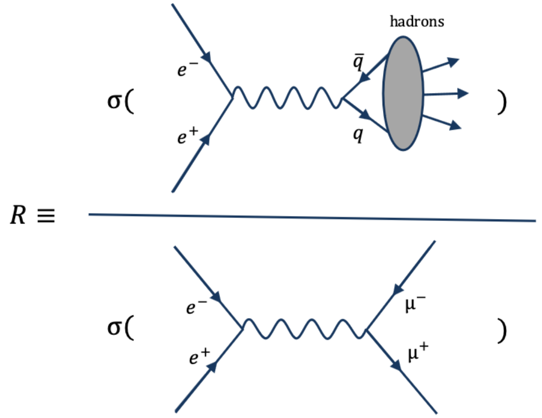
R-value measurements@BESIII

Prof. Francesca De Mori
Università degli studi di Torino e INFN Torino
On behalf of the BESIII collaboration

R-value definition

$$R \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)} \equiv \frac{\sigma^0_{\text{had}}}{\sigma^0_{\mu\mu}}$$



as the leading-order production cross section ratio of hadrons and muon pairs in electron-positron annihilation

With $\sigma^0_{\mu\mu}$ for pure QED process:

$$\sigma^0_{\mu\mu}(s) = \frac{4\pi\alpha^2}{3s}\frac{\beta_\mu(3-\beta_\mu^2)}{2} \qquad \beta_\mu = \sqrt{1-4m_\mu^2/s}$$

<u>**Important input to current tests of Standard Model,**</u>
critical to the determination of the anomalous magnetic moment of the muon and the value of the QED running coupling constant

- About 20 experiments contribute to its measurements (~10 in the lower energy region).
- From 2 to 5 GeV the precision of R measurements the best accuracy was achieved by BESII and KEDR at a few energy points(about 3.3%).
- The systematic uncertainties dominate in all R measurements.

QED running electromagnetic coupling constant, $\Delta\alpha(s)$

$\alpha\ (m^2_Z)$ →one of three essential observables for electroweak precision physics

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

analytically using perturbation theory.

Top quark contribution, small ($10^{-7} \sim 10^{-10}$ in BESIII energy region).

Hadronic Vacuum Polarization contribution

$\Delta\alpha^{(5)}_{\text{had}}$ limits precision physics (EW fit) at M_Z

the contribution of 5 light quarks not computable by perturbative QCD in lower Energy range

$$\Delta\alpha^{(5)}_{\text{had}}(s) = -\frac{\alpha s}{3\pi} \text{Re} \int_{E_{\text{th}}}^{\infty} \text{d}s' \frac{R(s')}{s'(s' - s - i\varepsilon)}$$

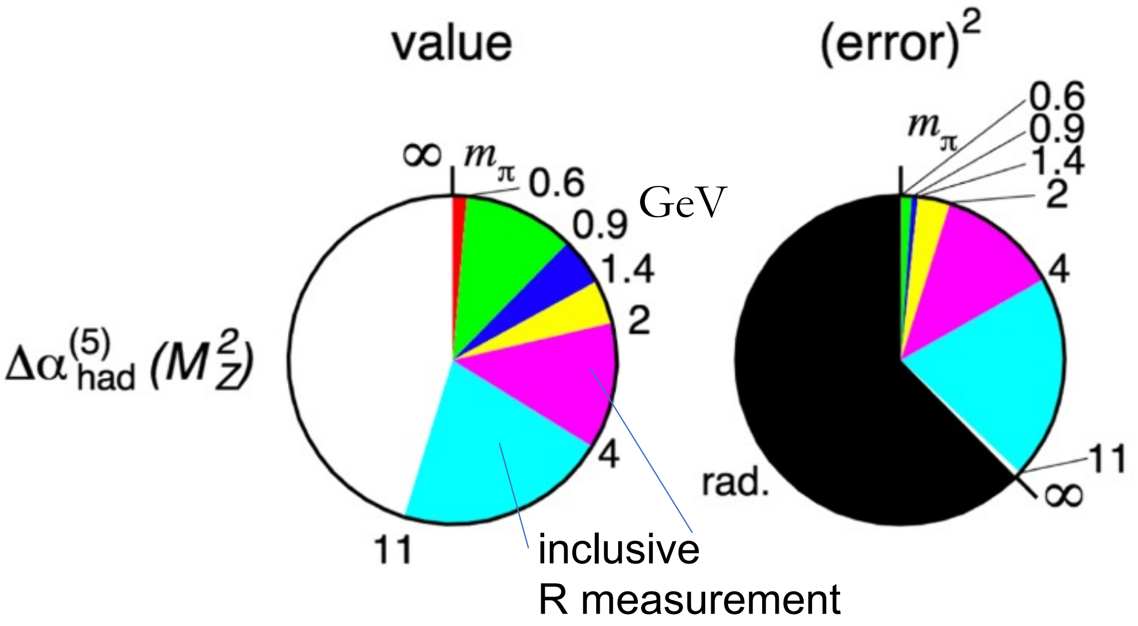
Optical theorem→dispersion integral

HVP calculated using the R value

QED running fine structure constant $\Delta\alpha(s)$

$\alpha\,(m^2_Z)$ →one of three essential observables for electroweak precision physics

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



Source	Contribution($\times 10^{-4}$)
$\Delta\alpha_{lepton}(M^2_Z)$	314.979 ± 0.002
$\Delta\alpha^{(5)}_{had}(M^2_Z)$	276.0 ± 1.0
$\Delta\alpha_{top}(M^2_Z)$	-0.7180 ± 0.0054

Eur.Phys.J. 80 (2020) 241

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R-Value in a wide energy range important input

