Dark Z's

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INFN – Roma 3

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Z'

L_μ - L_τ

- Vienna/HEPHY: G. Inguglia
- Pisa: L. Corona, L. Zani
- Roma3: G. de Pietro, E.G., A. Martini

LFV (e-μ)

- Vienna/HEPHY: G. Inguglia
- DESY: I. Komarov
- Napoli: M. Campajola, F. di Capua
- Roma3: G. de Pietro, E.G.

The L_μ-L_τ model in the context of dark sector searches: a "dark" Z'

G. Inguglia

- Simple extension of the standard model, new coupling to heavy leptons.

- Complements LHC searches.

- Invisible decay channel to be explored for the first time: phase II physics.

- Only one low mass search performed so far in the muonic channel:
https://arxiv.org/pdf/1606.03501.pdf

- Branching ratio to invisible final states possibly enhanced by low mass dark matter if kinematically allowed, for example sterile neutrino
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.89.113004

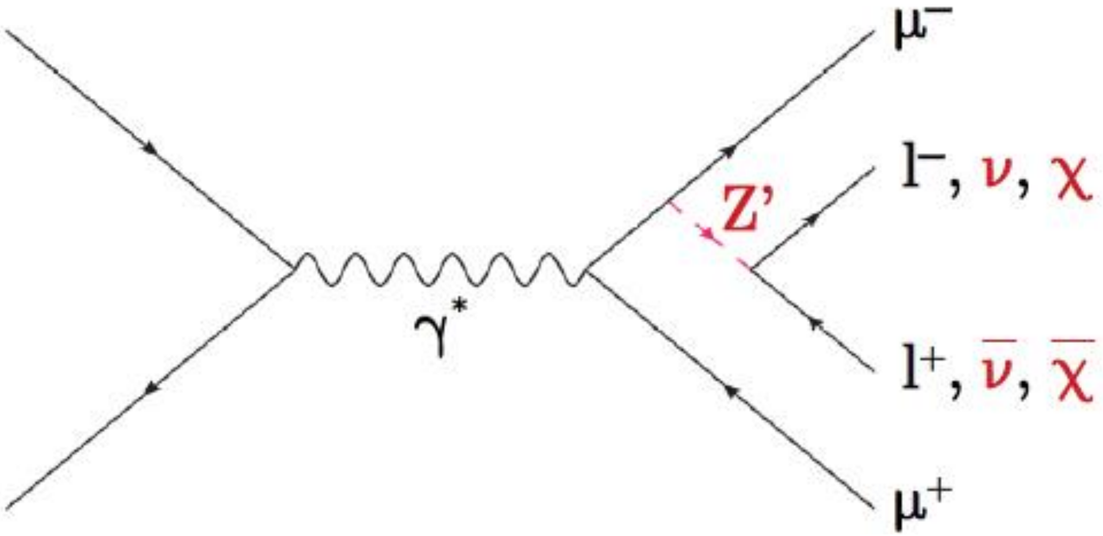
- **May explain $(g\text{-}2)_\mu$**
- **Visible channel (4 μ) covered by I.Jaegle (already published by BaBar)**

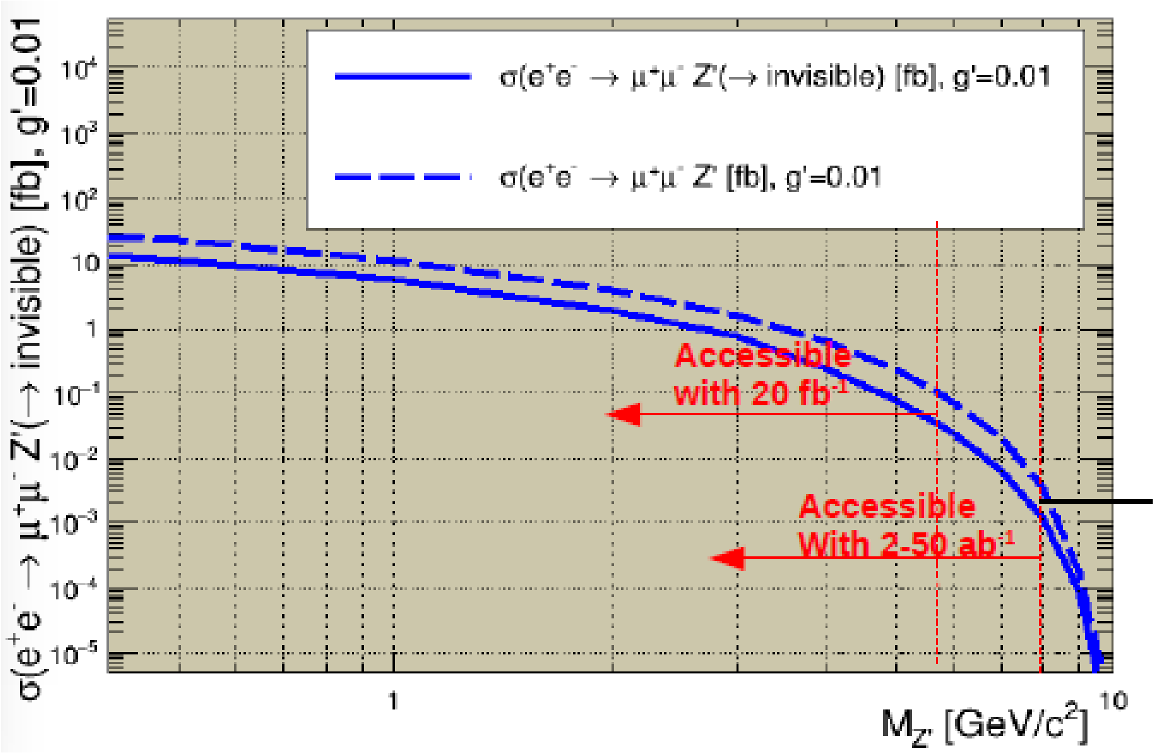
- Vienna/HEPHY: G. Inguglia — signal (ISR/no ISR), trigger, sensitivity
- Pisa: L. Corona, L. Zani — resonance background (J/ψ), resolution
- Roma3: G. de Pietro, E.G., A. Martini — background suppression ($\mu\mu\gamma$, $\tau\tau\gamma$, $ee\mu\mu$)

It's possible to consider a gauge boson Z'
that couples only to **2nd and 3rd**
leptonic generation (**$L_\mu - L_\tau$ model**)

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}$$

Shuve et al. (2014), arXiv:1403.2727





Branching ratios:

$$M_{Z'} < 2M_\mu \rightarrow \Gamma(Z' \rightarrow \mathrm{inv.}) = 1$$

$$2M_\mu < M_{Z'} < 2M_\tau \rightarrow \Gamma(Z' \rightarrow \mathrm{inv.}) \sim 1/2$$

$$M_{Z'} > 2M_\tau \rightarrow \Gamma(Z' \rightarrow \mathrm{inv.}) \sim 1/3$$

arXiv:1803.02804v1 [hep-ph] 7 Mar 2018

Severely Constraining Dark Matter Interpretations of the 21-cm Anomaly

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[b]*Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, IL, USA*
[c]*University of Chicago, Kavli Institute for Cosmological Physics, Chicago IL, USA and*
[d]*University of Chicago, Department of Astronomy and Astrophysics, Chicago IL, USA*
(Dated: March 8, 2018)

The EDGES Collaboration has recently reported the detection of a stronger-than-expected absorption feature in the global 21-cm spectrum, centered at a frequency corresponding to a redshift of $z \sim 17$. This observation has been interpreted as evidence that the gas was cooled during this era as a result of scattering with dark matter. In this study, we explore this possibility, applying constraints from the cosmic microwave background, light element abundances, Supernova 1987A, and a variety of laboratory experiments. After taking these constraints into account, we find that the vast majority of the parameter space capable of generating the observed 21-cm signal is ruled out. The only range of models that remains viable is that in which a small fraction, $\sim 0.3-2\%$, of the dark matter consists of particles with a mass of $\sim 10-80$ MeV and which couple to the photon through a small electric charge, $\epsilon \sim 10^{-6}-10^{-4}$. Furthermore, in order to avoid being overproduced in the early universe, such models must be supplemented with an additional depletion mechanism, such as annihilations through a $L_\mu - L_\tau$ gauge boson or annihilations to a pair of rapidly decaying hidden sector scalars.

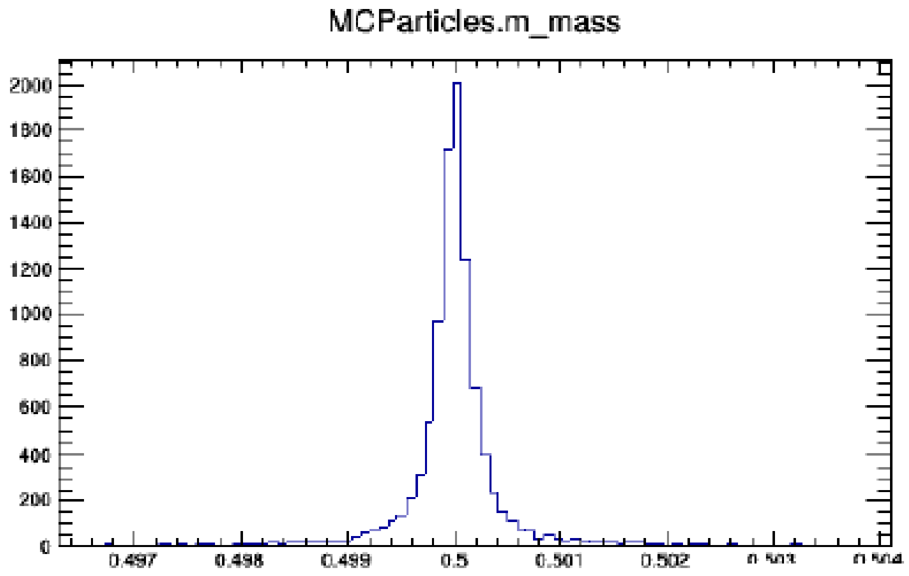
Conclusions

straints, we find that the only range of models that could potentially explain the reported 21-cm signal are those in which a small fraction $\sim 0.3-2\%$ of the dark matter consists of particles with a mass of $\sim 10-80$ MeV and which couple to the photon through a small electric charge of $\epsilon \sim 10^{-6} - 10^{-4}$.

Furthermore, throughout this range of models, the dark matter is predicted to have reached thermal equilibrium with the Standard Model in the early universe, thus requiring that the model be supplemented with an additional mechanism to deplete the dark matter abundance to an acceptable level. We consider scenarios in which the dark matter annihilates through a new vector to neutrinos, or to particles within a hidden sector which are themselves depleted through rapid decays or 3-to-2 processes. Specific possibilities include annihilations to neutrinos through a $U(1)_{L_\mu - L_\tau}$ gauge boson, which is expected to be within the reach of future measurements by the SPS experiment.

Generated samples and physical width (release01-00-00)

G. Inguglia



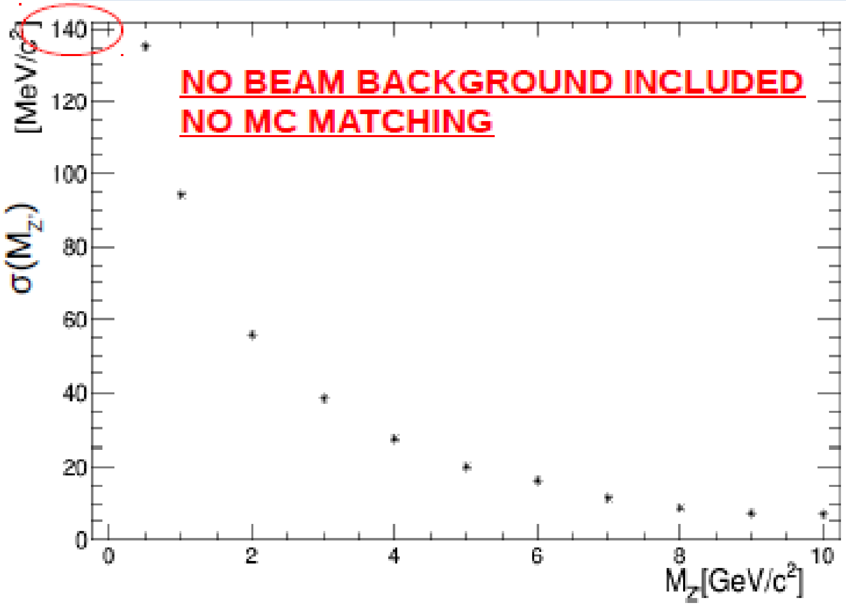
10K events generated for 10 mass points with BASF2/MG5: 1-9 GeV, 1 GeV step size.

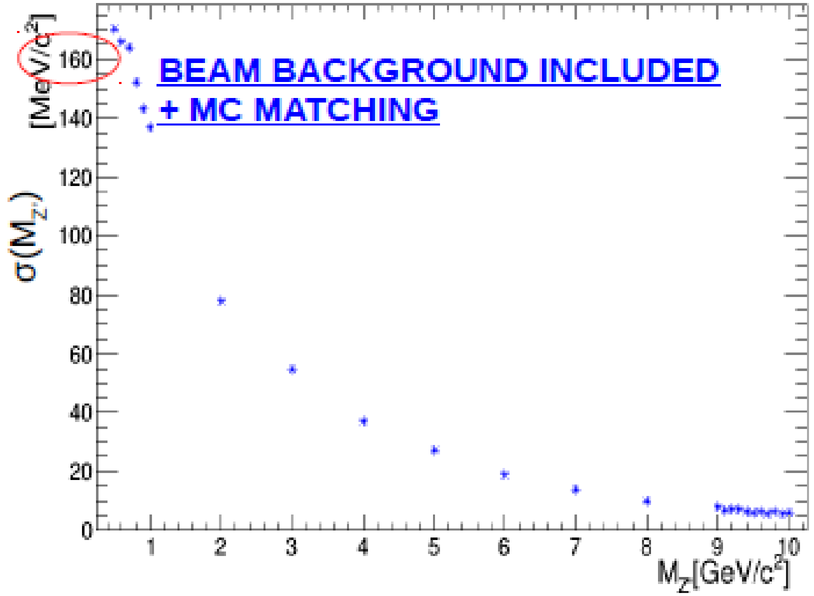
10K events for 5 mass points BASF2/MG5 in 0.5-09 GeV, 100 MeV step size.

