Overview of Tau Physics

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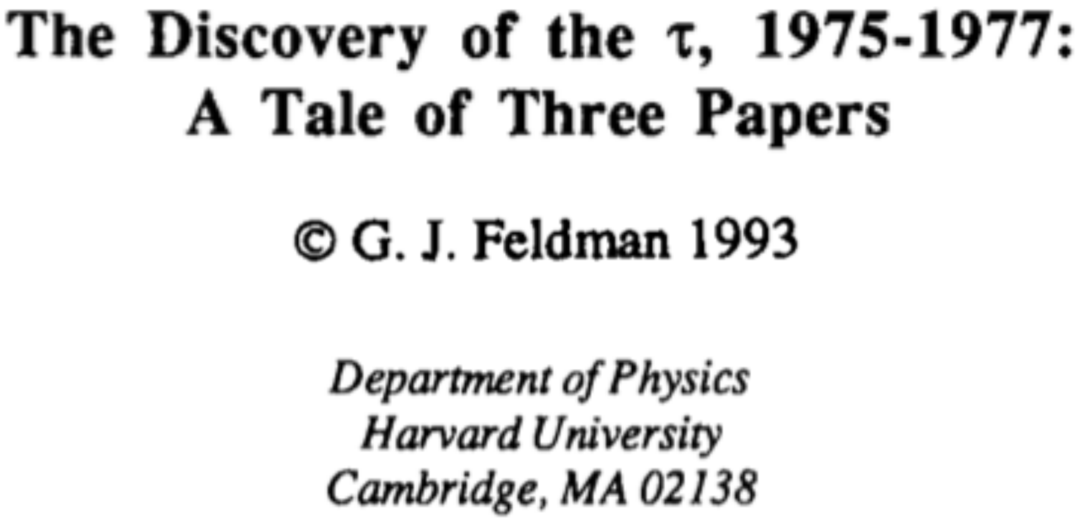
UNIVERSITY OF LOUISVILLE®

Mini-Workshop on Tau Physics

May 22-23, 2017

Mexico City, Mex.

40th anniversary of the "tau" nomenclature



The Discovery of the τ, 1975-1977:
A Tale of Three Papers

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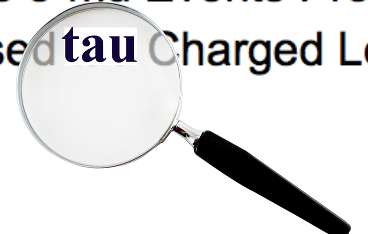
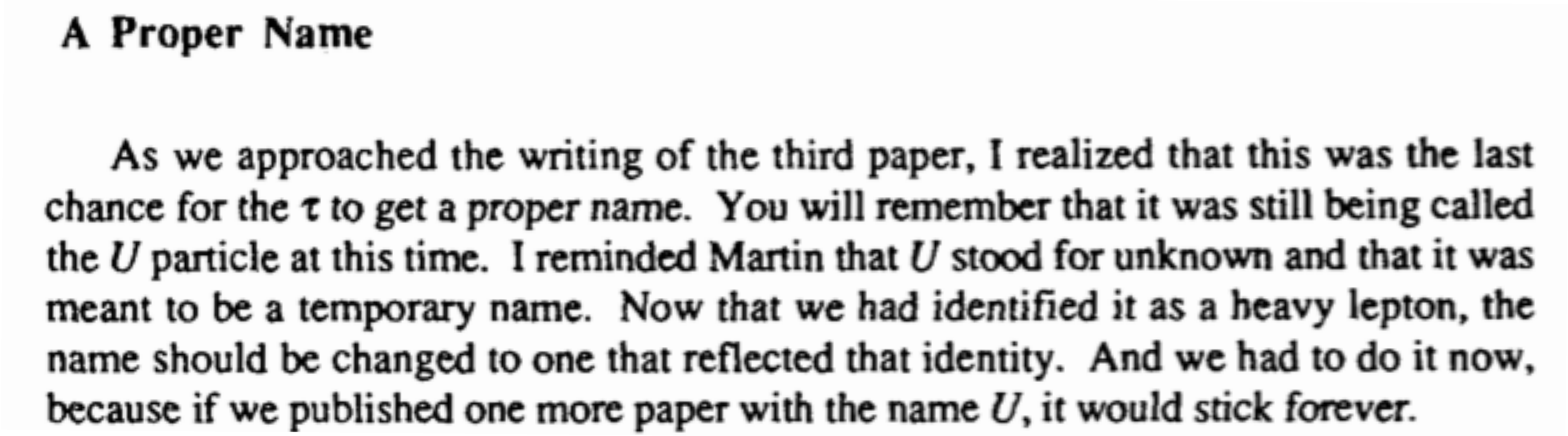
Department of Physics
Harvard University
Cambridge, MA 02138

1. Evidence for Anomalous Lepton Production in e^+ - e^- Annihilation; *Physical Review Letters*, Vol. 35, Issue 22, 1489-1492; 1975
2. "Properties of Anomalous e-mu Events Produced in e+e-Annihilation"; *Physics Letters*, Vol. 63B, Issue 4, 466; August 16, 1976
3. "Properties of the Proposed **tau** Charged Lepton"; *Physics Letters*, Vol.70B, Issue 4, 487; October 24, 1977



first mention of "tau" in a published journal



A Proper Name

As we approached the writing of the third paper, I realized that this was the last chance for the τ to get a proper name. You will remember that it was still being called the *U* particle at this time. I reminded Martin that *U* stood for unknown and that it was meant to be a temporary name. Now that we had identified it as a heavy lepton, the name should be changed to one that reflected that identity. And we had to do it now, because if we published one more paper with the name *U*, it would stick forever.

Overview of τ physics

Contents of this talk:

- Physics with τ decays
  - Mass, lifetime
  - Lepton universality
  - $|V_{us}|$ from τ decays
  - Lepton Flavor violation in τ decays

- Physics with τ produced
  - from B decays
  - from Top decays
  - from Higgs decays

Apologies for not covering α_s, g-2, SUSY, exotica, Lepton Flavor violation at the LHC, CP Violation : this list is not exhaustive!

Overview of τ physics

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Part 1

- Physics with τ produced
  - from B decays
  - from Top decays
  - from Higgs decays

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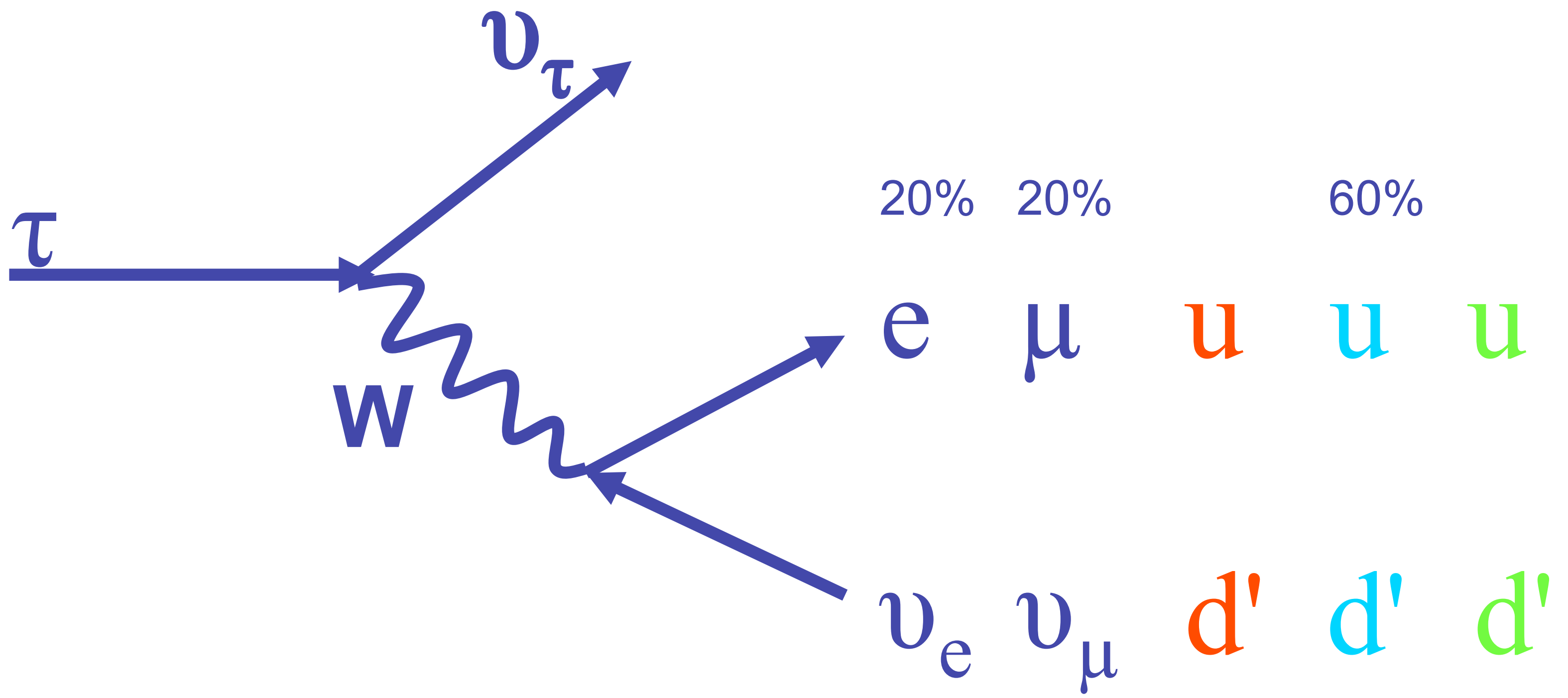
Introduction to τ decays

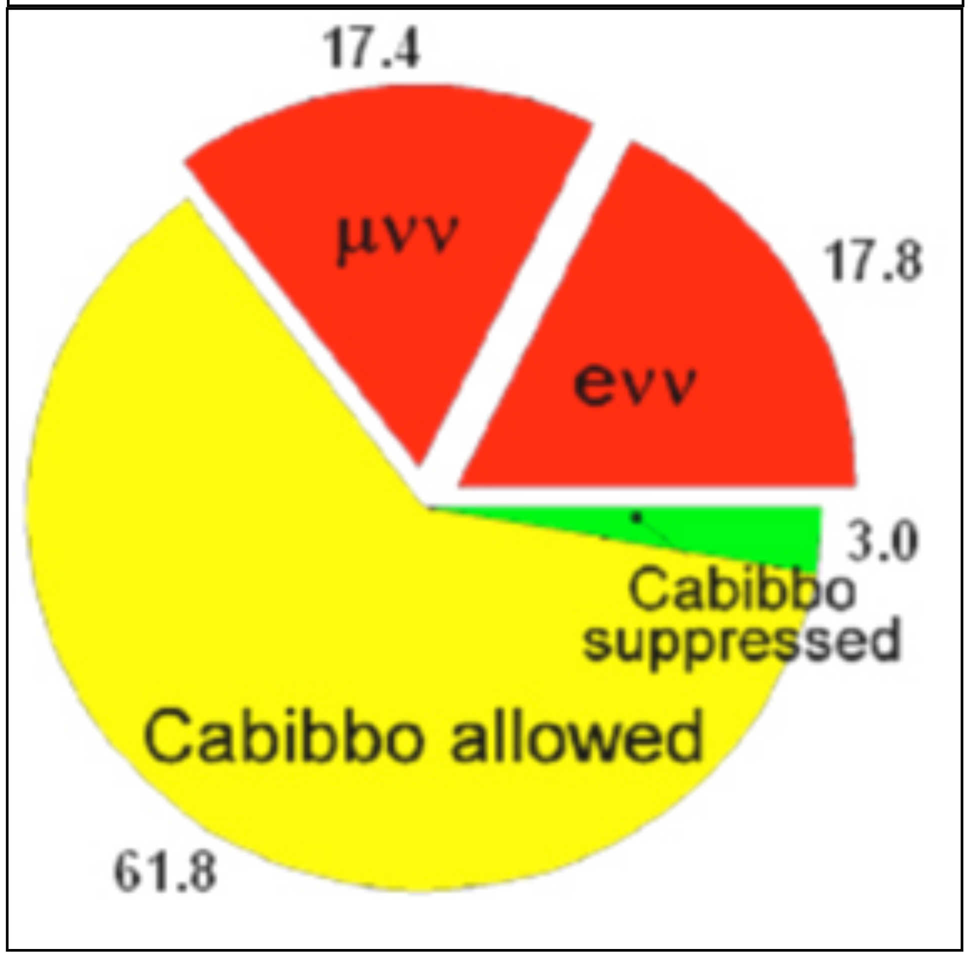
Experiment	Number of τ pairs
LEP	~3x10^5
CLEO	~1x10^7
BaBar	~5x10^8
Belle	~9x10^8
Belle II	~10^{12}

Naive prediction:

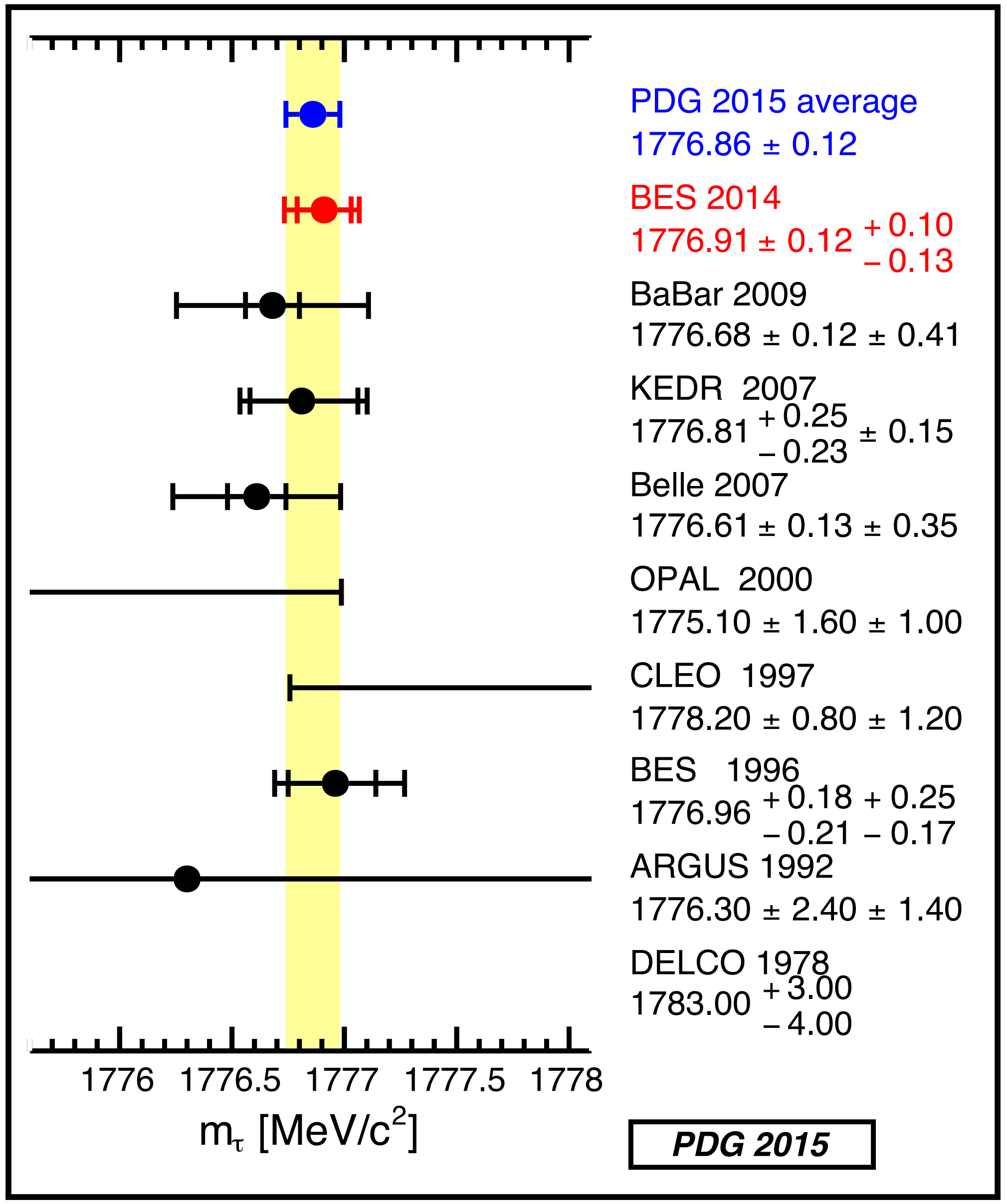


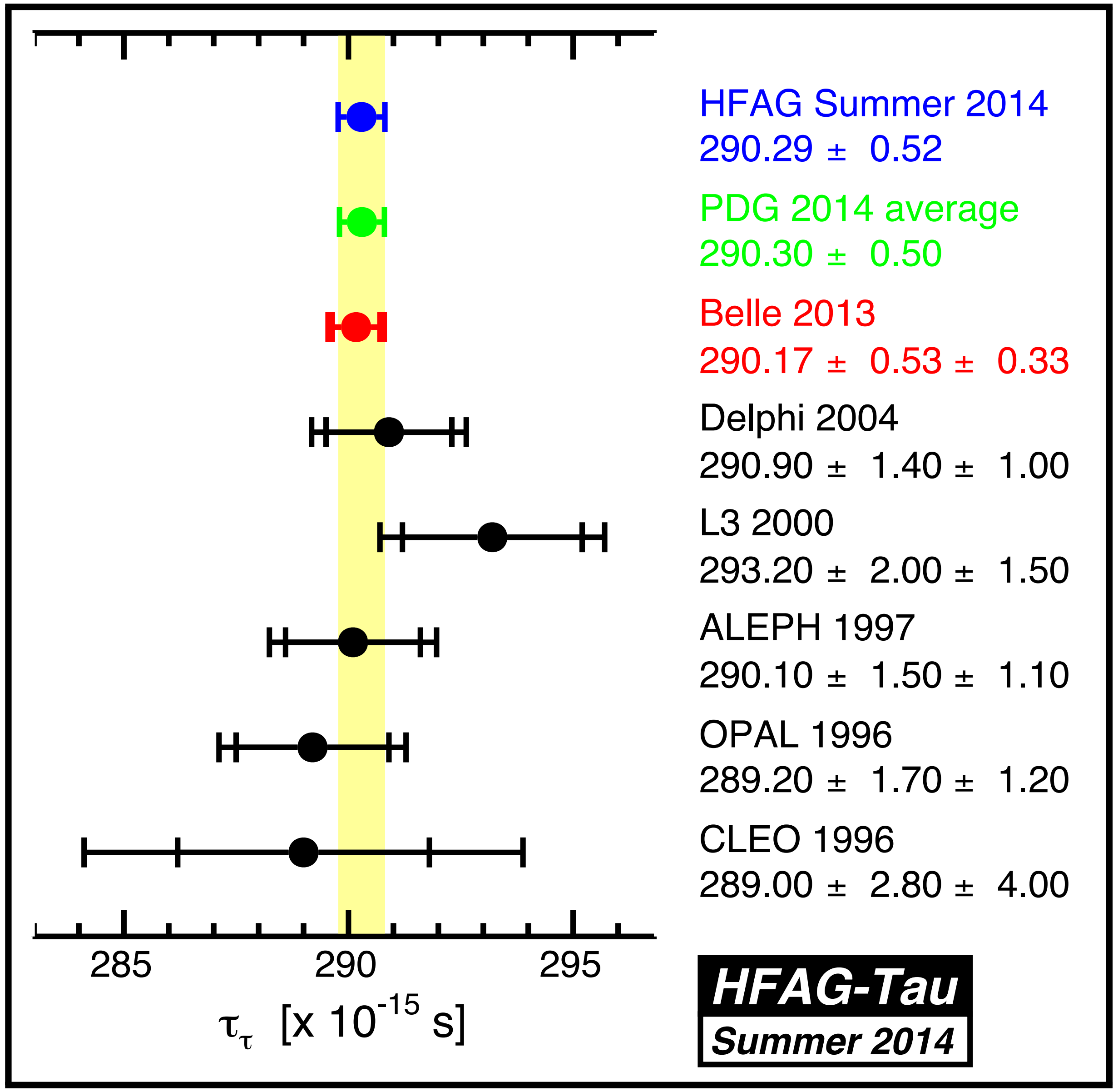
$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle$$

Including QED & QCD corrections:



τ mass and lifetime





- most precise measurements by **e^+e^- colliders at $\tau^+\tau^-$ threshold**
  - few events but very significant

- Belle
  - 3-prong vs. 3-prong decay length
  - largest syst. error: alignment

Lepton universality from leptonic τ decays

Standard Model for leptons $\lambda,\ \rho = e, \mu, \tau$ (Marciano 1988)

$$\Gamma[\lambda \to \nu_\lambda \rho \bar{\nu}_\rho(\gamma)] = \Gamma_{\lambda\rho} = \Gamma_\lambda \mathcal{B}_{\lambda\rho} = \frac{\mathcal{B}_{\lambda\rho}}{\tau_\lambda} = \frac{G_\lambda G_\rho m_\lambda^5}{192\pi^3} f\left(\frac{m_\rho^2}{m_\lambda^2}\right) r_W^\lambda r_\gamma^\lambda \ ,$$

$$G_\lambda = \frac{g_\lambda^2}{4\sqrt{2}M_W^2} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \qquad f_{\lambda\rho} = f\left(\frac{m_\rho^2}{m_\lambda^2}\right)$$

where

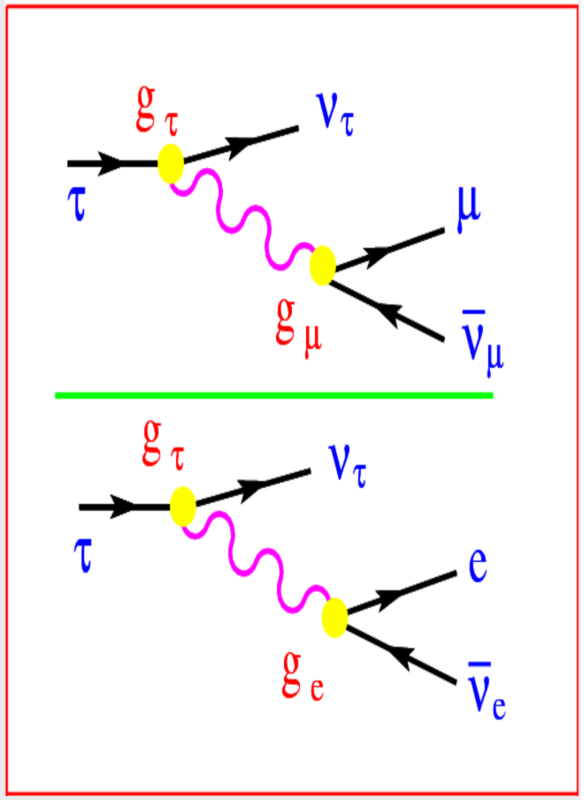
$$r_W^\lambda = 1 + \frac{3}{5}\frac{m_\lambda^2}{M_W^2} \qquad r_\gamma^\lambda = 1 + \frac{\alpha(m_\lambda)}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Tests of lepton universality from ratios of above partial widths:

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau e} r_W^\tau r_\gamma^\tau}} = \mathbf{1.0010 \pm 0.0015} = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\tau e}^{\mathrm{SM}}}}$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau\mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau\mu} r_W^\tau r_\gamma^\tau}} = \mathbf{1.0029 \pm 0.0015} = \sqrt{\frac{\mathcal{B}_{\tau\mu}}{\mathcal{B}_{\tau\mu}^{\mathrm{SM}}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau\mu}}{\mathcal{B}_{\tau e}} \frac{f_{\tau e}}{f_{\tau\mu}}} = \mathbf{1.0019 \pm 0.0014}$$

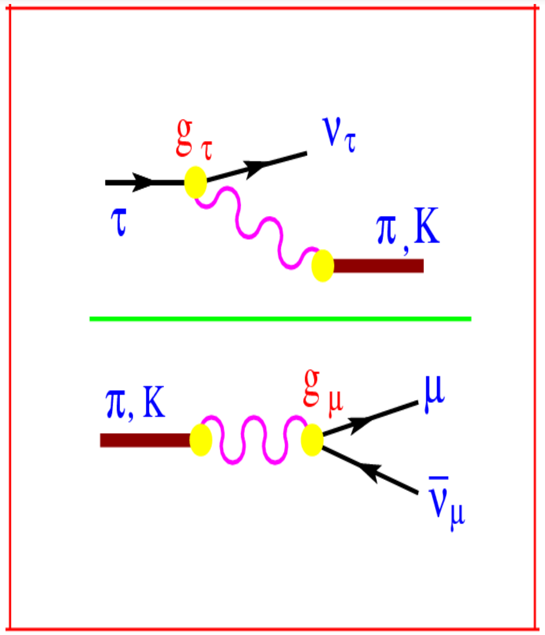


- precision: **0.20—0.23%** pre-*B*-Factories ⇒ **0.14—0.15%** today
  thanks essentially to the Belle tau lifetime measurement, PRL 112 (2014) 031801

Lepton universality tests limited by precision of $B_{e/\mu}$, not any more by τ_τ

Lepton universality from hadronic τ decays

$$\frac{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)}{\mathcal{B}(\pi^- \to \mu^- \overline{\nu}_\mu)}$$



$$\frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(K^- \to \mu^- \overline{\nu}_\mu)}$$

Standard Model:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(h \to \mu\bar{\nu}_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_h) m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2 \qquad (h = \pi \text{ or } K)$$

rad. corr. $\delta_\pi = (0.16 \pm 0.12)\%$, $\delta_K = (0.90 \pm 0.22)\%$ (Decker 1994)

$$\left(\frac{\boldsymbol{g_\tau}}{\boldsymbol{g_\mu}}\right)_\pi = \mathbf{0.9961 \pm 0.0027} \ , \qquad \left(\frac{\boldsymbol{g_\tau}}{\boldsymbol{g_\mu}}\right)_K = \mathbf{0.9860 \pm 0.0070} \ .$$

(electron tests less precise because hadron two body decays to electrons are helicity-suppressed)

Averaging the three g_τ/g_μ ratios:

$$\left(\frac{\boldsymbol{g_\tau}}{\boldsymbol{g_\mu}}\right)_{\tau+\pi+K} = \mathbf{1.0000 \pm 0.0014} \ , \qquad \text{(accounting for statistical correlations)}$$

[recent useful contribution from *BABAR* $\frac{K^-\nu_\tau}{e^-\bar{\nu}_e\nu_\tau}$ measurement, PRL 105 (2010) 051602]

Lepton universality improved B_e^{univ}

Universality improved $\mathcal{B}(\tau \to e\nu\bar{\nu})$

- (M. Davier, 2005): assume SM lepton universality to improve $\mathcal{B}_e = \mathcal{B}(\tau \to e\bar{\nu}_e\nu_\tau)$ fit $\mathcal{B}_e$ using three determinations:
  - $\mathcal{B}_e = \mathcal{B}_e$
  - $\mathcal{B}_e = \mathcal{B}_\mu \cdot f(m_e^2/m_\tau^2)/f(m_\mu^2/m_\tau^2)$
  - $\mathcal{B}_e = \mathcal{B}(\mu \to e\bar{\nu}_e\nu_\mu) \cdot (\tau_\tau/\tau_\mu) \cdot (m_\tau/m_\mu)^5 \cdot f(m_e^2/m_\tau^2)/f(m_e^2/m_\mu^2) \cdot (\delta_\gamma^\tau \delta_W^\tau)/(\delta_\gamma^\mu \delta_W^\mu)$ [above we have: $\mathcal{B}(\mu \to e\bar{\nu}_e\nu_\mu) = 1$]
- $\boldsymbol{\mathcal{B}_e^{\text{univ}} = (17.815 \pm 0.023)\%}$ HFAG-PDG 2016 prelim. fit

⇒ improvement by almost a factor of 2 from the value of $B_e = (17.816 \pm 0.041)\%$

The $|V_{us}|$ element of CKM Matrix

V_{ij}: Mixing between Weak and Mass Eigenstates

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1}$$

- $|V_{ud}| = 0.97417 \pm 0.00021$ (from nuclear β decays)

J.C.Hardy & I.S.Towner, PRC 91 (2015) 025501

- $|V_{ub}| = (4.09 \pm 0.39) \times 10^{-3}$ (from $B \rightarrow X_u \ell \nu$ decays)

