Loophole in $K \to \pi\nu\nu$ Search & $K_L \to \pi^0\nu\nu$ Beyond Grossman-Nir Bound

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15 Sept @ KAON 2016, Birmingham

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Outline

I. Intro: Kaon, as old as Particle Physics

... KOTO's public neglect, Until Now!

II. Blinding $[K^+ \to \pi^+]\pi^0$: Blessed are the Blind

— $K_L \to \pi^0 + \text{Nothing}$ above "GN Bound"? —

CMS → Kaon

III. A Motivated Model (existence proof)

Gauged $L_\mu - L_\tau$ related to muon g – 2 + ...

IV. What Then? — an Illustration of Impact

"Exotic" Rare K & B Decays

V. Conclusion

Fuyoto, WSH, Kohda, 1412.4397 (PRL'15)
and 1512.09026 (PRD'16)

69+

I. Intro: Kaon, as old as Particle Physics

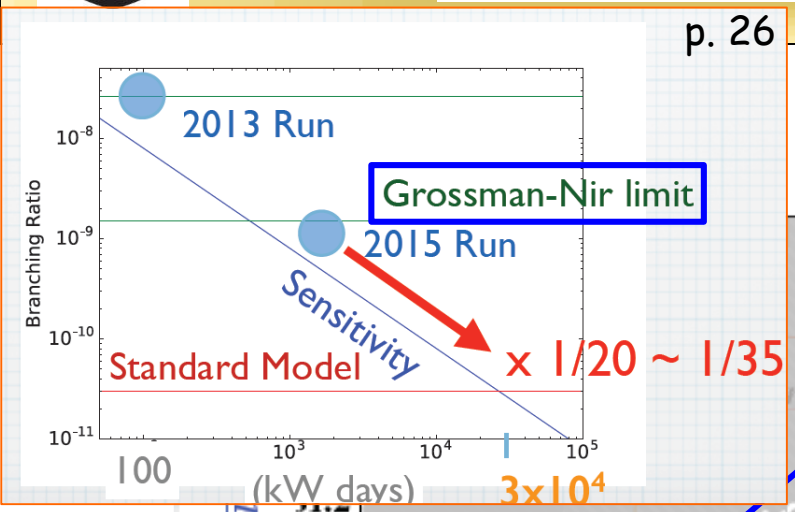
and Andrzej

- V particles from cosmic
- $g-2=\alpha/\pi$ at one loop
- But still NP Frontier:

$K^+ \to \pi^+\nu\nu$ vs $K_L \to \pi^0\nu\nu$

Taku at FPCP2016, Caltech

p. 26

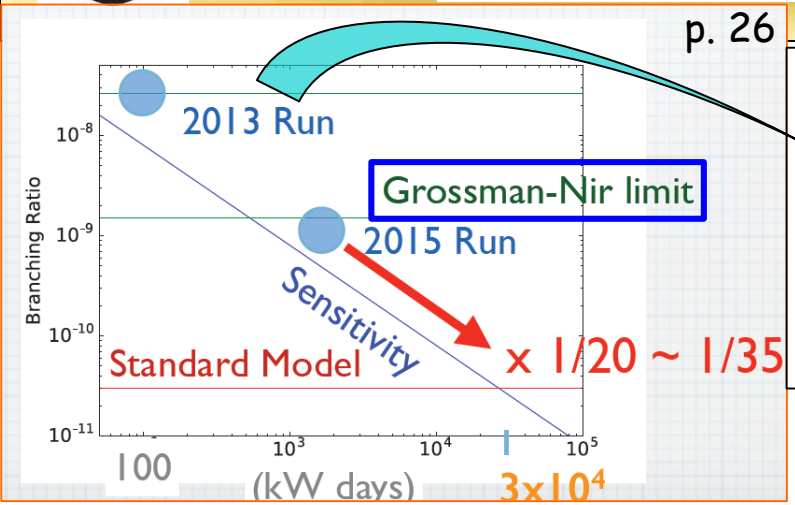


Relative Mute @ ICHEP

p. 14

... KOTO's public neglect, Until Now!

p. 26



1609.03637, and Shiomi's talk

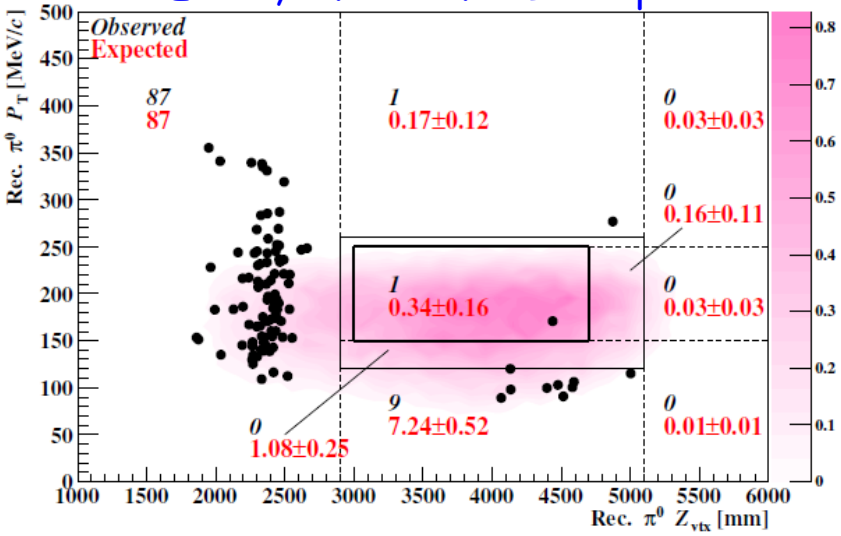
PTEP
Prog. Theor. Exp. Phys. **2015**, 00000 (11 pages)
DOI: 10.1093/ptep/0000000000

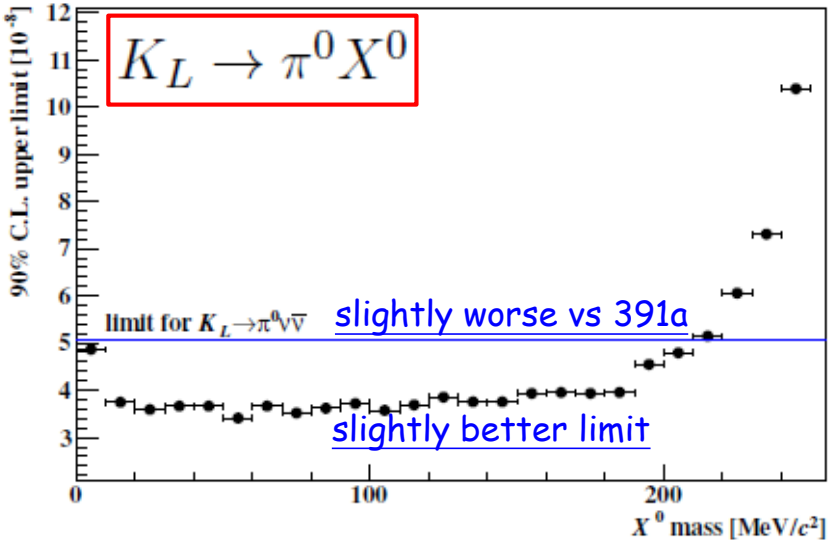
A New Search for the $K_L \to \pi^0\nu\bar{\nu}$ and $K_L \to \pi^0 X^0$ decays

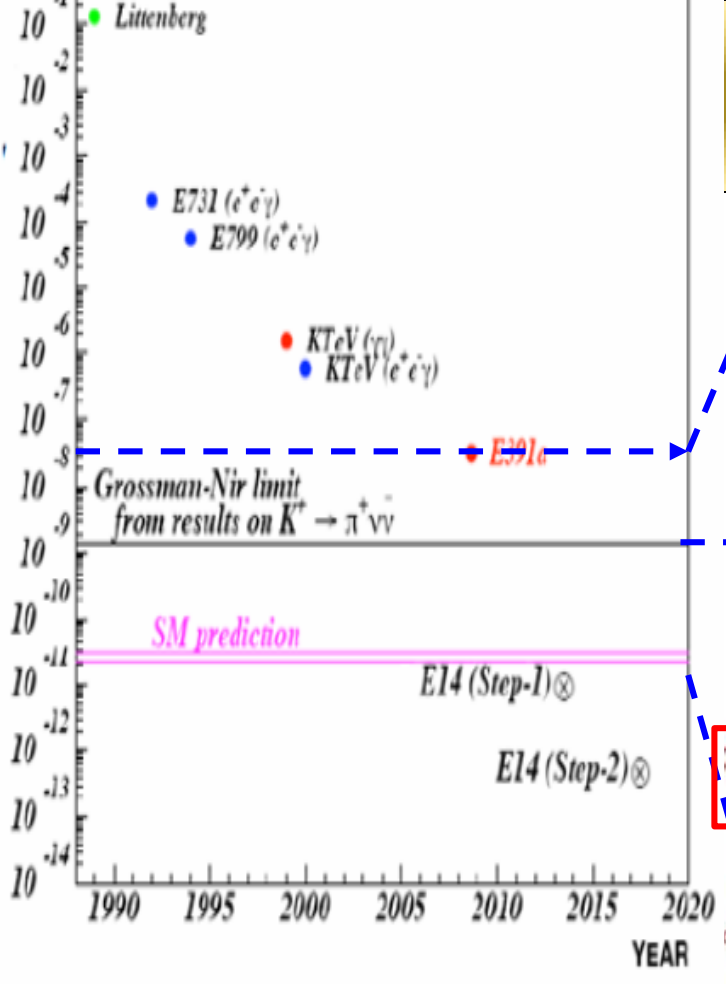
J-PARC KOTO collaboration

We searched for the CP-violating rare decay of neutral kaon, $K_L \to \pi^0\nu\bar{\nu}$, in data from the first 100 hours of physics running in 2013 of the J-PARC KOTO experiment. One candidate event was observed while 0.34 ± 0.16 background events were expected. We set an upper limit of 5.1×10^{-8} for the branching fraction at the 90% confidence level (C.L.). An upper limit of 3.7×10^{-8} at the 90% C.L. for the $K_L \to \pi^0 X^0$ decay was also set for the first time, where X^0 is an invisible particle with a mass of 135 MeV/c^2.

One Event, 0.34 ± 0.16 BG expected







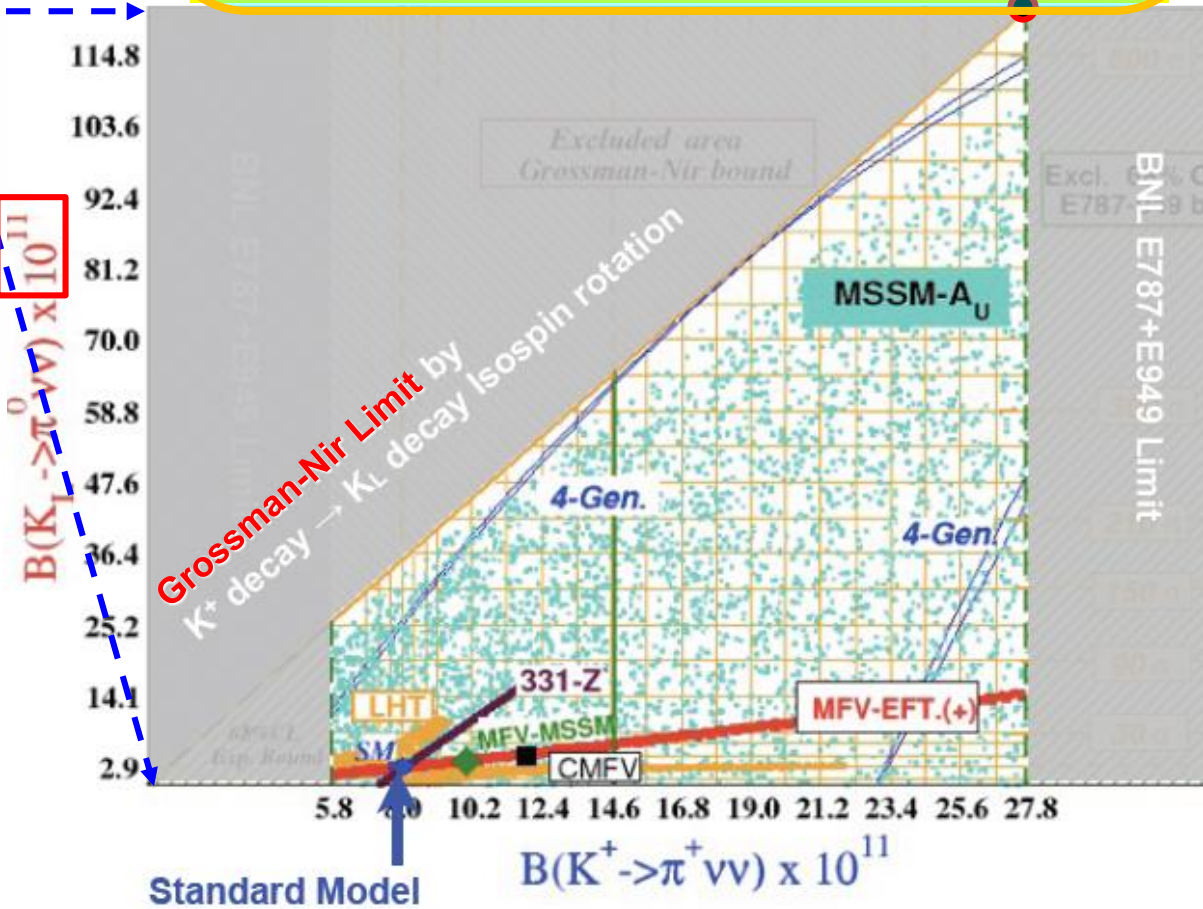
Now ...

