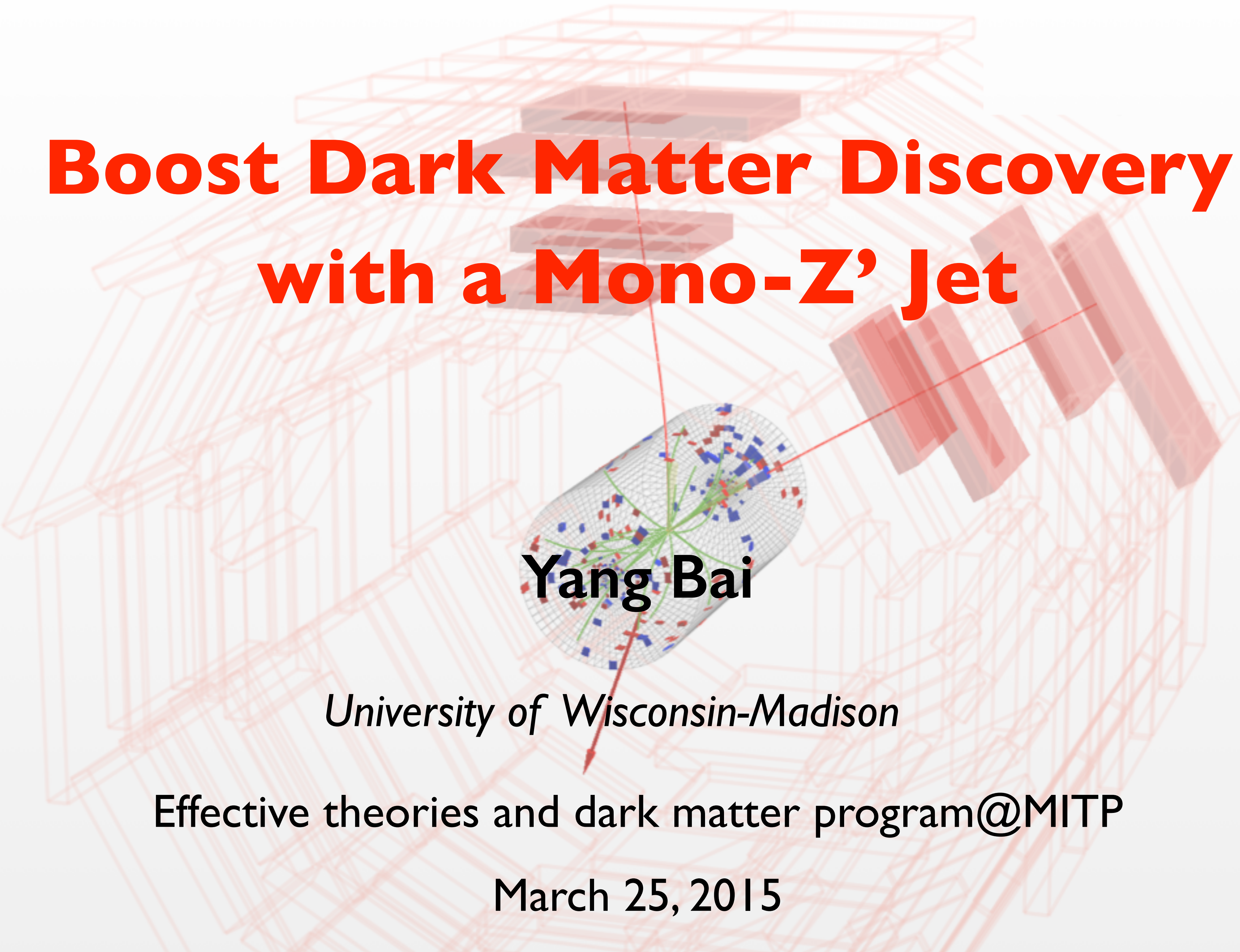


Boost Dark Matter Discovery with a Mono-Z' Jet

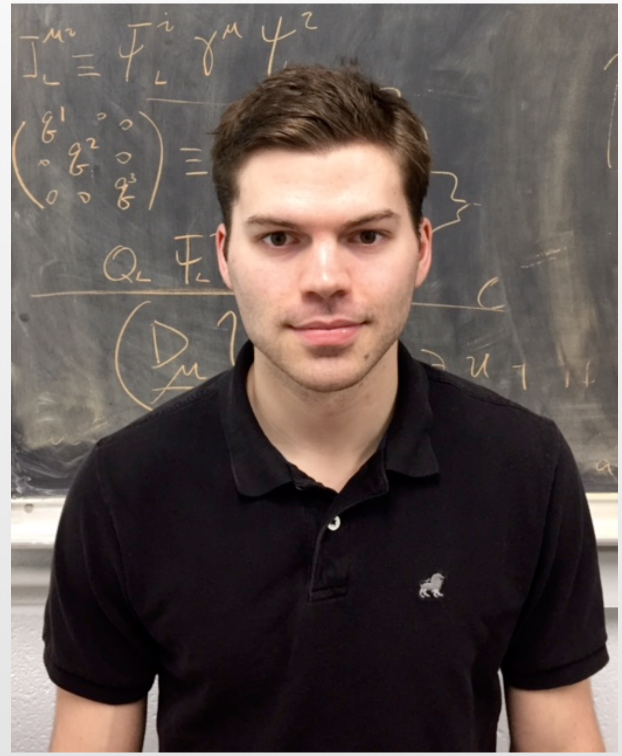
Yang Bai

University of Wisconsin-Madison

Effective theories and dark matter program@MITP

March 25, 2015

In collaboration with:



Tongyan Lin

KICP, Univ. of Chicago

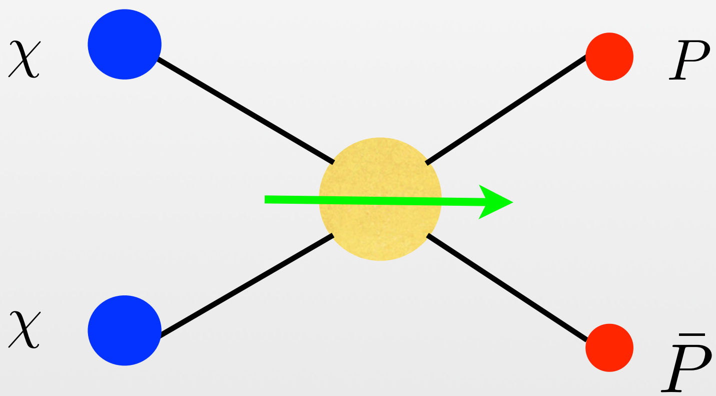
James Bourbeau

Univ. of Wisconsin-Madison

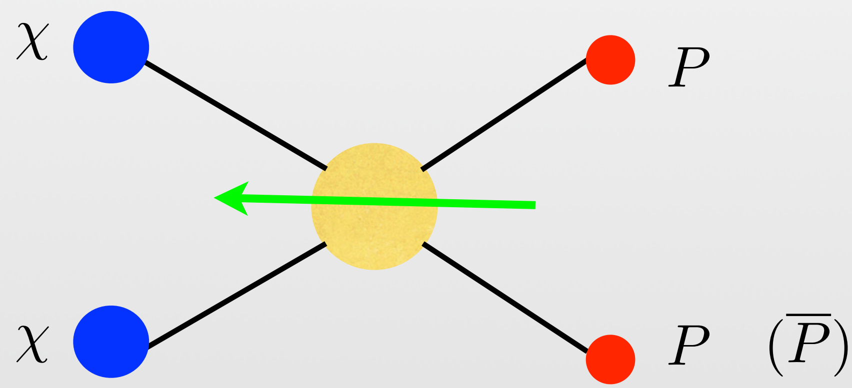
1504:xxxxx

Hunt of Dark Matter

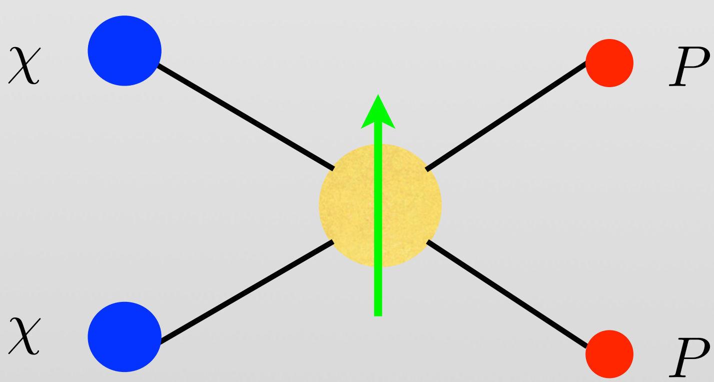
Indirect Detection



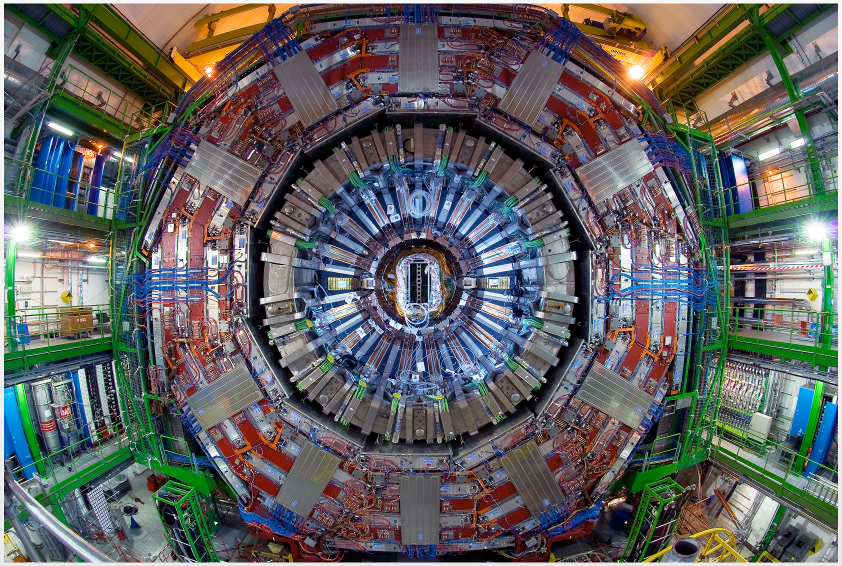
Colliders



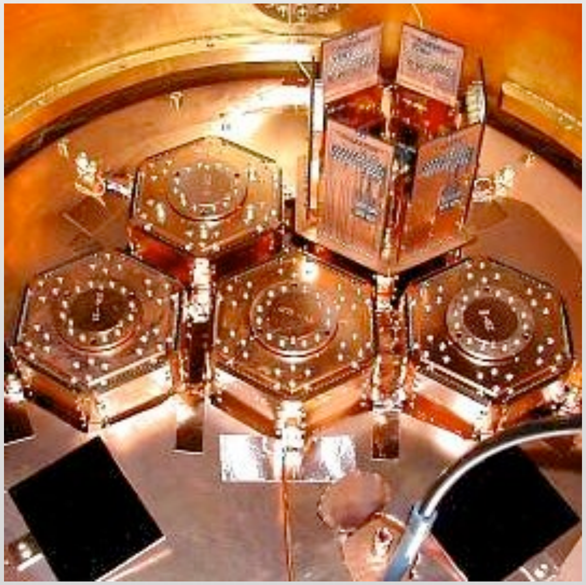
Direct Detection



Collider vs. Direct Detection

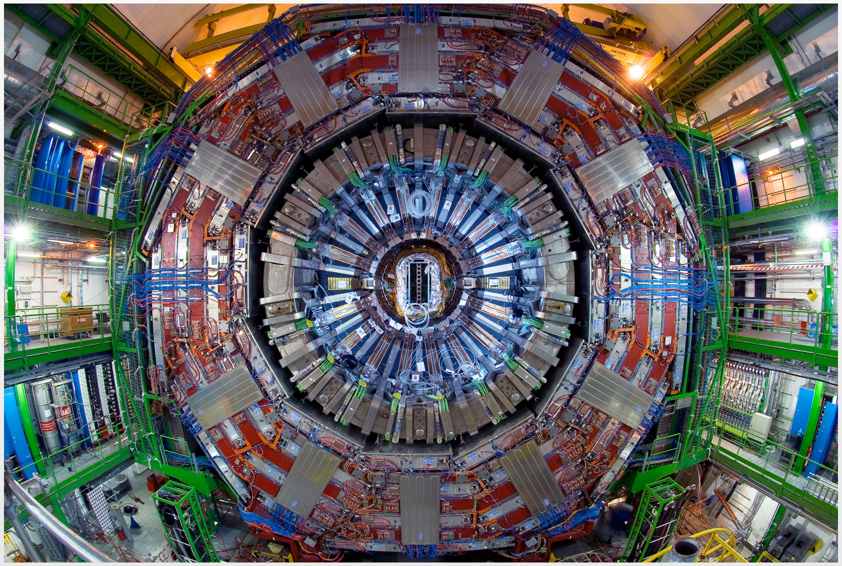


- more complicated detector
- know when to produce DM
- don't know whether it is *the* dark matter
- limited for very heavy mass

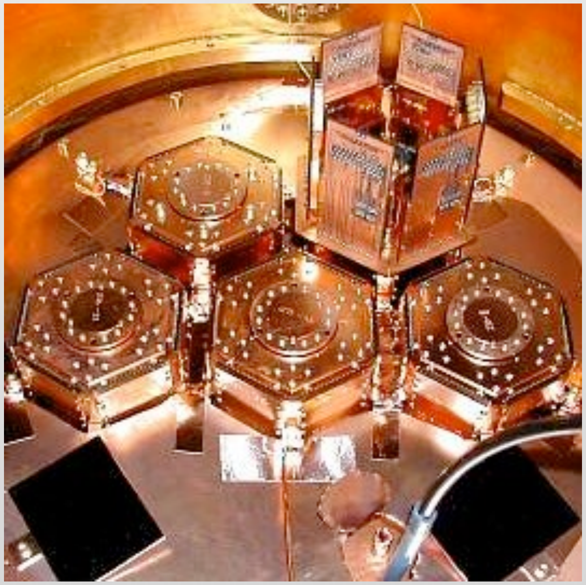


- less complicated detector
- wait for DM collision
- search for *the* dark matter
- limited for very light mass

