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University of Ljubljana/Jožef Stefan Institute
& Belle/Belle II Collaboration

University of Ljubljana

"Jožef Stefan" Institute

Heavy Flavor 2016
Quo Vadis?

Introduction

(Examples of...)
LFU

LFV

CPV

Summary

"SuperKEKB" Accelerator

e^- (HER): 7.0 GeV
e^+ (LER): 4.0 GeV

$E_{cms} = m(\Upsilon(4S))c^2$

$dN_f/dt = \sigma(e^+e^- \to f)\,\mathcal{L}$
$\mathcal{L} = 8\text{x}10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$

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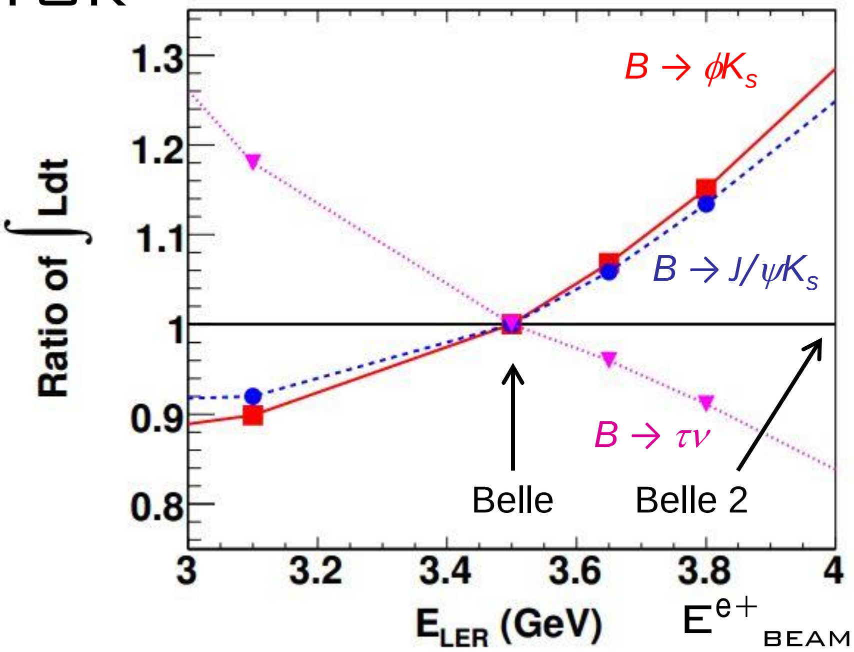
Lumi ratio for same sensitivity



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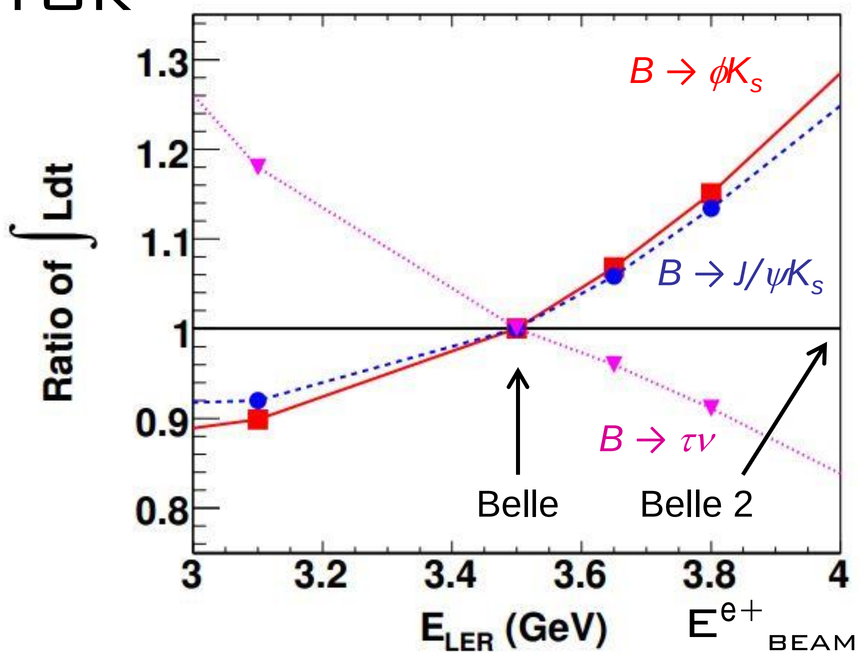
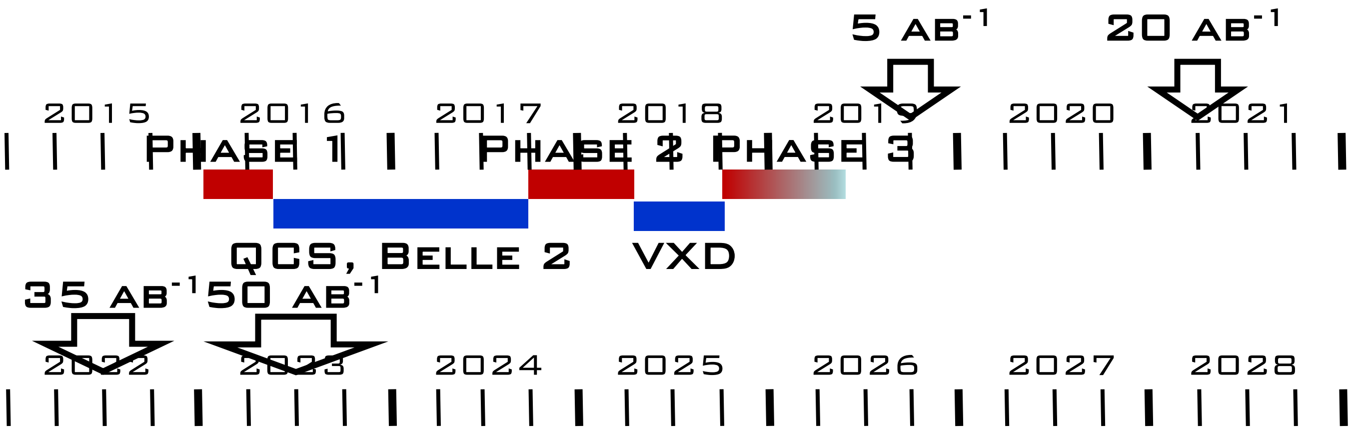


E^{e+}_{beam}



Phase 1:
w/o QCS, Belle 2
Phase 2:
w/ QCS, Belle 2
(no VXD)
Phase 3:
full Belle 2

Methods and processes where Belle 2 can provide important insight into NP complementary to other experiments:

E_{miss}:
$\mathcal{B}(B \to \tau\nu)$, $\mathcal{B}(B \to X_c \tau\nu)$, $\mathcal{B}(B \to h\nu\nu)$,...

(Semi)Inclusive:
$\mathcal{B}(B \to s\gamma)$, $A_{CP}(B \to s\gamma)$, $\mathcal{B}(B \to s\ell\ell)$, ...

Neutrals:
$S(B \to K_S \pi^0 \gamma)$, $S(B \to \eta' K_S)$, $S(B \to K_S K_S K_S)$, $\mathcal{B}(\tau \to \mu\gamma)$, $\mathcal{B}(B_s \to \gamma\gamma)$, ...

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Detailed description of physics program at Belle 2 in:

A.G. Akeroyd et al., arXiv: 1002.5012

Physics at Super B Factory

Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley, Eur. Phys. J. C74 (2014) 3026

The Physics of the B Factories

B. O'Leary et al., arXiv: 1008.1541

Super$B$
Progress Reports
Physics

B.G.,, K, Trabelsi, P. Urquijo, BELLE2-NOTE-PH-2015-002

Impact of Belle II on Flavor Physics

P. Urquijo, BELLE2-NOTE-PH-2015-002

Belle II - LHCb measurement extrapolation comparisons

$B \to \tau\nu,\ H\nu\nu,\ X_c\tau\nu,...$

possible to reconstruct
events with ν's;

LFU/Missing energy

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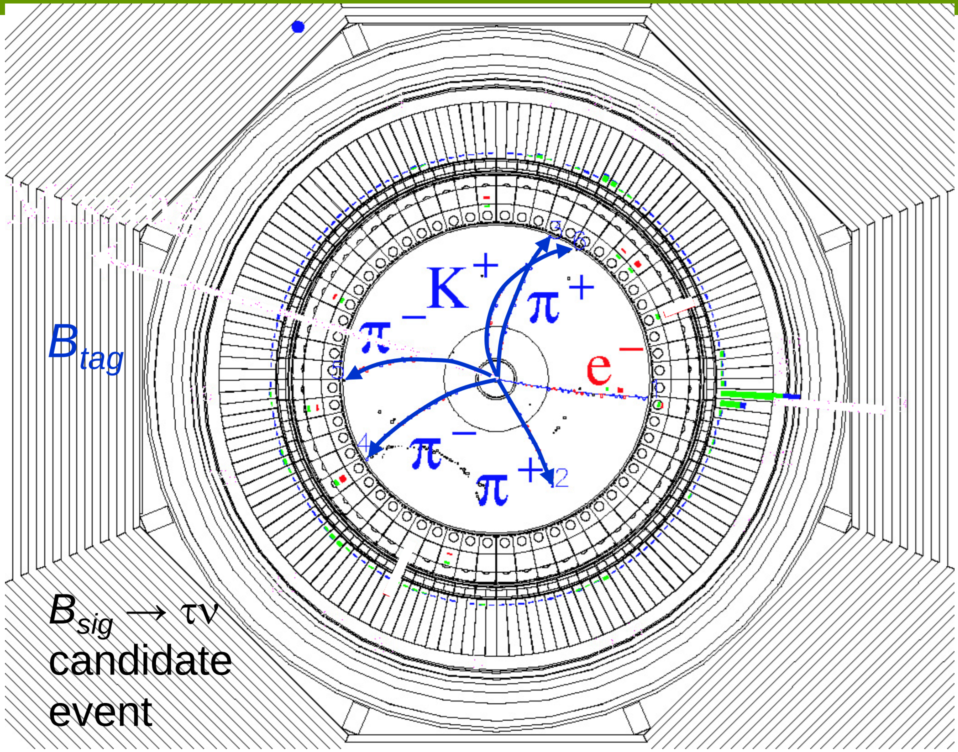
possible to reconstruct events with ν's;

fully (partially) reconstruct B_{tag};



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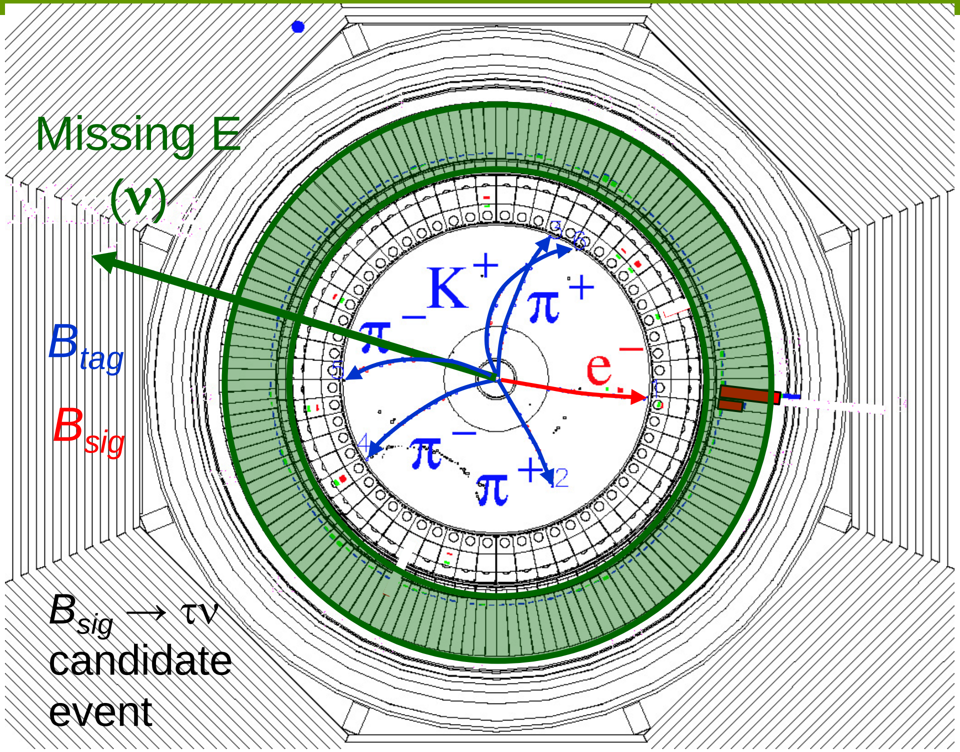
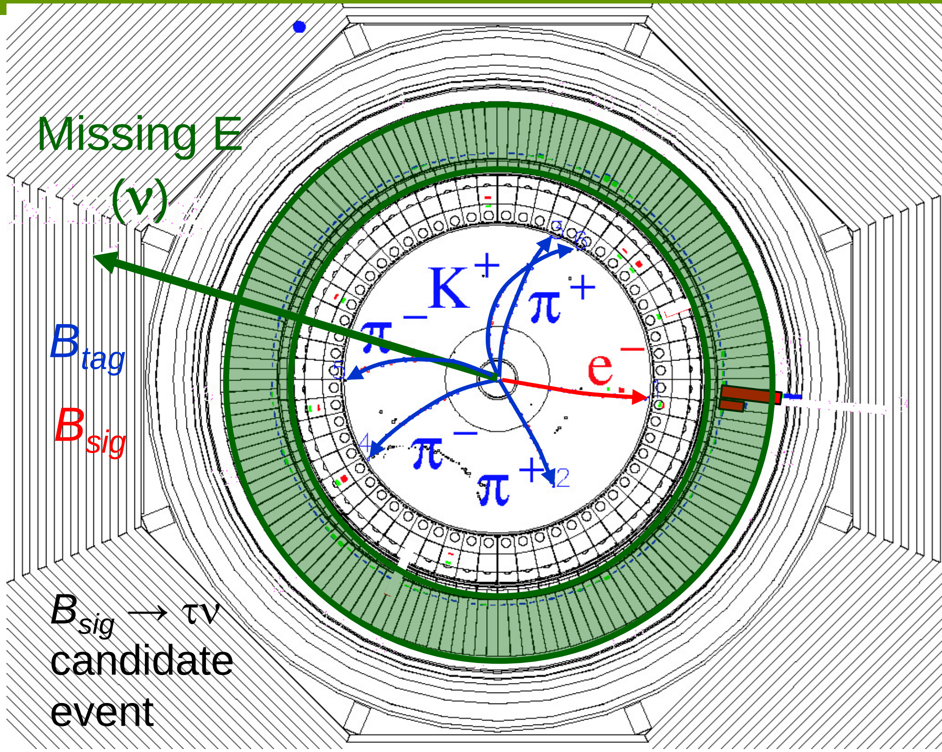
possible to reconstruct events with ν's;

fully (partially) reconstruct B_{tag};
reconstruct $H^{\pm}$ from B_{sig};
no additional energy in EM calorim.;
signal at $E_{ECL}\sim 0$;



LFU/Missing energy

$B \to \tau\nu,\ H\nu\nu,\ X_c\tau\nu, \ldots$



possible to reconstruct events with ν's;

fully (partially) reconstruct B_{tag};
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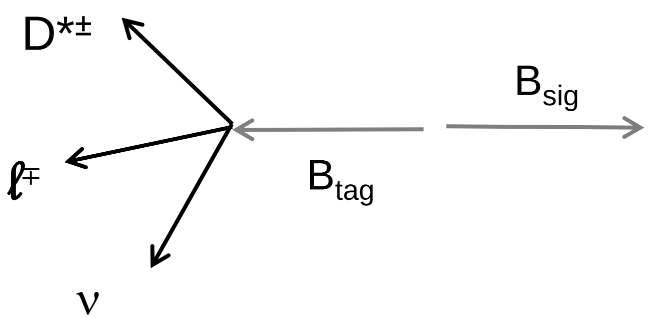
signal at $E_{ECL} \sim 0$;

Partial reconstruction (semileptonic tagging):

$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\text{beam}}E_{D^*\ell} - m_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|}$$



$\varepsilon_{TAG} \sim 1\,\%$

LFU/Missing energy

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

Belle, arXiv:1603.06711, 700 fb^{-1}

$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)} \qquad \ell = e, \mu$$

R(D$^{(*)}$)

$R(D)_{SM} = 0.300 \pm 0.008$

H. Na et al., Phys.Rev.D 92, 054410 (2015)

$R(D^*)_{SM} = 0.252 \pm 0.003$

S.Fajfer et al., Phys.Rev.D85(2012) 094025

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$$M^2_{\rm miss} = (p_{e^+e^-} - p_{\rm tag} - p_{D^{(*)}} - p_\ell)^2/c^2$$

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use NN with $M^2_{\rm miss}$, $E_{\rm vis}$, $\cos\theta_{B\text{-}D^*\ell}^{\rm sig}$.

