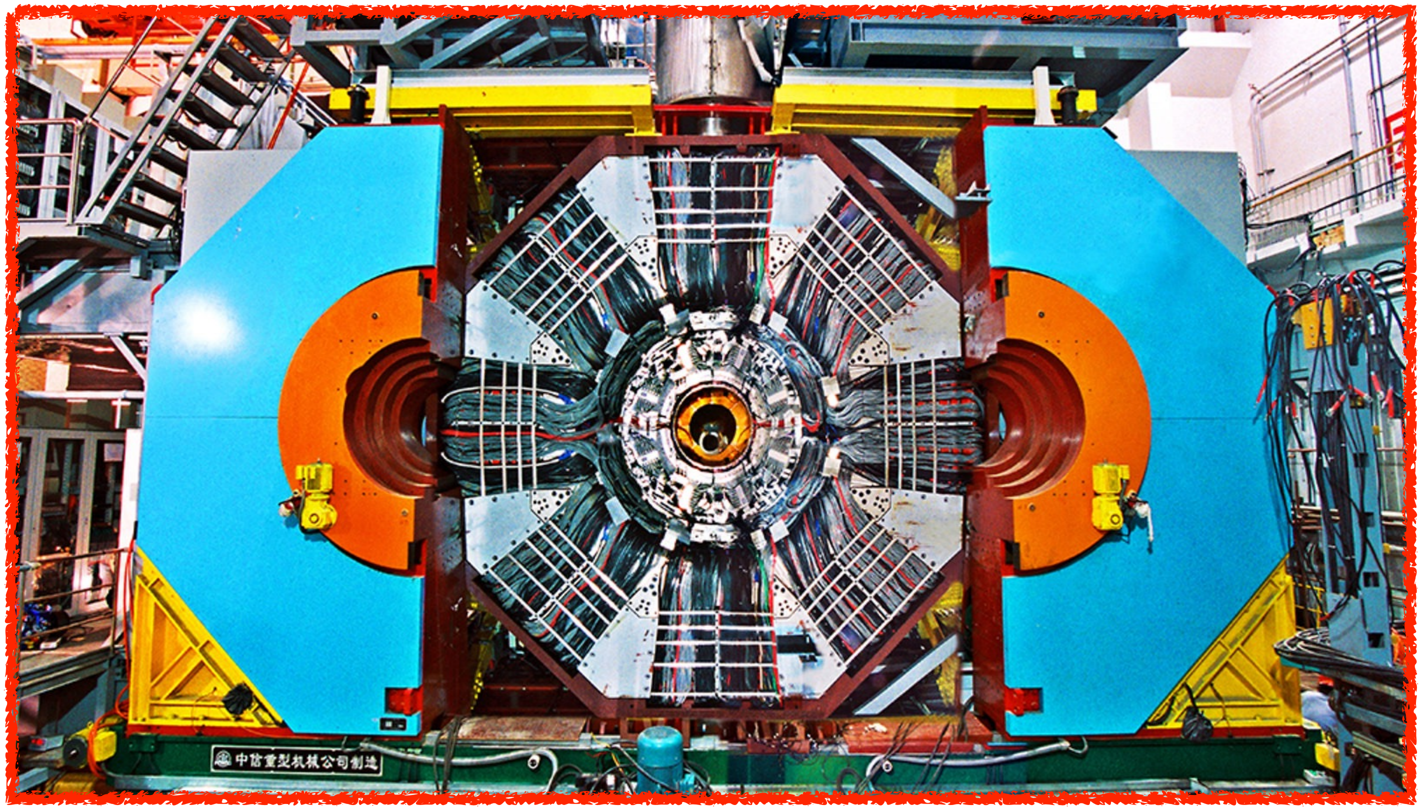
Study of D_s decays at BESIII



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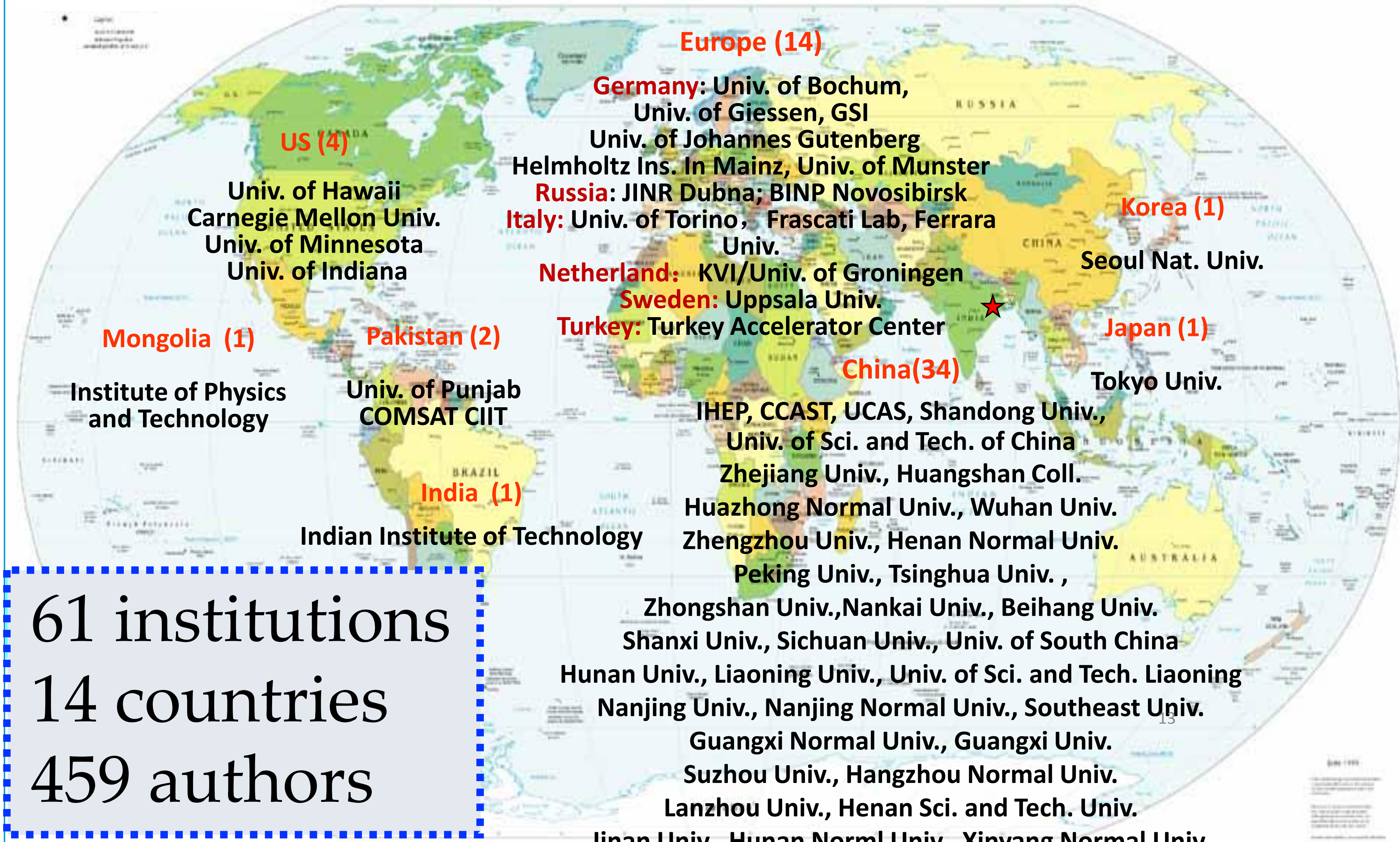
Haji

The third generation of Beijing Spectrometer

BESIII Collaboration



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Russia: JINR Dubna; BINP Novosibirsk
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Netherland: KVI/Univ. of Groningen
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Turkey: Turkey Accelerator Center

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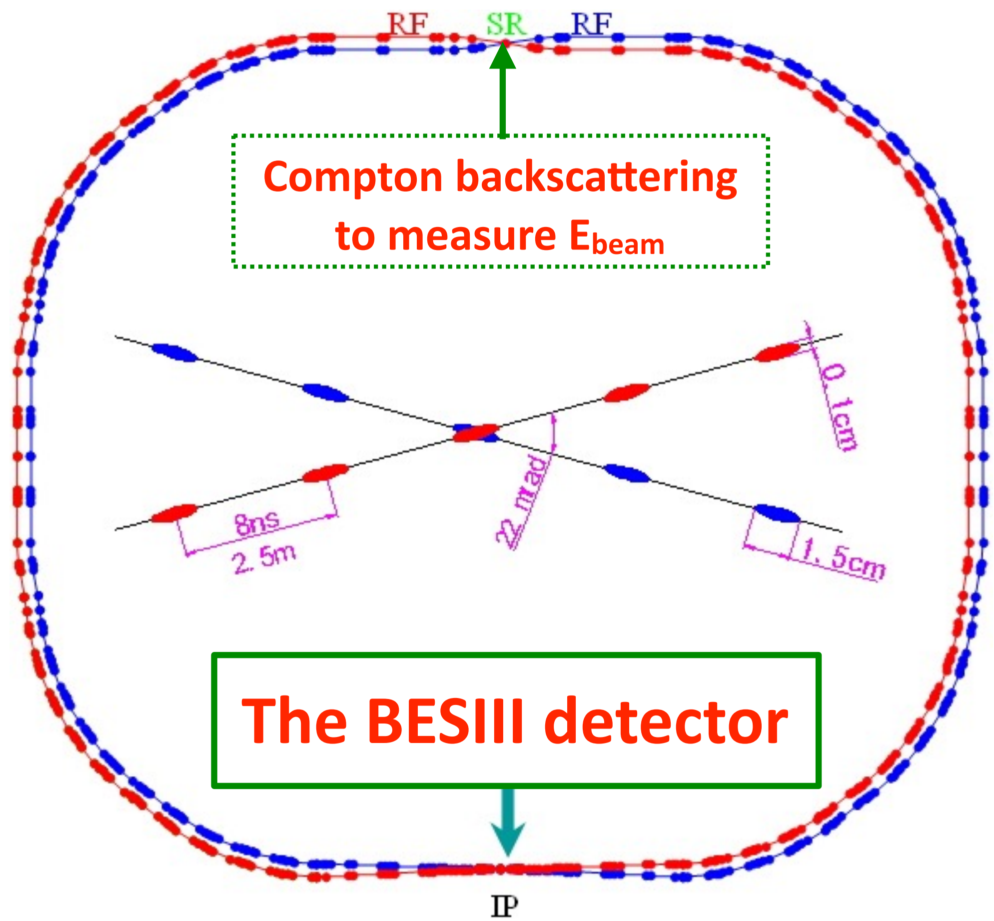
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Jinan Univ., Hunan Norml Univ., Xinyang Normal Univ.

61 institutions
14 countries
459 authors

BEPC II
(Beijing Electron-Positron Collider II)

- Double ring collider.
- Operating since 2008.
- E_{beam} = 1-2.3 GeV.
  Optimal @ 1.89 GeV.



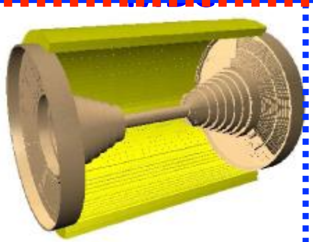
- Can fill up to 93 bunches in each ring w/ max current of 0.9A.
- Designed luminosity = 1×10^{33} $cm^{-2}s^{-1}$ was achieved in April 2016!

BEPC II and BESIII

BESIII detector

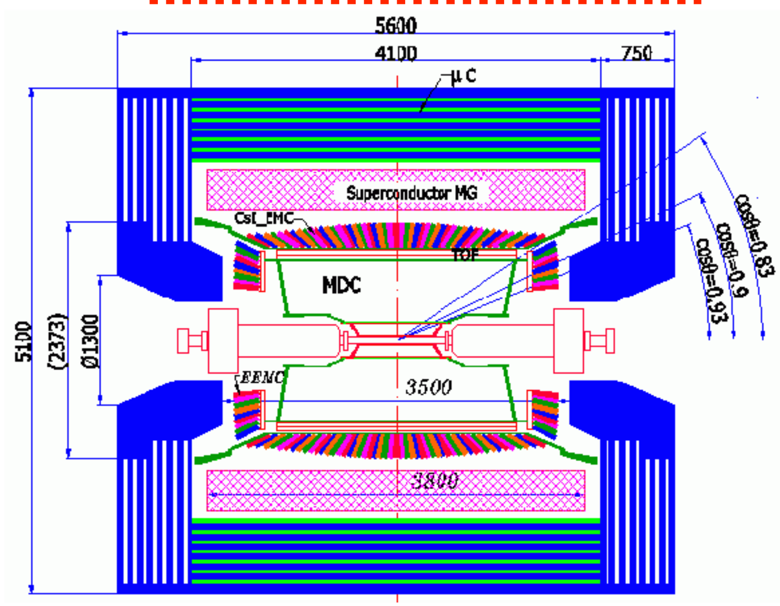
- A powerful general purpose detector.
- Excellent neutral/charged particle detection/identification with a large coverage.
  - ✓ Precision tracking
  - ✓ CsI calorimeter
  - ✓ PID via dE/dx & Time of Flight

MDC: small cell & Gas: He/C_3H_8 (60/40), 43 layers σ_p/p=0.5%@1GeV, σ_{dEdx}=6%

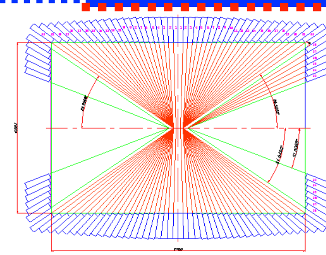


R inner: 63mm ;
R outer: 810mm
Length: 2582 mm
Layers: 43

Magnet: 1T Super conducting

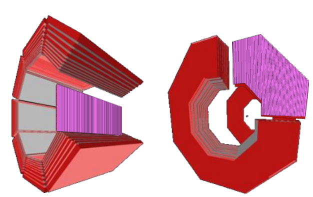


EMCAL: CsI(Tl) crystal ΔE/E=2.5 @1GeV



Crystals: 28 cm(15 X_0)
Barrel: $|\cos\theta|<0.83$
Endcap:
$0.85 < |\cos\theta| < 0.93$

