Search for dark photons with CMS and PADME

Andre Frankenthal on behalf of PADME and LPC-DM

Cornell University

Outline

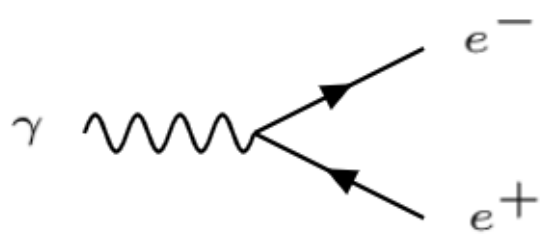
- Motivation: dark photons
- Fixed-target vs collider experiments
- Search for dark photons @ PADME
- Search for inelastic DM with dark photons @ CMS
- Conclusions

Motivation: dark photons

- Dark matter with a complex dark sector is well-motivated by theory and experimental particle and astrophysics results
- Dark photons (A′), arising from an additional U(1) dark symmetry, could be the bridge between the dark sector and the Standard Model
- Similar to photon, A′ is gauge mediator of new U(1)

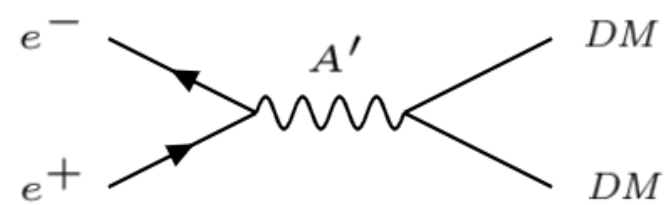
Ordinary photon

- Massless (EM infinite range)



Dark photon

- Massive (fifth force finite range)



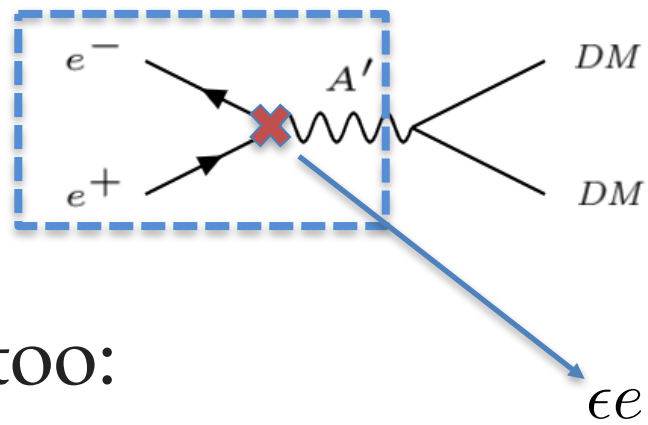
Kinetic mixing

- Mixing between photon and dark photon kinetic terms in the Lagrangian:

$$-\frac{1}{4}F'_{\mu\nu}B^{\mu\nu}$$

- Enables interaction between A′ and SM:

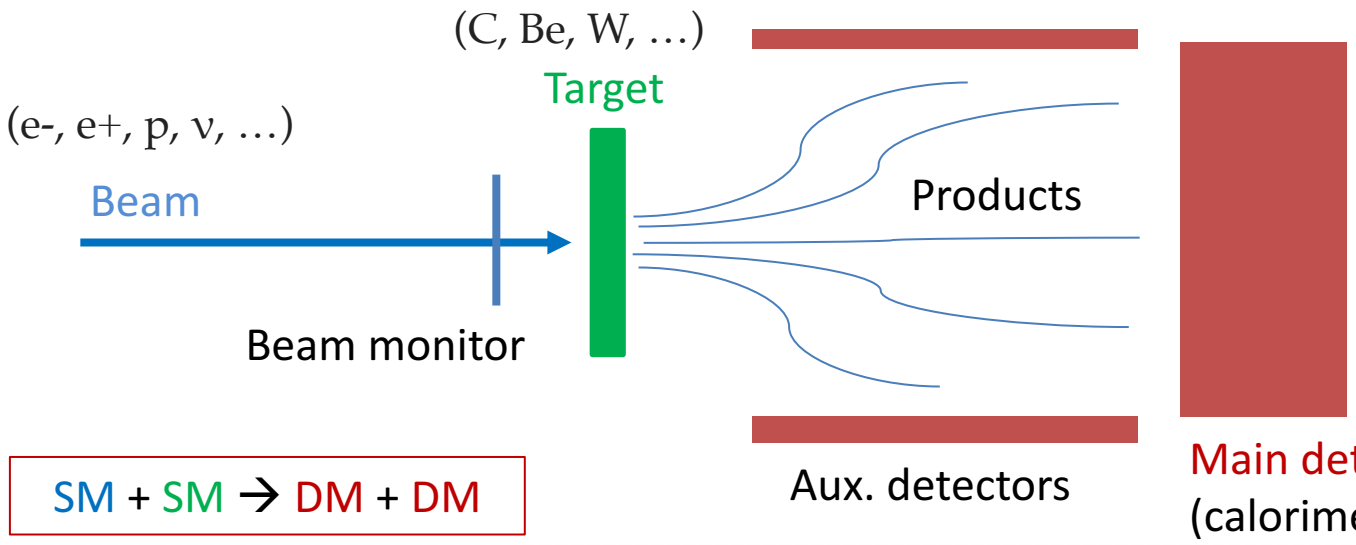
$$+\epsilon e A'^{\mu} J_{\mu}^{EM}$$



- Mass term allowed too:

$$+\frac{1}{2}m_{A'}^2 A'^{\mu} A'_{\mu}$$

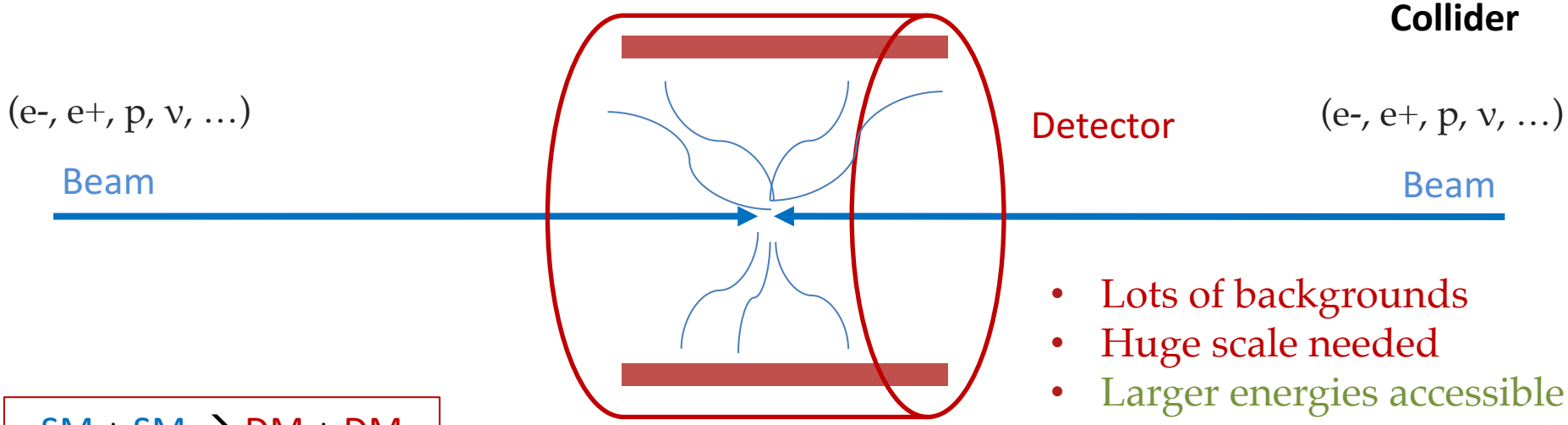
Fixed-target vs collider expts.



- Fewer backgrounds
- Smaller scale
- Less energy (phase space coverage)
- Not hermetic

SM + SM → DM + DM

Collider

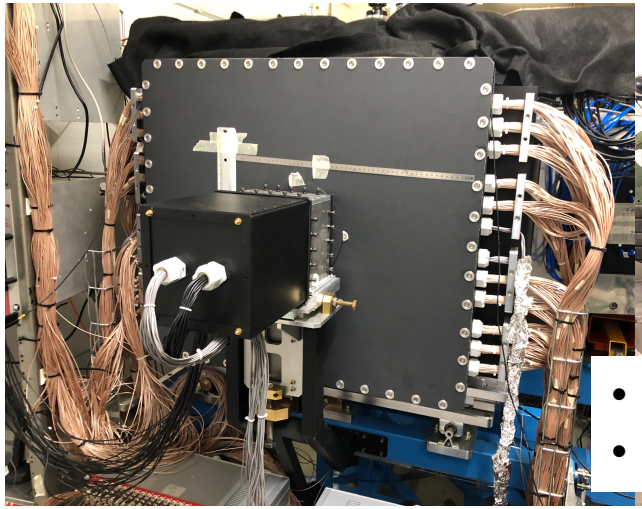


- Lots of backgrounds
- Huge scale needed
- Larger energies accessible
- Hermetic coverage possible

SM + SM → DM + DM

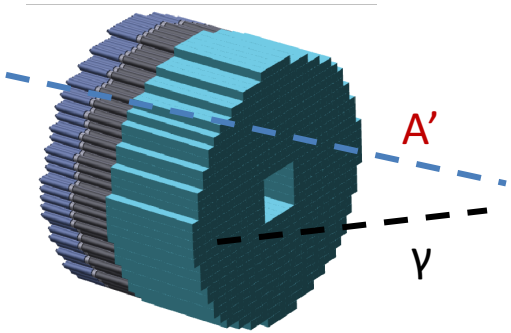
Search for dark photons @ PADME

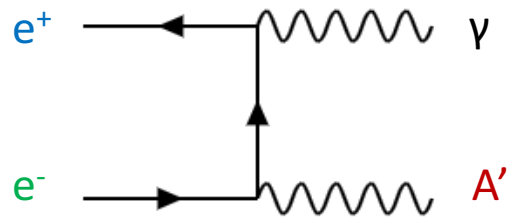
- Positron Annihilation into Dark Matter Experiment
- Fixed-target, missing-mass experiment, search for DP
- Beam: 550 MeV positrons (e+)
- Target: Diamond (C)
- Detectors: Electromagnetic calorimeter (ECAL), Small-Angle Calorimeter (SAC), e/p vetos, active target
- Magnetic field to bend beam after target



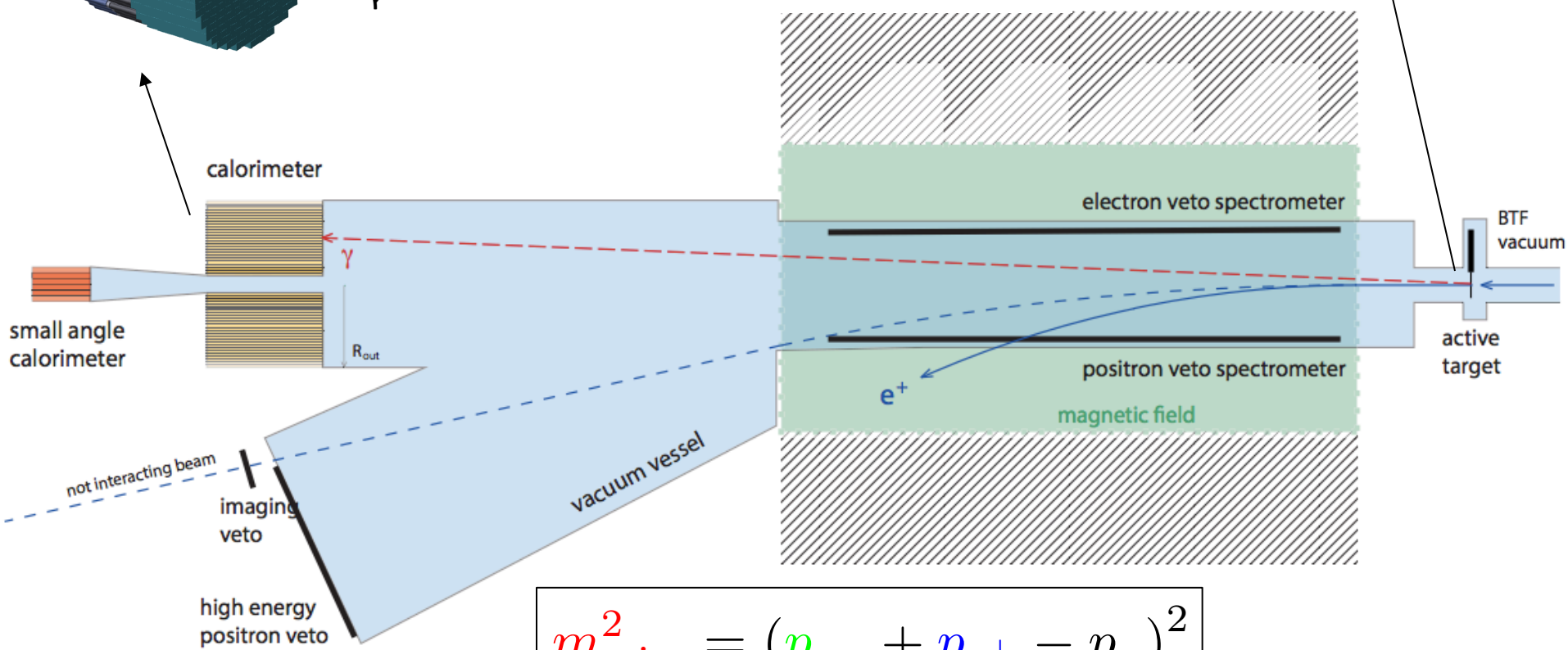
- At LNF, near Rome, Italy
- ~ 30 people collaboration

