CDF II

UC DAVIS
UNIVERSITY OF CALIFORNIA

A Search for Dark Matter in the Monojet + Missing Transverse Energy Signature in 6.7 fb^{-1}

S.Z. Shalhout [UC Davis]
on behalf of
the CDF collaboration, P. Fox, R. Harnik, Y. Bai

Outline

- Present results of a new CDF search for dark matter in monojet + missing transverse energy
- Search was performed in collaboration with authors of :

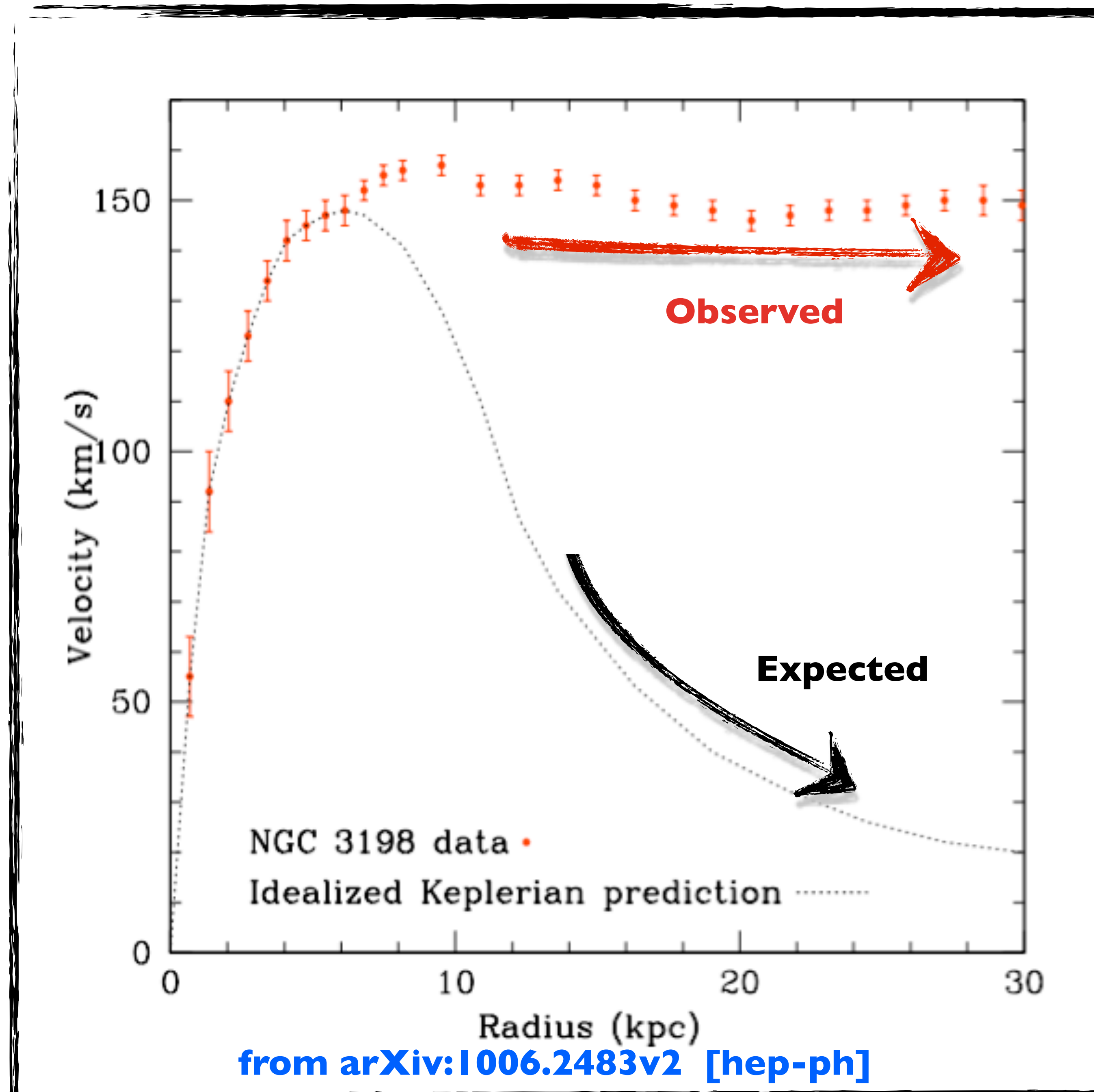
"The Tevatron at the Frontier of Dark Matter Direct Detection"
Yang Bai, Patrick J. Fox, Roni Harnik
arXiv:1005.3797v2 JHEP 1012:048,2010

See W&C by P. Fox on 4/22/2011

- Introduction & motivation
- Search strategy
- Results
- Comparison to other searches

Introduction

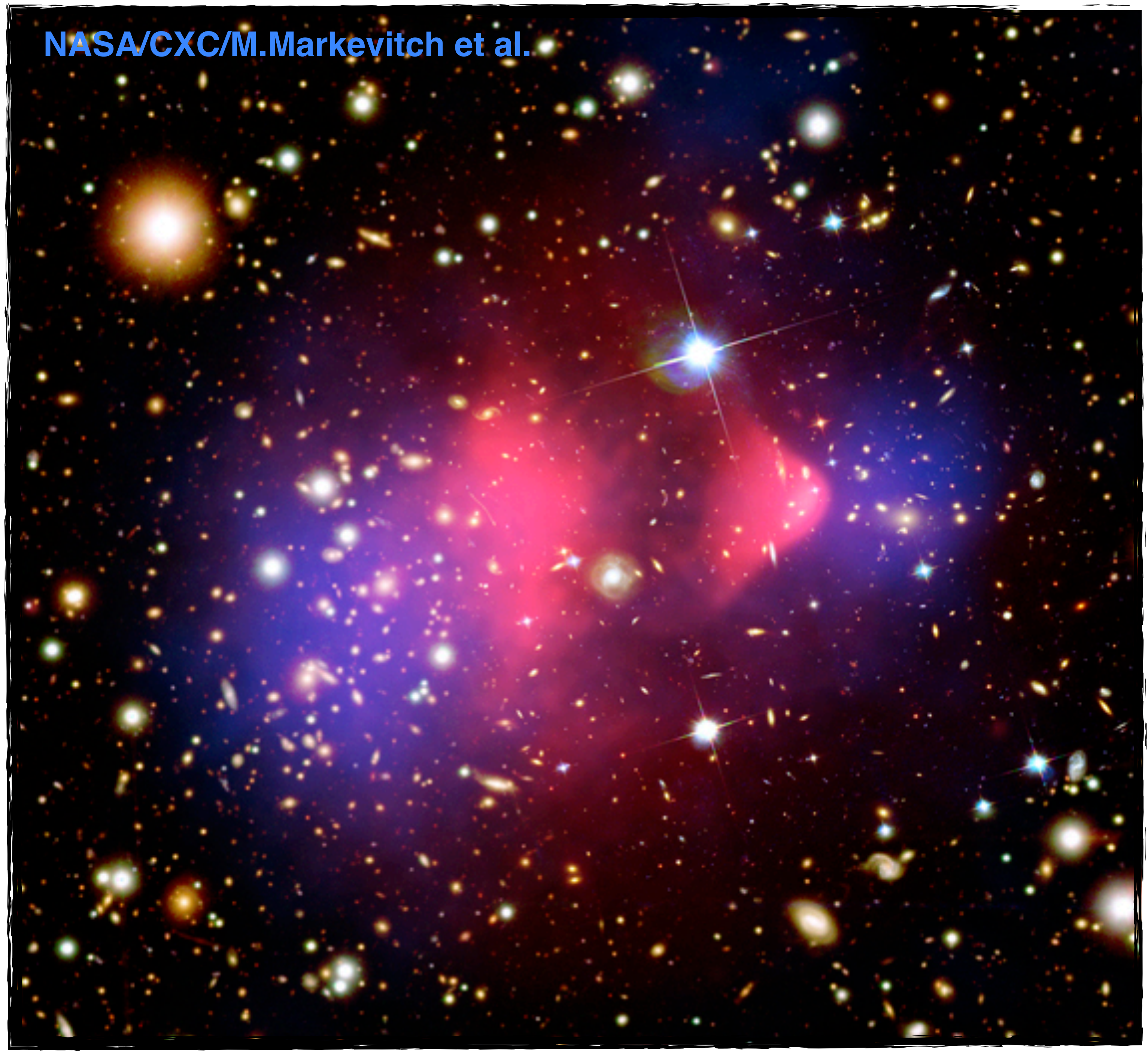
- There is strong evidence for the existence of dark matter.



