

# Lepton Jets: Experimental overview and searches at ATLAS

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ATLAS Work with B. Demirkoz (CERN)  
in collaboration with I. Yavin (Princeton)

# Dark Matter Model

- **New theory of Dark Matter motivated by results from PAMELA, ATIC, DAMA et al**
  - **Hides Dark Matter via a small coupling to the SM**
  - **Possibility to directly produce it at colliders**
- **Specific model developed by a Princeton group, collaborated with Itay Yavin for ATLAS MC events**
  - **Kinetic mixing between DM/SM through hypercharge**
  - **M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin: arXiv 0901.0283**
  - **C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin: arXiv 0902.3246**
  - **See Itay's talk for more details**

# Dark Matter Signal

- To explain PAMELA results DM must annihilate primarily to electrons and/or muons

- **No anti-proton excess**

$$\chi\chi \rightarrow \phi\phi \ ; \ \phi \rightarrow e^+e^- / \mu^+\mu^-$$

- **General feature of all models**

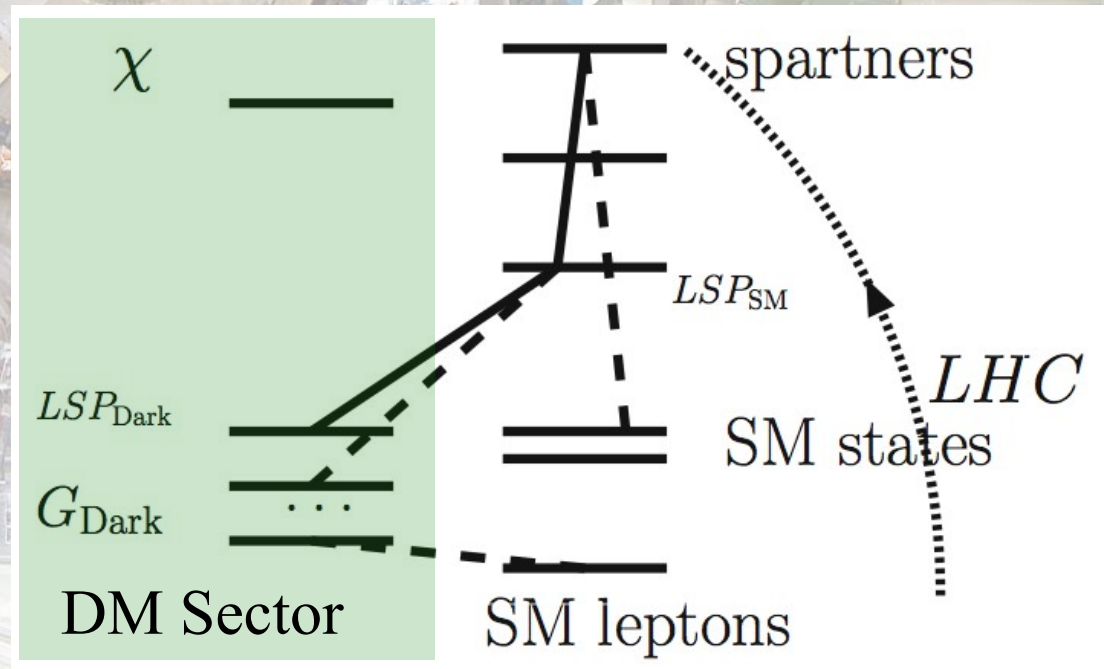
- **Produce dark gauge boson with a light mass ( $\sim 1-2$  GeV/c<sup>2</sup>) which decays mainly to electrons or muons**

- **Result: boosted jets of leptons in the detector**

- **The number of leptons in the jet is model dependent**
- **Jets are generally assumed to be produced promptly but this is not a requirement**

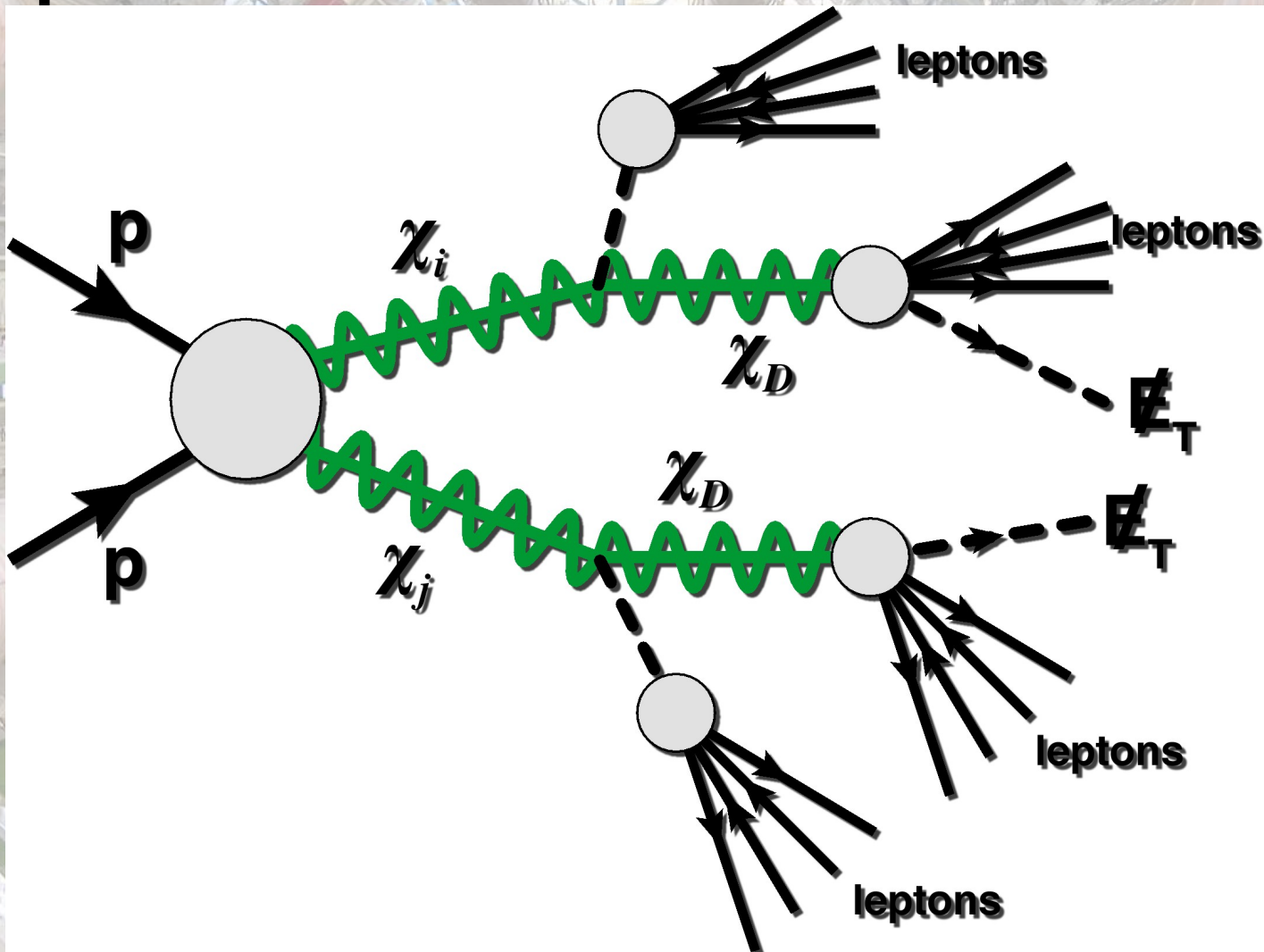
# Supersymmetry

- If SUSY included SM LSP no longer true LSP
  - ▶ Dark sector contains the real LSP
- Result: SUSY “LSP” will decay via DM sector
  - ▶ Multiple dark bosons produced with large boost since “SM” LSP has mass  $> \sim 100 \text{ GeV}/c^2$
  - ▶ Each decays into 2+ e or  $\mu$
  - ▶ Multiple “jets” of leptons