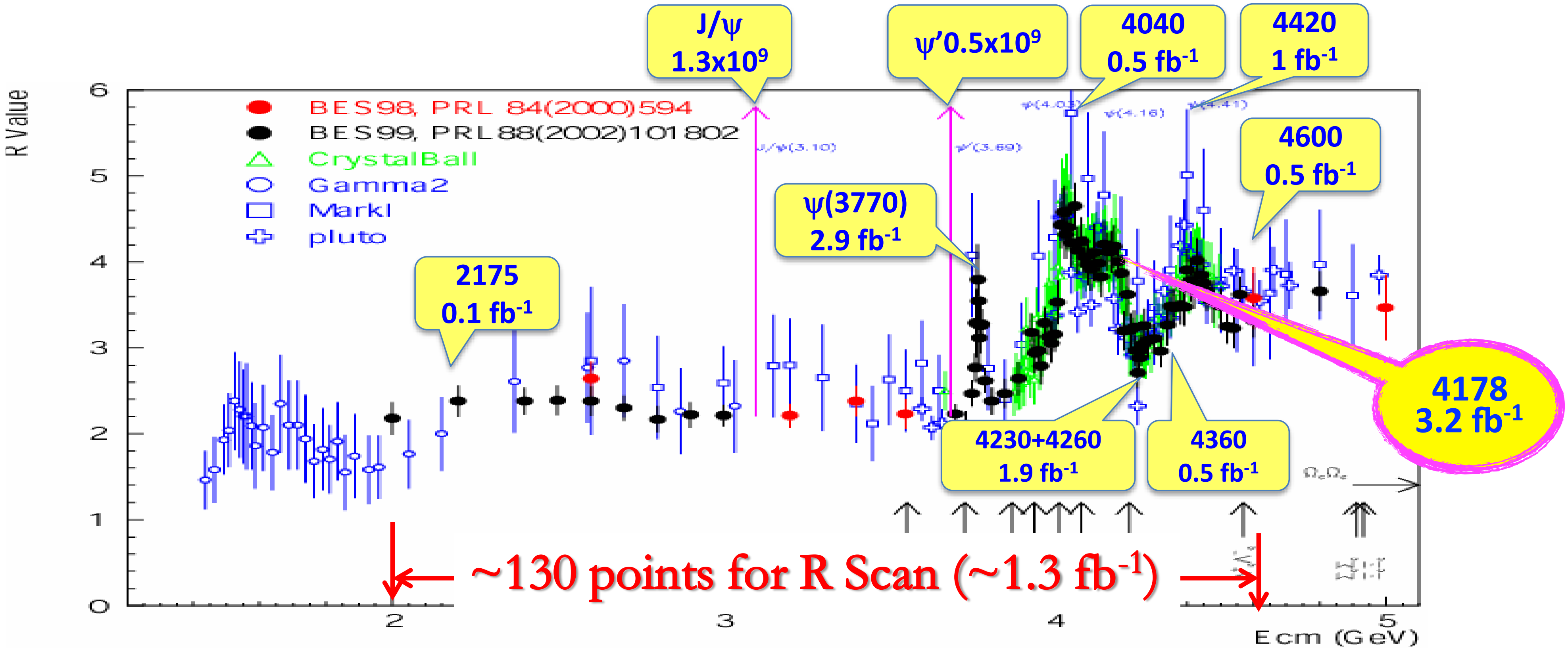
MUC: 9 layers RPC (8 layers in Endcap) $\sigma_{R\Phi}$=1.4~1.7cm



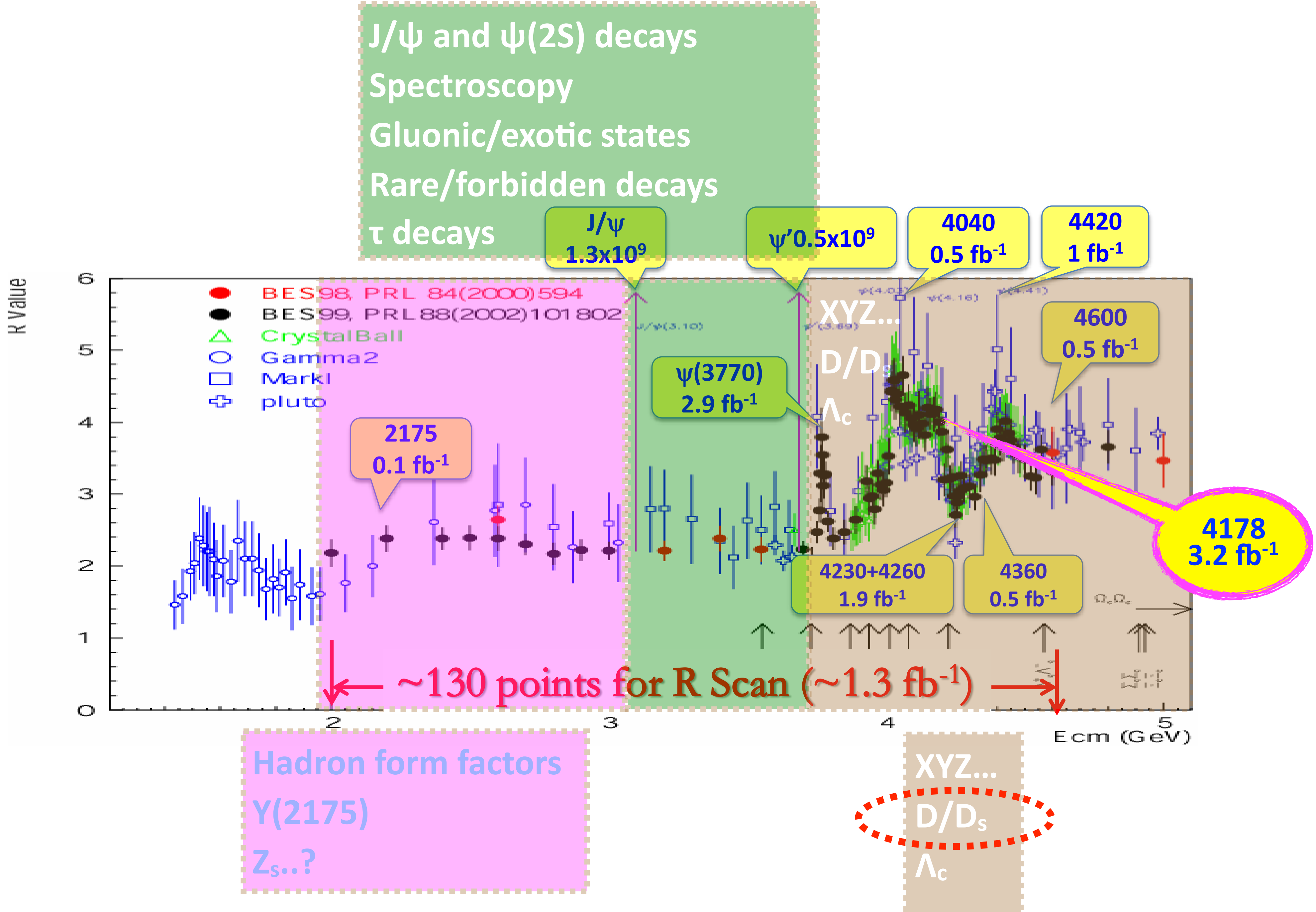
Time of Flight σ_T=100ps in Barrel 110ps in Endcap

BTOF: two layers
ETOF: 48 scintillators for each
MRPC --- new ETOF

e^+e^- annihilation samples taken E_{cm} from ~2 GeV up to ~4.6 GeV



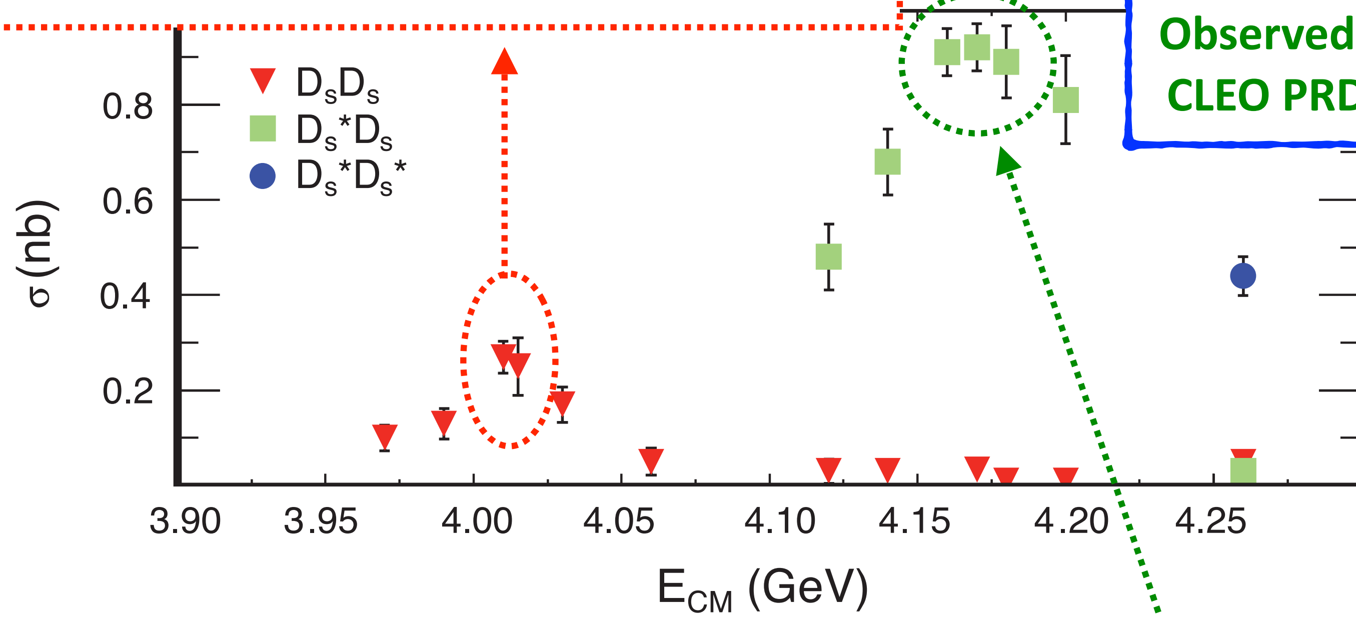
World largest J/ψ, ψ(2S), ψ(3770), ψ(4170), Y(4260), … produced directly from e^+e^- collision


J/ψ and ψ(2S) decays
Spectroscopy
Gluonic/exotic states
Rare/forbidden decays
τ decays
J/ψ 1.3x10^9
ψ'0.5x10^9
4040 0.5 fb^-1
4420 1 fb^-1
4600 0.5 fb^-1
ψ(3770) 2.9 fb^-1
2175 0.1 fb^-1
XYZ...
D/Ds
Λc
4178 3.2 fb^-1
4230+4260 1.9 fb^-1
4360 0.5 fb^-1
R Value
BES98, PRL 84(2000)594
BES99, PRL88(2002)101802
CrystalBall
Gamma2
MarkI
pluto
~130 points for R Scan (~1.3 fb^-1)
Ecm (GeV)
Hadron form factors
Y(2175)
Zs..?
XYZ...
D/Ds
Λc

Two main D_s samples at BESIII

- E_{cm} = 4009 MeV: 0.48 fb^{-1} :~0.3M $D_s^{\pm}$ produced.
- E_{cm} = 4178 MeV: 3.19 fb^{-1} :~6M D_s produced.

@ 4.009 GeV : $e^+e^- \to D_sD_s$ produced, simple/clean.
But lower production rate.



Observed $\sigma(e^+e^- \to D_s^{(*)} D_s^{(*)})$
CLEO PRD80, 072001 (2009)

@ 4.178 GeV : $e^+e^- \to D_s^*D_s$ produced w/ $BF(D_s^* \to \gamma D_s)$ ~ 94%.
But higher production rate.

Typical analysis method to measure BF

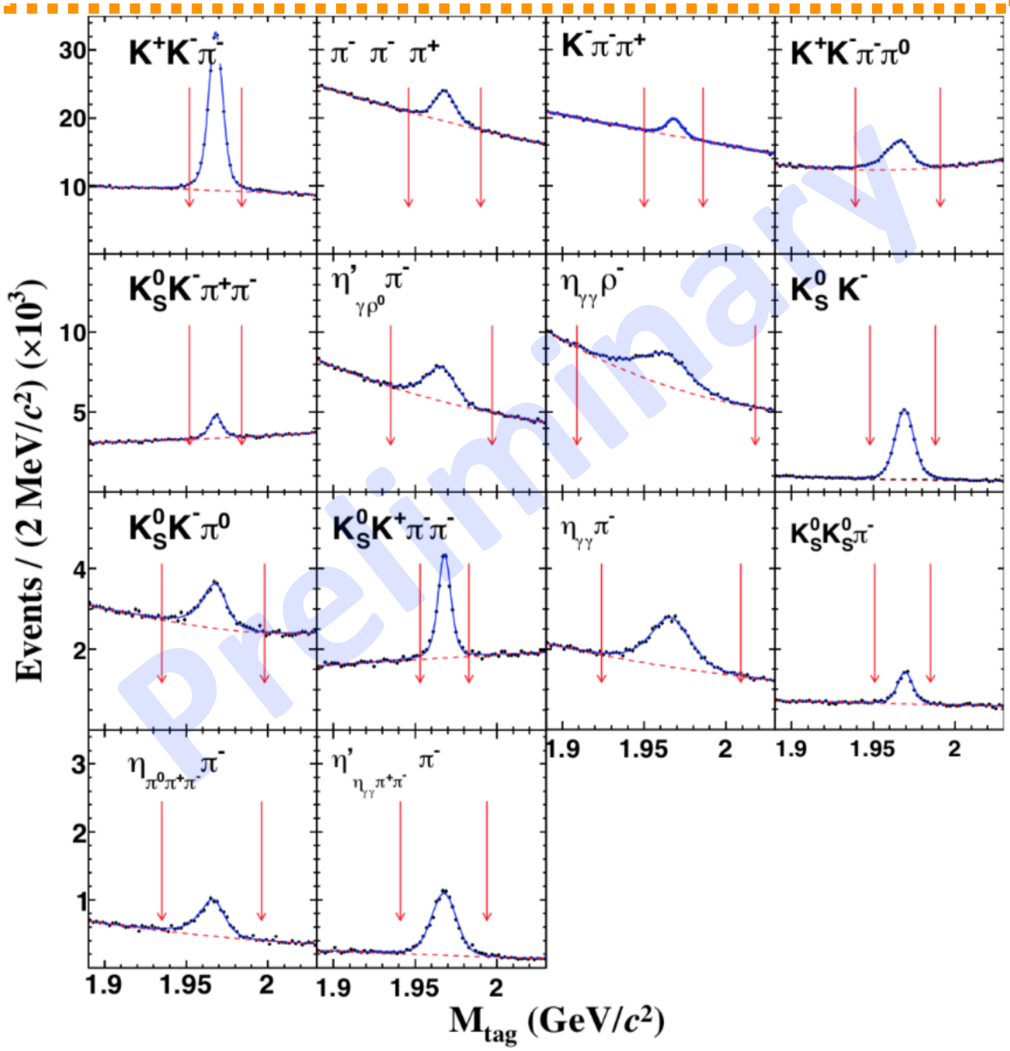
- In our sample, D_s mesons are produced in pair:
  @ E_{cm} = 4009 MeV : $e^+e^- \to D_s^+ D_s^-$
  @ E_{cm} = 4178 MeV : $e^+e^- \to D_s^{*+} D_s^-$, $D_s^{*+} \to (\gamma/\pi^0) D_s^+$ (+ c.c.)
- Reconstruct one of the D_s (tag),
  you know there must be the other D_s (signal),
  allowing measurements of absolute BFs.

I.e., $BF(D_s \to \mu\nu) = [B(D_s \to tag) \times BF(D_s \to \mu\nu)]/BF(D_s \to tag)$
= [Double Tag yields]/[Single Tag yields].