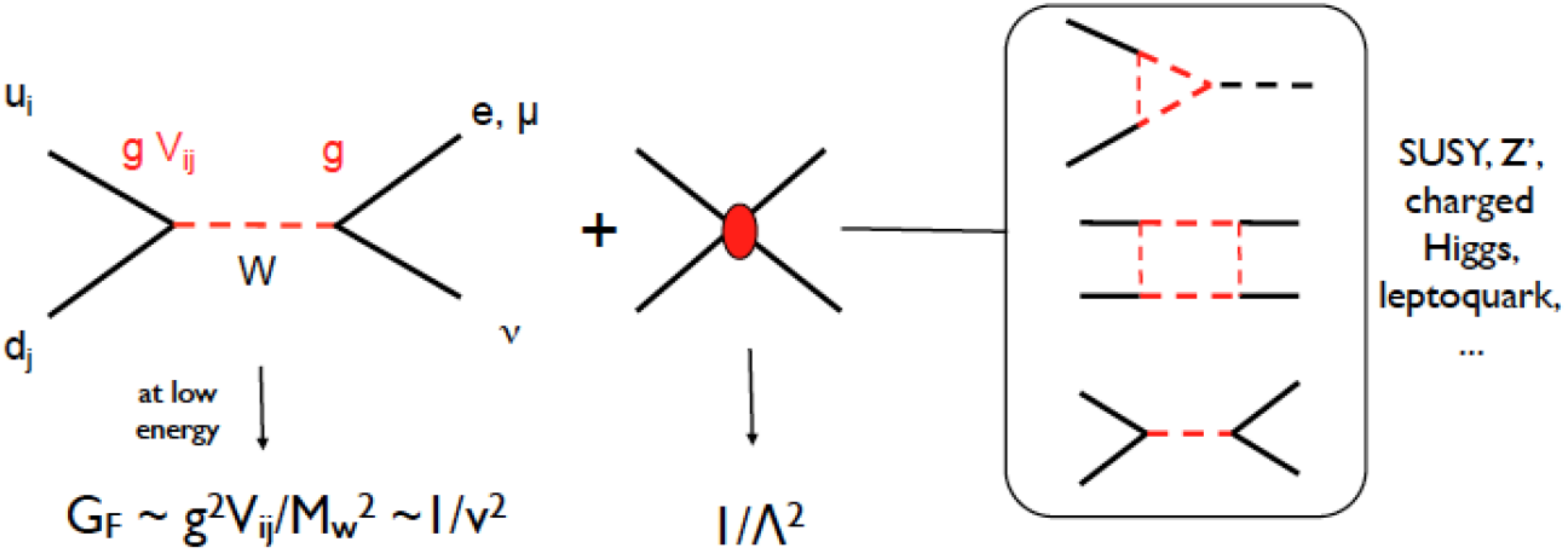
Particle Data Group 2016

$\Rightarrow |V_{us}|^{CKM} = 0.22582 \pm 0.00091$

Precision measurement of $|V_{us}|$ is a test of CKM unitarity

CKM Unitarity

V-A interaction via W-exchange with quarks have V_{ij}



Standard Model

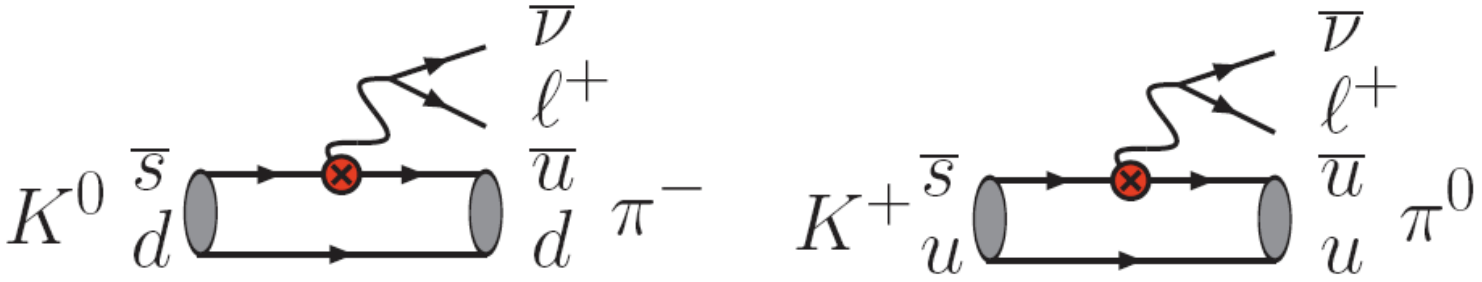
New Physics

$\Delta_{CKM} \sim (v/\Lambda)^2$ sensitive to new physics in large class of models

CKM Unitarity violation: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}$

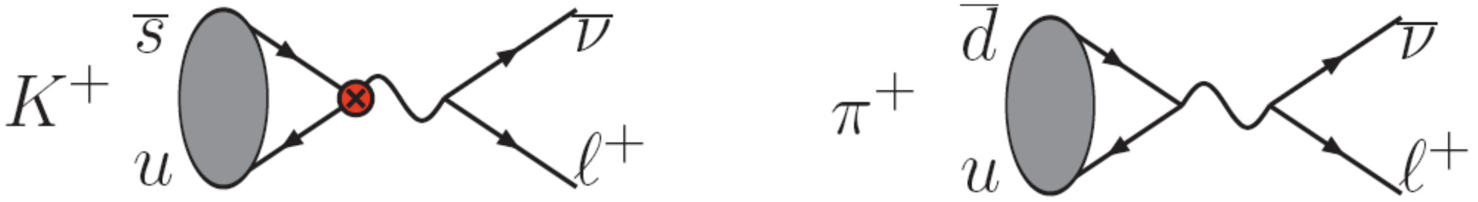
Approaches to $|V_{us}|$

Kl3 decays:



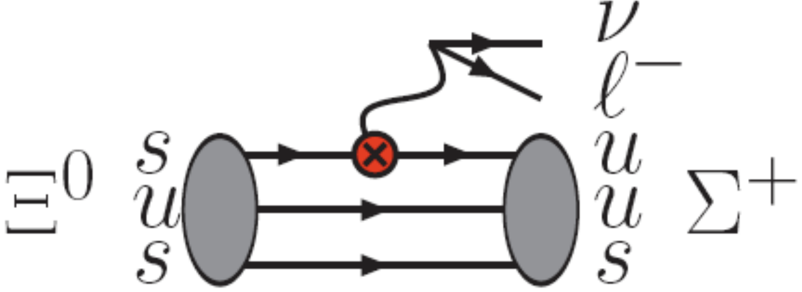
$\Rightarrow |V_{us}| f_+(0)$

Kl2 decays:



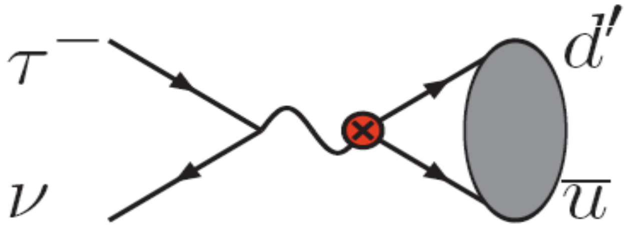
$\Rightarrow \frac{|V_{us}|}{|V_{ud}|} \frac{F_K}{F_\pi}$

Hyperon decays:



$\Rightarrow |V_{us}| f_1(0)$

τ decays:



$d' = V_{ud} d + V_{us} s$

$\Rightarrow m_s, \; |V_{us}|$

Hadronic width of the τ lepton

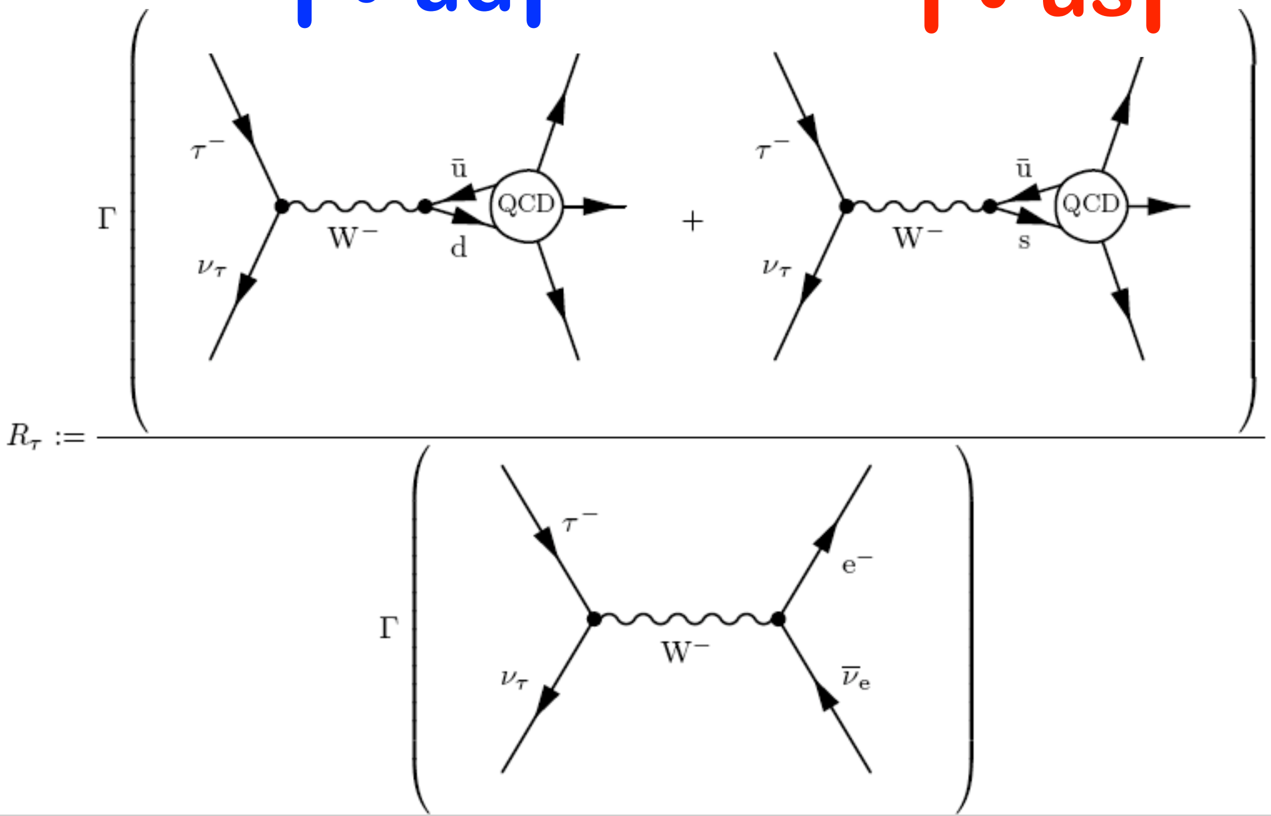
Parton model:

$$\boxed{R_\tau \equiv \frac{\Gamma\left(\tau^- \to \nu_\tau + \text{hadrons}\right)}{\Gamma\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e\right)} \approx N_C}$$

QCD:

$$\boxed{R_\tau = R_\tau^{NS} + R_\tau^{S} \approx \left|V_{ud}\right|^2 N_C + \left|V_{us}\right|^2 N_C}$$

$\propto |V_{ud}|^2$ $\propto |V_{us}|^2$



Hadronic width of the τ lepton

QCD corrections : $R_\tau = |V_{ud}|^2 N_C + |V_{us}|^2 N_C + O(\alpha_s)$

Spectral Moments: $R_\tau^{kl} = \int_0^1 dz (1-z)^k z^l \frac{dR_\tau}{dz}, \quad z = \frac{q^2}{m_\tau^2}$

Zeroth order moments are simply the τ branching fractions

Finite energy sum rules ⇒ SU(3) breaking sensitive to m_s :

$$\boxed{\delta R_\tau^{kl} = \frac{R^{kl}_{\tau,non-strange}}{|V_{ud}|^2} - \frac{R^{kl}_{\tau,strange}}{|V_{us}|^2}}$$

$$\begin{aligned}\delta R^{00}_{\tau,\mathrm{th}} &= 0.1544\,(37) + 9.3\,(3.4)\,m_s^2 \\ &+ 0.0034\,(28) = 0.242\,(32)\end{aligned}$$

$m_s = 95.00 \pm 5.00$ MeV [PDG2015]

E.Gamiz, M.Jamin, A.Pich, J.Prades & F. Schwab, arXiv 0709.0282 [hep-ph]

Truncation errors studied with QCD lattice inputs in terms of weights:

$$|V_{us}| = \sqrt{R^w_{V+A;us}(s_0) / \left[\frac{R^w_{V+A;ud}(s_0)}{|V_{ud}|^2} - \delta R^{w,OPE}_{V+A}(s_0)\right]}$$

K.Maltman, R.J.Hudspith, R.Lewis, C.E.Wolfe, J.Zanotti, arXiv 1511.08514 [hep-ph]

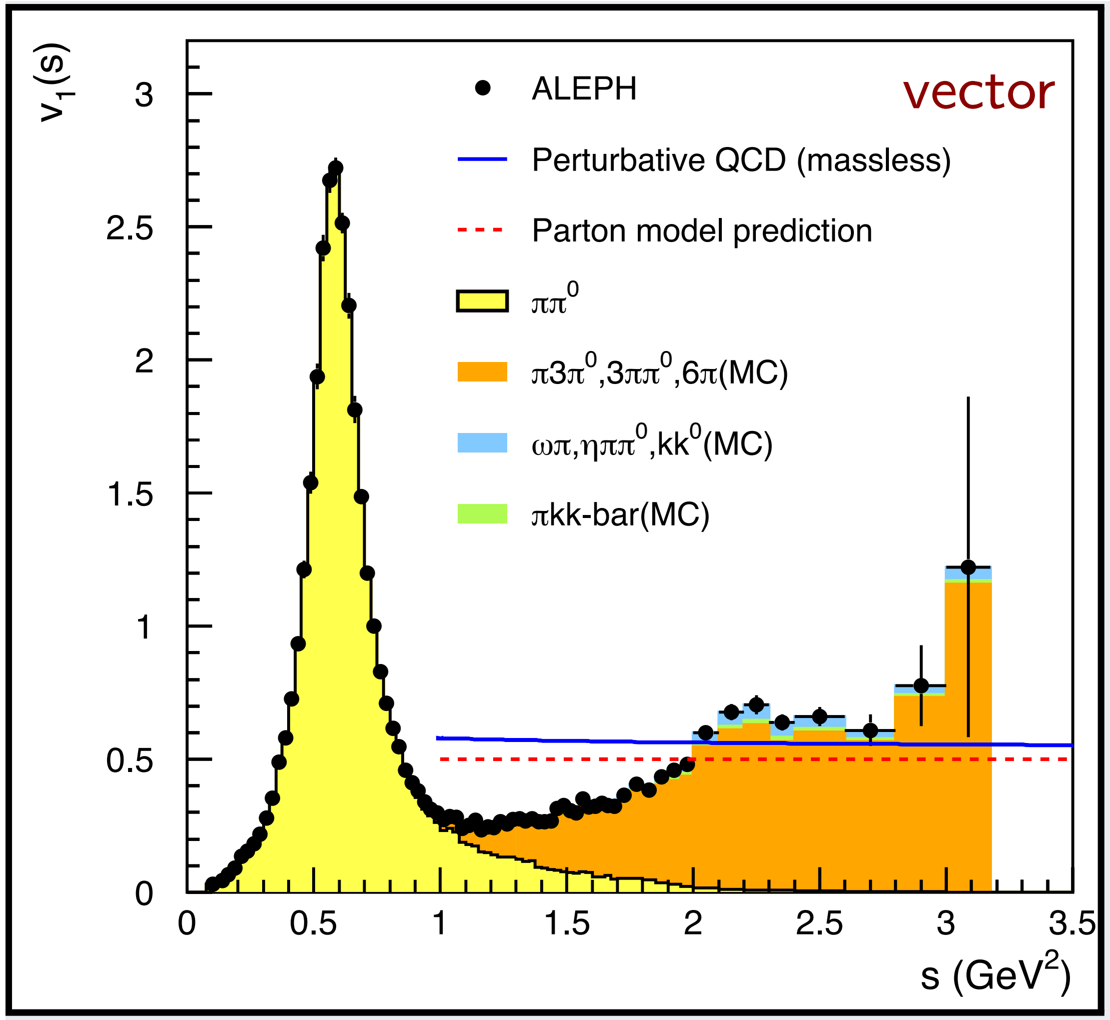
Non-strange spectral functions

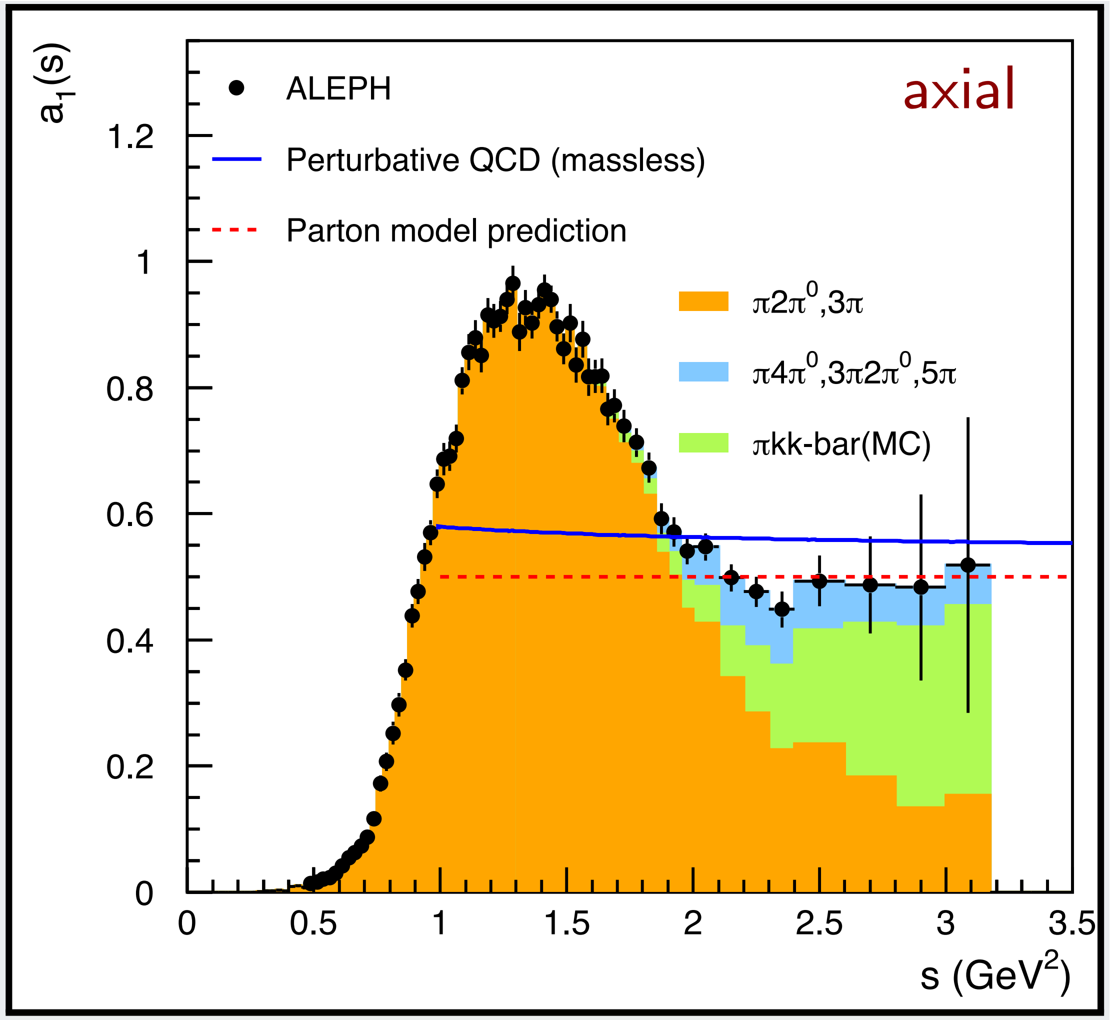
$R_{\tau,V} \Rightarrow \tau^- \to \nu_\tau + h_{v,s=0}$

(even number of pions)

$R_{\tau,A} \Rightarrow \tau^- \to \nu_\tau + h_{A,s=0}$

(odd number of pions)





Originally published in 2005, Revised calculations in 2014

M.Davier, A.Hoeker, B.Malaescu, C.Z.Yuan & Z.Zhang, EPCJ 74 (2014) 2803

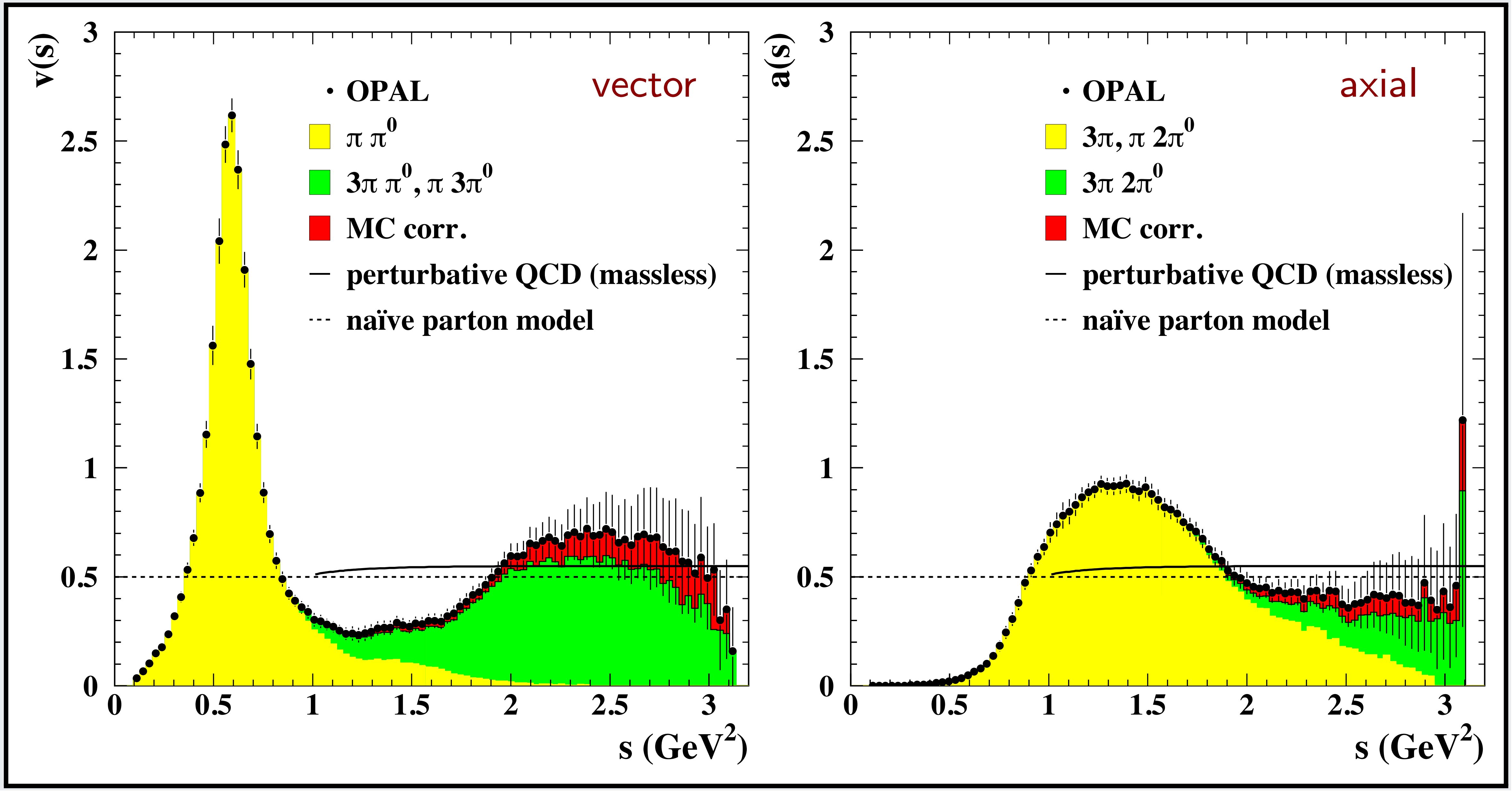
Non-strange spectral functions

$R_{\tau,V}$ ⇨ $\tau^- \to \nu_\tau + h_{v,s=0}$

(even number of pions)

$R_{\tau,A}$ ⇨ $\tau^- \to \nu_\tau + h_{A,s=0}$

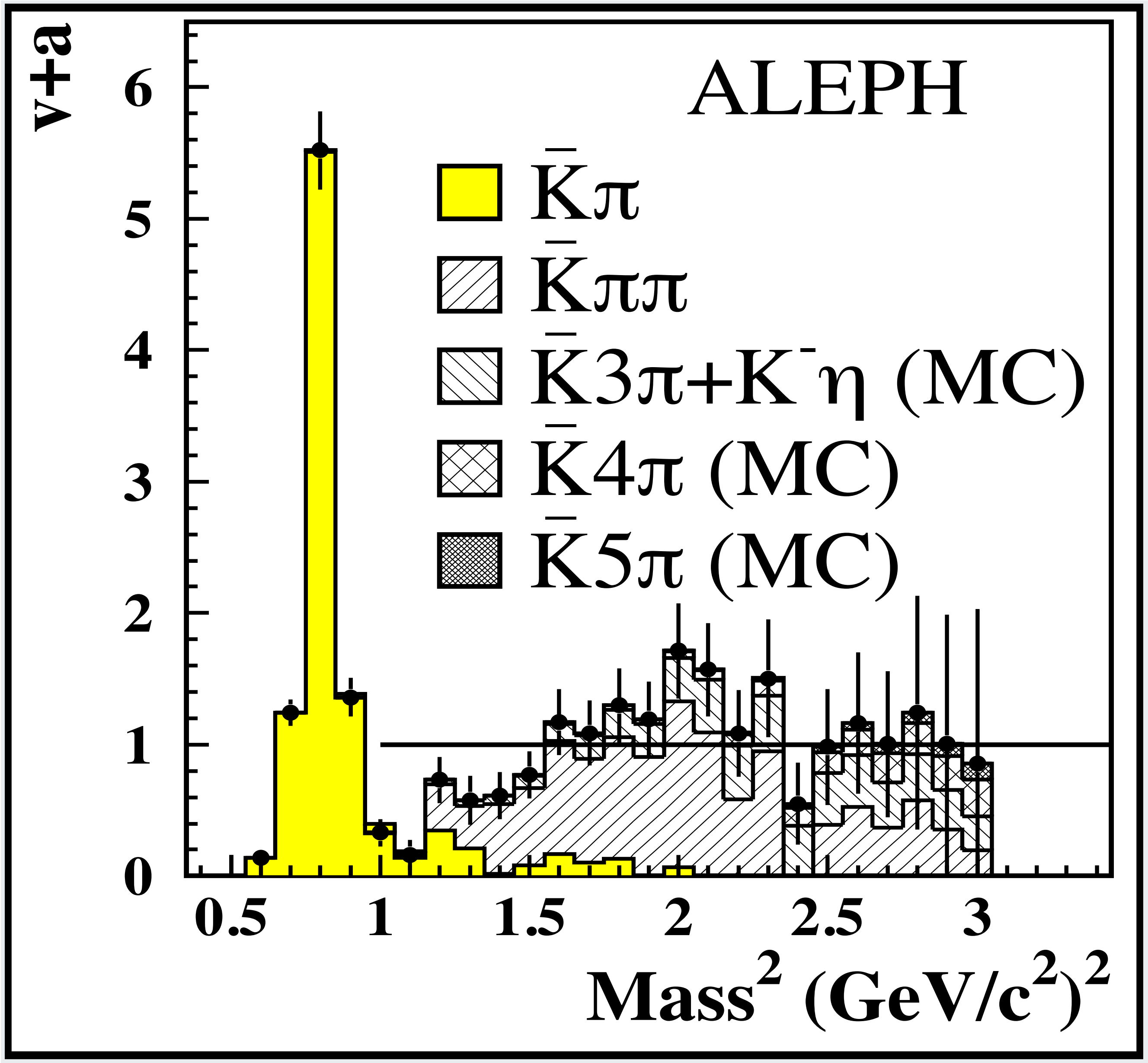
(odd number of pions)