- Clear deviation from expected $1/\sqrt{r}$ behavior

Introduction

- more evidence from the bullet cluster



Astrophys.J.648:L109-L113,2006
arXiv:astro-ph/0608407v1

Direct Detection

- Gravitational evidence is compelling and has motivated several dedicated direct-detection searches
- Aim to observe recoil of dark matter off of nucleus

DAMA/LIBRA +

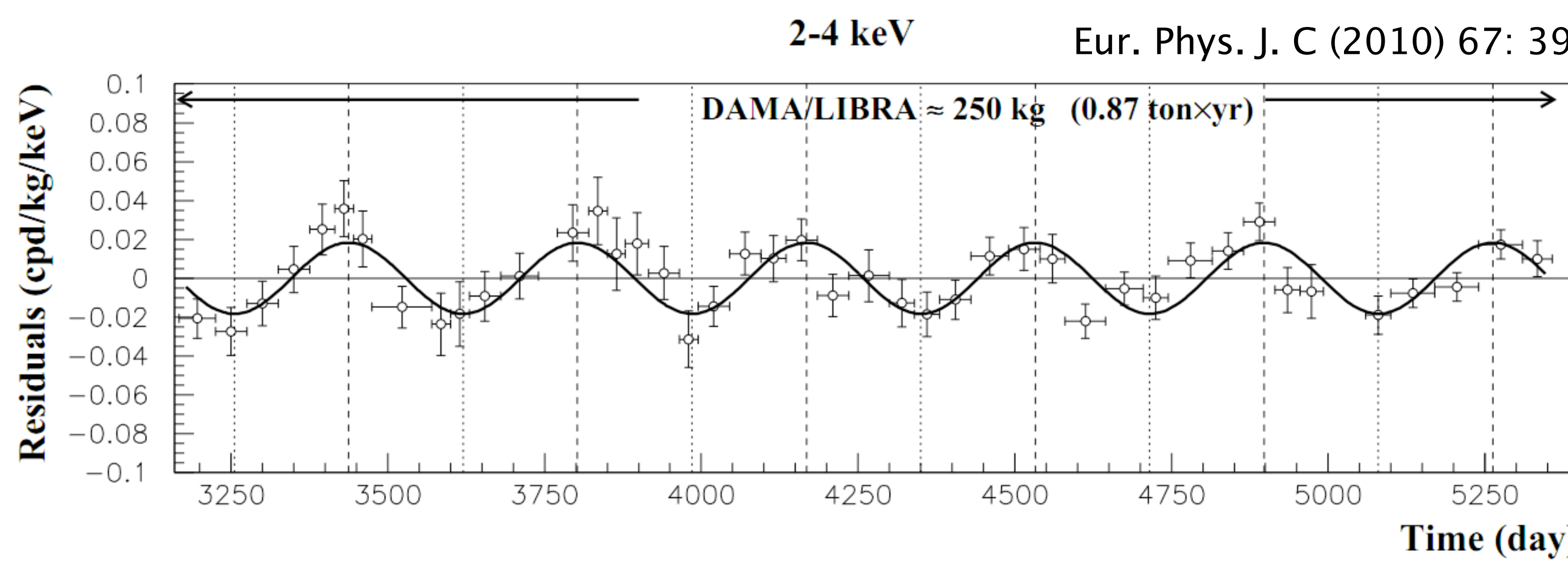
CoGent +

CRESST-II +

CDMS -

XENON-100 -

Eur. Phys. J. C (2010) 67: 39–49



excesses in several recent experiments hint at ~10GeV DM

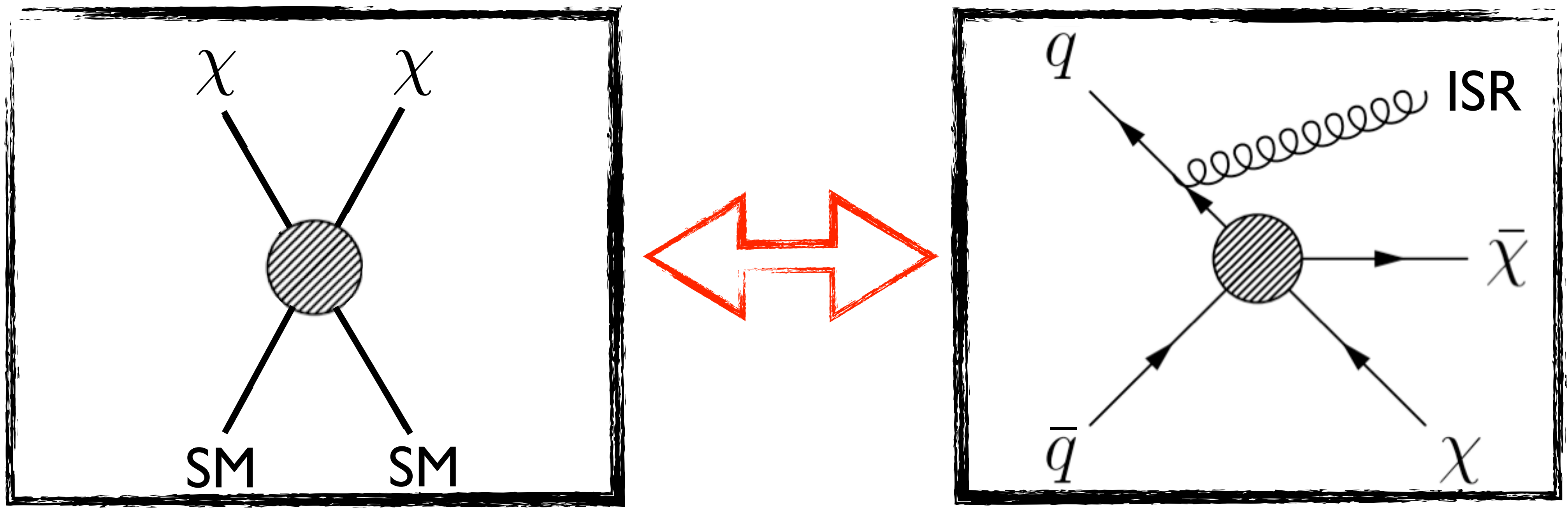
Strong limits on dark matter nucleon scattering rate from others

open question

Collider Input

- Assuming dark matter couples to the SM (quarks & gluons) can relate direct detection to collider production of dark matter