PADME





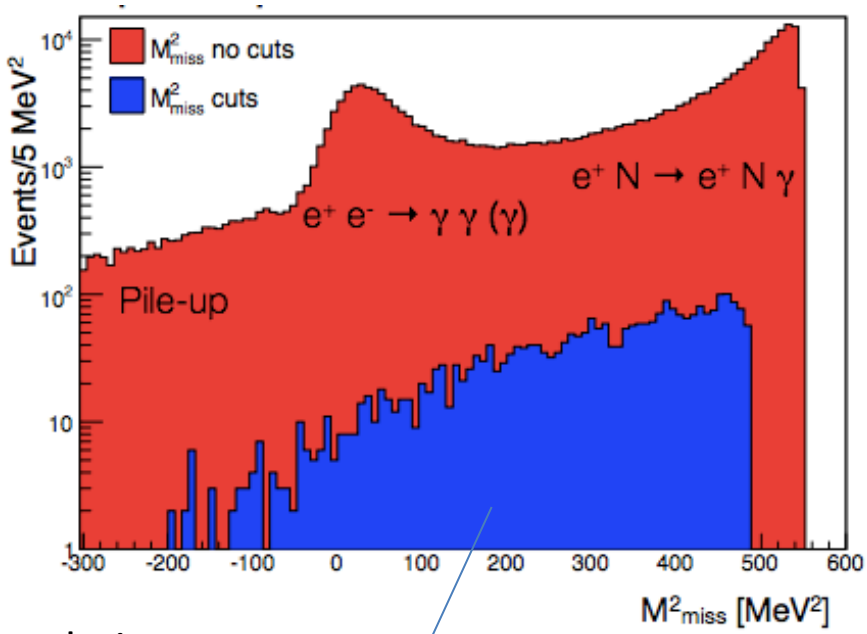
$e^+ + e^- \rightarrow \gamma + A'$



$$m^2_{\text{miss}} = (p_{e^-} + p_{e^+} - p_\gamma)^2$$

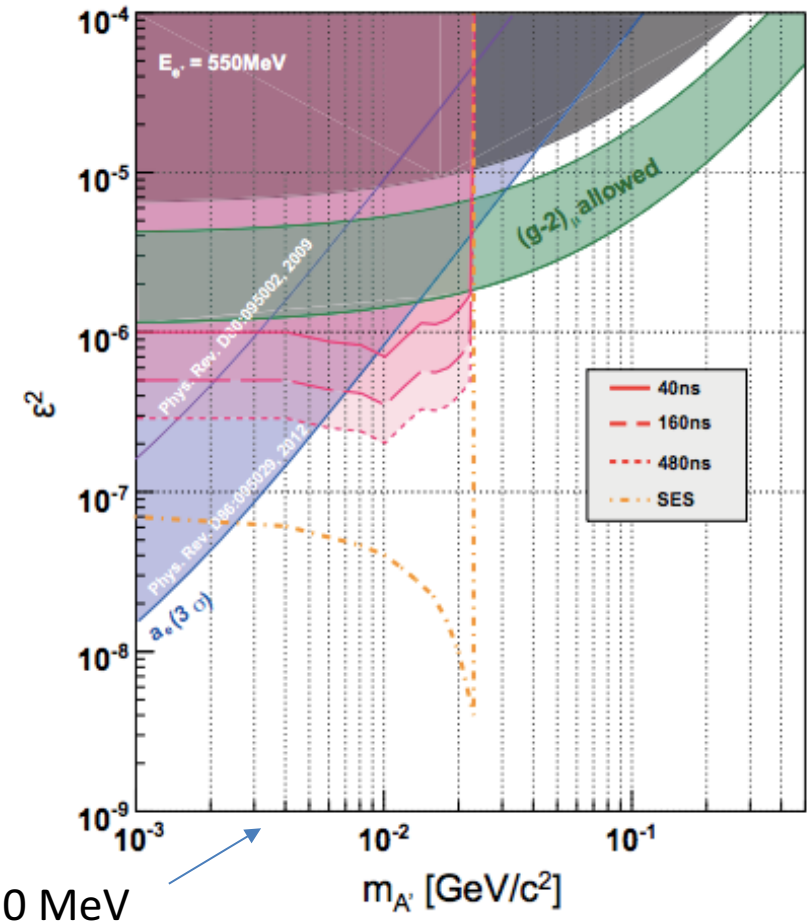
Mitigating backgrounds

J. Phys. Conf. Ser. 770 (2016) 012039



Simulation

Sensitivity:



Main backgrounds mitigated with auxiliary detectors, e/p vetoes and small-angle calorimeter (backup)

DM mass region: ~ 1-20 MeV

PADME – summary

- Search for dark photons using missing mass technique with a C fixed target
- First data run collected for 5 months in 2018/19
- Beam, detector commissioning analysis ongoing
- Preliminary physics analysis next
- Next run starting in July

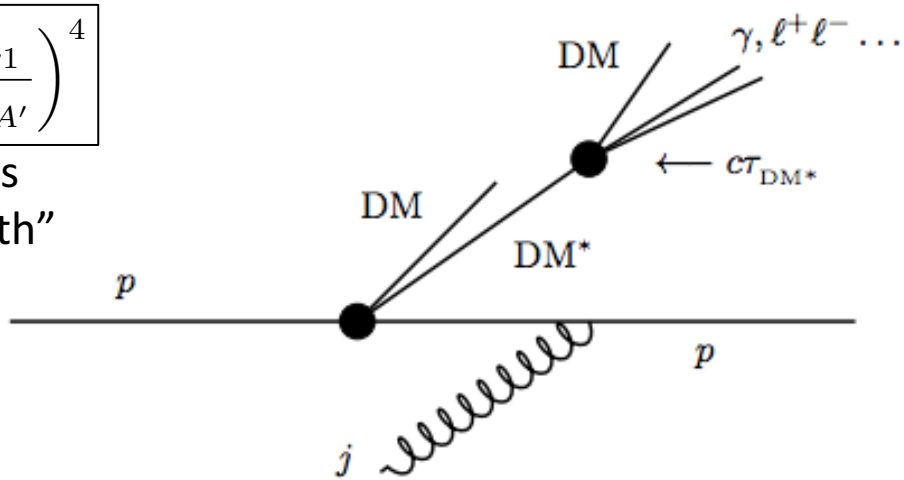
Inelastic DM with dark photons @ CMS

1508.03050

- Two dark matter states and a dark photon:
  - heavier: **DM***, lighter: **DM**, dark photon: **A'**
- Heavier DM* decays to stable lighter DM via off-shell A'
- A' decays to lepton pair via kinetic mixing

$$\sigma v \propto y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}}\right)^4$$

y = "Dimensionless interaction strength"

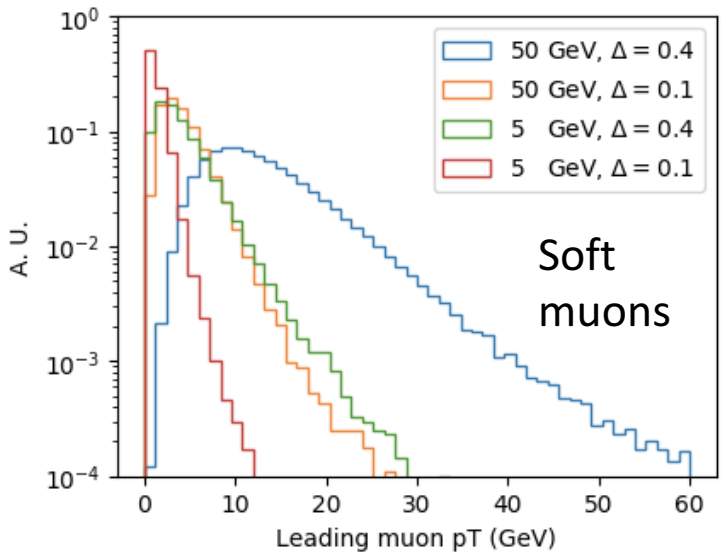


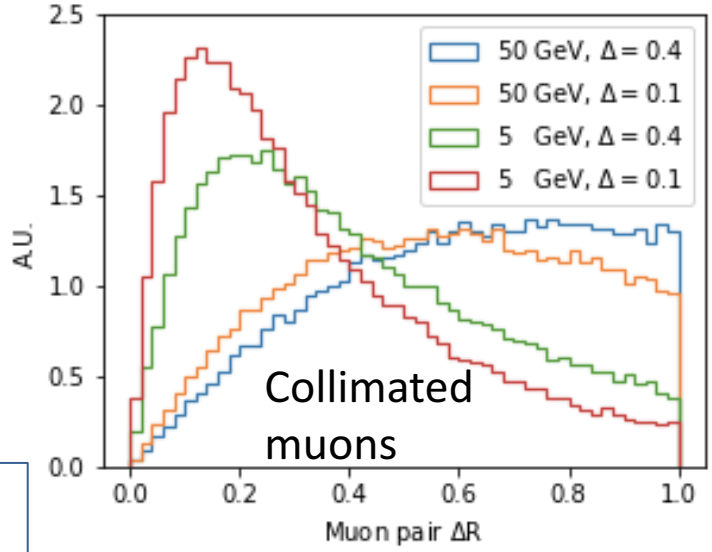
Parameters:
- Light DM mass: m_1
- Mass splitting: Δ
- Heavy DM lifetime: cτ
- A' mass = $3*m_1$

- m_1 : O(1 – 100 GeV)
- Δ : O(0.1 – 0.5 m_1)
- cτ : O(1 – 1000 mm)

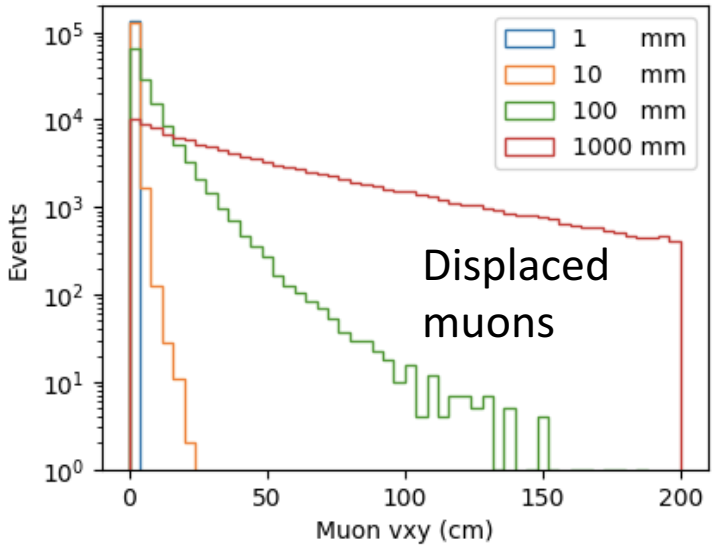
Final state signature: MET collimated w/ soft, displaced, narrow di-lepton pair, recoiled against ISR

