R measurements at BESIII

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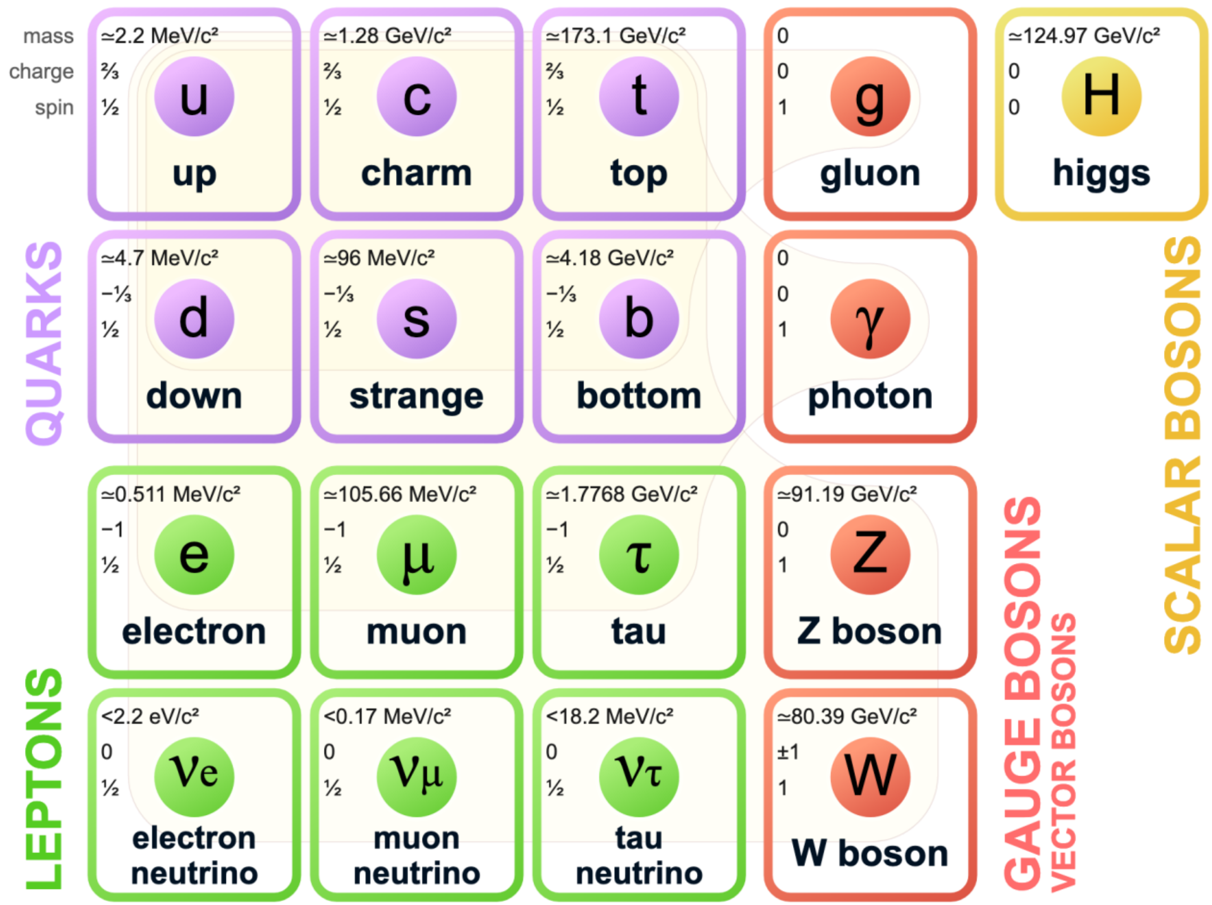
Outline

- Introduction
- Recap of BESII R measurements
- R scans at BESIII
  - 4 points test run
  - 104 points in 3.85-4.6 GeV
  - 22 points in 2.0-3.08 GeV
- First R values at BESIII
- Summary

Standard Model

- Successful, but many parameters;
- Precision test needed!



SM parameters

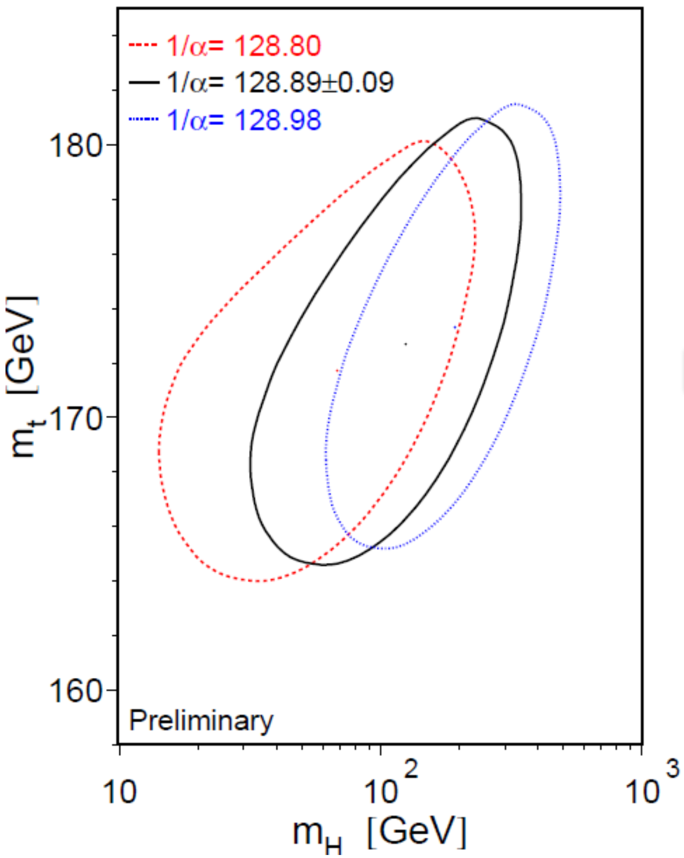
Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1882 ± 0.0020	-0.3
Γ_Z [GeV]	2.4955 ± 0.0023	2.4942 ± 0.0009	0.6
$\sigma_{\rm had}$ [nb]	41.481 ± 0.033	41.482 ± 0.008	0.0
R_e	20.804 ± 0.050	20.736 ± 0.010	1.4
R_μ	20.784 ± 0.034	20.735 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.781 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21581 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01619 ± 0.00007	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0996 ± 0.0016	0.1030 ± 0.0002	-2.1
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0736 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1031 ± 0.0002	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23153 ± 0.00004	0.7
	0.23148 ± 0.00033		-0.2
	0.23129 ± 0.00033		-0.7
A_e	0.15138 ± 0.00216	0.1469 ± 0.0003	2.1
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

Quantity	Value	Standard Model	Pull
m_t [GeV]	172.89 ± 0.59	173.19 ± 0.55	-0.5
M_H [GeV]	125.30 ± 0.13	125.30 ± 0.13	0.0
M_W [GeV]	80.387 ± 0.016	80.361 ± 0.006	1.6
	80.376 ± 0.033		0.5
	80.370 ± 0.019		0.5
Γ_W [GeV]	2.046 ± 0.049	2.090 ± 0.001	-0.9
	2.195 ± 0.083		1.3
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0001	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0476 ± 0.0002	1.4
$Q_W(p)$	0.0719 ± 0.0045	0.0711 ± 0.0002	0.2
$Q_W(\mathrm{Cs})$	-72.82 ± 0.42	-73.23 ± 0.01	1.0
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.02	0.1
$\hat{s}_Z^2(\mathrm{eDIS})$	0.2299 ± 0.0043	0.23121 ± 0.00004	-0.3
τ_τ [fs]	290.75 ± 0.36	288.90 ± 2.24	0.8
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.18 \pm 0.78) \times 10^{-9}$	$(4508.74 \pm 0.03) \times 10^{-9}$	3.1

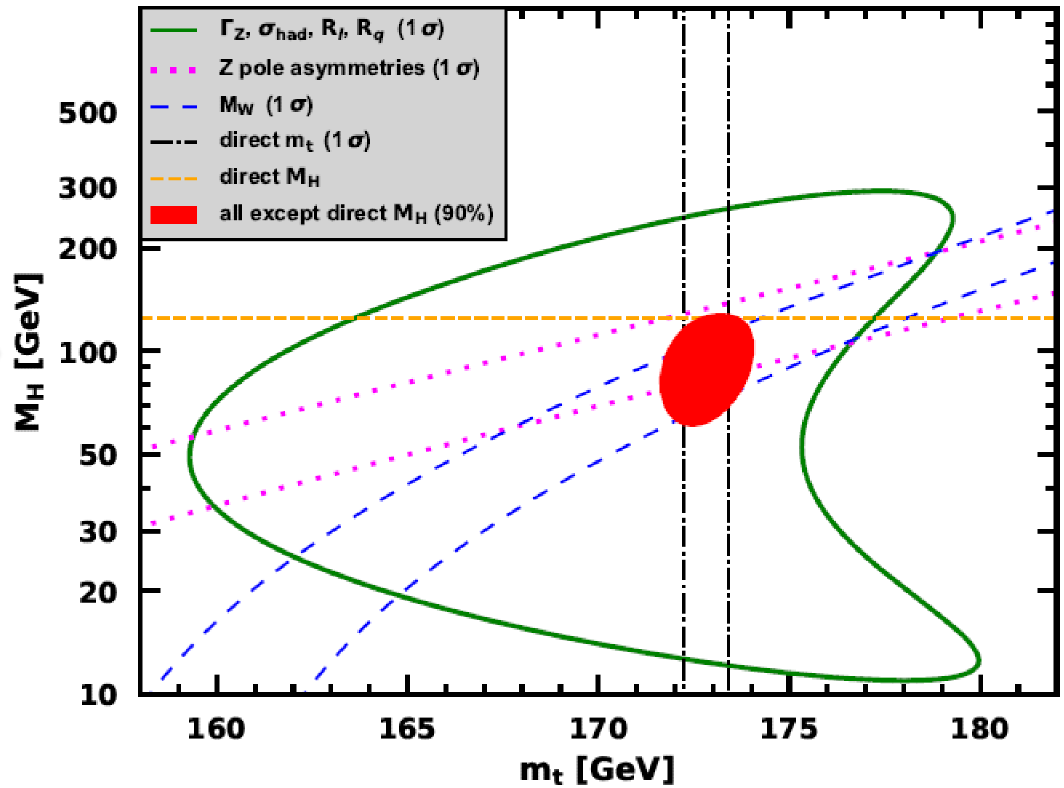
- 3 independent ones: α, G_F and M_Z;
- Global fit preferred.

