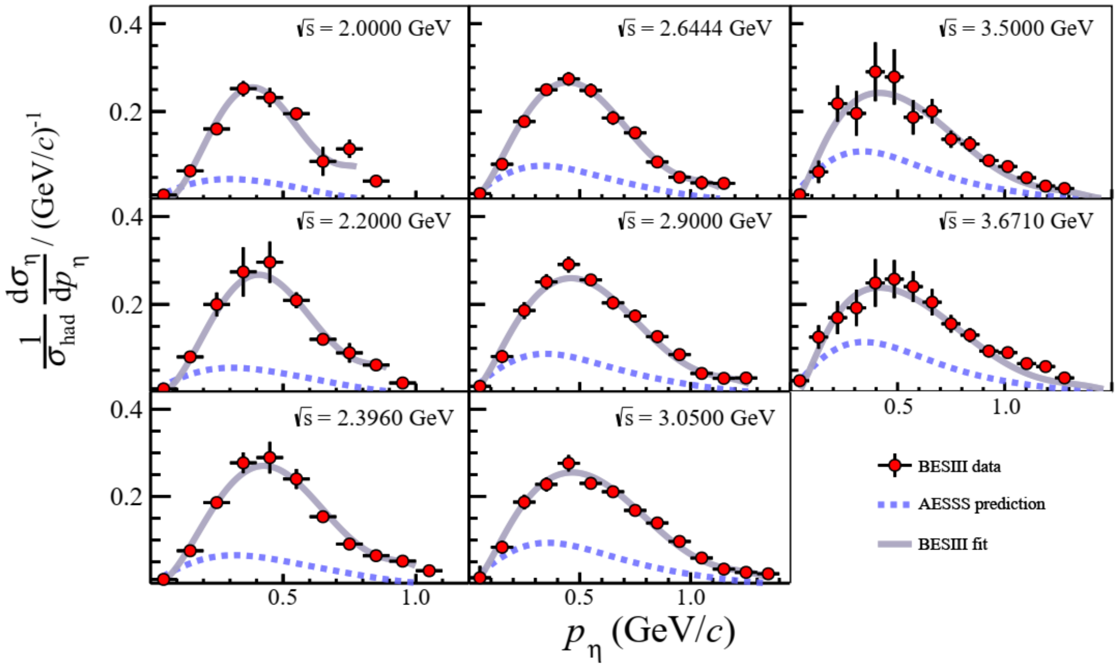




- **η: a Goldstone boson due to spontaneous breaking of QCD chiral symmetry**
- **η FF @ NLO: data at $\sqrt{s}$ > 10 GeV e^+e^- collision**
  - ✓ **Missing theory uncertainty**
- **Theory improvement:**
  - ✓ **NNLO accuracy, hadron mass correction & higher twist**
- **BESIII results and its possible impact ?**