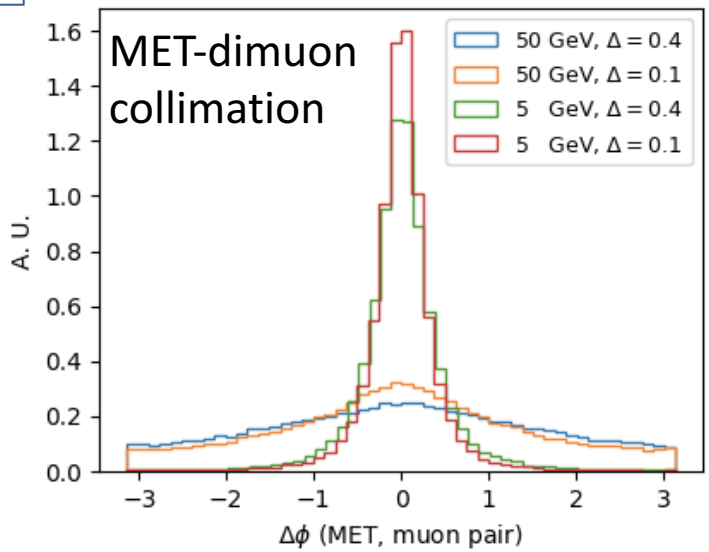
Signal kinematics





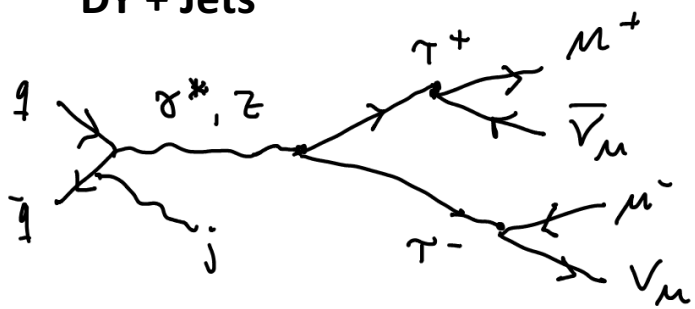
Generator-level MC plots



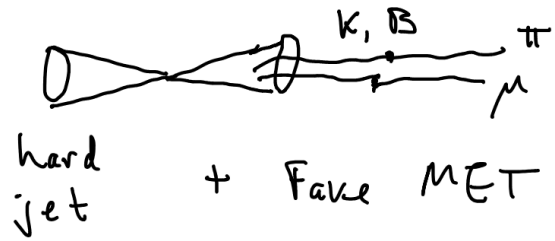


Backgrounds

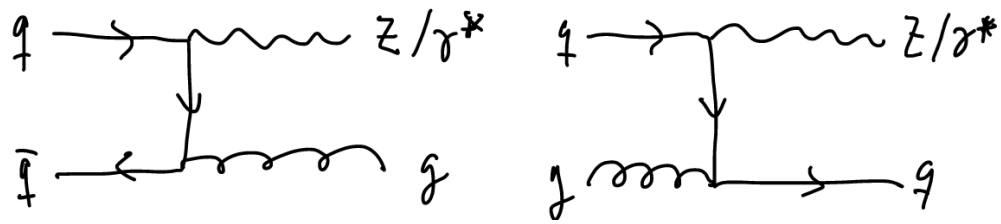
DY + Jets

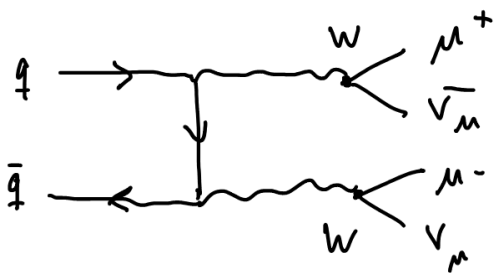


QCD

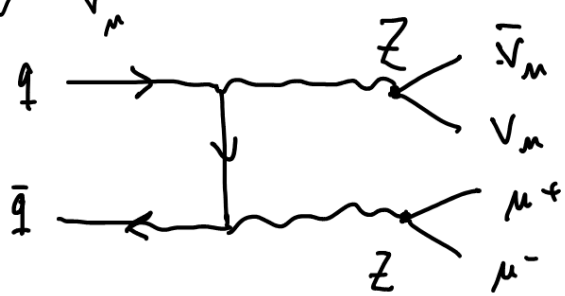


V + Jets

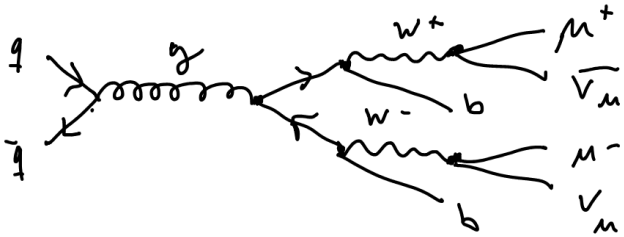




Di-boson



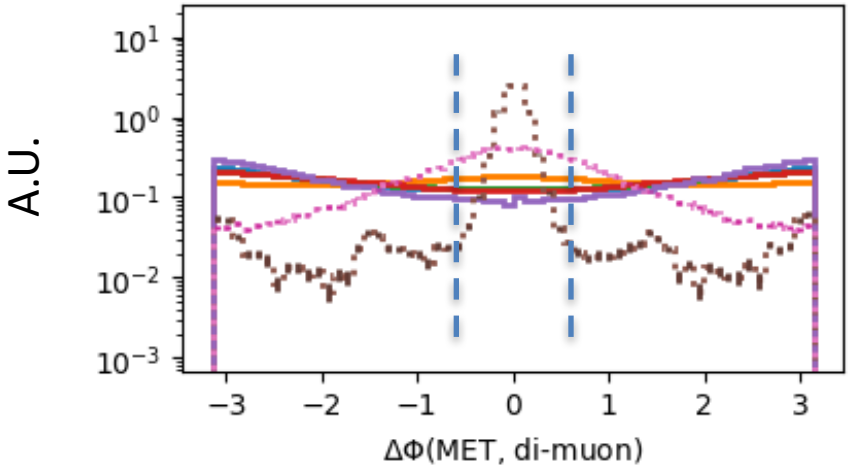
TTbar



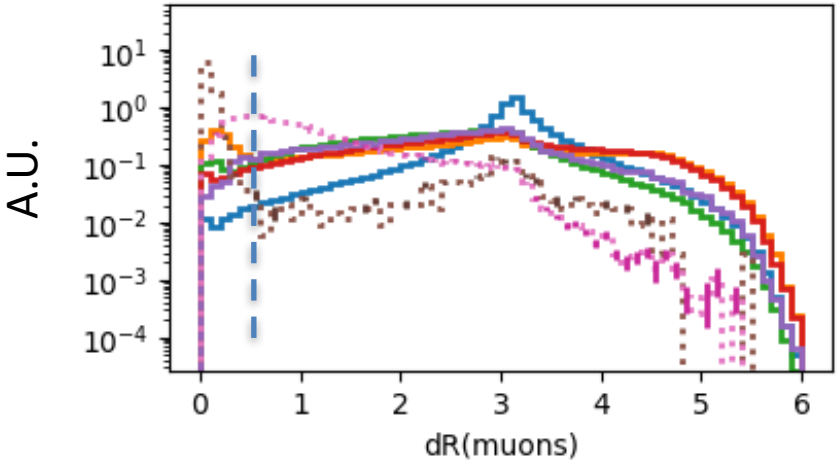
Backgrounds (shape comparison)

Reconstructed MC events

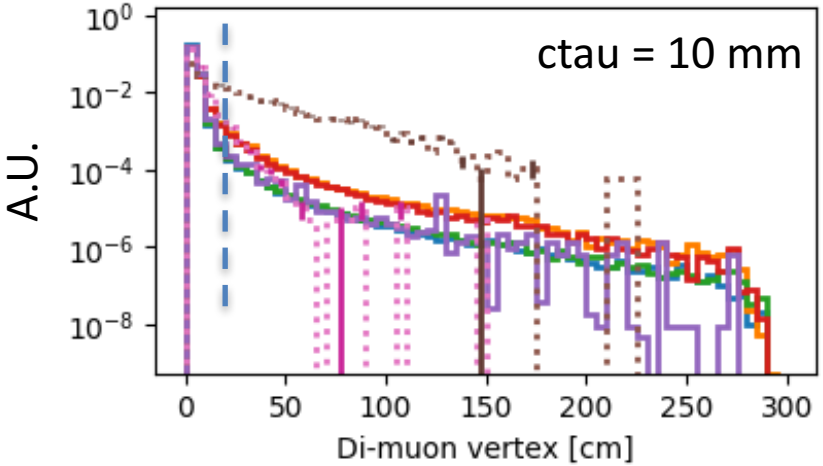
Signal muon pair collimated with MET



Signal muon pair collimated

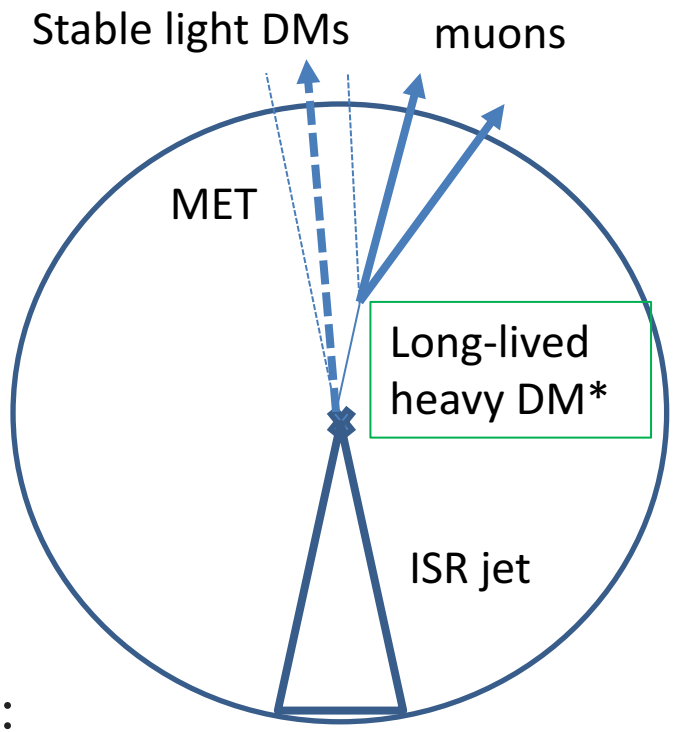


Signal muons displaced



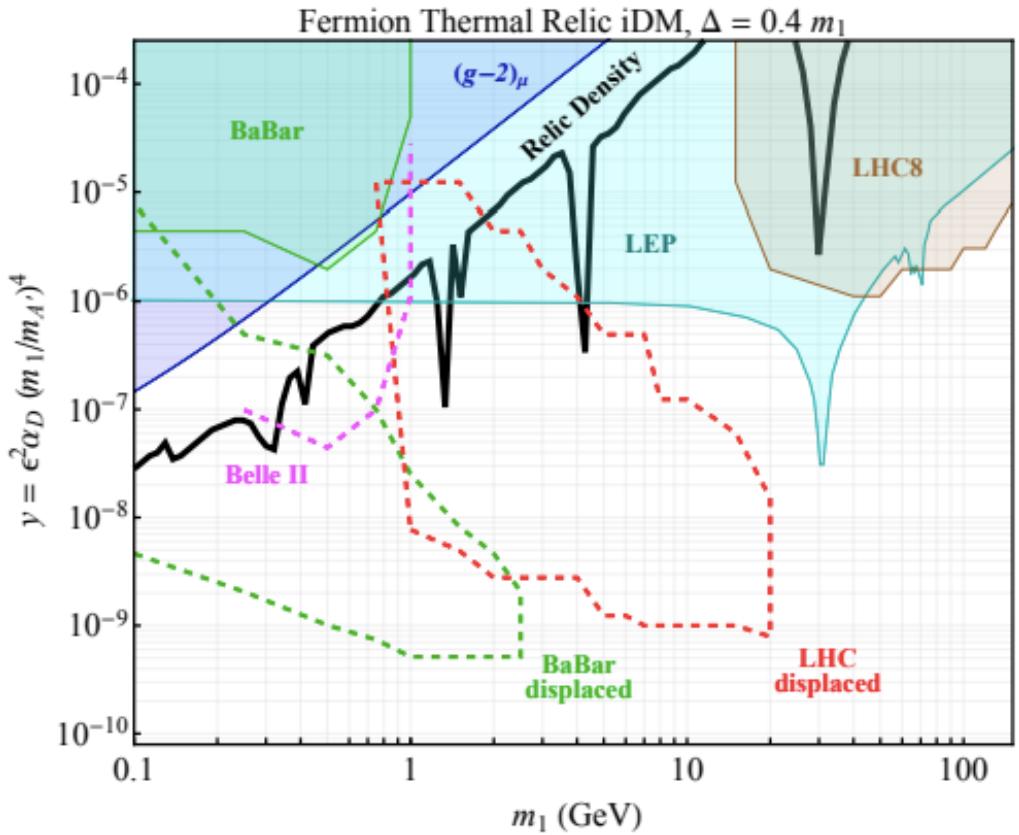
Preliminary event selection

- Trigger on MET: 120 GeV
- Select ISR jet:
  - **pT > 120 GeV**
  - At most 1 other jet with pT > 30 GeV
- Select displaced muon pair:
  - Muon track quality requirements:
    - Muon chamber planes: > 2
    - Muon chamber total hits: > 12
    - Reduced chi2 of fit: < 10
  - **pT > 5 GeV**
  - **$0.1 < d_{xy} < 700$ cm**
- Require MET and muon pair collimated:
  - **$\Delta\phi < 0.4$** between MET and muons
- QCD only major remaining background in signal region. Selection optimization and data-driven background estimation in progress



Expected sensitivity

1508.03050



$\Delta = 0.4\ m_1$
$\alpha_D = 0.1$
$m_{A'} = 3\ m_1$

- Projected LHC sensitivity can reach relic density
- LHC search complementary to B-factory and fixed target (lower DM mass)
- Results dependent on coupling assumptions (more plots in backup)

Conclusions

- Dark photons provide interesting avenue for BSM physics exploration
- Different search strategies allow complementary coverage, across several metrics
- Two such searches discussed:
  - Fixed-target, missing-mass approach with PADME
  - Inelastic dark matter search with CMS
- CMS finished Run-2 run with 2016/17/18 data
  - iDM analysis ongoing with these datasets
- PADME preliminary physics analysis ongoing
- Stay tuned!

