R value and some QCD study @ BESIII

鄢文标

For BESIII Collaboration

中国科学技术大学

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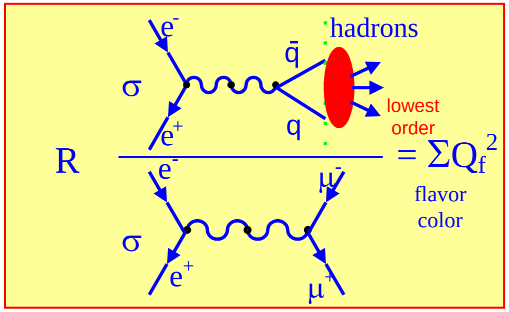
Outline

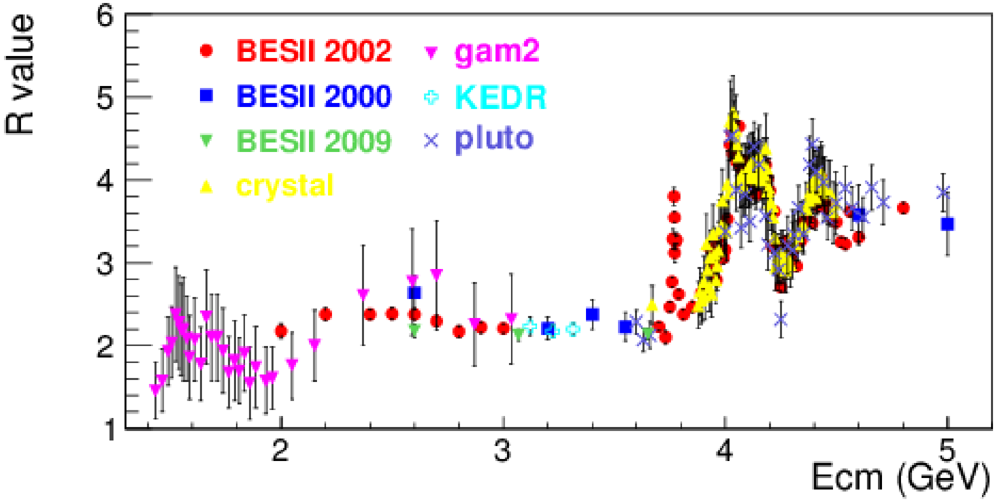
- Status of R value
- Pion form factor with ISR method
- Baryon form factor
- Fragmentation function
- Exclusive decay modes @ R scan data

R value

- R value: The born cross section of e^+e^- annihilation into hadrons normalized by theoretical $\mu^+\mu^-$ cross section.



- Uncertainty of R value @ $\sqrt{s} \in [2, 5]$GeV:
  - ✓ by BESII: average 6.6%
  - ✓ Few points by BESII and KEDR: about 3%

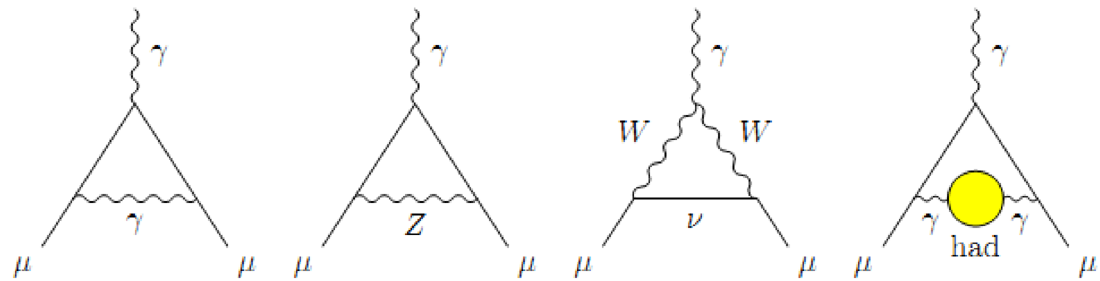


Precision !!!

Muon magnetic moment $(g\text{-}2)_\mu$

- **The Standard Model prediction for muon $a_\mu=(g_\mu-2)/2$**

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}$$



- **muon a_μ @ PDG2014:**
  - $a_\mu^{\mathrm{QED}} = 116584718.95(0.08)\times10^{-11}$
  - $a_\mu^{\mathrm{EW}} = 153.6(1.0)\times10^{-11}$
  - $a_\mu^{\mathrm{Had}}[\mathrm{LO}] = 6923(42)(3)\times10^{-11}$ $\quad a_\mu^{\mathrm{Had}}[\mathrm{LO}] = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds\, \frac{K(s)}{s} R^{(0)}(s)$
  - $a_\mu^{\mathrm{Had}}[\mathrm{NLO}] = 7(26)\times10^{-11}$
  - $\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 288(63)(49)\times10^{-11}$,
    - ✓ **3.6σ!!! Error or New Physics ???**
  - **New experiments at FNAL/JPARC: $\delta a_\mu^{\mathrm{exp}} = \pm16 \cdot 10^{-11}$**

EM fine structure constant

- **The running of the electromagnetic fine structure constant is Governed by the renormalized vacuum polarization function.**

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha_{lep}(s) - \Delta\alpha_{top}(s) - \Delta\alpha_{had}^{5}(s)}$$

$$\Delta\alpha_{lep}(M_Z^2) = 0.03142$$

$$\Delta\alpha_{top}(M_Z^2) = 0.00007(1)$$ **top quark very heavy**

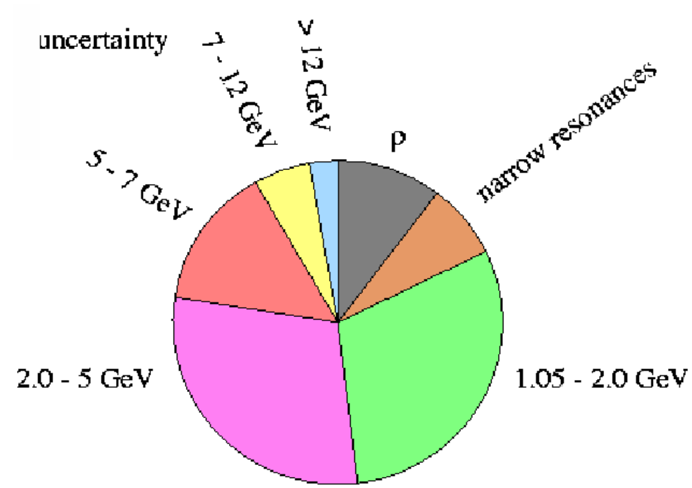
$$\Delta\alpha_{had}^{5}(M_Z^2) = 0.0280 \pm 0.0009$$

$$\Delta\alpha_{had}^{5}(M_Z^2) = -\frac{\alpha(0)M_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s-M_Z^2)-i\varepsilon}$$

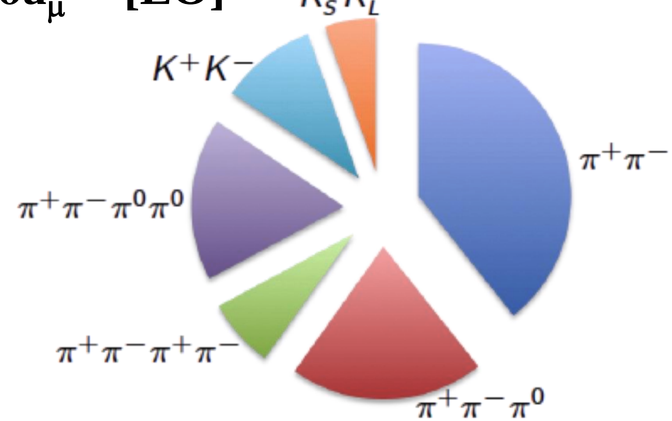
$\Delta\alpha^{5}_{had}(M^{2}_{Z})$ and δa_{μ}^{Had}

TABLE I: Contributions to $\Delta\alpha^{(5)}_{\rm had}(m^2_Z)$

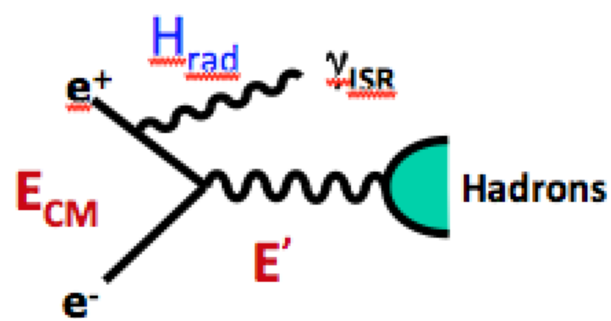
Range $\sqrt{s}$, GeV	$\Delta\alpha$	Relative error
ρ	0.00349	0.5 %
Narrow resonances	0.00184	3.1 %
1.05 – 2.0	0.00156	15 %
2.0 – 5.0	0.00371	5.0 %
5 – 7	0.00183	6 %
7 – 12	0.00304	1.4 %
> 12	0.01203	0.2 %
	0.02750	1.2 %



δa_{μ}^{Had}[LO]

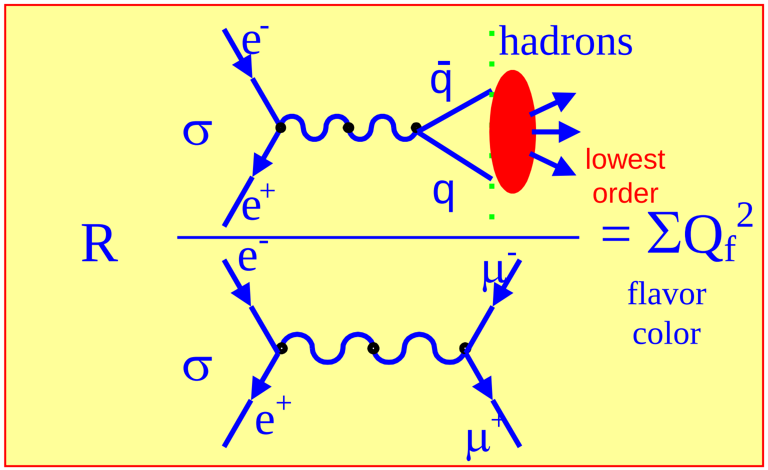


- **R value @ [2, 5] GeV by energy scan**
- **Exclusive modes < 2GeV by ISR**



R value

- **R values are measured as**



$$R = \frac{1}{\sigma_{\mu+\mu-}} \cdot \frac{N_{had} - N_{bg}}{L \cdot \varepsilon_{had} \cdot (1+\delta)}$$