m_H, m_t and α in SM fit

EW Group 1997

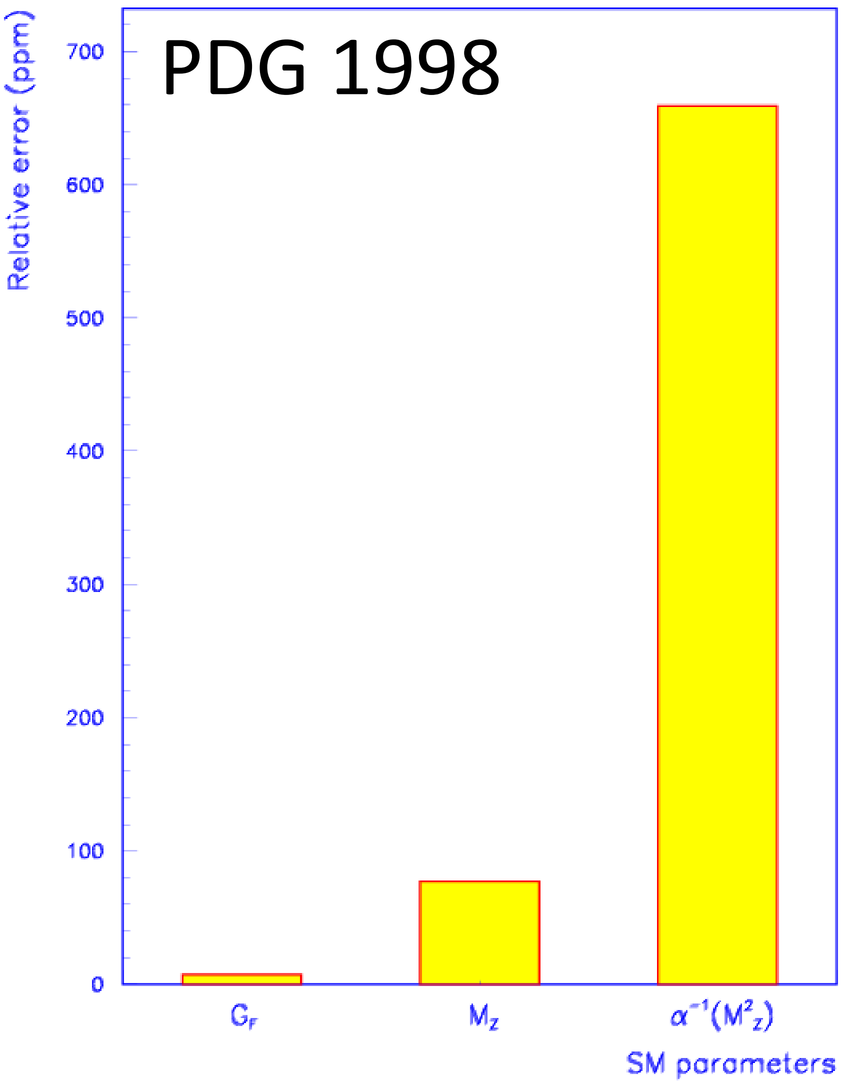


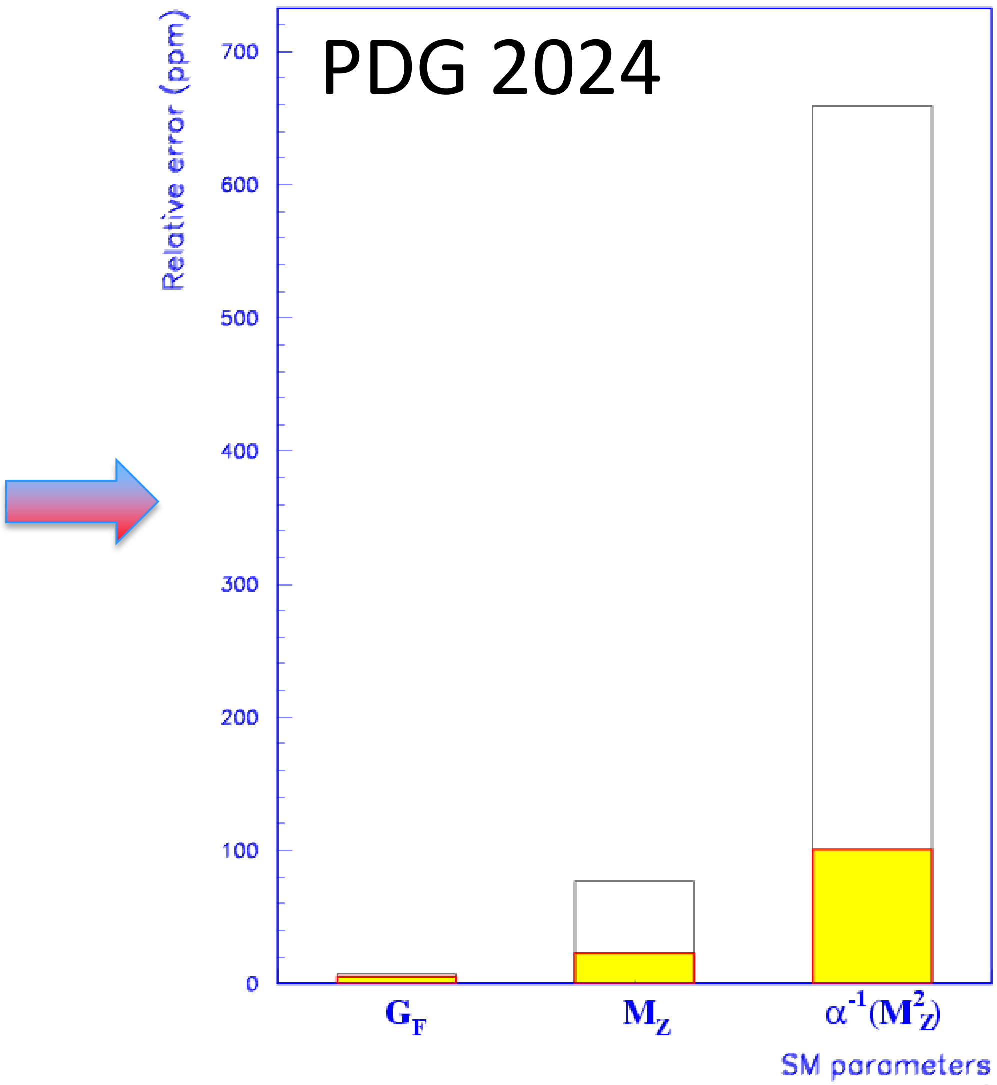
PDG 2024



Improvement due to better precision of α, …

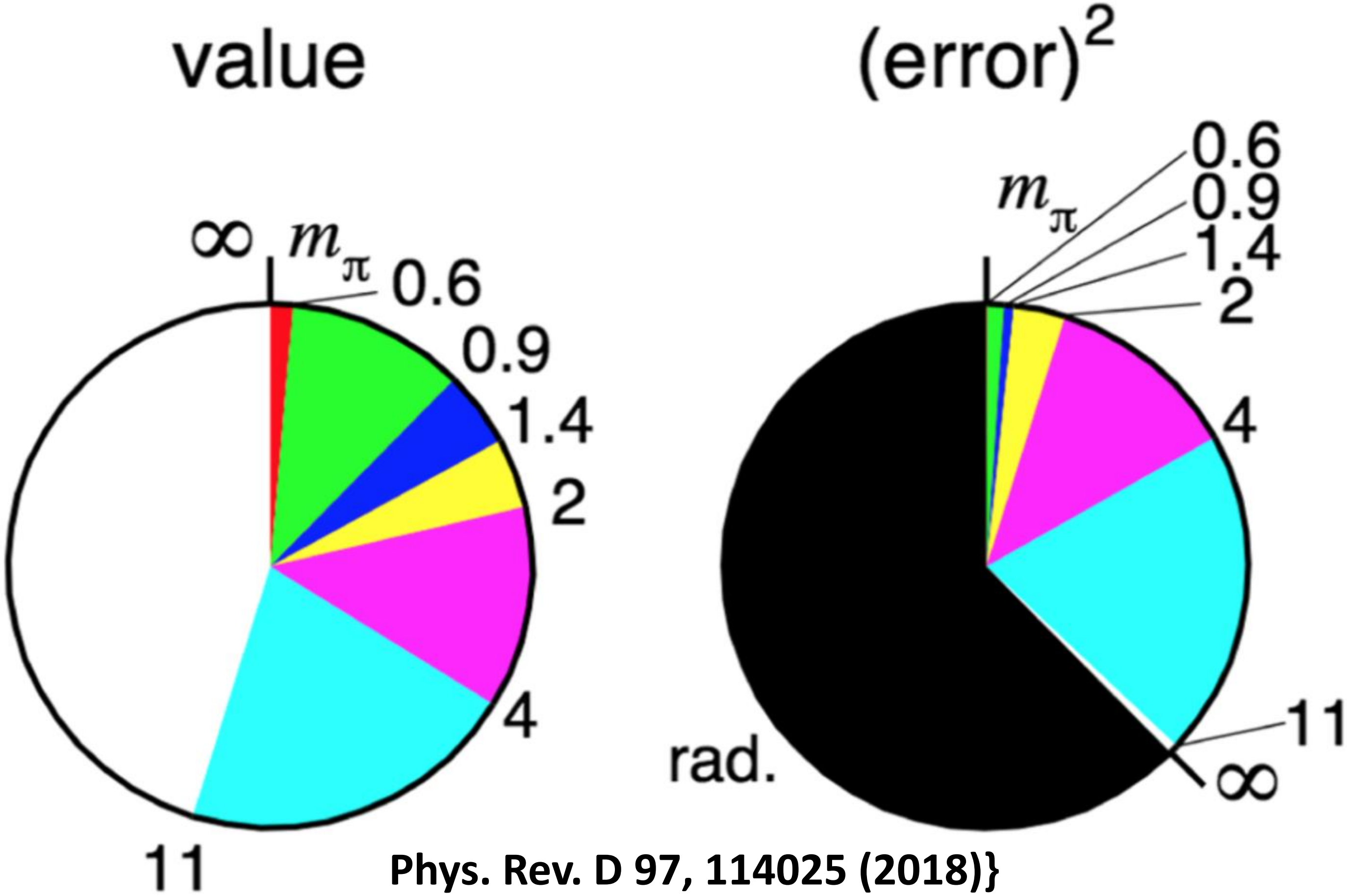
Uncertainties of SM parameters





$\Delta\alpha(M_Z^2)$

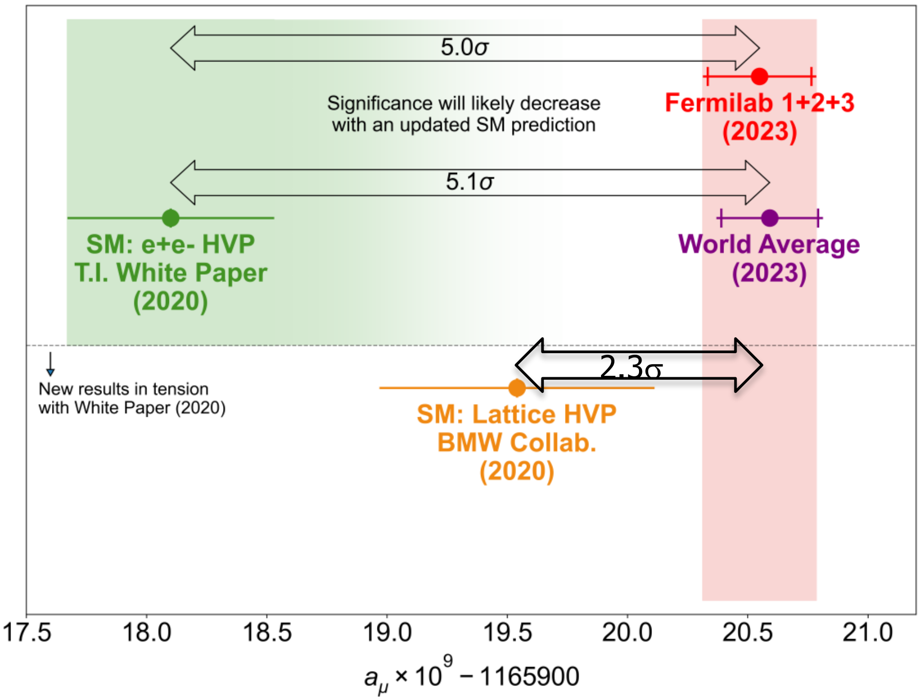
- $\Delta\alpha(s)=\Delta\alpha(s)_{lepton}+\Delta\alpha(s)_{top}+\Delta\alpha^{(5)}{}_{had}(s)$;
- Dominant: $\Delta\alpha^{(5)}_{\mathrm{had}}(s) = -\frac{\alpha s}{3\pi}\,\mathrm{Re}\int_{E_{\mathrm{th}}}^{\infty} \mathrm{d}s' \frac{R(s')}{s'(s'-s-i\varepsilon)}$

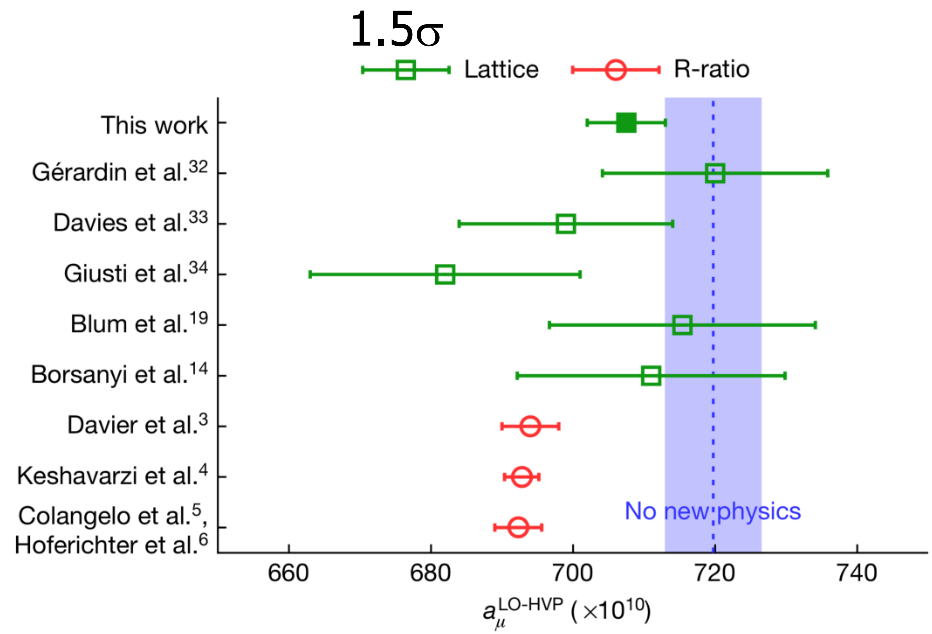


Phys. Rev. D 97, 114025 (2018)}

$a_\mu \equiv (g_\mu - 2)/2$

- ~5σ discrepancy?





FNAL measurements:
Phys. Rev. Lett. 126, 141801 (2021)
Phys. Rev. Lett. 131, 161802 (2023)

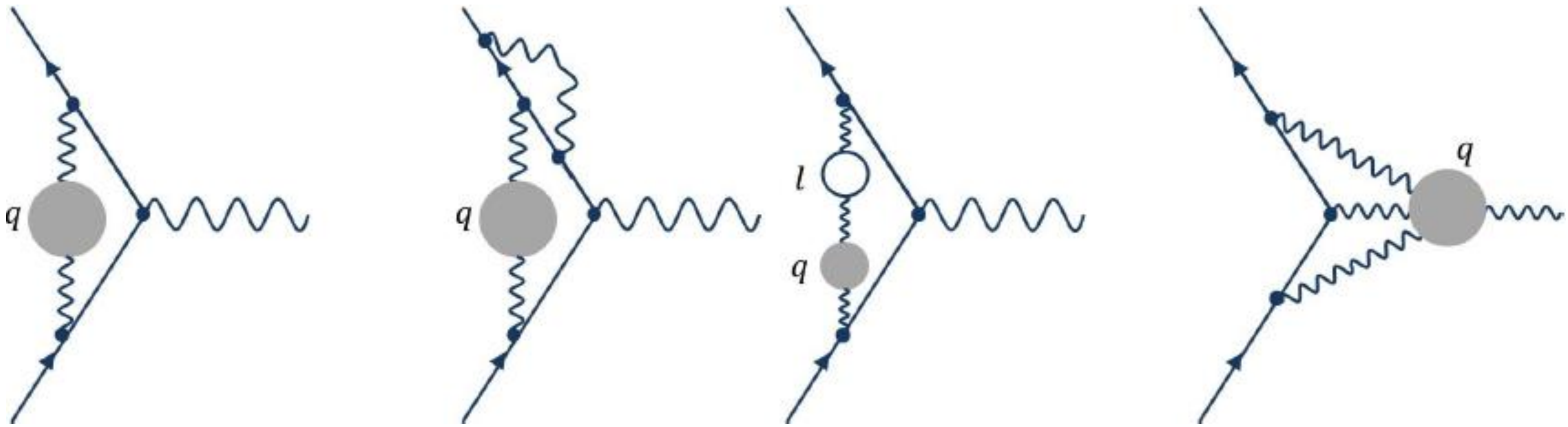
Nature 593, 51 (2021)

$a_\mu^{\text{LO-HVP}}$ (*R*-ratio)	6931 ± 40
$a_\mu^{\text{LO-HVP}}$ (lattice)	7075 ± 55

Tension also from $\pi^+\pi^-$ in [0.32, 1.2] GeV by CMD-3 (arXiv:2302.08834)

$a_\mu \equiv (g_\mu - 2)/2$

$$a_\ell^{\mathrm{SM}} = a_\ell^{\mathrm{QED}} \surd + a_\ell^{\mathrm{Weak}} \surd + a_\ell^{\mathrm{had}} \ \mathbf{X}$$

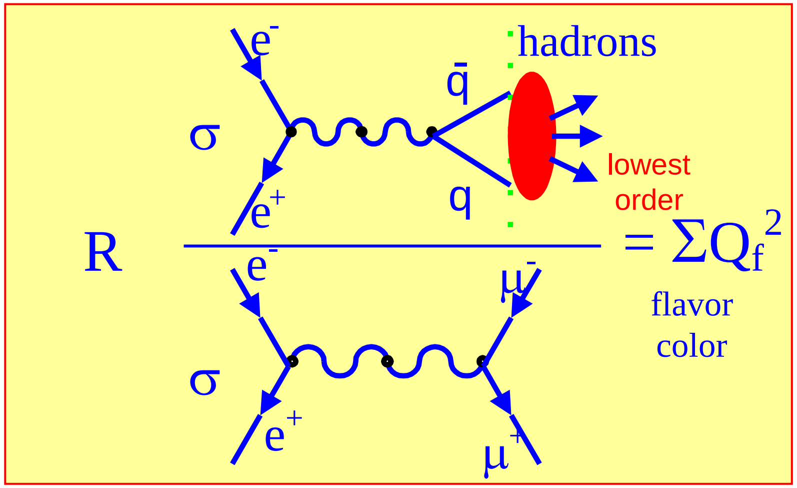


$$a_\ell^{\mathrm{had}} = a_\ell^{\mathrm{LO\text{-}HVP}} + a_\ell^{\mathrm{NLO\text{-}HVP}} + a_\ell^{\mathrm{HLbL}}$$

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

- R in low energy matters more!

Definition of R:



- At lowest order

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{\sum_q \sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_q Q_q^2$$

Number of quark colors

- At higher order

$$R = 3\, K_{QCD} \sum_q Q_q^2 ,$$

$$K_{QCD} = 1 + \frac{\alpha_S(\mu^2)}{\pi} + \sum_{n\geq 2} C_n \left(\frac{s}{\mu^2}\right) \left(\frac{\alpha_S(\mu^2)}{\pi}\right)^n$$

- R is one of the most fundamental quantities in particle physics that directly reflect the flavor and color of quarks.
- Directly test quark model & QCD, and discover new particles.

Measurement of R Values

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

N_{had}: observed hadronic events

N_{bg}: background events

L: integrated luminosity

ε_{had}: detection efficiency for N_{had}

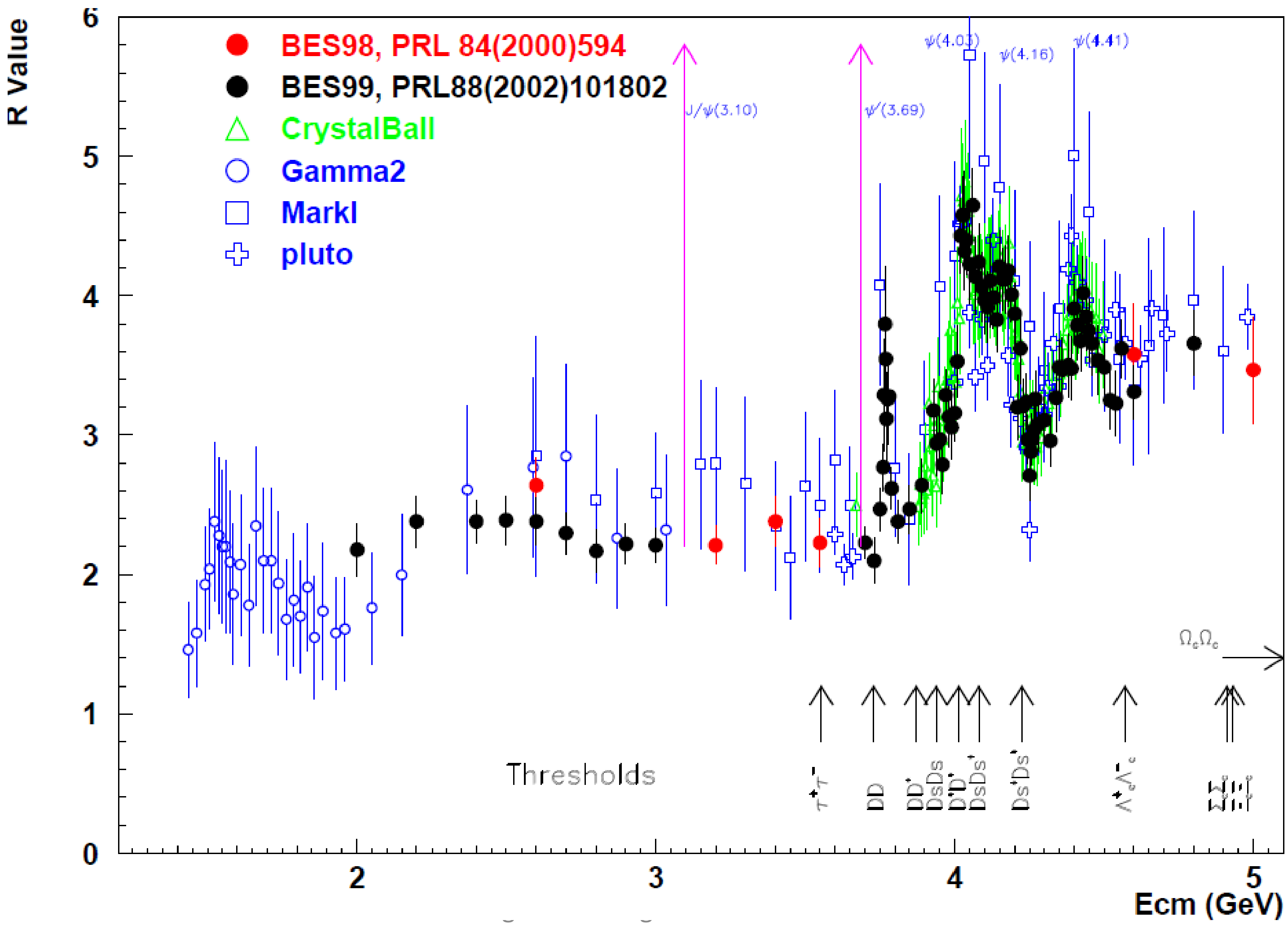
δ: radiative correction factor

$\sigma_{\mu\mu}$: can be precisely calculated(QED). Measurement of R is to measure the total $\sigma(e^+e^- \rightarrow hadrons)$

Except for controlling each item to the precision requested, stable long term machine and detector performance is crucial.

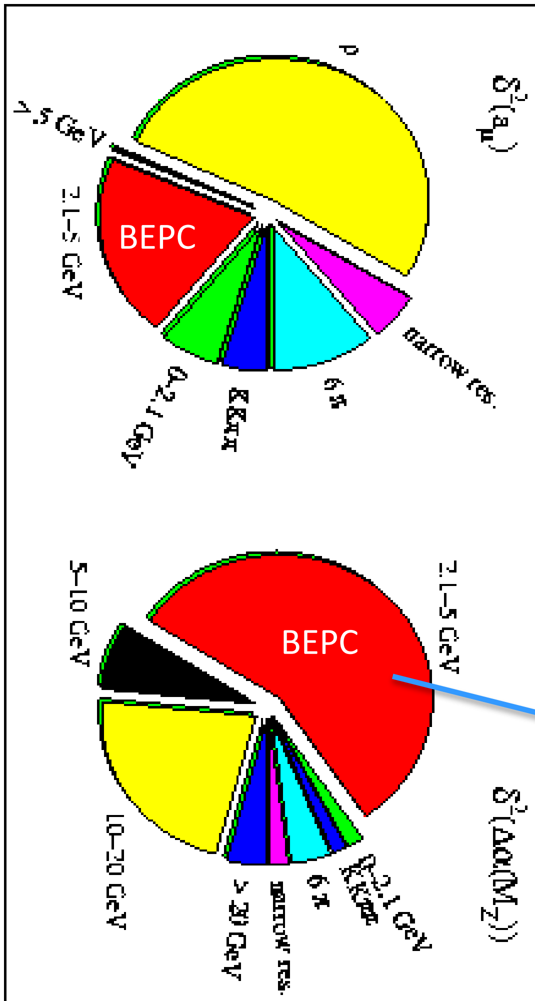
R Scans at BESII

- 6 + 85 energy points, total ~5 pb^{-1} data, average uncertainty 6.6%, factor of 2~3 better.