Systematics associated with the reconstruction of $D_s \to tag$ also tend to be canceled in this ratio.

Typical analysis method continued

Total D_s single-tag yield ~0.4M events



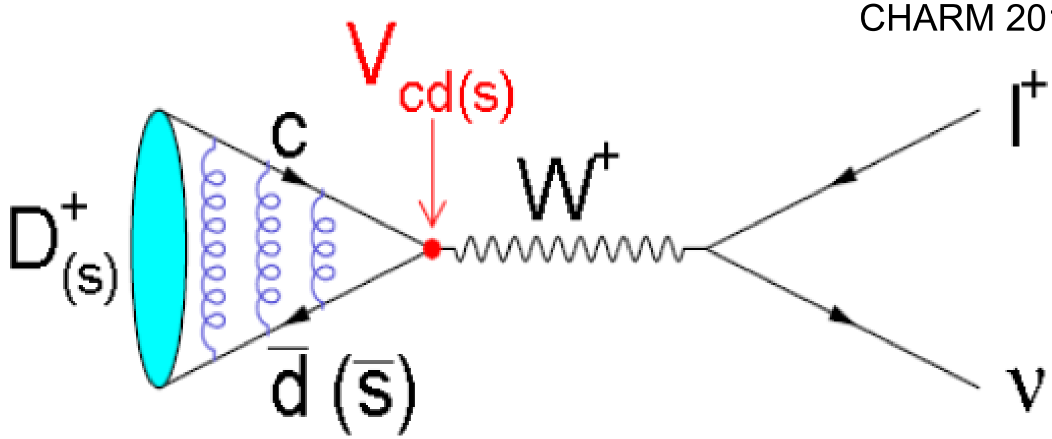
To obtain **Single Tag yields**, we fit to:
- $M_{bc} = \sqrt{(E_{beam}^2 - |\vec{p}_D|^2)}$ in the 4009 sample
- $M_{inv}(D_s)$ in the 4178 sample.
  Shown here as an example.

To obtain **Double Tag yields**, we fit to:
- Select signal region in $M_{inv}(D_s)$ (red arrows in the left plot).
- Look at their recoil sides.
  If a missing particle (e.g., ν or n), use missing mass-squared;

$$MM2 = E_{miss}^2 - |\vec{p}_{miss}|^2 = (E_{cm} - E_{tag} - E_l)^2 - |-\vec{p}_{tag} - \vec{p}_l|^2$$

  which peaks @ 0 if a ν is missing.

Pureleptonic decays



To the lowest order;

$$\Gamma(D^+_{(s)} \to l^+\nu) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_l^2 m_{D^+_{(s)}} (1 - \frac{m_l^2}{m^2_{D^+_{(s)}}})^2$$

-The decay rate goes as $f_{D(s)}^2 \times |V_{cd(s)}|^2$.

The game is to measure the BF, and then

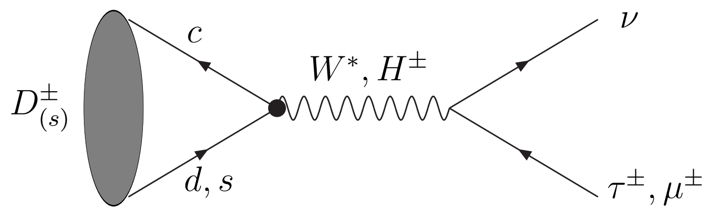
- **use the CKM elements predicted by unitarity to obtain experimental values for $f_{D(s)}$. This provides tests of lattice QCD methods under the assumption that new-physics contributions to leptonic decays can be neglected, or**
- **or $f_{D(s)}$ predicted by lattice QCD to determine elements of CKM elements.**

Also, ratio of the decay rates between $D_{(s)} \to \mu\nu$ and $D_{(s)} \to \tau\nu$ are very interesting!
For instance;

$$R \equiv \frac{\Gamma(D_s^+ \to \tau^+ \nu)}{\Gamma(D_s^+ \to \mu^+ \nu)} = \frac{m_{\tau^+}^2 (1 - \frac{m_{\tau^+}^2}{M_{D_s^+}^2})^2}{m_{\mu^+}^2 (1 - \frac{m_{\mu^+}^2}{M_{D_s^+}^2})^2}$$

- **With the known masses, $R_{Ds+} = 9.74 \pm 0.01$.**
  Allows us to check lepton universality!
- **Any deviation from the expected R could indicate non-SM effects.**

Speaking of R and lepton universality



- In certain models, such as the two-Higgs-doublet, the lepton universality still holds
  I.e., A.G. Akeroyd et. al. (PRD75,075004(2007));
  For the case of D_s, the SM rate is modified by a factor of

$$r_{D_s} \equiv \left[1 + \left(\frac{1}{m_c + m_s}\right)\left(\frac{M_{D_s}}{m_{H^+}}\right)^2 \left(m_c - \frac{m_s \tan^2\beta}{1 + \epsilon_0 \tan\beta}\right)\right]^2$$,where

  ε_0 is a higher order correction (= 0 @ tree level).

- This only affects the absolute rates:
  E.g., for $D_s \to \mu\nu$,

$$BF_{exp} = \Gamma_{SM} \times \tau_{Ds} \times r_{Ds} = (5.28 \pm 0.05) \times 10^{-3} \times r_{Ds},$$

  where f = 249.0±1.2 MeV and $|V_{cs}|$ = 0.973394 are used.
  The uncertainty is dominated by the D_s lifetime.

Experimental status on D_s^+ pureleptonic decays and advantage of data taken @ mass threshold

CLEO/BESIII : statistically limited

Belle/BaBar : $\Delta_{stat.}$ ~ $\Delta_{syst.}$ or Systematically limited

$\Gamma(D_s^+ \to \mu^+\nu_\mu)/\Gamma_{total}$

VALUE (10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
5.50 ± 0.23	**OUR AVERAGE**				
4.95 ±0.67 ±0.26	69	1 ABLIKIM	2016O	BES3	e^+e^- at 4.009 GeV
5.31 ±0.28 ±0.20	492 ±26	2 ZUPANC	2013	BELL	e^+e^- at $\Upsilon(4S), \Upsilon(5S)$
6.02 ±0.38 ±0.34	275 ±17	3 DEL-AMO-SANCH..	2010J	BABR	e^+e^- , 10.58 GeV
5.65 ±0.45 ±0.17	235 ±14	ALEXANDER	2009	CLEO	e^+e^- at 4170 MeV

CLEO : μν : Systematically most precise : Rel. syst. error = 3%
Our MC study showed ~3 fb^{-1} would give us ~3% stat. error

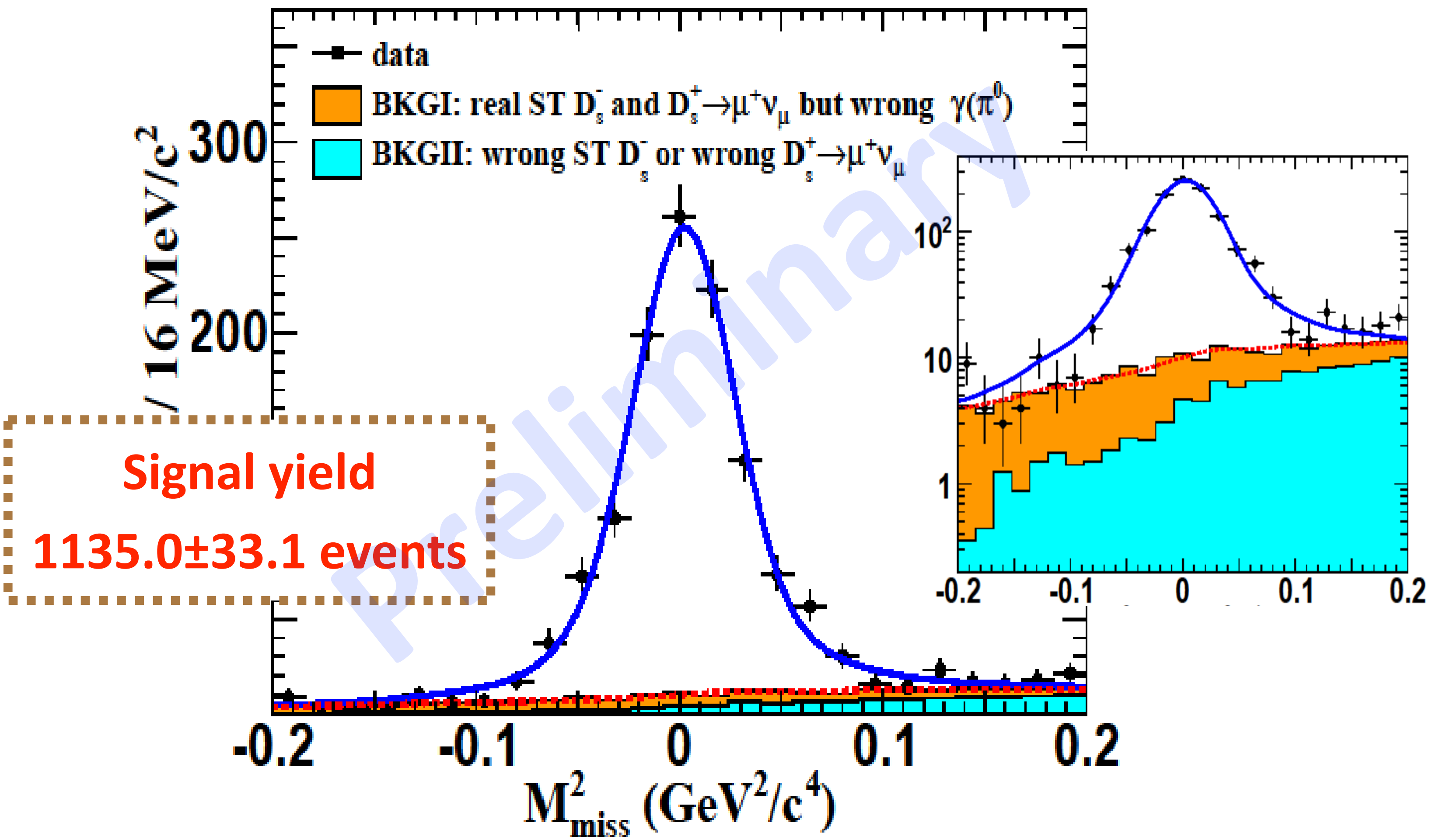
$\Gamma(D_s^+ \to \tau^+\nu_\tau)/\Gamma_{total}$

VALUE (10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
5.48 ± 0.23	**OUR AVERAGE**				
4.83 ±0.65 ±0.26	33	1 ABLIKIM	2016O	BES3	e^+e^- at 4.009 GeV
5.70 ±0.21 $^{+0.31}_{-0.30}$	2.2k	2 ZUPANC	2013	BELL	e^+e^- at $\Upsilon(4S), \Upsilon(5S)$
4.96 ±0.37 ±0.57	748 ±53	3 DEL-AMO-SANCH..	2010J	BABR	$e^-\overline{\nu}_e\nu_\tau$, $\mu^-\overline{\nu}_\mu\nu_\tau$
6.42 ±0.81 ±0.18	126 ±16	4 ALEXANDER	2009	CLEO	$\tau^+ \to \pi^+\overline{\nu}_\tau$
5.52 ±0.57 ±0.21	155 ±17	4 NAIK	2009A	CLEO	$\tau^+ \to \rho^+\overline{\nu}_\tau$
5.30 ±0.47 ±0.22	181 ±16	4 ONYISI	2009	CLEO	$\tau^+ \to e^+\nu_e\overline{\nu}_\tau$

$D_s^+ \to \mu^+ \nu_\mu$ based on the 4178 data

- Demanding the track penetrate deep in MUC

—> Suppress backgrounds effectively, including $D_s^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$.



- **Preliminary result:**

  BF($D_s \to \mu\, \nu_\mu$) = $(5.28 \pm 0.15_{stat} \pm 0.14_{syst}) \times 10^{-3}$.

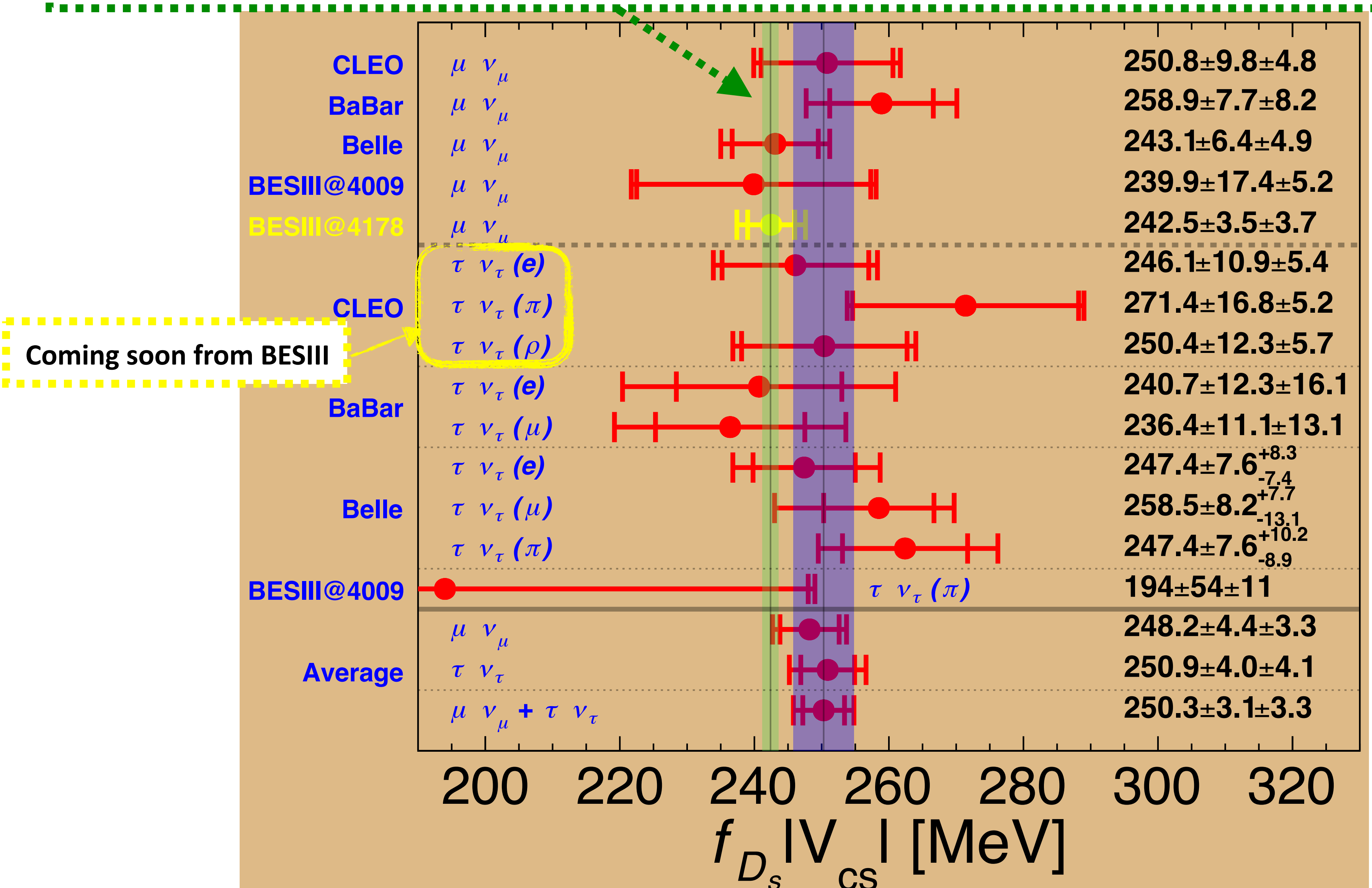
  Consistent with other existing results.

