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BESIII

Tests of lepton flavour universality with (semi-)leptonic decays of charmed mesons

Evelina Gersabeck on behalf of the BESIII collaboration

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SSP2022

8th International Symposium on Symmetries in Subatomic Physics (SSP2022)

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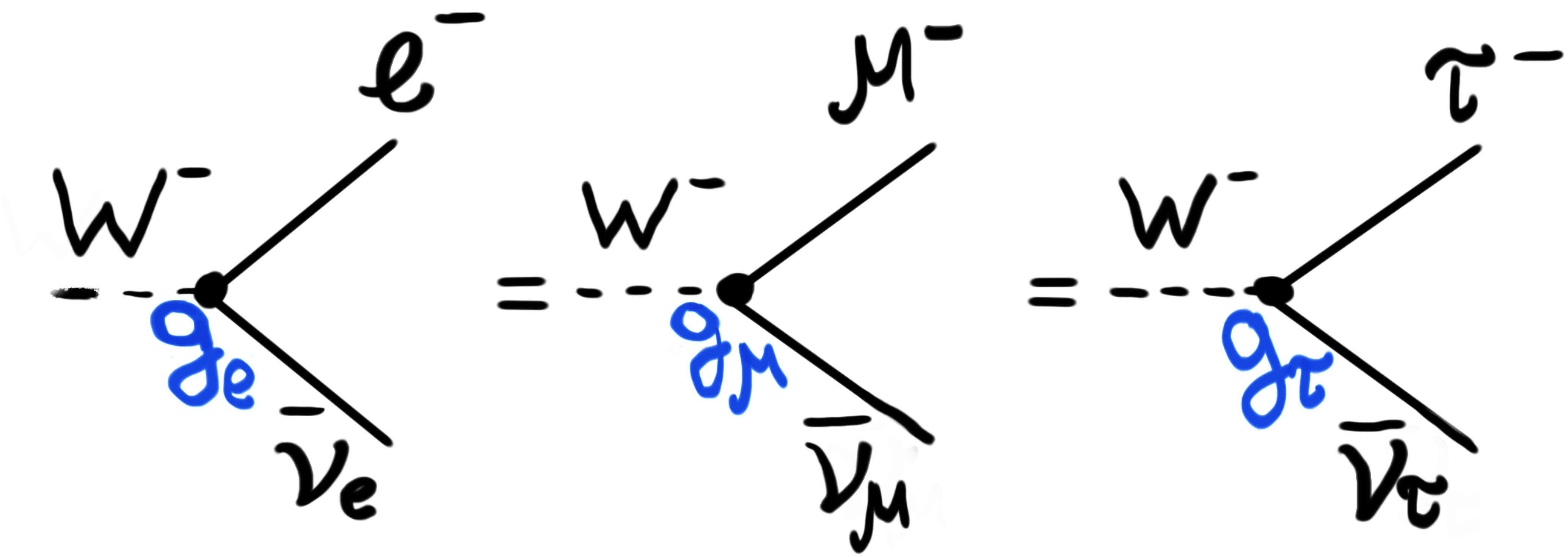
Testing the lepton flavour universality



Intrinsic to the SM

The only difference here should be the masses of the leptons

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LFU anomalies in B meson decays

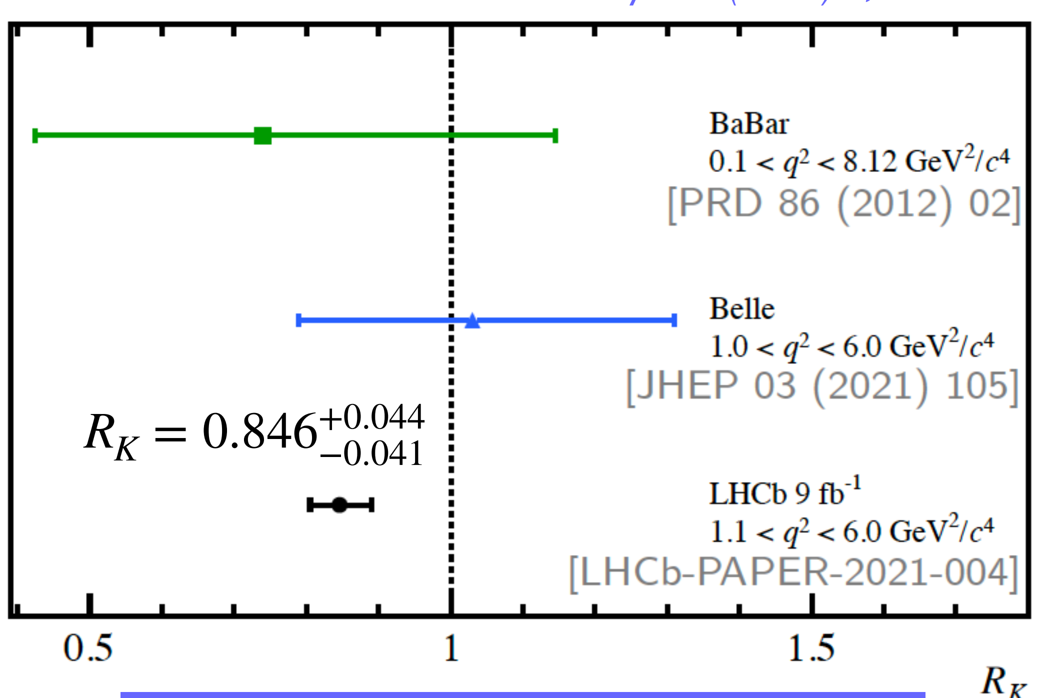
LFU in b→sll

- Theoretically very clean $R_K = 1 + \mathcal{O}(10^{-2})$
- Experimentally very clean:
  - Measured as a double ratio using $B^+ \to K^+ J/\psi(\to \ell^+\ell^-)$ decays

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \Big/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\to(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to(e^+e^-))}$$

- Observation of non-LFU would be a clear sign of new physics

Nature Phys. 18 (2022) 3, 277-282

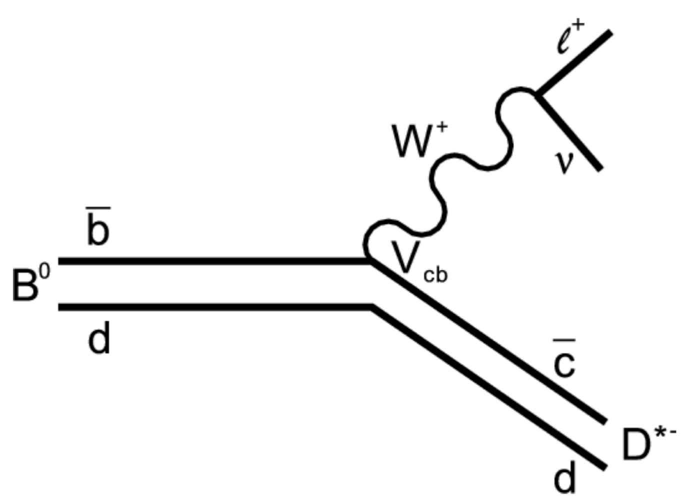


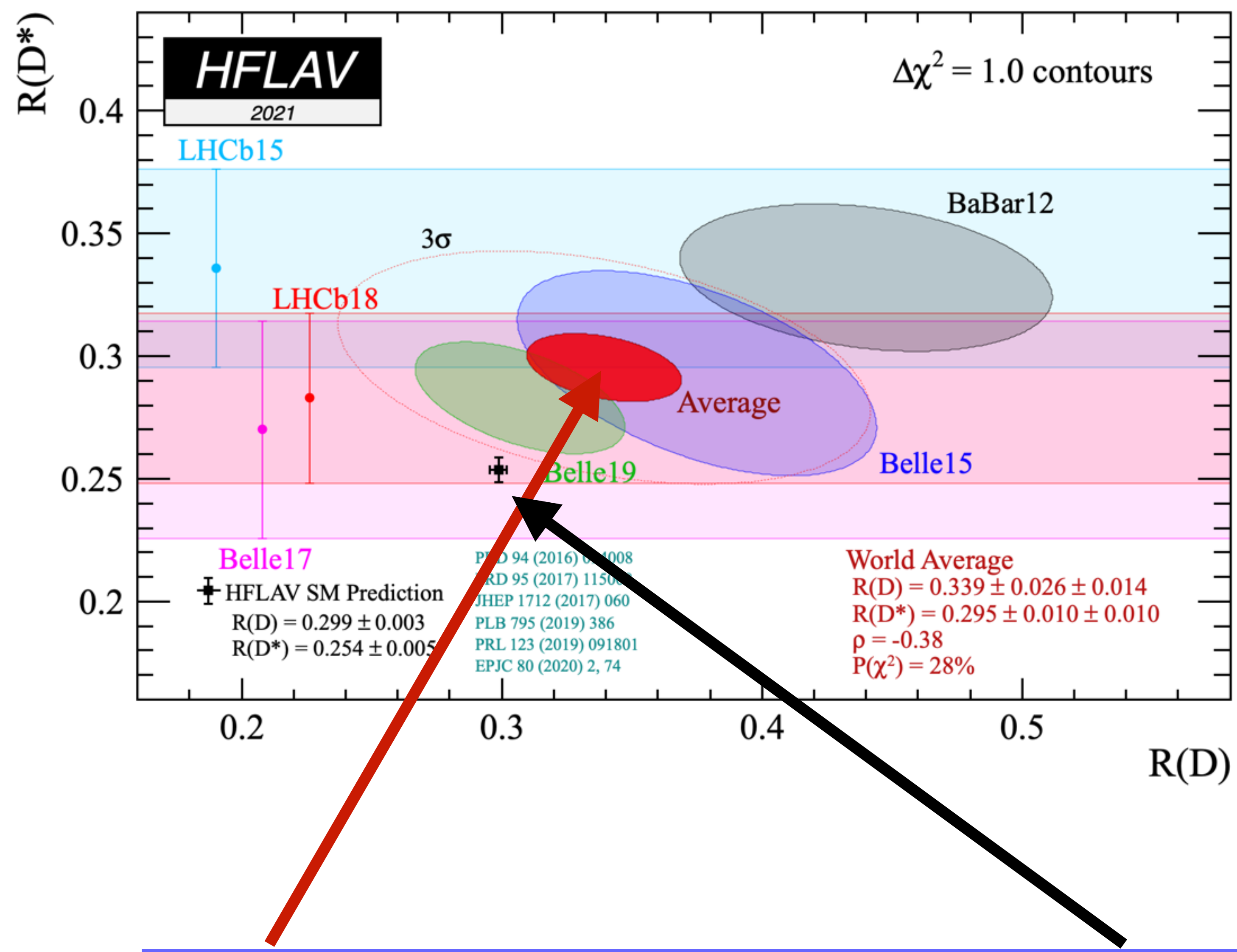
~3.1 σ away from the SM prediction

Lepton Universality in b→clν transitions

Measure the ratio $R_{D^{(*)}} = \frac{\mathscr{B}(B^0 \to D^{(*)}\tau\nu_\tau)}{\mathscr{B}(B^0 \to D^{(*)}\mu\nu_\mu)}$ with $\tau \to \mu\nu_\mu\bar{\nu}_\tau$, $\tau \to \pi\pi\pi(\pi^0)\bar{\nu}_\tau$