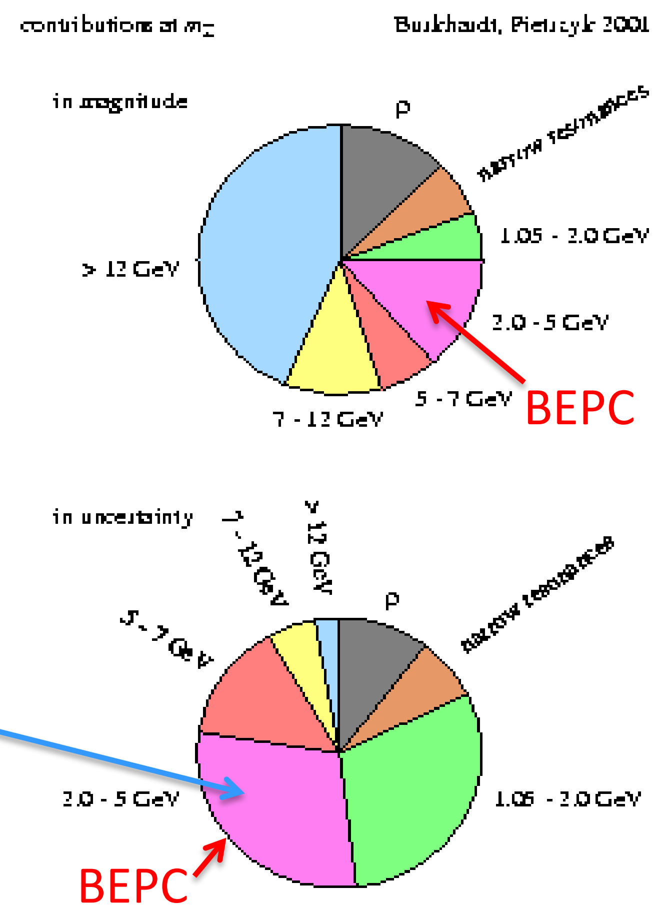


Relative Contributions to the Uncertainties of a_μ and $\Delta\alpha(M_Z^2)$

Before BESII R scan

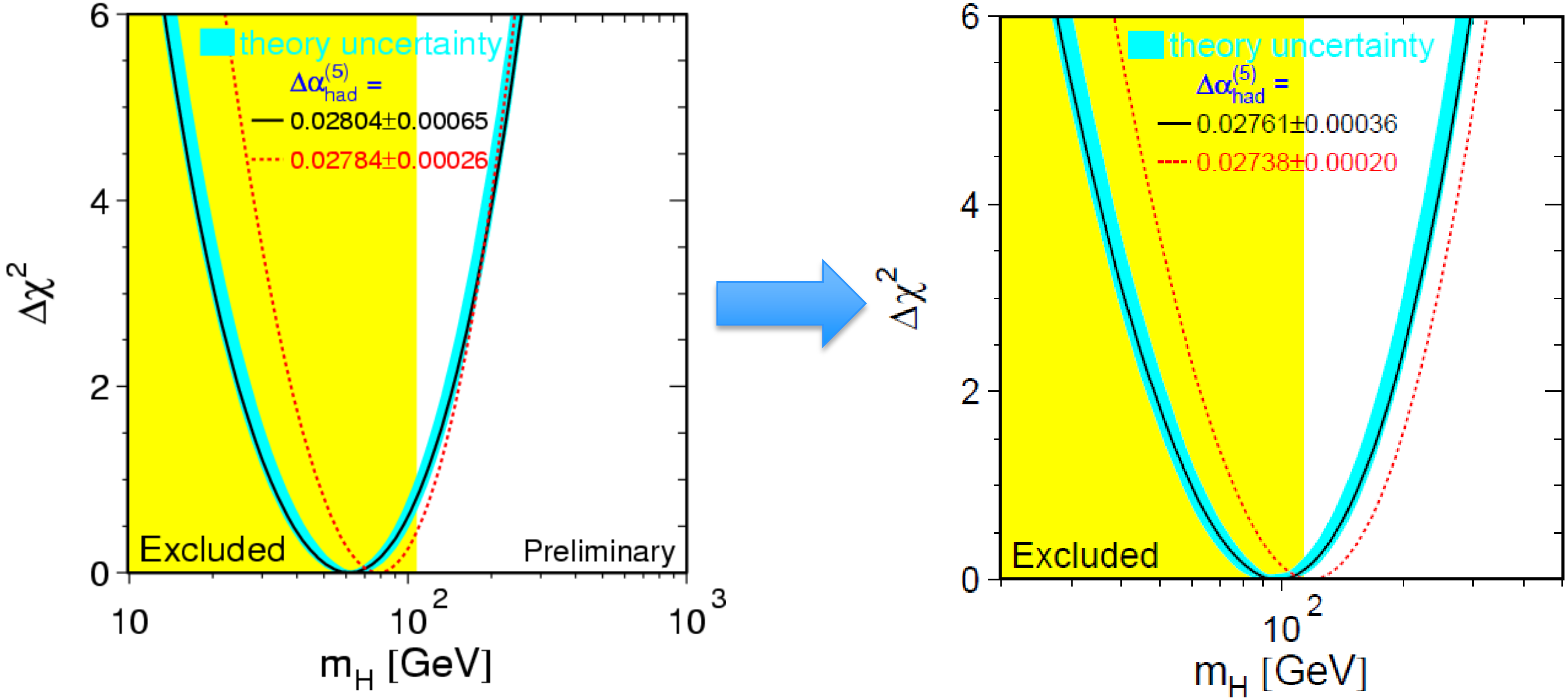


After BESII R scan



Impact of BESII R to Higgs mass

From SM fit:



before: $62^{+53}_{-30}\mathrm{GeV}$

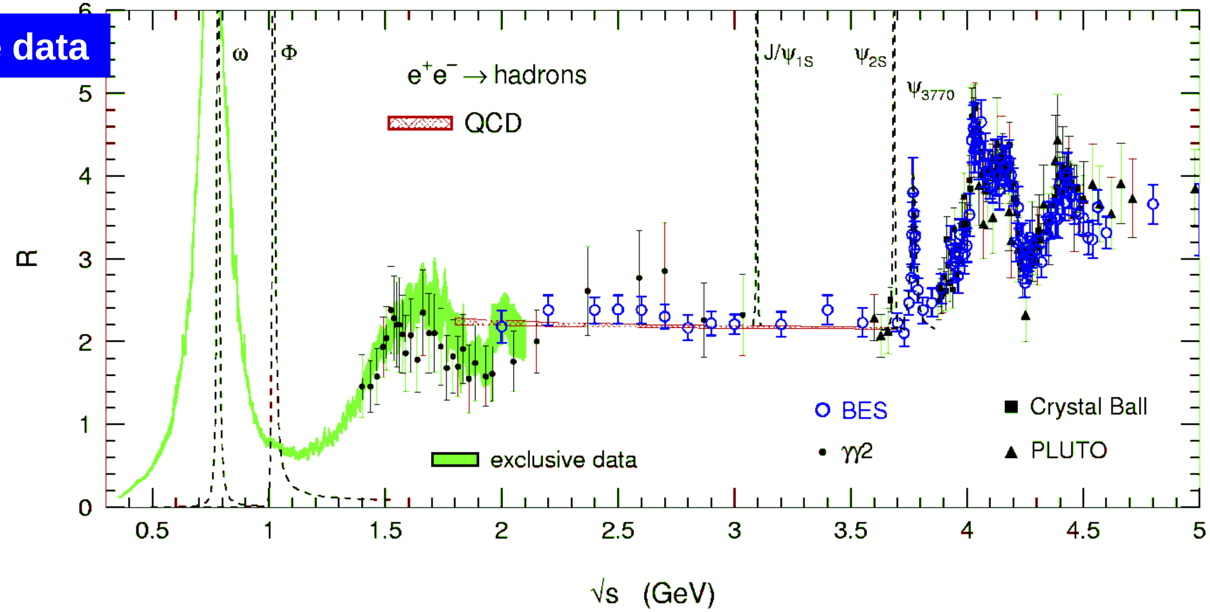
< 170 95%C.L.

after: $98^{+58}_{-38}\mathrm{GeV}$

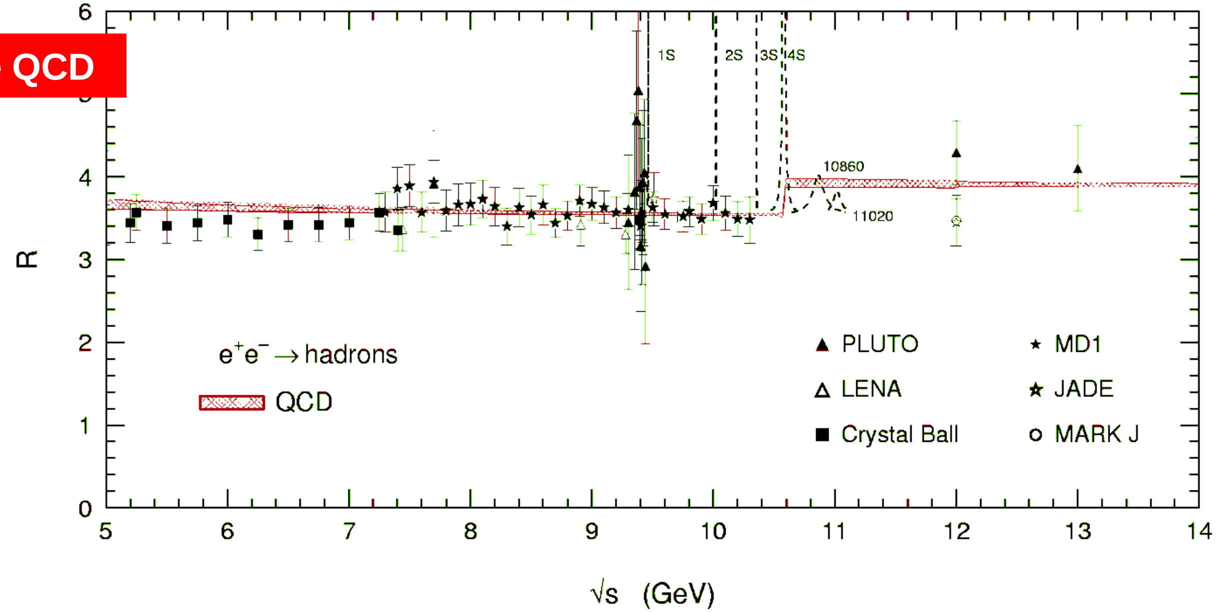
< 210 95%C.L.

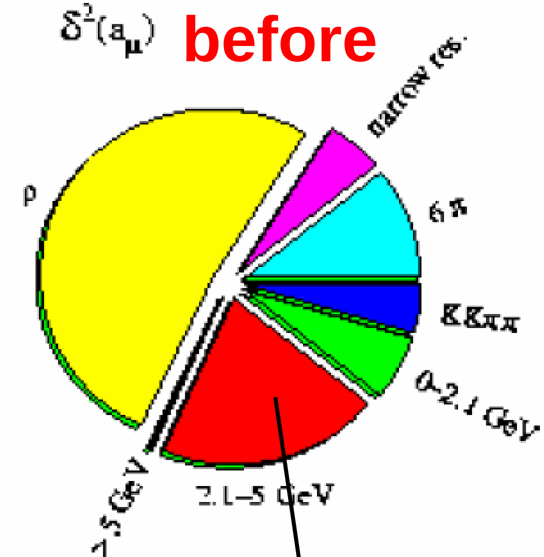
Impact of BESII R to muon $(g_\mu - 2)$

use data



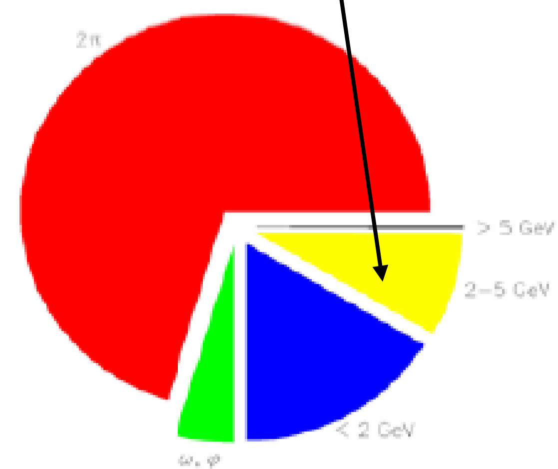
use QCD





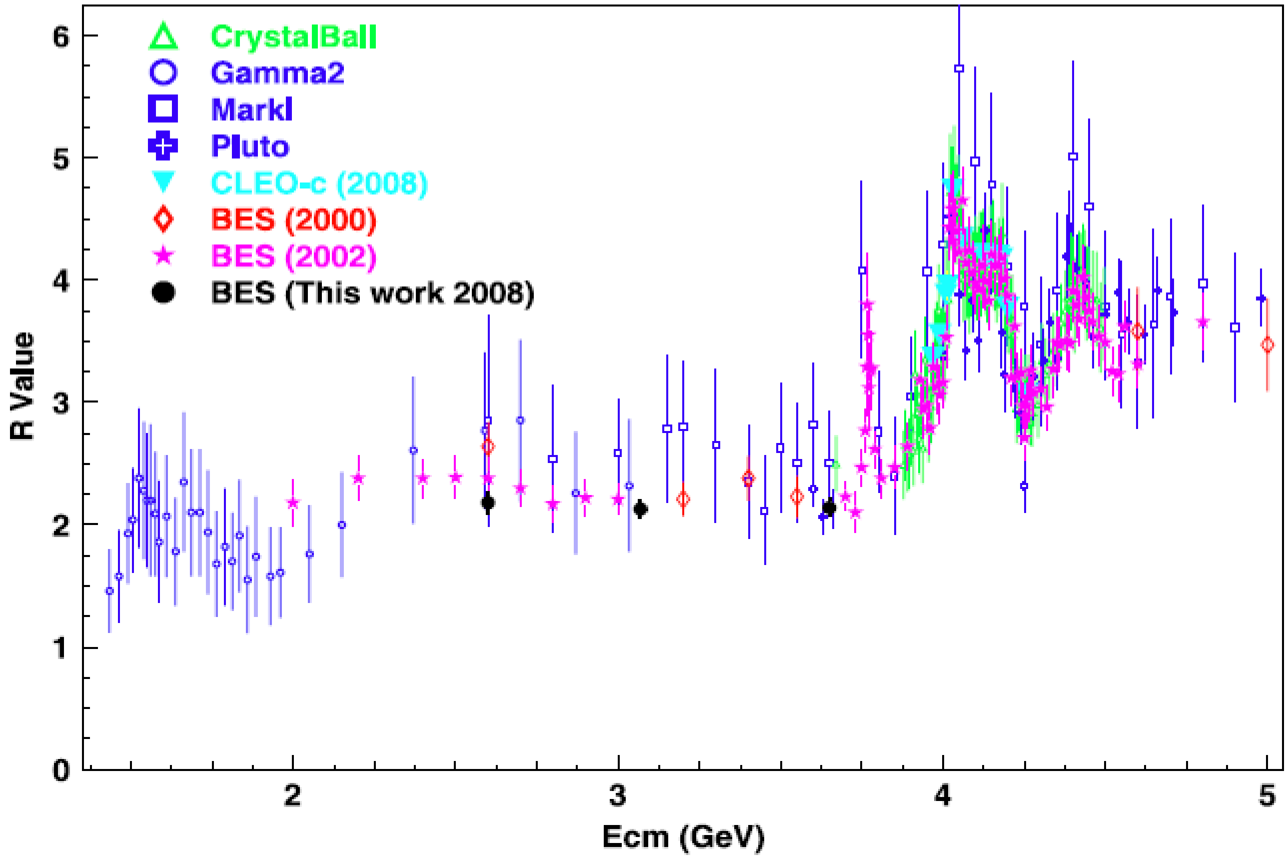
2.6σ → 1.7σ

after



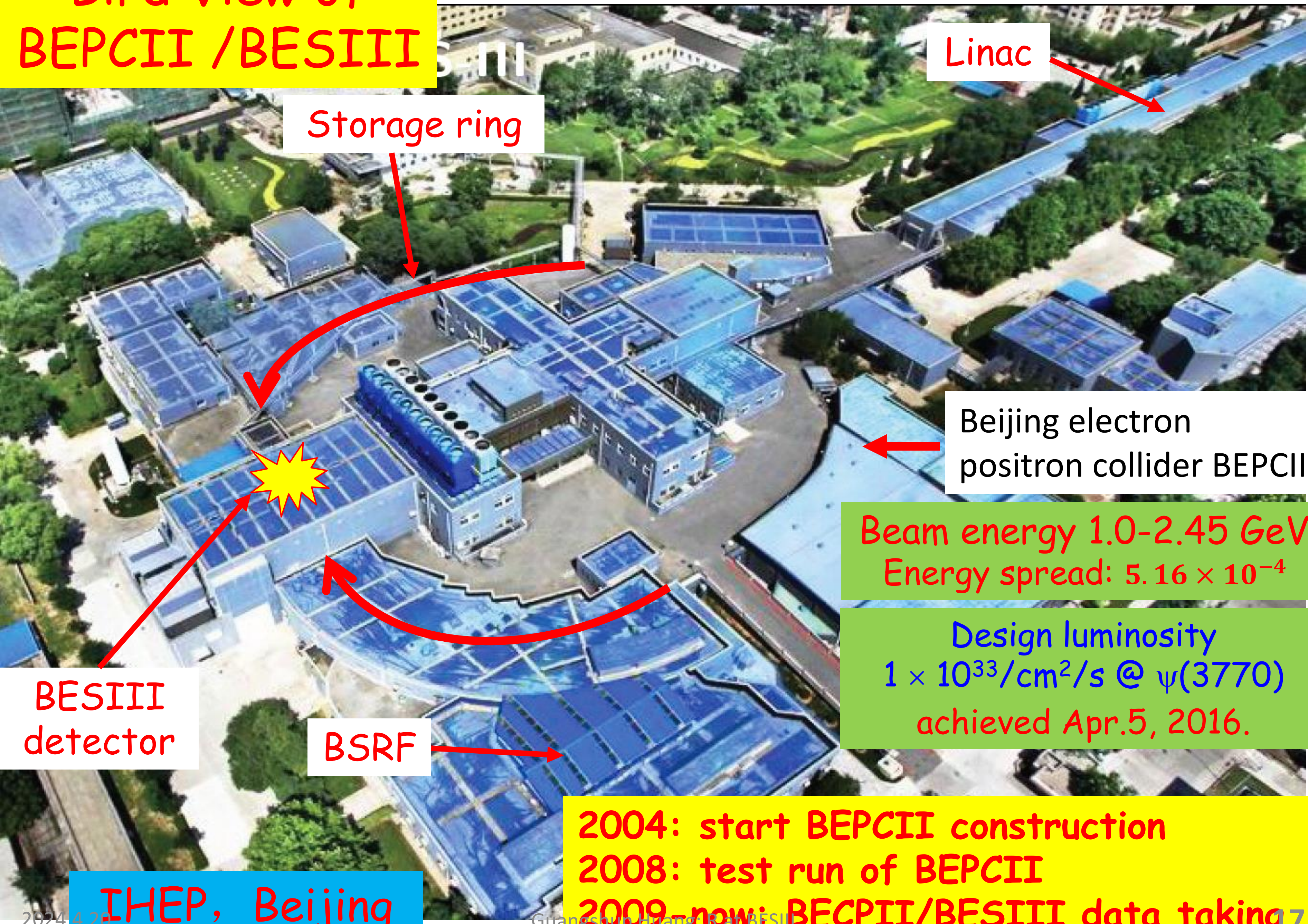
Last data at BESII

- **Large samples at 2.6, 3.07, 3.65 GeV just before shutdown, ~10 pb^{-1}, uncertainties ~3.5%**