Different Backgrounds

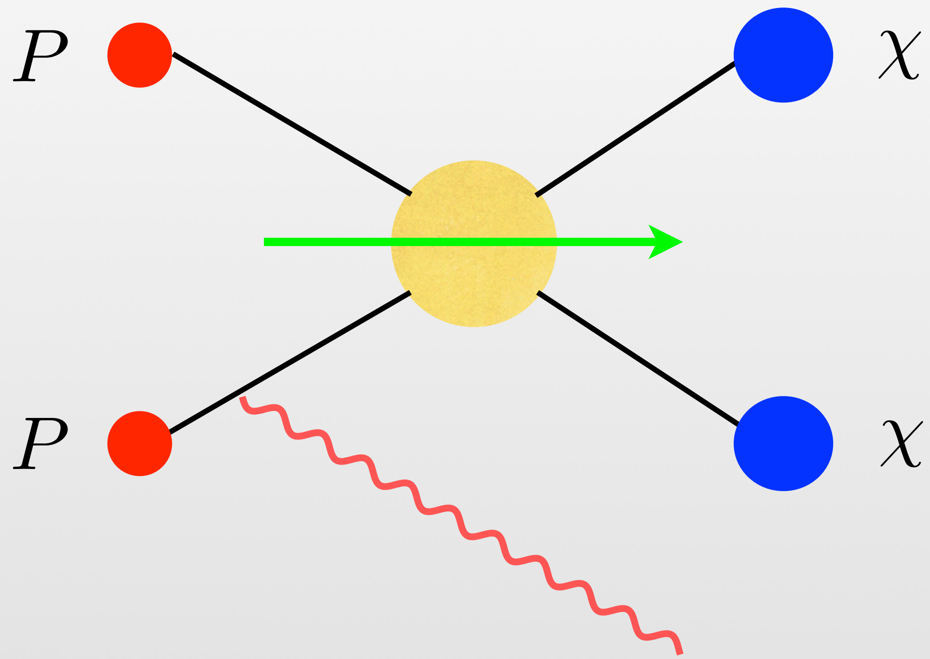


- Standard Model processes
- background-rich environment



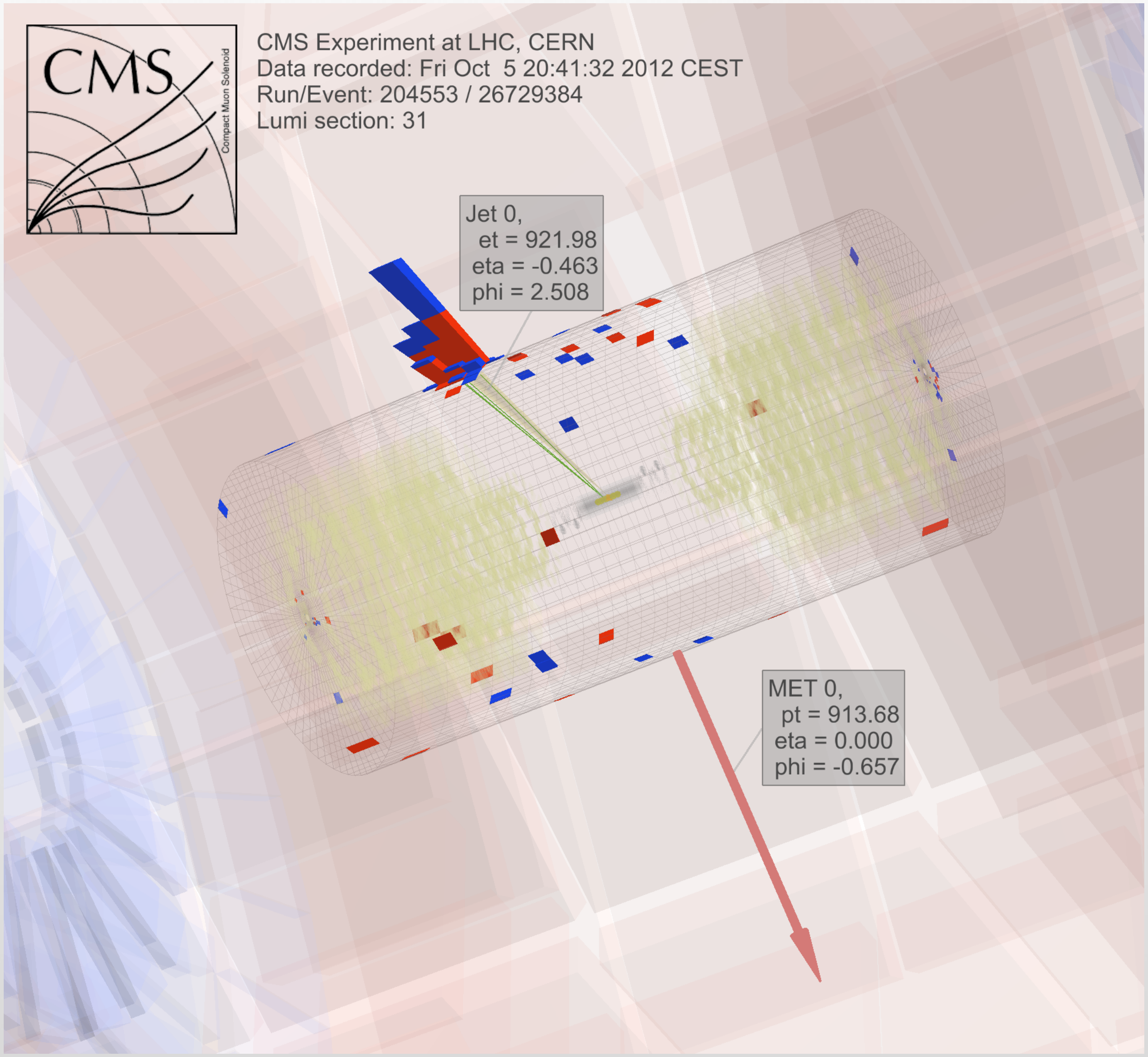
- backgrounds for detectors
- cosmic rays
- small background

Model Independent Signature

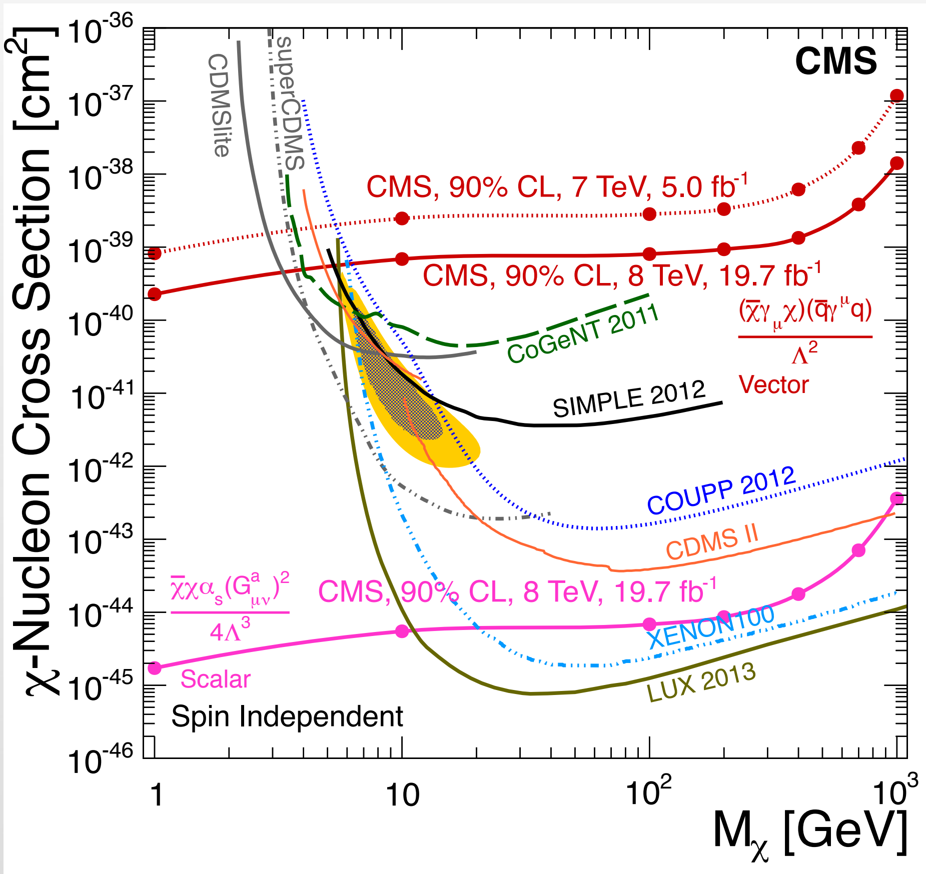


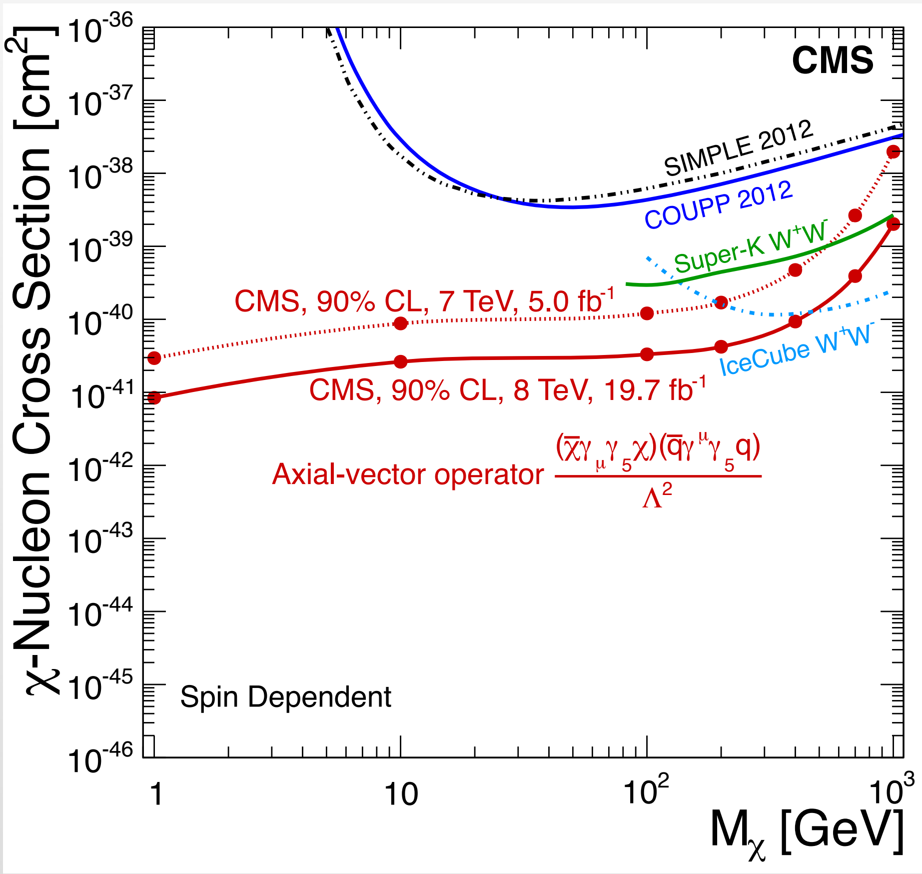
$j \quad \gamma \quad Z \quad W \quad h \quad t$