Tree level decays





Combination ~3.3 standard deviations away from SM prediction

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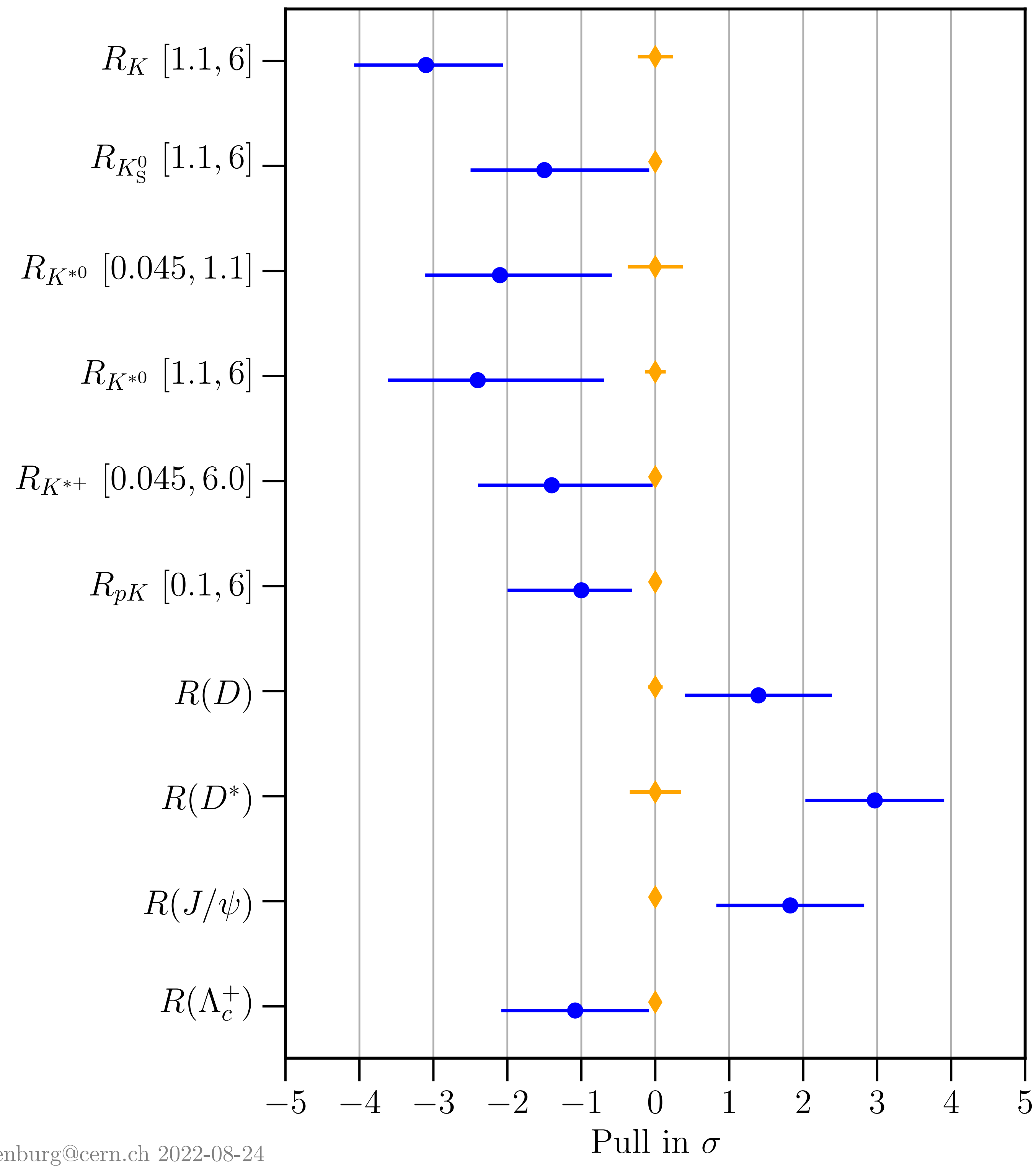
LFU tests and tensions

Image credit Patrick Koppenburg
https://www.nikhef.nl/~pkoppenb/anomalies.html



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What about LFU in charm meson decays?

Precision tests of LFU in charm decays will be essential in understanding the nature of these anomalies

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What about LFU in charm meson decays?

We can probe LFU in charm meson decays at the BESIII experiment

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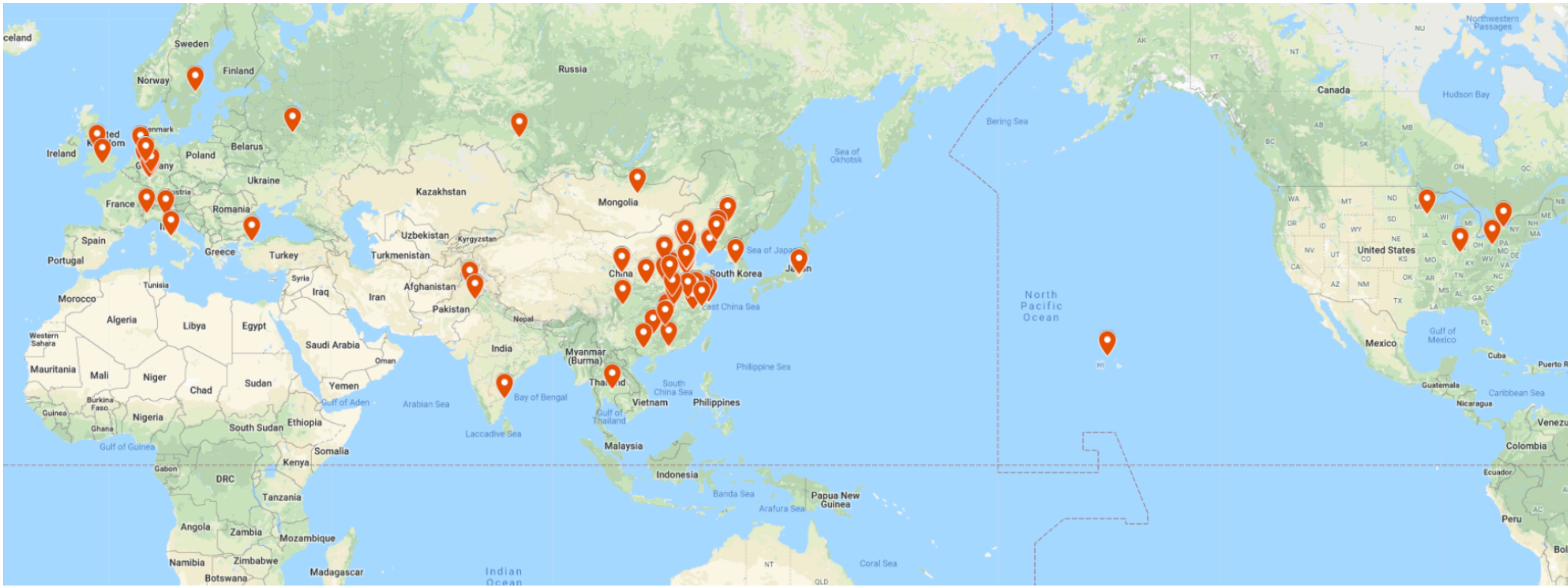
The BESIII collaboration



About 500 members from 72 institutions in 15 countries.

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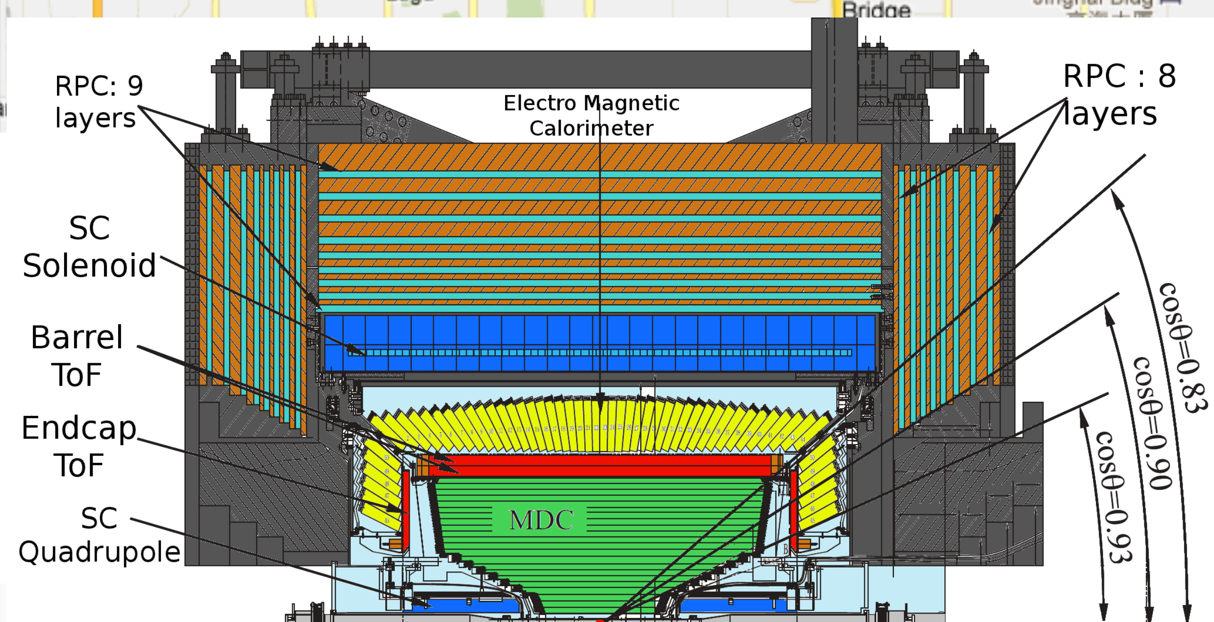
Experiment downtown Beijing



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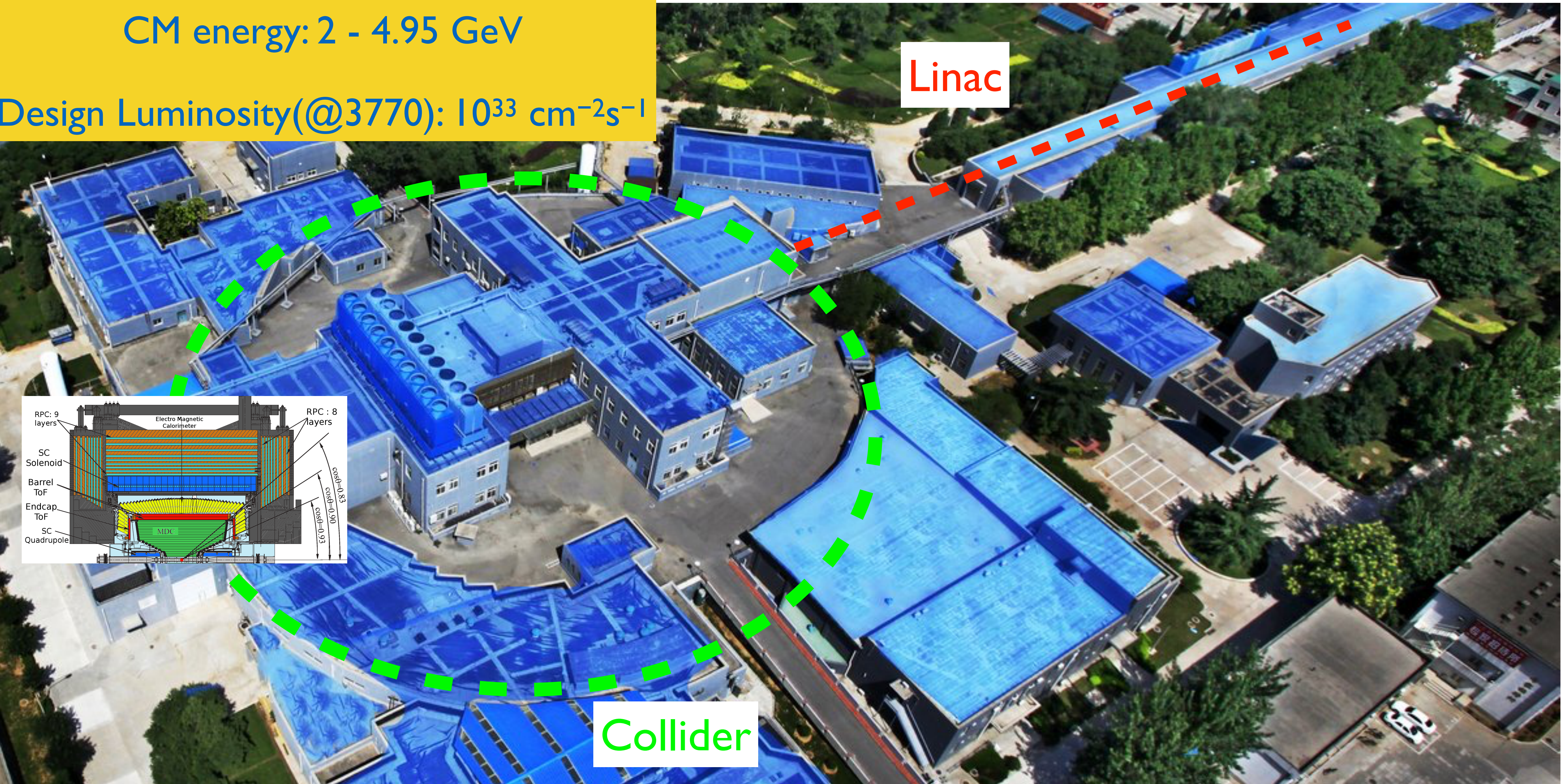
slide from W.Gradl