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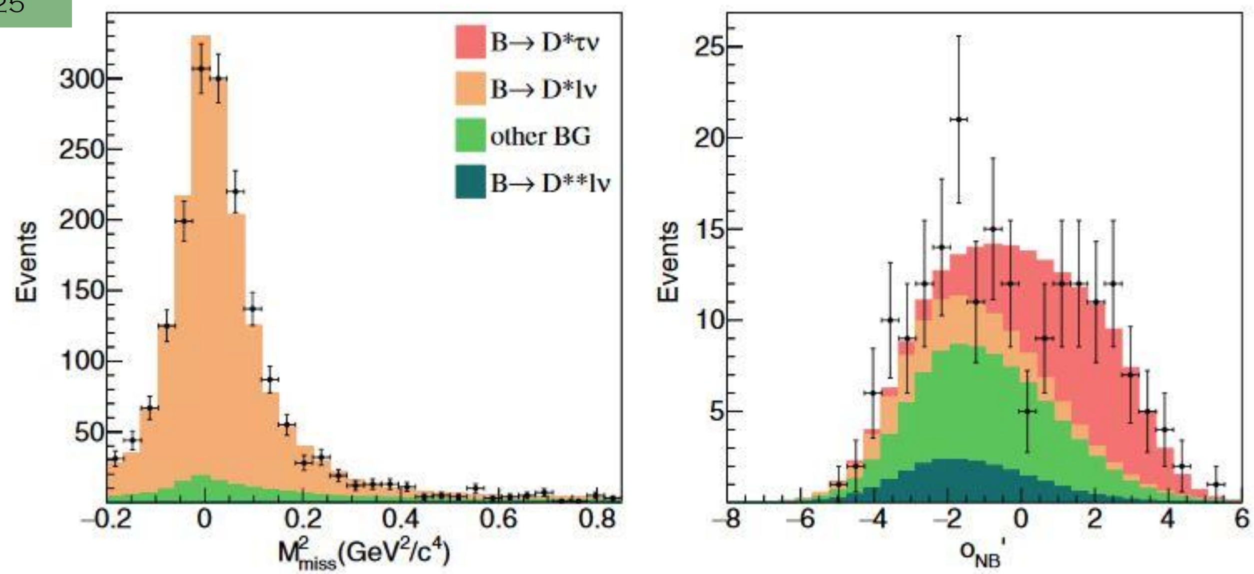
use NN with $M^2_{\rm miss}$, $E_{\rm vis}$, $\cos\theta_{B\text{-}D^*\ell}^{\rm sig}$.

data sample with low $M^2_{\rm miss}$ used to fit the background contribution



signal is to the right →

NN output for data with $M^2_{\rm miss} > 0.85$ GeV^2

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

R(D*)=0.302±0.030±0.011

Belle, arXiv:1603.06711, 700 fb^{-1}

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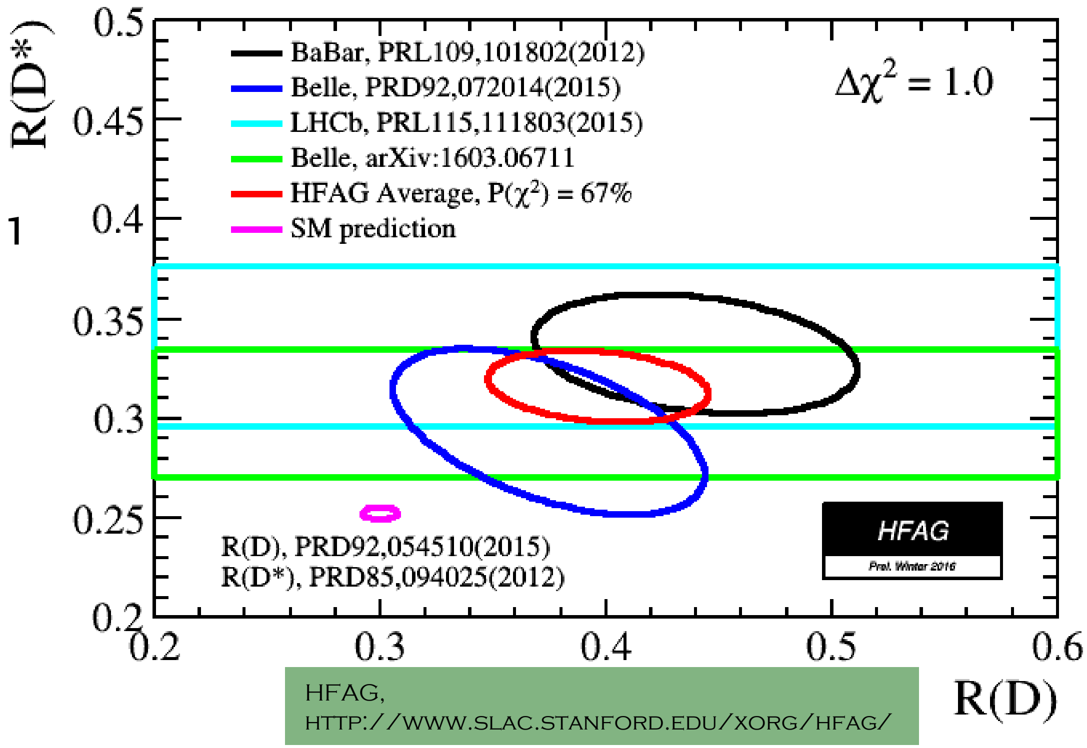


HFAG, http://www.slac.stanford.edu/xorg/hfag/

4σ discrepancy with SM

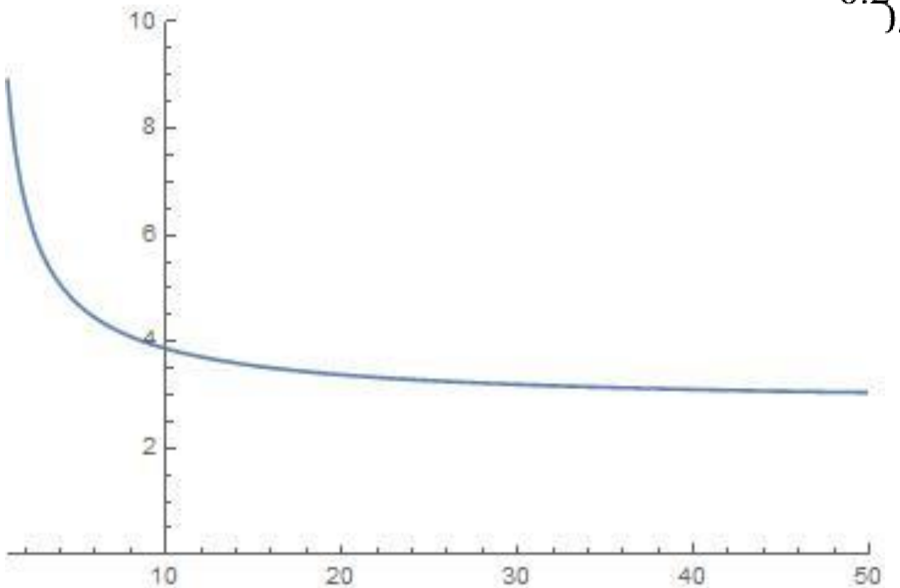
LFU/Missing energy

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

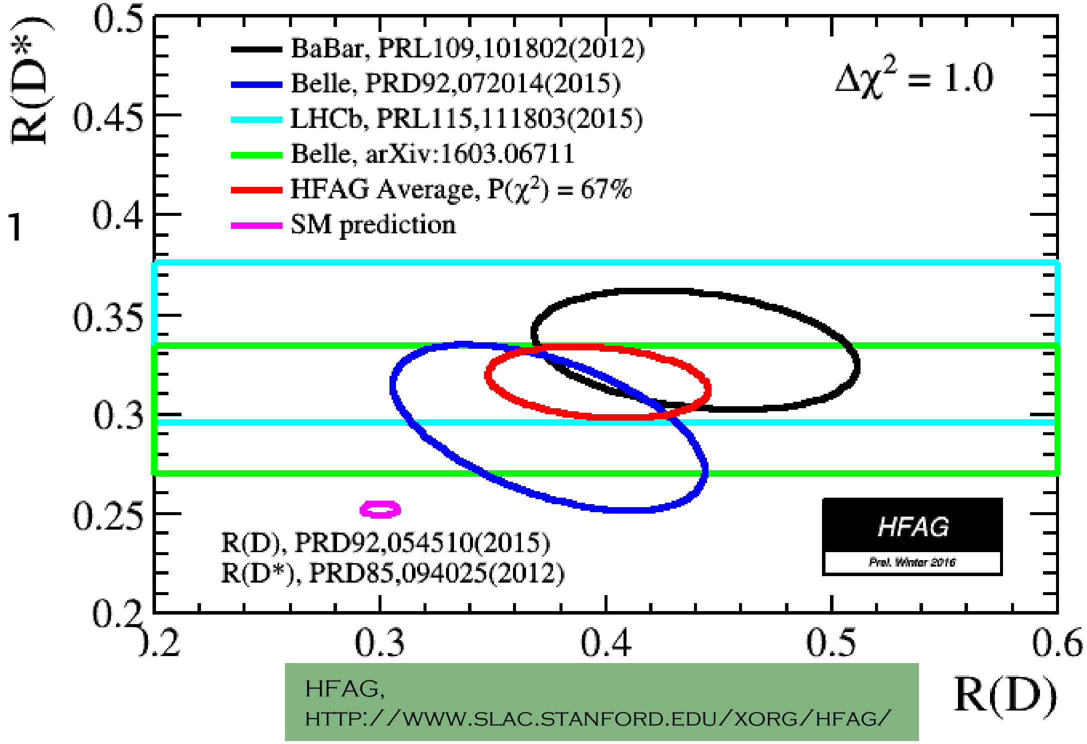
$R(D^*) = 0.302 \pm 0.030 \pm 0.011$

Belle, arXiv:1603.06711, 700 fb^{-1}

$\sigma(R(D^*))/R(D^{(*)})[\%]$



$\mathcal{L}$ [ab^{-1}]



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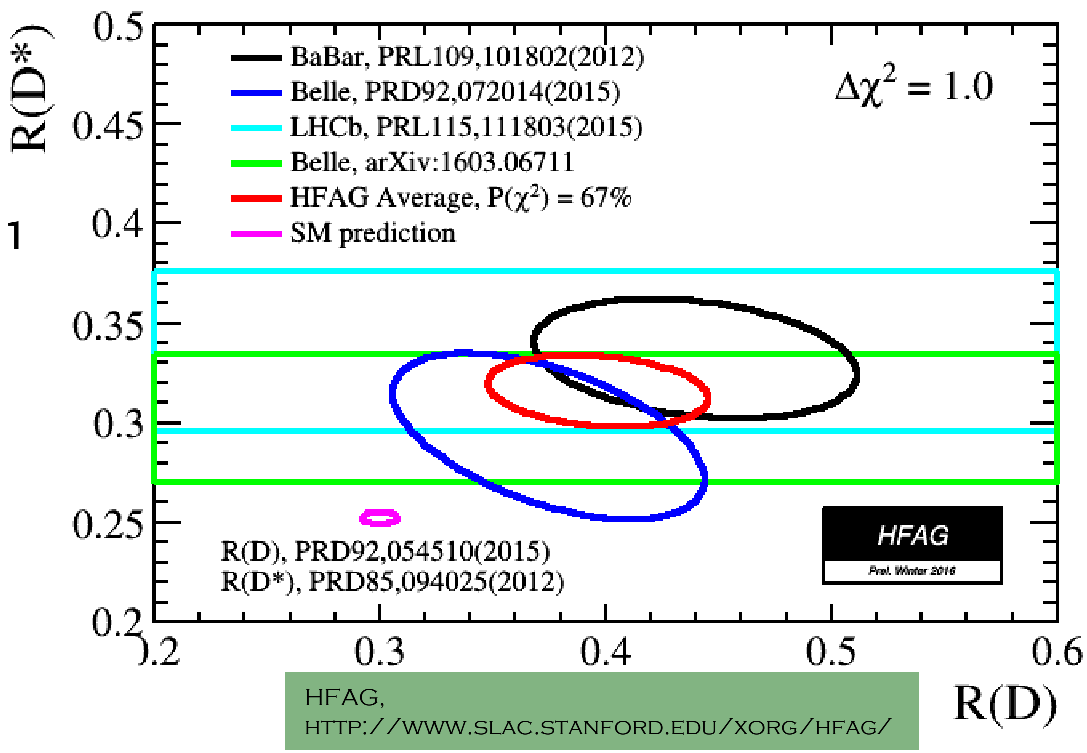

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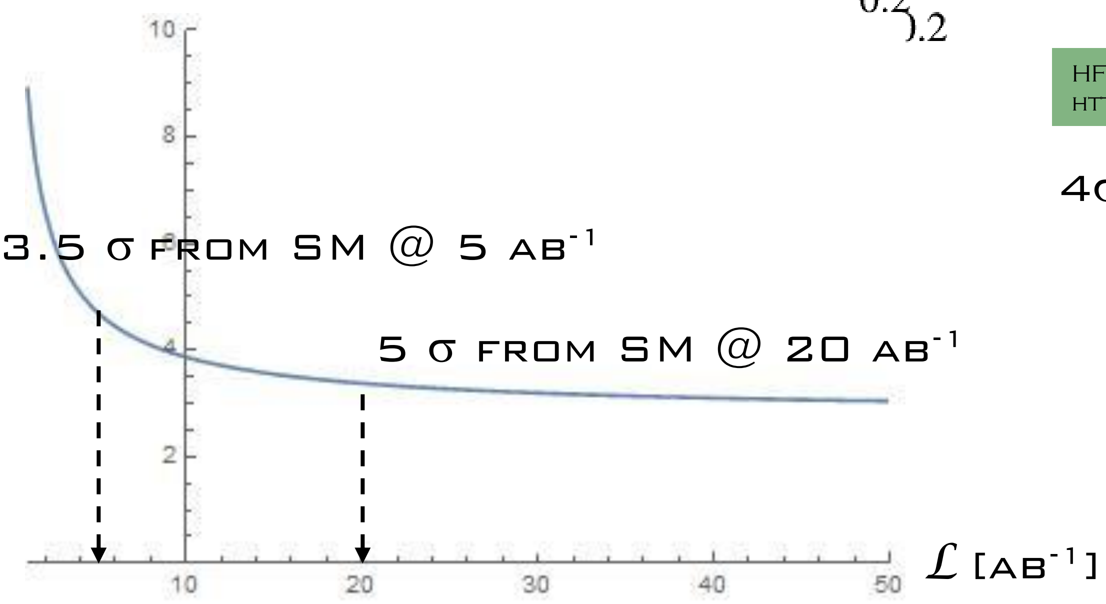
4σ discrepancy with SM

$\sigma(R(D^*))/R(D^{(*)})[\%]$



$D_s \to \ell \nu$

Belle, JHEP09, 139 (2013), 900 fb^{-1}

inclusive D meson reconstr.

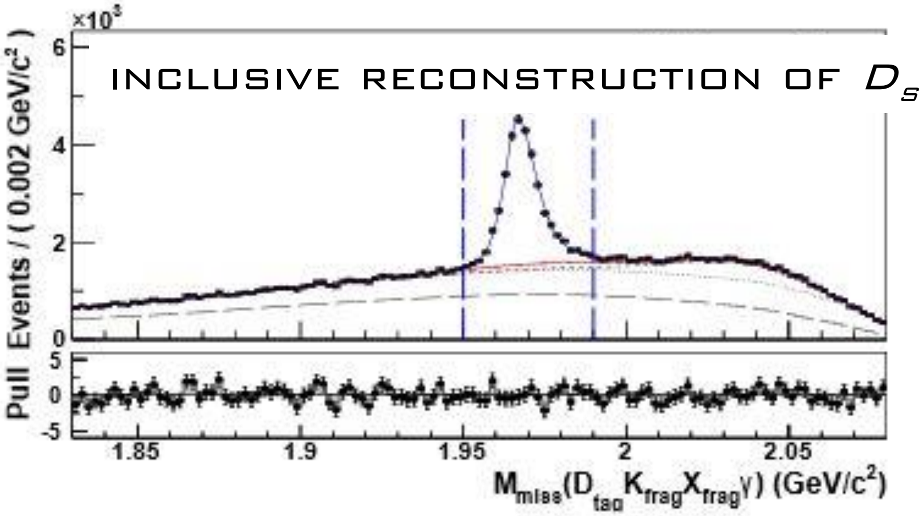
$D_s \to \ell \nu$

Belle, JHEP09, 139 (2013), 900 fb[-1]

inclusive D meson reconstr.