- PLB677, 239 (2009)

Bird View of BEPCII /BESIII



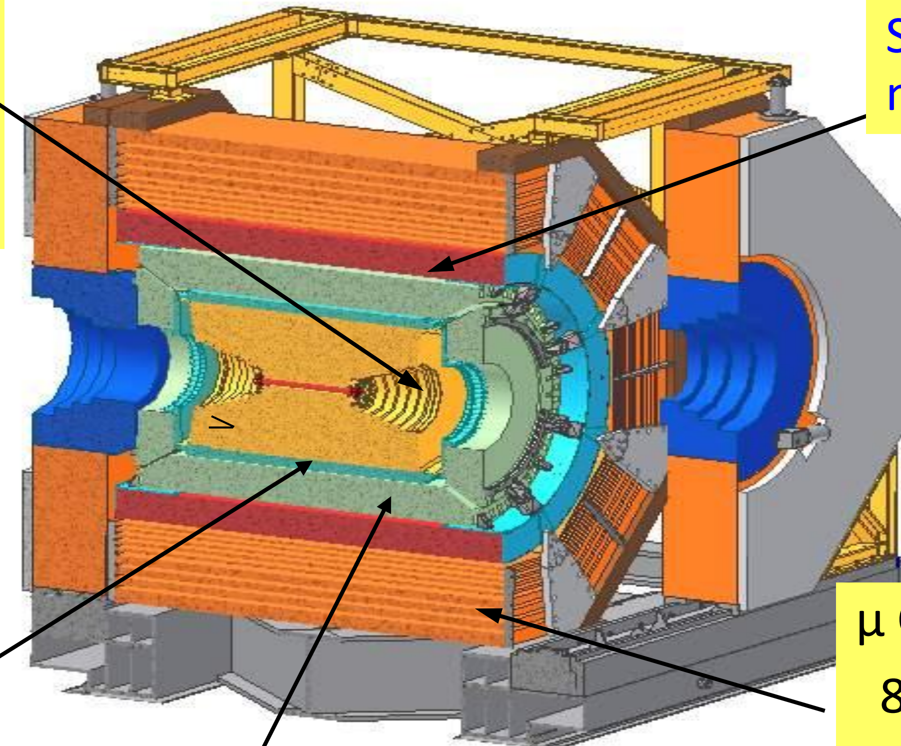
The BESIII Detector

Drift Chamber (MDC)

$\sigma p/p$ ($^0/_0$) = 0.5%(1GeV)

$\sigma_{dE/dx}$ ($^0/_0$) = 6%

Super-conducting magnet (1.0 Tesla)



Time of Flight (TOF)

σ_T: 90 ps for Barrel;

110 ps $\rightarrow$ 65 ps for Endcaps

μ Counter

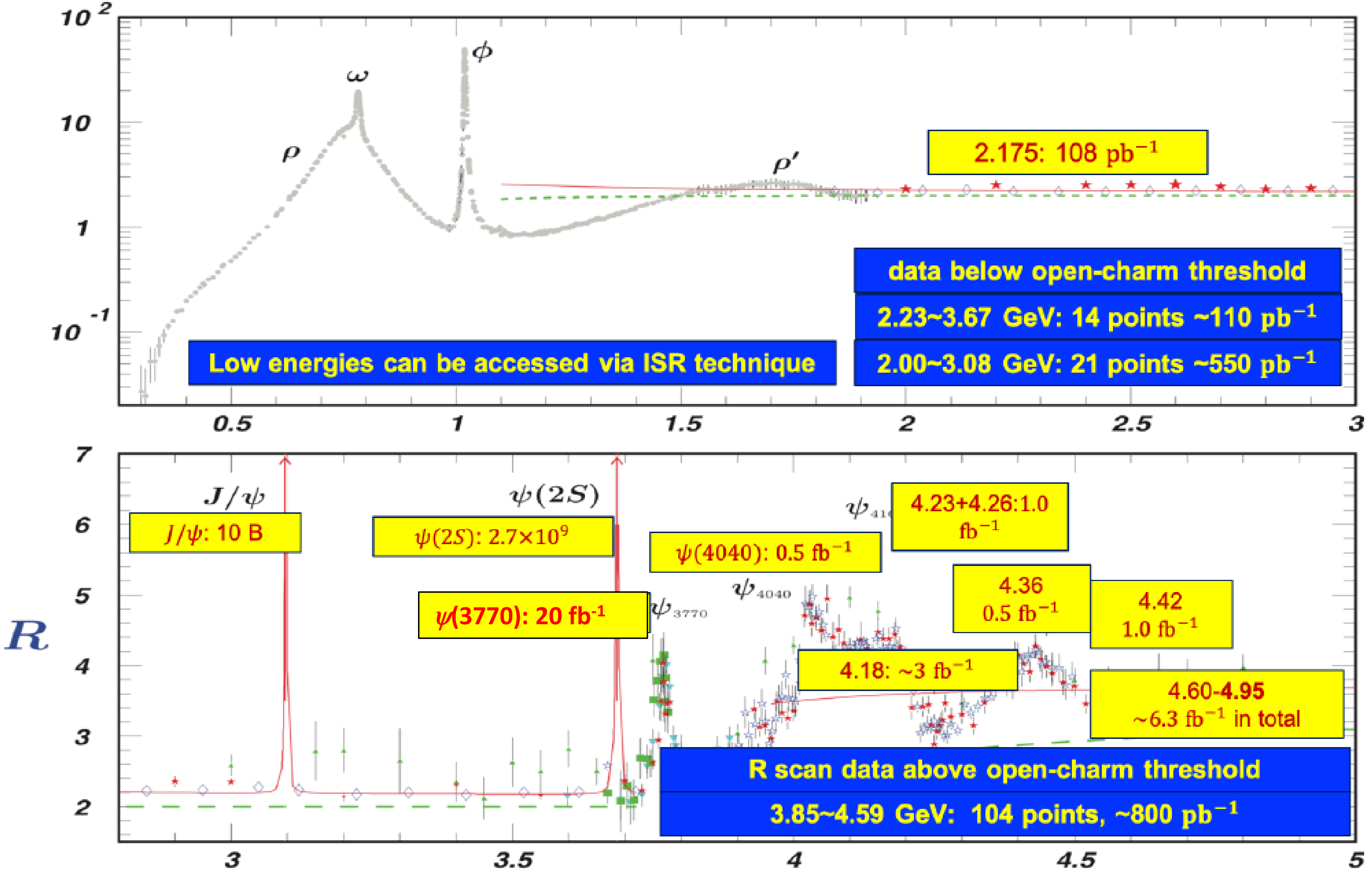
8 - 9 layers RPC

δR=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}$($^0/_0$) = 2.5 % (1 GeV)

(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

BESIII Data sets



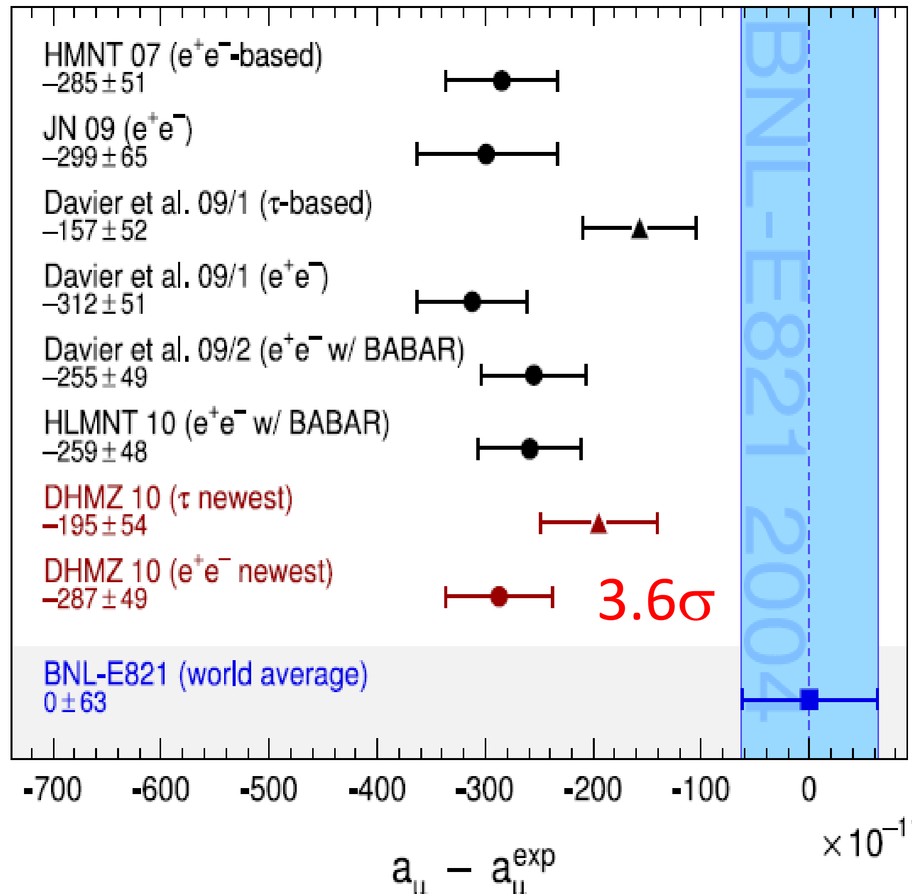
$\Delta\alpha(M_Z^2)$ and a_μ: Status BESIII starting

Burkhardt, Pietrzyk 2011

TABLE I. Contributions to $\Delta\alpha_{had}^{(5)}(m_Z^2)$.

Range $\sqrt{s}$, GeV	$\Delta\alpha$	Relative error
$\rho\ (\pi^+\pi^-)$	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%

Still the 2nd largest one.

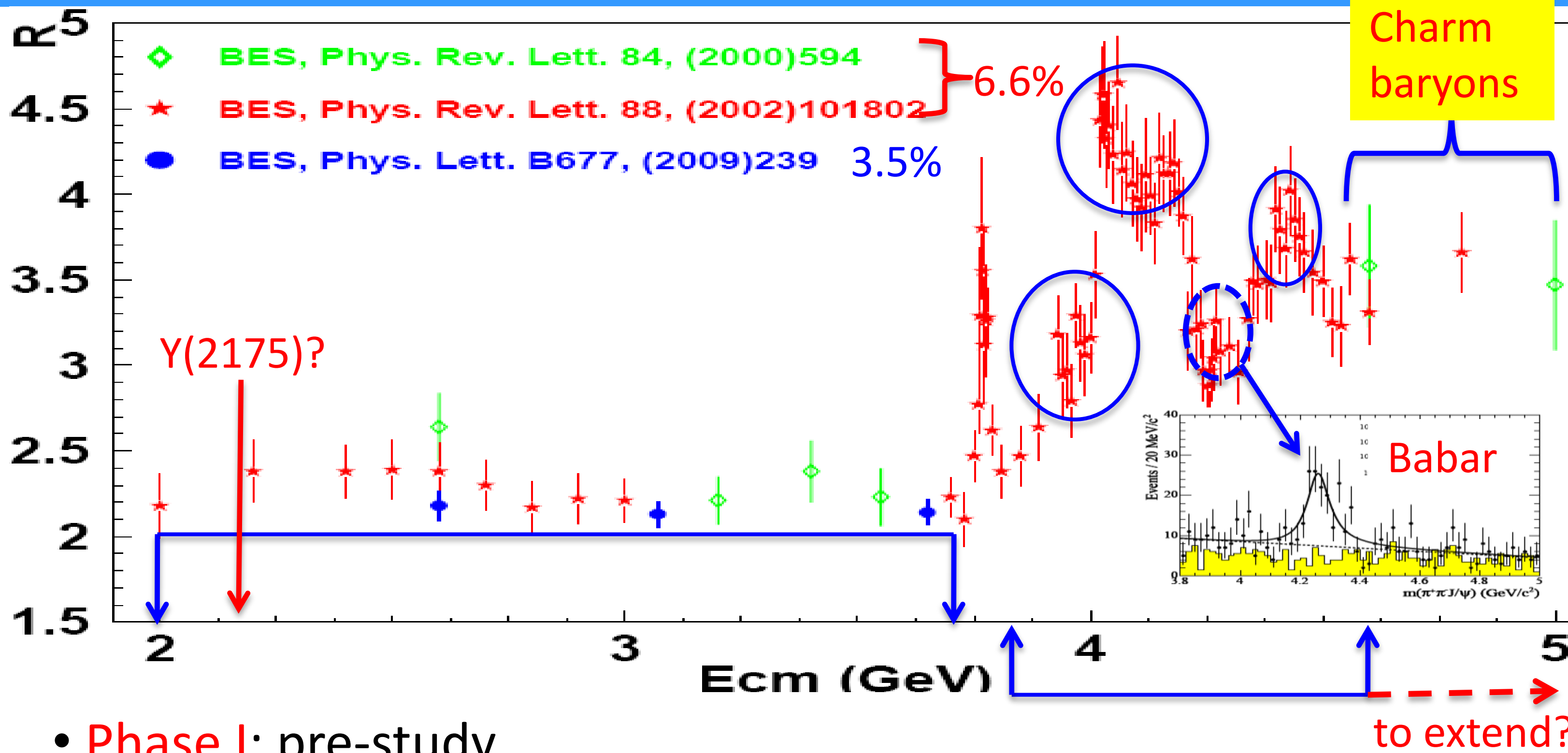


$a_\mu^{exp} = (11\ 659\ 208.9 \pm 6.3) \times 10^{-10}$ (E821)

$a_\mu^{SM} = (11\ 659\ 180.2 \pm 4.9) \times 10^{-10}$

Davier 2010

R Scan Strategy at BESIII (original plan)



- Phase I: pre-study,

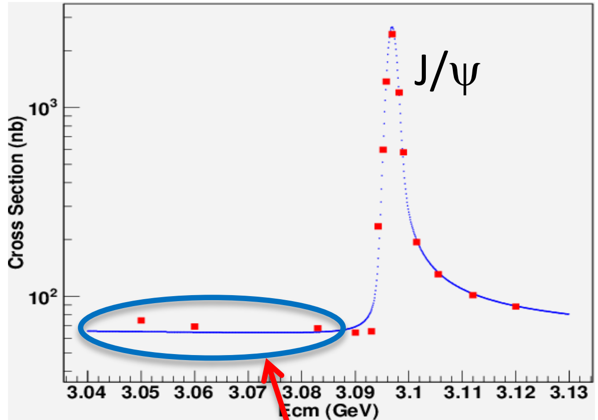
  Machine study at 2.0, 2.5 and 4.2(4.6) GeV, MC tuning, …
- Phase II: scan continuum region,

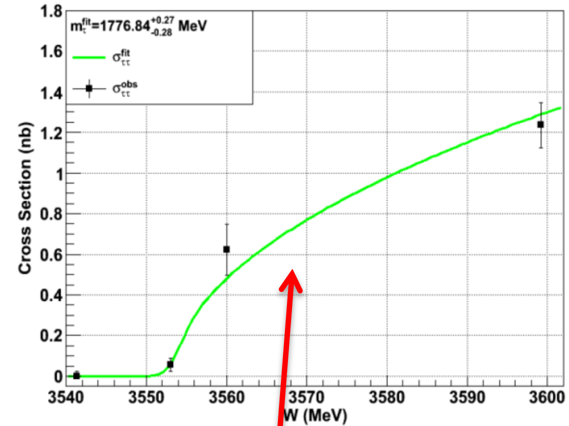
  15 points in 2.0–3.6 GeV, step 100 MeV, 100k+ hadrons<3 GeV.
- Phase III: scan resonance region,

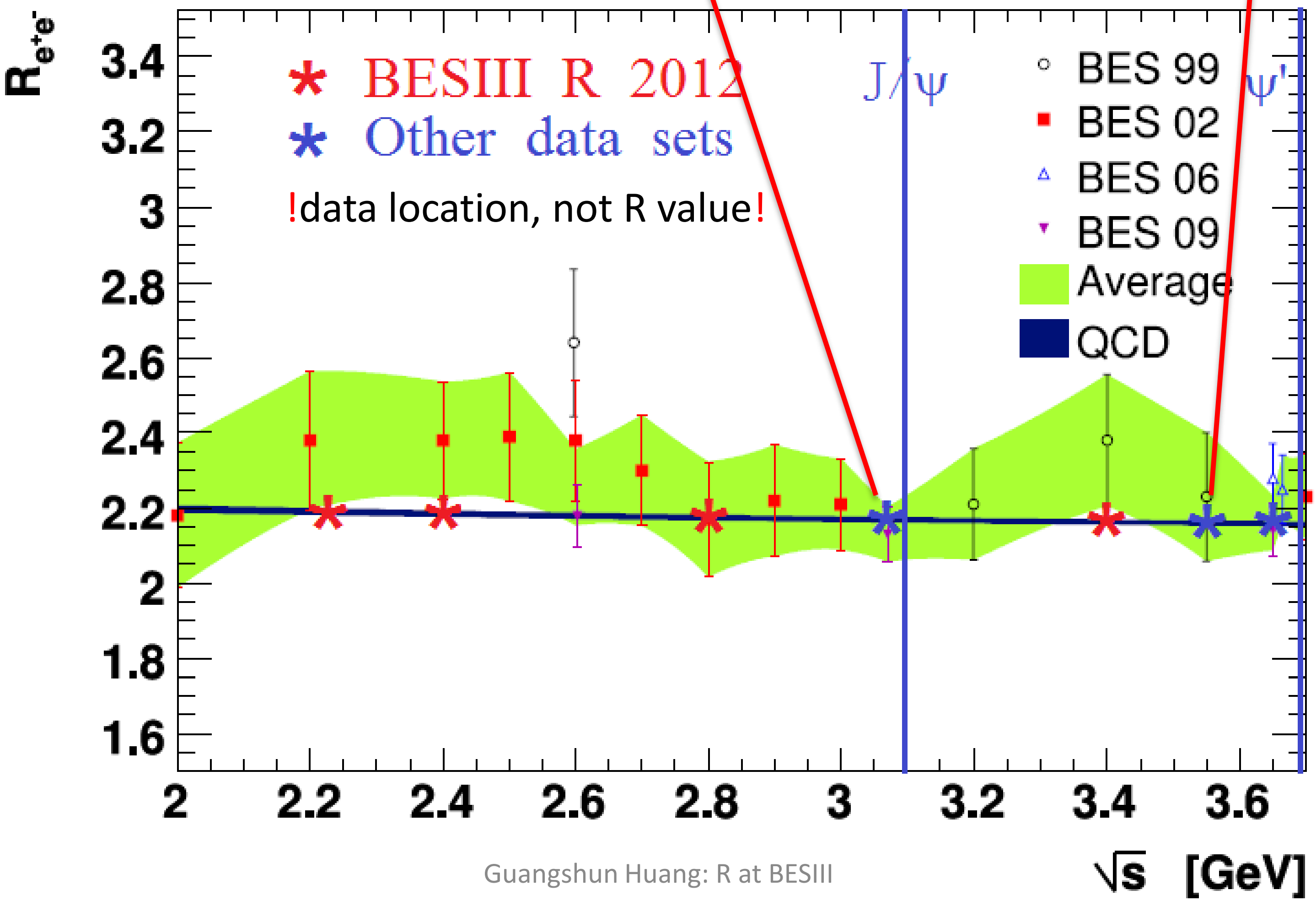
  ~100 points in 3.8–4.6 GeV, 100k events, step 2, 5,10, 20 MeV.