BEPCII @ IHEP (Beijing, PRC)

e^+e^- central collider

CM energy: 2 - 4.95 GeV

Design Luminosity(@3770): 10^{33} $cm^{-2}s^{-1}$



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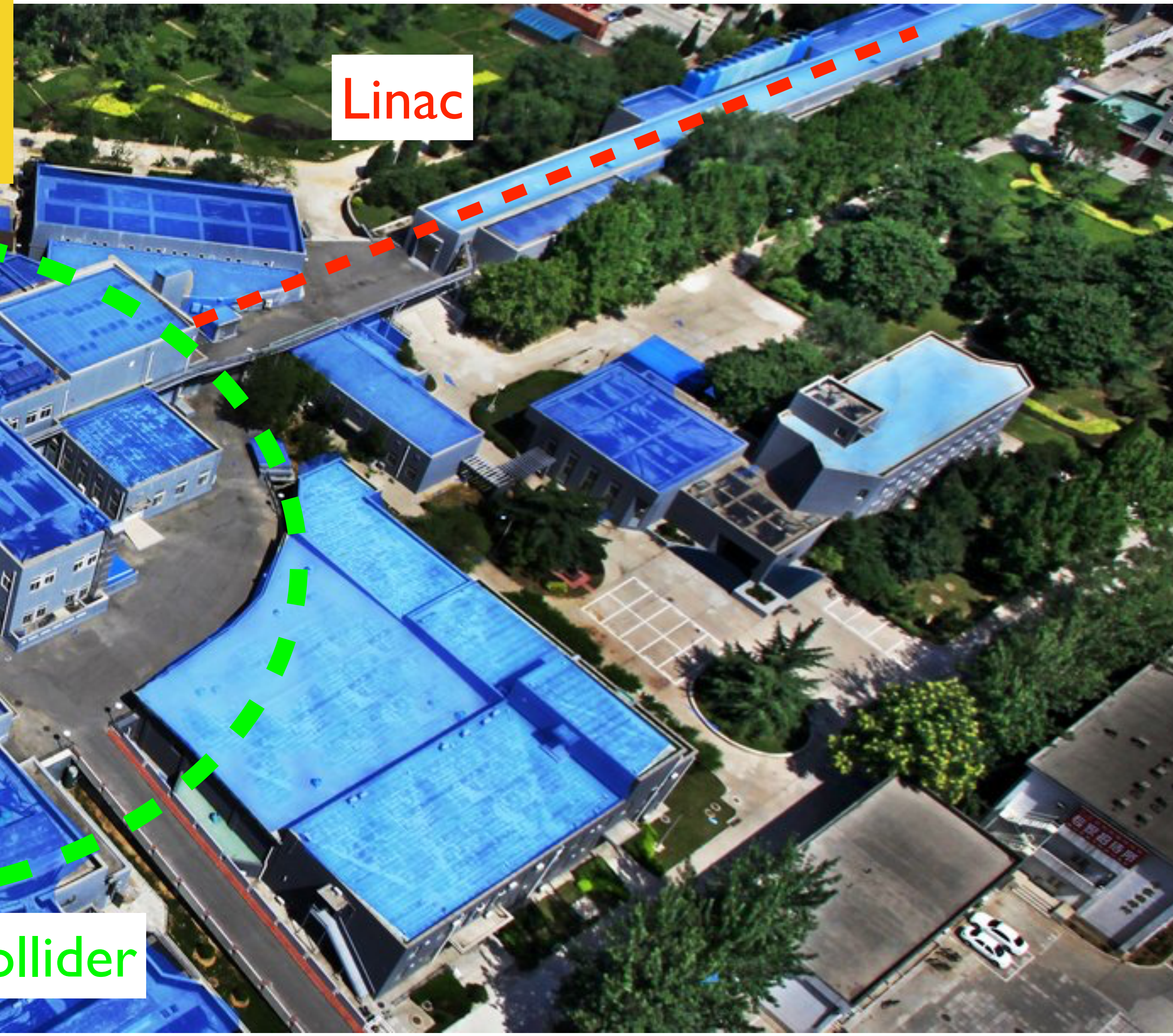

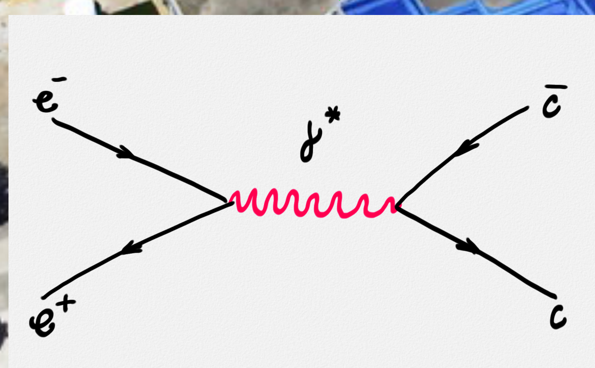

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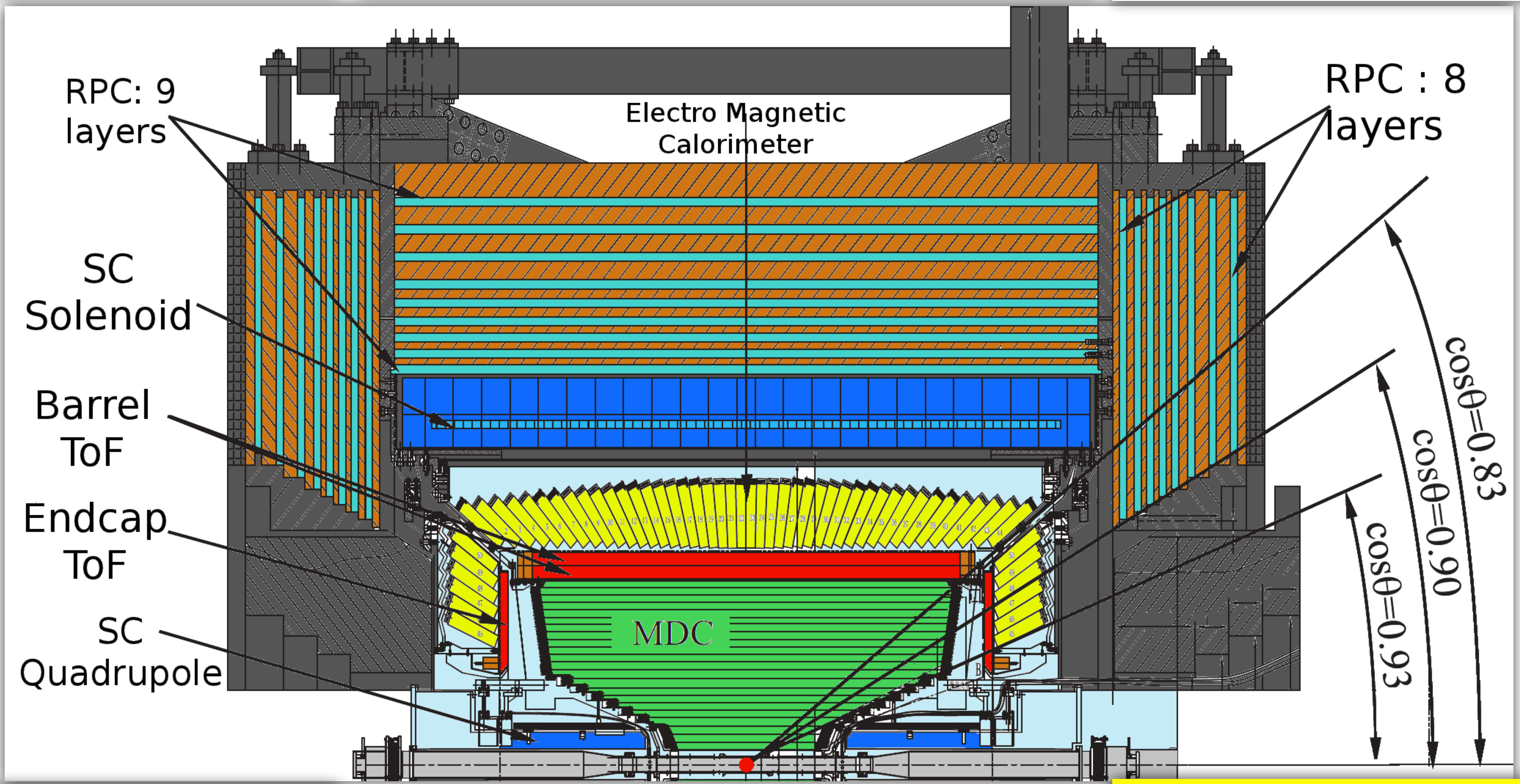
BESIII @ BEPCII

Nucl.Instrum.Meth.A614 (2010) 345-399

PID: Time Of Flight
2 layer plastic scintillators
time resolution σ_t (barrel) ~ 90 ps
σ_t (endcap) ~ 110 ps, (65 ps after the 2015 upgrade)

Superconducting magnet 1 T

Muon ID: Muon counters
9 layers of RPC
Spatial resolution $\delta_{r\phi}$ = 1.4 cm -1.7 cm



Main Drift Chamber
gas: He/ C_3H_8 60/40
43 layers
spatial resolution σ_x (1GeV/c) ~ 130 μm
momentum resolution dp/p (1GeV/c) = 0.5%

hermetic

barrel $|\cos\theta| < 0.83$

endcap $0.85 < |\cos\theta| < 0.93$

Electromagnetic Calorimeter
CsI (Tl) scintillating crystals 6240
energy resolution $dE/\sqrt{E}$ (1 GeV) = 2.5%
Spatial resolution σ_x (1 GeV) = 6 mm

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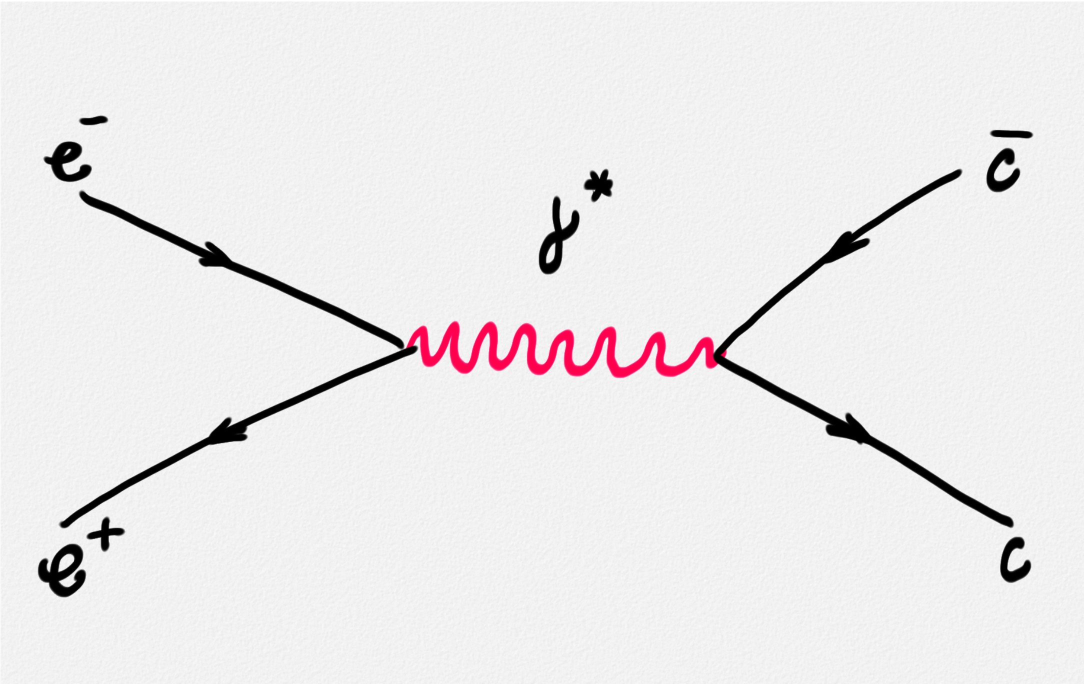
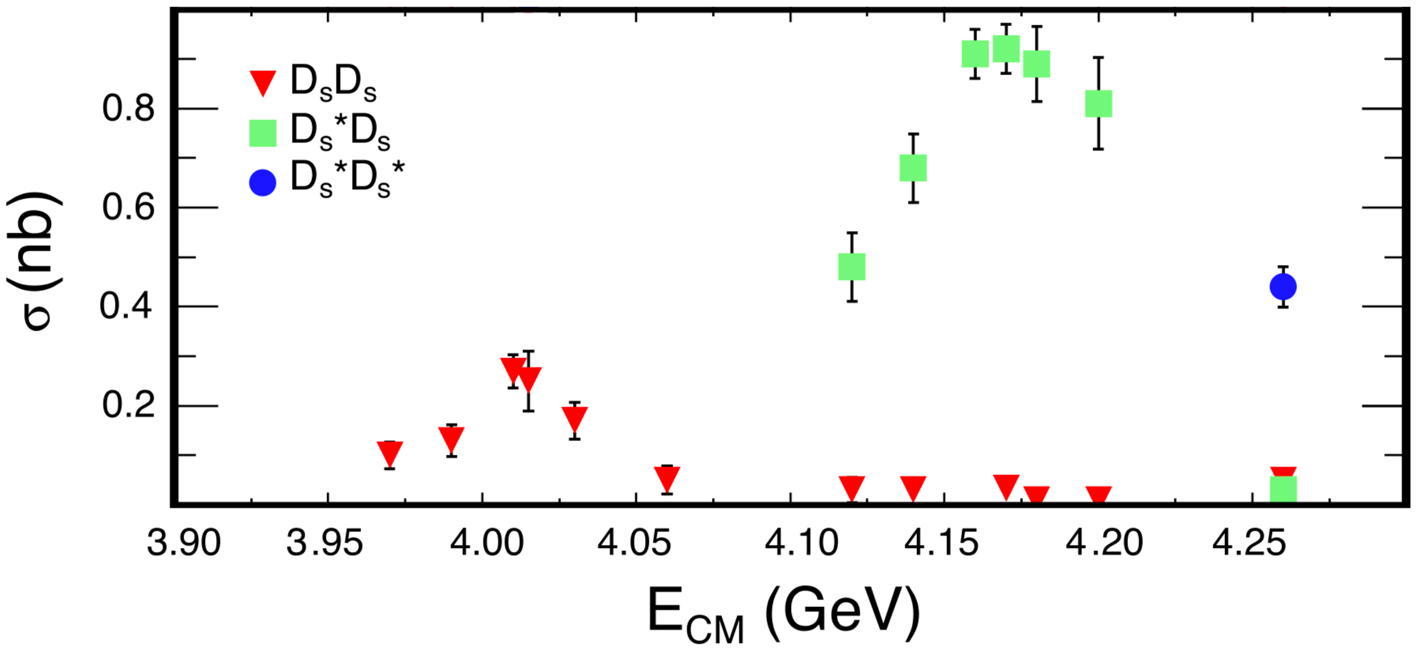
Charm meson production