$c\bar{c} \to D_{tag}\ D_s{}^{*}\ (\to D_s\ \gamma)\ K_{frag}\ X_{frag}$

$M_{miss}(D_{tag}\ \gamma K_{frag} X_{frag}) = M_{Ds}$



LFU/Missing energy

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Belle, JHEP09, 139 (2013), 900 fb^{-1}

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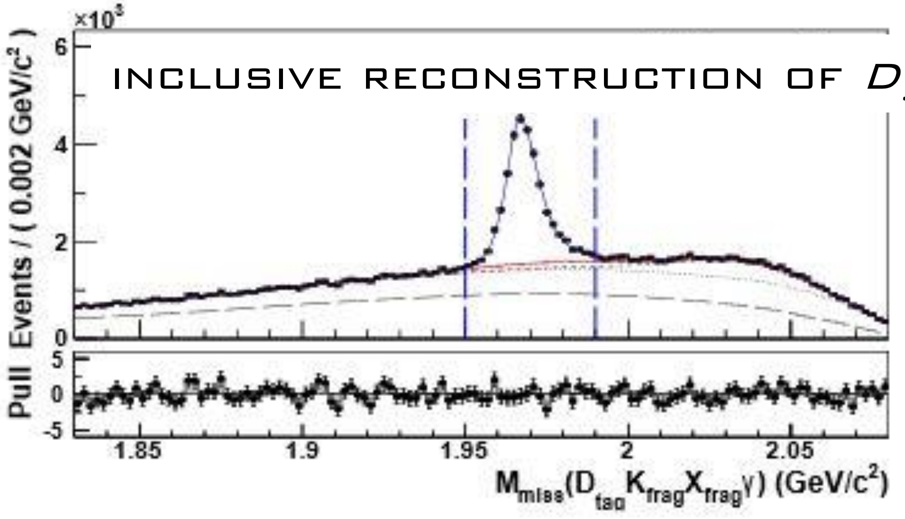
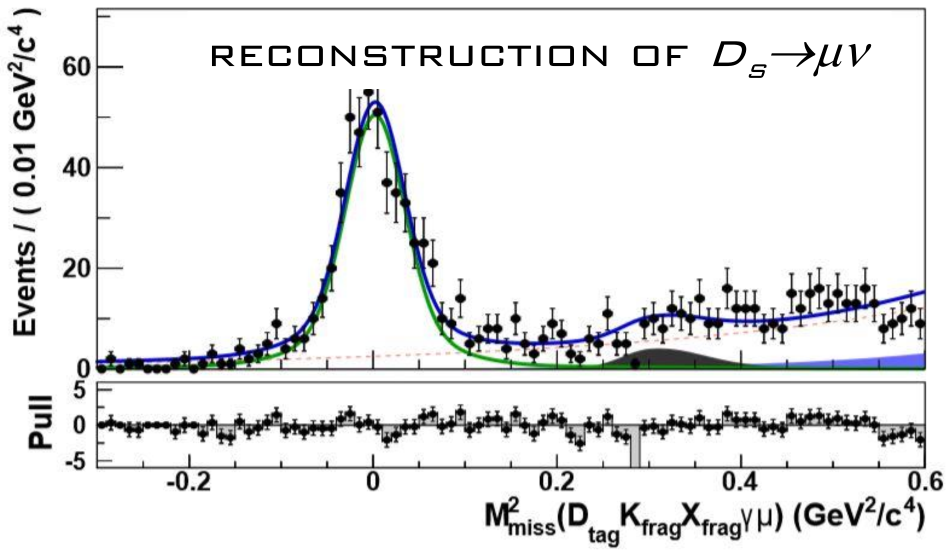
$D_s \to \mu\nu$

$M_{miss}(D_{tag}\ \gamma K_{frag} X_{frag}\ \mu) = M_\nu$





$D_s \to \ell \nu$

Belle, JHEP09, 139 (2013), 900 fb^{-1}

$D_s \to \tau \nu$

E_{ECL}

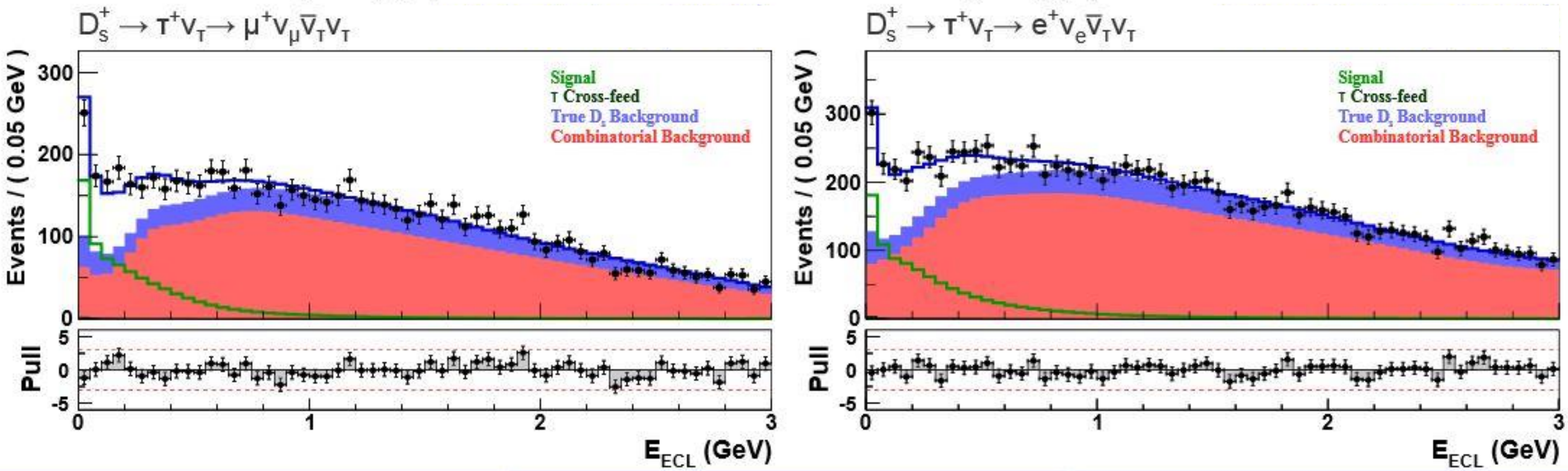
$D_s \to \ell \nu$

Belle, JHEP09, 139 (2013), 900 fb^{-1}

$D_s \to \tau\nu$

E_{ECL}

$N^{excl}_{D_s \to \tau(\mu)\nu_\tau} = 758 \pm 48$ $N^{excl}_{D_s \to \tau(e)\nu_\tau} = 952 \pm 59$



$D_s \to \ell \nu$

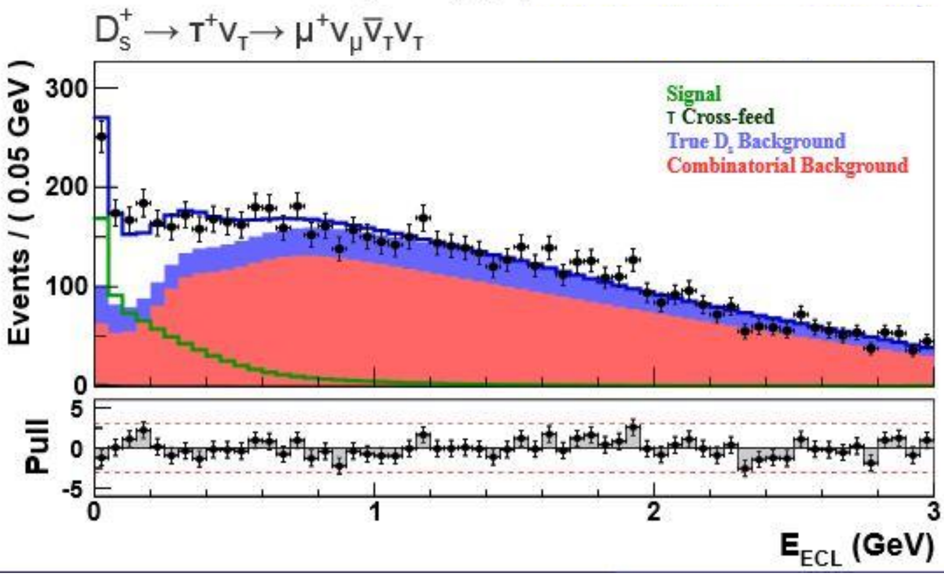
Belle, JHEP09, 139 (2013), 900 fb^{-1}

$D_s \to \tau\nu$

E_{ECL}

$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.31 \pm 0.28(\text{stat.}) \pm 0.20(\text{syst.})) \times 10^{-3},$$
$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.70 \pm 0.21(\text{stat.})^{+0.31}_{-0.30}(\text{syst.})) \times 10^{-2},$$

$$N^{\text{excl}}_{D_s\to\tau(\mu)\nu_\tau} = 758 \pm 48$$



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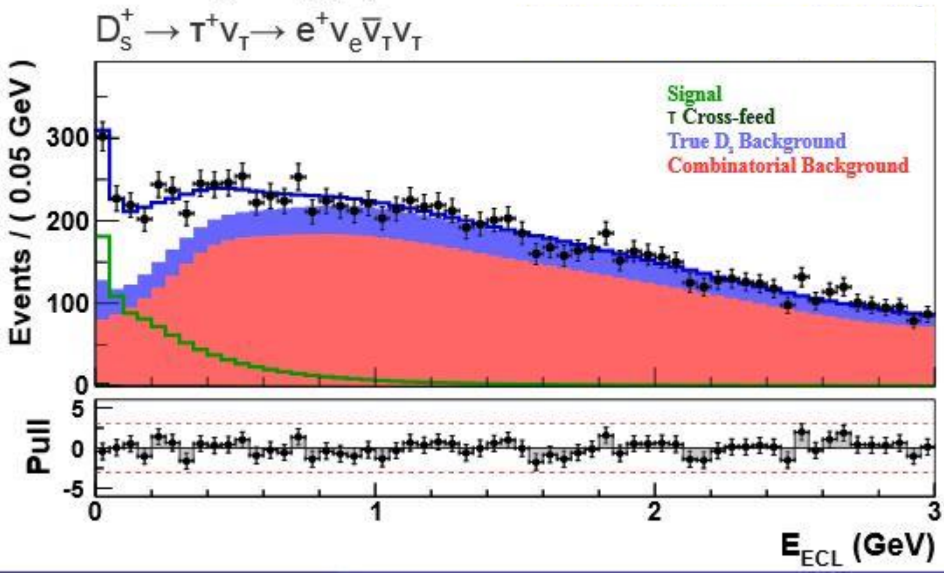


$D_s \to \ell\nu$

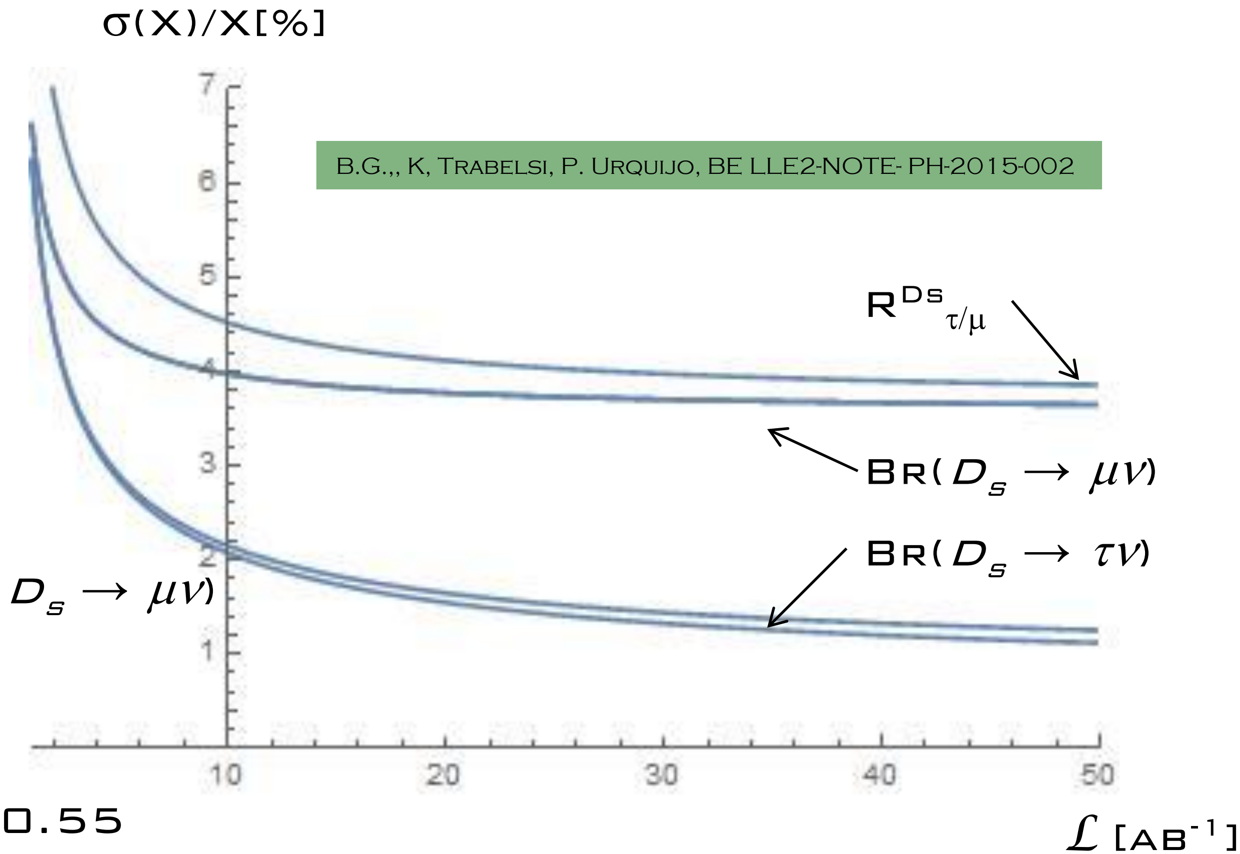
$R^{Ds}_{\tau/\mu}$ = Br($D_s \to \tau\nu$) / Br($D_s \to \mu\nu$)

Belle, JHEP09, 139 (2013), 900 fb^{-1}

$R^{Ds}_{\tau/\mu} = 10.73 \pm 0.69 \pm 0.55$

$(R^{Ds}_{\tau/\mu})_{SM} = 9.762 \pm 0.031$

$D_s \to \ell\nu$



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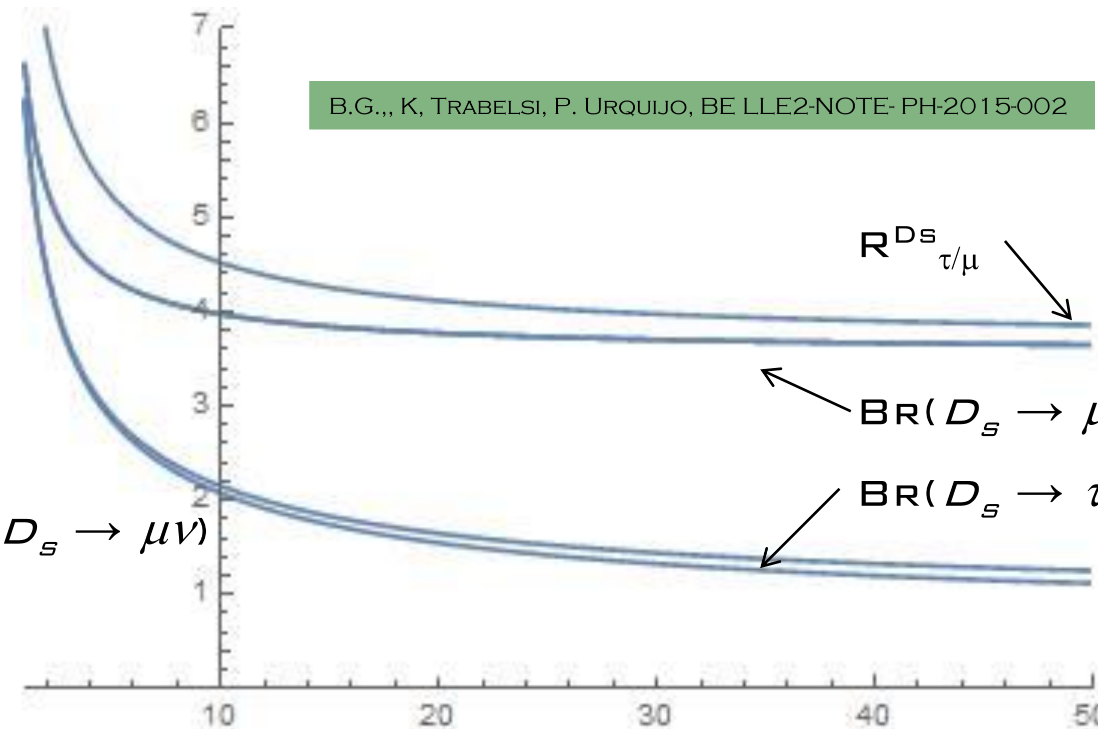

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Belle, JHEP09, 139 (2013), 900 fb^{-1}

