
FLAVOR PHYSICS & CP VIOLATION
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Charm physics theory

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Outline

Disclamer:
Impossible for me to do justice to all aspects of charm physics theory.
Will give a personal view, emphasizing recent developments.

- Charm physics as QCD laboratory
  - Production, spectroscopy, m_c
- Testing CKM paradigm with charm
  - (Semi)leptonic decays vs. CKM unitarity

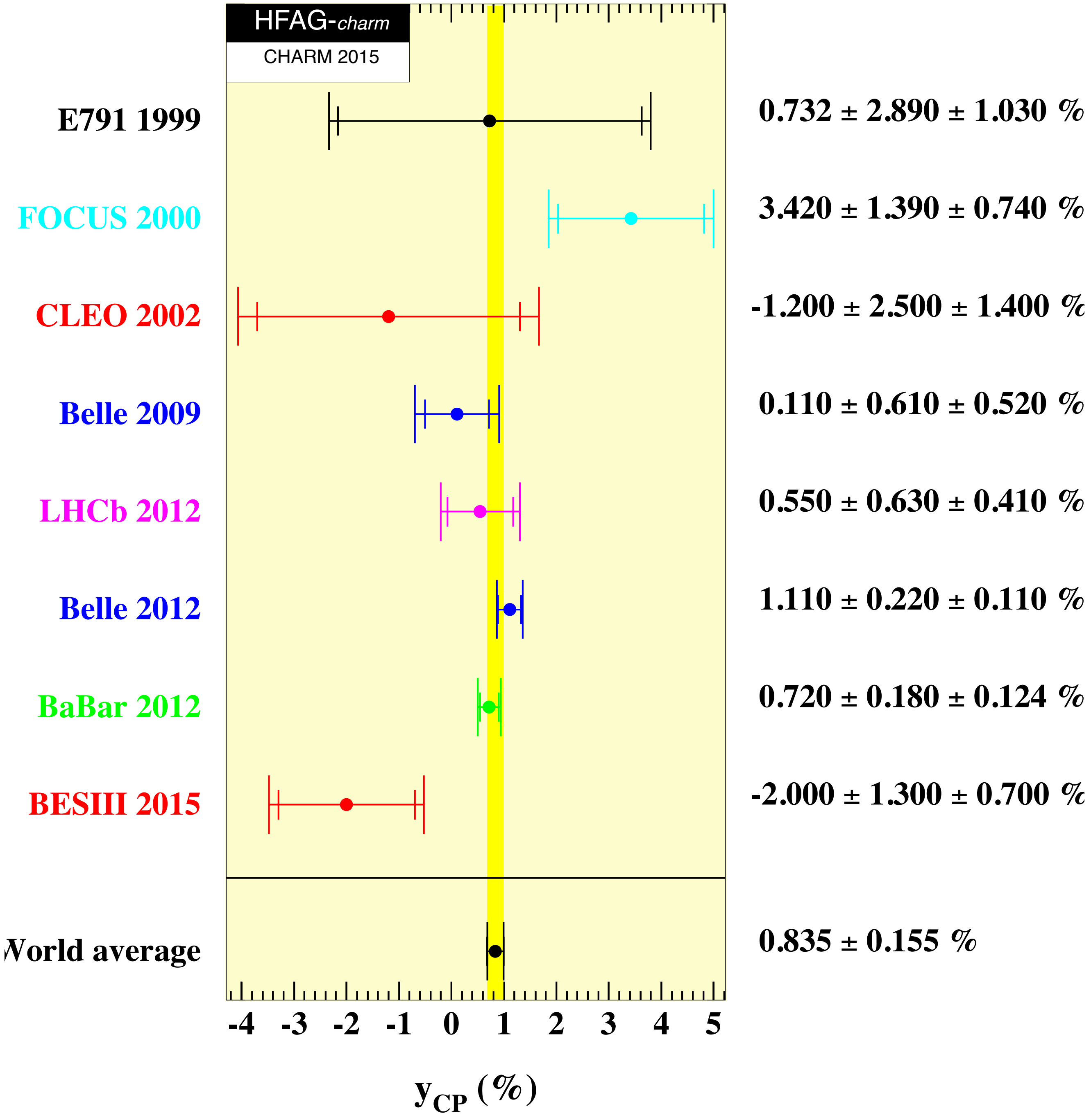
for Lattice QCD results
see talks by OKA, VLADIKAS

- Charming windows to NP
  - CPV in D-meson mixing & decays
  - Disentangling LD from NP in rare charm decays
  - Searches for hidden particles with charm

Context

- Spectacular exp. progress continuously pushing the envelope of precision charm physics, challenging theoretical advances

- Charm remains at the forefront of NP searches, selected few observables still offer ample room for improvements



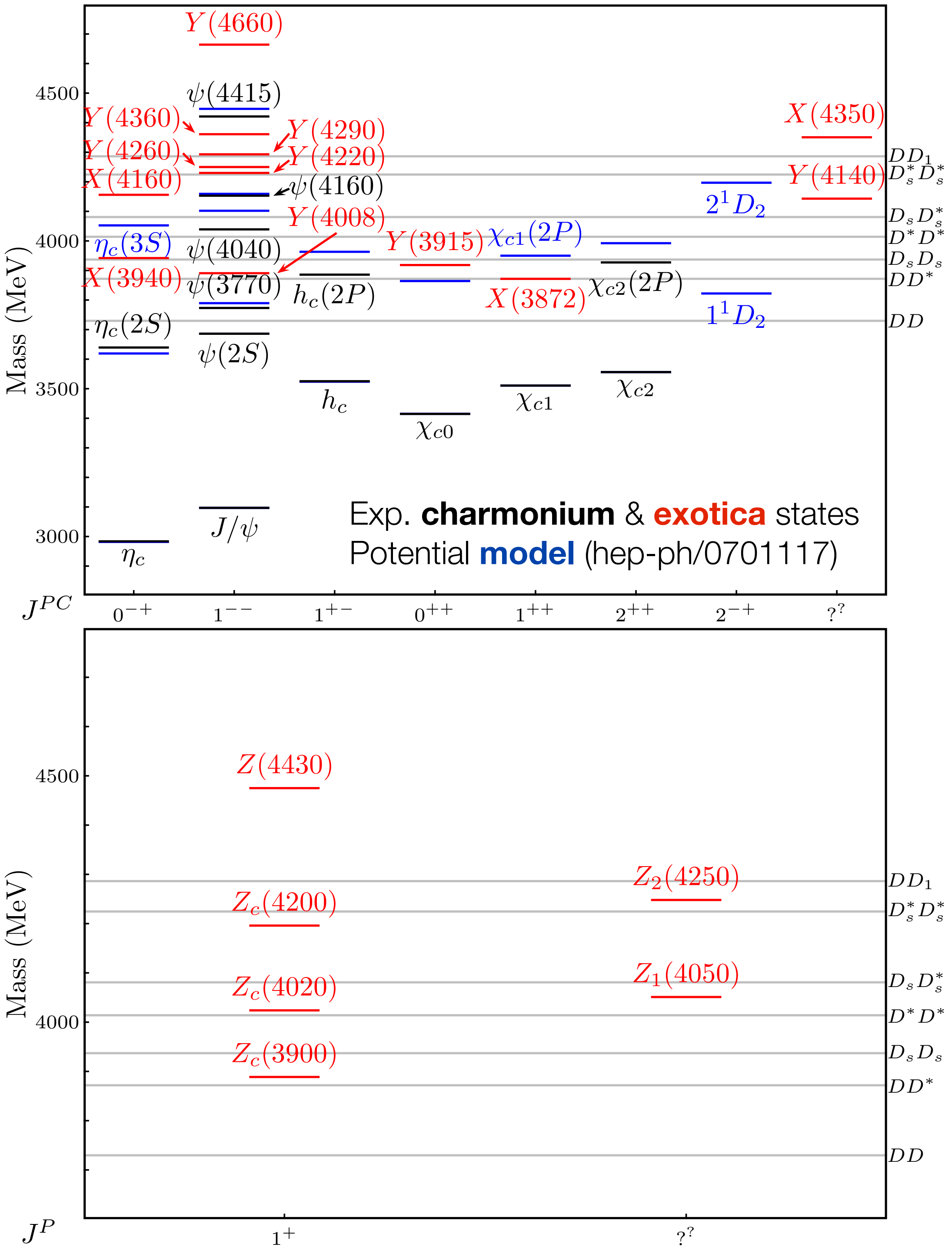
Charm physics as QCD laboratory

Charm spectroscopy

Experimentally very active field

- All $\underline{c}c$ states below open c threshold experimentally identified
- New neutral and charged particles above threshold
- Some may be charmonia, others (in particular charged) not (exotica, X, Y, Z)