N_{had} observed hadronic events

N_{bg} from background events

L integrated luminosity

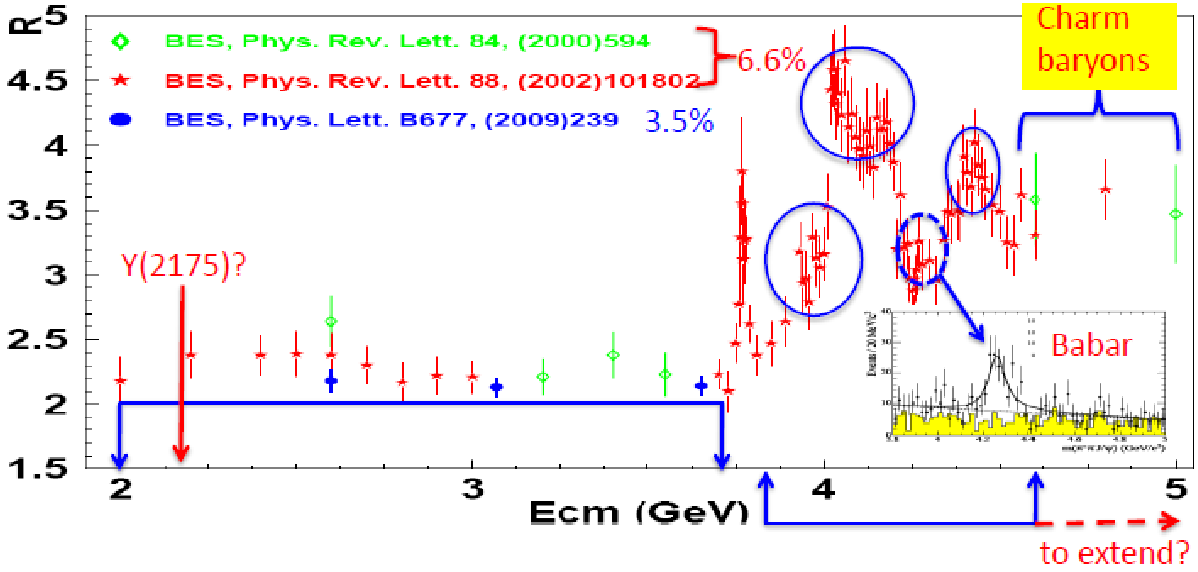
ε_{had} selection efficiency

$1+\delta$ radiative correction factor

$\sigma_{\mu\mu}$ Born cross section of μ pair production in QED

Data sets for R value

- **Phase I: test run @ 2012**
  - ✓ **Ecm = 2.2324/2.400/2.800/3.400 GeV, ~12pb^{-1}**
- **Phase II: fine scan for heavy charm resonant @2013-2014**
  - ✓ **Ecm ∈ [3.800, 4.590]GeV, 104 energy points, ~800pb^{-1}**
- **Phase III: R & QCD scan @ 2015**
  - ✓ **Ecm ∈ [2.000, 3.080]GeV, 21 energy points, ~500pb^{-1}**

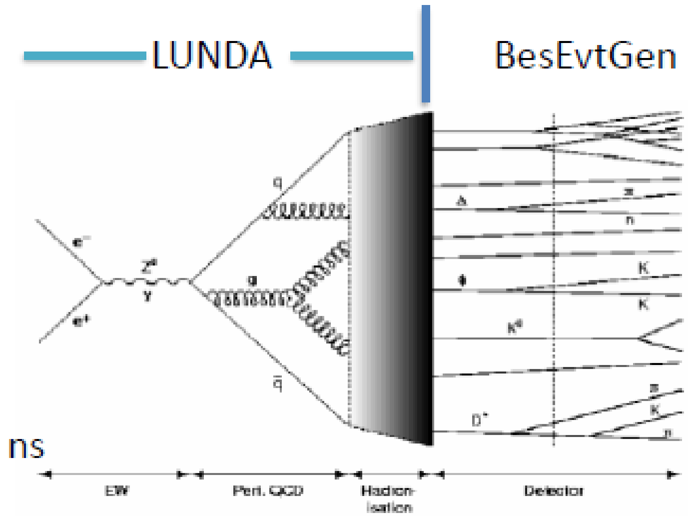


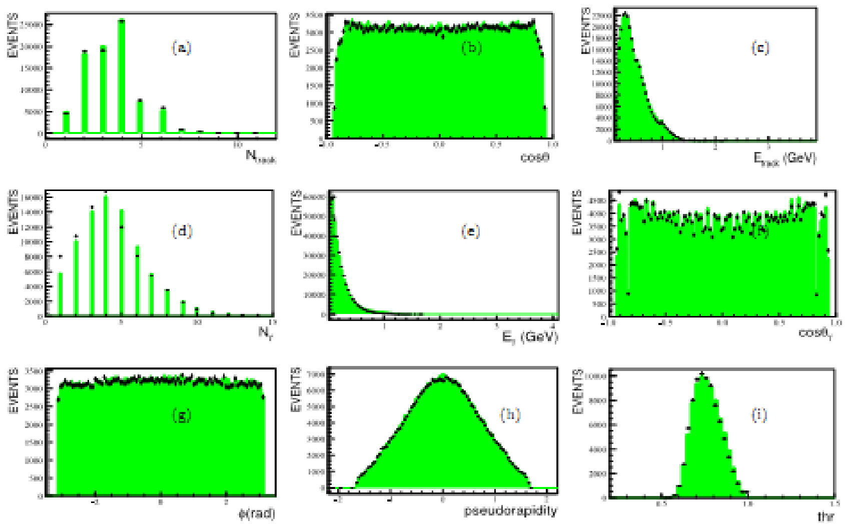
Status of R value

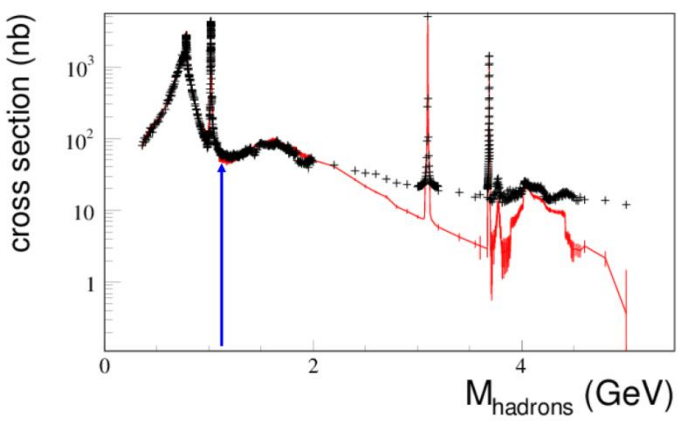
$$R = \frac{1}{\sigma_{\mu+\mu-}} \cdot \frac{N_{had} - N_{bg}}{L \cdot \varepsilon_{had} \cdot (1+\delta)}$$

- **N_{had} and N_{bg}: hadronic event selection**
  - ✓ **below open charm finished; above open charm in progress**
- **Luminosity L:**
  - ✓ **Finish, with 1% uncertainty**
- **1+δ: theoretical calculations:**
  - ✓ **Compare different schemes, with 1.5% uncertainty**
- **ε_{had}: MC generators**
  - ✓ **Two schemes, cross check, largest contribution to uncertainty**
- **Uncertainty analysis: goal ΔR/R ~ 3%**

MC generator



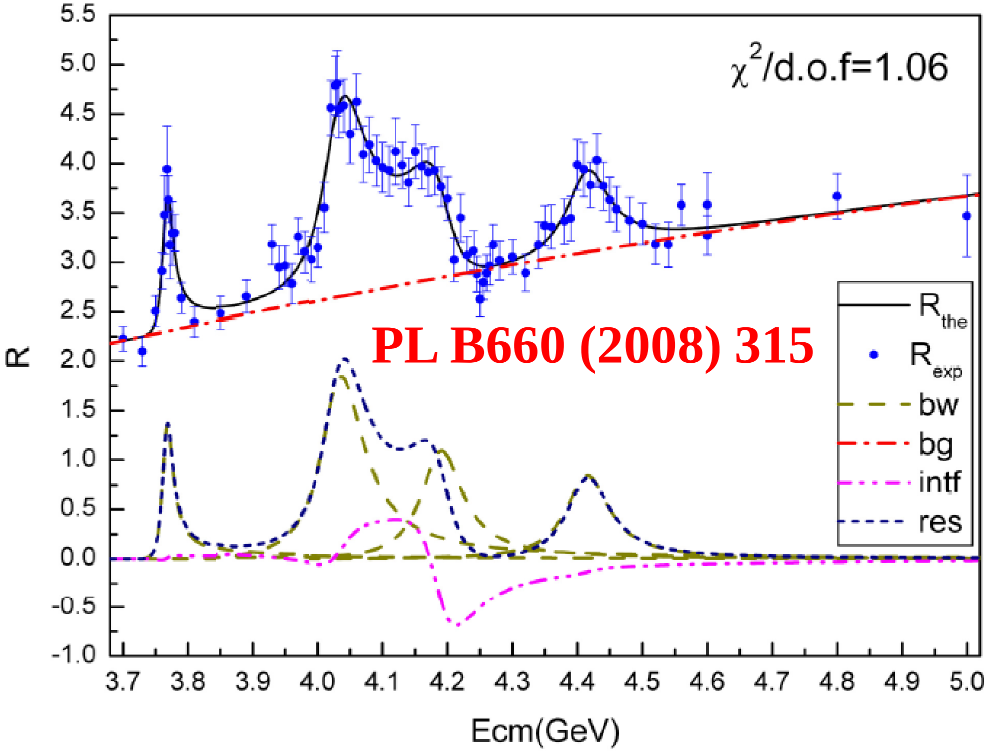




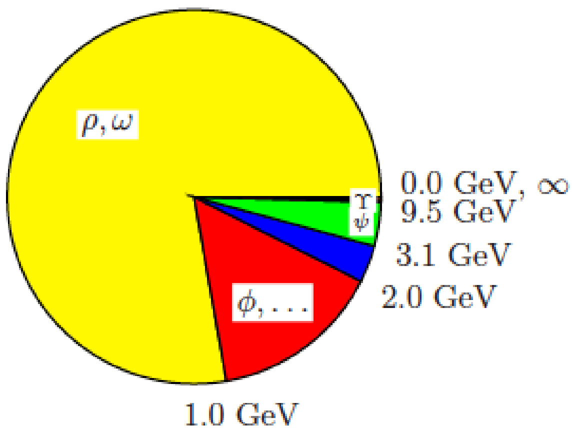
- LUNDA: LUND Area Law
- Generator: ConExc & LUNDA
  - ✓ Exclusive processes (measured)
  - ✓ Unknown: LUNDA
  - ✓ Similar J/ψ decay

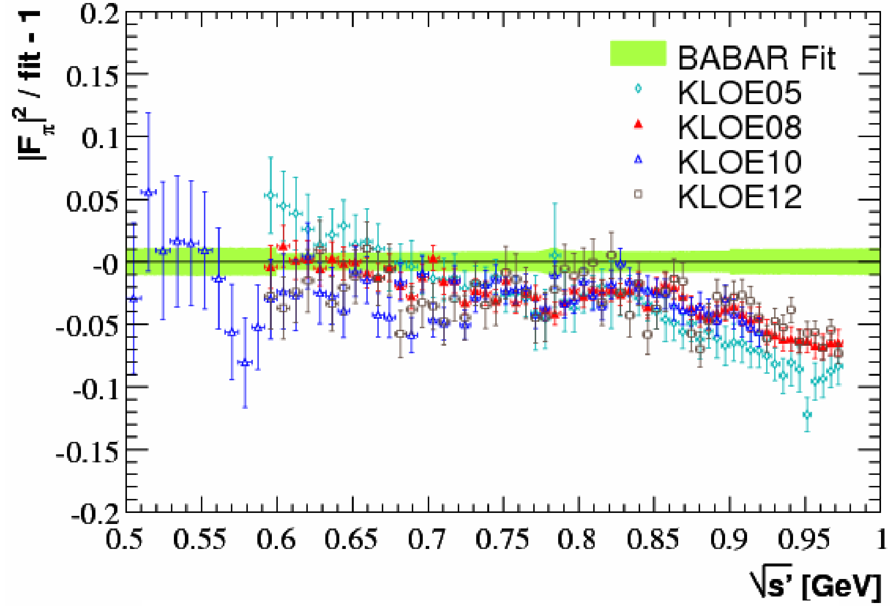
Heavy vector charmonia

- **Fit to R values: resonance parameters of $J^{PC}=1^{-}$ conventional charmonium ψ(3770), ψ(4040), ψ(4160) and ψ(4410).**

