

QED Backgrounds at Missing-Momentum Fixed-Target Experiments

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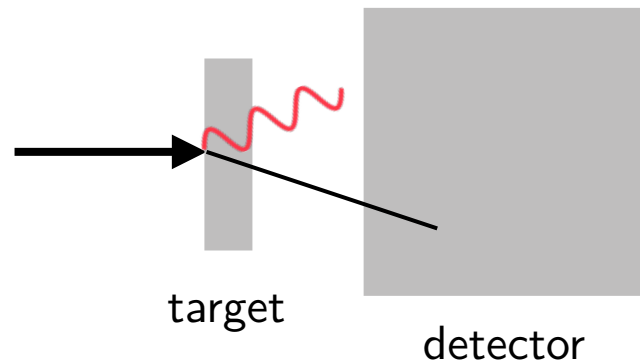
University of Bonn, October 1, 2026



Standard Model Bremsstrahlung

In a target of thickness T , many photons are produced with $\omega_\gamma \sim E_{\text{beam}}$

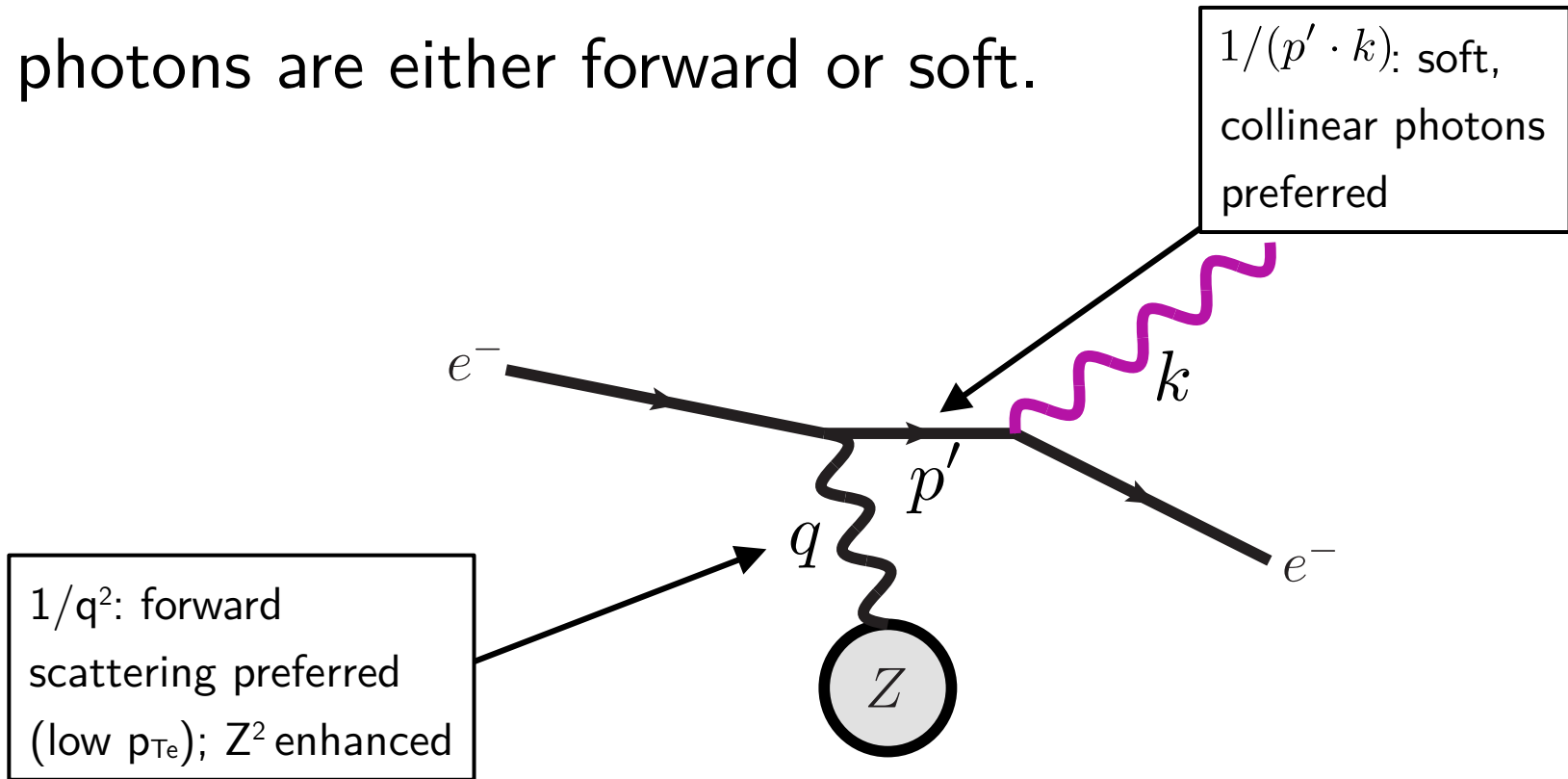
$$N_\gamma \sim \frac{T}{X_0} N_{\text{EOT}} = 10^{13} \frac{T}{0.1 X_0} \frac{N_{\text{EOT}}}{10^{14}}$$