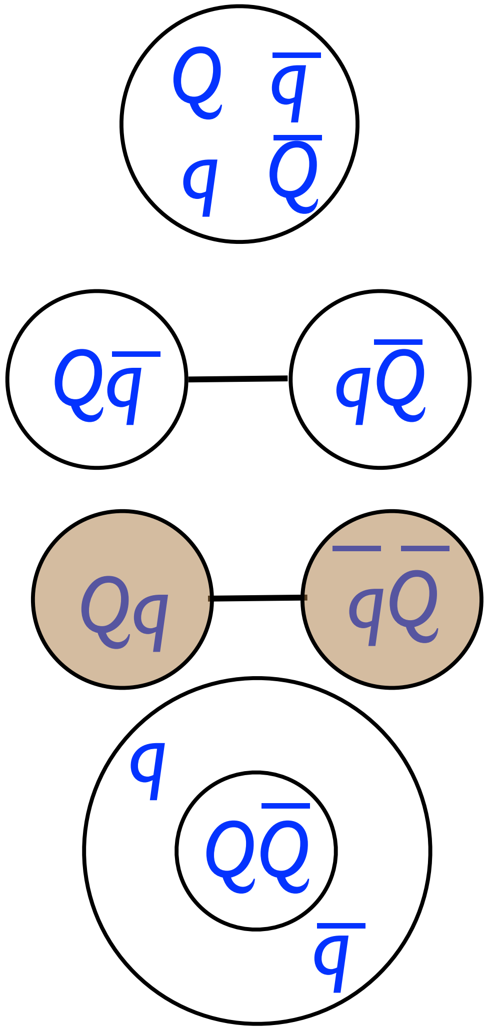
Esposito et al., 1411.5997



Models of XYZ Mesons

quarkonium tetraquarks

- compact tetraquark
- meson molecule
- diquark-onium
- hadro-quarkonium



see E. Braaten @ Charm’13

Decays in specific channels could discriminate between models

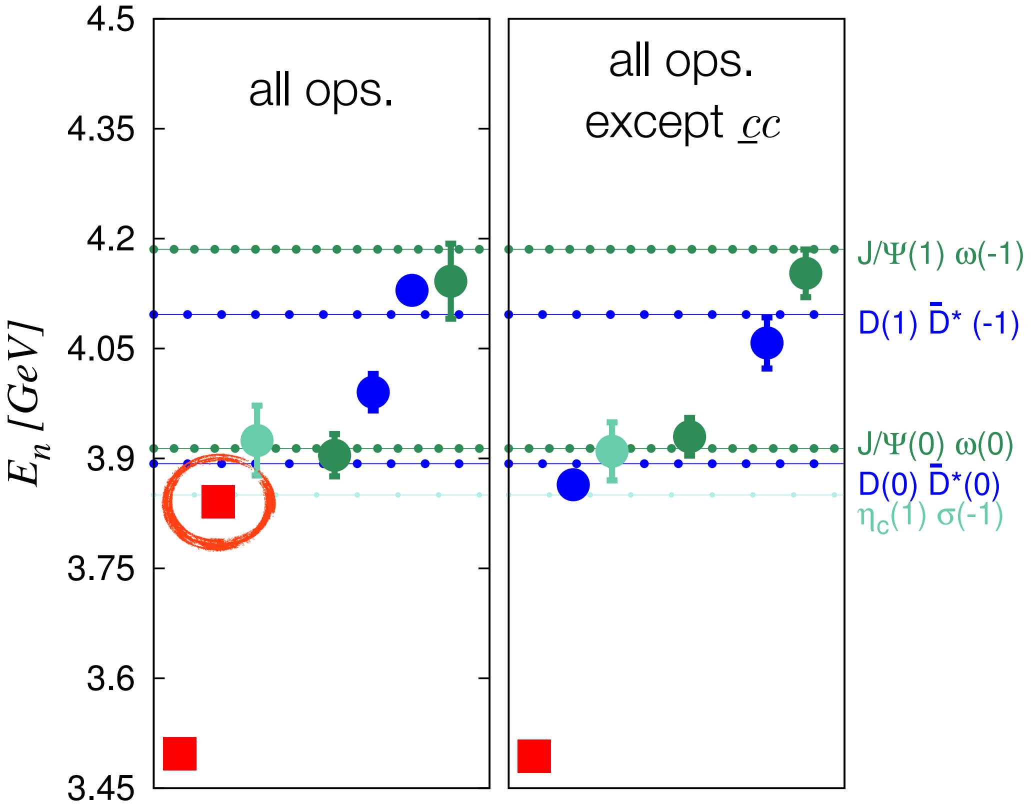
In principle all configurations can contribute in (lattice) QCD

Disentangling Fock Components on the Lattice

- Example: X(3872) with I=0
  - Testing the relevant ensemble of interpolating fields

$$\mathcal{O}: \quad \bar{c}\,c, \quad D\bar{D}^*, \; J/\psi\omega, \; \chi_{c1}\eta, \; \eta_c\sigma, \; [\overline{cu}]_{3_c}[cu]_{3_c}, \; [\overline{cu}]_{6_c}[cu]_{6_c}$$

  - Candidate state found only if $\underline{c}c$ in basis
  - $[\underline{cu}][cu]$ do not seem essential



Padmanath, Lang & Prelovsek,
1503.03257

Charmonium production

- (Semi)exclusive quarkonium production powerful tool for testing understanding of QCD in hot matter

- At high-p_T, expect factorization in v exp. :

$$\sigma \approx (\sigma_{\bar{Q}Q} \times \mathrm{pdf}) \times (\bar{Q}Q \to \mathrm{quarkonium})$$

  - Proven only at NLO

  - Predictions depend on LD matrix elements

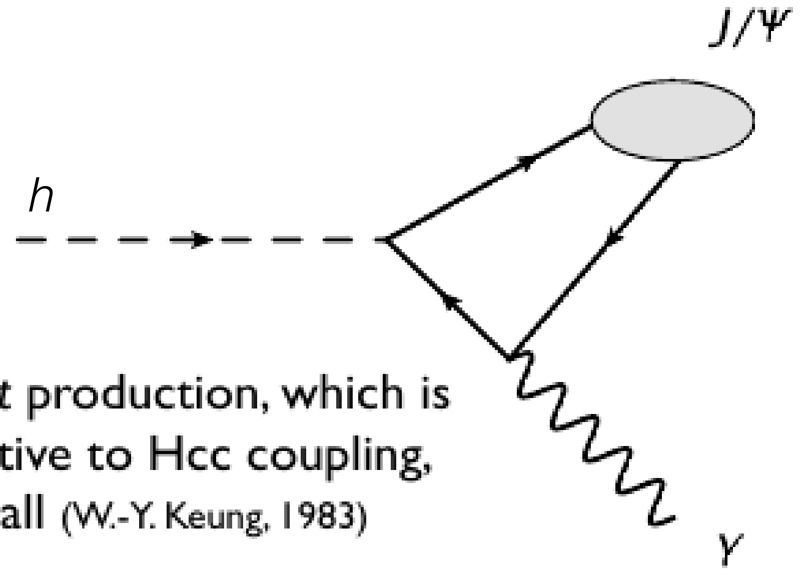
- Combine w. L ($1/{p_T}^4$) and NL (${m_Q}^2/{p_T}^6$) fragm. to get dominant effects at large p_T

- J/Ψ hadroproduction well described, problems with photoproduction and and with η_c hadroproduction

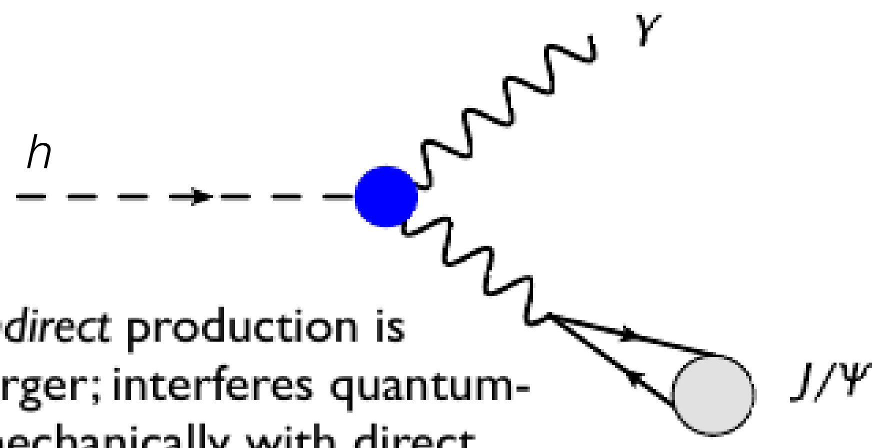
G. Bodwin @ Charm’15

see also talks by Lewis, Stone, Liu

Charmonium production in Z & Higgs decays



Direct production, which is sensitive to Hcc coupling, is small (W.-Y. Keung, 1983)



Indirect production is larger; interferes quantum-mechanically with direct production