Shaken It Off !

mostly τ_{K_L}/τ_{K^+}

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \lesssim 4.3 \times \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$$
$$< 1.4 \times 10^{-9}. \quad \text{(GN bound)}$$

KOTO @ 100 hrs (2013), paper finally ...



@ J-PARC

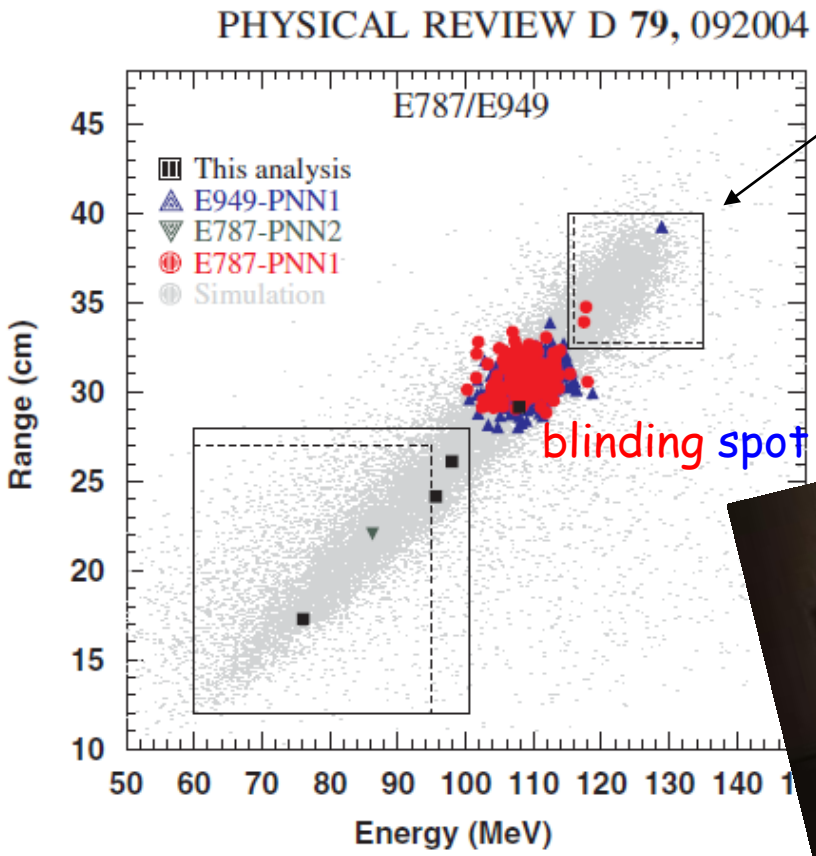
$K_L \to \pi^0\nu\nu$ > GN ?

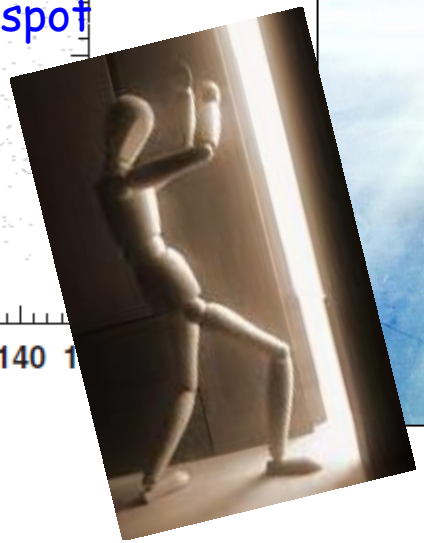
II. Blinding [$K^+ \to \pi^+$]π^0: Blessed are the Blind

Or: Stupid is as stupid does.

The Blinding $K^+ \to \pi^+\pi^0$

I (We) have (all) stared at this gazillion times, and became numb.



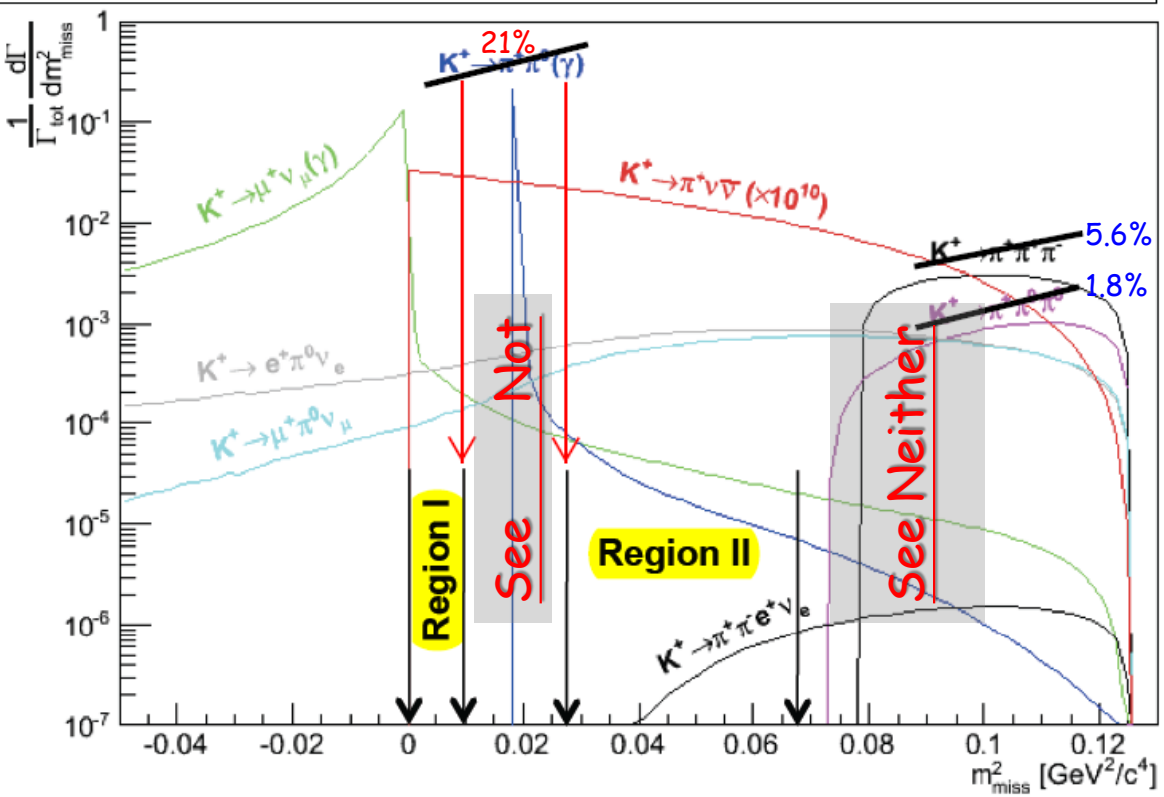


The Blinding $K^+ \to \pi^+\pi^0$

NA62 @ CERN

Window basically Same as E787/949 @ BNL

Kinematic exclusion:
exclude 0.01 - 0.025 GeV^2 [(100)^2 - (160)^2 MeV^2]



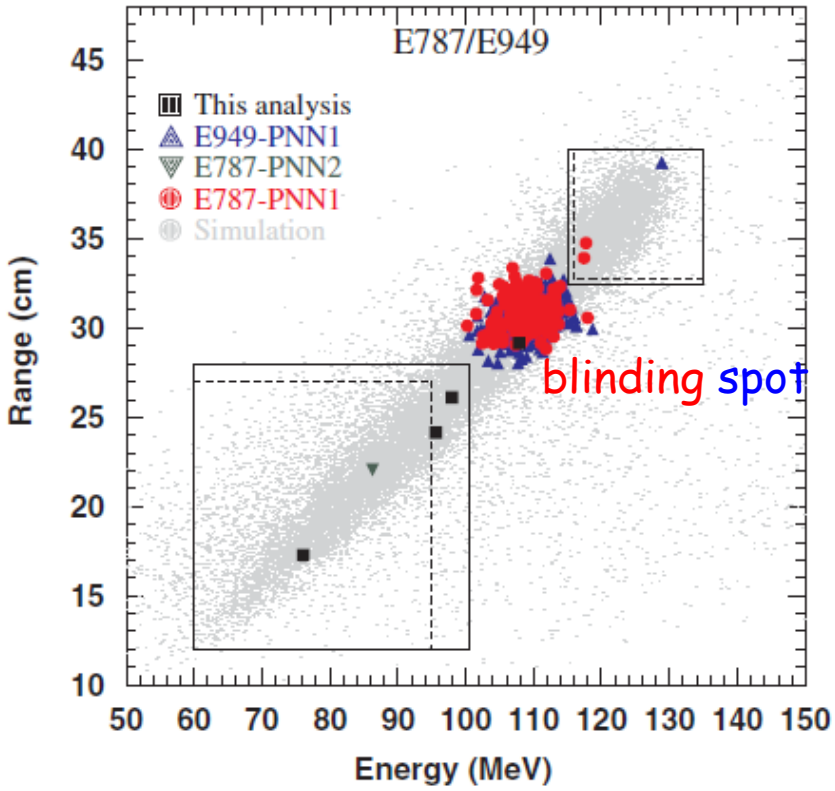
Kinematic Control:
use K^+ and π^+ momenta
to block out blinding zone

The Blinding $K^+ \to \pi^+\pi^0$

Not a great limit

BV. The E949 limit of $\mathcal{B}(\pi^0 \to \nu\bar{\nu}) < 2.7 \times 10^{-7}$ at 90% C.L. [60] can be combined with the world average value of $\mathcal{B}(K^+ \to \pi^+\pi^0)$ [24] to set a 90% C.L. limit of $\mathcal{B}(K^+ \to \pi^+ X) < 5.6 \times 10^{-8}$ for $M_X = M_{\pi^0}$ with X stable

PHYSICAL REVIEW D 79, 092004 (2009)



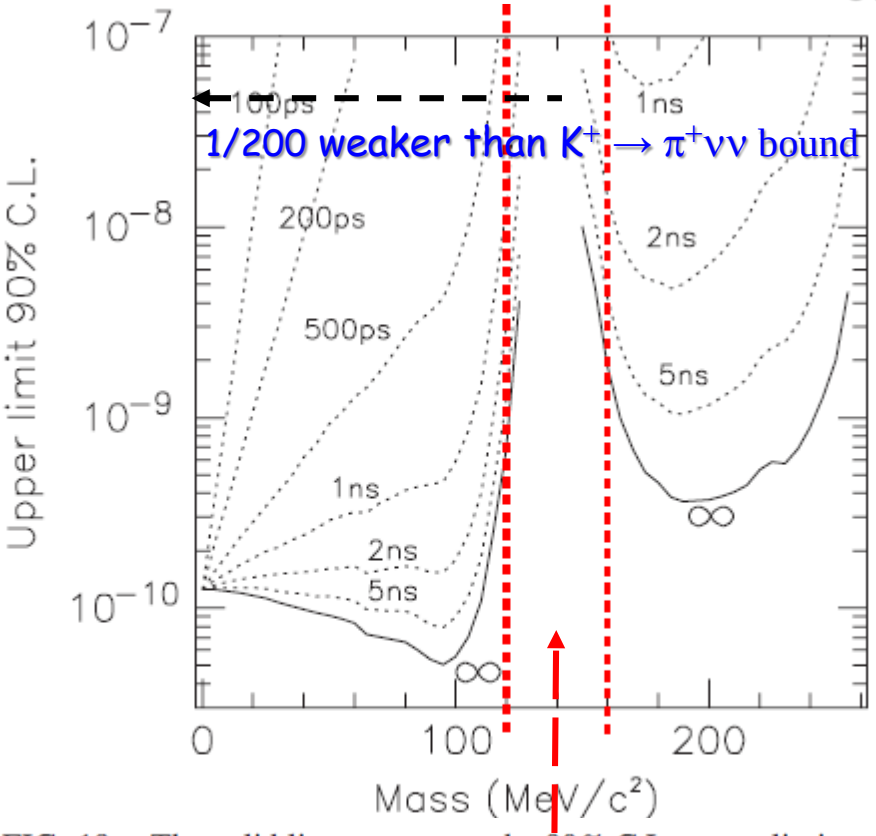


FIG. 18. The solid lines represent the 90% C.L. upper limit on $\mathcal{B}(K^+ \to \pi^+ X)$ as a function of the mass of X assuming X is

