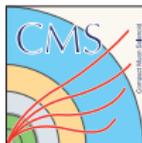


Phenomenological scenarios to fit a possible excess in the di-muon + jets channel

Luca Panizzi

University of Genova, IT



Outline

- 1 The excess in ALEPH
 - Phenomenological interpretations

- 2 Searches at CMS
 - Work in progress

LEP data

Reanalysis of ALEPH data in 1610.06536 [hep-ex] by Arno Heister

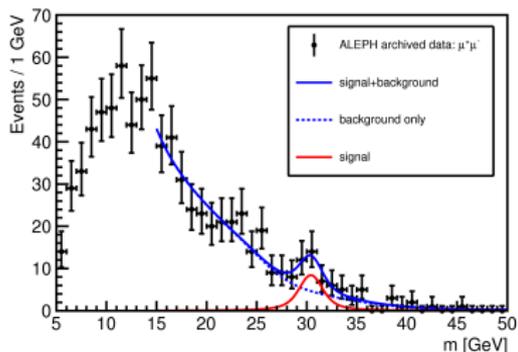
Mild excess in the opposite sign di-muon spectrum of $Z \rightarrow b\bar{b} + \mu^+\mu^-$

$M_X = 30.46 \pm 0.46 \text{ GeV}$ $\Gamma_X = 1.78 \pm 1.14 \text{ GeV}$ significance = 2.63σ

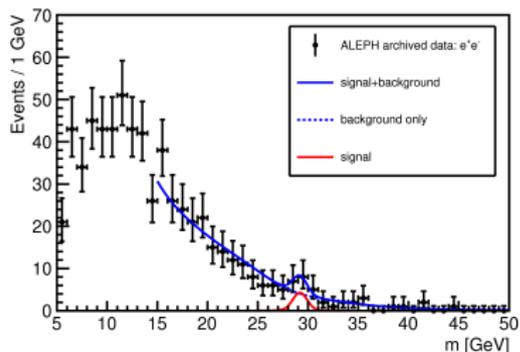
$$BR(Z \rightarrow \mu^+\mu^-b\bar{b}) \sim 3 \times 10^{-4}$$

Non-significant excess in the opposite sign di-electron spectrum too, $Z \rightarrow b\bar{b} + e^+e^-$

$M_X = 29.1846 \pm 0.47 \text{ GeV}$ $\Gamma_X = 0.10 \pm 1.82 \text{ GeV}$ significance = 1.15σ



Signal: Breit-Wigner+Gaussian

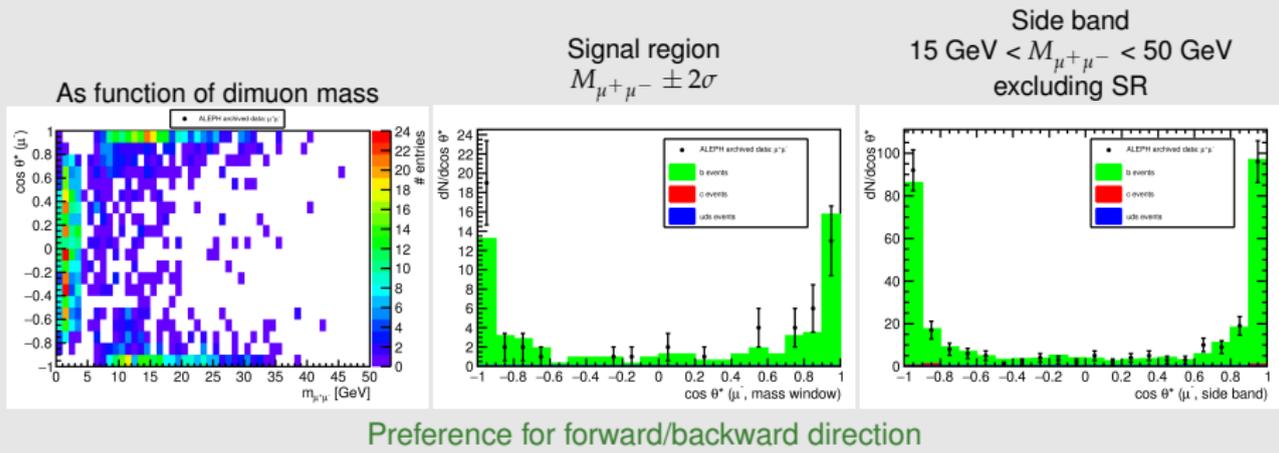


Signal: Crystal Ball+Gaussian

What is this: (yet again another) fluctuation or (finally) hint of something new?