- Interference with indirect contribution enhances sensitivity to Hcc coupling

Bodwin et al., 1306.5770

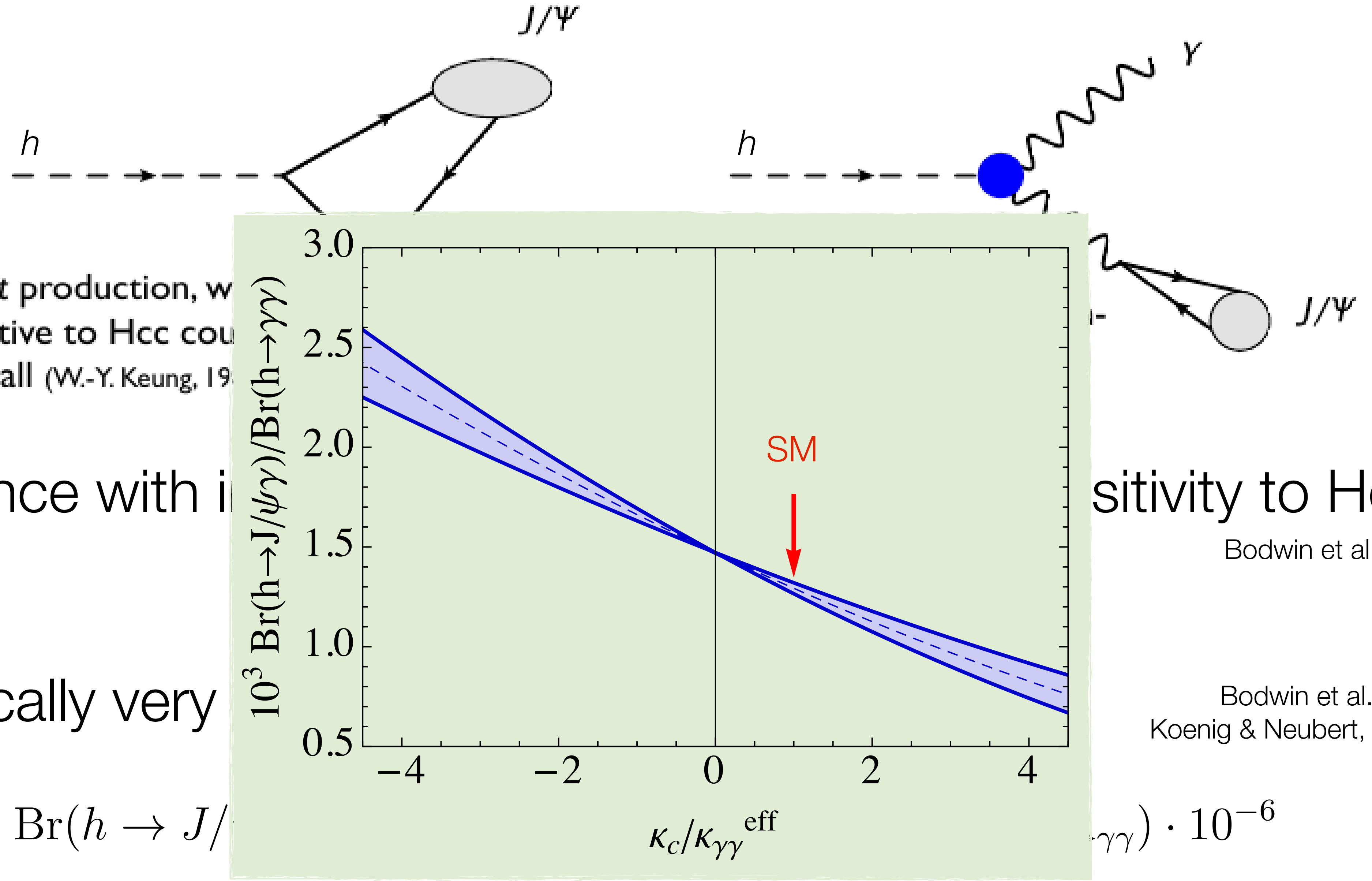
- Theoretically very clean; few-percent uncertainties

Bodwin et al., 1407.6695
Koenig & Neubert, 1505.03870

$$\mathrm{Br}(h \to J/\psi\,\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\mathrm{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}$$

- Interference gives unique information on sign (phase) of Hcc coupling

Charmonium production in Z & Higgs decays



Direct production, w
sensitive to Hcc cou
is small (W.-Y. Keung, 19

- Interference with i sitivity to Hcc coupling

Bodwin et al., 1306.5770

- Theoretically very

Bodwin et al., 1407.6695
Koenig & Neubert, 1505.03870

$\mathrm{Br}(h \to J/$ $\gamma\gamma) \cdot 10^{-6}$

- Interference gives unique information on sign (phase) of Hcc coupling

Charm quark mass

Masses are inputs to theoretical expressions for many observables

- $\Gamma(h \to c\bar{c})_{\mathrm{SM}}[m_h = 126\,\mathrm{GeV}] = 0.119(8)_{\alpha_s}(7)_{m_c}(2)_{\mathrm{th}}\,\mathrm{MeV}$

[LHC Higgs CSWG]
1307.1347

(using $m_c(m_c) = 1.28(3)\,\mathrm{GeV}$)

Projected 500GeV ILC sensitivity (@ 500fb^{-1}): $\Delta\mathcal{B}/\mathcal{B}(h \to c\bar{c}) = 4.6\%$

Could test $m_c(m_h)$ at 2% level

ILC TDR, 1306.6352

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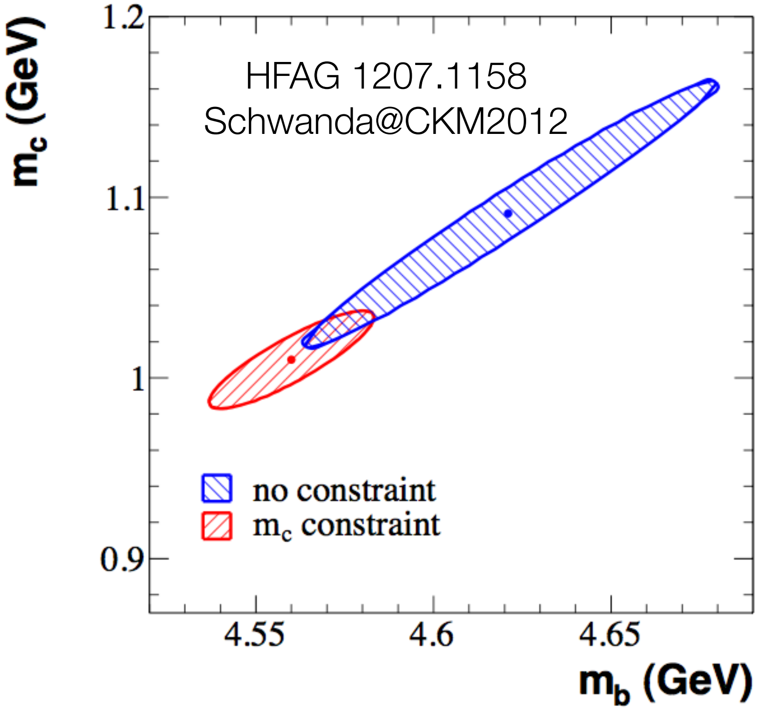
ILC TDR, 1306.6352

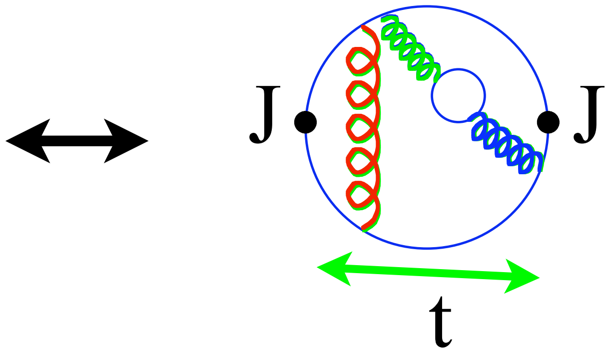
- Determination of $|V_{cb}|$ from fit to $B \to X_c \ell \nu$


HFAG 1207.1158
Schwanda@CKM2012

(using $m_c(m_c) = 1.275(13)\,{\rm GeV}$)