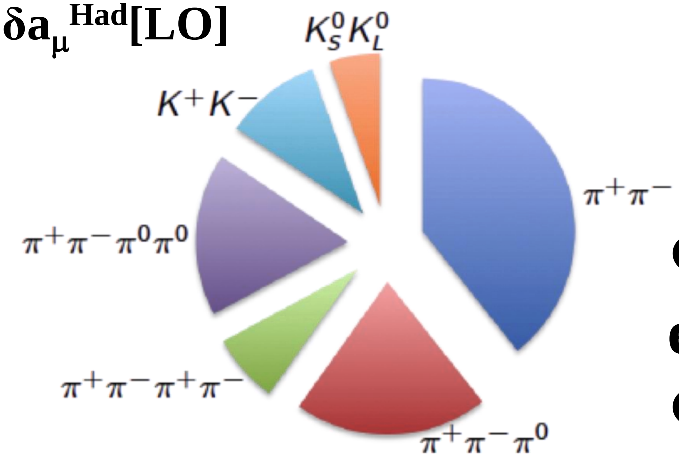


$e^+e^- \to \pi^+\pi^-$ and pion form factor





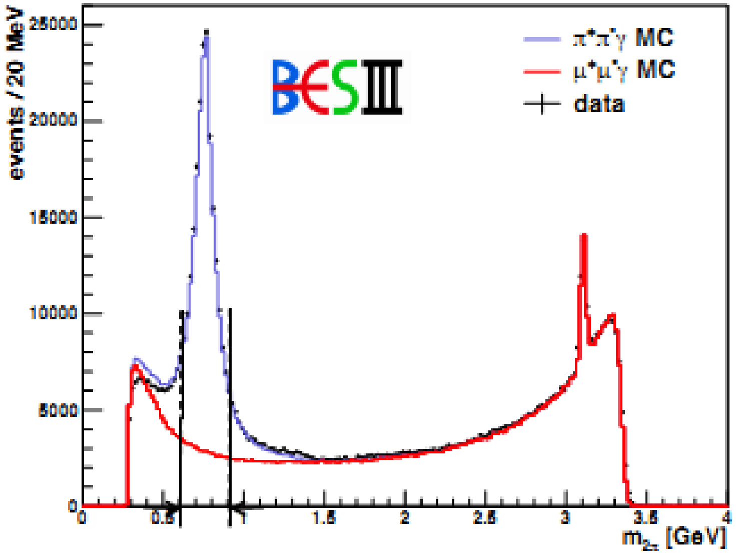
δa_μ^{Had}[LO]

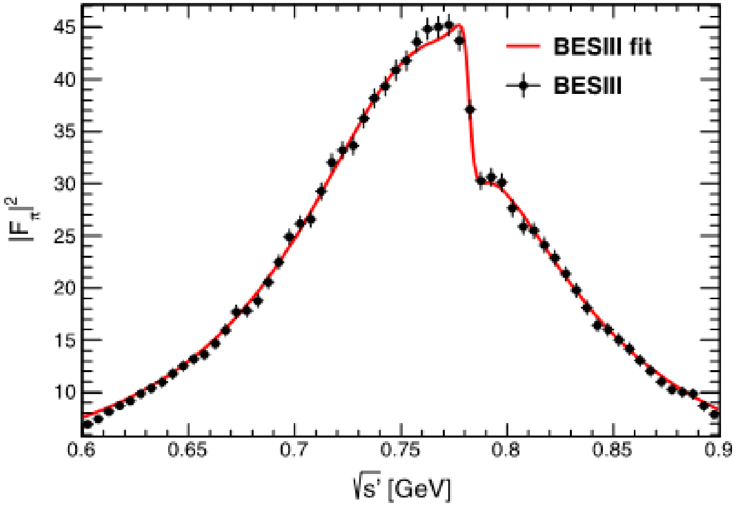


$$\left|F_\pi\right|^2(s') = \frac{3s'}{\pi\alpha\beta_\pi^3(s')}\sigma(e^+e^- \to \pi^+\pi^-)(s')$$

- **Large contribution to a_μ: < 1GeV, $e^+e^- \to \pi^+\pi^-$ is the most important.**
- **KLOE and BABAR (1% uncertainty) dominate world average. relatively large systematical difference,**

$e^+e^- \to \pi^+\pi^-$ and pion form factor





- **ISR method with ψ(3770) data, with 0.9% uncertainty**
- **Gounaris-Sakurai fit with phase $c_\omega=|c_\omega|\exp(i\phi_\omega)$**

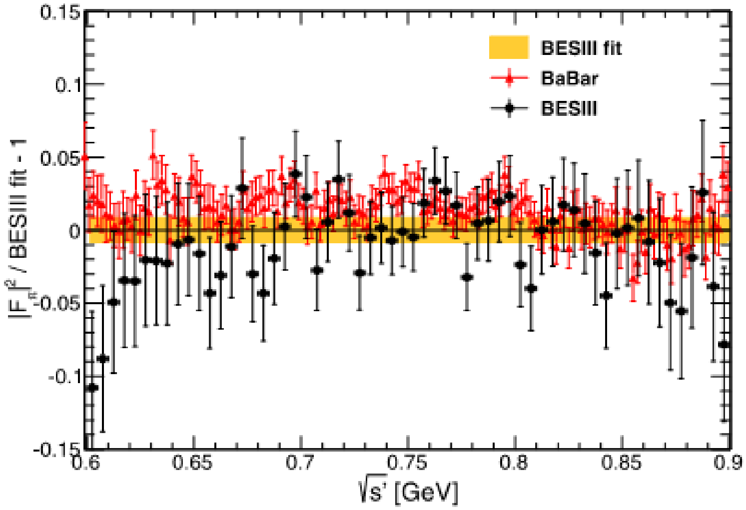
Table 3
Fit parameters and statistical errors of the Gounaris-Sakurai fit of the pion form factor. Also shown are the PDG 2014 values [33].

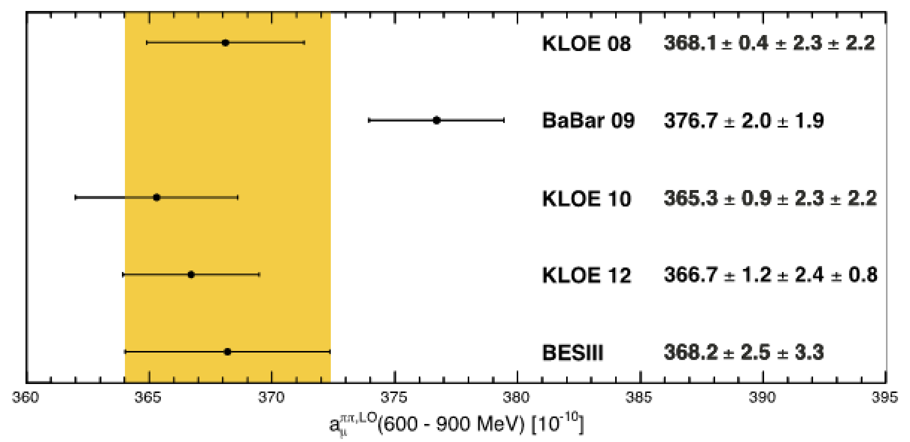
Parameter	BESIII value	PDG 2014
m_ρ [MeV/c^2]	776.0 ± 0.4	775.26 ± 0.25
Γ_ρ [MeV]	151.7 ± 0.7	147.8± 0.9
m_ω [MeV/c^2]	782.2 ± 0.6	782.65 ± 0.12
Γ_ω [MeV]	fixed to PDG	8.49 ± 0.08
$\|c_\omega\|$ [10^{-3}]	1.7± 0.2	-
$\|\phi_\omega\|$ [rad]	0.04 ± 0.13	-

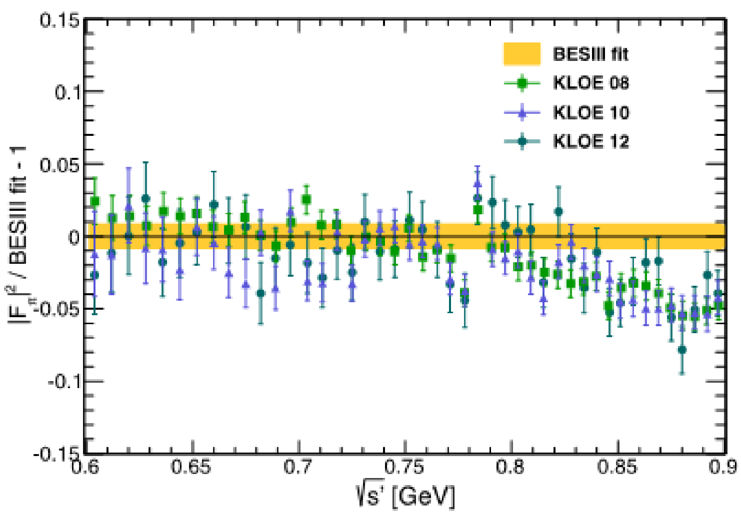
PL B753 (2016) 629

Impact on δa_μ^{Had}

PL B753 (2016) 629



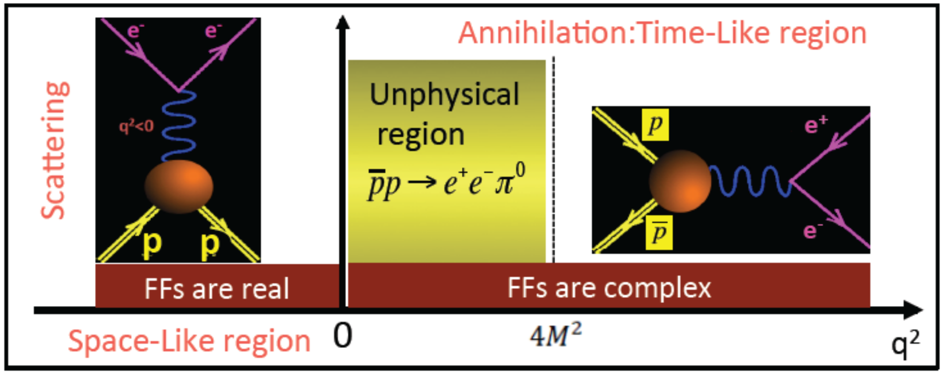




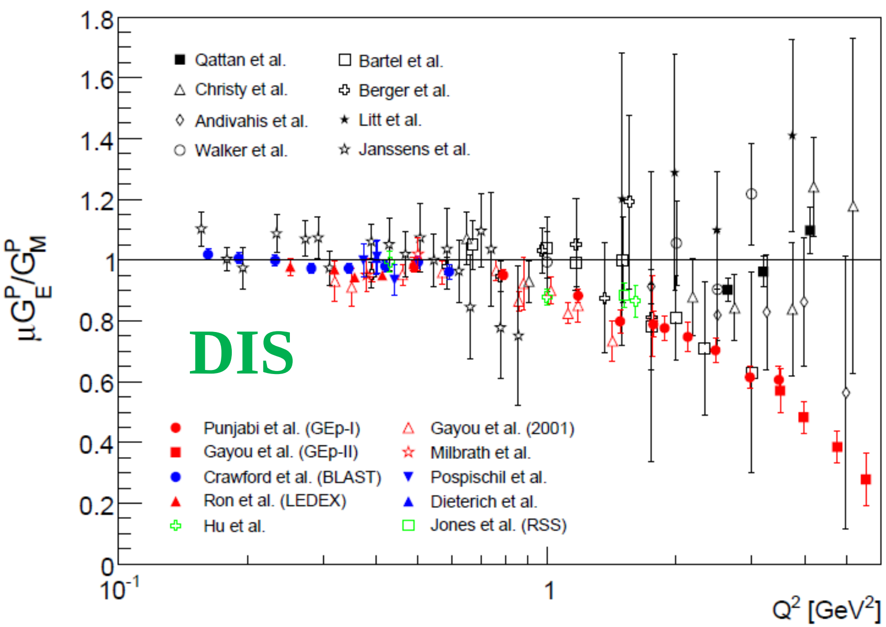
$$a_\mu^{\pi\pi,\mathrm{LO}}(0.6\text{–}0.9\,\mathrm{GeV}) = \frac{1}{4\pi^3}\int_{(0.6\mathrm{GeV})^2}^{(0.9\mathrm{GeV})^2} ds'\,K(s')\,\sigma^{\mathrm{bare}}_{\pi\pi(\gamma)}$$