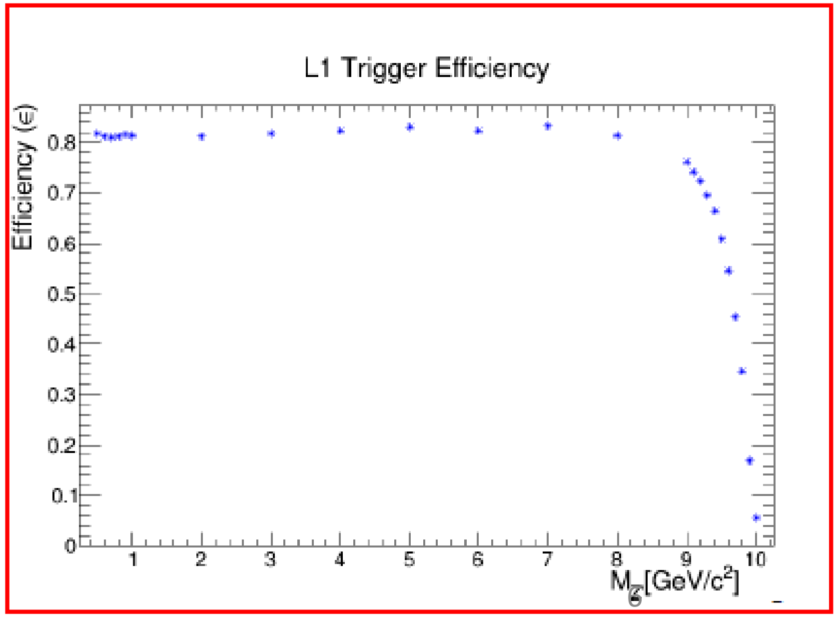
10K events for 10 mass points BASF2/MG5 in 9.1-10.0 GeV, 100 MeV step size.

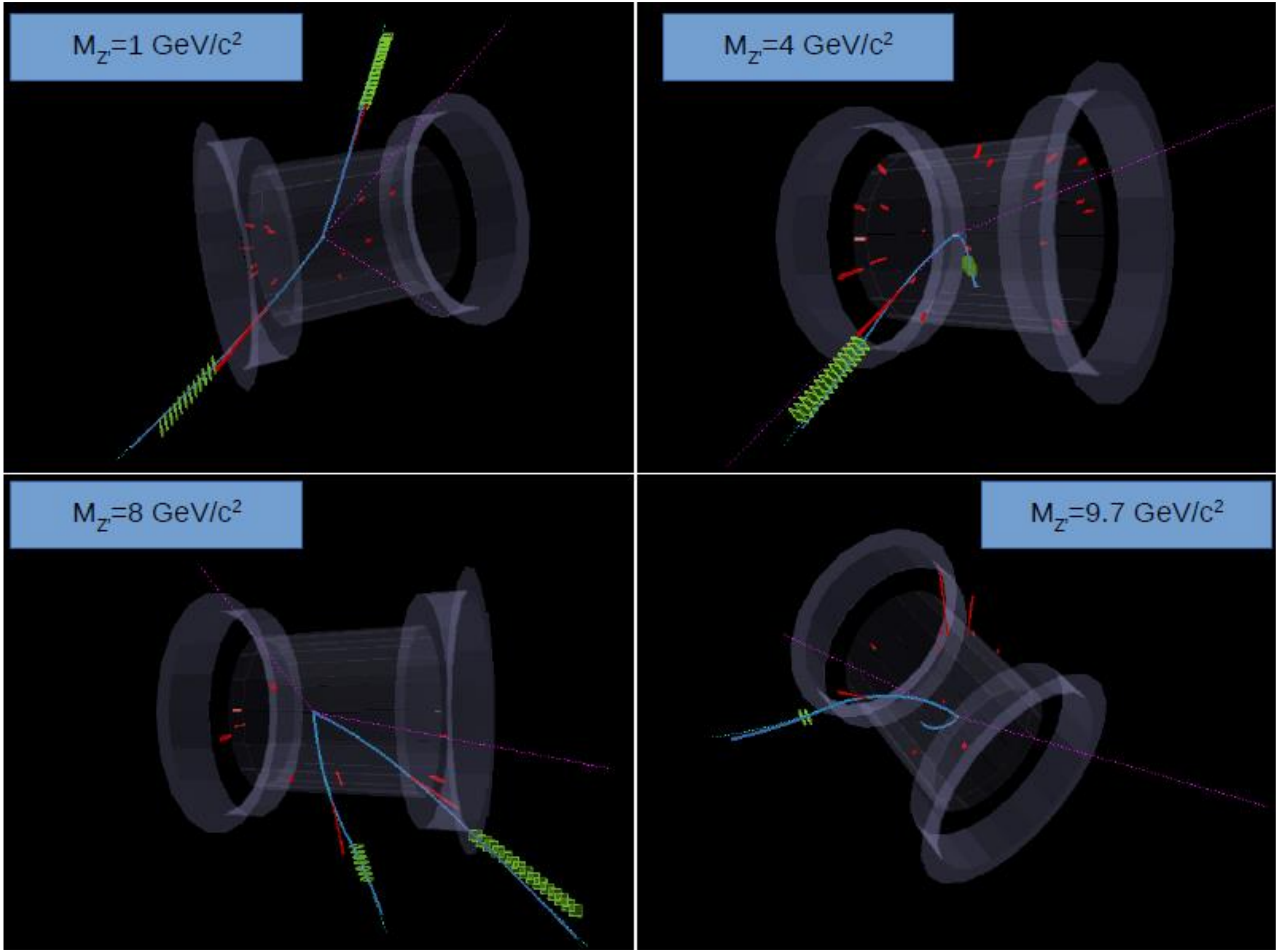
Generated Phys. Width

Standard deviation of the fitted missing Z' mass distribution








$M_{Z'}$=1 GeV/c^2
$M_{Z'}$=4 GeV/c^2
$M_{Z'}$=8 GeV/c^2
$M_{Z'}$=9.7 GeV/c^2

Laura & Luigi

Istituto Nazionale di Fisica Nucleare

Planned background studies

GOAL: Muon momentum calibration → *study the impact of the energy loss in the Beast2 detector* & Missing Energy resolution expected for Phase2 → *study the recoil against the dimuon-candidate.*

Why? Resolution on the recoil mass limits the sensitivity region for the Z' search to invisible

1) Generated samples with Phase2 geometry (expList=1002) and rel/01-00:

- KKMC: $e^+e^- \to \mu^+\mu^-$ events (ISR included)
- EvtGen: $e^+e^- \to J/\psi\ (\to\mu\mu)\gamma_{ISR}$ events

2) Performed studies:

- $M_{J/\psi}$ resolution, P_μ resolution

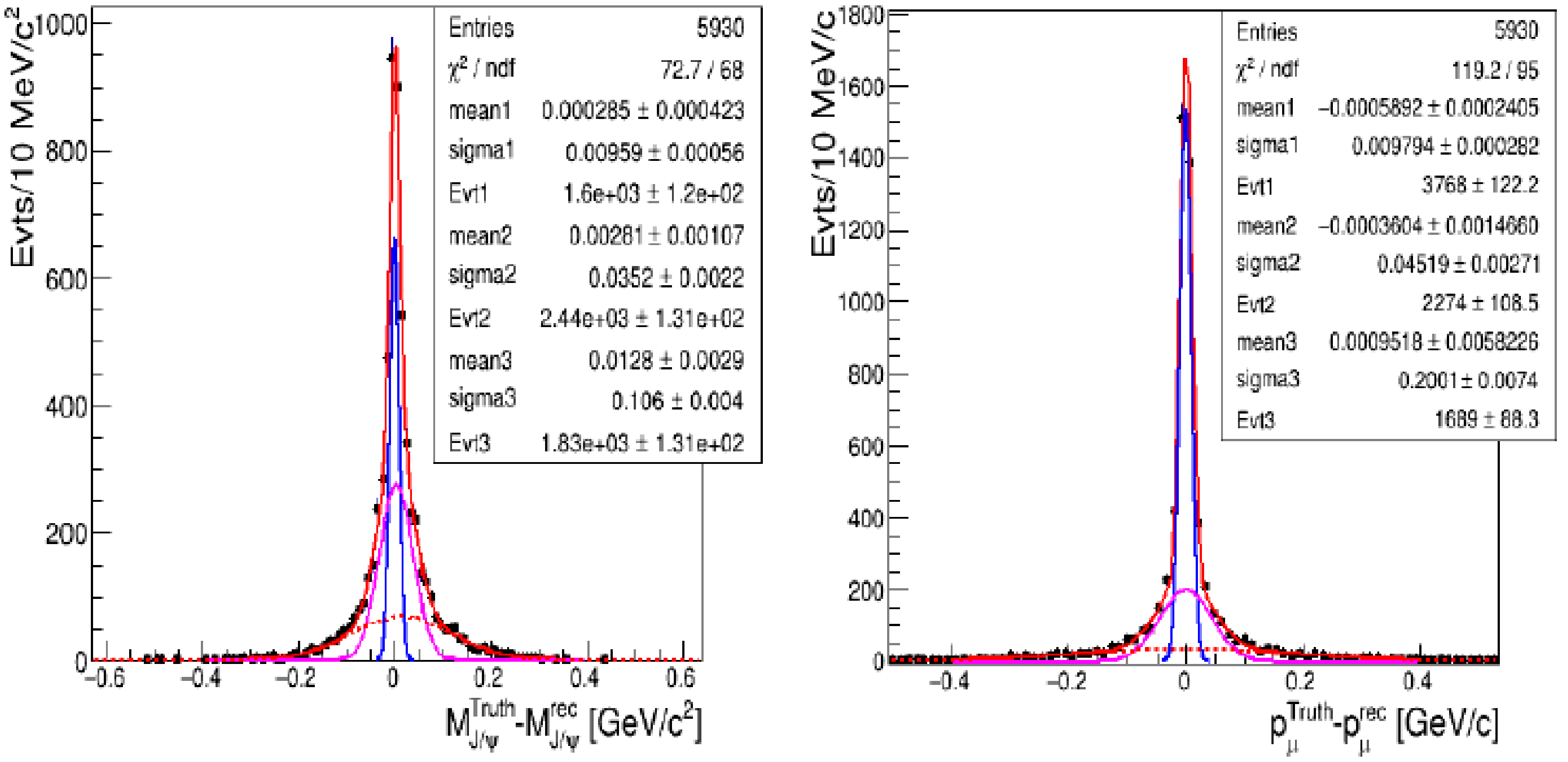
3) Outlook:

- Angular distributions → Optimization of the selection and its impact
- Compare and validate different generators: KKMC, EvtGen, BABAYAGA@NLO, Phokhara...
- Increase the statistics + Add the beam background

Laura & Luigi

First steps: sanity checks on resolutions

- 25k events $e^+e^- \to J/\psi (\to \mu\mu)\gamma_{ISR}$
- SELECTION CRITERIA: MuonID >0.1, Prob(χ^2)>0.001, (2.7< $M_{J/\psi}$ <3.5) GeV/c² + vertex Rave fit



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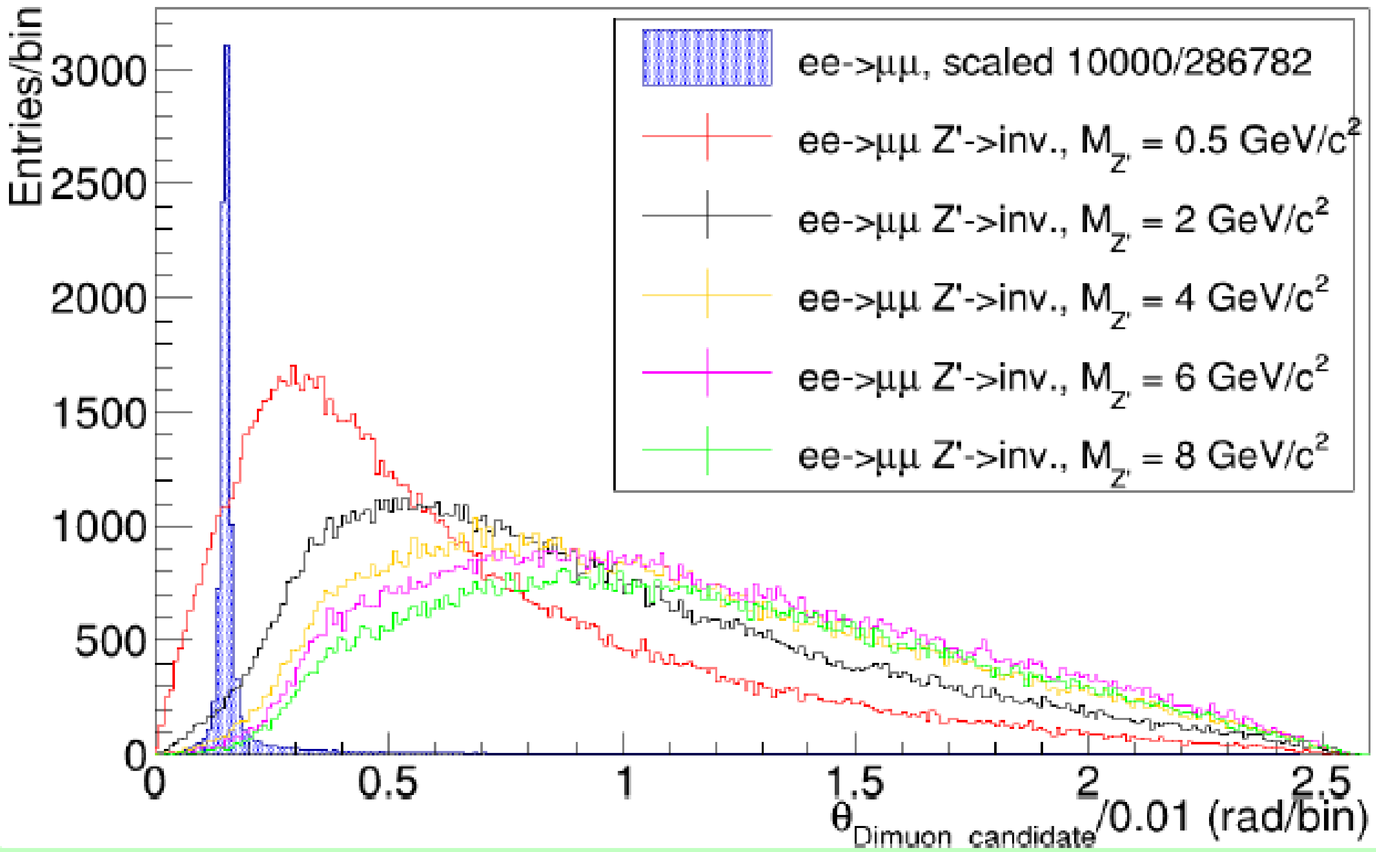
Discriminant Variable