For background-free searches: missing momentum experiments must be incredible photon vetos

Kinematics

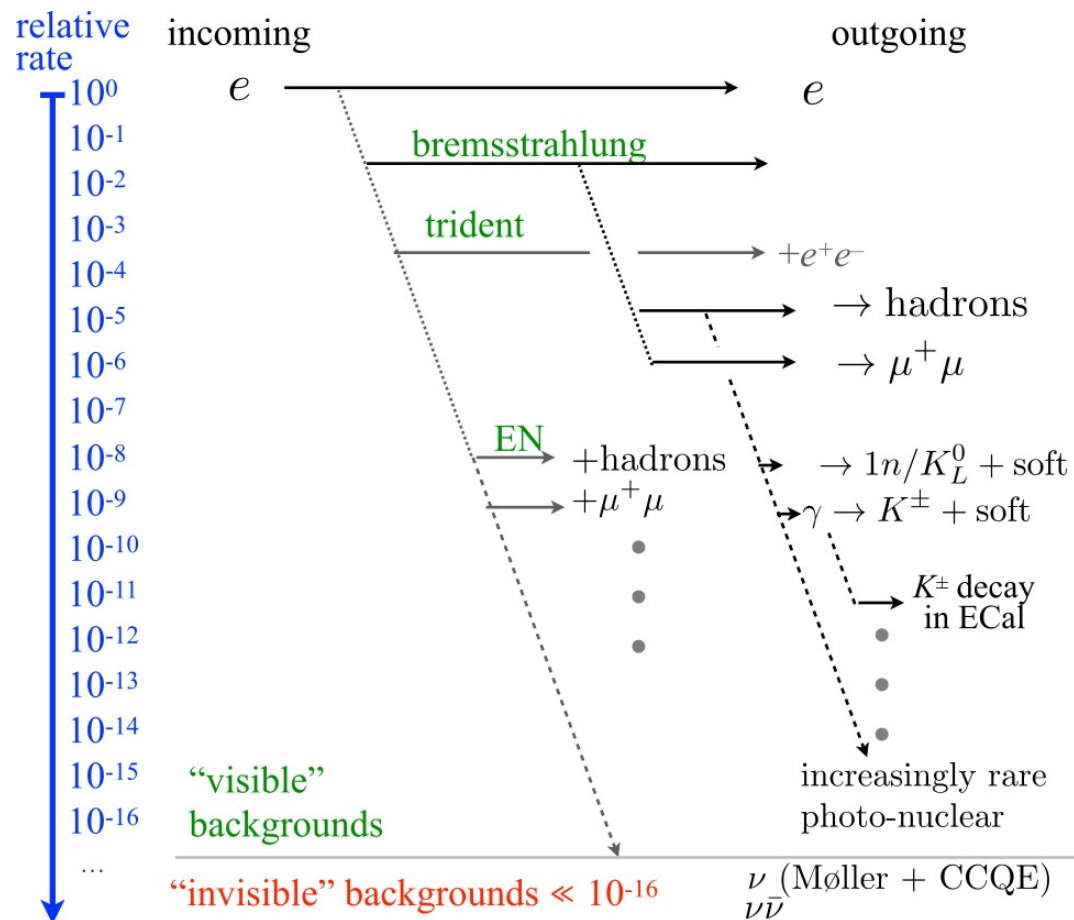
Kinematic singularities mean that the vast majority of photons are either forward or soft.