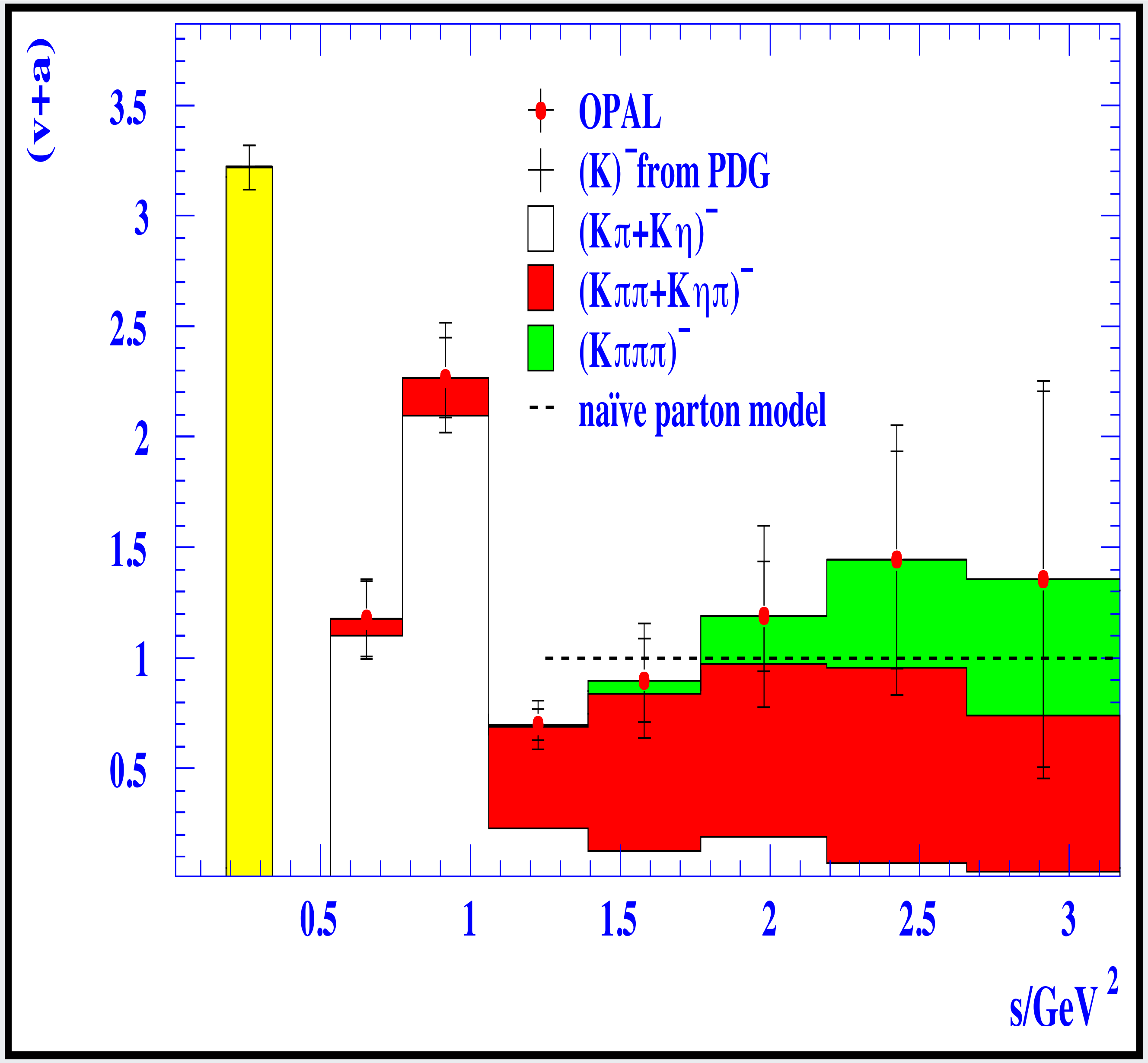
OPAL Collaboration, EPCJ 7 (1999) xxxx

Strange spectral functions

Strange spectral functions from ALEPH & OPAL are not so precise



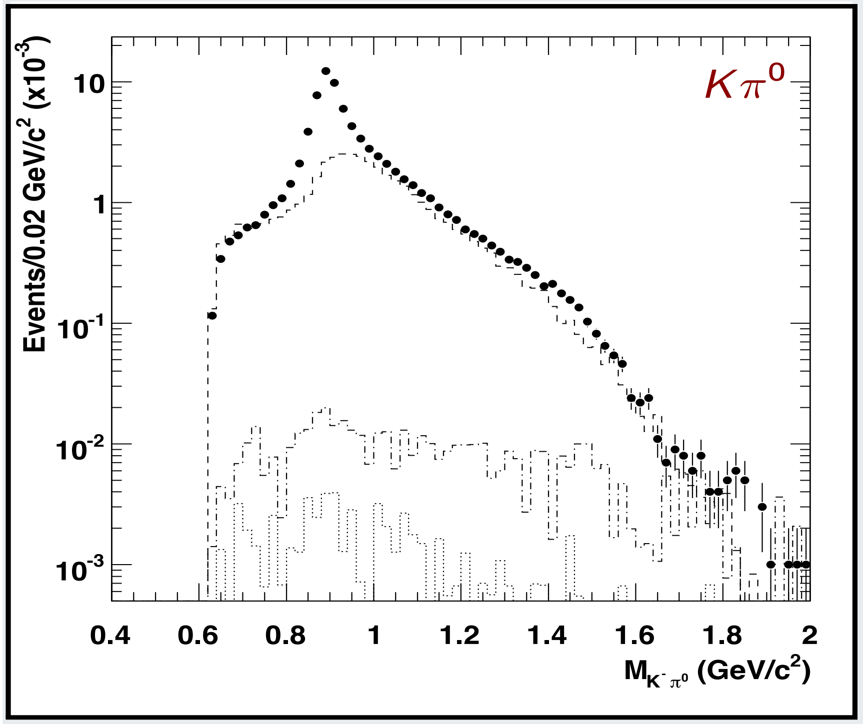
ALEPH, Phys. Rep. 421 (2005) 191



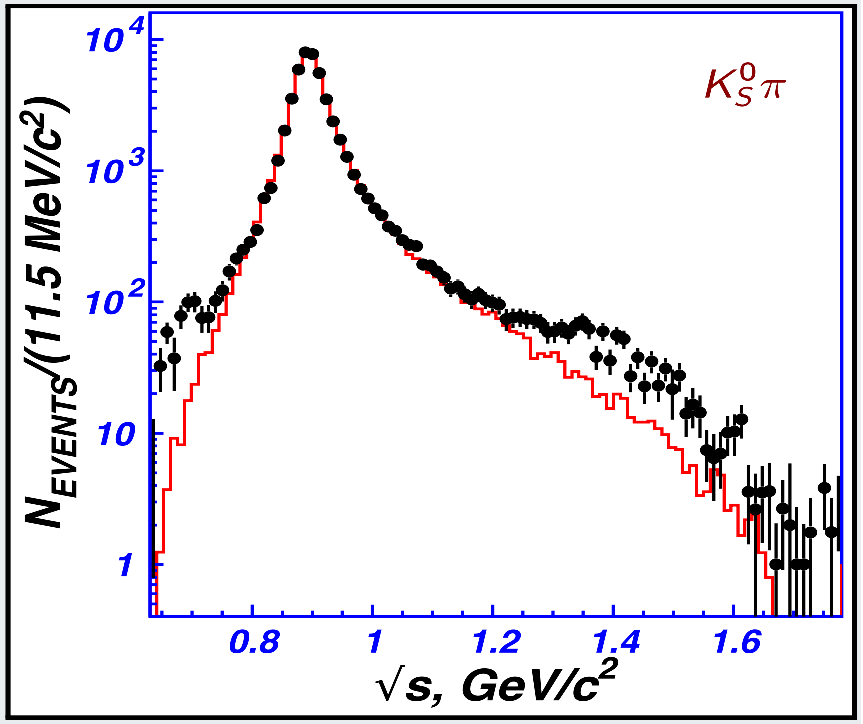
OPAL, EPJC 7 (1999)

Strange spectral functions

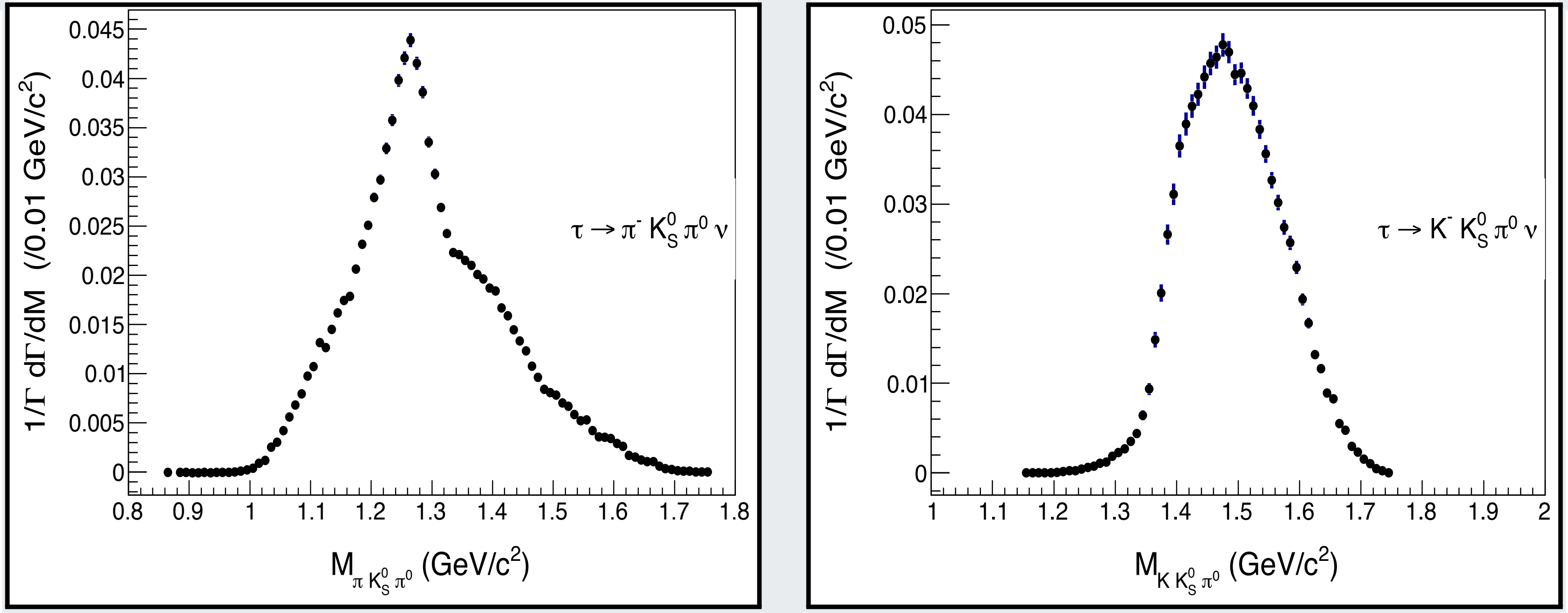
Some [preliminary] measurements from B-Factories are available



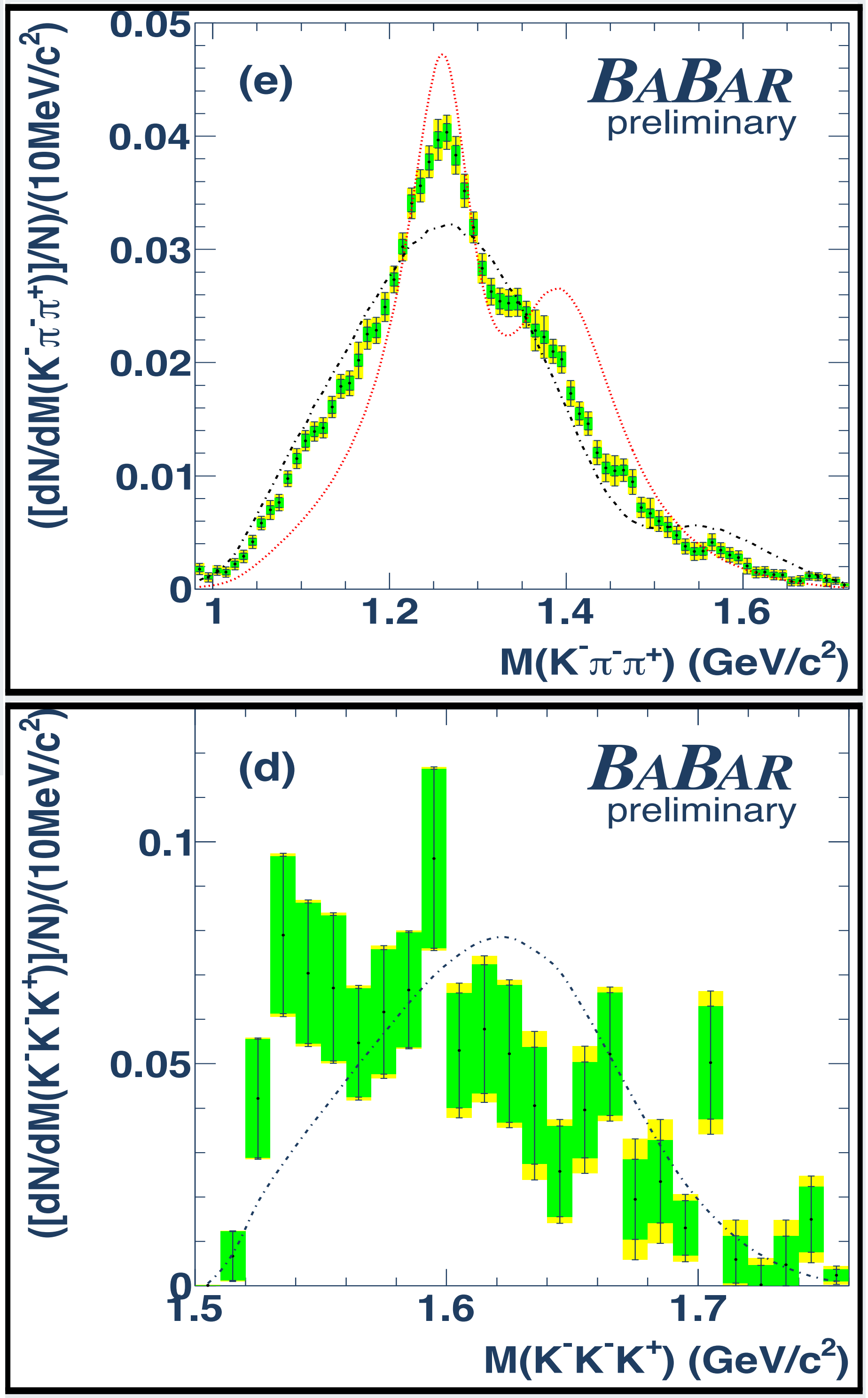
BABAR, PRD 76 (2007) 051104
(not background-subtracted)



Belle, PLB 654 (2007) 65



Ryu [Belle] Nucl.Phys.Proc.Suppl. 253-255 (2014) 33



Nugent, Nucl.Phys.Proc.Suppl. 253-255 (2014) 38.

τ branching fractions are well measured

- Most of the branching fractions are highly correlated.
- Sources of correlation between the same experiment:
  - Track reconstruction ~ 1% for 1-vs-1 topology
  - Secondary vertex reconstruction ~ 1.5% for K_S
  - Calorimeter bump reconstruction ~ 1-3% for π^0
  - Particle identification ~ 2-4 %
  - Luminosity uncertainty ~ 1%

Sources of correlation between different experiments:

  - Tau-pair cross-section uncertainty ~ 0.36%
  - Uncertainty on Branching Fractions of backgrounds

➡Simultaneous averaging of all branching fractions

Heavy Flavor Averaging Group (HFLAV)

- Global fit to 170 measurements of τ Branching Fractions:
  - 39 from ALEPH
  - 35 from CLEO
  - 23 from BaBar
  - 19 from OPAL
  - 15 from Belle
  - 14 from DELPHI
  - 11 from L3
  - 6 from CLEO3
  - 3 from TPC
  - 2 from ARGUS
  - 2 from HRS
  - 1 from CELLO

HFLAV tries to take into account correlations between measurements, as well as dependence on common external parameters such as tau-pair cross-section and background normalization errors between experiments.

As much as possible, HFLAV tries to avoid inflating measured uncertainties using old PDG-style scale factors to account for spread between the different measurements. Instead, a confidence level (CL) for the average is quoted.

HFLAV style fits in PDG

From 2016, HFLAV-style fits have been adopted by PDG.
Chin.Phys. C40 (2016) no.10, 100001.

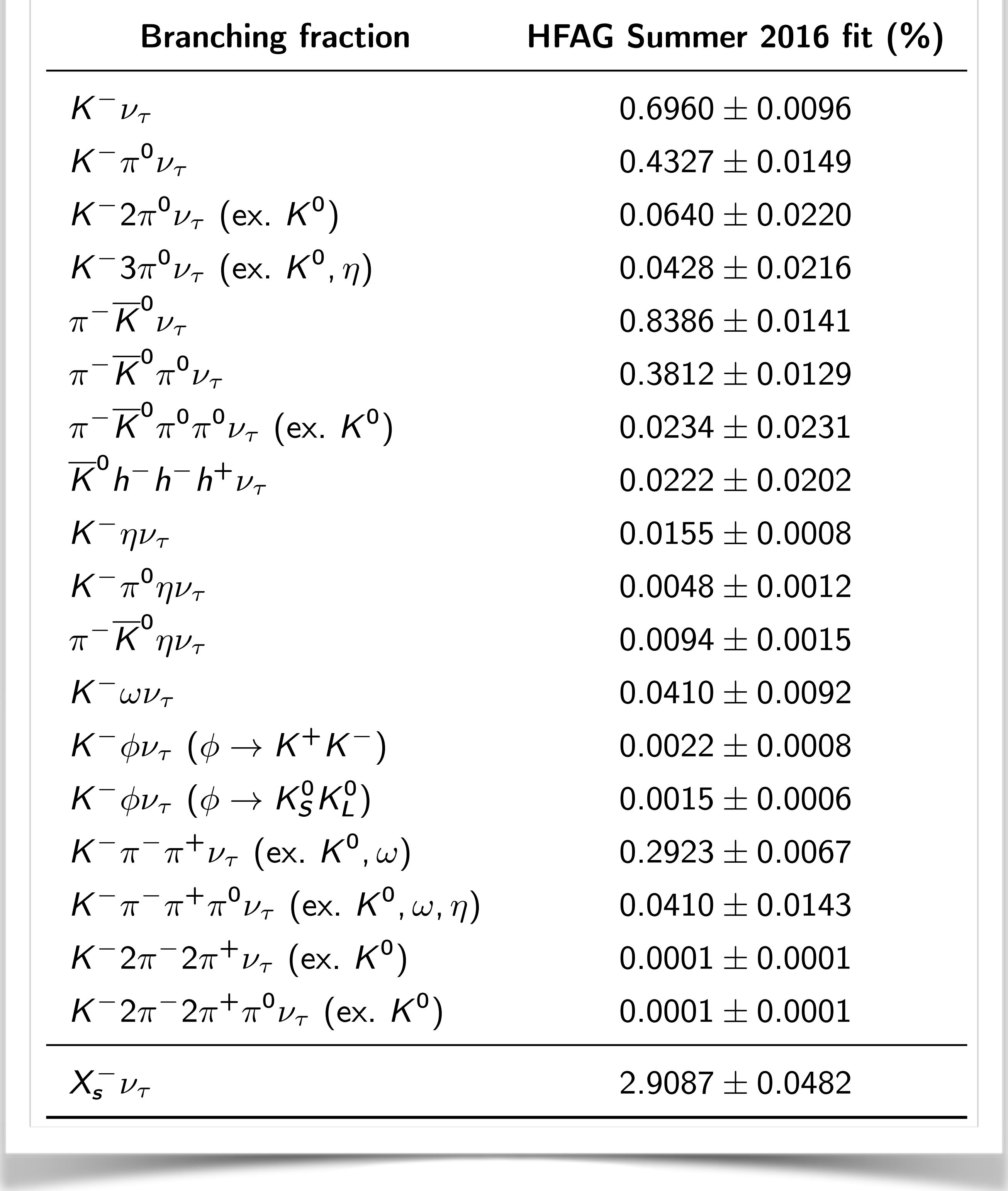
According to PDG naming convention,
47 basis nodes are fitted to 170 measurement
with constraint that linear sum of basis nodes add up to unity
⇒ 170 - 47 + 1 = 124 degrees of freedom

In HFLAV notation, 135 quantities consisting of 47 basis nodes
and 88 linear combinations or ratios of linear combinations
are expressed as constraints.
Both the methods are equivalent.

Quality of fit:
Unity-constrained fit: χ^2 / dof = 137.4/124, CL = 19.3%
Non-Unity-constrained fit: χ^2 / dof = 137.3/123, CL = 17.8%
Residual from unity in un-constrained fit = (0.035 ± 0.103)%

|Vus| from inclusive strange decays

[Preliminary]



Branching fraction	HFAG Summer 2016 fit (%)
$K^-\nu_\tau$	0.6960 ± 0.0096
$K^-\pi^0\nu_\tau$	0.4327 ± 0.0149
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.0640 ± 0.0220
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.0428 ± 0.0216
$\pi^-\overline{K}^0\nu_\tau$	0.8386 ± 0.0141
$\pi^-\overline{K}^0\pi^0\nu_\tau$	0.3812 ± 0.0129
$\pi^-\overline{K}^0\pi^0\pi^0\nu_\tau$ (ex. K^0)	0.0234 ± 0.0231
$\overline{K}^0 h^- h^- h^+\nu_\tau$	0.0222 ± 0.0202
$K^-\eta\nu_\tau$	0.0155 ± 0.0008
$K^-\pi^0\eta\nu_\tau$	0.0048 ± 0.0012
$\pi^-\overline{K}^0\eta\nu_\tau$	0.0094 ± 0.0015
$K^-\omega\nu_\tau$	0.0410 ± 0.0092
$K^-\phi\nu_\tau$ ($\phi \to K^+K^-$)	0.0022 ± 0.0008
$K^-\phi\nu_\tau$ ($\phi \to K^0_S K^0_L$)	0.0015 ± 0.0006
$K^-\pi^-\pi^+\nu_\tau$ (ex. K^0, ω)	0.2923 ± 0.0067
$K^-\pi^-\pi^+\pi^0\nu_\tau$ (ex. K^0, ω, η)	0.0410 ± 0.0143
$K^-2\pi^-2\pi^+\nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$K^-2\pi^-2\pi^+\pi^0\nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$X_s^-\nu_\tau$	2.9087 ± 0.0482

$$|V_{us}|_{\tau s} = \sqrt{R_s / \left[\frac{R_{\text{VA}}}{|V_{ud}|^2} - \delta R_{\text{theory}}\right]}$$

$$B_s = (2.909 \pm 0.048)\%$$

$$B_{\text{hadrons}} = B_{\text{all}} - B_e - B_\mu = (64.76 \pm 0.10)\%$$

$$B_{\text{VA}} = B_{\text{hadrons}} - B_s = (61.85 \pm 0.10)\%$$

To get R, we normalize by

$$B_e = (17.816 \pm 0.041)\%$$

However, the error on B_e can be improved using lepton universality and improved measurements of mass (m_τ) and lifetime (τ_τ).

Lepton universality improved $|V_{us}|$

$R_{had} = \Gamma(\tau \to \text{hadrons})/\Gamma_{univ}(\tau \to e\nu\bar{\nu})$

- $R_{had} = \dfrac{\Gamma(\tau \to \text{hadrons})}{\Gamma_{univ}(\tau \to e\nu\bar{\nu})} = \dfrac{\mathcal{B}_{hadrons}}{\mathcal{B}_e^{univ}} = \dfrac{1 - \mathcal{B}_e^{univ} - f(m_\mu^2/m_\tau^2)/f(m_e^2/m_\tau^2) \cdot \mathcal{B}_e^{univ}}{\mathcal{B}_e^{univ}}$
  - ▸ two different determinations, second one not "contaminated" by hadronic BFs
- **$R_{had} = 3.6349 \pm 0.0082$** HFAG-PDG 2016 prelim. fit
- **R_{had}(leptonic BFs only) $= 3.6397 \pm 0.0070$** HFAG-PDG 2016 prelim. fit

$\Rightarrow |V_{us}| = (0.2186 \pm 0.0021)$ [Preliminary]

The measured $|V_{us}|$ values & errors are numerically almost identical using

- measured $B_{had} = B_{non\text{-}strange} + B_s$ from unity non-constrained τ BR fit, OR
- $B_{had} = 1 - (1 + f_\mu/f_e)\, B_e^{univ}$ from unity constrained τ BR fit

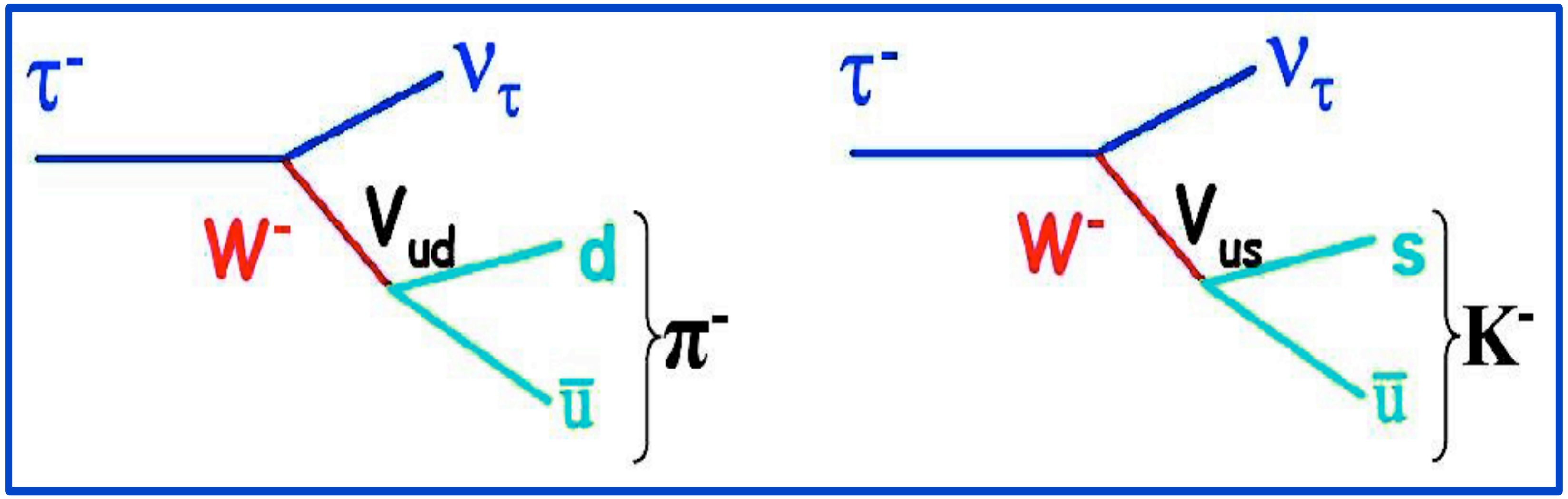
This is because error on R_{had} feeds to error on $R_{non\text{-}strange}$ in calculation of $|V_{us}|$

In both cases, R_{had} is normalized using B_e^{univ}

Dominant contribution to error on $|V_{us}|$ comes from error on the measured $R_{strange}$.

δR_{theory} contributes to 47% of the relative error on $|V_{us}|$.