# Supersymmetry

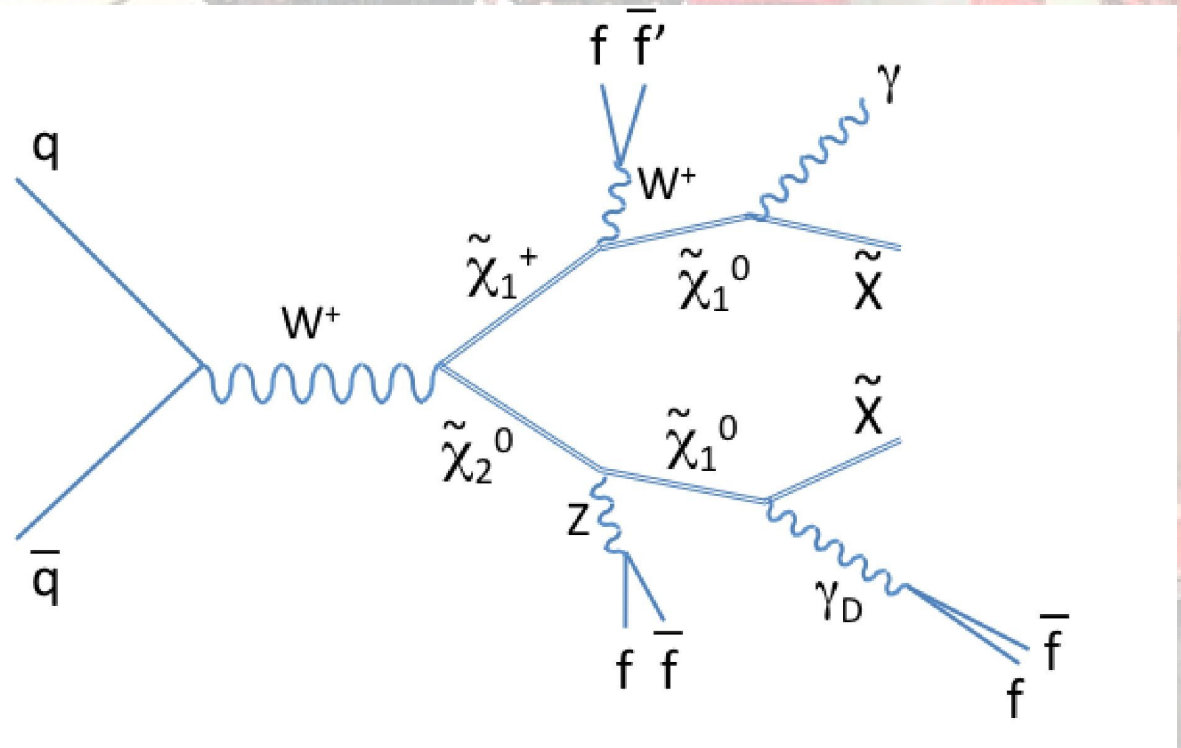
## • Example of SUSY DM event



# Tevatron Results

- DØ has already performed a search for lepton “jets” assuming SUSY
  - ▶ Look for chargino+neutralino production and one dark photon emitted which decays to two leptons
  - ▶ Signature: pair close leptons, gamma and MET
  - ▶ See Andy Haas' talk

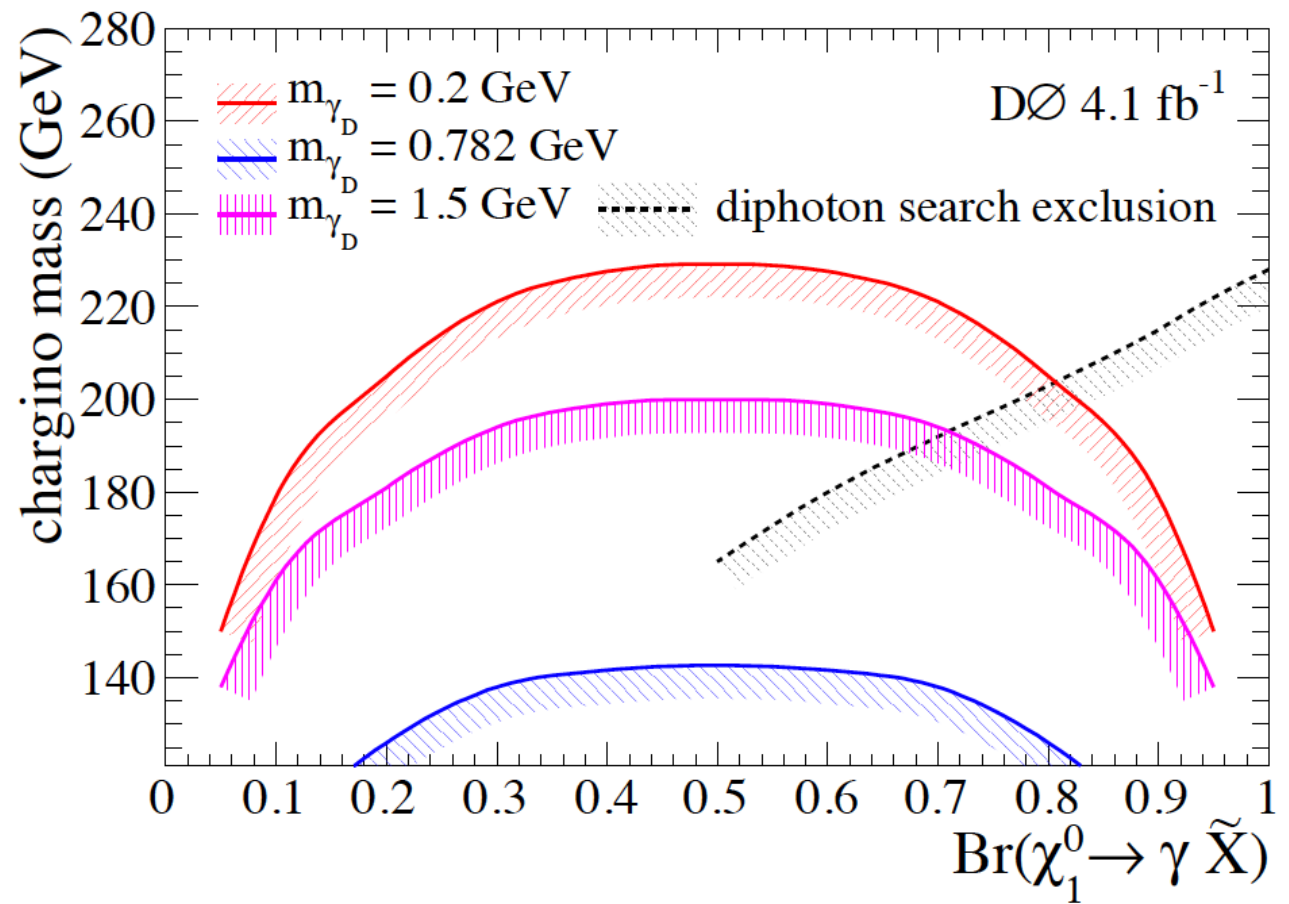
arXiv.org:0905.1478



# Tevatron Lepton Jets

- Analysis uses  $4.1 \text{ fb}^{-1}$  data sample
- No excess of events observed over SM

▶ Exclude chargino mass as a function of the BR of the neutralino



arXiv.org:0905.1478

# Tevatron Lepton Jets

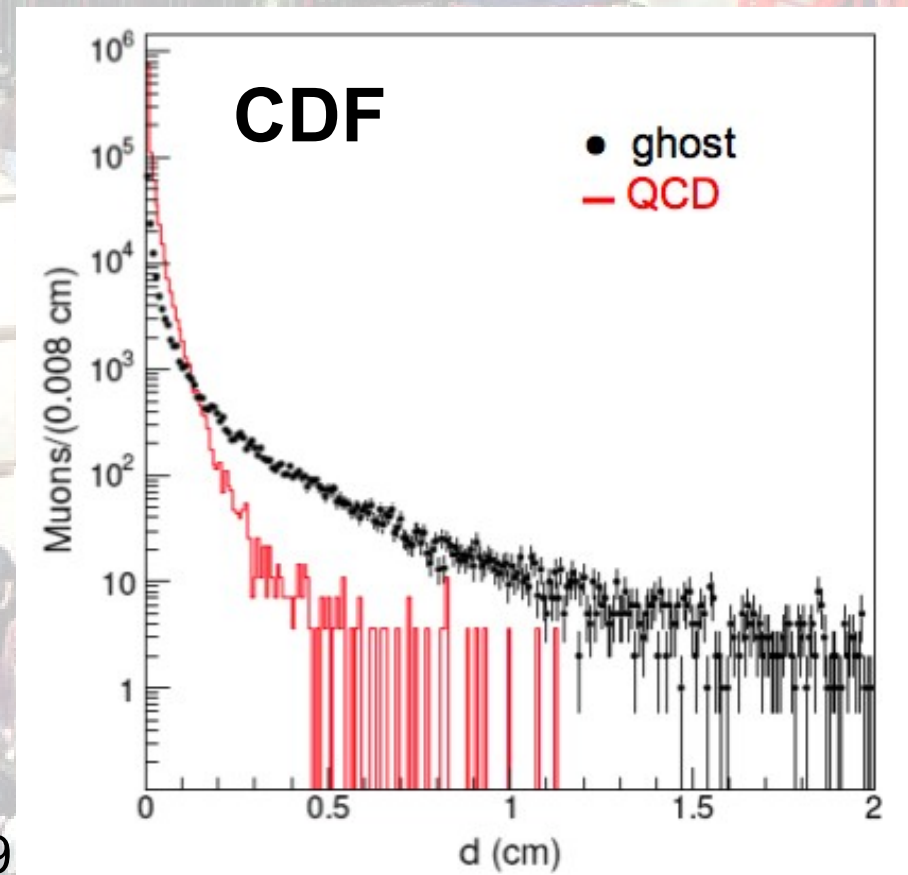
- $D\emptyset$  result is very interesting but avoids issues with many lepton jet models by making simplifying assumptions
- Leptons from dark photon assumed to be very close together
  - ▶ EM clusters fully merged
  - ▶ EM isolation condition applied
- This may/will not work with larger (4+ leptons) or less highly boosted lepton jets
  - ▶ Clusters partially merged: isolation/shape cuts may reduce efficiency substantially



# Tevatron Signal?

- **CDF claim to have observed an excess of muon events with displaced vertices**
  - ▶ Large impact parameters: unlike QCD
  - ▶ High muon multiplicities: 3-4+
  - ▶ Consistent with  $\sigma_{bb}$  discrepancy vs. theory
  - ▶ Excess not explained by  $K/\pi$  decays
- **Not confirmed by DØ with similar analysis**