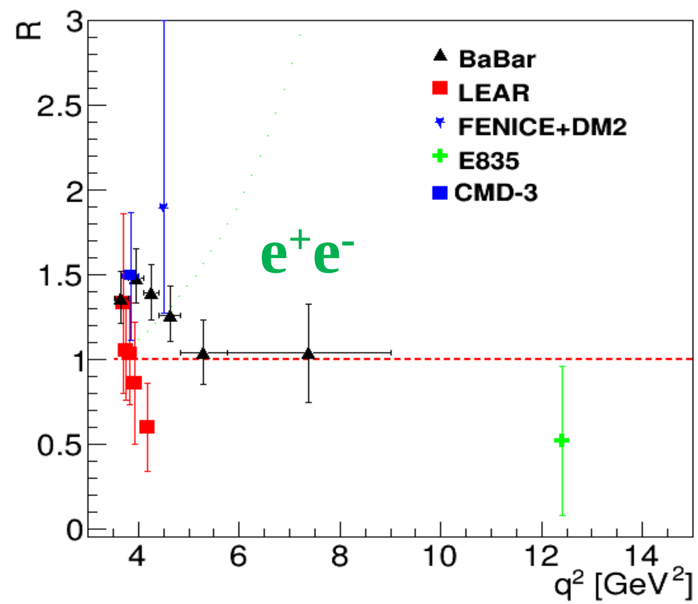
- **Reduction of $\delta a_\mu^{2\pi} = \pm(3.0 \rightarrow 2.6)\times 10^{-10}$ by BESIII data**
- **Goal @ arXiv:1311.2198, $a_\mu^{Had} = \pm(4.2 \rightarrow 2.6)\times 10^{-10}$**

Proton form factor

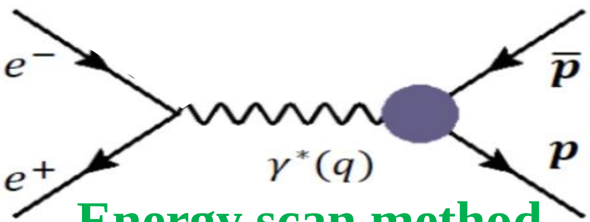


- Proton: electric G_E, magnetic G_M
  - ✓ probe size of proton @ low q^2
  - ✓ test QCD scaling @ high q^2
- $R=G_E/G_M$ ratio at DIS: a few %
- R at e^+e^-: large uncertainty

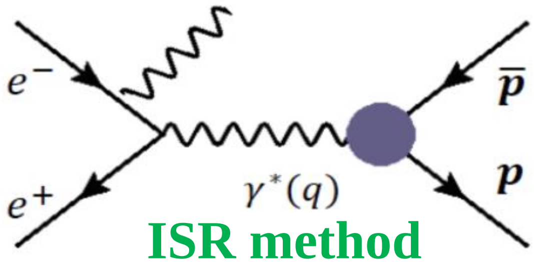




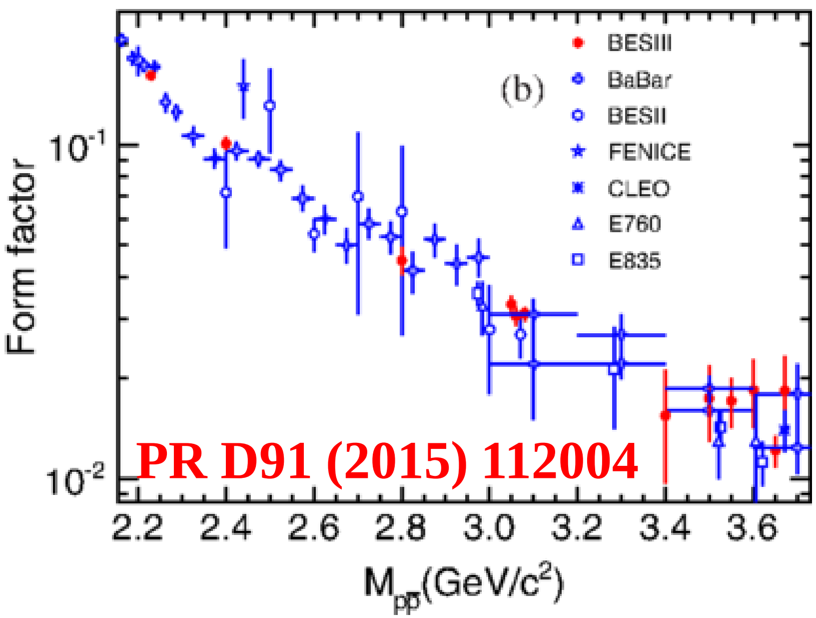
Proton form factor

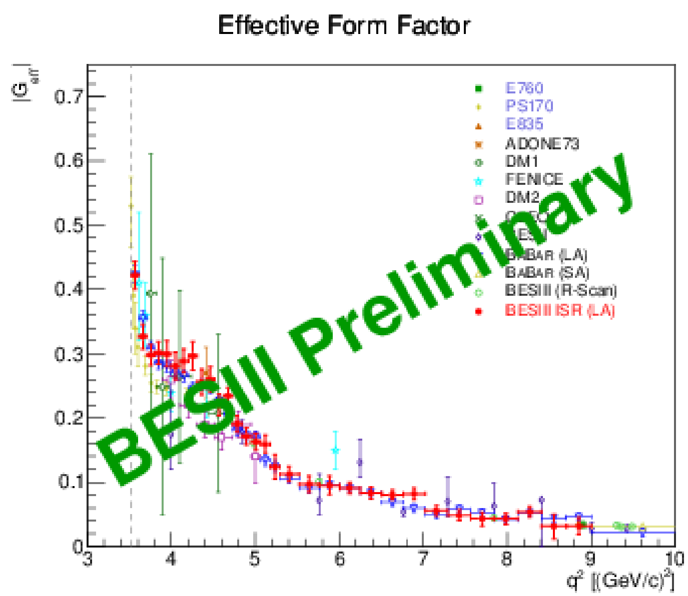


Energy scan method



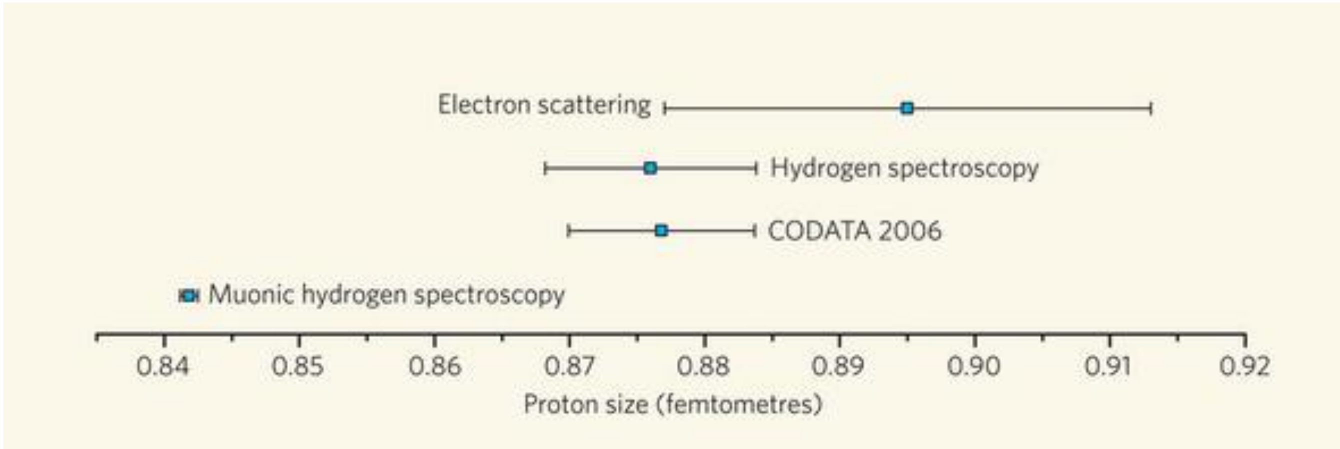
ISR method

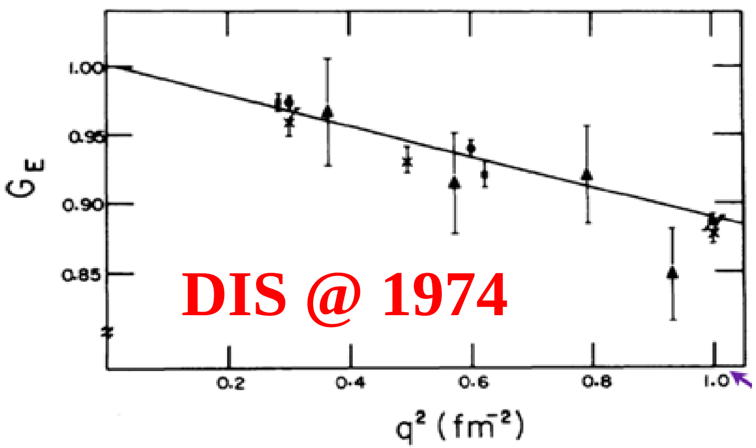




Details @ Zhaoxia's talk

Size of proton





$$-6\frac{dG_{E,M}}{dQ^2}\Big|_{Q^2=0} = \langle r^2_{E,M}\rangle \equiv r^2_{E,M}$$

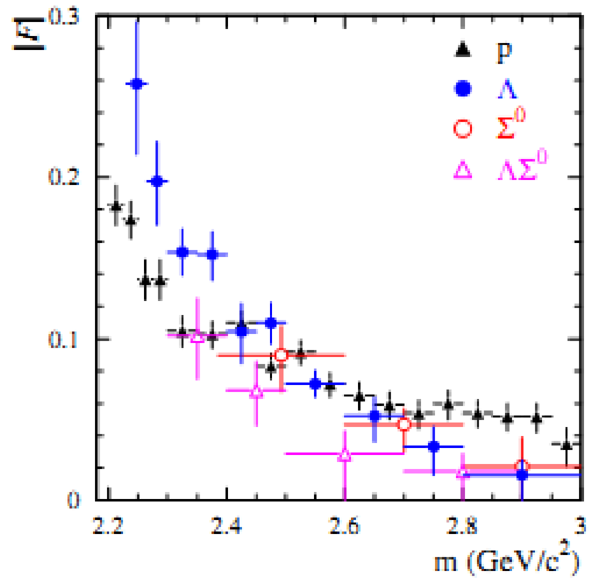
- **atom physics & DIS: about 7σ**
- **use G_E @ e^+e^- ?**
  - ✓ **Contribution from resonance**
  - ✓ **How to extrapolate**

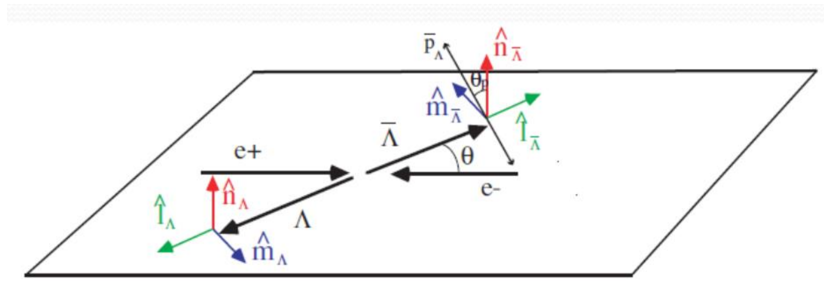
$$G_{E,M}(Q^2) = 1 - \frac{1}{6}\langle r^2_{E,M}\rangle Q^2 + \frac{1}{120}\langle r^4_{E,M}\rangle Q^4 - \frac{1}{5040}\langle r^6_{E,M}\rangle Q^6 + \cdots$$