$|V_{us}|$ from exclusive τ decays

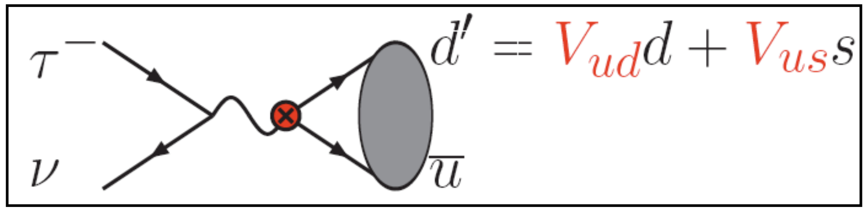


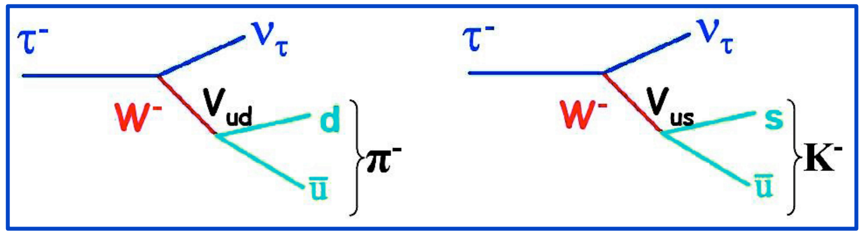
$$\frac{B(\tau \to K^-\nu_\tau)}{B(\tau \to \pi^-\nu_\tau)} = \frac{f_K^2|V_{us}|^2}{f_\pi^2|V_{ud}|^2}\frac{\left(1 - m_K^2/m_\tau^2\right)^2}{\left(1 - m_\pi^2/m_\tau^2\right)^2} R_{\tau K/\tau\pi}$$

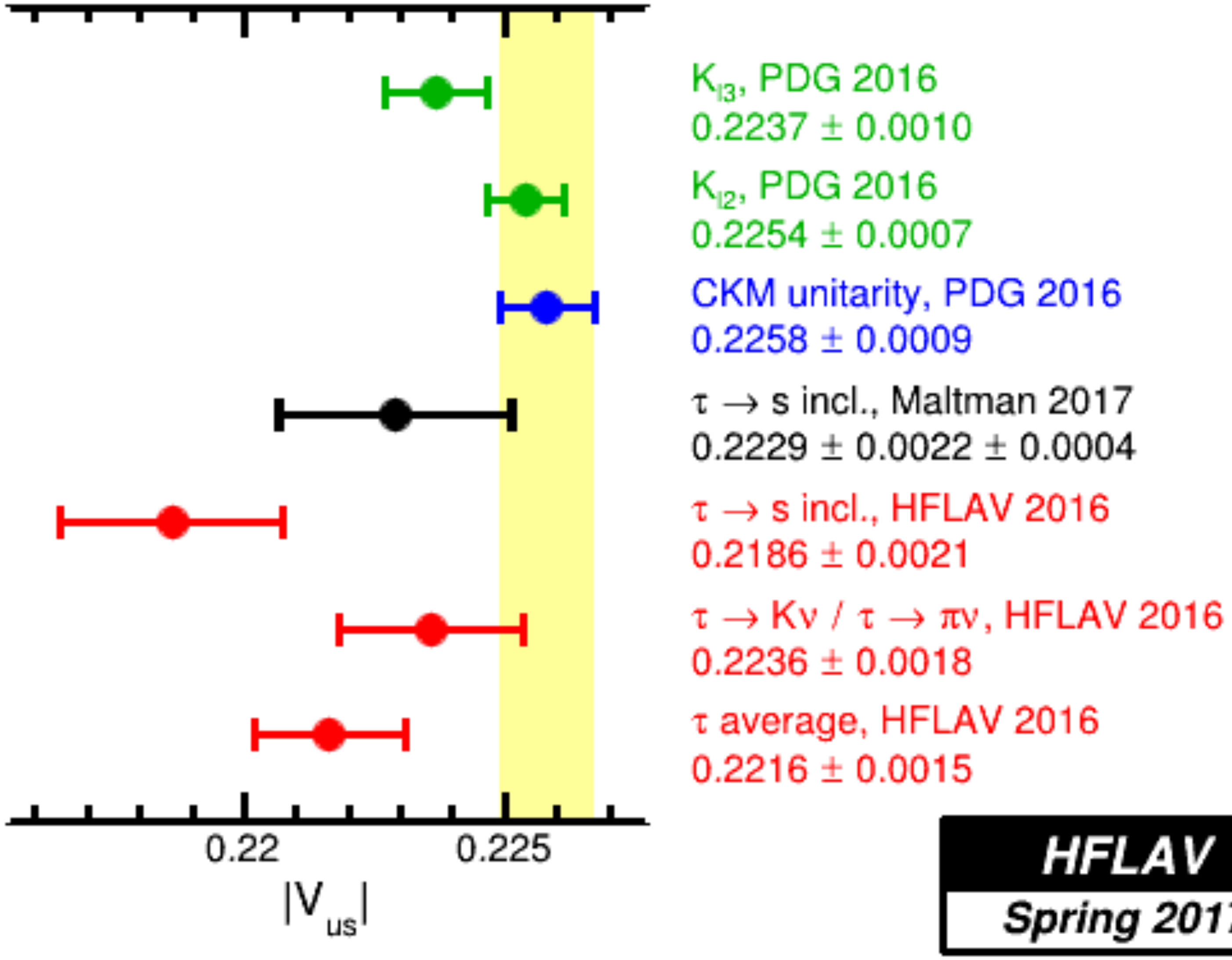
- Independent of convergence of OPE, as electroweak corrections cancel
- Radiative corrections S_{EW} = 1.02010 ± 0.00030 [Erler 2004]
- Long Distance effects ($R_{\tau K/\tau\pi}$) known [Decker & Finkmeier 1995, Marciano 2004]
- All non-perturbative QCD effects encapsulated as ratio of meson decay constants:

f_K/f_π = 1.193 ± 0.003, f_K = 155.6 ± 0.4 MeV [FLAG 2016 Lattice Averages]

Summary of $|V_{us}|$ results







-3.1σ

-1.1σ

-2.4σ

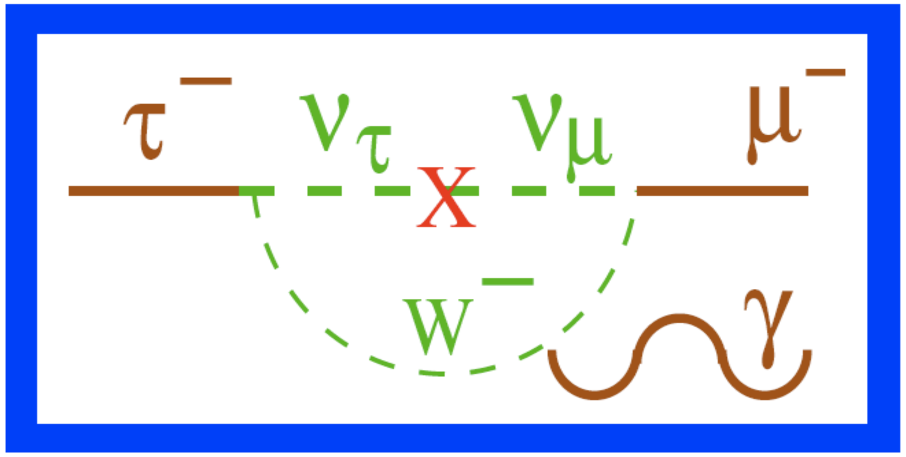
HFLAV
Spring 2017

[Preliminary]

- $|V_{us}|$ has been measured using inclusive and exclusive tau decays.
- Preliminary results from Maltman’s estimate agrees with unitarity.

Search for lepton flavor violation in τ decays

- Lepton flavor violation (LFV)
  - not forbidden by SM gauge symmetry
  - most new models naturally include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
- Now we have clear indication that ν's have finite mass
  $\Rightarrow$ Lepton Flavor is violated in Nature: but by how much?
- SM extended to include finite ν mass and mixing predicts LFV



$\mathcal{B}(\tau^\pm \to \mu^\pm\gamma)$ [Lee-Shrock, Phys. Rev. D **16**, 1444 (1977)]

$$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\text{mix}}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$$

With $\Delta \sim 10^{-3}\,\text{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\text{eV}$

$\approx \mathcal{O}(10^{-54})$ (θ_{mix} : max)

... many orders below experimental sensitivity!

- Observation for LFV $\Rightarrow$ unambiguous signature of new physics

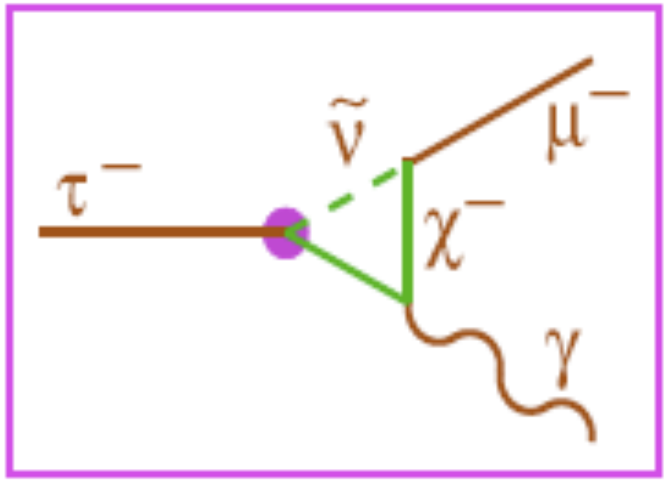
Search for lepton flavor violation in τ decays

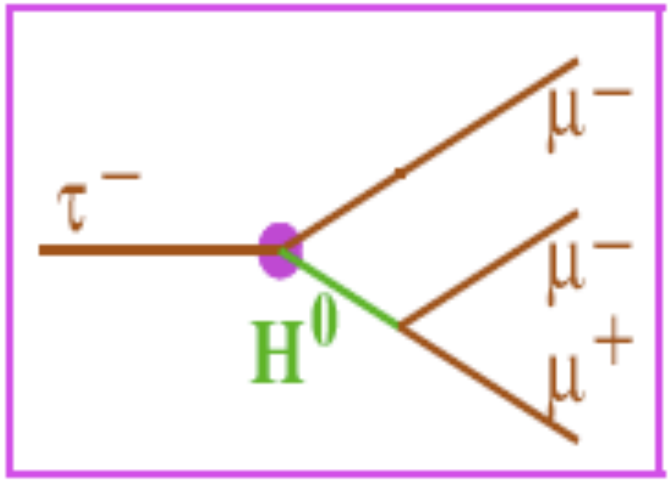
- Some models predict LFV upto existing experimental bounds

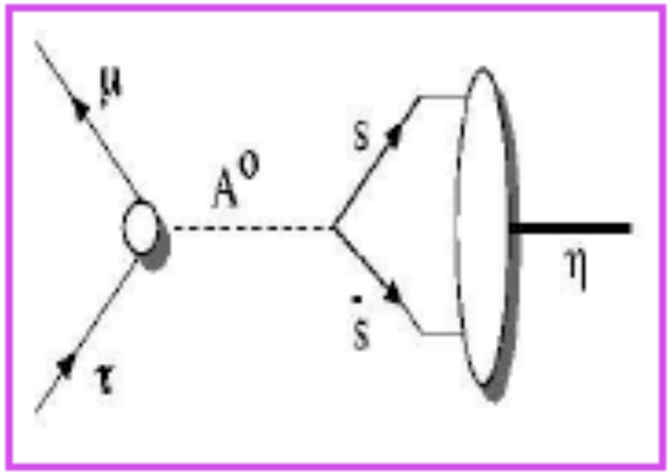
	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
SM+ν-mixing (PRL95(2005)41802,EPJC8(1999)513)	10^{-54}	10^{-14}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}

MSSM+seesaw (PRD66 (2002) 057301) $\mathcal{B}(\tau \to \mu\gamma) : \mathcal{B}(\tau \to \mu\mu\mu) : \mathcal{B}(\tau \to \mu\eta) = 1.5 : 1 : 8.4$

Illustrations:

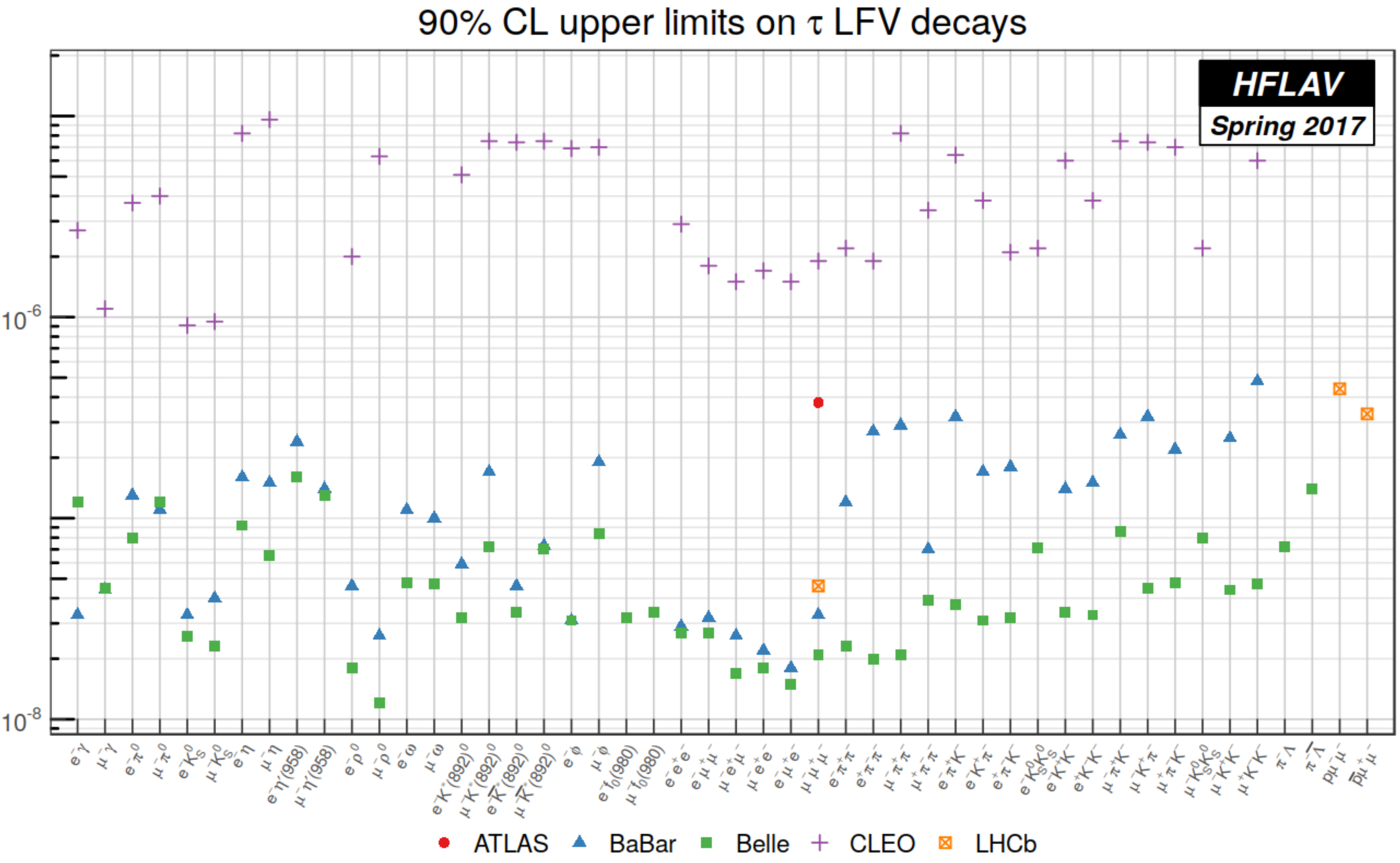




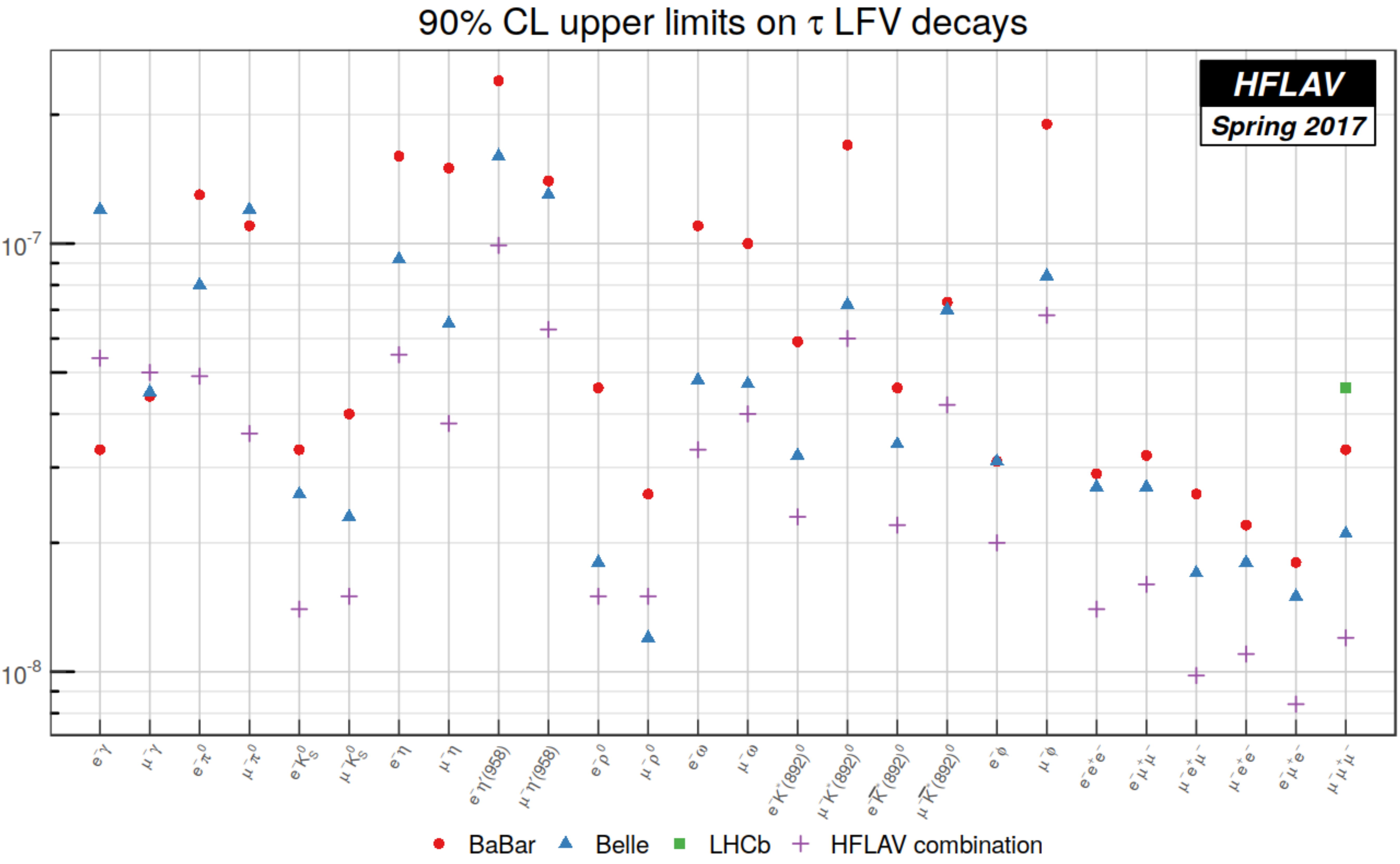


☞ Search for $\tau \to \ell\gamma/\pi^0/\eta/\eta'$, $\tau \to \ell\ell\ell$, $\tau \to \ell h h'$ $(\ell = e, \mu; h = \pi, K)$

Status of lepton flavor violating limits

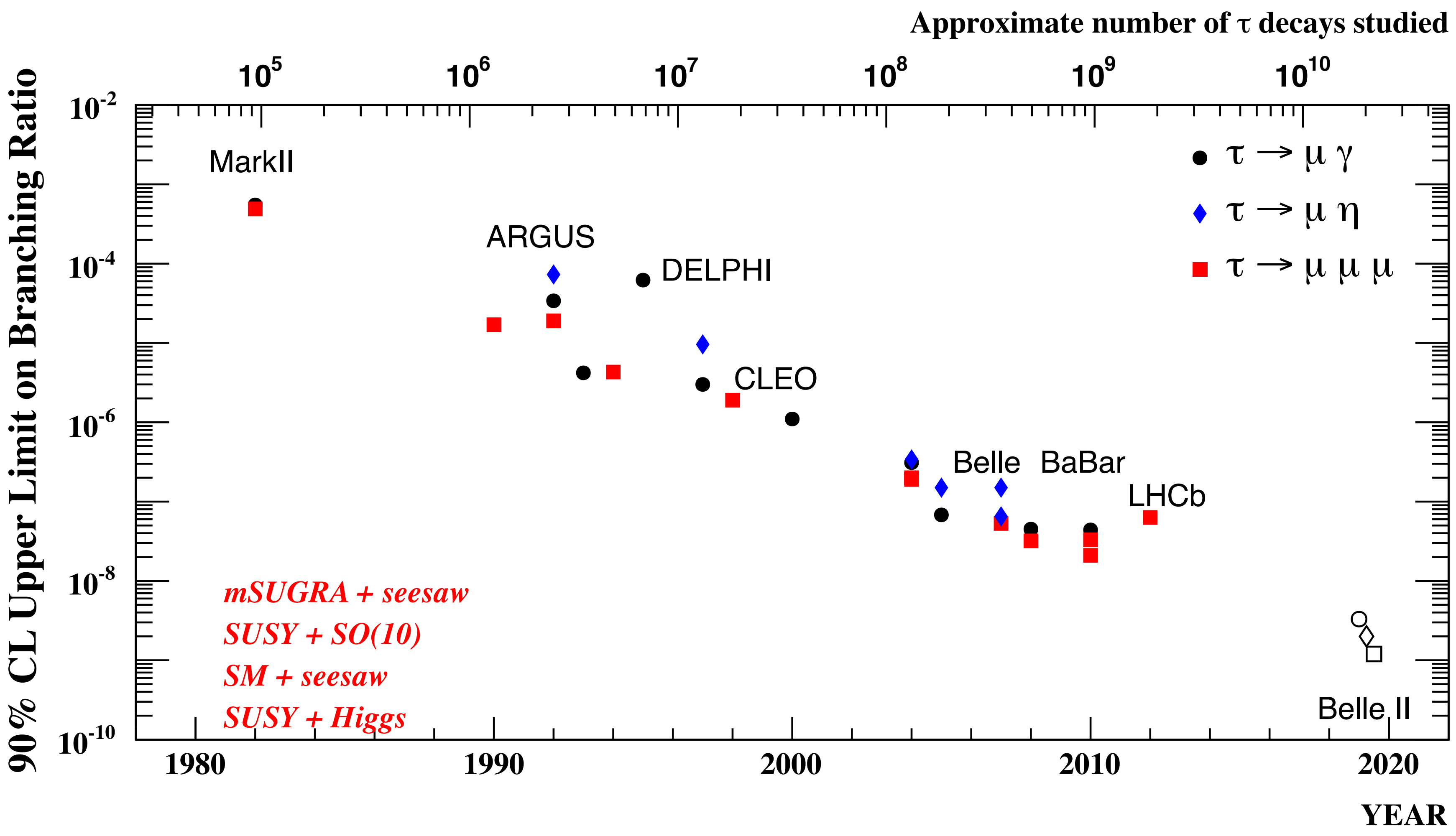


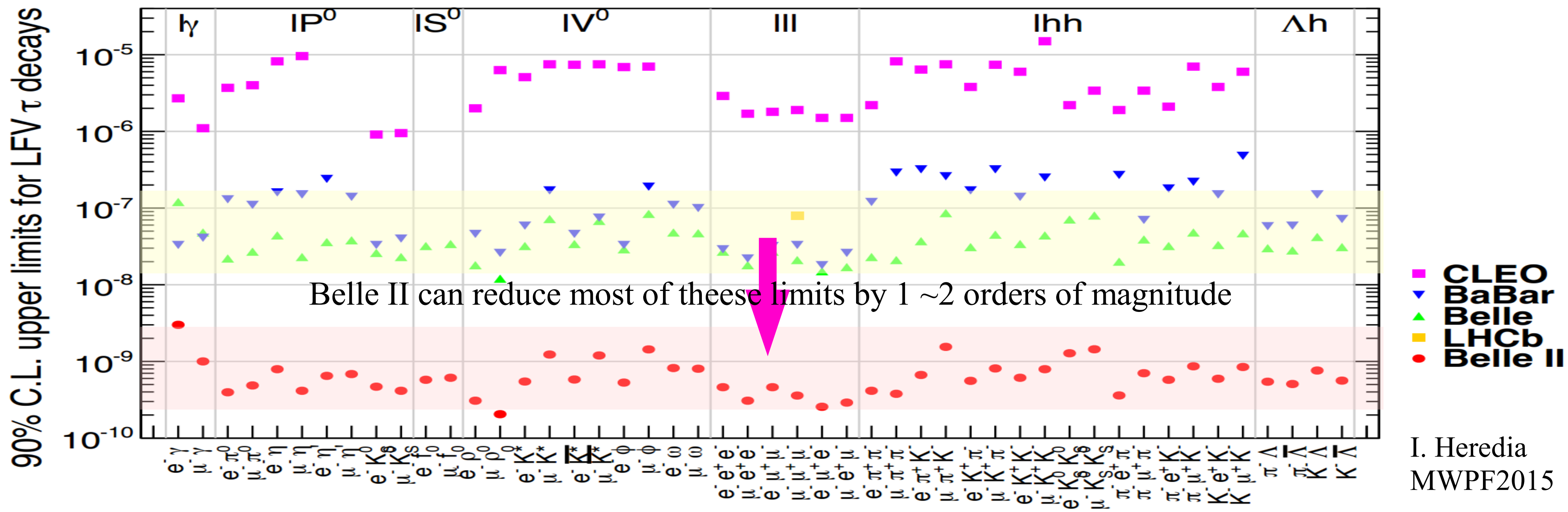
Combined upper limits



90% CL upper limits on τ LFV decays

Evolution of LFV limits





Belle II can reduce most of theese limits by 1 ~2 orders of magnitude

I. Heredia
MWPF2015

Overview of τ physics

Contents of this talk:

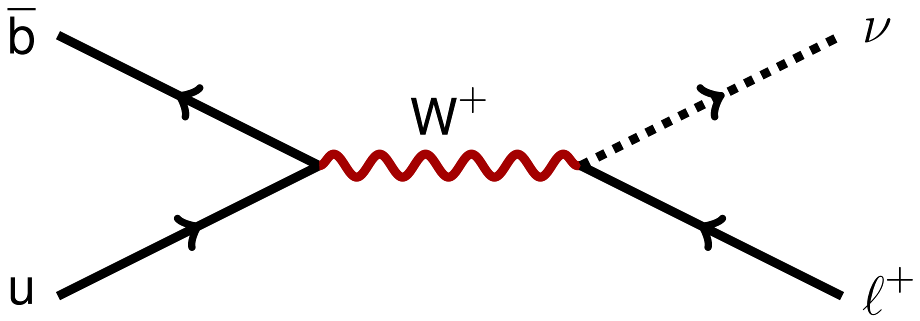
- Physics with τ decays
  - Mass, lifetime
  - Lepton universality
  - $|V_{us}|$ from τ decays
  - Lepton Flavor violation in τ decays

- Physics with τ produced
  - from B decays
  - from Top decays
  - from Higgs decays

Part 2

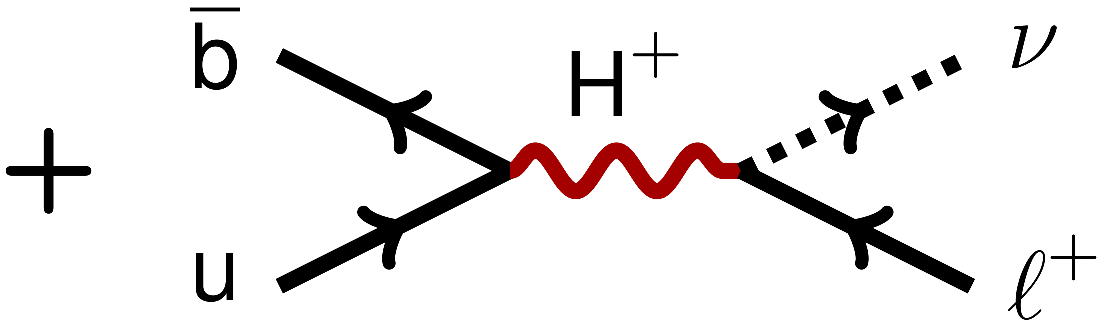
Apologies for not covering α_s, g-2, SUSY, exotica, Lepton Flavor violation at the LHC, CP Violation : this list is not exhaustive!