$e^+e^- \to \eta + X$ @ BESIII

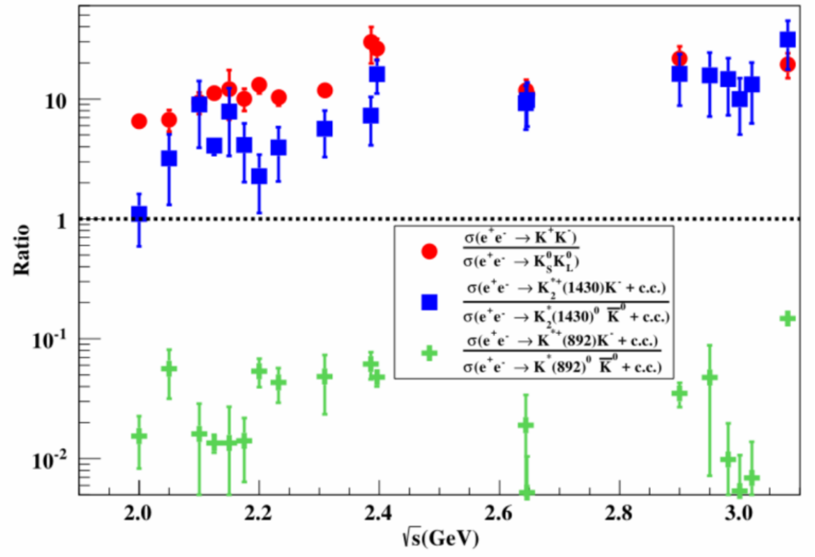


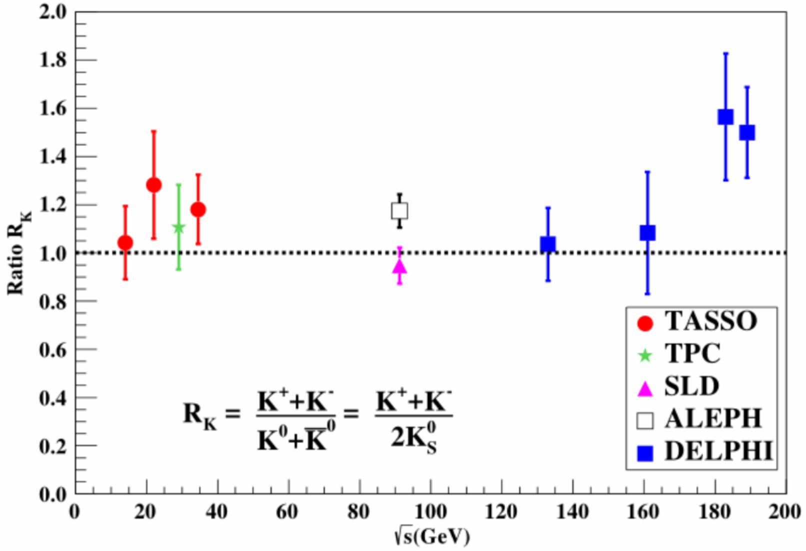


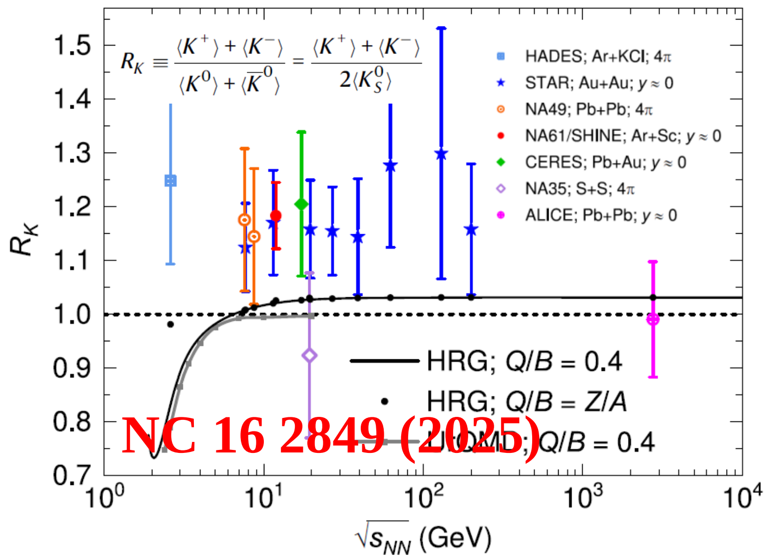
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N_{\rm had}^{\rm tot}$	$N_{\rm bkg}$
2.0000	10.074	350 298 ± 591	8722 ± 93
2.2000	13.699	445 019 ± 666	10 737 ± 103
2.3960	66.869	1 869 906 ± 1365	47 550 ± 218
2.6444	33.722	817 528 ± 902	21 042 ± 145
2.9000	105.253	2 197 328 ± 1478	56 841 ± 238
3.0500	14.893	283 822 ± 531	7719 ± 87
3.5000	3.633	62 670 ± 249	1691 ± 41
3.6710	4.628	75 253 ± 273	6461 ± 80

- **PRD83 (2001) 034002 prediction vs. BESIII data**
  - ✓ **tension !**
- **BESIII fit: detail @ PRD 111 034030 (2025)**
  - ✓ **$\sqrt{s}$ > 10 GeV e^+e^- data + BESIII data**
  - ✓ **NNLO accuracy, hadron mass correction & higher twist**