Fabio Happacher, Aoste 2009



# Supersymmetry?

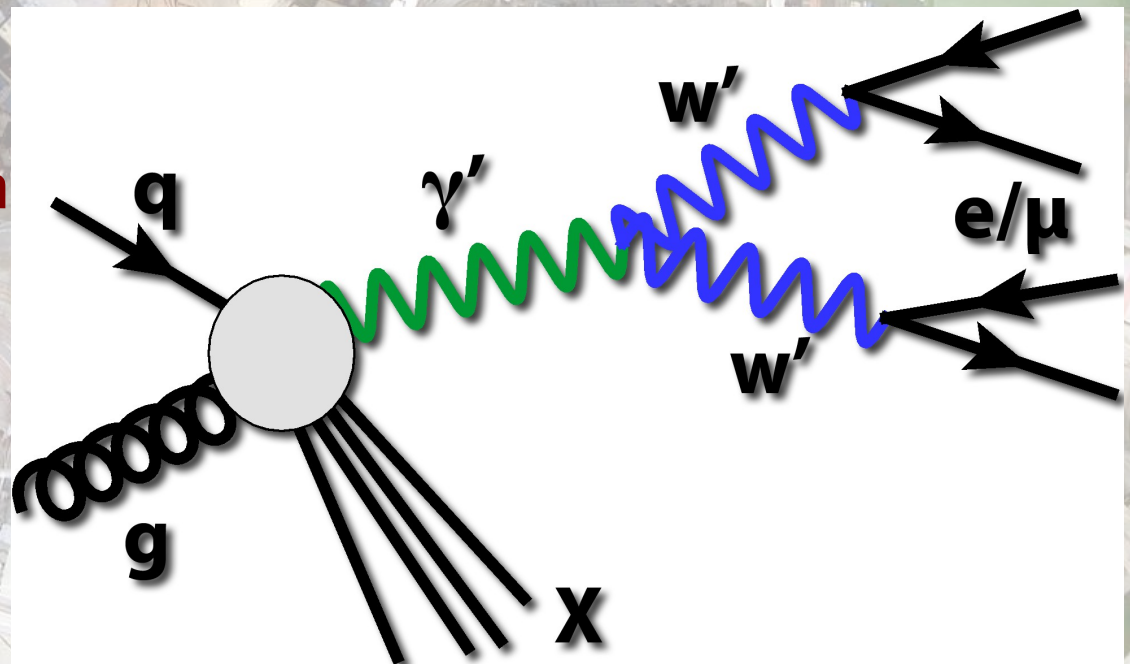
- $D\bar{0}$  analysis also assumes that SUSY exists
  - ▶ Additional assumption on top of DM model
- SUSY events may involve multiple lepton jets
  - ▶ Should be easier to detect than non-SUSY events which contain as few as one lepton jet
- SUSY “SM LSP” has large mass so higher lepton  $p_T$ s will result
  - ▶ Generally easier to detect more highly boosted particles
  - ▶ ...downside is less separation

# Non-SUSY Signal

- Use standard SM photon events + DM mixing
- Produce prompt dark photon recoiling off a quark jet (same as SM photon+jet events)
  - ▶ Decay chain depends on model parameters
  - ▶ Initially study 4 lepton jet model

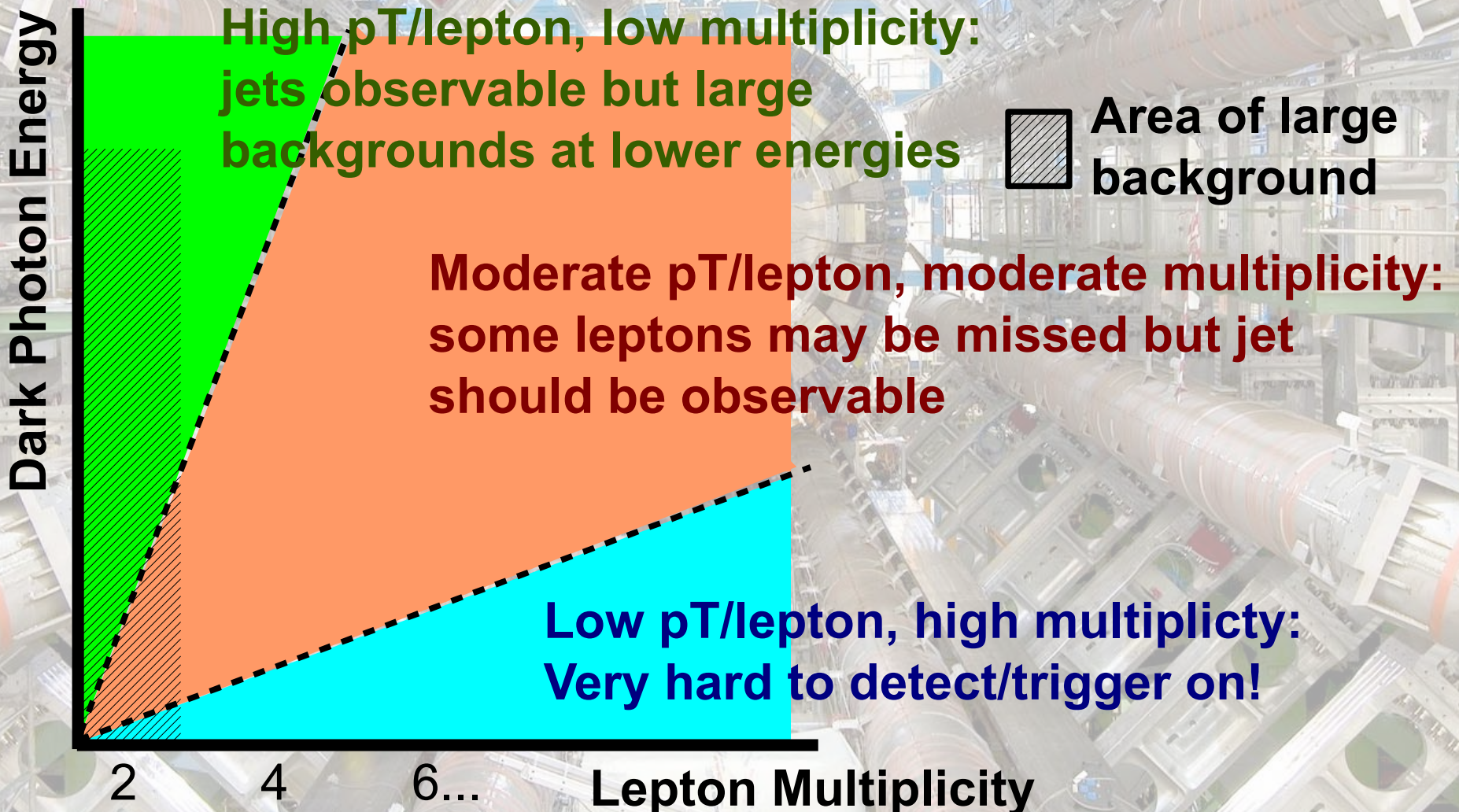
-2-lepton mode will have larger backgrounds from SM and detector effects

-More leptons will make individual leptons softer



# Energy vs. Lepton Number

- Different parameters have different issues...

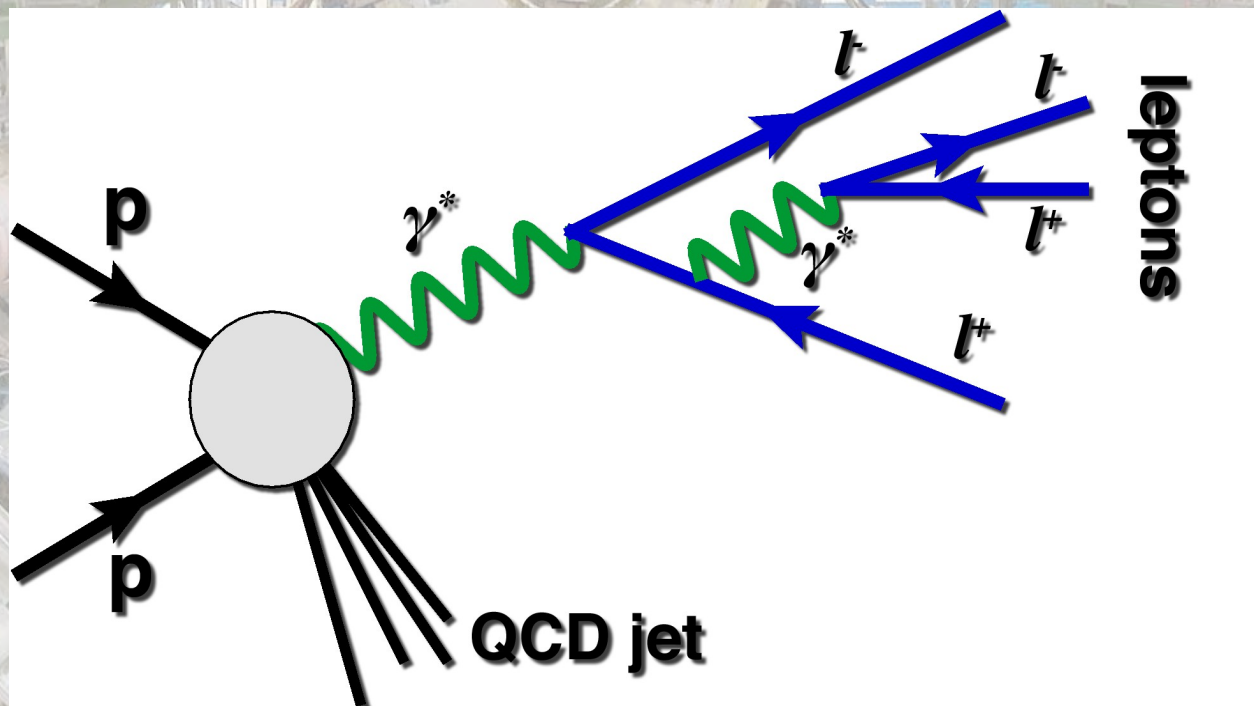


# LHC Lepton Jets

- **Initial impression: lepton jets should be extremely easy to spot at a hadron collider**
  - ▶ **Electrons and muons “easy” to distinguish from high rate QCD backgrounds**
- **...but life is never that easy for experimentalists!**
  - ▶ **Highly collimated nature of the leptons in the jets may cause problems separating them**
  - ▶ **Need moderate  $p_T$  boost to separate from background at LHC e.g. muons make it to muons counters**
    - **Easier at Tevatron: e.g.  $\mu$ 's need  $\sim 3$  GeV/c  $p_T$  at DØ vs.  $\sim 6$  GeV/c at ATLAS to be efficiently reconstructed in the muon counters**
  - ▶ **Long-lived particles have unique additional problems**
    - **Displaced vertices**