  (10^8 hadrons at 4040, 4160, 4415 for radiative decay search?)

First R scan @BESIII: 4-energy test run

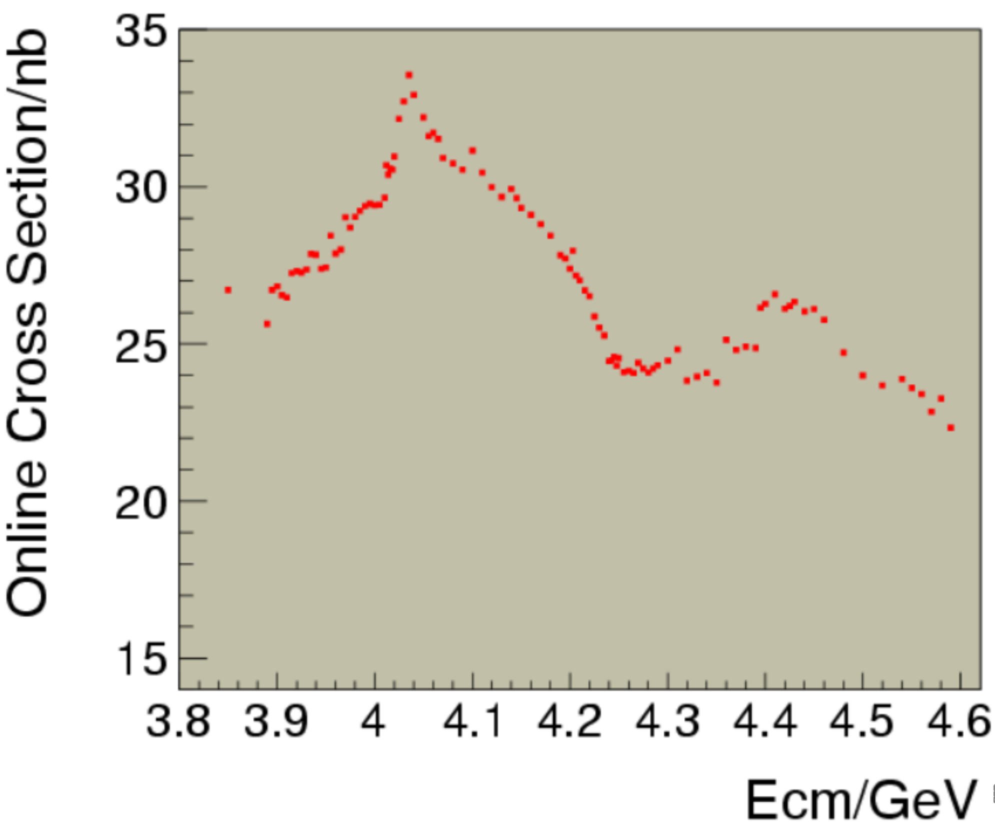


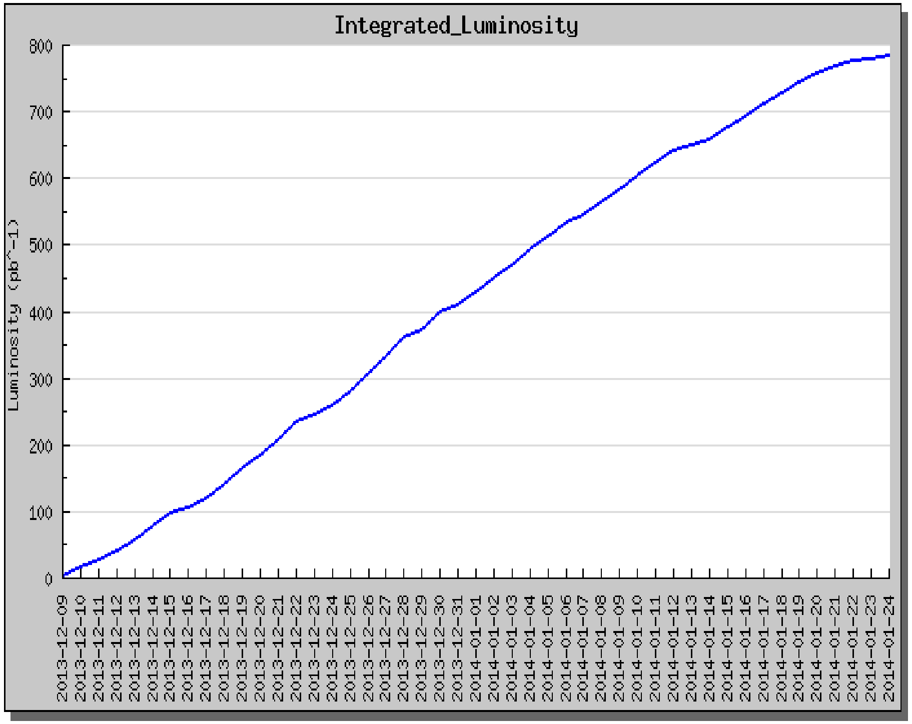




BESIII R Scan in 3.8 - 4.6 GeV

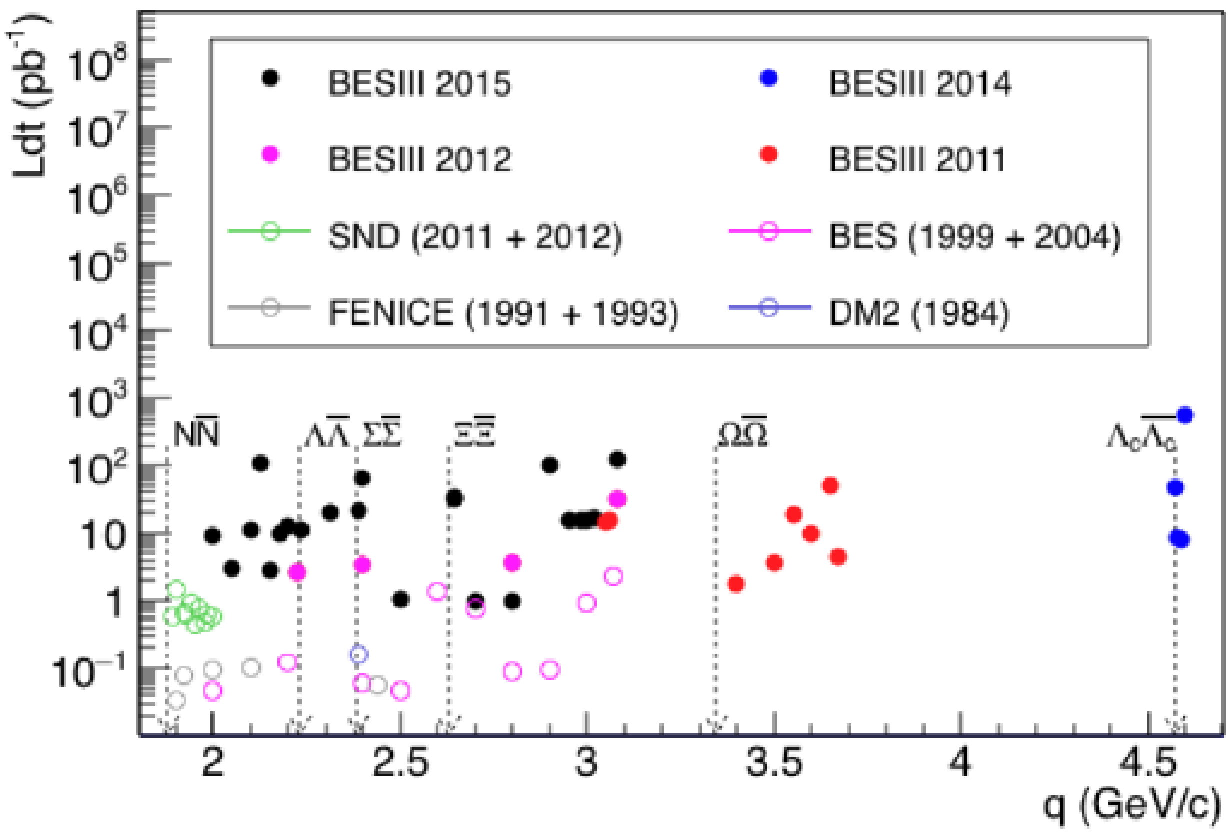
- Data taken in 2013.12.9 – 2014.1.24;
- 104 energy points in total, ~800 pb^{-1};
- >100k hadronic events each points.





Low energy run in 2.0 – 3.08 GeV

- Data taken in 2014.12.30 – 2015.6.16;
- 22 points, ~650 pb^{-1};
- Unique sample in the energy range.



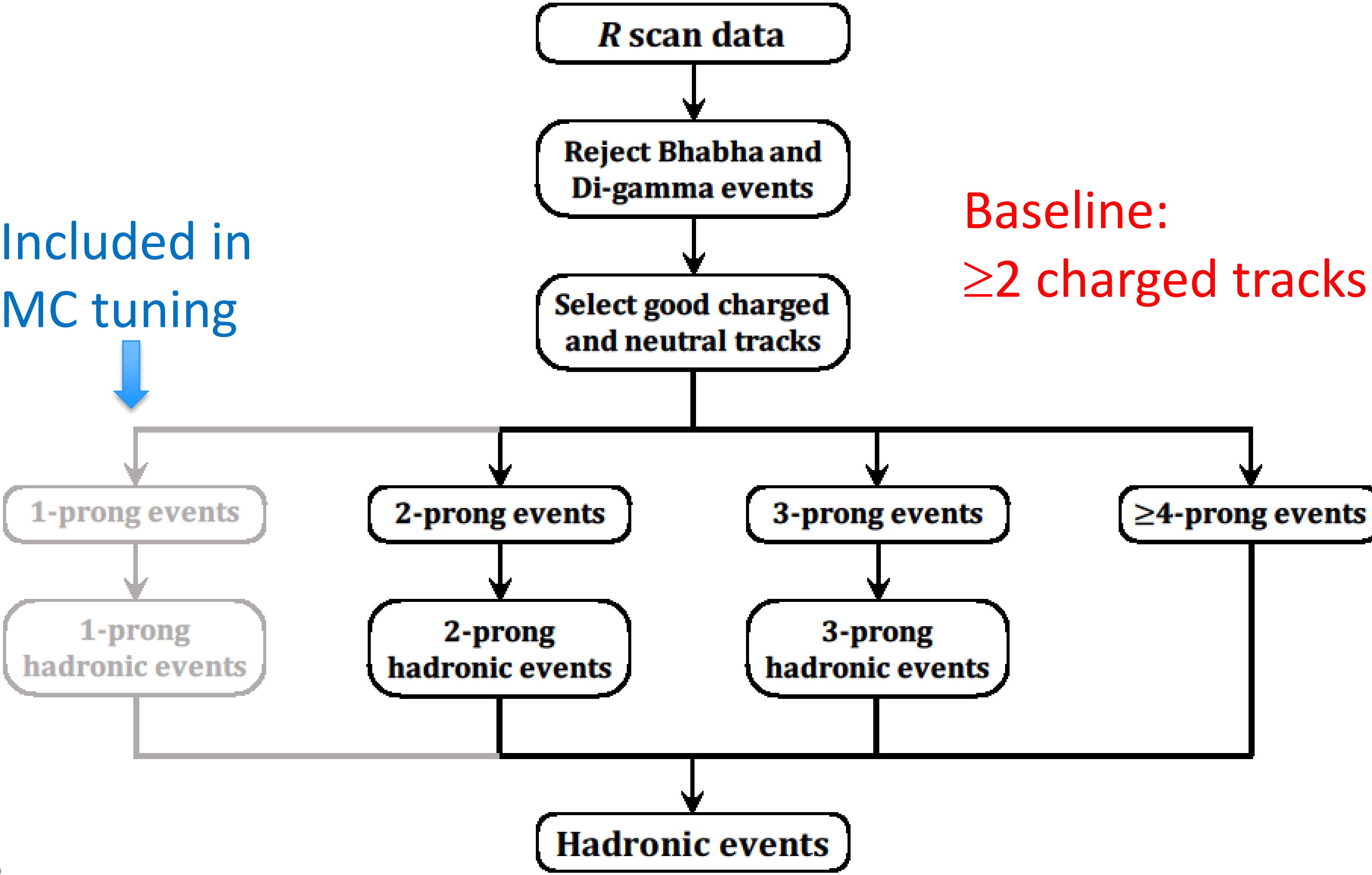
Analysis with continuum data

- 14 points in 2.2324 - 3.671 GeV:
  - 4 of test run: 2.2324, 2.4, 2.8, 3.4 GeV;
  - 3 of J/ψ scan: 3.05, 3.06, 3.08 GeV;
  - 4 of τ scan: 3.5424, 3.5538, 3.5611, 3.6002 GeV;
  - 2 off ψ(3770): 3.5, 3.671 GeV;
  - 1 off ψ(3686): 3.65 GeV.
- Goal: 3% precision;