Kinematics of the excess

Decay angle with respect to the boost axis



Other distributions analysed in 1610.06536 [hep-ex]:

- Minimum angle between μ and leading b : **muons close to b-jets**
- Minimum angle of the μ with the other b : **larger separation** (not expected if it was from semi-leptonic b decay)
- relative transverse momentum of the closest pair: **in accordance with simulations**

Outline

- 1 The excess in ALEPH
 - Phenomenological interpretations

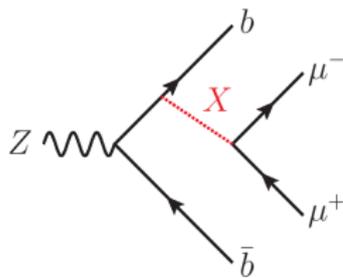
- 2 Searches at CMS
 - Work in progress

Dedicated literature

- P. Ko, J. Li and C. Yu, "Implication of the ALEPH 30 GeV dimuon resonance at the LHC," arXiv:1610.07526 [hep-ph]
Interpretation of the excess in terms of different simplified models
- K. Lane and L. Pritchett, "The 30 GeV Dimuon Excess at ALEPH," arXiv:1701.07376 [hep-ph]
Interpretation in terms of two-Higgs doublets models

Simplified models

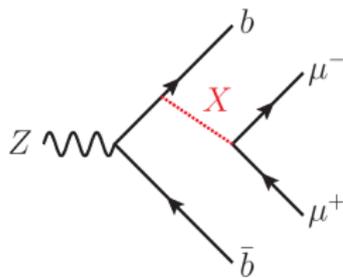
P. Ko, J. Li and C. Yu, arXiv:1610.07526 [hep-ph]



(a)

Simplified models

P. Ko, J. Li and C. Yu, arXiv:1610.07526 [hep-ph]



(a)

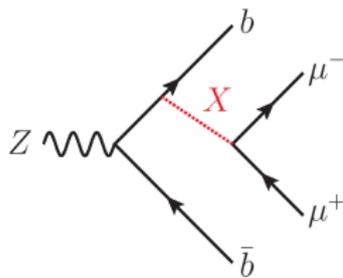
Constraints:

- Since $X \rightarrow b\bar{b}$, DY at LHC
- If also $X \rightarrow e^+e^-$, DY at LEP
- Other bounds from $Z \rightarrow 4\mu$,
 $Z \rightarrow 4b$, $t \rightarrow WbX$ or
 $pp \rightarrow b\bar{b}X$

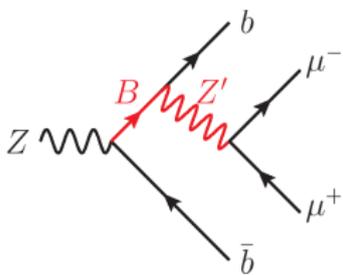
Strongly constrained

Simplified models

P. Ko, J. Li and C. Yu, arXiv:1610.07526 [hep-ph]



(a)



(b)

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 $Z \rightarrow 4b$, $t \rightarrow WbX$ or
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Strongly constrained

What are vector-like quarks?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

What are vector-like quarks?

and where do they appear?

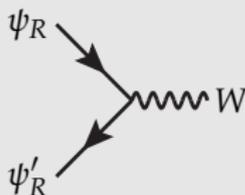
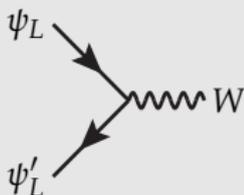
The left-handed and right-handed chiralities of a vector-like fermion ψ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

Peculiar Properties

$$\mathcal{L}_M = -M\bar{\psi}\psi$$

Gauge invariant mass term without the Higgs

Charged currents both in the left and right sector



What are vector-like quarks?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

Why are they called “vector-like”?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left(J^{\mu+} W_\mu^+ + J^{\mu-} W_\mu^- \right) \quad \text{Charged current Lagrangian}$$

- SM chiral quarks: ONLY left-handed charged currents

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} \quad \text{with} \quad \begin{cases} J_L^{\mu+} = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\ J_R^{\mu+} = 0 \end{cases}$$

- vector-like quarks: BOTH left-handed and right-handed charged currents

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d = V$$

What are vector-like quarks?

and where do they appear?

