A Very Light Z′ for Muon g−2 and Its Implications

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Outline

I. Frontiers of Flavour Physics

FCNC — Top, Bottom, Strange …

II. Very Light Z′: $t \to cZ'$ w/ constraints

Gauged $L_\mu - L_\tau$: from P_5' to Muon g – 2

III. Kaon: the Oldest Frontier

Grossman-Nir Bound — Evade by $K \to \pi Z'$

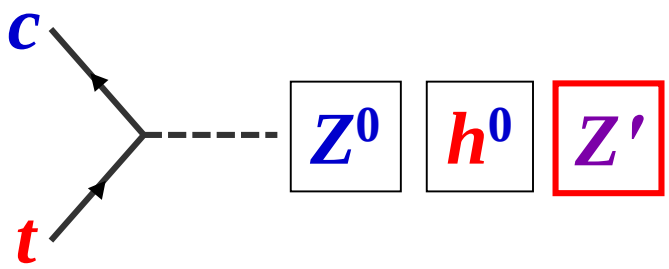
IV. Where Else? — an Illustration

"Exotic" Rare K & B Decays

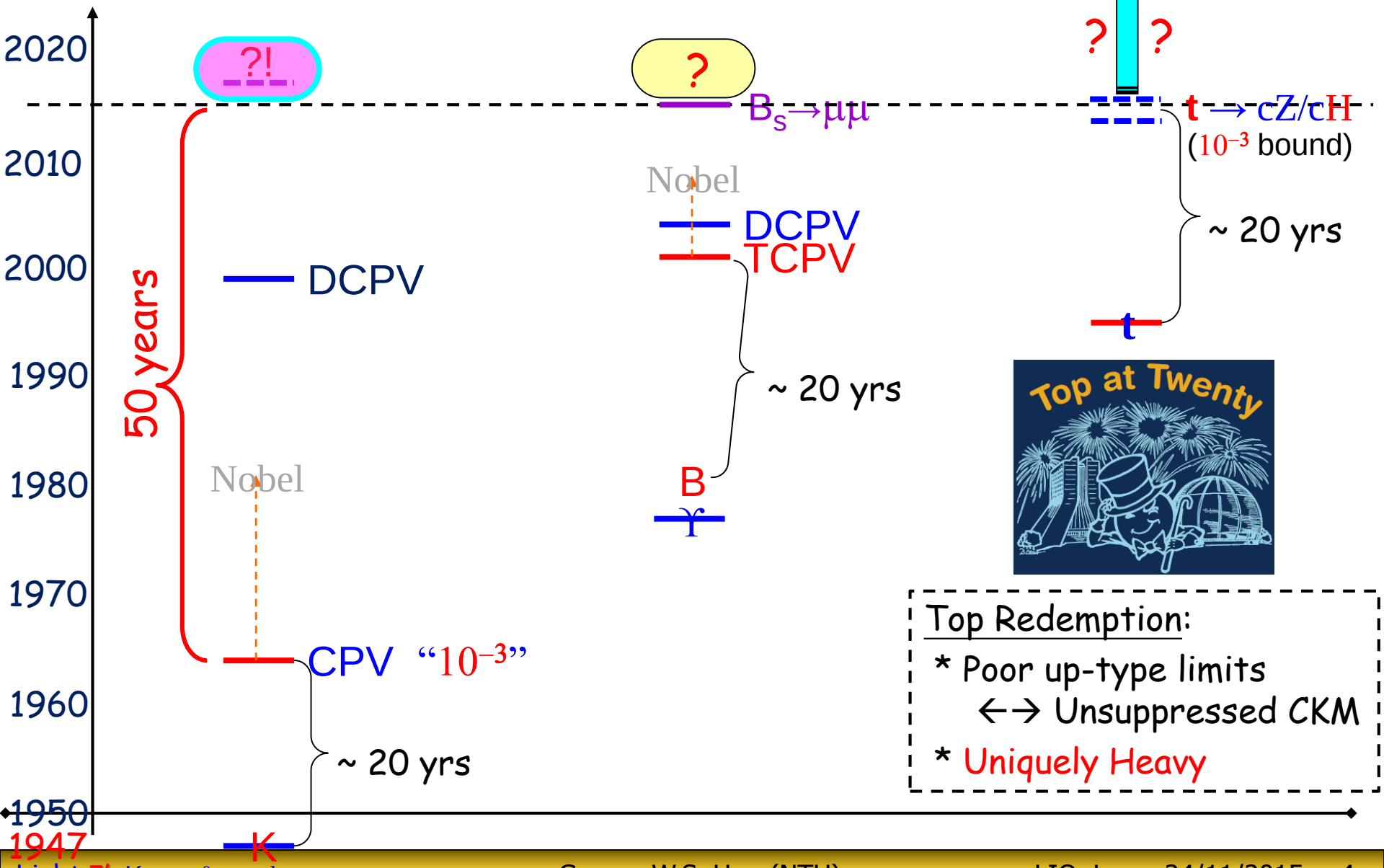
V. Conclusion

Fuyoto, WSH, Kohda, 1412.4397 (PRL'15), and to appear

I. Frontiers of Flavour Physics

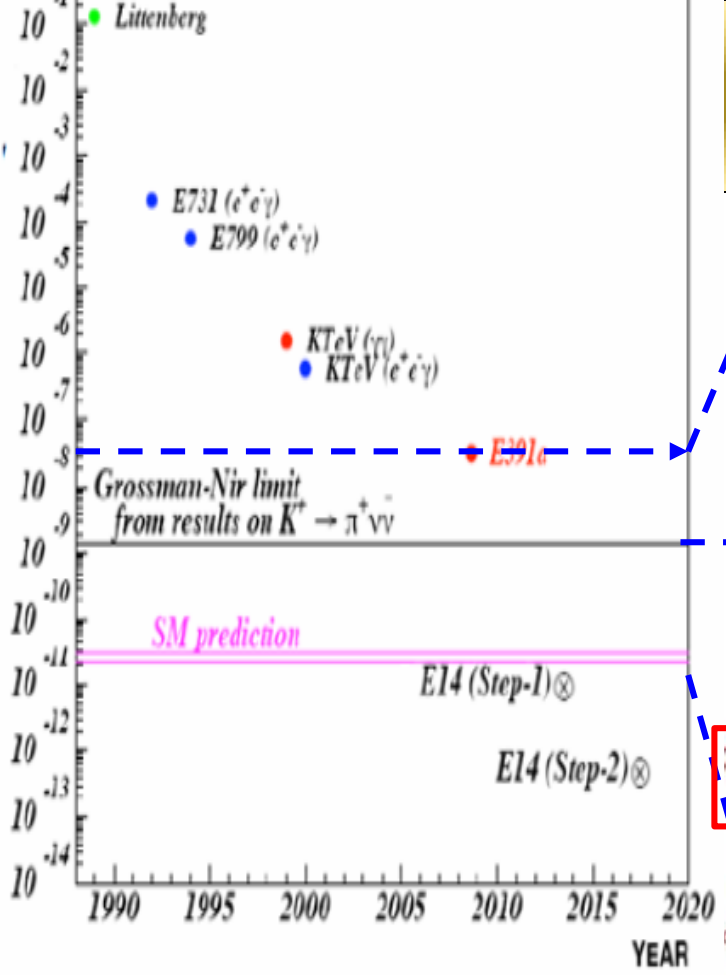


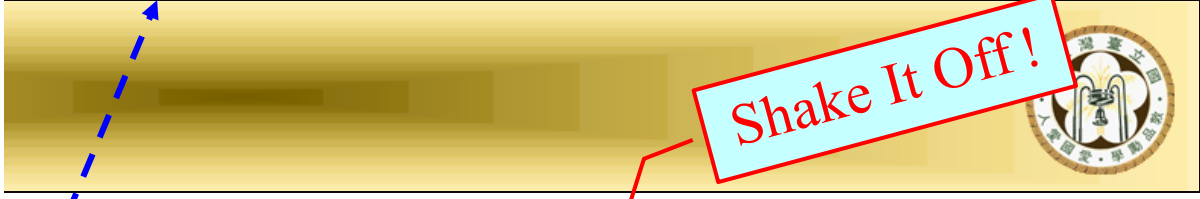
Flavor Physics Template



Top Redemption:

* Poor up-type limits
  ←→ Unsuppressed CKM
* Uniquely Heavy



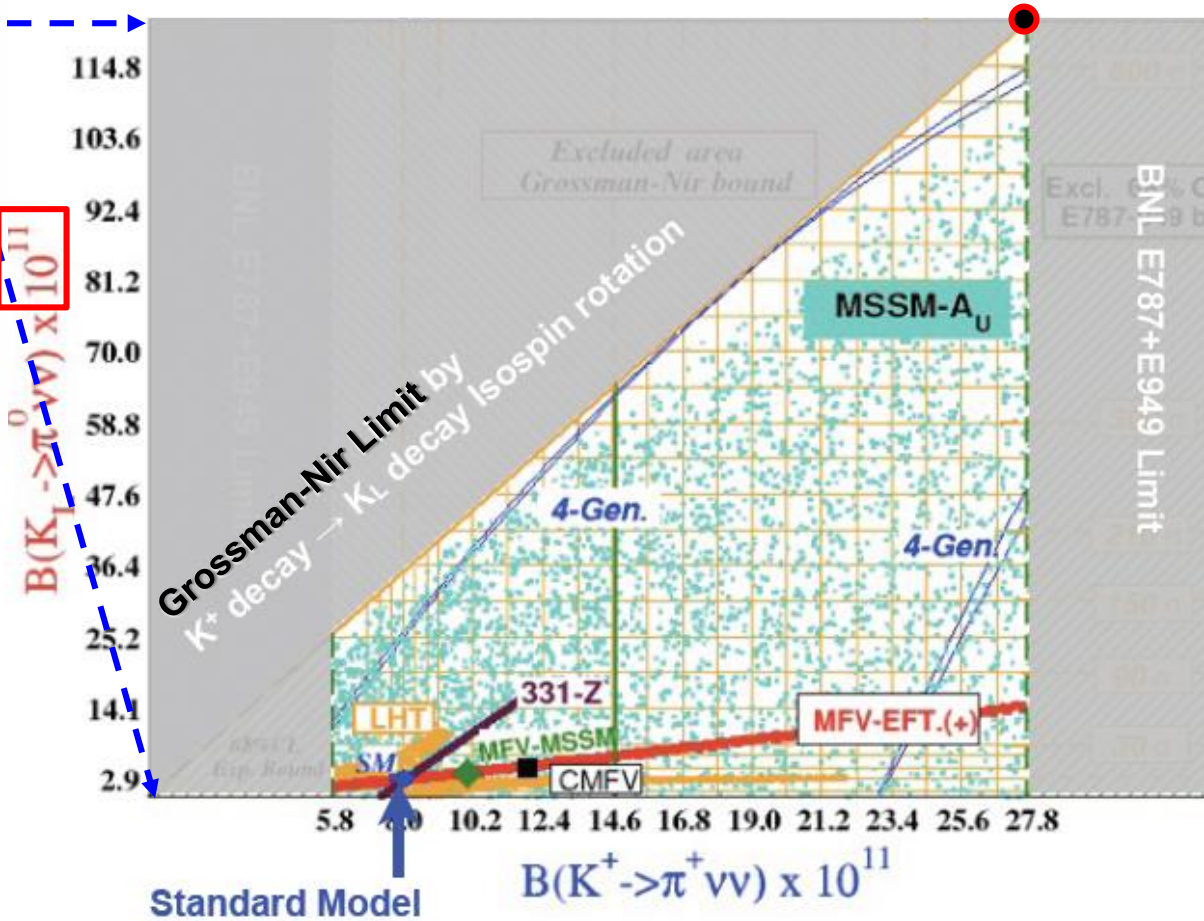


mostly τ_{K_L}/τ_{K^+}

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

KOTO @ 100 hrs (2013) ~ E391a, but ...