$K^+ \to \pi^+ \text{“}\pi^0\text{”}$ Loophole vs $K_L \to \pi^0 X^0$

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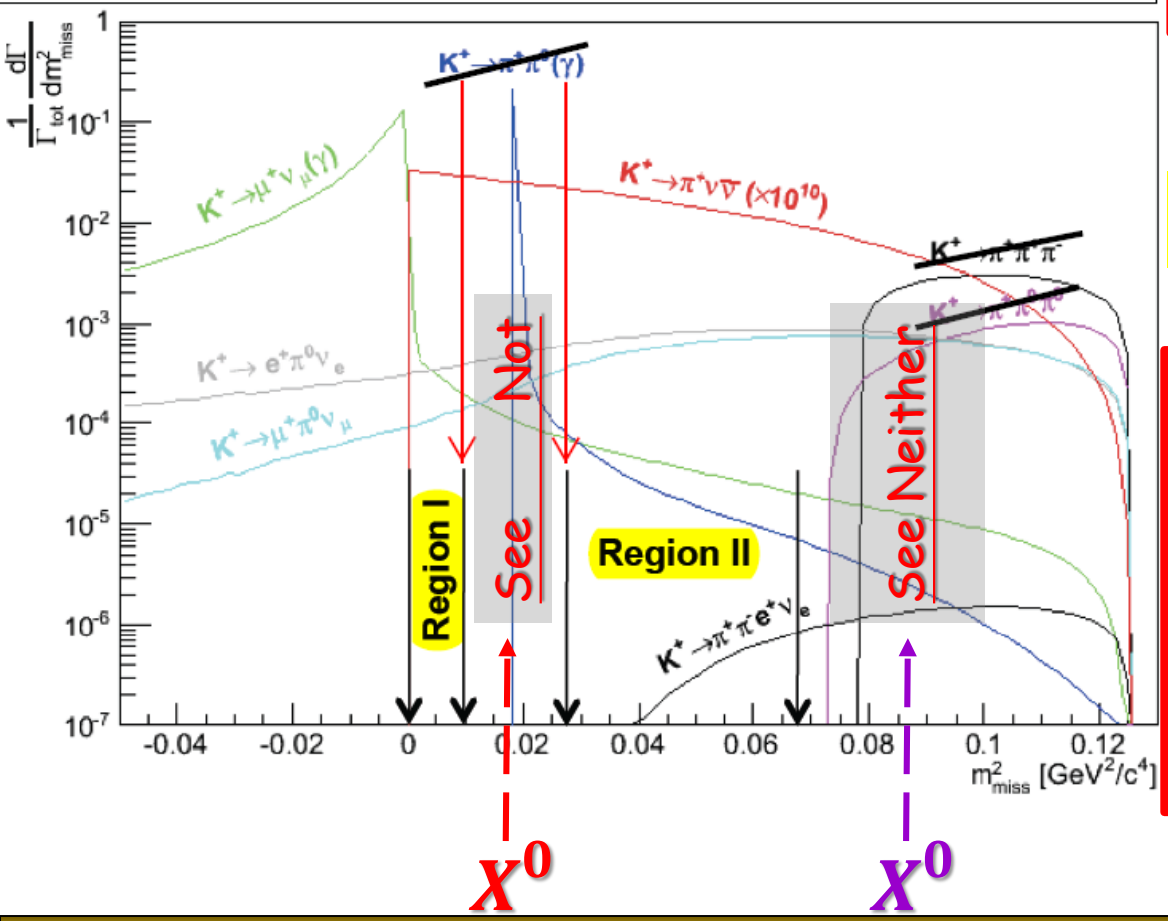


The KOTO Expt at J-PARC can discover $K_L \to \pi^0 X^0$ above the Grossman-Nir Bound !

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \lesssim 4.3 \times \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) < 1.4 \times 10^{-9}. \quad \text{(GN bound)}$$

“Blessed are the Blind.”

A Surprise! “Trivial”

$K_L \to \pi^0\nu\nu$

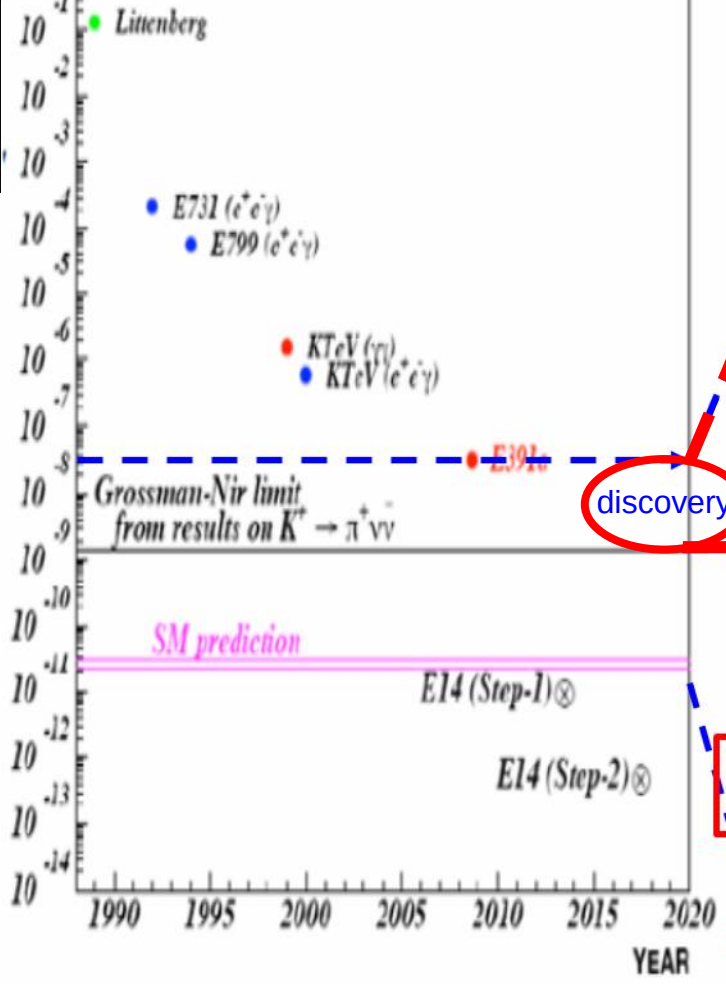
“Nothing to Nothing” (just $\gamma\gamma$)

— *Veto Everything !*

But: Cannot Veto WILPs.

(**W**eakly **I**nt. **L**ight **P**article)

Fuyoto, WSH, Kohda, PRL'15

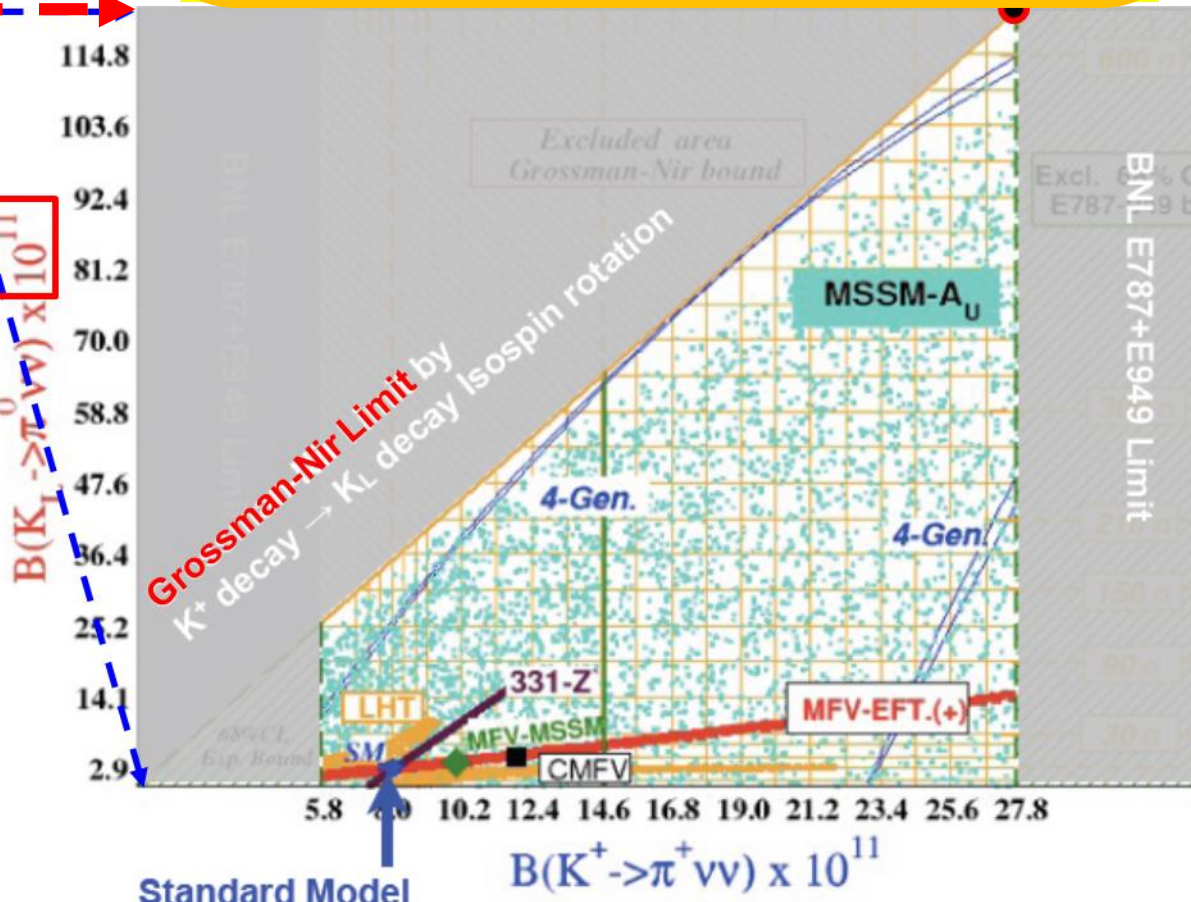


discovery

Discovery Starting "Now" ! It Off !

The KOTO Expt at J-PARC can discover $K_L \to \pi^0 X^0$ above the Grossman-Nir Bound !

KOTO @ 100 hrs (2013), paper finally ...



@ J-PARC

$K_L \to \pi^0 \nu\nu$ > GN ?

Continuing from what Pospelov left off this morning … K_L

— $K_L \to \pi^0 + \text{Nothing}$ above "GN Bound"? —

- What you learned in "school" not quite right
- Seeing the possibility was inadvertent
- It all started from CMS & TopCNC Pheno …

A Story of CMS-related work leading to Kaon physics … ☺

III. A Motivated Model (existence proof)

gauged $L_\mu - L_\tau$ related to muon $g - 2$

\+ ...

Gauged $L_\mu - L_\tau$ model

Altmannshofer, Gori, Pospelov and Yavin, PRD89, 095033 (2014)

- U(1)': gauging $L_\mu - L_\tau$ (μ-number minus τ-number)
  → anomaly free within SM particle content — X.G. He et al., PRD1991
- U(1)' breaking: $\langle \Phi \rangle = \frac{v_\Phi}{\sqrt{2}}$
  - SM singlet
  - U(1)' charge +1
  - Z' mass: $m_{Z'} = g' v_\Phi$
  - $L_\mu - L_\tau$ current:

$$\mathcal{L} \supset -g' Z'_\alpha (\bar{\mu}\gamma^\alpha \mu + \bar{\nu}_{\mu L}\gamma^\alpha \nu_{\mu L} - \bar{\tau}\gamma^\alpha \tau - \bar{\nu}_{\tau L}\gamma^\alpha \nu_{\tau L})$$

  - Quarks? Introduce New Vector-like Quarks

"4G" chiral quarks			chiral partners		
$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}$	U_R	D_R	$\tilde{Q}_R = \begin{pmatrix} \tilde{U}_R \\ \tilde{D}_R \end{pmatrix}$	$\tilde{U}_L$	$\tilde{D}_L$
U(1)' charges: +1	-1	-1	+1	-1	-1

g.i. mass, plus Yuk. Mixing w/ SM Quarks

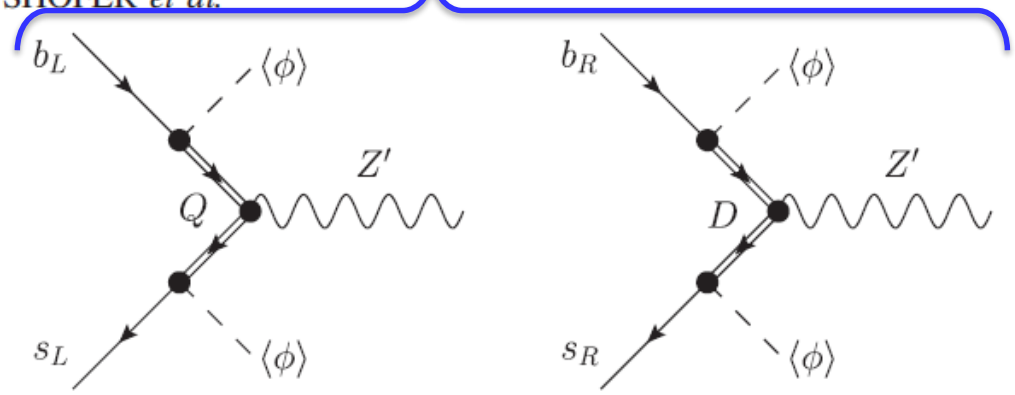
P_5'-motivated Z' induces $t \to cZ'$ also

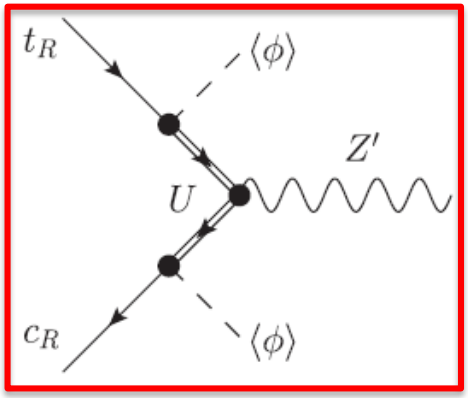
$B \to K^* \mu^+ \mu^-$

Our Original Interest

ALTMANNSHOFER *et al.*

PHYSICAL REVIEW D **89,** 095033 (2014)





Q, D, U: vector-like quarks with Z' charge

$$\mathrm{BR}(t \to Z'c) \simeq \frac{2(1-x')^2(1+2x')}{(1-x)^2(1+2x)} \times \left(|Y_{Qt} Y_{Qc}^*|^2 \frac{v^2 v_\Phi^2}{4m_Q^4} + |Y_{Ut} Y_{Uc}^*|^2 \frac{v^2 v_\Phi^2}{4m_U^4} \right)$$

$$x = \frac{m_W^2}{m_t^2}, \qquad x' = \frac{m_{Z'}^2}{m_t^2}$$

"unconstrained"

⇒ Should Search for $t \to cZ' \to c\mu^+\mu^-$

$Z' \to \mu^+\mu^-$

BR ~ 1/3!