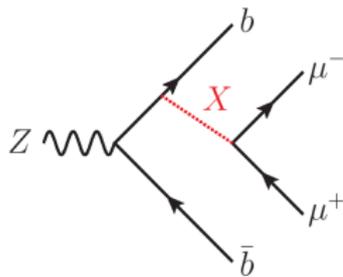
The left-handed and right-handed chiralities of a vector-like fermion ψ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

Vector-like quarks in many models of New Physics

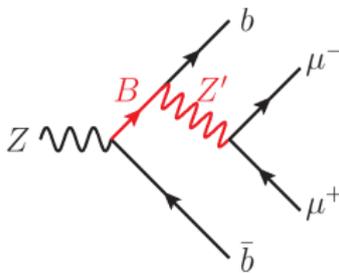
- **Warped or universal extra-dimensions**
KK excitations of bulk fields
- **Composite Higgs** models
VLQ appear as excited resonances of the bounded states which form SM particles
- **Little Higgs** models
partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- **Gauged flavour group** with low scale gauge flavour bosons
required to cancel anomalies in the gauged flavour symmetry
- **Non-minimal SUSY extensions**
VLQs increase corrections to Higgs mass without affecting EWPT

Simplified models

P. Ko, J. Li and C. Yu, arXiv:1610.07526 [hep-ph]



(a)



(b)

Constraints:

- Since $X \rightarrow b\bar{b}$, DY at LHC
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Strongly constrained

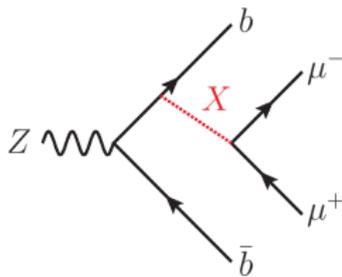
Constraints:

- B pair production with $B \rightarrow Zb$ or $B \rightarrow Z'b \rightarrow \mu\mu b$
- Mixing between Z and Z'

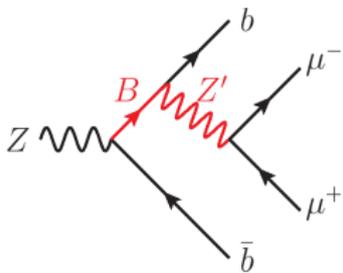
Recasting of LHC data and/or new searches

Simplified models

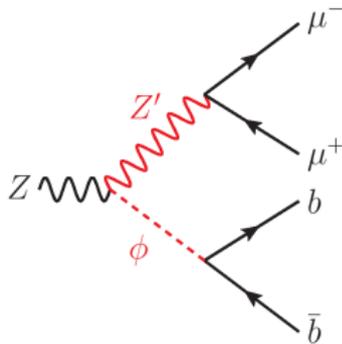
P. Ko, J. Li and C. Yu, arXiv:1610.07526 [hep-ph]



(a)



(b)



(c)

Constraints:

- Since $X \rightarrow b\bar{b}$, DY at LHC
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Strongly constrained

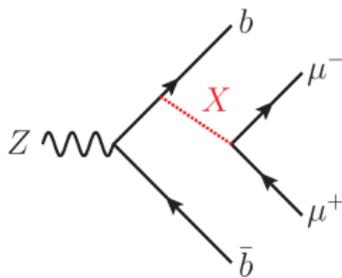
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**Recasting of LHC data and/or
new searches**

Simplified models

P. Ko, J. Li and C. Yu, arXiv:1610.07526 [hep-ph]

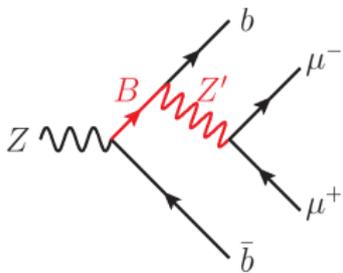


(a)

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Strongly constrained

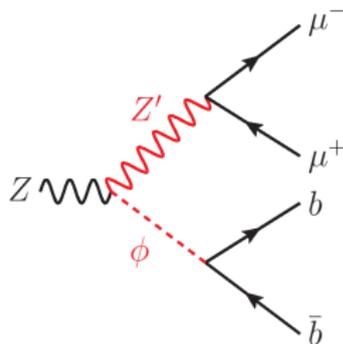


(b)

Constraints:

- B pair production with $B \rightarrow Zb$ or $B \rightarrow Z'b \rightarrow \mu\mu b$
- Mixing between Z and Z'

Recasting of LHC data and/or new searches



(c)