  But most precise single measurement.

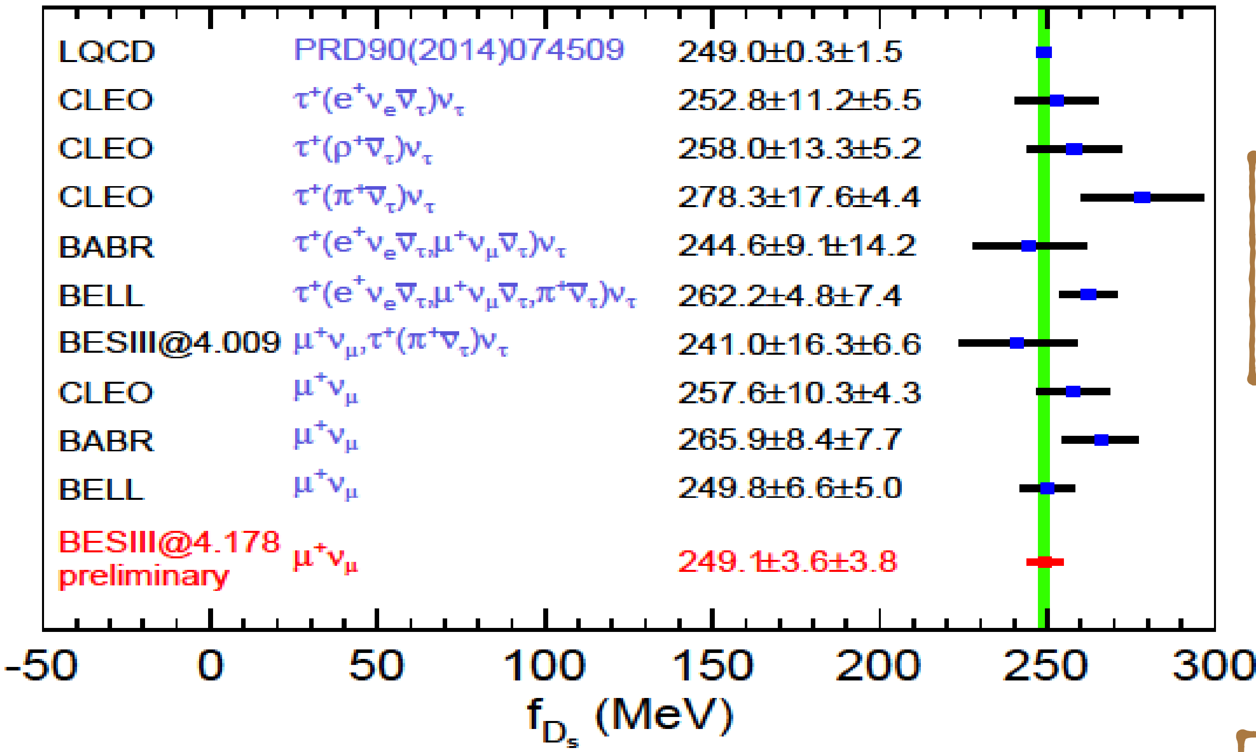
$\Gamma(D_s^+ \to \mu^+ \nu_\mu)/\Gamma_{total}$ Γ_{20}/Γ

VALUE (10^{-3})	EVTS		DOCUMENT ID		TECN	COMMENT
5.50 ± 0.23	**OUR AVERAGE**					
4.95 ±0.67 ±0.26	69	1	ABLIKIM	2016O	BES3	e^+e^- at 4.009 GeV
5.31 ±0.28 ±0.20	492 ±26	2	ZUPANC	2013	BELL	e^+e^- at $\Upsilon(4S)$, $\Upsilon(5S)$
6.02 ±0.38 ±0.34	275 ±17	3	DEL-AMO-SANCH..	2010J	BABR	e^+e^- , 10.58 GeV
5.65 ±0.45 ±0.17	235 ±14		ALEXANDER	2009	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
6.44 ±0.76 ±0.57	169 ±18	4	WIDHALM	2008	BELL	See ZUPANC 2013
5.94 ±0.66 ±0.31	88	5	PEDLAR	2007A	CLEO	See ALEXANDER 2009
6.8 ±1.1 ±1.8	553	6	HEISTER	2002I	ALEP	Z decays

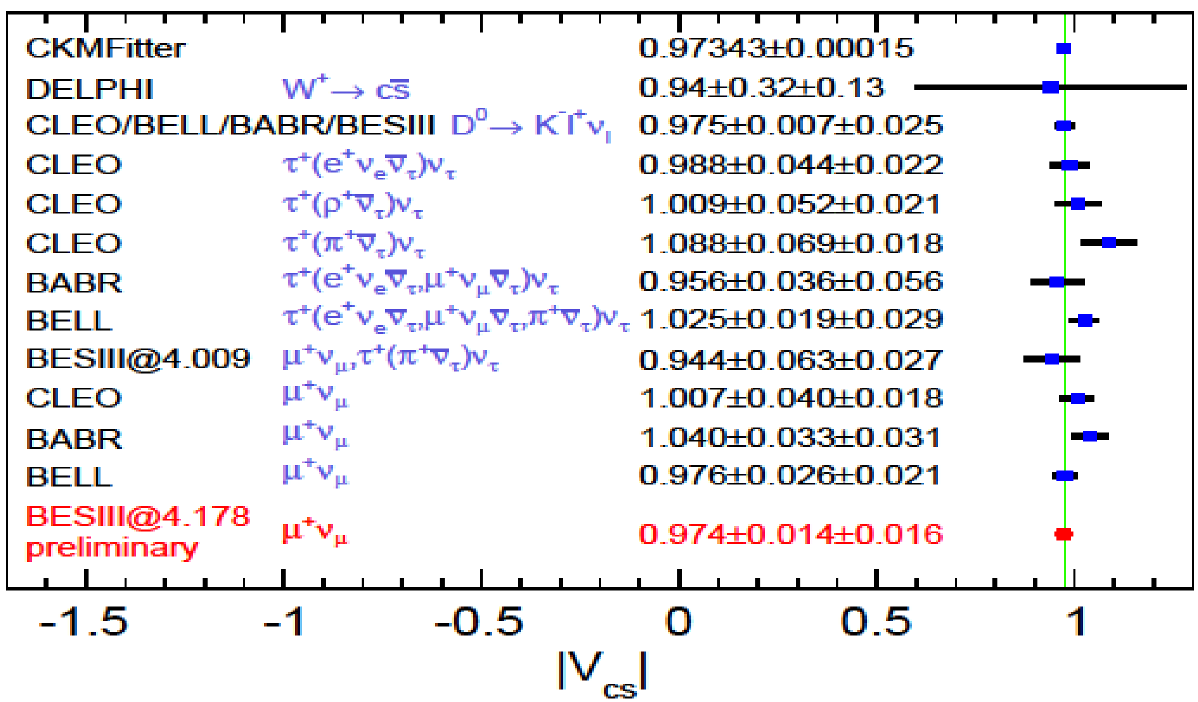
With f_{Ds} = 249.0±1.2 MeV (From Rosner and Stone, PDG 2016 mini-review) and $|V_{cs}| = 0.973394^{+0.000074}_{-0.000096}$ from CKM-fitter (2015)



Consistent within 1.7σ w/OUT the new BESIII measurement.
It will be interesting to revisit this once we have the "τν" measurements from BESIII!!



- Taking $|V_{cs}|^{CKMfitter}$ as an input, we have f_{D_s} = 249.1±3.6±3.8 MeV.



- Taking f_{D_s} (LQCD;PRD90,074509) as an input, we have $|V_{cs}|$ = 0.974±0.014±0.016.
- Our preliminary result on $D^0 \to K^- \mu \nu$, with a help of $f_D^K(0)$ (LQCD;PRD82,114506), also gives a consistent result; $|V_{cs}|$ = 0.9569±0.0051±0.0241. Here, statistically superior, but suffered by the uncertainties from FFs as in all SL analyses.

and the R

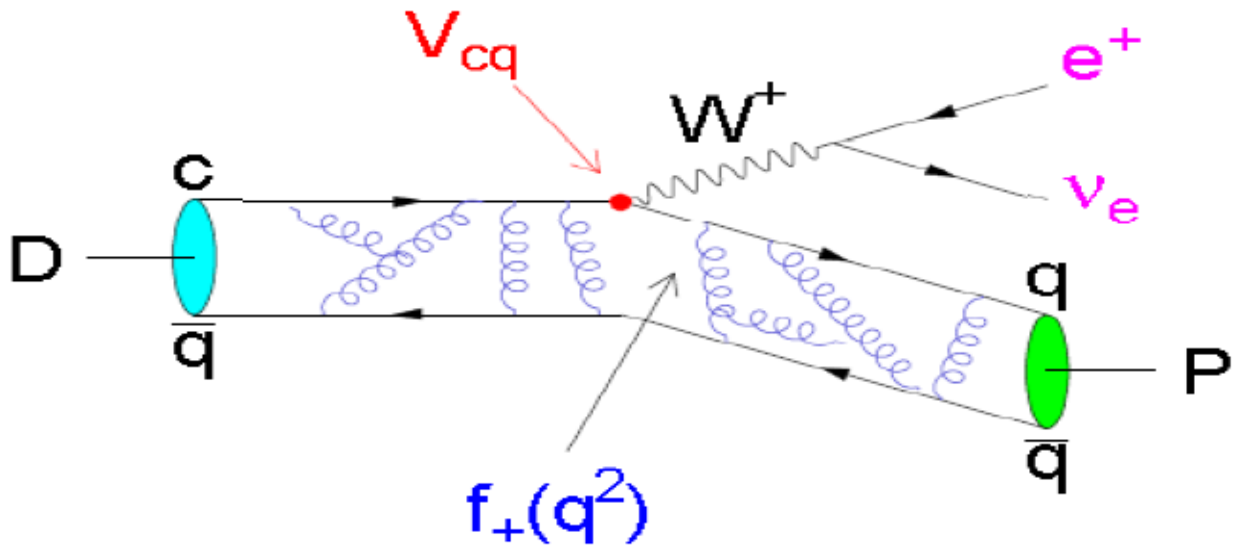
Taking the weighted average between our preliminary result of BF($D_s \to \mu\,\nu_\mu$) and the current PDG average gives BF($D_s \to \mu\,\nu_\mu$) = (5.38±0.15)×10^{-3}.
With the current PDG average of BF($D_s \to \tau\,\nu_\tau$), we have

$$R \equiv \frac{\Gamma(D_s^+ \to \tau^+ \nu)}{\Gamma(D_s^+ \to \mu^+ \nu)} = \frac{m_{\tau^+}^2 (1 - \frac{m_{\tau^+}^2}{M_{D_s^+}^2})^2}{m_{\mu^+}^2 (1 - \frac{m_{\mu^+}^2}{M_{D_s^+}^2})^2}$$

= 10.2±0.5.
Consistent with the expectation, 9.74±0.01 at 0.9σ.

We should also improve BF($D_s \to \tau\,\nu_\tau$) soon…

Semileptonic decays



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 p^3}{24\pi^3} |f_+(q^2)|^2 |V_{cd(s)}|^2$$

-The differential decay rate goes as $|f_+(q^2)|^2 \times |V_{cd(s)}|^2$.

Still, the game is to measure the BF, and then

- use the CKM elements predicted by unitarity to obtain experimental values for $f_+(q^2=0)$.
- or $f_+(q^2=0)$ predicted by lattice QCD to determine elements of CKM elements.

Some popular parametrization of form factors

- Simple pole:

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M^2_{\rm pole}}$$

- Modified pole:

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M^2_{\rm pole}}\right)\left(1 - \alpha \frac{q^2}{M^2_{\rm pole}}\right)}$$

- ISGW2:

$$f_+(q^2) = f_+(q^2_{\rm max})(1 + \frac{r^2}{12}(q^2_{\rm max} - q^2))^{-2}$$

- Series expansion:

$$f_+(t) = \frac{1}{P(t)\Phi(t,t_0)} a_0(t_0)\left(1 + \sum_{k=1}^{\infty} r_k(t_0)[z(t,t_0)]^k\right)$$

$D_s \to \eta\ (\eta')\ e\ \nu$ based on the 4178 data

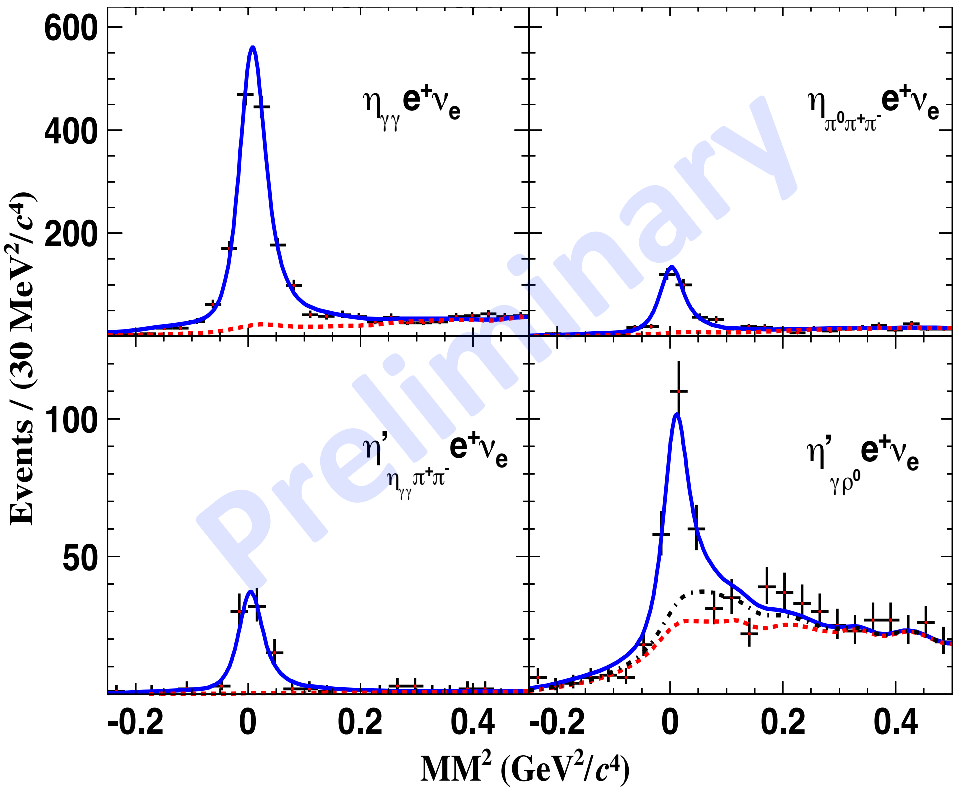
Allows us to:

- extract $f_+^{\eta^{(\prime)}}(0)$ and compare to LQCD prediction … **for the 1st time!**
- extract $|V_{cs}|$!
- extract the mixing angle between η and η' (C. Di Donato et al. PRD 85, 013016 (2012));

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi_P & -\sin\phi_P \\ \sin\phi_P & \cos\phi_P \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \end{pmatrix}$$

$$\frac{\Gamma(D_s^+ \to \eta' e^+ \nu)/\Gamma(D_s^+ \to \eta e^+ \nu)}{\Gamma(D^+ \to \eta' e^+ \nu)/\Gamma(D^+ \to \eta e^+ \nu)} \simeq \cot^4\phi_P,$$

assuming the phase space and form factors cancel in the ratios between D and D_s.