Standard Signature: monojet+MET

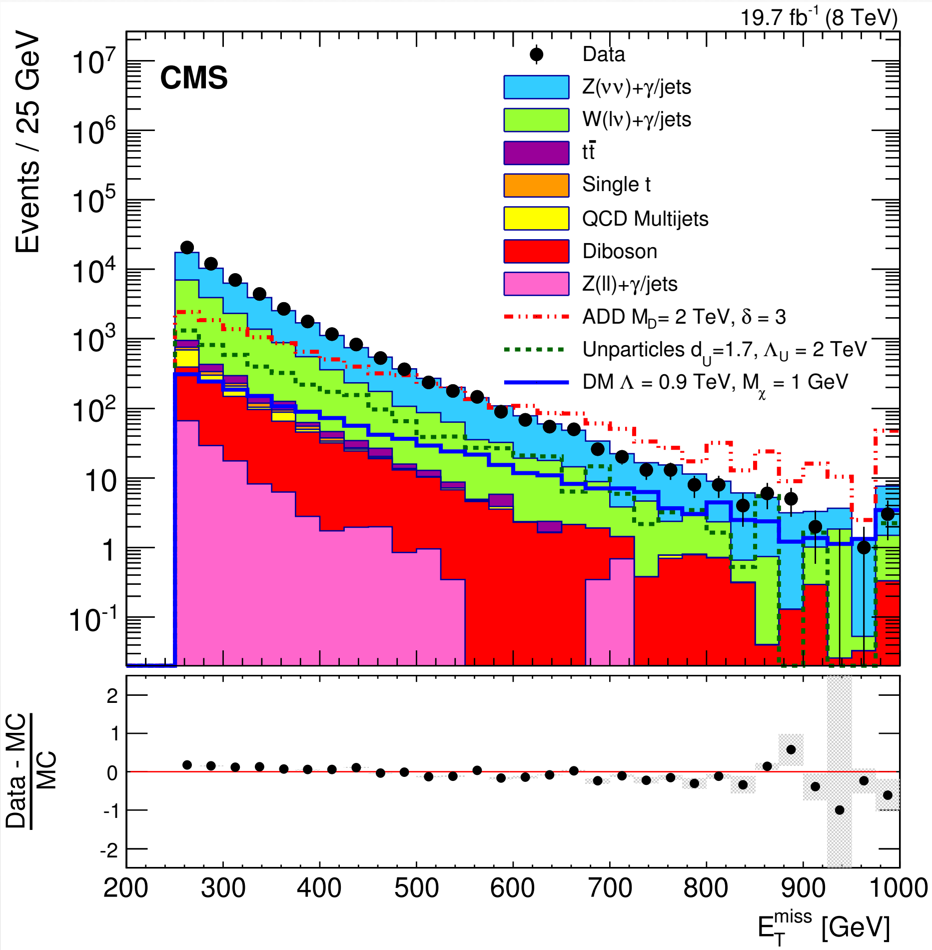


Fermi-theory for Dark Matter





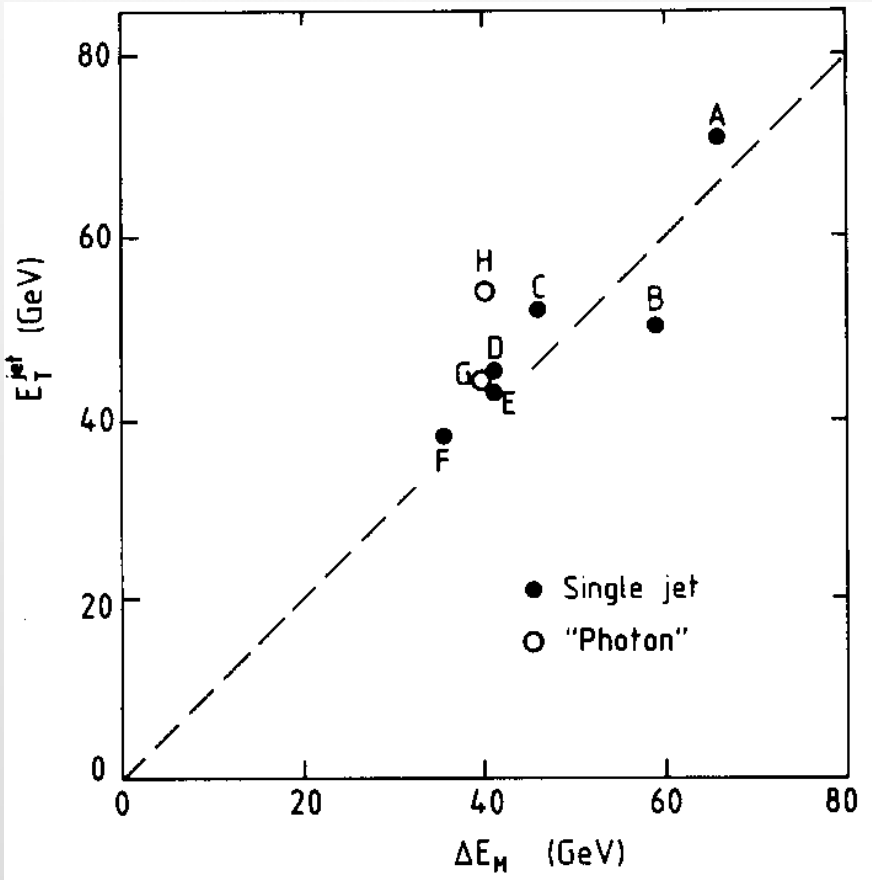
Standard Signature: monojet+MET



E_T^{miss} (GeV) $\rightarrow$	>500
$Z(\nu\nu)$+jets	747 ± 96
W+jets	249 ± 22
$t\bar{t}$	6.6 ± 3.3
$Z(\ell\ell)$+jets	2.3 ± 1.2
Single t	—
QCD multijets	1.0 ± 0.6
Diboson	36 ± 18
Total SM	1040 ± 100
Data	934

dominated by systematic errors

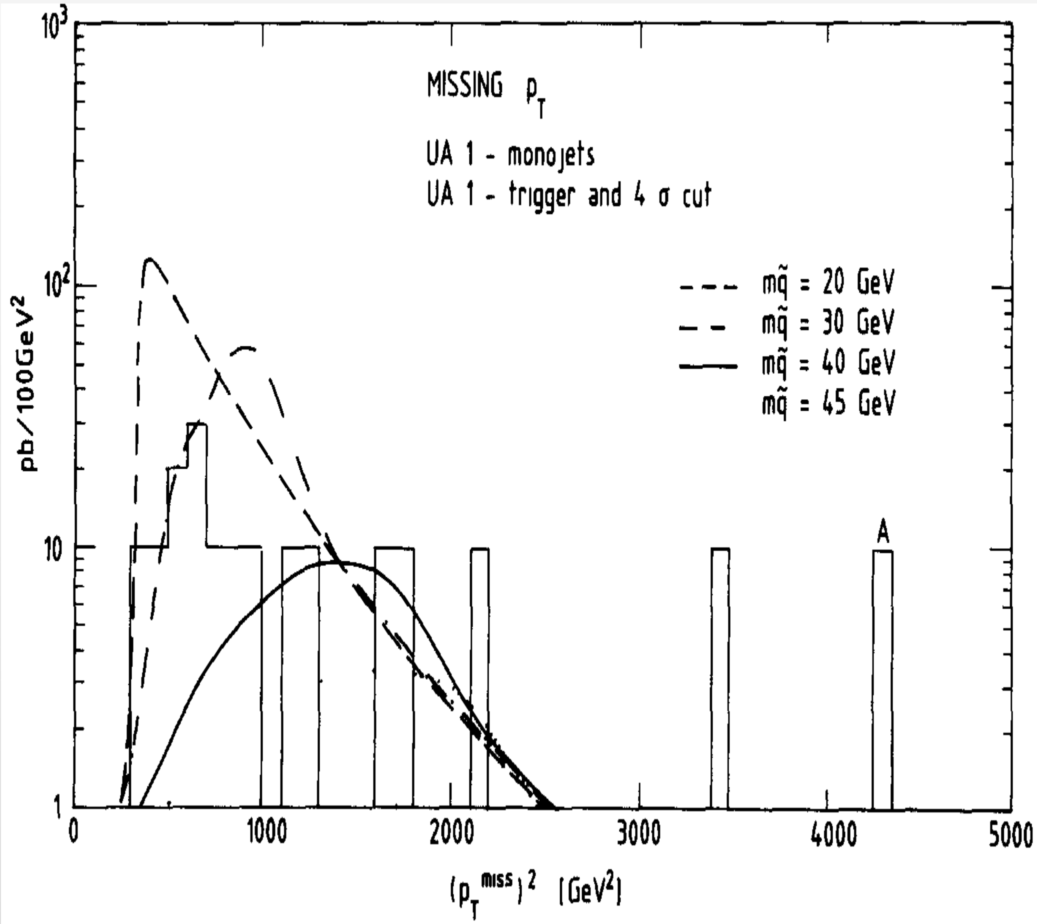
Historical “Discovery” of SUSY in Monojet



UA1, PLB, 139, 115 (1984)

Historical "Discovery" of SUSY in Monojet

SUSY



J. Ellis and H. Kowalski, NPB, 246, 189 (1984)

SM

Channel	1 Jet	2 Jets (a)	2 Jets (b)	Total
$Z \to \nu\bar\nu$	2.89	0.68	1.17	4.74
$W \to \not{e}$	1.34	0.21	0.29	1.84
$W \to \not{\mu}$	0.03	0.008	0.005	0.04
$W \to \tau \to \not{e}$	0.35	0.10	0.15	0.60
$W \to \tau \to \not{\mu}$	0.12	0.03	0.05	0.20
$W \to \tau \to h$	1.61	0.31	0.57	2.49
TOTAL	6.34	1.34	2.23	9.91

S. Ellis, R. Kleiss and W. Stirling, PLB, 158, 341 (1985)

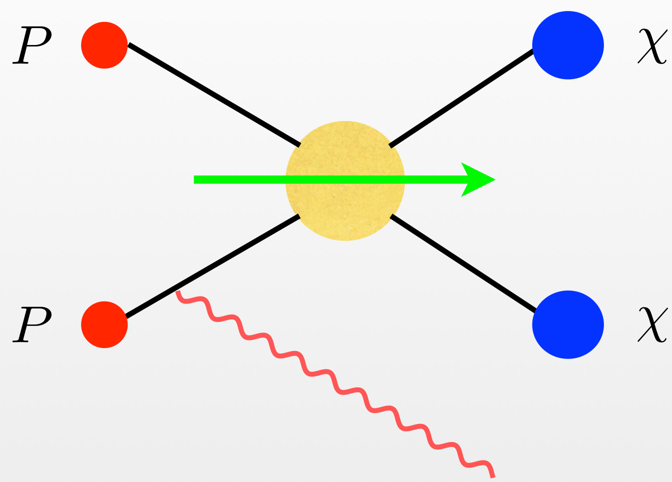
Cleaner Signatures for Dark Matter

EFT Framework

other radiated particles from proton can be better measured

Simplified Models

UV-complete the EFT operators may lead to cleaner signatures



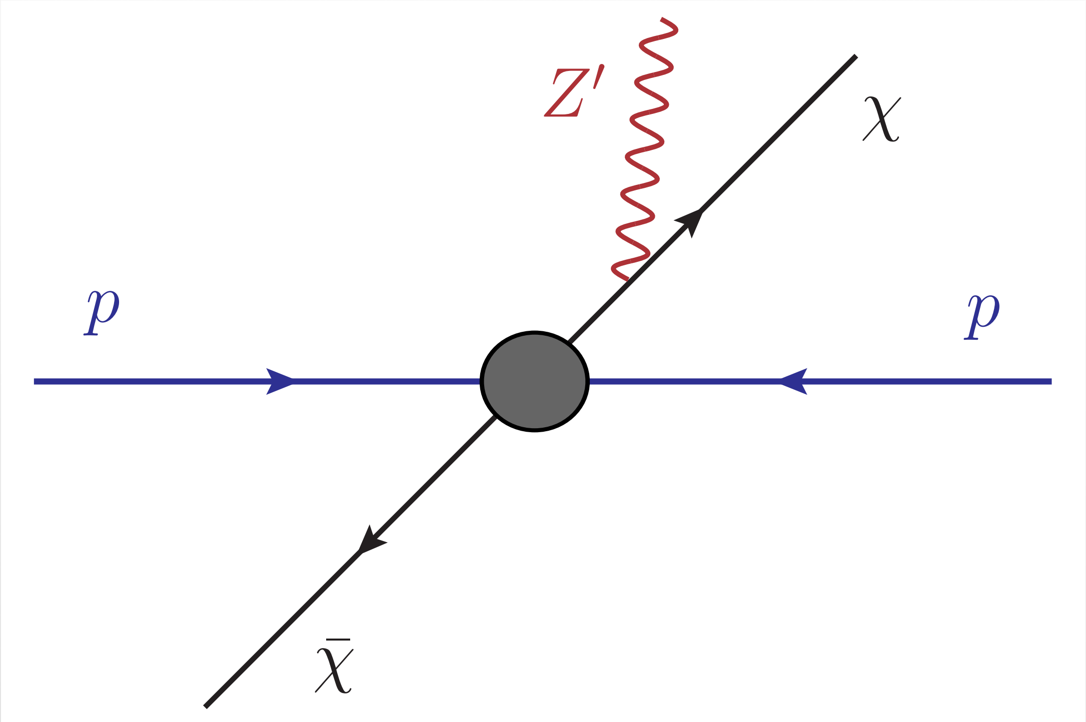
so far, we have considered only initial state radiation of visible particle

Dark sector could be more interesting:

- It may has its own dark U(1)'

- It may also have some nearby states

Probing Dark U(1)' at the LHC



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

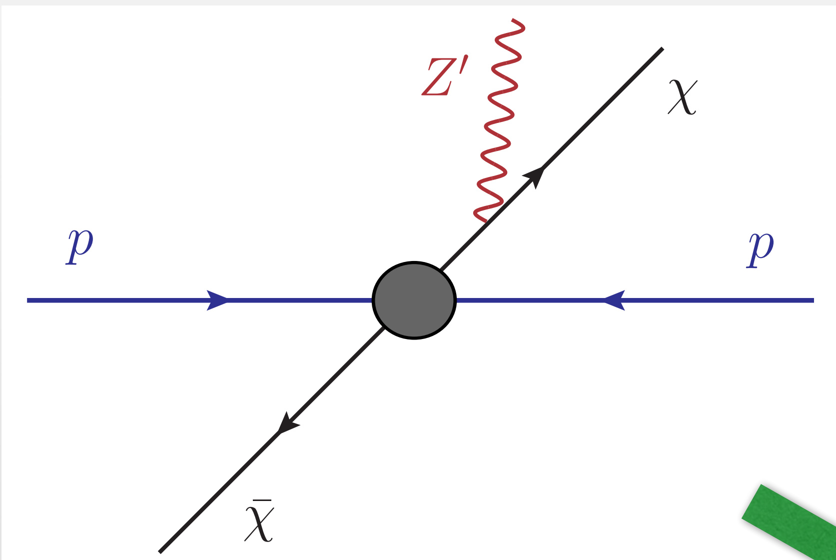
$$g_\chi Z'_\mu \overline{\chi}\gamma^\mu\chi$$