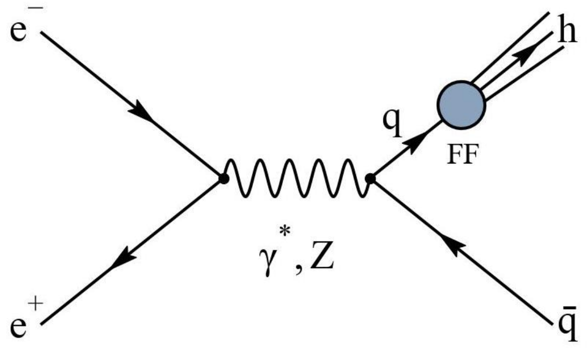
Isospin symmetry







- $e^+e^- \to K^*K$: charged vs. neutral channel
  - ✓ Isospin symmetry violation
- Inclusive kaon production @ $e^+ e^-$
  - ✓ Consistent with one ? precision !!!
- Inclusive kaon production @ AA
  - ✓ Large isospin symmetry breaking
- SU(2) isospin symmetry @ FFs



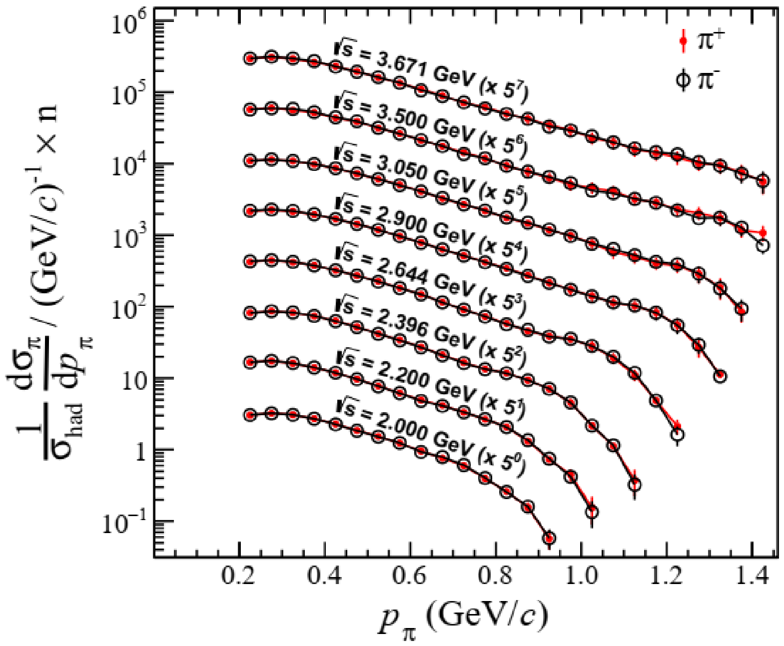
$$D_i^{\pi^0}(z,Q) = \frac{1}{2} D_j^{\pi^\pm}(z,Q)$$

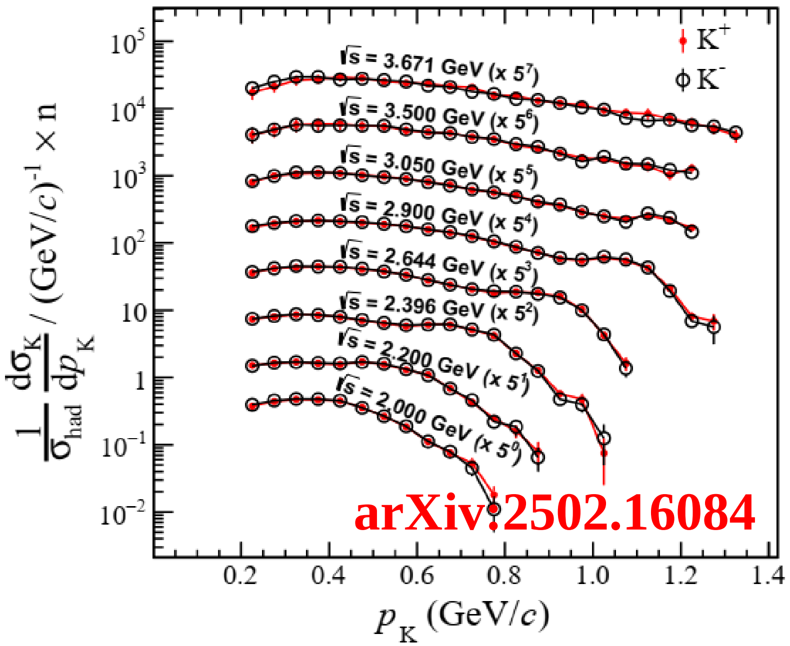
$$D_i^{K_S^0}(z,Q) = \frac{1}{2} D_j^{K^\pm}(z,Q)$$