@ J-PARC



Light Z', $K_L \to \pi^0\nu\nu$, other

$t \to cZ$

Agashe, Perez, Soni, PRD'07

… such as warped extra dimensions. Our limit can be translated into a constraint on the KK gluon to be heavier than 1.1 TeV [9].

Anomalous decays of top quark in $t\bar{t}$ events

$pp \to t\bar{t} \to Wb\ qZ$ (CMS)

PRL 112 (2014) 171802

Also, ATLAS 1508.05796

Processes are categorized on the number of b-quark:

No b-quark: Diboson, Drell-Yan

Only one b-quark: signal

At least 2 b-quark: $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}W$, tbZ

Two opposite sign same flavor lepton (e or μ)

$78 < m_{ll} < 102$(GeV)

One extra charged lepton

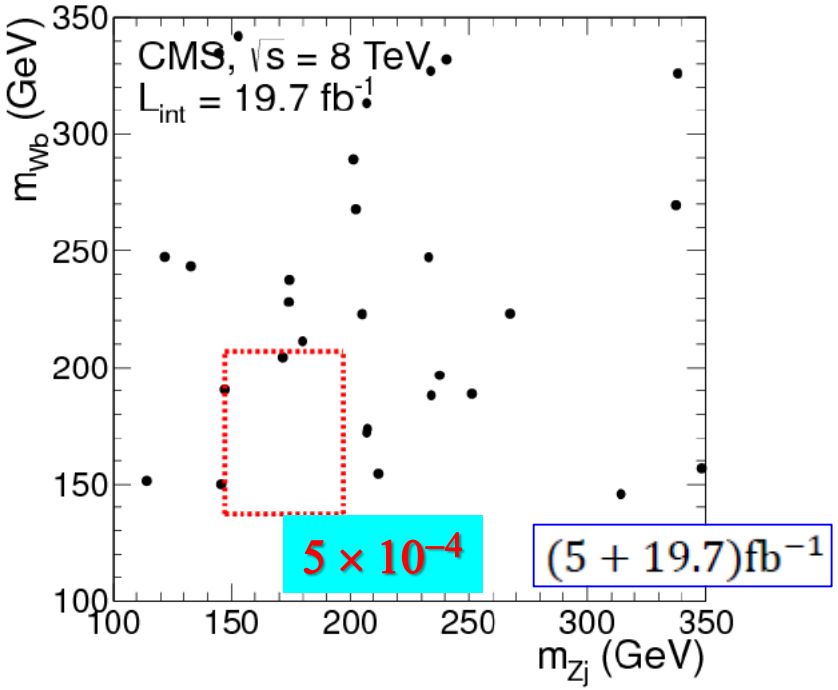
No 4th lepton

MET>30

Only one b-jet

$147.5 < m_{Zj} < 197.5$(GeV)

$137.5 < m_{Wb} < 207.5$(GeV)



$$BR(t \to cZ) \sim 10^{-5} \left(\frac{700}{M_*}\right)^4$$

Top Compositeness

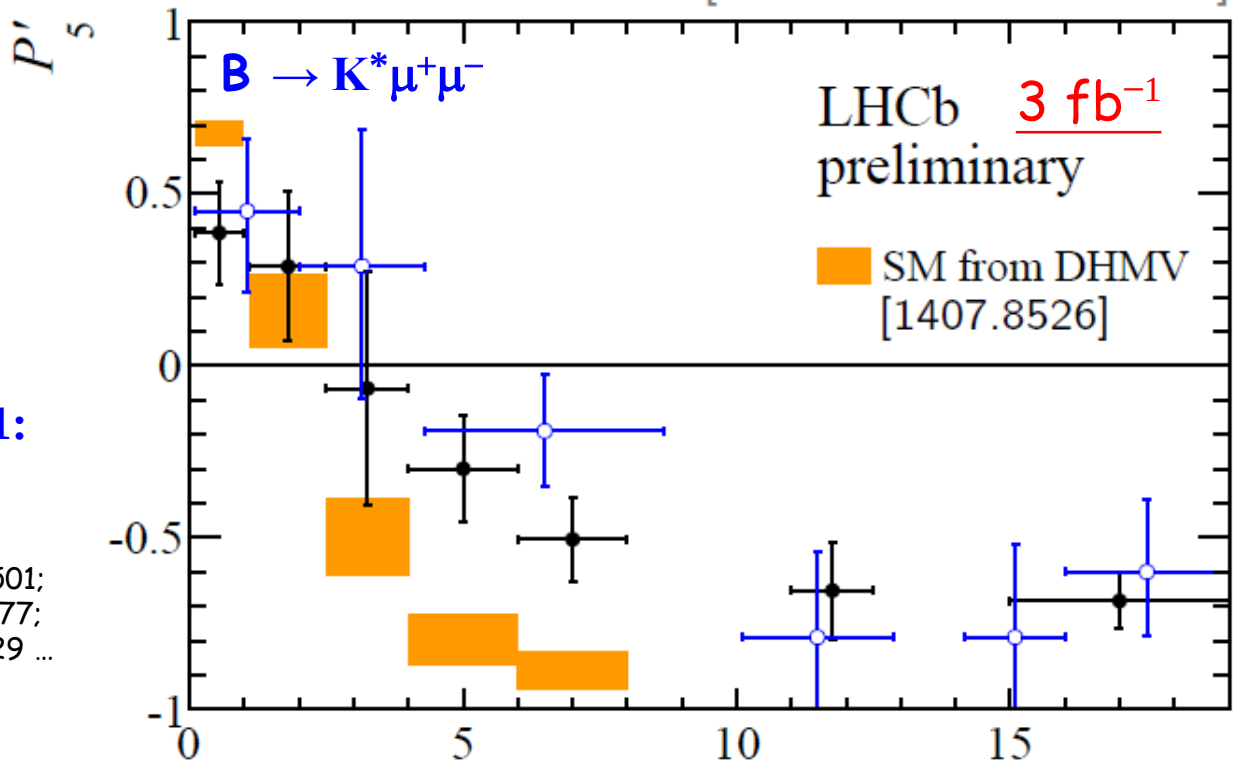
taken from Goldouzian, Top2014

Azatov, Panico, Perez, Soreq, JHEP2014

P_5'

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
- 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

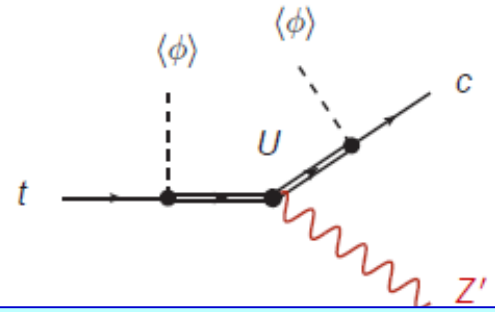
X.G. He et al., PRD1991

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 $\mathrm{BR}(t \to cZ') \sim 10^{-4}$

P'_5-motivated Z' induces $t \to cZ'$ also

ALTMANN

$$\delta_{Qq} \equiv \frac{Y_{Qq} v_\Phi}{\sqrt{2} m_Q}, \quad \delta_{\mathcal{U}q} \equiv \frac{Y_{\mathcal{U}q} v_\Phi}{\sqrt{2} m_{\mathcal{U}}} \quad (q = t, c).$$

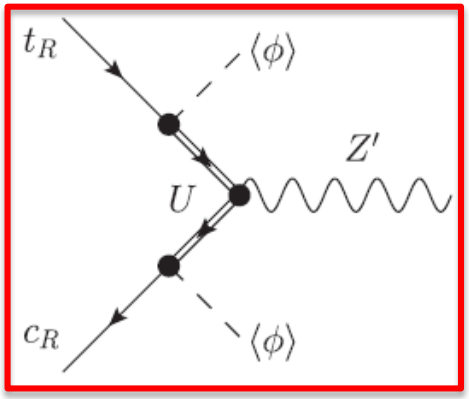
recast the branching ratio as

$$\mathcal{B}(t \to cZ') \simeq \frac{(1-x')^2(1+2x')}{2(1-x)^2(1+2x)} \frac{v^2}{v_\Phi^2} \times \left(|\delta_{\mathcal{U}t} \delta^*_{\mathcal{U}c}|^2 + |\delta_{Qt} \delta^*_{Qc}|^2 \right)$$

Fuyuto
WSH
Kohda

Our Original Interest

PHYSICAL REVIEW D 89, 095033 (2014)



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

"unconstrained"

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

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

$$\delta \simeq \lambda, \ \mathcal{B}(t \to cZ') \lesssim 0.8 \times 10^{-4}$$

$Z' \to \mu^+\mu^-$
BR ~ 1/3!
"gauged $L_\mu - L_\tau$"