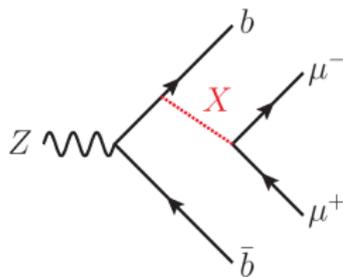
Constraints:

- Mixing between Z and Z'
- Mixing between ϕ and the Higgs

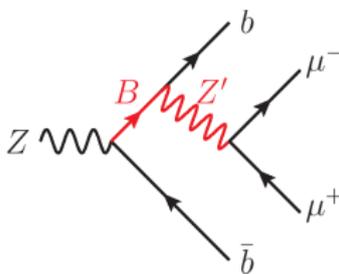
Careful tuning of parameters

Simplified models

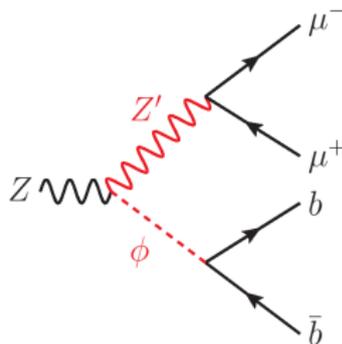
P. Ko, J. Li and C. Yu, arXiv:1610.07526 [hep-ph]



(a)



(b)



(c)

Constraints:

- Since $X \rightarrow b\bar{b}$, DY at LHC
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Strongly constrained

Constraints:

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Recasting of LHC data and/or new searches

Constraints:

- Mixing between Z and Z'
- Mixing between ϕ and the Higgs

Careful tuning of parameters

Kinematic properties of the different hypotheses not in good agreement with ALEPH data

Two Higgs doublet model

K. Lane and L. Pritchett, arXiv:1701.07376 [hep-ph]

$$\phi_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_i^+ \\ \phi_{i0} - i\phi_{i3} \end{pmatrix} \rightsquigarrow \underbrace{H^0, h^0}_{\text{CP-even}}, \underbrace{\eta_A}_{\text{CP-odd}}, h^+$$

ϕ_1 couples to all fermions except e and μ and ϕ_2 couples only to e and μ

Two options:

$$\textcircled{1} M_{H^0} = 125 \text{ GeV}, M_{h^0} \simeq M_{\eta_A} = 30 \text{ GeV} \implies \left\{ \begin{array}{l} Z \rightarrow h(\rightarrow \mu^+\mu^-/b\bar{b})\eta_A(\rightarrow b\bar{b}/\mu^+\mu^-) \text{ ok} \\ Z \rightarrow Z^*(\rightarrow b\bar{b}) + h/\eta_A(\rightarrow \mu^+\mu^-) \\ Z \rightarrow b^*(\rightarrow b + h/\eta_A(\rightarrow \mu^+\mu^-))\bar{b} \end{array} \right\} \text{too suppressed}$$

$$\textcircled{2} M_{H^0} \simeq M_{\eta_A} = 125 \text{ GeV}, M_{h^0} = 30 \text{ GeV} \implies \left\{ \begin{array}{l} Z \rightarrow Z^*(\rightarrow b\bar{b}) + h(\rightarrow \mu^+\mu^-) \\ Z \rightarrow b^*(\rightarrow b + h(\rightarrow \mu^+\mu^-))\bar{b} \end{array} \right\} \text{too suppressed}$$

Problems:

- Angular distribution of muons isotropic
- Muons not close to b-jets

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Problems:

- Angular distribution of muons isotropic
- Muons not close to b-jets

Difficult to tune the parameters of the model to fit both excess and constraints

Test at LHC: modification of searches for Higgs decaying to light bosons

Outline

- 1 The excess in ALEPH
 - Phenomenological interpretations
- 2 Searches at CMS
 - Work in progress

Searches at CMS

HIG-16-015, 8 TeV, 19.7/fb

Search for Higgs decay into two light bosons

2 muons + 2 b-jets, invariant mass in the Higgs window

$$p_T(\mu_1) > 24 \text{ GeV} \quad p_T(\mu_2) > 9 \text{ GeV} \quad p_T(\text{b-jets}) > 15 \text{ GeV} \quad |m_{\mu\mu b\bar{b}} - 125| < 25 \text{ GeV}$$