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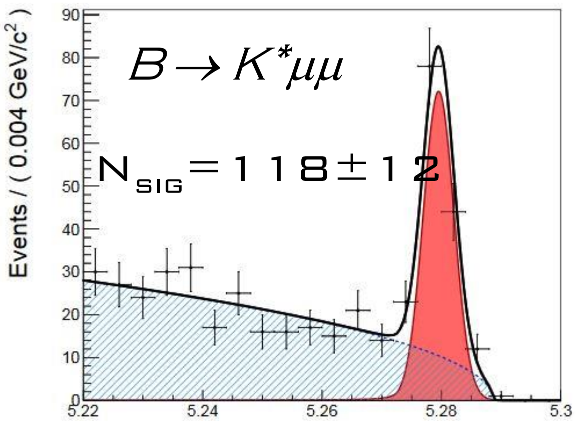
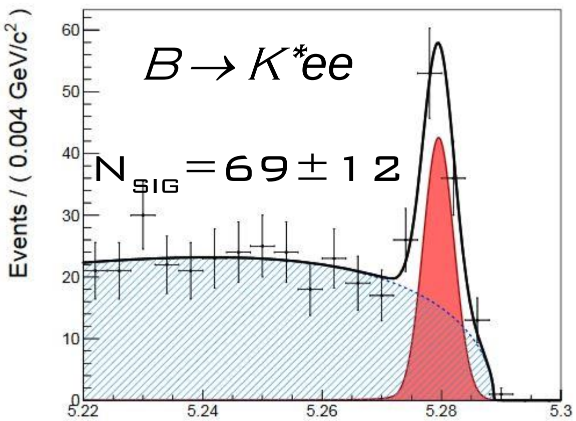
n.b.: $\sigma(R(D^*))/R(D^{(*)}) \sim 4\%$ @20 ab^{-1}

$B \to K^* \ell\ell$

Belle, arXiv:1604.04042, 700 fb[-1]

ANGULAR ANALYSIS





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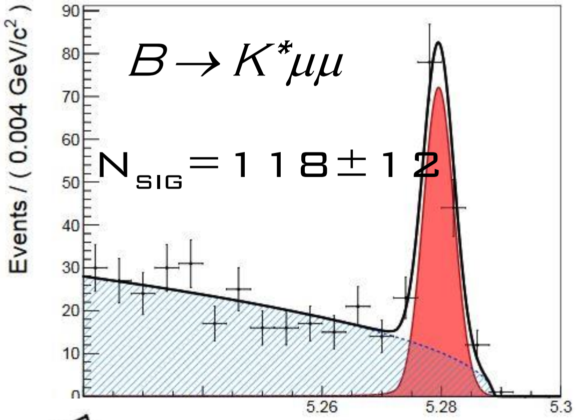
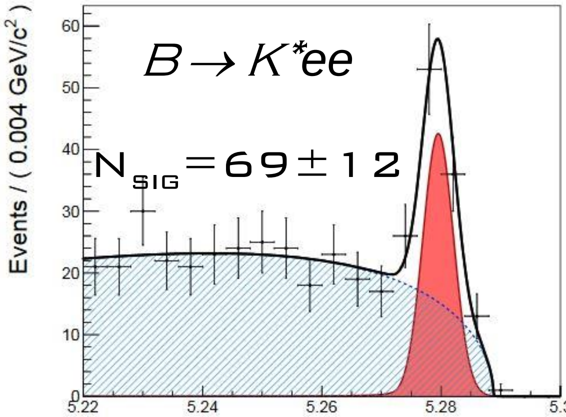
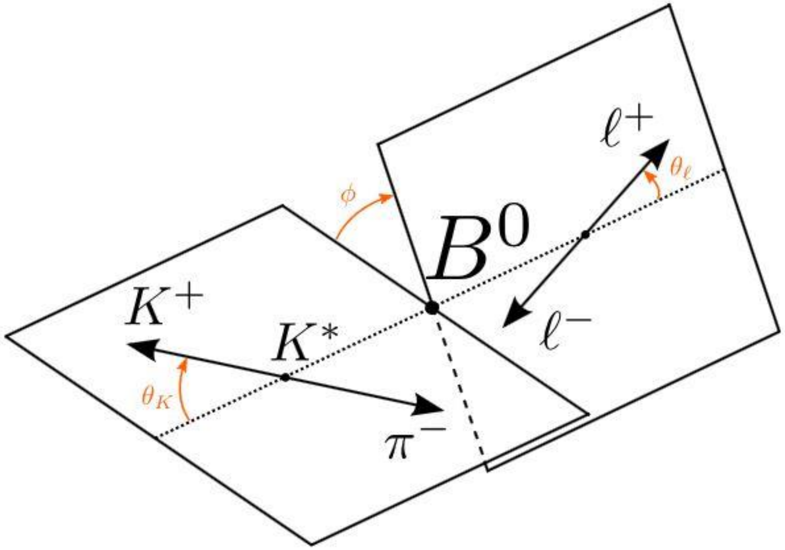




ANGULAR ANALYSIS

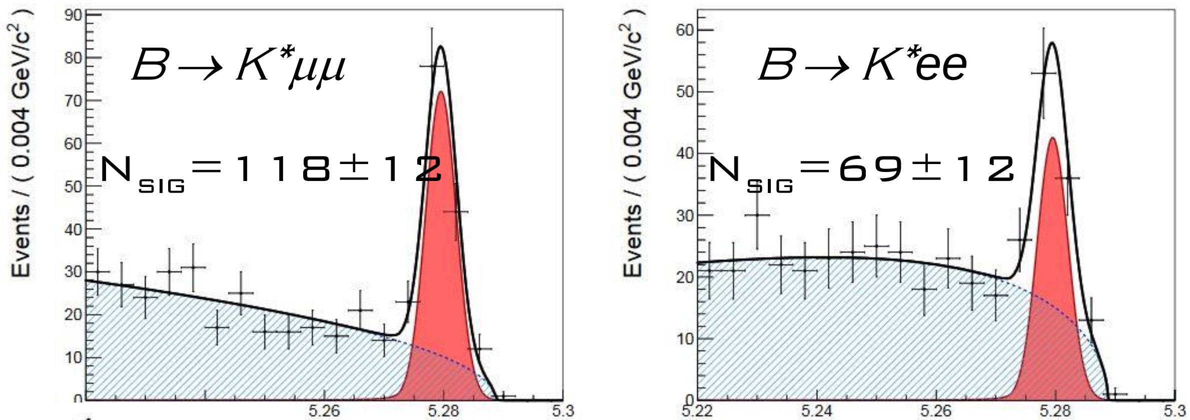


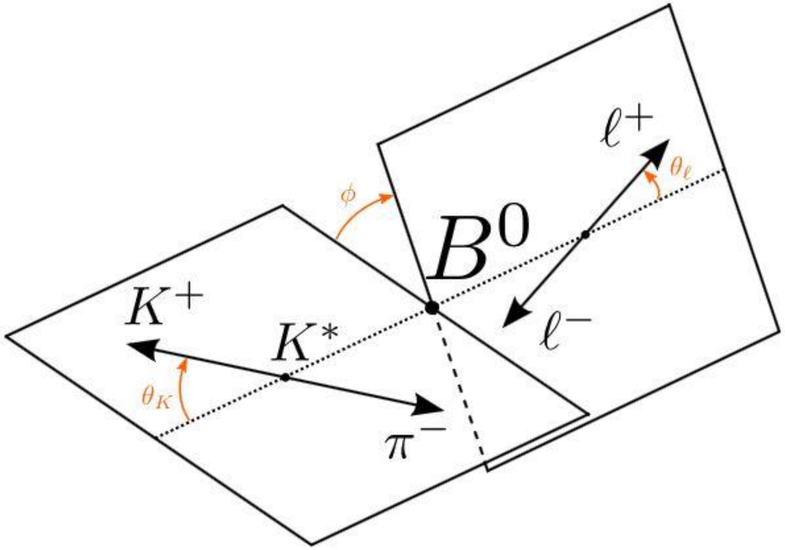
LHCb, JHEP 1308 (2013) 131

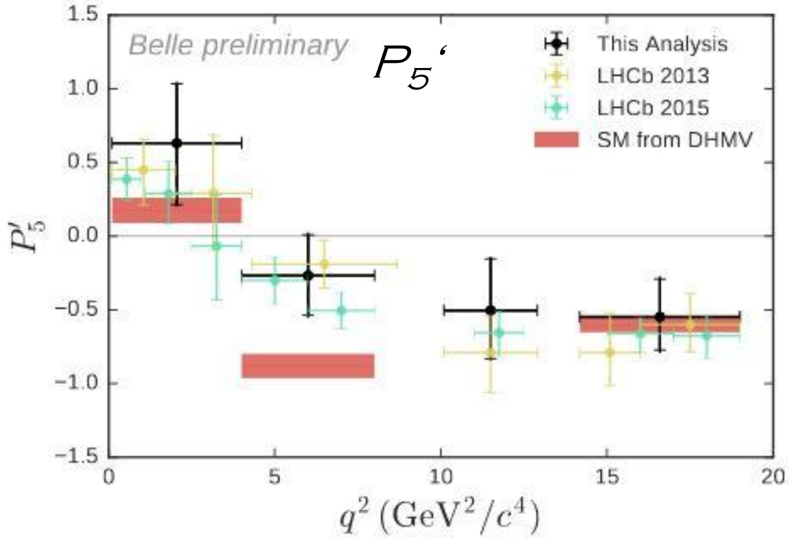
$B \to K^* \ell\ell$

Belle, arXiv:1604.04042, 700 fb^{-1}

ANGULAR ANALYSIS





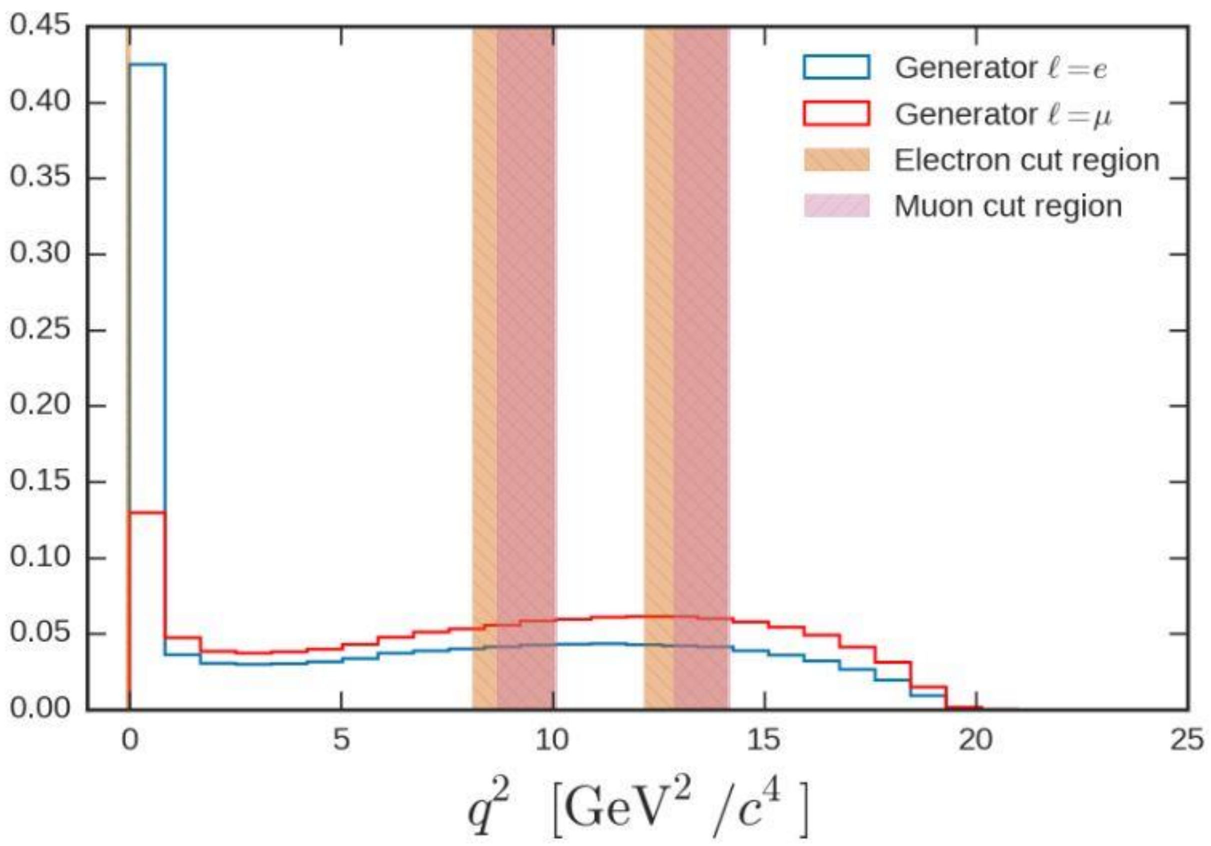


LHCb, JHEP 1308 (2013) 131

$B \to K^* \ell\ell$

Belle, arXiv:1604.04042, 700 fb[-1]

$$R(K^*) = \frac{N(B \to K^* ee)}{N(B \to K^* \mu\mu)}$$



LFU/$B \to K^* \ell\ell$

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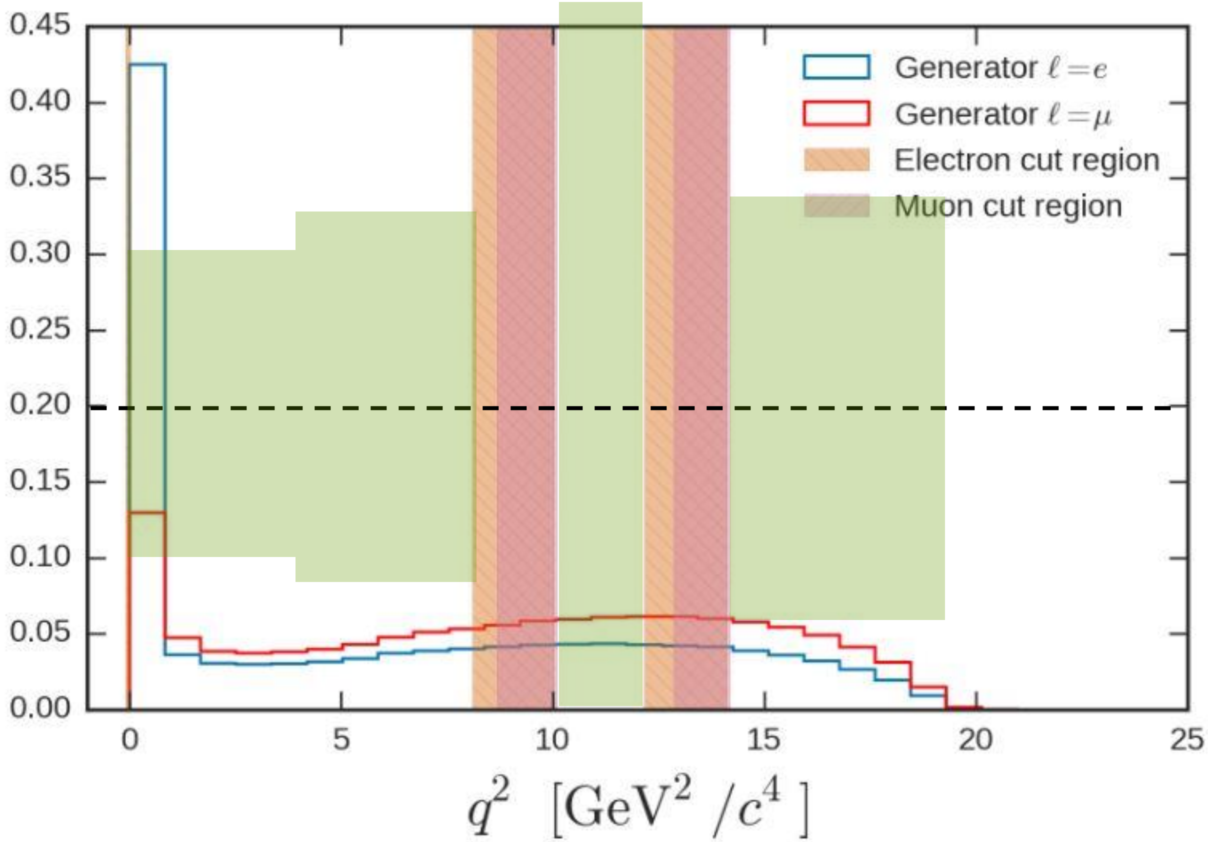
approximate stat. uncertainty on R(K*)