II. Very Light Z′: $t \to cZ'$ w/ constraints

Linking Leptonic Z' to Muon g – 2

gauged $L_\mu - L_\tau$

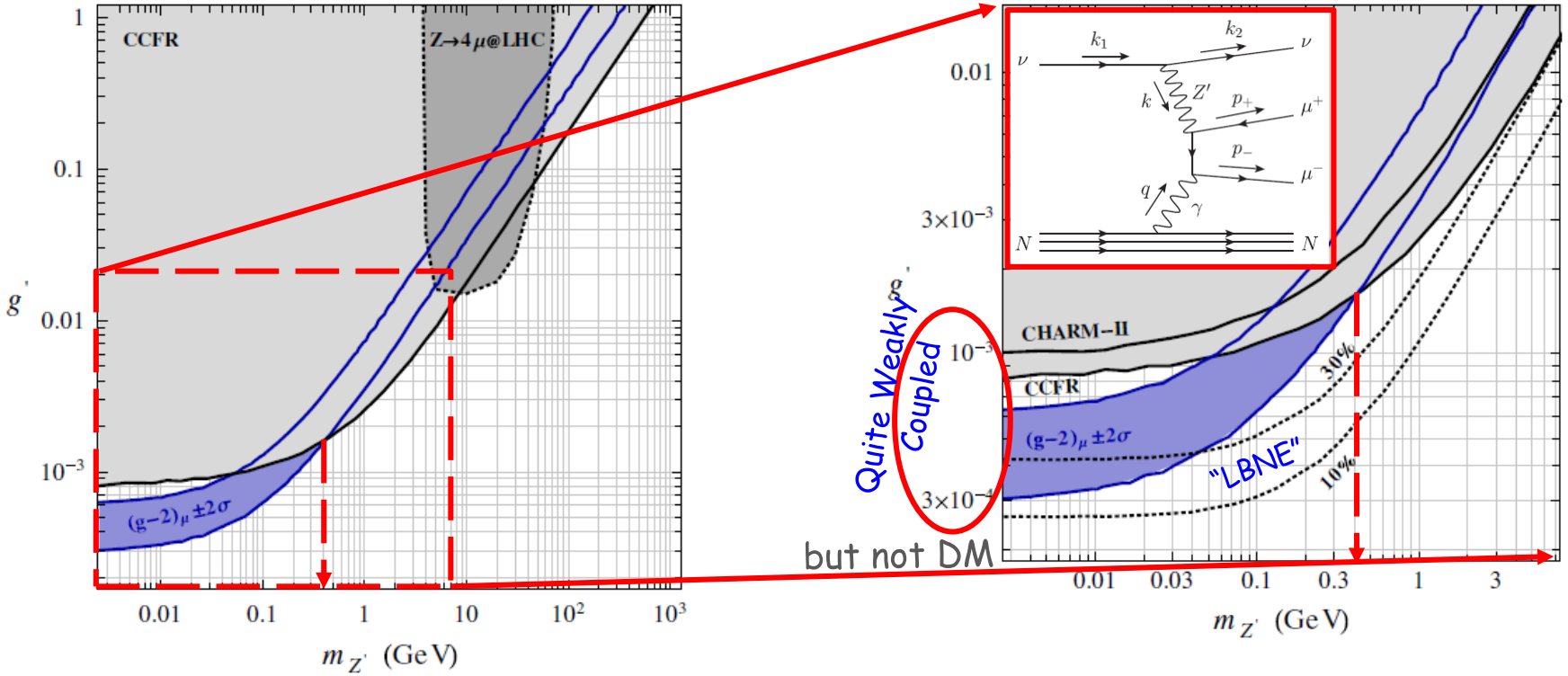
Cannot Affect P'_5

1406.2332

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

"Neutrino Trident Production"

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

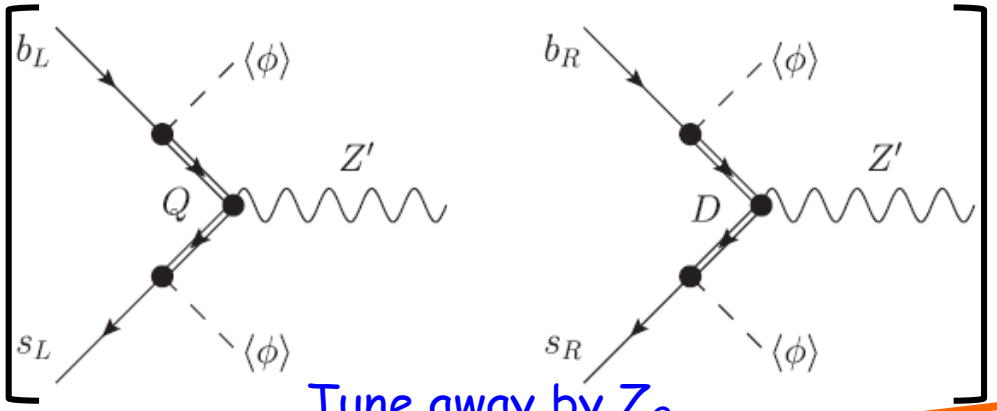


Muon g – 2 related Z' ≲ 400 MeV < m_K?

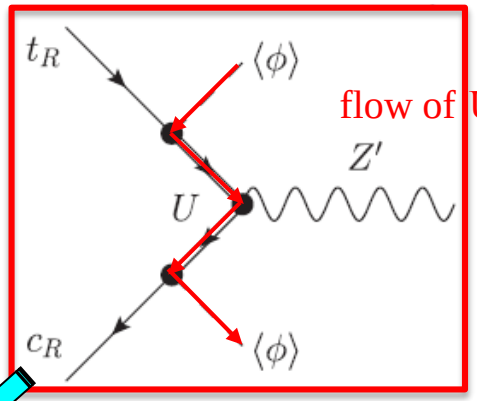
New Physics from Light Particle!?

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

gauged $L_\mu - L_\tau$

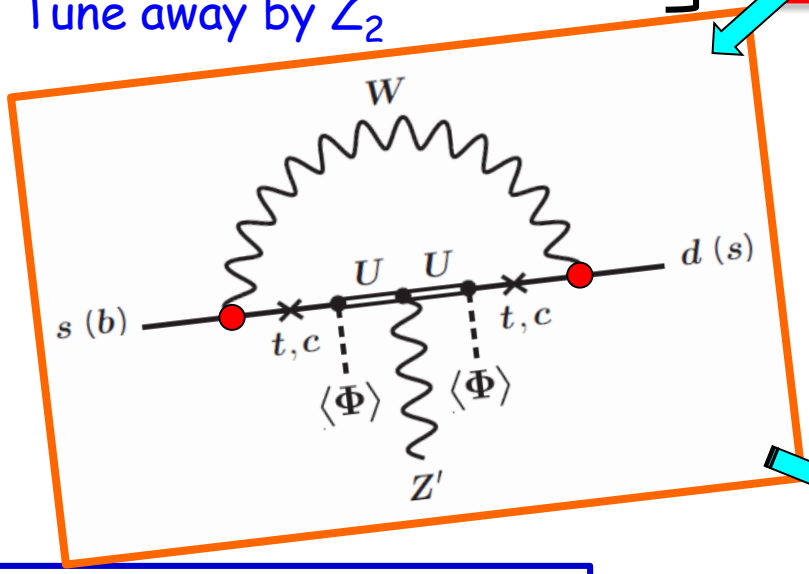


Tune away by Z_2



flow of U(1)′ charge

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



SM-assisted loop
$s \to d Z'$; $b \to s Z'$

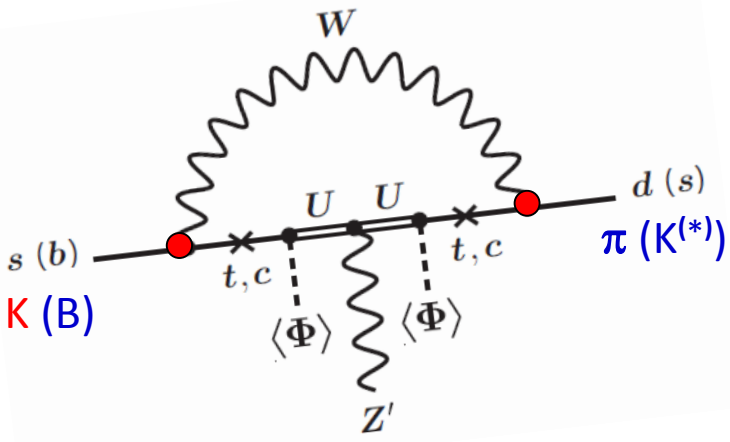
Fuyoto, WSH, Kohda, 1412.4397

$K_L \to \pi^0 Z'$

Muon g – 2 related Z' ≲ 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 $\mathrm{Im}\, g_{ds}$.

... ...

possible KOTO surprise

and more …

III. Kaon: the Oldest Frontier

68+

NA62

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

KOTO

Fixation

1997 Grossman-Nir Bound mostly τ_{K_L}/τ_{K^+}

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \lesssim 4.3 \times \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$$

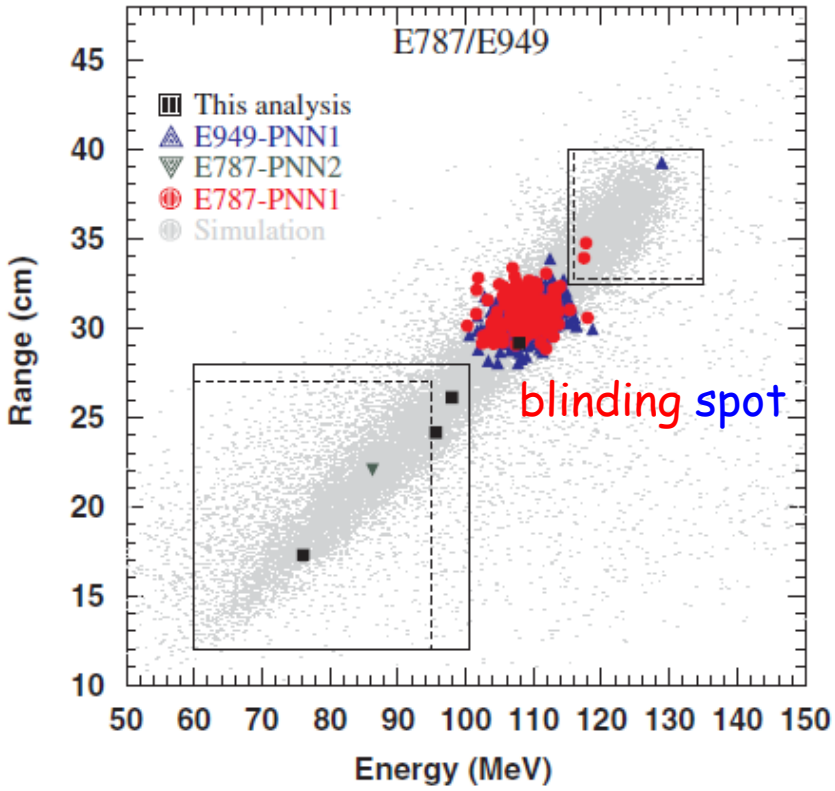
$$< 1.4 \times 10^{-9}. \quad \text{(GN bound)}$$

Shake It Off!