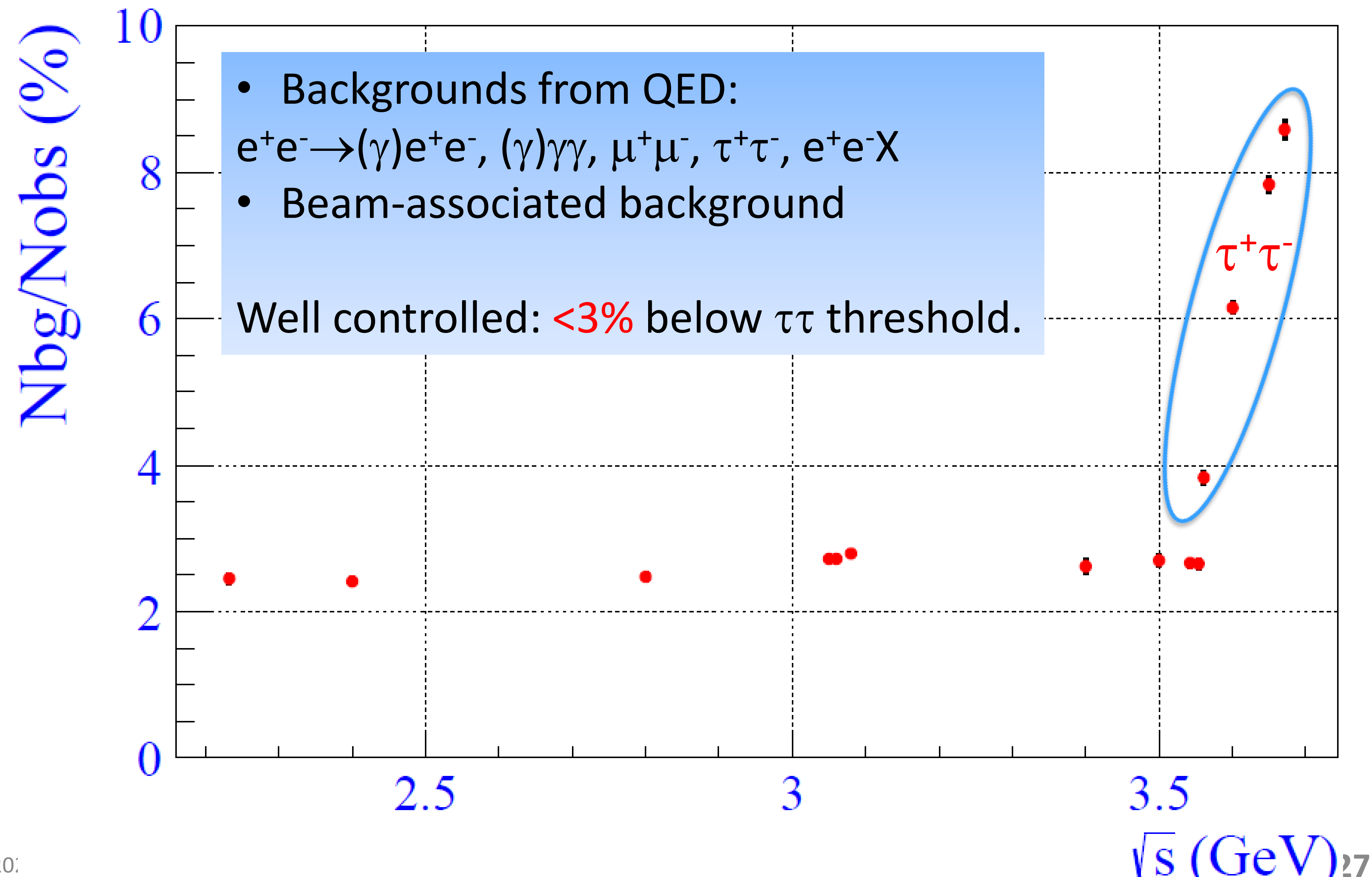
Strategy of hadron selection

Included in MC tuning

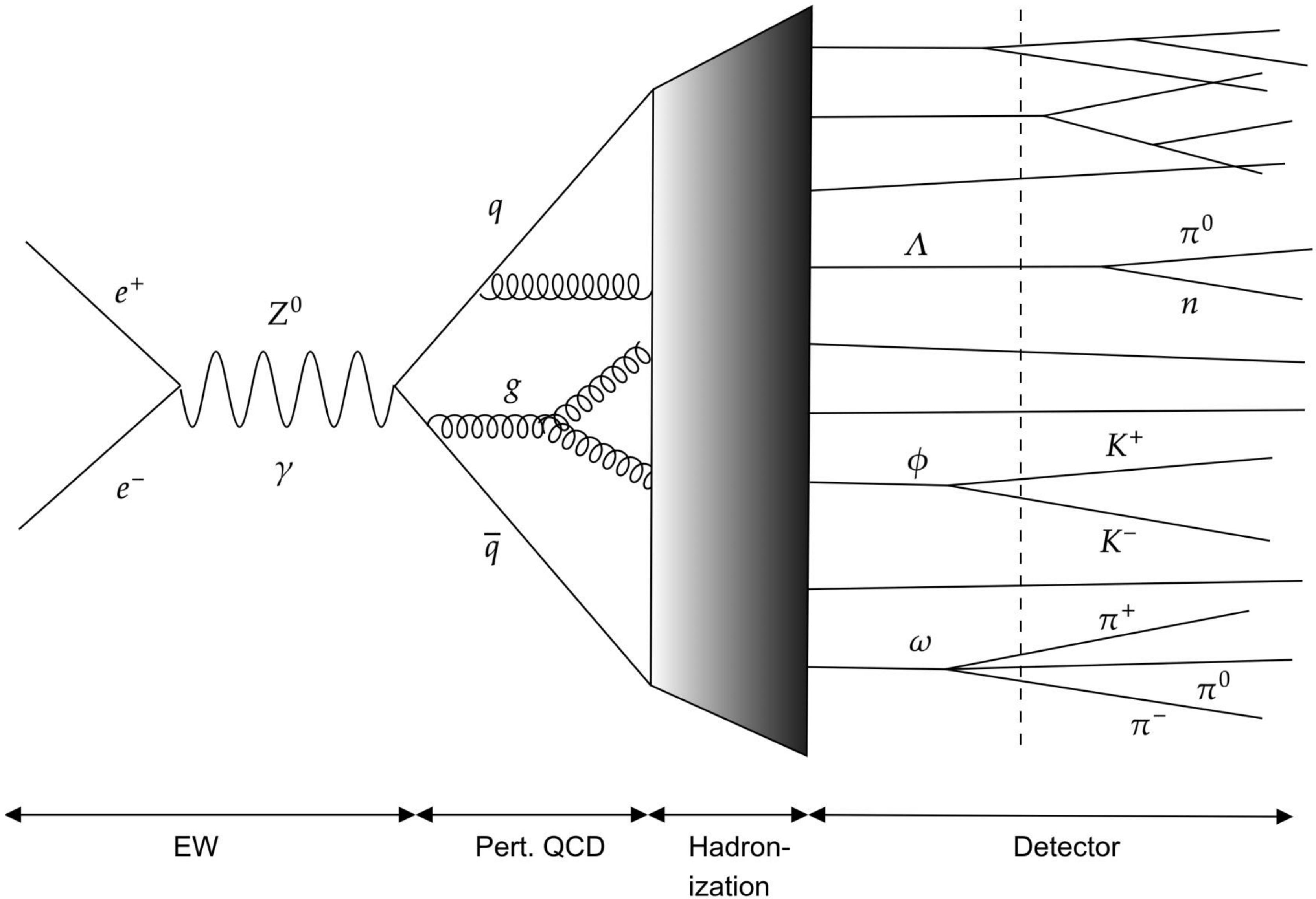
Baseline: ≥2 charged tracks



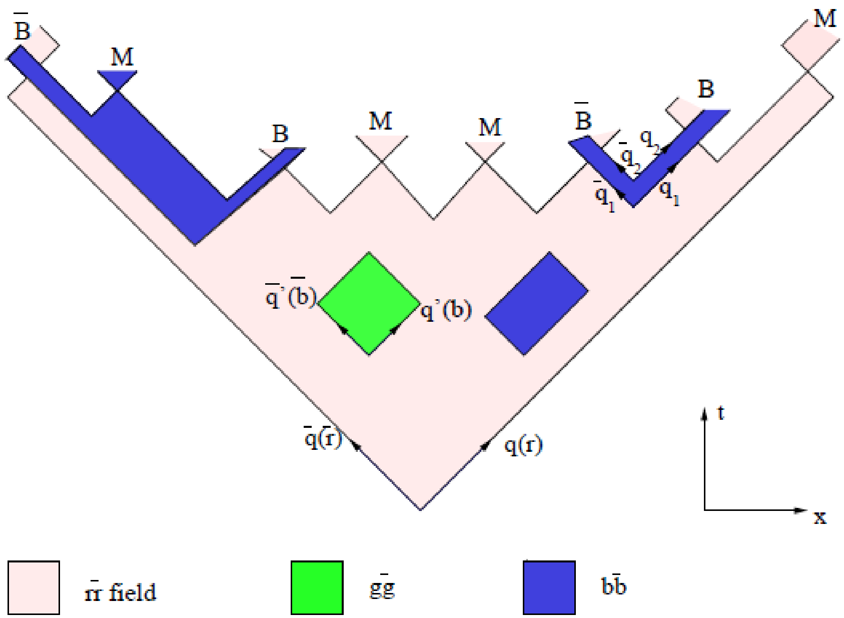
Background level



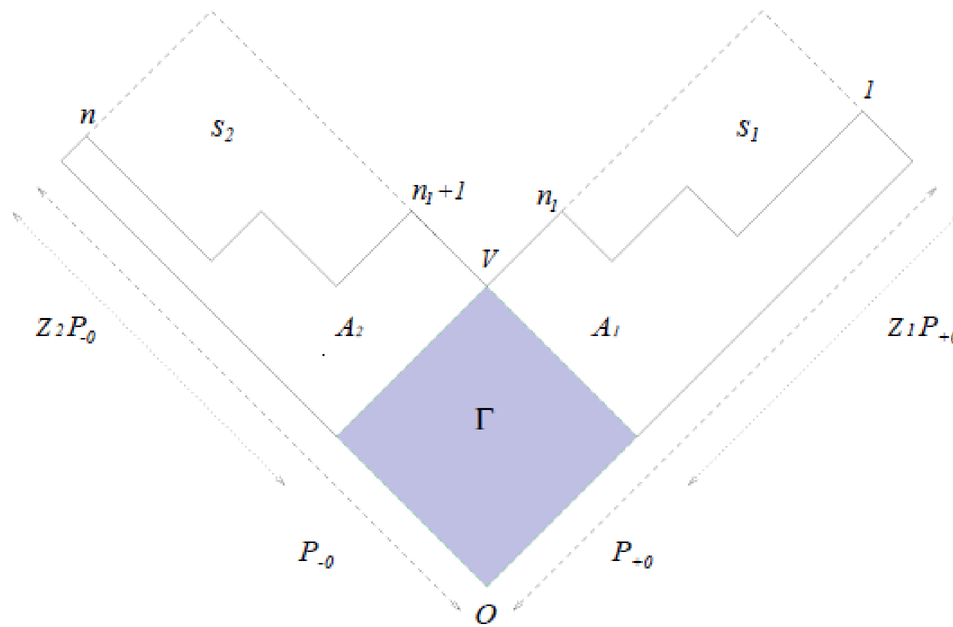
Hadron production and detection



String fragmentation scheme: LUARLW

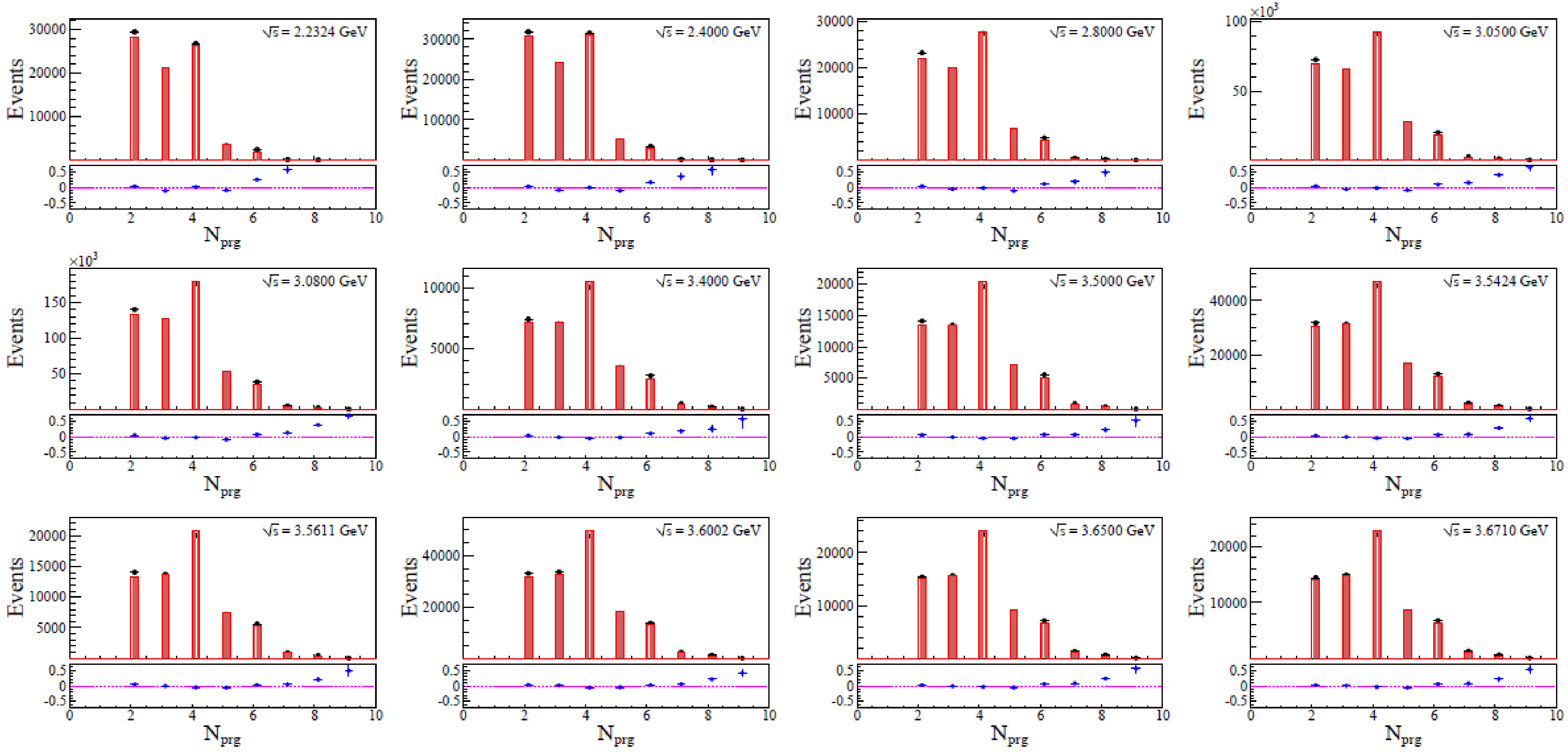


String fragmentation in t-x space

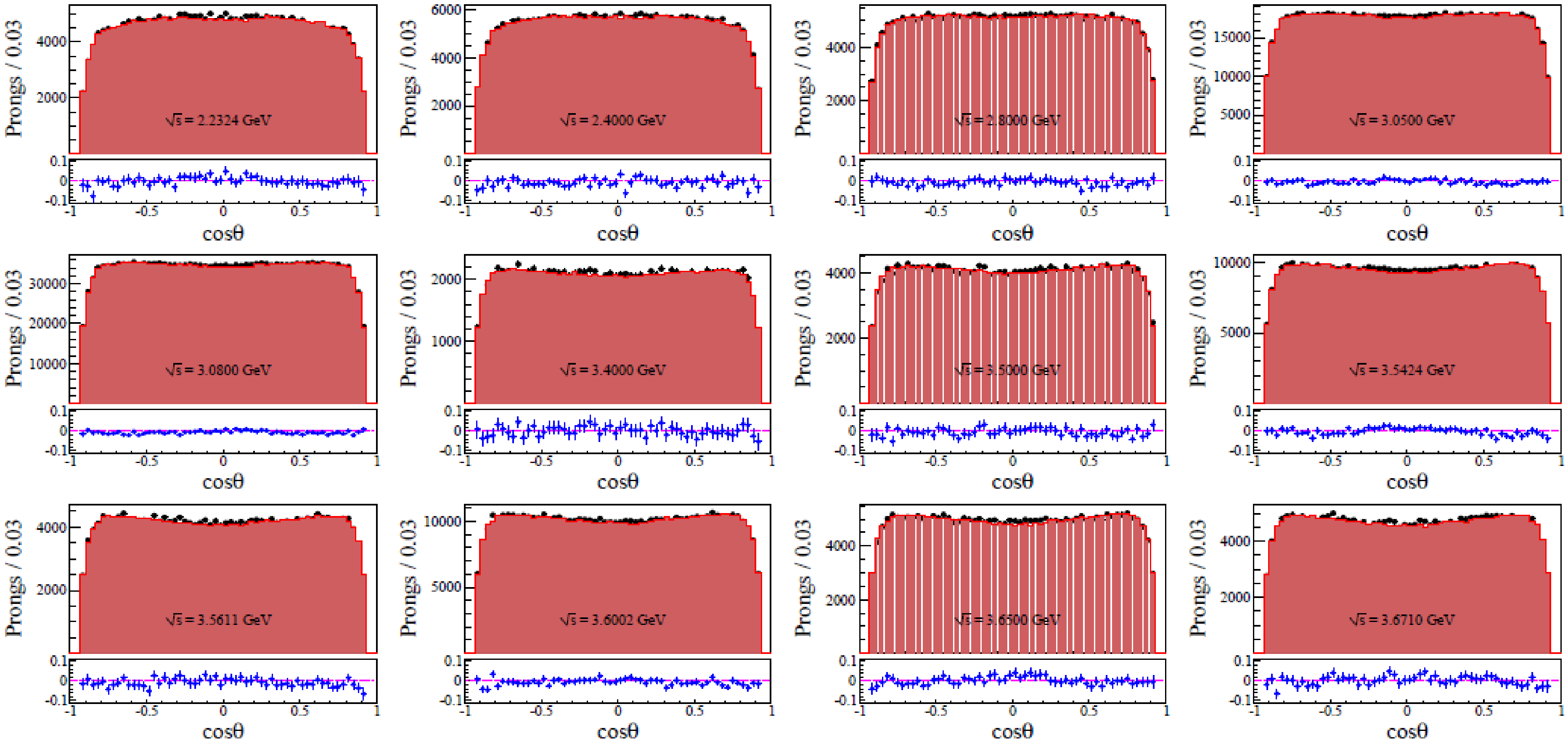


2 cluster divided at vertex V

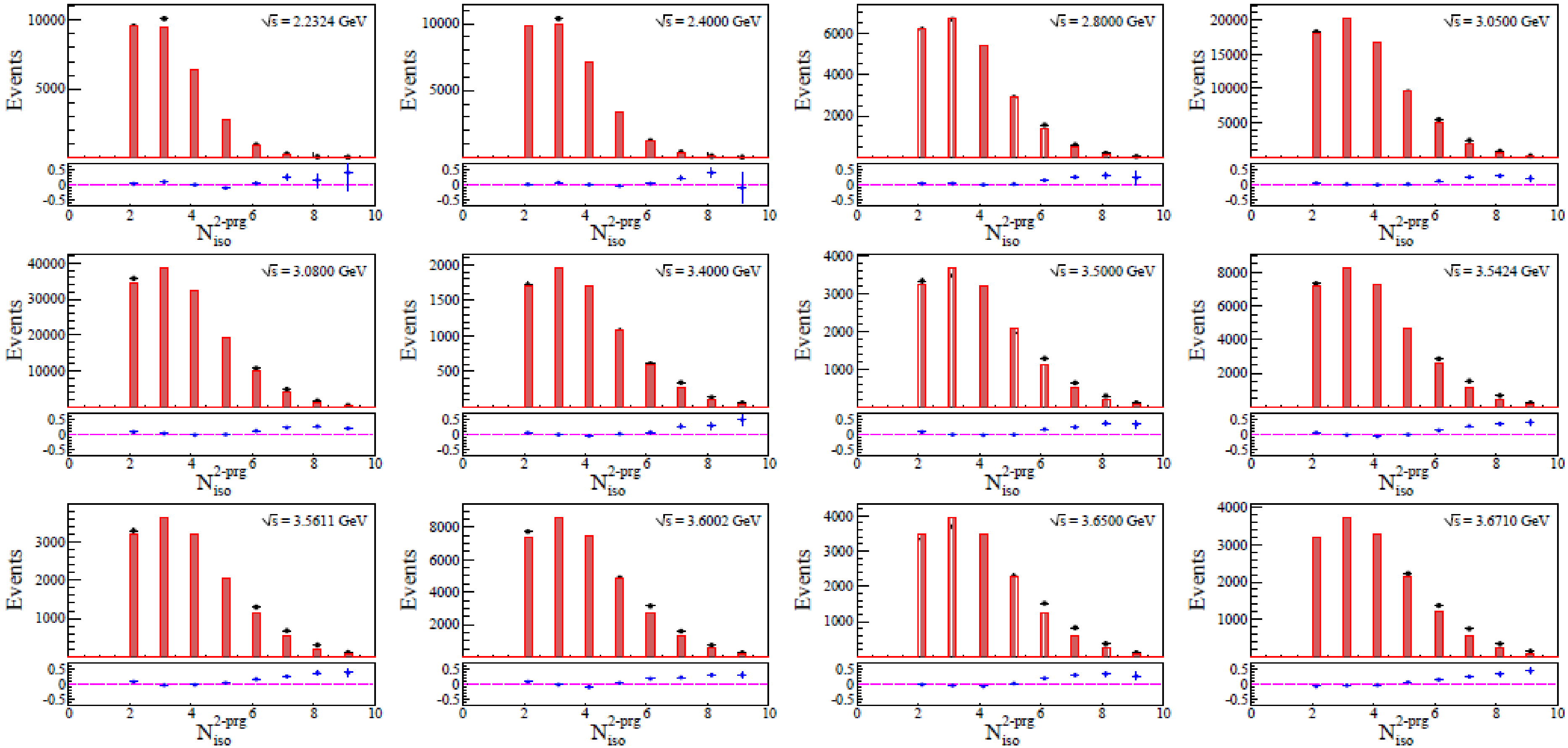
LUARLW: charged multiplicity



LUARLW: polar angle cosθ



LUARLW: neutral multiplicity for 2-prg