Direct Detection | Collider Monojet + MET

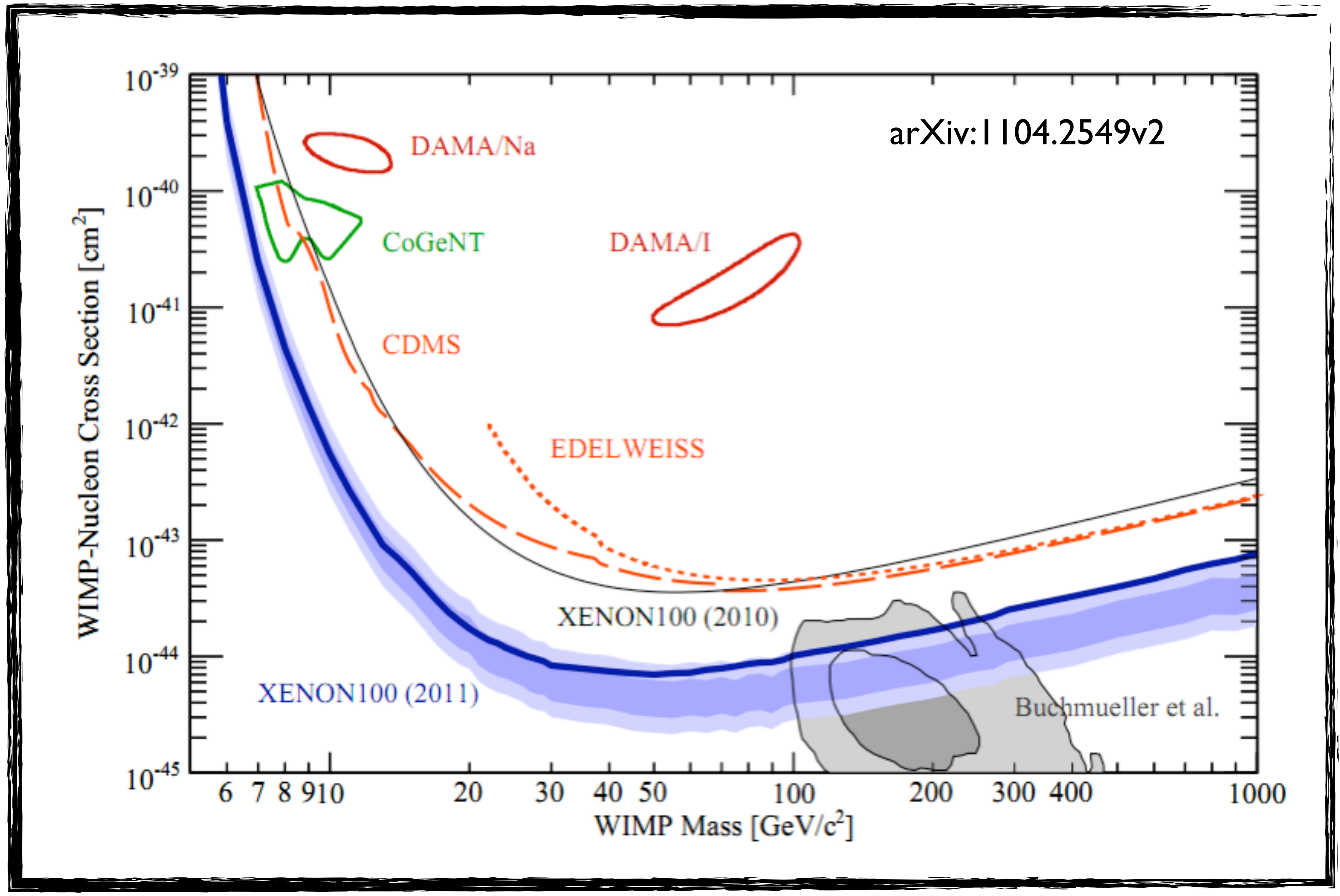


- In collider production, dark matter (χ), passes through the detector resulting in a transverse energy imbalance (MET)

- When produced in events with additional an ISR-jet, it is possible to detect & analyze these events

Collider Advantages

- Advantage #1 : no detection threshold



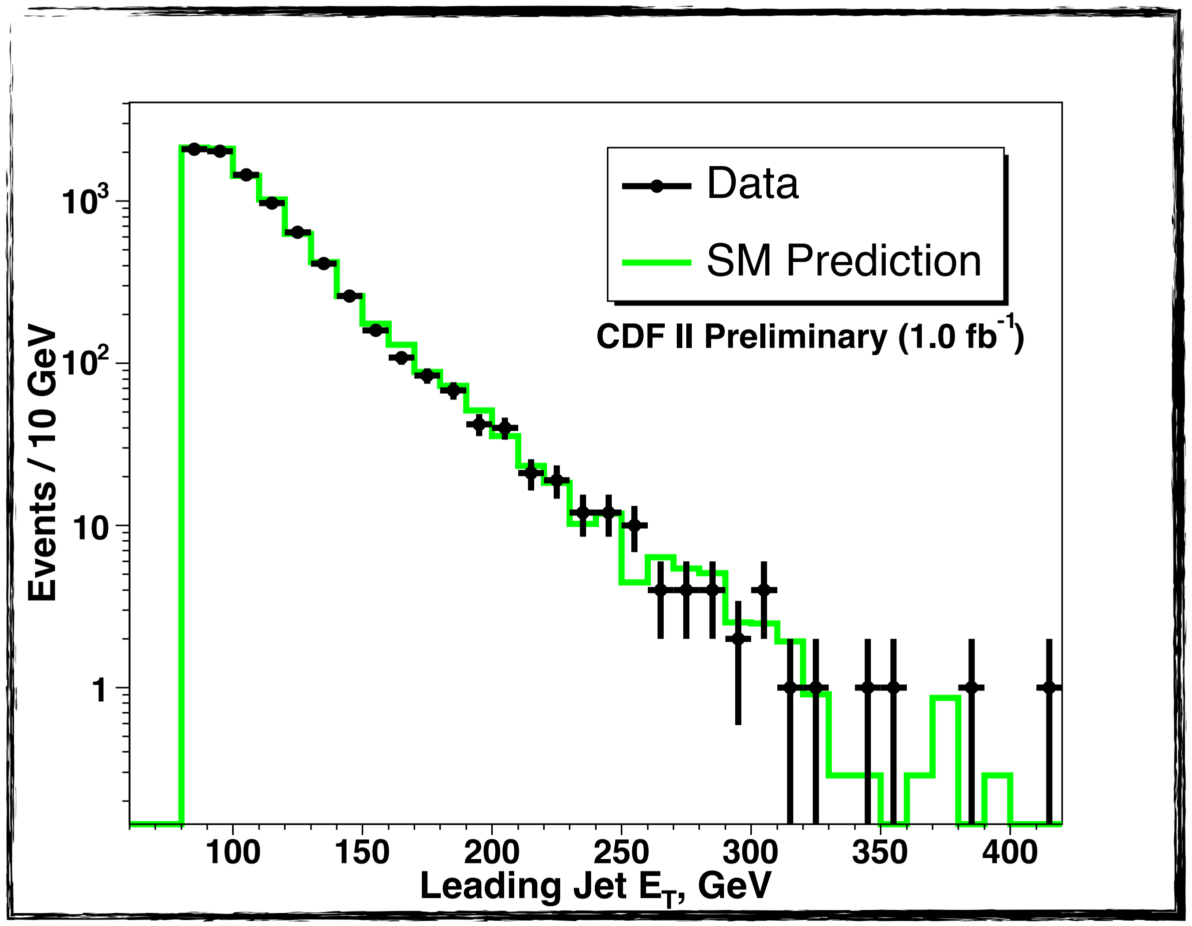
- While (~1GeV) DM-recoil can fall below direct-detection threshold, collider searches have no such limitation

Collider Advantages

- Advantage #2: No Spin independence vs Spin dependence
  - For direct detection Spin-dependent vs Spin-independent DM-nucleon interactions matter
  - With spin-dependence, DM couples to spin of a nucleon
  - In the spin-independent case, get a coherent interaction with the nucleus as a whole (A^2 enhancement)
- Direct detection limits are much weaker for SD interactions than for SI
- A collider search is insensitive to this effect
- In short, a collider monojet+MET search can set competitive bounds for light DM, and for spin-dependent interactions

Previous Monojet Searches

- Previously studied at CDF, ATLAS, and CMS in the context of Large Extra Dimensions



- There exists several indirect translations of the results into bounds on dark matter scattering rates

[arXiv:1109.4398]

JHEP 1012:048,2010

Phys.Rev.D82:116010,2010

Phys.Lett.B695:185-188,2011

- CDF result in 6.7/fb is the first dedicated dark matter search in monojet + MET.