Bound on $K \to \pi X^0$

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)



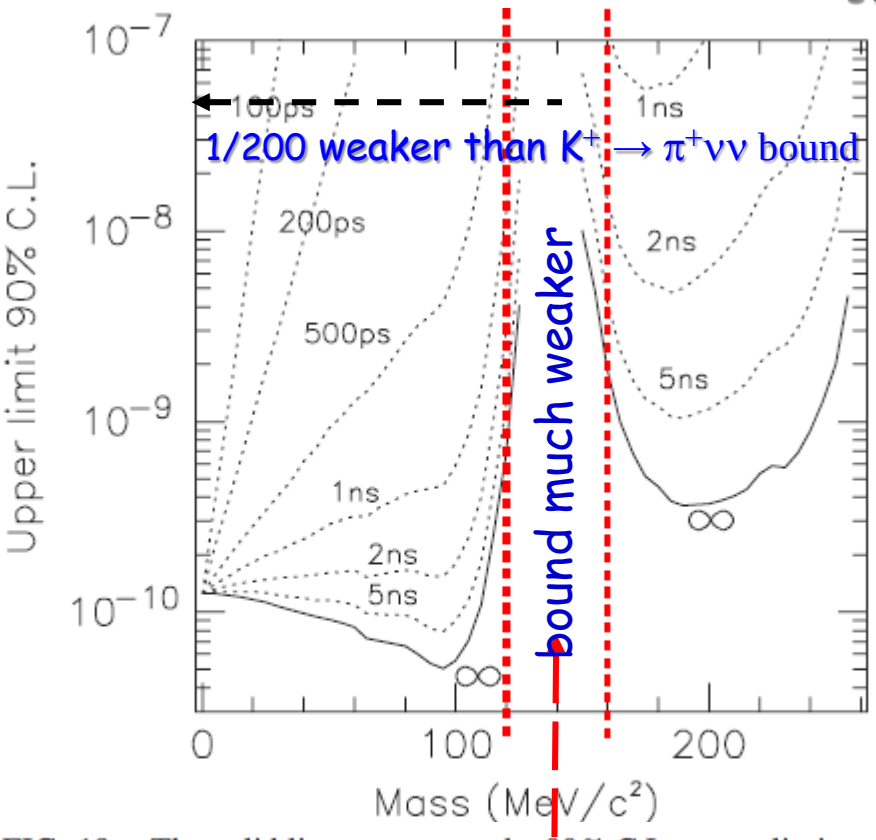


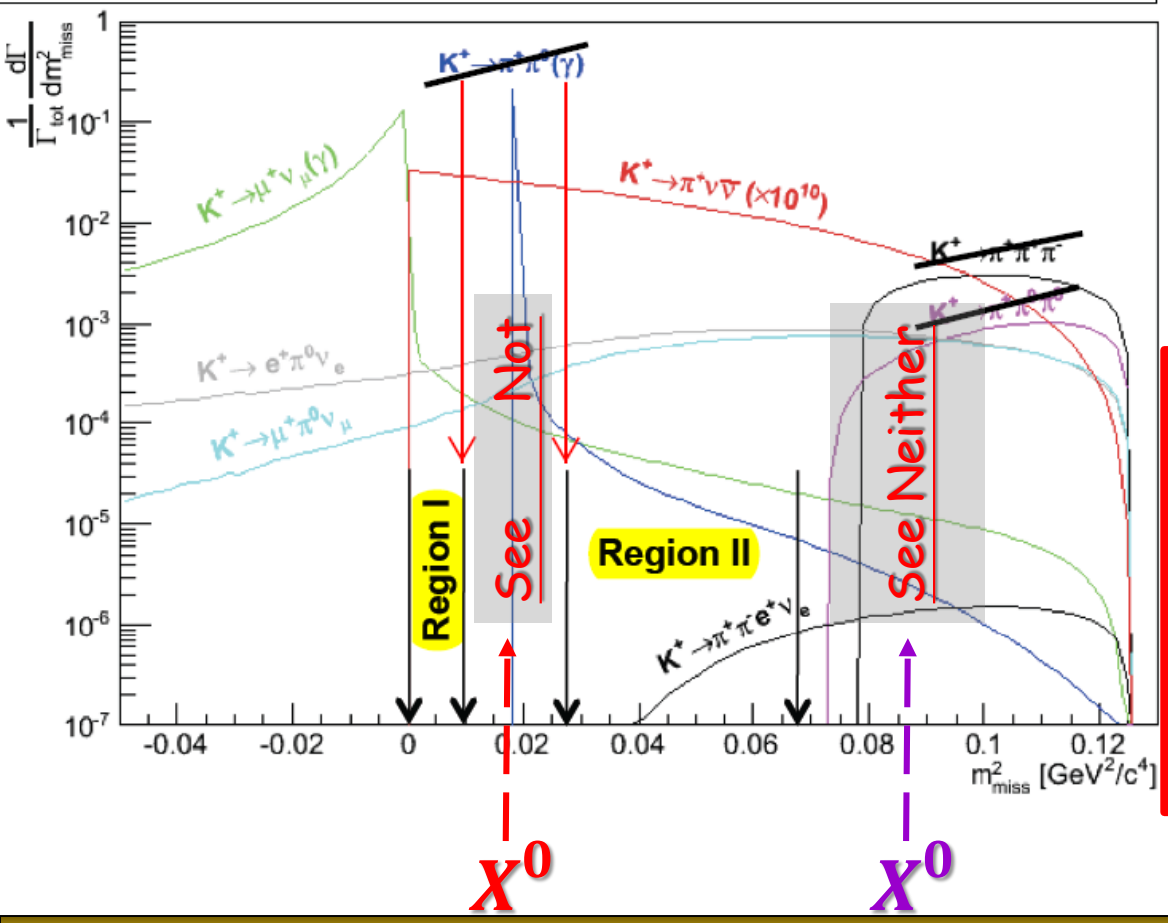
FIG. 18. The solid lines represent the 90% C.L. upper limit on $\mathcal{B}(K^+ \to \pi^+ X)$ as a function of the mass of X assuming X is

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

NA62 @ CERN

Window basically Same as E787/949 @ BNL

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



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

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

“Blind man Blessed by Senses.”

A Surprise! “Trivial”

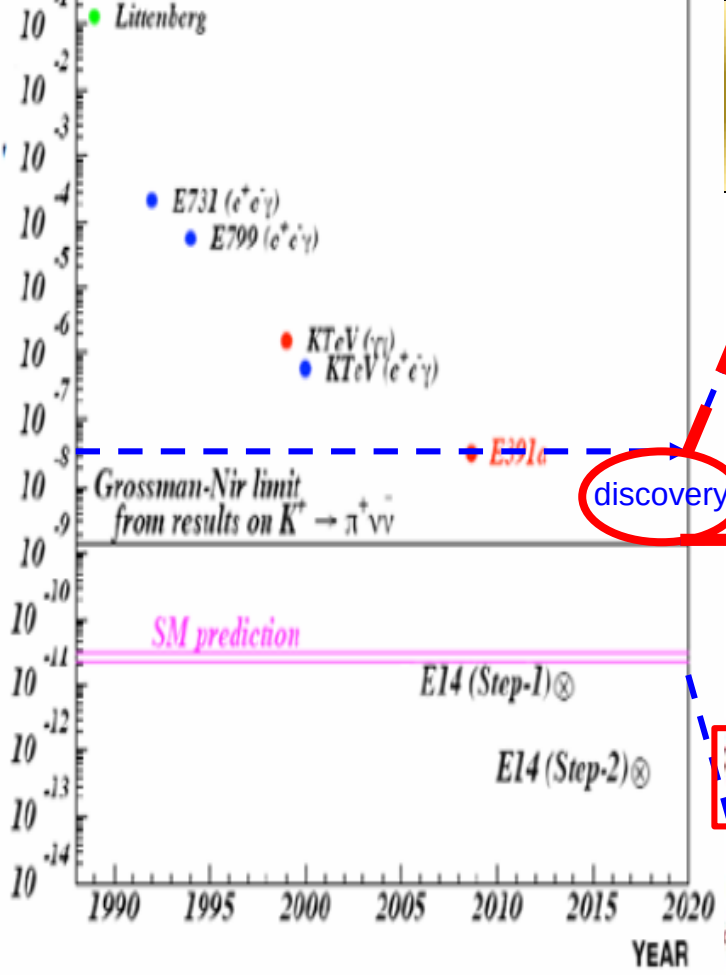
$K_L \to \pi^0 \nu\nu$

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

— *Veto Everything !*

But: Cannot Veto WILPs.

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



discovery

Discovery Starting "Now" !

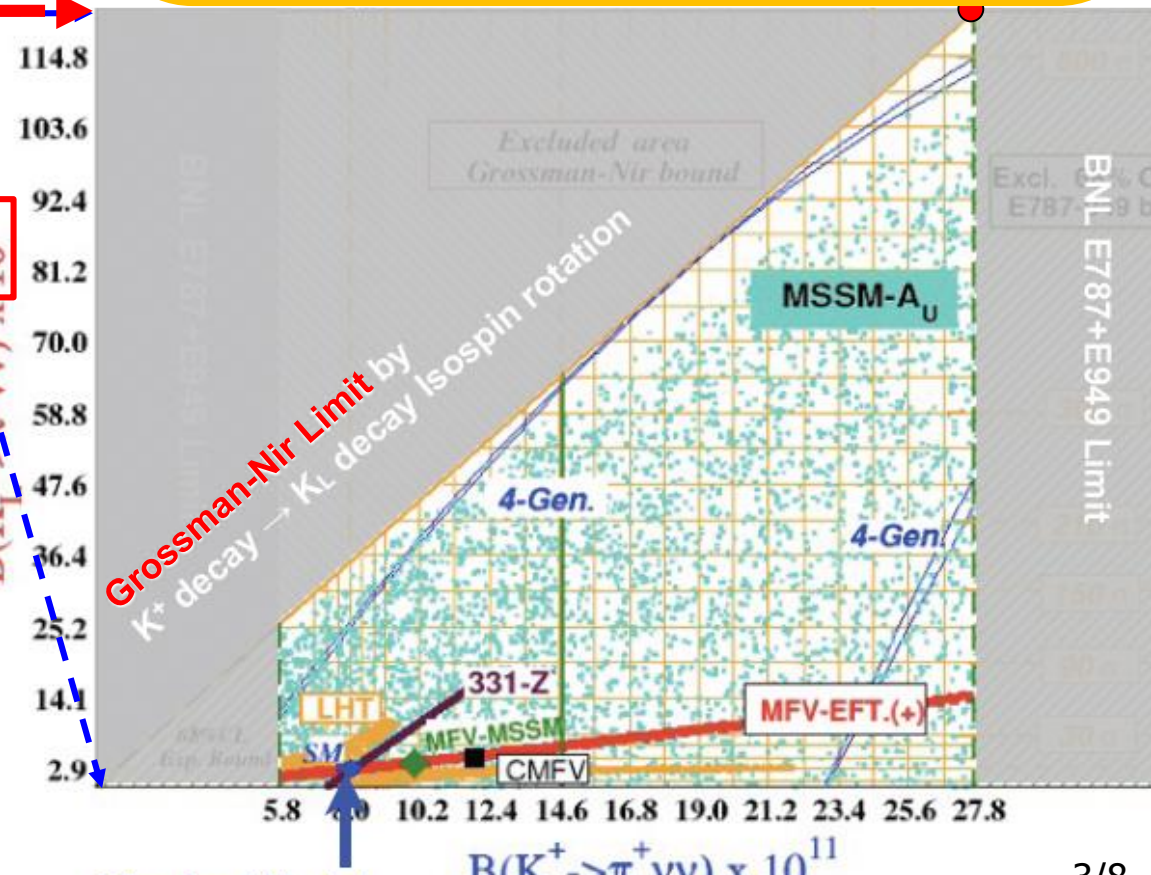
Shake It Off !

mostly τ_{K_L}/τ_{K^+}

$\mathcal{B}(K_L \to$ ... und)

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

KOTO @ 100 hrs (2013) ~ E391a, **but** ...