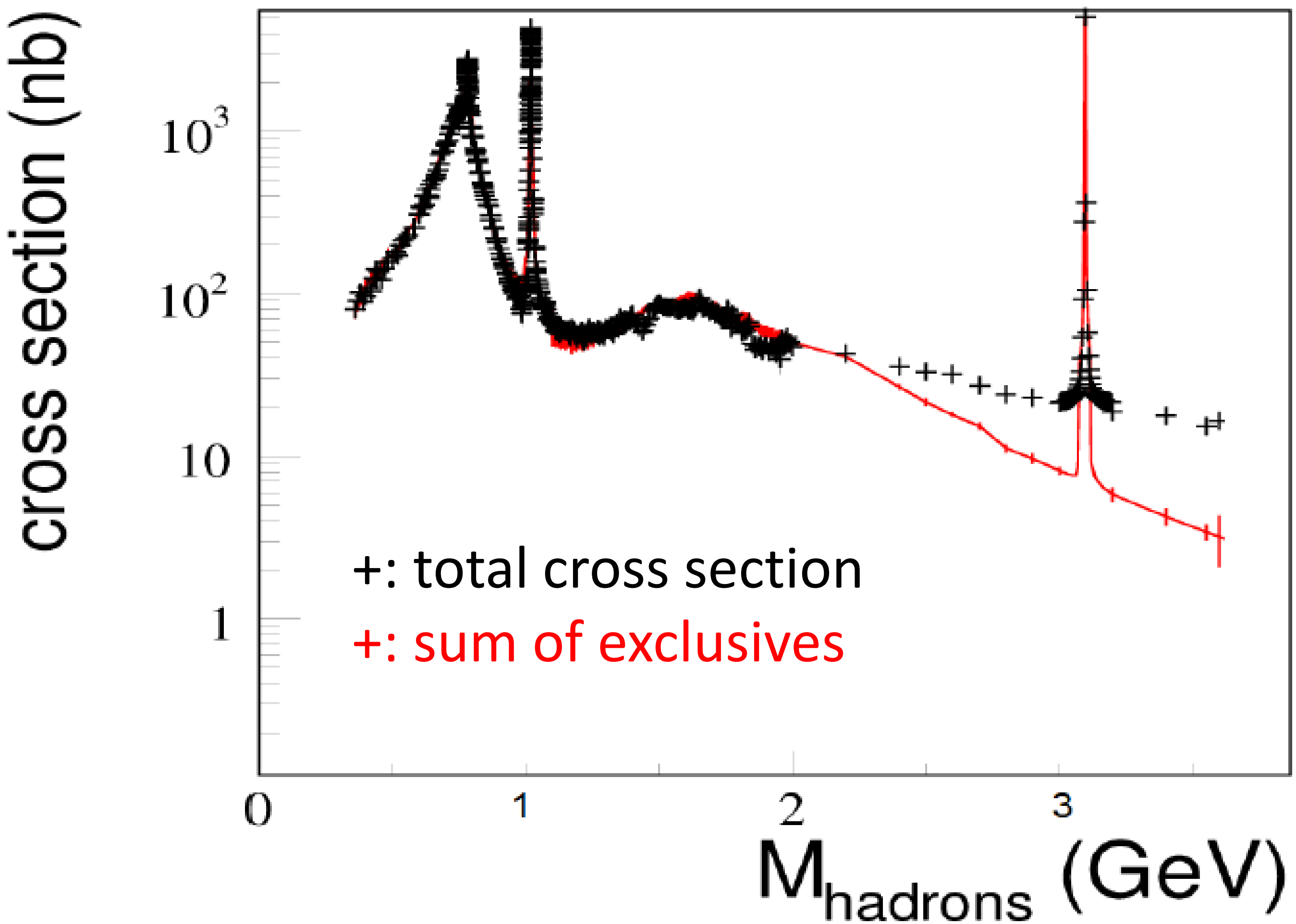
HYBRID: an alternative generator

- Combination of Phokhara, ConExc, LUARLW;
- Phokhara: 10 measured exclusive processes with intermediate states (2π, 3π, 4π,…);
- ConExc: 47 measured exclusive processes assuming PHSP model ($KK\pi$, $KK\pi\pi$, $\gamma J/\psi$,…);
- LUARLW: for the rest, but no repeating.

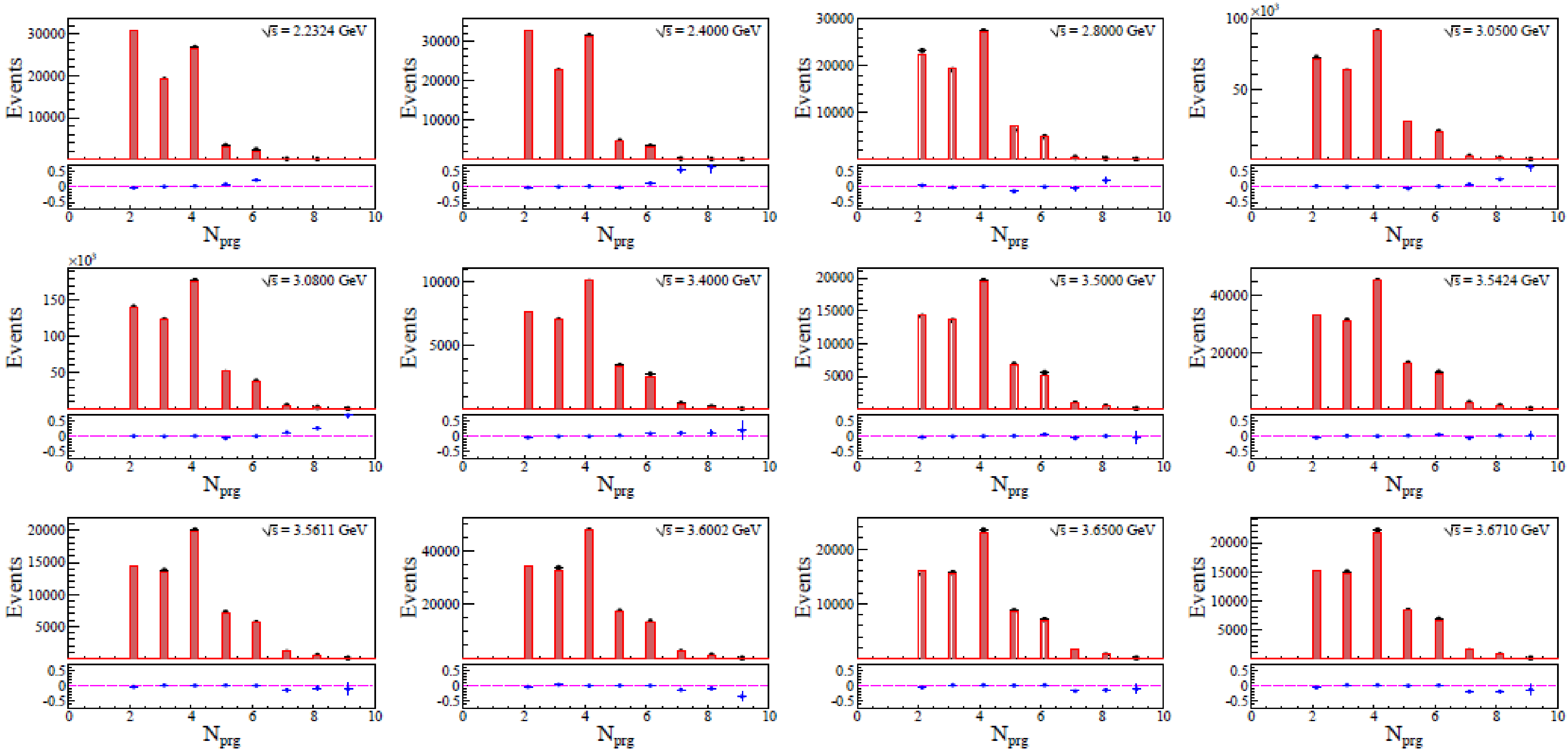
- Idea: as much experimental info as possible.

Why HYBRID?

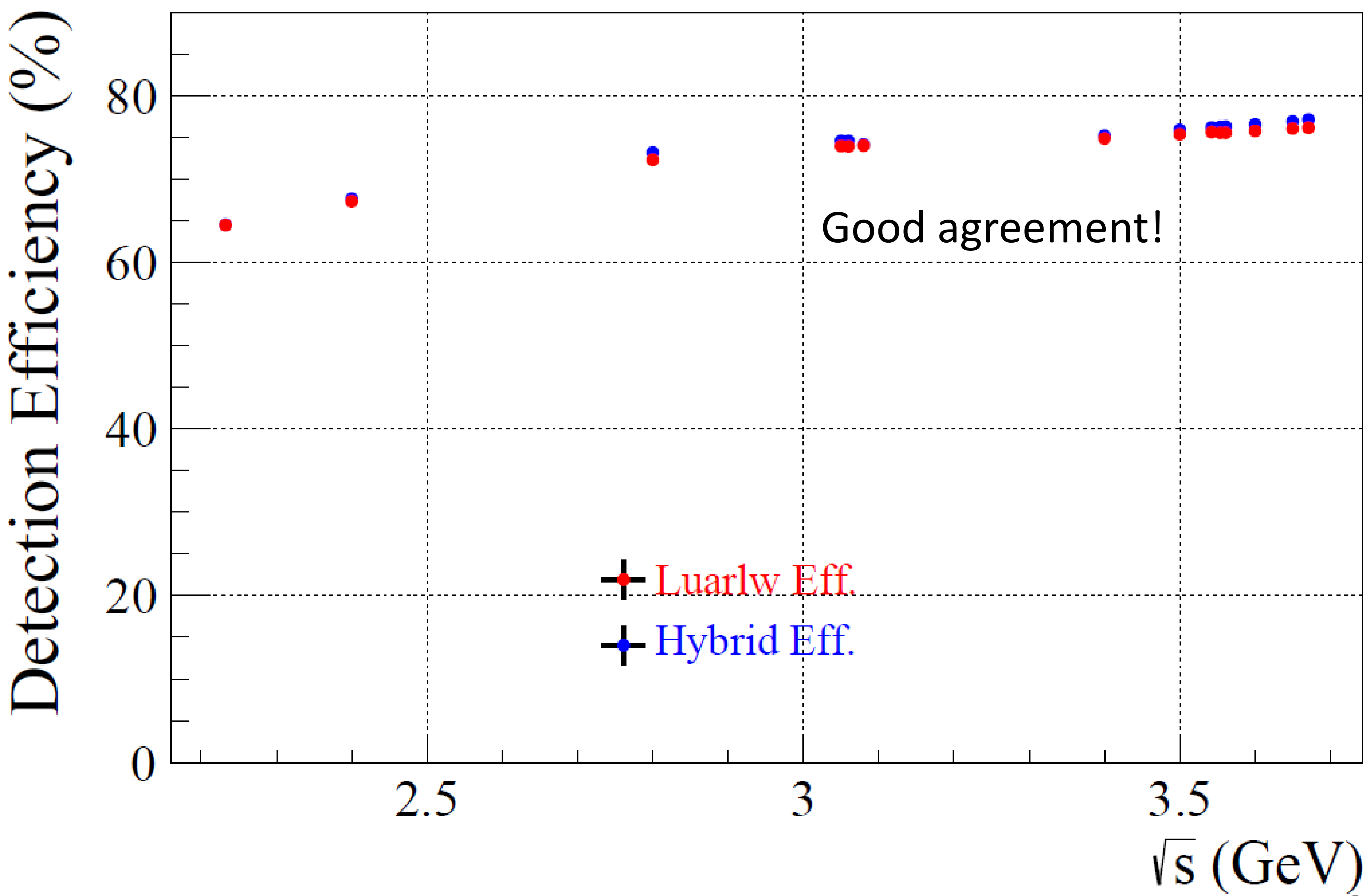
At low energy, cross sections were largely measured:



HYBRID: charged multiplicity

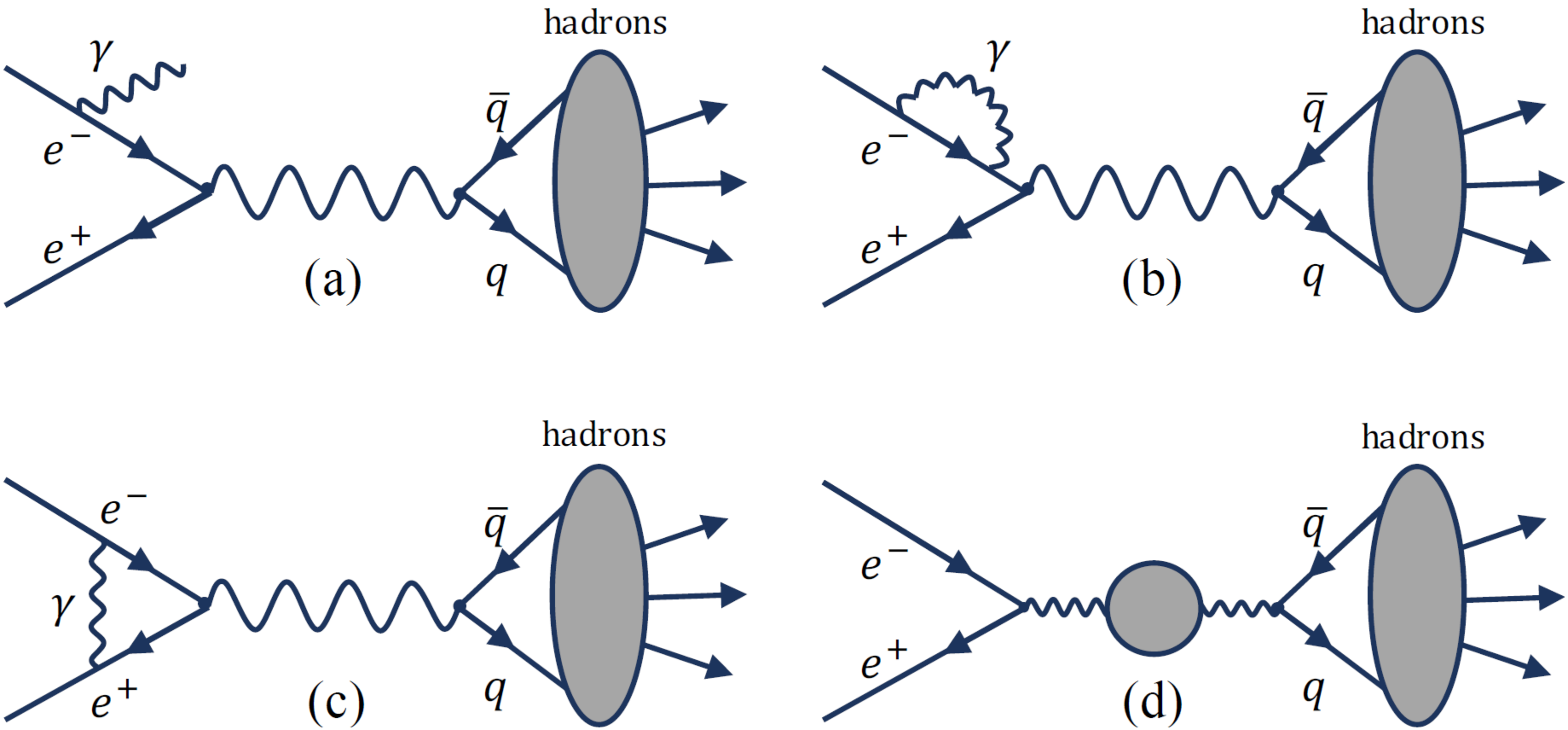


Efficiencies



ISR correction (1+δ)