Anomalous magnetic Moment of the muon

Magnetic moment of the muon

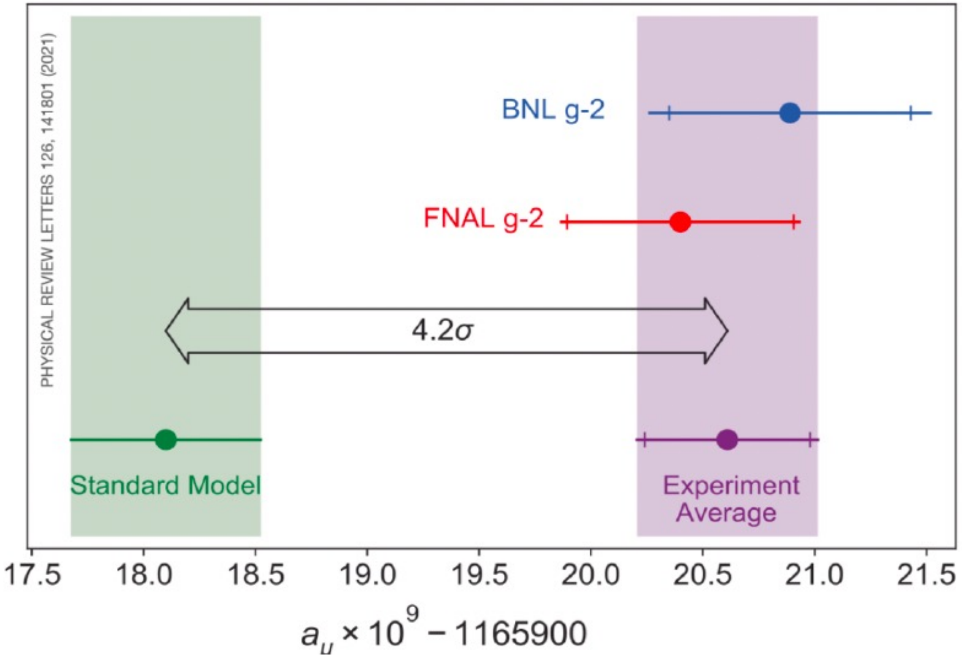
$$\vec{\mu} = g_\mu \frac{e}{2m_\mu} \vec{S}$$

From Dirac theory g_μ is 2

provides an extremely clean test of electroweak theory and may give hints on possible deviations from the SM.

$$a_\mu = \frac{|g_\mu - 2|}{2}$$ **MUON ANOMALY**

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{QCD} + a_\mu^{weak}$$



Less than 0.5 ppm accuracy in experiment and theory

- Exp: 116 592 061(41)× 10^{-11} (Phys.Rev.Lett. 126, 141801 (2021))
- SM : 116 591 810(43))× 10^{-11} (Phys. Rep. 887 (2020)

4.2σ discrepancy → Is it BSM?

Hadronic contribution dominates uncertainties of a_μ^{SM}

HLBL hadronic light-by-light Scattering contribution seems irreducible,

Hadronic Vacuum Polarization

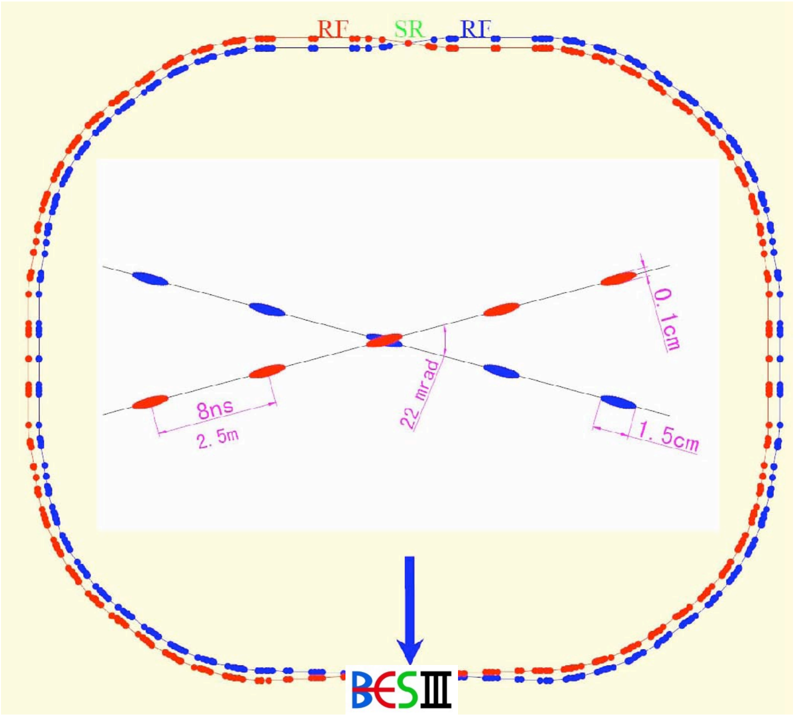
- Cannot be calculated from first principles
- dispersion integral
- R value is experimental input

$$a_\mu^{\text{LO-HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$$

K(s) is a kernel varying from 0.63 at $s = 4m_\pi^2$ to 1.0 at $s = \infty$.

more sensitive to lower energies

Beijing e^+e^- collider :BEPCII



Double ring electron-positron collider, operated @ IHEP (Beijing, PRC) since 2008

Beam energy tunable (RECORD ECM 4.946 GeV in feb 2021)