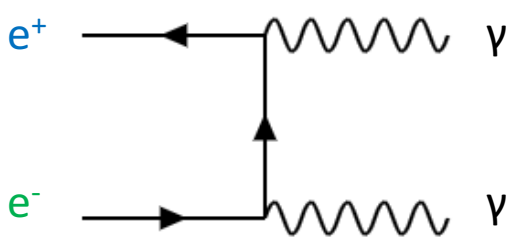
BACKUP

PADME backgrounds

- Other physics processes could mimic A' signature
- Need to veto background events to see A' peak
- Aux. detectors exist for that purpose

2-gamma production:

$e^+ + e^- \rightarrow \gamma + \gamma$

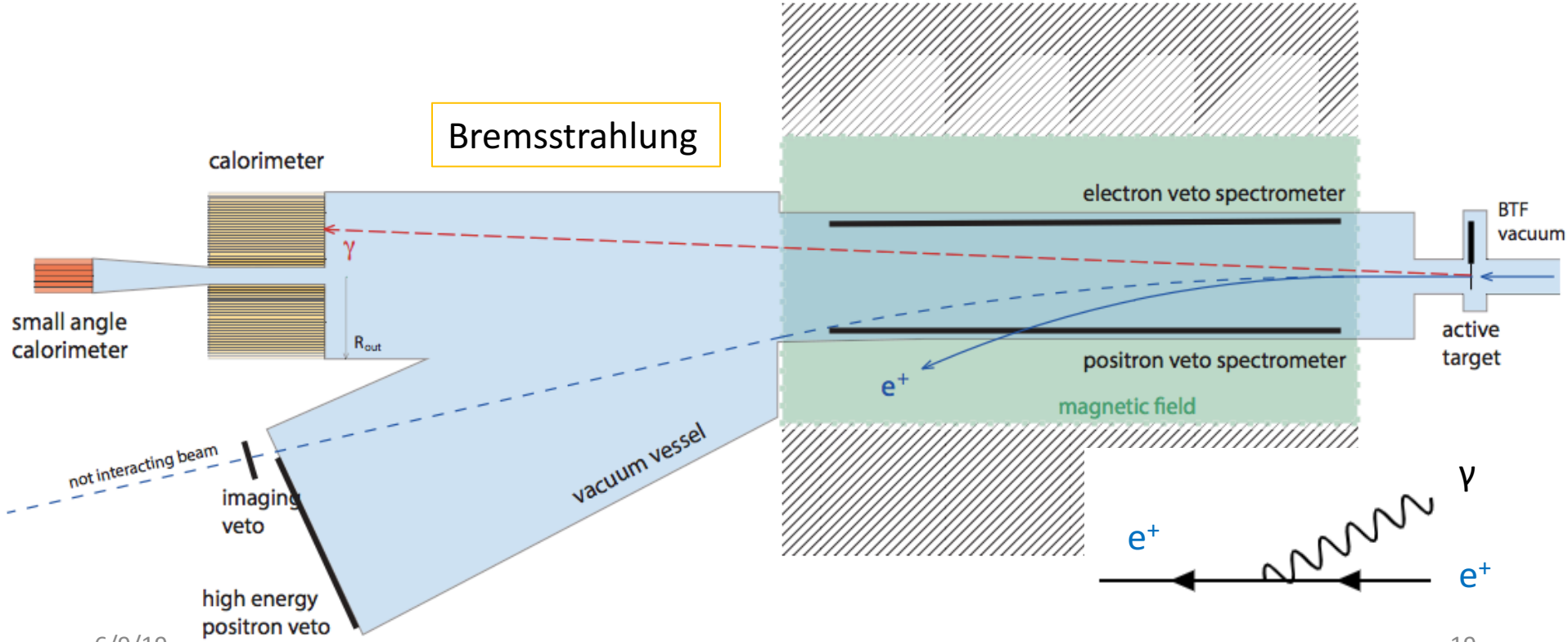


Positron bremsstrahlung:

$e^+ + N \rightarrow e^+ + N + \gamma$

Mitigating backgrounds

- Auxiliary detectors tag a background event
- When event is tagged, it is rejected



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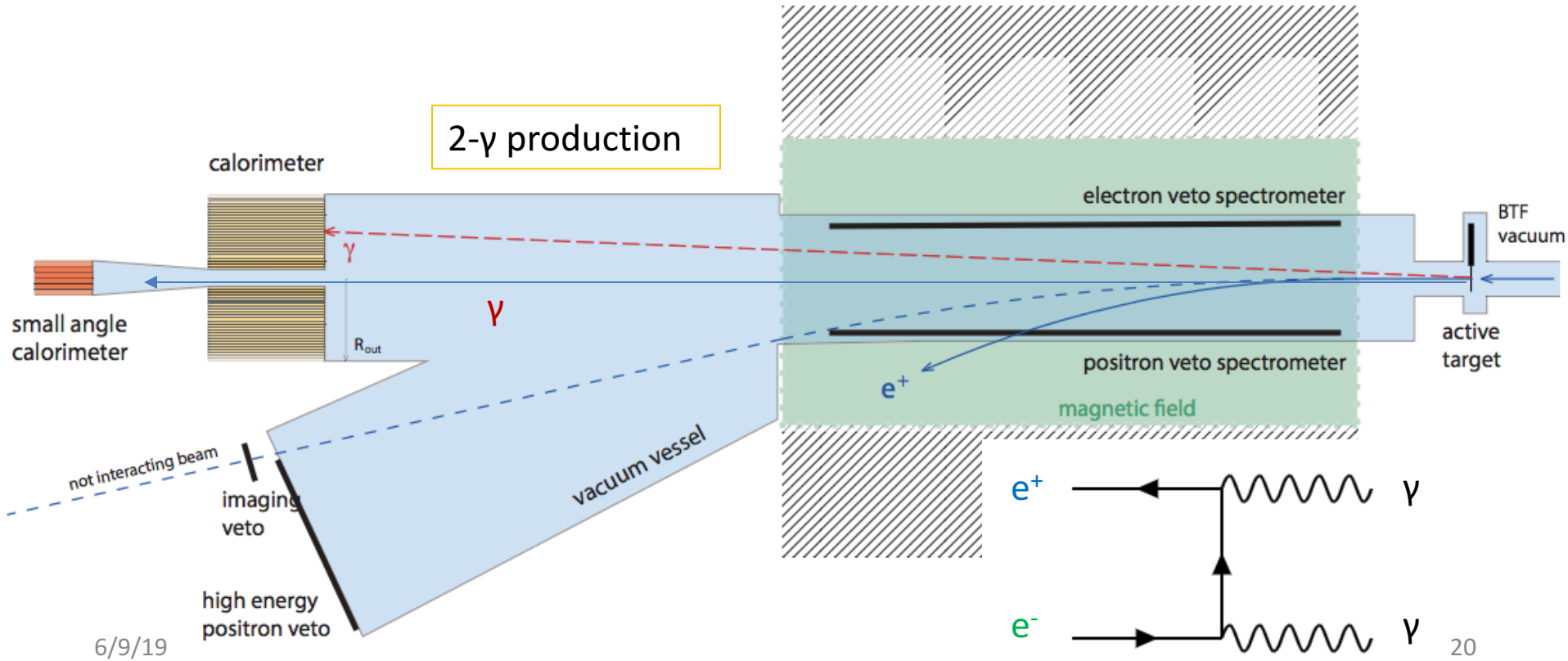

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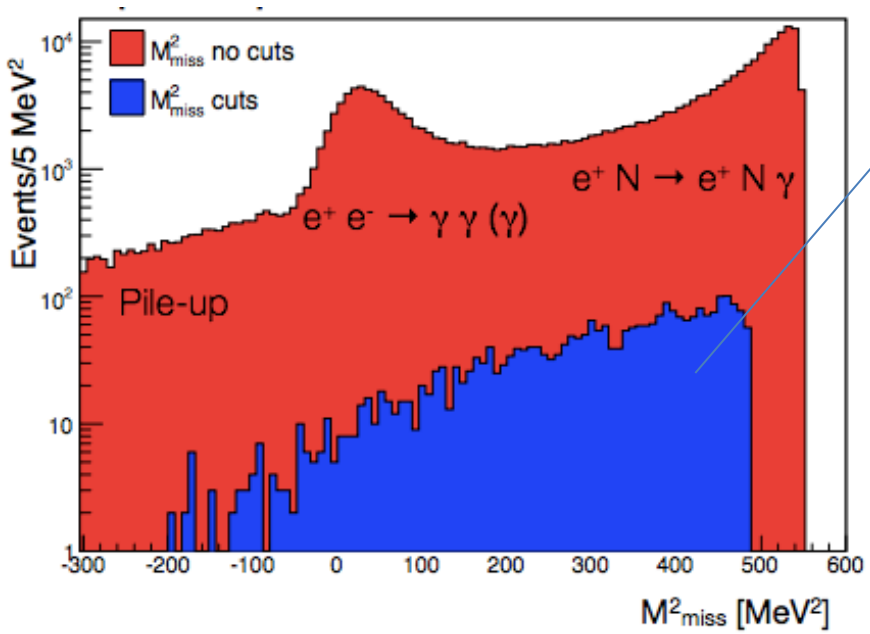
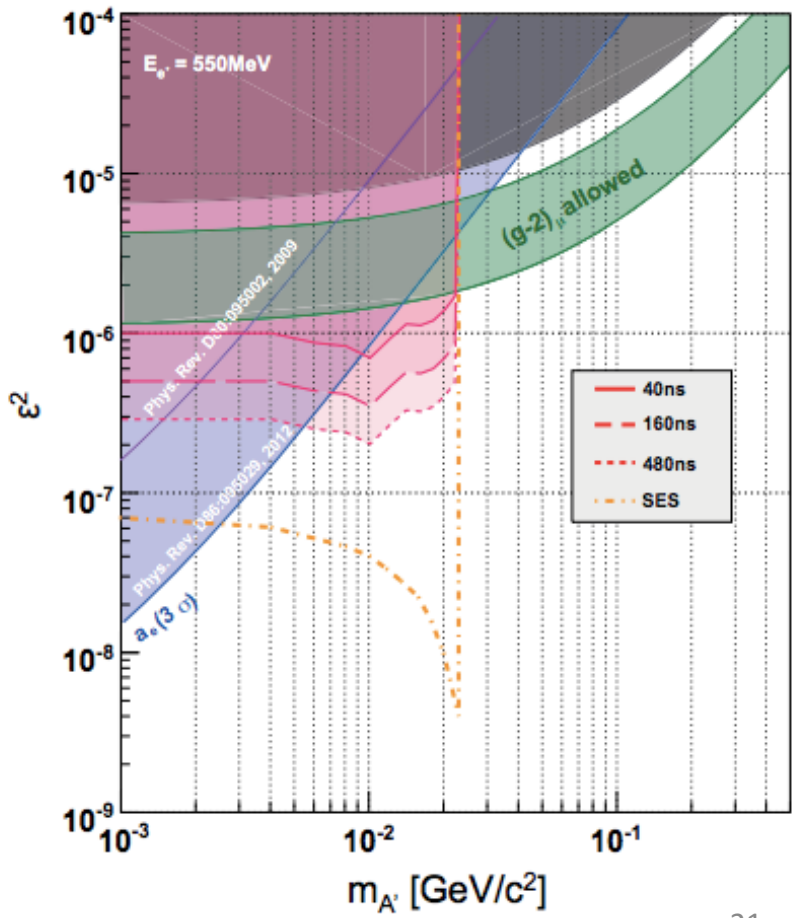
Mitigating backgrounds



Log scale, much better!