- $D\bar{D}$ pairs @ 3.770 GeV
- Can produce $D_s^+D_s^-$ @ threshold but
- $D_s^+D_s^{-*}(\rightarrow D_s^-\gamma$ or $D_s^-\pi^0)$ has a higher cross section @4.160 GeV

CLEO Phys. Rev. D 80, 072001 (2009)



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Tagging method for charm@threshold

- Single tag: fully reconstruct the signal $D_{(S)}$: typically a clean mode
- Double tag:
  - Fully reconstruct the tag $D_{(S)}$ taking advantage of kinematic constrains
  - Search for the signal mode in the recoil system

@ threshold = full kinematic constraint of the decays

Excellent for neutral and invisible particles

Tagging method for charm@threshold

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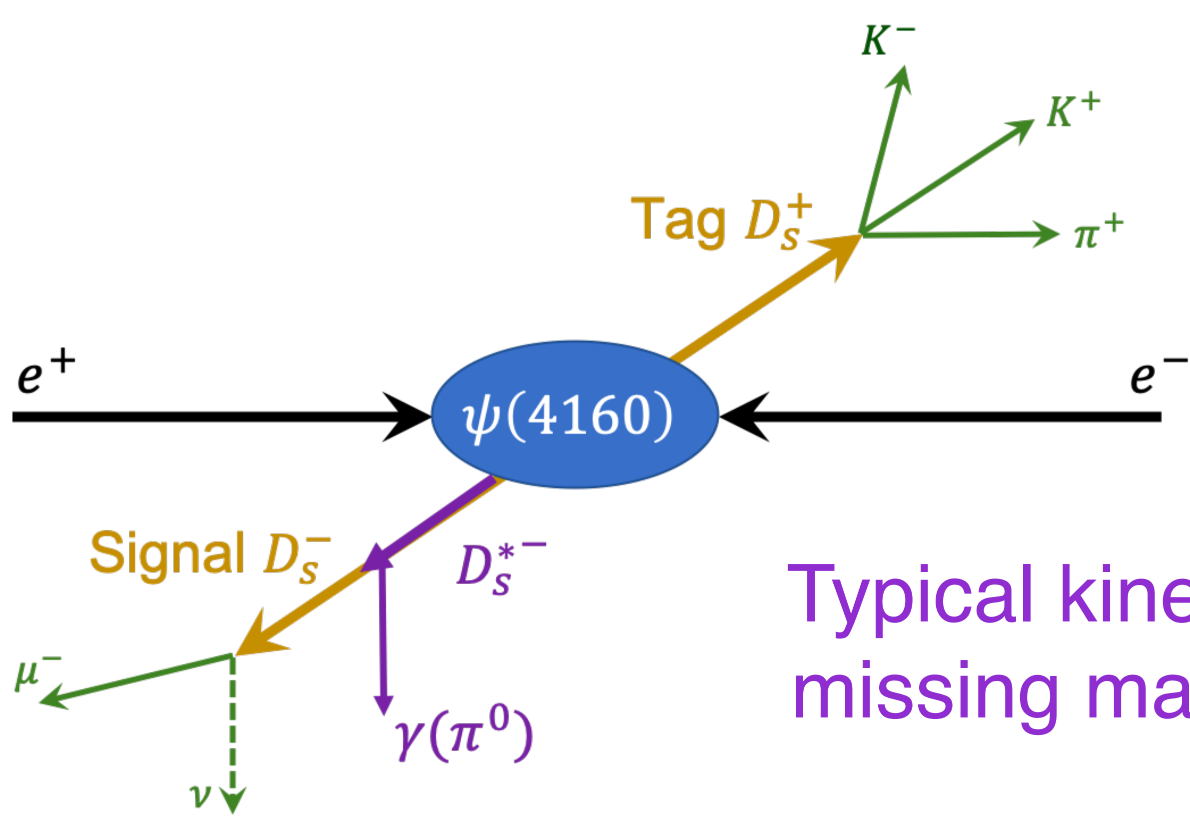
  - Fully reconstruct the tag $D_{(S)}$ taking advantage of kinematic constrains
  - Search for the signal mode in the recoil system



Typical kinematic variables we use are the missing mass, M_{miss}, or $U_{miss} = E_{miss} - p_{miss}$

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Absolute BF measurement at BESIII

- Possible to measure absolute Branching Fraction

$$\mathscr{B}(D \to (X)\ell\nu_\ell) = \frac{N_{DT}}{\Sigma_i N^i_{tag} \,.\, (\epsilon^i_{DT}/\epsilon^i_{tag})}$$

- No need to know the total number of $D\bar{D}$ pairs
- A lot of systematic uncertainties cancel

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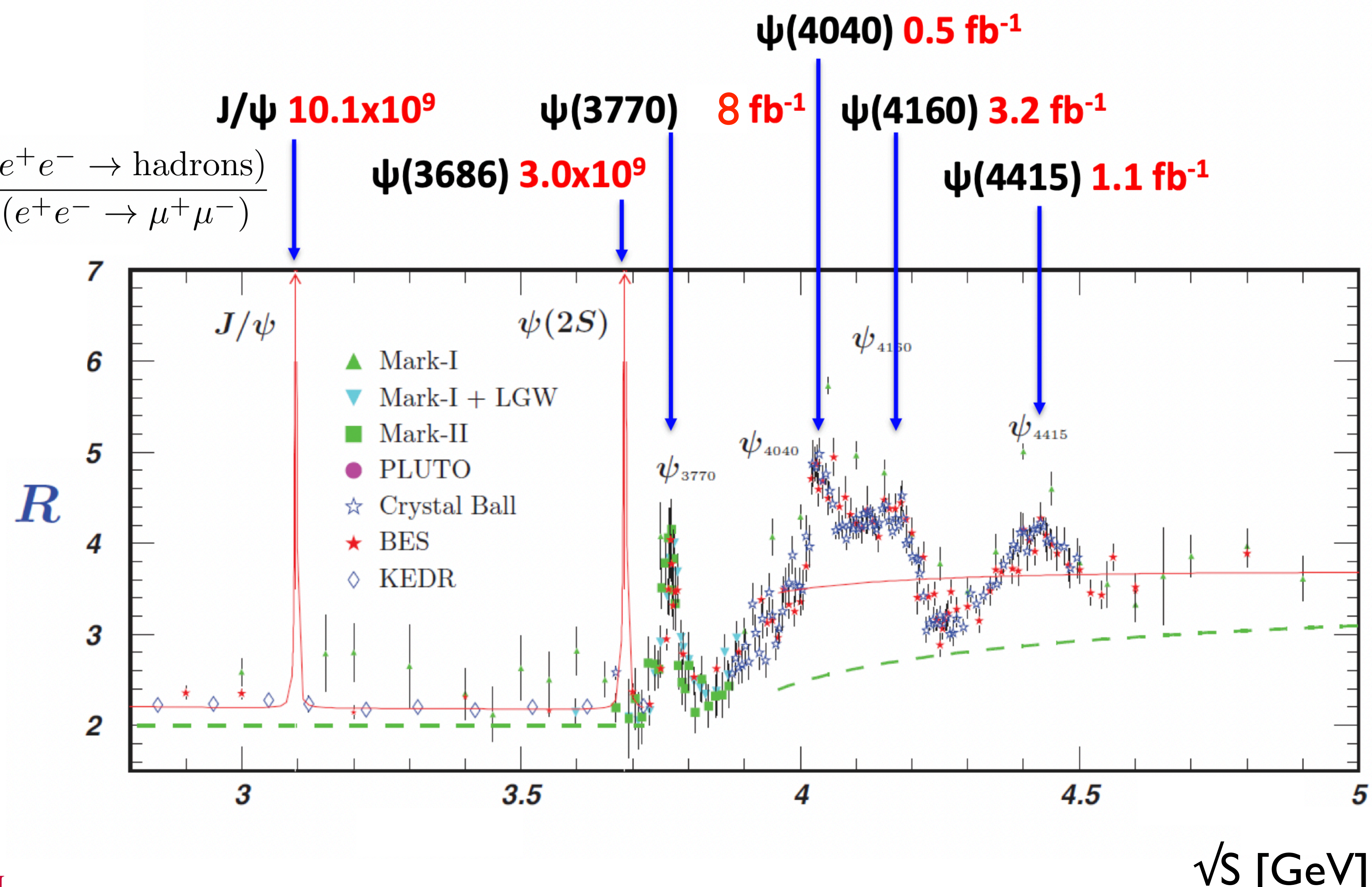
Collected datasets

Optimised for flavour physics in the tau-charm region

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



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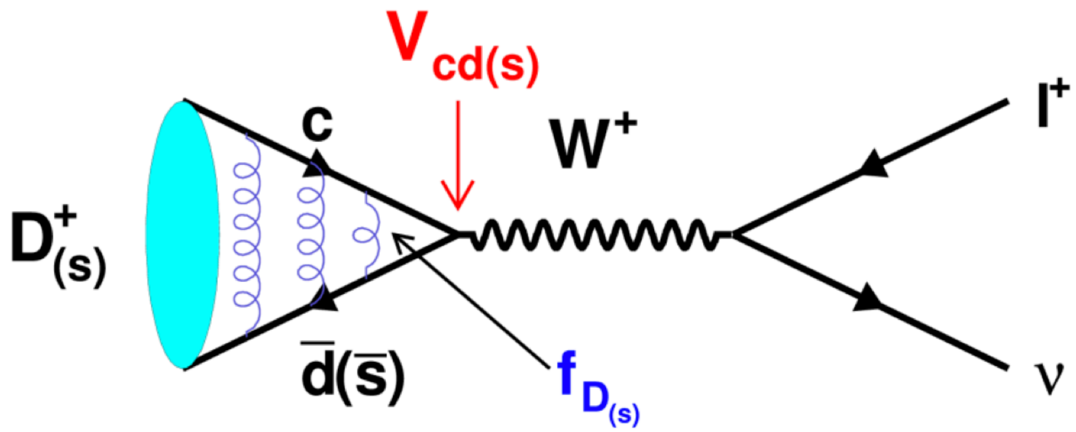
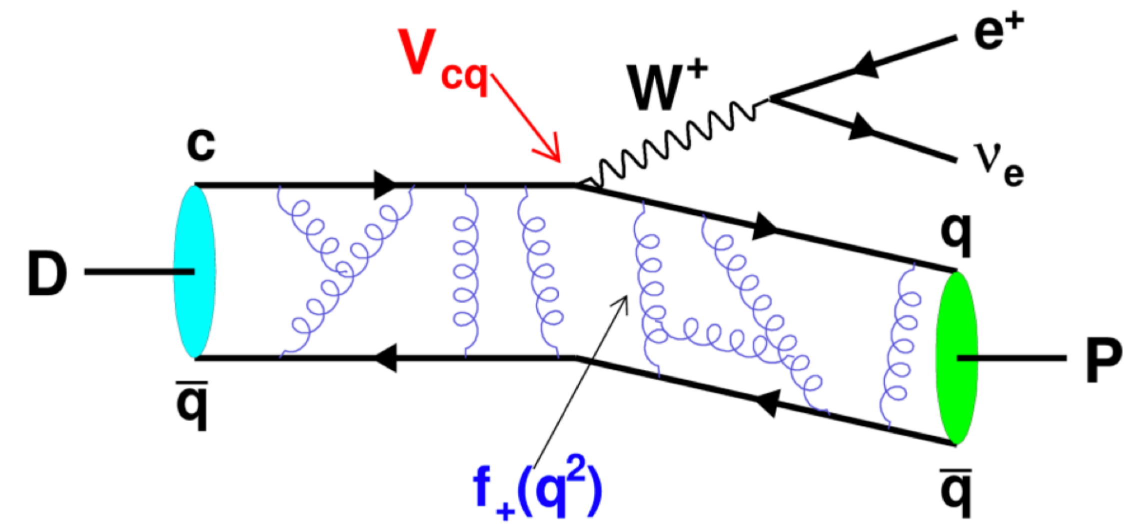
Leptonic and semi-leptonic charm meson decays