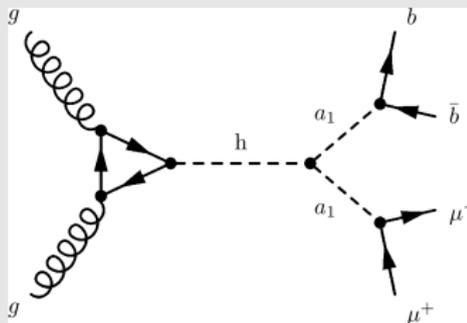
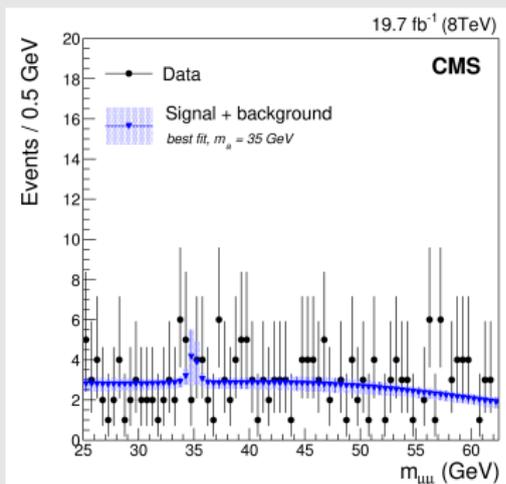


diagram from PAS-HIG-14-041
(same channel)



No statistically significant excess is observed

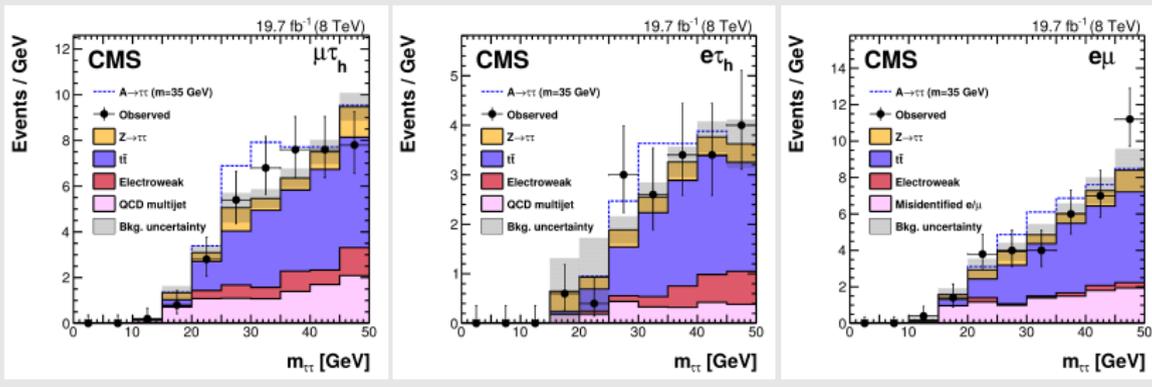
Different interactions assumed

but the analysis can be modified to be sensitive to $Z \rightarrow \mu^+ \mu^- b\bar{b}$

Searches at CMS

HIG-14-033, 8 TeV, 19.7/fb

Search for light pseudoscalar Higgs decaying into $\tau\tau$ in association with $b\bar{b}$
di-tau in different channels, at least 1 b-jet



No clear hint of an excess
Different interactions assumed

Searches at CMS

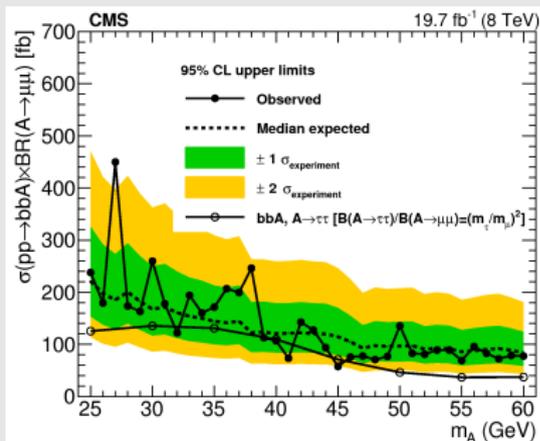
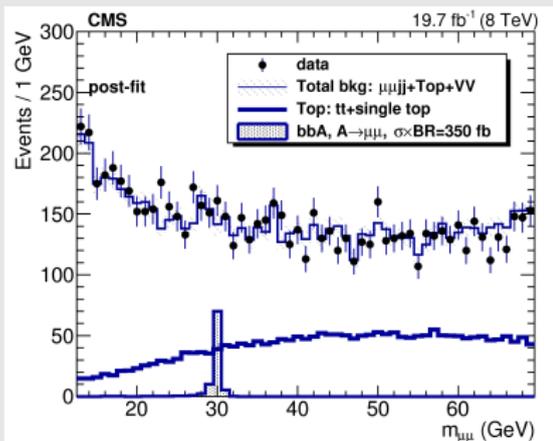
HIG-15-009, 8 TeV, 19.7/fb