# Backgrounds

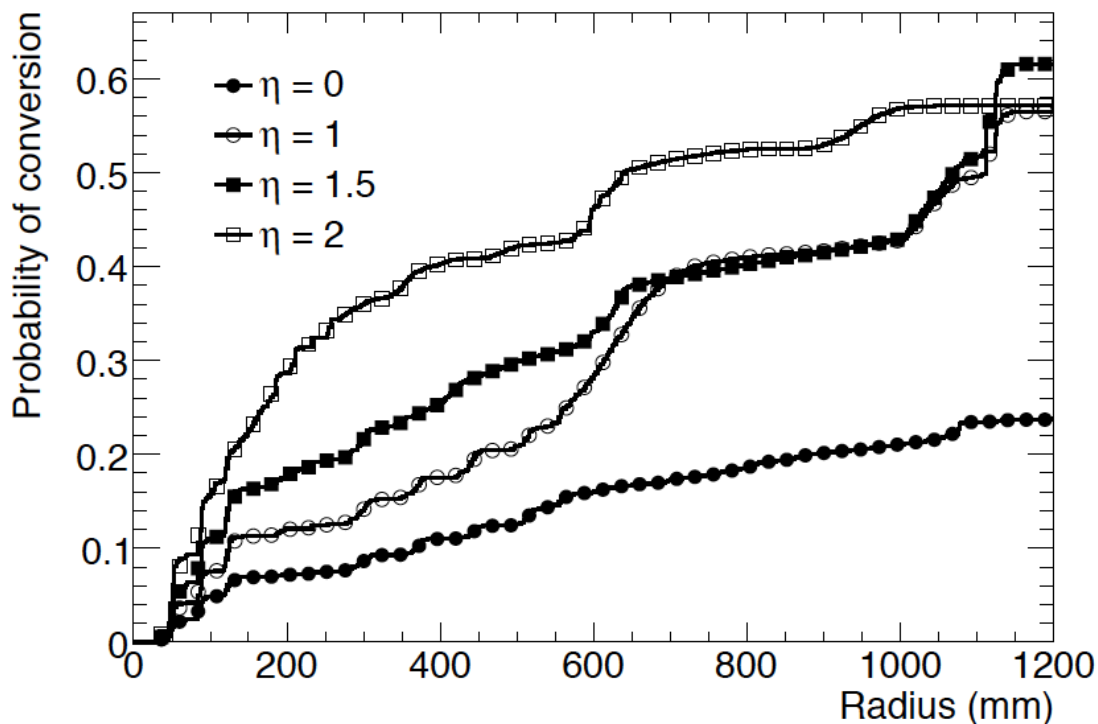
- **Backgrounds expected to be predominantly instrumental in nature**
  - ▶ **Hard to generate SM lepton jets since it requires higher order diagrams for processes with already low cross-sections**



# Instrumental Backgrounds

## • Photon conversion

- ▶ Photons may convert in the material of the beam pipe or first few layers of the tracker
- ▶ Background for both muon and electron jets



Probability of photon  
Conversion for ATLAS

Jinst 3 S08003 (2008)

# Instrumental Backgrounds

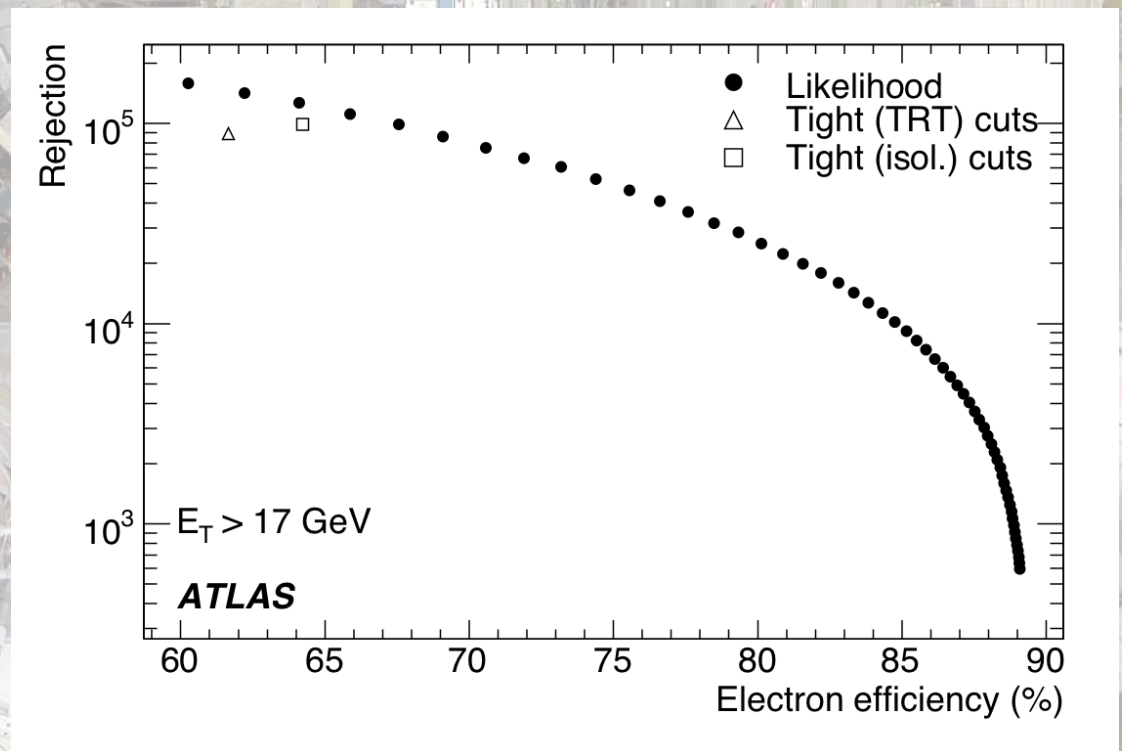
- **QCD jets faking electrons**

- ▶ **Jets with significant  $\pi^0$  fractions can fake electrons due to large EM component**
- ▶ **Fake rate generally reduced by applying EM fraction and shape cuts**
- ▶ **Shape cuts may not work with electron jets since there will be multiple, overlapping EM clusters**
  - **Model dependent: determined by the opening angle and energies of the leptons in the jet**



# Fake Electrons

- Expected QCD jet rejection factor for multivariate electron reconstruction algorithm
  - ▶ With cut based approach jet rejection drops from  $(4.7 \pm 0.5) \times 10^4$  to  $510 \pm 10$  when track and shape cuts are loosened or removed (ATLAS TRT vs. loose electrons)



Jinst 3 S08003 (2008)

# Distilling Dark Matter



- Level 1
- Level 2
- Level 3/  
Event Filter
- Physics  
analysis
- Physics



# Triggering

- Getting lepton jet events past the trigger may not be trivial
  - ▶ Algorithms more primitive than full reco
  - ▶ Limited information available
- L1 trigger is hardest: 40MHz  $\rightarrow$  75-100kHz
  - ▶ Custom-built hardware so not flexible
- L2+L3/EF called “high level trigger” (HLT)
  - ▶ Runs on commodity PC farm hardware
  - ▶ Very flexible but L2 has limited detector data: confined to “regions of interest” (RoI) [ATLAS]
  - ▶ Still need to be careful of CPU time budget