Sensitivity:

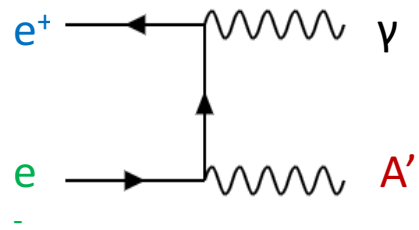


Cuts:

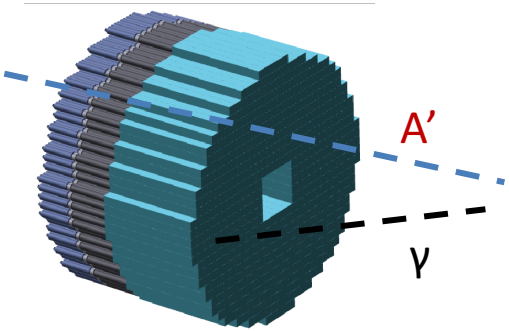
- 1 cluster in ECAL
- No hits in vetos
- No γ in SAC w/ energy > 50 MeV
- 20-150 MeV < ECAL energy < 120-350 MeV depending on dark photon mass

PADME – how it works

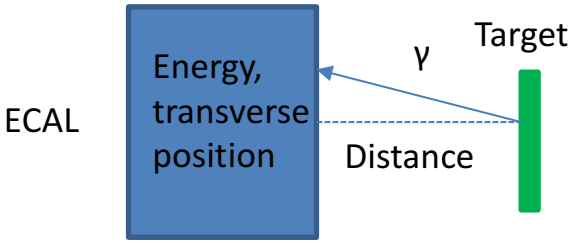
- Positron and electron interact, producing a photon and a dark photon



- Dark photon invisible, escapes detector



- Photon momentum measured by ECAL



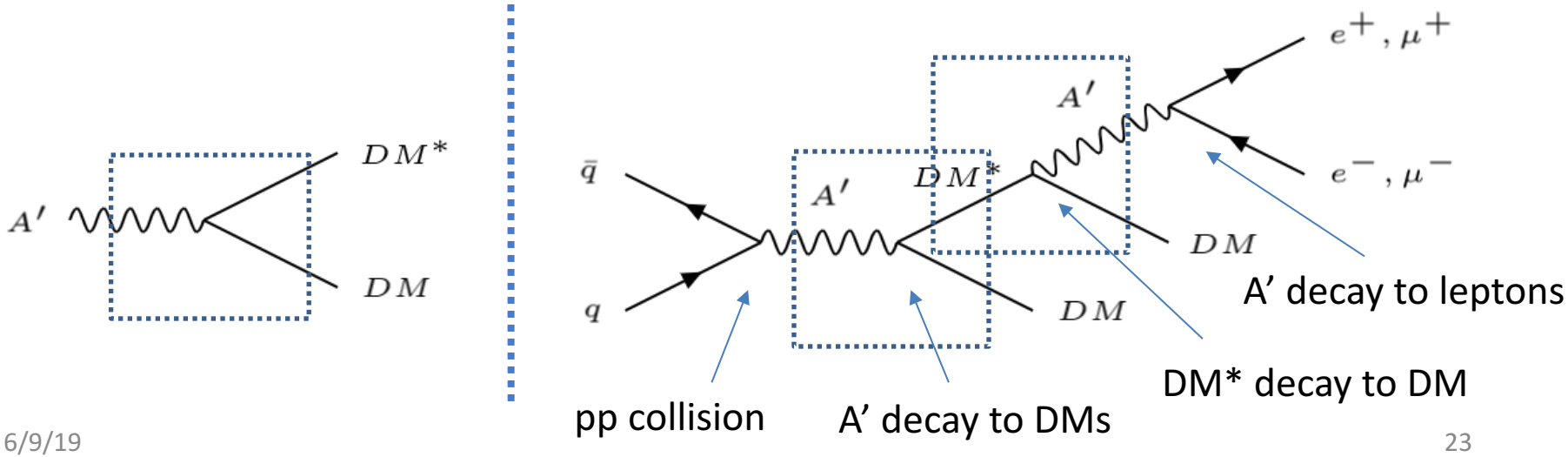
- Subtracting from beam (positron) and target (electron) momentum, missing mass is inferred:

$$m^2_{\text{miss}} = (p_{e^-} + p_{e^+} - p_\gamma)^2$$

Phys. Rev. D 93, 063523 (2016)

Inelastic dark matter

- A more specific extension to DM picture:
- What if instead of 1 WIMP, have 2 DM states?
- A heavier unstable one, and a lighter stable one
- Extra assumption enriches dynamics:

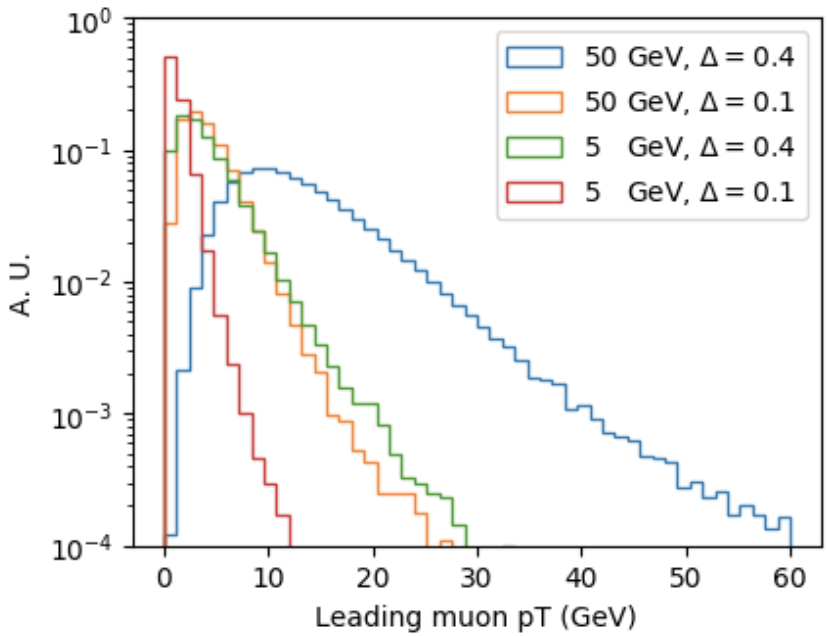


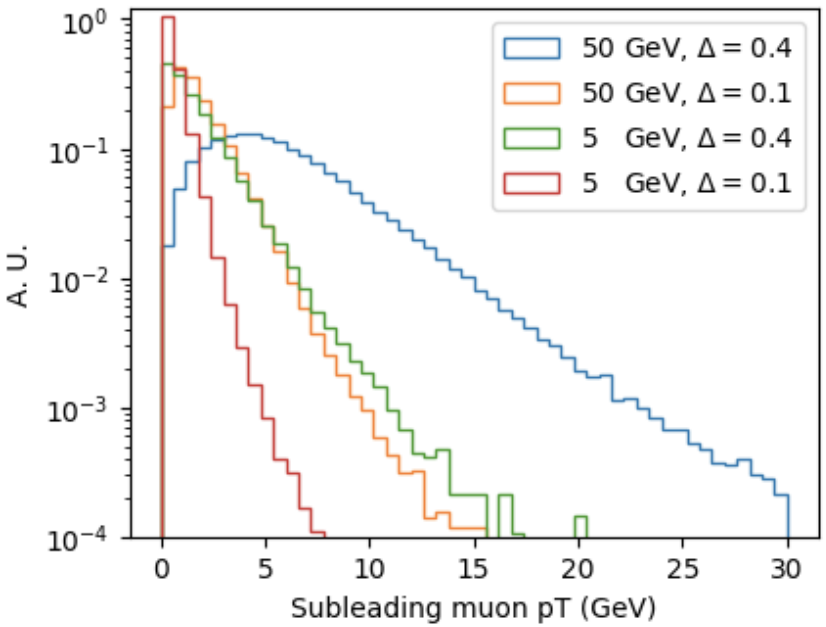
Signal kinematics

MG5 2.6.0 LO + Pythia 8

Gen-level plots

– Features:
  - Soft and collimated muons
  - Displaced muon pair vertex
  - MET aligned with muon pair
  - ISR and muons-MET system back-to-back





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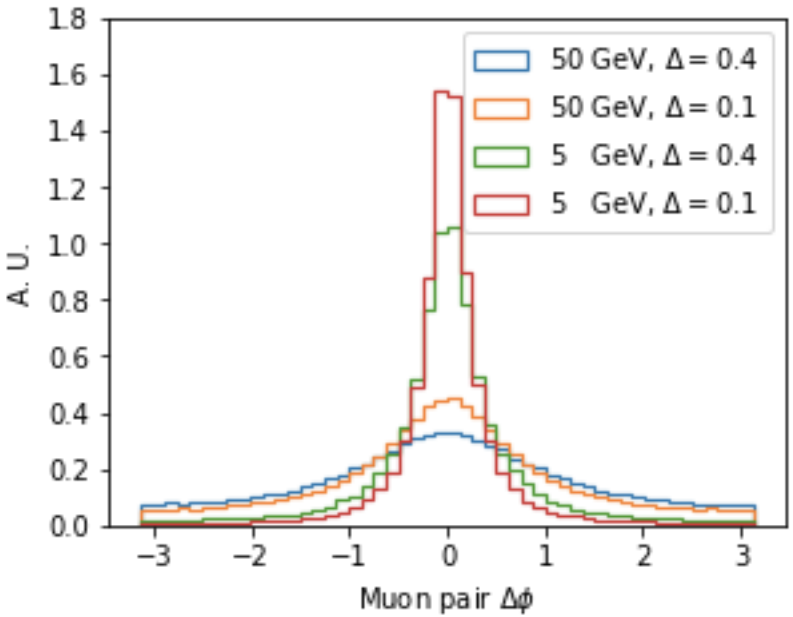

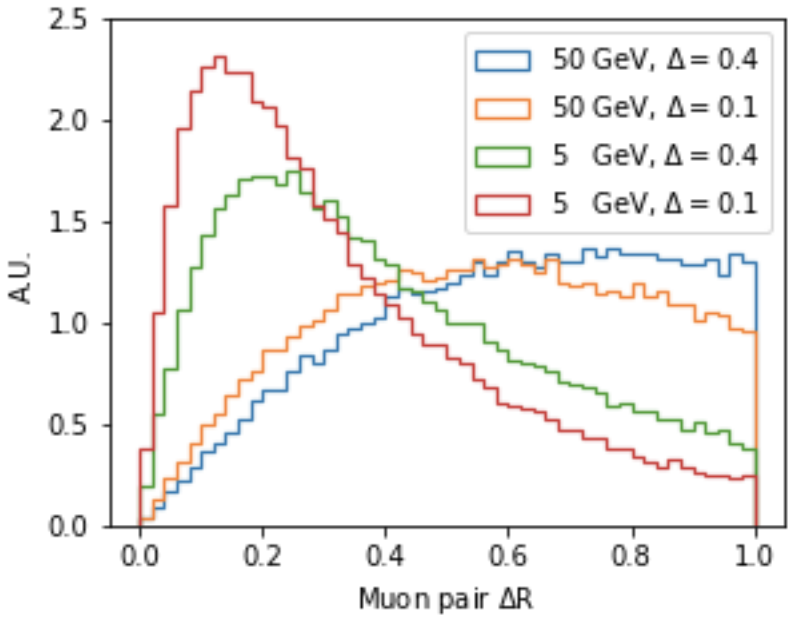

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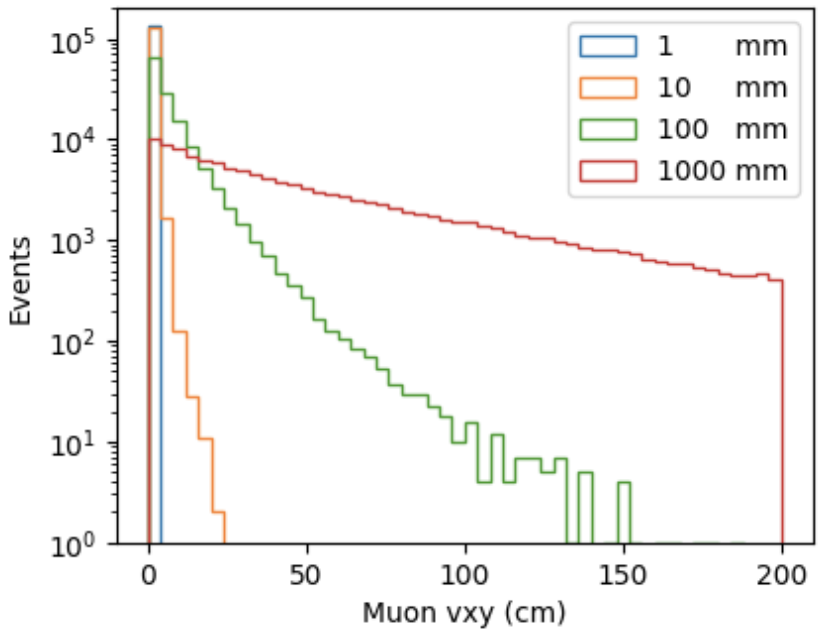

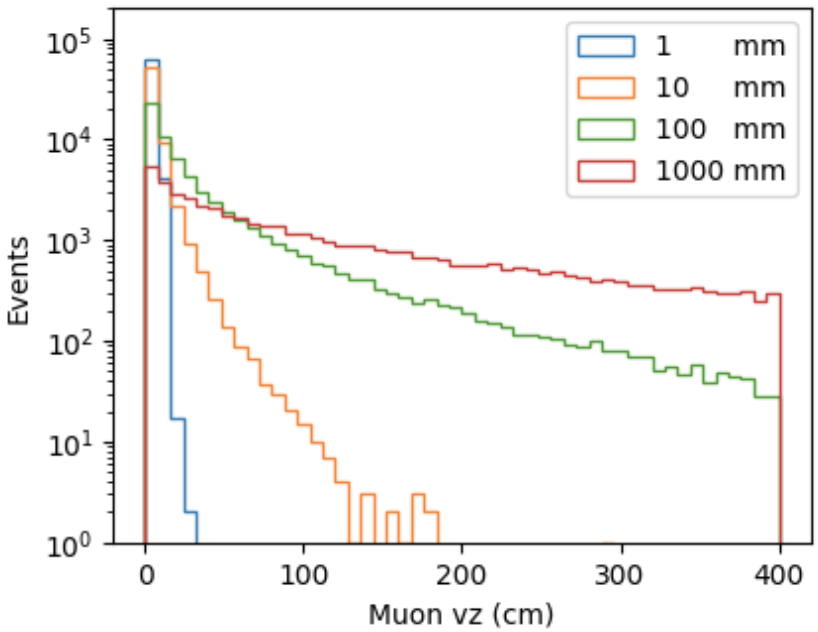

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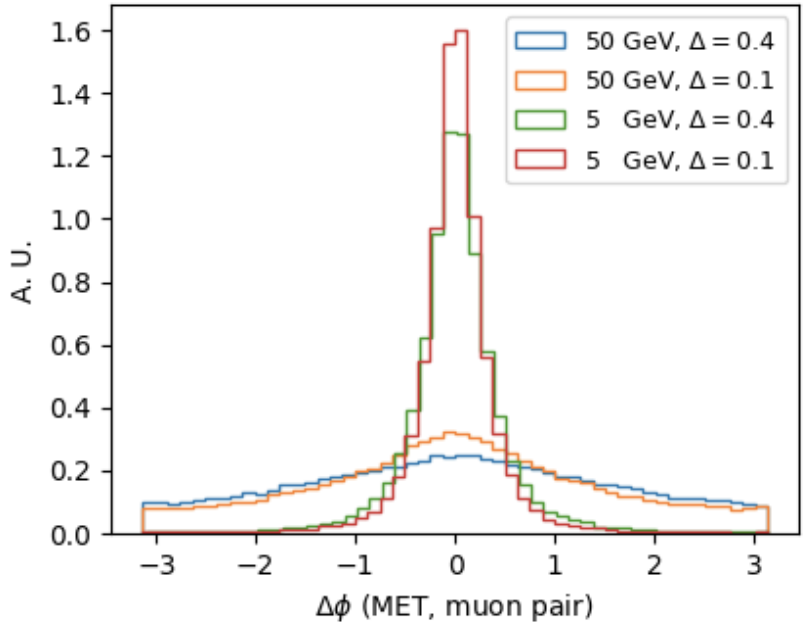