Kuehn, Steinhauser & Sturm
hep-ph/0702103

$$R_{e^+e^-}(s) = \frac{\sigma(e^+e^- \to {\rm hadrons})}{4\pi\alpha^2/(3s)}$$



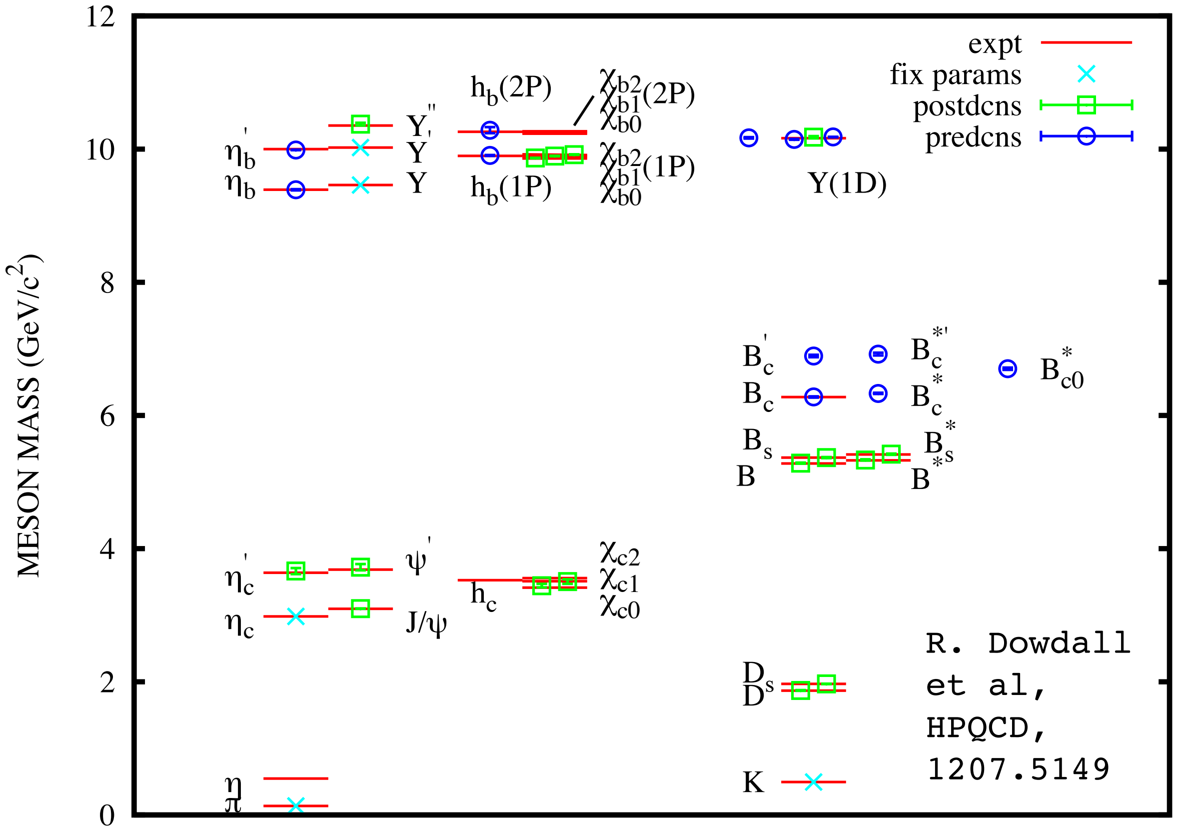
known through α_s^3 for first few moments in *s*

Charm quark mass from lattice

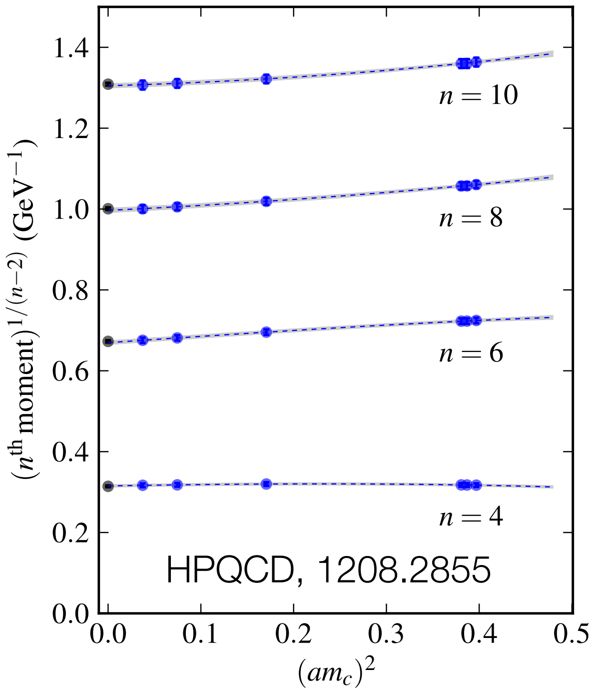
- Lattice quark masses from fit to hadronic spectra

- HQ masses indirectly from matching to continuum (axial) current-current correlators