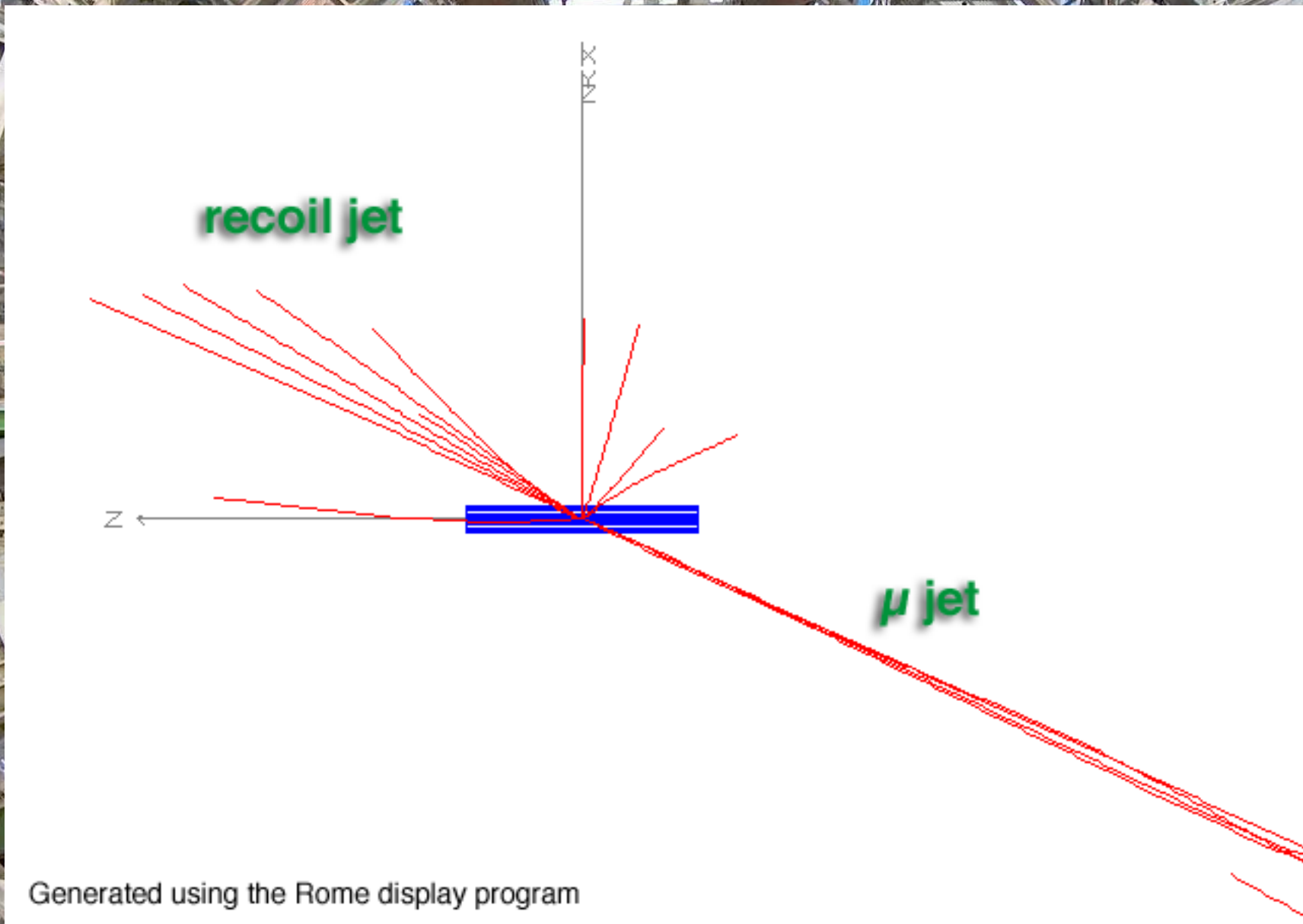
# Prompt Lepton Jets at ATLAS

- Use kinetic mixing model at the basis for our studies (Cheung, Ruderman, Wang, Yavin arXiv:0901.0283)
  - ▶ Work currently performed by Bilge Demirkoz (CERN) and myself but group growing quickly...
- Primary initial goal: ensure lepton jet events will pass the ATLAS trigger
  - ▶ Concentrating on muon signal initially since we expect this to be the easiest to detect
  - ▶ Examining reconstruction efficiencies in tandem
- Use model with 4 leptons/jet
  - ▶ Less background but lower  $p_T$  than 2 leptons/jet

# Monte-Carlo Simulation

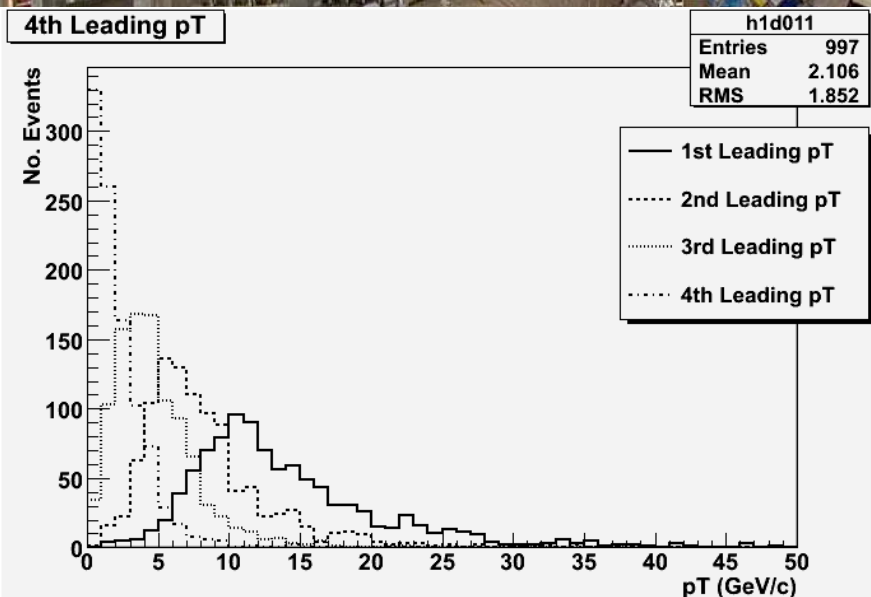
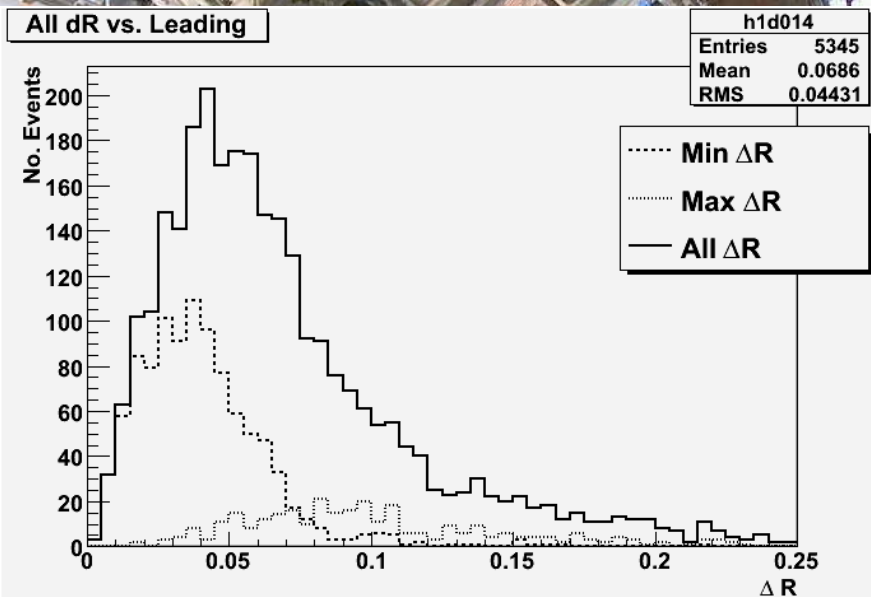
- Use Monte-Carlo event samples kindly pre-generated by Itay Yavin
  - ▶ 4e, 4 $\mu$  and 2e+2 $\mu$  for  $p_T \geq 20$  and 50 GeV/c
- Feed these through the full ATLAS simulation
  - ▶ ATLAS reporting restrictions now in effect as “practice” before real data
    - Cannot show you any plots derived from ATLAS code without a multiple month approval process!
    - Restricted to plots directly from Itay's MC events and plots from the published notes and papers...

# Event Display



Generated using the Rome display program

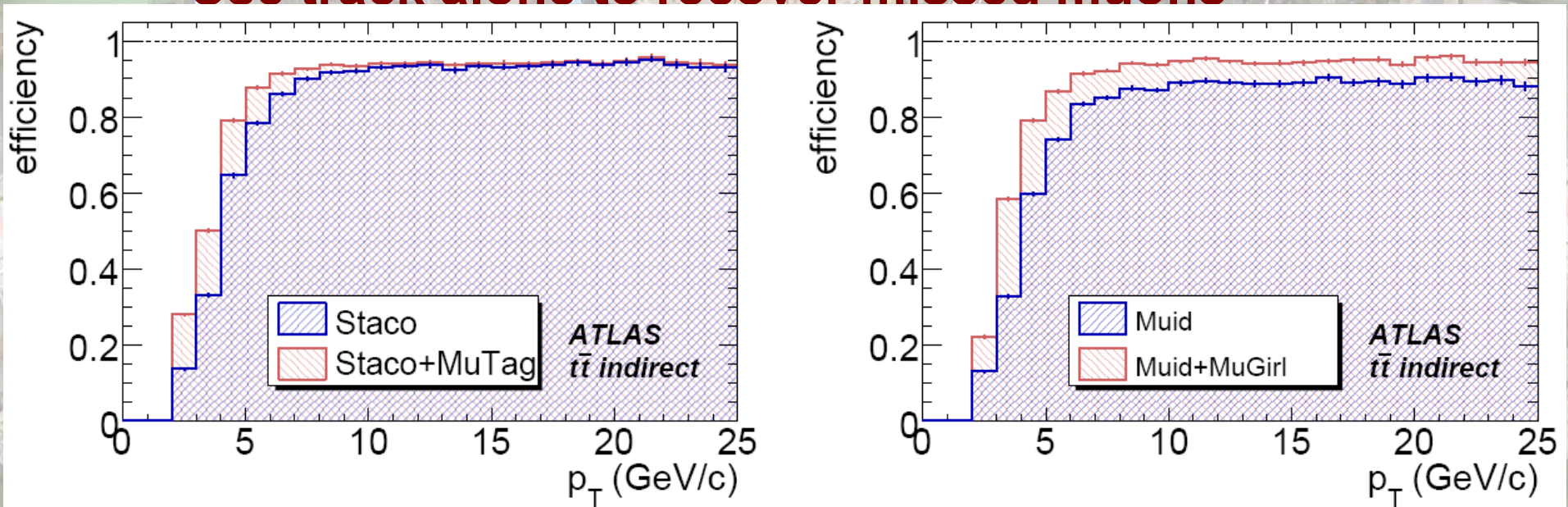
# Monte-Carlo Kinematics



- 4e, 4 $\mu$  or 2e+2 $\mu$  “jets”
- Boosted so small  $\Delta R$ 
  - ▶ Typically  $\Delta R < 0.1$
- 20+GeV/c  $p_T$  shared over 4 leptons
  - ▶ Low  $p_T$  threshold required
- Unique challenge for trigger and reconstruction