But rare hard, wide-angle emissions still possible.

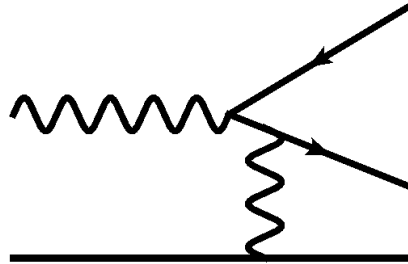
QED vs Photonuclear Backgrounds

Most challenging backgrounds are photon-induced, rather than pure QED



Conversion Backgrounds

Brem photons convert into muons in the ECal



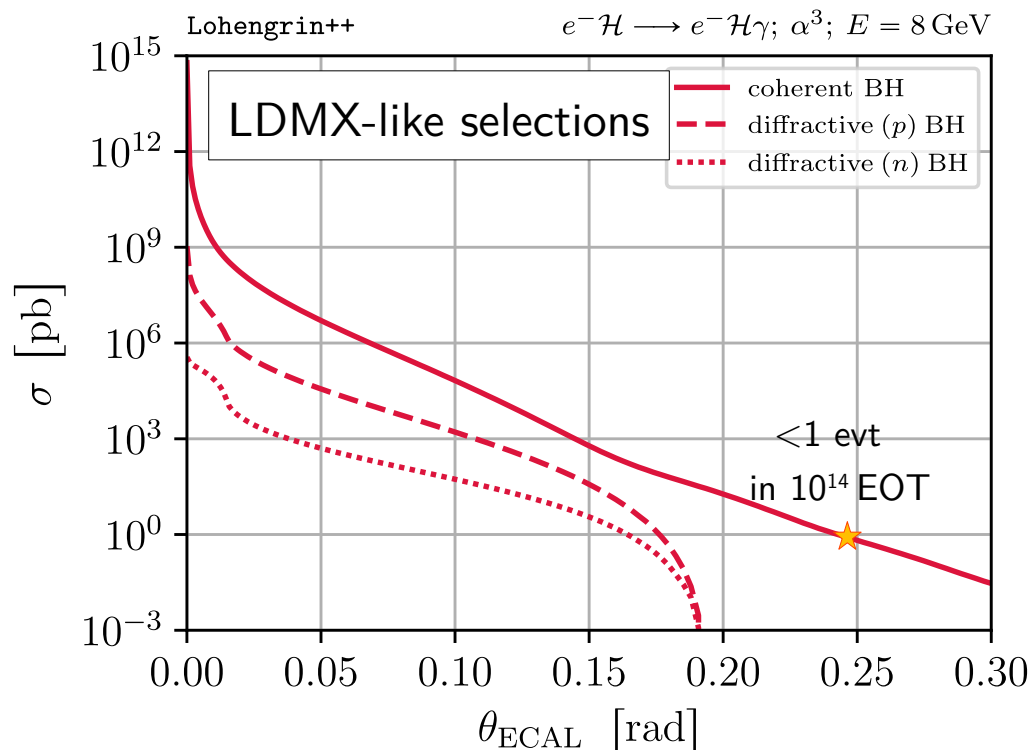
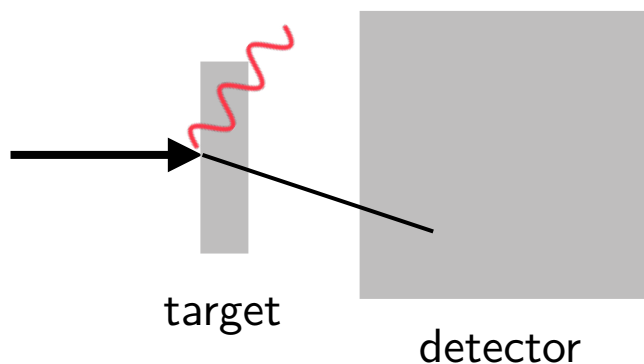
Reject using information from ECal