"gauged $L_\mu - L_\tau$"

Linking Leptonic Z' to Muon g – 2

gauged $L_\mu - L_\tau$

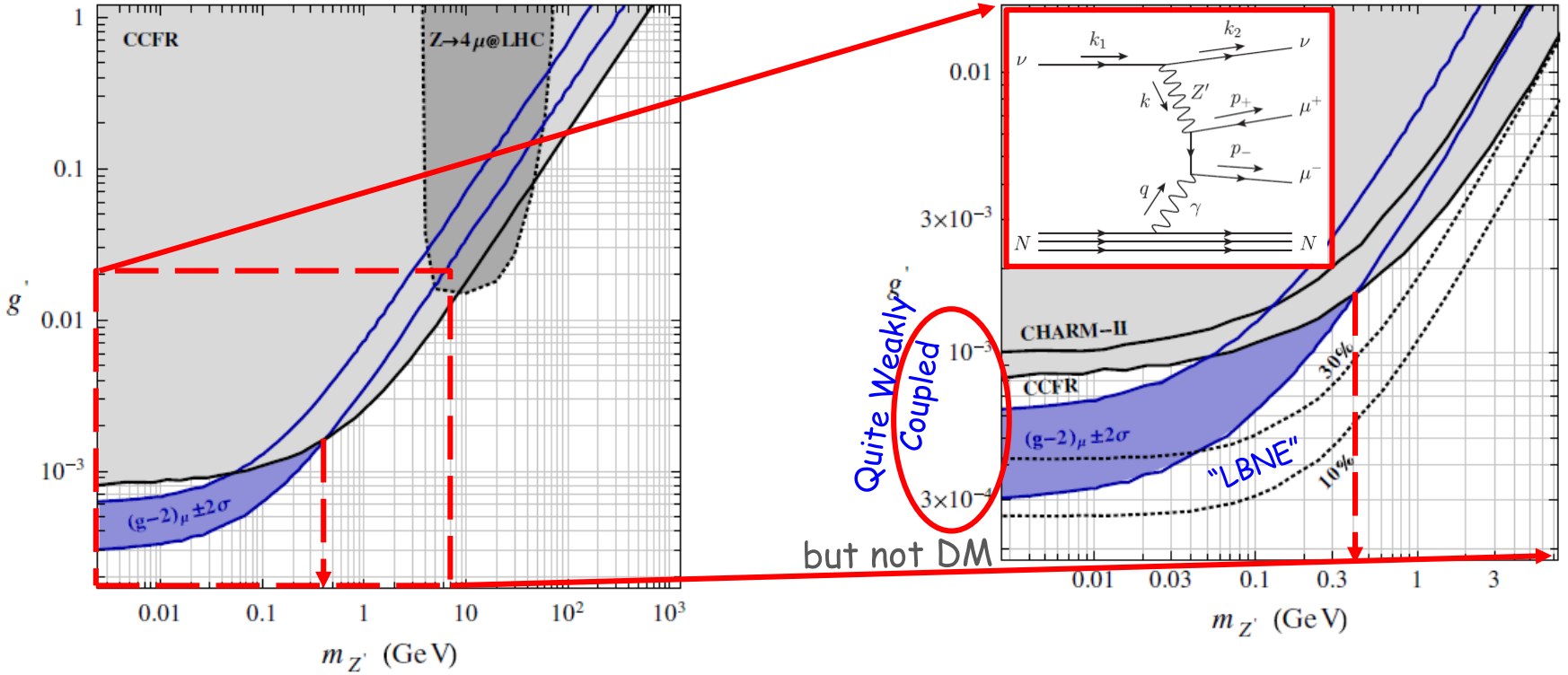
Cannot Affect P_5'

1406.2332

Altmannshofer, Gori, Pospelov, Yavin [PRD → PRL]

"Neutrino Trident Production"

PRL 113, 091801 (2014) PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2014

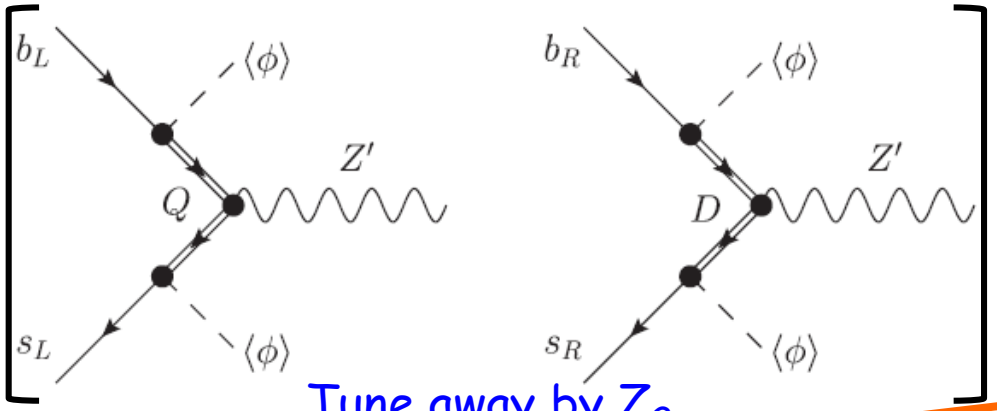


Muon g – 2 related $Z' \lesssim$ 400 MeV < m_K?

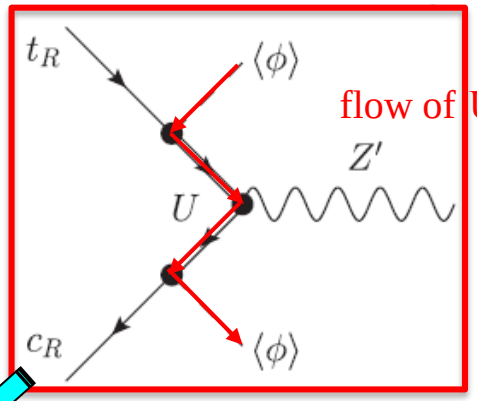
New Physics from Light Particle!?

Leptonic Z'_{g-2}-induced FCNC

gauged $L_\mu - L_\tau$

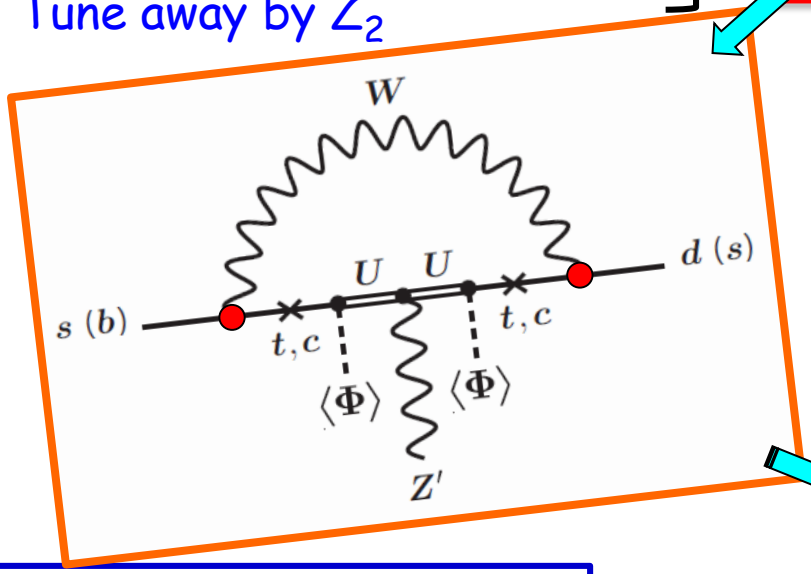


Tune away by Z_2



flow of U(1)′ charge

Q, D, U : vector-like quarks with Z' charge
$\langle\phi\rangle$: generates Z' mass



SM-assisted loop
$s \to dZ'$; $b \to sZ'$

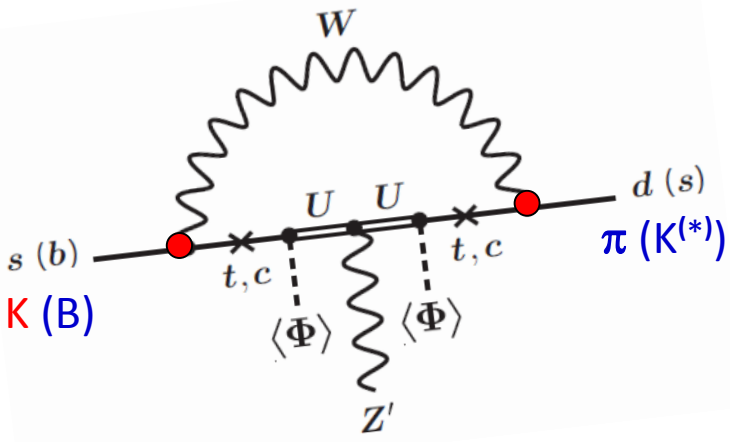
Fuyoto, WSH, Kohda, PRL'15

$K_L \to \pi^0 Z'$

Muon g – 2 related $Z' \lesssim$ 400 MeV < m_K!

New Physics from Light Particle!?

A Little Some Work ...



$Z' \lesssim$ 400 MeV < m_K

Aim: allowed $t \to cZ'$ rate

But,

$K_L \to \pi^0 Z'$?

The effective $\bar{d}_L \gamma^\mu s_L Z'_\mu$ coupling [16] has coefficient

$$g_{ds} = \frac{g' v_\phi^2}{32\pi^2 v^2} \left[c_{cc} f_{cc} + (c_{tc} + c_{ct}) f_{ct} + c_{tt} f_{tt} \right], \qquad (6)$$

where v_ϕ is the extra U(1)′ breaking scale, $c_{ij} = V_{is} V_{jd}^* Y_{Ui} Y_{Uj}^* m_i m_j / m_U^2$, Y_{Ui} are Yukawa couplings, and

$$f_{ct} = 1 + \log \frac{m_U^2}{m_t^2} + \frac{3m_W^2}{m_t^2 - m_W^2} \log \frac{m_t^2}{m_W^2},$$

$$f_{tt} = \frac{3m_W^2}{m_t^2 - m_W^2} \left(1 - \frac{m_W^2}{m_t^2 - m_W^2} \log \frac{m_t^2}{m_W^2} \right) + \log \frac{m_U^2}{m_t^2},$$

with f_{cc} obtainable from f_{tt} in $m_t^2 \ll m_W^2$ limit. These

$$\mathcal{B}(K^+ \to \pi^+ Z') = \frac{m_{K^+}}{\Gamma_{K^+}} \frac{|g_{ds}|^2}{64\pi \hat{m}_{Z'}^2} \lambda^{3/2} \left(1, \hat{m}_{\pi^+}^2, \hat{m}_{Z'}^2\right) \left[f_+^{K\pi} \left(m_{Z'}^2 \right) \right]^2, \qquad (7)$$

where $\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2(xy + yz + zx)$, $\hat{m} \equiv m / m_{K^+}$, and $f_+^{K\pi}$ is a form factor. The formula for $K_L \to \pi^0 Z'$ is analogous, with $|g_{ds}|$ replaced by $\mathrm{Im}\, g_{ds}$.

... ...