ϑ of the Dimuon Candidate

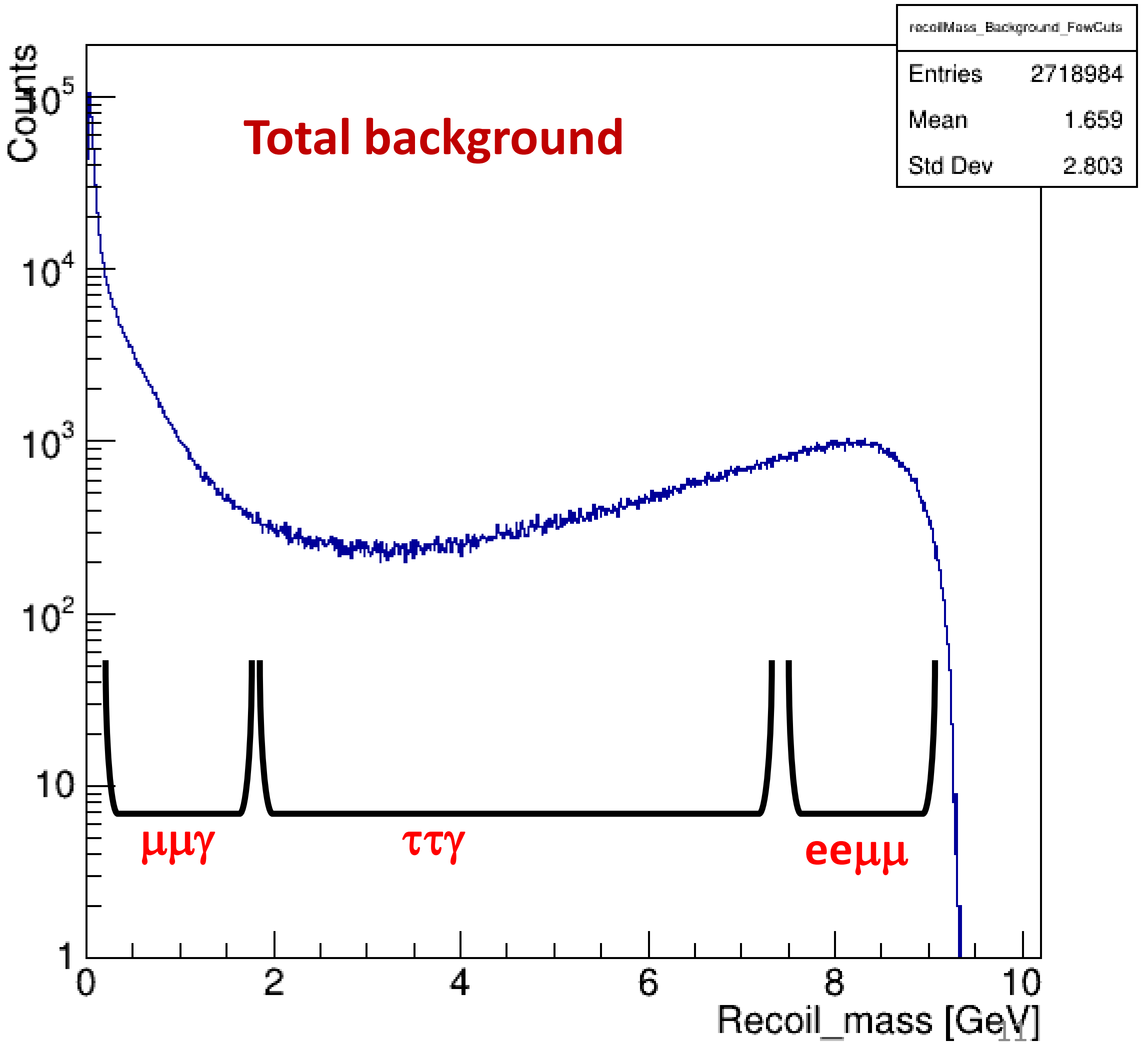


Background suppression studies

10 fb^{-1} di eventi di fondo:
- mu^+mu^- (KKMC, BGx1, rel-01)
- tau^+tau^- (KKMC, BGx1, rel-01)
- $e^+e^-mu^+mu^-$ (AAFH, BGx1, rel-01)

Candidati muoni:
- chiProb > 0.001
- muonID > 0.9

Candidato dimuone:
- $theta_{CMS}$ tra 0.29 e 2.61
- vertexRave con chiProb > 0



Recoil:

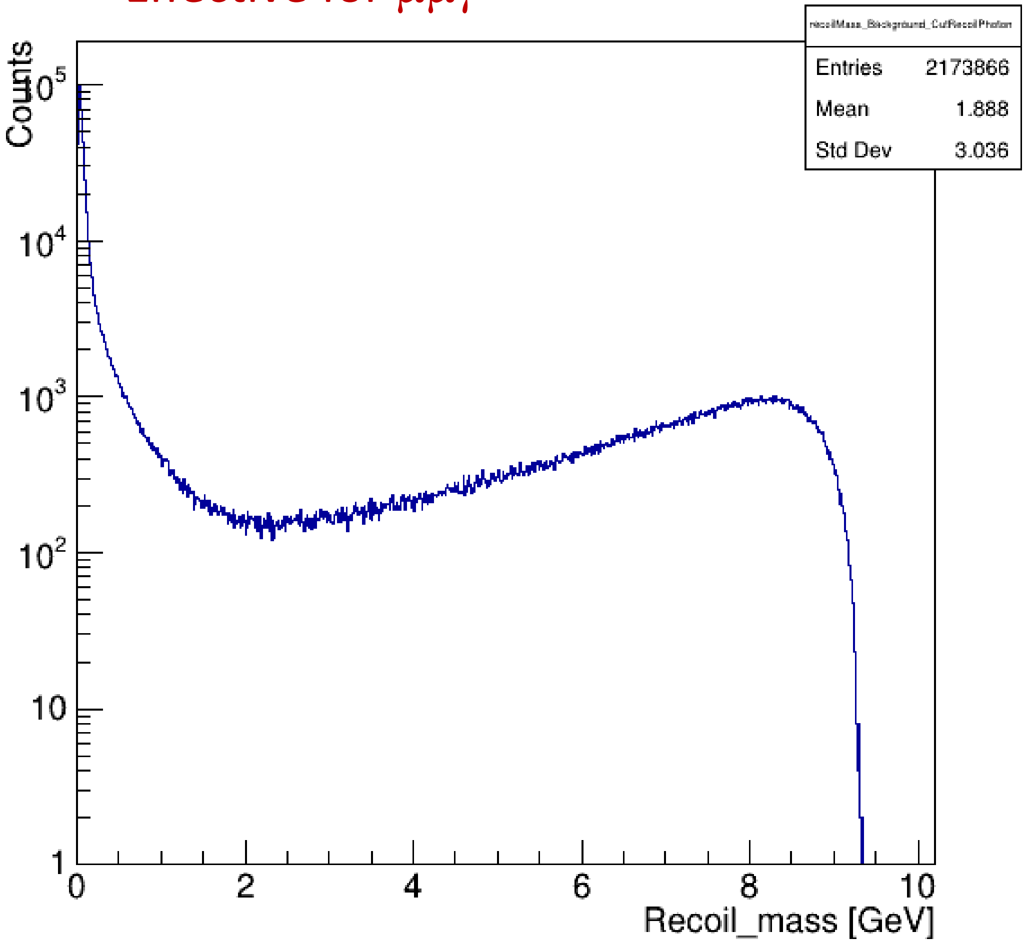
- $theta_{LAB}$ tra 33° e 128°
- no fotoni "ripuliti" entro 15°
- per $E_{fotone} > 0.5$ GeV: $abs(E_{recoil} - E_{fotone}) > 1$ GeV

ROE ("ripulito"):