$e^+e^- \to B\bar{B}$

E_{cm} (GeV)	E_{th} (GeV)	L_{Needed} (pb^{-1})	t_{beam} ($days$)	Purpose
2.0		$\geq$8.95	14.6	Nucleon FFs
2.1		10.8	14.8	Nucleon FFs
2.15		2.7	2.29	Y(2175)
2.175		10(+)	8.5	Y(2175)
2.2		13	11	Nucleon FFs, Y(2175)
2.2324	2.2314	11	4	Hyp threshold ($\Lambda\bar{\Lambda}$)
2.3094	2.3084	20	16	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Lambda}$)
2.3864	2.3853	20	8.7	Hyp Threshold ($\Sigma^0\bar{\Sigma}^0$) Hyp FFs
2.3960	2.3949	$\geq$64	27.8	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^-\bar{\Sigma}^+$)
2.5		0.4895	8h	R scan
2.6444	2.6434	65	18	Nucleon & Hyp FFs Hyp Threshold ($\Xi^-\bar{\Xi}^+$)
2.7		0.5542	4.2h	R scan
2.8		0.6136	4h	R scan
2.9		100	18.5	Nucleon & Hyp FFs
2.95		15	2.8	$m_{p\bar{p}}$ step
2.981		15	2.8	η_c , $m_{p\bar{p}}$ step
3.0		15	2.8	$m_{p\bar{p}}$ step
3.02		15	2.8	$m_{p\bar{p}}$ step
3.08		120	13.2	Nucleon FFs (+30 pb^{-1})

$B\bar{B}$	E (GeV)
$\Lambda\bar{\Lambda}$	2.232
$\Sigma^0\bar{\Lambda}$	2.309
$\Sigma^+\bar{\Sigma}^-$	2.386
$\Sigma^+\bar{\Sigma}^-$	2.386
$\Sigma^0\bar{\Sigma}^0$	2.386
$\Sigma^+\bar{\Sigma}^-$	2.395
$\Sigma^+\bar{\Sigma}^-$	2.395
$\Sigma^-\bar{\Sigma}^+$	2.395
$\Xi^0\bar{\Xi}^0$	2.644
$\Xi^-\bar{\Xi}^+$	2.644

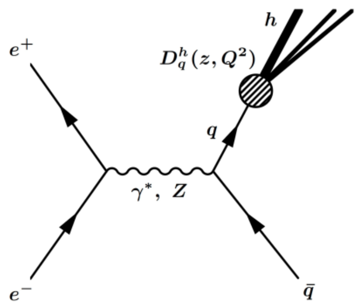


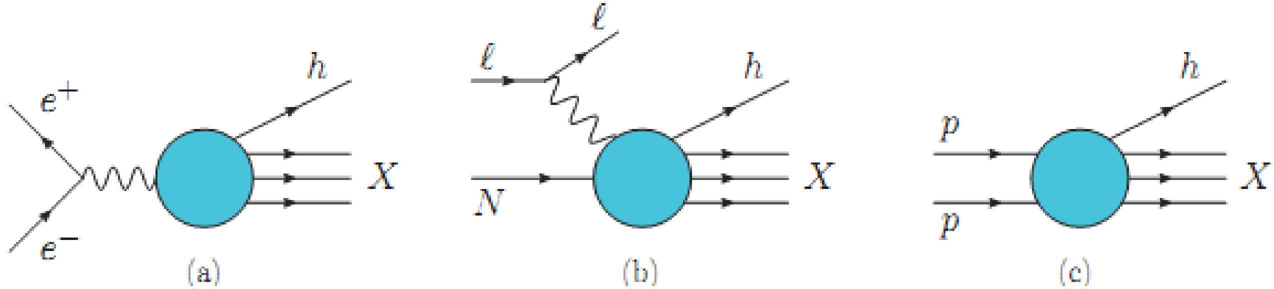


- **Λ form factor G_E/G_M, and phase angle between G_E and G_M for polarization effect**

Fragmentation function (FF)

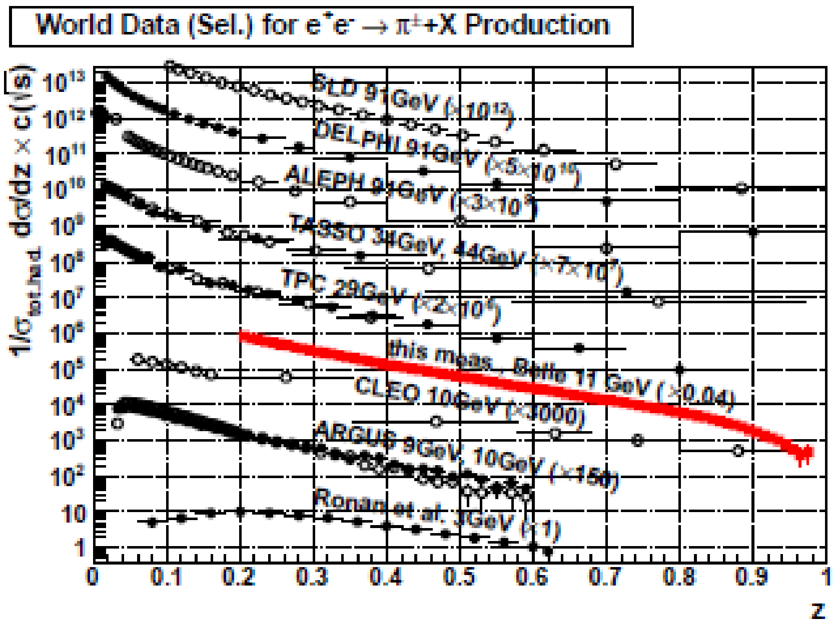
- Fragmentation function $D^{h}{}_{q}(z)$: probability that hadron h is found in the debris of a parton carrying a fraction $z=2E_h/\sqrt{s}$ of parton's Momentum.

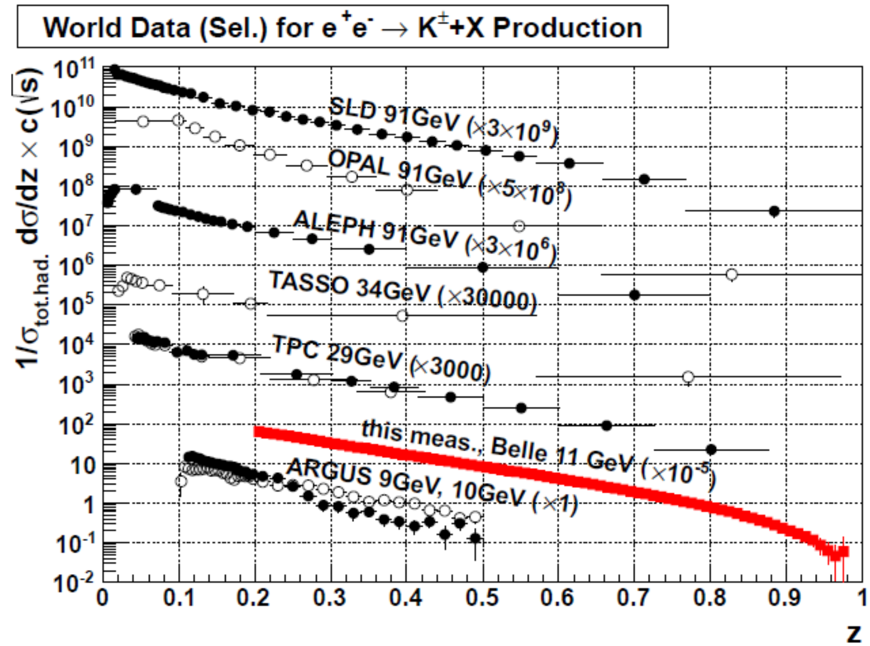




- FF: QCD first principle (NOT YET)
  - ➢ FF evolution function: DGLAP (similar to that of PDF)
  - ➢ Fitting: parametrization & experimental data
  - ➢ Universality: e^+e^-, DIS, pp, $p\bar{p}$

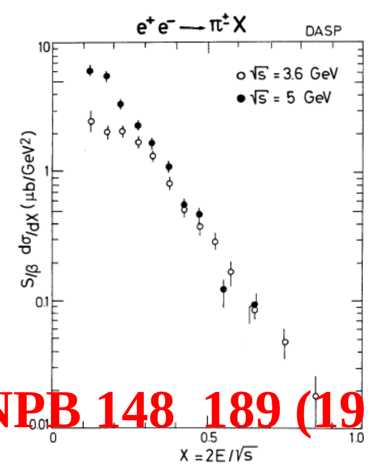
$e^+e^-\to\pi/K + X$





PRL 111 062002 (2013)

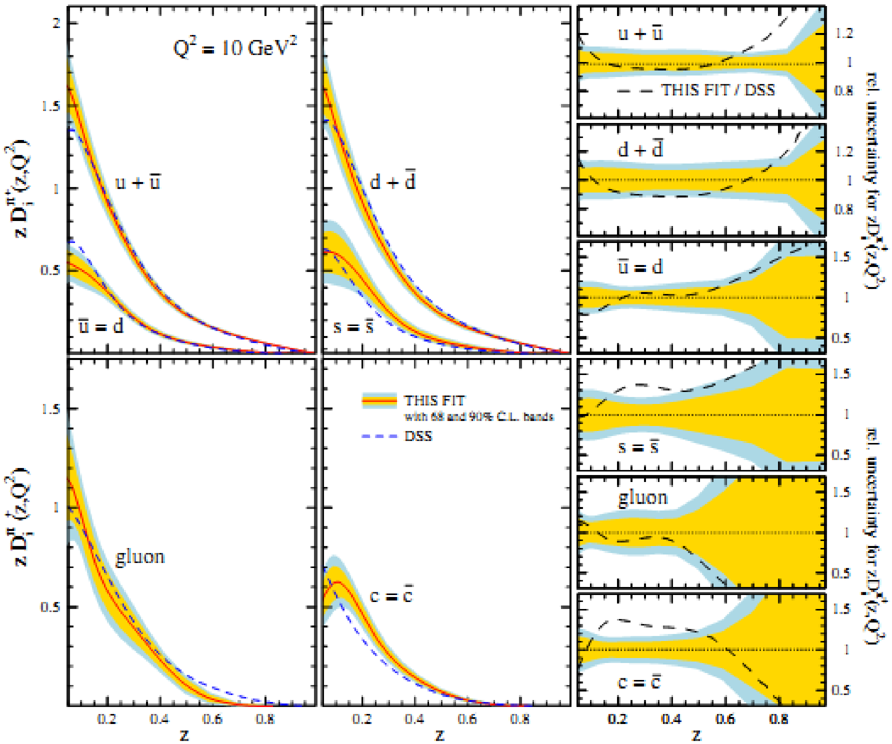
- **Lack of data at low energy and high z**
  - **Poor precision**
  - **BESIII energy: [2, 4.6]GeV**

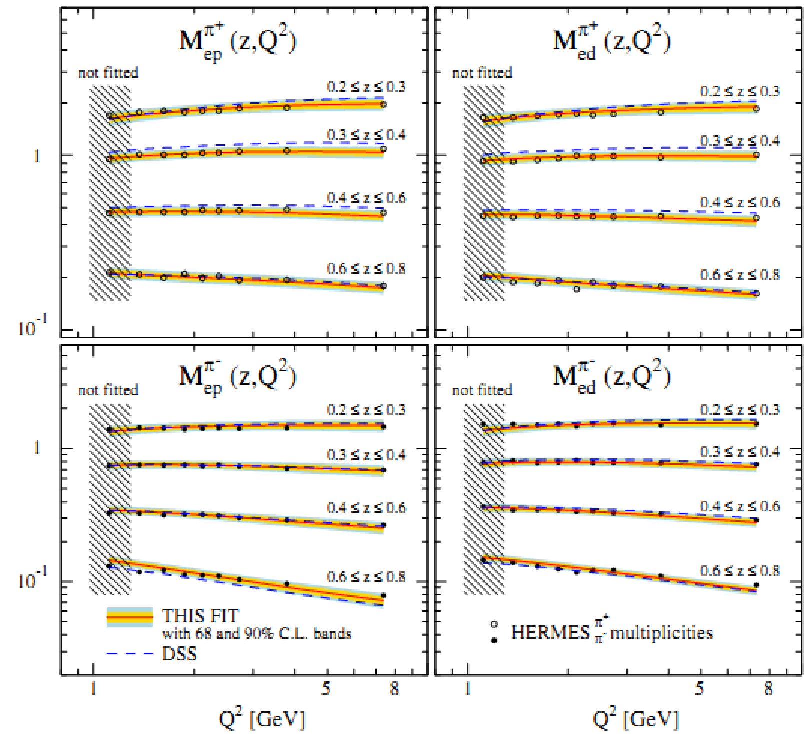


NPB 148 189 (1979)