$K^+ \to \pi^+ \text{“}\pi^0\text{”}$ Loophole vs $K_L \to \pi^0 X^0$

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Kinematic exclusion:
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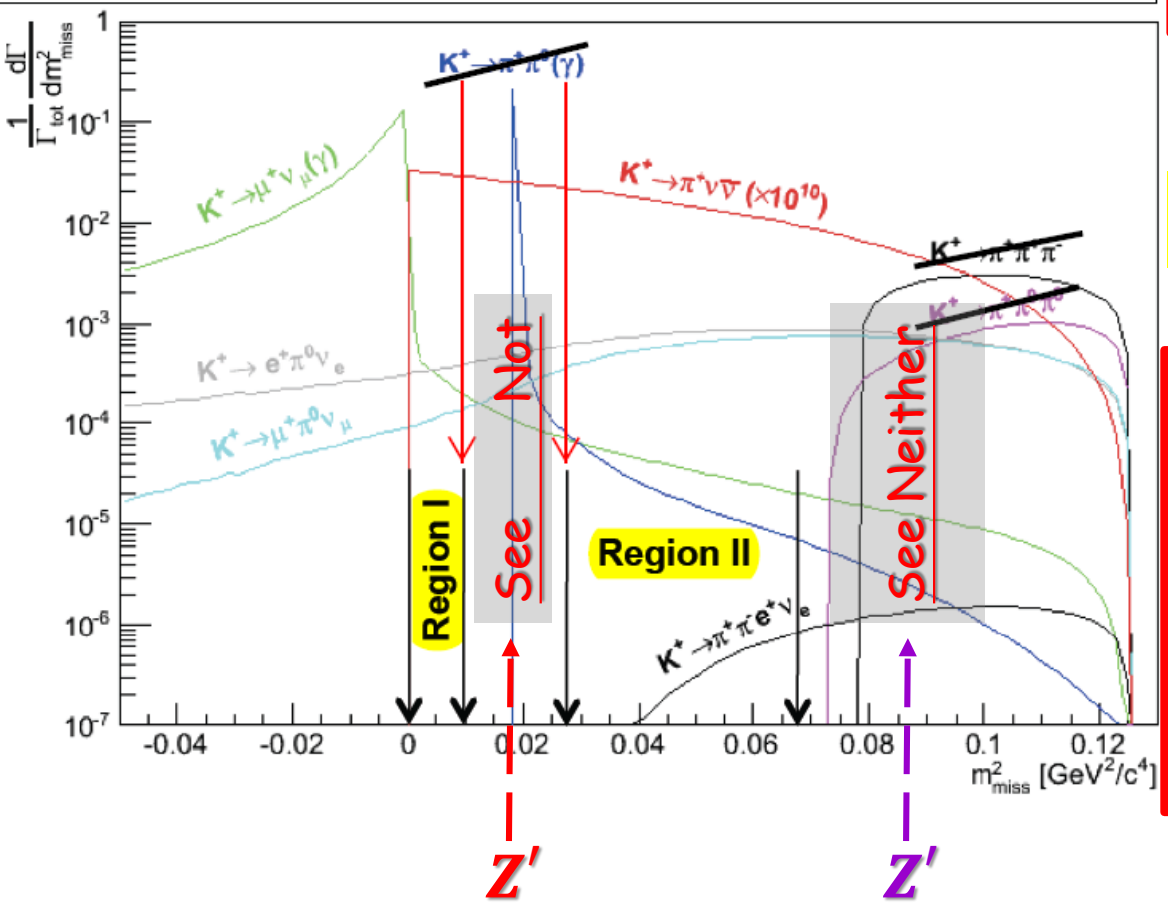

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A Surprise! “Trivial”

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— *Veto Everything !*

But: Cannot Veto WILPs.

(**W**eakly **I**nt. **L**ight **P**article)

Fuyoto, WSH, Kohda, PRL'15

IV. What Then? — an Illustration of Impact

Circumstantial Hints/Possibilities in Rare B & K Decays

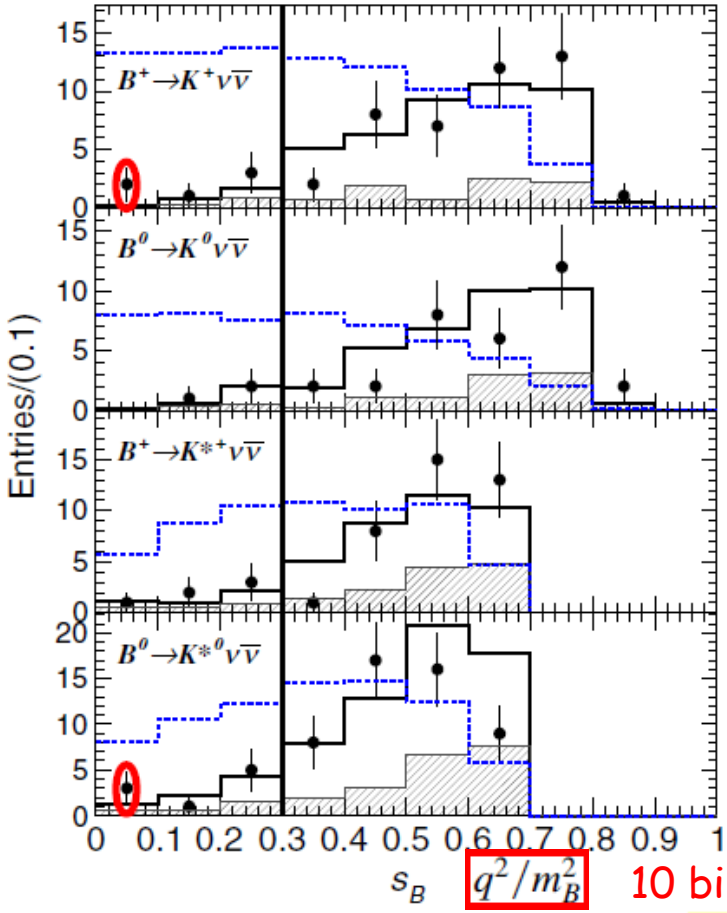
$Z' < 2m_\mu$: νν only

$Z' > 2m_\mu$: νν/μμ

BaBar: mild hint in $B^+ \to K^+\nu\nu$

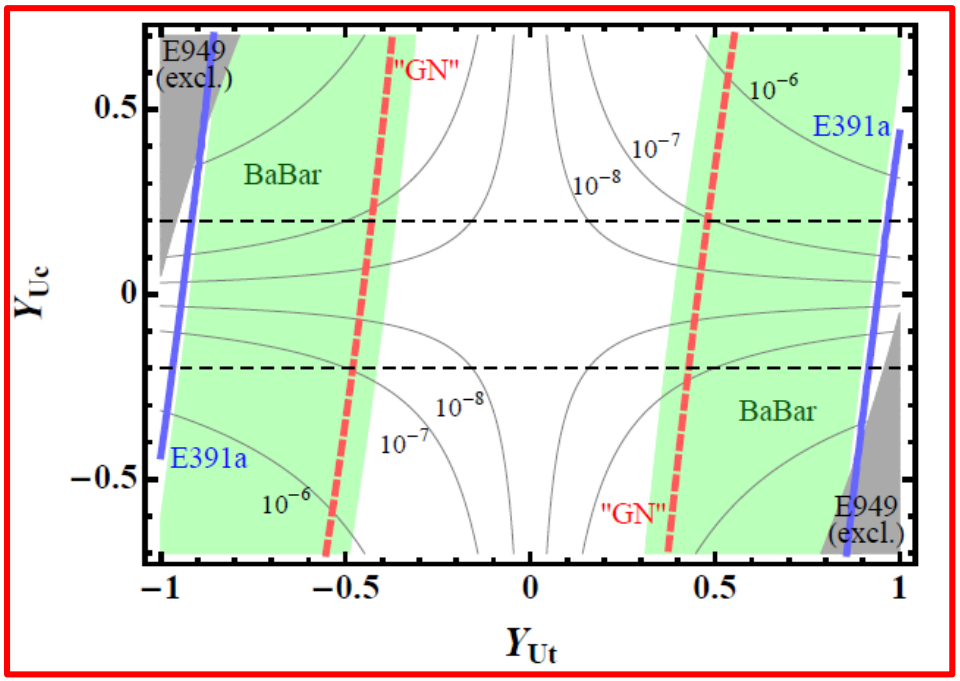
N.B. $B(B \to K\pi^0) \ll B(K \to \pi\pi^0)$

SEARCH FOR $B \to K^{(*)}\nu\bar{\nu}$ AND ... BaBar'13 (471M BB(bar))



10 bins

small excess over the expected background in the K^+ channel, we report a two-sided 90% confidence interval. driven by lowest bin Gaussian significance of about 1.4σ. Therefore, this excess is not considered significant.

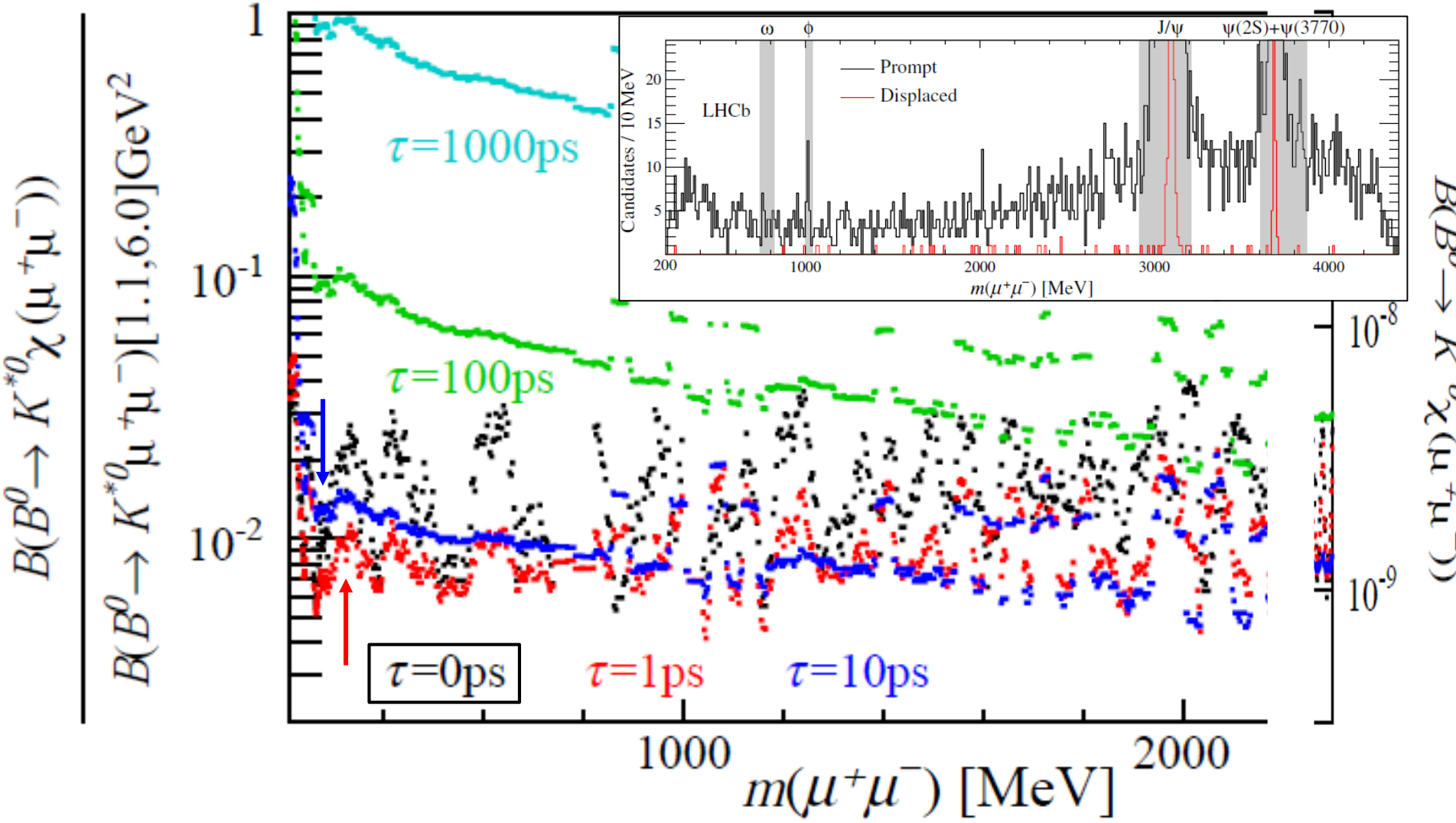


Belle needs to follow up with the Binned m_{mis} analysis. (→ Belle II)

