Dark sectors and missing energy searches at the LHC

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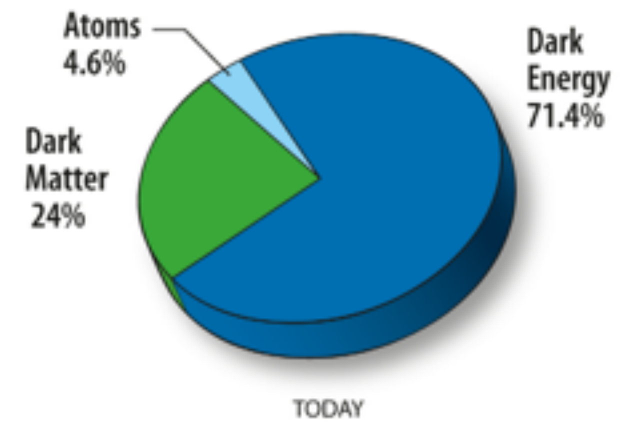
October 9, 2015
GGI workshop, “Gearing up for LHC13”

with M. Autran, K. Bauer, D. Whiteson (1504.01386)
with Y. Bai, J. Bourbeau (1504.01395)

Is there dark matter?

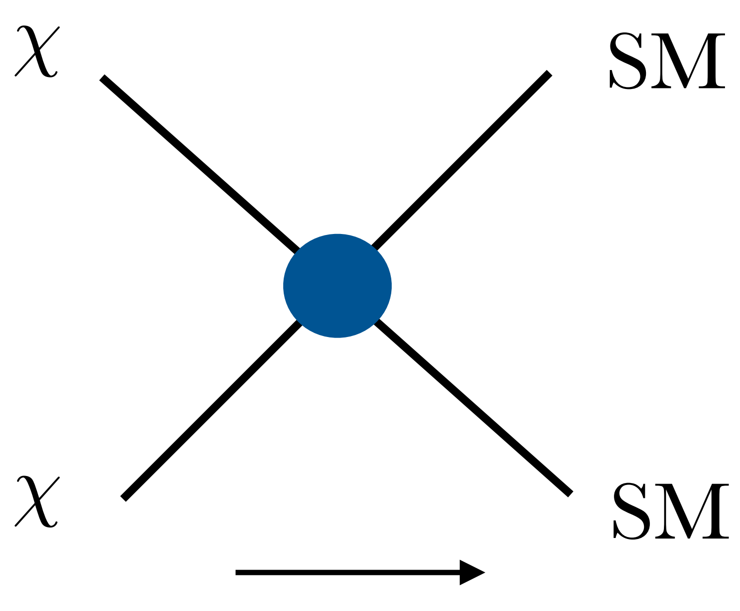


Is dark matter a new field/ particle?

Does the dark matter have (non-gravitational) interactions?

Does dark matter have gauge interactions?

- Interactions mediated by SM gauge bosons are highly constrained, if we want those same interactions to set a thermal relic abundance.



Thermal WIMP freezeout:

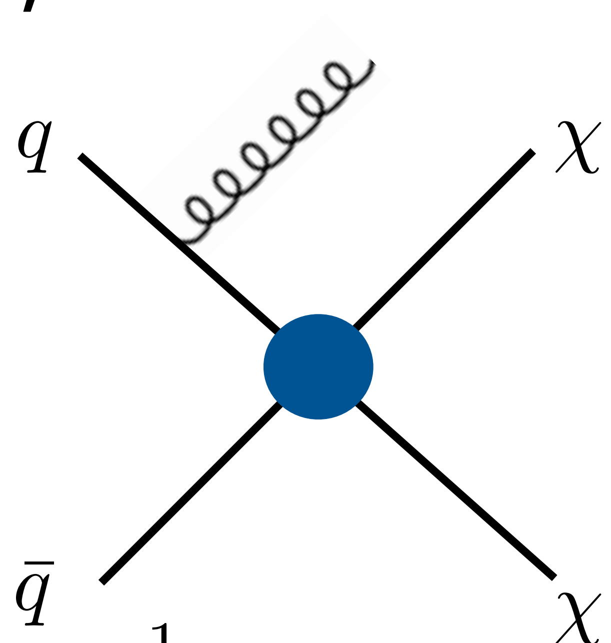
$$\Omega_{cdm} \propto \frac{1}{\langle \sigma v \rangle} \qquad \langle \sigma v \rangle \propto \frac{1}{M_W^2}$$

Matches observed abundance when annihilation rate (interactions) are "weak-scale"…

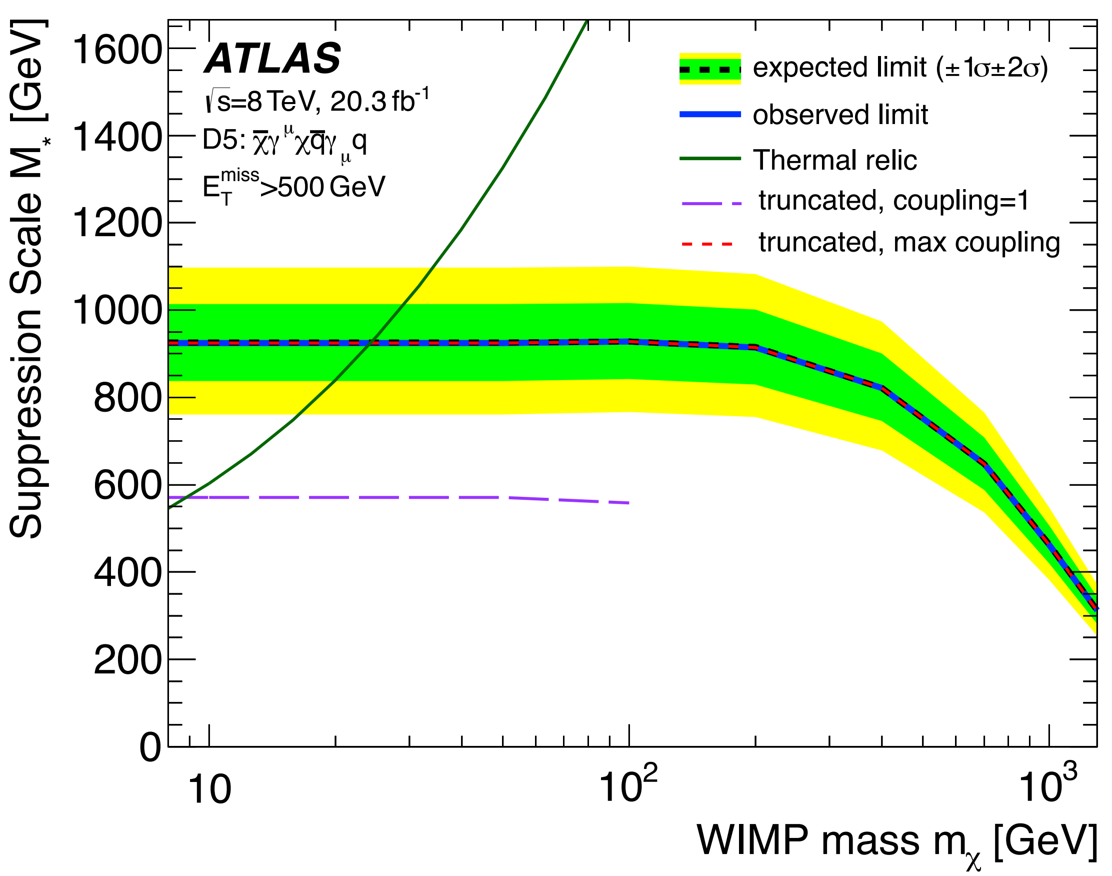
Does dark matter have gauge interactions?

- The framework of WIMP dark matter has guided many dark matter searches, but has not yielded any clear signals in direct detection, indirect detection, or colliders.

Initial state radiation to tag on dark matter events:



$$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

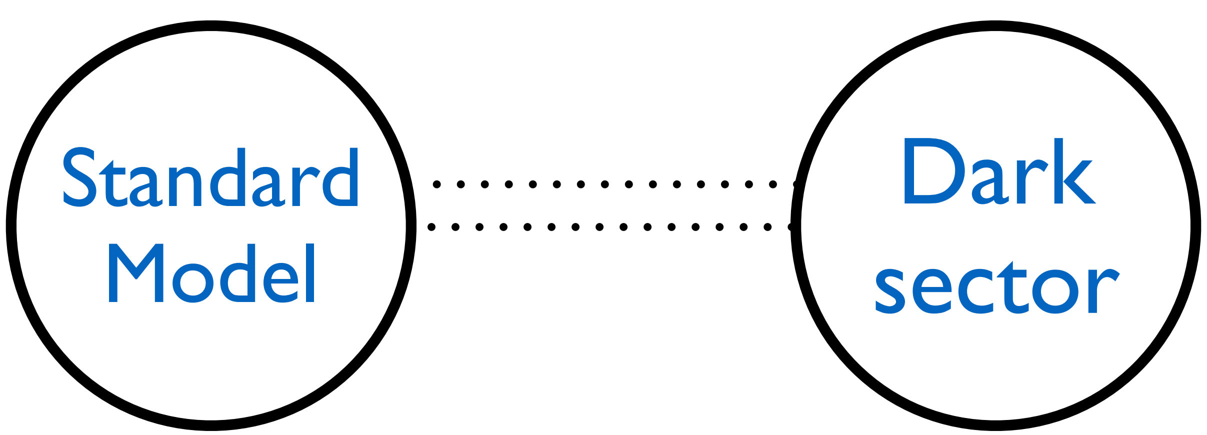


What if dark matter is charged under new gauge interactions?

- We can have a dark sector including dark matter (plus other states) and dark gauge group.

- SM states neutral, talk to dark sector by weak coupling or high mass scale.

- How can this scenario be probed in experiments?



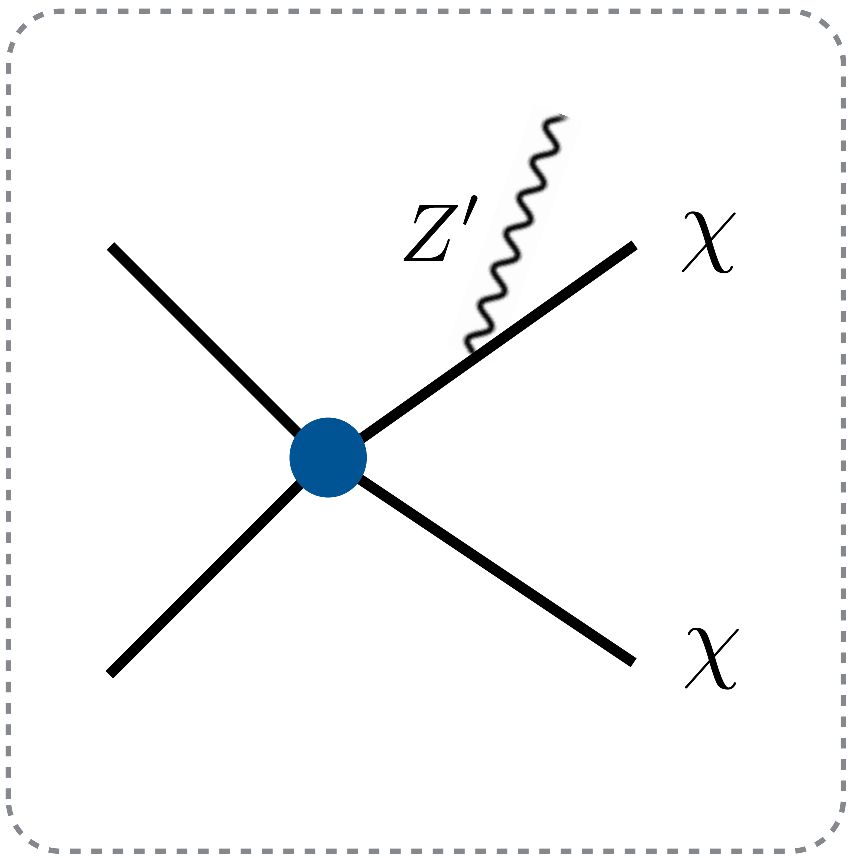
New opportunities for dark sector searches with colliders

Mass scale of dark sector: O(1) GeV – O(100) GeV

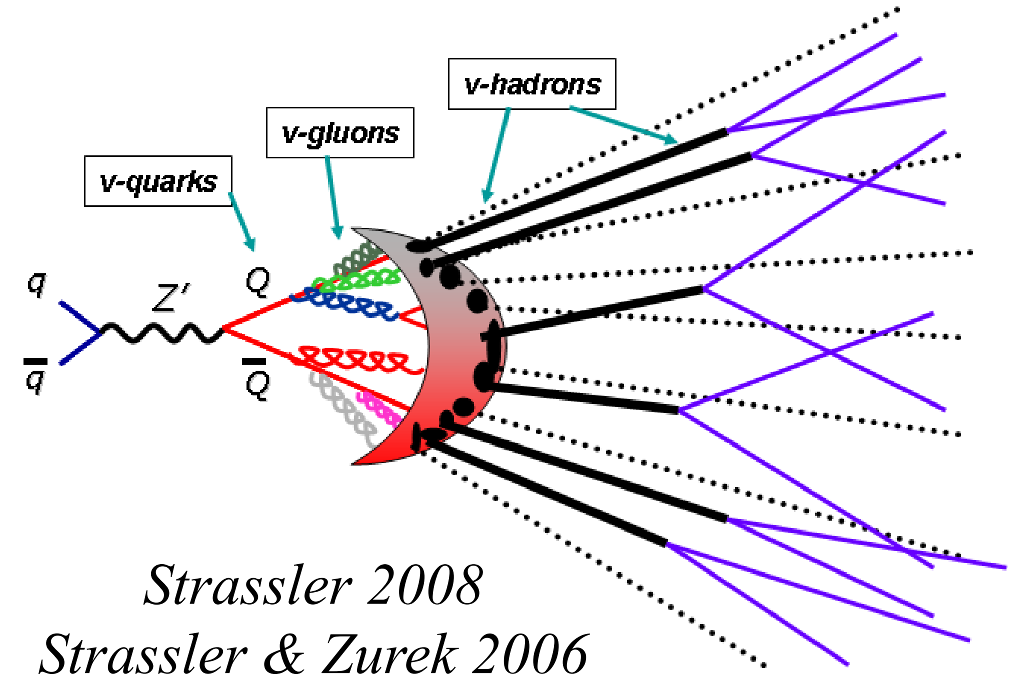
- Qualitatively new signals from hidden sector dynamics
- There can be radiation of new gauge bosons, including from the dark matter itself.
- Many cases can be experimentally challenging… motivates understanding of data, SM better.

Search strategies

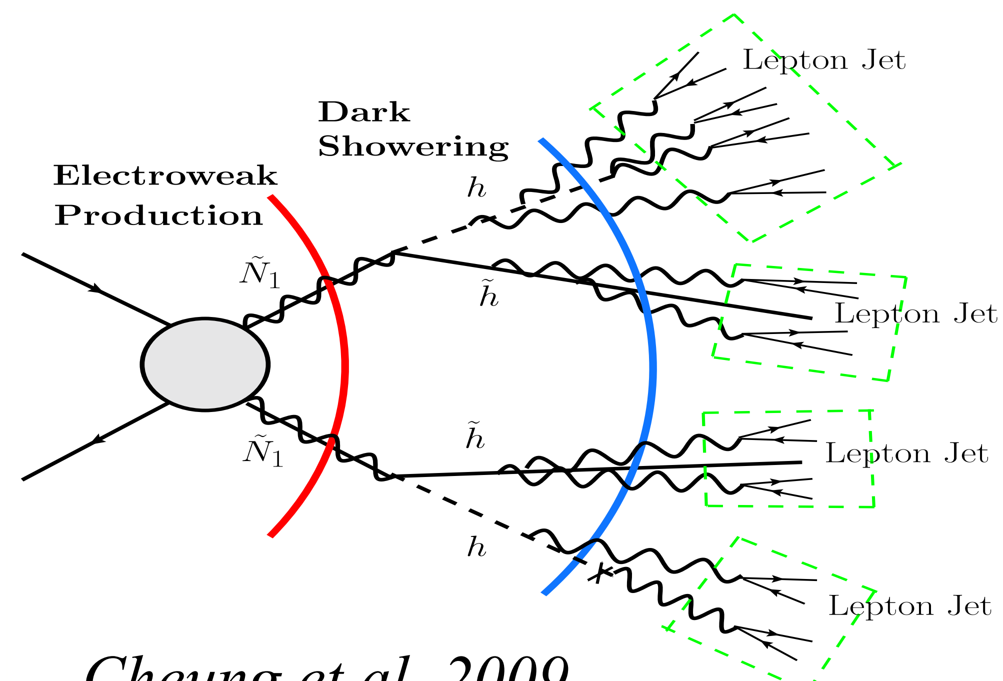
size of gauge group / dark sector coupling