Pion FF

PRD 91 014015 (2015)

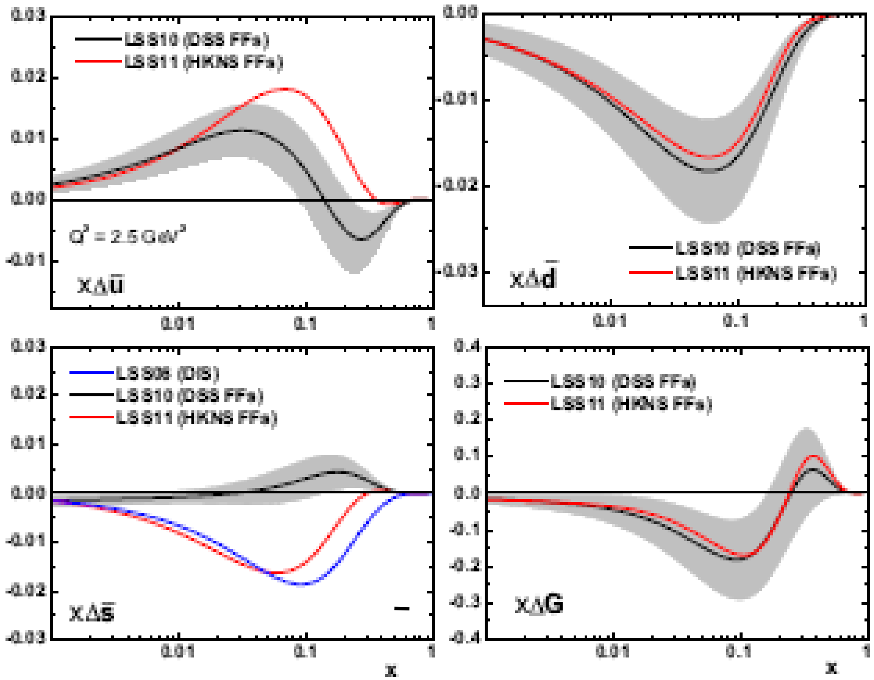




- **For z≥0.8, uncertainty rapidly increase because of the lack of experimental data.**

Strange quark polarization puzzle

- Polarization strange parton PDFs: Δs(x)+Δs(x)
  - ➢ Polarized inclusive DIS: negative for all values of x
  - ➢ Semi-inclusive DIS: positive for most of measured x
  - ➢ PRD 84 014002 (2011) : HKNS FF, negative for SIDIS

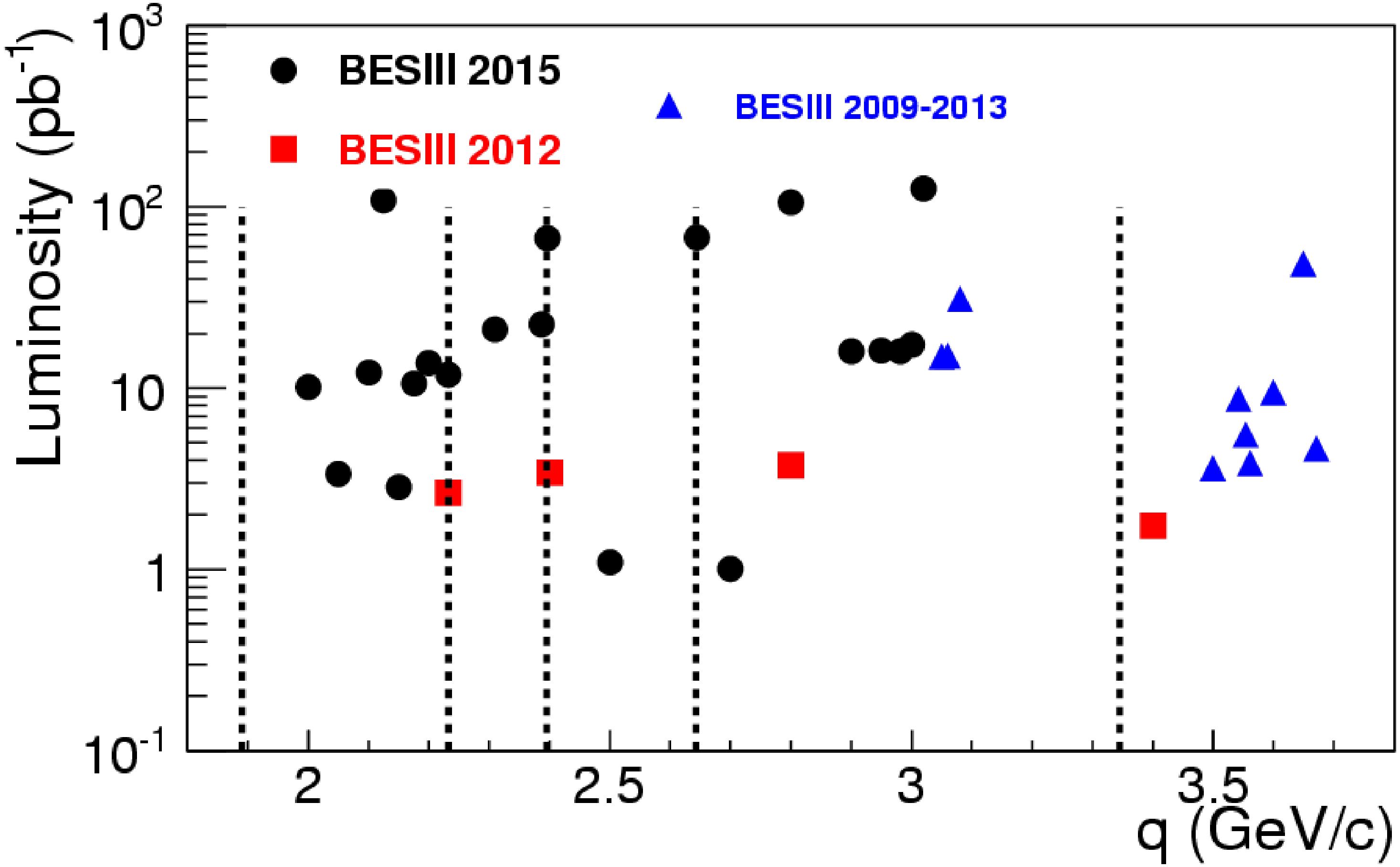


PRD 84 014002 (2011)

- Inclusive DIS: e+N→e’+X
  - ➢ PDF
- Semi-inclusive e+N→e’+h+X
  - ➢ PDF and FF

Inclusive kaon production

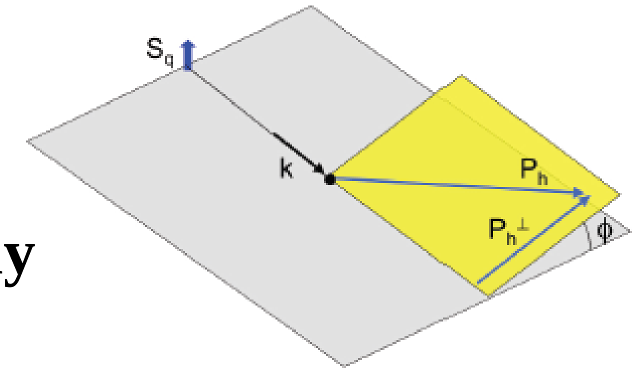
$e^+e^- \rightarrow \pi^0/K_s + X$



- **Study of $e^+e^- \rightarrow \pi^0/K_s + X$ at BESIII**

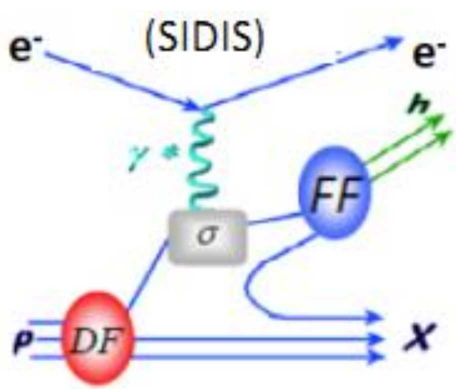
Spin-dependent Fragmentation

- Relate the polarization of quark to that of the final hadron.
- Collins FF: chiral odd function that describe fragmentation of a transversely Quark into a spinless hadron



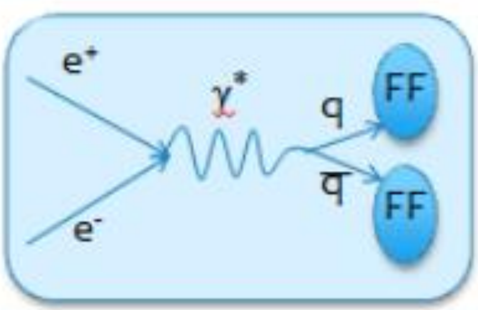
unpolarized FF　　　Collins FF

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



Collins FF ⊗ transversity

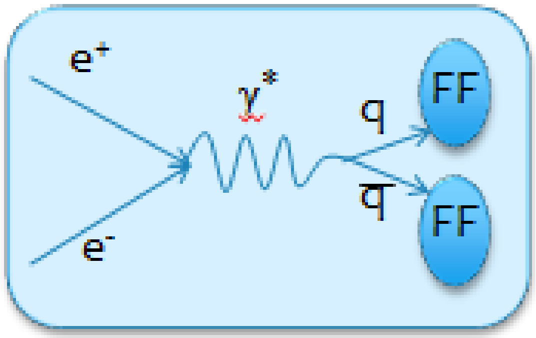
Unpolarized e+e- annihilation

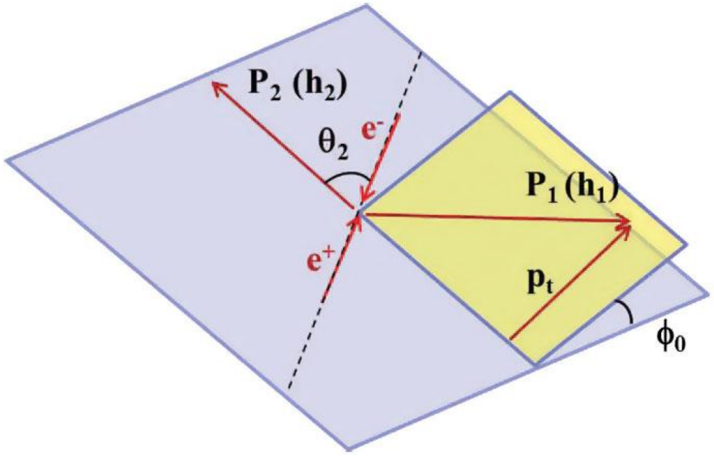


Collins FF ⊗ Collins FF

Collins Effect

- **Collins effect: transverse quark spin relates to an azimuthal asymmetry.**
- **Correlation of quark and anti-quark @ unpolarized beams**