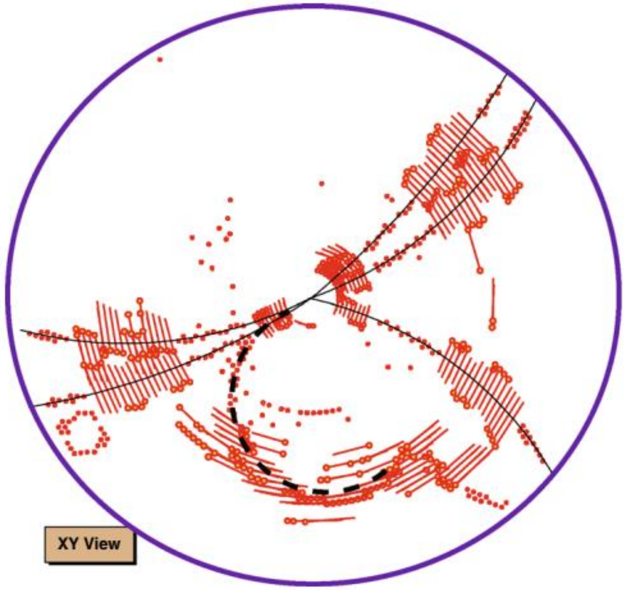
@NPB 803 42 (2008)

$$\begin{cases} \text{if } i = d(u),\ j = u(d) \\ \text{otherwise } i = j \end{cases}$$