@ J-PARC

Light Z', $K_L \to \pi^0\nu\nu$, other

Violation of Grossman-Nir Bound, but not quite, and possible implications

Fuyoto, WSH, Kohda, PRL 5/2015

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment, however, cannot do kinematic reconstruction: besides detecting two photons (assumed as π^0), it measures "nothing to nothing". The K_L and "π^0" momenta are not known. The approach is thus to veto everything and to learn while pushing down the sensitivity. However, the $\nu\bar{\nu}$ being the target, one cannot veto weakly interacting light particles (WILP). Thus, for $K \to \pi X^0$ where X^0 is *any* WILP that falls into the missing mass window, the K^+ experiment would be oblivious, *but the K_L experiment can have a blunt feel!* Although the GN relation of Eq. (4) is in no way violated, ~~the perceived GN bound of Eq. (2)~~ does not apply. This is the main and rather simple point of this Letter, independent of model discussion. The X^0 need not be the leptonic force, as it simply goes undetected.

But our Z′ is existence proof

IV. Where Else? — an Illustration w/ Z'

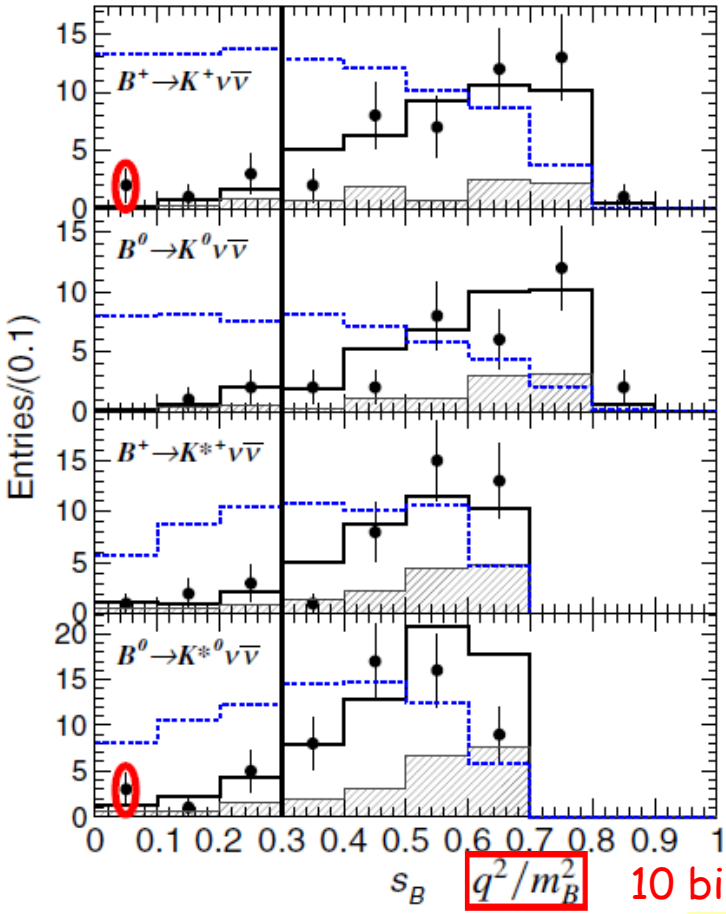
Circumstantial Hints/Possibilities in Rare B & K Decays

$Z' < 2m_\mu$: $\nu\nu$ **only**

$Z' > 2m_\mu$: $\nu\nu/\mu\mu$

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

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



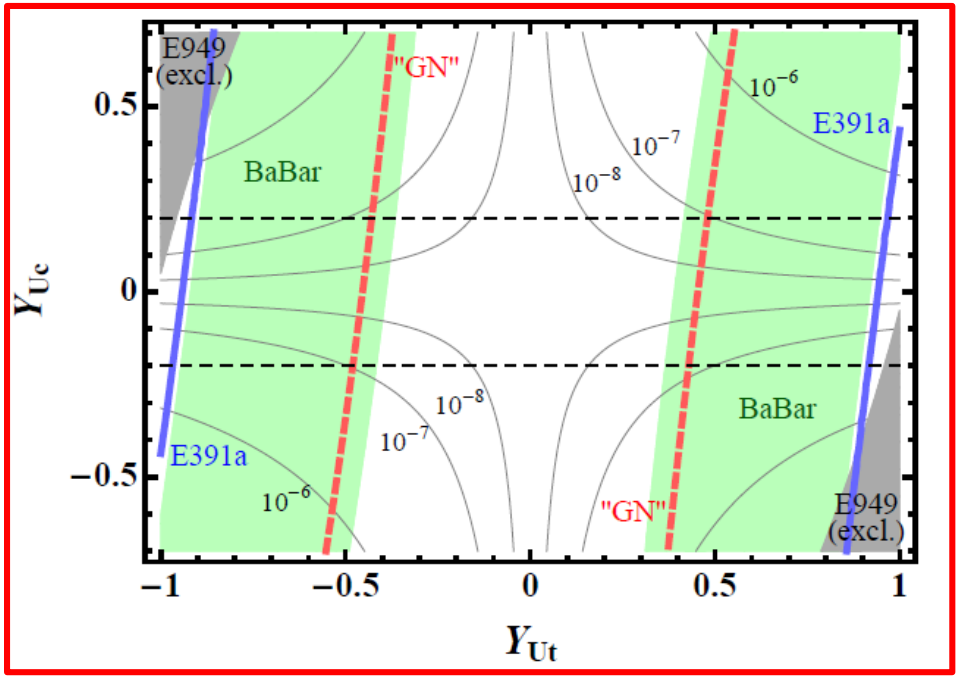
10 bins

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.

$m_{Z'} < 2m_\mu$: $\nu\nu$ only

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



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

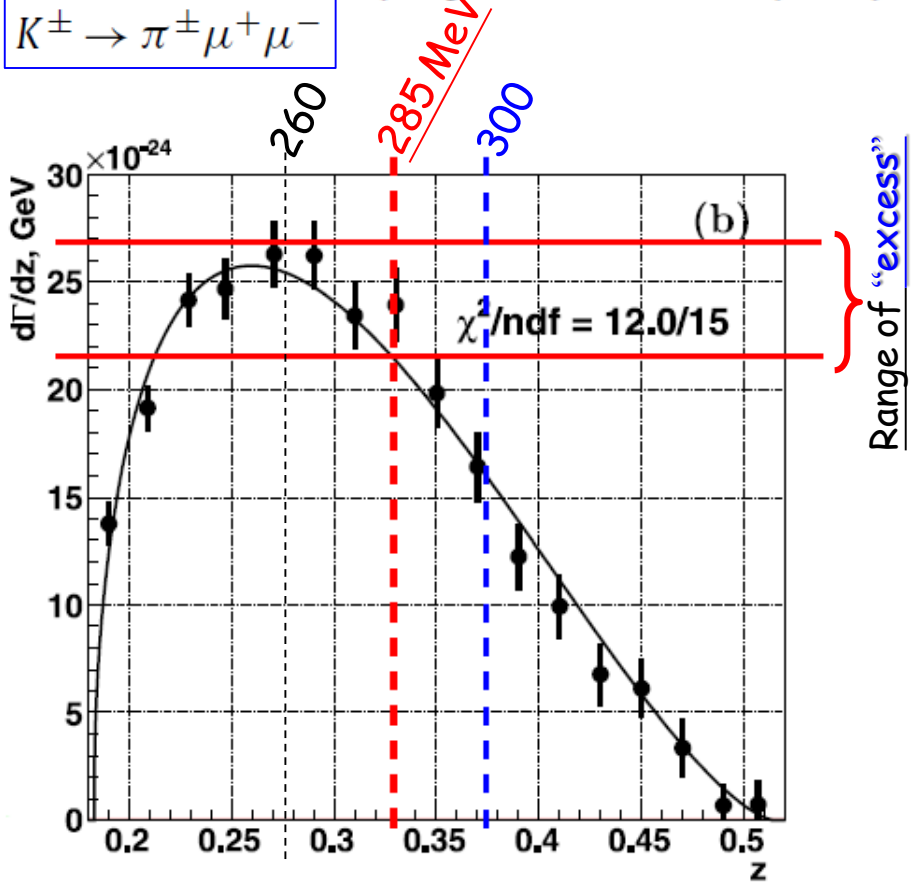
Fuyoto, WSH, Kohda, 1412.4397

$Z' > 2m_\mu$: νν/μμ

The 2nd Window

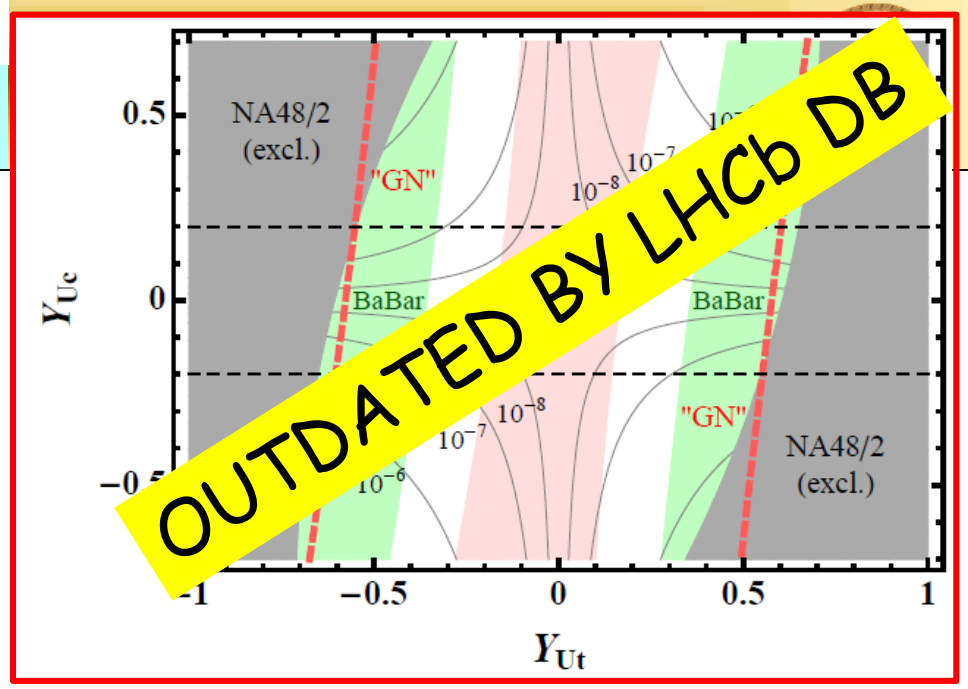
NA48/2 Collaboration / Physics Letters B 697 (2011)