# Reconstruction Efficiency

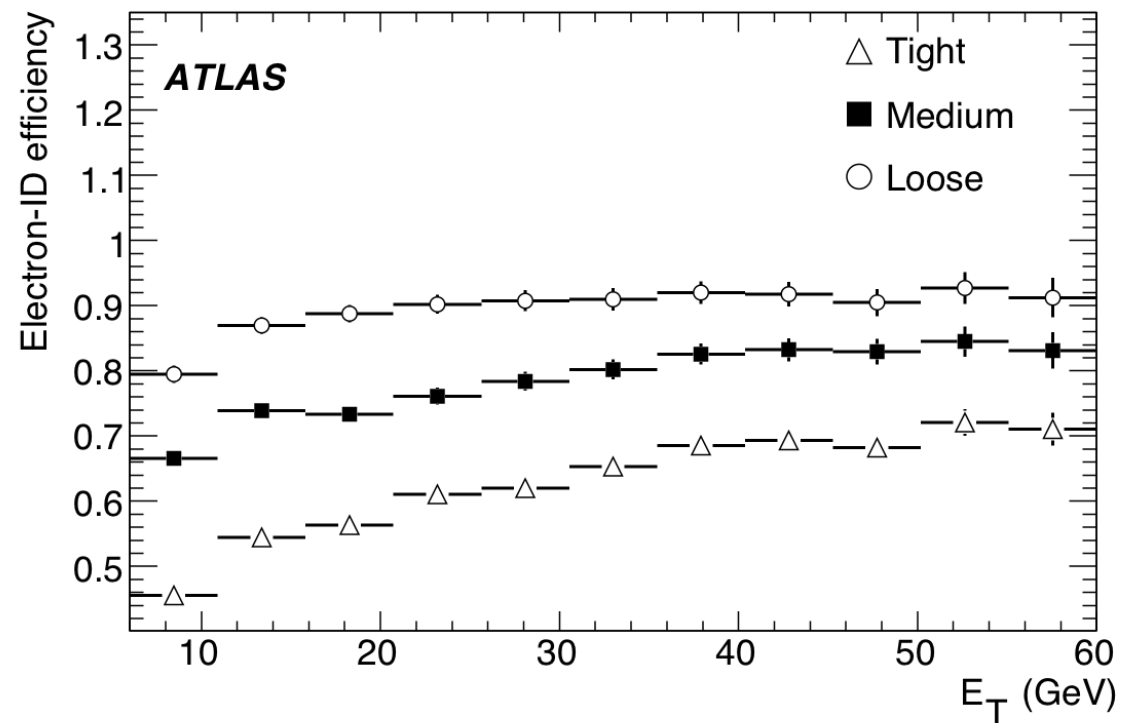
- Should not be a problem for the  $4\mu$  channel
  - ▶ Tracking resolution far better than separation
    - ...but possible issues with multiple hits. Trust MC?
  - ▶ Expect to fully reconstruct 3-4 of the muons
    - May miss one due to very low  $p_T$
    - Use track alone to recover missed muons





# Reconstruction Efficiency

- Electron channel a lot trickier
  - ▶ Electrons close enough that showers will merge
  - ▶ Investigating ways around this
    - Use a new “ring” algorithm being developed
    - Look in the first, extremely fine-grained layer for peaks associated with the start of the shower



# L1 Triggering

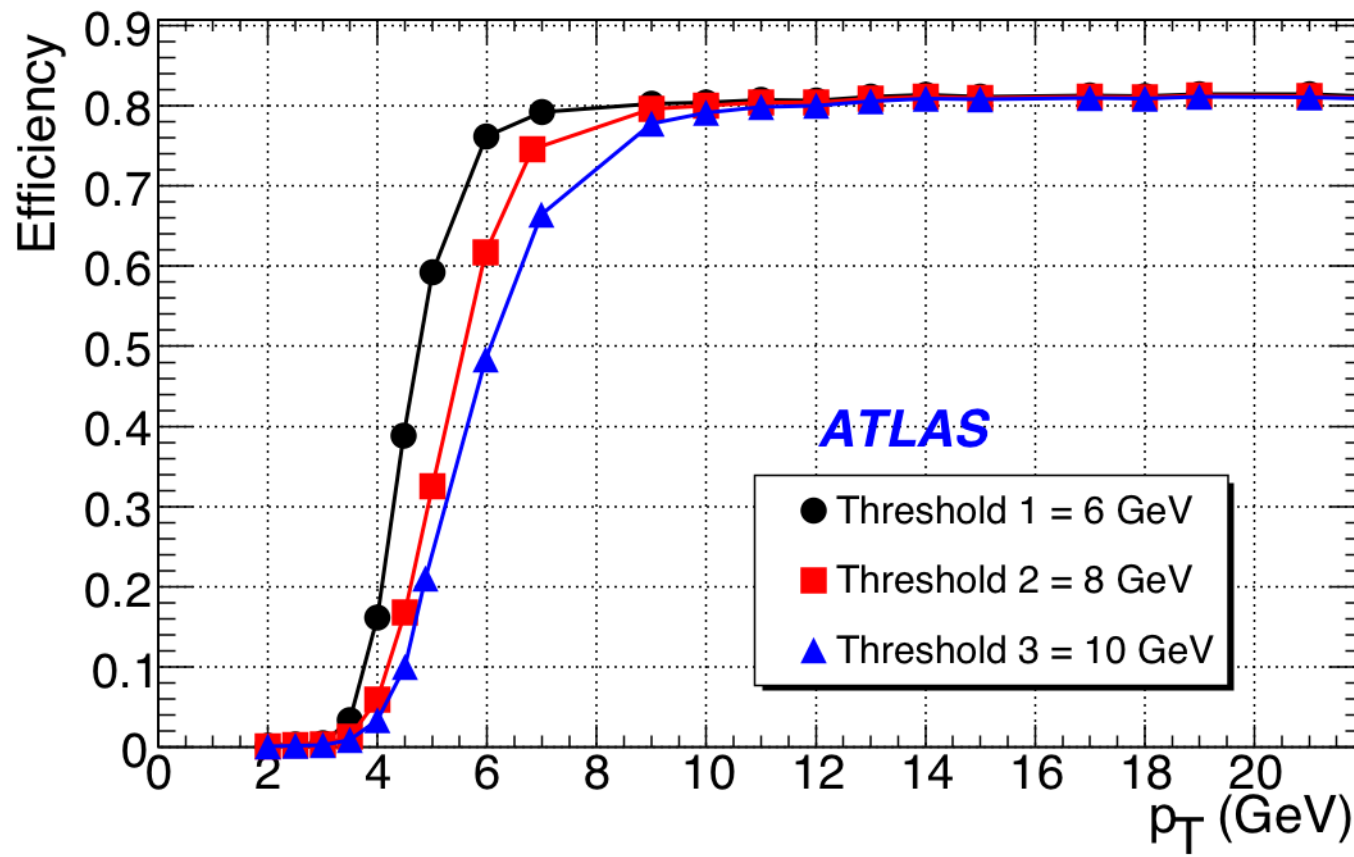
- **Hard to get events past L1 trigger**
  - ▶ No single lepton has large  $p_T$  (leading  $\sim 10$  GeV/c)
  - ▶ Fixed, large “regions of interest” for the muon counters mean that most/all of jet hit single region=one muon to L1 trigger
  - ▶ Merging of coarse EM clusters means that jet merges into 1-2 L1 “EM objects”
- **Use single object, low threshold triggers**
  - ▶ As luminosity increases so will single object thresholds which will impact efficiency
  - ▶ Recoil jet may help a little
  - ▶ Investigating other ideas...