DM Signals Considered

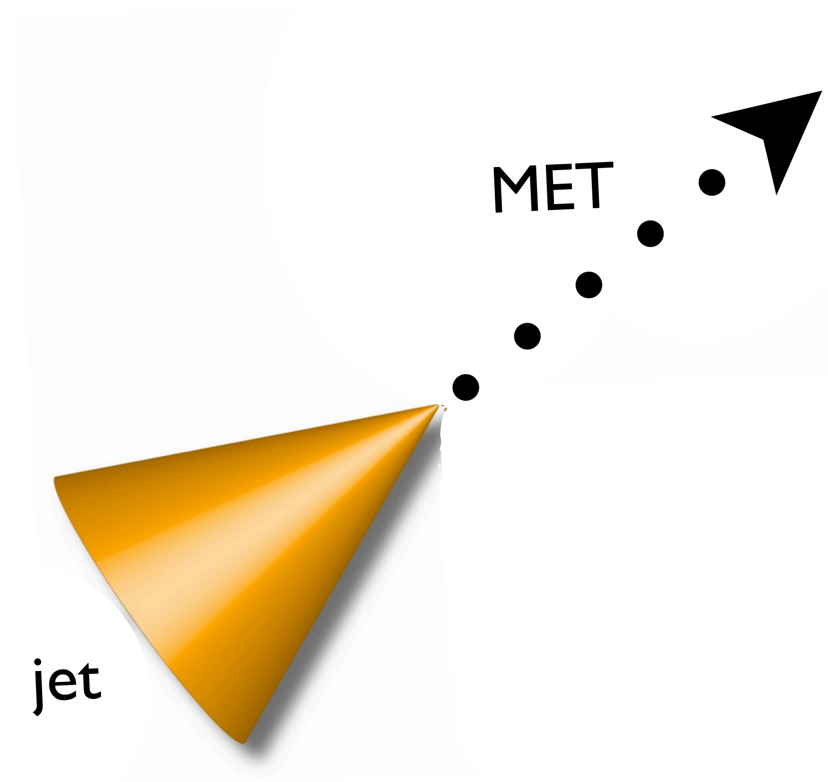
- Aim is to observe DM production or set upper limits on

$$\sigma[p\bar{p} \rightarrow X\bar{X} + jet]$$

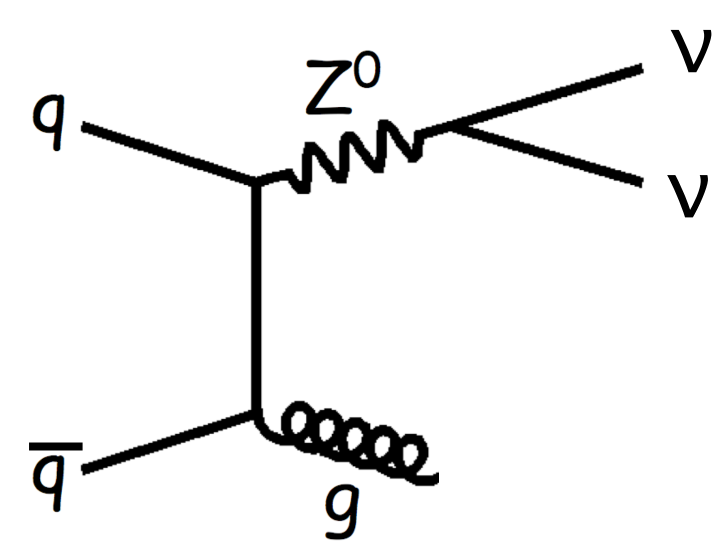
- Consider three models of dark matter production in which some mediator couples to DM and standard model quarks :
  - Axial vector mediated production (A-V) → spin dep. interactions in direct detection
  - Vector mediated production (V) → spin indep. interactions in direct detection
  - t-channel mediator exchange (T)
- Study very heavy mediators (10 TeV) where you can assume an effective theory (mediator drop out), as well as lighter (~100 GeV) mediators
- Consider several dark matter masses between 1 and 300 GeV