B → τ ν



$$\mathcal{B}\left(B^+ \to \ell^+\nu\right)_{\mathrm{SM}} = \frac{G_F^2 M_B M_\ell^2}{8\pi}\left(1-\frac{M_\ell^2}{M_B^2}\right)^2 f_B{}^2|V_{ub}|^2\tau_B$$

	SM Prediction	PDG 2016
$\mathcal{B}\left(B^+ \to e^+\nu_e\right)$	$(1.09 \pm 0.21)\cdot 10^{-11}$	$< 9.8\cdot 10^{-7}$ CL=90%
$\mathcal{B}\left(B^+ \to \mu^+\nu_\mu\right)$	$(4.65 \pm 0.91)\cdot 10^{-7}$	$< 1.0\cdot 10^{-6}$ CL=90%
$\mathcal{B}\left(B^+ \to \tau^+\nu_\tau\right)$	$(1.03 \pm 0.2)\cdot 10^{-4}$	$(1.06 \pm 0.20)\cdot 10^{-4}$



$$\mathcal{B}\left(B^+ \to \ell^+\nu\right)_{\mathrm{2HDM}} = \mathcal{B}\left(B^+ \to \ell^+\nu\right)_{\mathrm{SM}}\cdot\left(1-\frac{M_B^2\tan^2\beta}{M_{H^+}^2}\right)^2$$

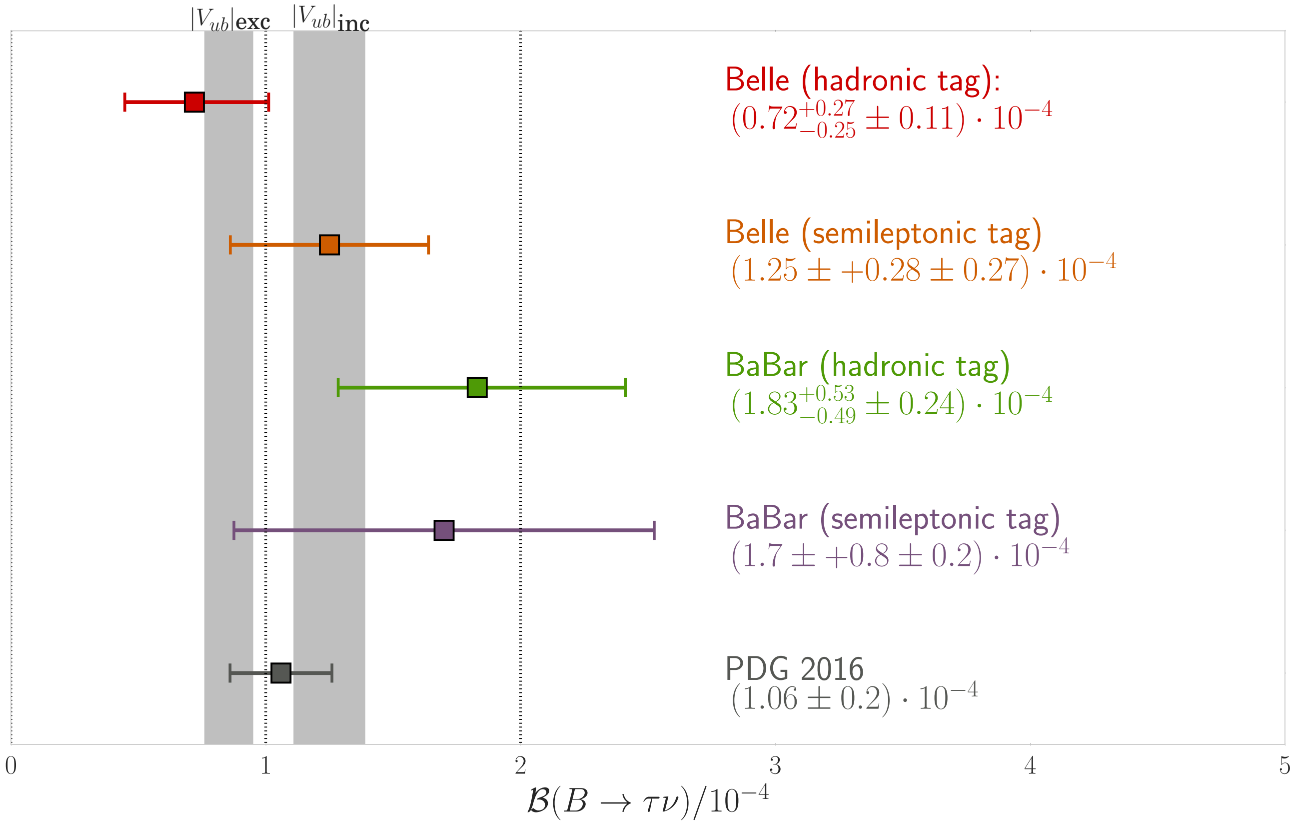
The B decay constant f_B encapsulates all hadronic effects

Lattice QCD: $f_B = 0.191 \pm 0.009$ GeV

HFAG-2014: $|V_{ub}| = (3.53 \pm 0.29)\ 10^{-3}$

Eur. Phys. J. C74:2890 (2014)

$B^+ \to \tau^+\nu_\tau$: Current status



Already tightly constrained by weak radiative B meson decays

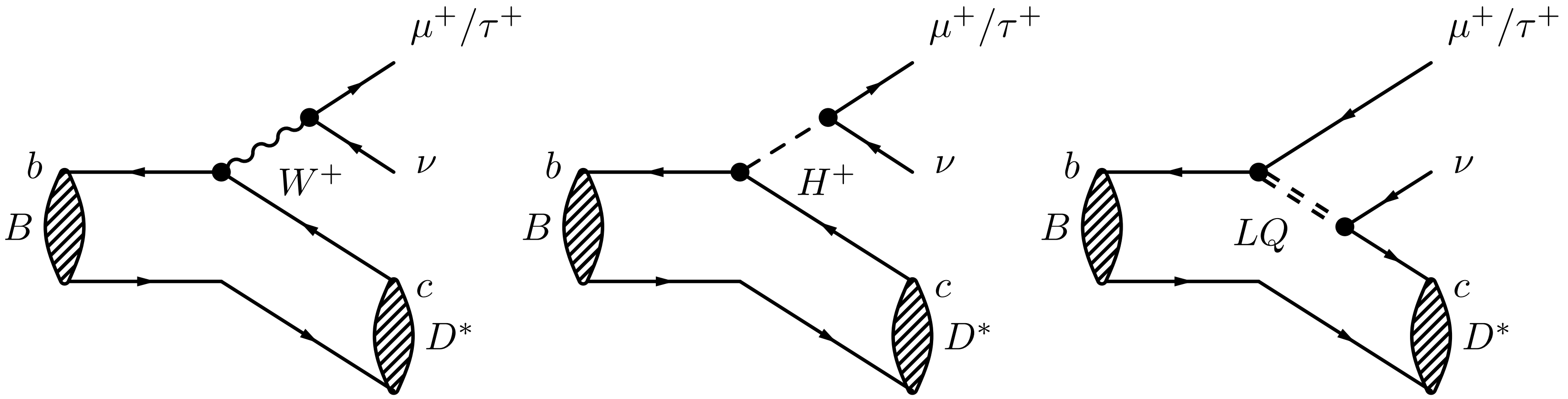
$M_{H^+} > 580$ GeV

Steinhauser, https://arxiv.org/pdf/1702.04571.pdf

Belle II (50 ab^{-1}) sensitivity ∝ 1/√L

$B \to D^{(*)} \tau \nu$

- Ratio $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu) \,/\, \mathcal{B}(B \to D^{(*)}\mu\nu)$ is sensitive to charged Higgs, leptoquark



- S.L. decays involving a $\tau^\pm$ have an additional helicity amplitude (for $D^*\tau\nu$)

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\mathbf{p}^*_{D^{(*)}}| q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}|H_s|^2\right]$$

For $D\tau\nu$, only H_{00} and H_s contribute!

- A charged Higgs (2HDM type II) of spin 0 coupling to the τ will only affect Hs

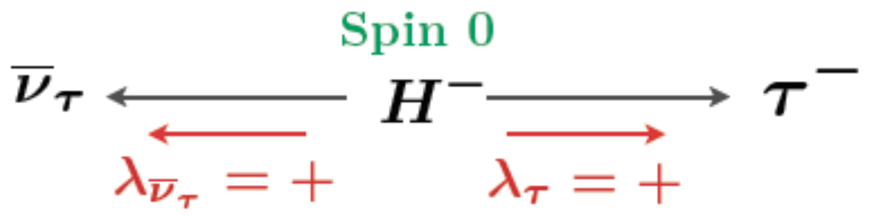
$$\boxed{H_s^{2\mathrm{HDM}} = H_s^{\mathrm{SM}} \times \left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2}\,\frac{q^2}{1 \mp m_c/m_b}\right)}$$

- for $D\tau\nu$
\+ for $D^*\tau\nu$

PRD 78, 015006 (2008)
PhD 85, 094025 (2012)

This could enhance or decrease the BF, depending on $\tan\beta/m_H$

- **τ^- polarization in $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$**
  - **SM:** Left-handed **70%**, Right-handed **30%**



- **2HDM:** Left-handed **0%**, Right-handed **100%**

Strategy in e^+e^- colliders

Hadronic or
Semi-leptonic }

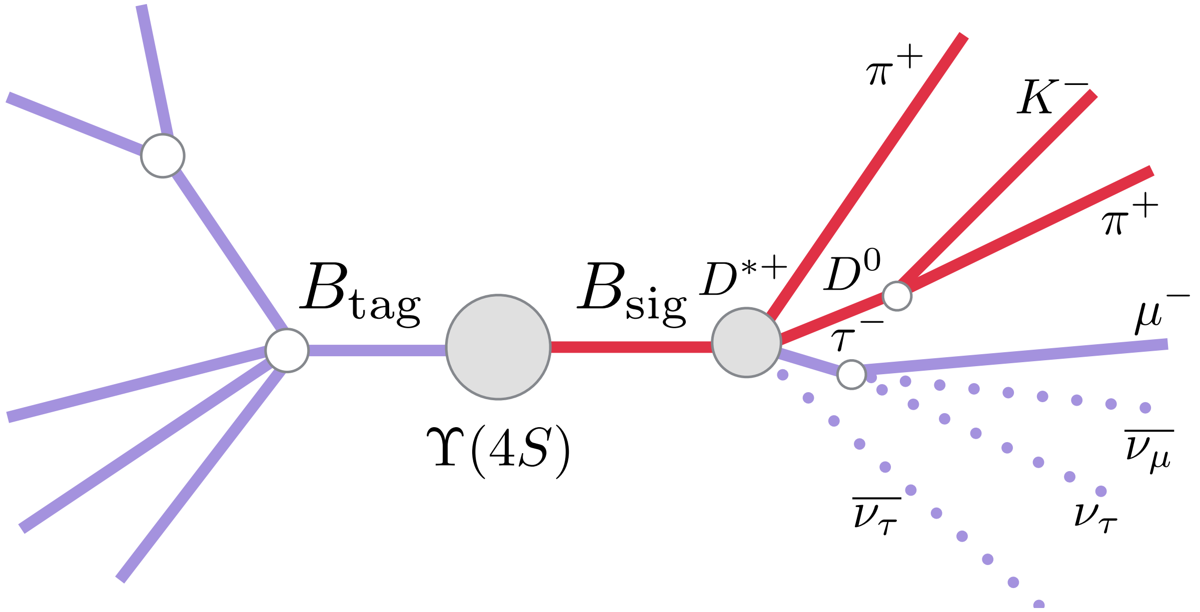
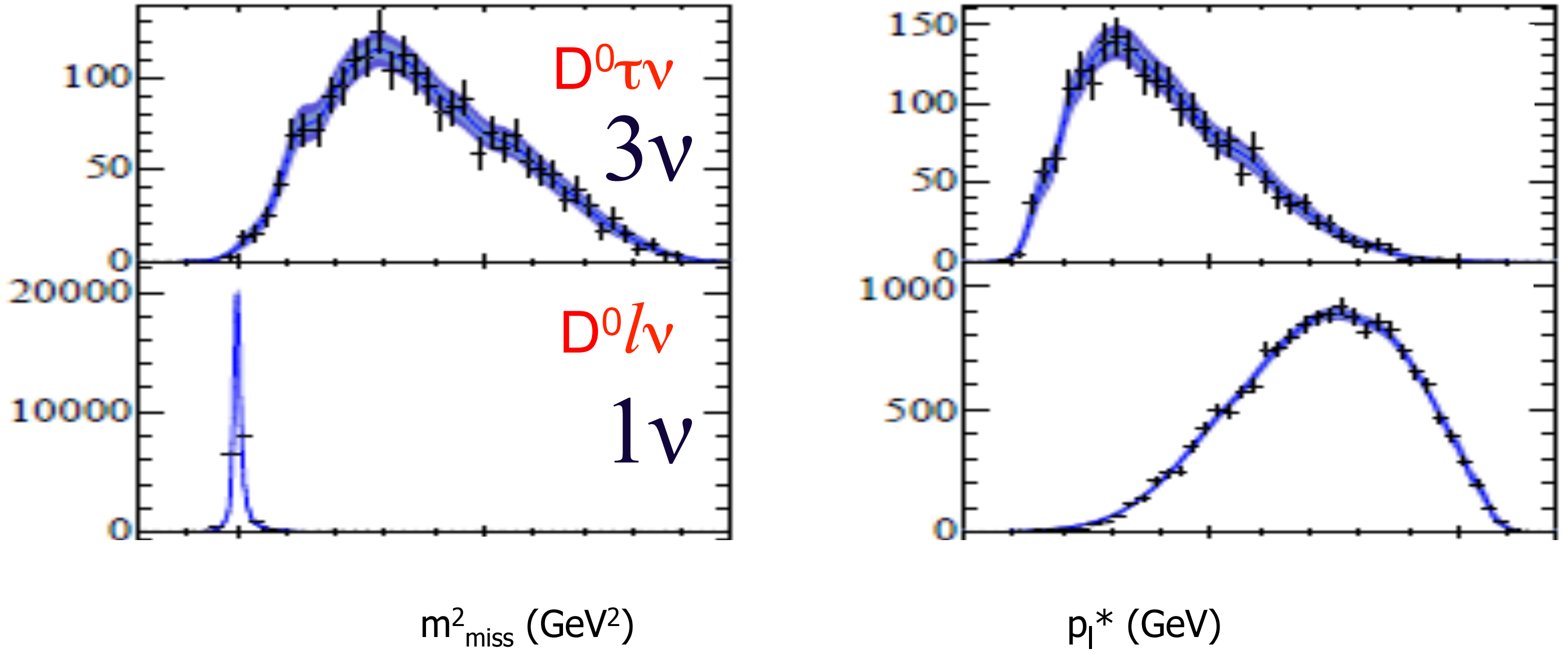


Illustration of background separation for hadronic tag

$$m^2_{miss} = (P_{ee} - P_{Btag} - P_{D(*)} - P_\ell)^2 \qquad p^*_\ell$$

Missing mass squared $e^\pm, \mu^\pm$ momentum in B rest frame



Strategy in e^+e^- colliders

Hadronic or
Semi-leptonic

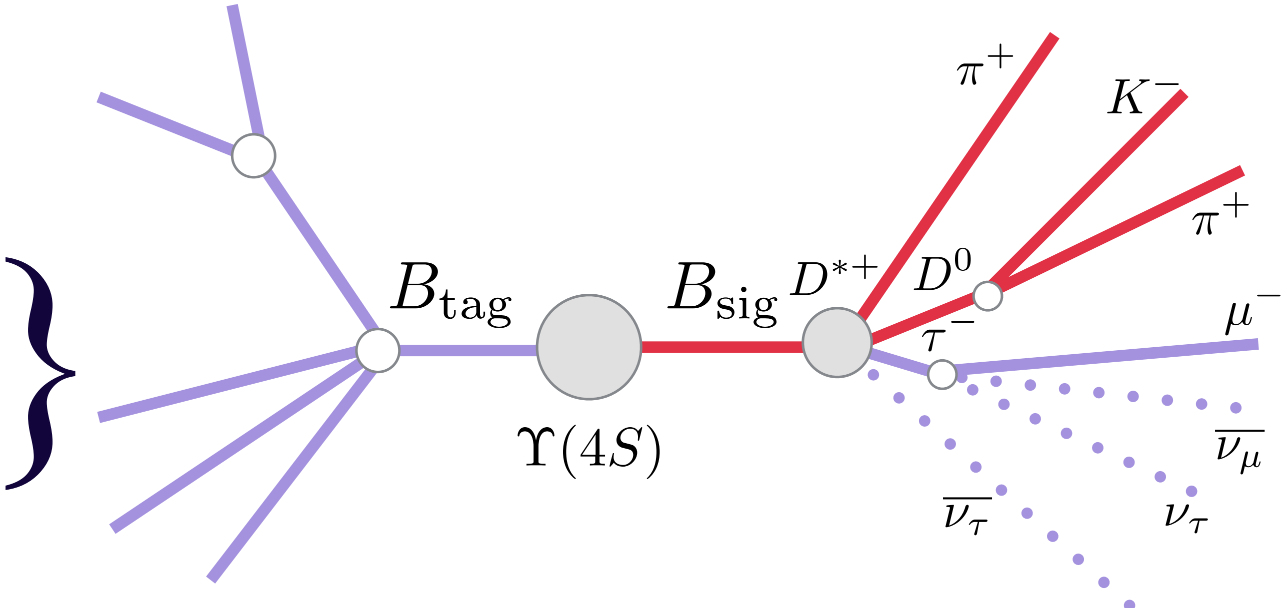
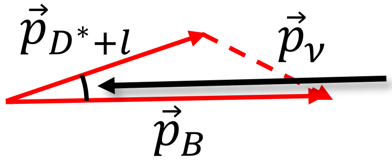
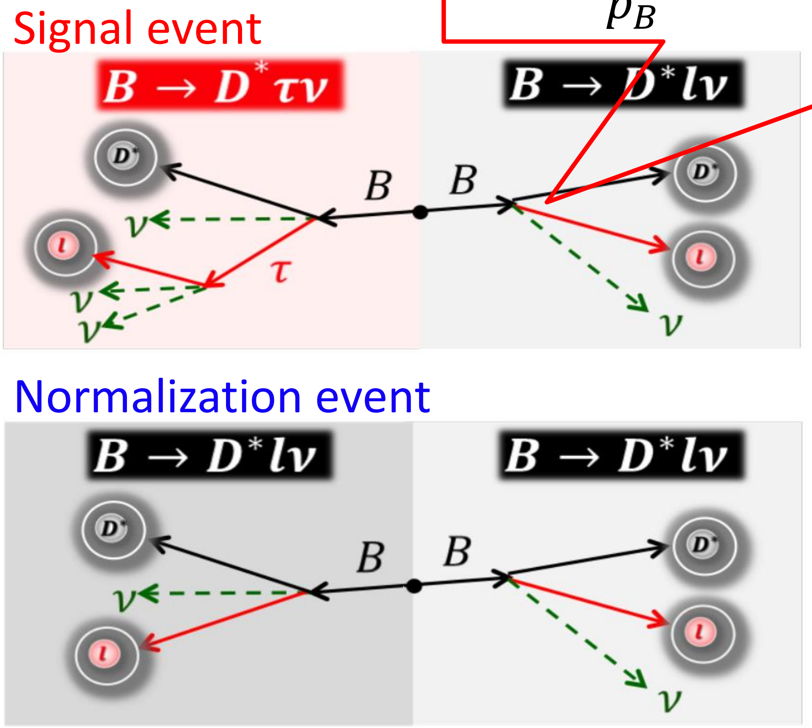


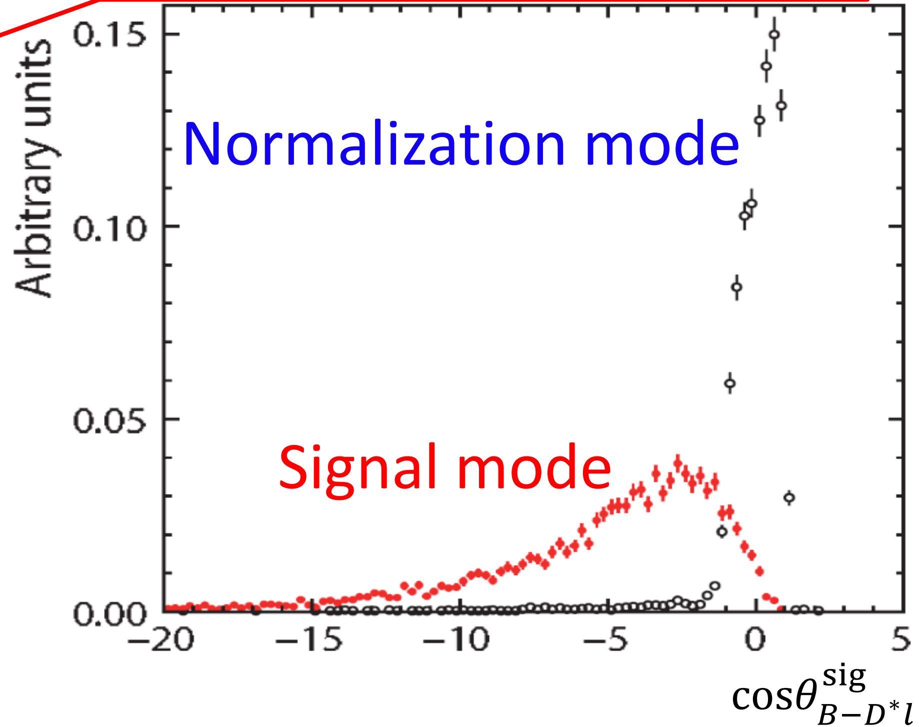
Illustration of background separation for semi-leptonic tag

- Signal/normalization separation based on smaller $\cos\theta_{B-D^*l}$



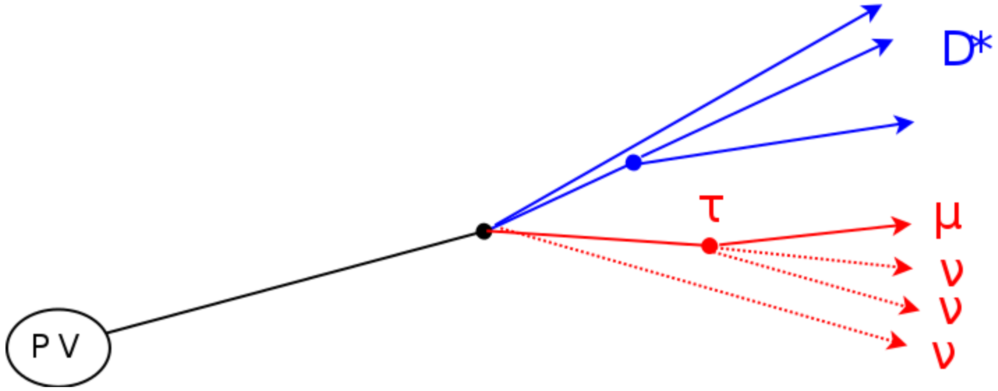
$$\cos\theta_{B-D^*l} = \frac{E^*_{\rm beam}E^*_{D^*l} - m_B^2 - m_{D^*l}^2}{2|p^*_{\rm beam}||p^*_{D^*l}|}$$