# L1 Trigger Efficiencies

- L1 muon trigger efficiencies for barrel region
  - ▶ End cap region shows similar results

Only one muon needed to fire this trigger:  
compare to lead muon  $p_T$

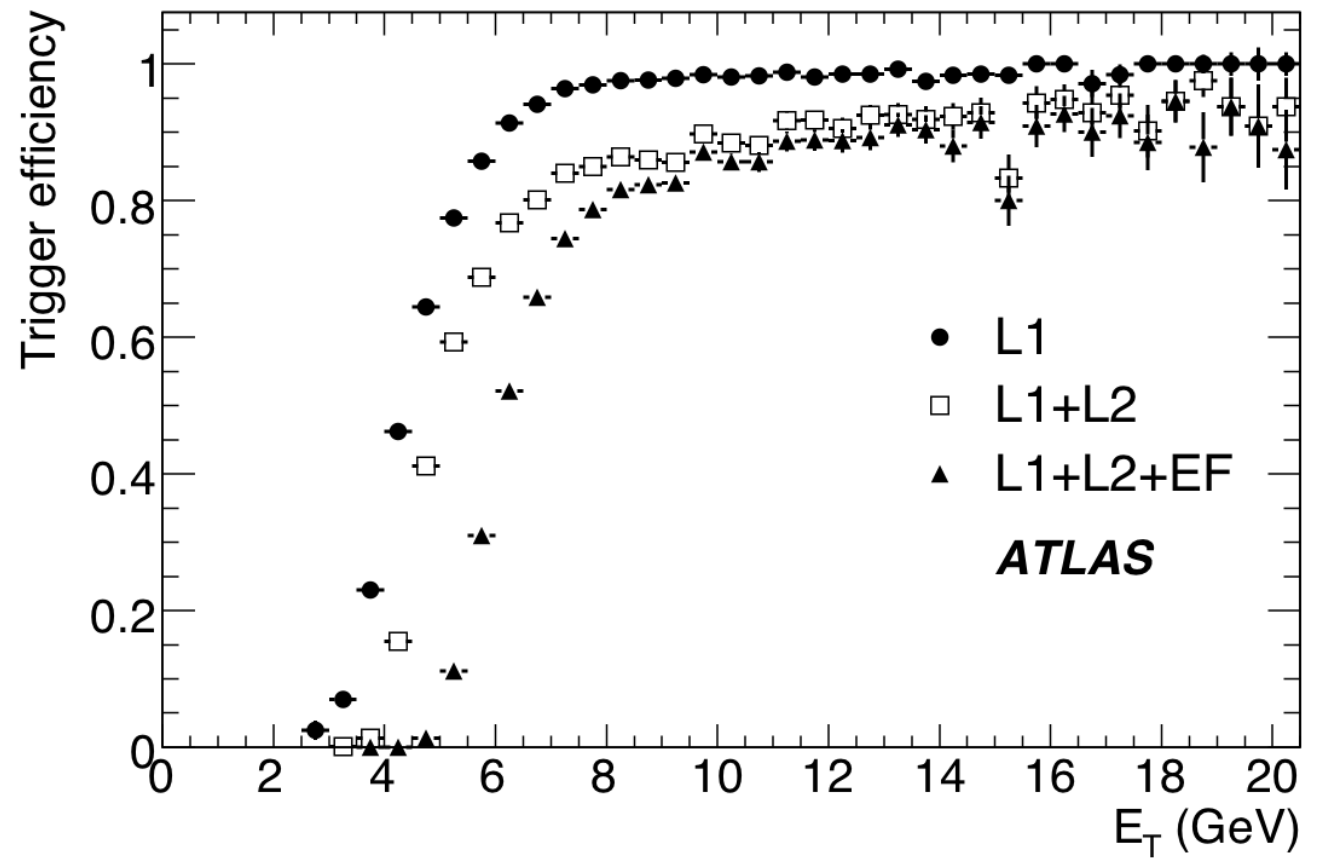
ATLAS Trigger  
CSC Note



# L1 Trigger Efficiencies

- Trigger efficiency for 'e5' ATLAS trigger
  - ▶ Measured using  $J/\psi$  decays to electrons

– Very similar to electron lepton jets!



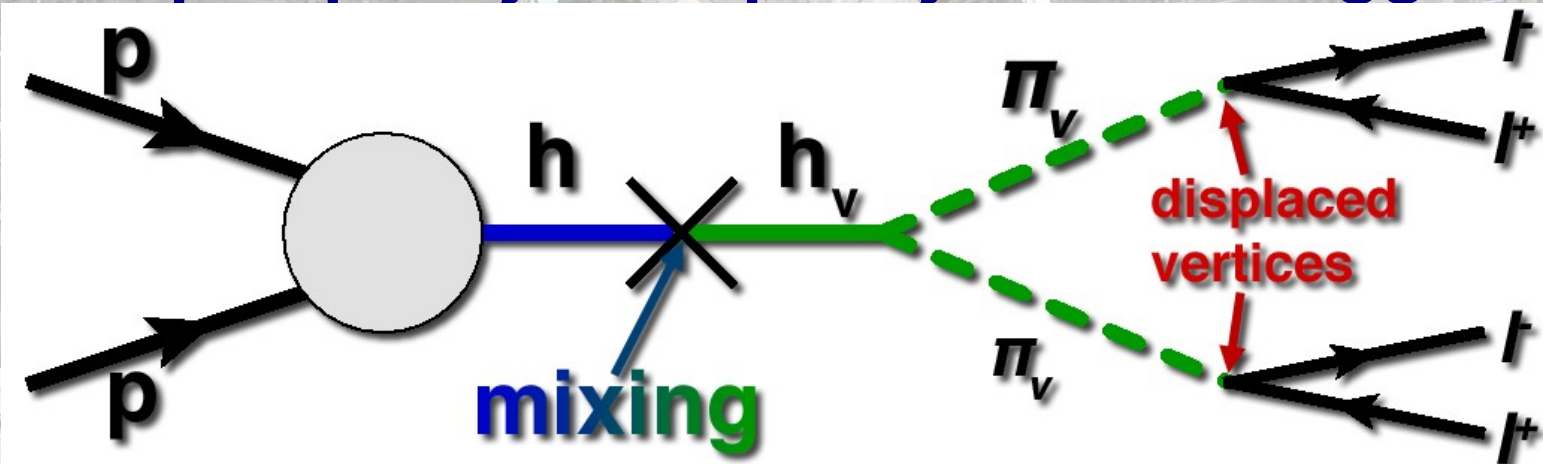
ATLAS Trigger  
CSC Note

# High Level Trigger

- **HLT can use event topology**
  - ▶ **Require leptons to be close together**
- **Tracking available**
  - ▶ **Require hits in tracker layers close to beam to reduce photon conversion background**
- **QCD jets faking electrons will bite here**
  - ▶ **Tune existing shape cuts for electron-jets**
  - ▶ **Investigating ideas for new algorithms using the fine-grained calorimeter layer**
  - ▶ **Very preliminary stages...**

# Displaced Vertex Lepton Jets

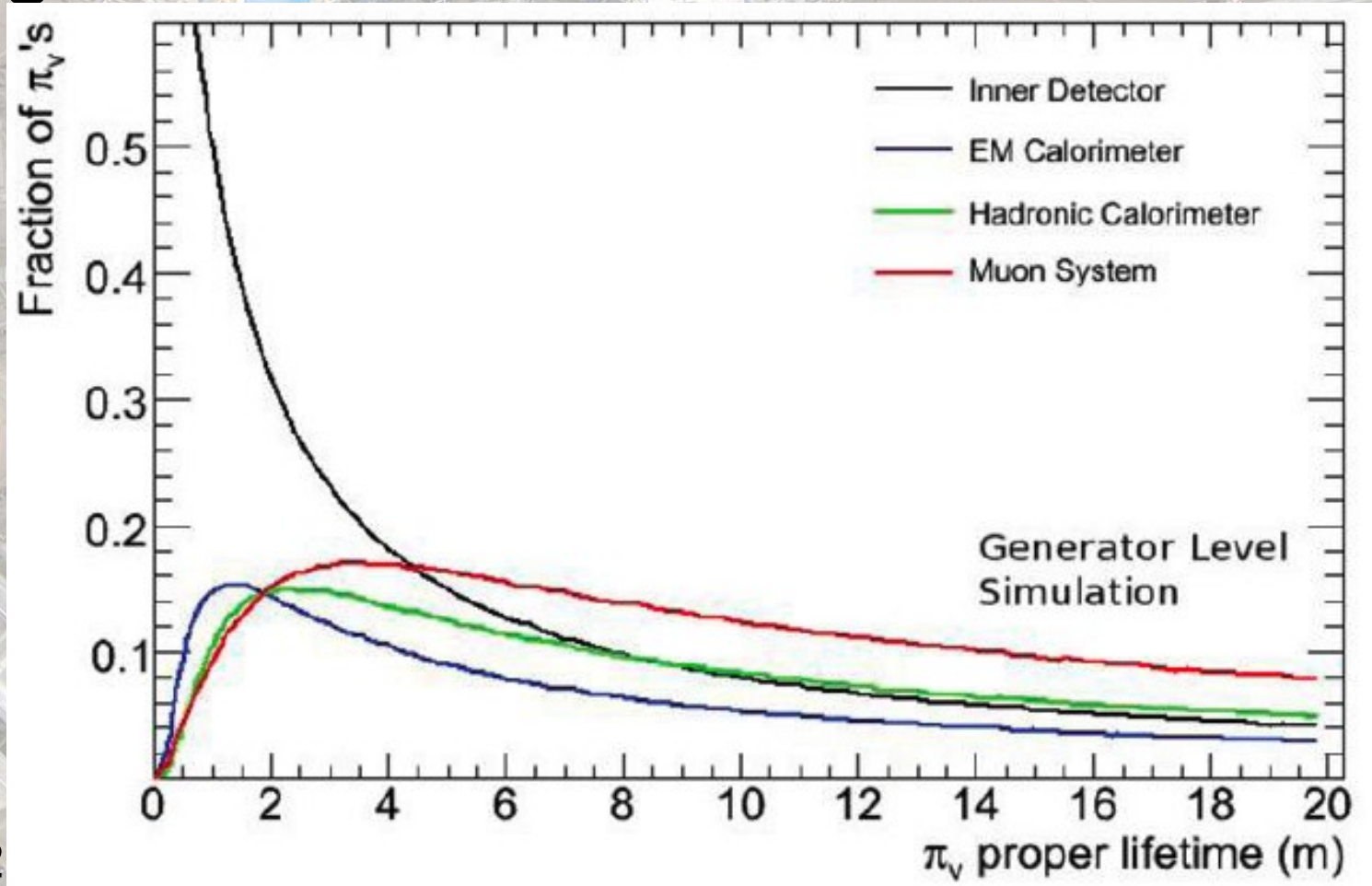
- Consider lepton jets from long-lived particles
  - ▶ Model used assumes a larger boost than for prompt lepton jets: lepton jets from Higgs decay