$\mathcal{L}$ [ab^{-1}] 0.7 5.0 20.0

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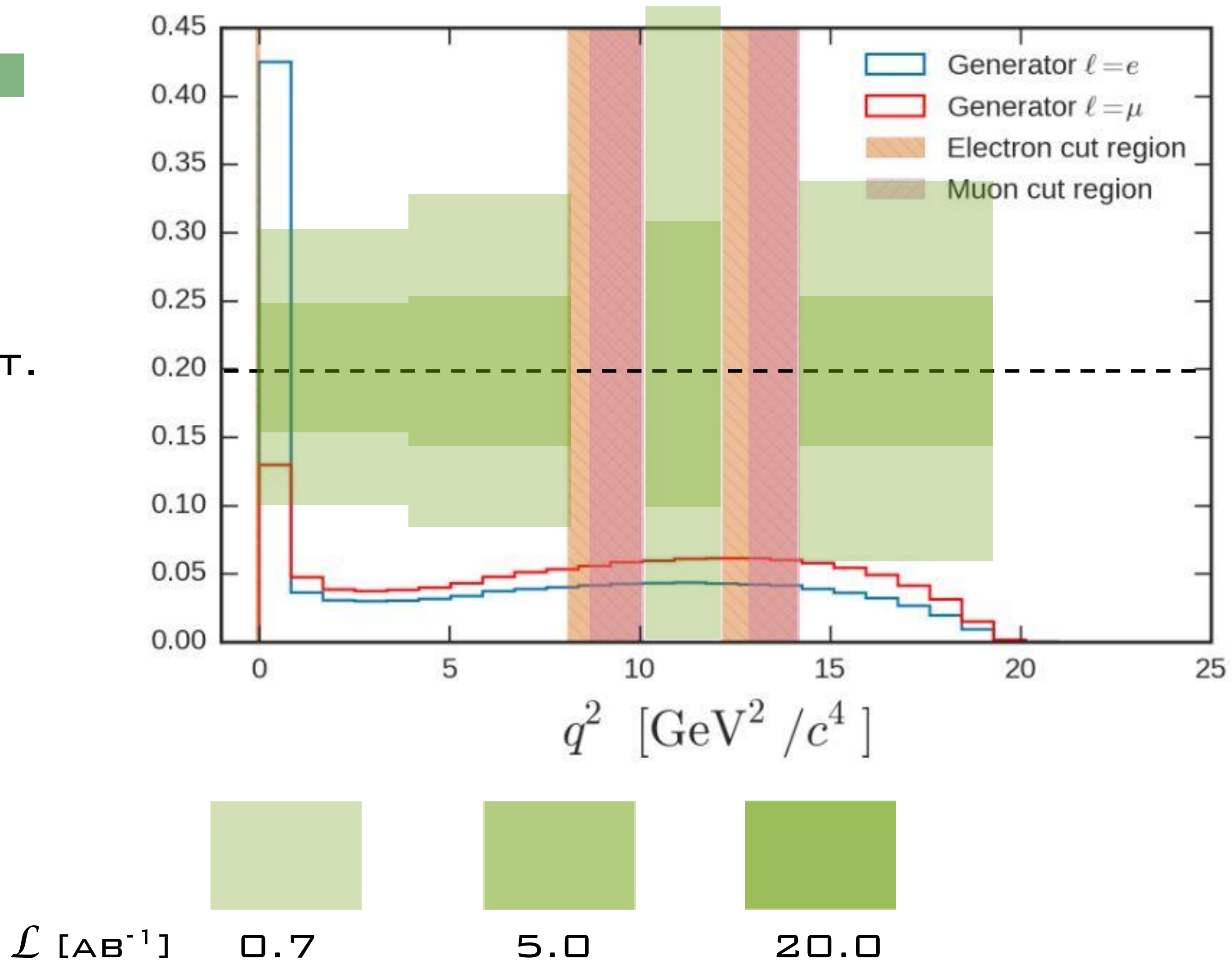

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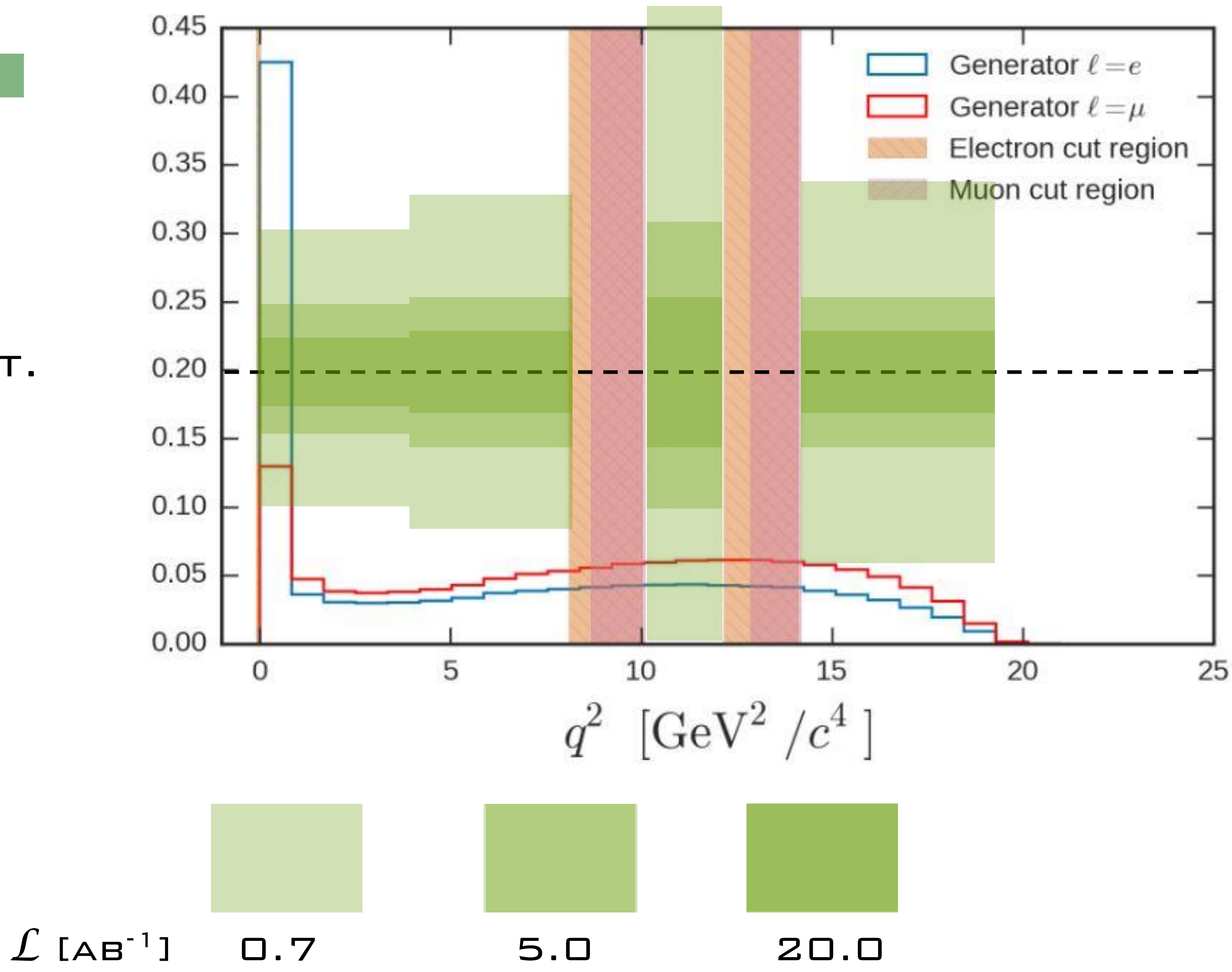


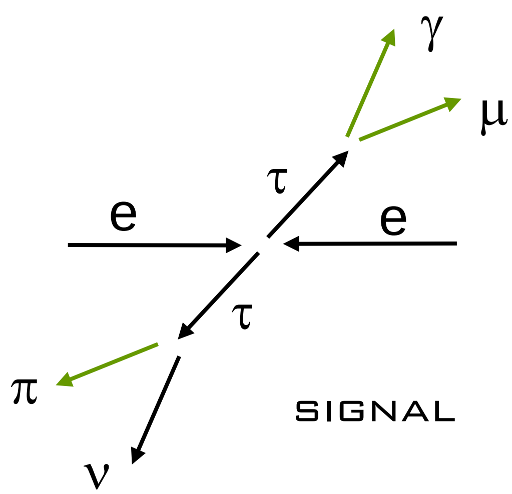
$\tau \to \mu\gamma$

Belle, PLB66, 16 (2008), 535 fb^{-1}

kinematic variables for signal isolation:

$\Delta E = E^{CM}(\mu\gamma) - E^{CM}(beam)$

$M_{inv} = m(\mu\gamma)$



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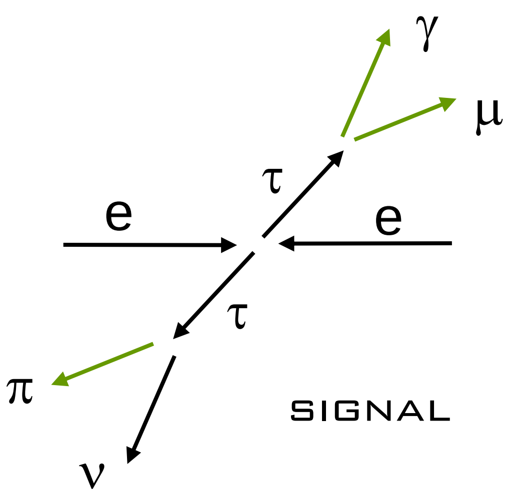
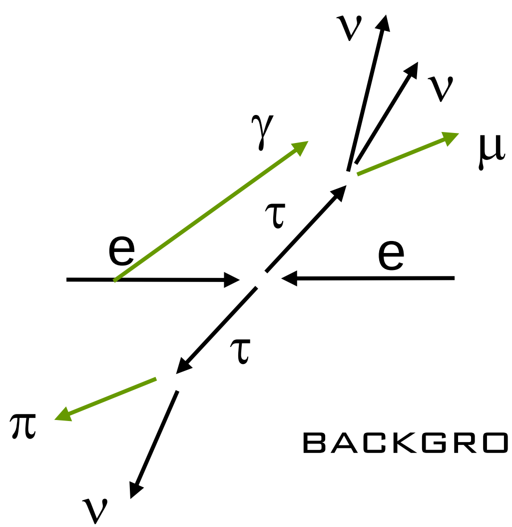


signal

main background from

$ee \to \tau(\mu\nu\nu)\,\tau(\pi\nu)\,\gamma_{ISR}$

$Br^{UL} \propto 1/\sqrt{\mathcal{L}}$



background

LFV/$\tau \to \mu\,\gamma$

$\tau \to \mu\,\gamma$

Belle, PLB66, 16 (2008), 535 fb^{-1}

Kinematic variables for signal isolation:

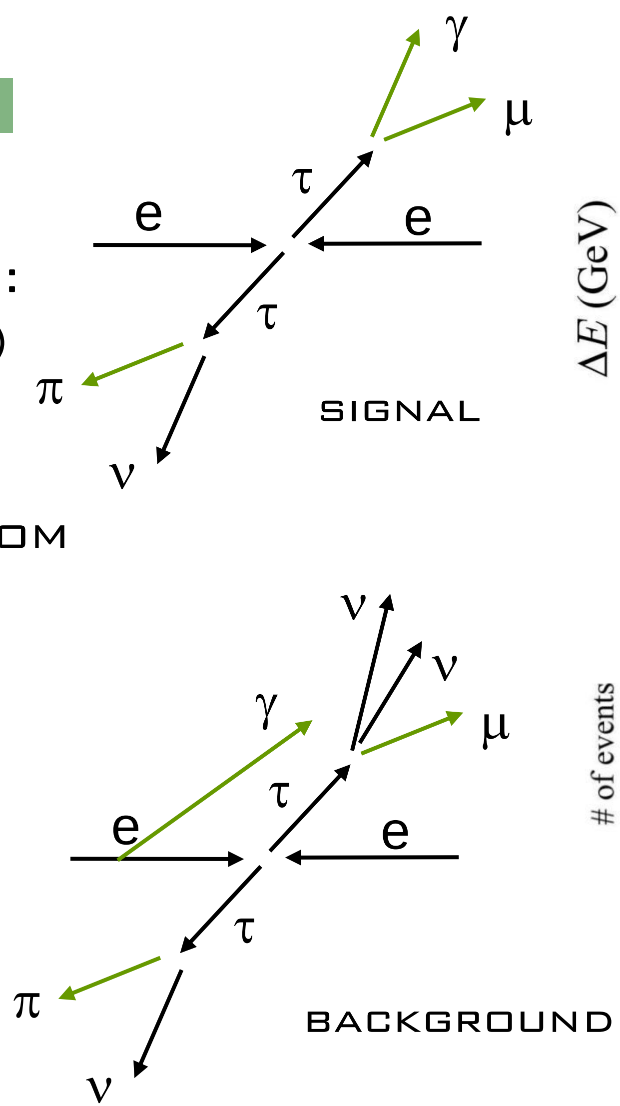
$\Delta E = E^{CM}(\mu\gamma) - E^{CM}(\text{beam})$

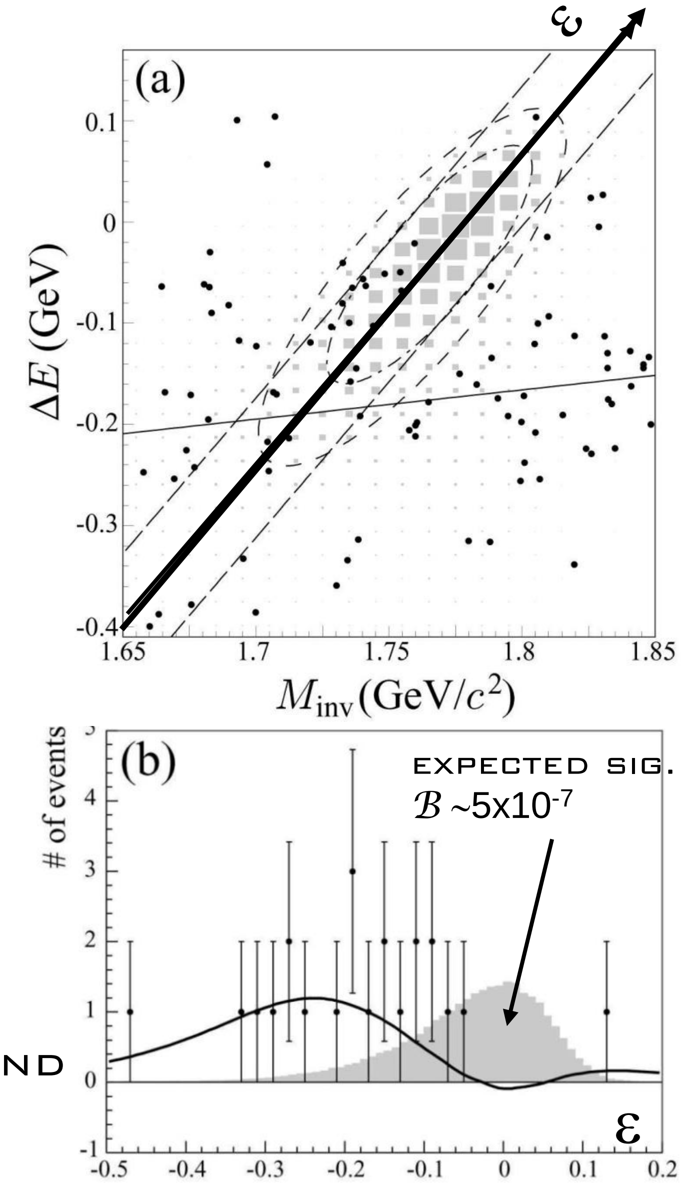
$M_{inv} = m(\mu\gamma)$

Main background from

$ee \to \tau(\mu\nu\nu)\,\tau(\pi\nu)\,\gamma_{ISR}$

$Br^{UL} \propto 1/\sqrt{\mathcal{L}}$





$\tau \to \mu \gamma$

Belle, PLB66, 16 (2008), 535 fb^{-1}

$\mathcal{B}(\tau \to \mu \gamma) < 4.4 \cdot 10^{-8}$

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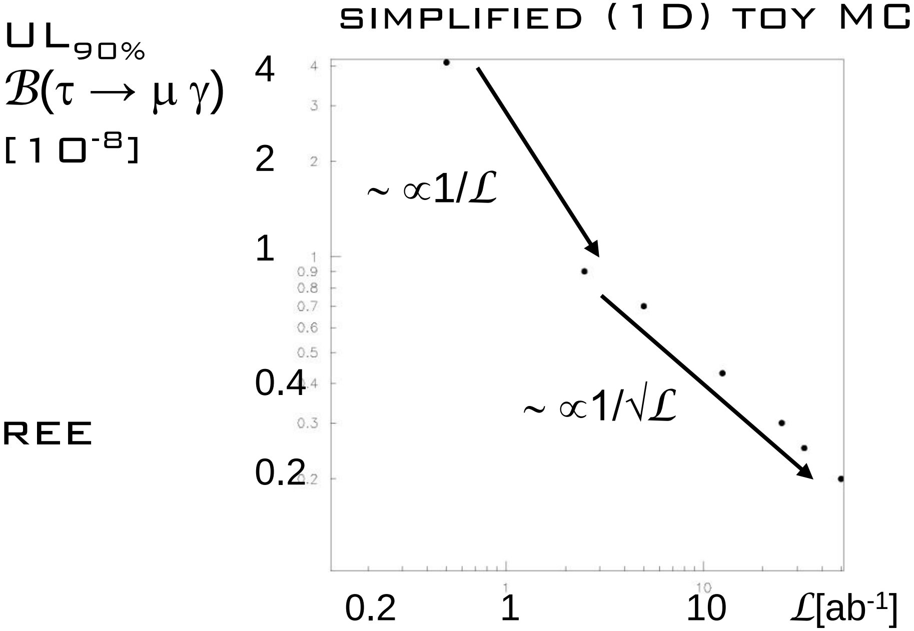
decays $\tau \to 3\ell, \ell h^0$ background free

simplified (1D) toy MC



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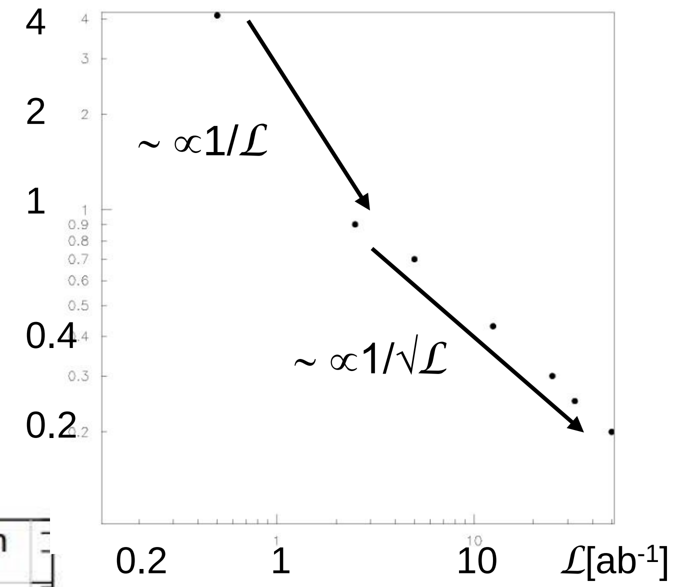