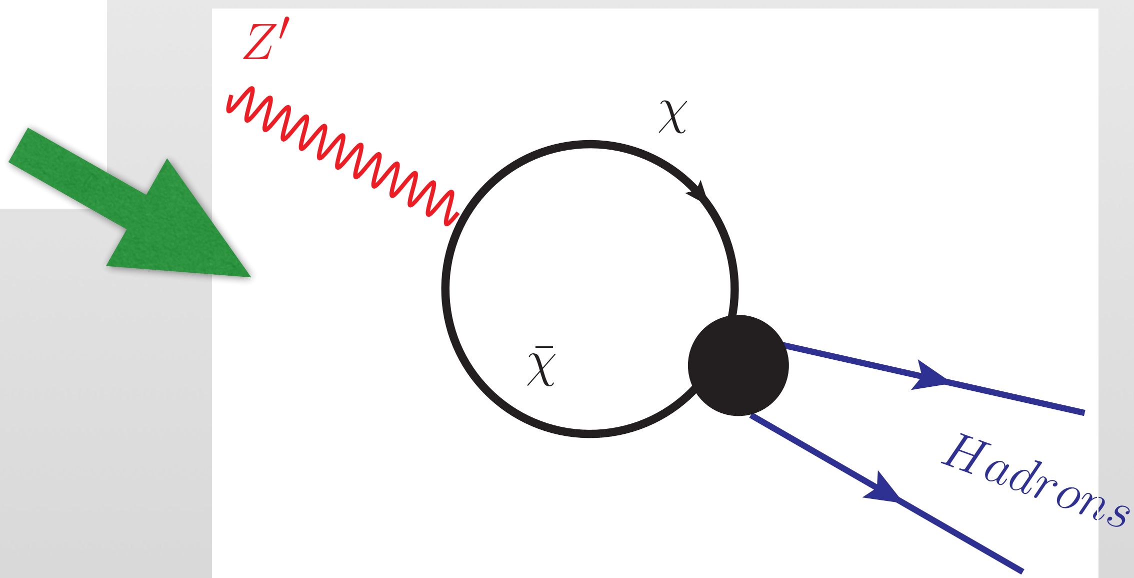
take dark matter as a vector-like Dirac fermion

Dark matter final state radiated a Z', the signature depends on how Z' decay

Probing Dark U(1)’ at the LHC

Given the fact that dark matter can be produced at the LHC and couple to Z’





Dark Z' Decay

Current-current interaction mediating Z' decays via a higher-dimensional operator

$$\frac{\tilde{c}}{\Lambda^2}\left(\phi'^{\dagger} D_\mu \phi' - \phi' D_\mu \phi'^{\dagger}\right)\left(\overline{u}\gamma^\mu u\right) \quad \longrightarrow \quad c\,\frac{M_{Z'}^2}{\Lambda^2}\,Z'_\mu\,\overline{u}\gamma^\mu u$$

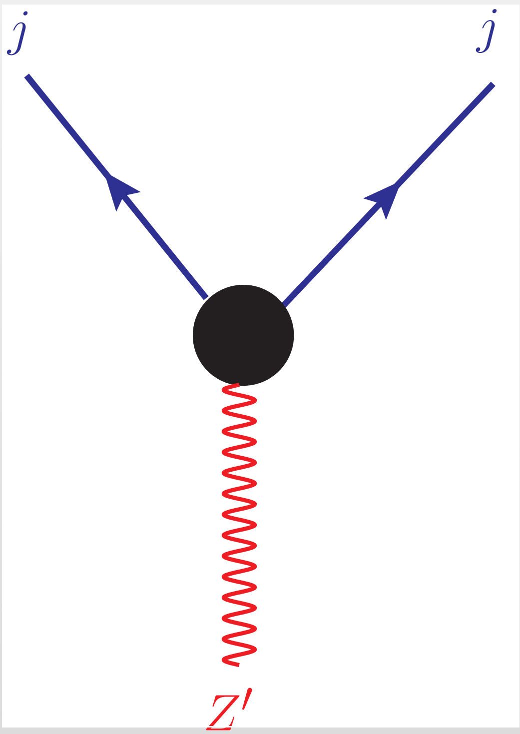
For a heavy Z', the signature is a 2j + MET with a dijet resonance

On the other hand, if the MET cut is stringent, we will have a boosted Z'. This Z' may just like a single Z' jet

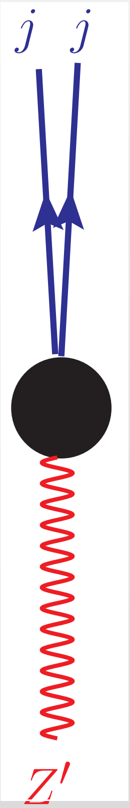
The signature is still "mono-jet"+MET

Dark Z' Decay

$p_T(Z') \approx M_{Z'}$



$p_T(Z') \gg M_{Z'}$



Dark Z' Decay

For a light Z' at O(1 GeV), the signature is more interesting

$$c\,\frac{M_{Z'}^2}{\Lambda^2}\,Z'_\mu\,\overline{u}\gamma^\mu u$$

Using chiral Lagrangian

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

$$\Gamma(Z' \to \pi^-\pi^+) = \frac{M_{Z'}}{48\,\pi}\left(\frac{c\,M_{Z'}^2}{\Lambda^2}\right)^2\left(1 - \frac{4\,m_\pi^2}{M_{Z'}^2}\right)^{3/2}$$

$$c\tau_0 \approx 3\ \mathrm{cm} \qquad\qquad c = 1,\ M_{Z'} = 1\ \mathrm{GeV\ and}\ \Lambda = 1\ \mathrm{TeV}$$

Mono-Z' jet: fewer hadrons and could be long-lived

Axi-vector Interaction

Similarly for axi-vector like interaction

$$d' \, \frac{M_{Z'}^2}{\Lambda^2} \, Z'_\mu \, \overline{u} \gamma^\mu \gamma_5 u$$

Using chiral Lagrangian

$$\bar{u} \gamma_\mu \gamma_5 u \to 2 i g_{\rho\pi\pi} \, f_\pi (\rho_\mu^+ \pi^- - \rho_\mu^- \pi^+)$$

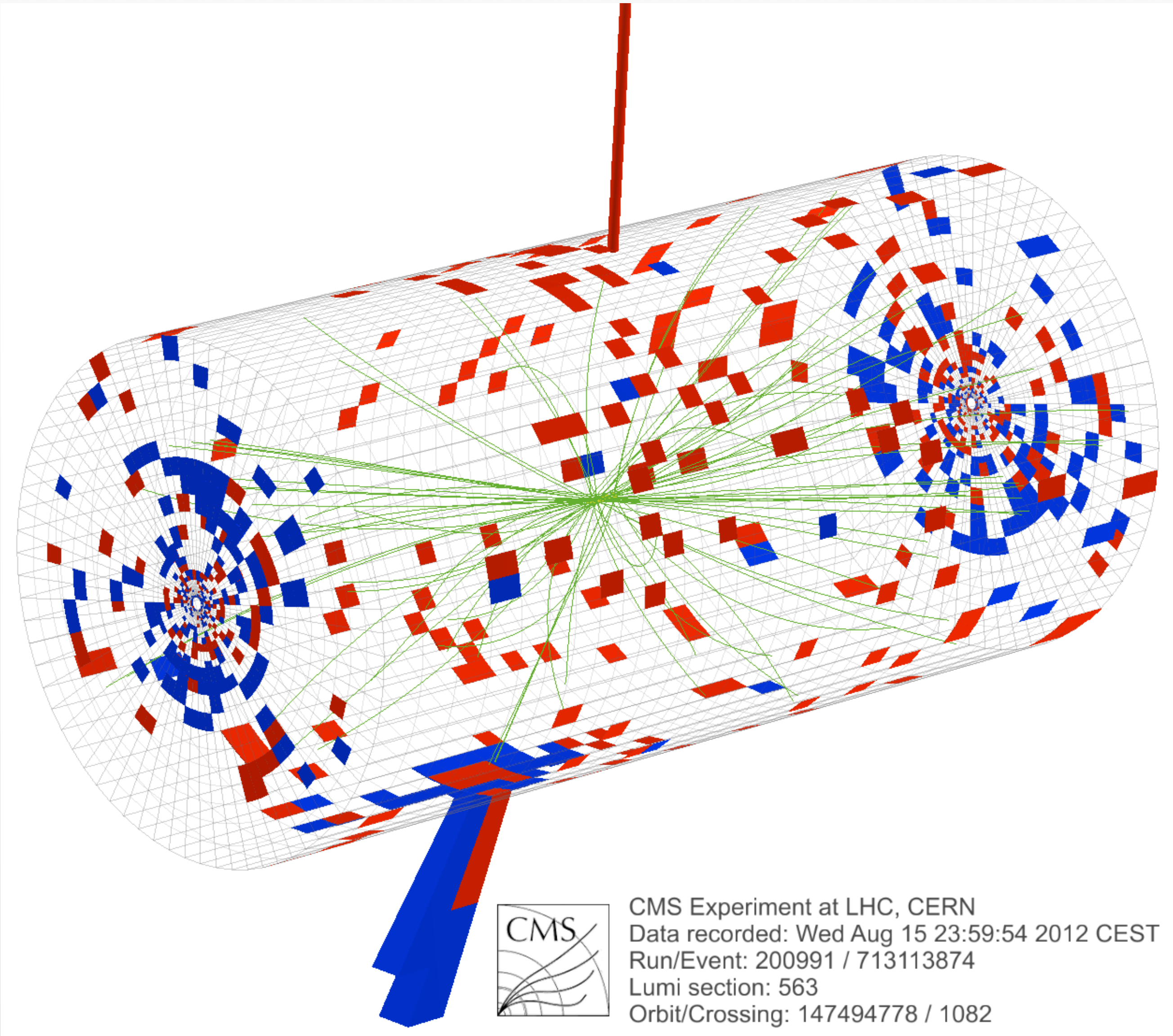
$$\Gamma(Z' \to \rho\pi) = 2\,\Gamma(Z' \to \rho^+ \pi^-) = \frac{d'^2 \, g_{\rho\pi\pi}^2 \, f_\pi^2 \, M_{Z'}^2 \, p}{3\pi \Lambda^4} \left(3 + \frac{p^2}{m_\rho^2} \right)$$

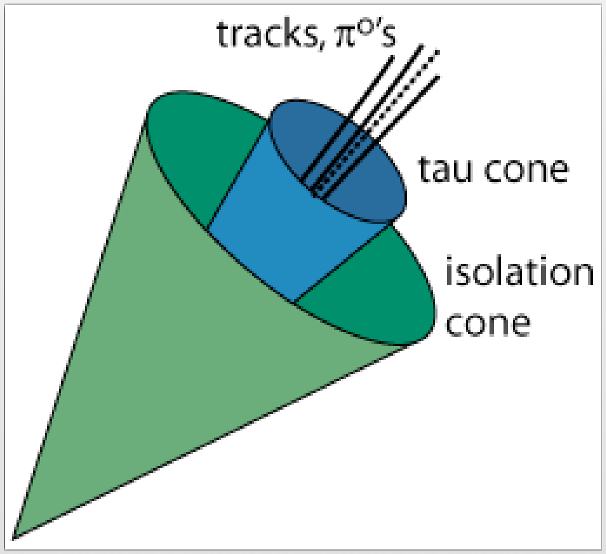
$c\tau_0 \approx 1.2 \text{ cm}$ $\qquad$ $d' = 1, \; M_{Z'} = 1 \text{ GeV and } \Lambda = 1 \text{ TeV}$

it decays to three hadrons with two charged one

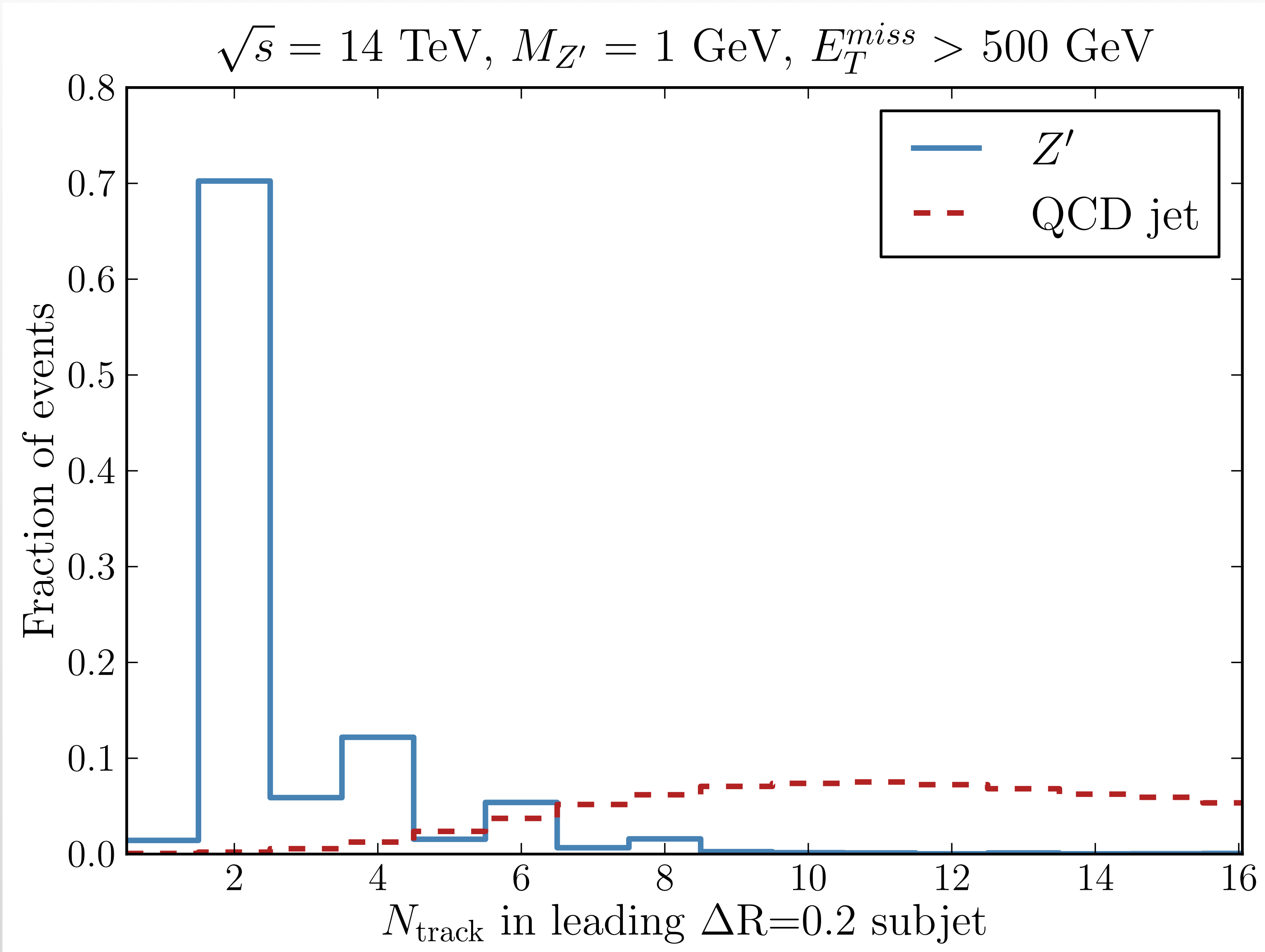
Mono-Z’ jet: fewer hadrons and could be long-lived