- Signature: lepton jet in middle of detector with no tracks coming from interaction point
  - ▶ Triggers generally designed to expect particles from interaction point: challenge to trigger on

# Displaced Vertex Lepton Jets

- Decays will occur throughout the detector depending on the lifetime



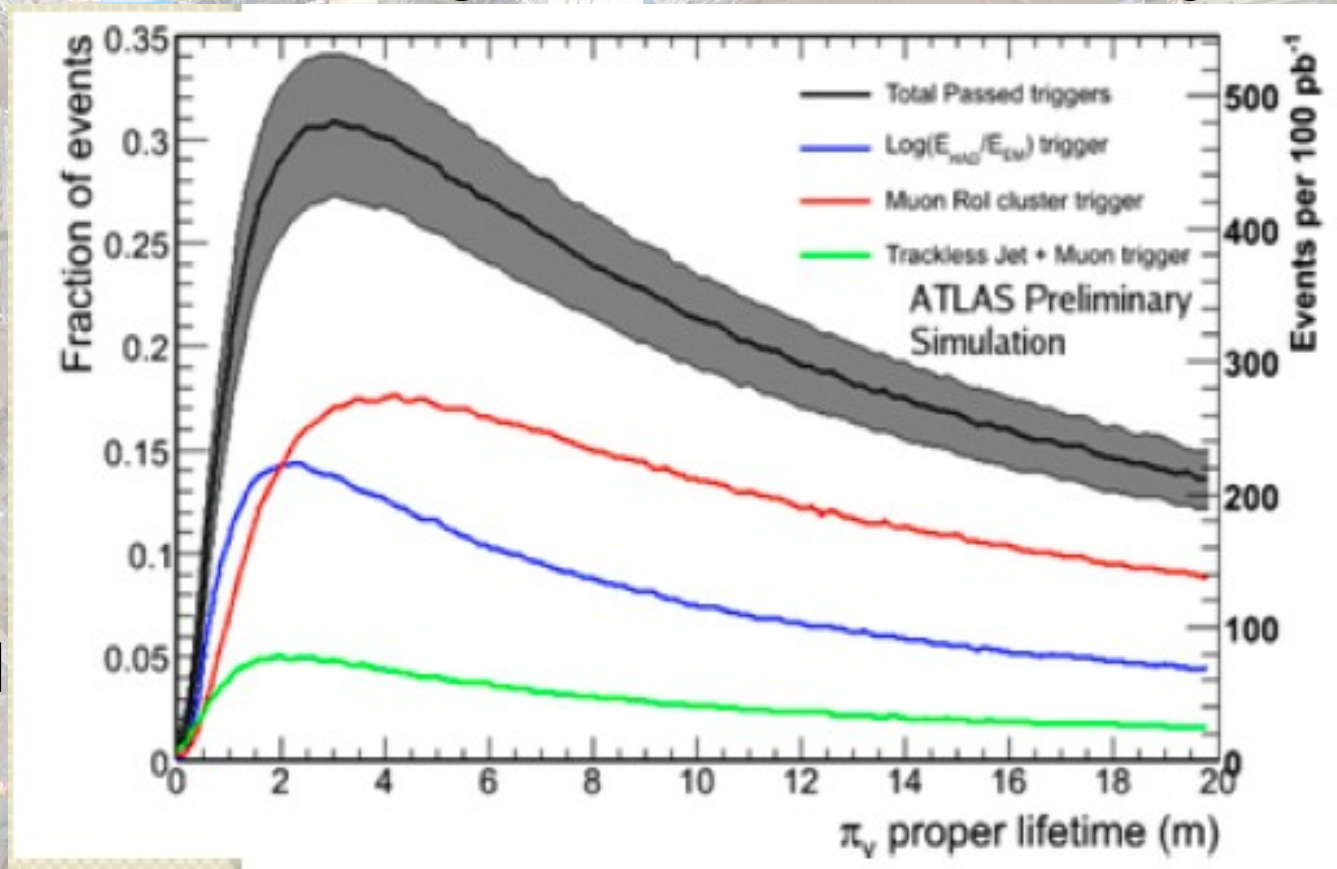
ATL-PHYS  
PUB-2009-082

# Displaced Vertex b-Jets

- Custom trigger algorithms allow for high trigger efficiencies: study performed for b-jets

- ▶ Backgrounds expected to be low based on analysis of 3M min. bias MC events

- Strategies being developed for other long-lived particle models



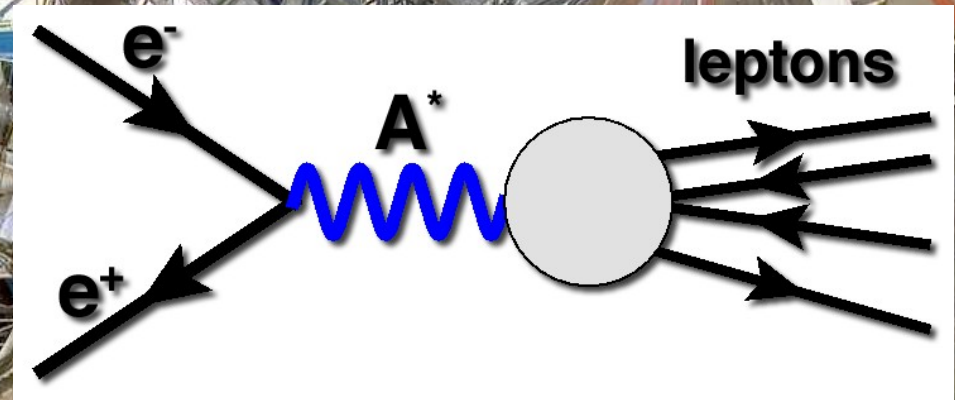
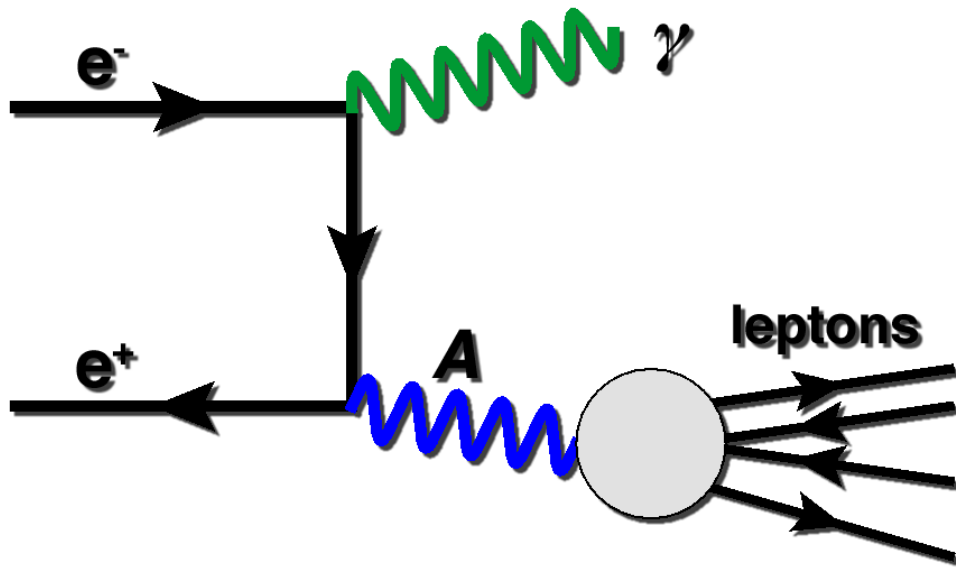
ATL-PHYS PUB-2009-082



# B Factories

- Lepton jets are low mass states needing high luminosities to produce sufficient events
  - ▶ Should be accessible at B factories ( $m < 10 \text{ GeV}/c^2$ )
- Detailed discussion of the production modes and signatures using U(1)<sub>d</sub> mixing model in
  - ▶ R. Essig, P. Schuster, N. Toro arXiv:0903.3941
- Two main production modes
  - ▶ Off-shell dark boson
  - ▶ On-shell dark boson plus photon
- Decay depends on model parameters

# B Factories



- **Signature 4+ leptons (+photon)**

- ▶ **Note: in virtual case lepton “jet” will be split back-to-back to conserve momentum**

- **Babar currently performing such an analysis**

- ▶ **No public results yet...**

# Conclusions

- **Most general analyses in their early stages**
  - ▶ **DØ result a first...but restrictive assumptions**
  - ▶ **Predicted performance hard to judge since backgrounds and reconstruction issues not yet well understood**
- **Golden opportunity for Tevatron and B Factories to produce first, “general” analyses**
  - ▶ **2009/10 physics run of LHC will deliver far less luminosity than Tevatron Run II dataset + less well understood detectors and machine**
  - ▶ **CoM energy is not a big advantage for non-SUSY events: integrated luminosity is more important**

# Conclusions

- **LHC analyses still in very early stages**
  - ▶ **Prompt muon channel looks very promising**
  - ▶ **Electron channel still has unknowns regarding QCD backgrounds which need to be resolved**
  - ▶ **Displaced vertex studies currently indicating very good trigger efficiencies out to large radii**
  - ▶ **J/Ψ decays offer chance to study lepton jet performance with real data...once we get it!**
- **Hope to see more new results from Tevatron and Babar within the next year**
  - ▶ **...with LHC results following shortly after**