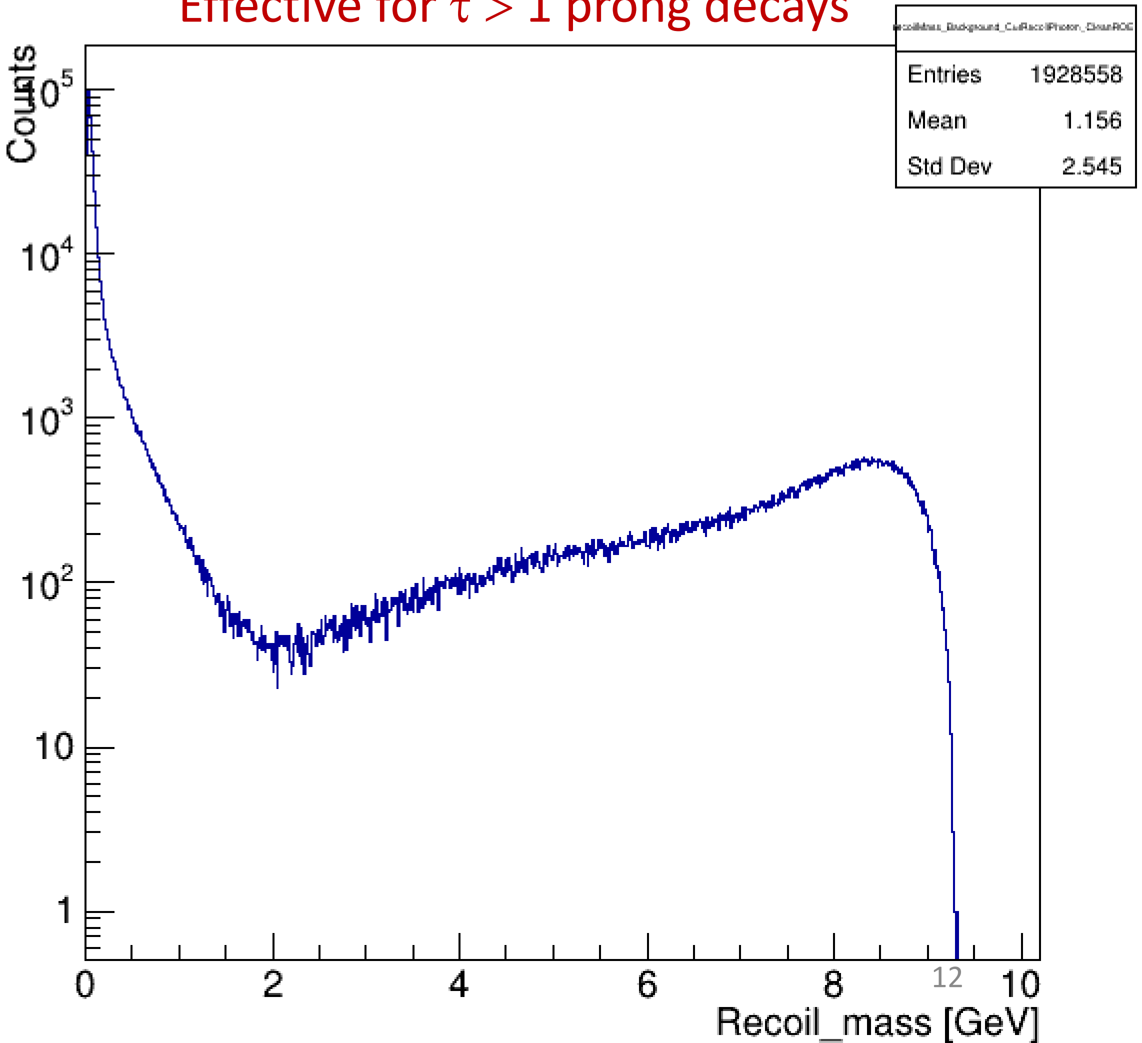
ROE_E < 1 GeV

nROE_Tracks = 0

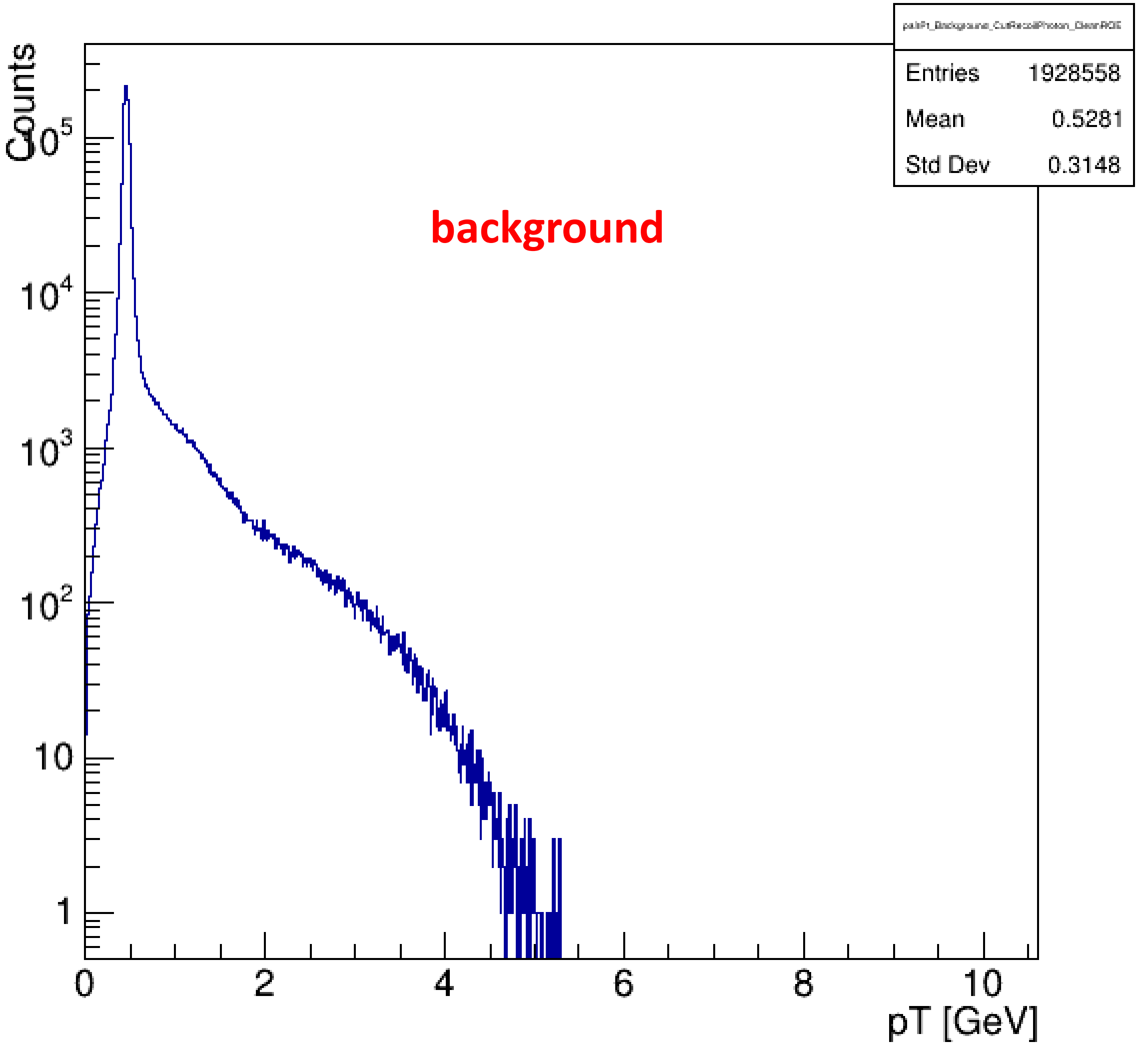
Effective for μμγ



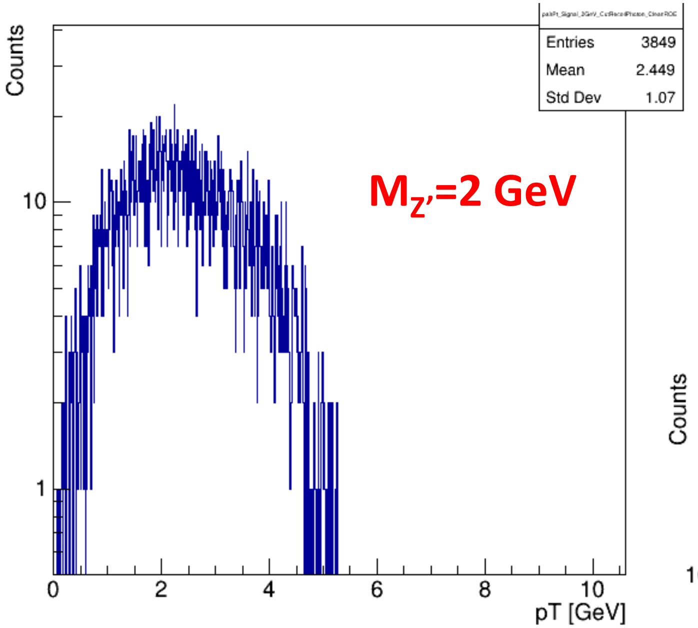
Effective for $\tau > 1$ prong decays



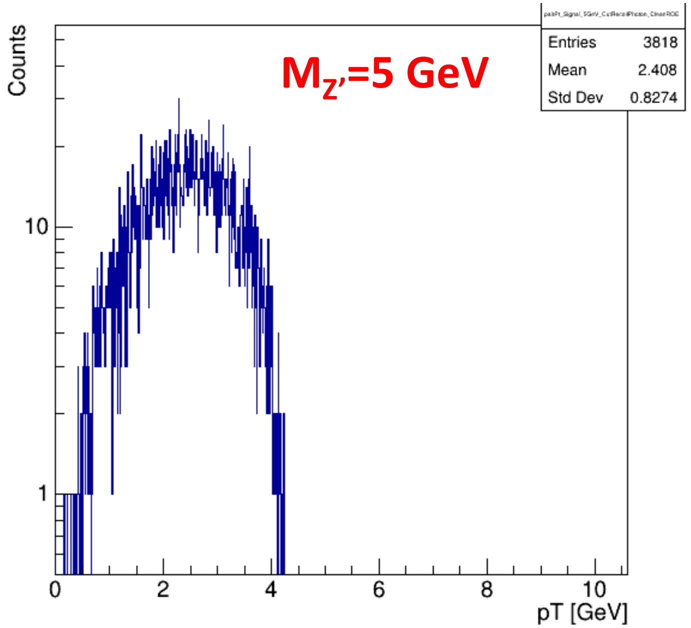
μμ pT



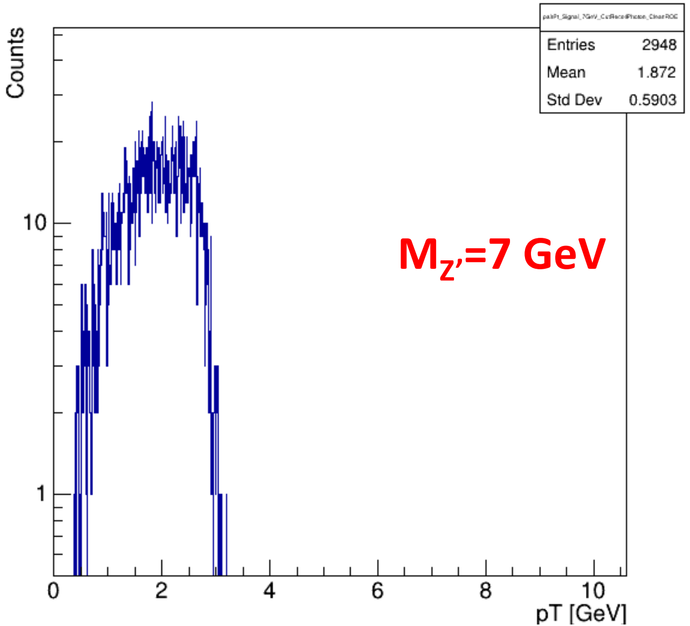
Counts
Entries 1928558
Mean 0.5281
Std Dev 0.3148
background
pT [GeV]



Counts
Entries 3849
Mean 2.449
Std Dev 1.07
M_Z'=2 GeV
pT [GeV]

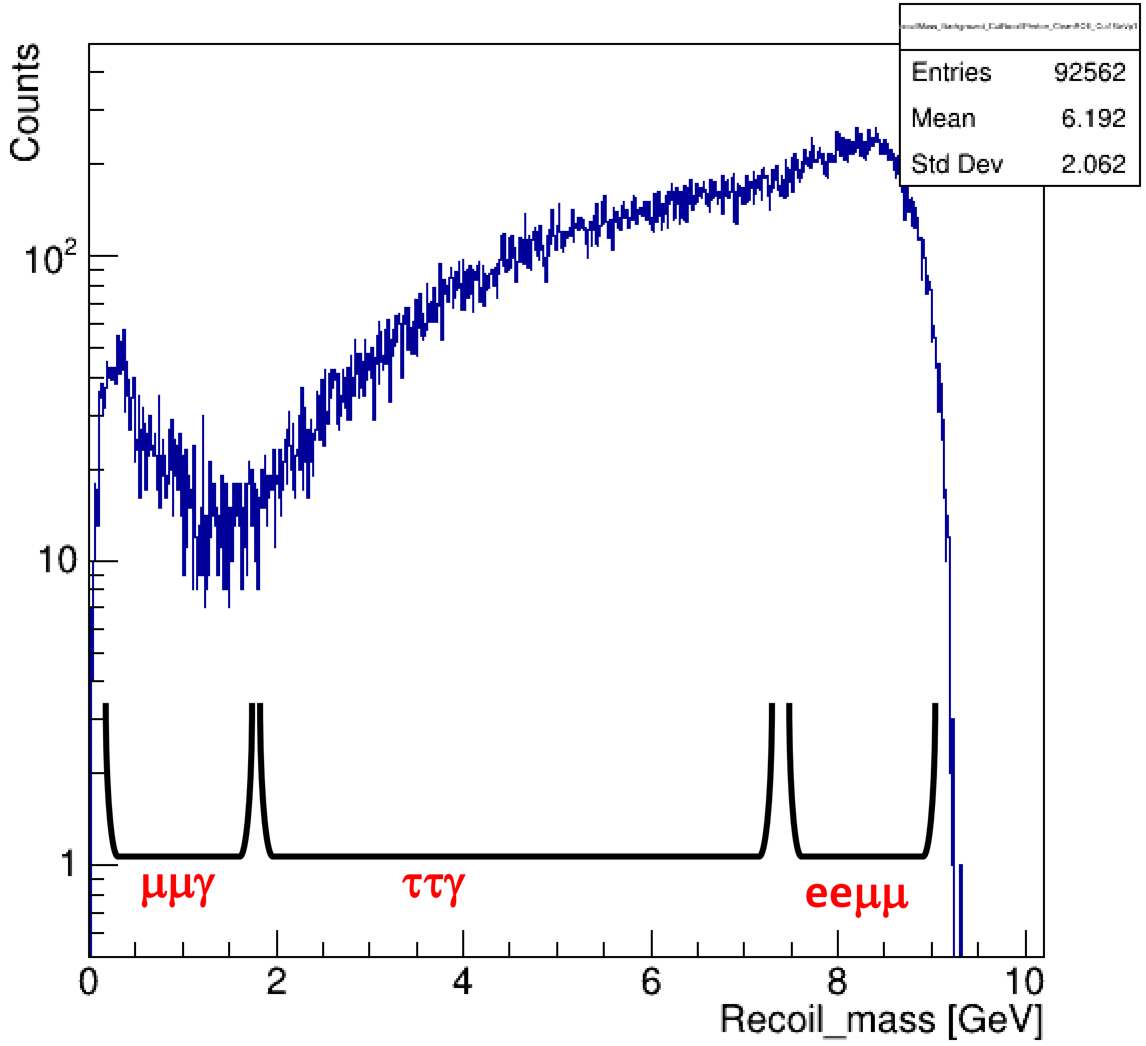


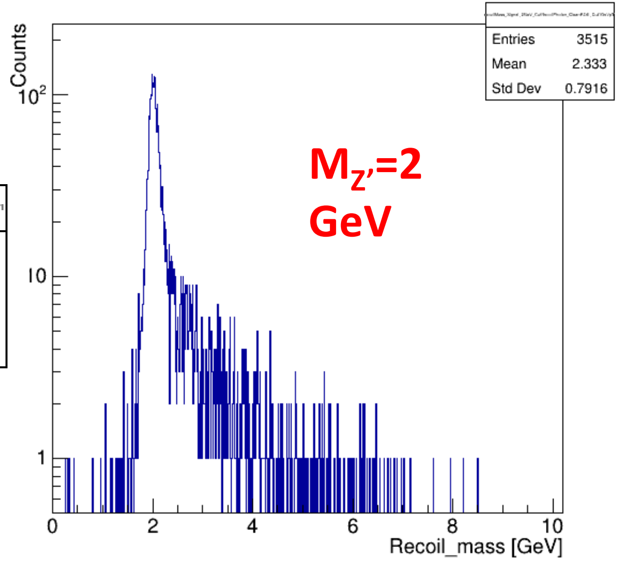
Counts
Entries 3818
Mean 2.408
Std Dev 0.8274
M_Z'=5 GeV
pT [GeV]

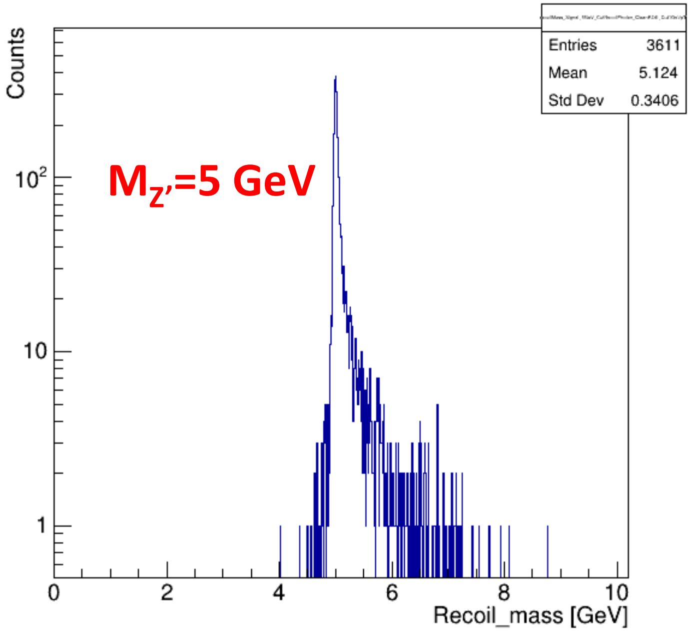


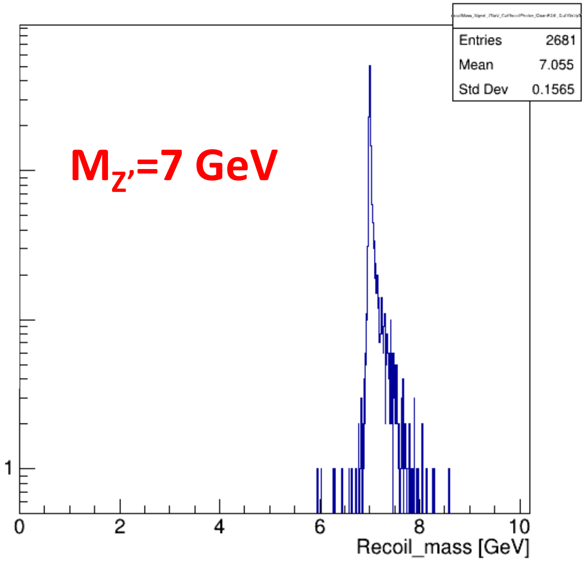
Counts
Entries 2948
Mean 1.872
Std Dev 0.5903
M_Z'=7 GeV
pT [GeV]