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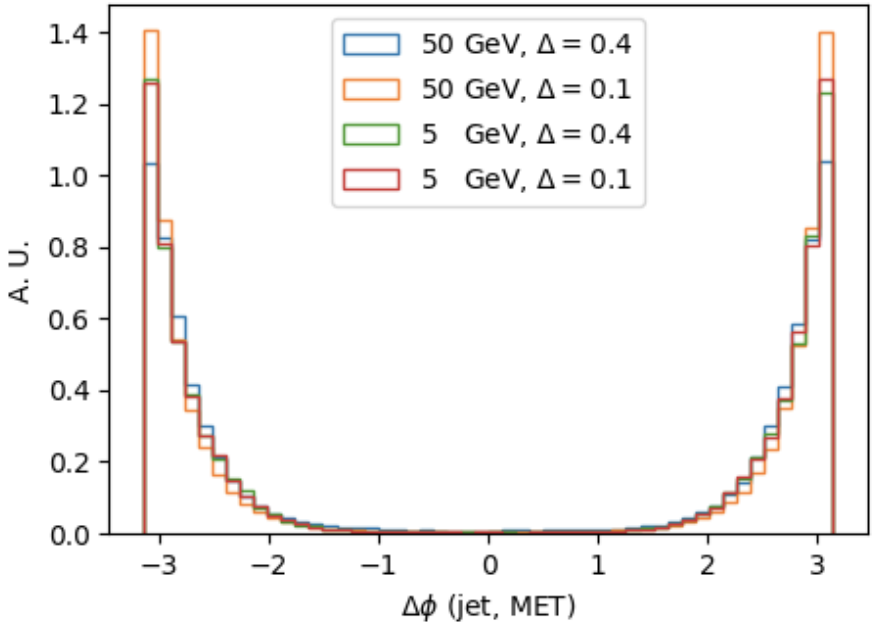
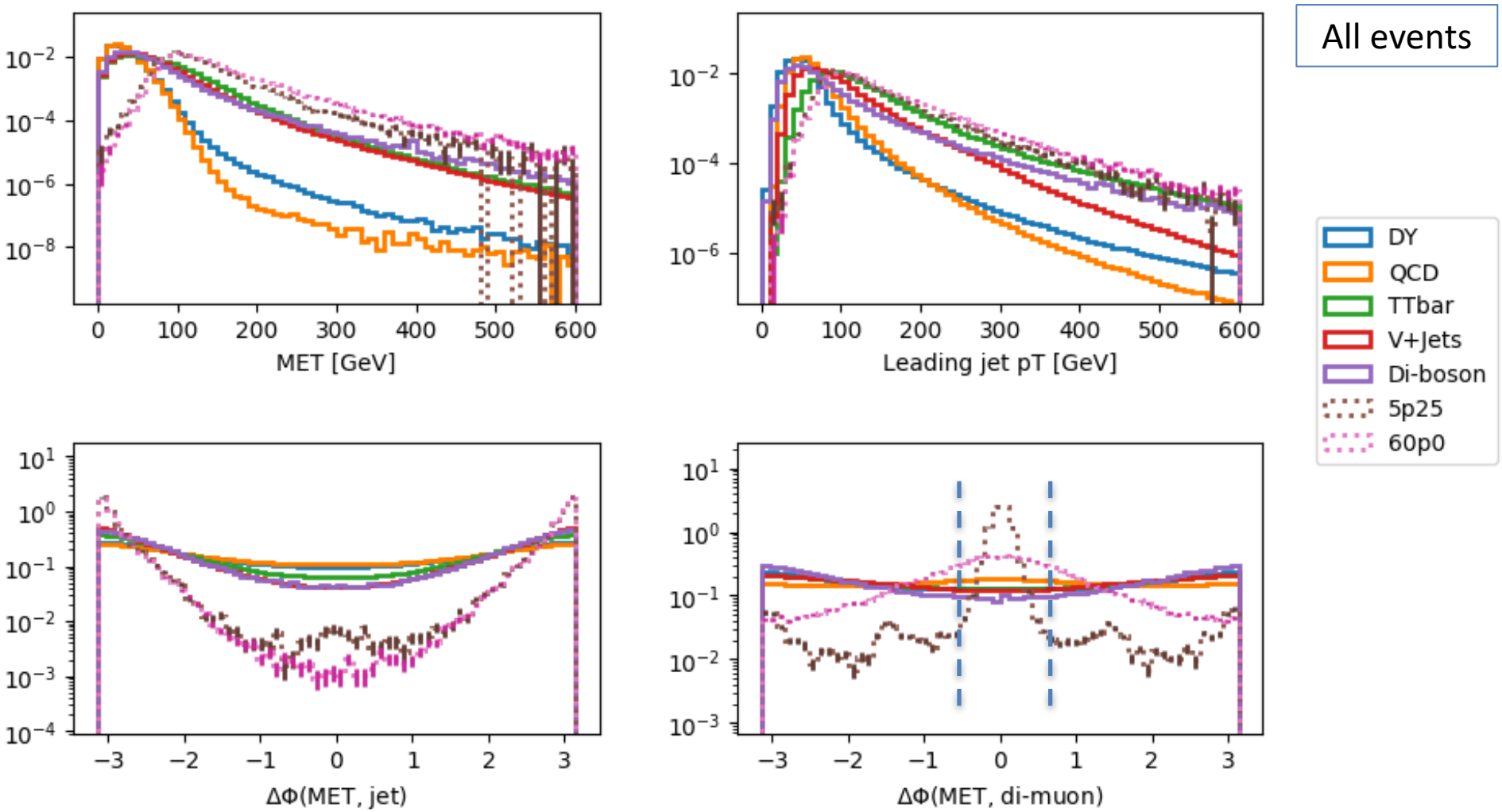


Backgrounds (shape comparison)



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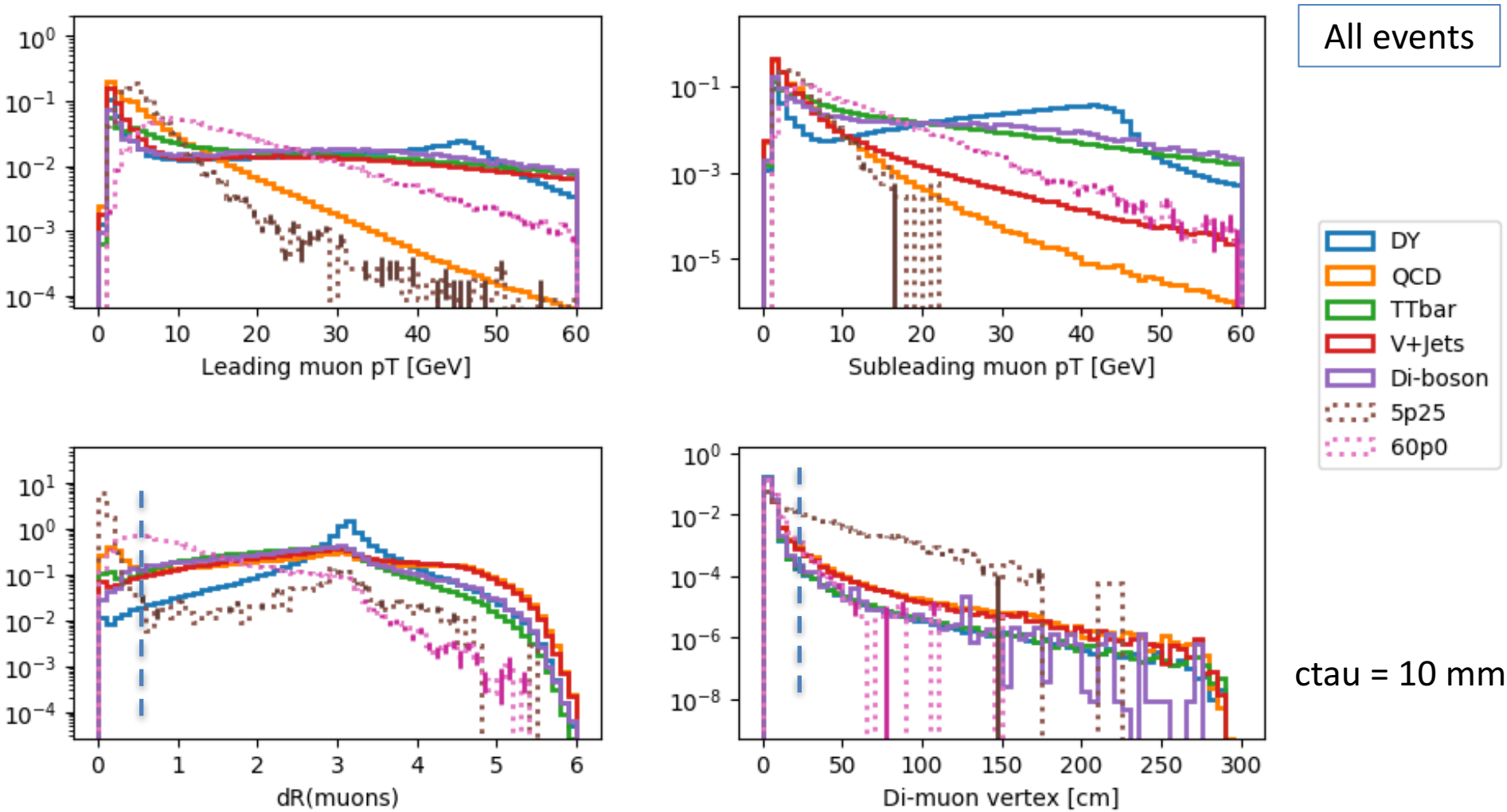
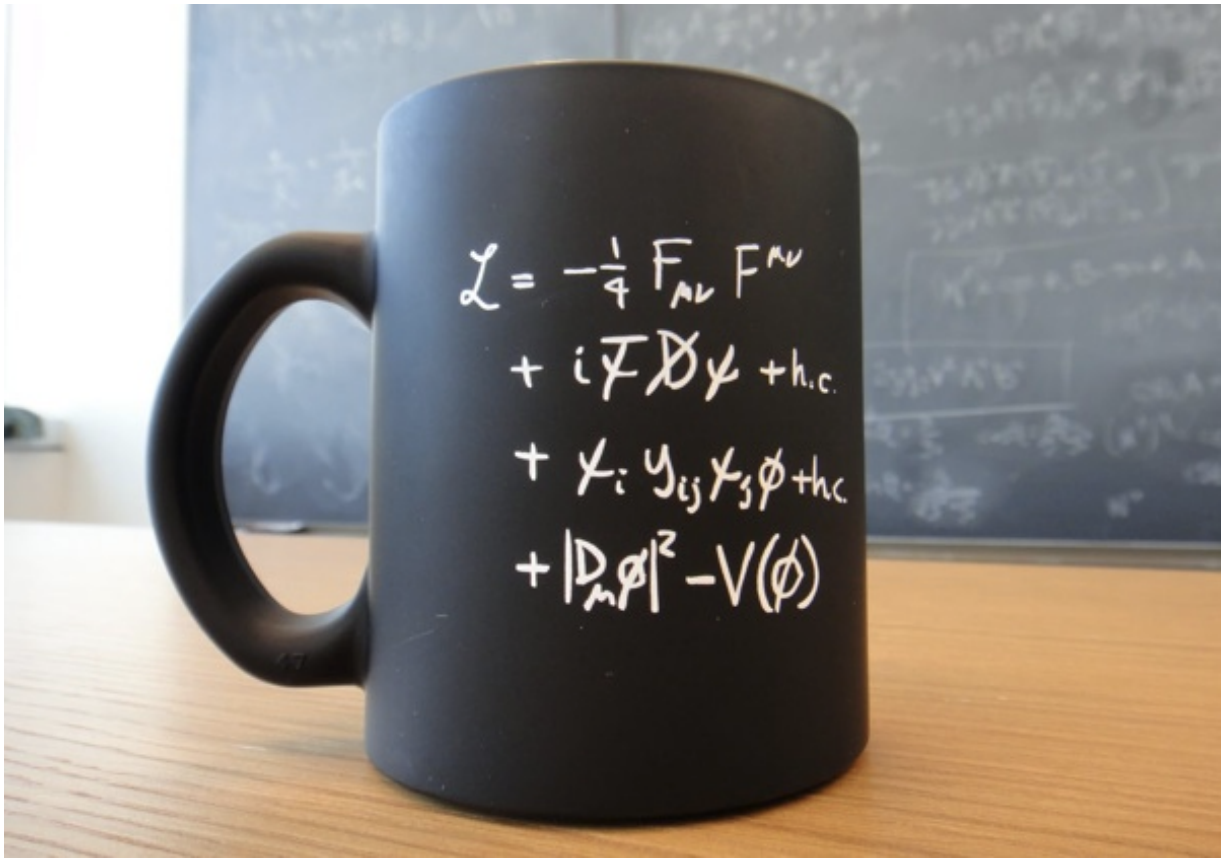
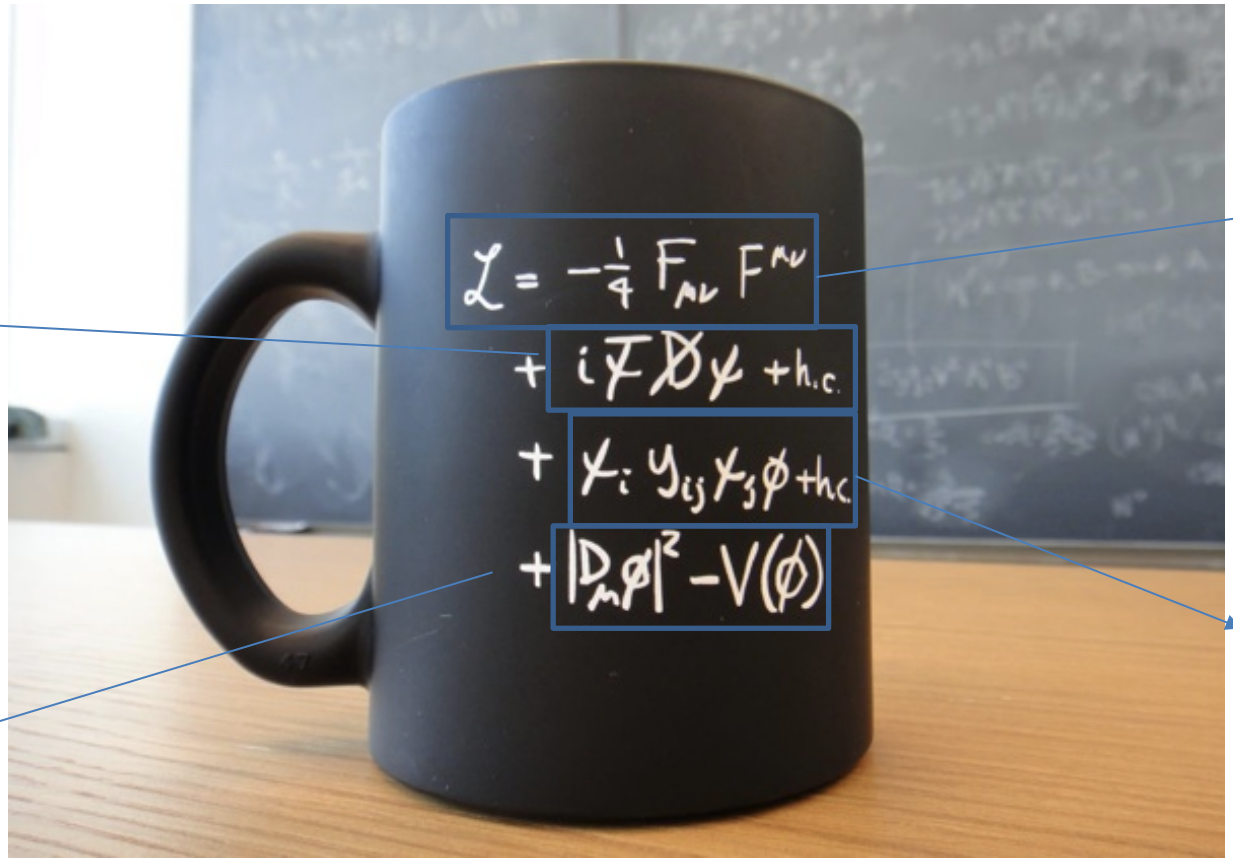