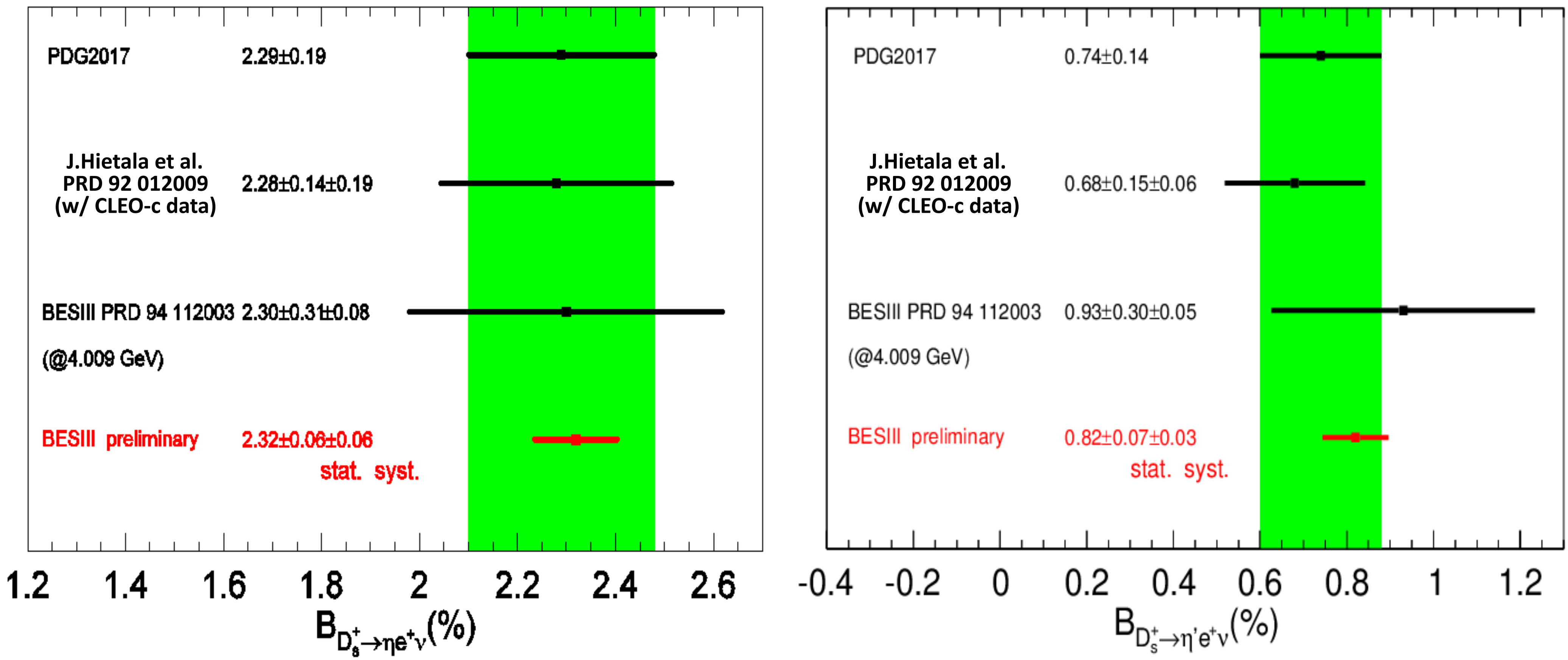


- **Detect:**
  - tag side (14 different decay modes).
  - the trans. photon from $D_s^* \to \gamma D_s$.
  - $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$.
    $\eta' \to \pi^+\pi^-\eta_{\gamma\gamma}$ and $\gamma\rho$.
- Yields are extracted from MM2.
- Fit to the two different final states simultaneously.

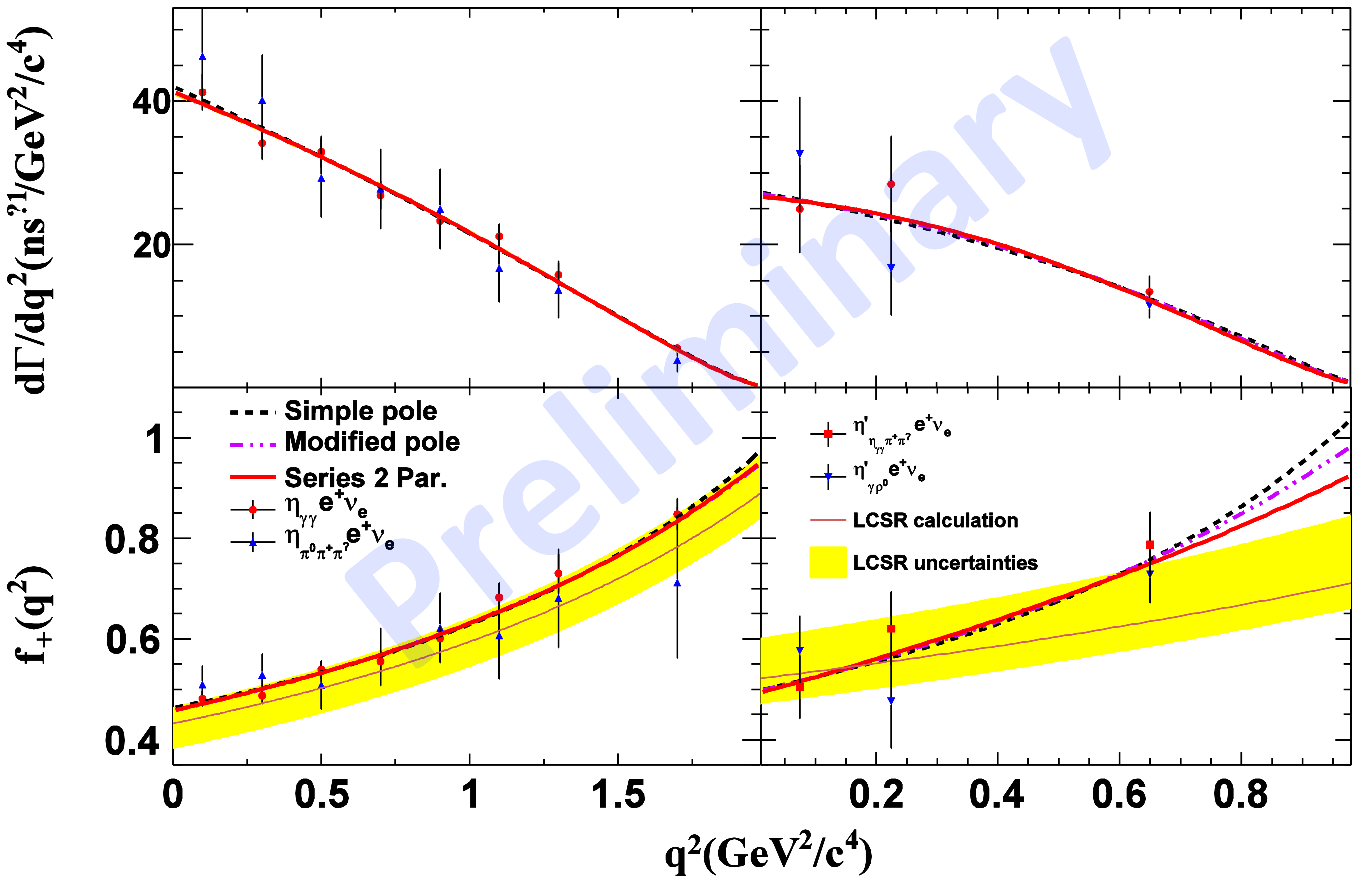
Decay	$\eta^{(\prime)}$ decay	$\epsilon_{\gamma(\pi^0)\mathrm{SL}}$ (%)	$N_{\mathrm{DT}}^{\mathrm{tot}}$	$\mathcal{B}_{\mathrm{SL}}$ (%)
$\eta e^+\nu_e$	$\gamma\gamma$	41.11±0.27	1834±47	2.32±0.06±0.06
	$\pi^0\pi^+\pi^-$	16.06±0.31		
$\eta' e^+\nu_e$	$\eta\pi^+\pi^-$	14.07±0.10	261±22	0.82±0.07±0.03
	$\gamma\rho^0$	18.98±0.10		

Preliminary

Consistent with previous measurements, but the most precise to date!



Fits to partial decay rates and projections onto form factors



- Again, fit to the two different final states simultaneously.

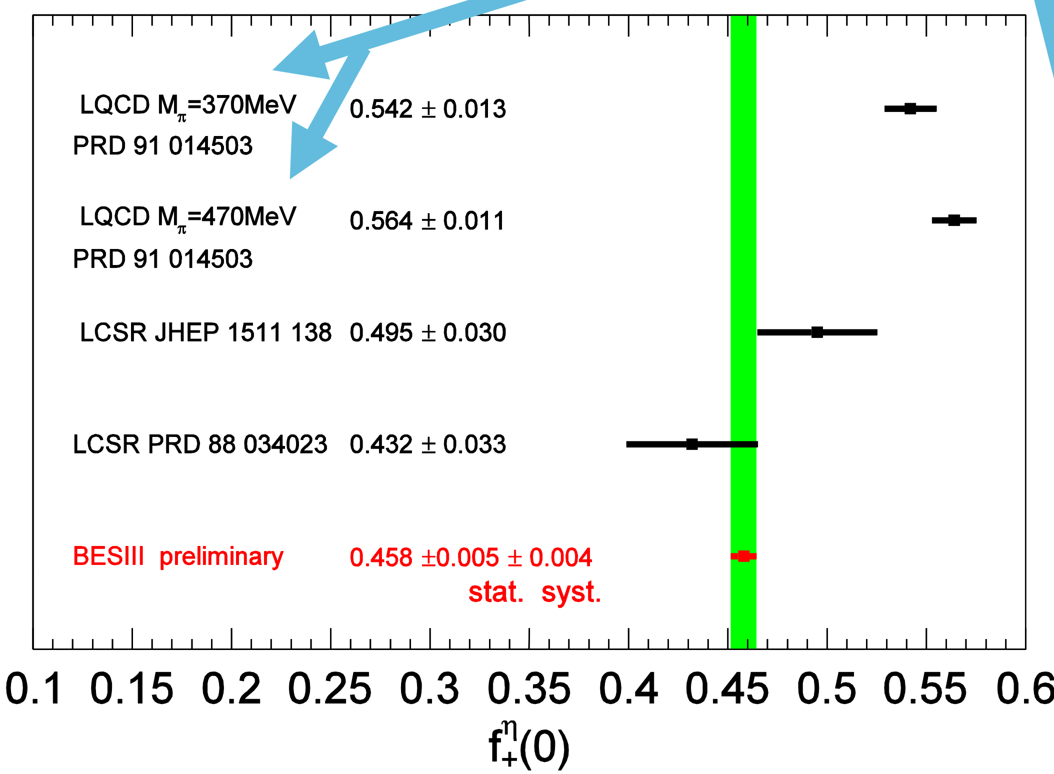
Case	Simple pole			Modified pole			Series 2 Par.		
	$f_+^{\eta^{(\prime)}}(0)\|V_{cs}\|$	$M_{\rm pole}$	χ^2/NDOF	$f_+^{\eta^{(\prime)}}(0)\|V_{cs}\|$	α	χ^2/NDOF	$f_+^{\eta^{(\prime)}}(0)\|V_{cs}\|$	r_1	χ^2/NDOF
$\eta e^+\nu_e$	0.450(5)(3)	3.77(8)(5)	12.2/14	0.445(5)(3)	0.30(4)(3)	11.4/14	0.446(5)(4)	−2.2(2)(1)	11.5/14
$\eta' e^+\nu_e$	0.494(45)(10)	1.88(54)(5)	1.8/4	0.481(44)(10)	1.62(91)(11)	1.8/4	0.477(49)(11)	−13.1(76)(11)	1.9/4

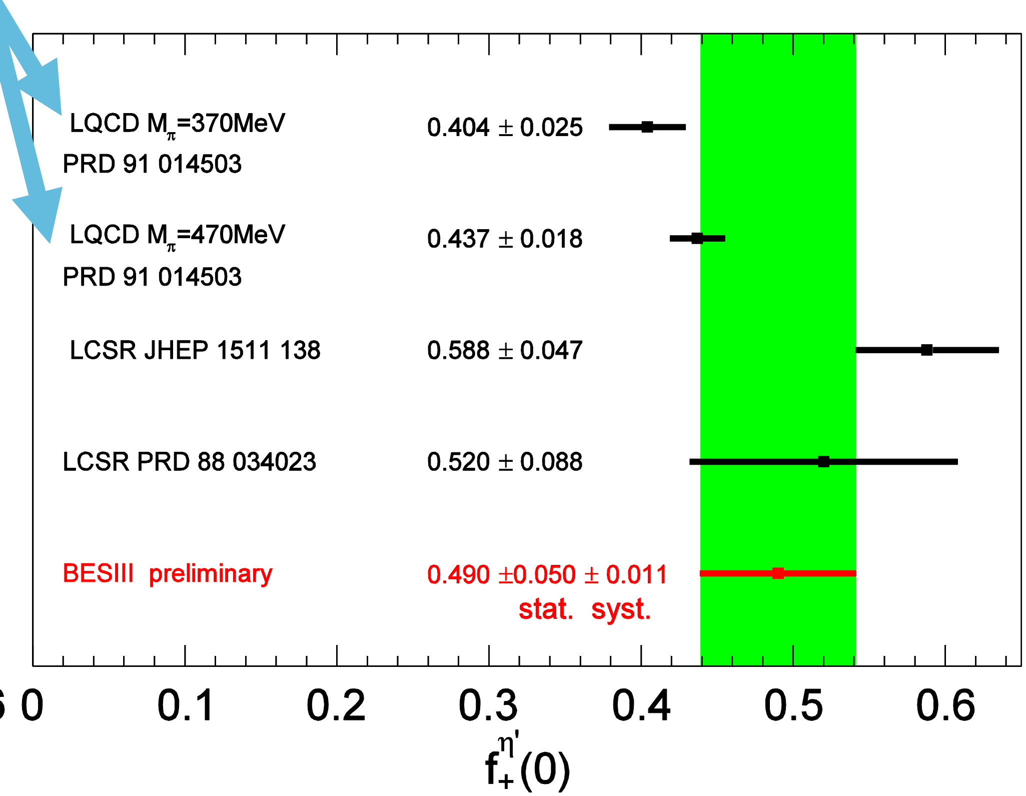
First measurement of $f_+^{\eta(\prime)}$