2604.14359 (LDMX)

	Muon photoproduction	
	Target	ECal
EoT equivalent	1.00×10^{15}	1.00×10^{14}
Trigger (front ECal energy < 3160 MeV)	4.56×10^6	1.47×10^7
Total ECal energy < 3160 MeV	3.46×10^6	1.02×10^7
Single track with $p < 2400$ MeV	16101	9.86×10^6
Missing-momentum ECal BDT	< 1	< 1
Main HCal energy > 4840 MeV	< 1	< 1
HCal Containment requirement	< 1	< 1
Visibles BDT	< 1	< 1

Wide-angle emissions

The differential distribution still allows for high energy, high- p_T photons



Schürmann, Dreiner & Gauld (2606.20327)

One of the main ECAL/HCAL geometry factors

See 2508.11833 (LDMX) for a comprehensive discussion

Other QED Processes

- Wide angle electron scattering (no photon): requires large momentum transfer to nucleus $\rightarrow$ secondary hadrons
- Wide angle electron scattering + brem: features of both previous processes

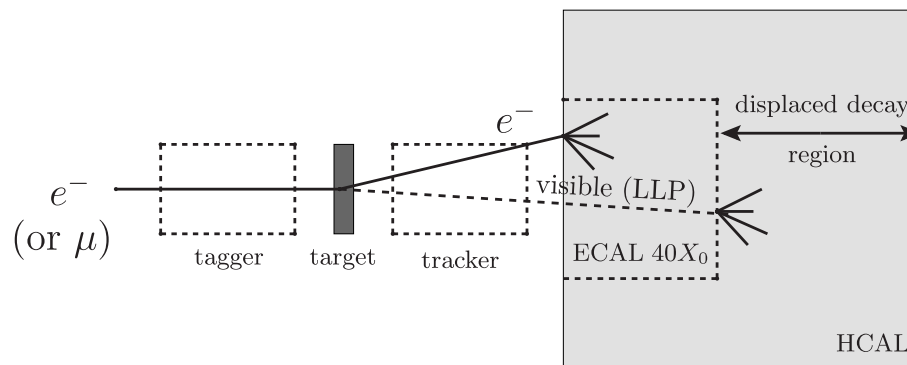
2508.11833 (LDMX)

Process	σ [pb]	Events per 1×10^{16} EoT
WAB	364.5 ± 1.6	$5.93 \times 10^5 \pm 35.2$
WASB	363.12 ± 1.7	$5.90 \times 10^5 \pm 37.4$
WAS	459456 ± 510	$7.38 \times 10^8 \pm 1.1 \times 10^4$

Backgrounds for Visible Searches

- Many of the same processes can be backgrounds for visible (long-lived-particle) searches

1807.01730 (Berlin, NB, Krnjaic, Schuster & Toro)