Leptonic and semileptonic charm decays





$$\Gamma\left(D^+_{(s)} \to \ell \nu^+_\ell\right) = \frac{G_F^2 |V_{cs(d)}|^2}{8\pi} M_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{M^2_{D^+_{(s)}}}\right)^2 m_\ell^2 f^2_{D^+_{(s)}}$$

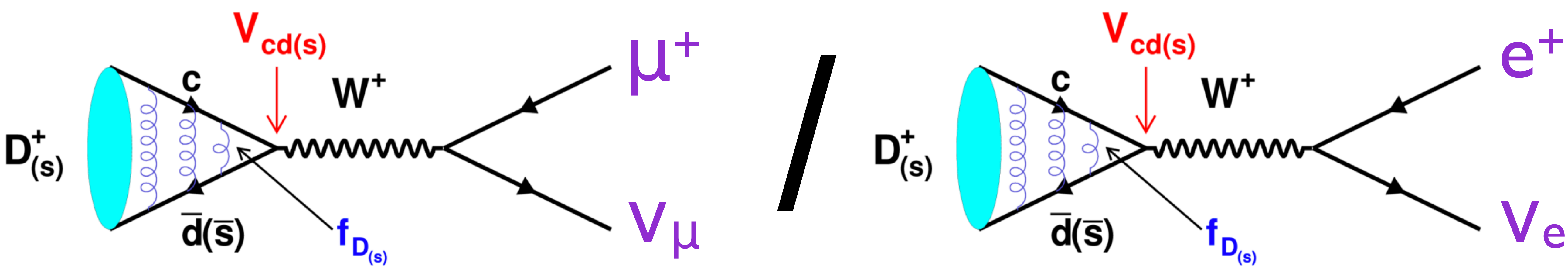
$$\frac{\Delta\Gamma(D \to P\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2 |V_{cq}|^2}{24\pi^3} |f_+^2(q^2)|^2 p^3$$

- Test CKM unitarity
- Test LFU
- Compare decay constants and form-factors to theory predictions

Lepton universality tests

- Essential to understand the nature of the anomalies **Svjetlana Fajfer, Ivan Nišandžić, and Urša Rojec Phys. Rev. D 91, 094009*

- Standard Model Ratios of pure leptonic decays require no input from theory



$$R = \left(1 - \frac{m_\mu^2}{M_{D_{(s)}^+}^2}\right)^2 m_\mu^2 \Big/ \left(1 - \frac{m_e^2}{M_{D_{(s)}^+}^2}\right)^2 m_e^2$$

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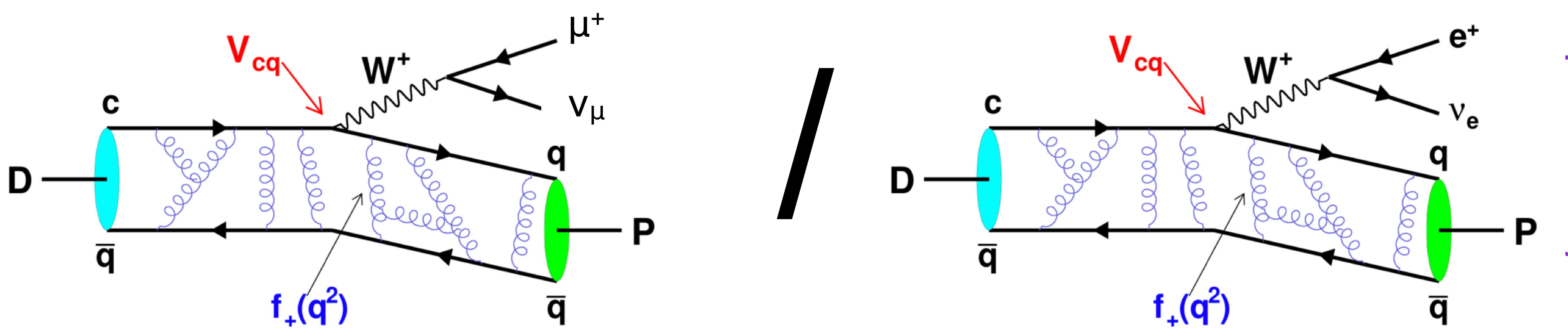
Lepton universality tests

- Essential to understand the nature of the anomalies **Svjetlana Fajfer, Ivan Nišandžić, and Urša Rojec Phys. Rev. D 91, 094009*
- SM Ratios of semileptonic decays are $\mathcal{O}(1)$, but require form factor-dependendent phase-space corrections



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LFU results with charm meson decays

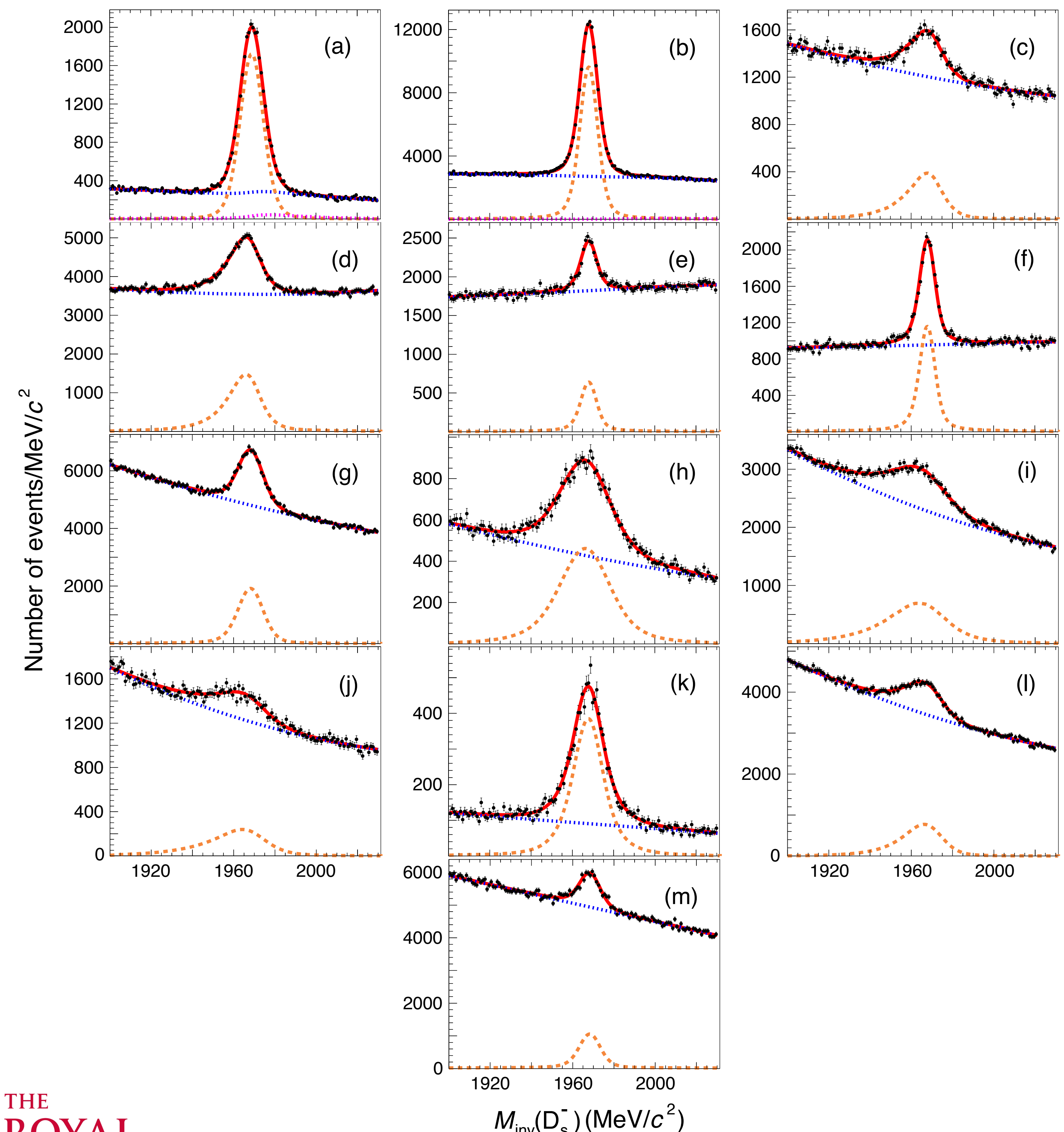
$D_s^+ \to \ell^+ \nu$ decays

PRD 104(2021)052009

- Using BESIII data @ E_{CM} = 4.178 - 4.226 GeV (6 energy points)
- Double tag with 13 D_s^+ tag modes
- Allow 1 charged track in addition to tag
- Event is fully reconstructed including γ from D_s^*
- Separate π^+/ μ^+ sample by energy deposition
- τ identified through $\pi^+\nu$ decay

The tag modes for $D_s^+ \to \ell^+ \nu$ decays

PRD 104(2021)052009



(a) $K_S^0 K^-$,

(b) $K^- K^+ \pi^-$,

(c) $K_S^0 K^- \pi^0$,

(d) $K^- K^+ \pi^- \pi^0$,

(e) $K_S^0 K^- \pi^+ \pi^-$,

(f) $K_S^0 K^+ \pi^- \pi^-$,

(g) $\pi^- \pi^+ \pi^-$,

(h) $\pi^- \eta$,

(i) $\rho^- \eta$,

(j) $\rho^- \eta_{3\pi}$,

(k) $\pi^- \eta'$,

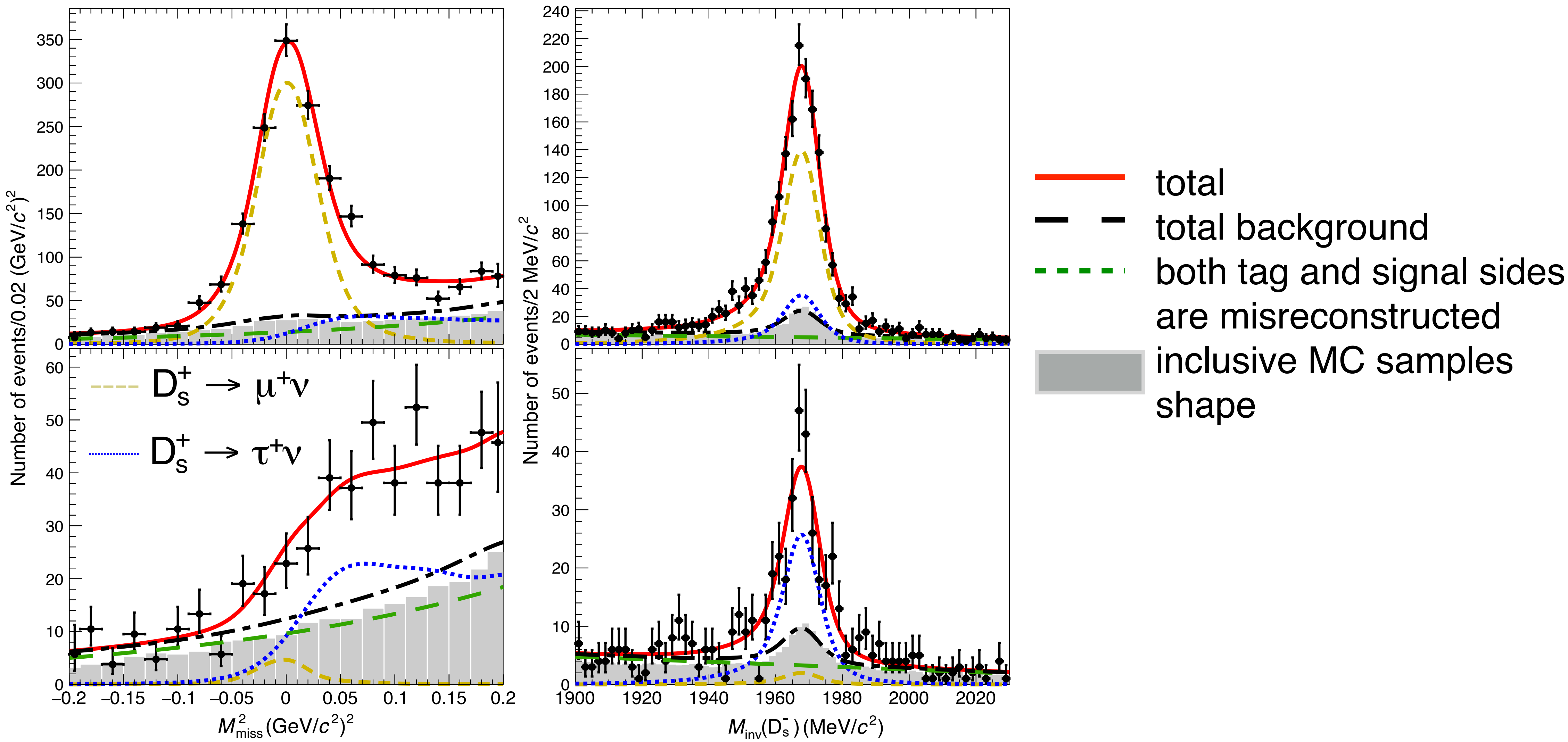
(l) $\pi^- \eta'$,

(m) $K^- \pi^+ \pi^-$.