DM Signal Characteristics

- Look for a high E_T jet back-to-back with missing E_T

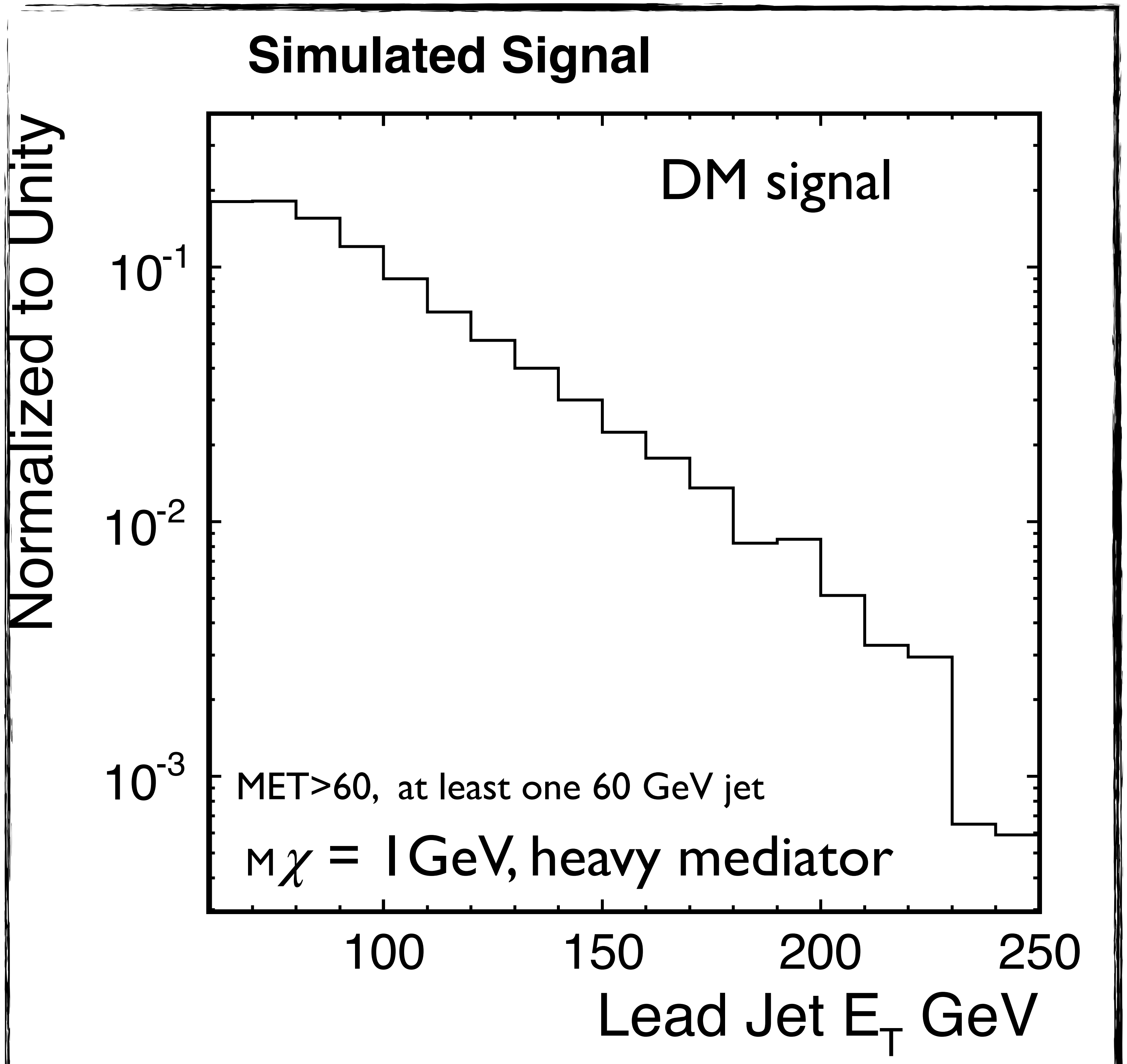


- Background processes with similar detector signature :
  - $Z \rightarrow \nu\nu$ + jet
  - $W \rightarrow l^{\pm} \nu$ + jet (where $l^{\pm}$ escapes detection)