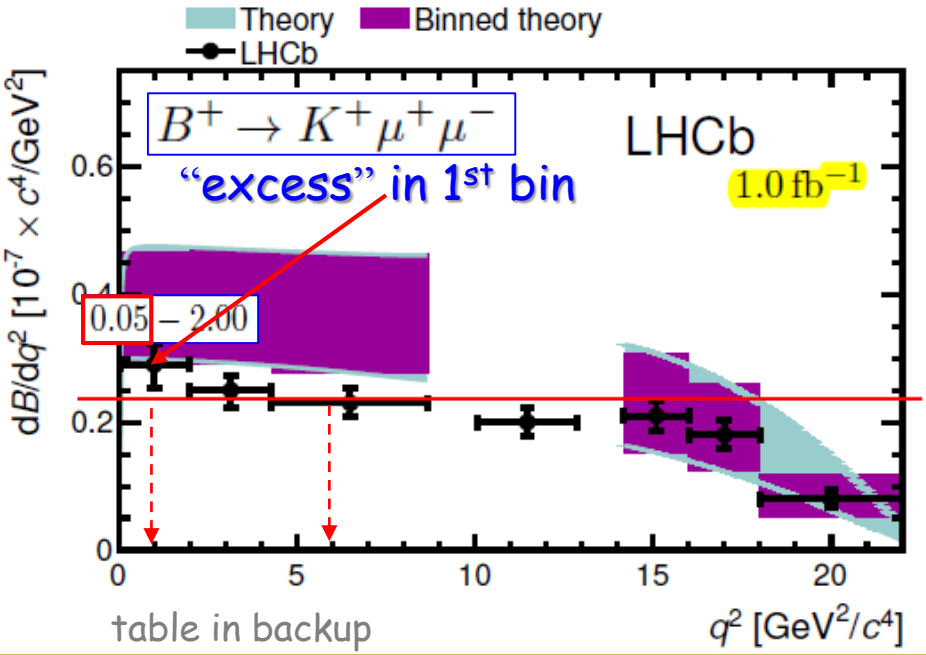
$K^\pm \to \pi^\pm \mu^+ \mu^-$



Can be *refined* by NA62

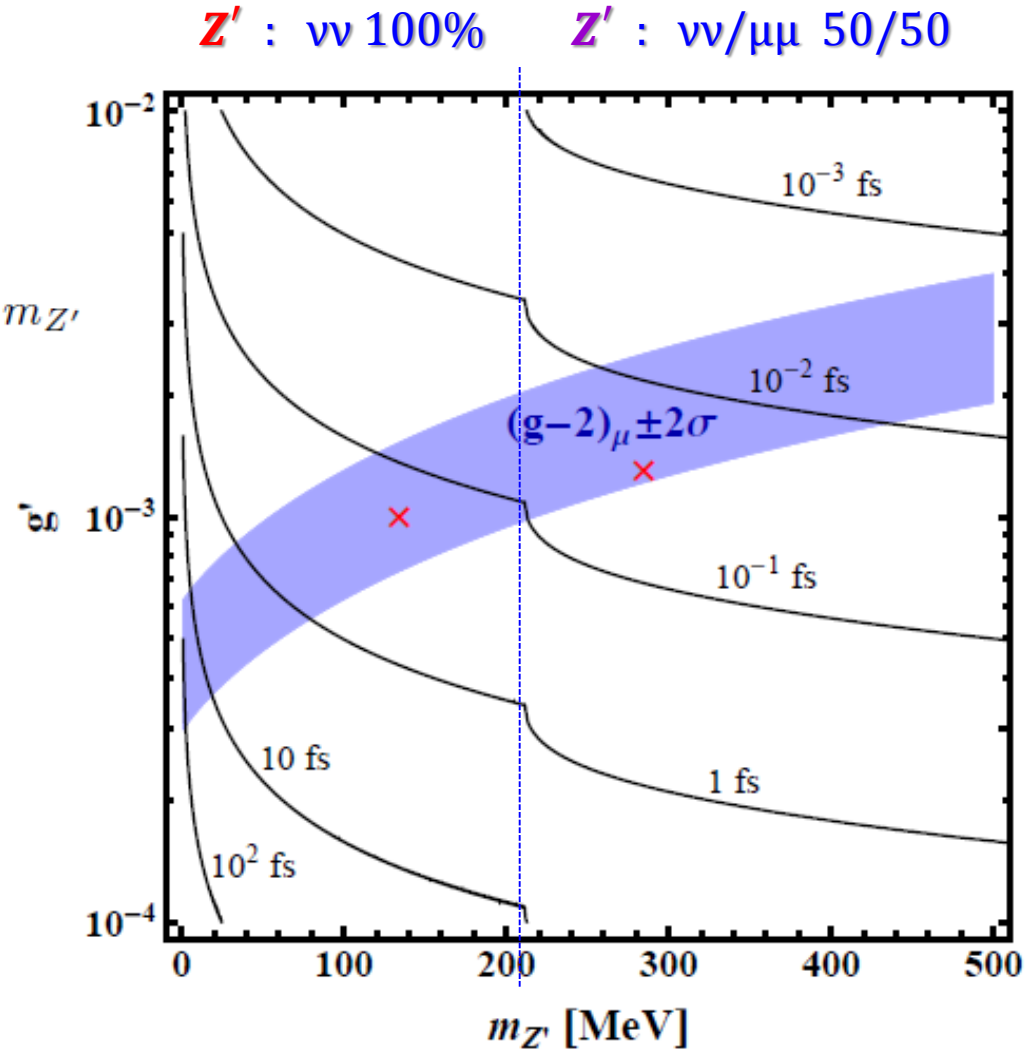
Fuyoto, WSH, Kohda, PRL'15





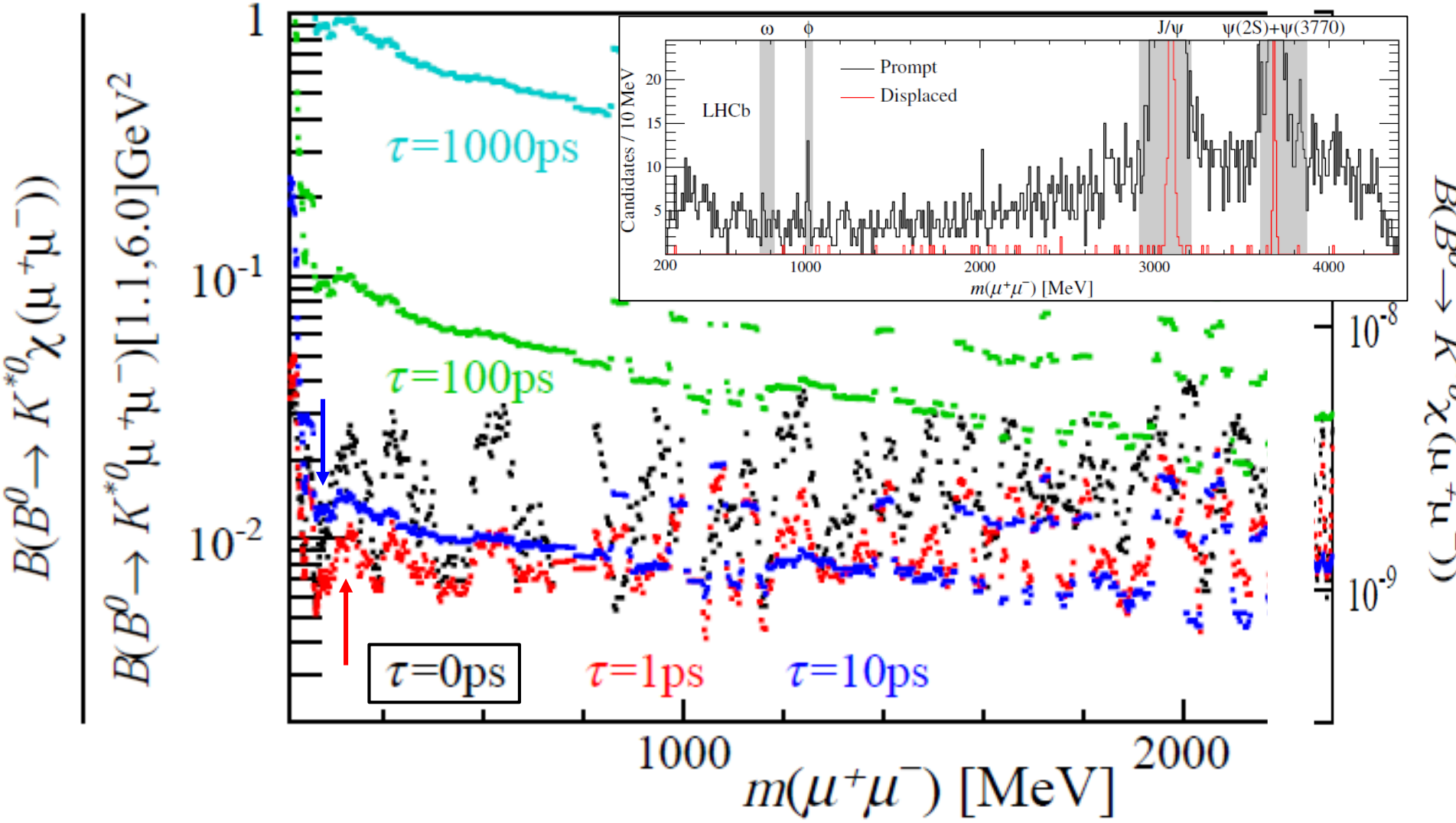
Comment: Light "g-2" Z′ decay is prompt, even when highly boosted.

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



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

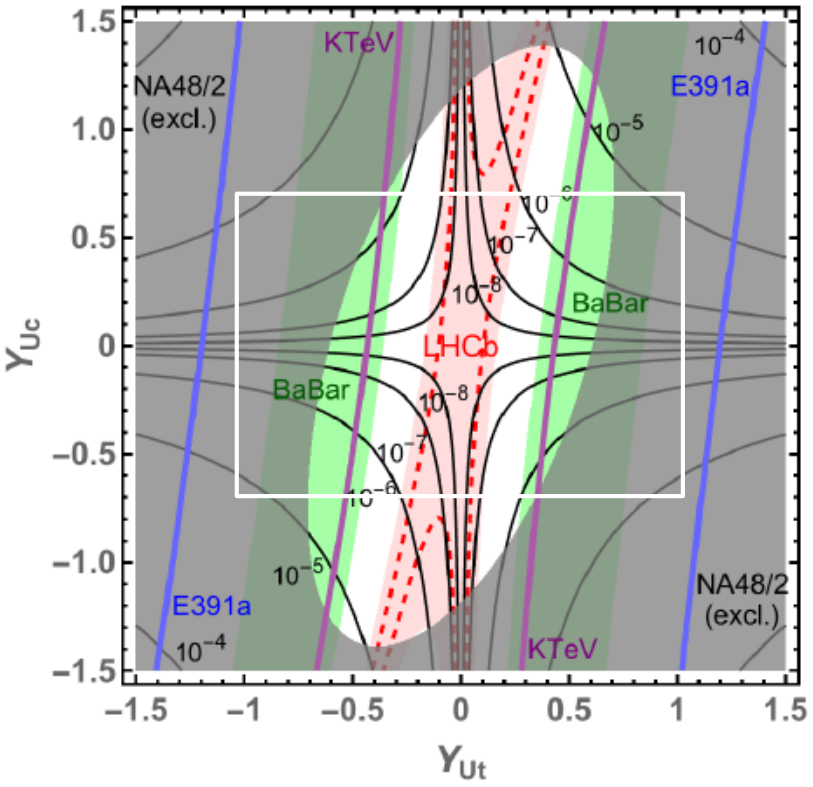
LHCb 1508.04094 [PRL'15 supplementary]