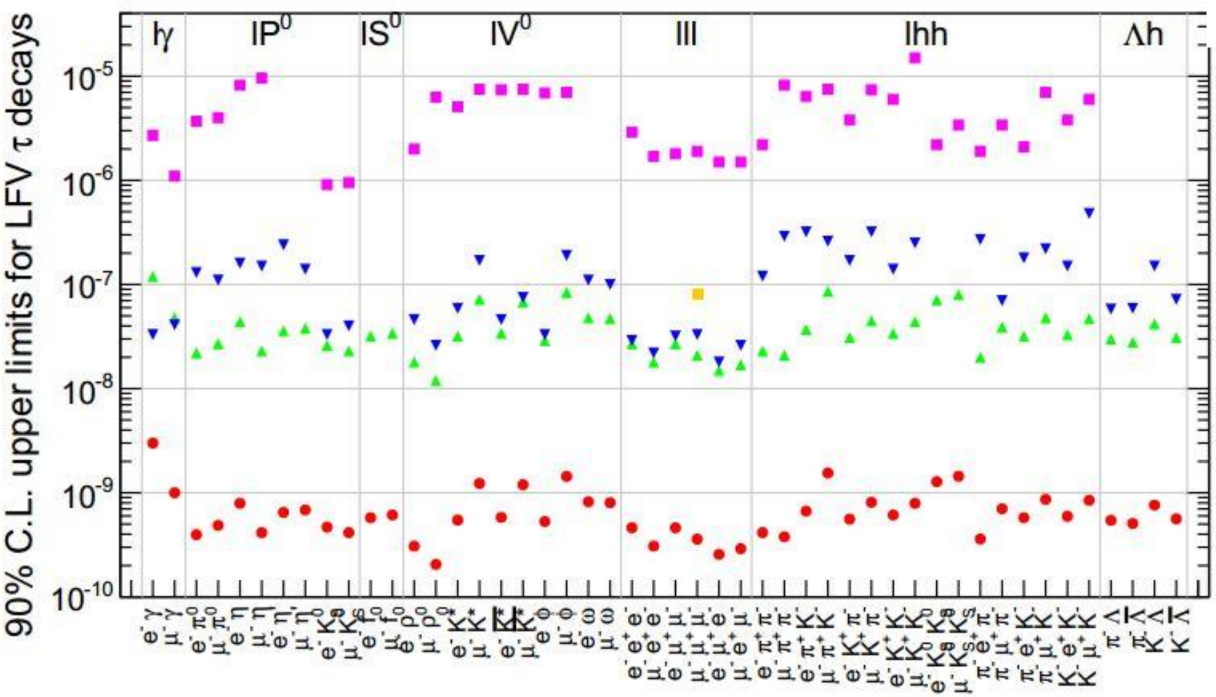

B.G.,, K, Trabelsi, P. Urquijo, BE LLE2-NOTE- PH-2015-002

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UL$_{90\%}$ $\mathcal{B}(\tau \to \mu\gamma)$ [10^{-8}]

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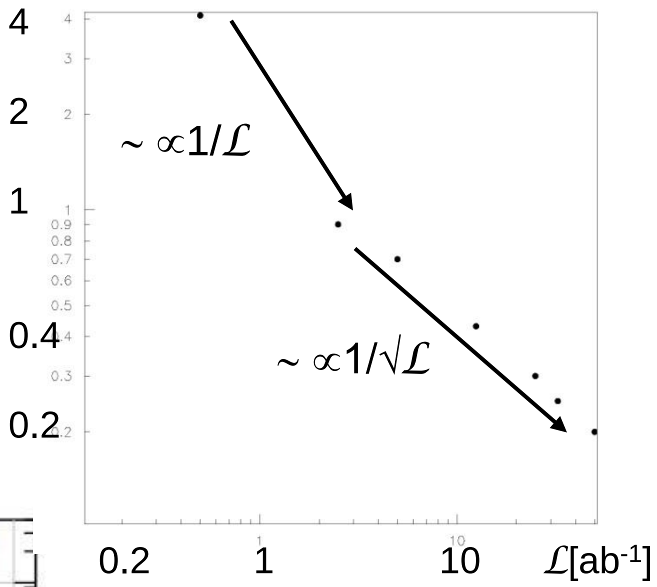

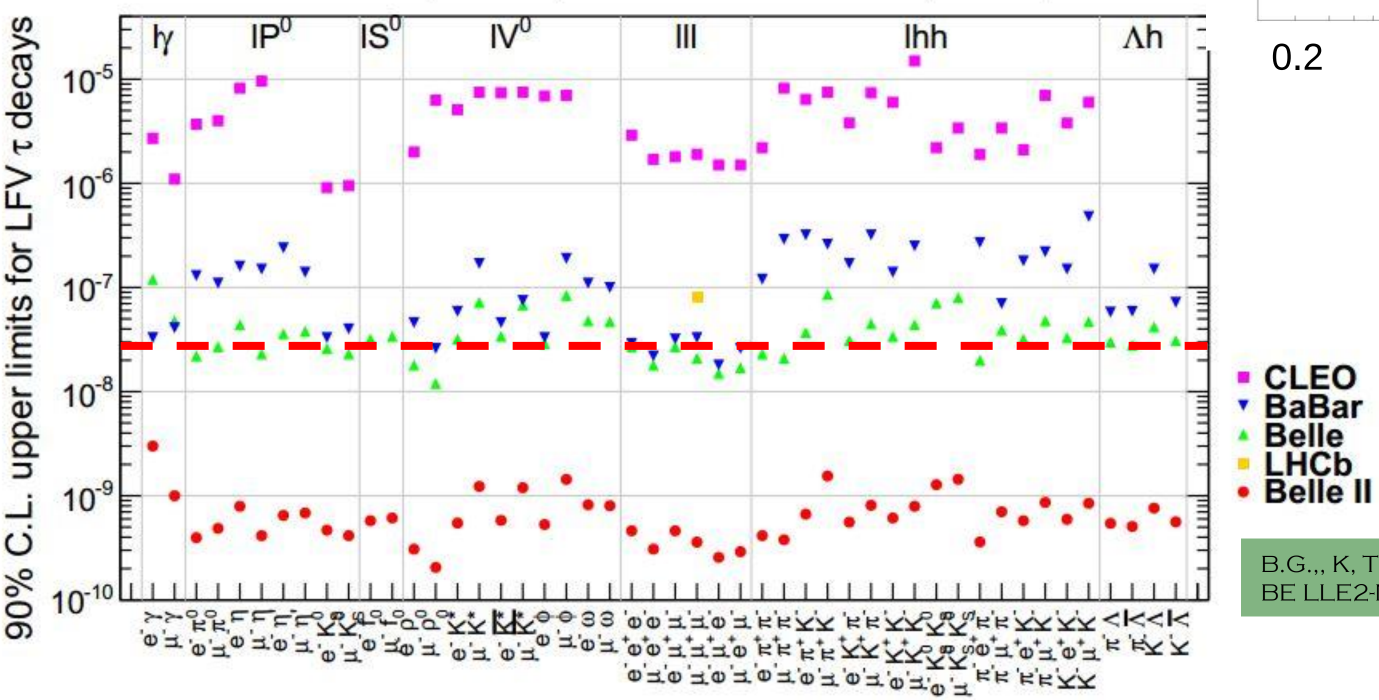

B.G.,, K, Trabelsi, P. Urquijo, BE LLE2-NOTE- PH-2015-002

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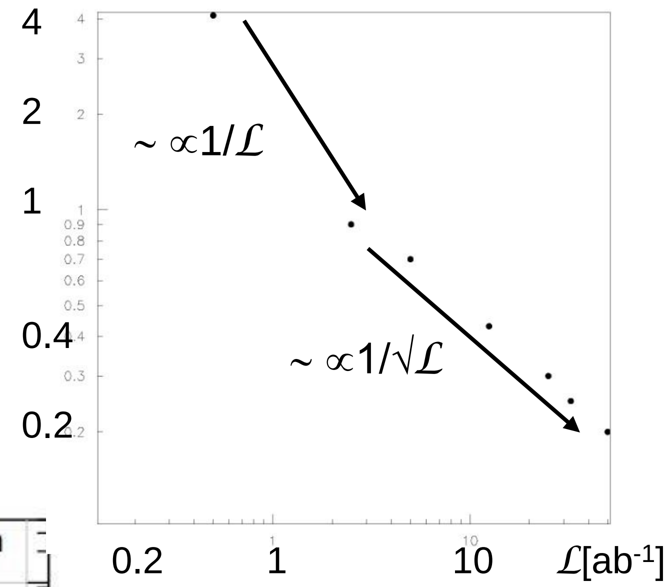

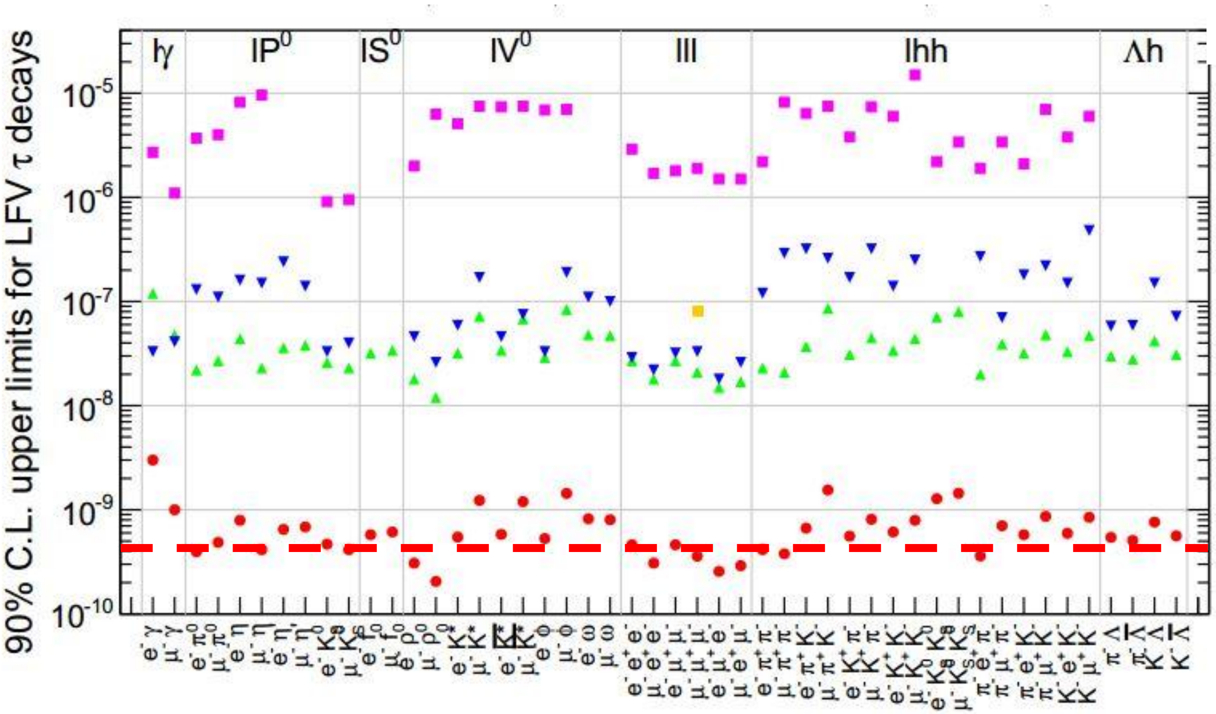

B.G.,, K, Trabelsi, P. Urquijo, BE LLE2-NOTE- PH-2015-002

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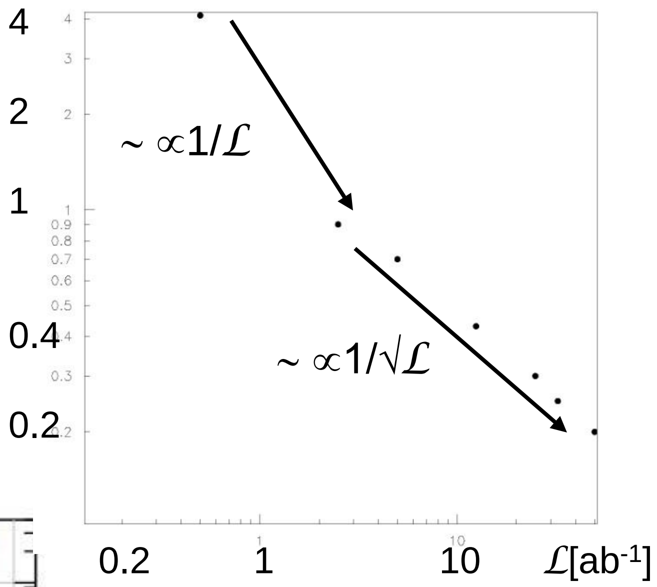