$p_T^{\mu\mu} > 1$ GeV

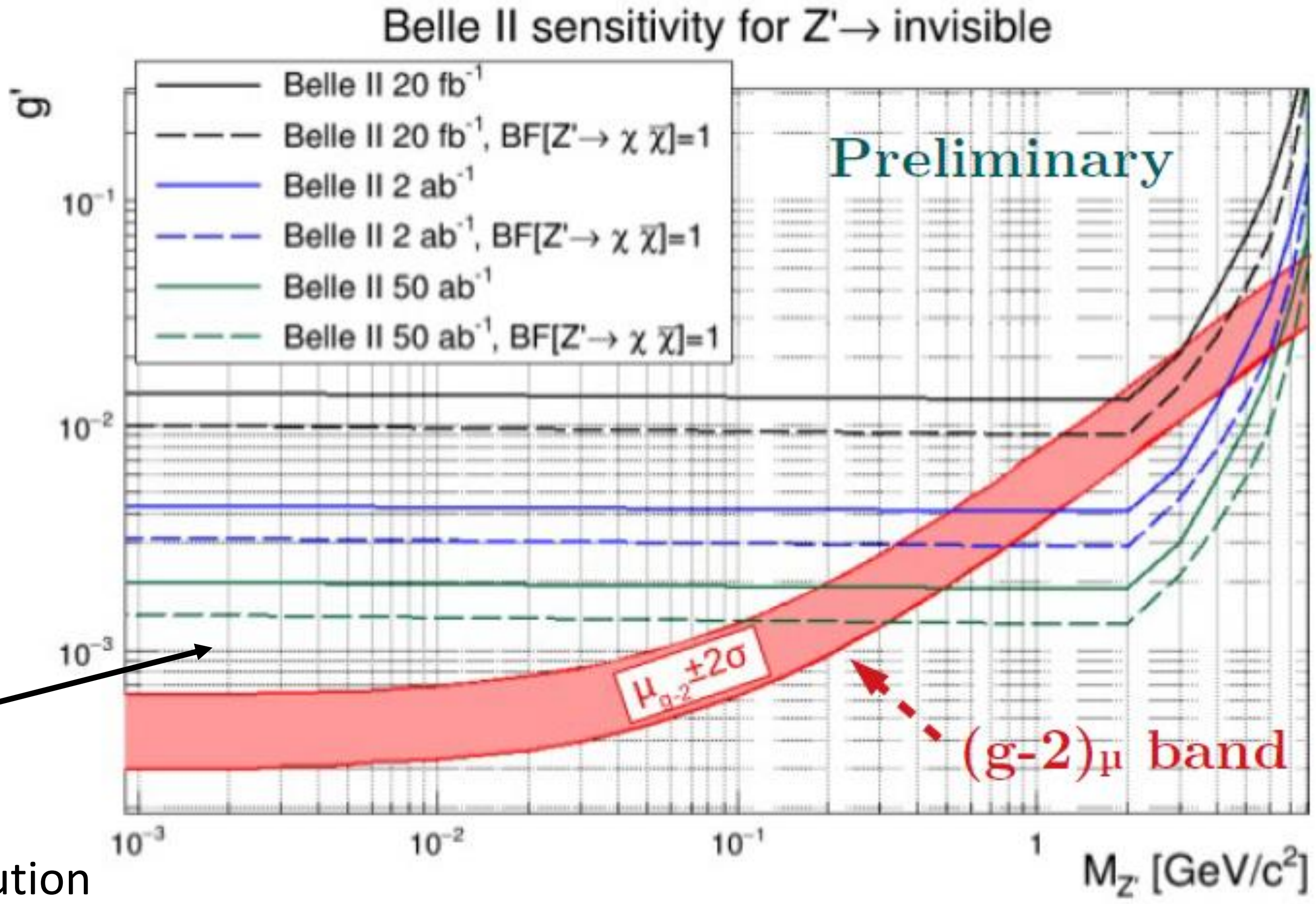








≥ 50% background is ττγ

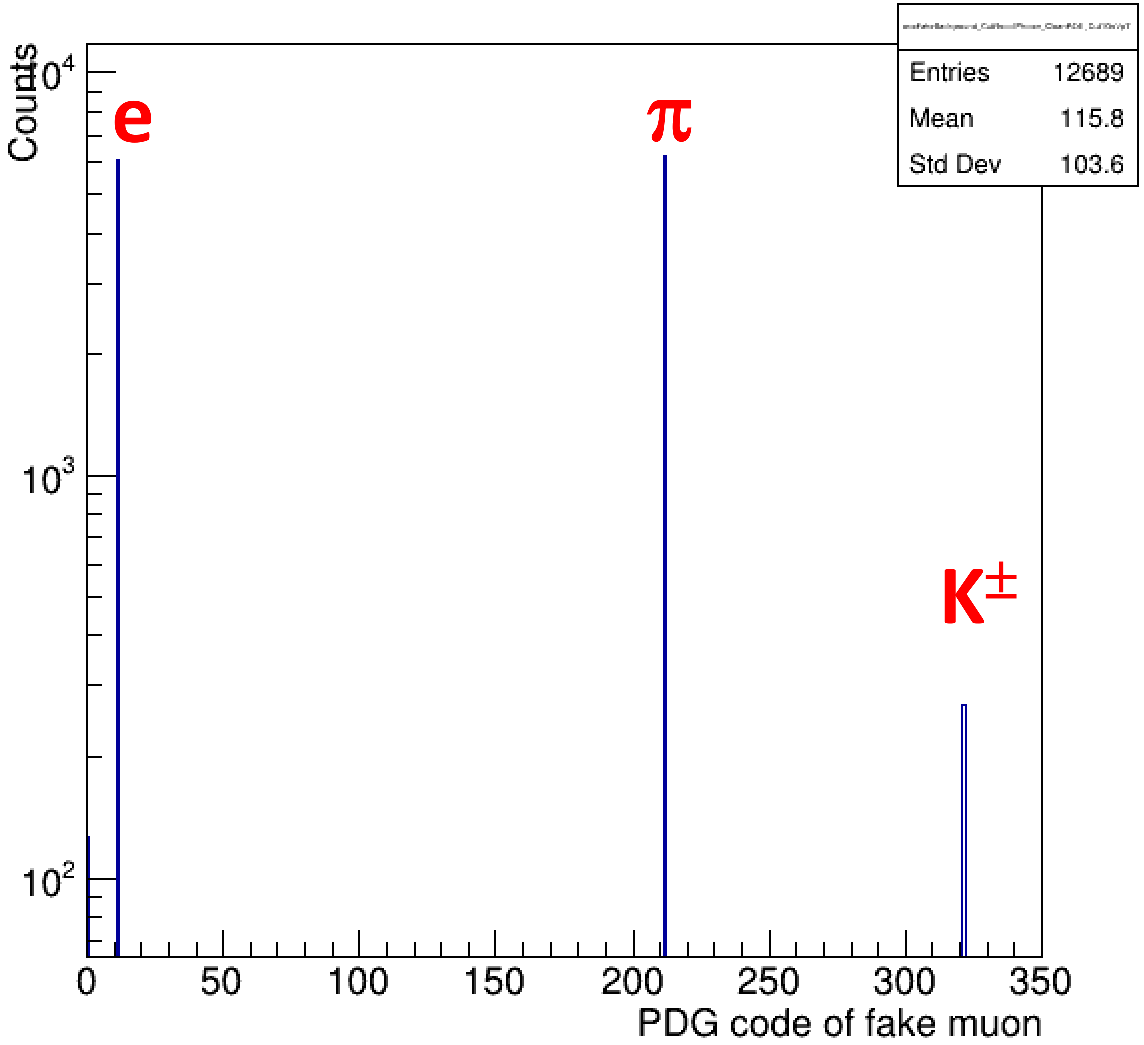


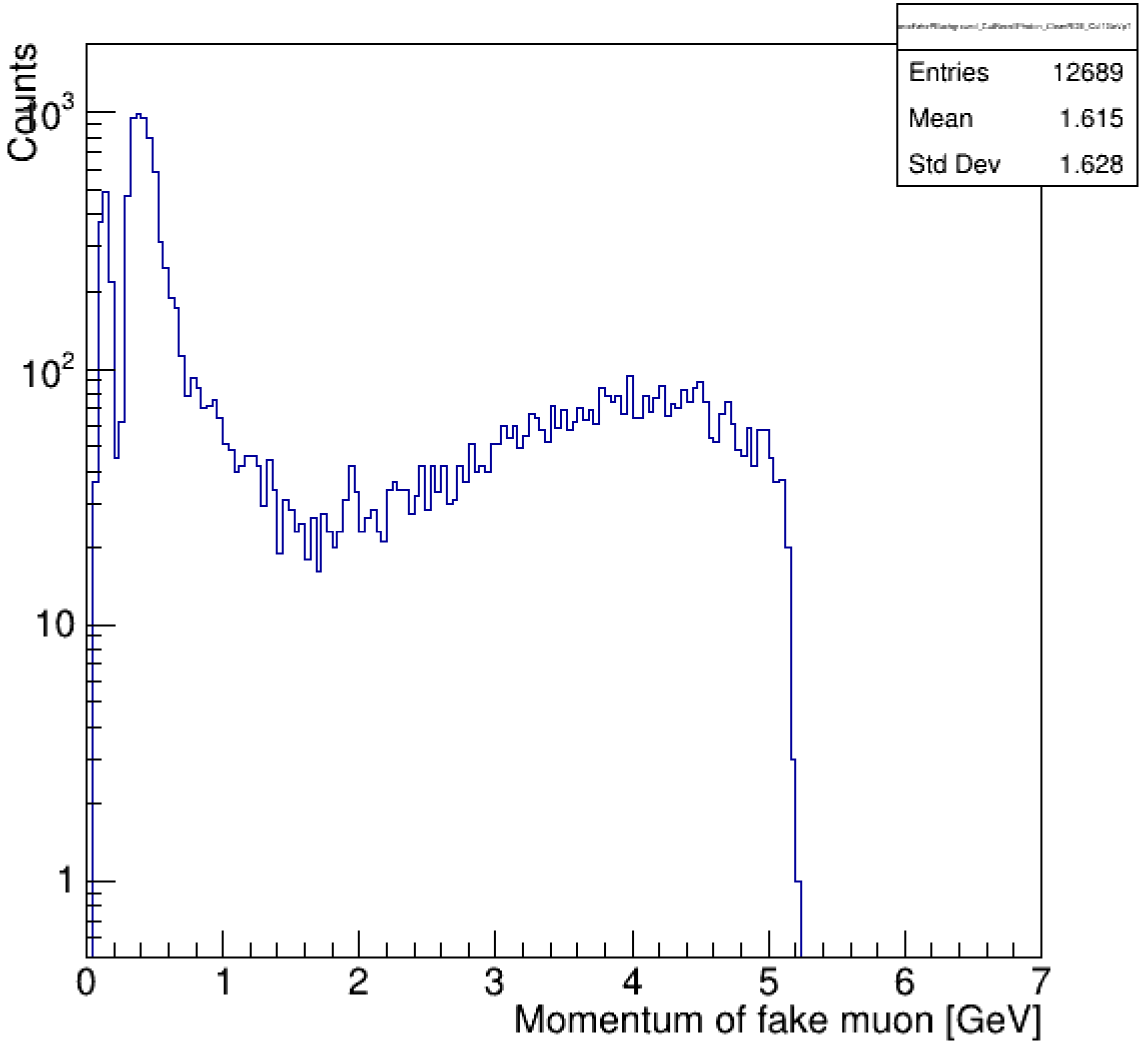
Poor recoil mass resolution

Very preliminary. Selections not optimised

Possible improvements: PID

ττγ only

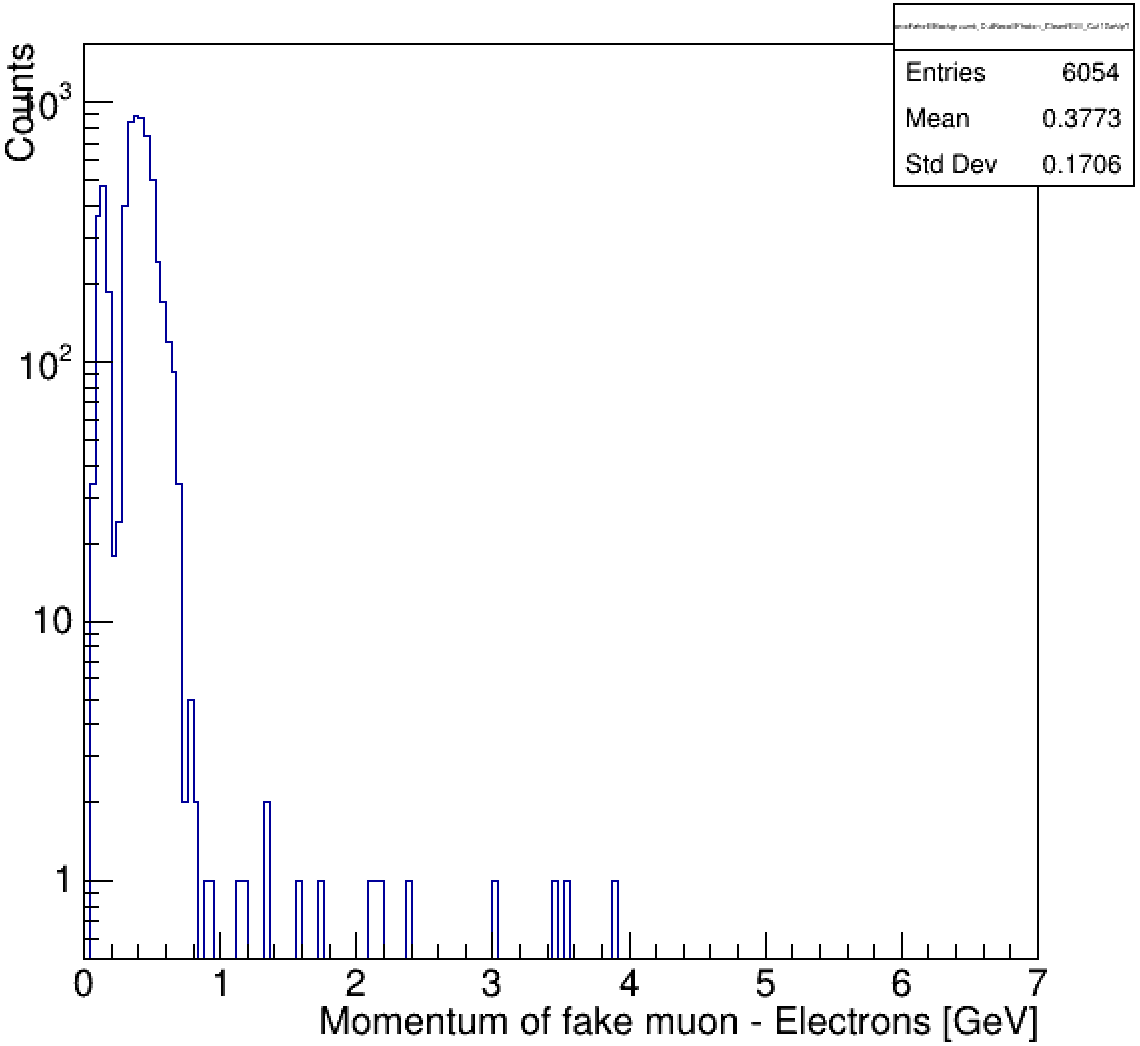


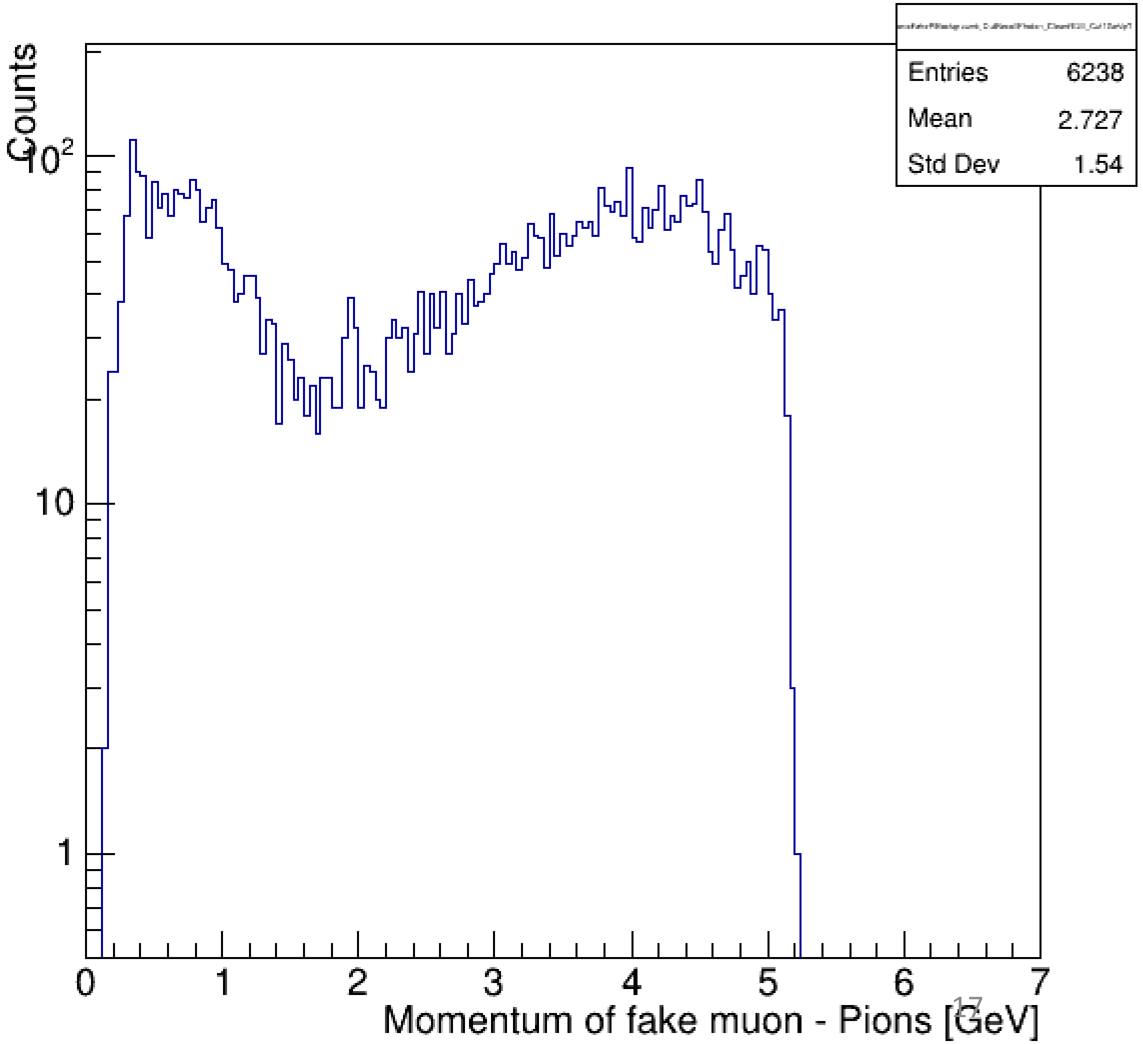


≈20% of the candidates (10% of the tracks) has a fake muon

Possible improvements: PID

background





Conclusions for Z' L_μ - L_τ

- No available results in the missing energy channel: interesting already in Phase 2
- All backgrounds reasonably included (more checks on continuum)
- Selections not optimised. Recoil mass dependent cuts probably needed
- PID definitely needs to be improved
- The τ background will benefit from PID and (in Phase 3) lifetime sensitivity due to the vertex detector
- Relations between kinematic observables (momenta and angles) being scrutinized to reduce the background
- After a better comprehension of the relevant variables, some MVA will surely improve the selections
- Thinking how to improve the sensitivity at low Z' mass: 4 leptons, radiated γ, … Much more luminosity needed, anyway
- Looking soon at real data!

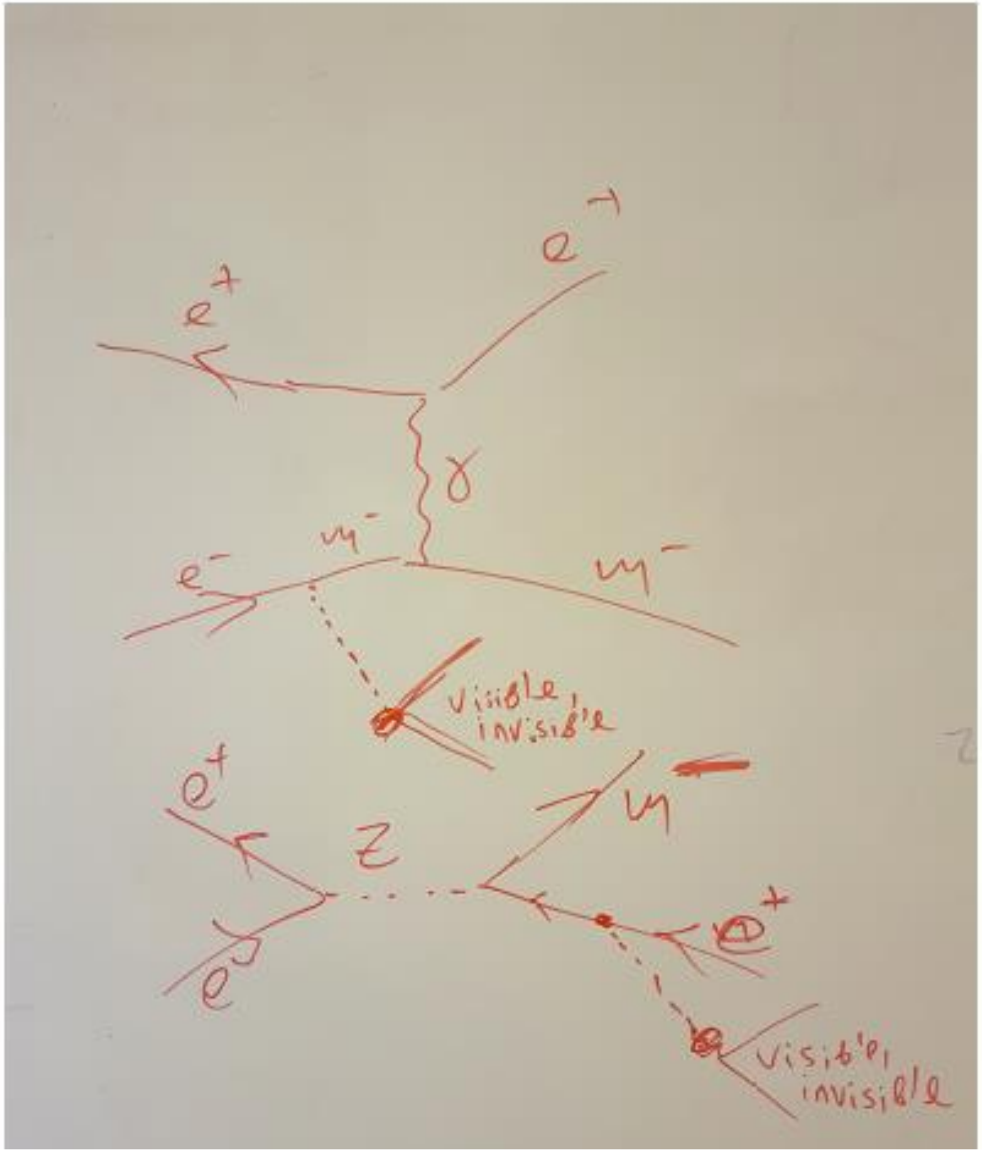
Z' FLV

One more search at Phase II

An idea