Single beam current 0.91 A

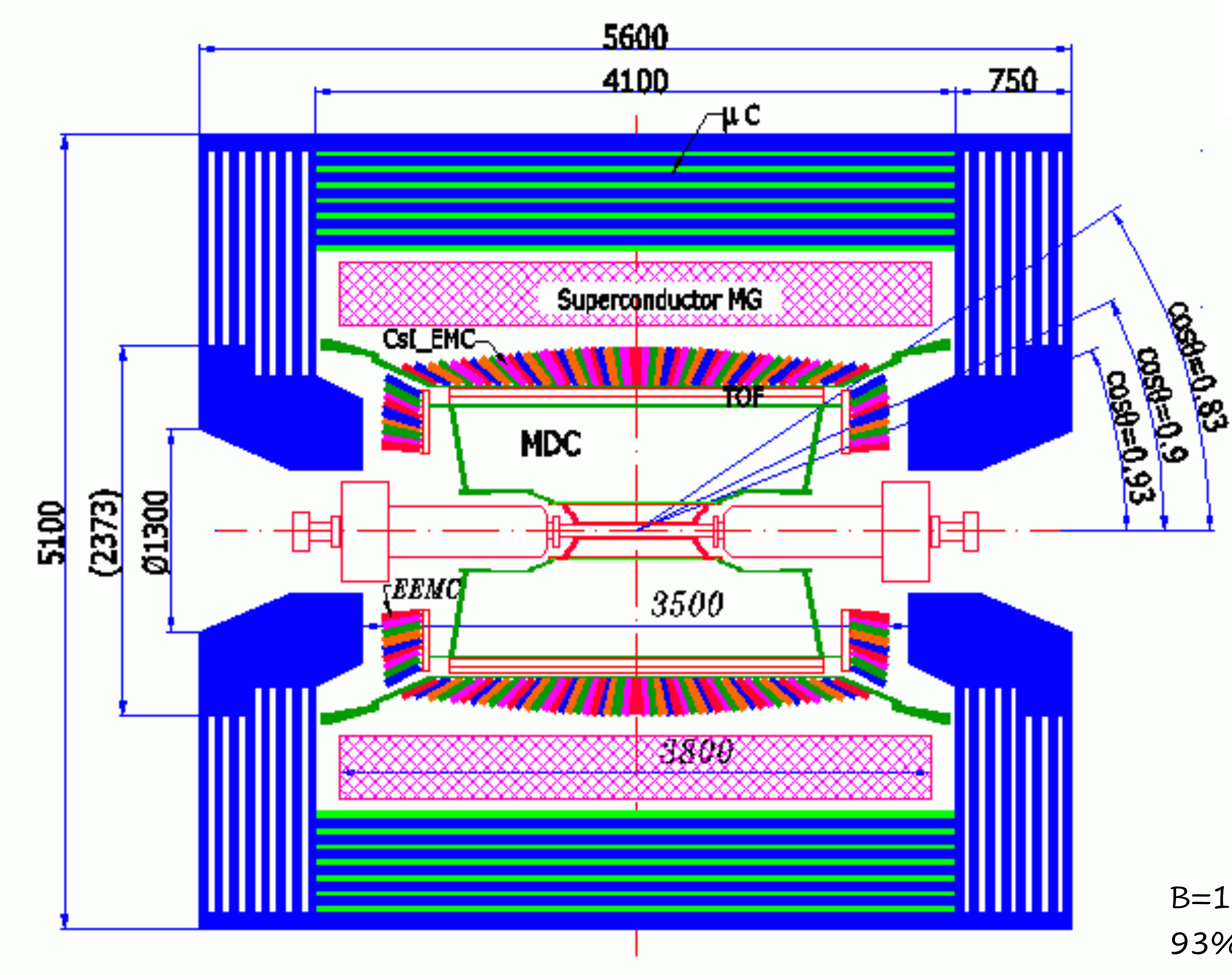
Crossing angle: ±11 mrad

Reached design luminosity @Y(3770)=10^{33} cm^{-2} s^{-1}

BEMS by Laser compton back

Scattering DE/E ≈5 *10^{-5}

Energy spread : 5.16 · 10^{-4}



MDC: main drift chamber (He 60%,propane 40%) σ(p)/p < 0.5 % @1 GeV, σ(xy) =130 mm, 6% dE/dx

TOF: time of flight

(2 layers plastic scintillator): σ~ 68 ps (barrel)): (MRPC) σ~ 60ps @0.8 GeV(end-caps)

EMC(neutral &charged):

Cs I(Tl), barrel+2 end-caps:

σ(E)/E < 2.5 %, σ(x) < 6mm for 1 GeV e^-
Position resolution: δz ~ 0.6/ E

MUC: time of flight (RPC): σ(xy) < 2 cm

Important upgrades in the (very)next future:

CGEM

TOF

About 600 members , 83 institution, 17 countries

B=1T

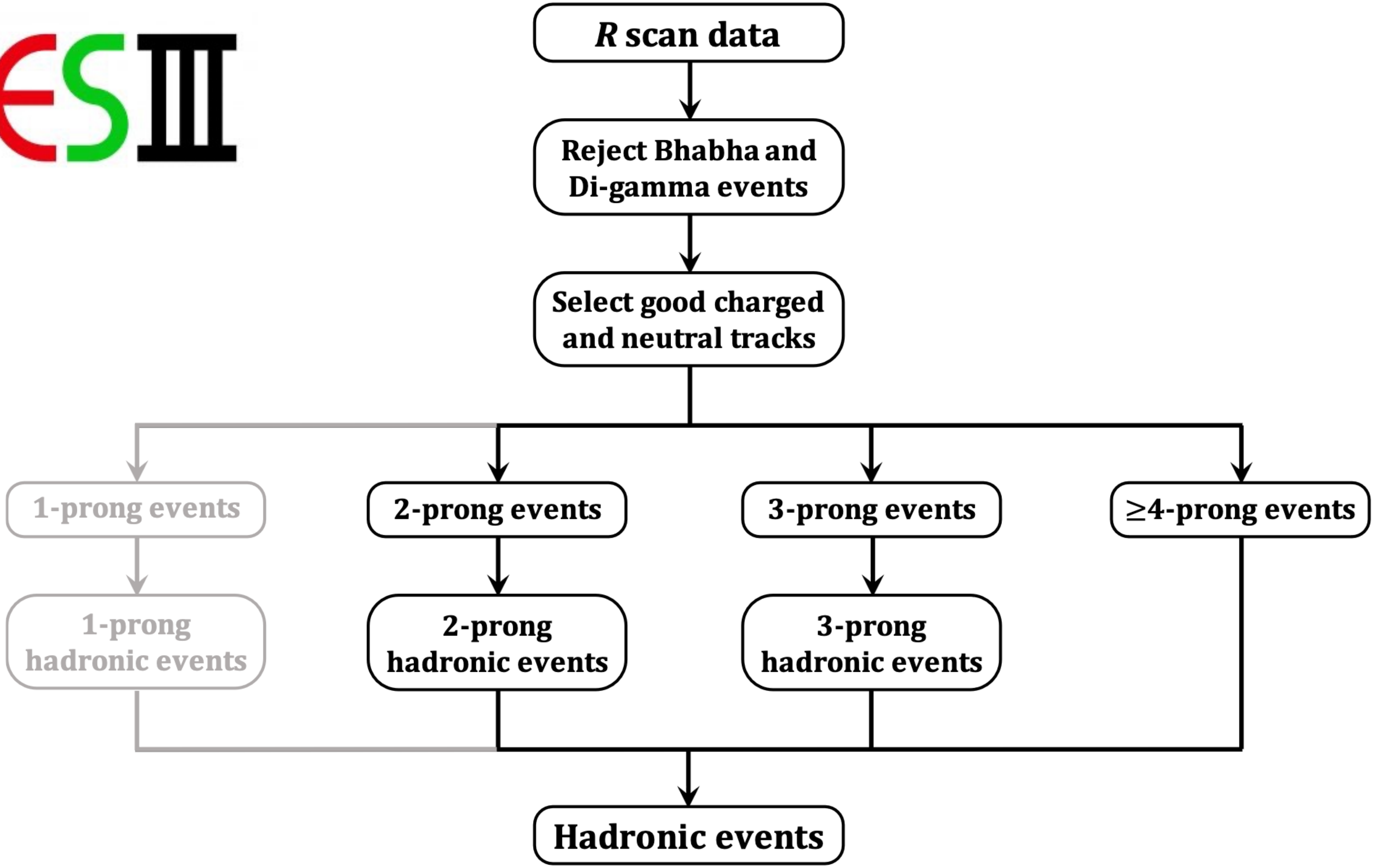
93% 4π acceptance

HOW WE MEASURED R-values in BESIII?