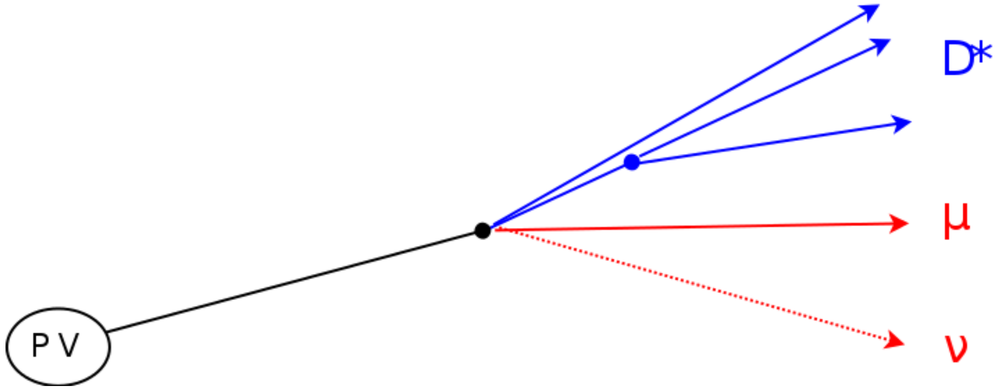


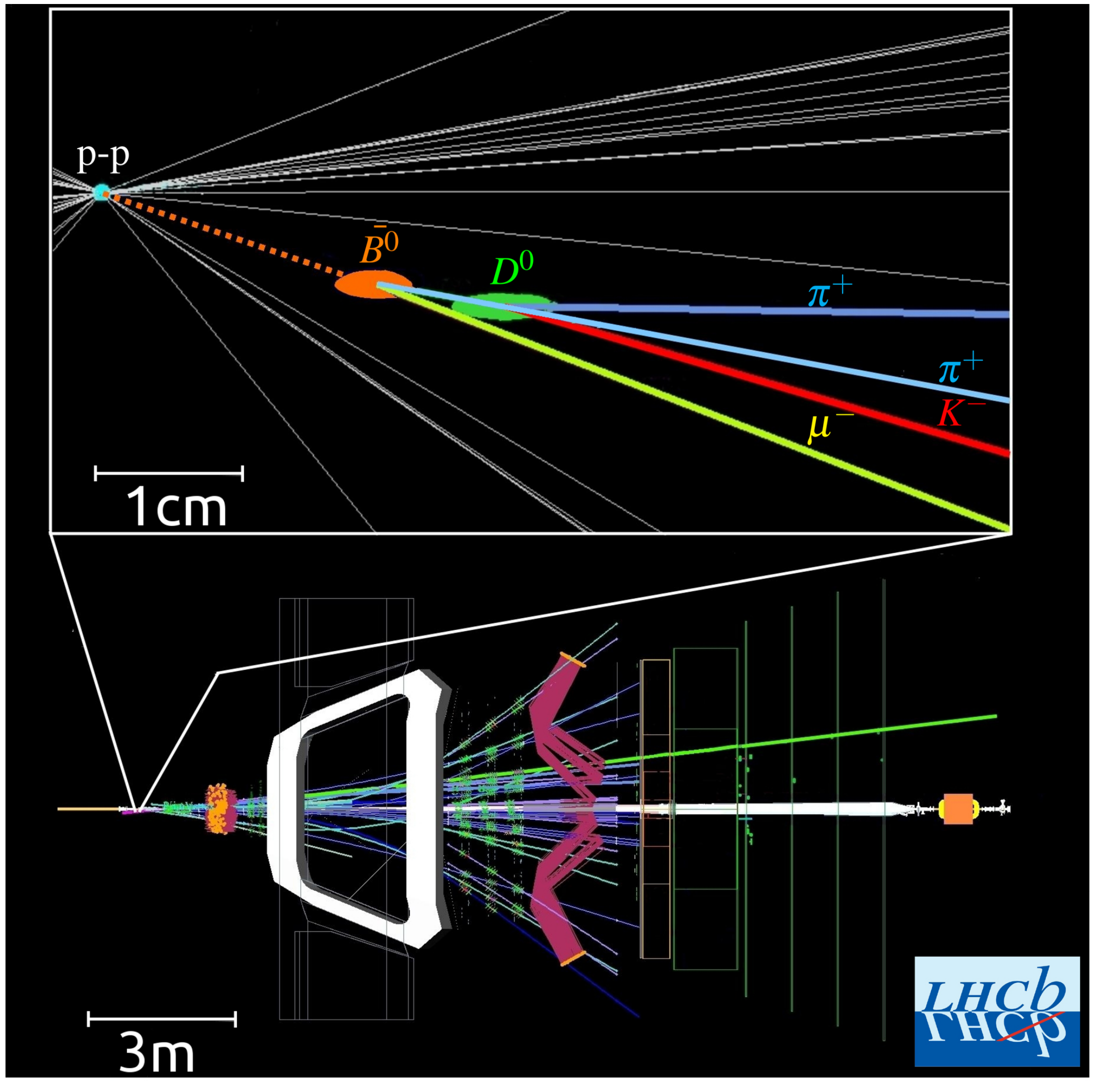
Strategy in hadron colliders

$B \to D^* \tau \nu$

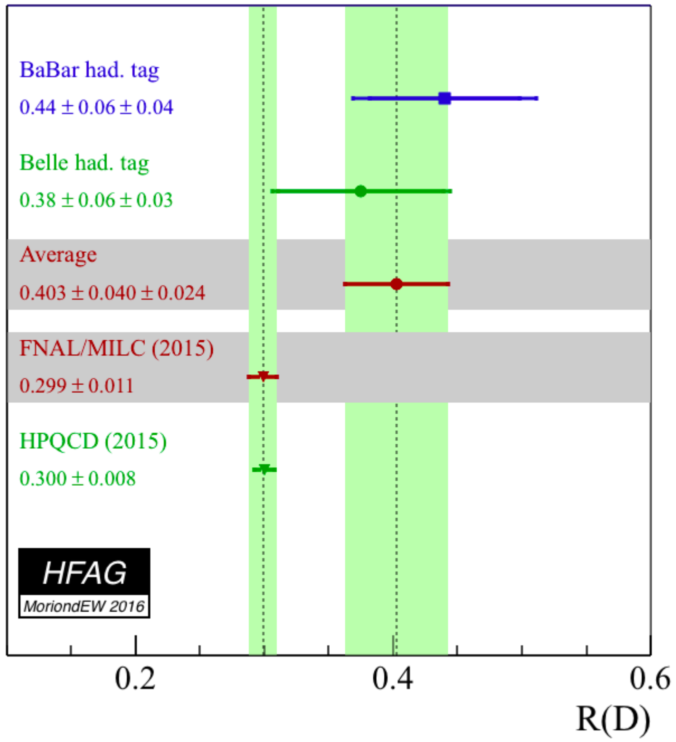


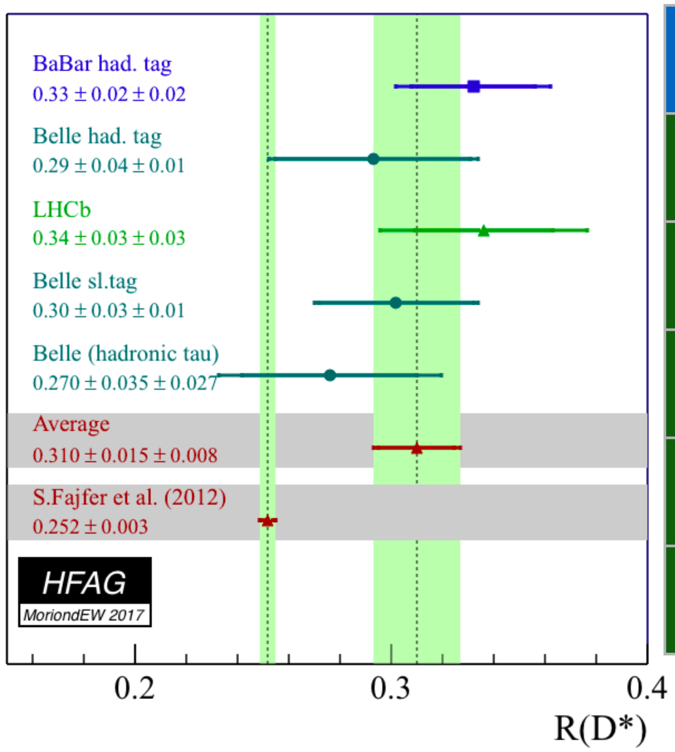
$B \to D^* \mu \nu$



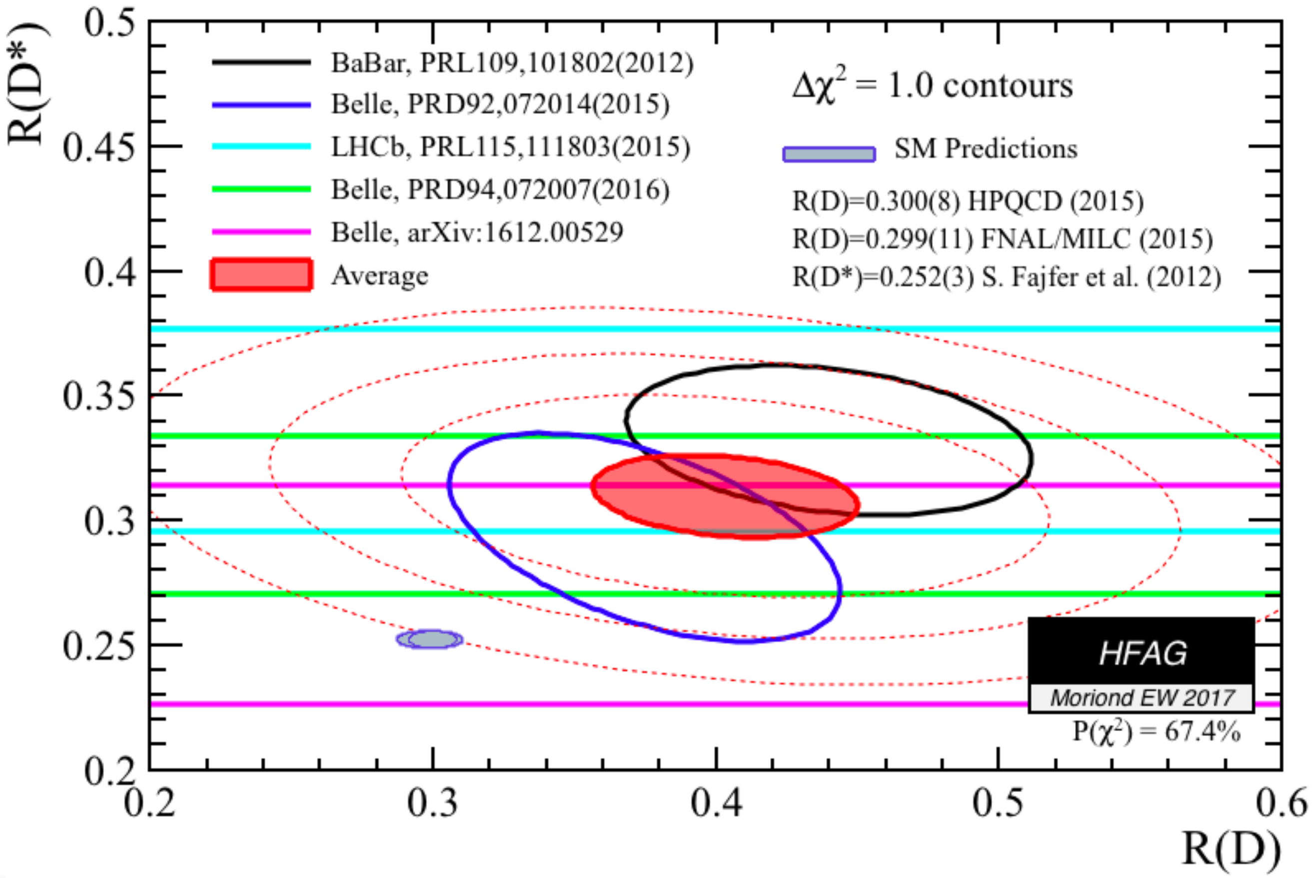


Current status



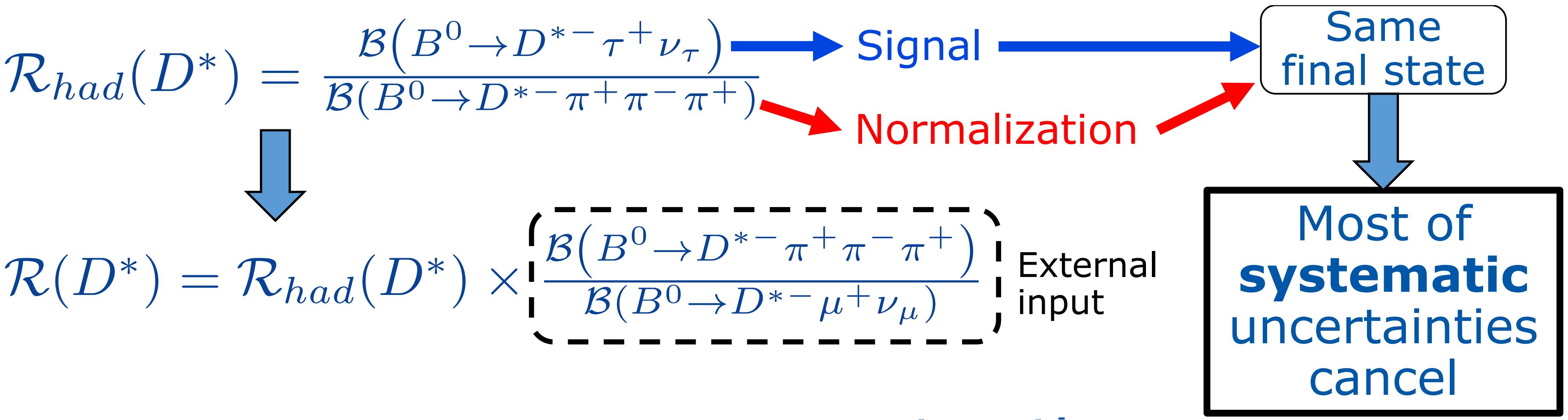


	Tag	Decay
BaBar (2012)	hadronic	$\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$
Belle (2015)	hadronic	$\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$
LHCb (2015)		$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
Belle (2016)	semi-leptonic	$\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$
Belle (2016)	hadronic	$\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$



R(D) and R(D*) exceed SM predictions by 2.2σ and 3.4σ respectively. Considering the R(D)-R(D*) correlation of -0.23, the resulting combined χ^2 is 18.62 for 2 degree of freedom, corresponding to a p-value of 8.8 x 10^{-5}. The difference with the SM predictions reported above, is at about 3.9σ.

Prospects of using $\tau^- \rightarrow a_1^- \nu_\tau$ at LHCb



$$\mathcal{R}_{had}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$$

Signal

Normalization

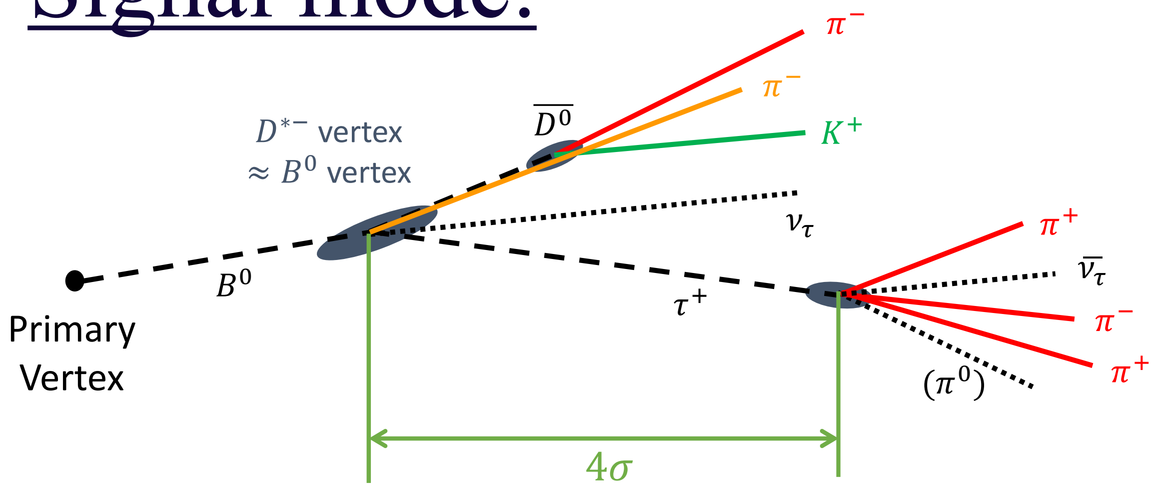
Same final state

Most of **systematic** uncertainties cancel

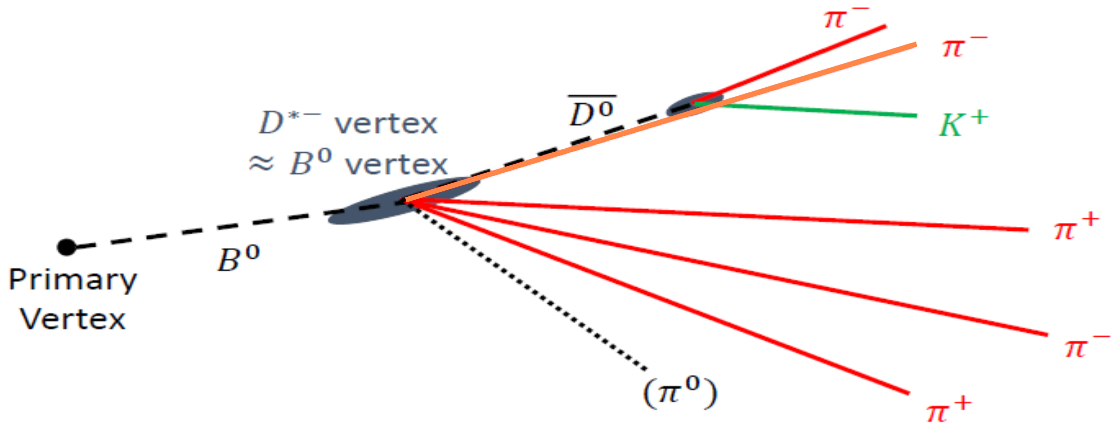
$$\mathcal{R}(D^*) = \mathcal{R}_{had}(D^*) \times \frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

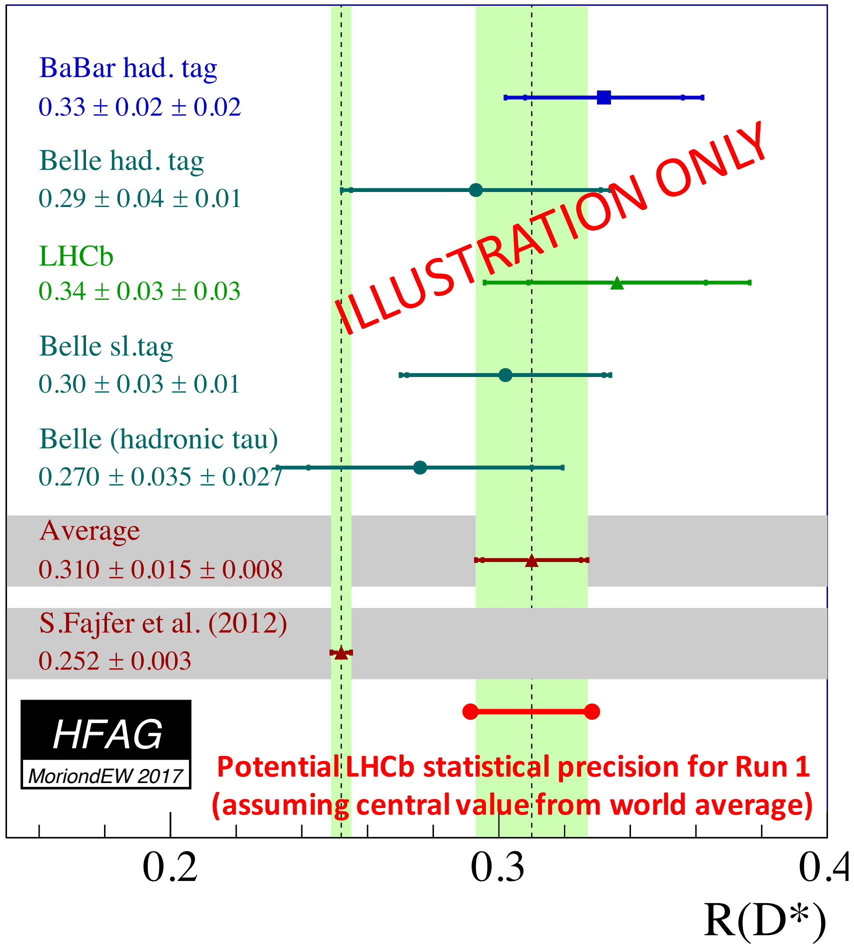
External input

Signal mode:



Normalization mode:

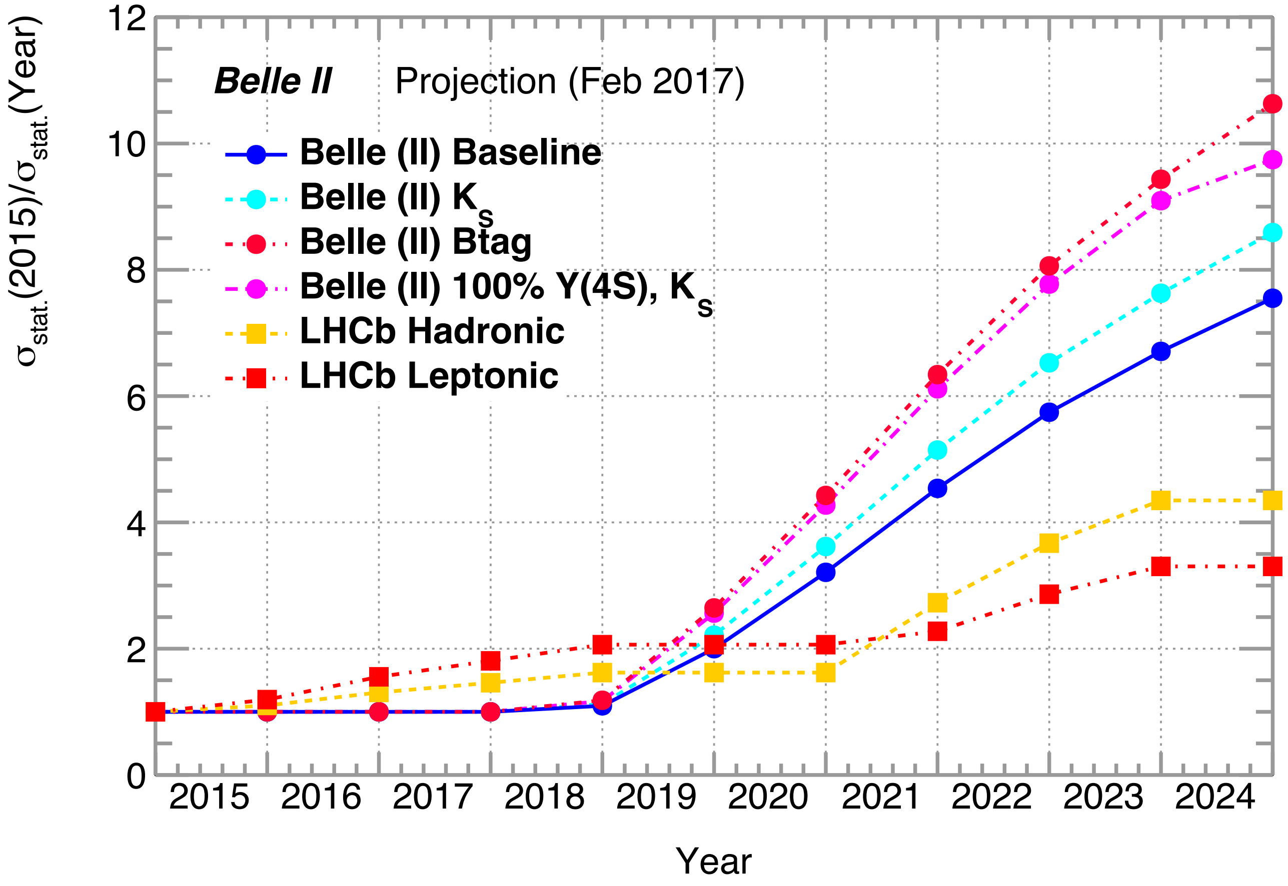


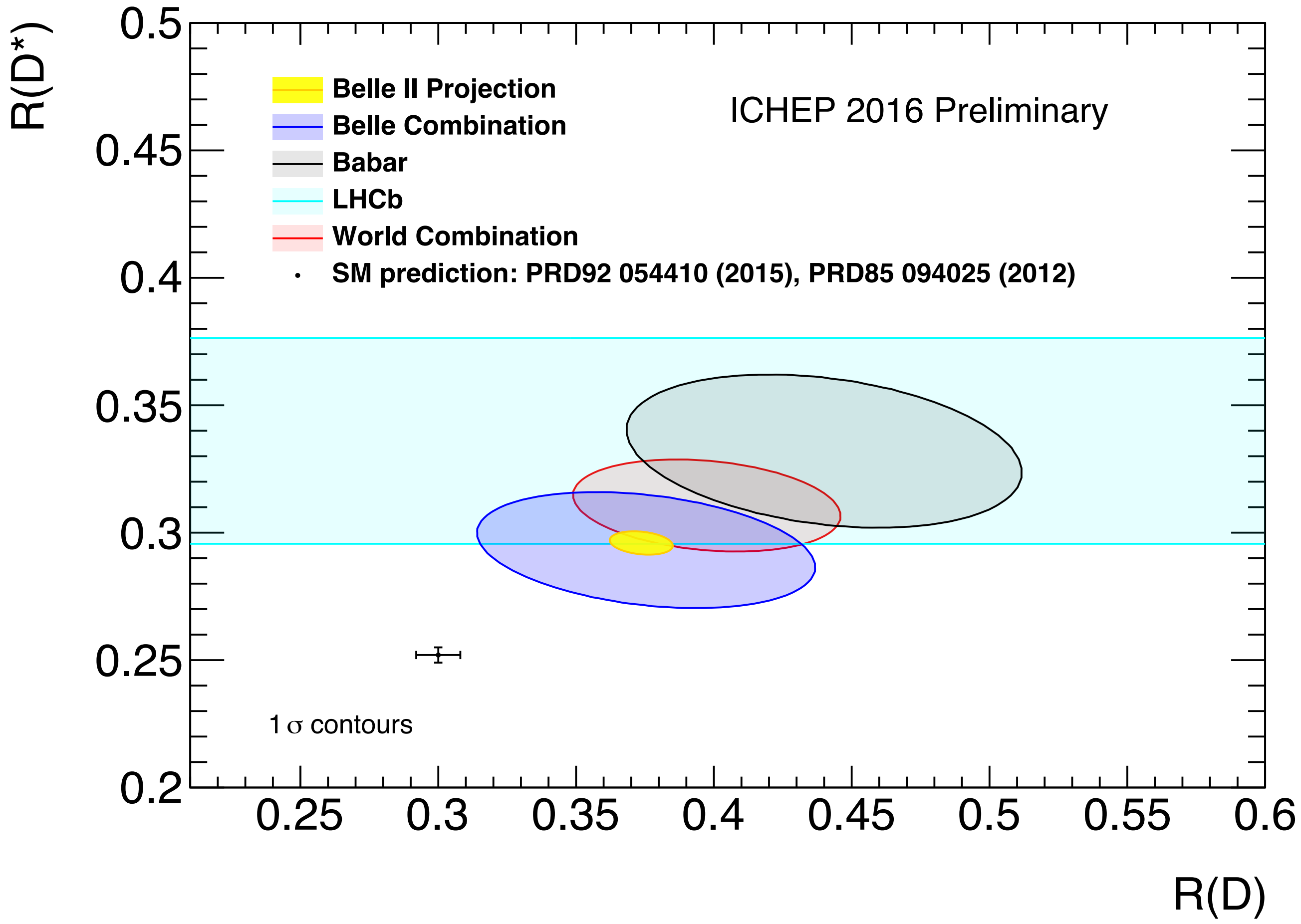


Potential LHCb statistical precision for Run 1 (assuming central value from world average)

Expect results later this year

Future prospects at Belle II

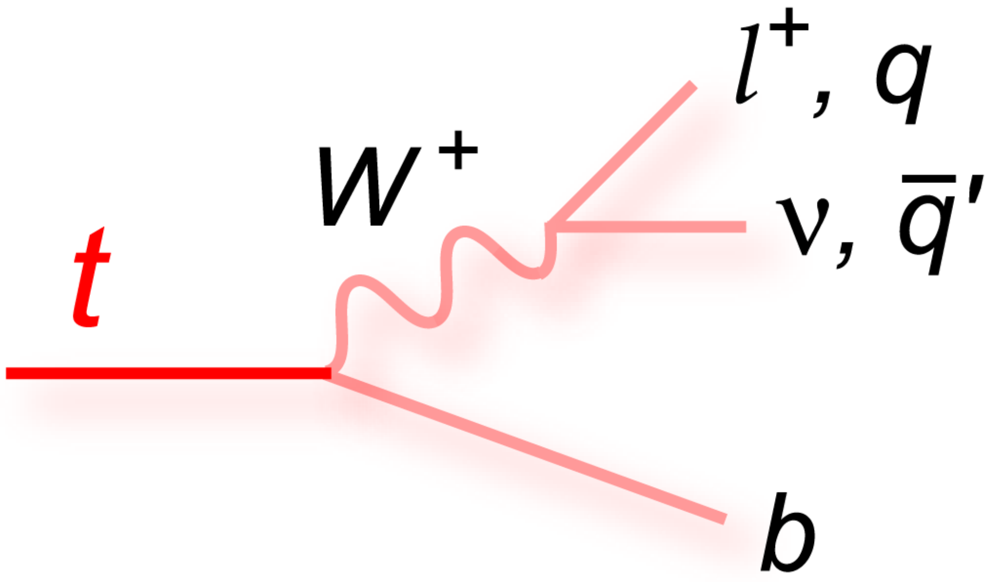




	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

Tau lepton from Top decays

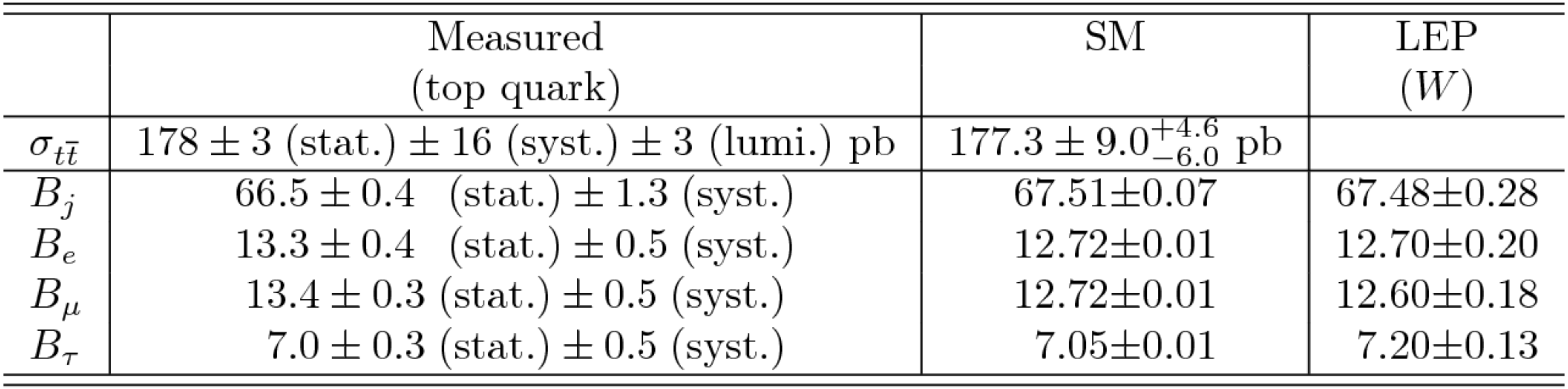
In the SM, BR of the t-quark into leptons are same.
But, in new physics models, the BR to τ-leptons could be different,
eg. via contributions from the charged Higgs ($t \to H^+ b$),
or decays containing supersymmetric stop quarks ($t \to \tilde{t} + X$).



At the LHC, pair production of $\tilde{t}$, decaying via $\tilde{t} \to b\, \nu_\tau\, \tilde{\tau}$ channel followed by $\tilde{\tau} \to \tau$ + gravitino could change BR to τ-leptons.
Predicted cross-section for pair production of $\tilde{t}$-quark is similar (or 12%) as that of pair production of t-quark for $m_{\tilde{t}} = 120$ (or 180) GeV. ICHEP2016 limits on $m_{\tilde{t}}$ from LHC are > 800 GeV.