U(1)′: Focus of talk today



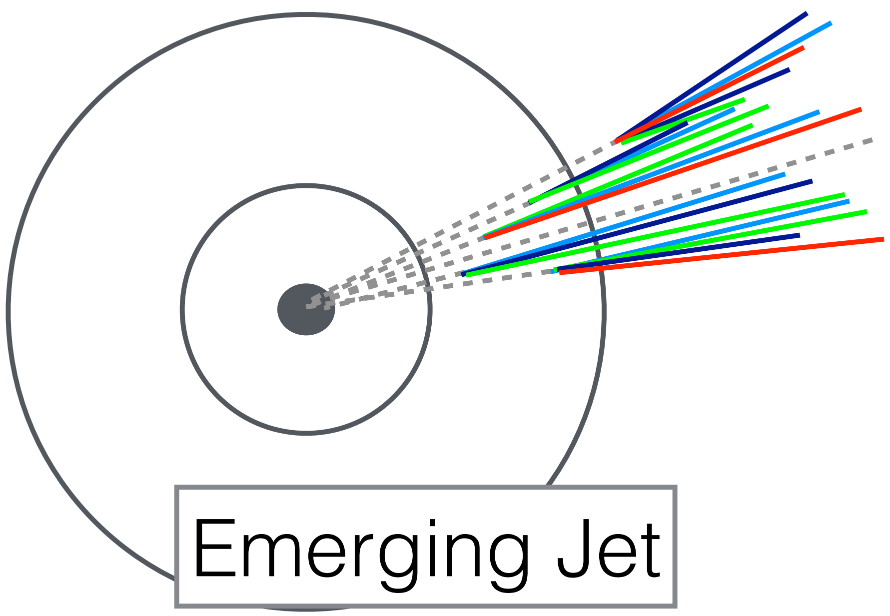
Strassler 2008
Strassler & Zurek 2006



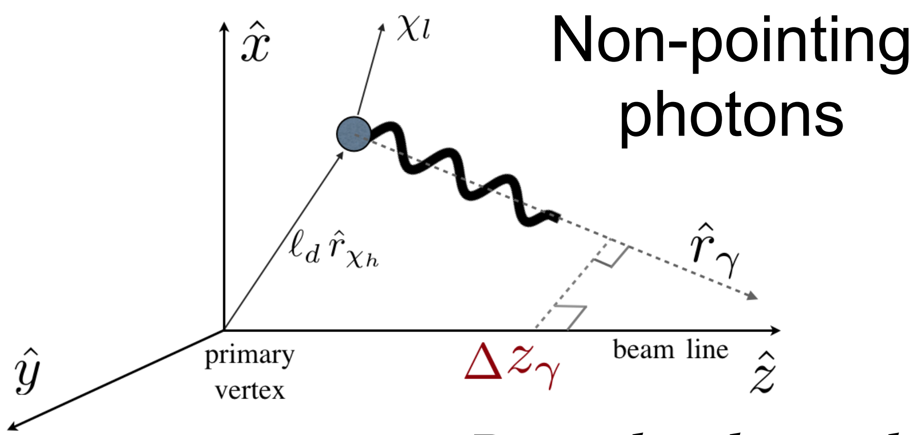
Cheung et al. 2009

MET multiplicity

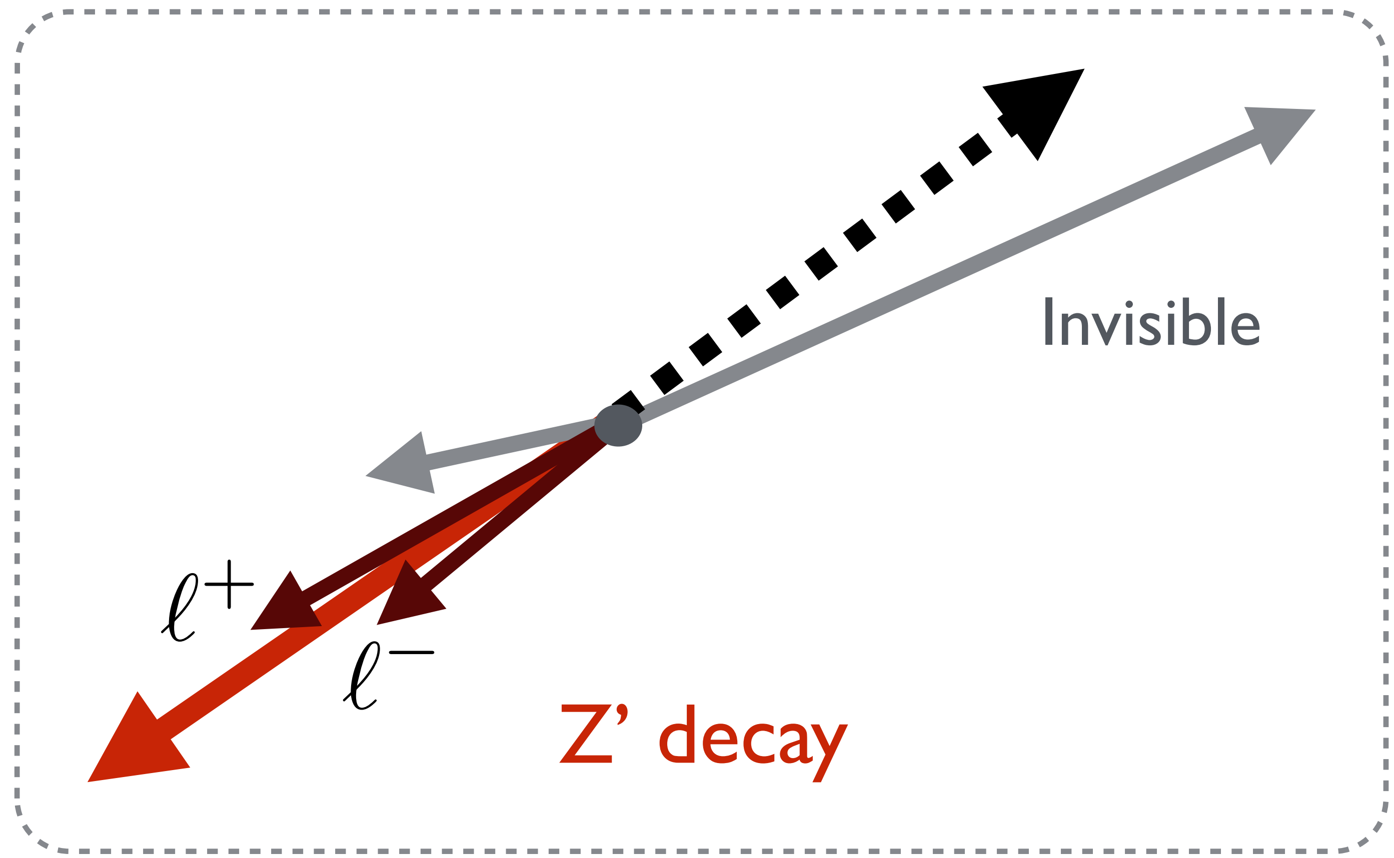
coupling to SM states



Schwaller et al. 2015



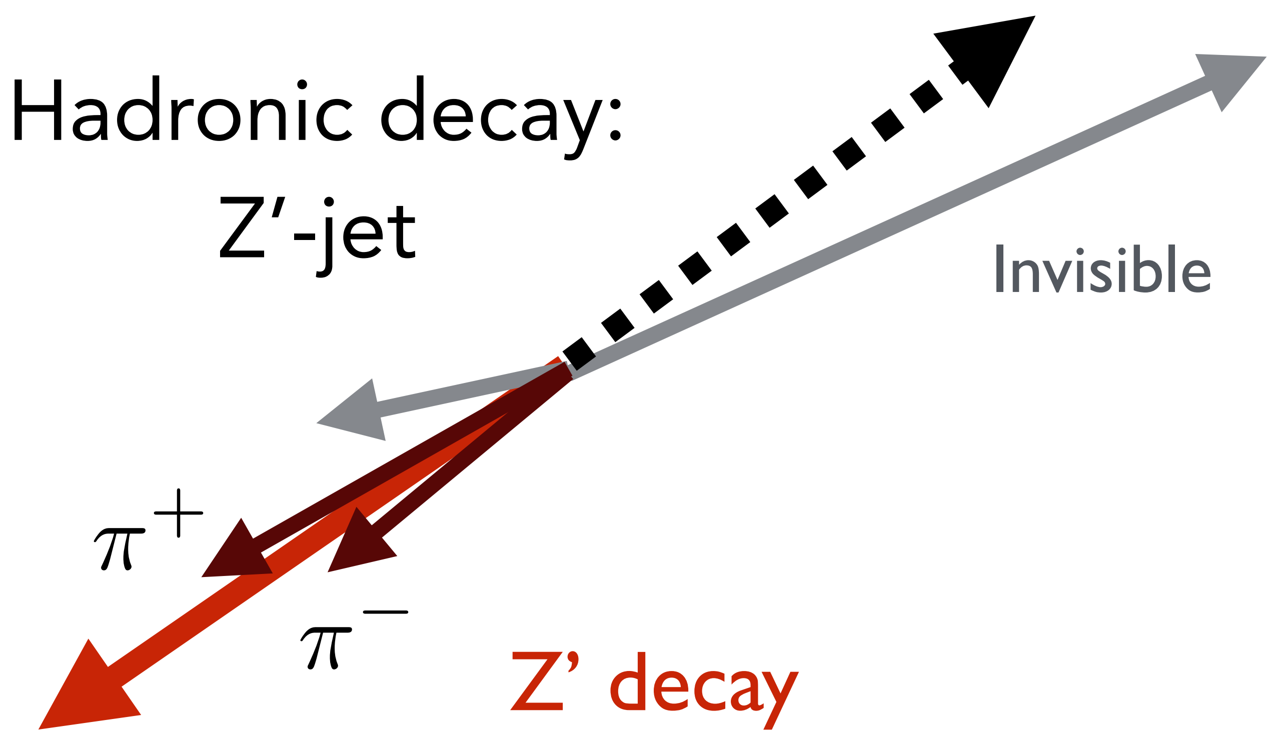
Primulando et al. 2015

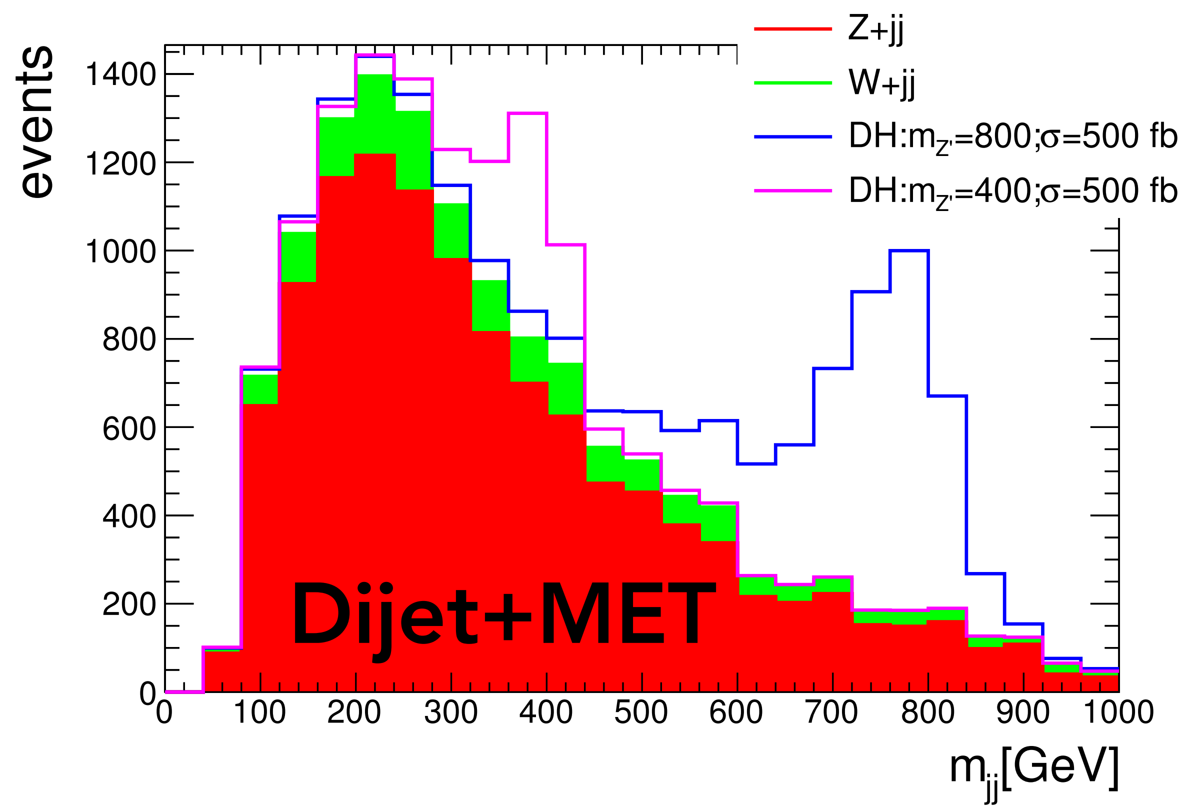


displaced

prompt

mass of new mediator





lepton jet/
narrow jet

resonance

Benchmarks

Dark matter and U(1)′

$$-m_\chi \bar{\chi}\chi + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

- Massive Z′ can decay to SM states
- Leptophobic couplings of light Z′, could be generated by operator like

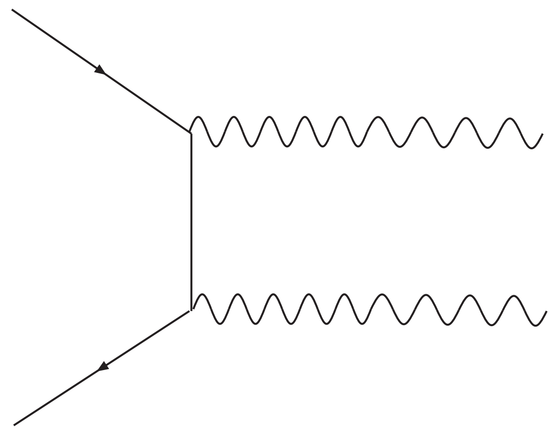
$$\frac{1}{\Lambda^2}\left(\phi^\dagger D_\mu \phi\right)\left(\bar{u}\gamma^\mu u\right)$$

- Could also consider kinetically mixed Z′ (epsilon constrained to 1e-3 for GeV mass)

Relic abundance:

$$\sigma v \sim \frac{\pi(\alpha_\chi)^2}{m_\chi^2}$$

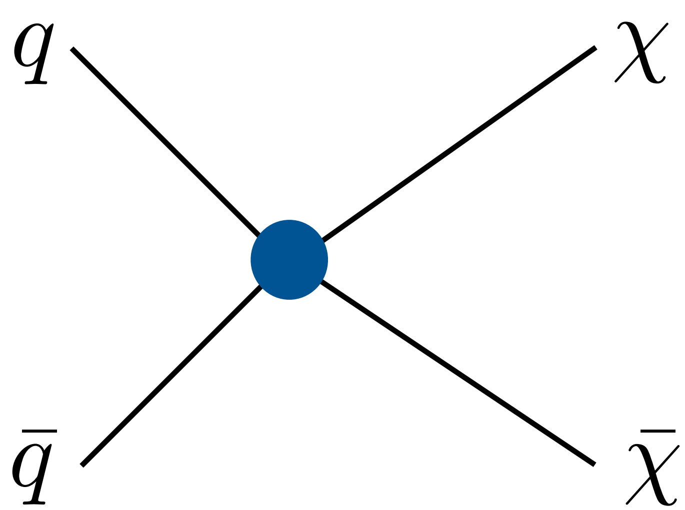
$$\alpha_\chi \gtrsim 5 \times 10^{-5}\left(\frac{m_\chi}{\mathrm{GeV}}\right)$$



Given CMB constraints, asymmetric DM for light vector, or symmetric if light scalar

Benchmarks

- Production through heavy states (hidden valley)



Assume contact operator

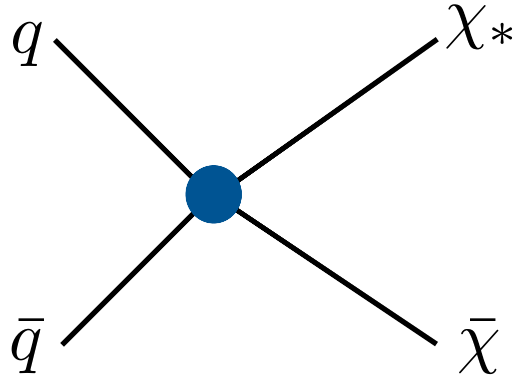
$$\mathcal{O}_V = \frac{\overline{\chi}\gamma^\mu\chi\,\overline{u}\gamma_\mu u}{\Lambda^2}$$

$$\mathcal{O}_A = \frac{\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{u}\gamma_\mu\gamma^5 u}{\Lambda^2}$$

- Part 2 (later): add a splitting (inelastic dark matter)

Adding dark higgs coupling / majorana mass:

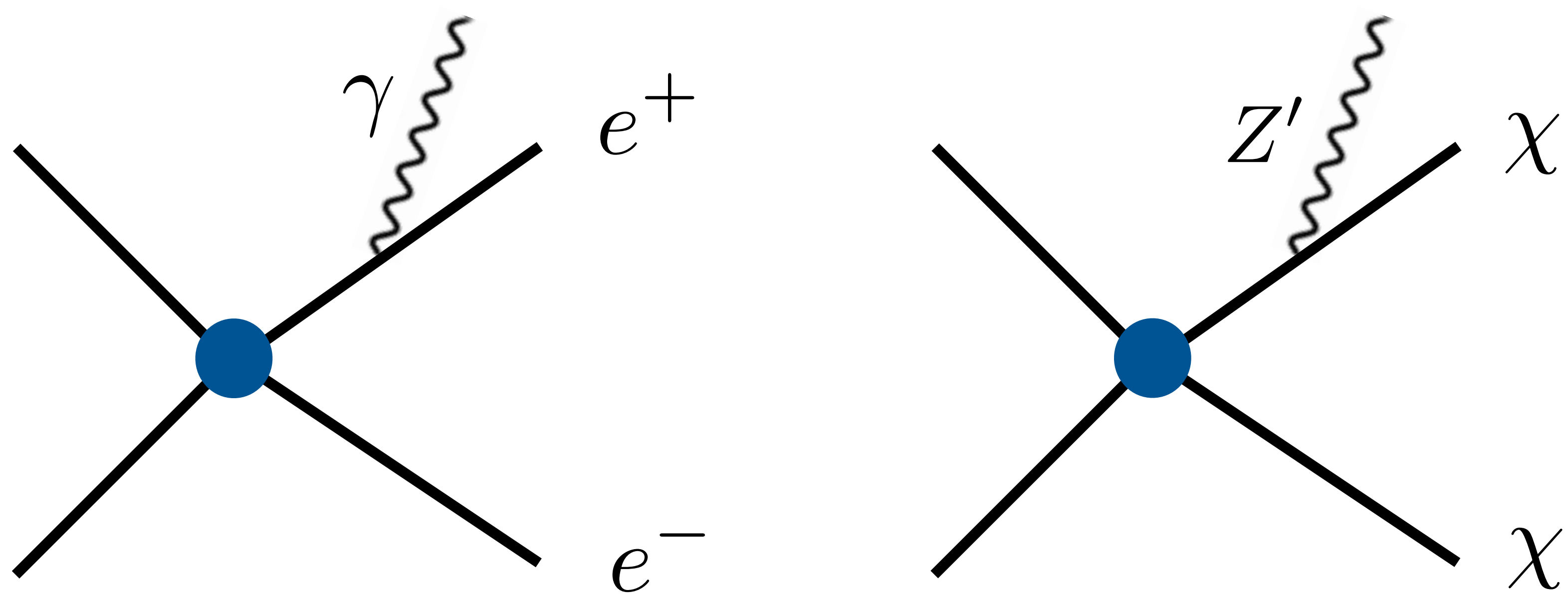
$$\frac{g_\chi}{2} Z'_\mu \left(\bar{\chi}_2\gamma^\mu\gamma^5\chi_1 + \bar{\chi}_1\gamma^\mu\gamma^5\chi_2\right)$$