$e^+e^- \to \pi^\pm/K^\pm + X$ @ BESIII



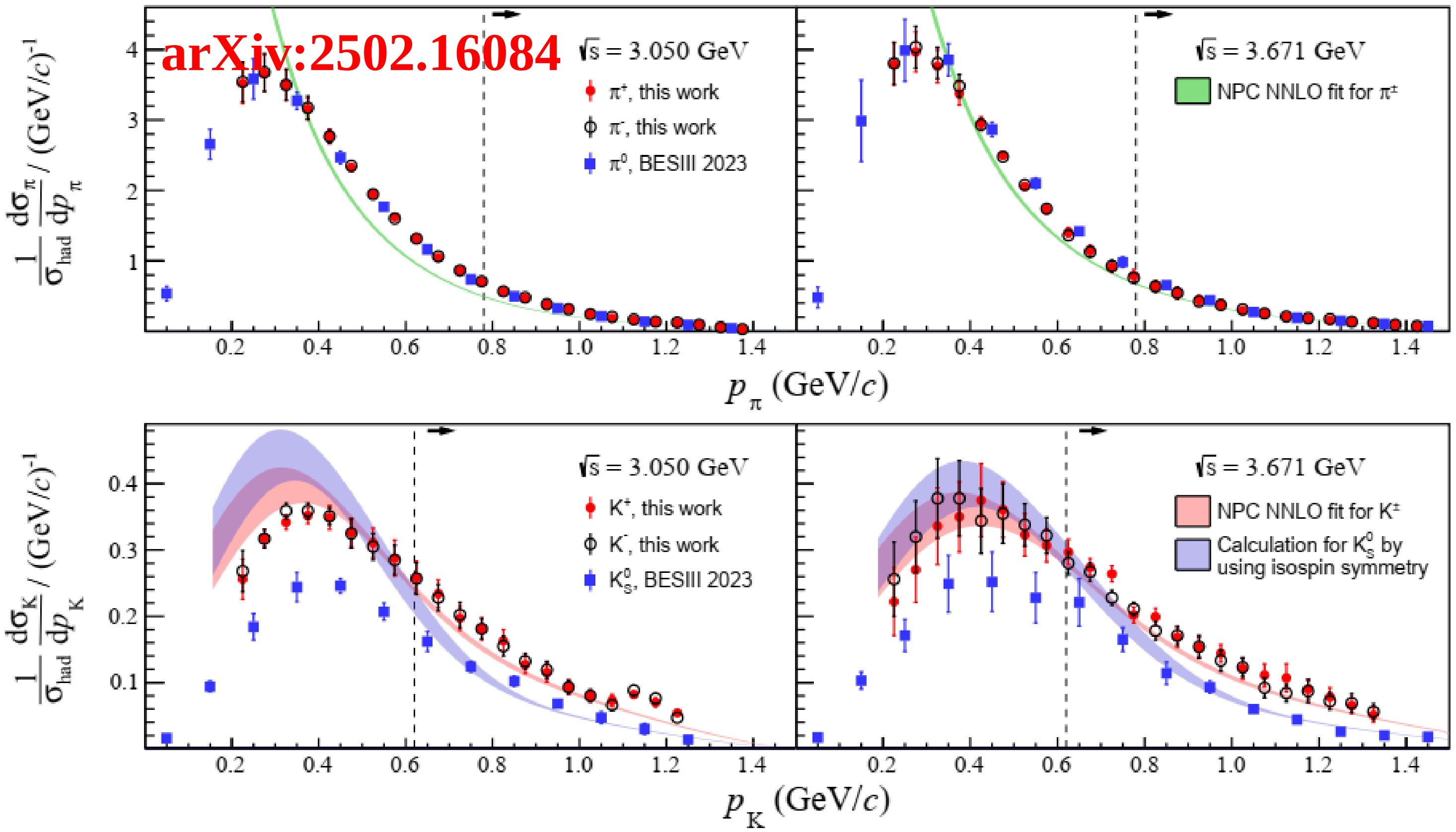




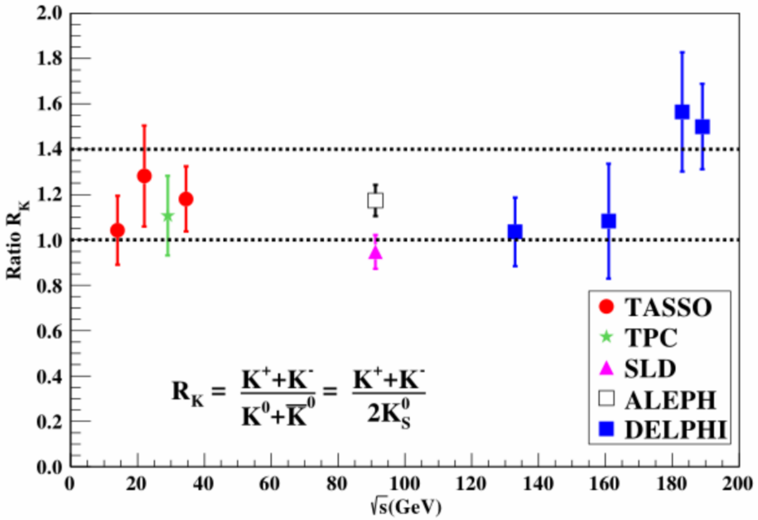
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	N_{had}^{tot}	N_{bkg}
2.0000	10.074	350298 ± 592	8722 ± 94
2.2000	13.699	445019 ± 668	10737 ± 104
2.3960	66.869	1869906 ± 1368	47550 ± 219
2.6444	33.722	817528 ± 905	21042 ± 146
2.9000	105.253	2197328 ± 1483	56841 ± 239
3.0500	14.893	283822 ± 533	7719 ± 88
3.5000	3.633	62670 ± 251	1691 ± 42
3.6710	4.628	75253 ± 275	6461 ± 81

- **$z = 2p/\sqrt{s}$ coverage**
  - ✓ **pion: 0.13 – 0.95**
  - ✓ **kaon: 0.30 – 0.90**
- **Missing bins with momentum < 0.2 GeV**
  - ✓ **Low p_t: curling track, not reconstructed**
- **Dominated uncertainty: MC generator**

$e^+e^- \to \pi^\pm/K^\pm + X$ @ BESIII



- Inclusive pion cross section
  - ✓ $\pi^+ \approx \pi^- \approx \pi^0$
  - ✓ Isospin symmetry
- Inclusive kaon cross section
  - ✓ $K^+ \approx K^- \approx 1.4\ K_S$
  - ✓ Large isospin violation ?