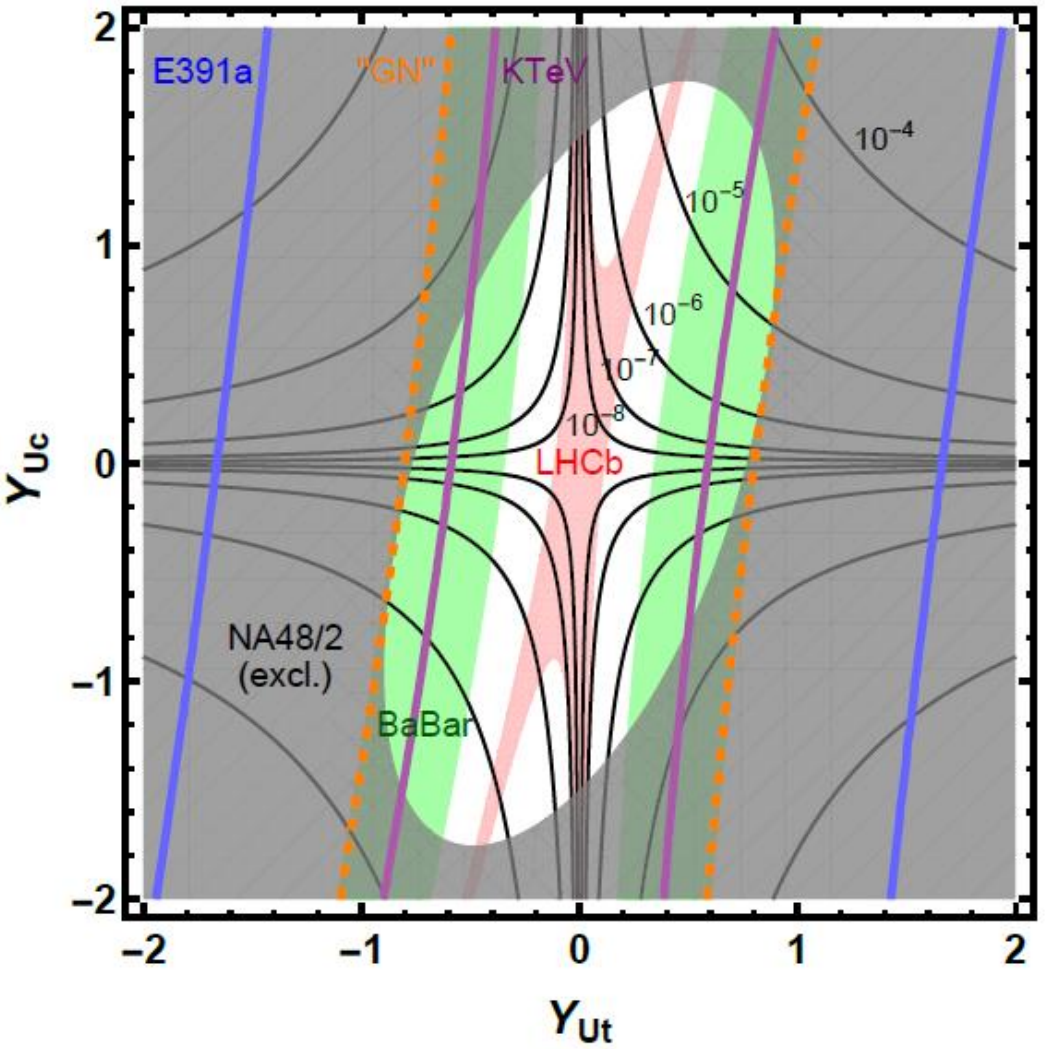
$Z' > 2m_\mu$: νν/μμ

The 2nd Window

285 MeV Z'



334 MeV Z'



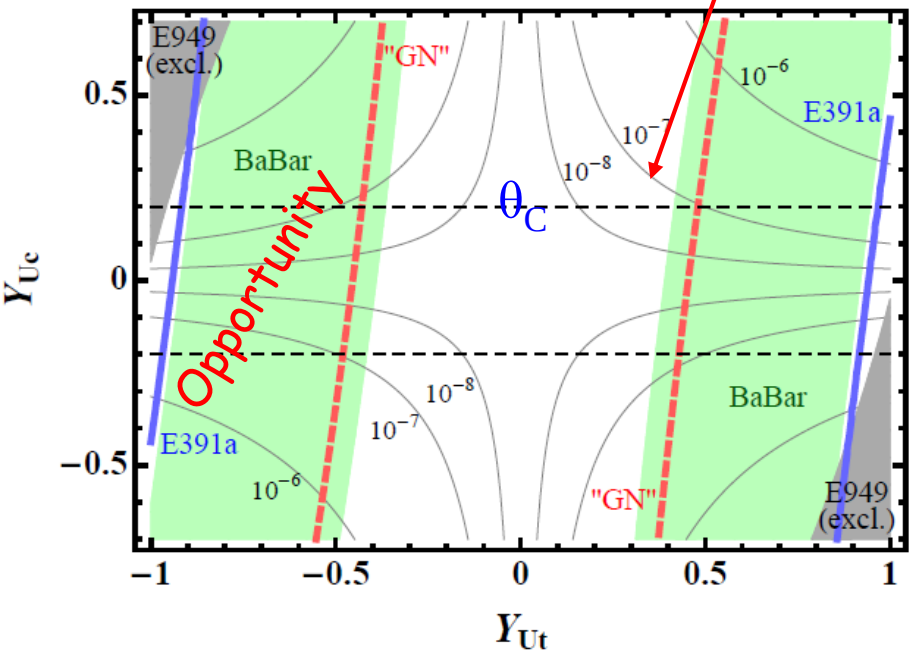
White frame as in FHK PRL,
red dashed is with LHCb DB

The Light Z'_{g-2} Landscape

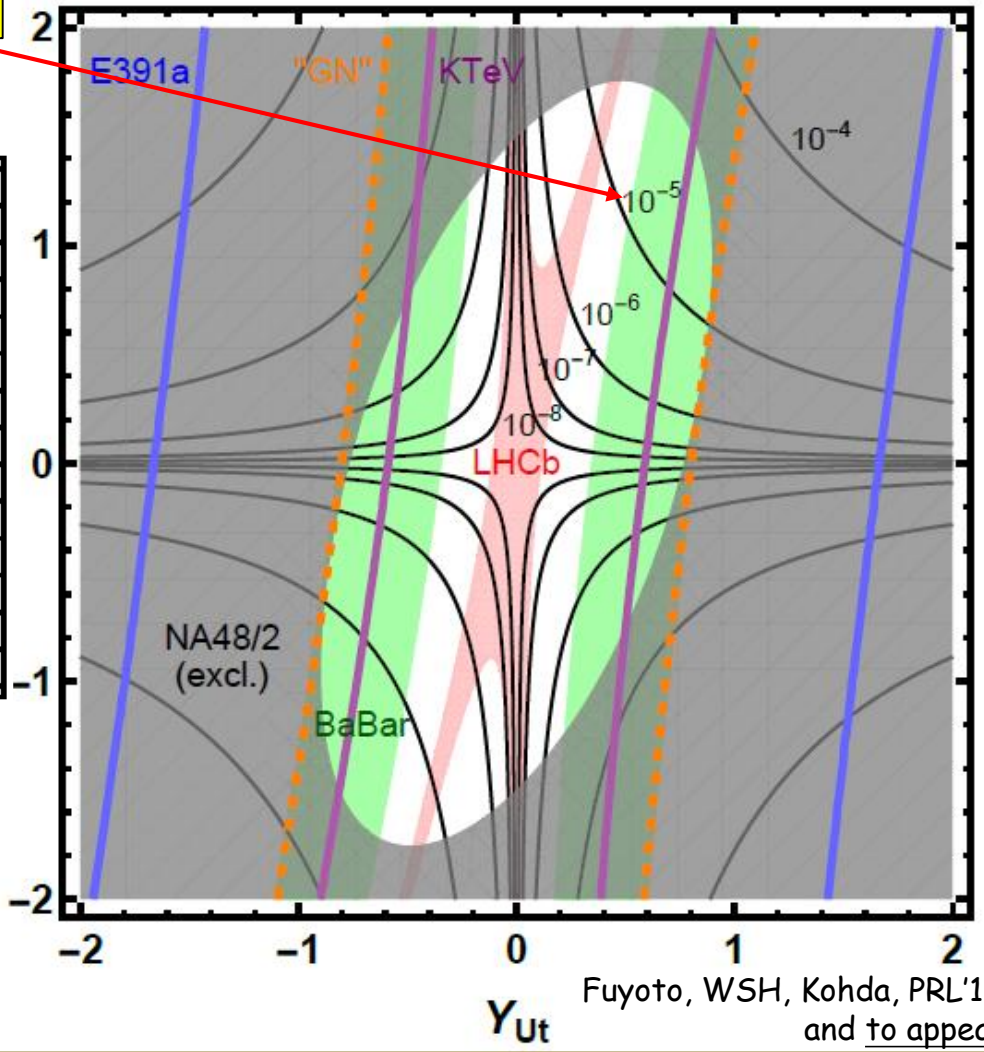
Perhaps 100 TeV SPPC/FCChh Needed .... Or not? [50% μμ]