Fuyoto, WSH, Kohda, PRL'15

Search for Hidden-Sector Bosons in $B^0 \to K^{*0}\mu^+\mu^-$

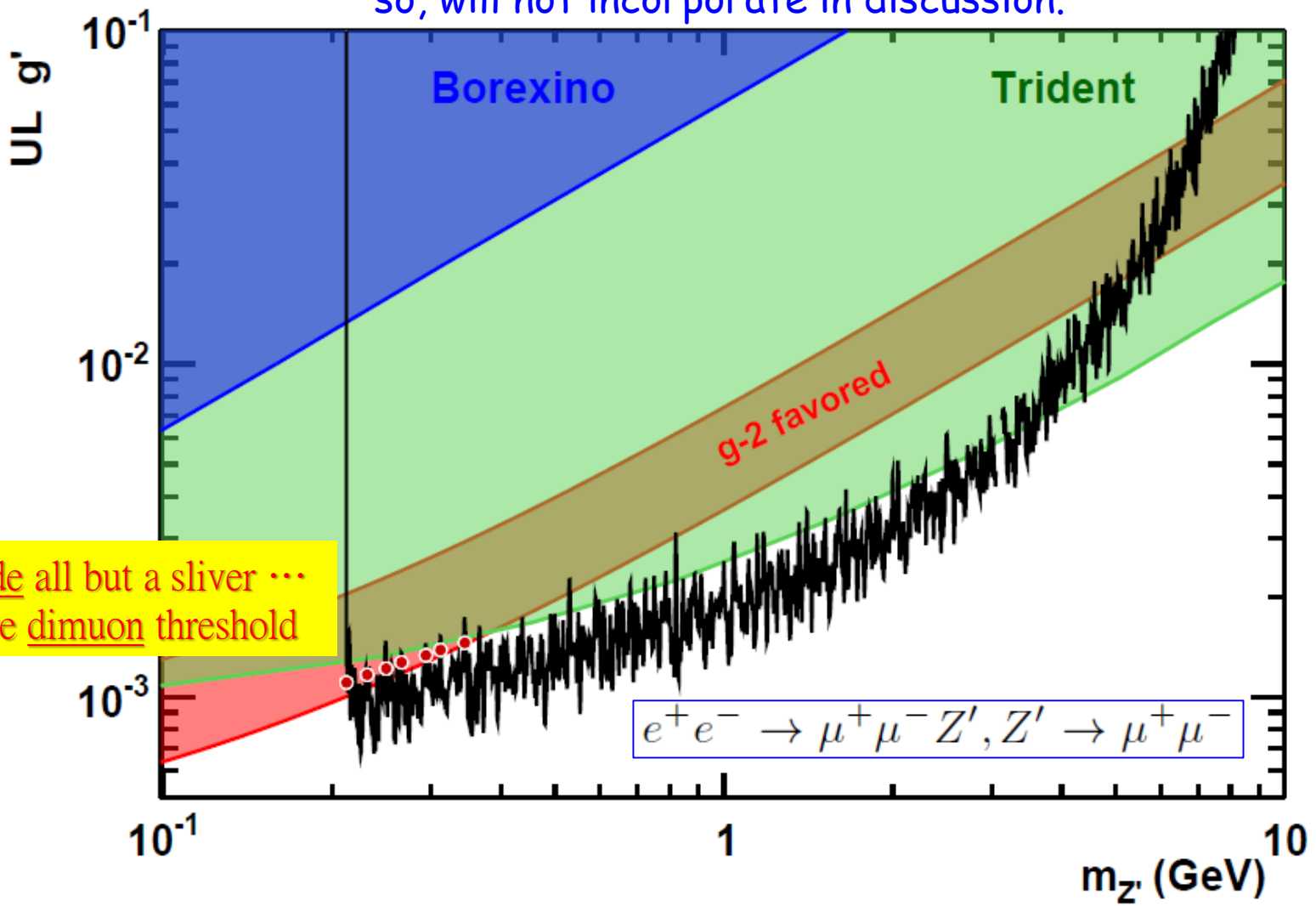
LHCb 1508.04094 [PRL'15 supplementary]



Search for a muonic dark force at *BABAR*

1606.03501

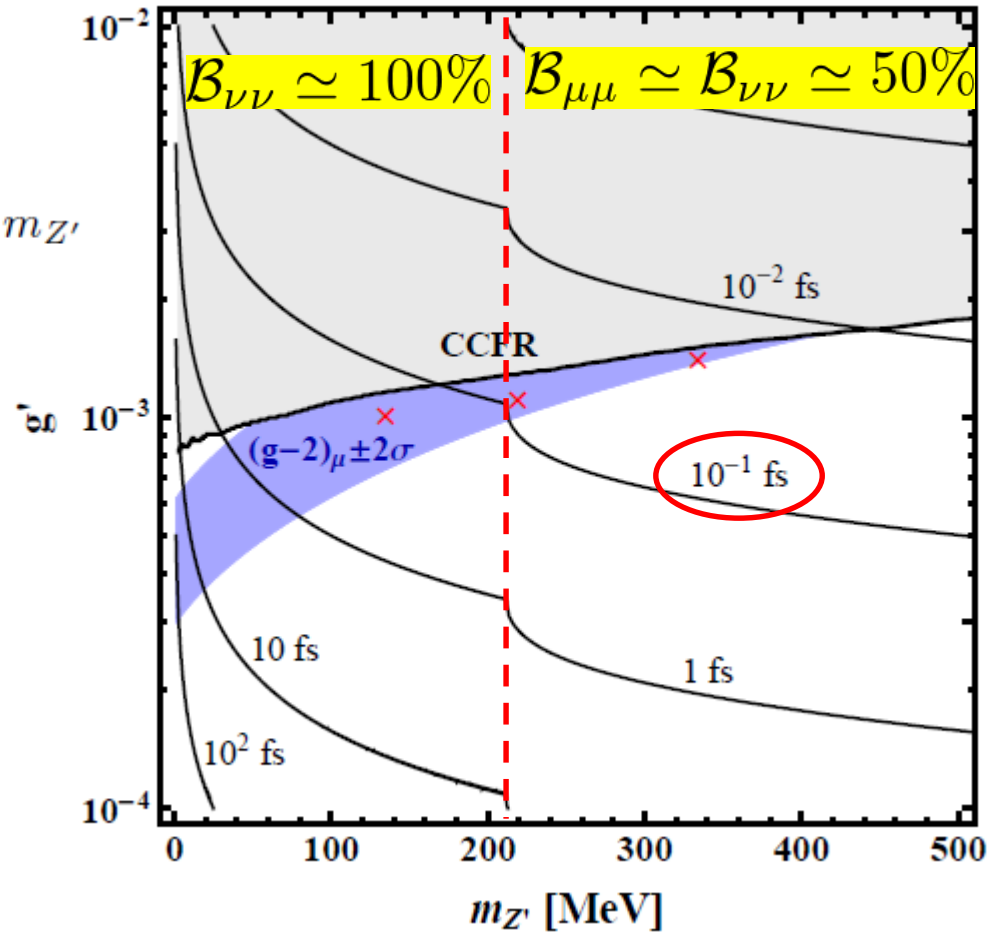
"Pockets" exist, but paper came after our PRD,
so, will not incorporate in discussion.



exclude all but a sliver ⋯
above dimuon threshold

Comment: Light "g-2" Z′ decay is prompt, even when highly boosted.

$$\Gamma(Z' \to \nu_\ell \bar{\nu}_\ell) = \frac{g'^2}{24\pi} m_{Z'}$$



$$\gamma c\tau_{Z'} \simeq 0.4\,\mu\text{m} \left[\frac{2}{N_{\text{eff}}}\right] \left[\frac{10^{-3}}{g'}\right]^2 \left[\frac{0.3\text{ GeV}}{m_{Z'}}\right]^2 \left[\frac{E_{Z'}}{10\text{ GeV}}\right]$$

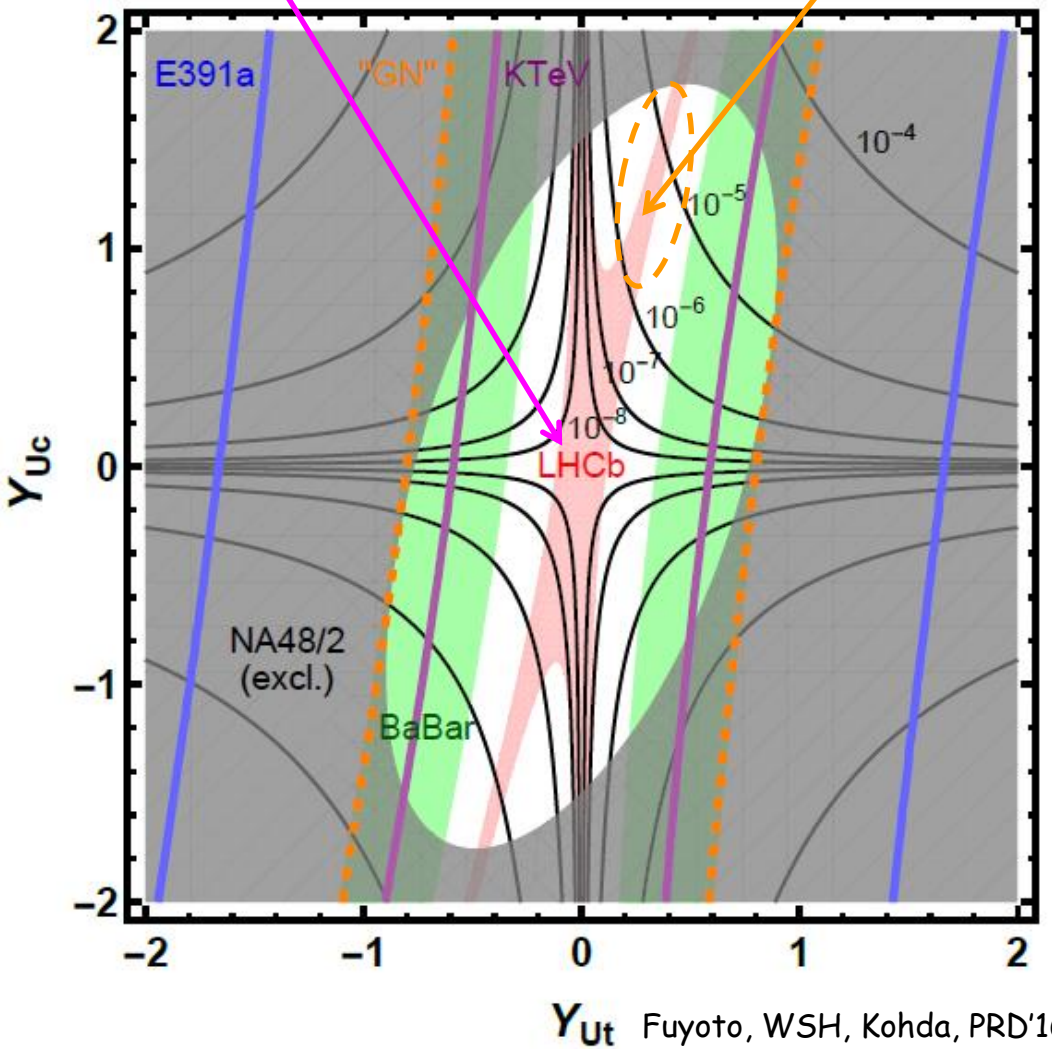
Fuyoto, WSH, Kohda, PRD'16

The 2nd Window: "pocket physics"