-inclusive R value measurement
- the expected dominant backgrounds are beam-associated and QED background
Events $(e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma, \text{etc.})$

PRL 128, 062004 (2022)

The analysis strategy



R-value experimentally!

BESIII

Residual background events
- MC simulations
- Beam related contributions from data(SB)

Leading order QED Born cross section for $e^+e^- \to \mu^+\mu^-$; $\sigma^0_{\mu\mu}(s) = 86.85$ nb/s

Radiative corrections
- Feynman diagrams
- Structure functions
- Agreement better than 1.4%

$$R = \frac{N_{\mathrm{had}}^{\mathrm{obs}} - N_{\mathrm{bkg}}}{\sigma^0_{\mu\mu}\mathcal{L}_{\mathrm{int.}}\varepsilon_{\mathrm{trig}}\varepsilon_{\mathrm{had}}(1+\delta)}$$

Integrated luminosity (by LA-Bhabha) 0.8% uncertainty

Trigger efficiency ~ 100%.

Detection efficiency

MOST CHALLENGING!!

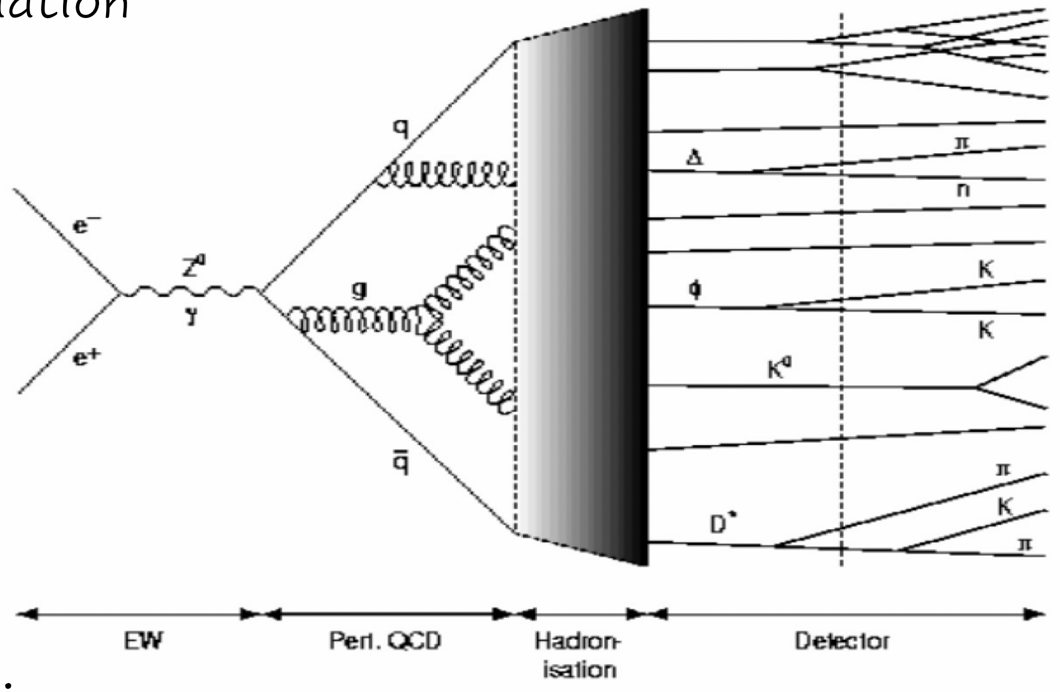
HOW to evaluate hadronic efficiency?

Two signal simulations developed, tuned and studied!!

Luarlw model: nominal model for signal simulation

Hadronization in e^+e^- annihilation

https://arxiv.org/pdf/hep-ph/9910285.pdf



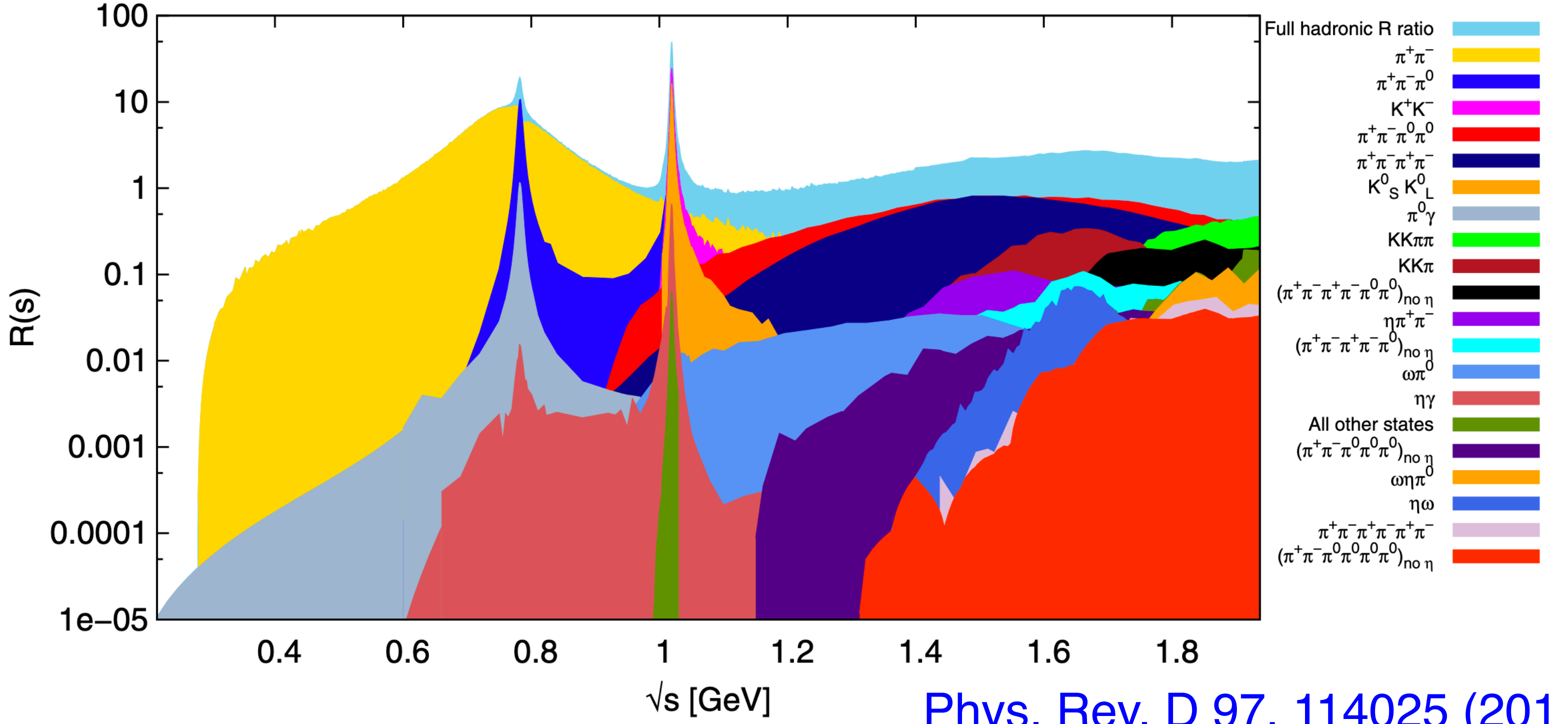
Main features :