Kinetic mixing



Kinetic mixing



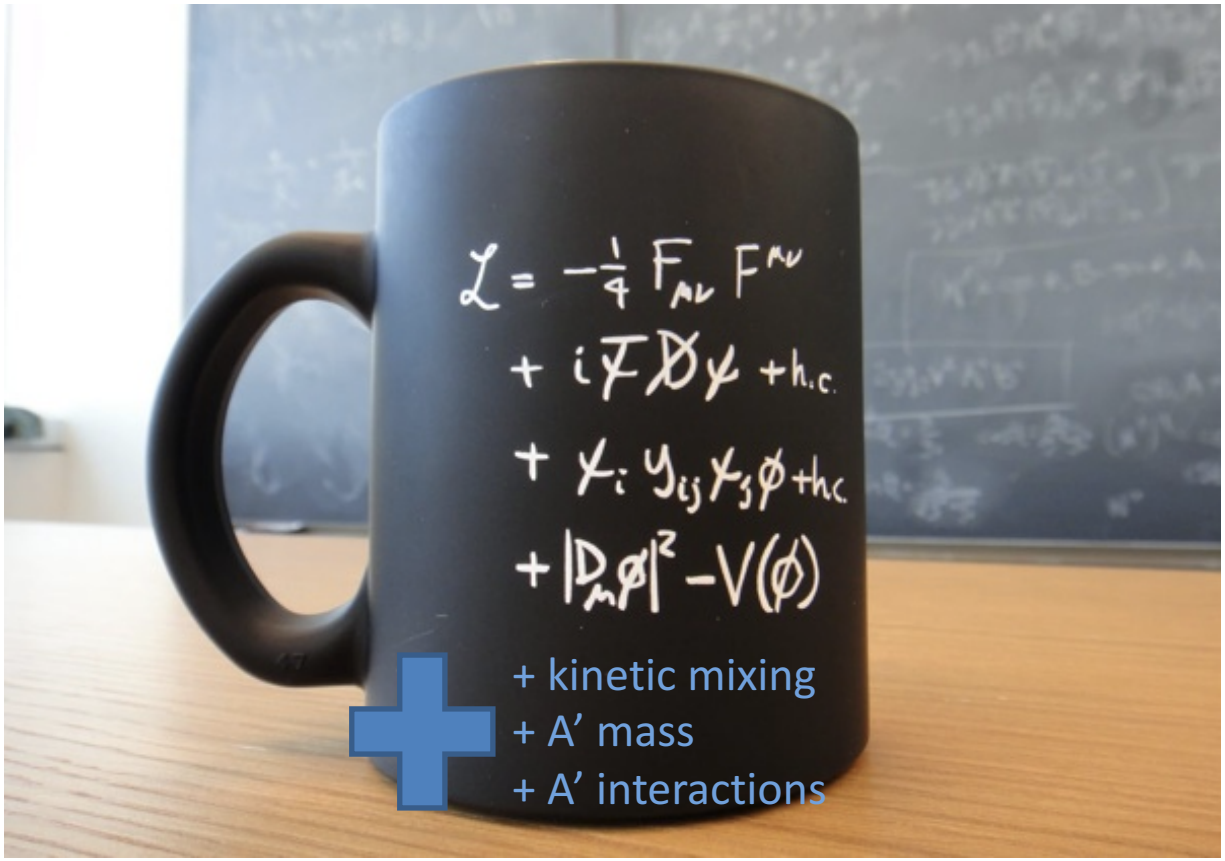
Kinetic terms for fermions

Kinetic terms for bosons (makes fields 'dynamic')

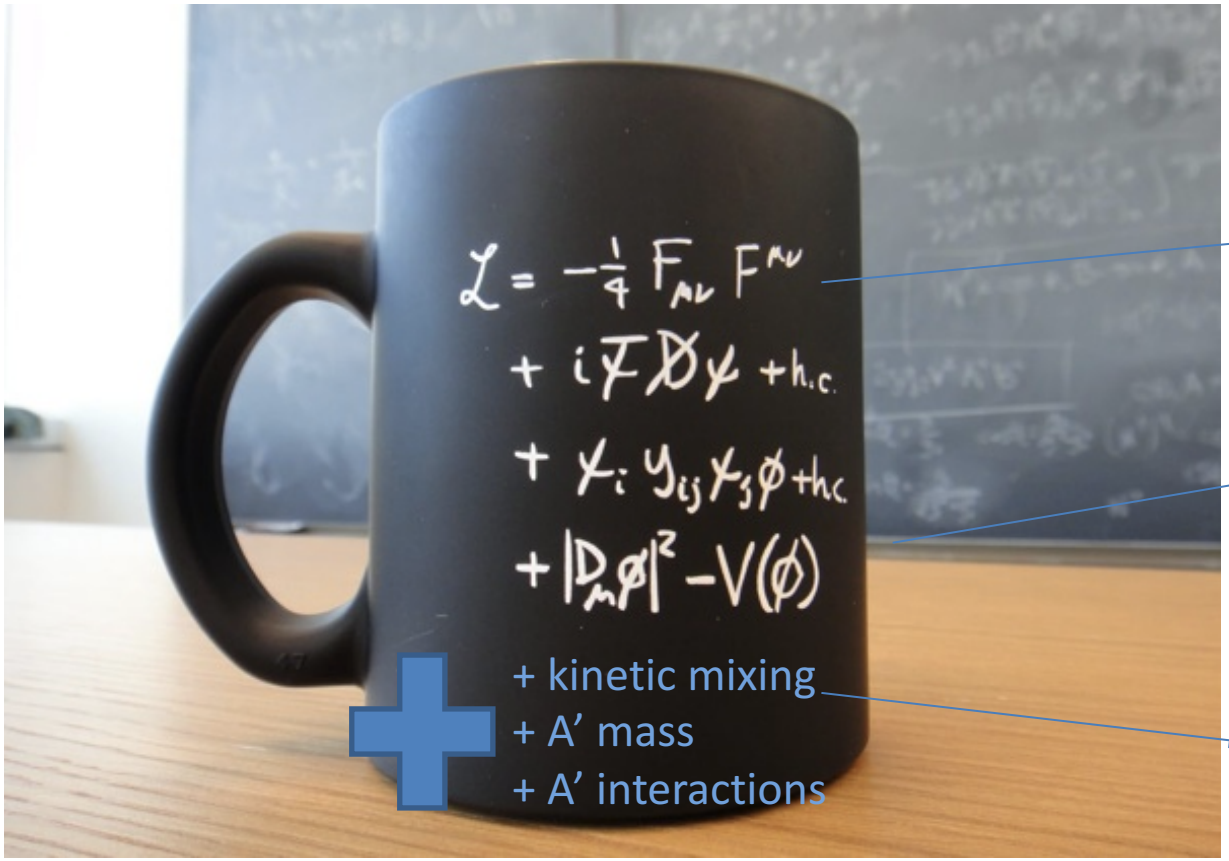
Higgs potential

Interaction terms (connects fields together)

Kinetic mixing



Kinetic mixing



Kinetic mixing

$$-\frac{1}{4} F'_{\mu\nu} B^{\mu\nu}$$

A' interactions

$$+\epsilon e A'^{\mu} J^{EM}_{\mu}$$

A' mass

$$+\frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$$

Renormalizable extension to SM!