Tau lepton from Top decays

Results presented here were recorded at center-of-mass energy of $\sqrt{s} = 7$ TeV,
the full 2011 data sample corresponding to an integrated luminosity of $\int L = 4.6\ \mathrm{fb}^{-1}$.
Reference: ATLAS Collaboration, Phys. Rev. D 92, 072005 (2015)

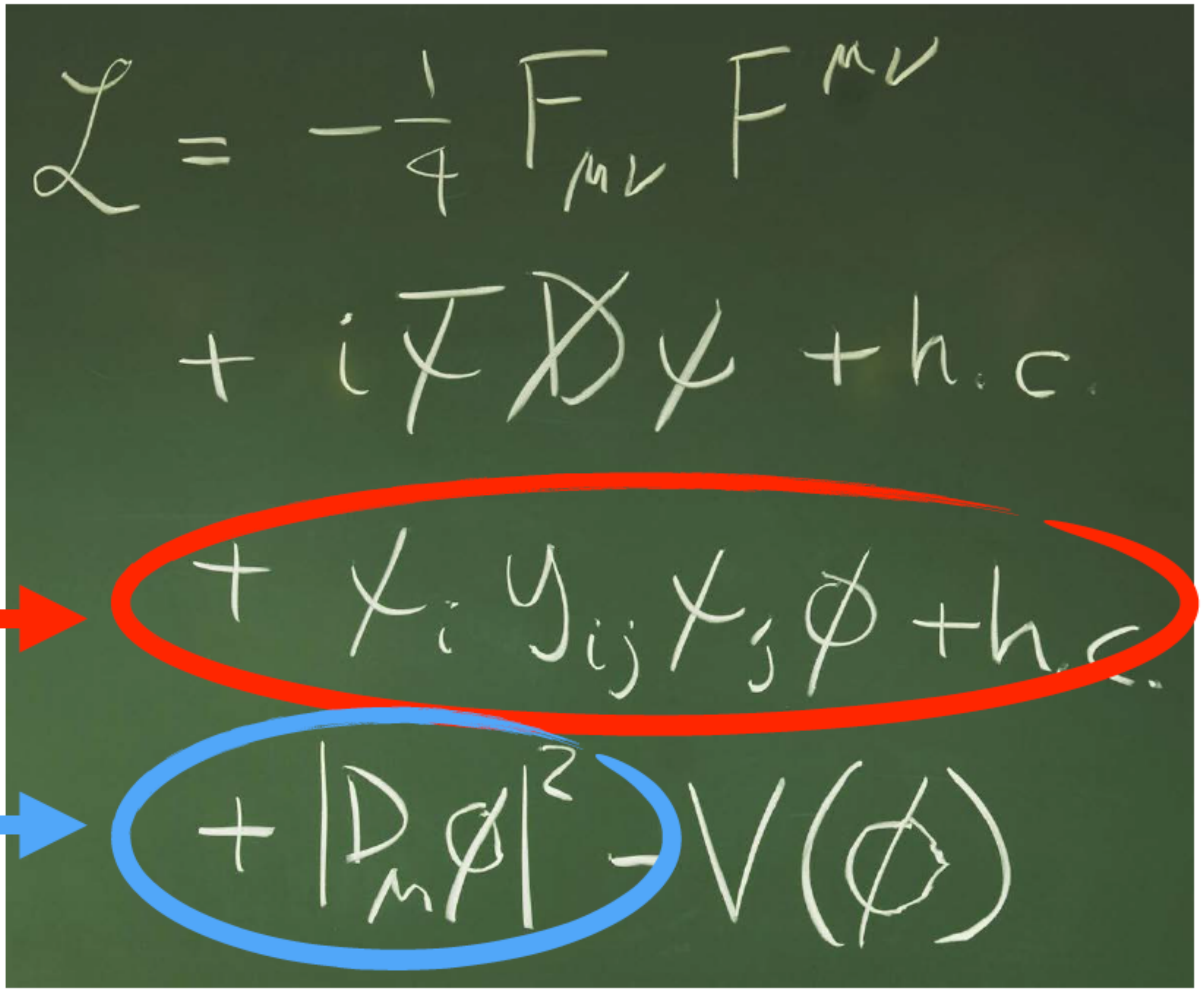


	Measured (top quark)	SM	LEP (W)
$\sigma_{t\bar{t}}$	178 ± 3 (stat.) ± 16 (syst.) ± 3 (lumi.) pb	$177.3 \pm 9.0^{+4.6}_{-6.0}$ pb	
B_j	66.5 ± 0.4 (stat.) ± 1.3 (syst.)	67.51±0.07	67.48±0.28
B_e	13.3 ± 0.4 (stat.) ± 0.5 (syst.)	12.72±0.01	12.70±0.20
B_μ	13.4 ± 0.3 (stat.) ± 0.5 (syst.)	12.72±0.01	12.60±0.18
B_τ	7.0 ± 0.3 (stat.) ± 0.5 (syst.)	7.05±0.01	7.20±0.13

- This analysis is the first measurement of top quark hadronic and semi-leptonic branching ratios. The precision ranges from 2.3% for $t \to$ jets to 7.6% for $t \to \tau_h + X$. The measured $\mathcal{B}_\tau$ will vary by more than observed uncertainty if $\mathcal{B}(\tilde{t} \to b\, \nu_\tau\, \tilde{\tau})$ times production cross-section of $\tilde{t}$-quark is > 3% of pair production of t-quark.

Origin of mass

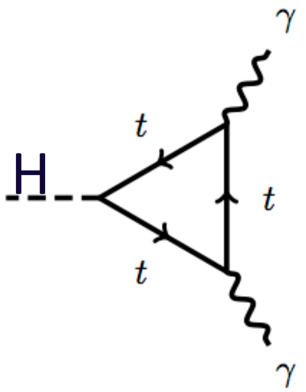
Direct observation of $H \rightarrow \tau^+\tau^-$ confirms the Higgs-like nature of the newly discovered particle.

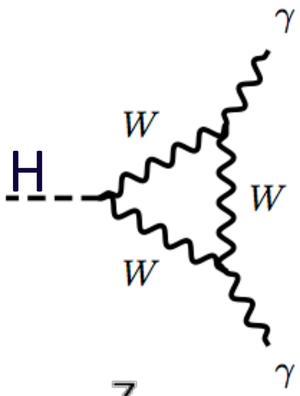


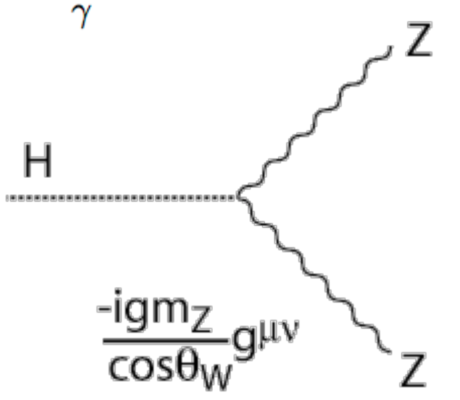
Fermions

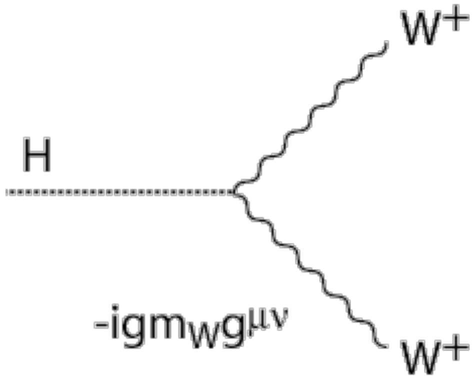
Bosons

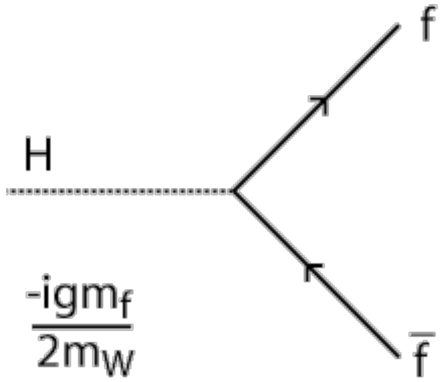
$B(H \rightarrow \tau^+\tau^-) \sim 6.3\%$ at 125 GeV
$B(H \rightarrow b\bar{b}) \sim 57.5\%$ at 125 GeV
but $\tau^+\tau^-$ has less backgrounds.





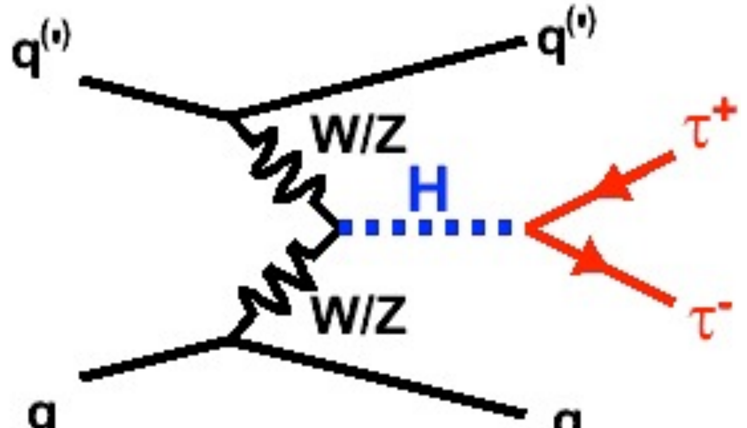




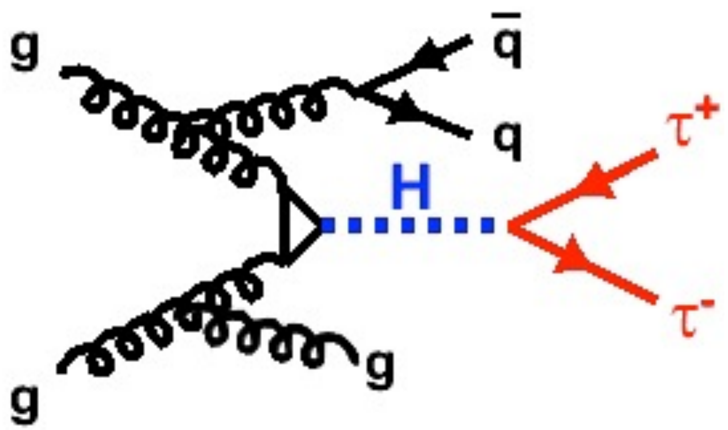


$H \rightarrow \tau^+\tau^-$: event topology

- Vector Boson Fusion (VBF) process (σ = 1.6 pb) with 2 well-separated jets
- Boosted Higgs recoiling against jets from gluon fusion process (σ = 19.4 pb)

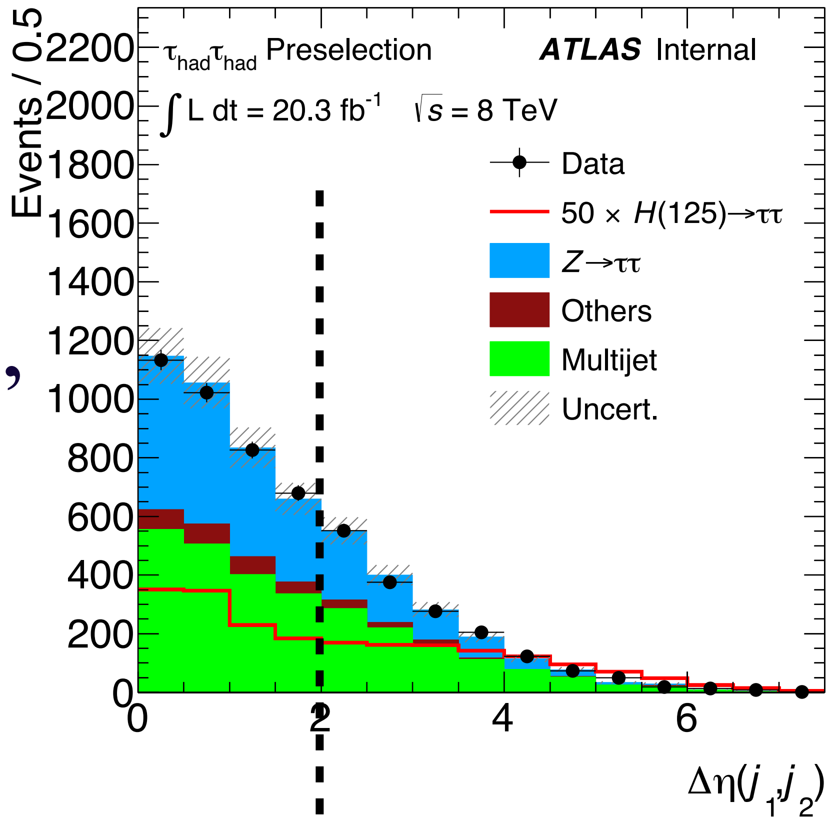


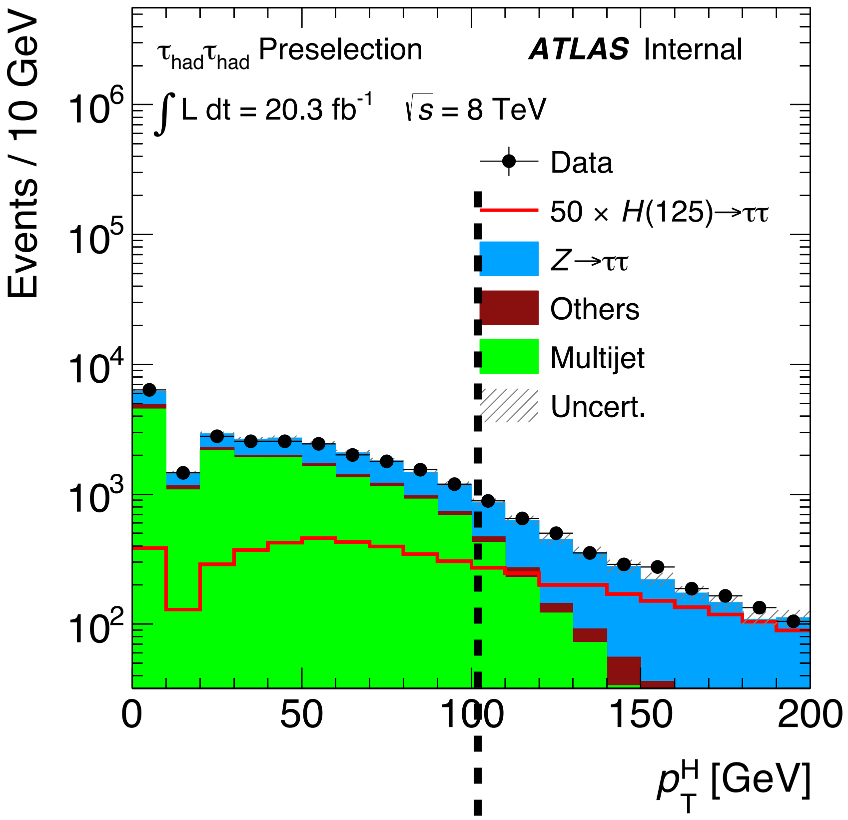
VBF Process



Gluon Fusion Process

"jet separation"



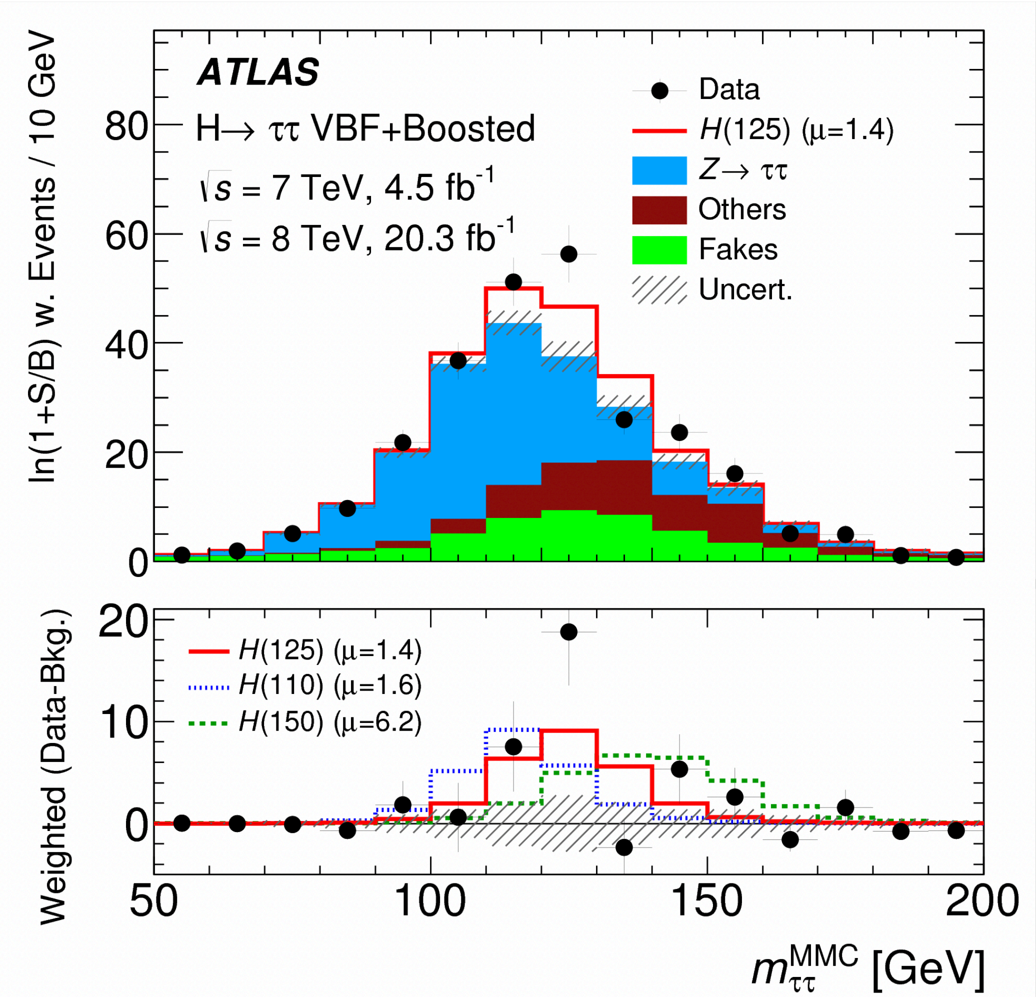


"total transverse momentum"

➔VBF

➔Boosted

$H \rightarrow \tau^+\tau^-$: status in Run1



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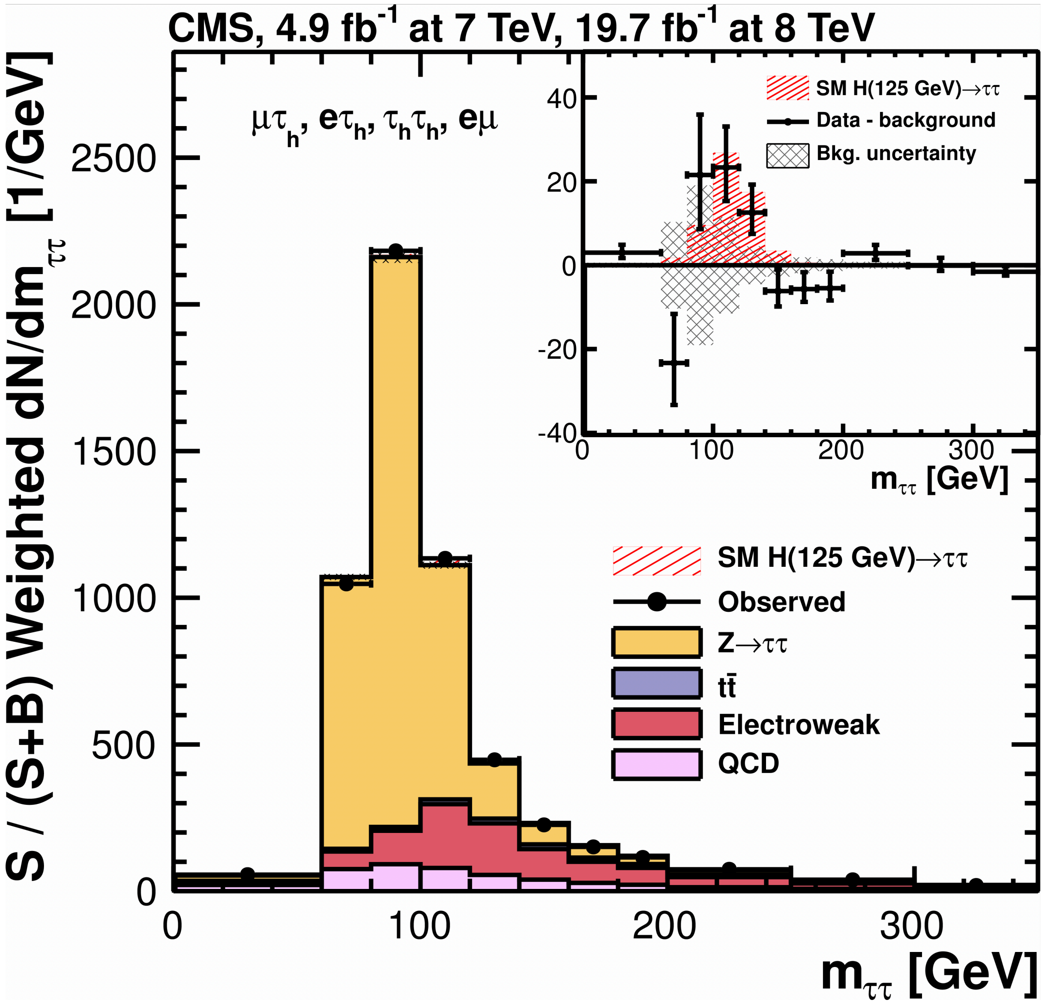

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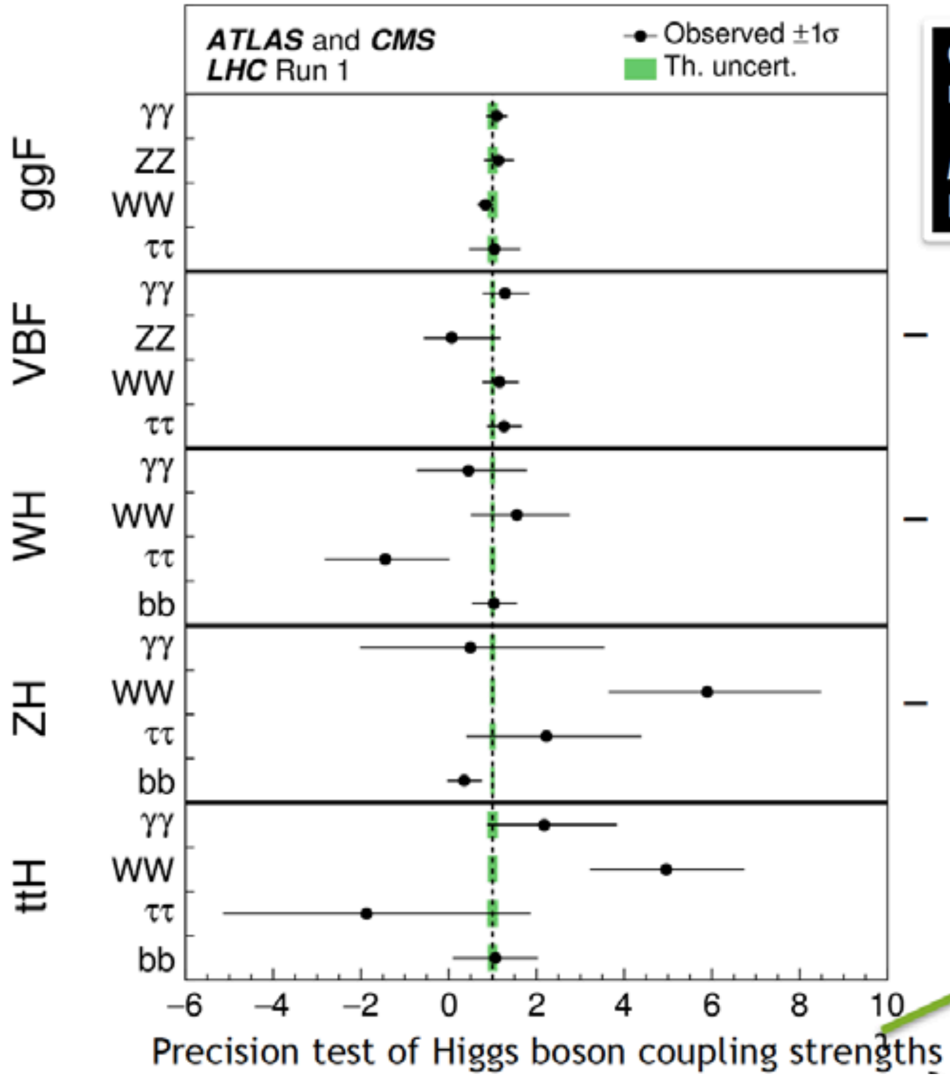
At 125 GeV	ATLAS	CMS
Observed Significance	4.5 σ	3.2 σ
Expected Significance	3.4 σ	3.7 σ
Signal Strength	1.40 +0.43 -0.37	0.78 ± 0.27

Highlights from Run1 at LHC



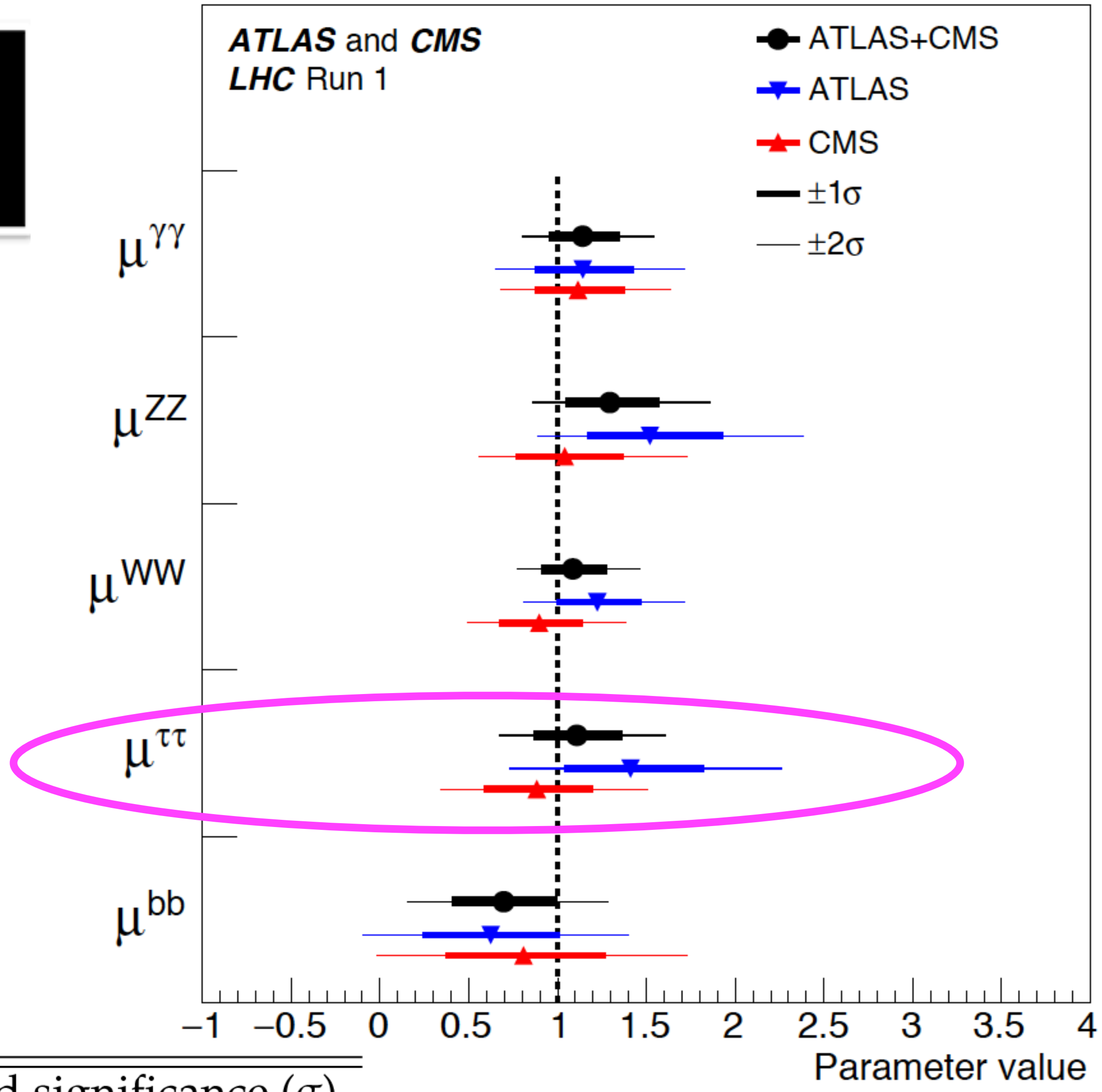
CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Mass: Phys. Rev. Lett. 114, 191803
Rates and couplings: arXiv:1606.02266

- Mass has been measured to 0.2% precision m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