- A self-consistent inclusive generator
- based on JETSET at low energies.
- Generation of continuum and resonant states and their decays
- Initial-state radiation (ISR) process implemented from $2m_\pi$ to $\sqrt{s}$ (Feynman diagram).
- Kinematics of initial hadrons determined by the Lund area law.
- Phenomenological parameters tuned to data
- Used in most previous R-measurements

(BESII and KEDR e.g.)

HYBRID:Alternative model

- The Idea behind: Use as much experimental information as possible!
- Combination of 3 well-established models:
  - Conexc (More than 50 channels with cross sections from experiment)
  - Phokhara (10 exclusive channels, hadronic models tuned to experiment)
  - Luarlw (Unknown processes)
- Up-to-date experimental knowledge implemented.
- Alternative ISR and VP correction schemes from the nominal ones adopted

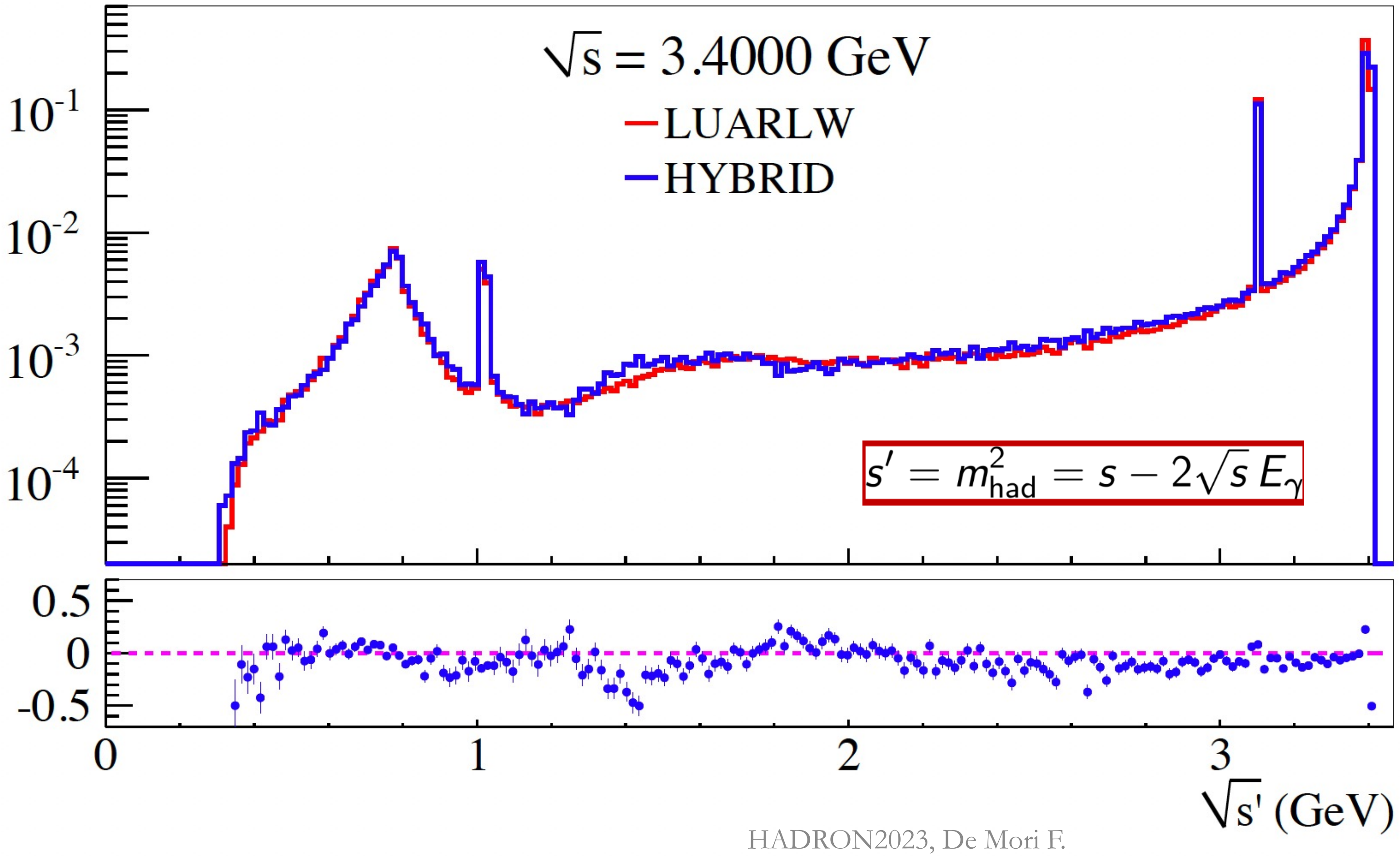


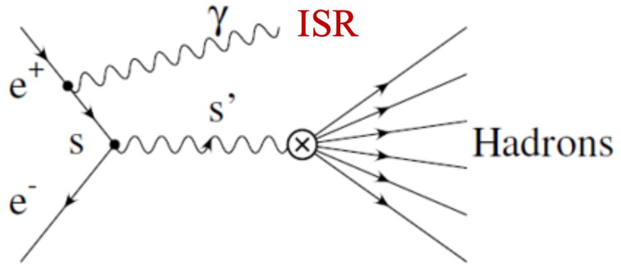
Diff with Luarlw<1.4%

Phys. Rev. D 97, 114025 (2018)