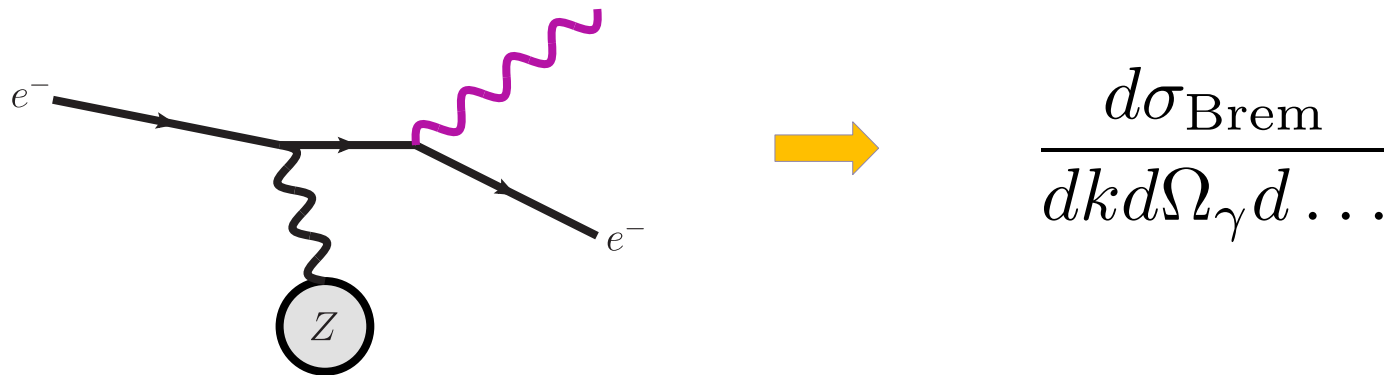


- QED-only: late-converting photons suppressed by requiring sufficiently-displaced energy deposition

$$N_\gamma \sim 0.01 N_{\text{EOT}} e^{-7T_{\text{shield}}/9}$$

Simulating QED Processes

No problem in principle: QED is perturbative, relatively small phase space



Challenge: slow MC for peaky, moderately-dimensional integrands.

Off-the shelf codes typically use many approximations

Bremsstrahlung

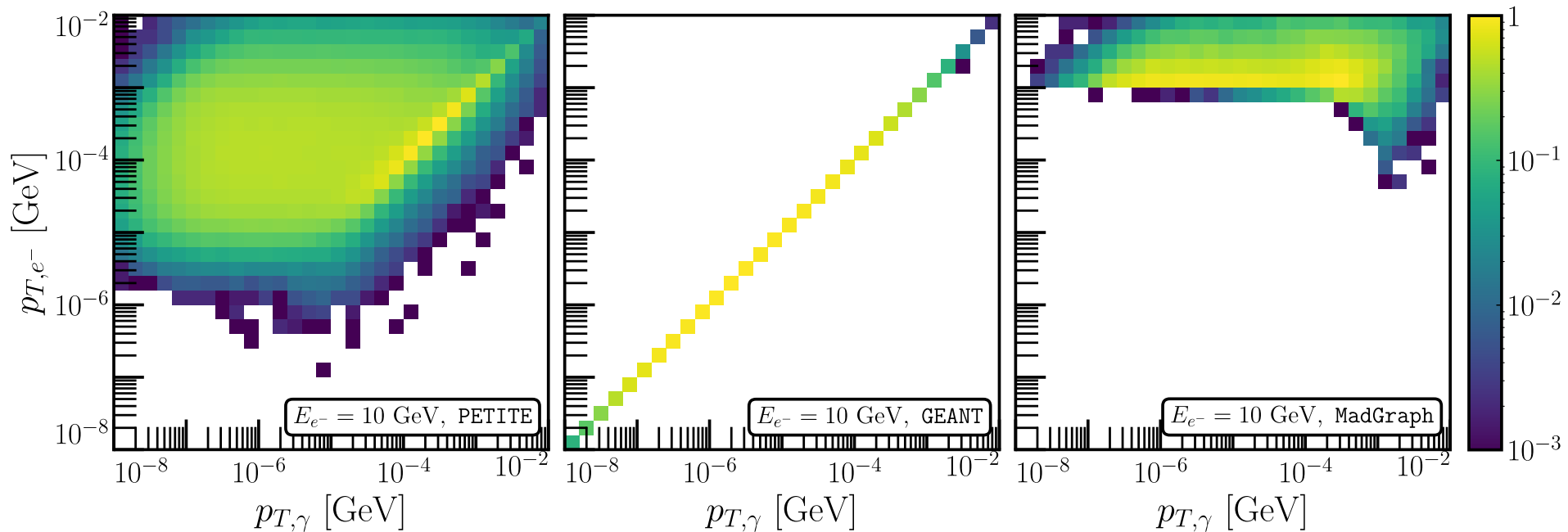
- 5D dimensional phase space (different for each incoming energy)
- Brute-force sampling using VEGAS:
seconds/minutes *per event*
- Need to do this many times per EOT

Common approach: use marginalized distributions (1D for photon energy and angle)

Simulating SM Bremsstrahlung

Let's compare different implementations of

$$\frac{d\sigma_{\text{brem}}}{dE_\gamma dp_{T,\gamma} dp_{T,e}}$$



2401.06843 (NB, Fox, Kelly, Machado & Plestid)

What's going on?