Radiation from dark matter

- Final state radiation of DM in colliders - especially important if the dark matter is light and there is also a light force carrier

Analogous to radiation from charged particles:

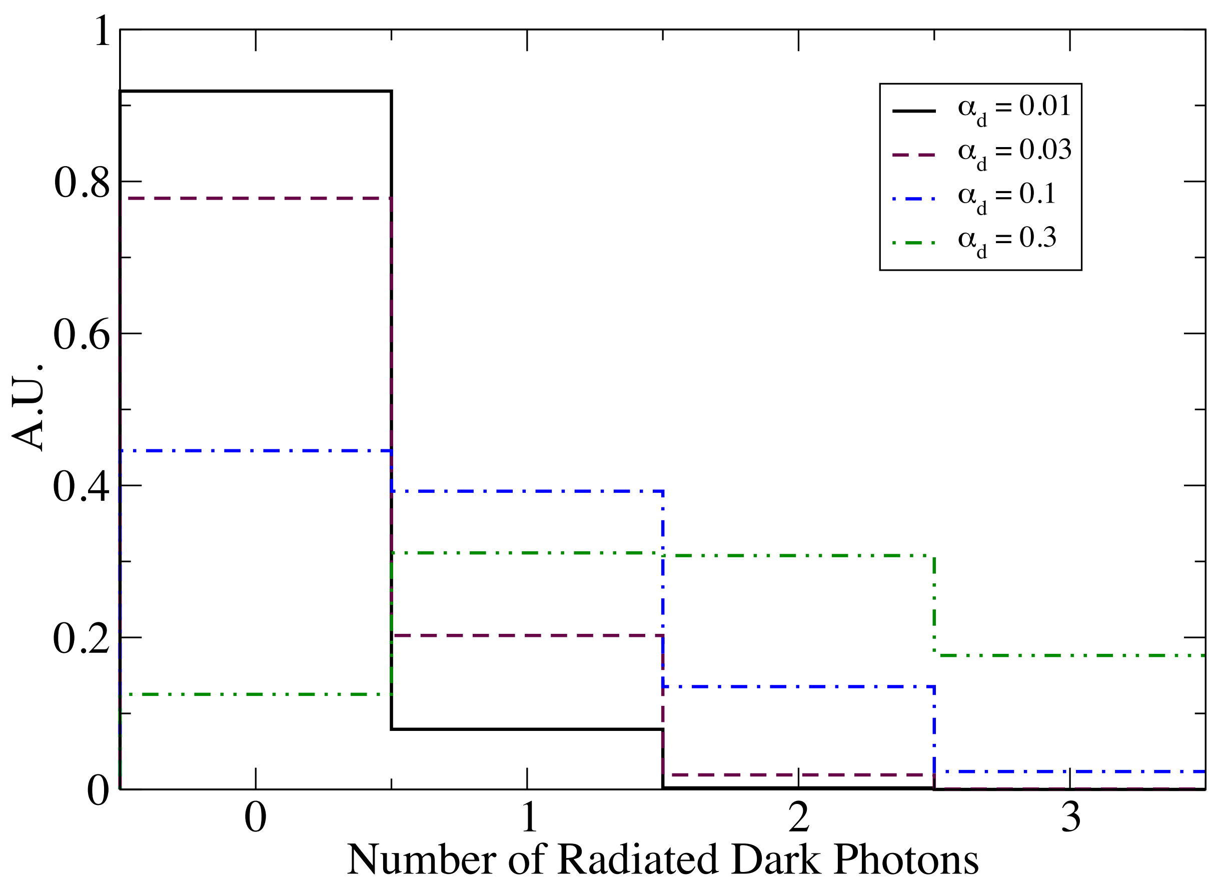


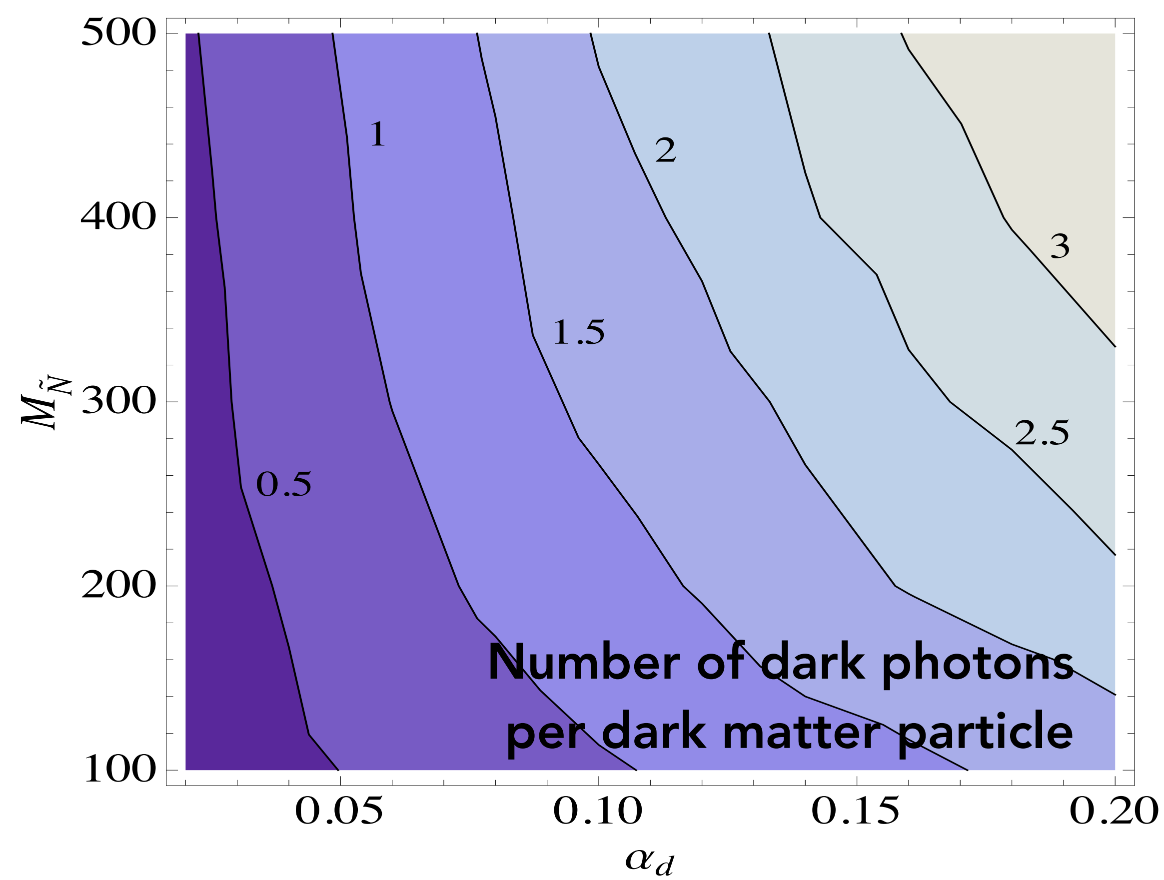
- I will focus on single emission of a somewhat high-pT Z'.

U(1)' case

- Emissions of Z' for large enough couplings and light mass scales.

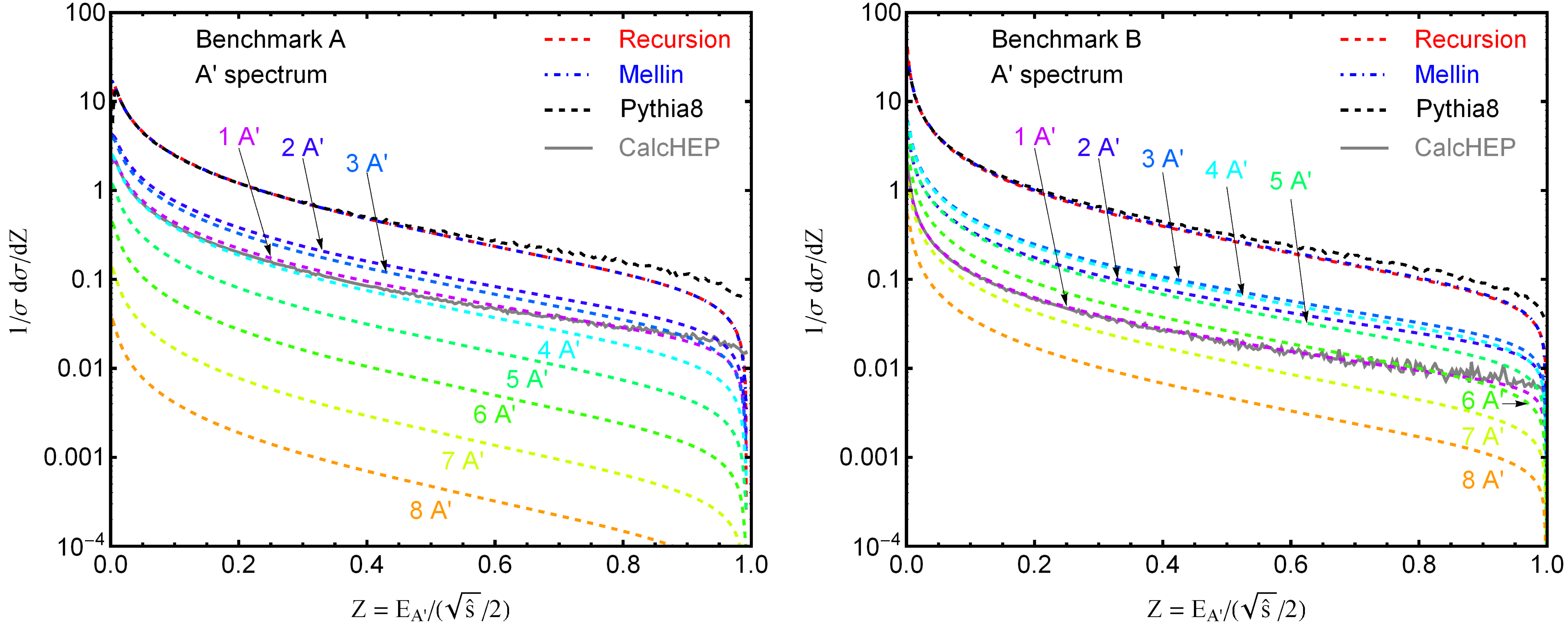
$$N \sim \frac{\alpha_\chi}{2\pi}\left[\log\left(\frac{q^2}{m_\chi^2}\right)\right]^2$$





Cheung, Ruderman, Wang, Yavin 2009

Spectrum of Z′ emitted



Z′ can carry away O(1) fraction of momentum

Buschmann, Kopp, Liu, Machado 2015

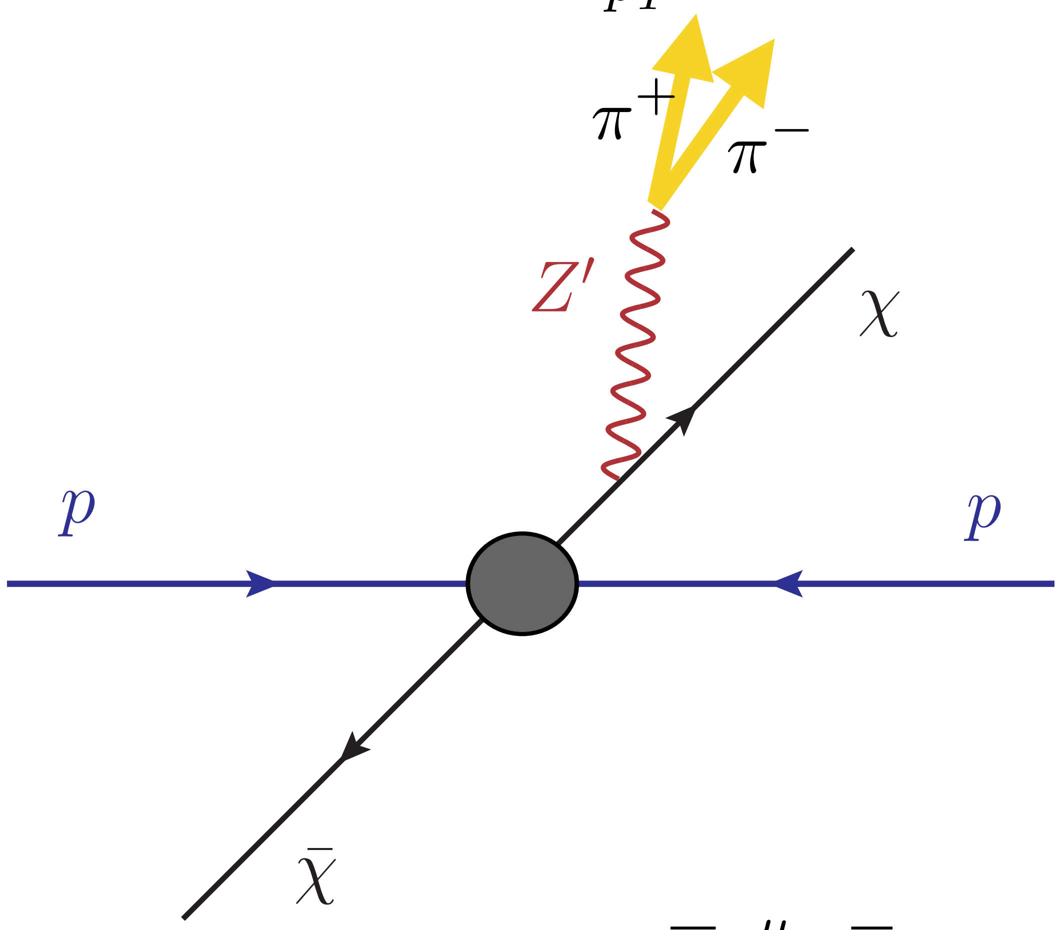
with Yang Bai & James Bourbeau, 2015

Mono-Z' jets

- GeV-scale Z' **decaying to hadrons** → new narrow jet signature in the highly boosted regime

- One way for GeV-scale Z's to couple to SM is through kinetic mixing. Expect both lepton jets, light Z' jets

$$\delta\theta \sim \frac{M_{Z'}}{p_T} \sim 10^{-3} - 10^{-2}$$



$$\mathcal{O}_V = \frac{\overline{\chi}\gamma^\mu\chi\,\overline{u}\gamma_\mu u}{\Lambda^2}$$

$$\mathcal{O}_A = \frac{\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{u}\gamma_\mu\gamma^5 u}{\Lambda^2}$$

Light Z′

- Assume Z′ has small coupling to SM fermions, with a prompt decay on collider scales as long as coupling is larger than roughly 1e-5

- Distinguishing variables not very sensitive to model (Z′ decay) specifics. For example:

$$\overline{u}\gamma_\mu u \to \pi^+\partial_\mu\pi^- - \pi^-\partial_\mu\pi^+ + K^+\partial_\mu K^- - K^-\partial_\mu K^+$$

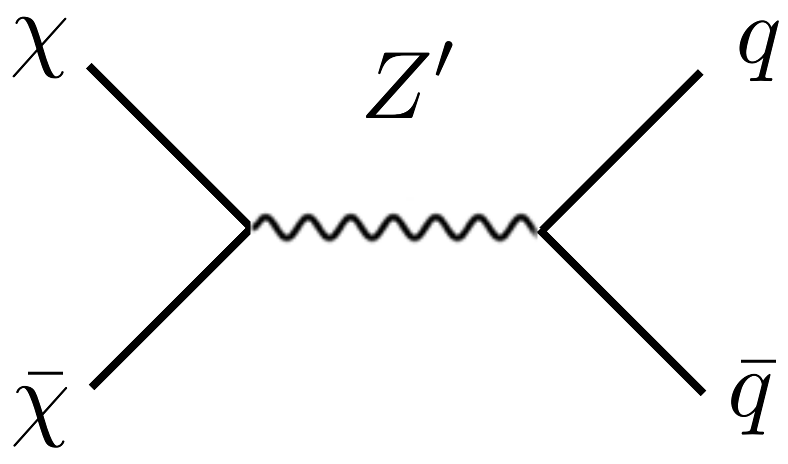
- Compare kinetic mixing, with constraints on ϵ down to 1e-3.