Search for light pseudoscalar Higgs decaying into $\mu\mu$ in association with $b\bar{b}$

Complementing HIG-14-033

2 muons + jets (at least one b-jet)

$$p_T(\mu_1) > 25 \text{ GeV} \quad p_T(\mu_2) > 5 \text{ GeV} \quad p_T(\text{b-jet}) > 20 \text{ GeV} \quad p_T^{\text{miss}} < 40 \text{ GeV}$$



No excess observed

Different interactions assumed

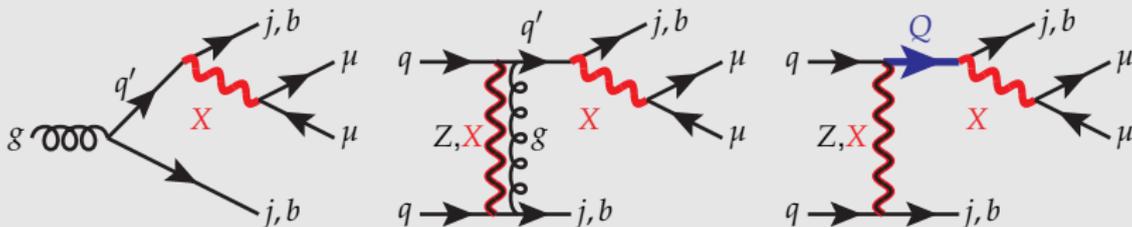
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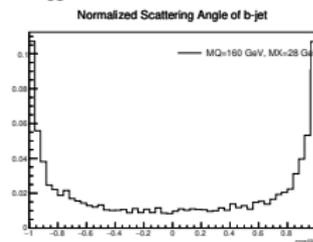
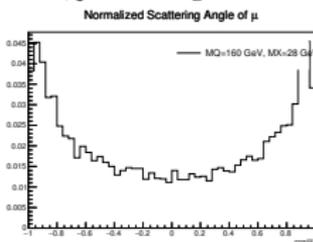
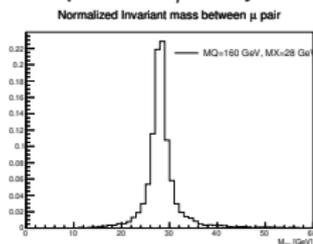
Di-muons plus jets (≥ 1 b-jet)

Work in progress with A. Nikitenko within CMS

Topologies with an X resonance (examples with a vector) and a VLQ



Example for $2\mu+b+j$ final state with $Q = B$, $M_B = 160\text{GeV}$ and $M_X=28\text{ GeV}$

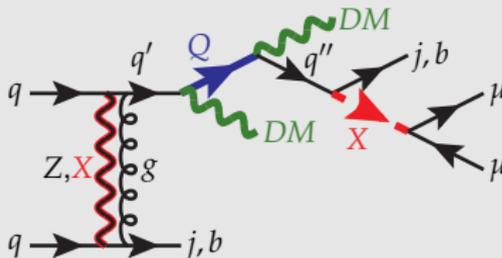


Tuning \implies $\left\{ \begin{array}{l} \text{Compatibility with ALEPH excess} \\ \text{If } X \text{ interacts with light quarks, DY at LHC} \\ \text{Bounds from pair/single production of } Q \text{ and decays into SM and } X \end{array} \right.$

Di-muons plus jets and E_T^{miss}

Work in progress with A. Nikitenko within CMS

Topologies with a Z_2 -even X resonance (example with a scalar), a Z_2 -odd VLQ and DM candidate (example with a vector)



Problems:

- Bounds from Q decaying to DM (di-jet + MET, mono- X)
- DY for X
- Compatibility with non-observation of MET in ALEPH events

Conclusions

- 2σ excess measured in ALEPH data of dimuon+2b-jets, corresponding to $M_{\mu\mu} 30\text{GeV}$
- Different phenomenological interpretations, all requiring careful tuning and with predictions for different channels
- Work in progress with CMS to study analogous channels, and testing different scenarios

Stay ~~tuned~~ connected...