HYBRID-LUARLW comparison: effective energy

The $\sqrt{s'}$ spectrum directly reflect the fraction of the ISR-returned processes





ISR process is simulated with different schemes

The results are consistent For effective energy spectrum!

maximum difference of the calculated ISR corr. factor between HYBRID and LUARLW simulations is 1.4%,

MC-DATA comparison

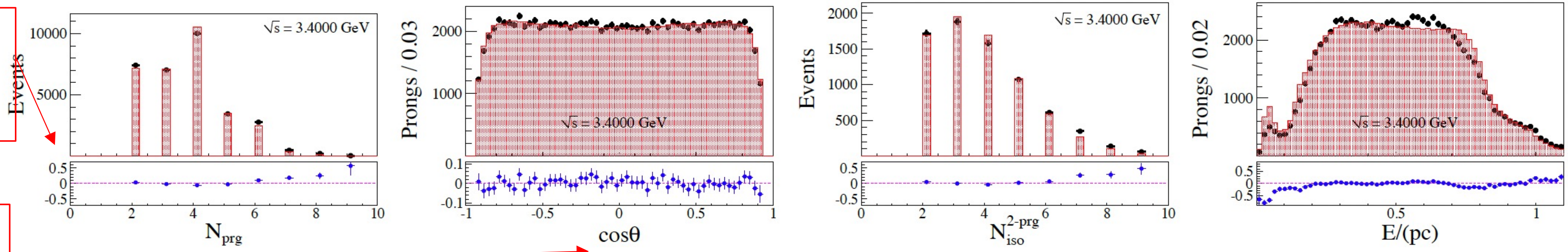
Kinematic observables

Number of isolated clusters in 2-prong events

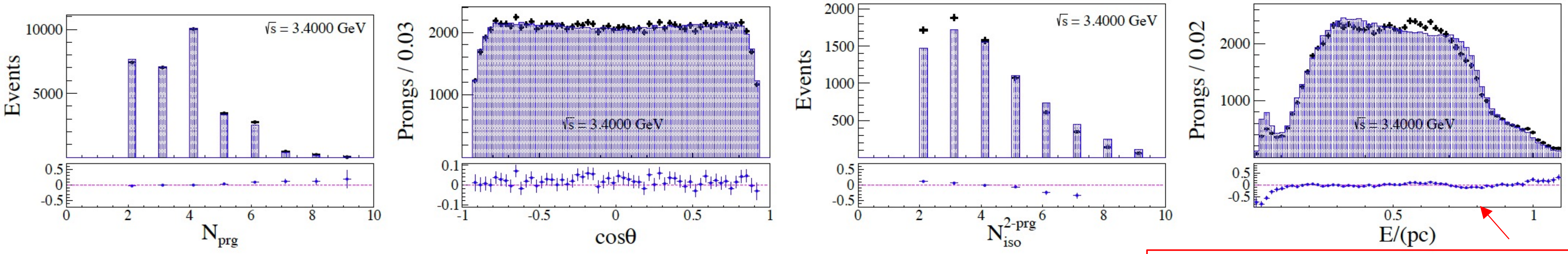
Number of good charged tracks (prongs)

polar angle of charged tracks

LUARLW



HYBRID



@3.4 GeV

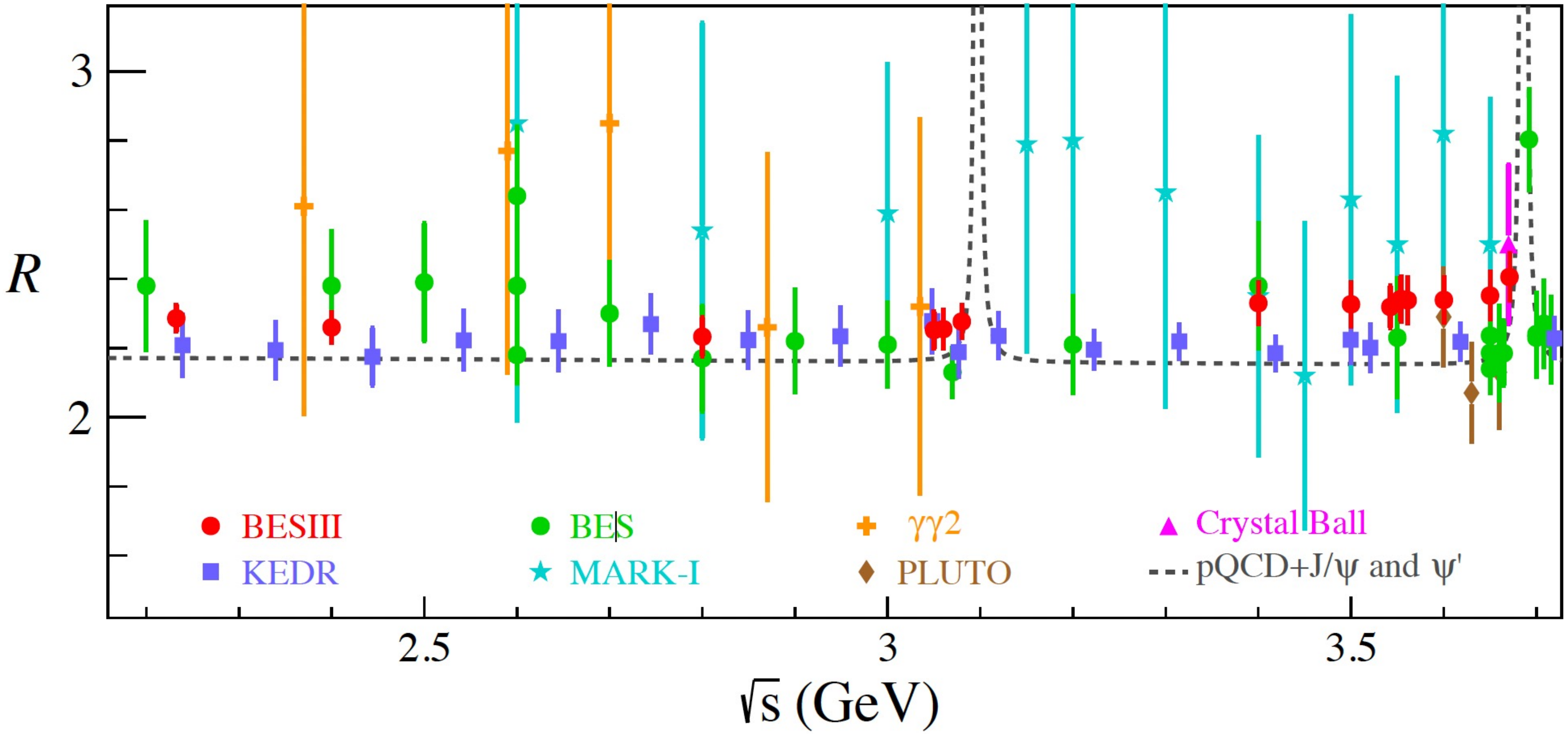
Ratio of EMC deposited energy and momentum