- **Feynman Diagram scheme used:**

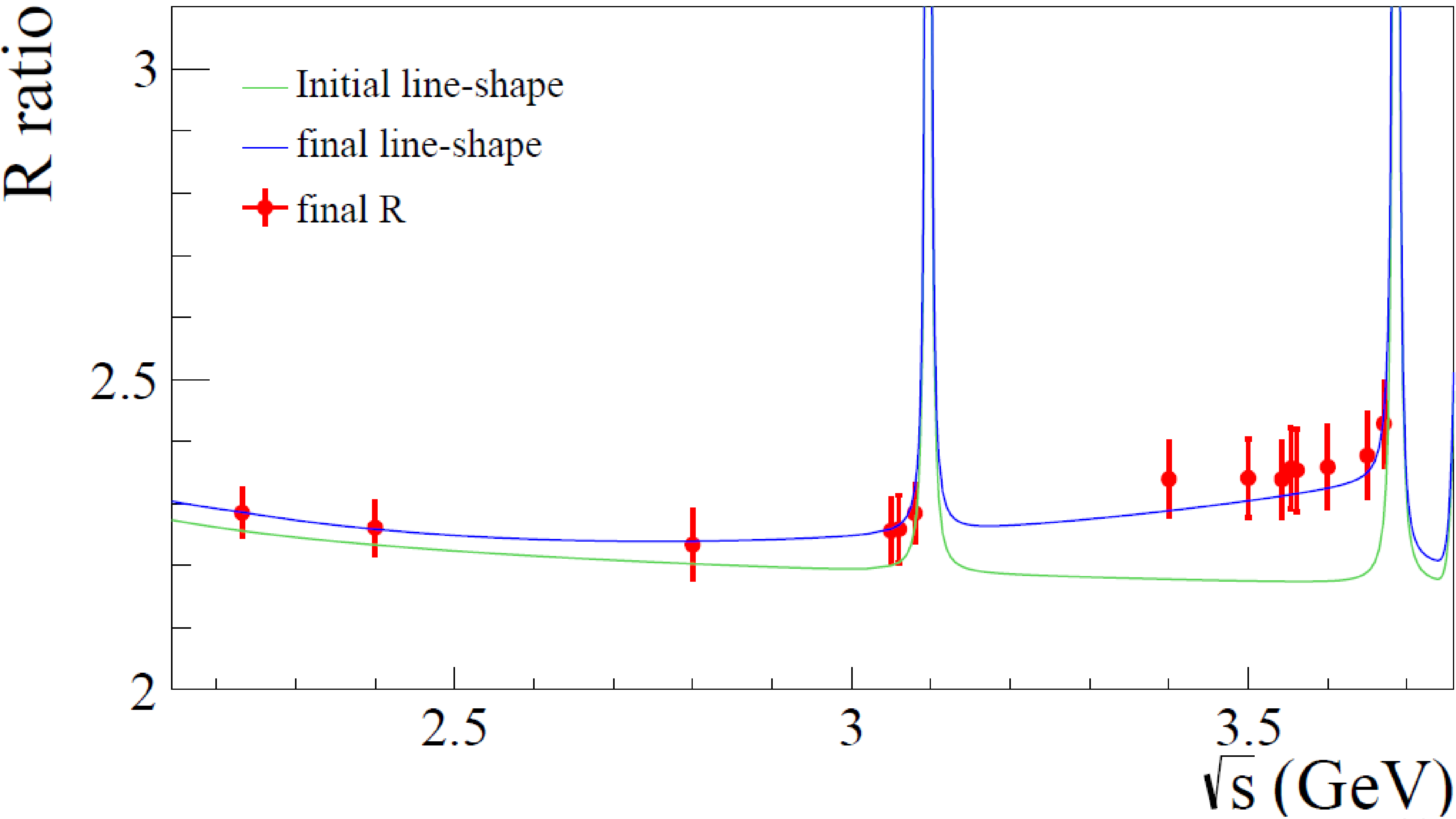


LUARLW vs HYBRID

$\sqrt{s}$ (GeV)	LUARLW ε_{had} (%)	HYBRID ε_{had} (%)	Diff. (%)	LUARLW $(1+\delta)$	HYBRID $(1+\delta)$	Diff. (%)
2.2324	64.45	64.50	-0.09	1.1955	1.2016	-0.52
2.4000	67.29	67.62	-0.49	1.2043	1.2118	-0.62
2.8000	72.25	73.16	-1.25	1.2185	1.2276	-0.74
3.0500	73.91	74.54	-0.85	1.1929	1.2040	-0.93
3.0600	73.88	74.54	-0.90	1.1825	1.1940	-0.97
3.0800	73.98	74.11	-0.18	1.1228	1.1357	-1.15
3.4000	74.81	75.19	-0.50	1.3817	1.4009	-1.39
3.5000	75.32	75.88	-0.75	1.3509	1.3690	-1.33
3.5424	75.58	76.17	-0.78	1.3413	1.3587	-1.30
3.5538	75.50	76.23	-0.97	1.3384	1.3557	-1.29
3.5611	75.50	76.27	-1.02	1.3368	1.3542	-1.30
3.6002	75.73	76.52	-1.05	1.3285	1.3453	-1.26
3.6500	76.00	76.89	-1.16	1.3082	1.3234	-1.16
3.6710	76.11	77.11	-1.30	1.2597	1.2718	-0.96

The differences in R are taken as systematic uncertainties.

Cross section line-shape



Systematic uncertainty

- Less than 3%;
- Dominated by generator model.

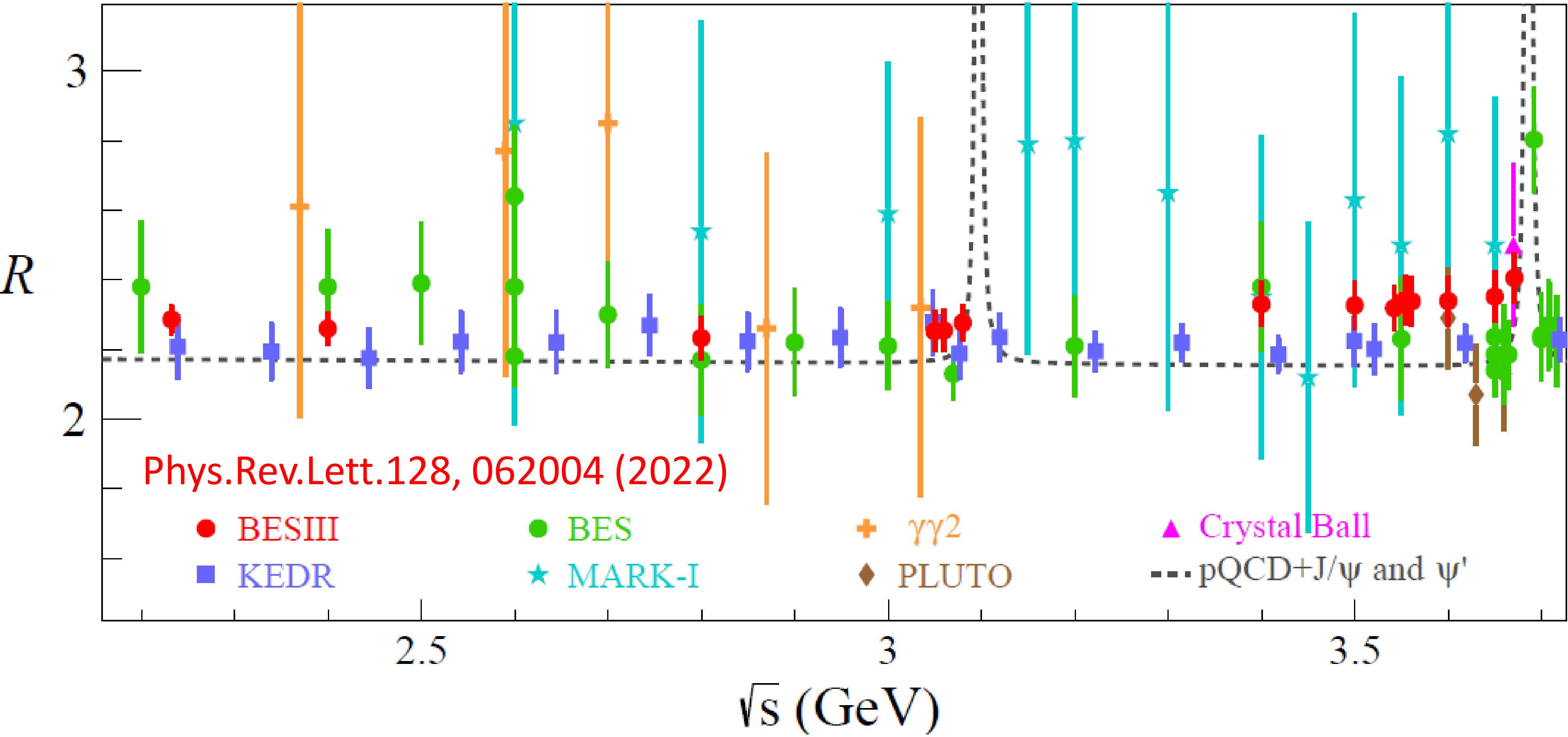
$\sqrt{s}$ (GeV)	Event selection	QED background	Beam background	Luminosity	Trigger efficiency	Signal model	ISR correction	Total
2.2324	0.41	0.23	0.28	0.80	0.10	0.60	1.15	1.62
2.4000	0.55	0.27	0.15	0.80	0.10	1.11	1.10	1.87
2.8000	0.58	0.28	0.34	0.80	0.10	1.97	1.06	2.48
3.0500	0.61	0.33	0.41	0.80	0.10	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

Final results

- R measured at 14 energies in continuum;
- Systematics dominant;
- Phys.Rev.Lett.128, 062004 (2022).

$\sqrt{s}$ (GeV)	$N_{\rm had}^{\rm obs}$	$N_{\rm bkg}$	$\sigma^0_{\mu\mu}$ (nb)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$\varepsilon_{\rm had}$ (%)	$1+\delta$	R
2.2324	83 227	2041	17.427	2.645	64.45	1.195	$2.286 \pm 0.008 \pm 0.037$
2.4000	96 627	2331	15.079	3.415	67.29	1.204	$2.260 \pm 0.008 \pm 0.042$
2.8000	83 802	2075	11.078	3.753	72.25	1.219	$2.233 \pm 0.008 \pm 0.055$
3.0500	283 822	7719	9.337	14.89	73.91	1.193	$2.252 \pm 0.004 \pm 0.052$
3.0600	282 467	7683	9.276	15.04	73.88	1.183	$2.255 \pm 0.004 \pm 0.054$
3.0800	552 435	15 433	9.156	31.02	73.98	1.123	$2.277 \pm 0.003 \pm 0.046$
3.4000	32 202	843	7.513	1.733	74.81	1.382	$2.330 \pm 0.014 \pm 0.058$
3.5000	62 670	1691	7.090	3.633	75.32	1.351	$2.327 \pm 0.010 \pm 0.062$
3.5424	145 303	3872	6.921	8.693	75.58	1.341	$2.319 \pm 0.006 \pm 0.060$
3.5538	92 996	2469	6.877	5.562	75.50	1.338	$2.342 \pm 0.008 \pm 0.064$
3.5611	64 650	2477	6.849	3.847	75.50	1.337	$2.338 \pm 0.010 \pm 0.066$
3.6002	159 644	9817	6.701	9.502	75.73	1.328	$2.339 \pm 0.006 \pm 0.065$
3.6500	78 730	6168	6.519	4.760	76.00	1.308	$2.352 \pm 0.009 \pm 0.067$
3.6710	75 253	6461	6.445	4.628	76.11	1.260	$2.405 \pm 0.010 \pm 0.067$

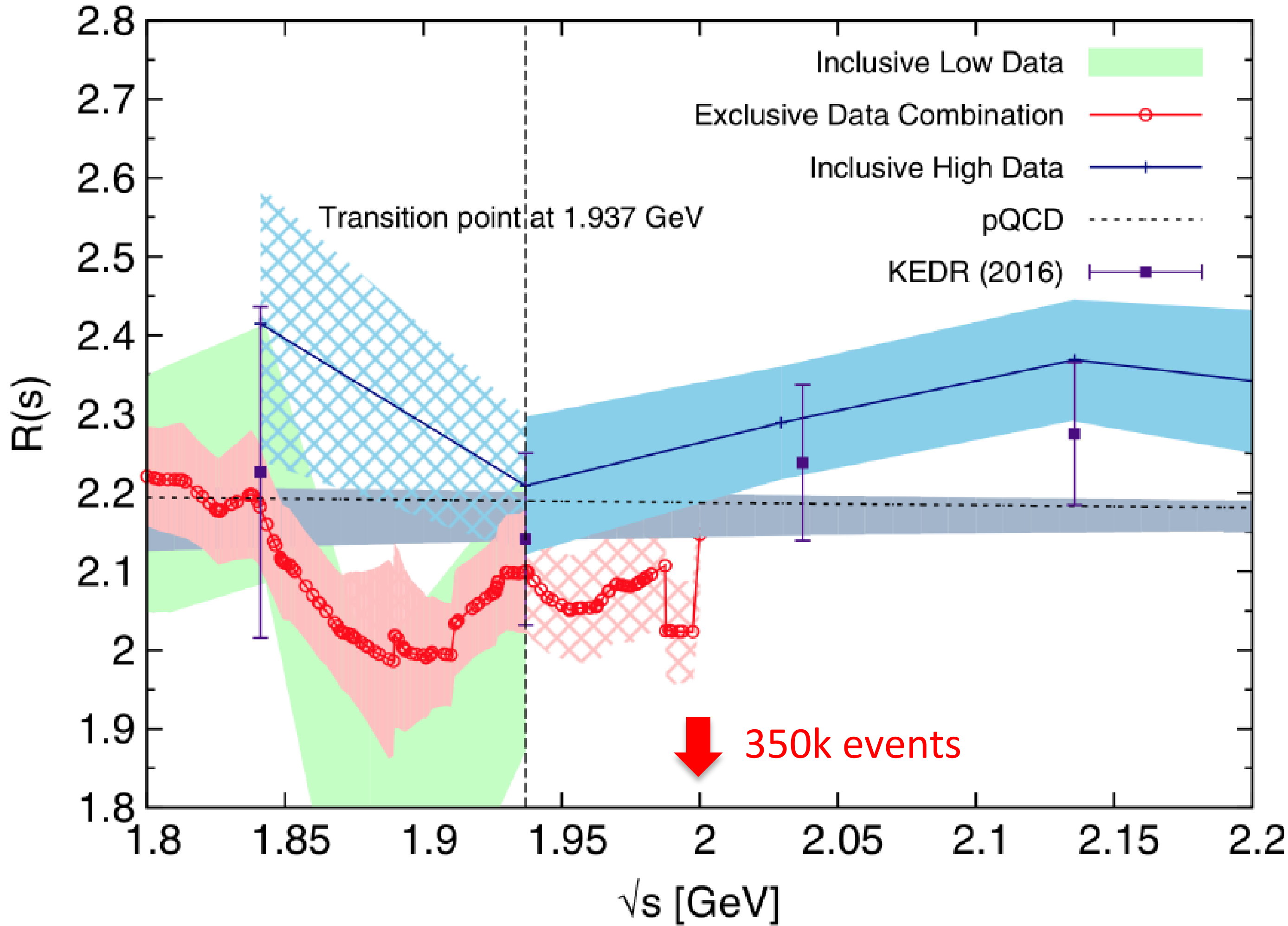
R value in [2.2324, 3.671] GeV



- Precision better than 3%;
- Larger than pQCD by 2.7σ in [3.4, 3.7] GeV.

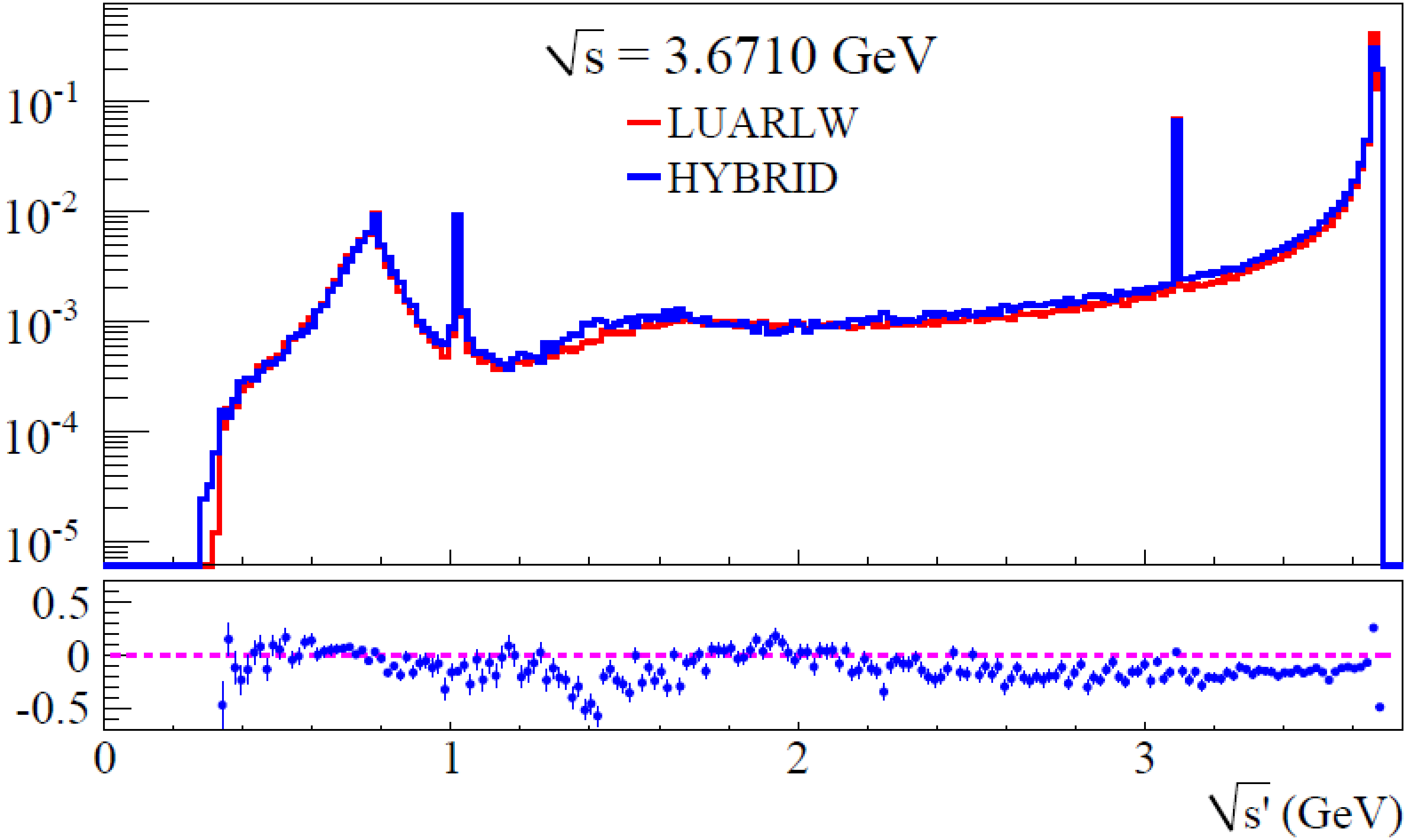
Ongoing studies and prospects

- R value in full energy range [2.0, 4.95] GeV;
- Comprehensive measurement at 2.0 GeV:



Ongoing studies and prospects

- R via ISR technique down to $\pi^+\pi^-$ threshold!



- Data taking in [1.8, 2.0] GeV right now!

Summary

- R measurements at BESII were a great success: 5(+10) pb^{-1}
  - 6+85 energies in 2–5 GeV, precision ~6%;
  - Ultimate 3.5% reached at 3 energies.
- R-QCD data taken at BESIII in 2–4.6 GeV: 1.5 fb^{-1}
  - Test run at 4 points in the low energy region;
  - A 104-point fine scan from 3.8 GeV to 4.6 GeV;
  - Data taken at 22 points between 2.0 GeV to 3.08 GeV.
- BESIII First R values with uncertainties <3% at 14 energies in [2.2324, 3.671] GeV published: PRL 128, 062004 (2022);
- Taking data in 1.8-2.0 GeV, exciting moment also for BEPCII!
- More results to come…