I. Komarov

- At this moment, we already have rich dark sector program for phase II:
    - Dark Photon, Dark Z', off-shell DM, ALPs…
- All these searches presume that symmetries of SM are kept in Dark Sector
- In my opinion, this is not necessary.
- What if DM violates Lepton Flavour?
    - In particular, let's assume it has eμ coupling



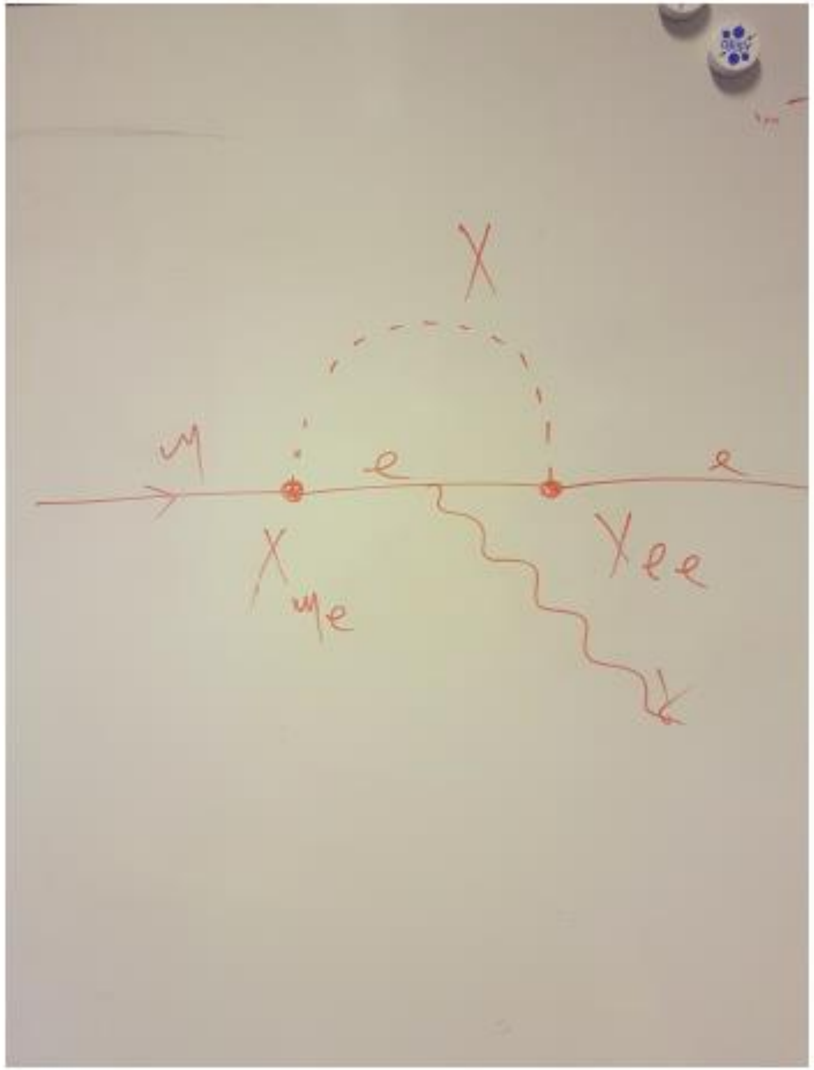
arXiv:1701.08767v1 [hep-ph] 30 Jan 2017

arXiv:1610.08060v1 [hep-ph] 25 Oct 2016

LFV in eμ? Isn't it already constrained?

I. Komarov

- So far, lepton flavour violation is constrained in three processes (they are more, but for us relevant only these three):
  - $\mu \rightarrow eee$ ($<1.0\times10^{-12}$)
  - $\mu \rightarrow e\gamma$ ($<4.2\times10^{-13}$)
  - $\mu N \rightarrow eN$ ($<6.1\times10^{-13}$)
- None of them doesn't exclude our model exactly
- But there are loops…



Guaranteed phase space

Coupling game

I. Komarov

- Hereby, in coupling phase space μ→eγ limits hyperbolic range, and our search will limit lines.
- We have internal trade between the two analysis modes:
  - $e^+e^- \to e^+\mu^- Z'$(→invisible) can put stronger constraint (since Br~$X_{e\mu}$), but has more backgrounds
  - $e^+e^- \to e^+\mu^- Z'$(→$e^+\mu^-$) puts softer constraints (since Br~$X_{e\mu}^2$) but has no SM backgrounds at all