What's going on with SM Bremsstrahlung?

The full differential cross-section looks like

$$d\sigma \propto \delta\delta' \times \left\{ \frac{\delta^2}{(1+\delta^2)^2} + \frac{\delta'^2}{(1+\delta'^2)^2} + \frac{\omega^2}{2\epsilon\epsilon'} \frac{\delta^2 + \delta'^2}{(1+\delta^2)(1+\delta'^2)} - \left(\frac{\epsilon'}{\epsilon} + \frac{\epsilon}{\epsilon'} \right) \frac{\delta\delta' \cos \phi}{(1+\delta^2)(1+\delta'^2)} \right\}$$
$$\delta \sim p_{T,\gamma} \quad \delta' \sim p_{T,e}$$

Landau & Lifshitz

SM Monte Carlos (GEANT, FLUKA, ...) instead sample the photon from a 1D distribution and set

$$p_{T,e} = p_{T,\gamma}$$

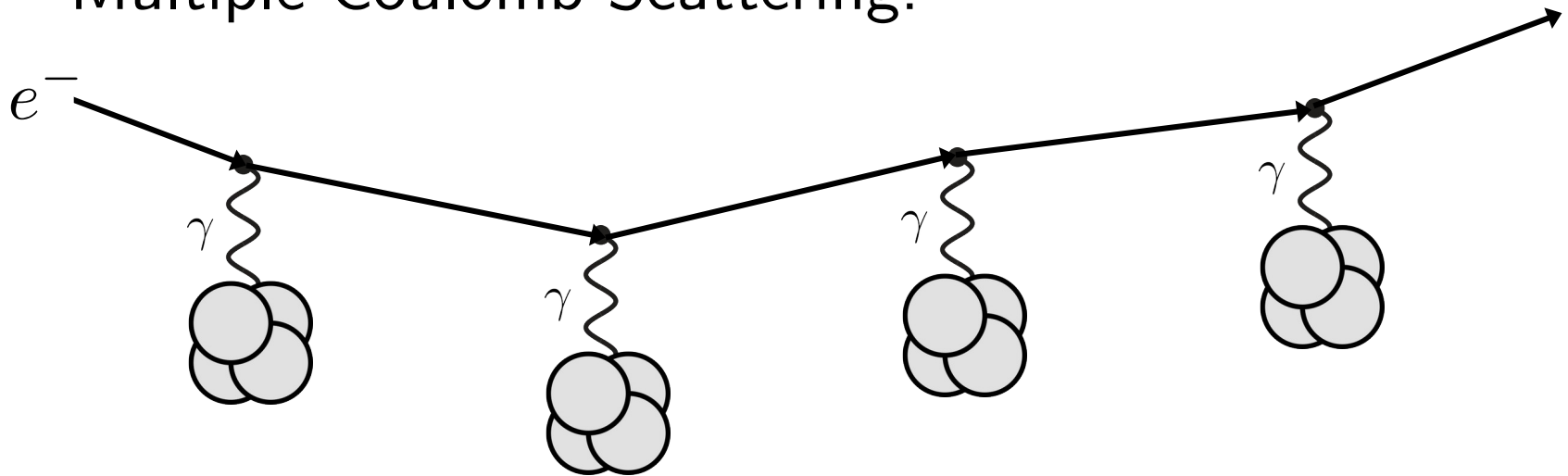
Angular distribution of recoil e is incorrect!

Is this important?

Is This Important?