“Hadronic Tau”

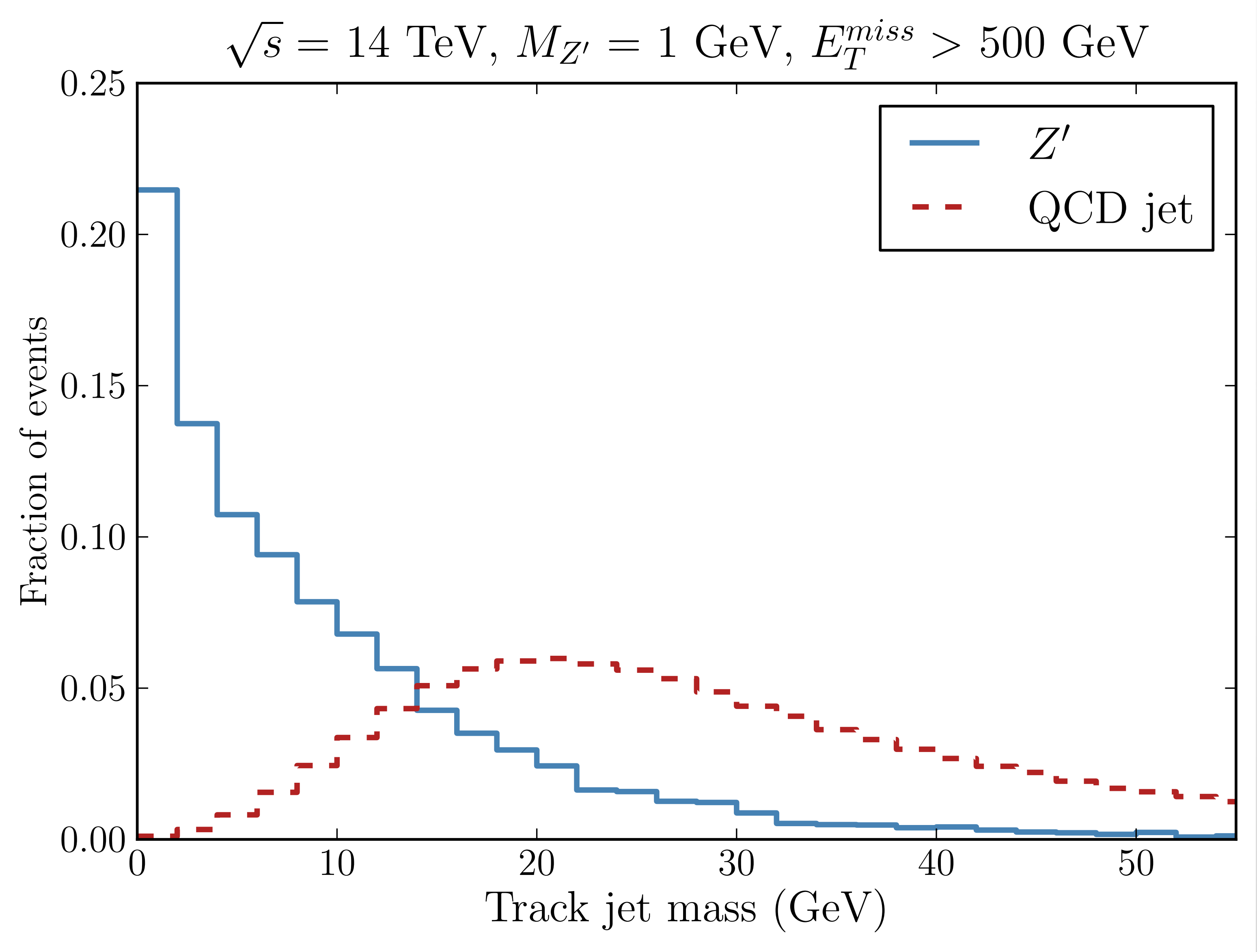




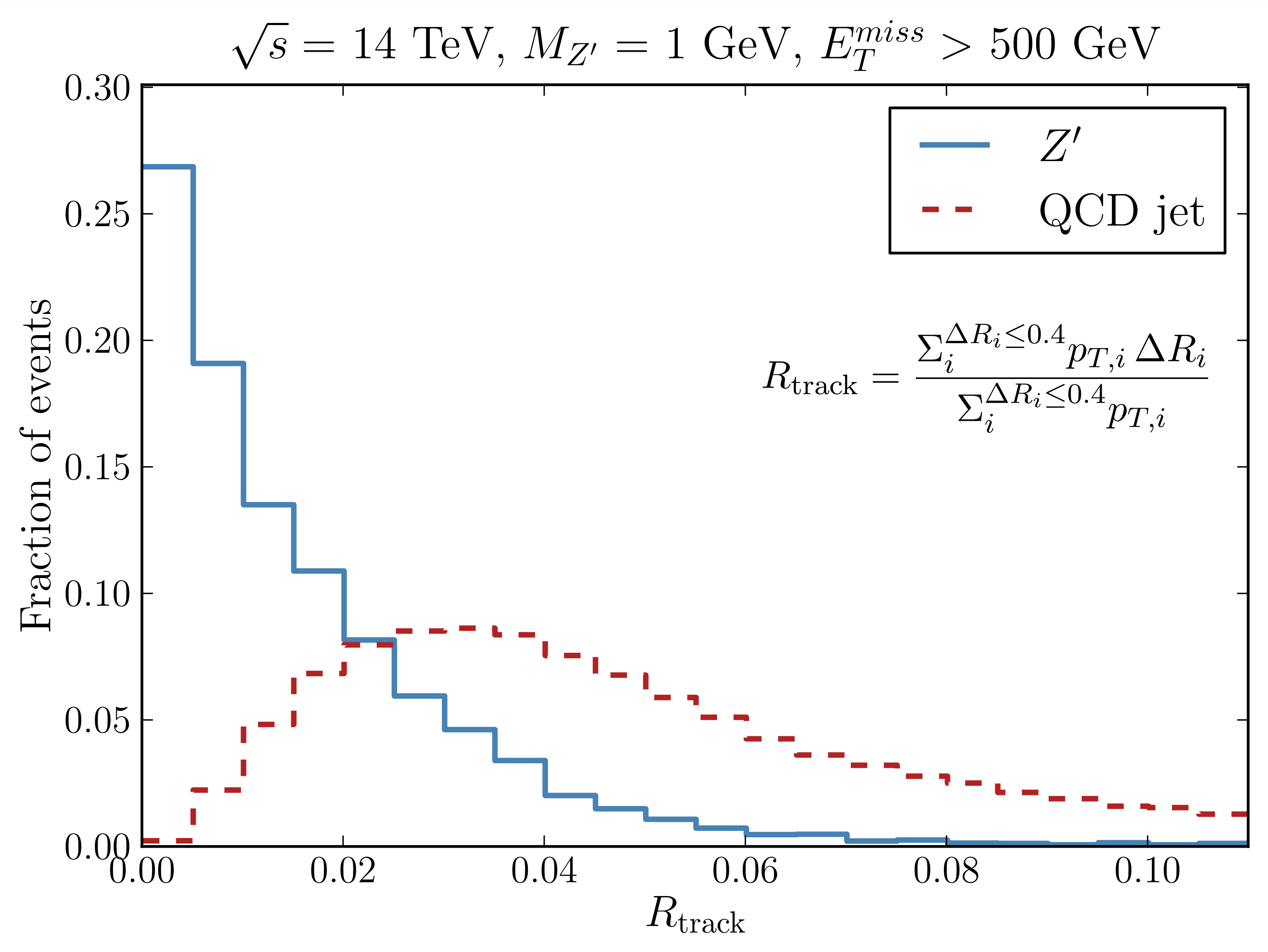
Kinematic Variables



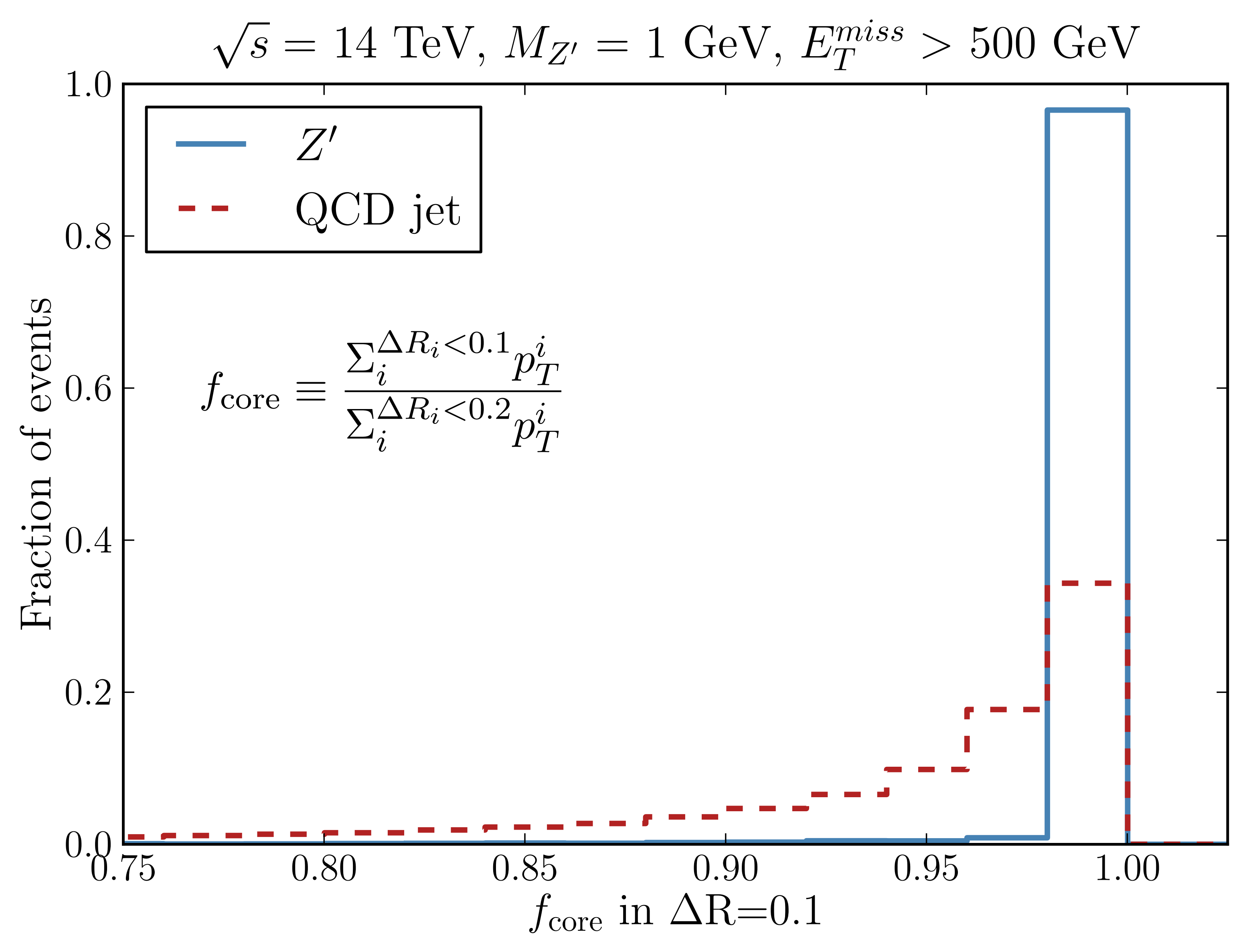
Kinematic Variables



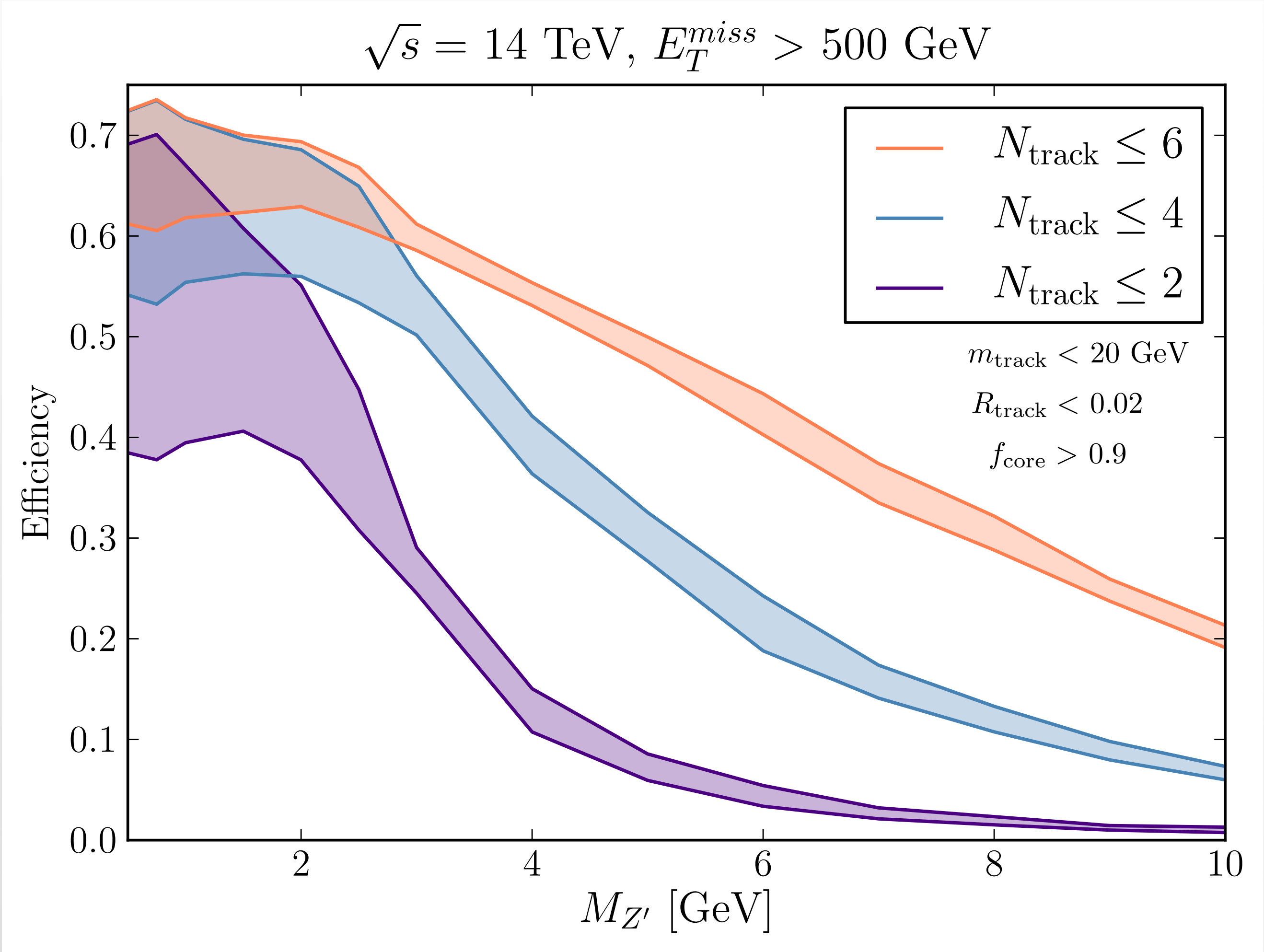
Kinematic Variables