- **The normalized di-hadron yield is parametrized as**

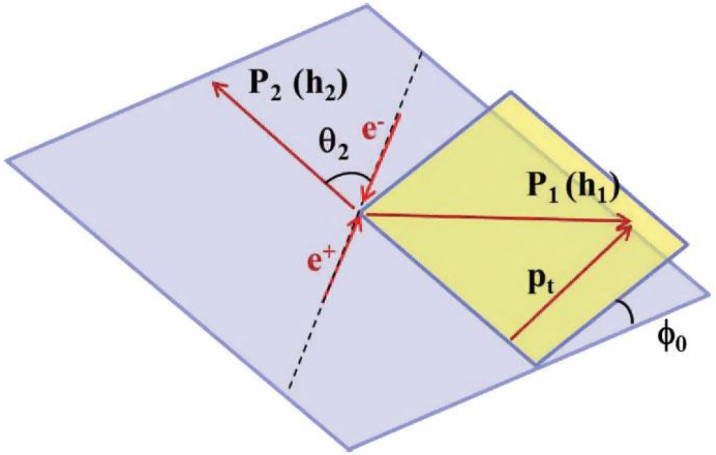
$$a \cos(2\phi_0) + b$$

$$a = a(\theta_2, z_1, z_2)$$

$$z = 2E_h / \sqrt{s}$$

$e^+e^- \to \pi\pi X$

- **Normalized ratio R=$\frac{N(2\phi_0)}{<N_0>}$**
- **$N(2\phi_0)$: dipion yield in each $2\phi_0$ subdivision**
- **$<N_0>$: averaged bin content**
- **Three types of ratio**
  - ✓ **Unlike sign ($\pi^{\pm}\pi^{\mp}$): R^U**
  - ✓ **Like sign ($\pi^{\pm}\pi^{\pm}$): R^L**
  - ✓ **Uall pion pairs ($\pi\pi$): R^C**

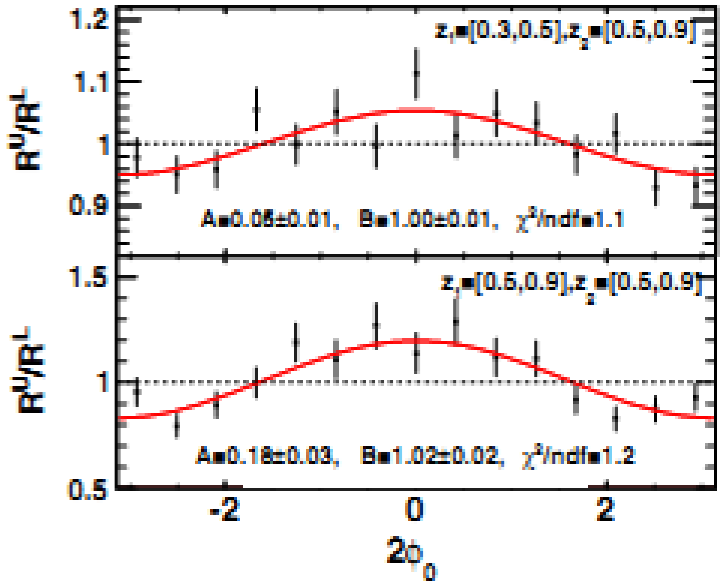


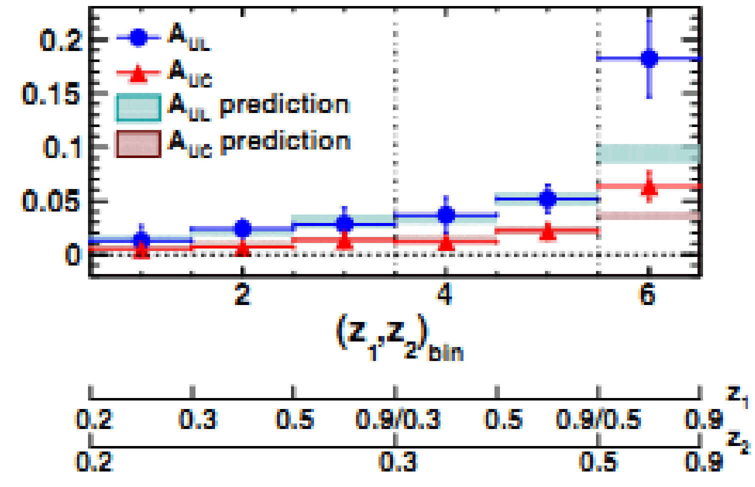
- **Double ratios: reduce acceptance and radiation effect**

$$\frac{R^U}{R^{L(C)}} = A\cos(2\phi_0) + B$$

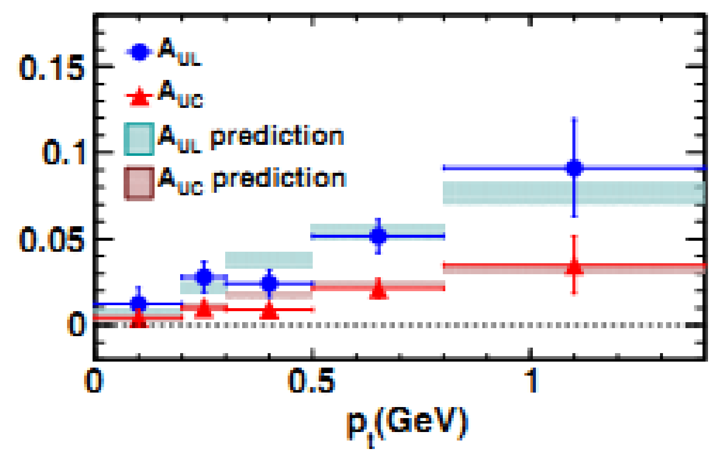
$A^{UL(UC)}$: mainly contains Collins effect
B: consistent with unity

Collins Effect

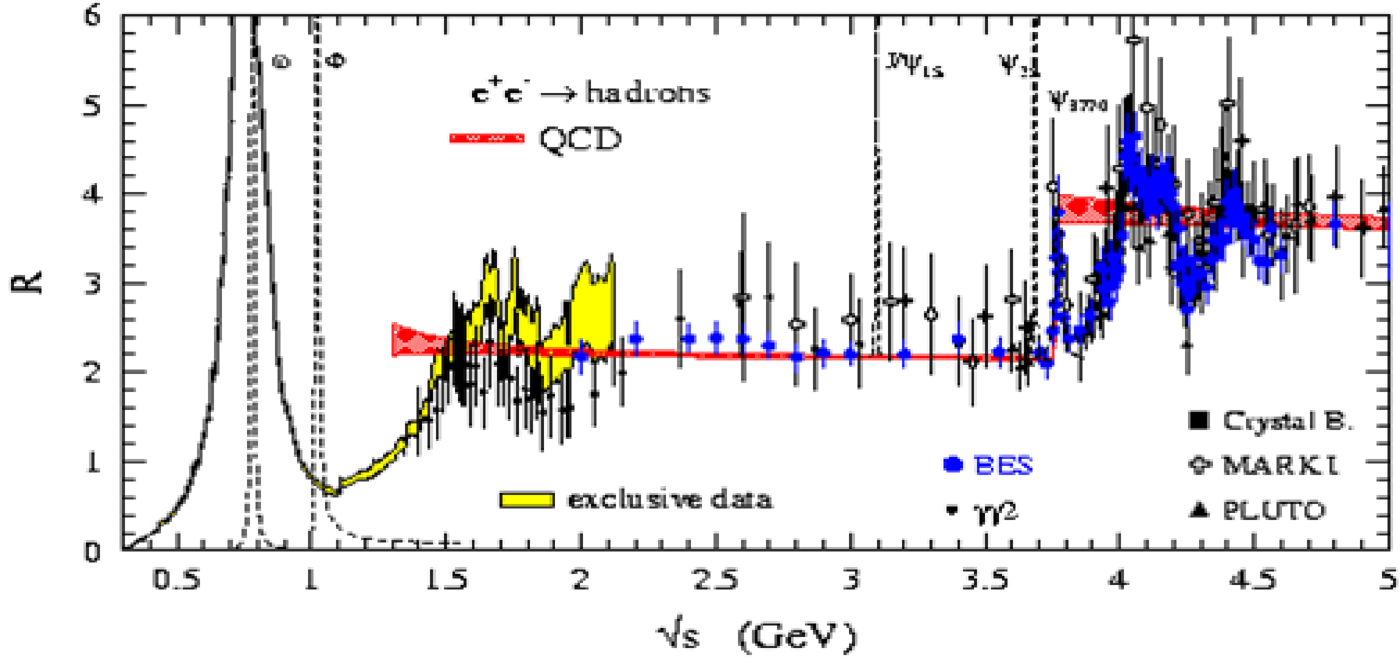




- Obvious asymmetry is observed
- Asymmetry dependence on transverse momentum.

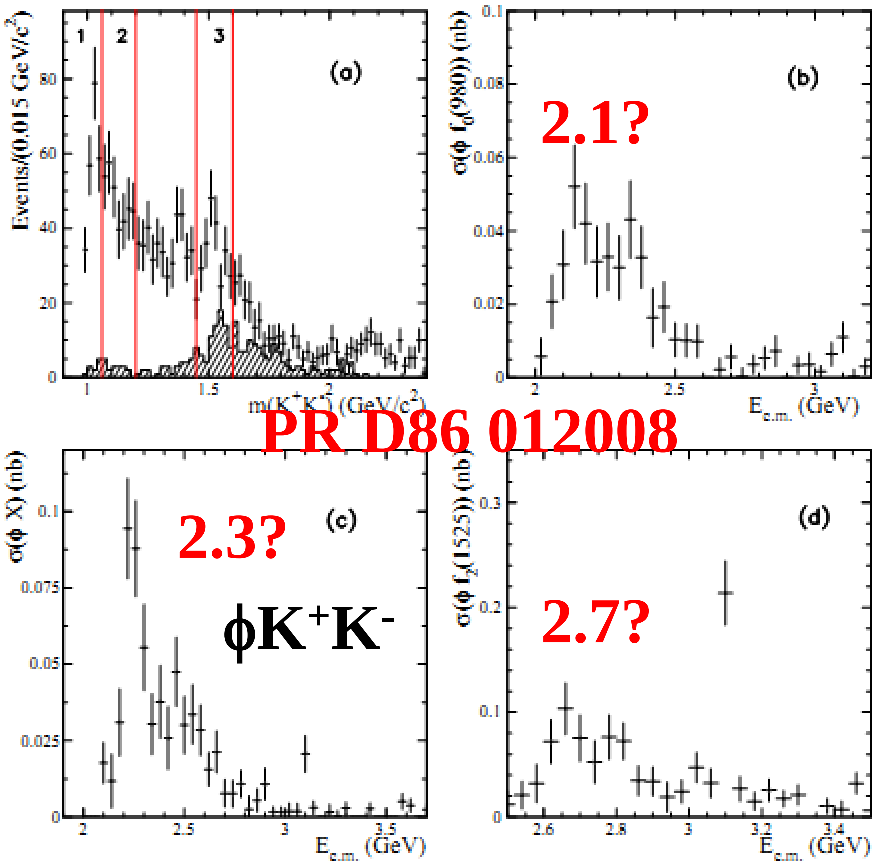


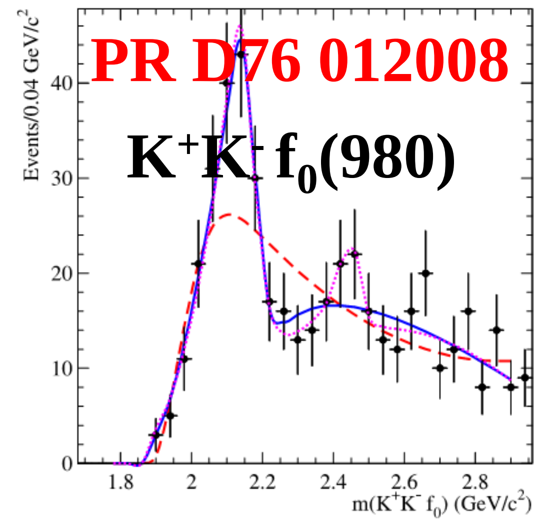
Exclusive decay @ [2.0-3.0]GeV

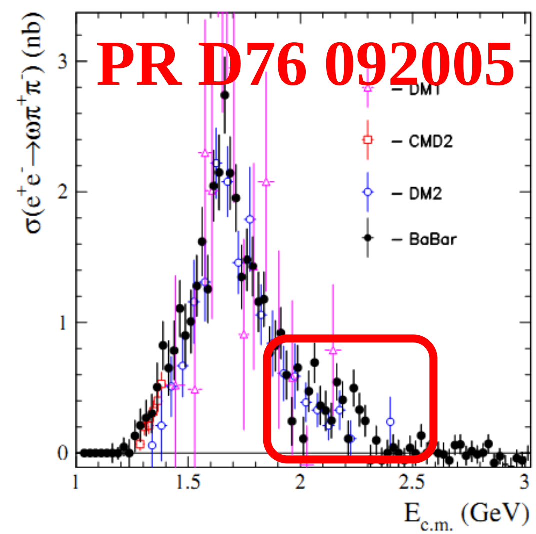


- $J^{PC}=1^{--}$ vector states can be produced directly
- $\sqrt{s} \in [2.0, 3.0]$GeV: ϕ(2170) and ρ(2150) states
- PDG2014 lists many "further states",
  - ✓ ρ(2000), ρ(2270)
  - ✓ ω(1960), ω(2205), ω(2290), ω(2330)