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}B^{\mu\nu}$$

Coupling of Z′ to SM fermions:

$$g_{\bar{f}fZ'} \simeq \begin{cases} -\epsilon c_w e Q_f & M_{B'} \ll \overline{M}_Z \\ -\epsilon g_y Y_f & M_{B'} \gg \overline{M}_Z \end{cases}$$

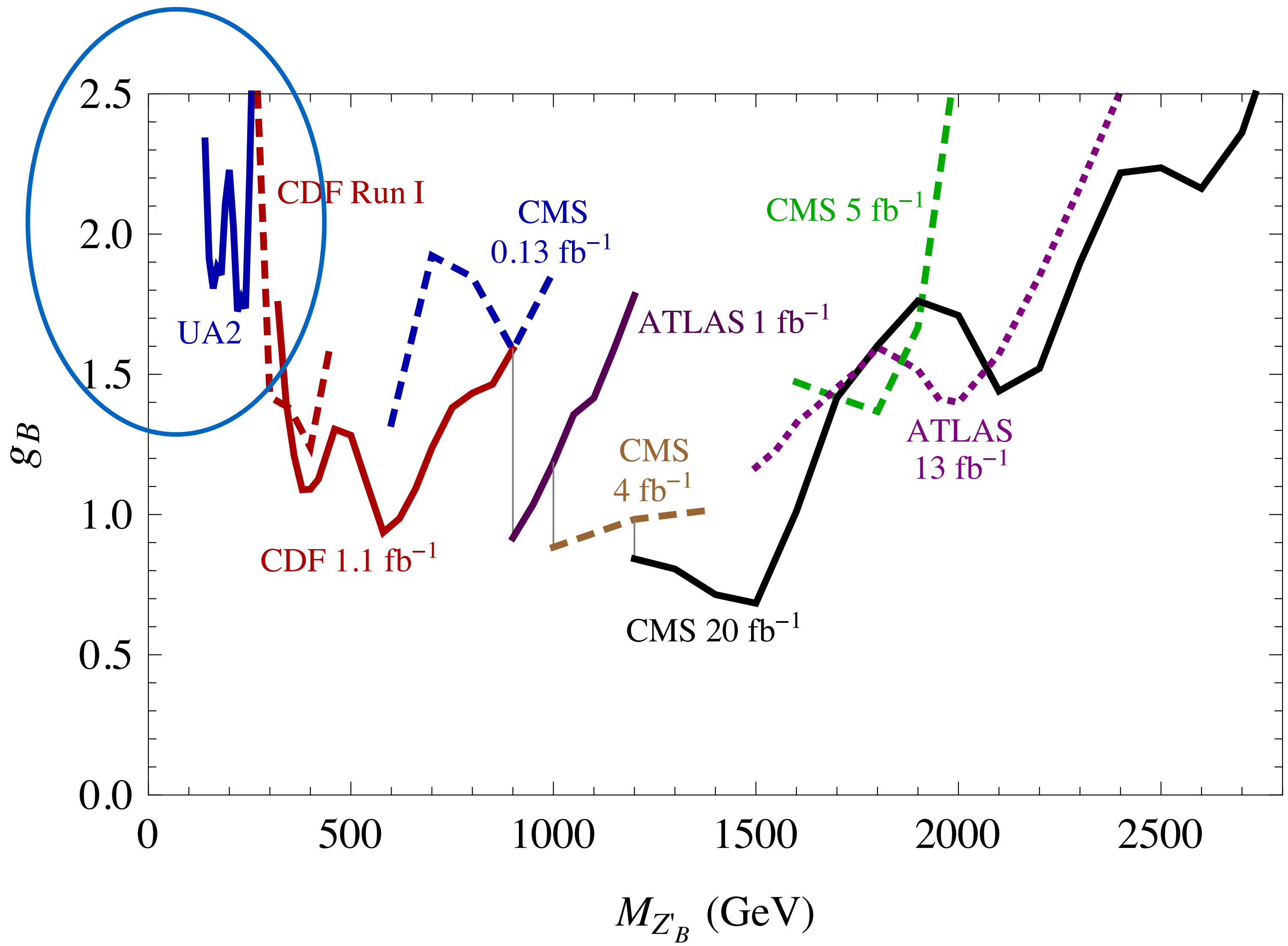
Z′ coupling to quarks



Low mass leptophobic Z′s:

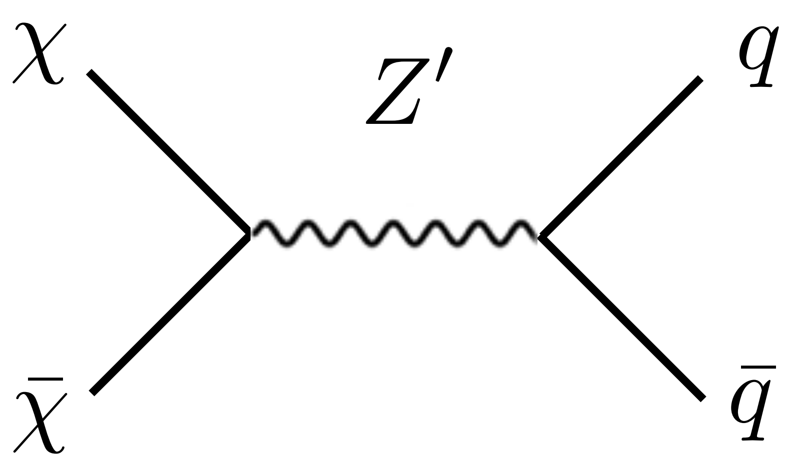
- *Carone & Murayama 1994*
- *Frugiuele & Dobrescu 2014*
- *Tulin 2014*
- …

Low mass Z′ is difficult to search for in dijets:



Dobrescu & Yu 2013

Z′ coupling to quarks



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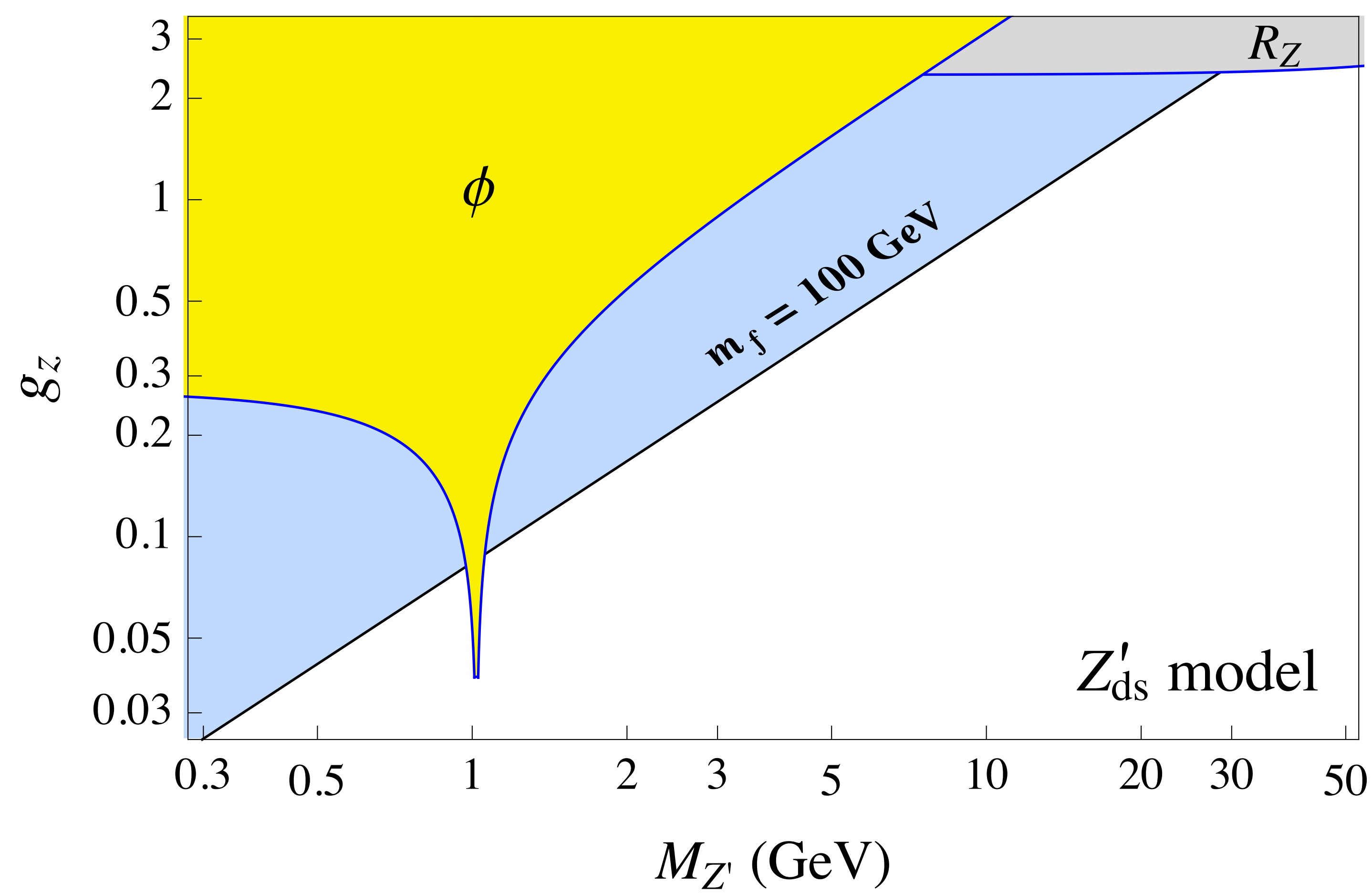
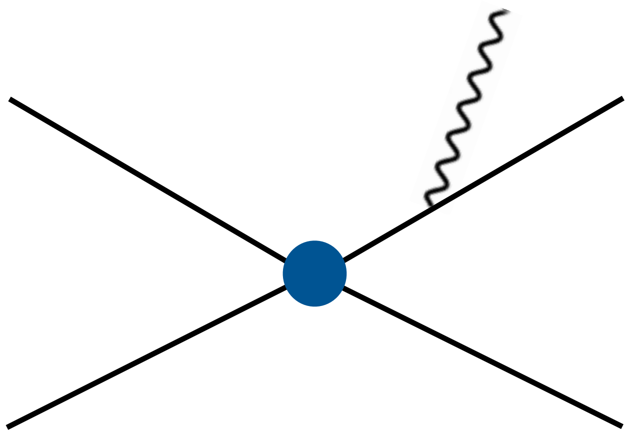


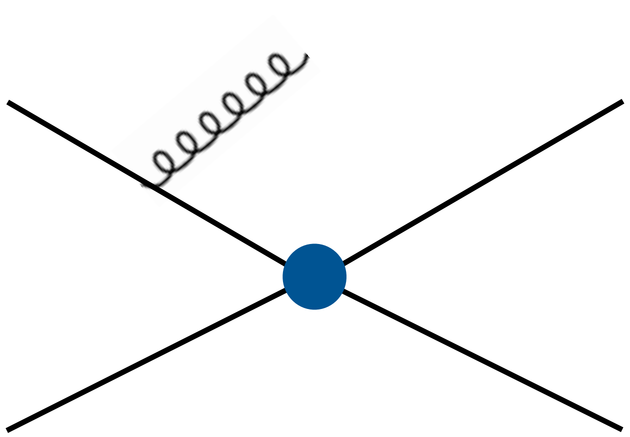
Dobrescu & Frugiuele 2014

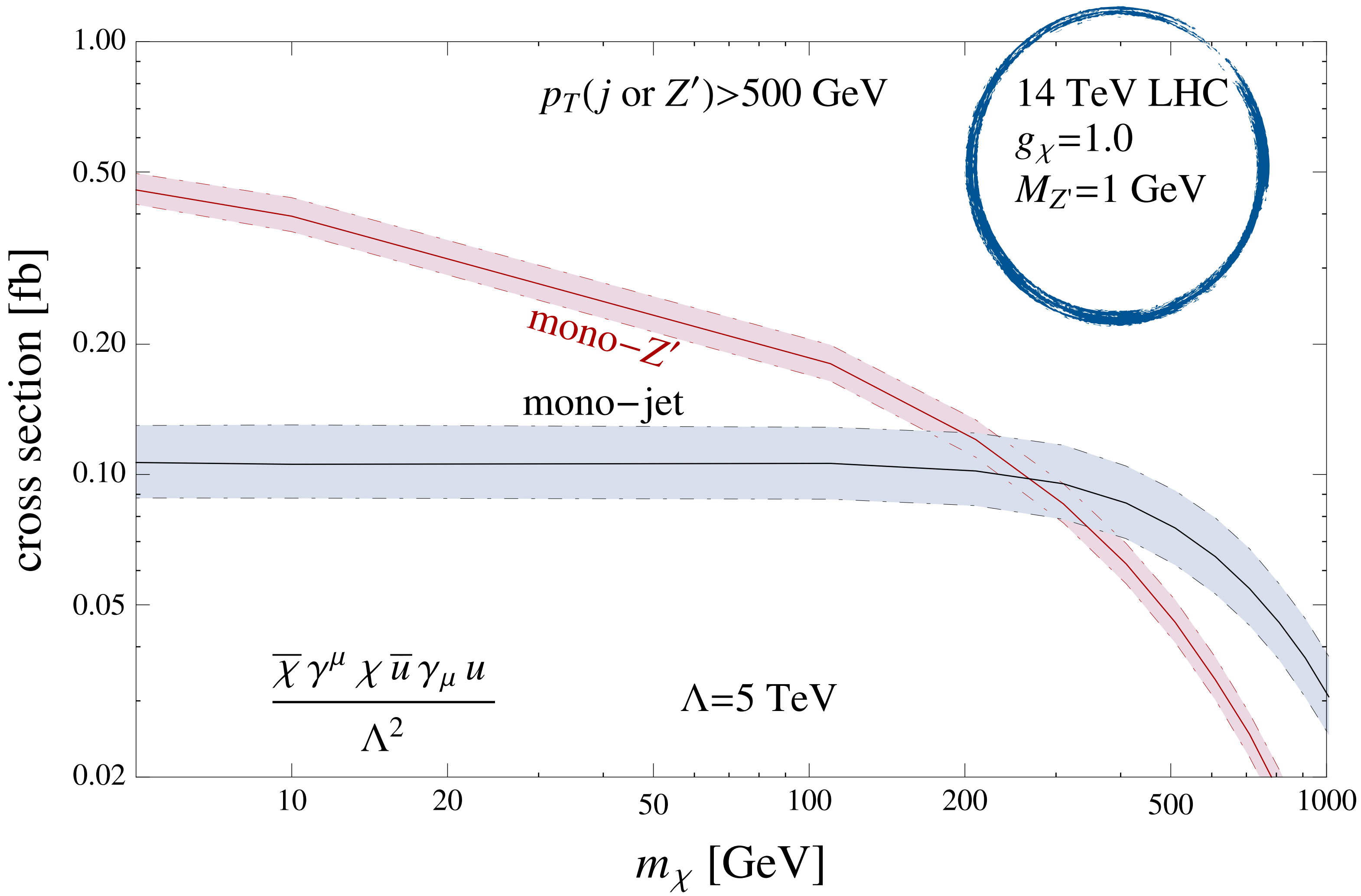
Final state radiation from dark matter

mono-Z′

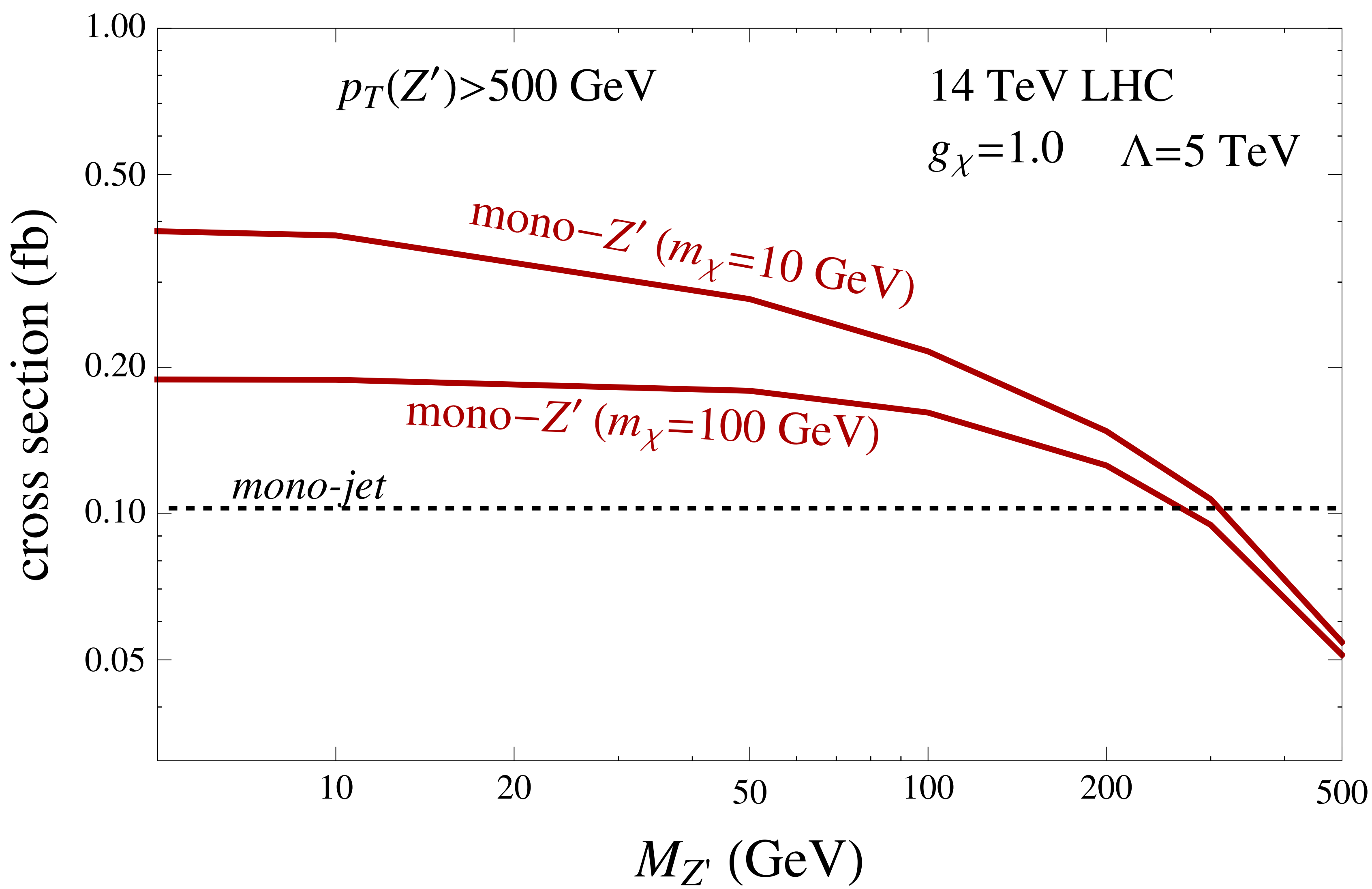


monojet





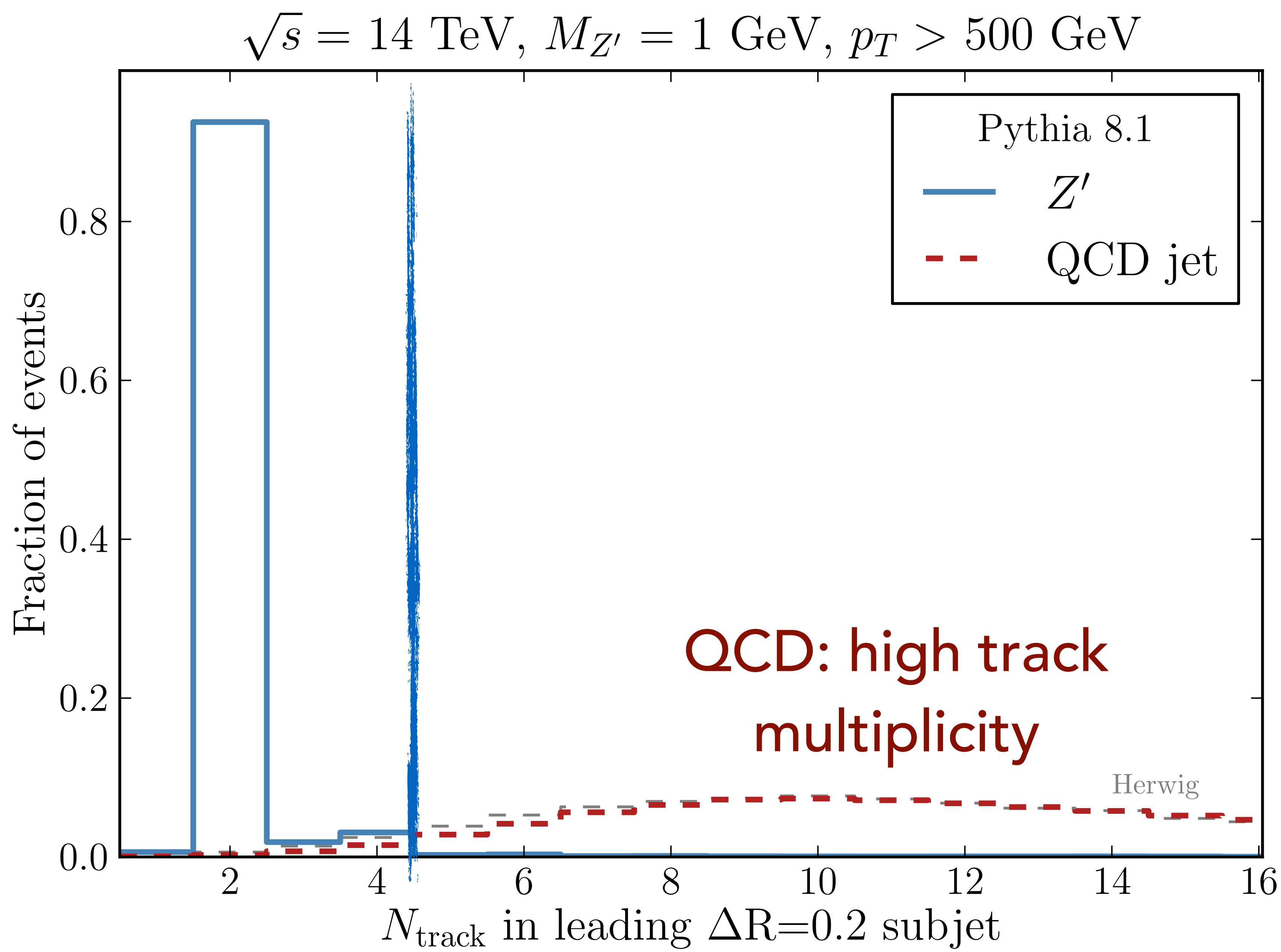
- Increased rate for Z′ radiation compared to initial state radiation (QCD jets)