  - QCD multijet events



DM Signal Characteristics

- Signal is MadGraph + Pythia + Full Detector Simulation



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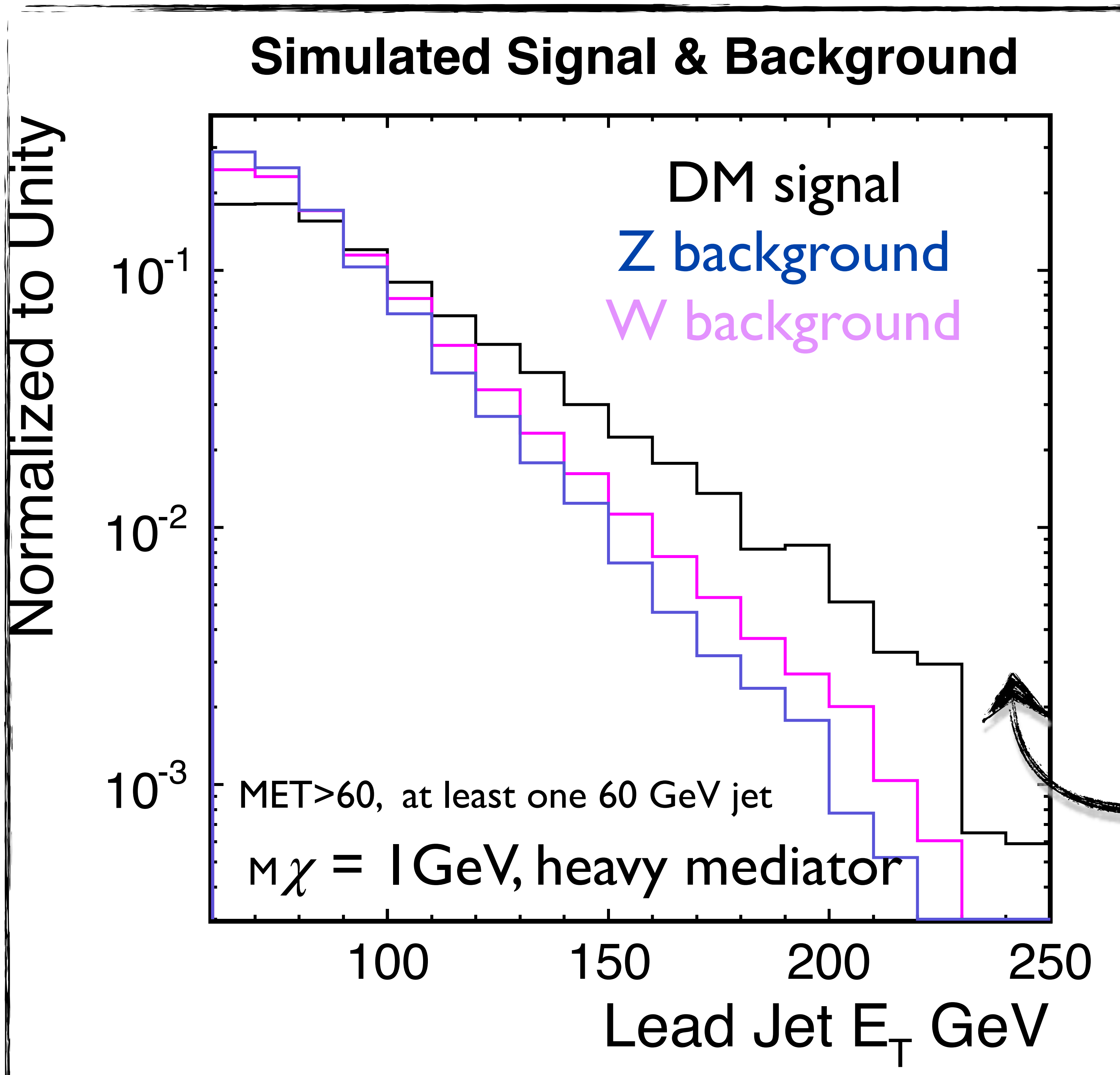
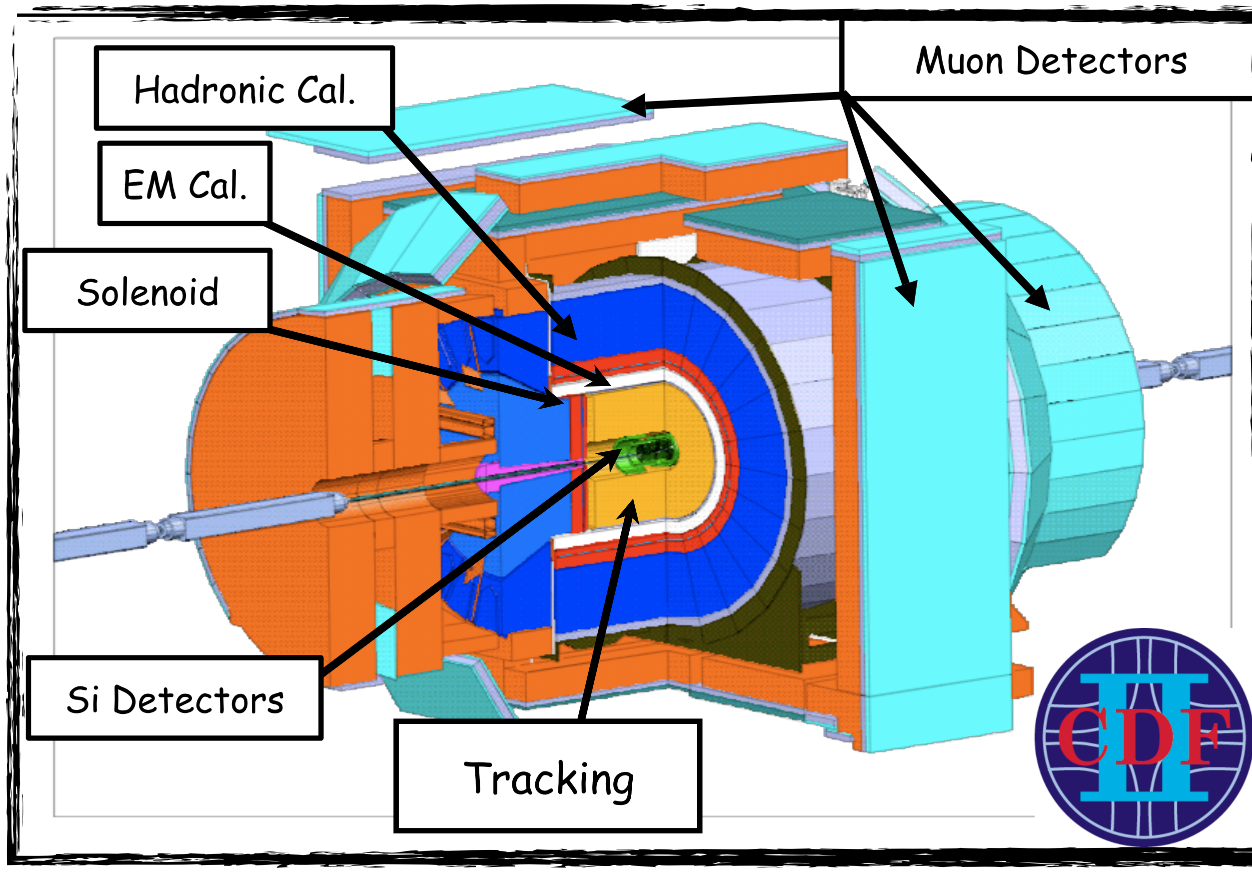
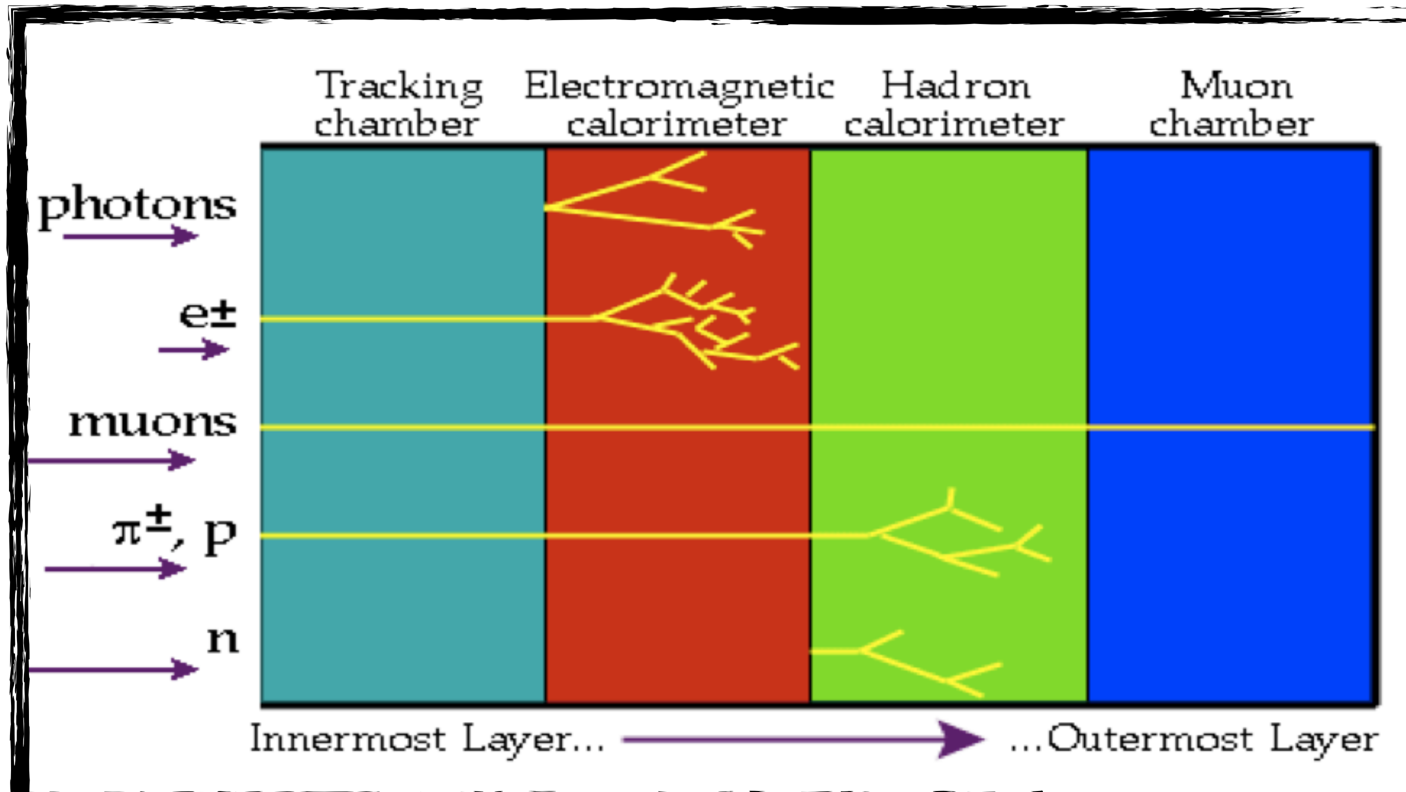