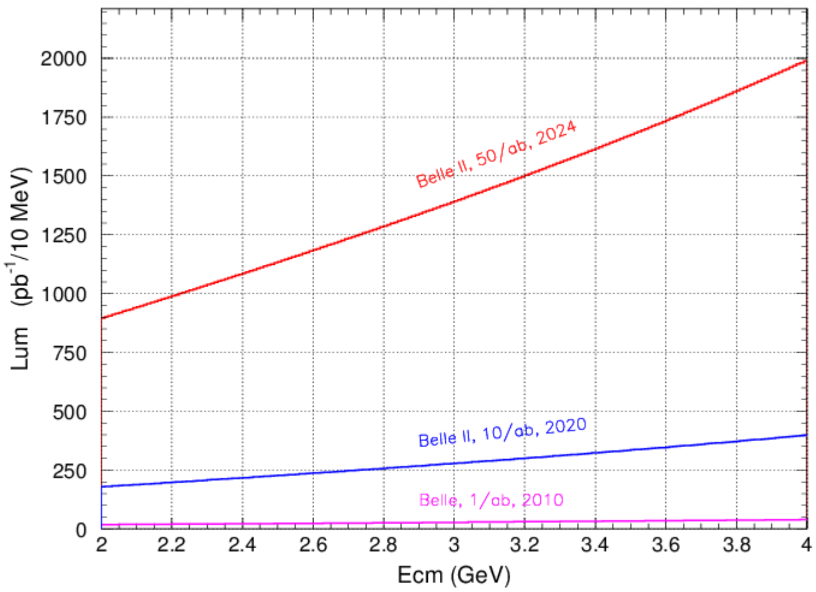
Some results by BABAR

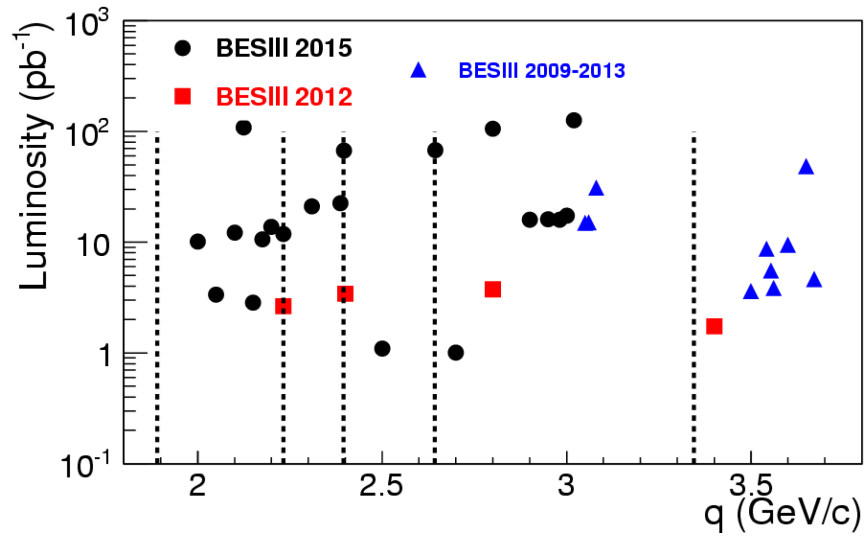


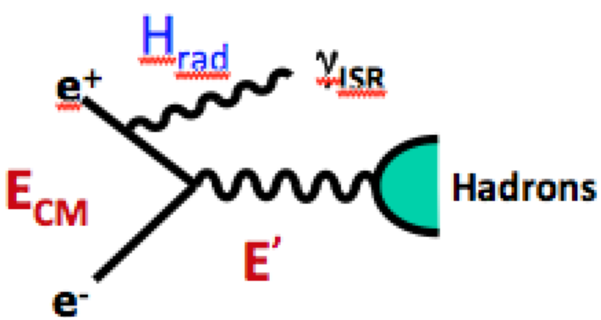




Exclusive decay @ [2.0-3.0]GeV





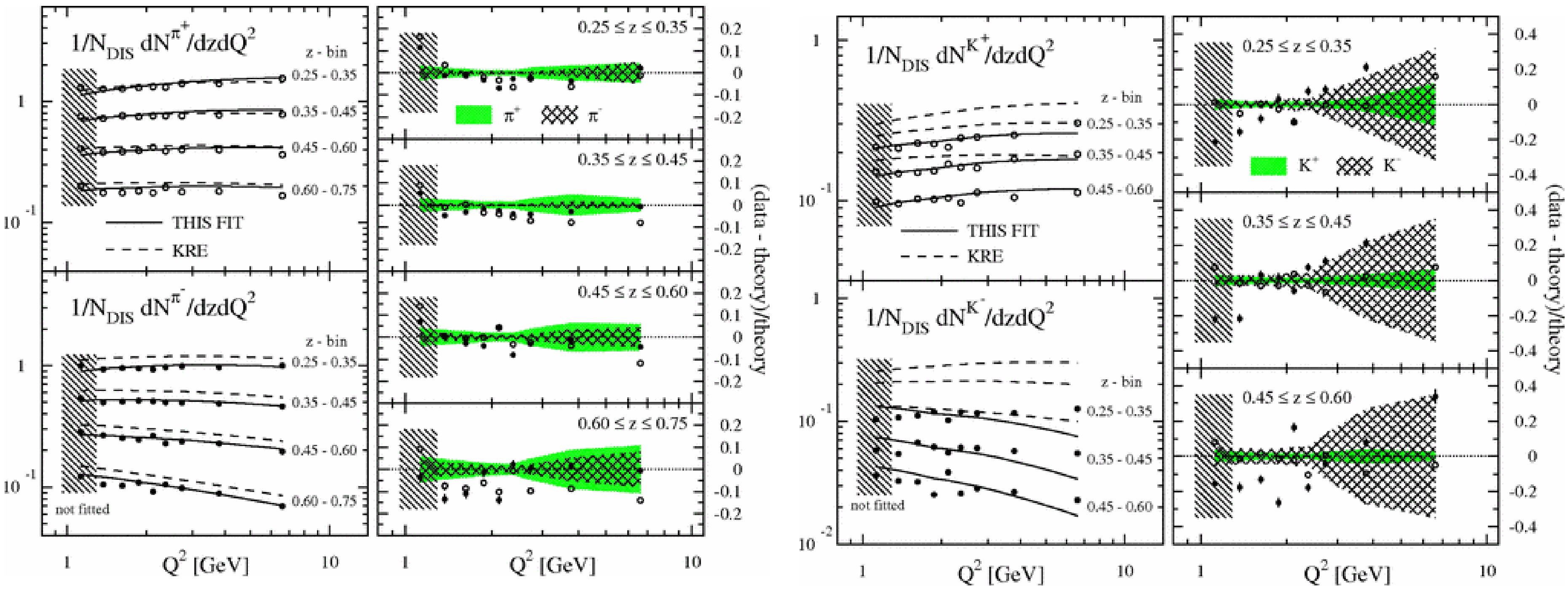


- Compared with BABAR's results, better results by BESIII.
- Belle II data !

Summary and outlook

- **BESIII already collected for R values, there are some progress.**
- **Pion form factor is measured with ISR method with 1% uncertainty, and has improvement on δa_μ**
- **BESIII study baryonform factor by energy scan method and ISR method .**
- **The Collins asymmetry is observed at BESIII.**
- **The energy dependence of exclusive decay modes is useful to $J^{PC}=1^{--}$ vector states.**

HERMES data

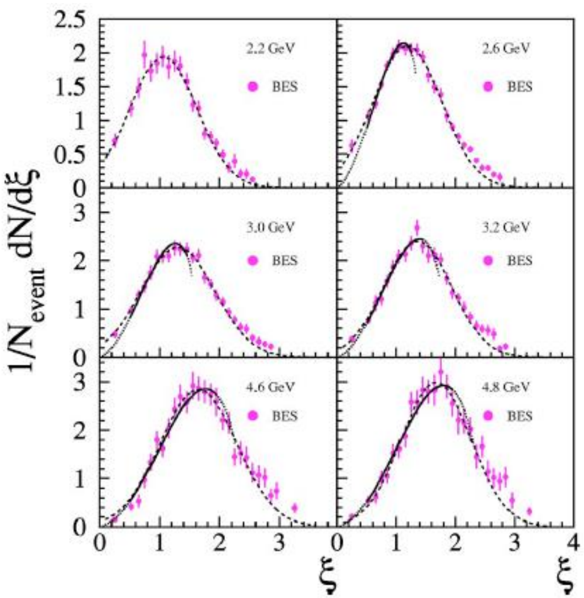


PRD 75 114010 (2007)

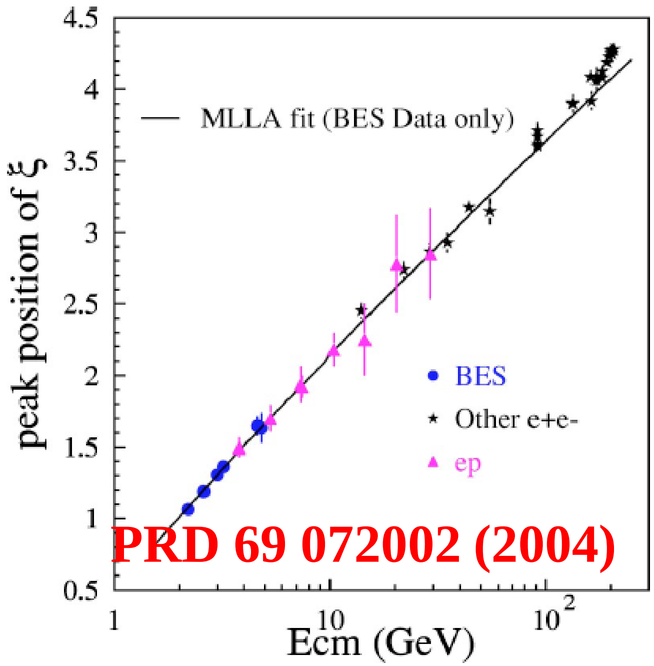
- **DSS FFs could describe HERMES ep pion data at 10% level.**
- **Born level: DIS Q^2 = e^+e^- cms s; e^+e^- data at low energy s: ???**

MLLA/LPHD prediction

- **MLLA: Modified Leading Log Approximation**
  - **calculating partonic distribution**
- **LPHD: : Local Parton Hadronic Duality**
  - **bridge of partonic distribution & hadronic distribution**



$$\xi = -\ln(2p/\sqrt{s})$$



PRD 69 072002 (2004)

- **The fitted line by BES data could describe e+e- & ep data at high energy at 5% level.**