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

135 MeV Z'



334 MeV Z'

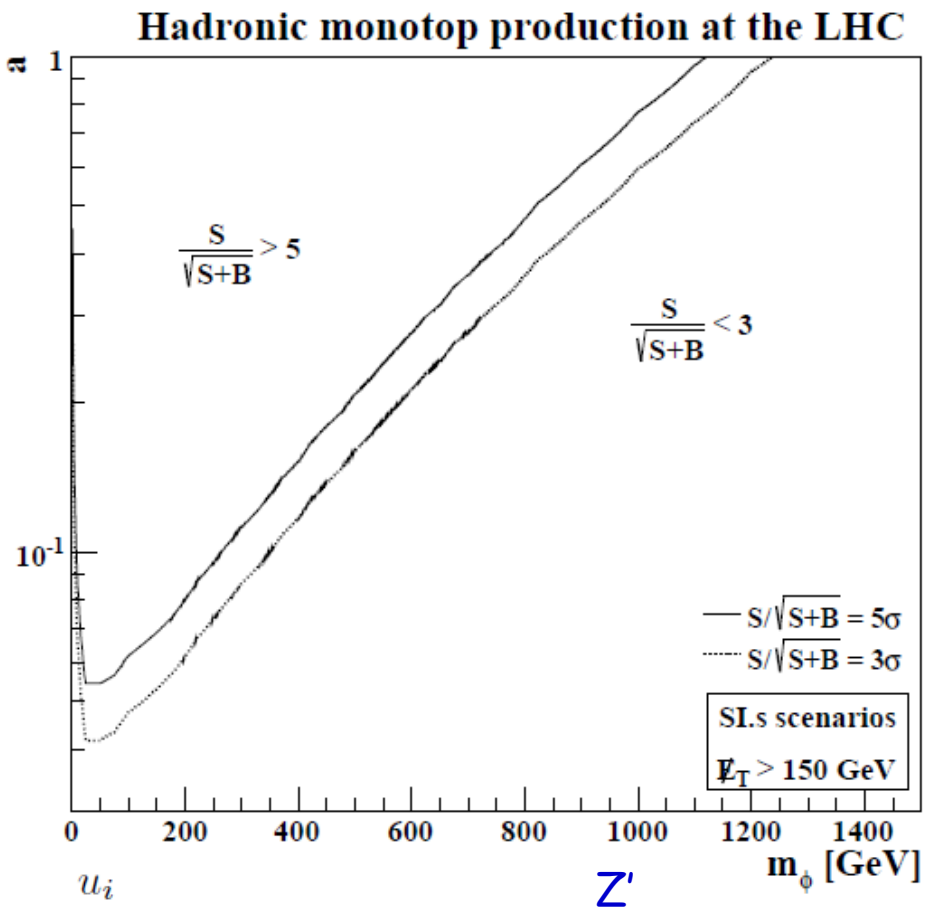


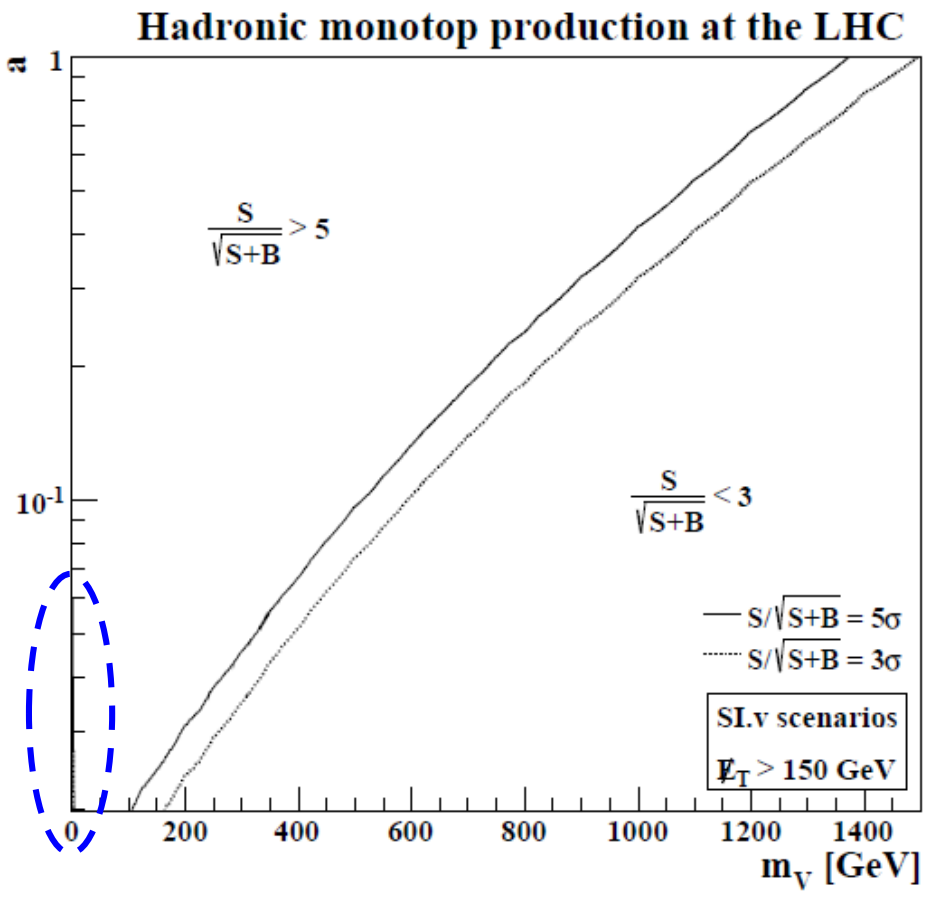
Y_{Uc} & Y_{Ut} reasonable strength?

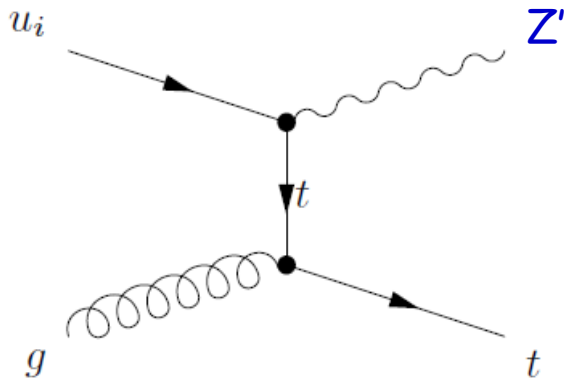
Fuyoto, WSH, Kohda, PRL'15 and to appear

Monotop ?

Agram et al., 1311.6478







Our typical number for "a" is $10^{-6}|Y_{ut}Y_{ct}|$

V. Conclusion

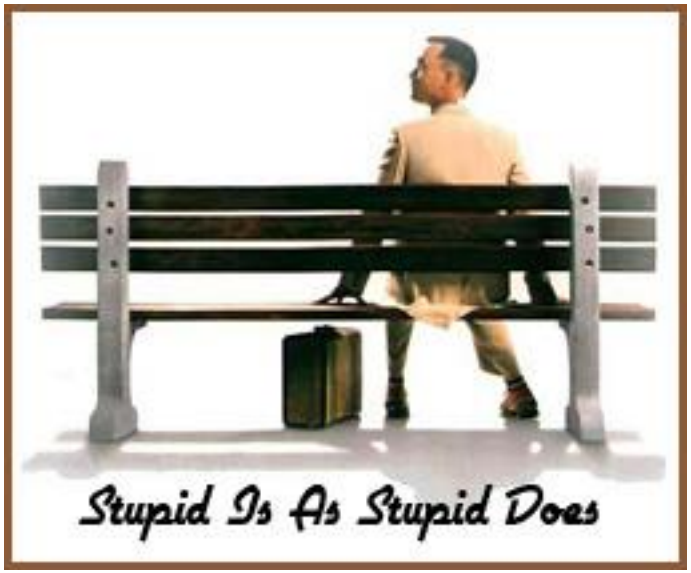
- $K_L \rightarrow \pi^0$ + nothing: can occur above Grossman-Nir Bound ➔ KOTO!

  If See Early Event(s), Try Hard to Kill ... But not Overly So.

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

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

  ➔ KOTO/NA62/LHCb/Belle(II) all in game (but LHCb takes lead?).



Run, KOTO, Run!

Have > 2 mo. Data at Hand!

N.B. Pursue also $t \rightarrow cZ'$

Low q^2 Spike Search in $B^+ \to K^+\mu^+\mu^-$

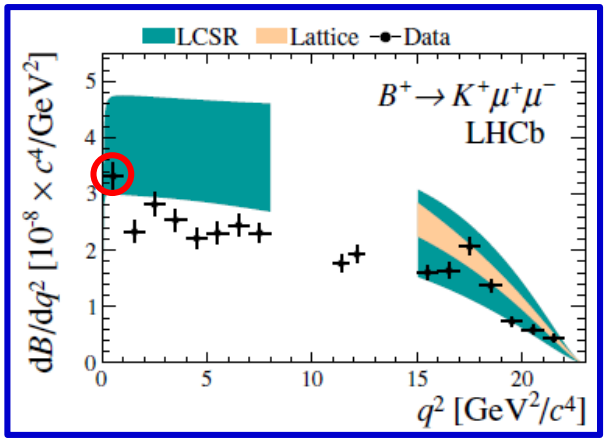
Fuyoto, WSH, Kohda, 1412.4397

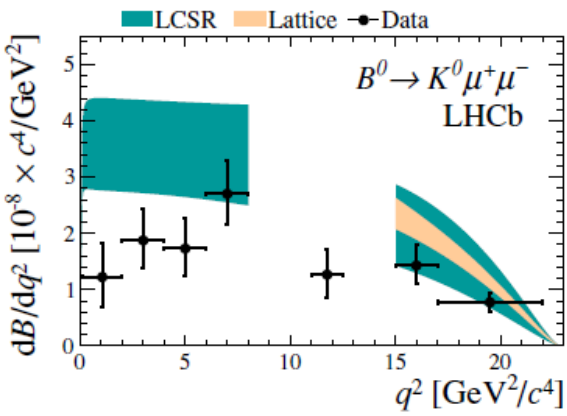
LHCb should do the "extra work"* for lowest q^2

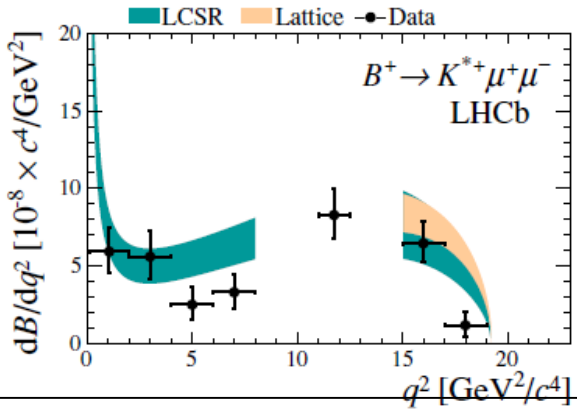
Z' ~ 0.285 GeV
→ q^2 ~ 0.09 GeV^2

q^2 range (GeV$^2/c^4$)	central value	stat	syst
$0.1 < q^2 < 0.98$	33.2	1.8	1.7
$1.1 < q^2 < 2.0$	23.3	1.5	1.2
$2.0 < q^2 < 3.0$	28.2	1.6	1.4
$3.0 < q^2 < 4.0$	25.4	1.5	1.3
$4.0 < q^2 < 5.0$	22.1	1.4	1.1
$5.0 < q^2 < 6.0$	23.1	1.4	1.2
$6.0 < q^2 < 7.0$	24.5	1.4	1.2
$7.0 < q^2 < 8.0$	23.1	1.4	1.2
$11.0 < q^2 < 11.8$	17.7	1.3	0.9
$11.8 < q^2 < 12.5$	19.3	1.2	1.0
$15.0 < q^2 < 16.0$	16.1	1.0	0.8
$16.0 < q^2 < 17.0$	16.4	1.0	0.8
$17.0 < q^2 < 18.0$	20.6	1.1	1.0
$18.0 < q^2 < 19.0$	13.7	1.0	0.7
$19.0 < q^2 < 20.0$	7.4	0.8	0.4
$20.0 < q^2 < 21.0$	5.9	0.7	0.3
$21.0 < q^2 < 22.0$	4.3	0.7	0.2

LHCb 3 fb^{-1}, JHEP **1406**







N.B. Talk by A. Mauri 7/23 on LHCb Dark Boson search in $K^{*0}\mu^+\mu^-$ probably more constraining

* Private Communication with LHCb