Analysis in brief

I. Komarov

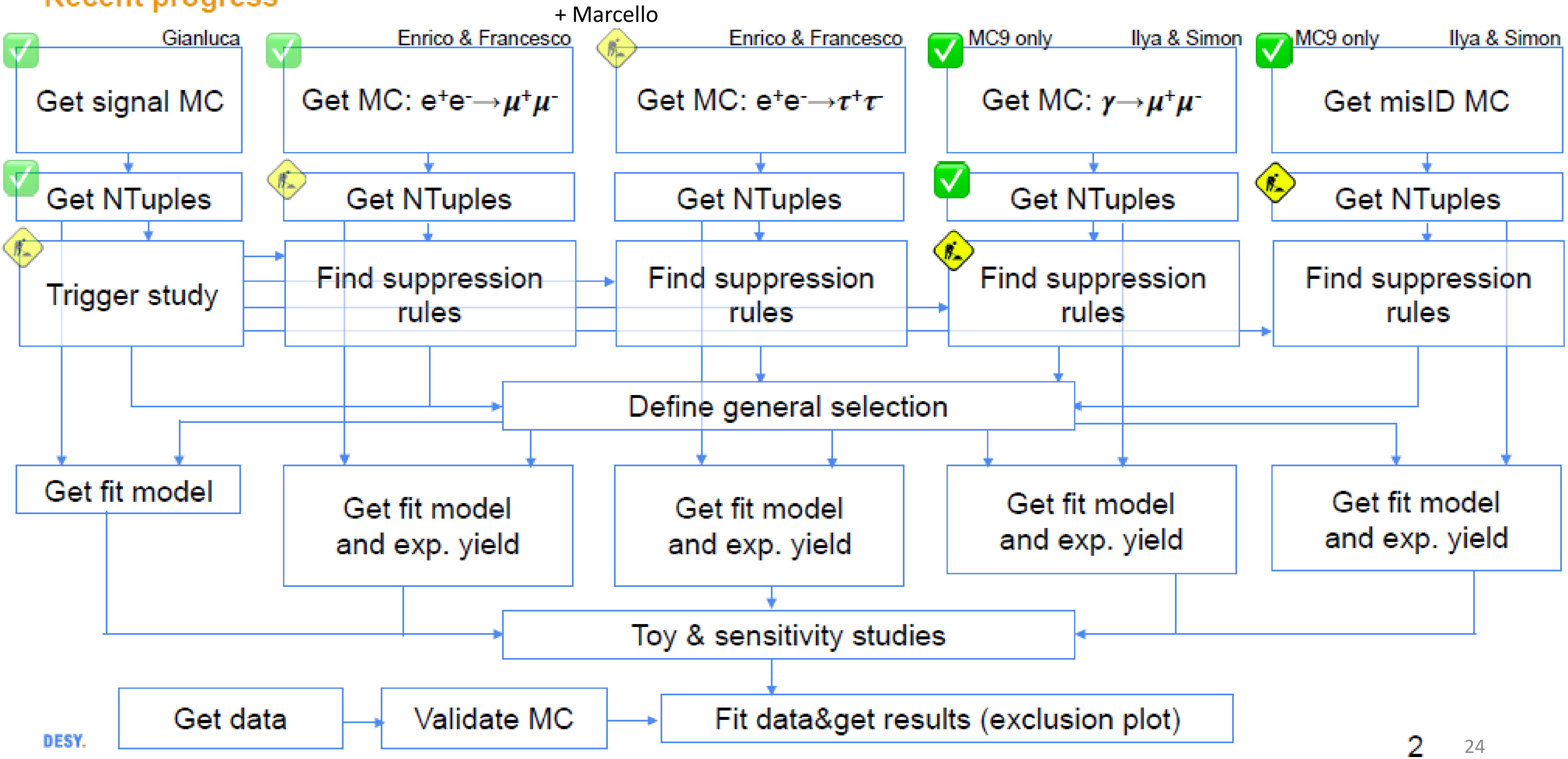
- Aim to get first results from Run II data
- Two processes are studied: $e^+e^- \to e^+\mu^- Z'(\to \text{invisible})$, $e^+e^- \to e^+\mu^- Z'(\to e^+\mu^-)$, search for doubly-charged mediators is given for free: $e^+e^- \to A^{++}(\to e^+e^+)A^{--}(\to \mu^-\mu^-)$
- Background rejection with event multiplicity, track kinematics and lepton ID
- Fit to recoil mass/dilepton mass to find a peak
- Control modes are ones used for LID calibration ($\gamma \to ee$, $\gamma \to \mu\mu$)
- Current experimental status: no direct measurements from BaBar or Belle, indirect constraints from $\mu \to e\gamma$
- Current theoretical status: LFV DM candidates can explain anomalous magnetic moment anomaly and a realistic structure of the charged lepton masses

- Vienna/HEPHY: G. Inguglia — signal (ISR, no ISR), trigger, sensitivity
- DESY: I. Komarov — lepton ID, $ee\mu\mu$ suppression
- Napoli: M.Campajola, F. di Capua
- Roma3: G. de Pietro, E.G. — background suppression ($\mu\mu\gamma$, $\tau\tau\gamma$, …)

Analysis flow: $e^+e^- \to e^+\mu^- Z'(\to \text{invisible})$

Recent progress

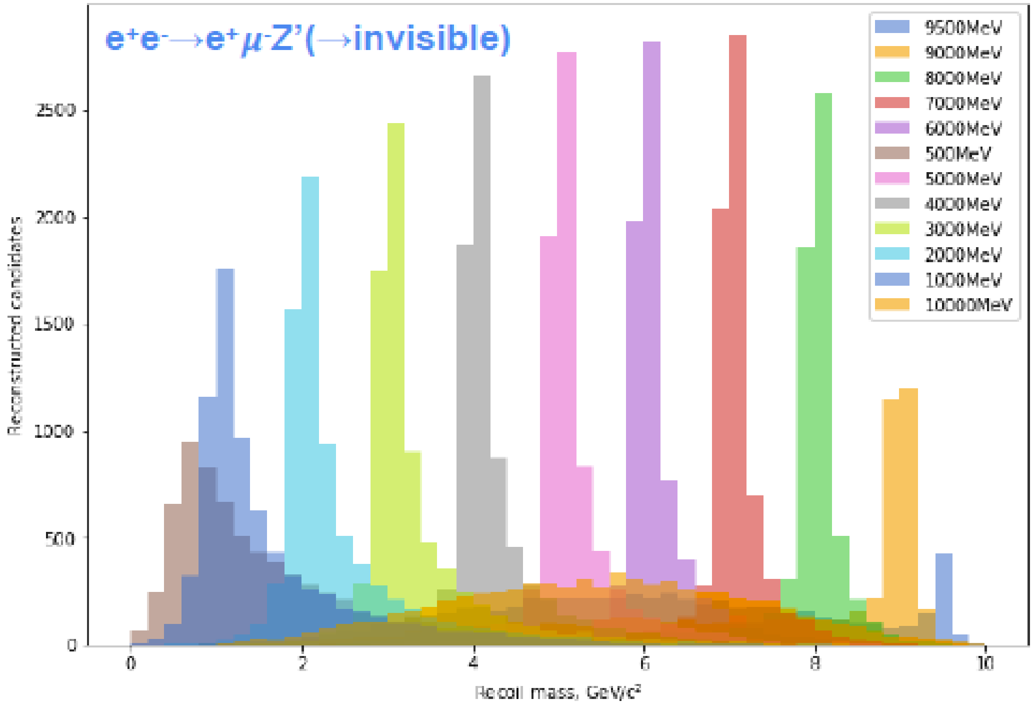
I. Komarov

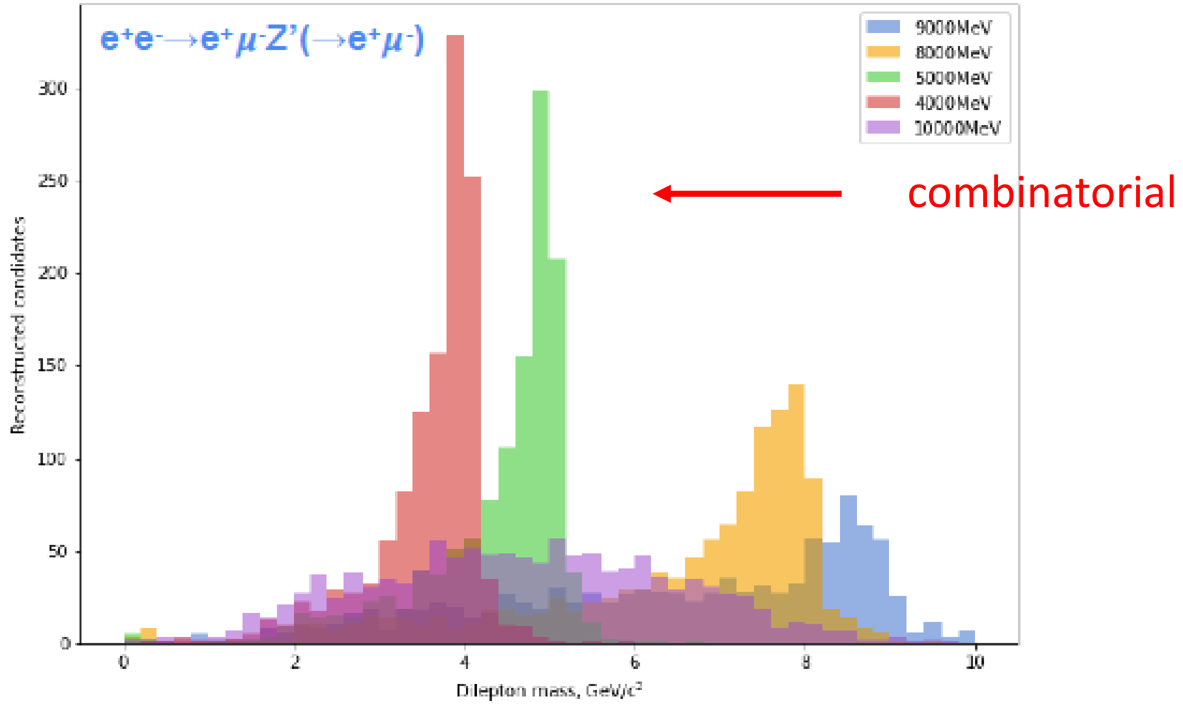


How our signal looks like

I. Komarov

Gianluca used MadGraph models provided by theorists and simulated signal event for various Z' masses.
That's we see after the reconstruction:



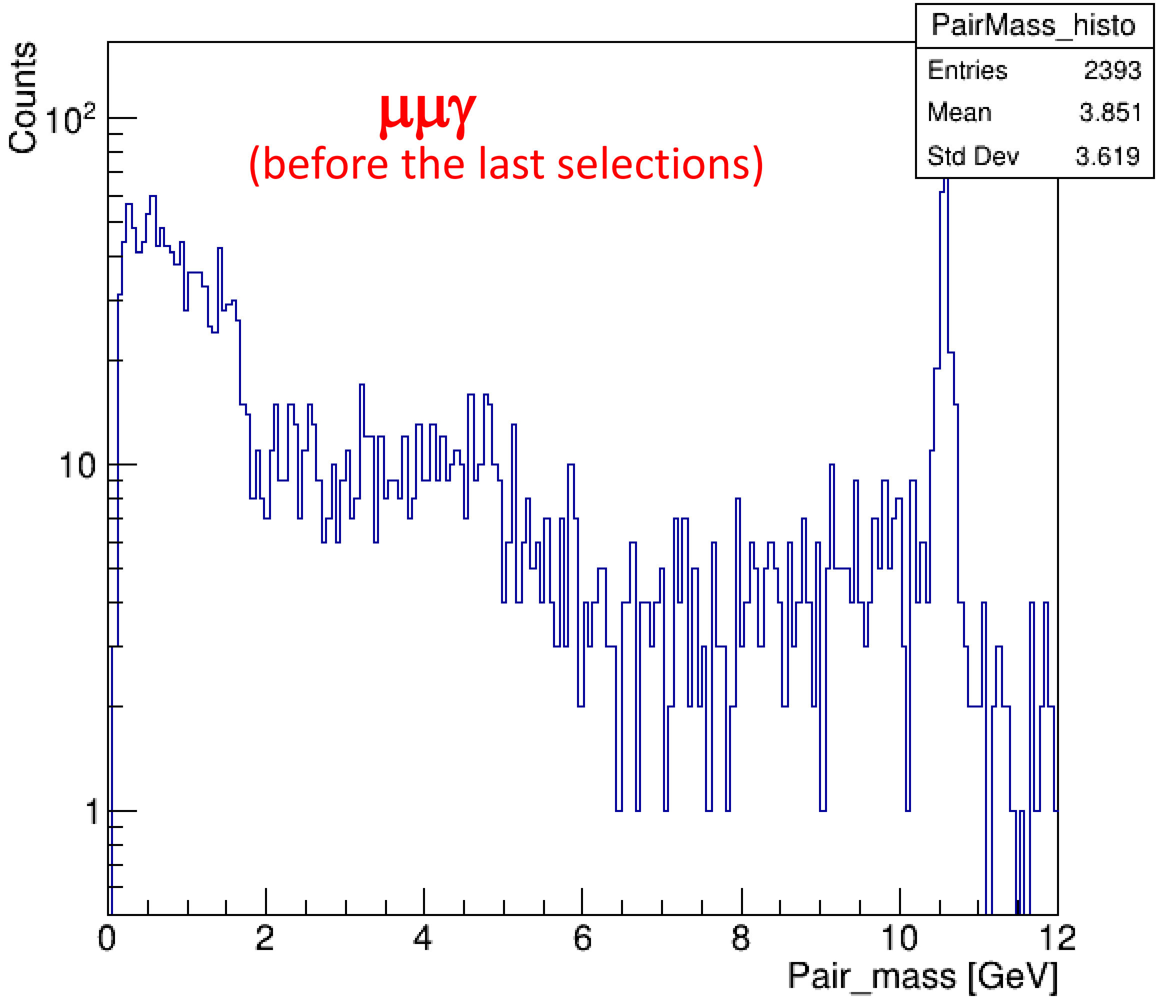


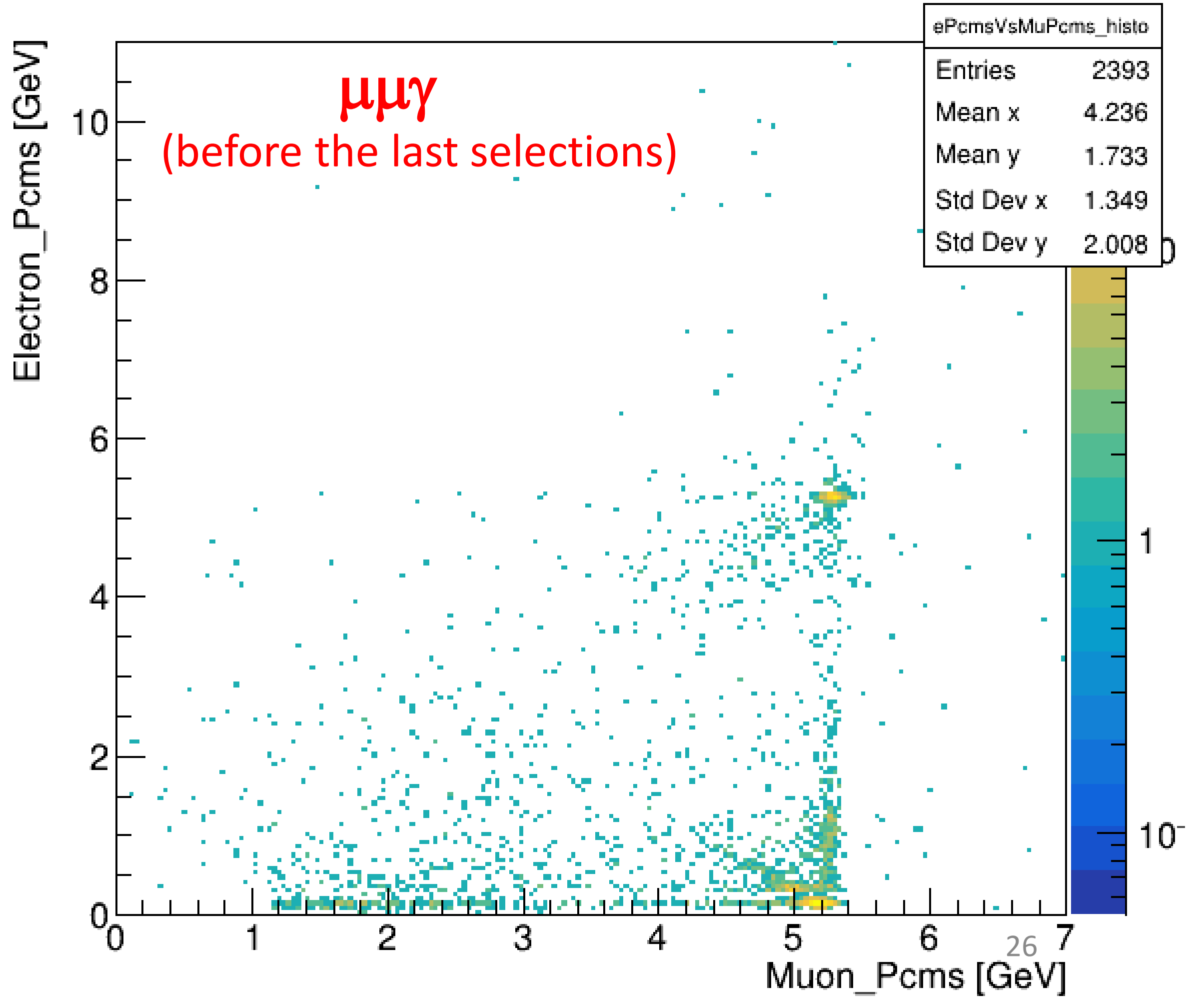
Sensitivity depends on mass of Z', but we are good from [0.5;9.5] GeV/c^2

Work just started. For the moment, mostly for technical reasons, we are focused on the invisible Z' channel.