- Possible to test (Lattice) QCD at 1% level



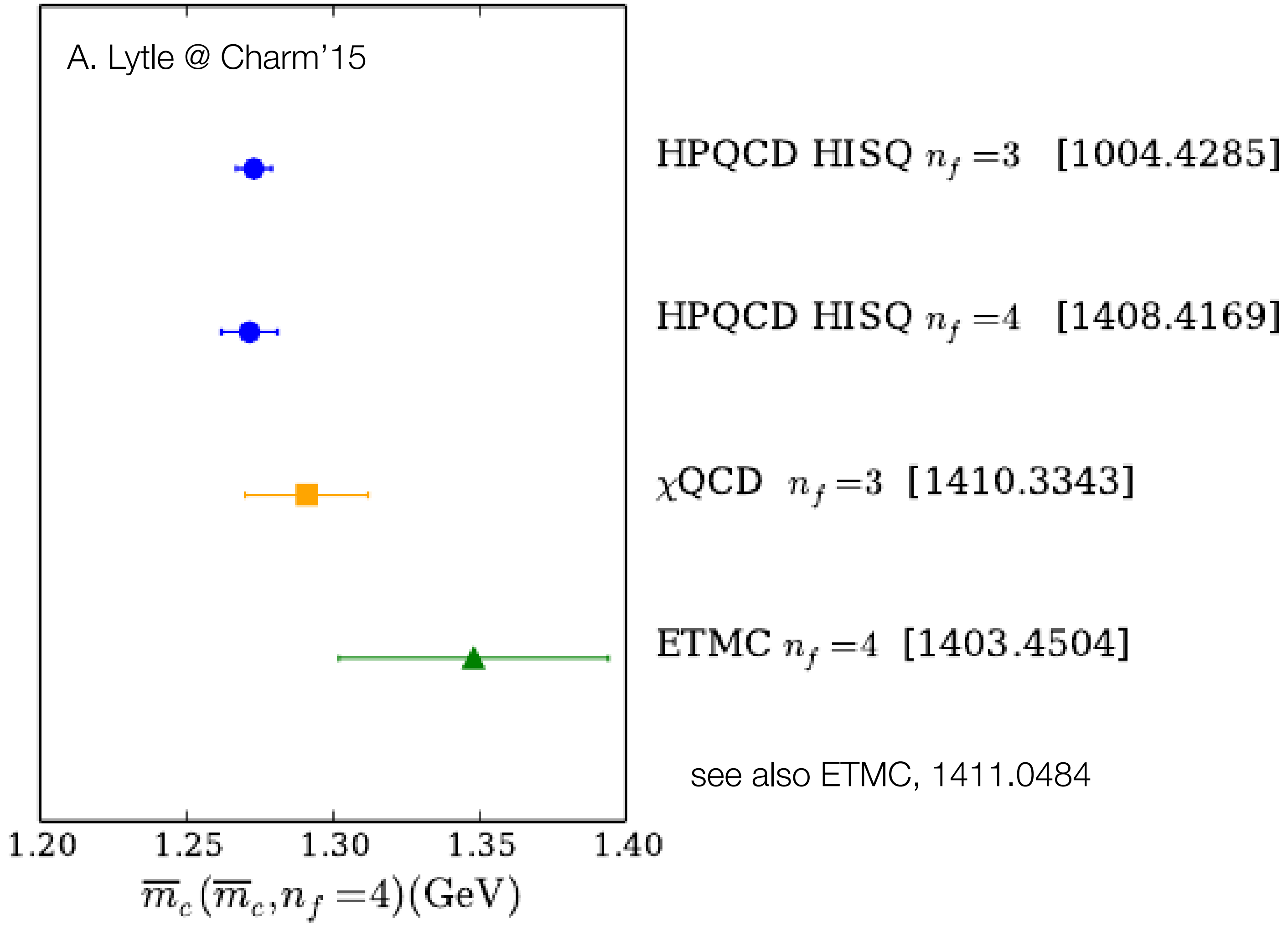
R. Dowdall et al, HPQCD, 1207.5149



HPQCD, 1208.2855

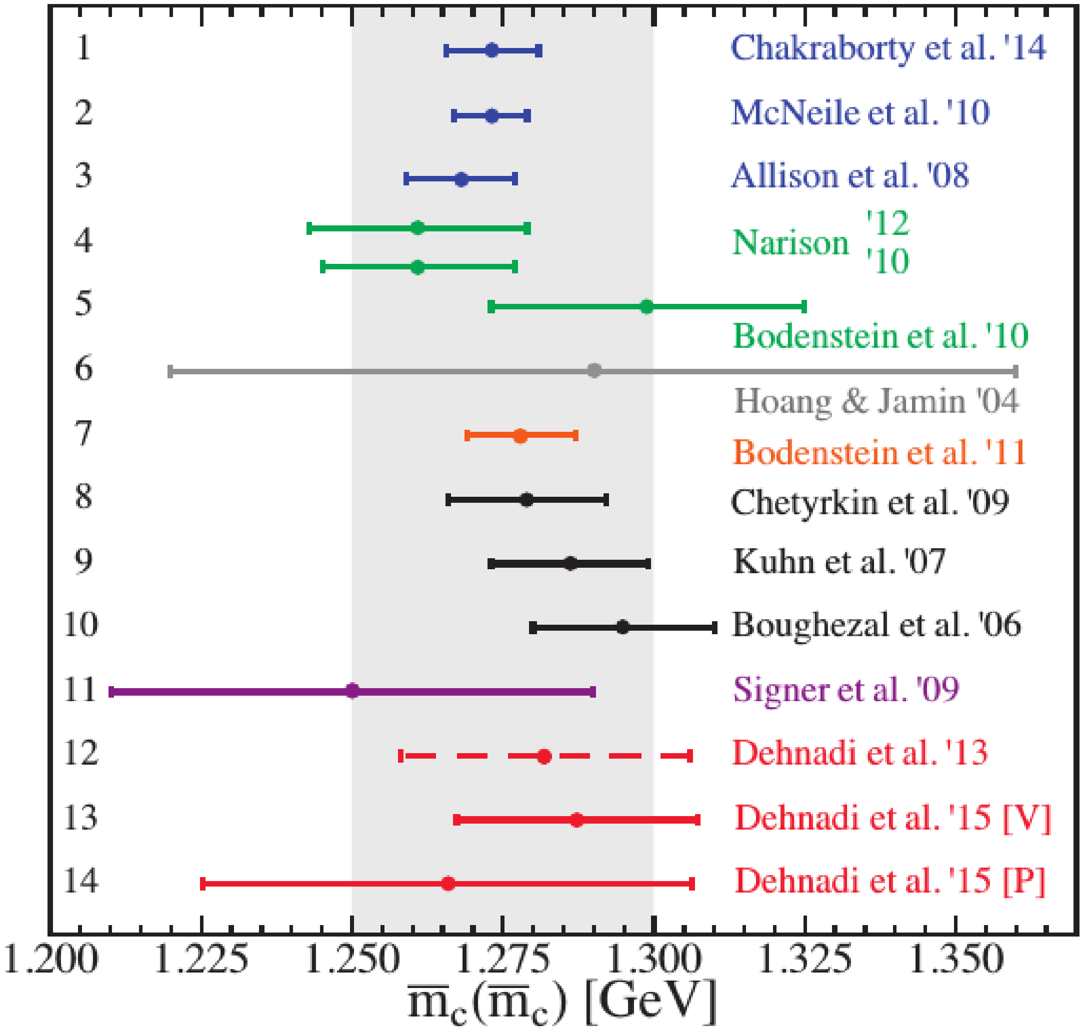
Charm quark mass

From Lattice



see also ETMC, 1411.0484

From QCD sum rules



Both m_c, m_c/m_b and m_s/m_c known to (1-2)%
⇒ (2-4)% uncertainty in $\mathrm{Br}(h \to c\underline{c},\ s\underline{s})$

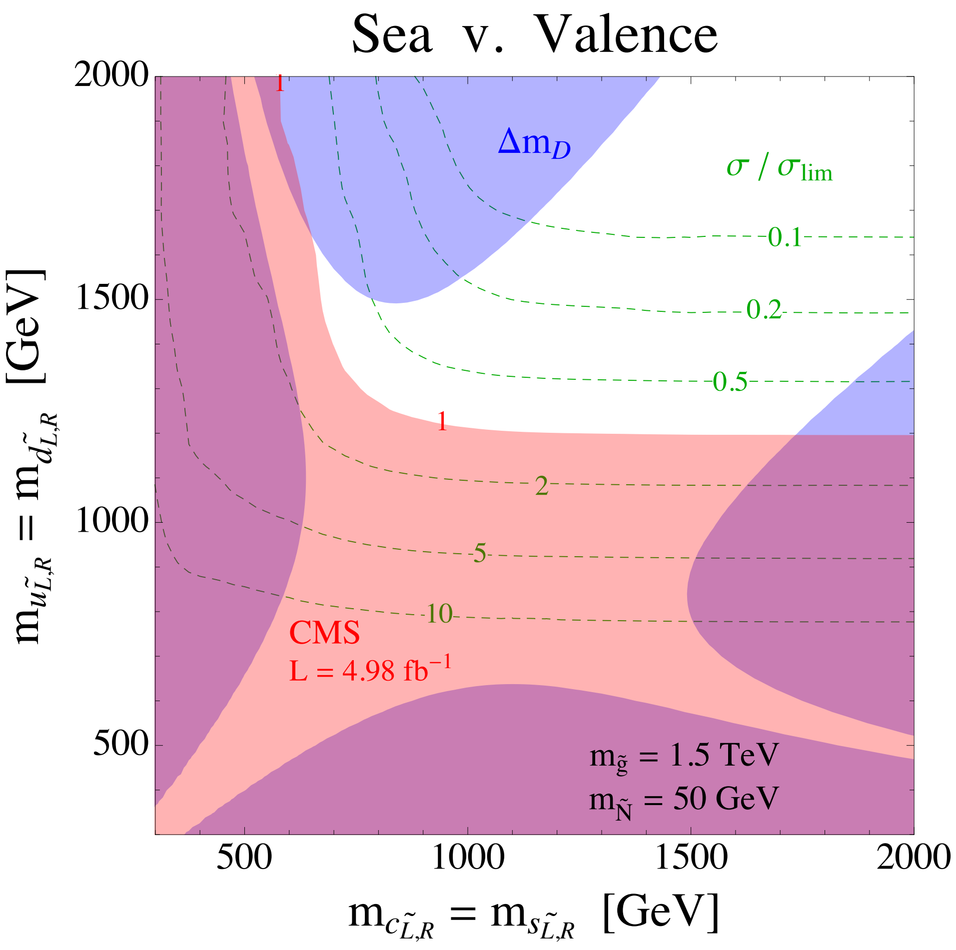
Charming windows to NP

NP in D-mixing

- Complementarity between K and D physics allows to fully exploit the constraining power of flavor physics

- Example: light SUSY vs LHC

Gedalia et al., 1202.5038
Mahbubani et al., 1212.3328



  - splitting 1st & 2nd generation squarks significantly relaxes LHC bounds
  - main constraints coming from Δm_D and ε_K

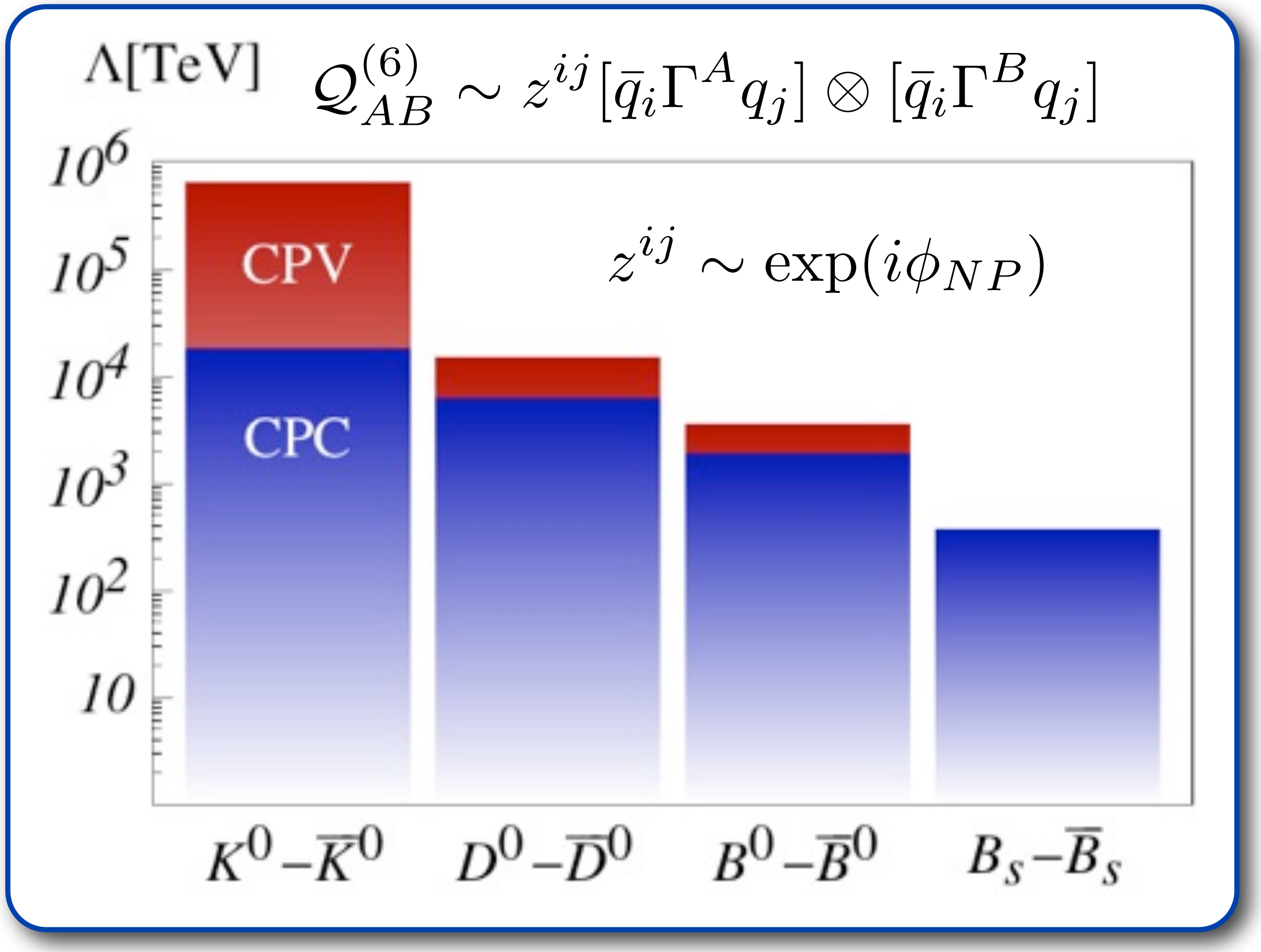
NP in D-mixing

- CP violation in $\Delta F=2$ processes is the most sensitive probe of NP, reaching scales of $O(10^5)$ TeV

$$\mathcal{L}_{\text{BSM}} \to \mathcal{L}_{\nu\text{SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

- CPV in D mixing gives best bound after ε_K

- How far can we push it?