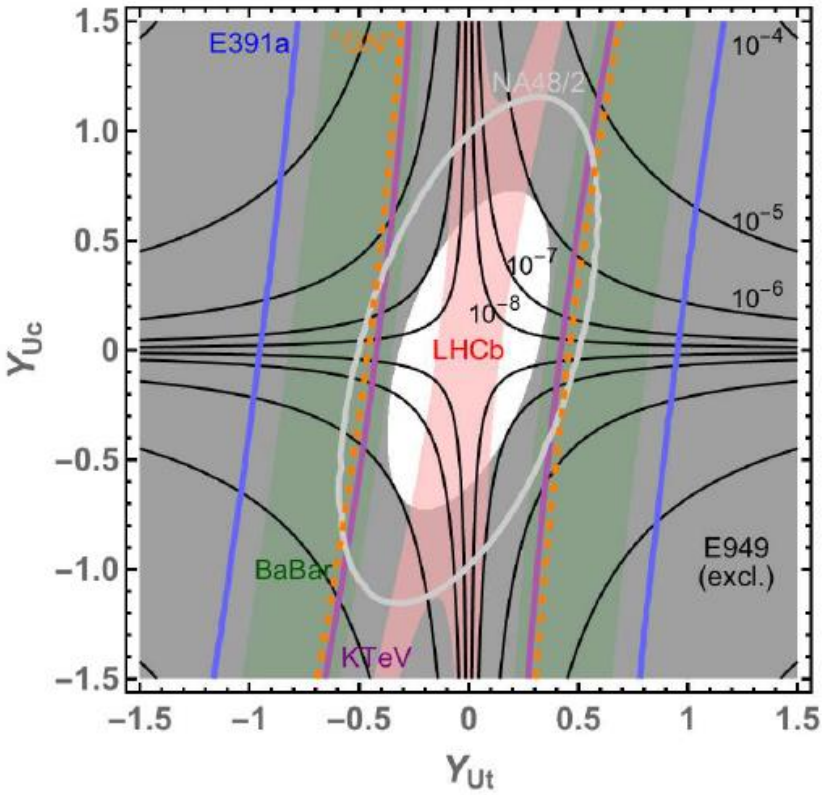
BR(t → c Z') > 10^{-6} possible

Allowed

334 MeV Z'



219 MeV Z'



Funnel regions excluded by E949 $K^+ \to \pi^+ X(\to \nu\nu)$: **no fun**

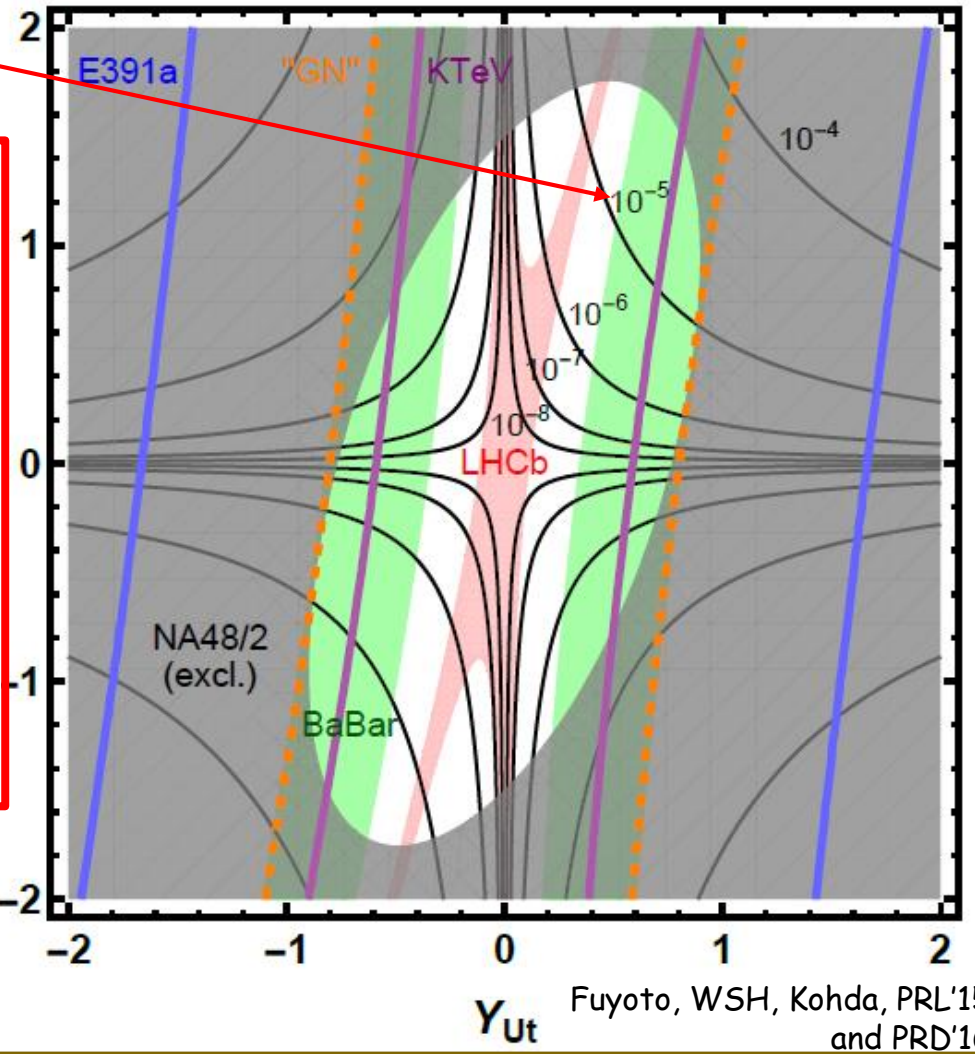
Fuyoto, WSH, Kohda, PRD'16

The Light Z'_{g-2} Landscape (illustration)

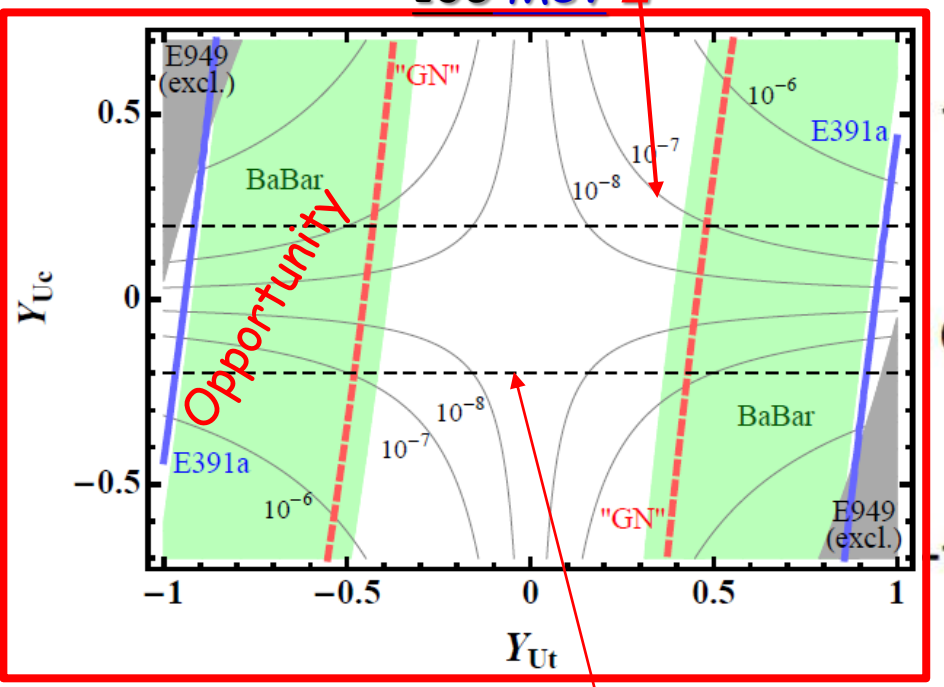
Perhaps 100 TeV SPPC/FCChh Needed .... Or not? [50% μμ]

Contour in backdrop is $t \to c Z'_{g-2}$

334 MeV Z'

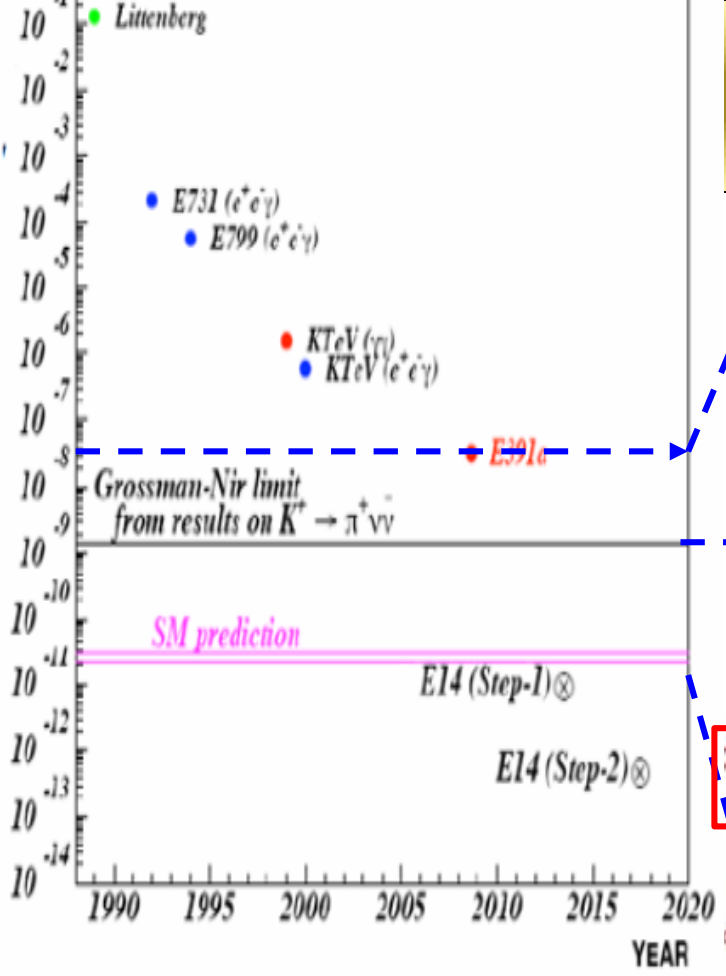


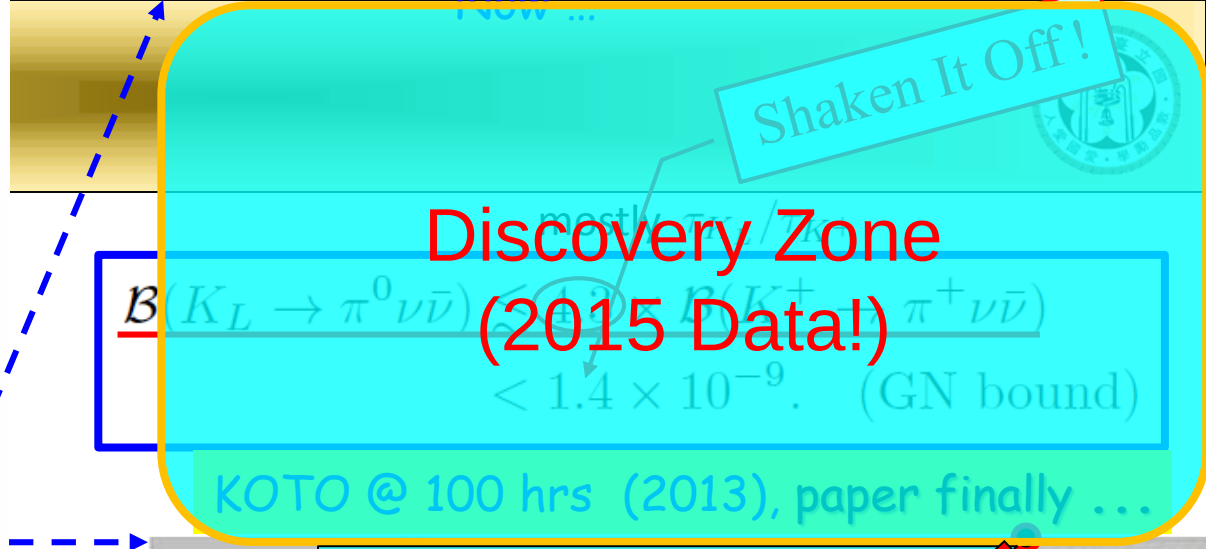
135 MeV Z'

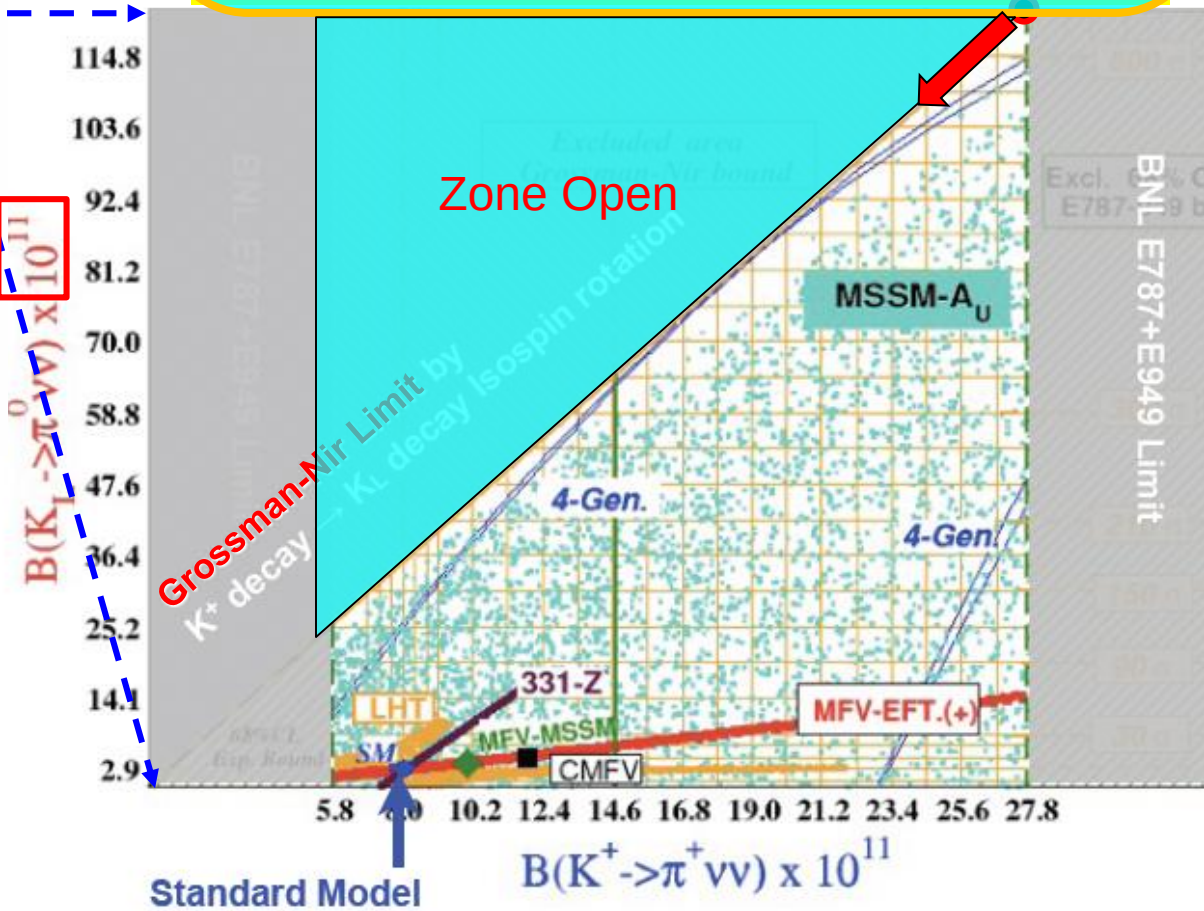


Y_{Uc} & Y_{Ut} reasonable in strength

Fuyoto, WSH, Kohda, PRL'15 and PRD'16







@ J-PARC

$K_L \to \pi^0 \nu\nu$ > GN ?