Both models in good agreement with data!

Crucial systematics on hadronic efficiency, evaluted using Hybrid ((ISR+eff) diff < 2.3%)

R-value measurements in 2.2-3.7 GeV energy range

PRL 128, 062004 (2022)



14 c.m. energies

- The accuracy better than 2.6% below 3.1 GeV and 3.0% above, dominated by systematic uncertainties.
- Average R value larger than the pQCD prediction by **2.7 σ** , higher than KEDR by 1.7 σ between 3.4 and 3.6 GeV.

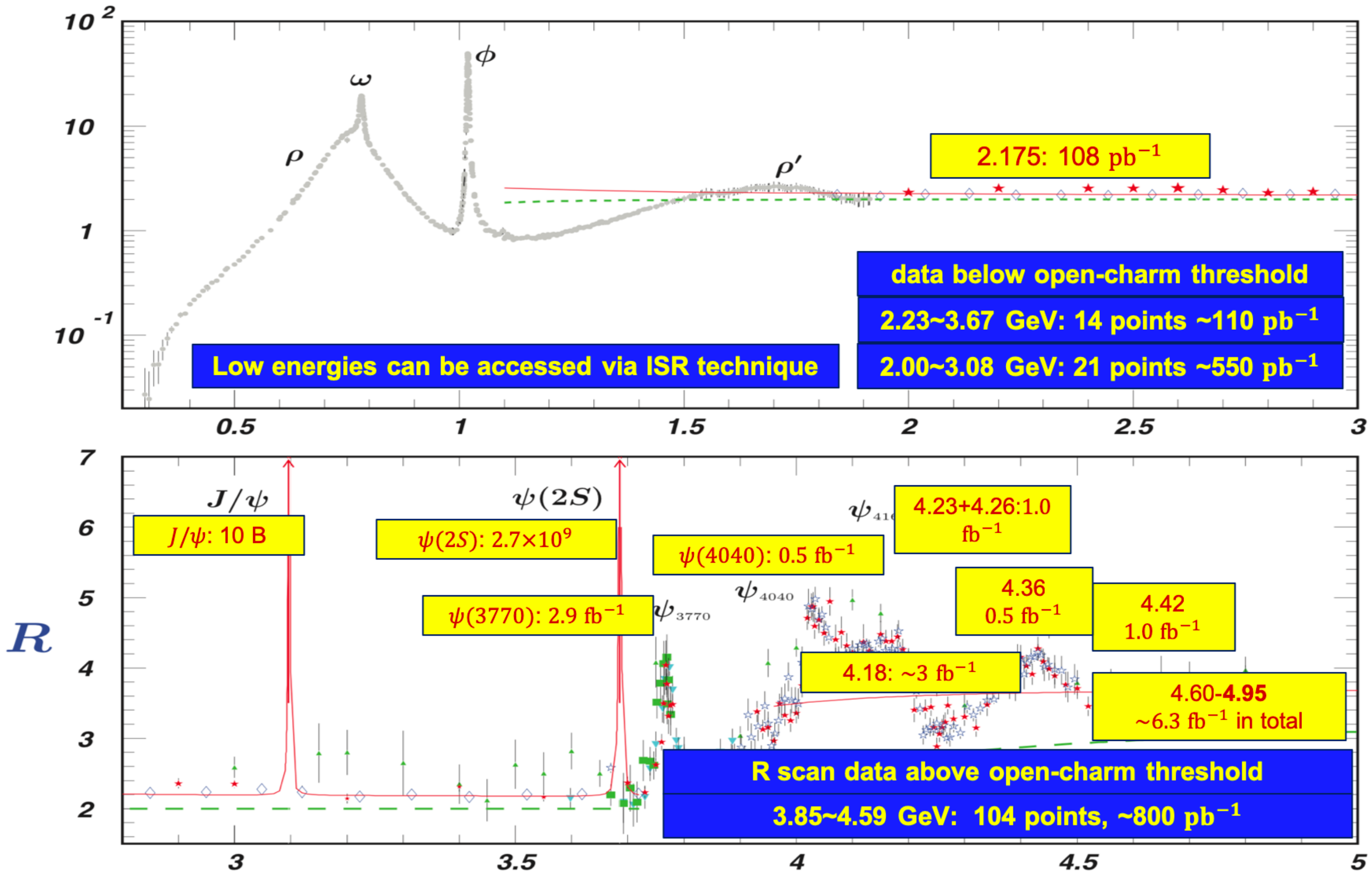
Systematic uncertainties

TABLE I. Summary of systematic uncertainties (in percent) at each c.m. energy, where the total uncertainty is the sum of the individual ones in quadrature. Uncertainties from the last four sources are correlated between the energy points.