LFU results for the $D_s^+ \to \ell^+\nu$ decays

Simultaneous un-binned maximum likelihood fit to the two-dimensional distributions of the tag-side invariant mass Min versus M_{miss}^2 for the six E_{CM} samples.

PRD 104(2021)052009



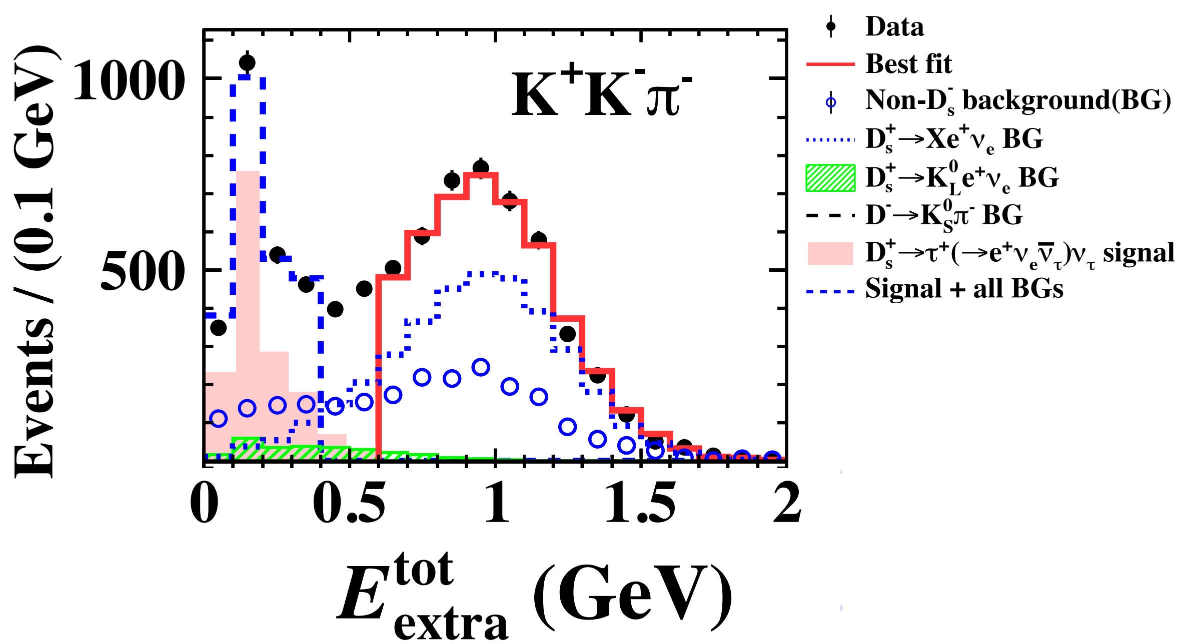
$$R = \frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = 9.73^{+0.61}_{-0.58} \pm 0.36$$

SM prediction of 9.75

With $D_s^+ \to \tau^+ \nu_\tau$ decays, $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$

- Using data @ E_{CM}= 4.178 - 4.226 GeV
- Double tag with 11 D_s^+ tag modes
- Event is fully reconstructed EXCEPT γ/π^0 from D_s^* decay
- Yields determined from fits to sum of extra energy in the calorimeter

PRL127(2021)171801



$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.10 \pm 0.12)\,\%$$

Combined with WA results:

$$R = \frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = 9.72 \pm 0.37$$

SM prediction of 9.75

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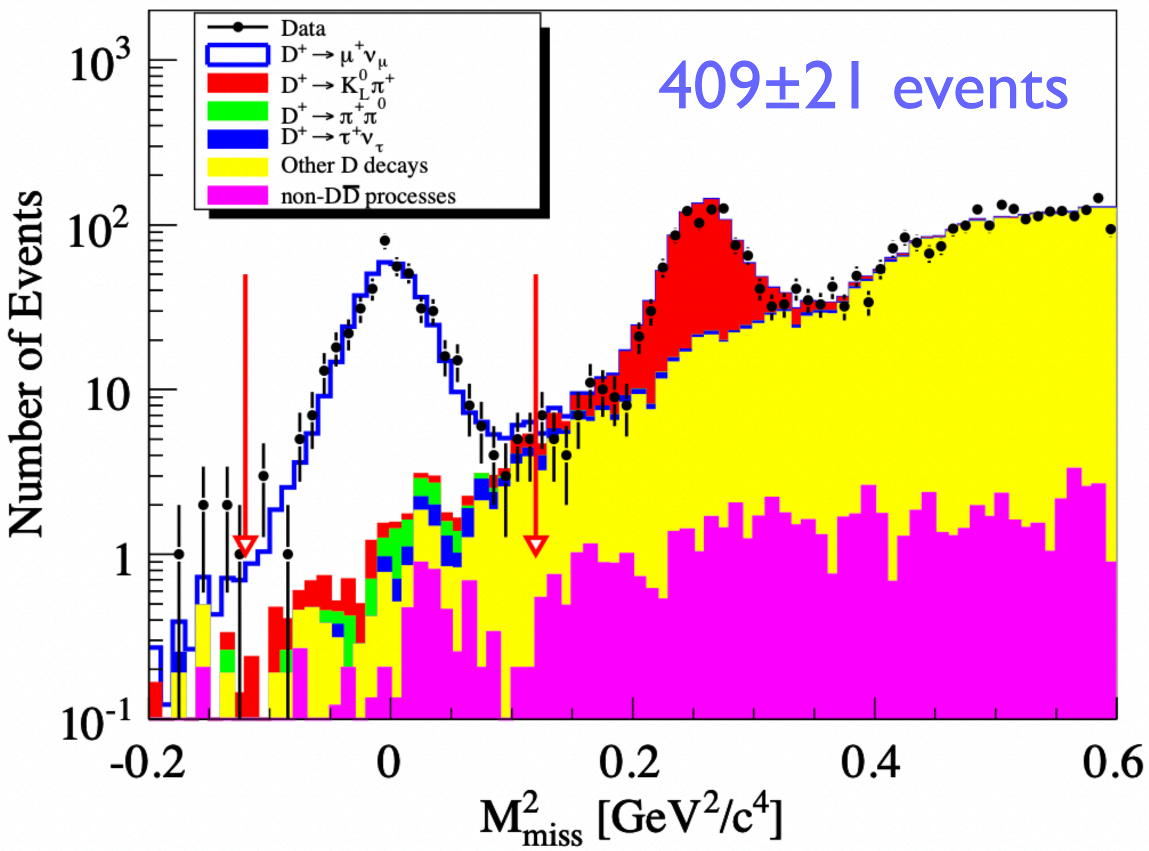
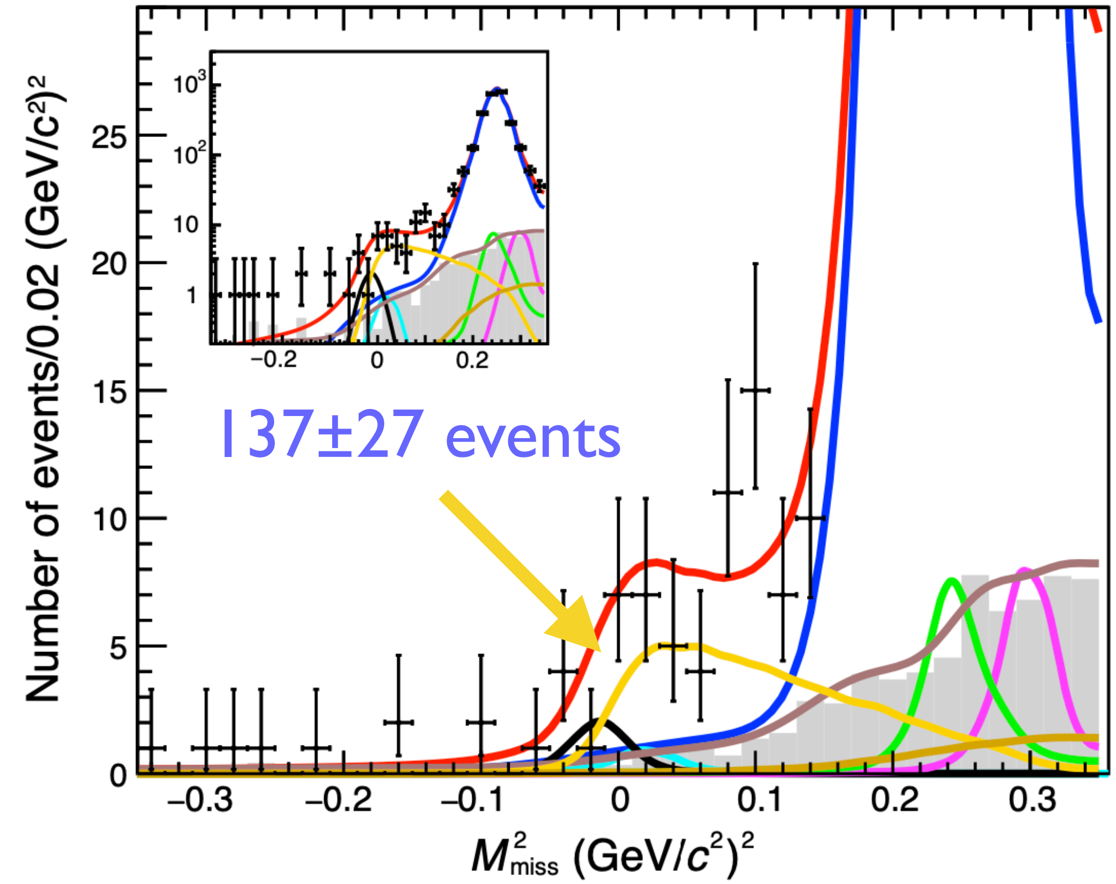
$D^+ \to \ell^+ \nu$ decays

2.93 fb^{-1}@3.773 GeV

PRD89(2014)051104

Phys. Rev. Lett. 123, 211802 (2019)





First observation with > 5.1σ significance

$$\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

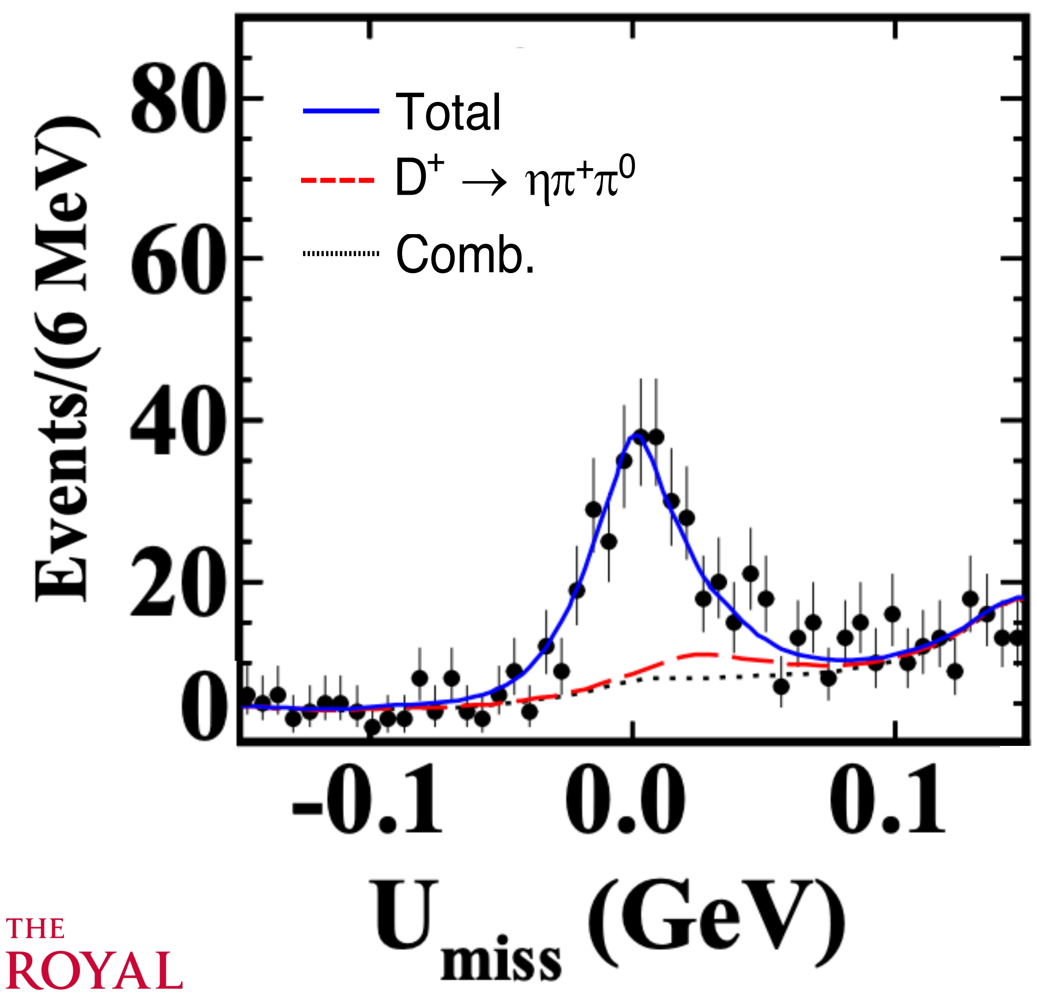
$$R = \frac{\mathcal{B}(D^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64$$