Kinematic Variables

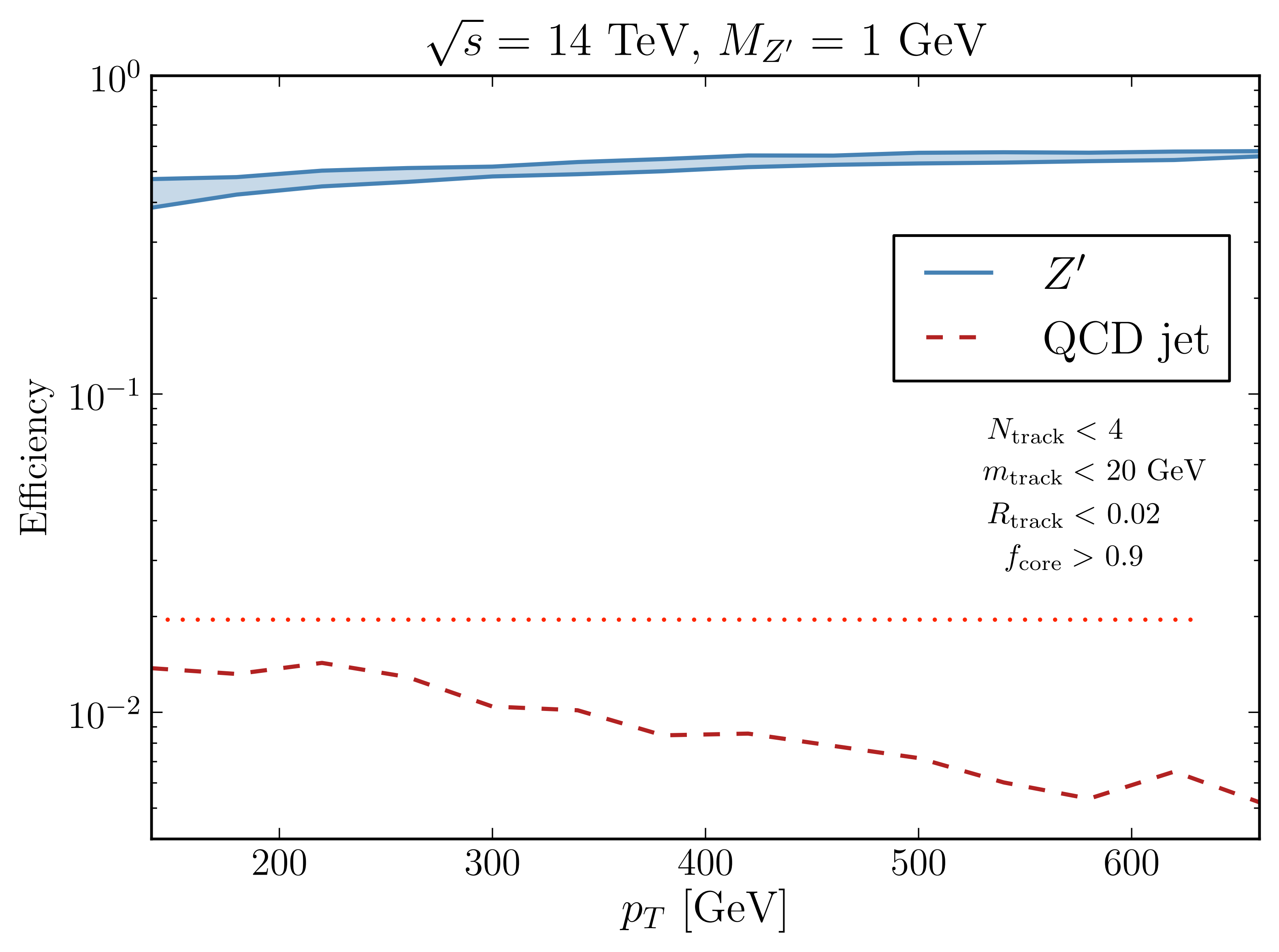


Signal Efficiency

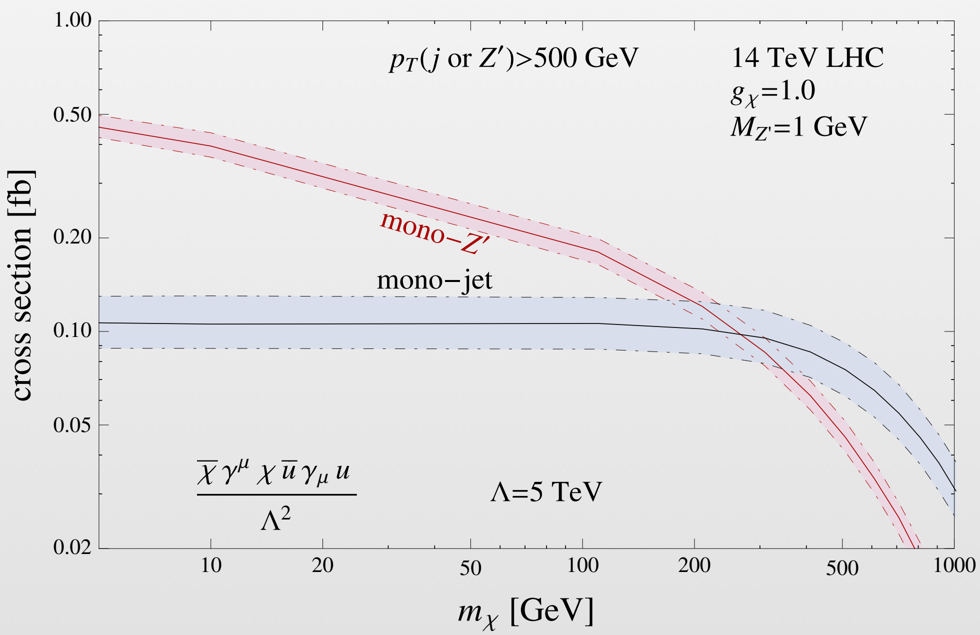


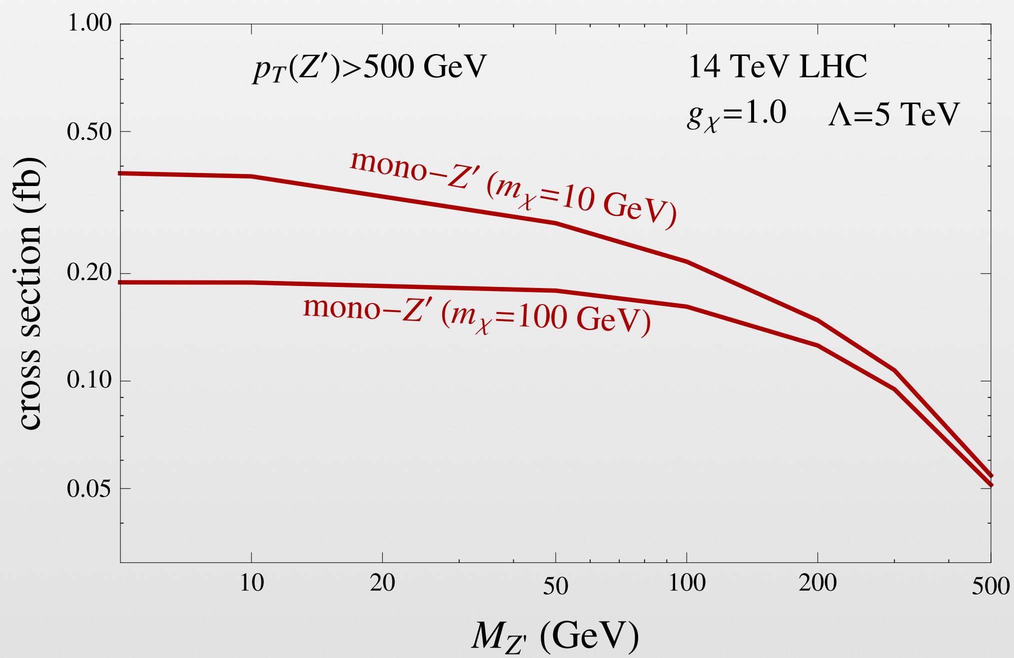
the band comes from different structures for the Z' coupling to light quarks