Taking $|V_{cs}|$ CKMfitter and $f_+^{\eta^{(\prime)}}(0)\,|V_{cs}|$ extracted with the series 2 Parameters as input, we obtain

$f_+^{\eta}(0) = 0.458 \pm 0.005_{stat} \pm 0.004_{syst}$ $f_+^{\eta'}(0) = 0.490 \pm 0.050_{stat} \pm 0.011_{syst}$

No systematic uncertainty is considered

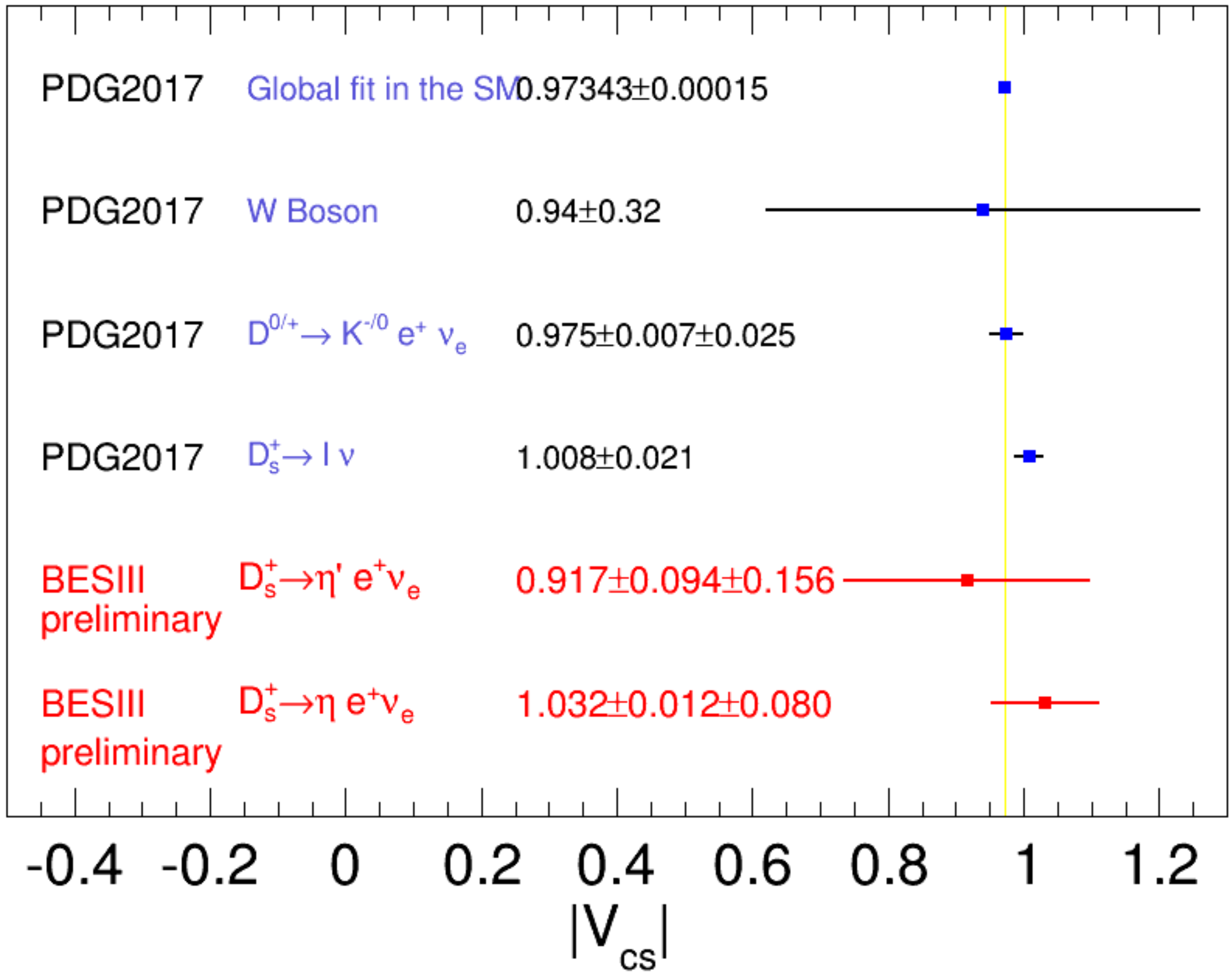




Extracting $|V_{cs}|$

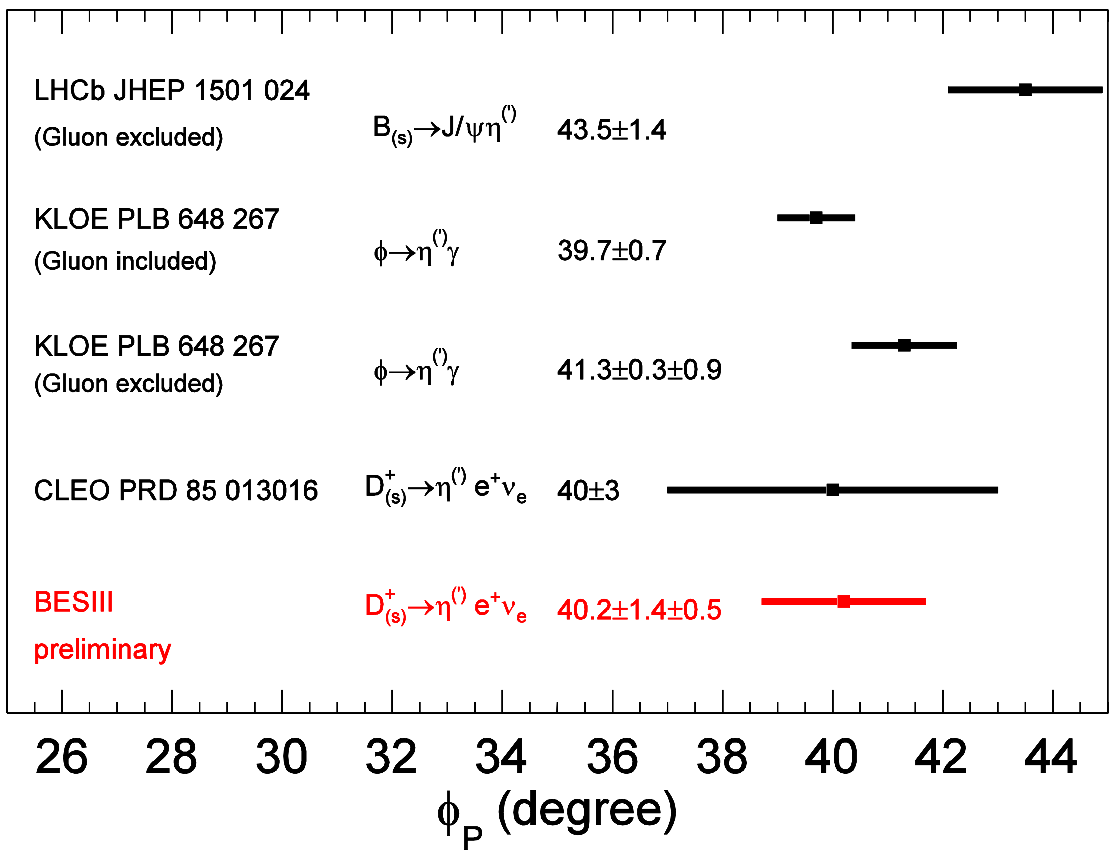
Only reported one uncertainty, but include both statistical and systematic

Taking $f_+^{D_s \to \eta^{(\prime)}}(0)$ PRD88 034023 as input, we obtain



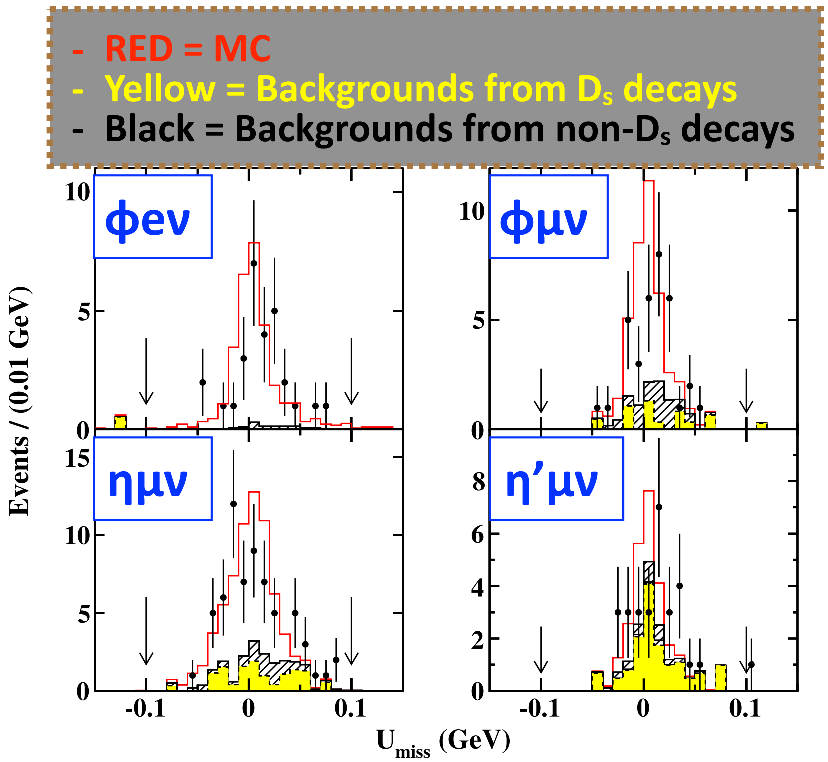
η/η' mixing angle

- **Combined this work and $B(D^+ \to \eta e \nu) = (10.74\pm0.81\pm0.51)\times10^{-4}$ and $B(D^+ \to \eta' e \nu) = (1.91\pm0.51\pm0.13)\times10^{-4}$ (BESIII arXiv:1803.05570: Submitted to PRD)**



- **Good consistency with the existing measurements.**

$D_s \rightarrow (\eta/\eta') \mu \nu$ and ϕ (e/μ) ν based on the 4009 data : PRD 97, 012006 (2018)



- Reconstruct: $\phi \rightarrow KK/\eta \rightarrow \gamma\gamma/\eta' \rightarrow (\pi\pi\eta/\gamma\rho)$
- First measurements of the muonic mode!
- Combined this work and our own earlier work (based on the 4009 data; PRD 94, 112003 (2016)), we also have the following unities;

$\Gamma(D_s \rightarrow \phi\mu\nu)/\Gamma(D_s \rightarrow \phi e\nu) = 0.86 \pm 0.29$

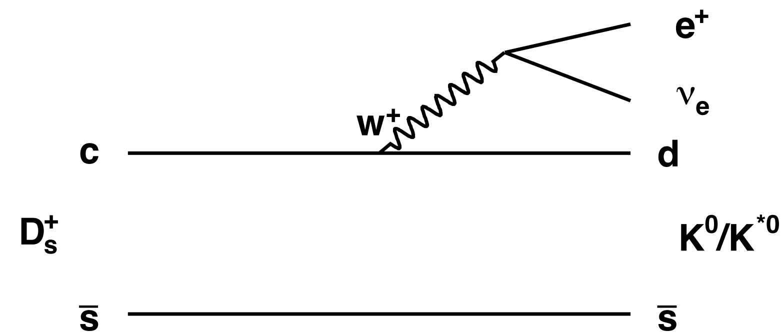
$\Gamma(D_s \rightarrow \eta\mu\nu)/\Gamma(D_s \rightarrow \eta e\nu) = 1.05 \pm 0.24$

$\Gamma(D_s \rightarrow \eta'\mu\nu)/\Gamma(D_s \rightarrow \eta' e\nu) = 1.14 \pm 0.69$.

μ^+ mode	$\mathcal{B}_{\mathrm{BESIII}}$ (%)	$\mathcal{B}_{\mathrm{PDG}}$ (%)	e^+ mode	$\mathcal{B}_{\mathrm{BESIII}}$ (%)	$\mathcal{B}_{\mathrm{PDG}}$ (%)
$D_s^+ \rightarrow \phi\mu^+\nu_\mu$	$1.94 \pm 0.53 \pm 0.09$	$\cdots$	$D_s^+ \rightarrow \phi e^+\nu_e$	$2.26 \pm 0.45 \pm 0.09$	2.39 ± 0.23
$D_s^+ \rightarrow \eta\mu^+\nu_\mu$	$2.42 \pm 0.46 \pm 0.11$	$\cdots$	$D_s^+ \rightarrow \eta e^+\nu_e$	$2.30 \pm 0.31 \pm 0.08$ [8]	2.28 ± 0.24
$D_s^+ \rightarrow \eta'\mu^+\nu_\mu$	$1.06 \pm 0.54 \pm 0.07$	$\cdots$	$D_s^+ \rightarrow \eta' e^+\nu_e$	$0.93 \pm 0.30 \pm 0.05$ [8]	0.68 ± 0.16

$D_s \rightarrow (K^0/K^{*0})$ e nu based on the 4178 data

- The current experimental results on this CS decay is rather sparse.
  We should be able to improve the situation with our 4178 data!