Rely on tail for most sensitivity

The Detector

- Dark matter passes through CDF, but we can still make good use of the full CDF detector
  - Tracking : reject events with leptonically decaying Z or W with a track veto
  - Calorimetry : reject photons and electrons
  - Muon detectors : reject cosmic rays



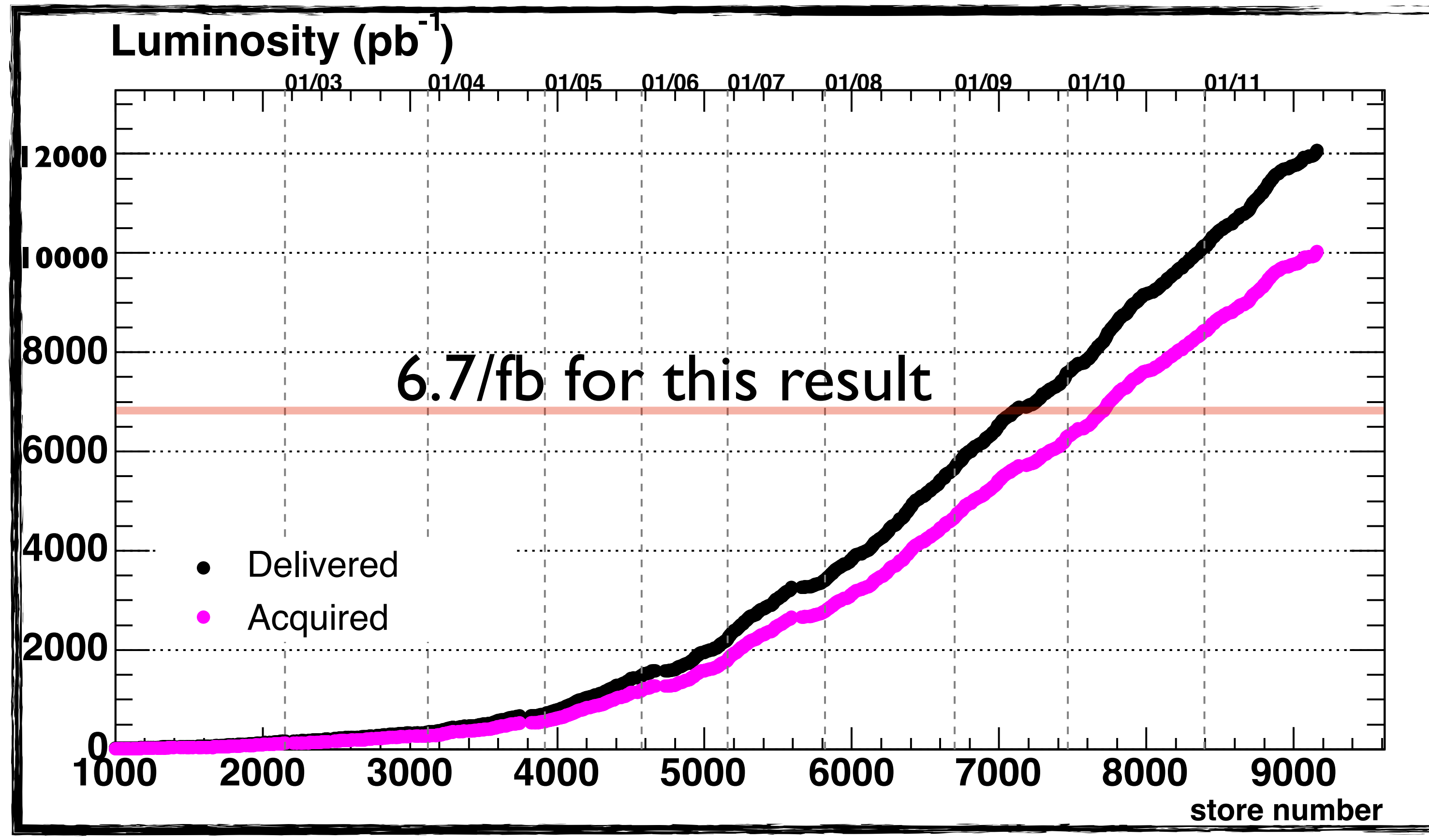


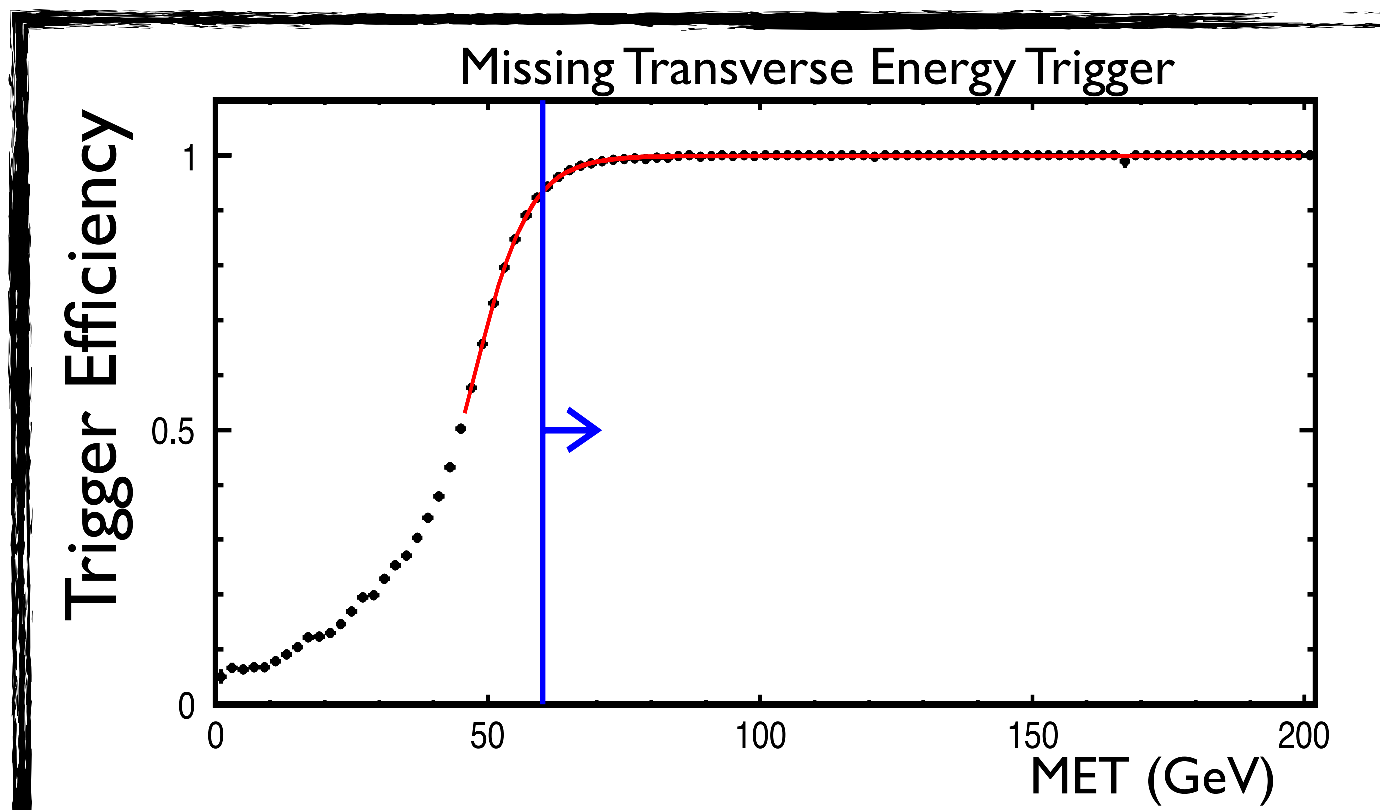
Data Sample

- Utilize a 6.7/fb data sample selected with missing transverse energy triggers (MET > 40 GeV)

- Special thanks to the Beams Division for providing us with this rich dataset!

- Impose an offline requirement of MET > 60 GeV for an efficiency close to one





Event Selection

- Analyze 6.7/fb recorded by missing energy triggers
- Require MET > 60 GeV
- One jet with transverse energy (E_T) > 60 GeV
- At most one additional jet with E_T < 30 GeV
- Define 3 additional selections for background modeling & analysis cross-checks

Signal Region
Includes data quality cuts, non-collision vetoes, multijet rejection, and track rejection (lepton veto)

Event Selection

Pre-Selection

Relaxed selection with at least one jet with E_T > 35 GeV and MET > 60 GeV & non-collision vetoes