Signal and Background Efficiency

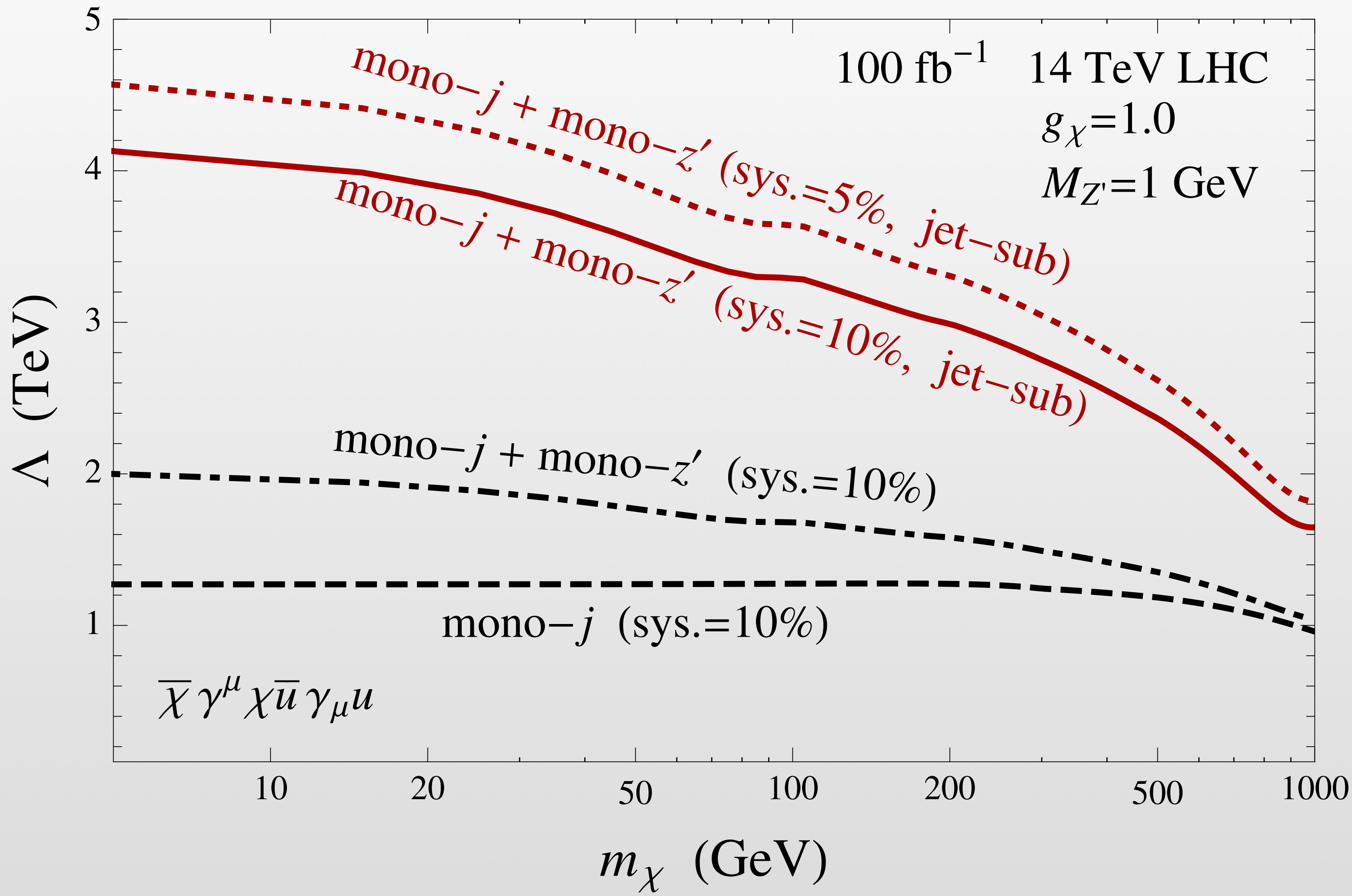


Production Cross Sections



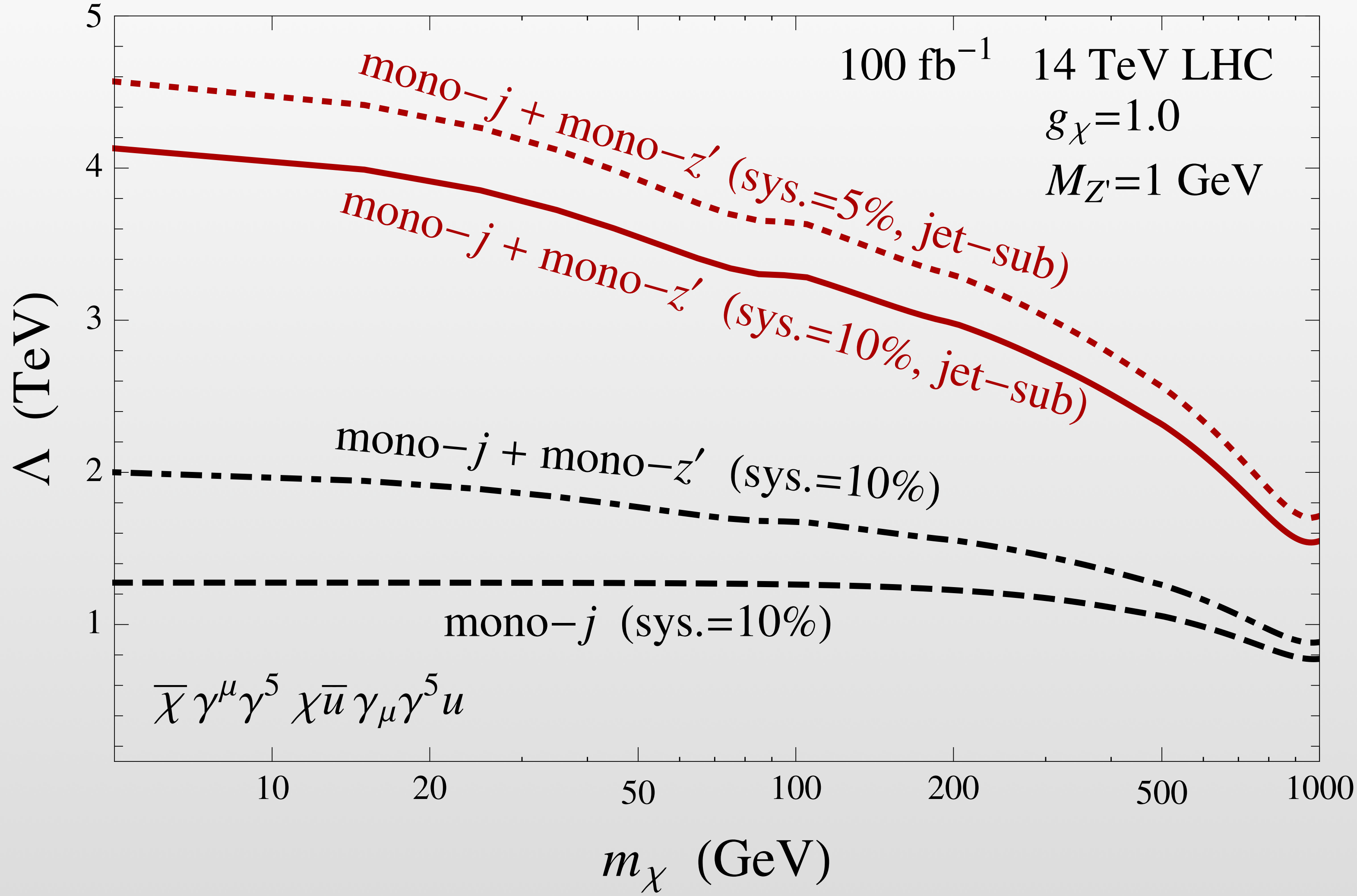


Discovery Potential (Vector)



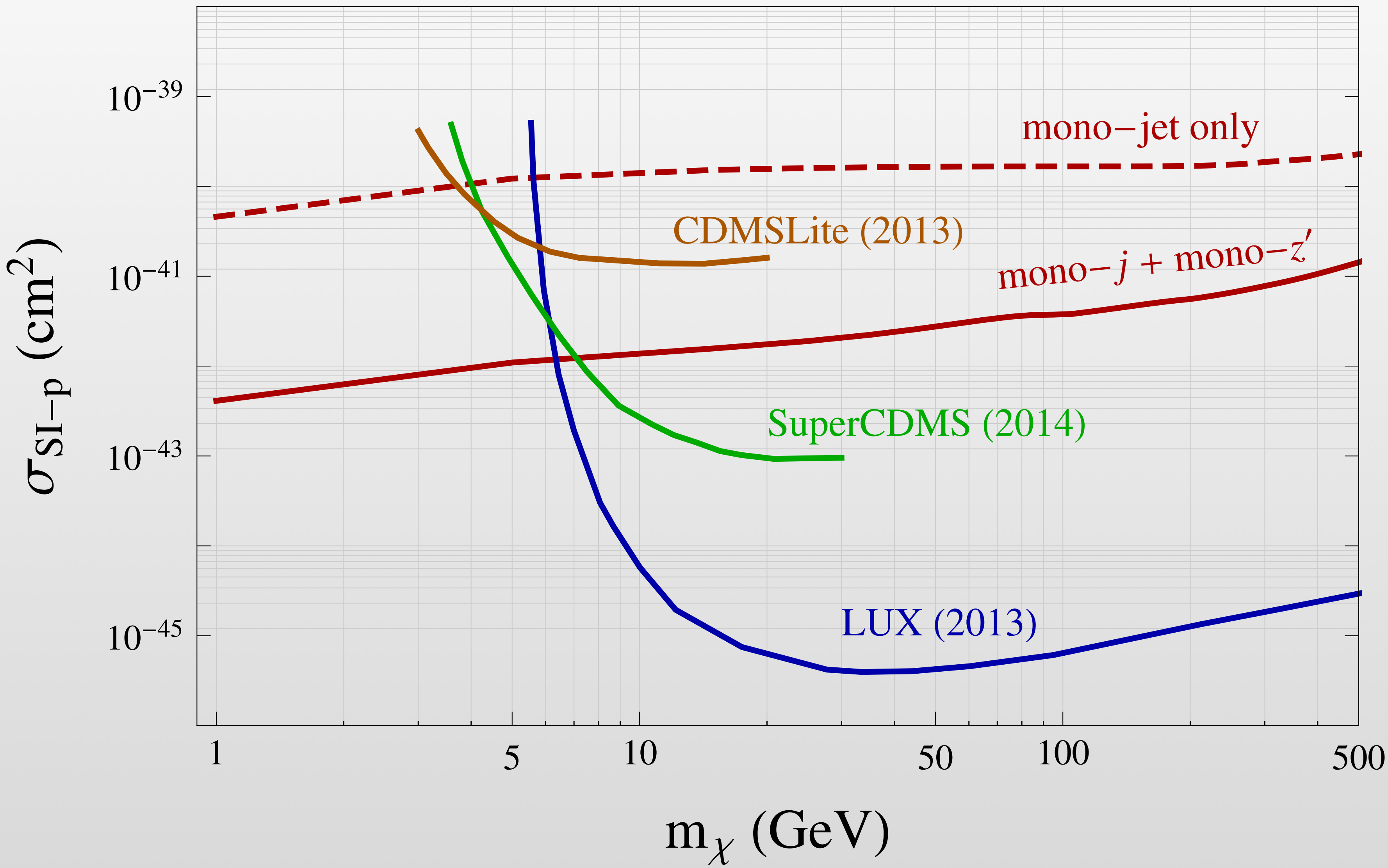
Tag-efficiency: 50% for signal, 2% for QCD

Discovery Potential (Axi-vector)