$\Gamma(D_s^+ \rightarrow K^0 e^+ \nu_e)/\Gamma_{total}$ — Γ_{28}/Γ

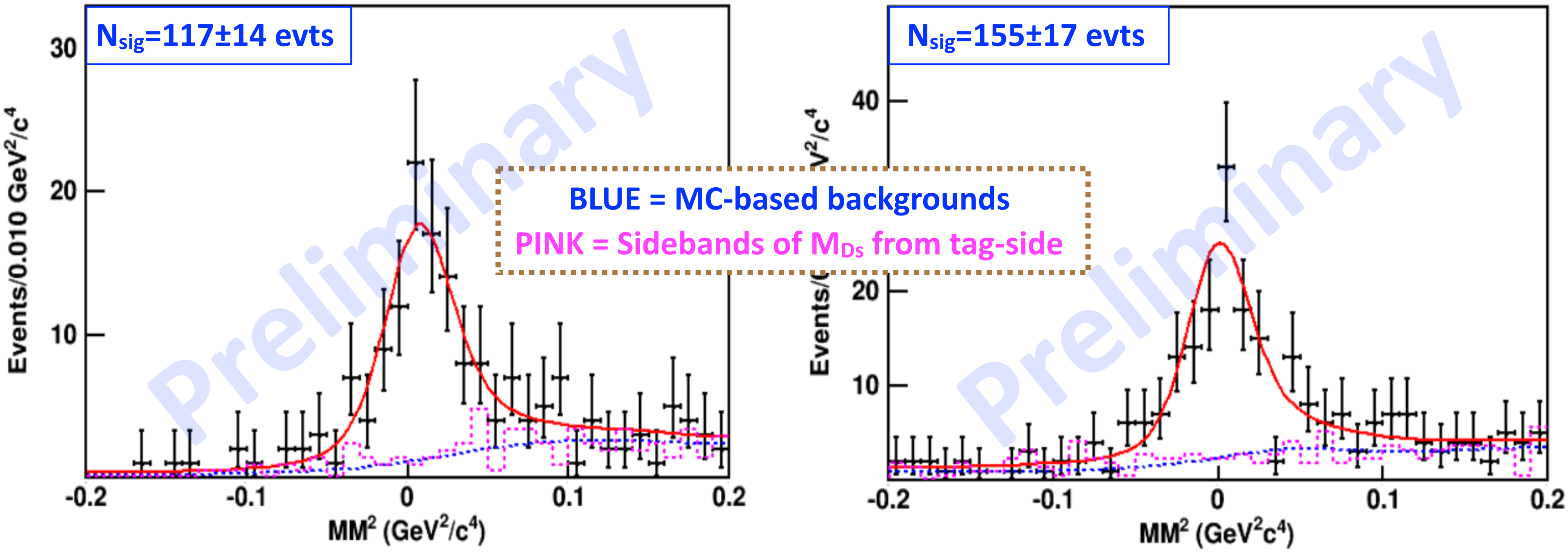
VALUE (10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.39 ±0.08 ±0.03	42	HIETALA	2015		Uses CLEO data
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.37 ±0.10 ±0.02	14	YELTON	2009	CLEO	See HIETALA 2015

$\Gamma(D_s^+ \rightarrow K^*(892)^0 e^+ \nu_e)/\Gamma_{total}$ — Γ_{29}/Γ

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE (10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.18 ±0.04 ±0.01	32	HIETALA	2015		Uses CLEO data
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.18 ±0.07 ±0.01	7.5	YELTON	2009	CLEO	See HIETALA 2015

$K^0(=K_S \rightarrow \pi^+\pi^-)e\nu$ $K^{*0}(\rightarrow K^+\pi^-)e\nu$



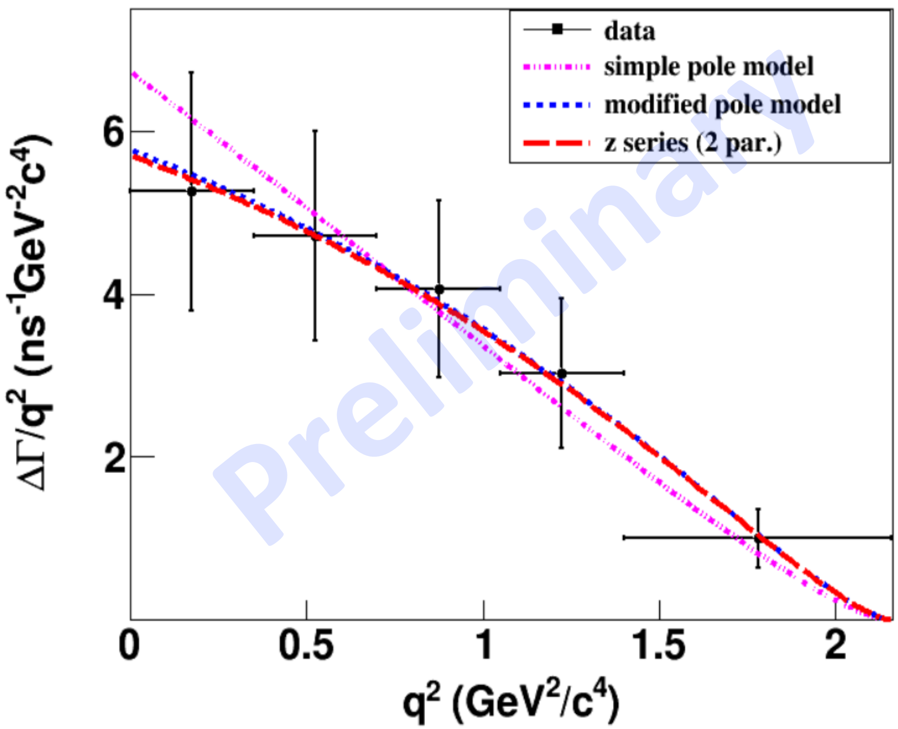
Preliminary results

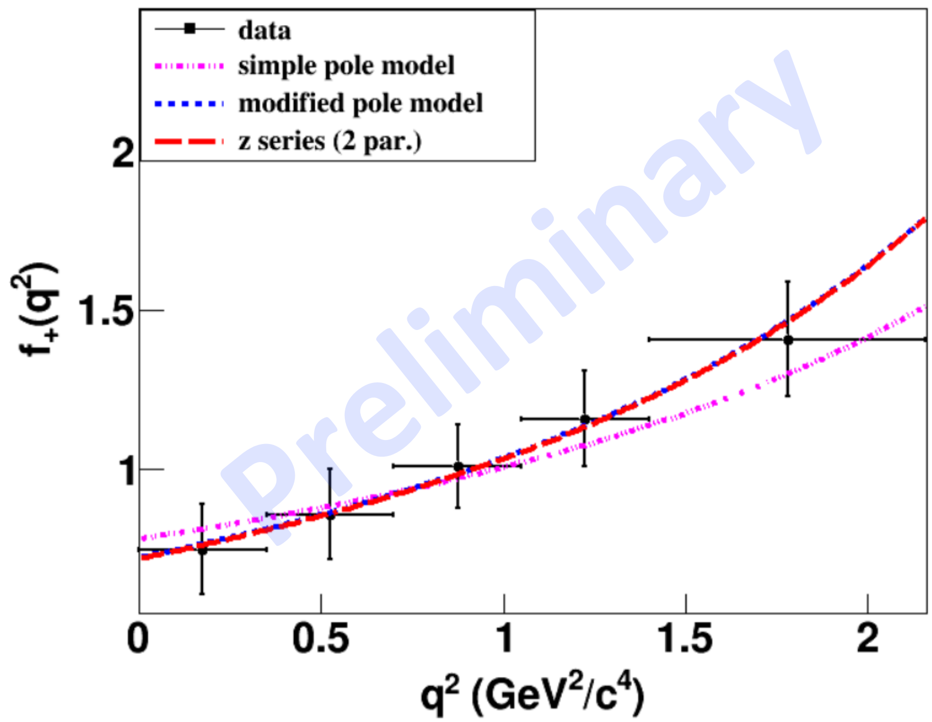
$BF(D_s \rightarrow K^0\ e\ \nu) = (3.25 \pm 0.38 \pm 0.14) \times 10^{-3}$: $(3.9 \pm 0.9) \times 10^{-3}$ [PDG2017]

$BF(D_s \rightarrow K^{*0}\ e\ \nu) = (2.38 \pm 0.26 \pm 0.12) \times 10^{-3}$: $(1.8 \pm 0.4) \times 10^{-3}$ [PDG2017]

- Good agreement with the existing result, but more precise!
- Still, statistically limited.

$D_s \rightarrow K^0 e \nu$: Fits to partial decay rate and projection onto its form factor





The FFs are extracted for the first time!

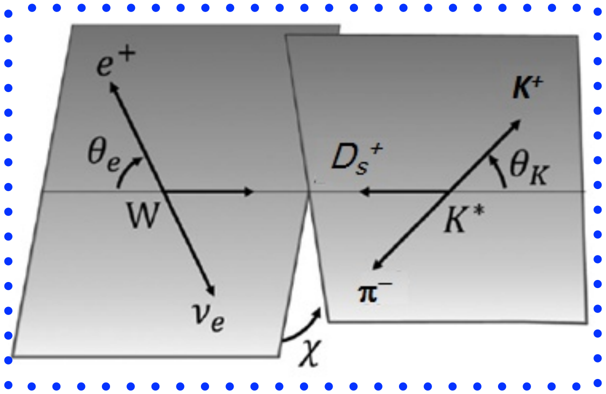
Model	Parameter	Value	$f_+(0)$
Simple pole	$f_+(0)\|V_{cd}\|$	$0.175 \pm 0.010 \pm 0.001$	$0.778 \pm 0.044 \pm 0.004$
Modified pole model	$f_+(0)\|V_{cd}\|$	$0.163 \pm 0.017 \pm 0.003$	$0.725 \pm 0.076 \pm 0.013$
	α	$0.45 \pm 0.44 \pm 0.02$	
Series two parameters	$f_+(0)\|V_{cd}\|$	$0.162 \pm 0.019 \pm 0.003$	$0.720 \pm 0.084 \pm 0.013$
	r_1	$-2.94 \pm 2.32 \pm 0.14$	

Inserting $|V_{cd}| = 0.22492 \pm 0.00050$ obtained by CKMfitter, the $f_+(0)$ can be obtained.

Extracting FF for $D_s \to K^{*0}$ e ν

- **The differential decay rate depends on 5 variables (PRL 110,131802) and cab be expressed in terms of 3 helicity amplitudes:**

$$\frac{d^5\Gamma}{dm_{K\pi}\,dq^2\,d\cos\theta_K\,d\cos\theta_e\,d\chi} = \frac{3}{8(4\pi)^4} G_F^2 |V_{cd}|^2 \frac{p_{K\pi} q^2}{M_{D_s}^2} \mathcal{B}(K^{*0} \to K^+\pi^-) |\mathcal{BW}(m_{K\pi})|^2$$
$$\times \left[(1+\cos\theta_e)^2 \sin^2\theta_K |H_+(q^2, m_{K\pi})|^2 \right.$$
$$+ (1-\cos\theta_e)^2 \sin^2\theta_K |H_-(q^2, m_{K\pi})|^2$$
$$+ 4\sin^2\theta_e \cos^2\theta_K |H_0(q^2, m_{K\pi})|^2$$
$$+ 4\sin\theta_e (1+\cos\theta_e) \sin\theta_K \cos\theta_K \cos\chi H_+(q^2, m_{K\pi}) H_0(q^2, m_{K\pi})$$
$$- 4\sin\theta_e (1-\cos\theta_e) \sin\theta_K \cos\theta_K \cos\chi H_-(q^2, m_{K\pi}) H_0(q^2, m_{K\pi})$$
$$\left. - 2\sin^2\theta_e \sin^2\theta_K \cos 2\chi H_+(q^2, m_{K\pi}) H_-(q^2, m_{K\pi}) \right].$$



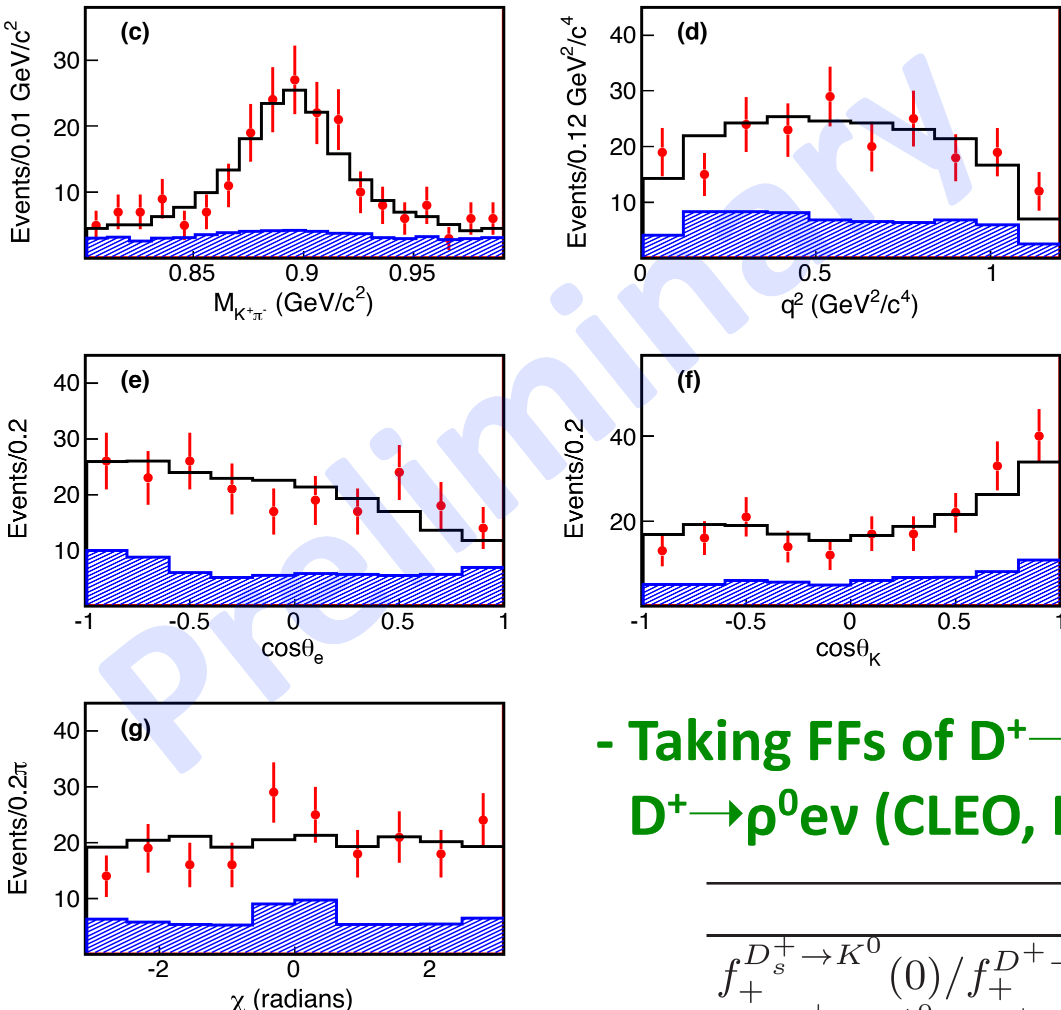
The helicity amplitudes of $H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$ take the form of
$H_\pm(q^2) = (M_{D_s} + m_{K\pi}) A_1(q^2) \mp \frac{2M_{D_s} P_{K\pi}}{M_{D_s} + M_{K\pi}} V(q^2)$ and

$$H_0(q^2) = \frac{1}{2m_{K\pi} q} \left[(M_{D_s}^2 - m_{K\pi}^2 - q^2)(M_{D_s} + m_{K\pi}) A_1(q^2) - \frac{4M_{D_s}^2 p_{K\pi}^2}{M_{D_s} + M_{K\pi}} A_2(q^2) \right],$$

$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2}$ and $V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$, $r_V = \frac{V(0)}{A_1(0)}$ and $r_2 = \frac{A_2(0)}{A_1(0)}$.