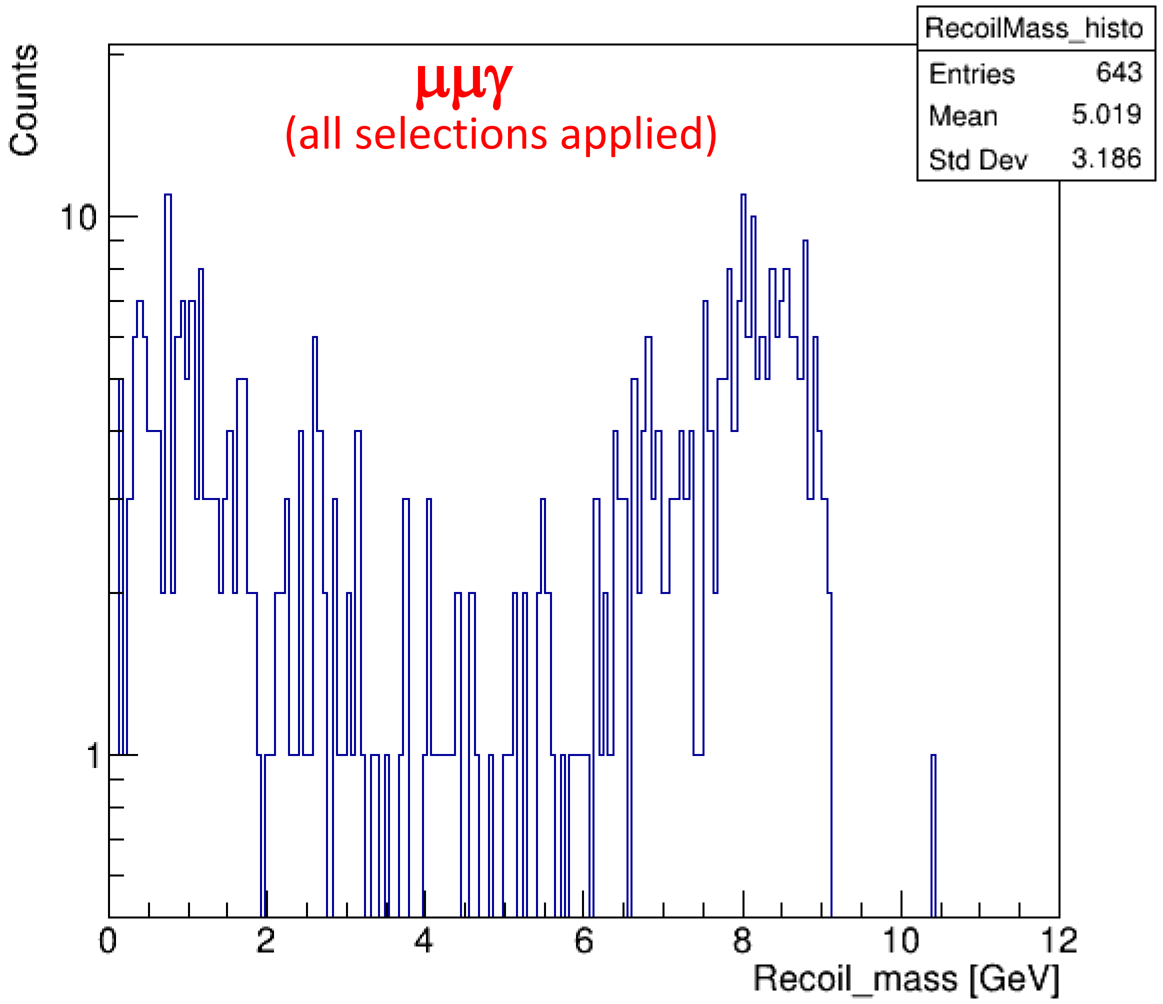
- We (Napoli + Roma3) heavily used the experience , the technical tools and the background samples from the non-LFV Z' search.

- Same selections as in non-LFV Z' search, looking for a e-μ pair with PID_{μ}>0.9 & PID_{e}>0.9

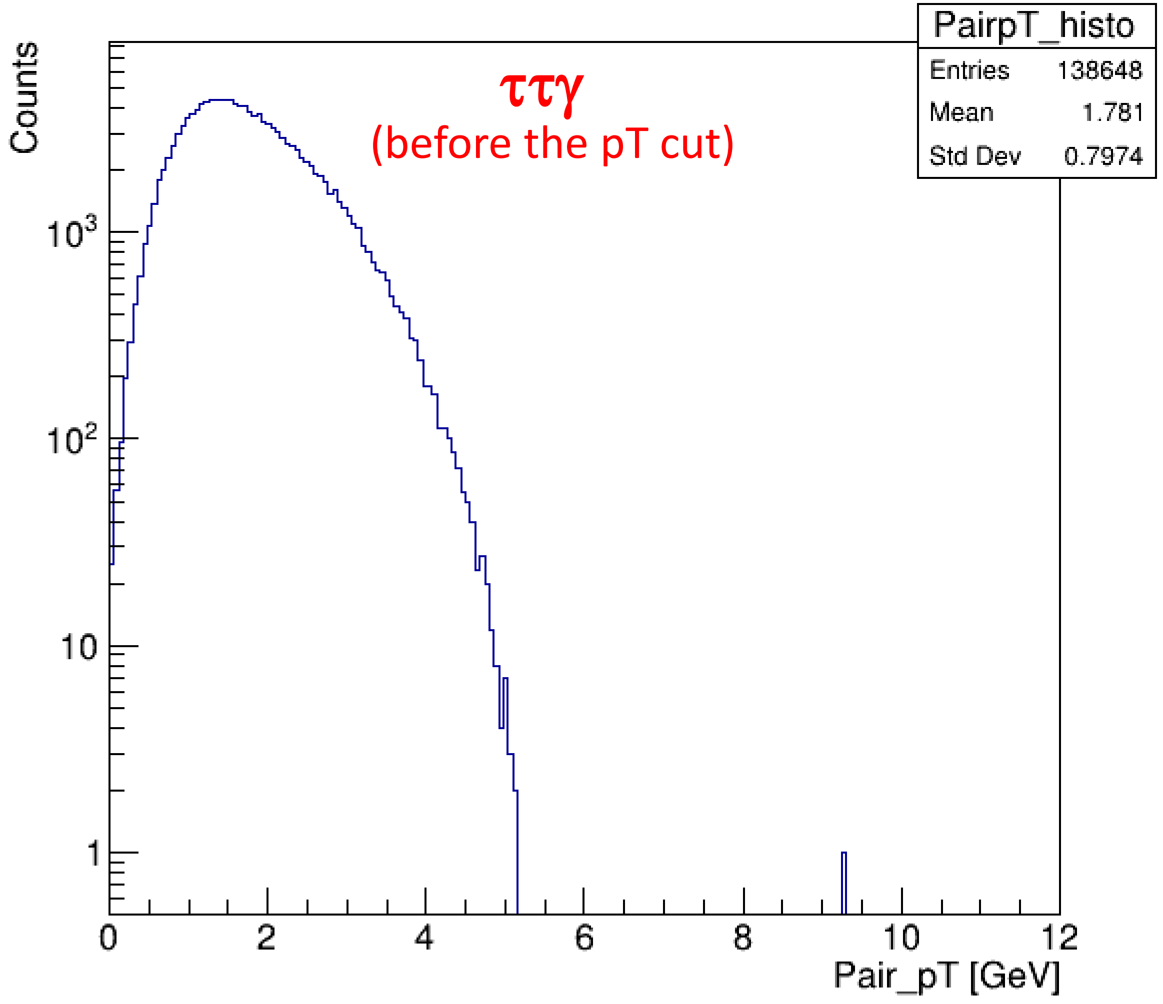


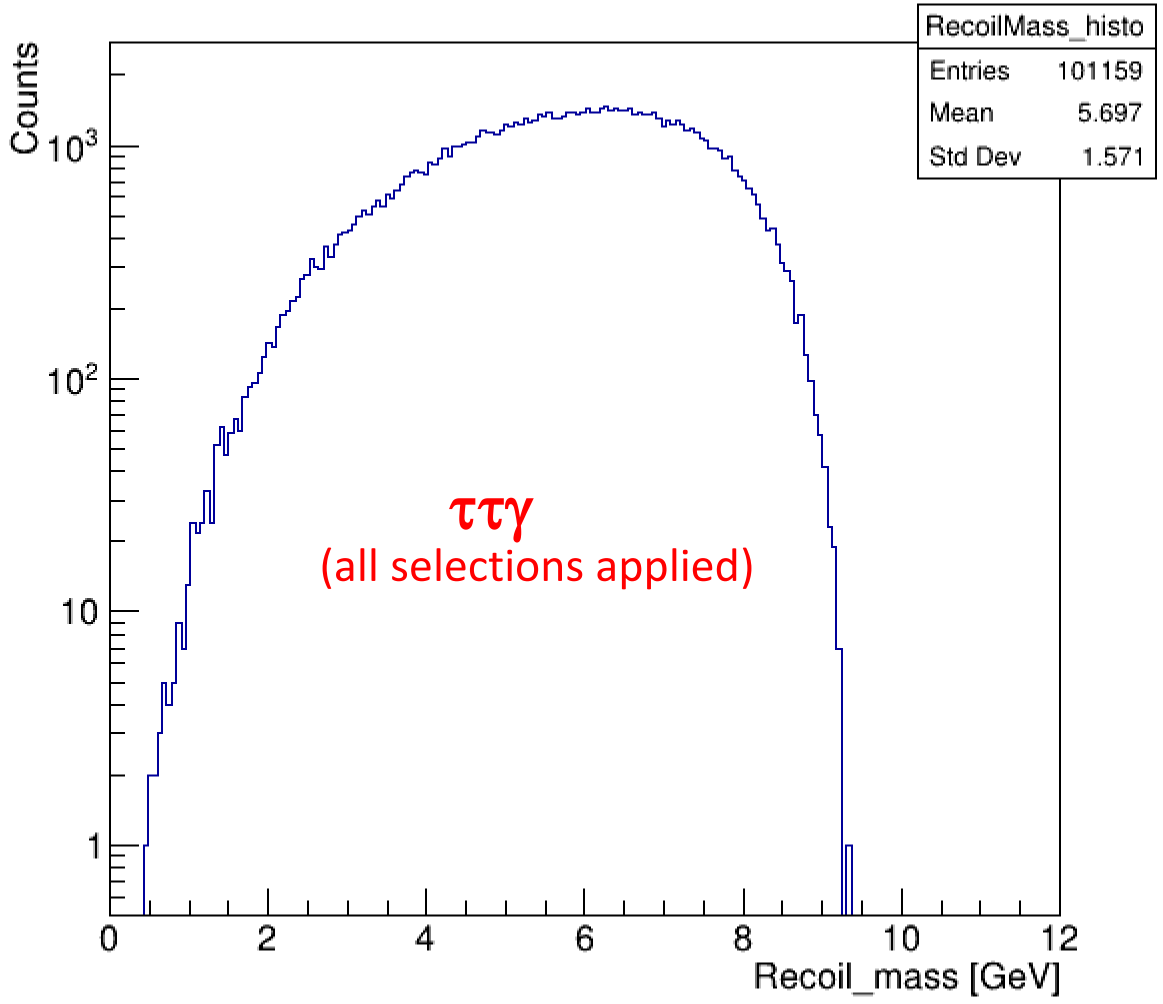


The contribution from the μμγ background is expected here to be much less important, because of the PID. Anyway, we applied all the dedicated selections from the non-LFV Z' search



On the contrary, the contribution from the ττγ background is expected here to be twice the non-LFV one (ττ → μe + eμ)





Conclusions for Z’ FLV

- No results available: interesting already in Phase 2
- Started later, but ramped up quicly due to the experience with the non-FLV Z’
- We are ready to include the $ee\mu\mu$ background
- The Bhabha background should be studied too, because of the PID issues and the huge cross section
- Different (pre)selections will be studied, because production mechanisms are different wrt non-FLV Z’
- The search looks anyway τ background dominated: special anti-τ cuts (other than PID) to be devised
- Sensitivity curves after all this
- Visible channel to be started yet

Lepton ID variables

A caveat

- At this point, I used muonID and electronID variables for lepton selection
- However, these variables compare likelihood of the lepton type with the likelihood of the pion.
- As a sequence, we have lots of muons that has high both muonID and electronID
- “Expert tools” will be implemented in the following iterations of analysis