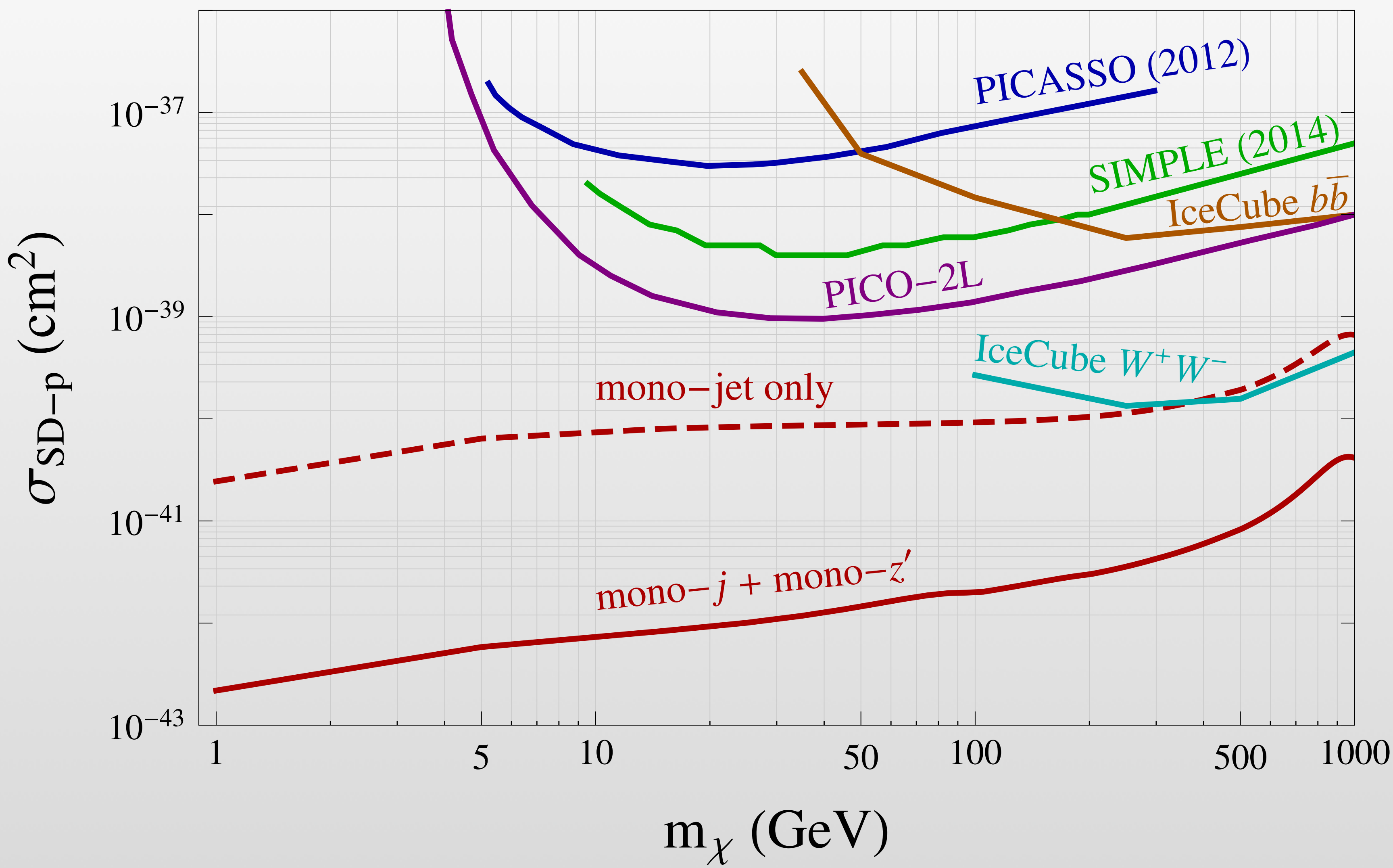


Tag-efficiency: 50% for signal, 2% for QCD

Spin-independent Cross Section



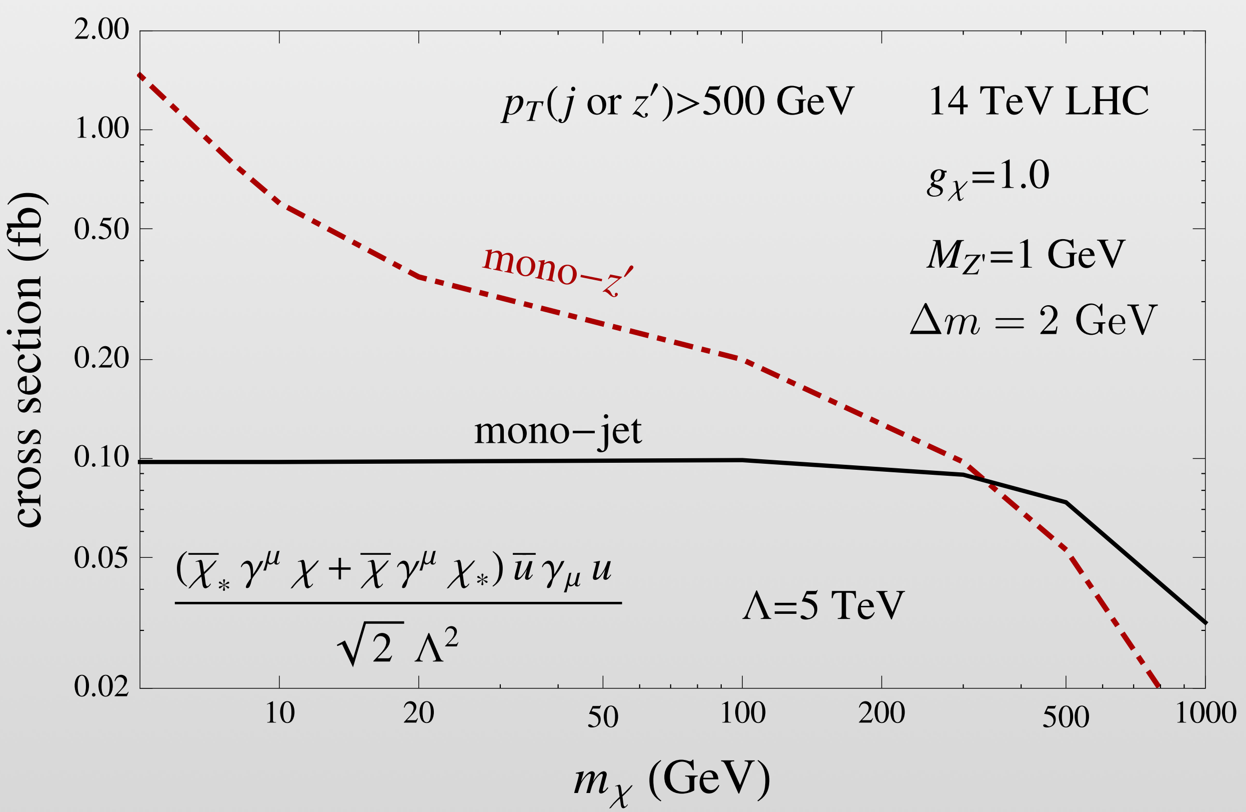
Spin-dependent Cross Section



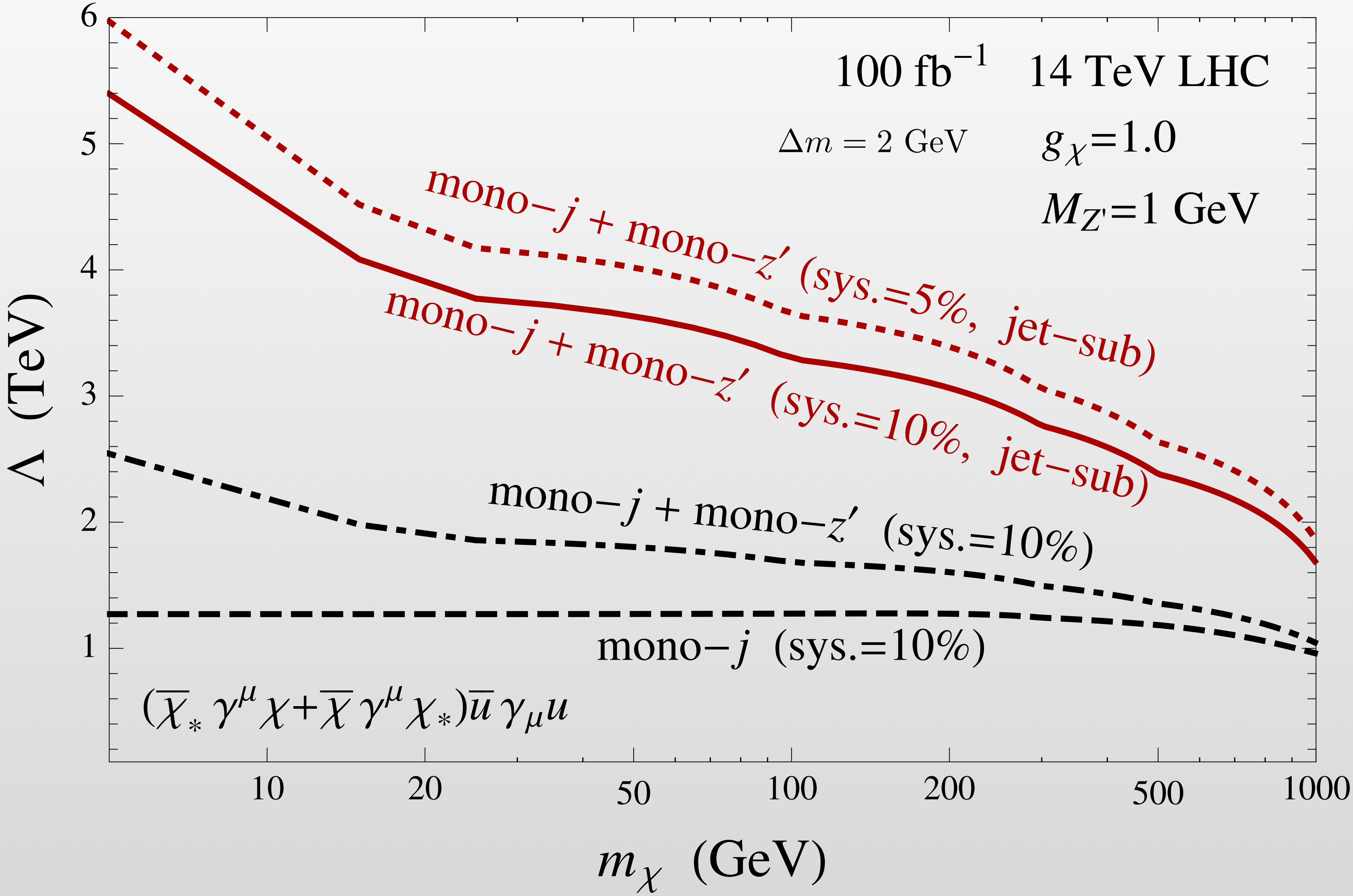
Inelastic Dark Matter Model

Direct detection experiments are insensitive to inelastic dark matter models with a mass splitting above 1 MeV

$$\mathcal{O}_V = \frac{(\overline{\chi}_* \gamma^\mu \chi + \overline{\chi}\gamma^\mu \chi_*)\, \overline{u}\gamma_\mu u}{\sqrt{2}\,\Lambda^2} \qquad g_\chi \left(\overline{\chi}_* \gamma^\mu \chi + \overline{\chi}\gamma^\mu \chi_*\right) Z'_\mu$$



Inelastic Dark Matter Model



U(1)' Models without Contact Interactions

To have SM quarks charged under U(1)', a non-trivial anomaly cancelation is needed.

Dobrescu, Frugiuele, 1404.3947

Tulin, 1404.4370

$$z_{u_R} = 1\,, \quad z_{d_R} = -1\,, \quad z_{\tau_R} = -1\,, \quad z_{\chi_R} = 1\,, \quad z_{\chi_L} = 0\,,$$

or

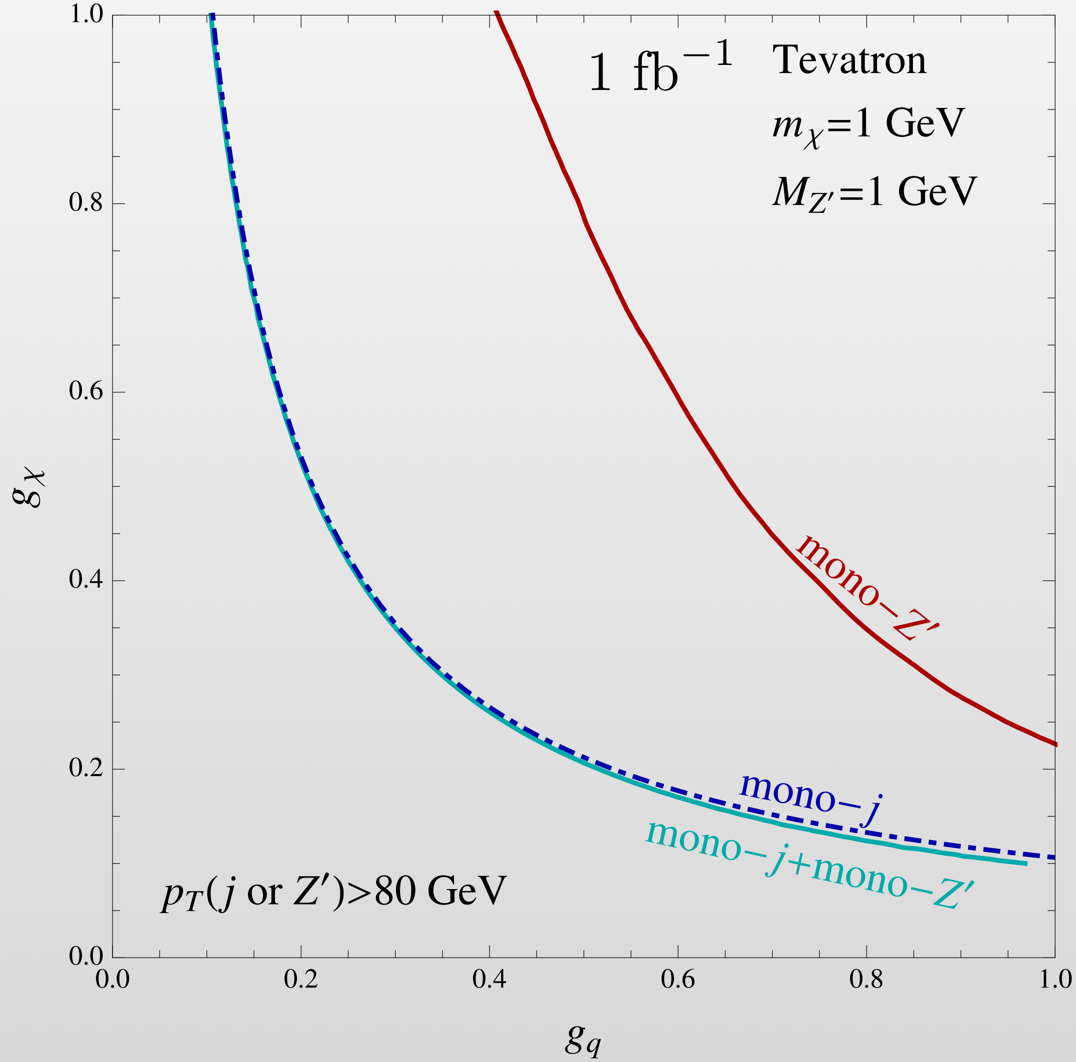
$$z_{u_R} = 1\,, \quad z_{d_R} = -1\,, \quad z_{\tau_R} = -1\,, \quad z_{\psi_R} = 1\,, \quad z_{\psi_L} = 0\,, \quad z_{\chi_R} = r\,, \quad z_{\chi_L} = r\,,$$

$$\sigma_{\chi A}^{\mathrm{SI}} = \frac{(A-2Z)^2}{\pi}\,\frac{g_q^2\, g_\chi^2\, \mu_{\chi A}^2}{4\, M_{Z'}^4}$$

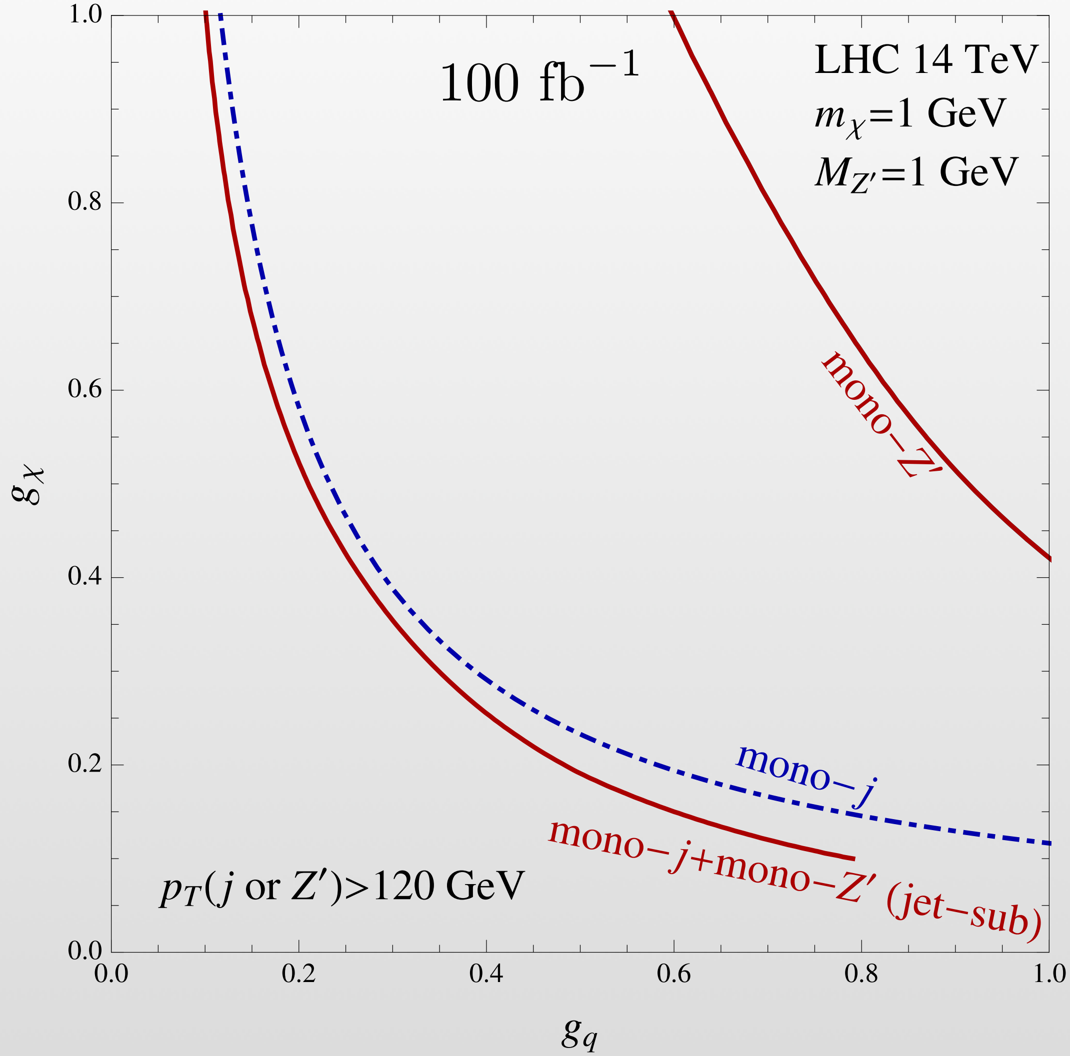
If dark matter is above 3 GeV, it is highly constrained by CRESST-II data.

Existing Bound at Tevatron

Tevatron still provides the current best constraint



Challenging for the LHC



also need to design a new mono-Z' trigger

Conclusions

- ★ There are more collider signatures for discovering dark matter particles
- ★ Dark matter can radiate its own charged Z' and have a mono-Z' jet
- ★ Jet-substructure techniques can help us to tag the mono-Z' jet
- ★ A dedicated search for mono-Z' jet events at the LHC can lead to an order-of-magnitude improvement in constraining dark matter-nucleon interactions

Thanks