SM expectation 2.66

$D^+ \to \eta\mu^+\nu$ decays

- Using BESIII data @ E_{CM} = 3.773 GeV
- Double tag with 6 D^+ tag modes
- Peaking background: $D^0 \to \eta\pi^+\pi^0$

PRL 124(2020)231801



$$\frac{\mathcal{B}(D^+ \to \eta\mu^+\nu)}{\mathcal{B}(D^+ \to \eta e^+\nu)} = 0.91 \pm 0.13$$

with PDG2020 Average of $\mathcal{B}(D^+ \to \eta e^+\nu)$

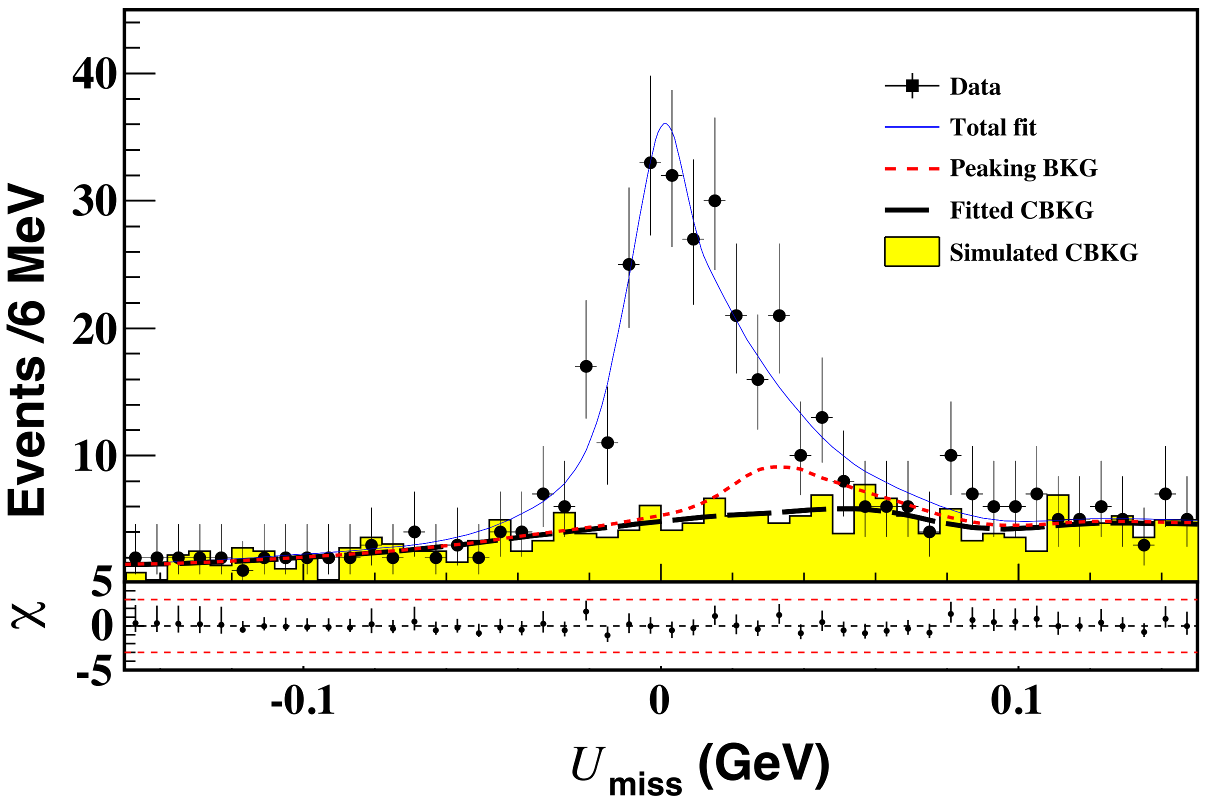
SM Prediction: 0.97 - 1.00

*for references, see the backup slides

$D^+ \to \omega\mu^+\nu$ decays

- Using BESIII data @ E_{CM} = 3.773 GeV
- Double tag with 6 D^+ tag modes
- Peaking background: $D^0 \to \omega\pi^+\pi^0$

PRD101(2020)072005



$$\frac{\mathcal{B}(D^+ \to \omega\mu^+\nu)}{\mathcal{B}(D^+ \to \omega e^+\nu)} = 1.05 \pm 0.14$$

with PDG2020 Average of $\mathcal{B}(D^+ \to \omega e^+\nu)$

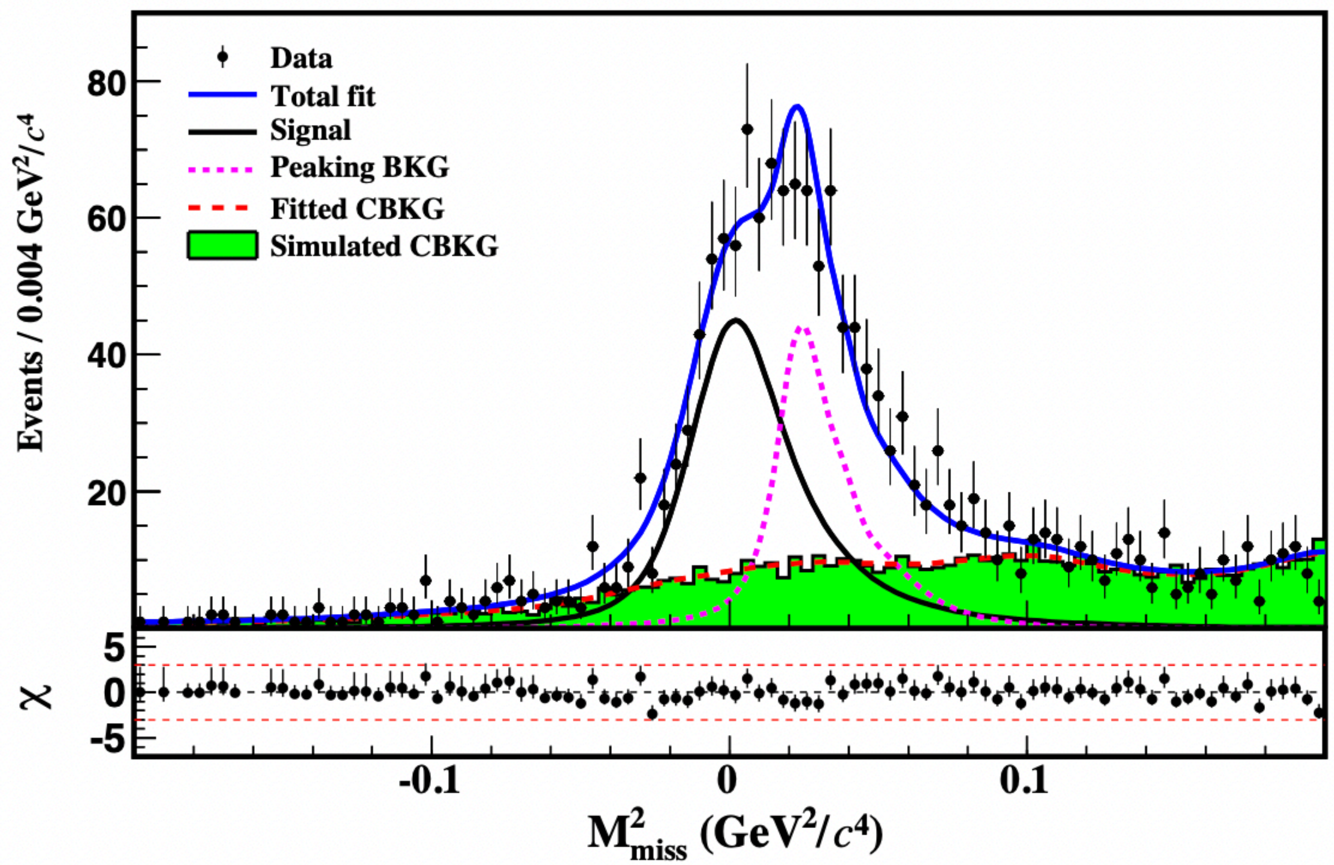
SM Prediction: 0.93 - 0.99 from

*for references, see the backup slides

$D^0 \to \rho^-\mu^+\nu$ decays

- Using BESIII data @ E_{CM} = 3.773 GeV
- Double tag with 3 $\bar{D}^0$ tag modes
- Peaking background: $D^0 \to \pi^+\pi^-\pi^0\pi^0$

Phys. Rev. D 104, L091103 (2021)



$$\frac{\mathcal{B}(D^0 \to \rho^-\mu^+\nu)}{\mathcal{B}(D^0 \to \rho^-e^+\nu)} = 0.90 \pm 0.11$$

with PDG2020 Average of $\mathcal{B}(D^0 \to \rho^-e^+\nu)$

SM Prediction: 0.93 - 0.96 from

- **for references, see the backup slides*

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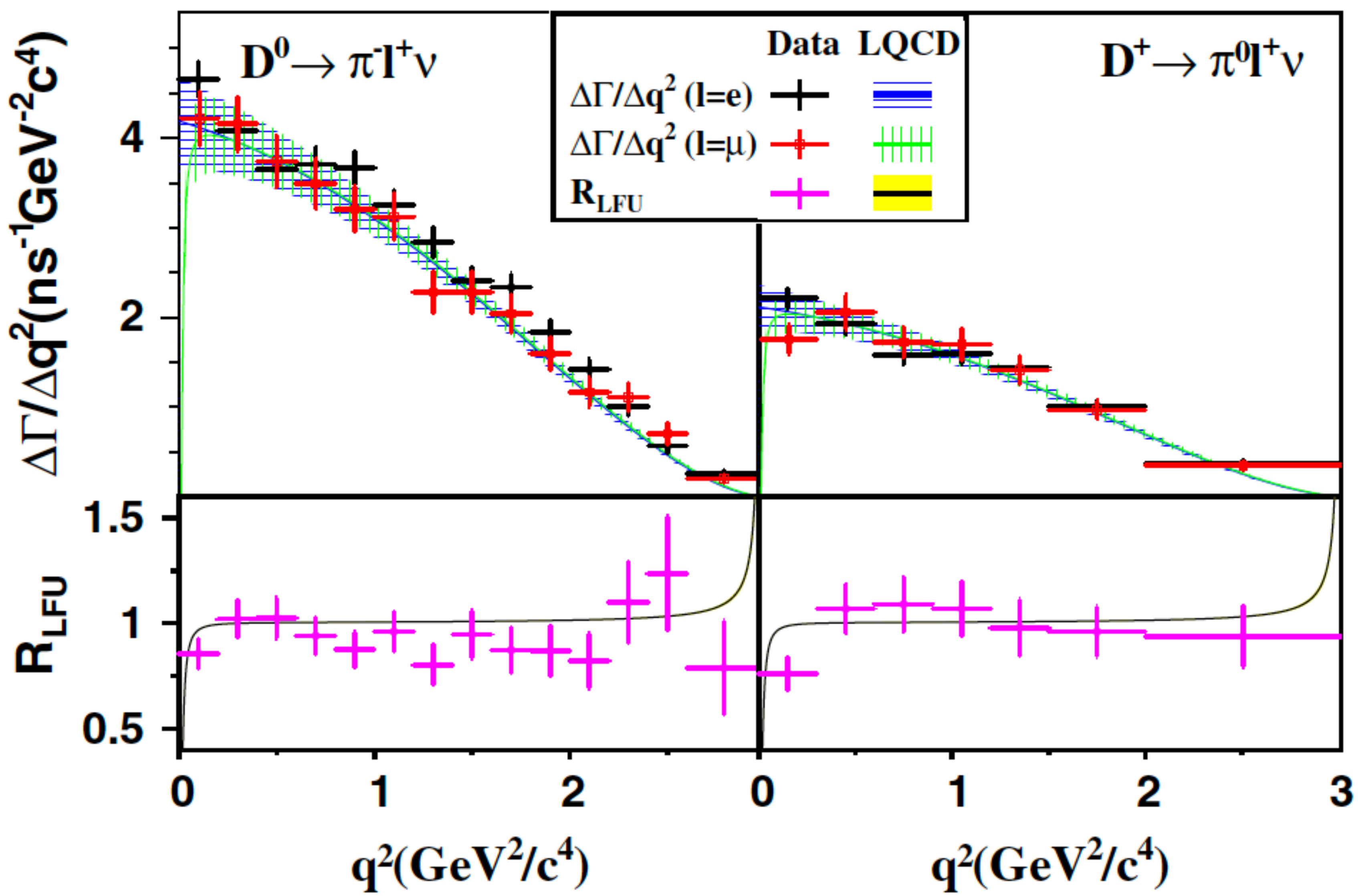
$D \to \pi \ell^+ \nu$ decays