- **We perform 5 dimensional fit to extract the form factor ratios, r_V and r_2.**

Projections of the fit onto the 5 variables



- **Preliminary: The ratio of FFs, extracted for the first time, are**
  r_V = 1.67±0.34±0.16
  r_2 = 0.77±0.28±0.07

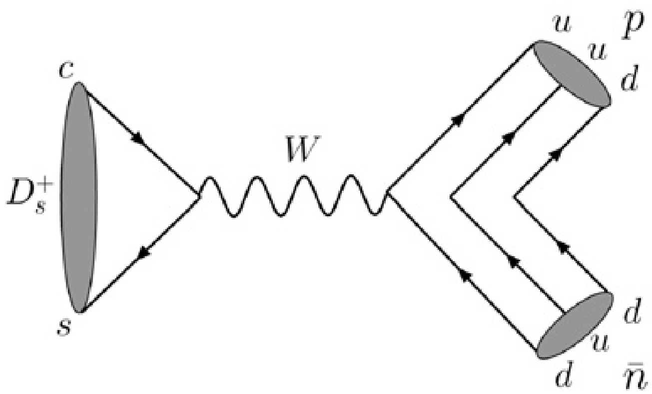
- **Taking FFs of $D^+ \to \pi^0 e\nu$ (BESIII, PRD96,012002) and $D^+ \to \rho^0 e\nu$ (CLEO, PRL110,131802), we also obtained;**

	Values
$f_+^{D_s^+ \to K^0}(0)/f_+^{D^+ \to \pi^0}(0)$	$1.16 \pm 0.14(\text{stat.}) \pm 0.02(\text{syst.})$
$r_V^{D_s^+ \to K^{*0}}/r_V^{D^+ \to \rho^0}$	$1.13 \pm 0.26(\text{stat.}) \pm 0.11(\text{syst.})$
$r_2^{D_s^+ \to K^{*0}}/r_2^{D^+ \to \rho^0}$	$0.93 \pm 0.36(\text{stat.}) \pm 0.10(\text{syst.})$

Preliminary

These provide a test of the LQCD predictions.

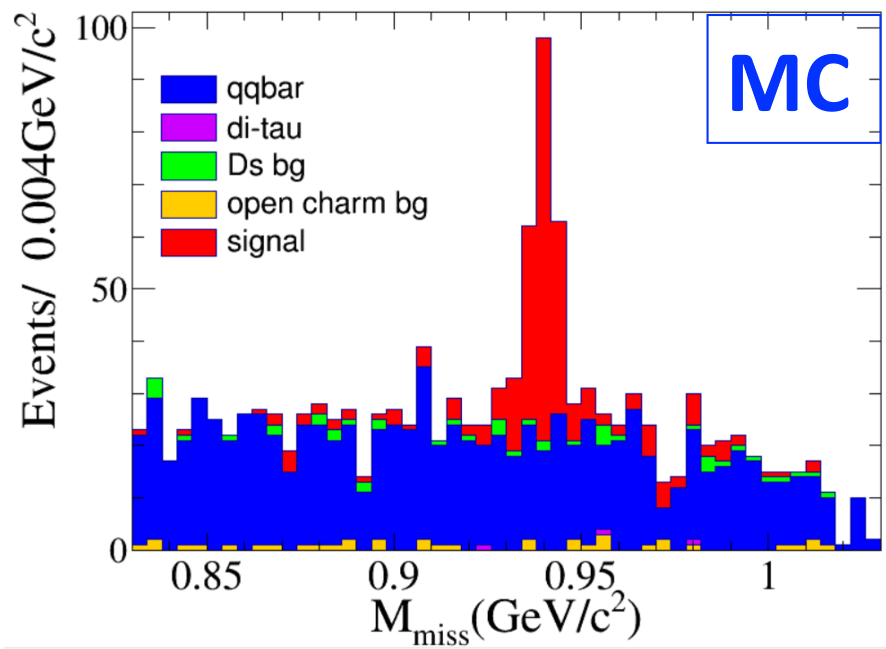
Hadronic decays

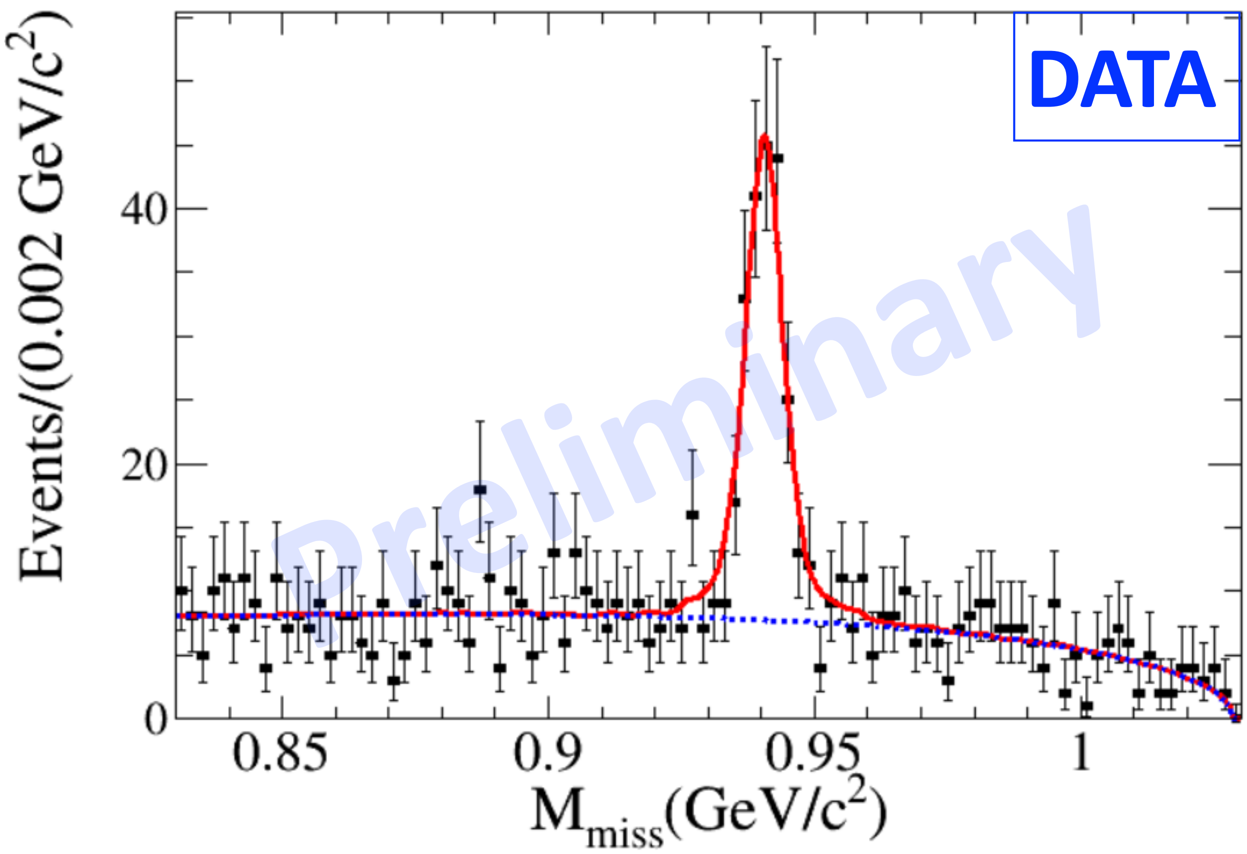


$D_s \rightarrow p\,\bar{n}$
based on the 4178 data

- The only kinematically allowed hadronic decay, involving baryons.
- Short-distance contribution is expected to be small : BF ~ 10^{-6}.
  But long-distance can enhance BF to ~10^{-3} (C.H. Chen, et al. PLB663, 326).
- First evidence was reported by CLEO with a signal of 13.0±3.6 events with BF = $(1.30\pm0.36^{+0.12}_{-0.16})\times10^{-3}$ (PRL100, 181802).

- Reconstruct everything, but the neutron.
- Our MC (scaled to the data size) predicts a trivial background shape.





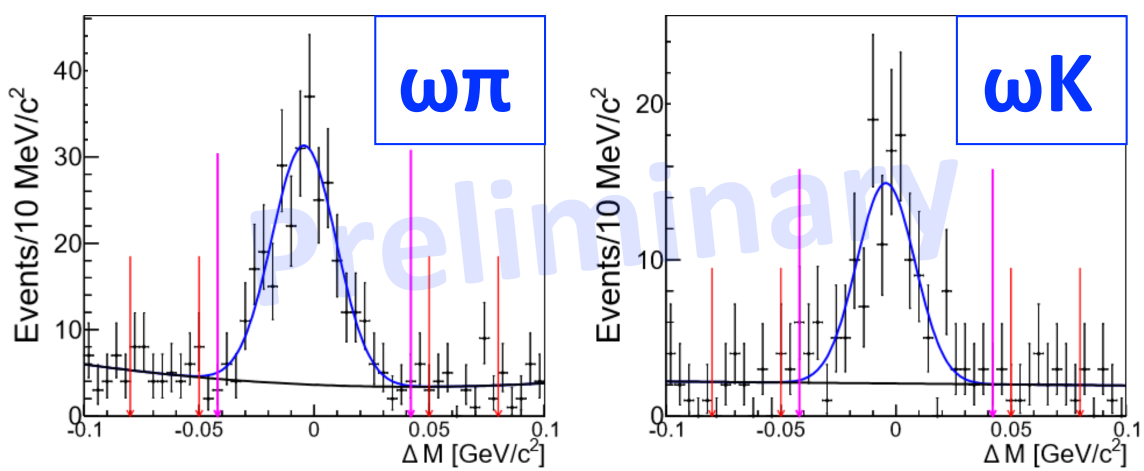
- **Preliminary:**

  BF($D_s \to p\bar{n}$) = $(1.22\pm0.10)\times10^{-3}$. Statistical uncertainty only.
- **Likely statistically limited (Syst. would be dominated by PID).**
- **Confirmed the CLEO's result with an improved precision.**

$D_s \to \omega\pi$ and ωK based on the 4178 data

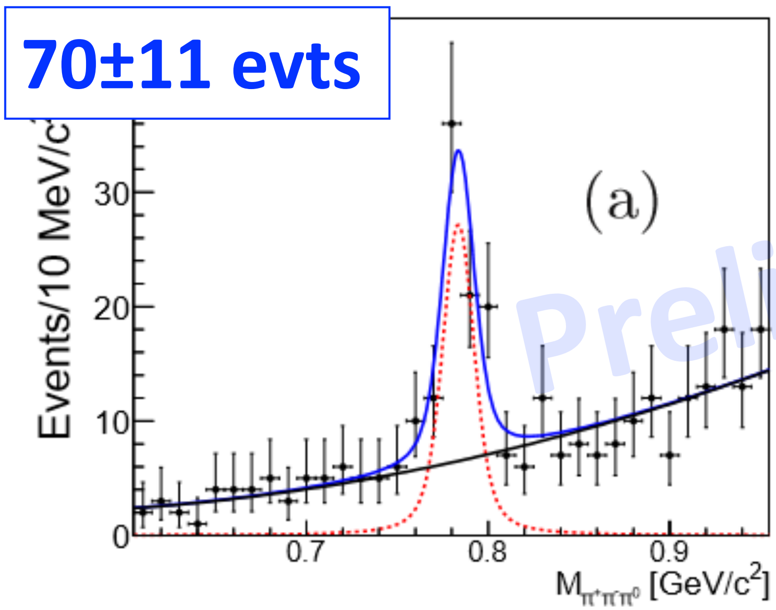
- $\omega\pi$: CF : Has seen by CLEO (PRD80,051102) : BF = $(2.1\pm0.9\pm0.1)\times10^{-3}$.
- ωK: SCS: CLEO (PRD80,051102) set an UL = 2.4×10^{-3} @ 90% C.L.
  Q. Qin et al. (PRD89, 054006) predicts (factorization)
  BF(ωK) ~ 10^{-3} or it could become ~10^{-4} if ρ-ω mixing is considered.

- Start with selecting $D_s \to$ tag and $D_s \to \omega$ (π/K) candidates.
  Here $\Delta M = M_{signal\text{-}side} - M_{tag\text{-}side}$.
- The sidebands in ΔM from both data and MC show no peaking backgrounds in $M_{\pi\pi\pi^0}$ of the M_ω region.

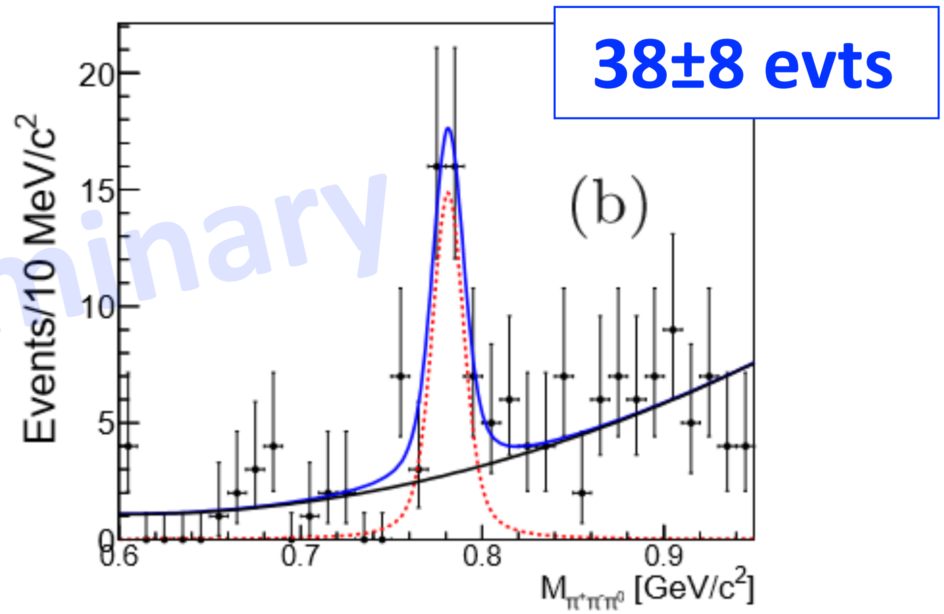


Projecting onto $M_{\pi\pi\pi 0}$ from the signal region of ΔM

ωπ



ωK



- Preliminary: BF($D_s \to \omega\pi$) = $(1.85\pm0.30\pm0.19)\times10^{-3}$: 7.7σ stat. sig.
  Consistent with CLEO's measurement, but more precise.
- Preliminary: BF($D_s \to \omega K$) = $(1.13\pm0.24\pm0.14)\times10^{-3}$: 6.2σ stat. sig.
  First observation!

Summary

- Our results on (semi-)leptonic D_s decays improve the precisions on the decay constant, form factors, and $|V_{cs}|$.
  More results on (semi-)leptonic decays are coming, including $D_s \rightarrow X\, e\, \nu$.

- Our preliminary results on hadronic decays have confirmed and improved the precisions over the previous results from CLEO.
  (a lot) More measurements in D_s hadronic decays are coming.

- Not mentioned in detail in this report:
  - $D_s^+ \rightarrow \mu^+ \nu_\mu$: PRD 94, 072004 (2016)
  - $D_s^+ \rightarrow \eta(\eta') e^+ \nu_e$: PRD 94, 112003 (2016)
  - $D_s^+ \rightarrow \eta' \rho^+$ and η' X : PLB 750, 466 (2015)