It depends. Transverse shower evolution sensitive to

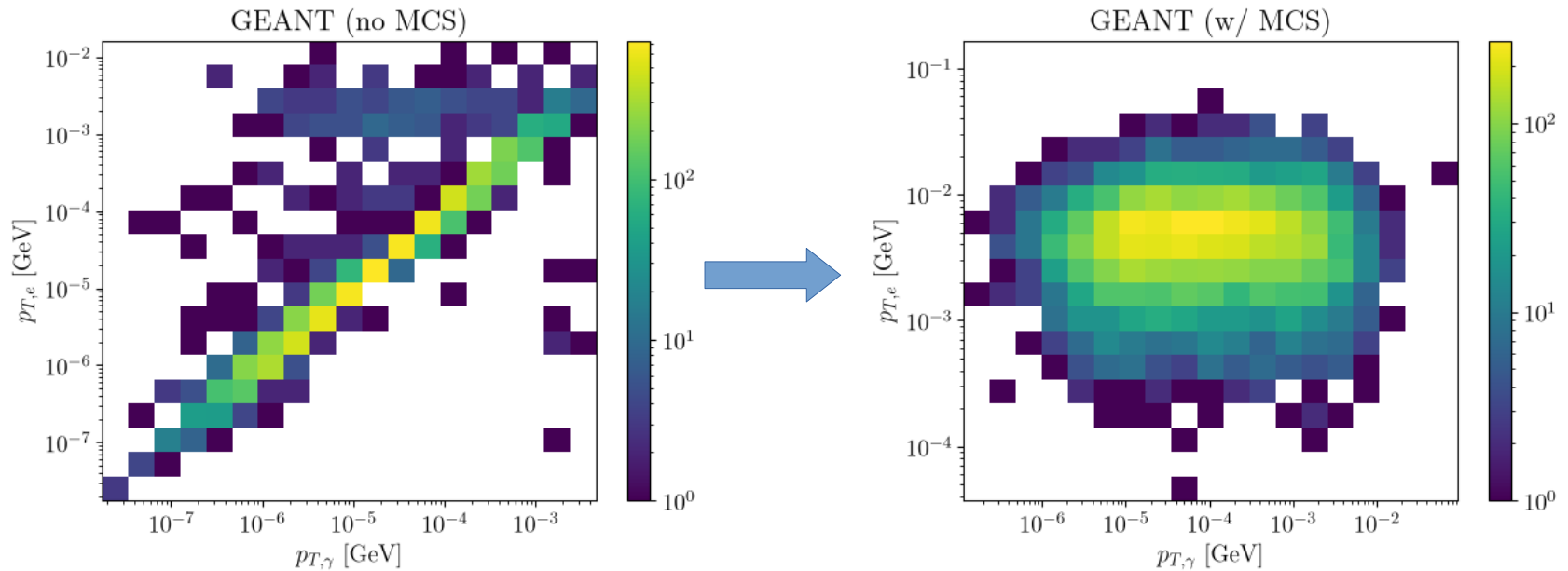
- Angular distributions of Brem, Compton, etc
- Multiple Coulomb Scattering:



$$\theta_{\text{MCS}} \sim 14 \left(\frac{\text{MeV}}{p} \right) \sqrt{t/X_0} \quad \text{vs} \quad \theta_{\text{Brem}} \sim \frac{m_e}{p}$$