- Using BESIII data @ E_{CM} = 3.773 GeV
- Double tag with 3 $\bar{D}^0$ and 6 D^- tag modes

μ / e ratios

BESIII, Phys. Rev. Lett. 121, 171803 (2018)



Overview of LFU results with charm meson decays

Mode	Measured $\mathcal{B}(\ell)/\mathcal{B}(\ell')$	SM Prediction
$D^+ \to \frac{\tau}{\mu}\nu$	3.21 ± 0.77	2.66
$D_s^+ \to \frac{\tau}{\mu}\nu$	9.72 ± 0.37	9.75
$D^0 \to \rho^- \frac{\mu}{e}\nu$	0.90 ± 0.11	$0.93 - 0.96$
$D^+ \to \eta \frac{\mu}{e}\nu$	0.91 ± 0.13	$0.97 - 1.00$
$D^+ \to \omega \frac{\mu}{e}\nu$	1.05 ± 0.14	$0.93 - 0.99$
$D^+ \to \pi^0 \frac{\mu}{e}\nu$	0.964 ± 0.045	~ 0.985
$D^0 \to \pi^+ \frac{\mu}{e}\nu$	0.922 ± 0.037	~ 0.985
$D^0 \to K^+ \frac{\mu}{e}\nu$	0.974 ± 0.014	~ 0.970

Credit Alex Gilman

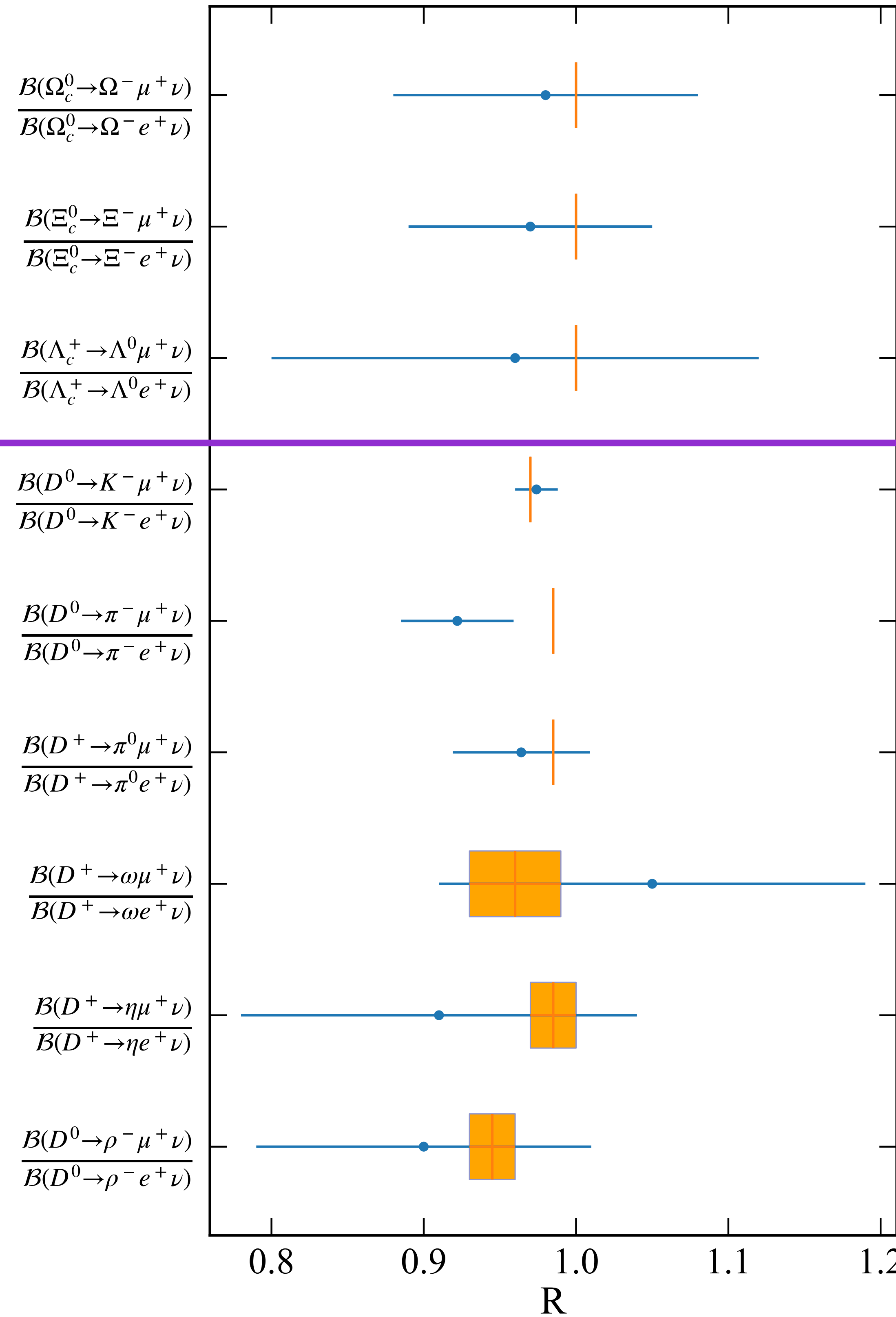
Values deviate from 1 because of the different available phase space

- No tensions with the SM expectation within the current precision

LFU with semileptonic charm meson and baryon decays overview

SL charm baryon decays

SL charm meson decays



Belle, Phys. Rev. D 105, L091101 (2022)

Belle, PRL127(2021)121803

BESIII, Phys. Lett. B, 767 (2017) p 42

BESIII, Phys. Rev. Lett. 122, 011804 (2019)

BESIII, Phys. Rev. Lett. 121, 171803 (2018)

BESIII, Phys. Rev. Lett. 121, 171803 (2018)

Image credit Adam Davis

Conclusions and prospects

- No evidence for LFUV in leptonic/ semileptonic charm decays
- Collection of ~20 fb^{-1}@ ψ (3770) well underway @ BESIII
- More detail on future prospects in BESIII white paper: Chin. Phys. C 44, 040001 (2020)
- Exciting prospects from Belle II, LHCb, and in a longer term from the future Tau-Charm factory

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SM references

SM predictions for $\mathscr{B}(D^+ \to \eta\ell^+\nu)$

SM Prediction: 0.97 - 1.00 from

- *Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A21,6125 (2006)*
- *H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)*
- *M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T.Tran, Front. Phys.14, 64401 (2019)*

SM predictions for $\mathscr{B}(D^+ \to \omega\ell^+\nu)$

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- *H.Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)*
- *T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)*
- *N. R. Soni, M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, and C. T. Tran, Phys. Rev. D98, 114031 (2018)*
- *M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)*
- *H.B. Fu, W. Cheng, L. Zheng, D.D. Hu, T. Zhong, Phys. Rev. Research 2, 043129 (2020)*
- *R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)*

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- *Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A 21, 6125 (2006)*
- *T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)*
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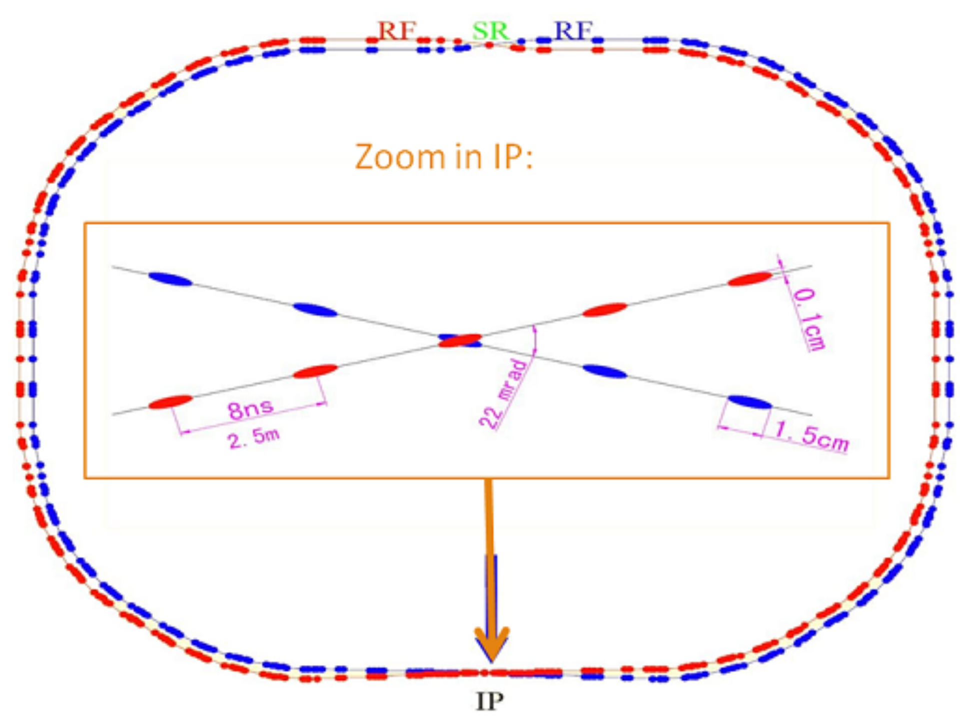
- *M. A. Ivanov, J. G. Korner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)*
- *H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)*
- *R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)*

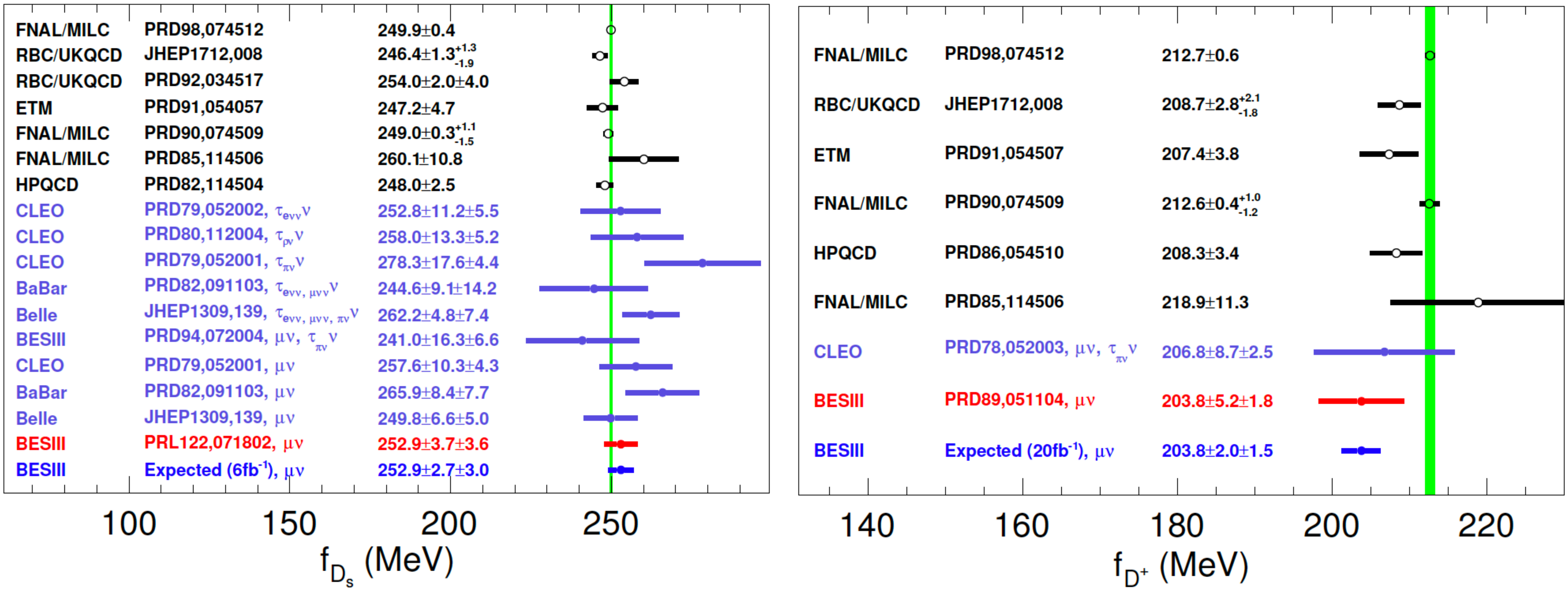
BEPCII: e^+e^- collider

- Upgrade of BEPC
  - (started 2004, first beams 2008)
- Beam energy 1 to 2.3 GeV
  - Optimum energy 1.89 GeV
  - Single beam current 0.91 A
- Two ring machine
- Design luminosity is 10^{33} cm^{-2} s^{-1}
  - Achieved in 2016
- Run: Typically 5-6 months per year



Comparing with the other experiments and the theory

BESIII white paper arXiv:1912.05983



THE ROYAL SOCIETY

Comparing with the other experiments and the theory

BESIII white paper arXiv:1912.05983