UTFit, 0707.0636
Isidori, Nir & Perez, 1002.0900
Lenz et al., 1203.0238
ETMC, 1207.1287

D-mixing theory

D-mixing is described by:

- Dispersive D-D amplitude M_{12}
  - SM: long-distance dominated, not calculable
  - NP: short distance, calculable with lattice
- Absorptive D-D amplitude Γ_{12}
  - SM: long-distance, not calculable
  - NP: negligible
- Observables: $|M_{12}|,\ |\Gamma_{12}|,\ \phi_{12} \equiv \arg(\Gamma_{12}/M_{12})$

D-mixing in SM

D-mixing is 2nd order effect in SU(3) breaking (x,y ~ 1% in SM)

- Threshold effects - not captured by inclusive OPE approach,
  leading x, y contributions suppressed by $1/m_c^6$

$$\Delta\Gamma = \sum_{S=\mp1,0} \sum_{f_S^D} \rho(f_S^D)\langle \bar{D}^0 | H_{-S} | f_S^D \rangle \langle f_S^D | H_S | D^0 \rangle + c.c.$$

$$\Delta m = -\frac{1}{2\pi} P \int_{2m_\pi}^{\infty} dE \left[\frac{\Delta\Gamma(E)}{E - m_D} + O\left(\frac{\Lambda_{QCD}}{E} \right) \right]$$

Gronau & Rosner, PRD86, 114029 (2012)

- Several sum rules in U-spin limit
- Extract size of their violations from exp.
- These contributions (especially 4 body) add up to physical value of y_D~1%

Reliable SM prediction of CPV in mixing possible?

CPV D-mixing in SM

GIM ~ SU(3)

- Use CKM unitarity: $V_{cs}V_{ud}^* + V_{cs}V_{us}^* + V_{cb}V_{ub}^* = \lambda_b + \lambda_s + \lambda_b = 0$
- Write LD contributions to $|M_{12}|$ and $|\Gamma_{12}|$ in terms of U-spin quantum numbers

$$\lambda_s^2(\Delta U = 2) + \lambda_s\lambda_b(\Delta U = 2 + \Delta U = 1) + \mathcal{O}(\lambda_b^2)$$

$$\sim \lambda_s^2\epsilon^2 + \lambda_s\lambda_b\epsilon$$

$$r \equiv \mathrm{Im}\lambda_b/\lambda_s = 6.5 \times 10^{-4}$$

- CPV effects at the level of $r/\varepsilon \sim 2\ 10^{-3} \sim 1/8^{o}$ for “nominal” SU(3) breaking $\varepsilon \sim 30\%$

CPV D-mixing in SM

Beyond the “real SM”

- CPV contributions to $\varphi_{\Gamma 12}$ are $1/\varepsilon$ enhanced
- Not the case of $\delta\varphi_{\mathrm{f}}$
  - Can go beyond “real SM” approximation by adding one universal phase, fitting for $\varphi_{\Gamma 12}$ and φ_{M12}. see A. Kagan @ Charm’15
  - Expected sensitivity at LHCb upgrade $\delta\varphi_{\Gamma 12}$, $\delta\varphi_{M12}$ ~ 1° ⇒ $\Lambda_{\mathrm{NP}} > 10^5$ TeV

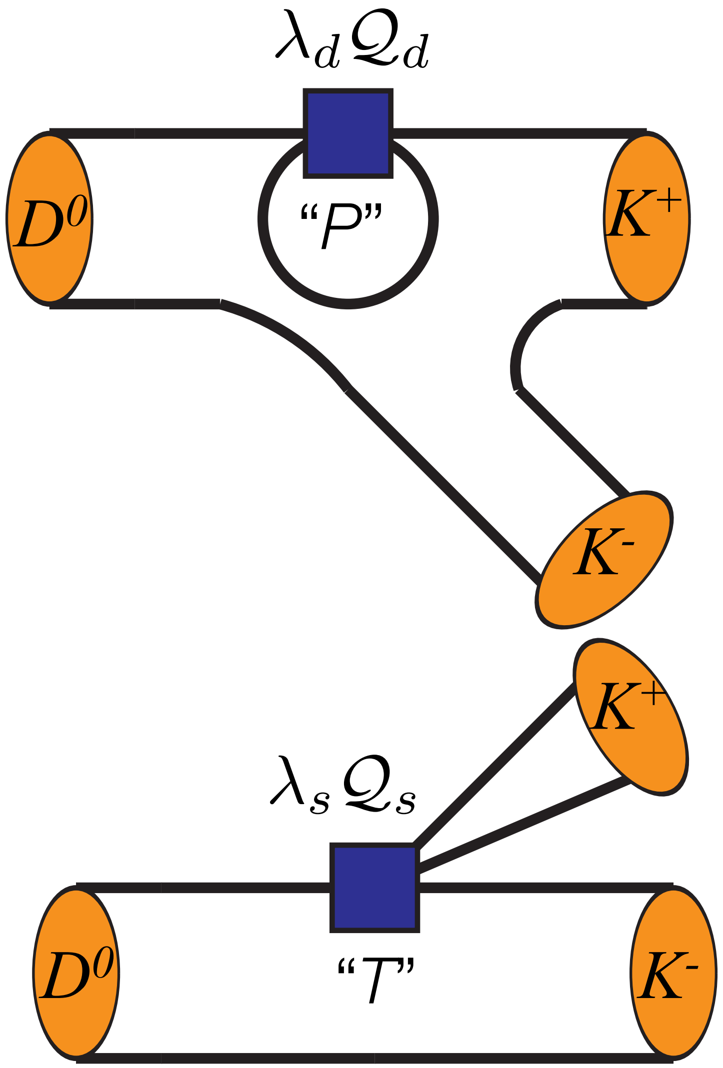
CPV in D decays

- CPV in SCS D decays suppressed by

$$\underbrace{\mathrm{Im}(V_{ub}V_{cb}/V_{us}V_{cs})}_{r} \times P/T$$

- Need an estimate of *P/T* to bound SM CPV & search for NP (unless A$_{CP}$>>10^{-3})

- Alternatively use symmetry arguments to cancel dependence on hadronic matrix elements



CPV in D decays

- SM has only $\Delta I{=}1/2$ P, any CPV in $\Delta I{=}3/2$ final state can only be due to NP (e.g. $D^+ \to \pi^+\pi^0$)

Grossman, Kagan & Zupan, 1204.3557

- Cannot isolate NP in $\Delta I{=}1/2$ with isospin - use SU(3)?
  - Beyond exact SU(3), all matrix elements generated (modulo few sum rules valid to ε^2)
  - SU(3) might help in identifying hierarchy of amplitudes, dynamical info needed to predict CPV

Brod, Kagan, Zupan, 1111.5000
Feldmann, Nandi & Soni, 1202.3795
Brod et al., 1203.6659
Franco, Mishima & Silvestrini, 1203.3131
Hiller, Jung & Schacht, 1211.3734
...

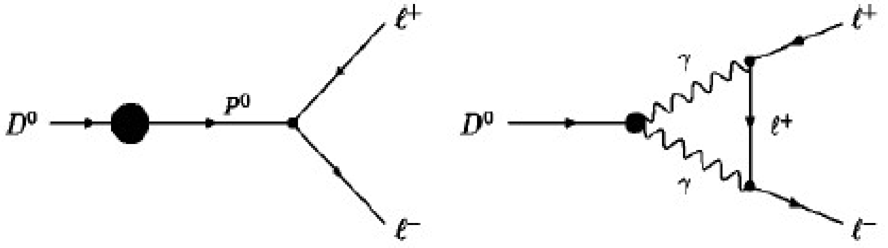
- NP due to chromomagnetic dipole ops.: $D \to P^+P^-\gamma, \rho^0\gamma, \omega\gamma$

Isidori et al., 1111.4987
Isidori & J. F. K., 1205.3164
Lyon & Zwicky, 1210.6546
Dimou, Lyon & Zwicky, 1212.2242
...