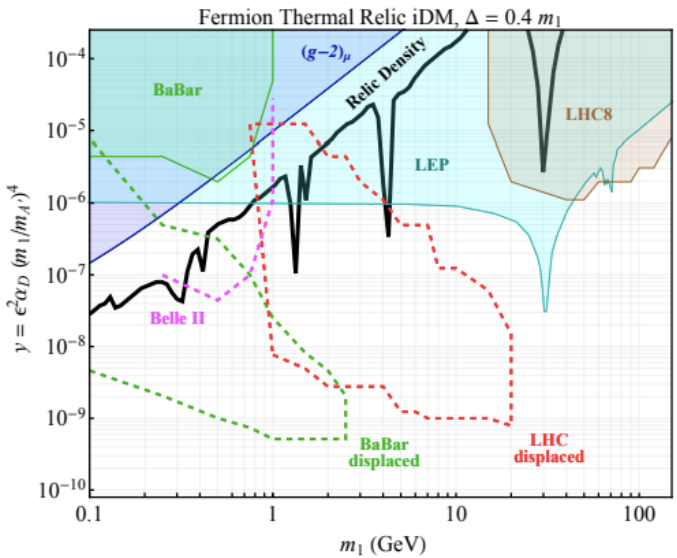
Preliminary event selection

- MC scaled to correct cross-sections, and CMS 2018 luminosity (59.97 1/fb)
- QCD only major leftover background

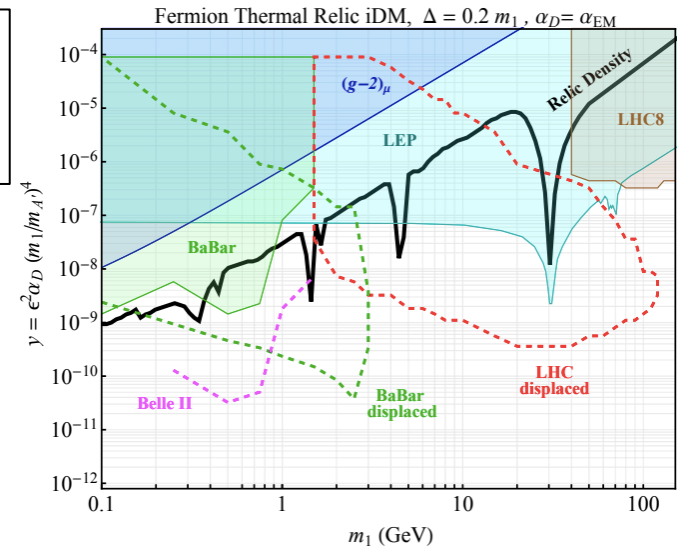
Cut	DY	QCD	TTbar	V+Jets	Di-boson
Initial	320,515,927	73,223,324,490	30,140,886	213,689,064	310,108
MET + MHT trigger (120 GeV)	135,564	1,685,736	1,163,196	7,621,102	22,300
Leading jet pT > 120 GeV, <= 2 jets w/ pT > 30 GeV	28,611	228,249	17,433	2,494,019	1,918
Leading mu pT > 5 GeV, 0.1 < dxy < 700 cm	99	13,629	202	6,653	6
Subleading mu pT > 5 GeV, 0.1 < dxy < 700 cm	0	362	2	16	0
DeltaPhi(MET, di-muon) < 0.4	0	317	0	0	0

Expected sensitivity

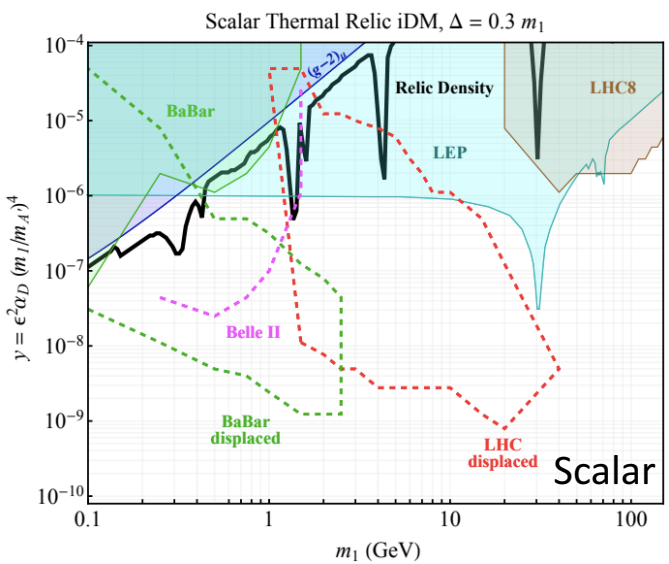
1508.03050



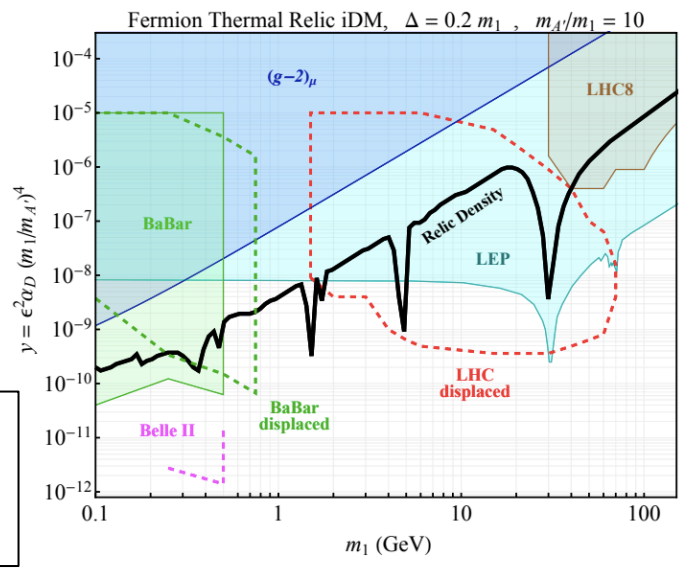
$\Delta = 0.2\ m_1$
$\alpha_D = \alpha_{EM}$
$m_{A'} = 10\ m_1$



$\Delta = 0.4\ m_1$
$\alpha_D = 0.1$
$m_{A'} = 3\ m_1$



$\Delta = 0.3\ m_1$
$\alpha_D = 0.1$
$m_{A'} = 3\ m_1$



$\Delta = 0.2\ m_1$
$\alpha_D = 0.1$
$m_{A'} = 10\ m_1$

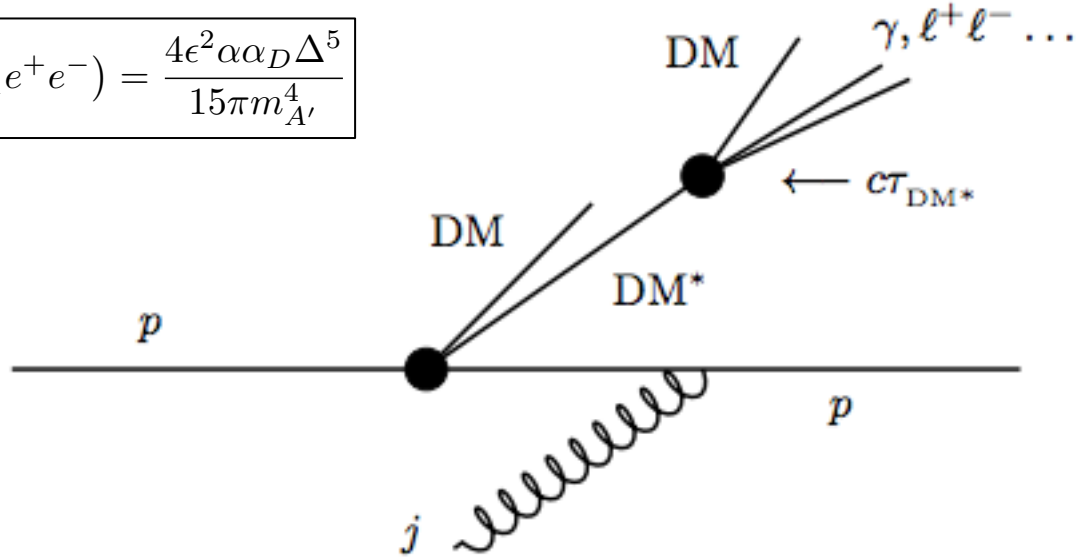
Inelastic DM with dark photons @ CMS

$$\sigma v \propto y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}}\right)^4$$

y = "Dimensionless interaction strength"

1508.03050

$$\Gamma\left(\chi_2 \to \chi_1 e^+ e^-\right) = \frac{4\epsilon^2 \alpha \alpha_D \Delta^5}{15\pi m_{A'}^4}$$



Parameters:

- Light DM mass: m_1
- Mass splitting: Δ
- Heavy DM lifetime: cτ
- A' mass = $3*m_1$

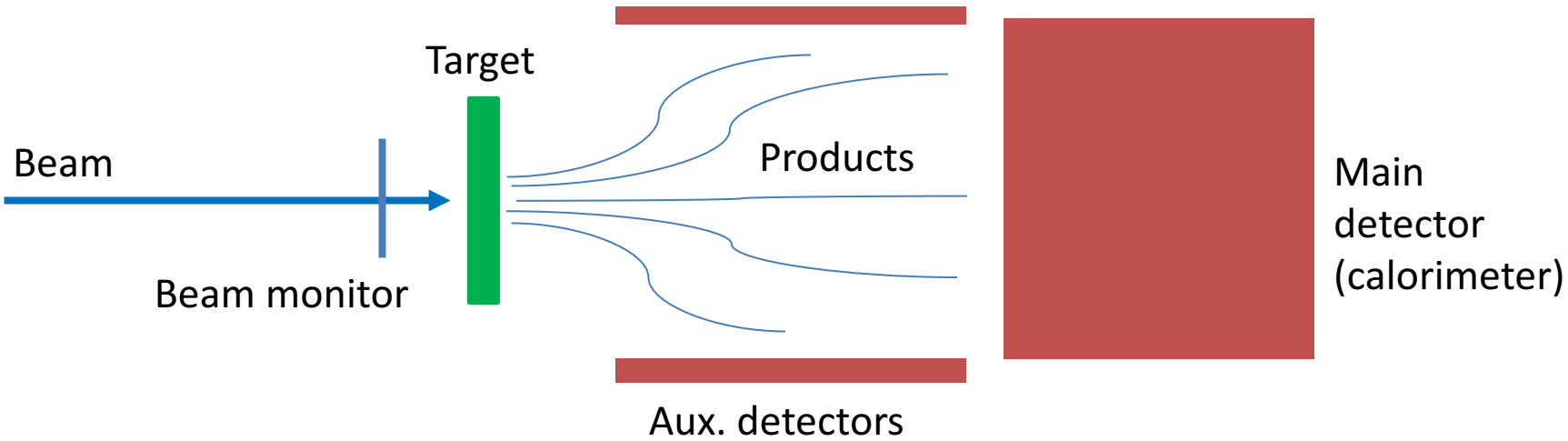
- m_1 : O(1 – 100 GeV)
- Δ : O(0.1 – 0.5 m_1)
- cτ : O(1 – 1000 mm)

- Final state signature: MET collimated w/ soft, displaced, narrow di-lepton pair, recoiled against ISR

Fixed-target experiments

SM + SM → DM + DM

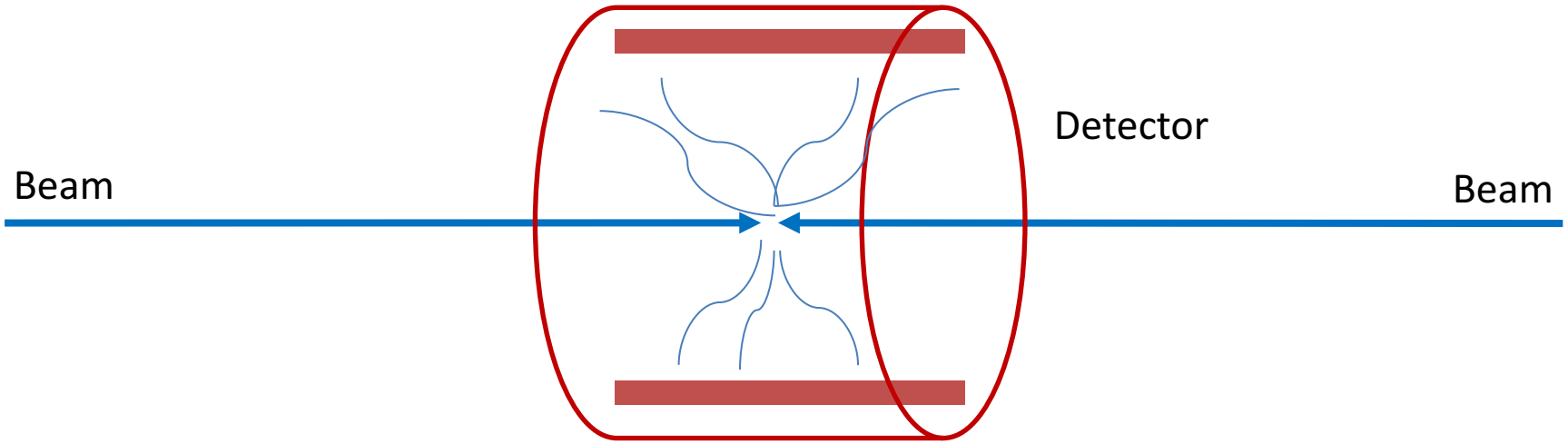
- General principles:
  - One beam (e-, e+, protons, neutrinos, …)
  - One target (C, Be, W, …)
  - Detectors in front of target to measure beam
  - Detectors behind target to measure products



General-purpose collider expts

SM + SM → DM + DM

- General principles:
  - Two beams (e-, e+, protons, …) collide
  - Detectors around collision, full solid angle
  - Cylindrical geometry
  - Large magnetic field inside detector



Fixed-target vs collider

- Fixed-target experiments:
  - Fewer backgrounds
  - Smaller scale
  - Less energy (phase space coverage)
  - Not hermetic
- Collider experiments:
  - Lots of backgrounds
  - Huge scale needed
  - Larger energies accessible
  - Hermetic coverage possible