Depending on DM mass, larger rate for a range of Z′ masses

Light Z′-jet tagging

Z′: Mostly 2-track decay due to mass scale, charge conservation



QCD: high track multiplicity

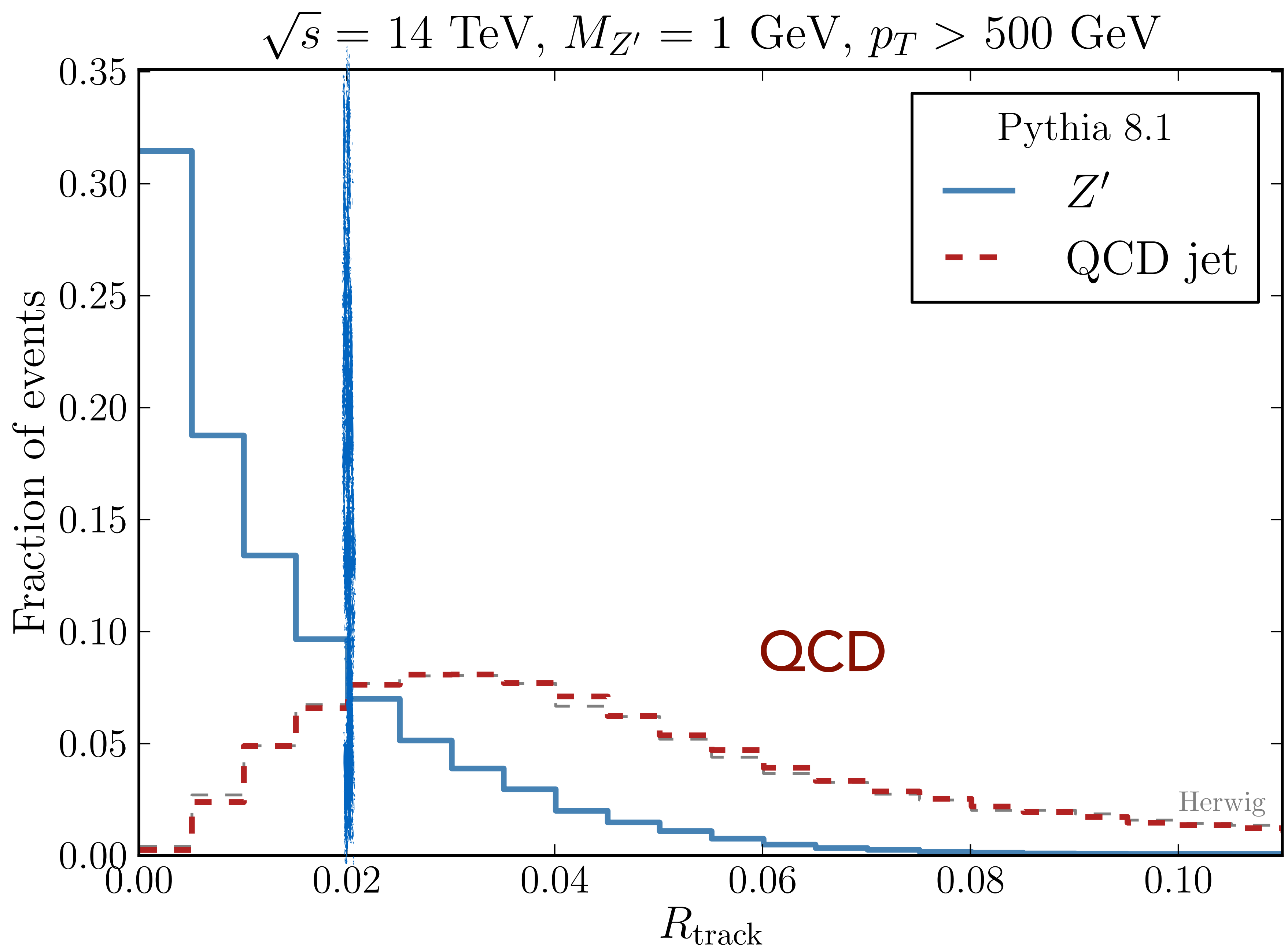
Track multiplicity - primary distinguishing variable

Light Z'-jet tagging

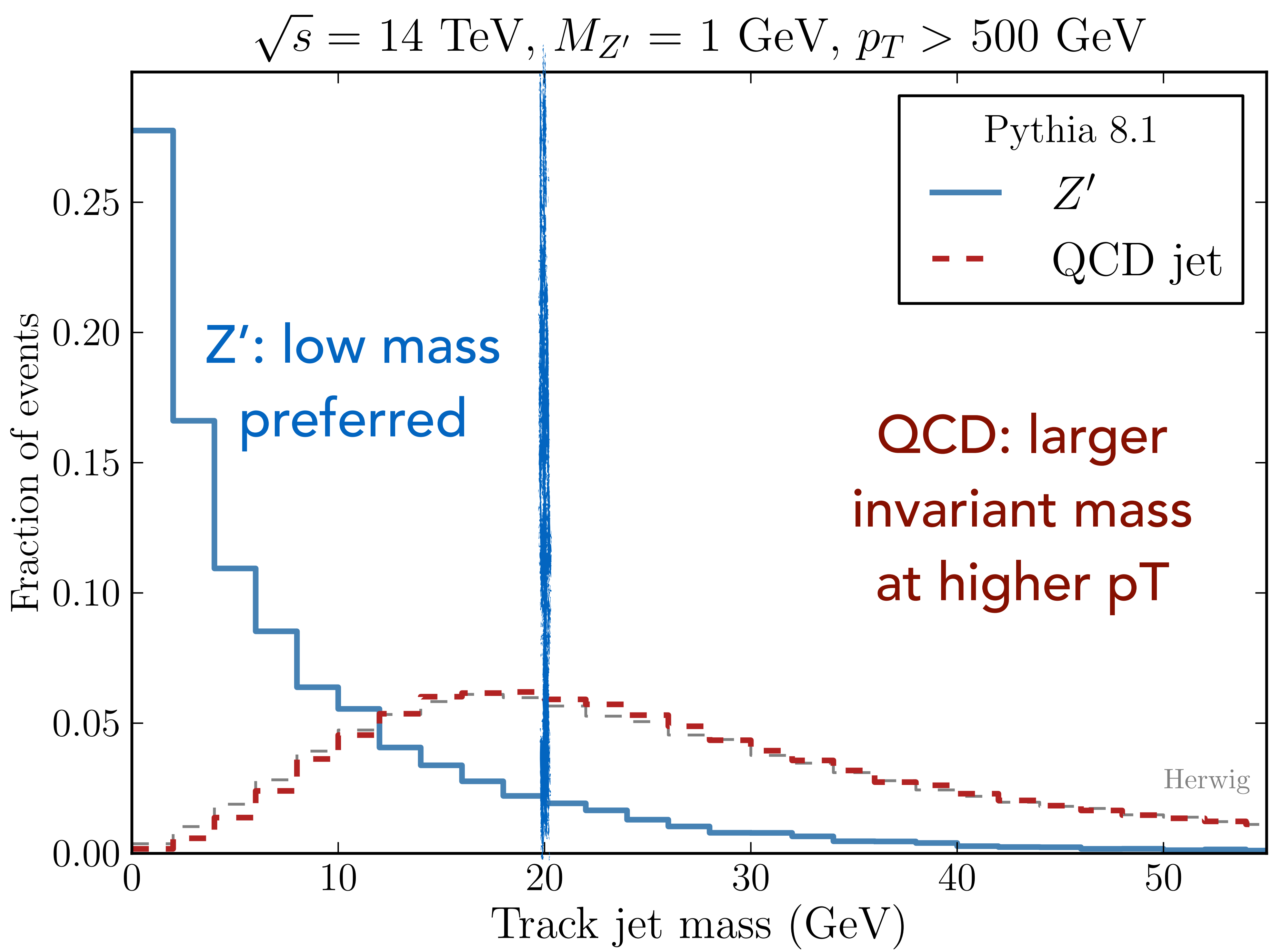
$$R_{\text{track}} = \frac{\sum_{i,\text{tracks}}^{\Delta R_i \leq 0.4} p_{T,i}\, \Delta R_i}{\sum_{i,\text{tracks}}^{\Delta R_i \leq 0.4} p_{T,i}}$$

Track radius: pT-weighted track radius

Z': small cone of radiation



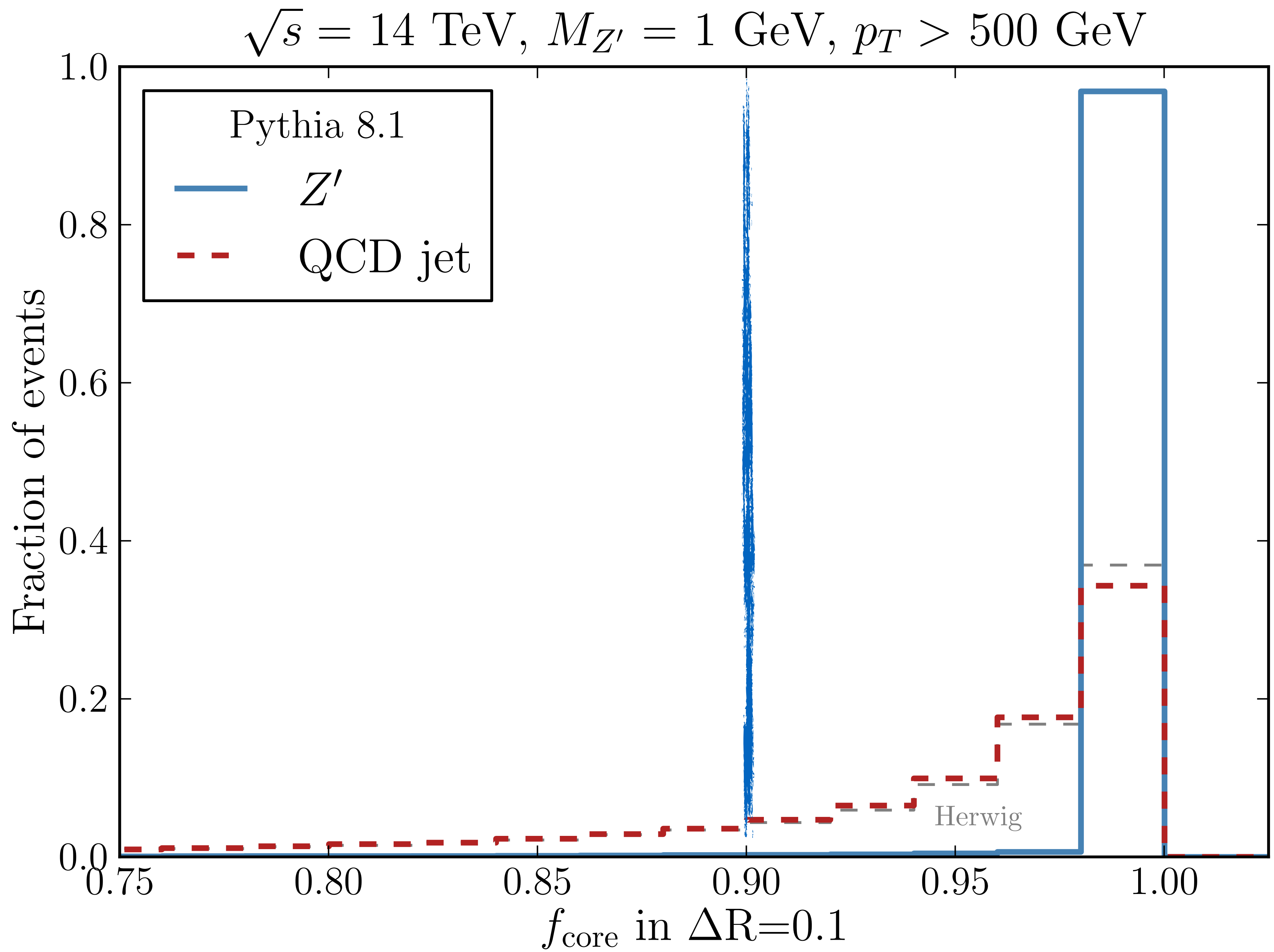
Light Z'-jet tagging



Light Z'-jet tagging

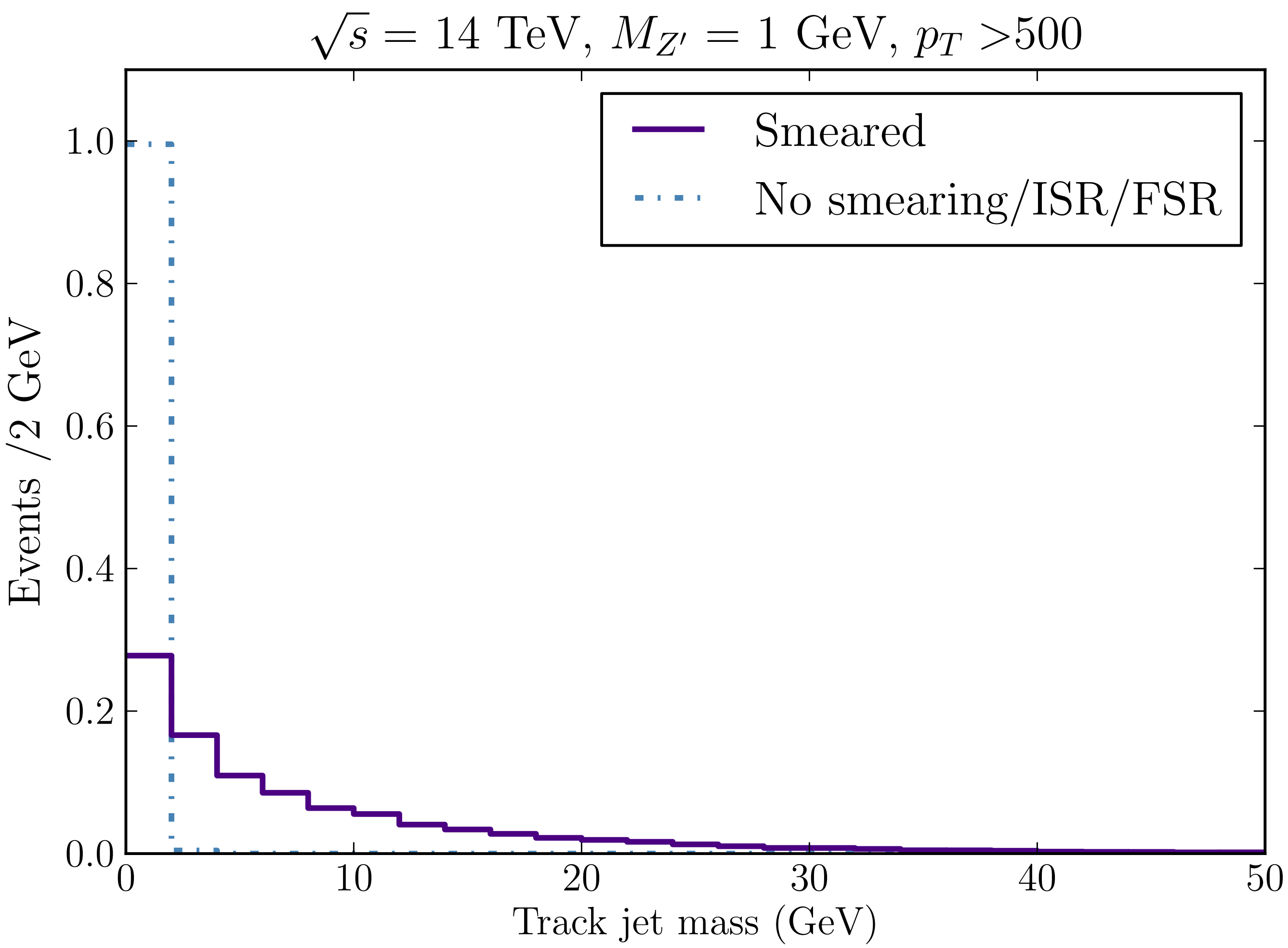
$$f_{\rm core} \equiv \frac{\sum_i^{\Delta R_i<0.1} p_T^i}{\sum_i^{\Delta R_i<0.2} p_T^i}$$