V. Conclusion

- $K_L \rightarrow \pi^0$ + nothing: can occur above "Grossman-Nir Bound" ➔ KOTO!

  If See Early Event(s), Try Hard to Kill ... But Not Overkill.

- If above GN Bound, then likely "π^0" mass object (that slips thru NA62)

- When KOTO reaches below current GN Bound, concept still effective.

  ➔ KOTO/NA62/Belle(II) (/LHCb) all in game.

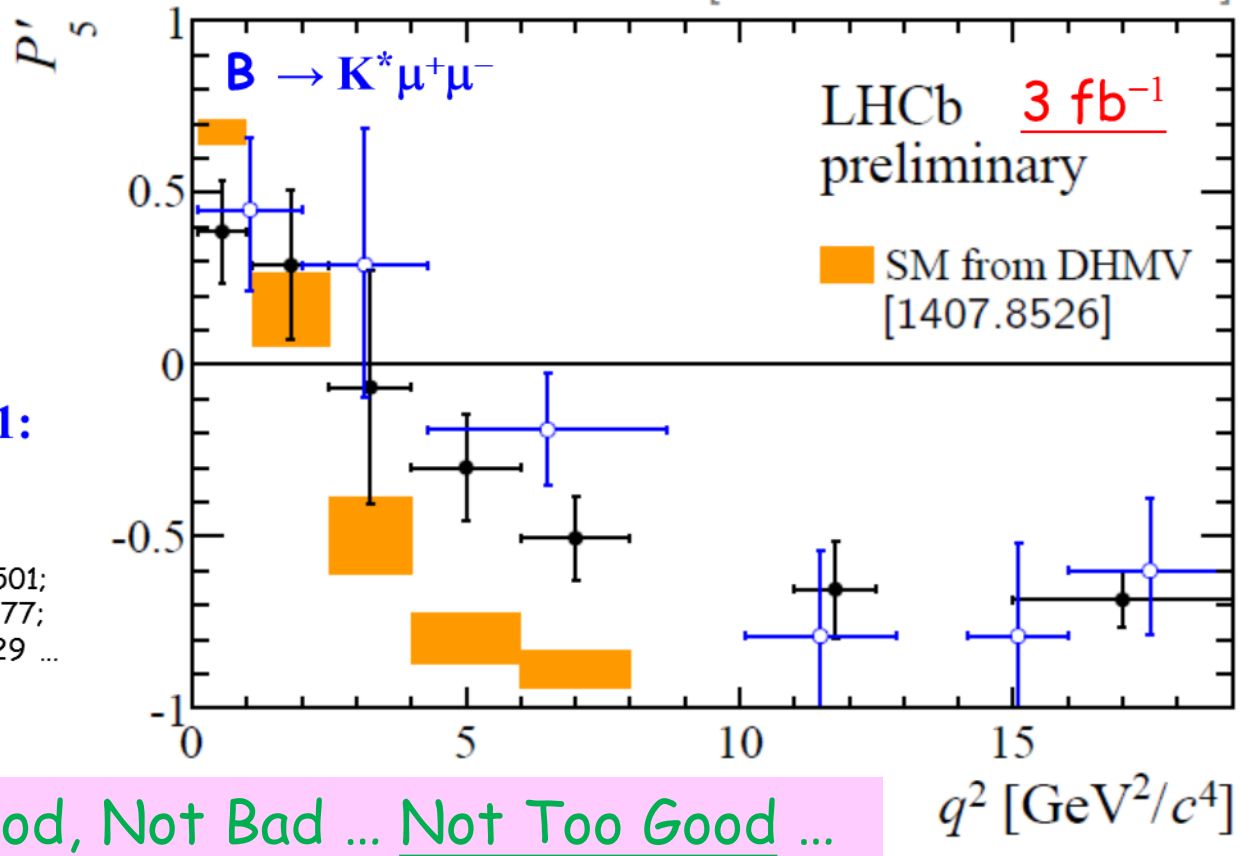
Analyze, KOTO, Analyze!


P_5'

Ex: Tolk yesterday;
Th: Turstall this morning

C. Langenbruch @ Moriond EW

[LHCb-CONF-2015-002]



NP? $\Delta C_9 \sim -1$: heavy Z′

e.g. 1307.5683; 1308.1501; 1310.2478; 1310.3877; 1310.1082; 1311.6729 …

Not Good, Not Bad … Not Too Good …

- Tension seen in P_5' in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ show deviations of 2.9σ each
- Naive combination results in a significance of 3.7σ 3.4σ
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement 3.7σ

Pick up $t \to cZ'$ topic at LHCP2014

Models with Light Z' Gauge Bosons

consider a Z' gauge boson at (or below) the electro-weak scale
associated with the anomaly free $L_\mu - L_\tau$ symmetry

difference between muon- and tau-lepton number

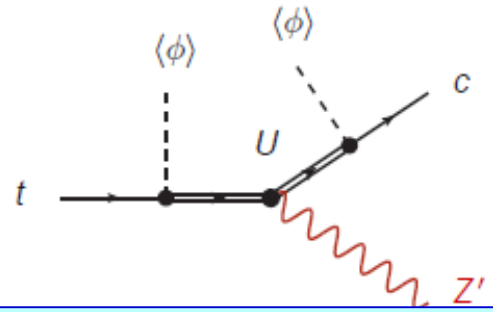
X.G. He et al., PRD1991

couple the Z' to quarks by mixing with heavy vector-like quarks

(such a Z' was proposed to solve an anomaly in the rare $B \to K^* \mu^+ \mu^-$ decay
WA, Gori, Pospelov, Yavin 1403.1269) 1403.1269

can also lead to
non-standard top decays

$$\mathrm{BR}(t \to cZ') \simeq |Y_{Ut} Y_{Uc}^*|^2 \frac{v^2 v_\Phi^2}{2 m_U^4}$$



I ask from back of room: "How to Search?".
Came the reply: "μμ or ττ" mode.

a dedicated search with existing LHC data should be able to constrain
this branching ratio at the level of $\mathrm{BR}(t \to cZ') \sim 10^{-3}$

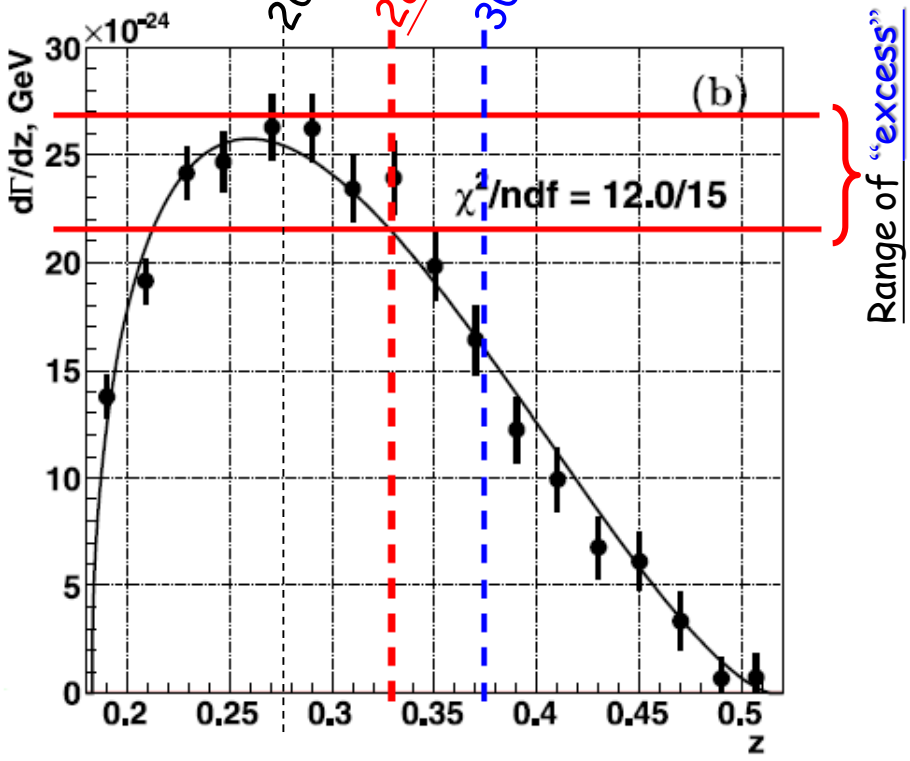
at run 2, the sensitivity could be at the level of $\mathrm{BR}(t \to cZ') \sim 10^{-4}$

$Z' > 2m_\mu$: νν/μμ

The 2nd Window

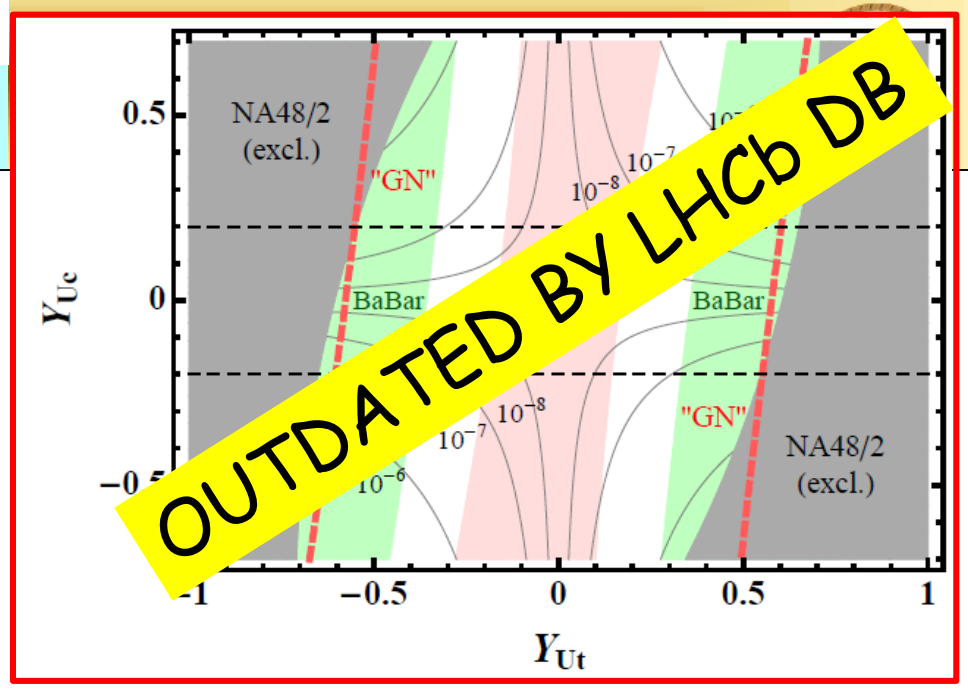
NA48/2 Collaboration / Physics Letters B 697 (2011)

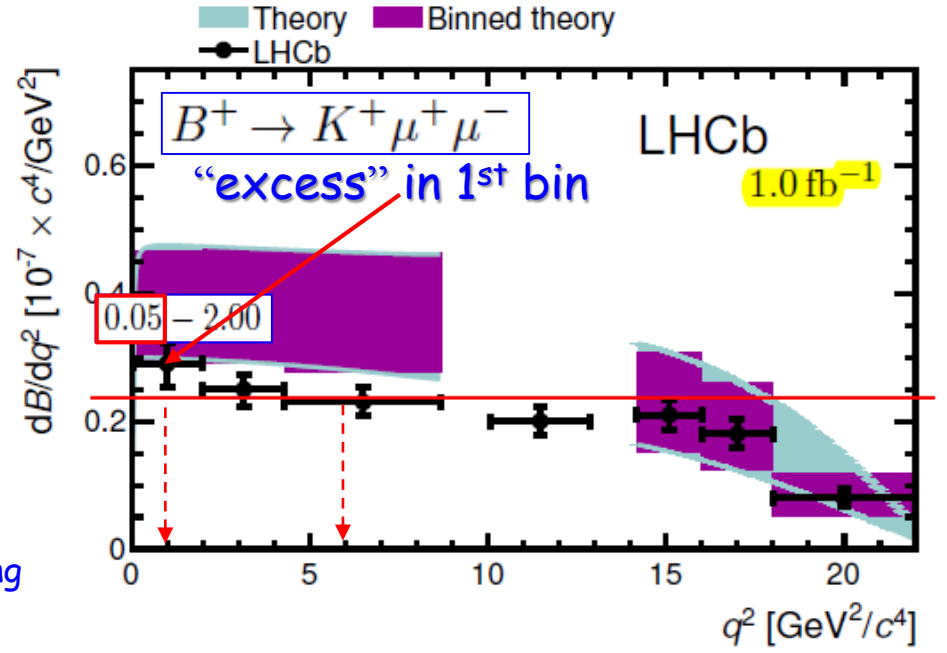
$K^\pm \to \pi^\pm \mu^+ \mu^-$



Can be *refined* by NA62

Piccini talk this morning





Fuyoto, WSH, Kohda, PRL'15

The Blinding $K^+ \to \pi^+\pi^0$

I (We) have (all) stared at this gazillion times, and became numb.