Brem + Multiple Coulomb Scattering

4 GeV electron beam on 0.1rl tungsten target

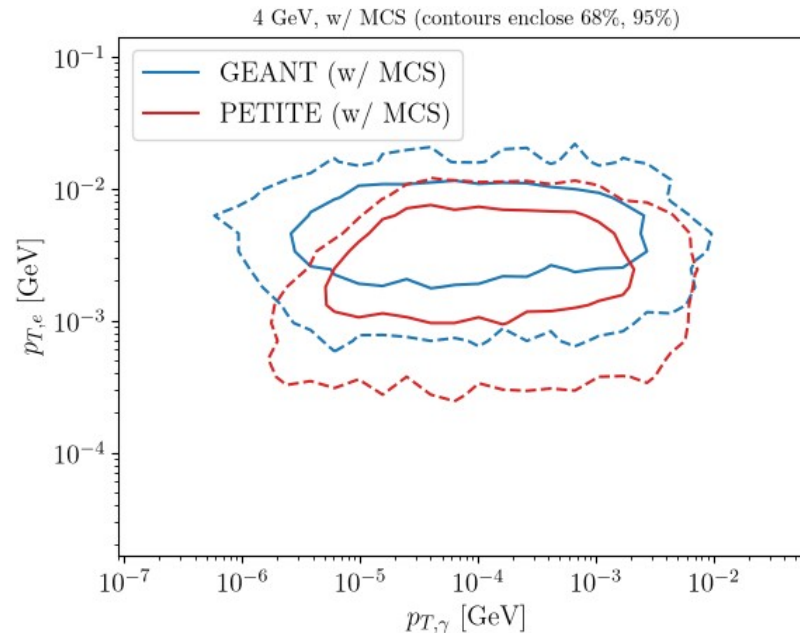


Scattering dilutes the artificial correlation in brem.

(nb: these do not show large-pt phase space)

Correlation Comparison

Prof. Pöttgen pointed out that ECAL BDT can be sensitive to electron-photon correlations



Even after including MCS, some differences remain – are they significant?

Simulating Wide-Angle Emissions

- Previous comparison was dominated by the soft/collinear emission. What about correlations in the wide angle regime?
- GEANT **cannot** produce wide-angle events that are accepted

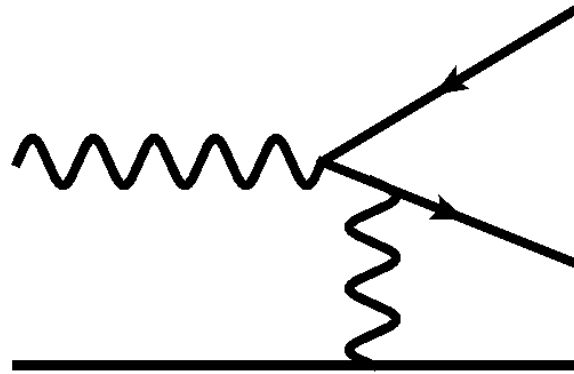
$$p_{T,e} = p_{T,\gamma}$$

means that if a wide-angle photon escapes ECAL, electron is likely to do the same

- Custom MC is probably needed for this phase space.

Bethe-Heitler Process

Similar issues arise for photon conversion



LDMX was aware and fixed it – see 2508.11833

$\mu^+\mu^-$ pairs via coherent scattering off a nucleus in the target or in the ECal. The default implementation of this process in `Geant4` was found to have an unphysical form factor, and approximations to the phase-space distribution of outgoing muons were inaccurate in the tails. Therefore, di-muon samples are generated with

Conclusion

- Pure QED backgrounds likely eliminated using ECAL with sufficient angular coverage and depth
- Despite simplicity, bremsstrahlung can be tricky to simulate; need to be careful with existing MC
- Correlations between electrons and photons are mostly washed out by multiple scattering; are residual effects ever significant?

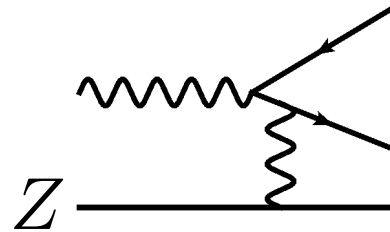
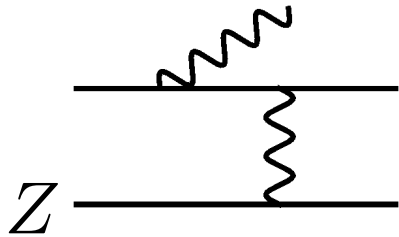
Thank you!

Appendix

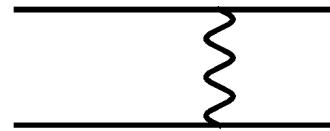
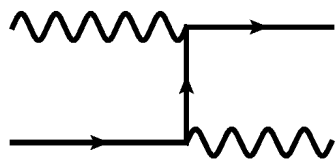
Electromagnetic Cascades

EM cascades of SM particles driven by:

- Bremsstrahlung & Pair production



- Electron/Positron/Photon scattering on atomic e



- Coulomb scattering & Ionization