pT-fraction of leading subjet

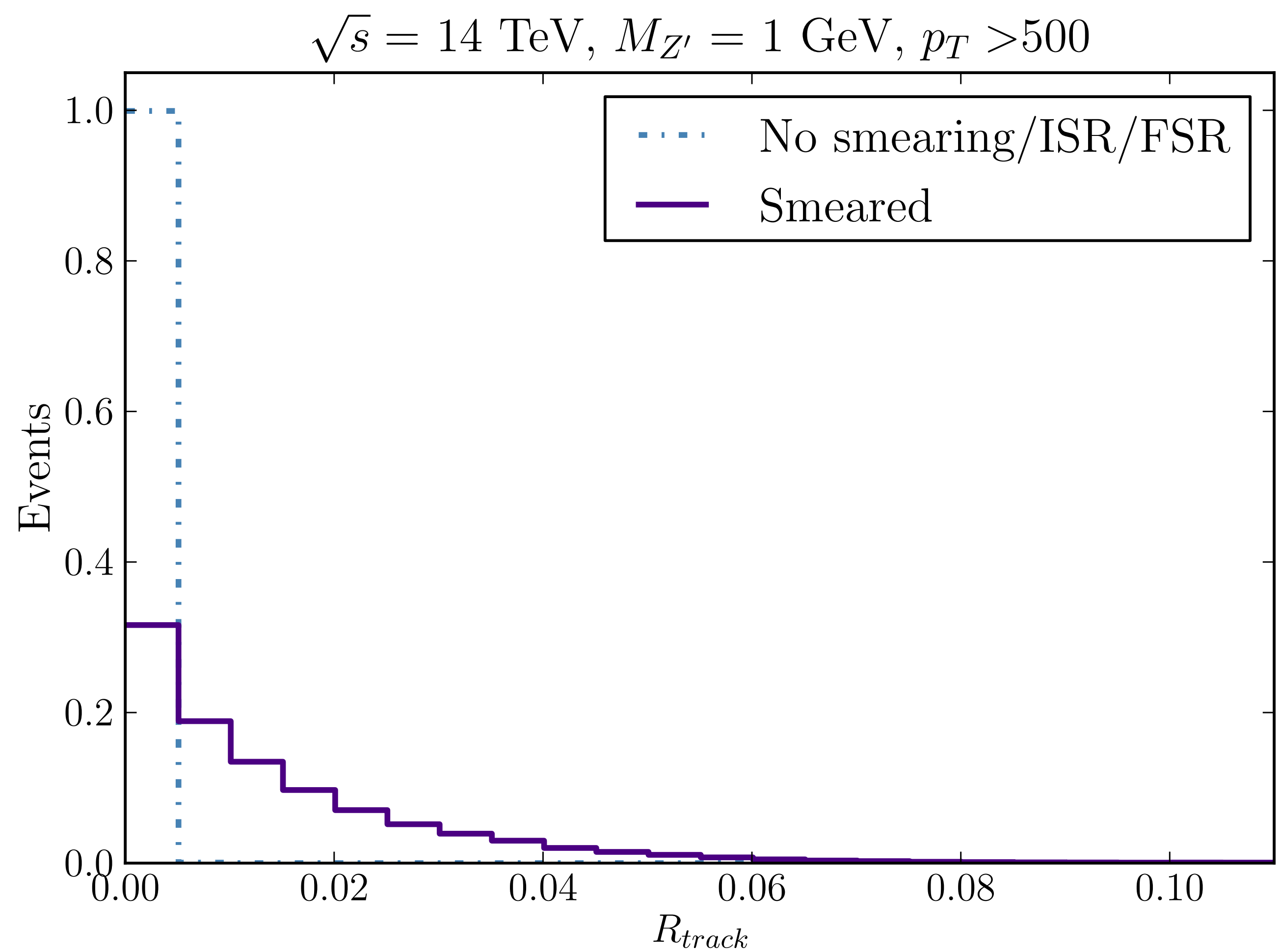


Jet-pT smearing

- Track-based observables, 5% uncertainty on track pT:



Track jet mass

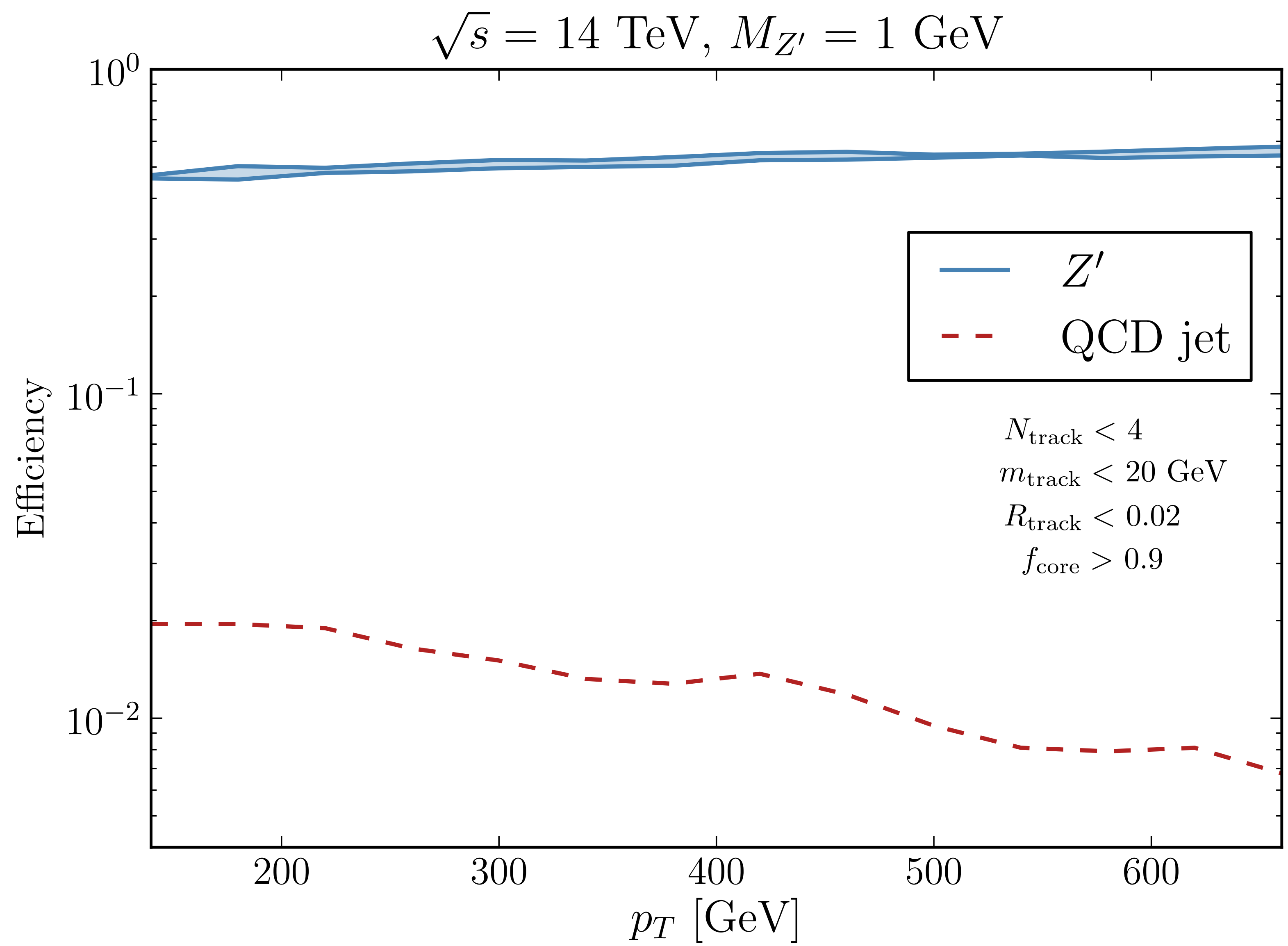


Track radius

Z'-jet tagging

- For default cuts, can reject QCD jets at high significance

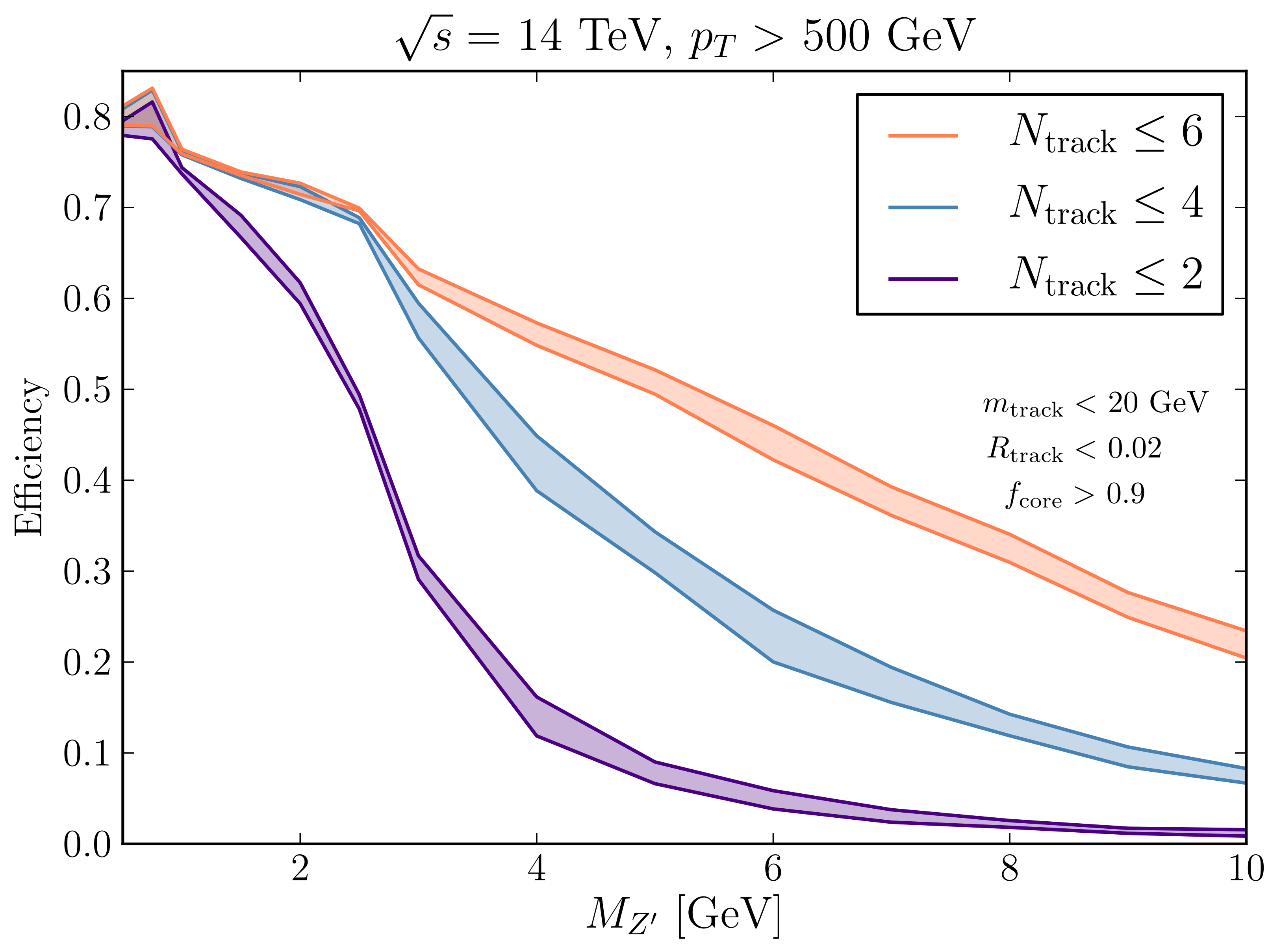
To estimate improvement in sensitivity, we take efficiencies as 50% signal, 1% background



Z′-jet tagging

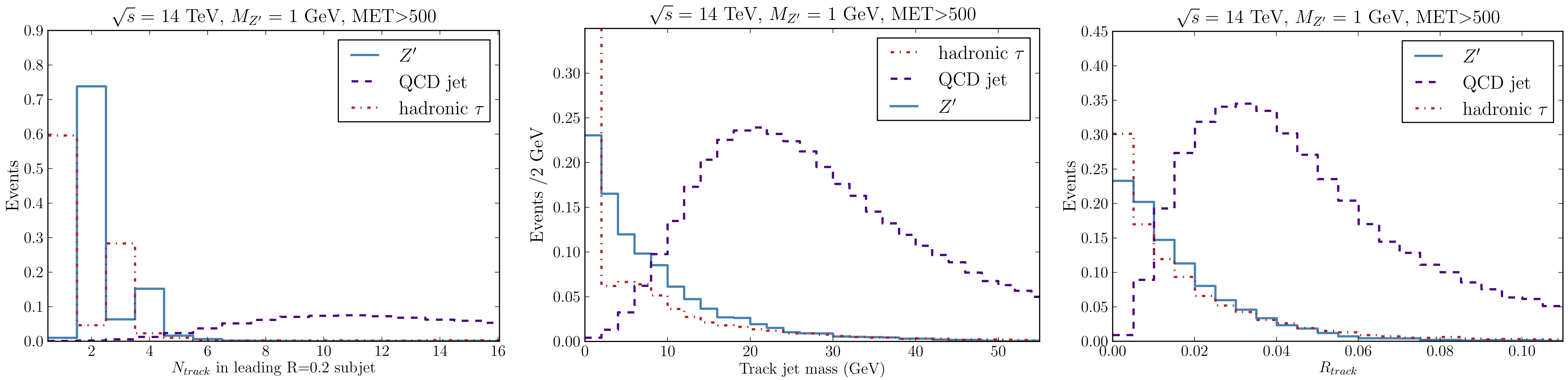
Range of values: test of model-dependence in PYTHIA

e.g. axial vs vector coupling, isospin-violating vs coupling only to u-quarks



Tagging can be implemented for a range of "GeV-scale" Z′ masses

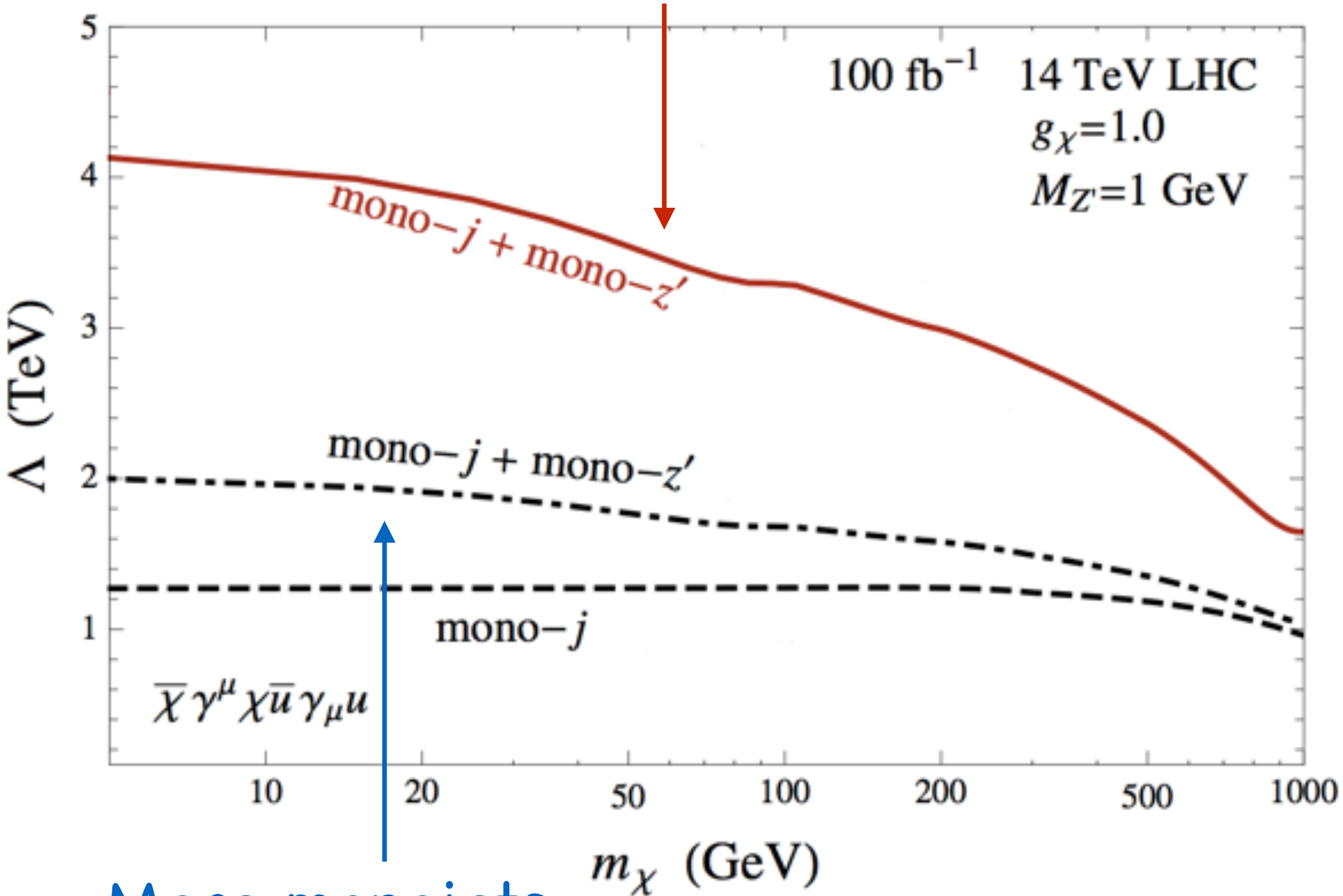
Hadronic τ_h



- (By definition) look very similar to GeV-scale Z's
- W* → $\tau_h\nu$ is also background, but sub-dominant for large MET, and could be further suppressed by vetoing 1- and 3-prong events
- Single hadronic tau trigger → Z'-jet trigger?