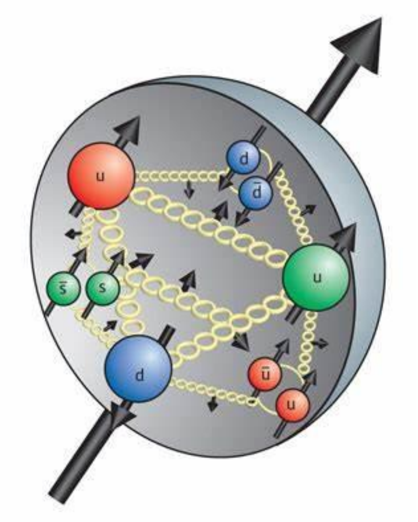
- NPC NNLO: $\sqrt{s}$ > 3.0 GeV & E_h > 0.8 GeV @ BESIII
- arXiv:2502.17837: Validity of QCD factorization and pQCD calculation at energy scales down to 3 GeV
- Test of isospin symmetry with FF fitting

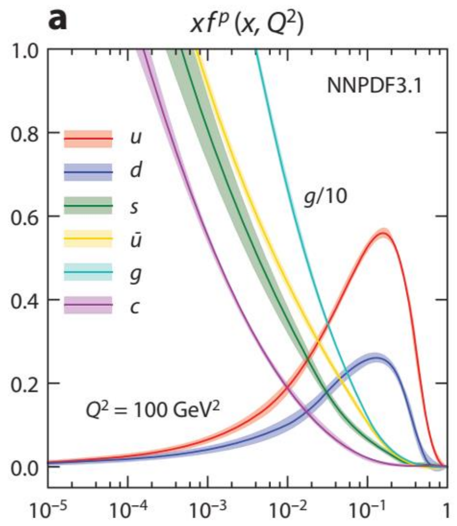
Summary

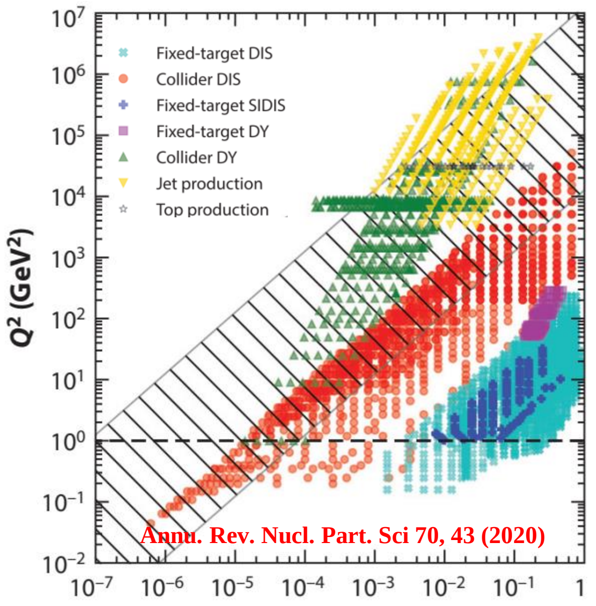
- The FF play a crucial role in describing hadronization process, and understanding of non-perturbative QCD dynamics.
- Inclusive π^0 & K_s: Large discrepancy with theory calculation. PRL 130 231901 (2023)
- Inclusive η: FF fitting with NNLO accuracy, hadron mass & higher twist correction, could describe BESIII data. PRL 133 021901 (2024)
- Inclusive π & K: Validity of QCD factorization and pQCD calculation at energy scales down to 3 GeV, test of isospin symmetry with FF fitting. arXiv:2502.16084
- Inclusive hadron production @ low energy e^+e^- annihilation: use or useless ???