Rare charm decays

$D^0 \to \mu^+\mu^-$

- LD dominance in SM



$$\mathrm{BR}^{\mathrm{SD}}_{\mathrm{SM}}\left(\mathrm{D}^0 \to \mu^+\mu^-\right) \sim 6 \times 10^{-19}$$

Paul et al., PRD 82 (2012) 094006
Burdman et al., PRD 66 (2002) 014009
Golovich et al., PRD 79 (2009) 114030

$$\mathrm{BR}^{\mathrm{LD}}_{\mathrm{SM}}(D^0 \to \mu^+\mu^-) = 2.7 \times 10^{-5} \times \mathrm{BR}(D^0 \to \gamma\gamma) \simeq 2.7 - 8 \times 10^{-13}$$

- Can be improved with more exp. data

- Current exp. bounds starting to put interesting constraints on ΔC=1 Z-penguins

R. Aaij et al. (the LHCb collaboration), PLB 725 (2013) 15.

$$\boxed{BR(D \to \mu^+\mu^-) < 6.2(7.6) \times 10^{-9}}$$

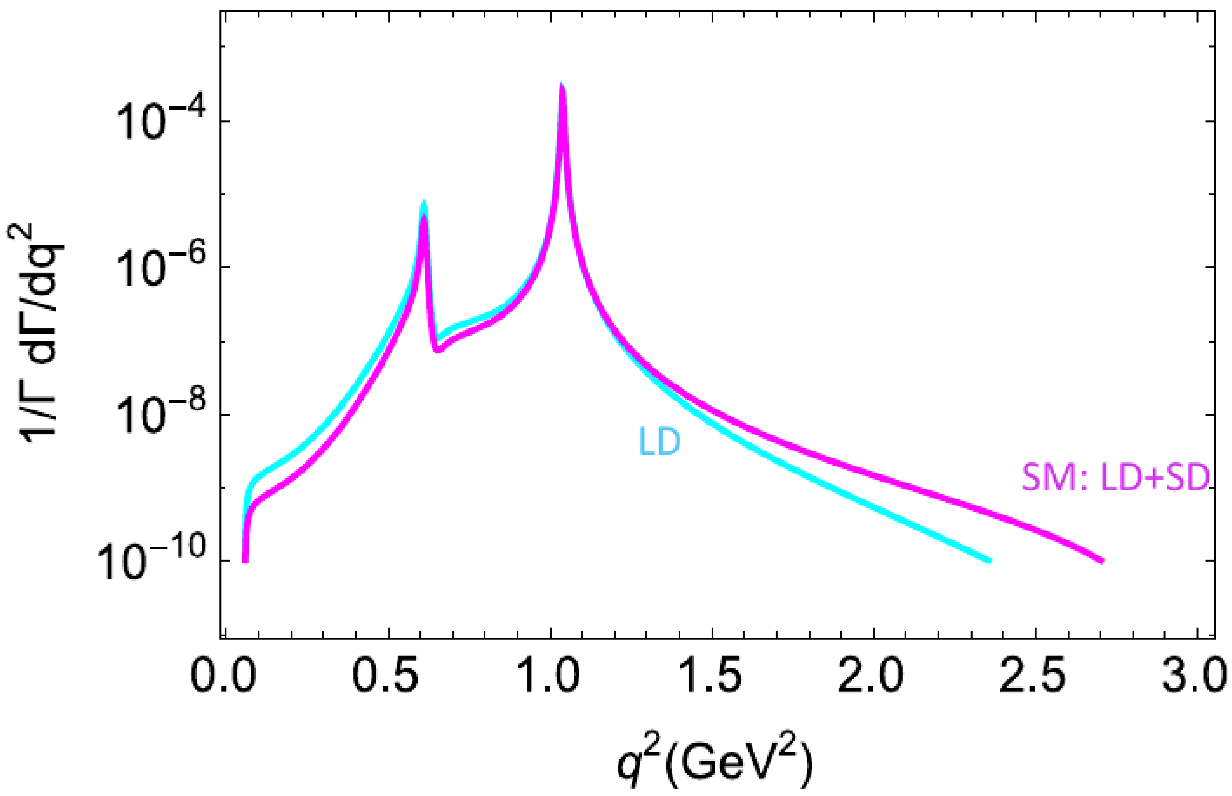
$$\boxed{\mathrm{V}_{\mathrm{ub}}\mathrm{V}^*_{\mathrm{cb}}|\mathrm{C}^{\mathrm{NP}}_{10}| < 0.364}$$

see Fajfer @ Charm'2015

Rare charm decays

$\underline{D^+ \to \pi^+\mu^+\mu^-}$

- LD dominance in SM
- Access to SD physics in resonance tails

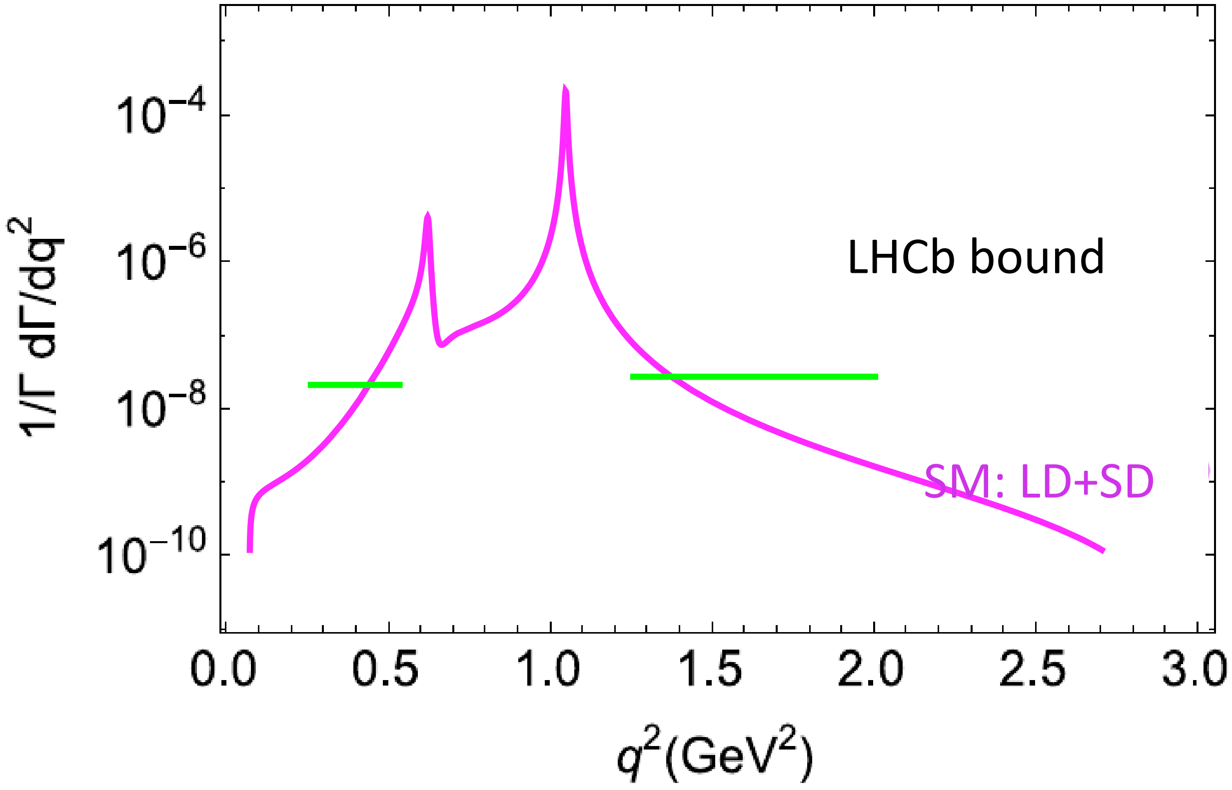


see Fajfer @ Charm'2015

Rare charm decays

$\underline{D^+ \to \pi^+ \mu^+ \mu^-}$

- LD dominance in SM
- Access to SD physics in resonance tails
- Sensitivity of current Exp. searches



$$\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)_{s \in [0.250, 0.525] GeV^2} < 2.0 \times 10^{-8}$$

$$\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)_{s \in [1.250, 2.000] GeV^2} < 2.6 \times 10^{-8}$$

$$\boxed{V_{ub} V_{cb}^* |C_9^{NP}| < 1.87}$$

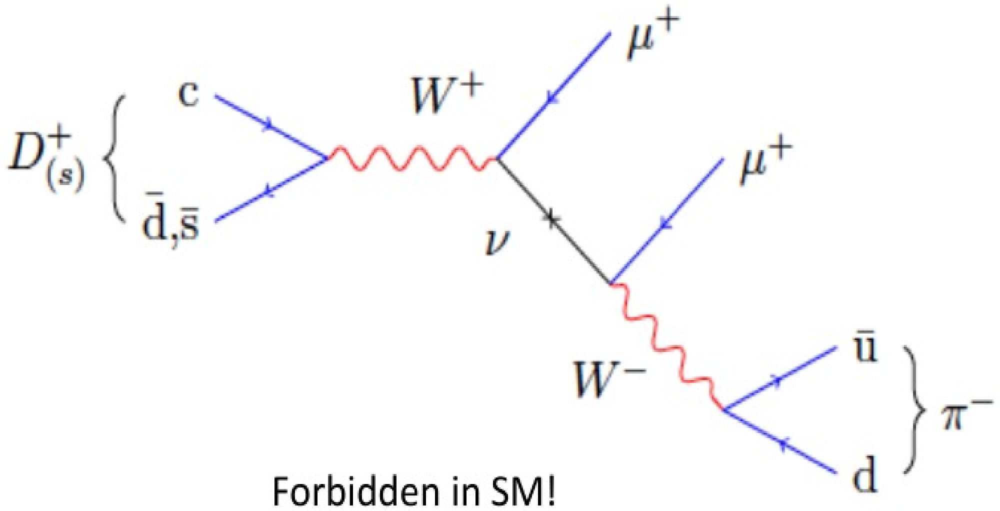
R. Aaij et al. (the LHCb collaboration),
PLB 724 (2013) 203.