Z′+MET sensitivity

With light Z′-tagging



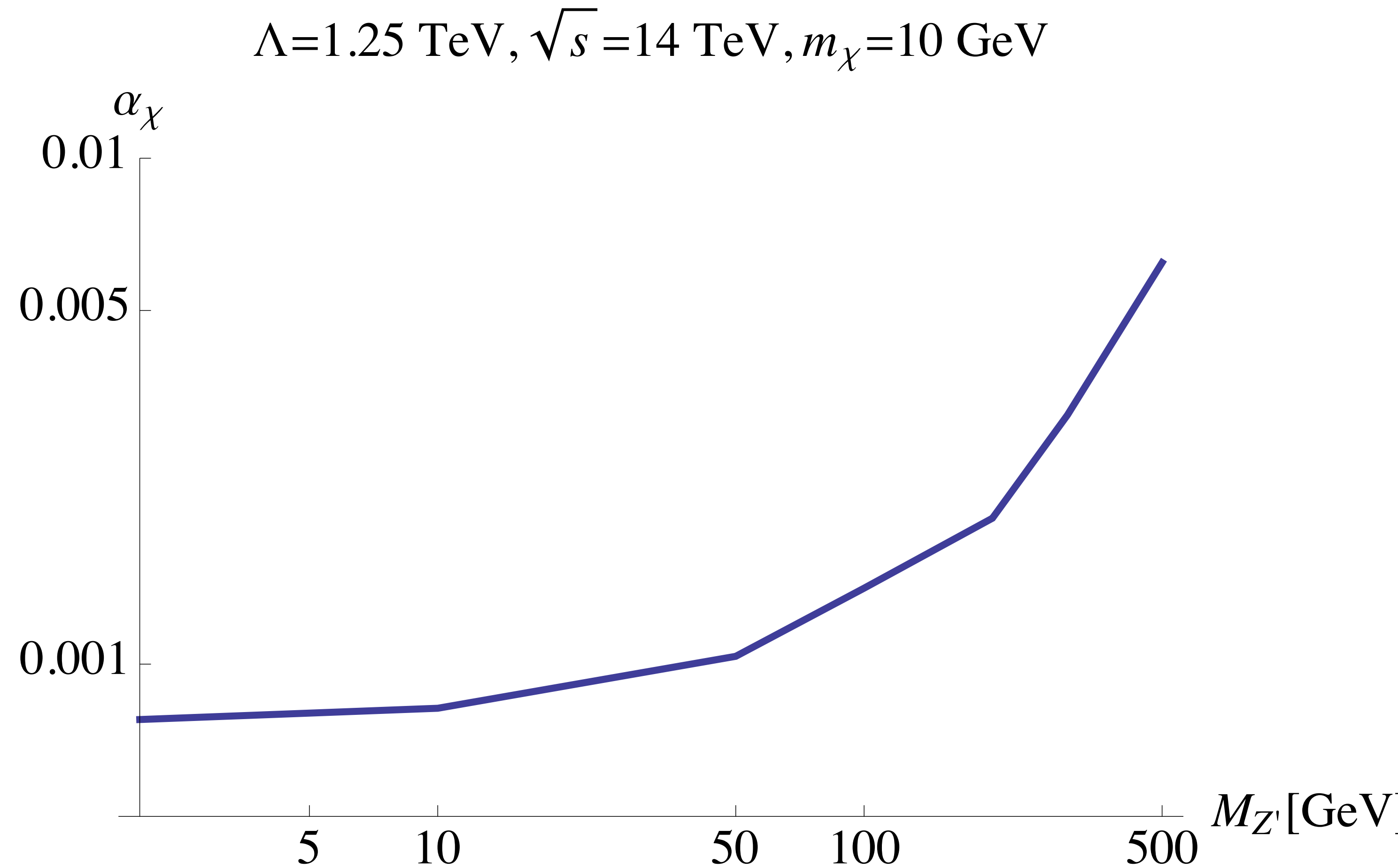
More monojets

Assumed 10% systematic uncertainty on background

- New collider signal
- Significant increase in sensitivity
- LHC probe of light DM with dark force

Z′+MET sensitivity

- We can probe perturbative gauge couplings.
- Projected **coupling** sensitivity, fixing the contact operator scale at the monojet limit:



Plot assumes MET > 500 GeV plus light Z′ tagging

Inelastic dark matter

Off-diagonal coupling can be generated by Dirac fermion DM + Majorana mass:

$$\mathcal{L} \supset \bar{\chi}(i\not{D} - M_d)\chi - \frac{M_m}{2}(\bar{\chi}\chi^c + \text{h.c.}).$$

$$M_{1,2} = |M_m \pm M_d|$$

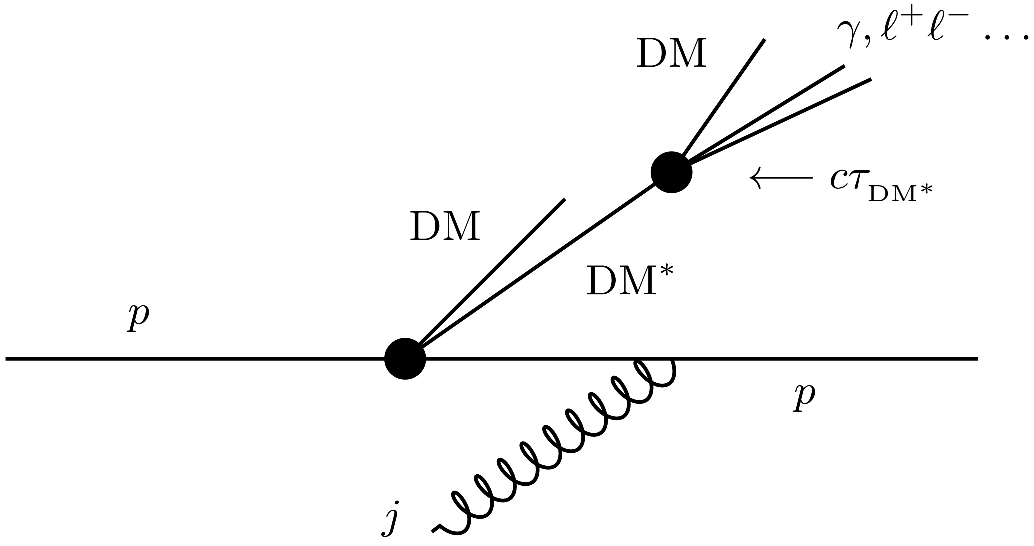
Splitting easily has similar scale as gauge bosons: $M_m \sim y_\chi \langle \Phi \rangle$

$$\frac{(\overline{\chi}_* \gamma^\mu \chi + \overline{\chi}\gamma^\mu \chi_*)\, \overline{u}\gamma_\mu u}{\sqrt{2}\,\Lambda^2}$$

$$g_\chi \, (\overline{\chi}_* \gamma^\mu \chi + \overline{\chi}\gamma^\mu \chi_*) \; Z'_\mu$$

—> primarily off-diagonal couplings of Z', no associated monojet signal

Can probe co-annihilating thermal relic region (w/ displaced leptons):

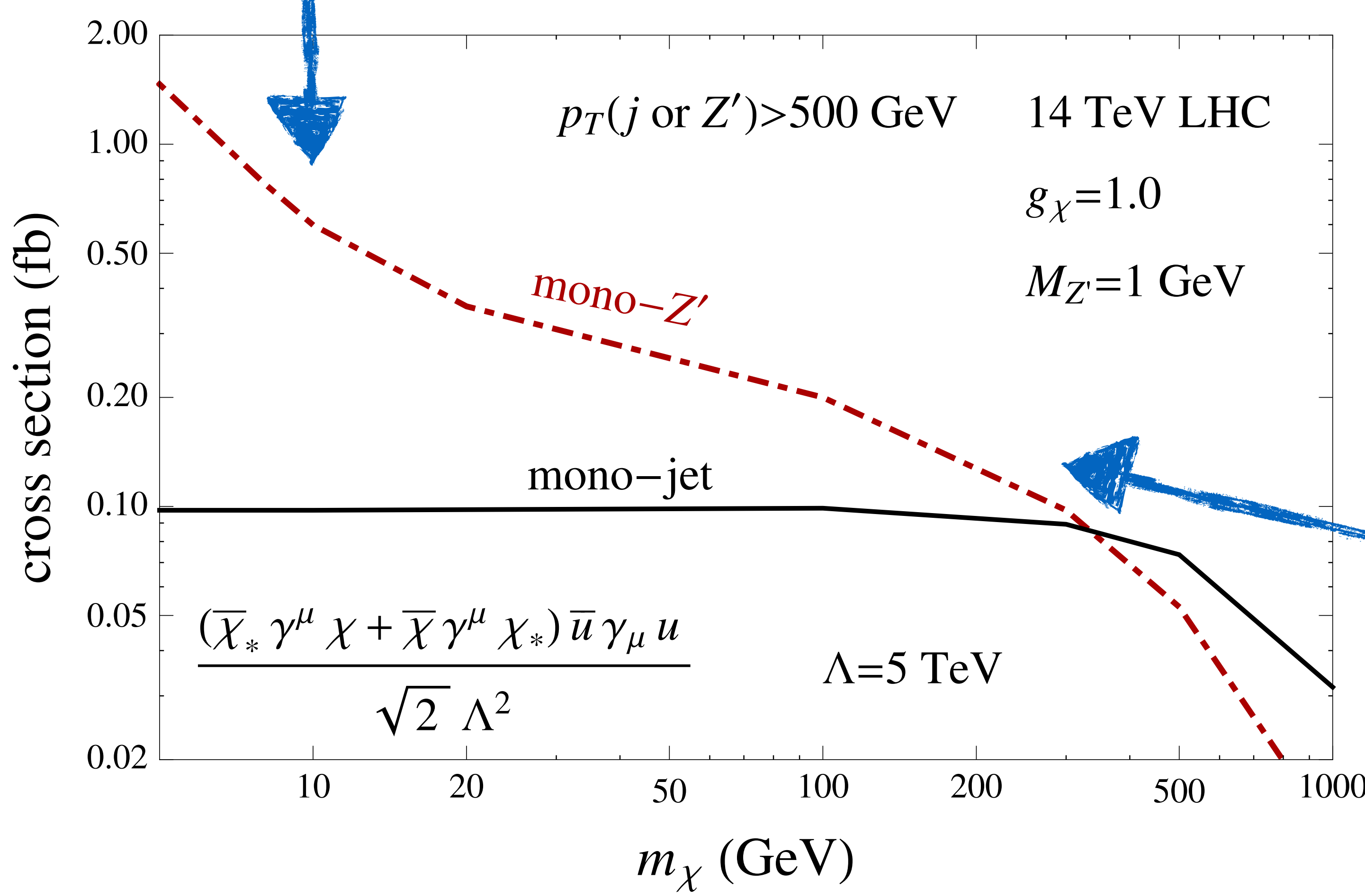


Izaguirre et al. 2015

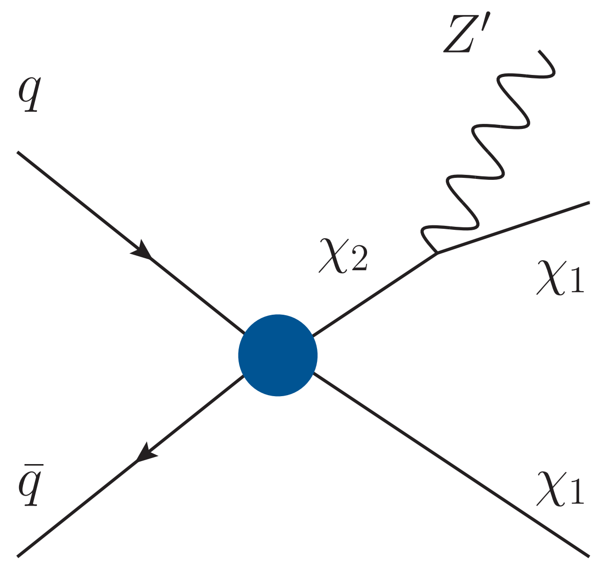
Displaced pion: Bai & Tait 2011

Inelastic dark matter

2 → 2 process
(χ_* decays to Z′+χ)

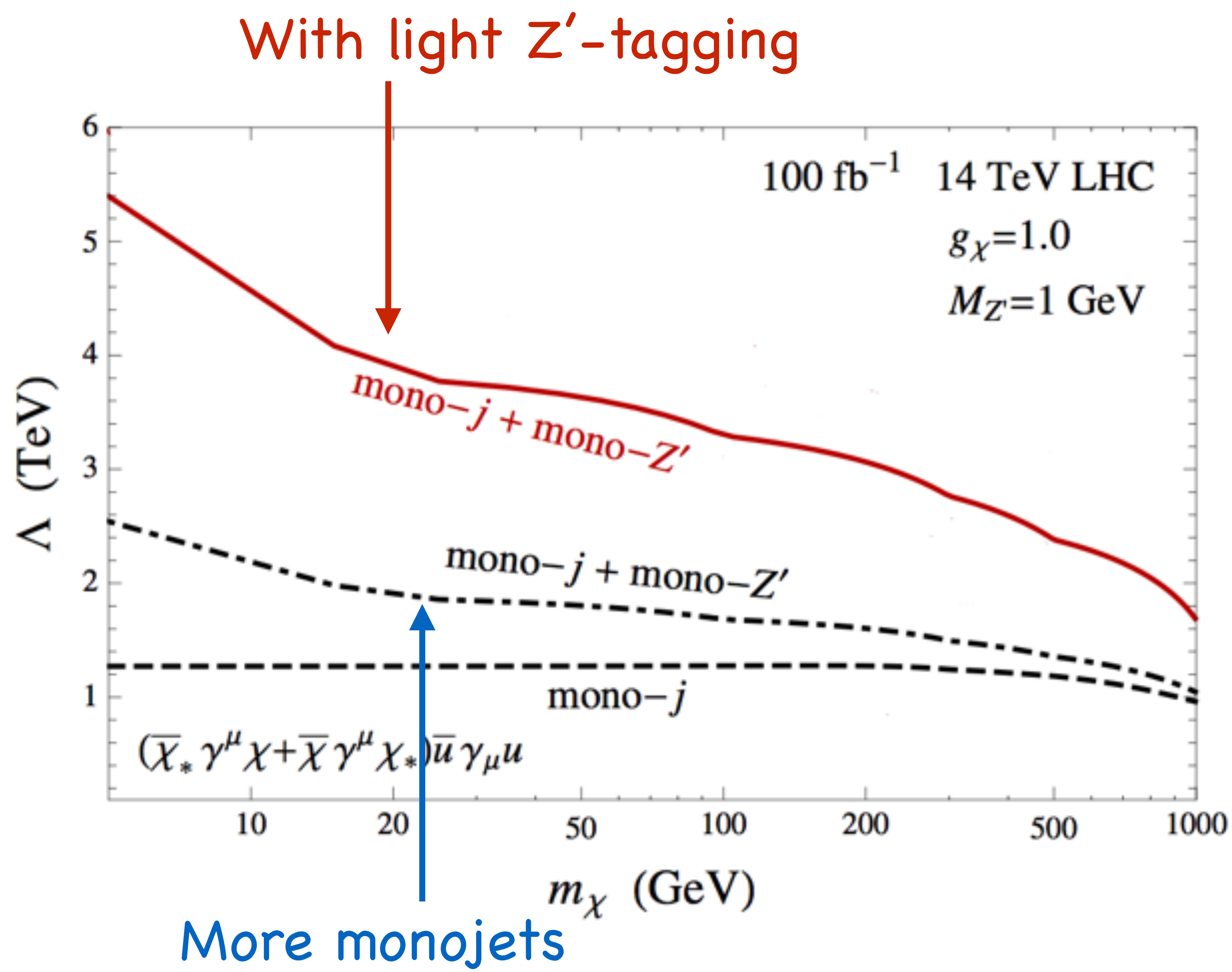


2 → 3 process
(χ_* is off-shell)



Mass splitting is $\Delta = 2\ \mathrm{GeV}$

Improvement in sensitivity for inelastic dark matter



Assumed 10% systematic uncertainty on background *with M. Autran, K. Bauer, D. Whiteson 2015*

Dijet & dilepton resonances

- In the inelastic case, heavier Z′ can be produced in the decay of the excited state without kinematic suppression
- We consider the mass range: MZ′ = 50-800 GeV
- The signal is not captured as efficiently by existing MET-based searches, and the presence of a resonance would be a strong indication of new particles/physics