Global PDF fits vs. Global FFs Fits

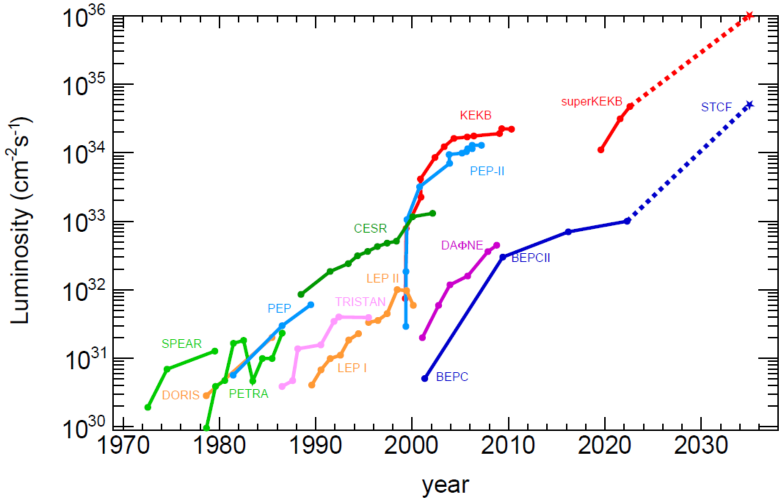
- **Parton distribution functions(PDF)**
  - ✓ **Probability of parton inside a hadron**
  - ✓ **A key ingredient in hadron collider physics**
- **Aim: high precision theory + wide range of data**
  = precise & accurate PDFs & FFs
- **Study of FFs < Study of PDFs**
  - ✓ **Data set at $\sqrt{s}$ < 10 GeV e^+e^- ???**







Annu. Rev. Nucl. Part. Sci 70, 43 (2020)



Experiment	Process	$\mathcal{L}[pb^{-1}]$	$Q^2[GeV^2]$	Final states
TPC [288–291]	e^+e^-	140	29	$\pi^\pm, K^\pm, p/\bar{p}$
TASSO				
[292–294]	e^+e^-	34	34–44	$\pi^\pm, K^\pm, p/\bar{p}, K^0_S, \Lambda/\bar{\Lambda}$
[295–298]				
SLD [299,300]	e^+e^-	20	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
ALEPH [301,302]	e^+e^-	800	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
DELPHI [303–306]	e^+e^-	800	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
OPAL [307–310]	e^+e^-	800	M_Z	$\pi^\pm, K^\pm, p, K^0_S, \Lambda/\bar{\Lambda}$
H1 [311–313]	$e+p$	500	27.5(e) + 920(p)	$h^\pm, K^S_0$
ZEUS [314–316]	$e+p$	500	27.5(e) + 920(p)	$h^\pm$
BELLE [317,318]	e^+e^-	10^6	Near 10.58	$\pi^\pm, K^\pm, p/\bar{p}$
BaBar [319,320]	e^+e^-	$557 \cdot 10^3$	Near 10.58	$\pi^\pm, K^\pm, \eta, p/\bar{p}$
HERMES [321,322]	$e+p(d)$	272 (p) 329 (d)	27.6 fixed target	$\pi^{\pm,0}, K^\pm$
COMPASS [323]	$\mu+p(d)$	775	160 GeV fixed target	$h^\pm$
PHENIX		16×10^{-3}	62.4	
[324–326]	pp	2.5	200	$\pi^{\pm,0}, \eta$
[327–329]		128	510	
STAR				
[330–332]	pp	8	200	$\pi^{0,\pm}, \eta, p/\bar{p}, K^0_S, \Lambda/\bar{\Lambda}$
[333–335]				
ALICE [336]	pp	6×10^{-3}	7×10^3	π^0, η
TOPAZ [337]	e^+e^-	278	52–61.4	$\pi^\pm, K^\pm, K^0_S,$
CDF [338,339]	$p+\bar{p}$	n/a	630 (1800)	$h^\pm, K^0_S \Lambda^0$

PPNP 91 136 (2016)