see Fajfer @ Charm'2015

Illuminating Hidden Particles with Charm

Search for Majorana ν's in LNV D decays

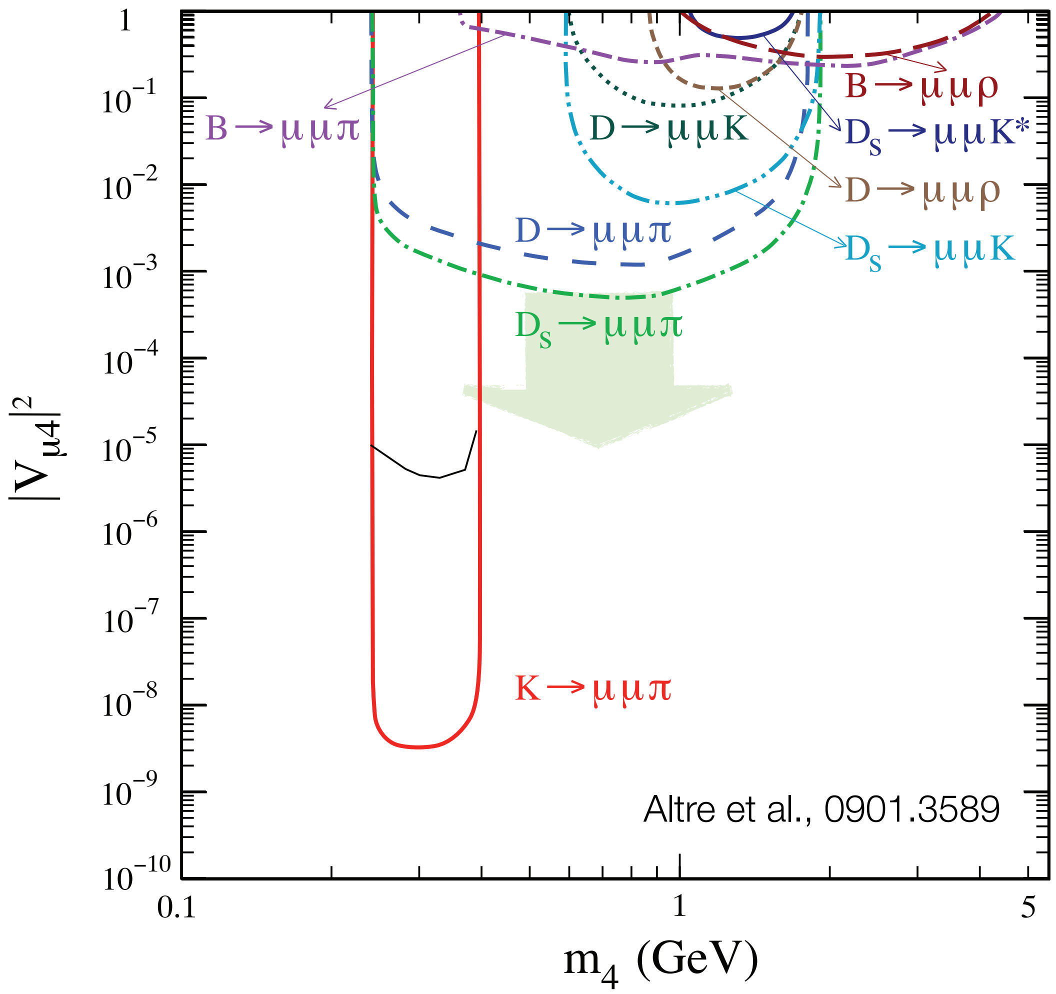
$\underline{D^+ \to \pi^- \mu^+ \mu^+}$



Forbidden in SM!

- Bounds improved by 2-3 orders of magnitude

R. Aaij et al. (the LHCb collaboration), PLB 724 (2013) 203.



Altre et al., 0901.3589

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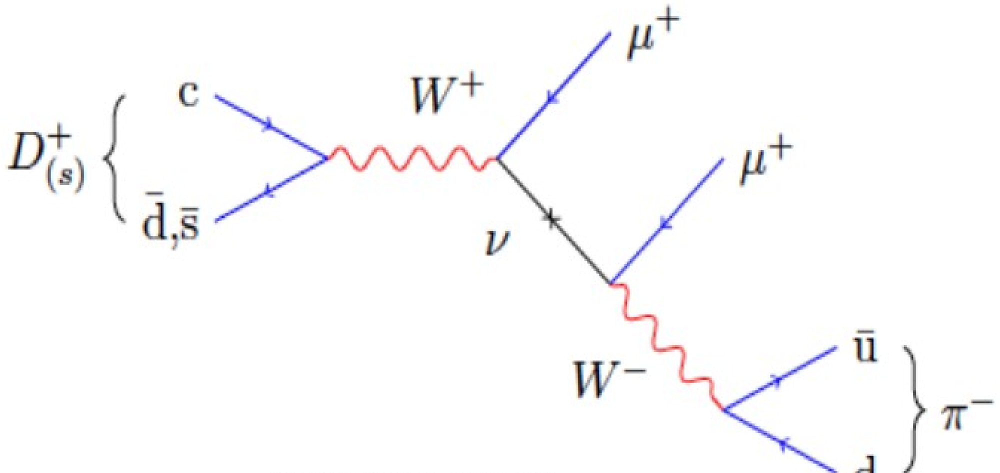

Forbidden in SM!

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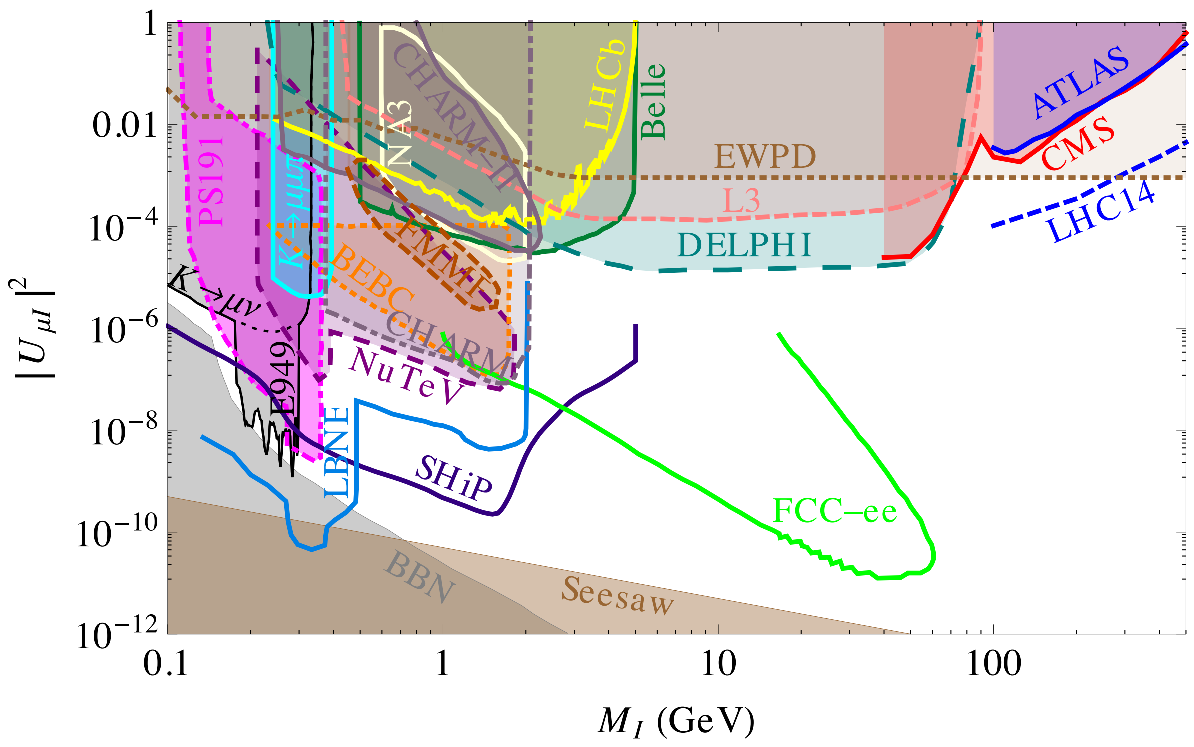
R. Aaij et al. (the LHCb collaboration), PLB 724 (2013) 203.

- Decays to long-lived ν's can be probed in beam-dump experiments

ShiP proposal
1504.04855



Conclusions

- Constantly improving experimental results are challenging our theoretical understanding of charm physics

- Interesting open problems in charm spectroscopy and production could eventually yield deeper understanding of QCD dynamics

- New wealth of data from LHCb and other heavy flavor factories might provide us with evidence for NP

- Combined theoretical approach to outstanding problems (such as nonleptonic D decays) using all possible tools should eventually allow us to fully exploit their potential NP sensitivity