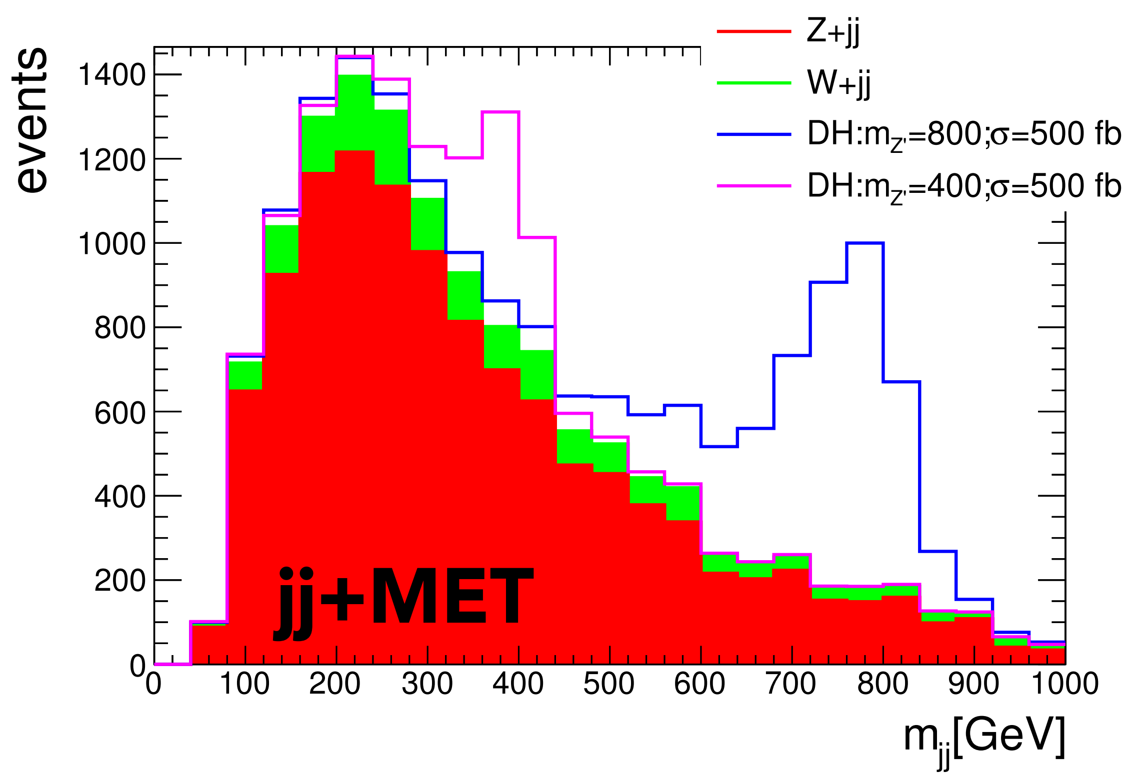
Dijet resonances plus MET

- We consider the mass range: MZ′ = 50-800 GeV

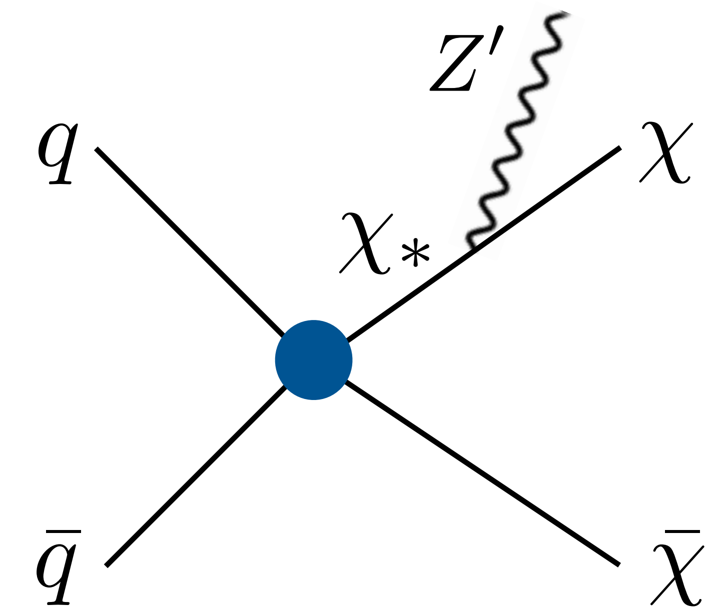
Dijet resonances

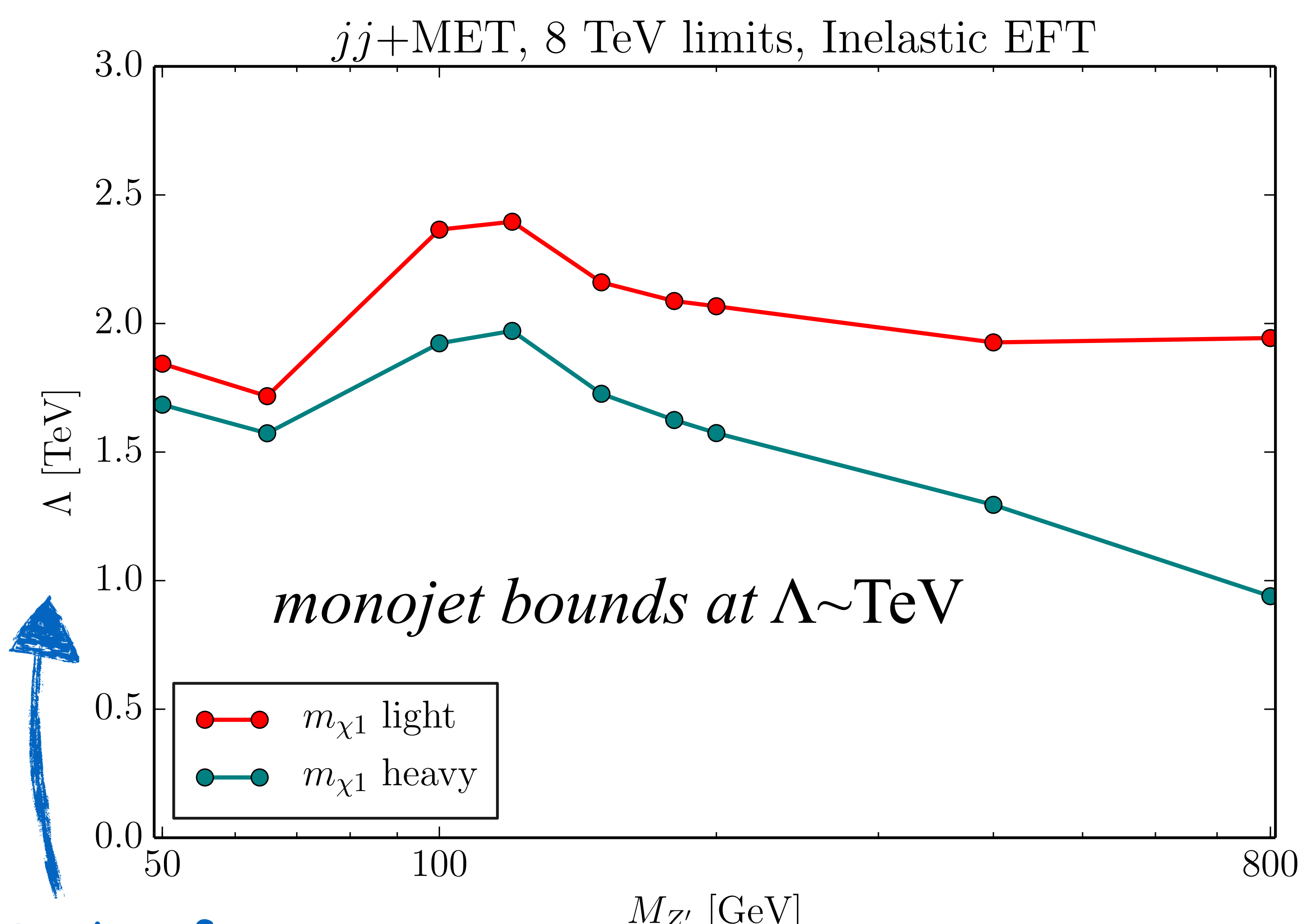
- Not covered well with standard jets +MET (squark) search, which has strong requirements on HT, etc.

- Possible gains with mass window, different jet pT and MET cuts



Dijet resonance sensitivity





Scale of contact operator

Z′ mass

Two benchmark spectra, allowing on-shell χ^* decay:

"Light" χ:

$$M_\chi = 5 \text{ GeV}$$

$$M_{\chi^*} = M_\chi + M_{Z'} + \Delta$$

$$\Delta = 25 \text{ GeV}$$

"Heavy" χ:

$$M_\chi = M_{Z'}/2$$

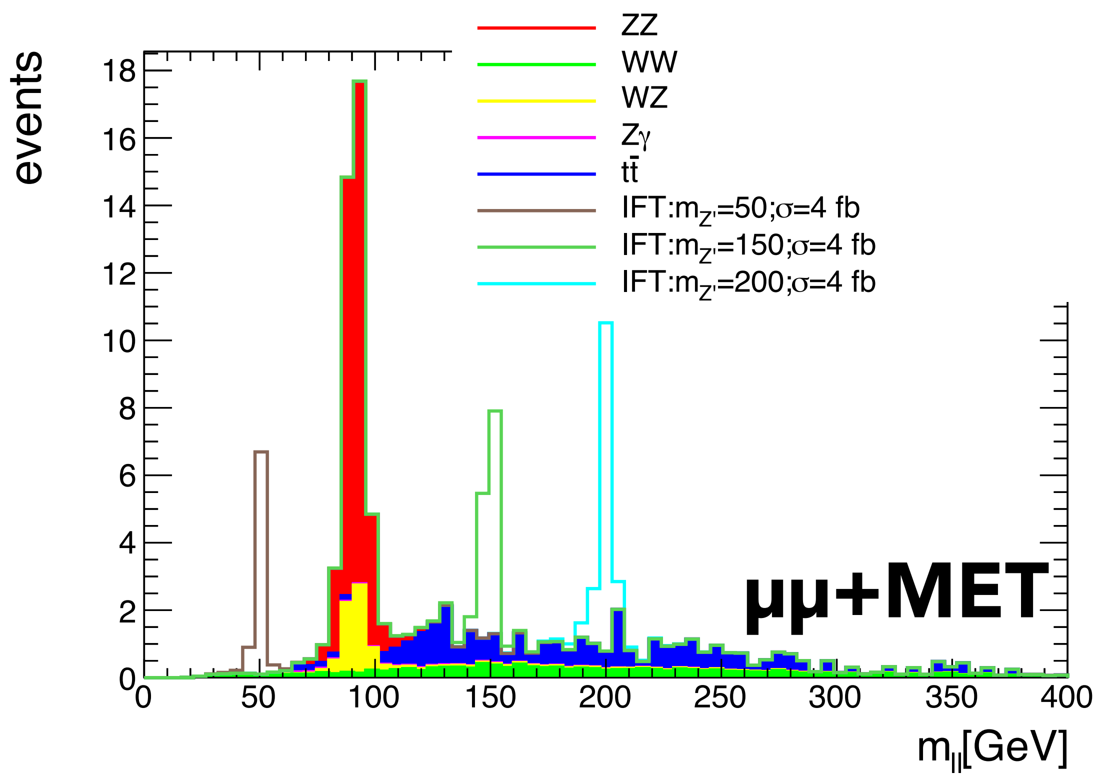
$$M_{\chi^*} = 2M_{Z'}$$

Dilepton resonances plus MET

- We consider the mass range: MZ' = 50-800 GeV

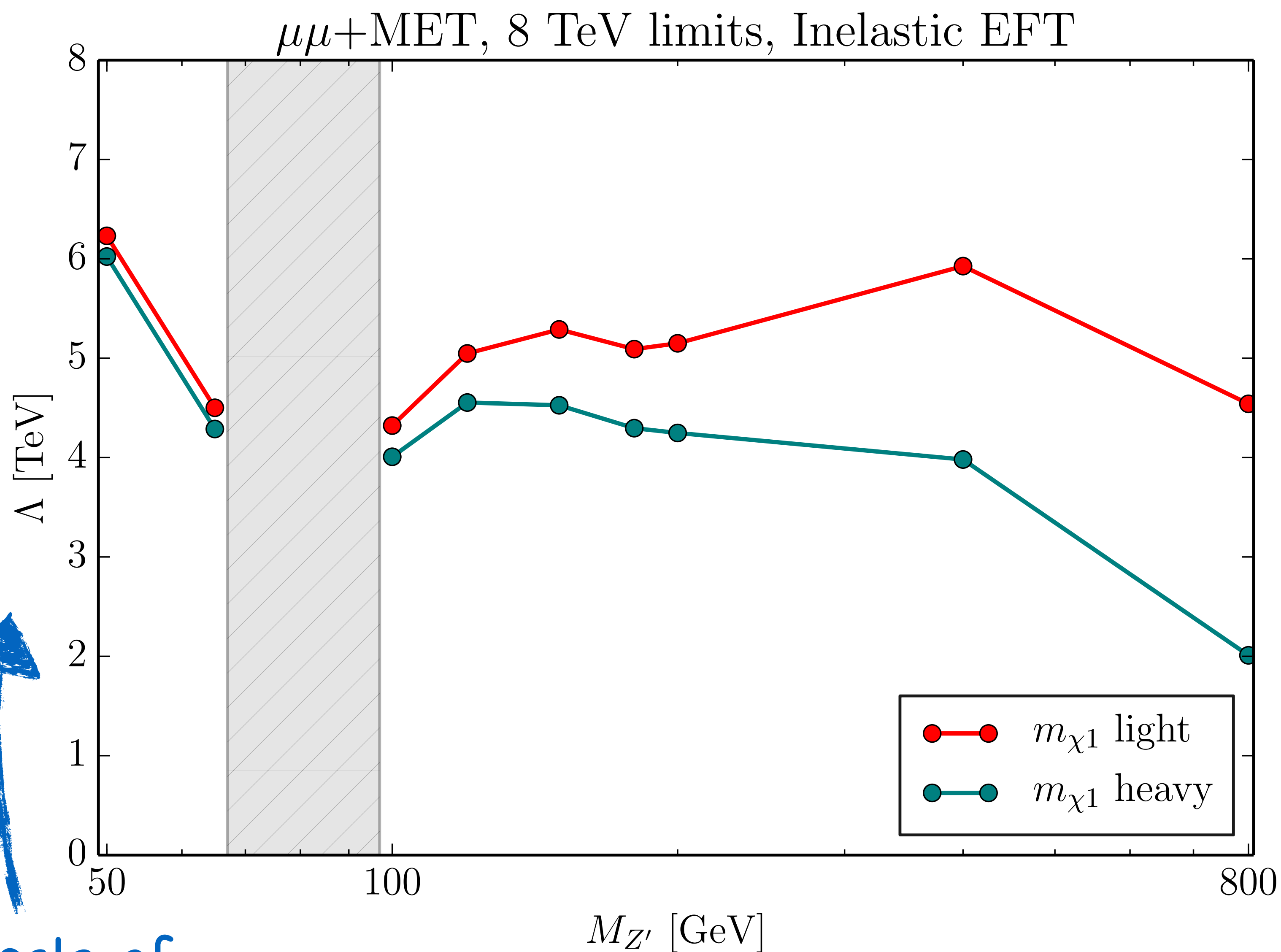
Dimuon resonances

- Overlap with chargino search
- Improvements possible with finer mass window, more stringent MET or pT(μμ) cuts



For more models and focus on dilepton resonance, see:
A. Gupta, R. Primulando, P. Saraswat arXiv:1504.01385

Dimuon resonance sensitivity



Scale of contact operator

Z' mass

Shown for BR(muons)=100%
For "kinetic mixing" case, $\Lambda \approx 3$ TeV instead

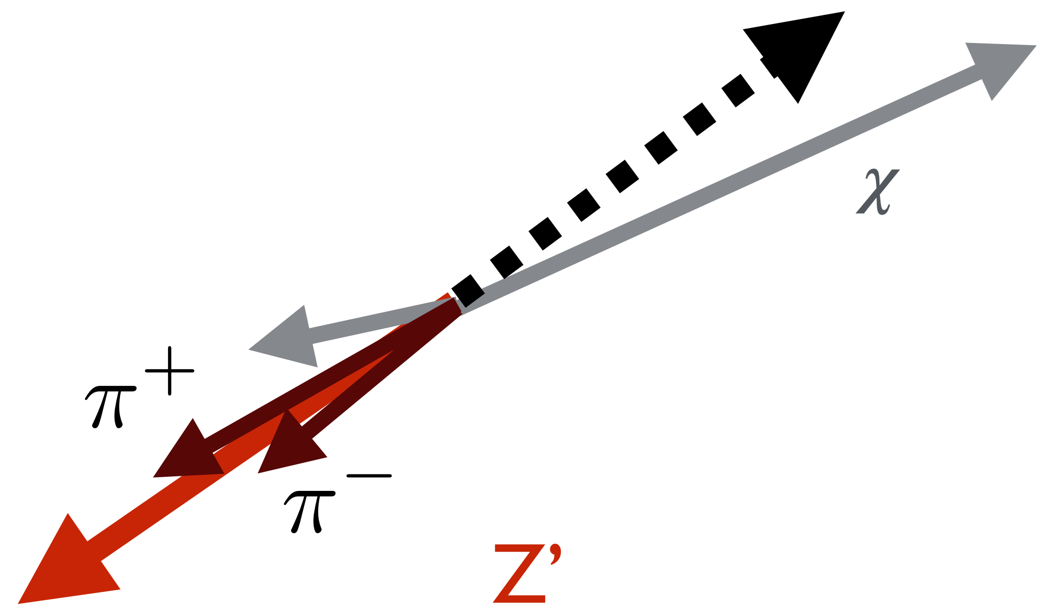
Summary

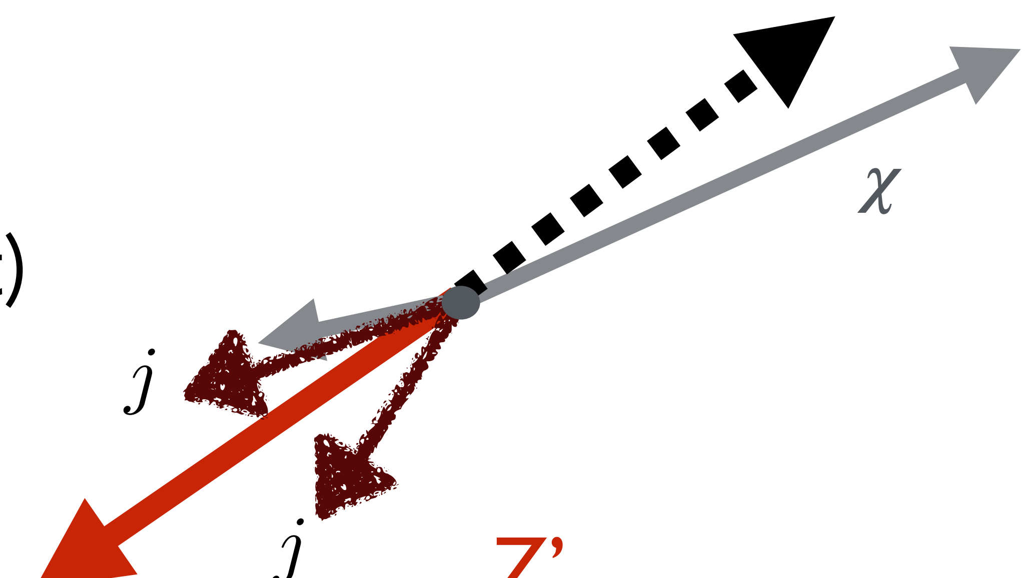
- Dark matter can radiate dark gauge bosons in high energy collisions

- For small gauge coupling, still have signals with substantial missing energy, but also other pheno:

- GeV-scale Z′ decaying hadronically are a new collider object (mono-Z′ jet)

- Significant increase in sensitivity compared to ISR monojets





Conclusions

Gauge interactions in the dark sector lead to novel LHC signals of radiation from the dark sector, where the data has not been fully analyzed. New opportunities and challenges!