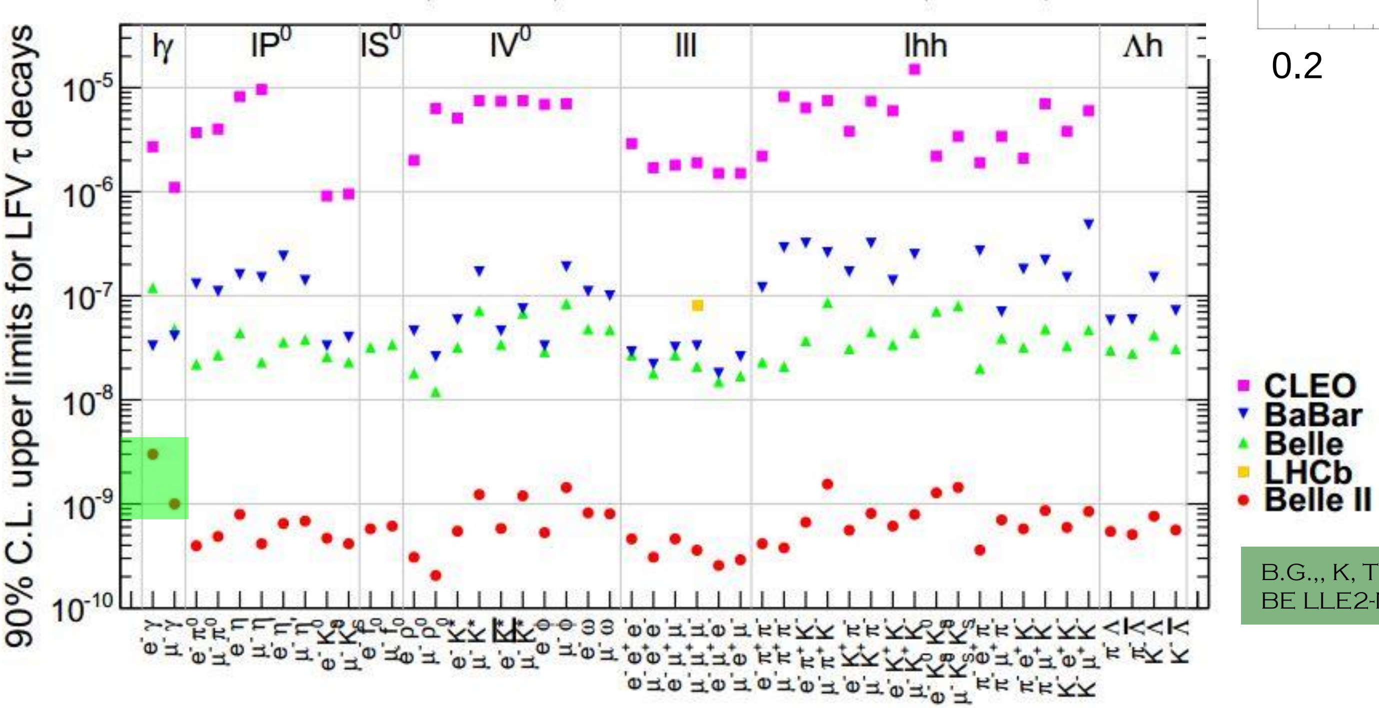

B.G., K. Trabelsi, P. Urquijo, BELLE2-NOTE-PH-2015-002

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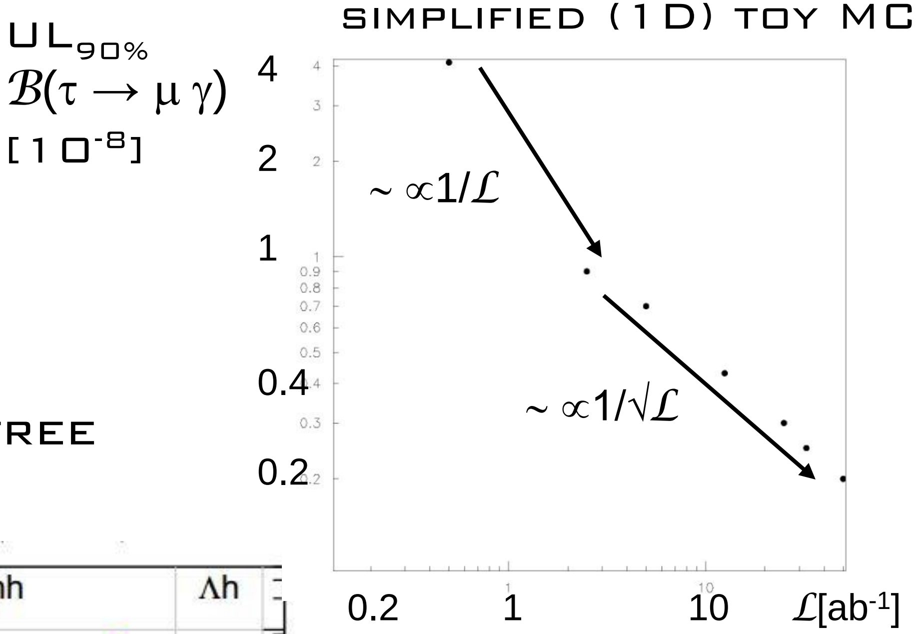
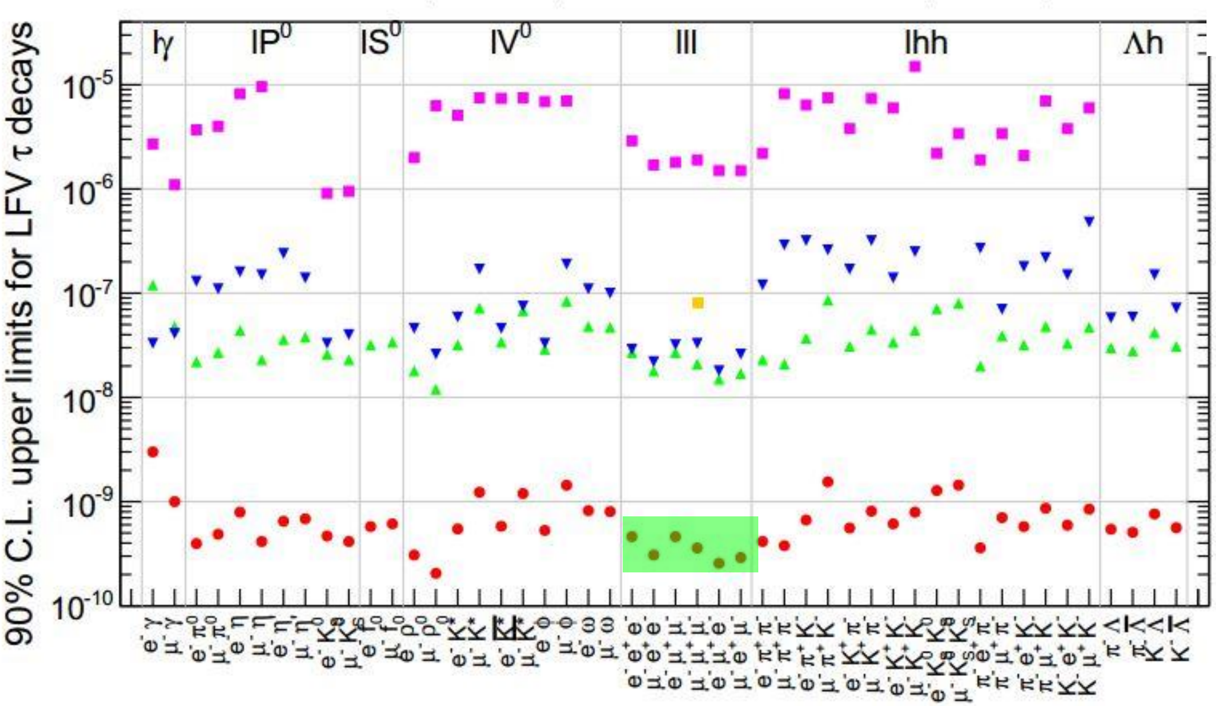
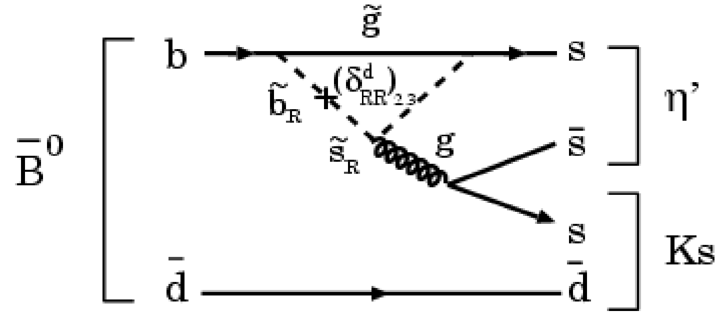




B.G.,, K, Trabelsi, P. Urquijo, BE LLE2-NOTE- PH-2015-002

$B \longrightarrow sqq$ t-dependent CPV

- some uncertainties cancel in ΔS (vtx reconstr., flavor tag, likelihood fit) ;
- better K_S eff. with vtx hits - larger vtx radius, 30%);
- vtx reconstr. improved with better tracking;



41 new phases in MSSM

$\Delta S = \sin 2\phi_1^{eff} - \sin 2\phi_1$

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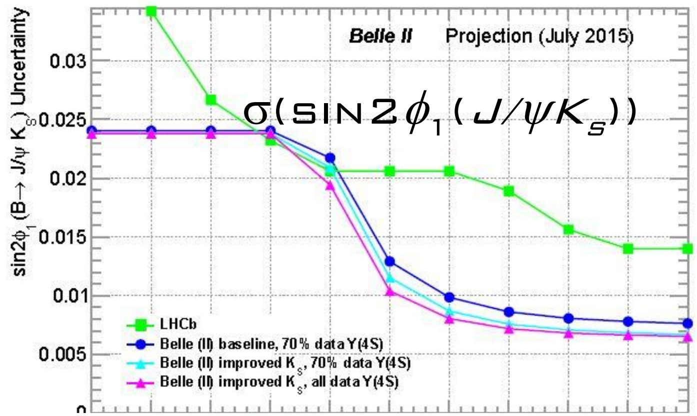
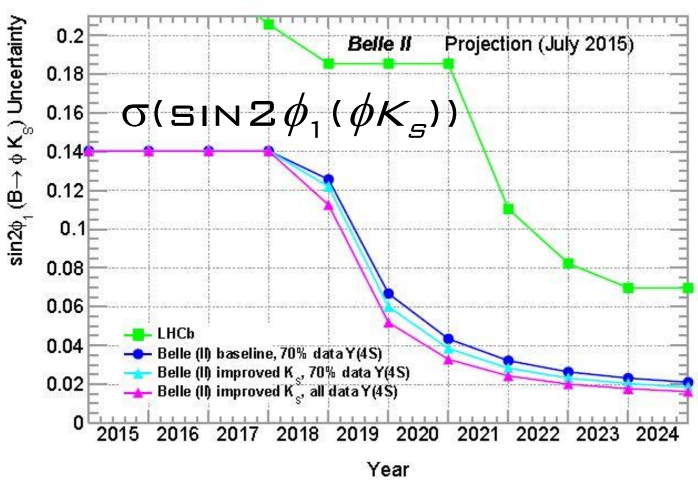
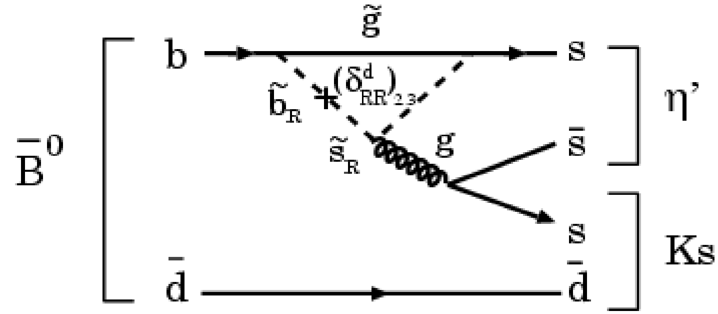


0.007



0.02

P. Urquijo, Belle2-note-ph-2015-004



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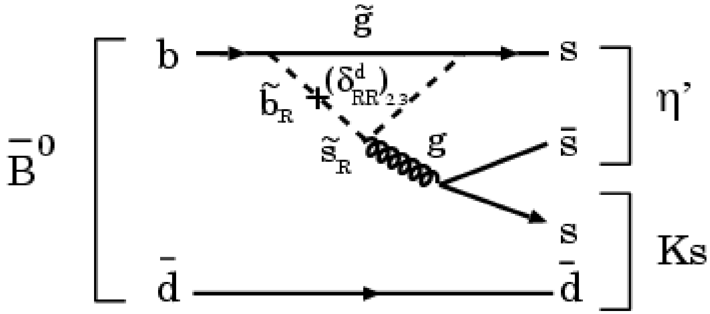

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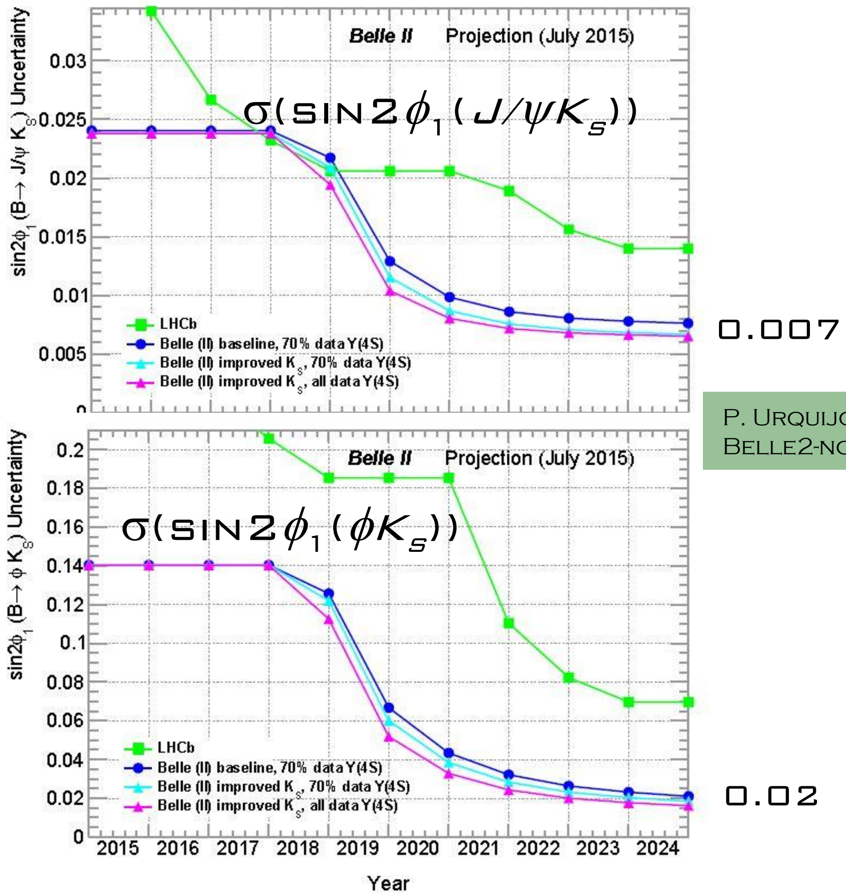
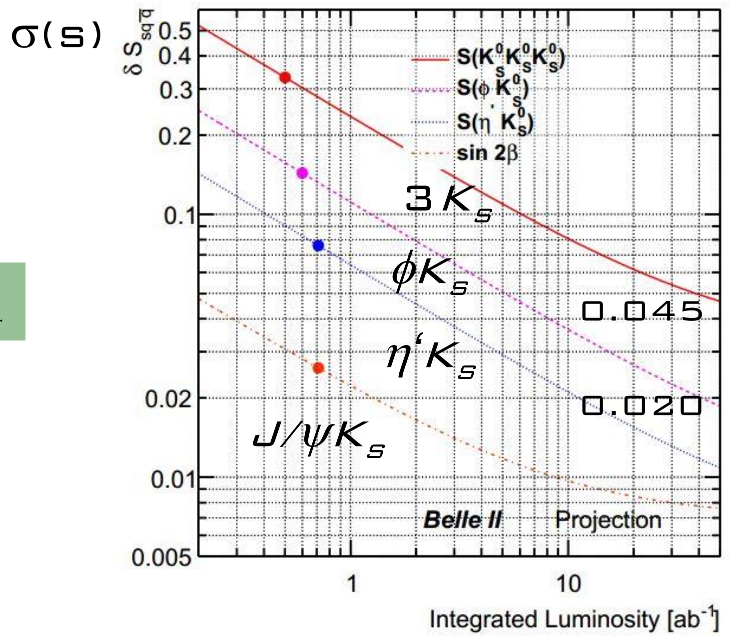


P. Urquijo, Belle2-note-ph-2015-004



B. Golob, K. Trabelsi, P. Urquijo, Belle2-note-ph-2015-002

B $\to$ K* ($\to K_S\pi^0$)γ

t-dependent CPV

t-dependent decays rate of $B \to f_{CP}$;
S and A: CP violating parameters

$$P(B^0 \to f;\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 + S_{CP}^f \sin(\Delta m \Delta t) + A_{CP}^f \cos(\Delta m \Delta t)]$$

$B \to K^* (\to K_S \pi^0)\gamma$

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SM:

$S_{CP}^{K^*\gamma} \sim -(2m_s/m_B)\sin 2\phi_1 \sim -0.04$

Left-Right Symmetric Models:

$S_{CP}^{K^*\gamma} \sim 0.67 \cos 2\phi_1 \sim 0.5$

D. Atwood et al., PRL79, 185 (1997)
B. Grinstein et al., PRD71, 011504 (2005)

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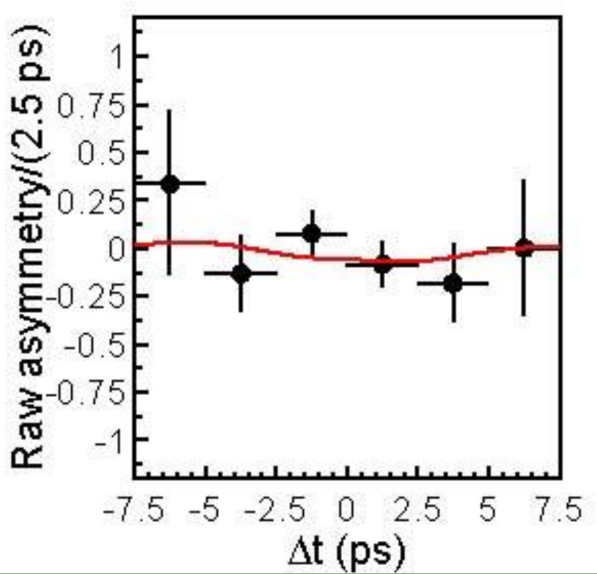


Belle, PRD74, 111104 (2006), 500 ab^{-1}

$S_{CP}(K_s\pi^0\gamma) = -0.10 \pm 0.31 \pm 0.07$
$A_{CP}(K_s\pi^0\gamma) = -0.20 \pm 0.20 \pm 0.06$
for $m(K_s\pi^0) < 1.8$ GeV (mainly $K^*\gamma$)