Coupling strengths

$$\mu = \frac{\sigma}{\sigma_{SM}}$$



Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Combined > 5σ

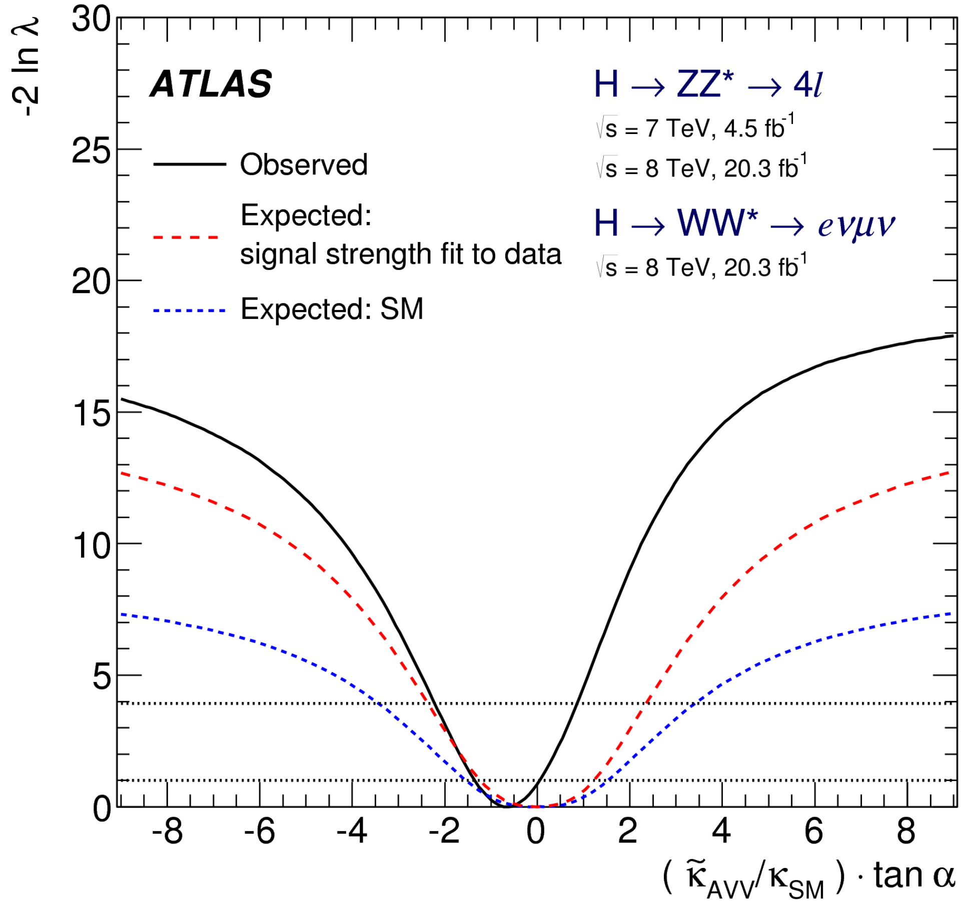
Higgs Parity

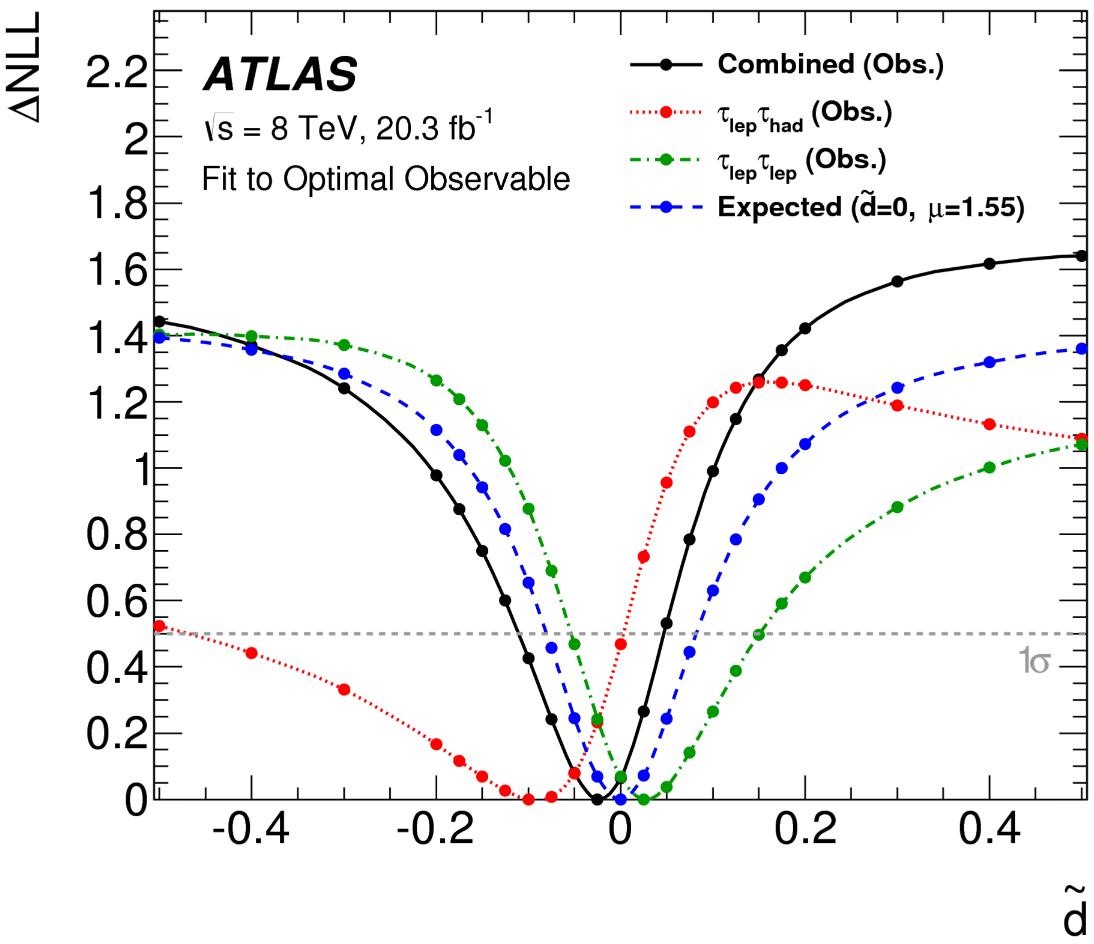
HWW: 2D distributions of BDT discriminants

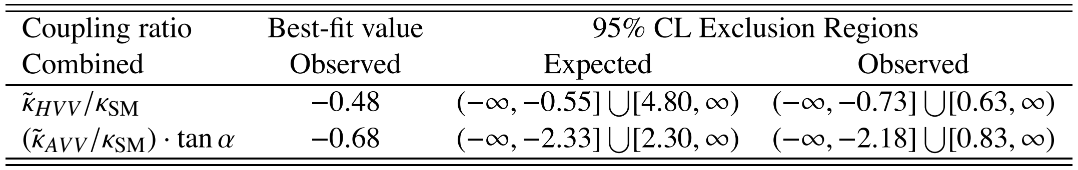
HZZ: ATLAS: 9D
($p_T^{4\ell}$, $\eta_{4\ell}$, $m_{4\ell}$, $m_{1,2}$, $\cos\theta_{1,2}$, ϕ, $\cos\theta^*$)

Hττ: $$O_1 = \frac{2\,\mathrm{Re}(M^*_{\mathrm{SM}} M_{\mathrm{odd}})}{|M_{\mathrm{SM}}|^2}$$

$$-\tilde{d} = \hat{\kappa}_V = \tilde{\kappa}_V / \kappa_{\mathrm{SM}} \tan\alpha \qquad M_{\mathrm{tot}} = M_{\mathrm{SM}} + \tilde{d} \cdot M_{\mathrm{odd}}$$

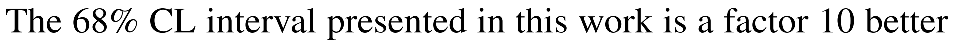






Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	−0.48	$(-\infty,-0.55]\bigcup[4.80,\infty)$	$(-\infty,-0.73]\bigcup[0.63,\infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}})\cdot\tan\alpha$	−0.68	$(-\infty,-2.33]\bigcup[2.30,\infty)$	$(-\infty,-2.18]\bigcup[0.83,\infty)$

violation. The regions $d < -0.11$ and $d > 0.05$ are excluded at 68% CL. The expected confidence intervals are $[-0.08, 0.08]$ ($[-0.18, 0.18]$) for an assumed signal strength of $\mu = 1.55$ (1.0). The constraints on the



The 68% CL interval presented in this work is a factor 10 better

68%

(-α,-1.5)U(1,α) (-α,-1.5)U(0,α)

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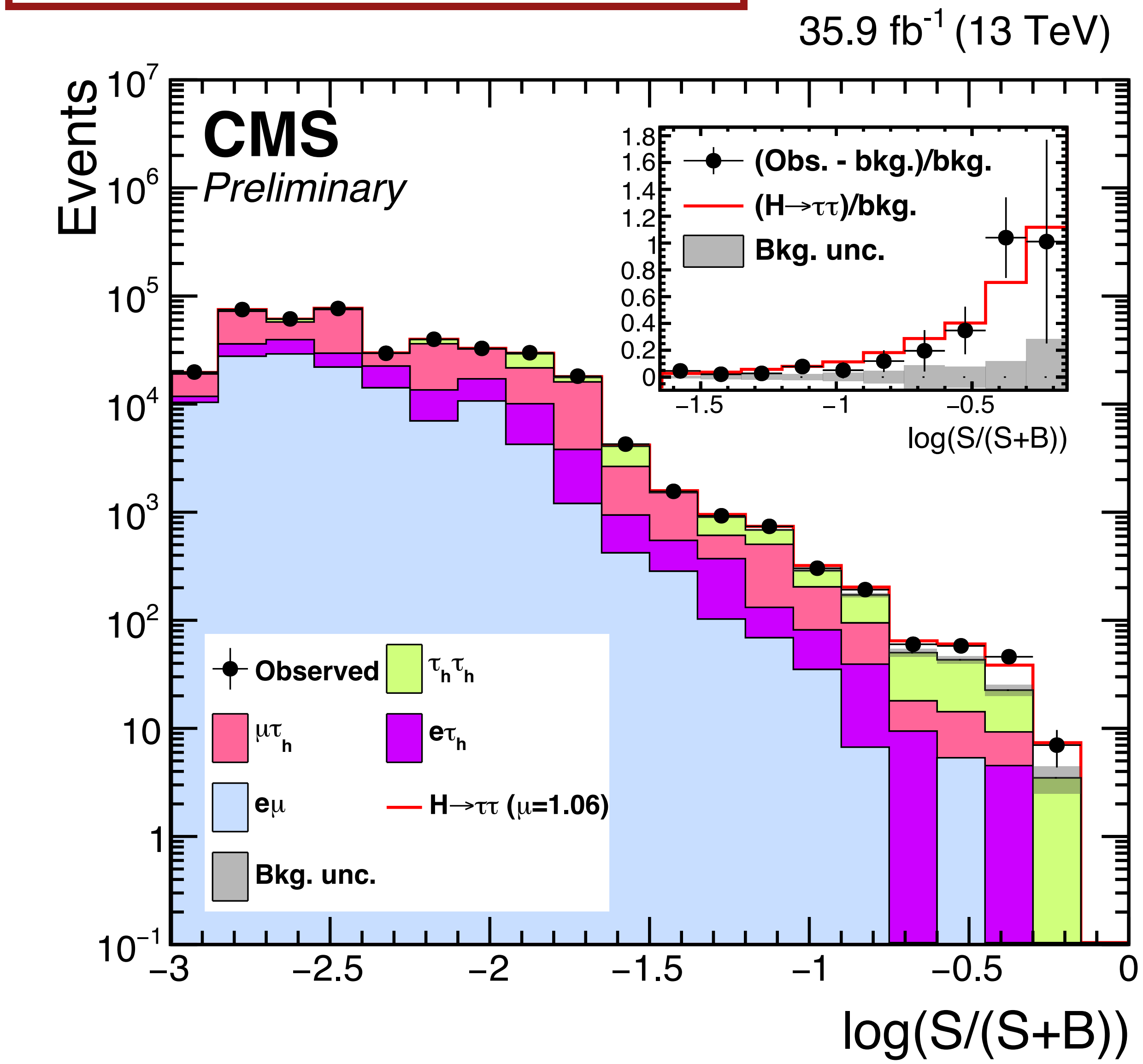
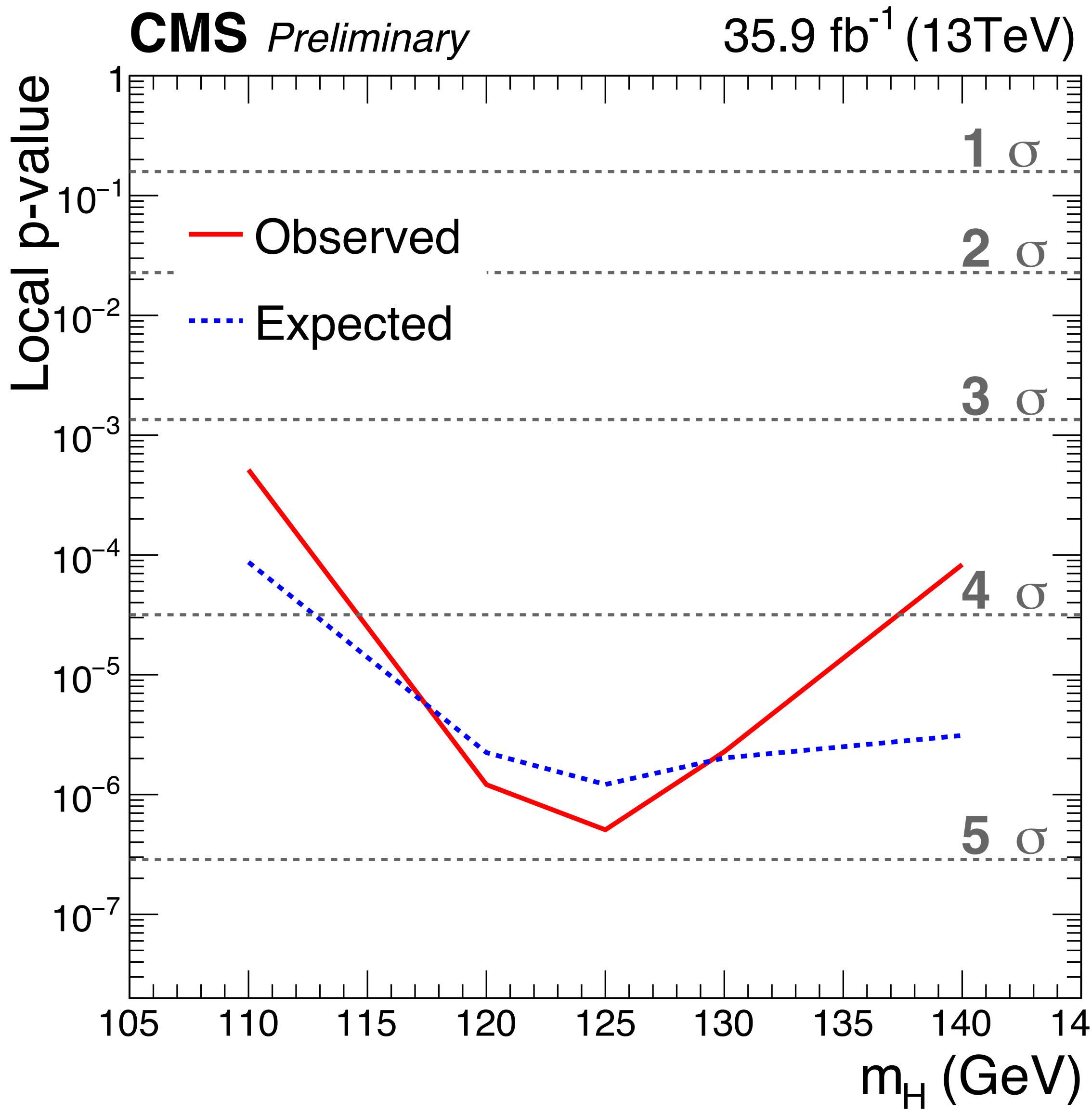
$H \rightarrow \tau^+\tau^-$: status in Run2

LHCP (May 2017)
Update from CMS:

HIG-16-043

- Four decay topologies for $\tau^+\tau^-$: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Three production modes: 0-jet (gg), VBF, boosted (additional objects)





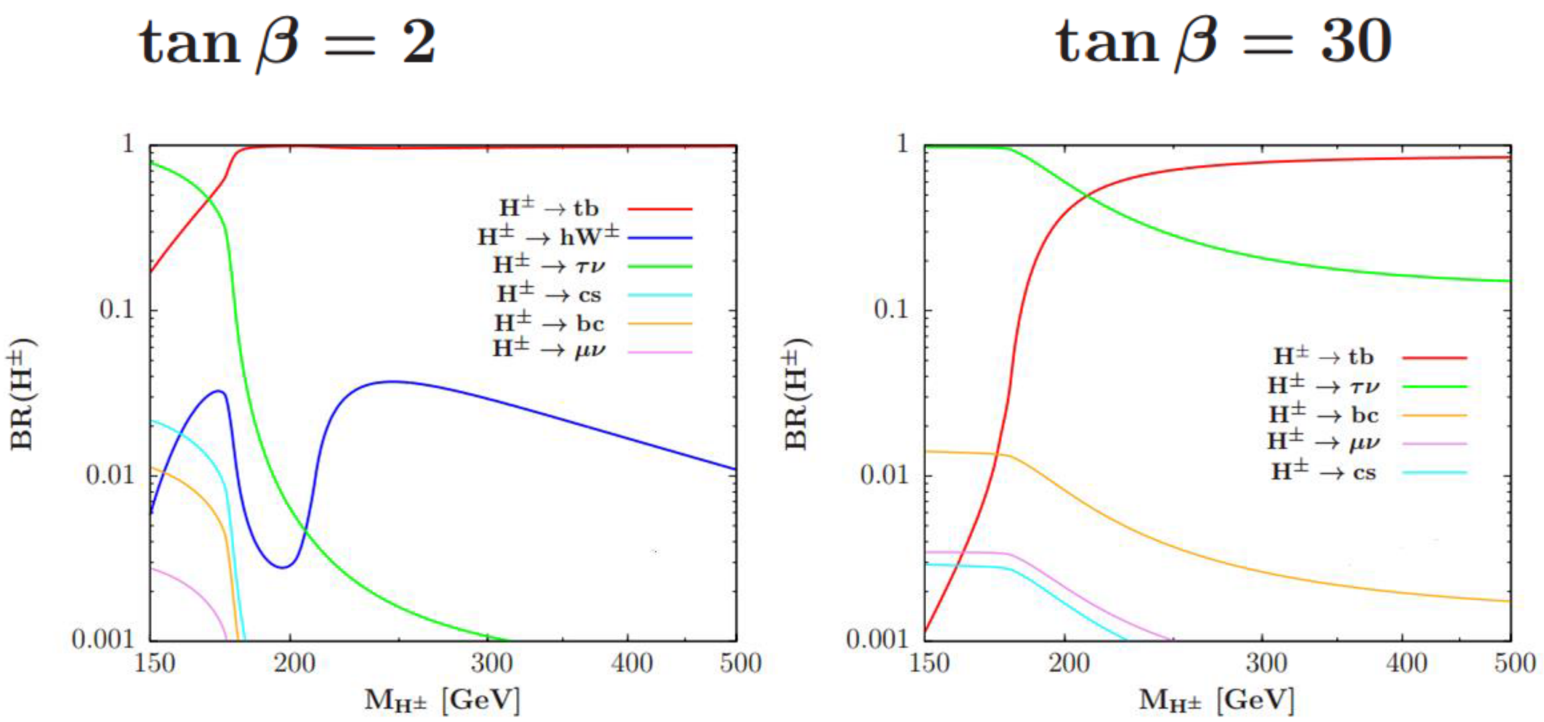
➢ **$H\rightarrow\tau\tau$ has been updated with full 2016 luminosity.**

$\mu = 1.06 +0.25 -0.24$

Expected: 4.7σ, Observed: 4.9σ

Combined CMS will be > 5σ

Charged Higgs decay modes



A. Djouadi, L. Maiani, A. Polosa, J. Quevillon, V. Riquer (**arXiv:1502.05653**)

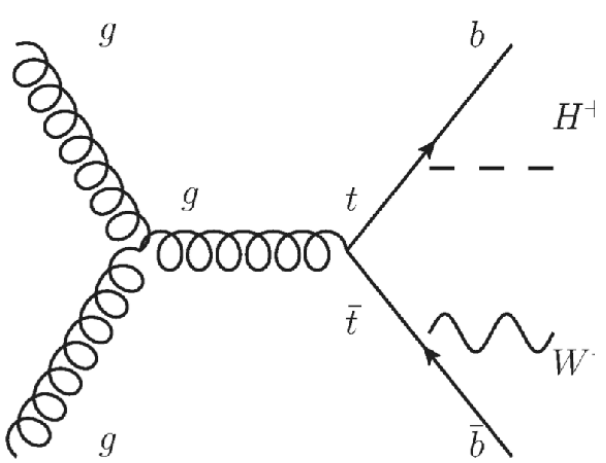
- **two different scenarios:**

heavy charged Higgs: **$m_{H\pm} > m_t - m_b$**

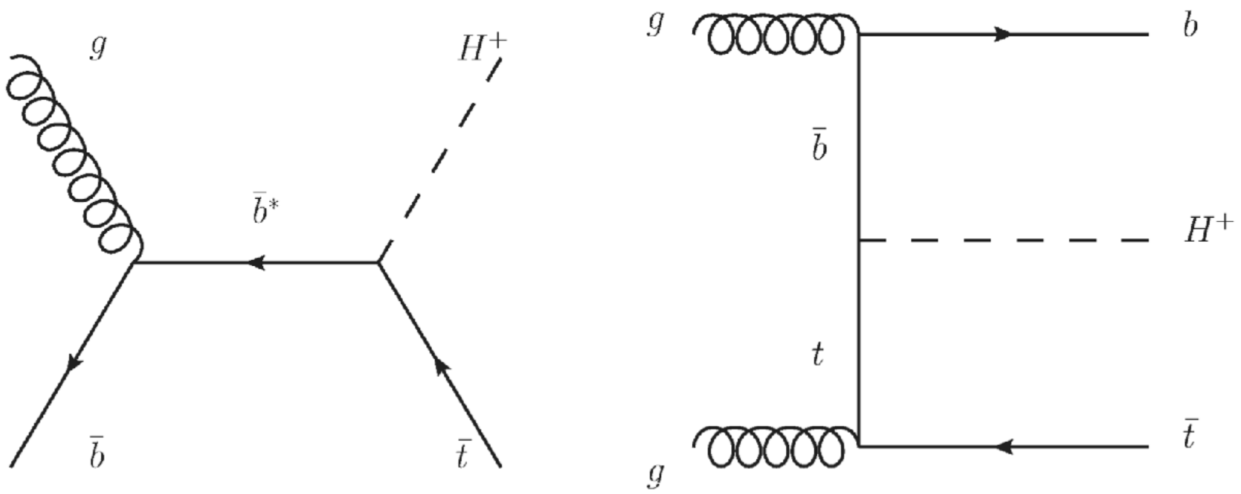
light charged Higgs: **$m_{H\pm} < m_t - m_b$**

sensitivity dominated by H±→tb

sensitivity dominated by H±→τν

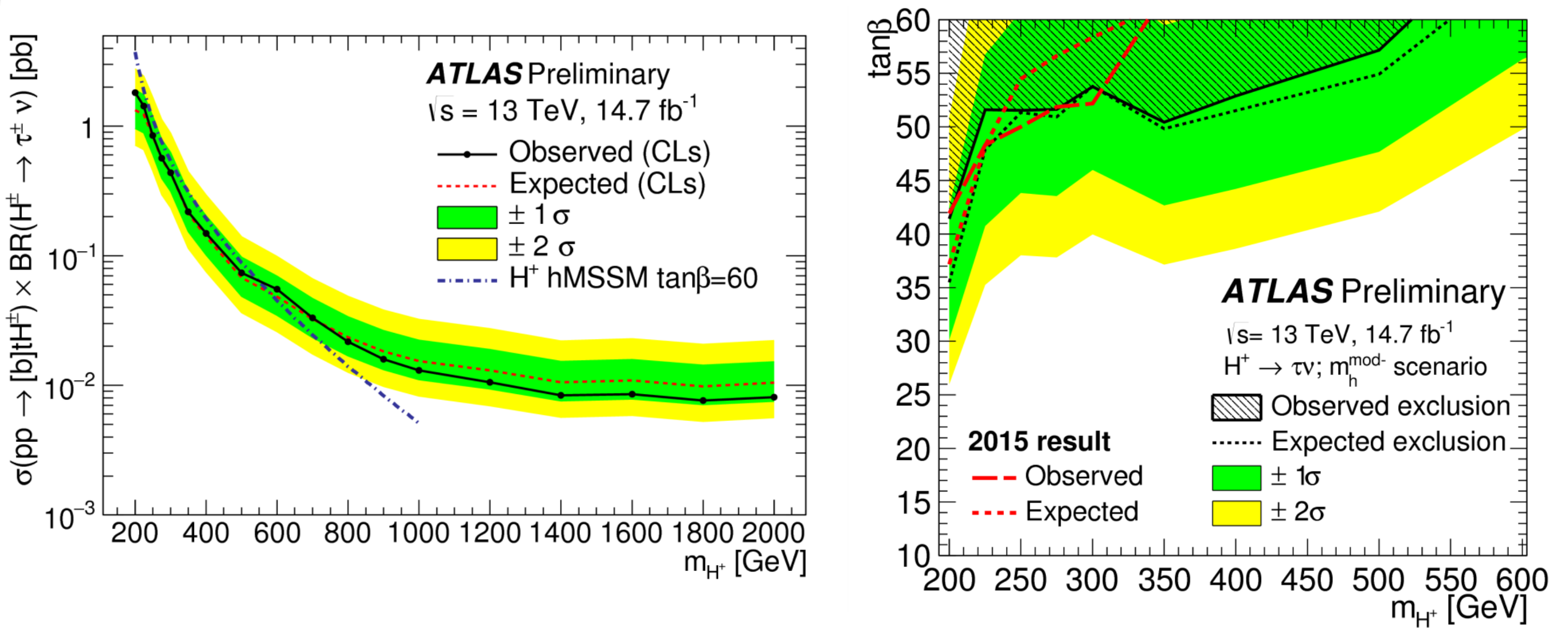


light H±

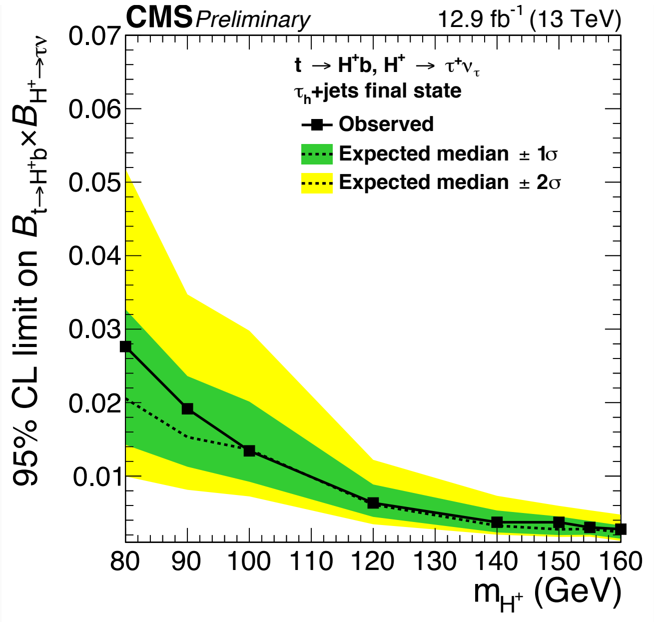


heavy H±

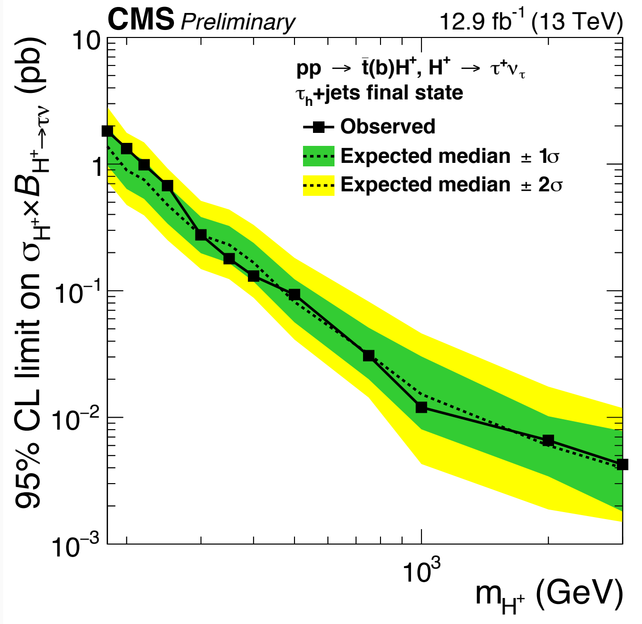
$H^{\pm} \rightarrow \tau\nu$: status in Run2



For 14.7 fb^{-1} @ 13 TeV, in mass range of m_H = 200-2000 GeV, upper limits were set in range of 2.0 pb^{-1} to 8fb^{-1}



m_{H^+} = 80–160 GeV
Observed limit: 2.8–0.28%



m_{H^+} = 180–3000 GeV
Observed limit: 1.8–0.0042 pb

- **light H± almost ruled out in MSSM m_h^{mod+}** (and most of other) **scenario**(s)

Lots of interesting physics with tau's