$\sqrt{s}$ (GeV)	Event selection	QED background	Beam background	Luminosity	Trigger efficiency	Signal model	ISR correction	Total
2.2324	0.41	0.23	0.28	0.80	0.10	0.60	1.15	1.62
2.4000	0.55	0.27	0.15	0.80	0.10	1.11	1.10	1.87
2.8000	0.58	0.28	0.34	0.80	0.10	1.97	1.06	2.48
3.0500	0.61	0.33	0.41	0.80	0.10	1.76	1.01	2.33
3.0600	0.60	0.34	0.48	0.80	0.10	1.84	1.00	2.39
3.0800	0.61	0.35	0.35	0.80	0.10	1.31	1.05	2.02
3.4000	0.65	0.33	0.16	0.80	0.10	1.86	1.24	2.49
3.5000	0.60	0.35	0.62	0.80	0.10	2.05	1.16	2.66
3.5424	0.61	0.37	0.01	0.80	0.10	2.05	1.14	2.58
3.5538	0.66	0.31	0.39	0.80	0.10	2.22	1.13	2.74
3.5611	0.74	0.34	0.34	0.80	0.10	2.28	1.12	2.81
3.6002	0.66	0.33	0.38	0.80	0.10	2.27	1.09	2.77
3.6500	0.53	0.35	0.69	0.80	0.10	2.28	1.13	2.83
3.6710	0.61	0.42	0.63	0.80	0.10	2.23	1.04	2.77

Statistic uncertainties about 0.35%

Towards further R measurements @ BESIII



Large amounts of additional data already collected
(130 scan data points >10^5 hadrons)

FULL PROGRAM will cover
2.0 - 4.96 GeV

R measurement both in the continuum and open-charm regions with high accuracy would have significant impact.

Measurements with different methods @BESIII?

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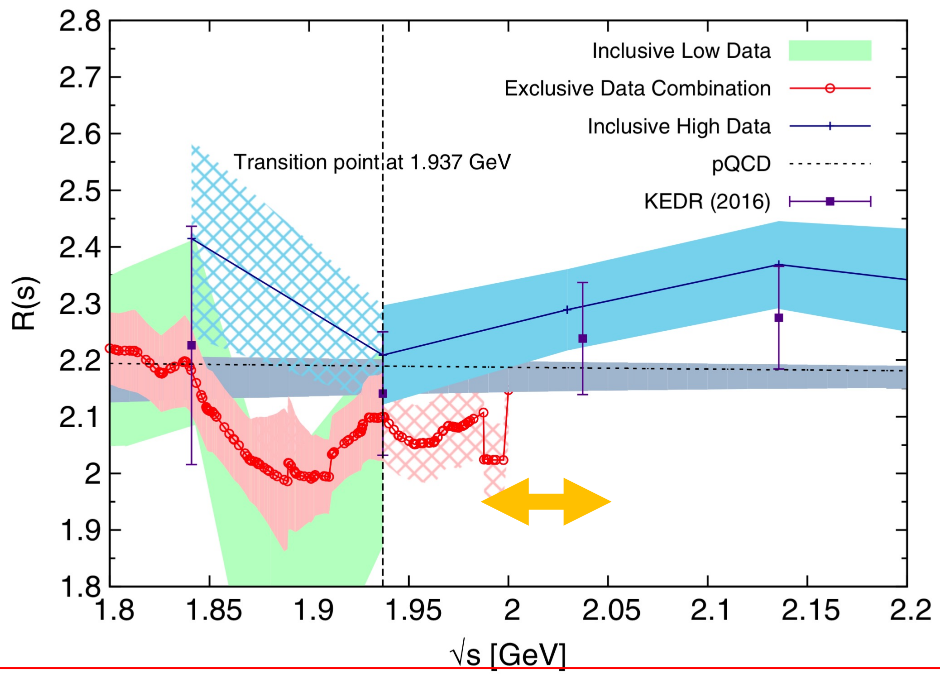

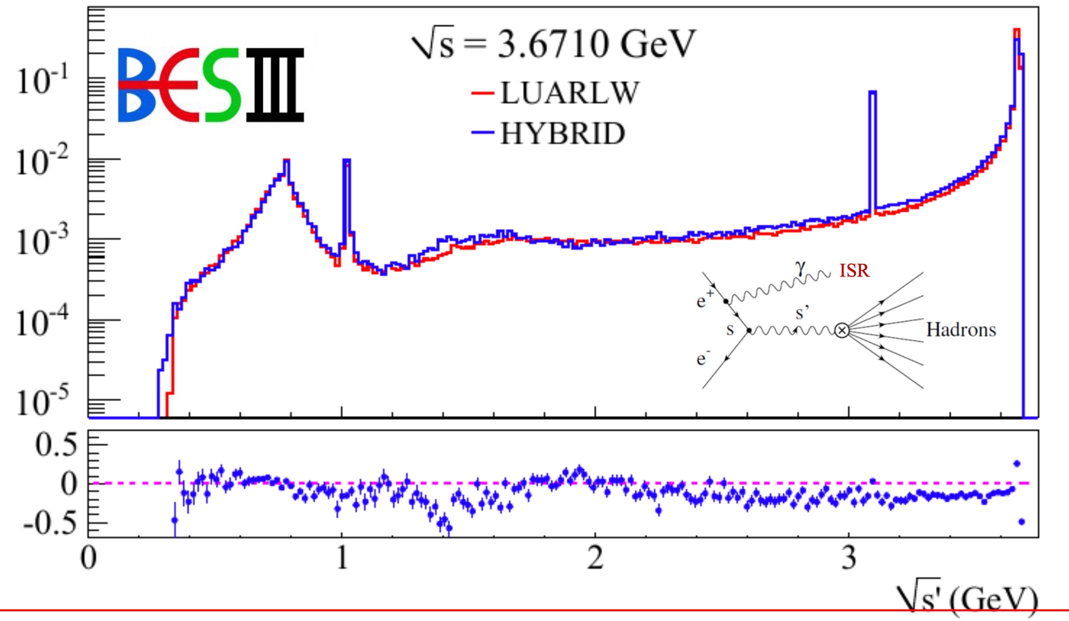

- ❖ Inclusive R measurements above 2.0 GeV
- ❖ Exclusive R measurement below 2.0 GeV
- ❖ Tension in the transition region!

- ❖ ISR technique
- ❖ Exploits large charmonia data (e.g. ψ(3770))
- ❖ It allows measurement from threshold to continuum
- ❖ Less dependent on MC event generator
- ❖ Better detection efficiency respect to scan
- ❖ It allows comparison btw inclusive and esclusive measurements.

Summary & Outlook

High accuracy R-value measurements is of great importance for SM tests on:

- muon anomaly a_μ
- running fine structure constant $\alpha\ (m^2_Z)$

First R-value BESIII measurements published!

✓ 2.2324 GeV $\leq \sqrt{s} \leq$ 3.6710 GeV

✓ Accuracy better than 2.6% below 3.1 GeV and 3.0% above.

→Other high statistics samples available

→Other approaches on-going @ BESIII! Stay tuned !!!!

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Thank you for your attention!

BESIII