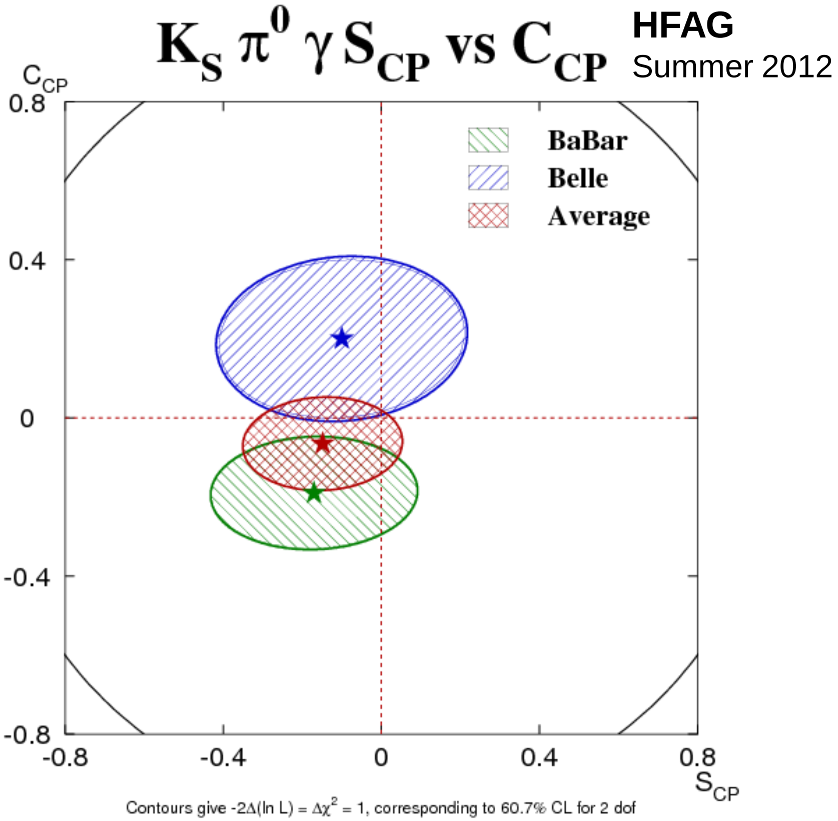
$B \to K^* (\to K_S\pi^0)\gamma$

t-dependent CPV

$S_{CP}^{K_S\pi^0\gamma} = -0.15 \pm 0.20$

$A_{CP}^{K_S\pi^0\gamma} = -0.07 \pm 0.12$

HFAG, Summer'12



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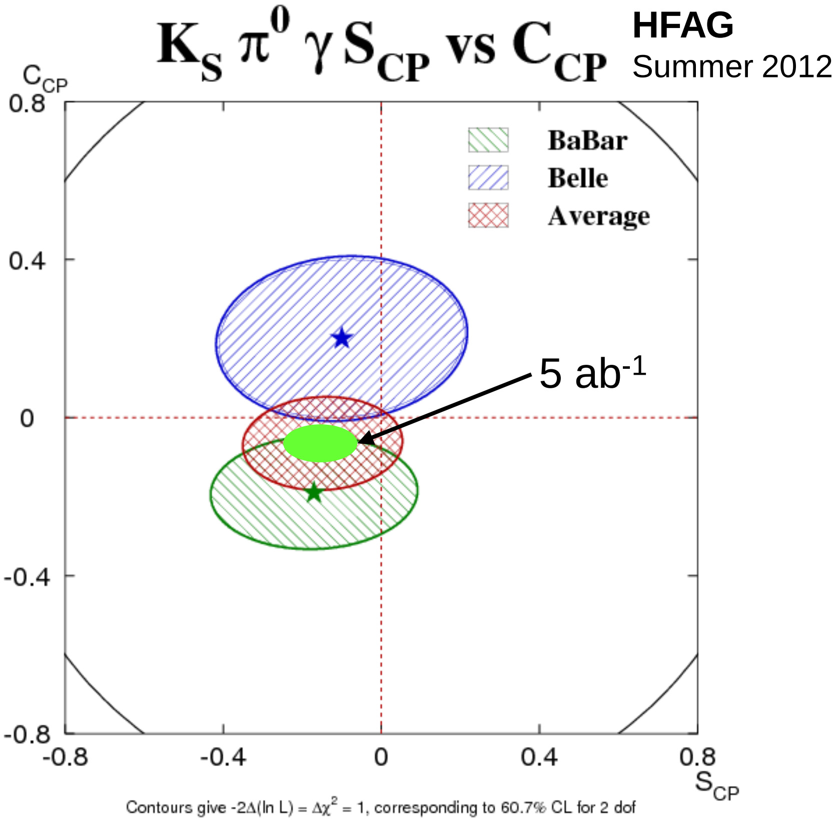
HFAG, Summer'12

$\sigma(S_{CP}^{K_S\pi^0\gamma}) = 0.11$ @ 5 ab^{-1}

B.G.,, K, Trabelsi, P. Urquijo, BE LLE2-NOTE- PH-2015-002



CPV/B $\to S\gamma$

B $\to$ K* ($\to K_S\pi^0$)γ

t-dependent CPV

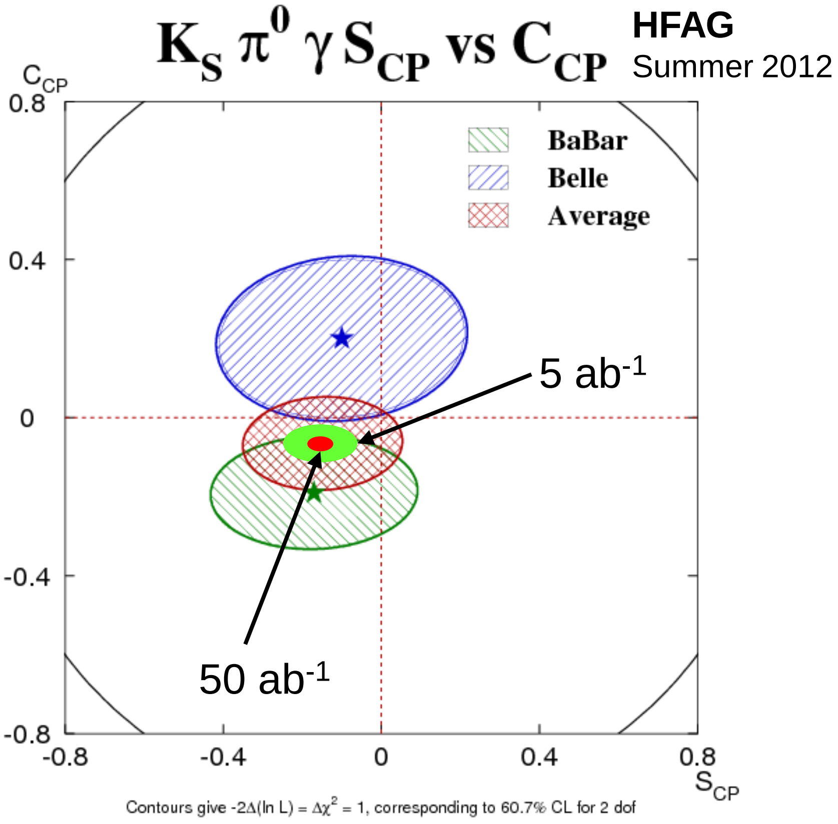
$S_{CP}^{K_S\pi^0\gamma}$ = -0.15 ±0.20
$A_{CP}^{K_S\pi^0\gamma}$ = -0.07 ±0.12

HFAG, Summer'12

$\sigma(S_{CP}^{K_S\pi^0\gamma})$ = 0.11 @ 5 ab^{-1}
0.04 @ 50 ab^{-1}

(~SM prediction)

B.G.,, K, Trabelsi, P. Urquijo, BE LLE2-NOTE- PH-2015-002



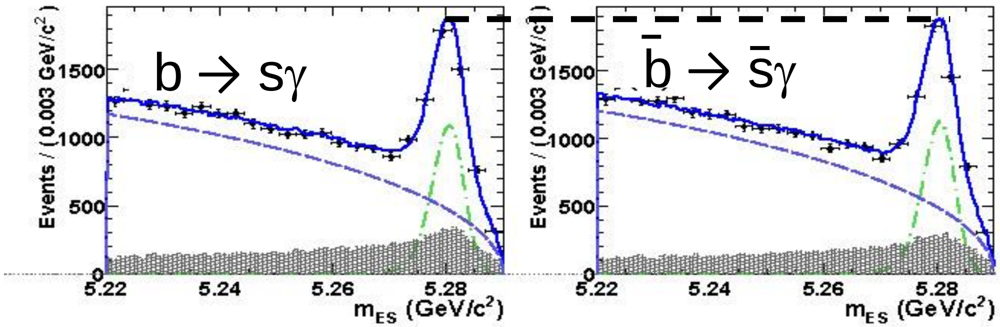
for $B\to \rho^0\gamma$ ~2x larger uncertainty

B → s(+d)γ direct CPV

Semi-inclusive, sum of many exclusive states: all flavor specific final states;

–

BaBar, PRL101, 171804(2008),350 fb[-1]



$B \to s(+d)\gamma$ direct CPV

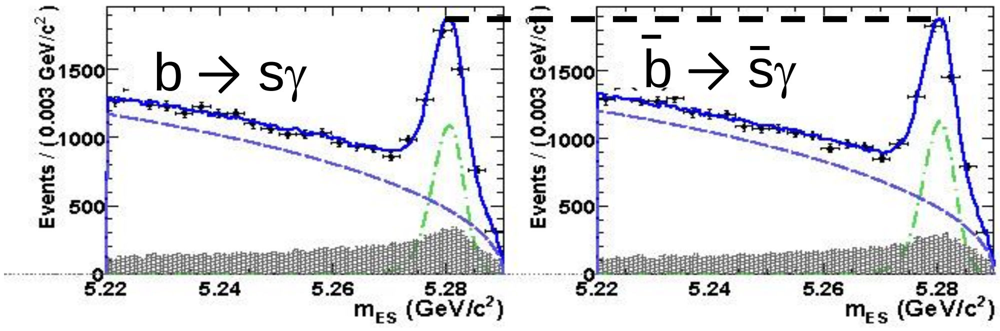
Semi-inclusive, sum of many exclusive states: all flavor specific final states;

<D>: average dilution due to flavour mistag, ~1

ΔD: difference between flavour mistag for B and B, << 1

A_{DET}: detector induced asymmetry

BaBar, PRL101, 171804(2008),350 fb-1



$$\frac{N_b - N_{\bar{b}}}{N_b + N_{\bar{b}}} = \langle D \rangle A_{CP} + \Delta D + A_{\text{det}}$$

$B \to s(+d)\gamma$ direct CPV

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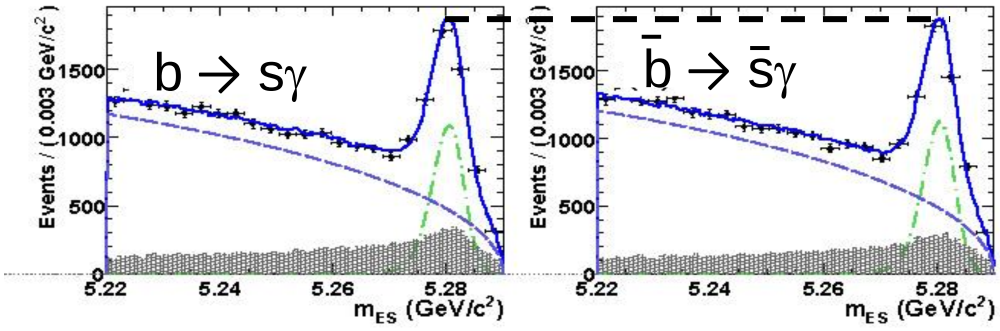


A_{DET}: careful study of K/π asymmetries in (p, θ_{lab}) using *D* decays or inclusive tracks from fragmentation;

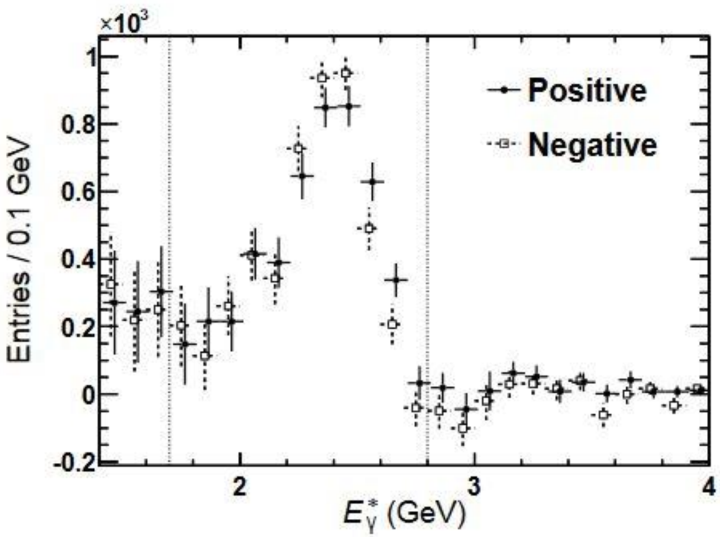
lots of work on system., → few 10^{-3} exp. sensitivity

DCPV/B $\to s\gamma$

B $\to s\gamma$
direct CPV

Inclusive, γ recontruction only;
bkg. suppression (kinematic event shape variables);
semileptonic tagging;

Belle, PRL114, 151601 (2015), 700 fb^{-1}



DCPV/$B \to s\gamma$

$B \to s\gamma$

direct CPV

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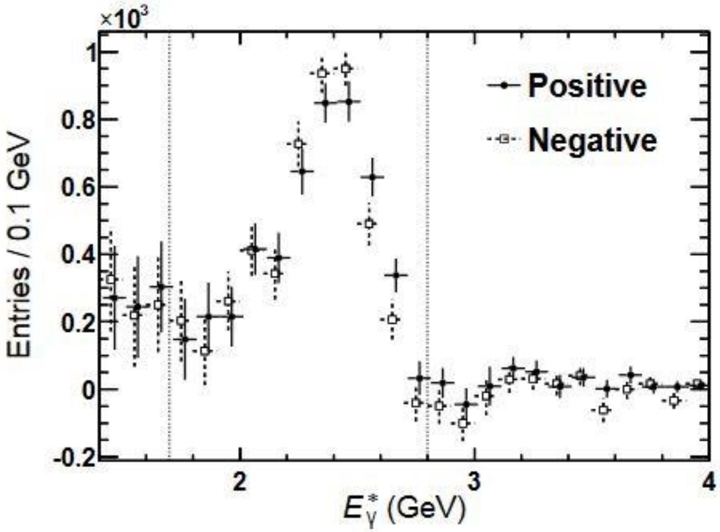
$A_{CP} = 0.015 \pm 0.020$ HFAG, 2014(?)

SM: $A_{CP} \sim (0.0044 \pm^{0.0024}_{0.0014})\%$

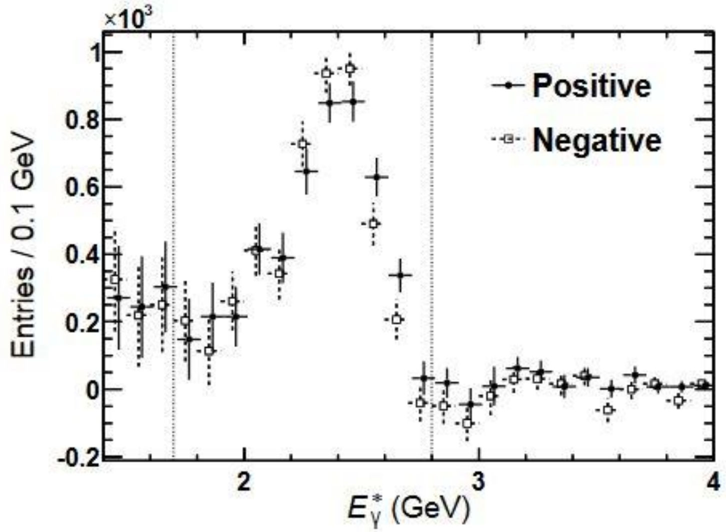
T. Hurth et al., Nucl.Phys. B704, 56 (2005)

Belle, PRL114, 151601 (2015), 700 fb^{-1}



DCPV/$B \to S\gamma$

BELLE, PRL114, 151601 (2015), 700 FB-1



$B \to s\gamma$
DIRECT CPV

INCLUSIVE, γ RECONTRUCTION ONLY;
BKG. SUPPRESSION (KINEMATIC EVENT SHAPE VARIABLES);
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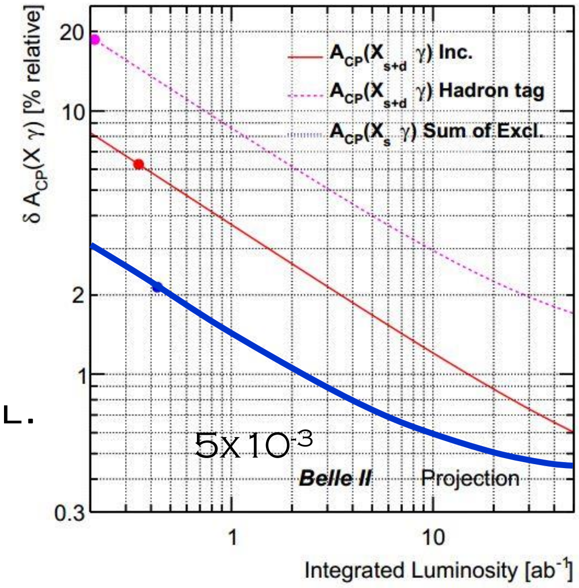
T. HURTH ET AL., NUCL.PHYS. B704, 56 (2005)

SIMILAR SENSITIVITY EXPECTED FOR SEMI-INCLUSIVE & FULLY INCLUSIVE



SUM OF EXCL.
INCL.

LFU:

important measurements to be performed already with 5 – 10 ab^{-1} (2019-2020)

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LFV:

50 ab^{-1} (2023) needed to reduce existing limits by > 10

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important measurements to be performed already with $5 - 10$ ab^{-1} (2019-2020)

LFV:

50 ab^{-1} (2023) needed to reduce existing limits by > 10

CPV:

in rare modes 20-50 ab^{-1} (2021-2023) needed to reach SM expectations