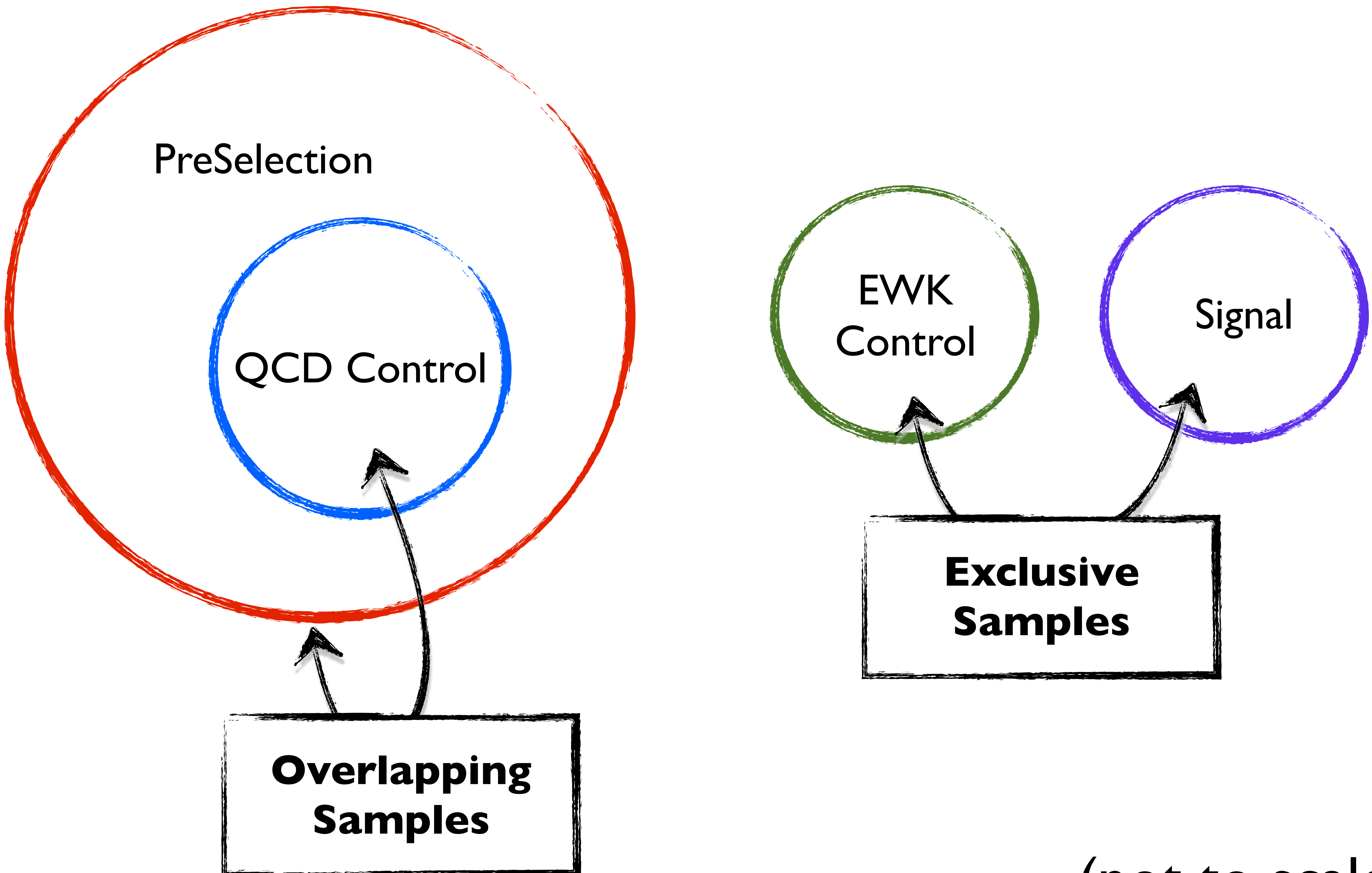
MultiJet Control

Identical to signal region except for inversion of cuts designed to reject multijet QCD backgrounds.

EWK Control

Identical to signal region except for inversion of the lepton veto, thereby boosting the fraction of $Z \rightarrow l^+l^-$ and $W \rightarrow l^{\pm}\nu$ events.

Event Selection



(not to scale)

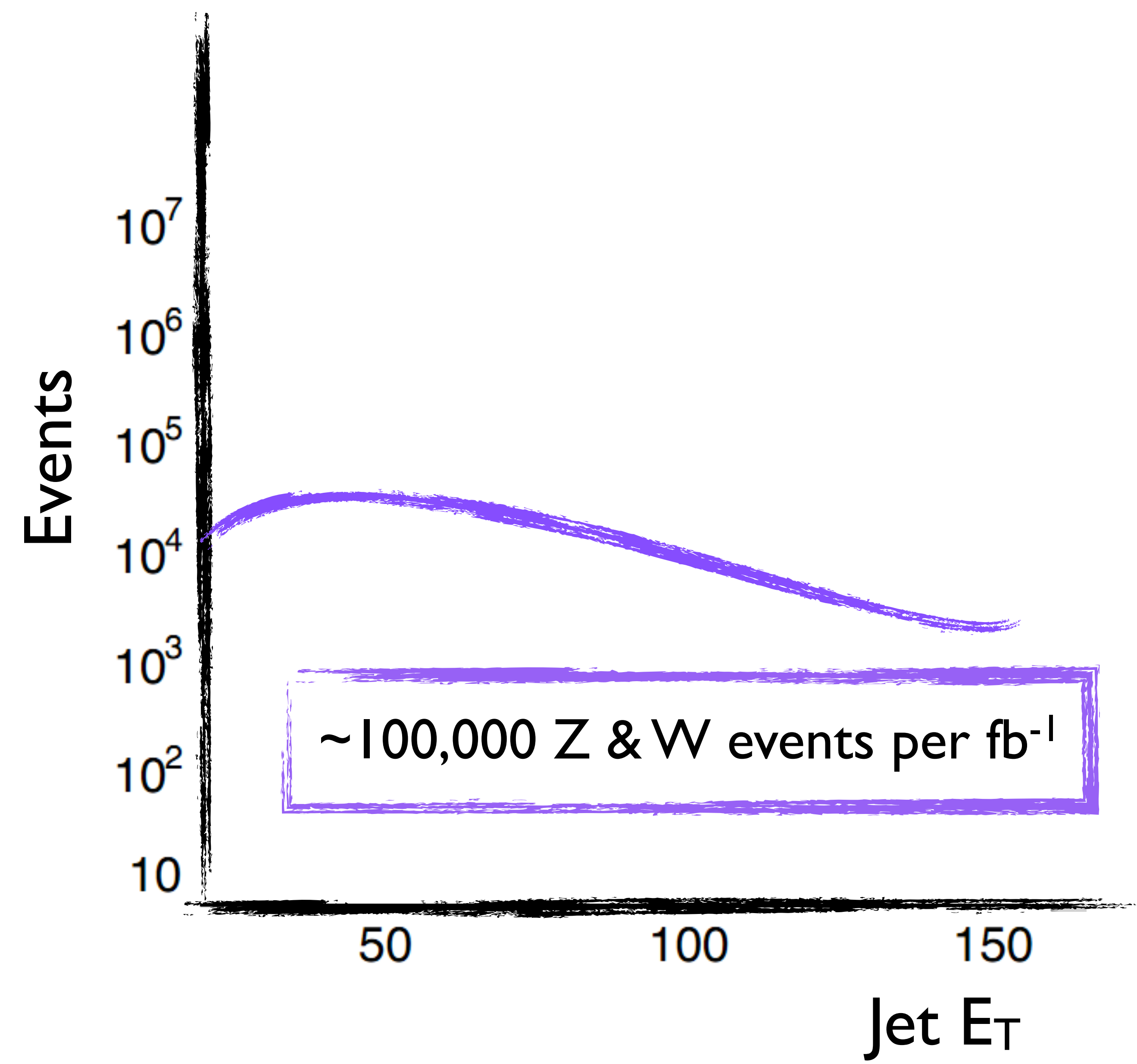
Search Backgrounds

- Monojet = one jet + missing energy (sounds easy!)
  - Select a jet
  - Select for large MET
- Model = simulated samples normalized to theory rates X luminosity with various efficiency corrections

Process	**Generator**
WW,WZ,ZZ	PYTHIA
tt	PYTHIA
W[e,μ,τ + ν]	ALPGEN+PYTHIA
Z[ee,μμ,ττ,νν]	ALPGEN+PYTHIA
single top	MadGraph+PYTHIA

Search Backgrounds

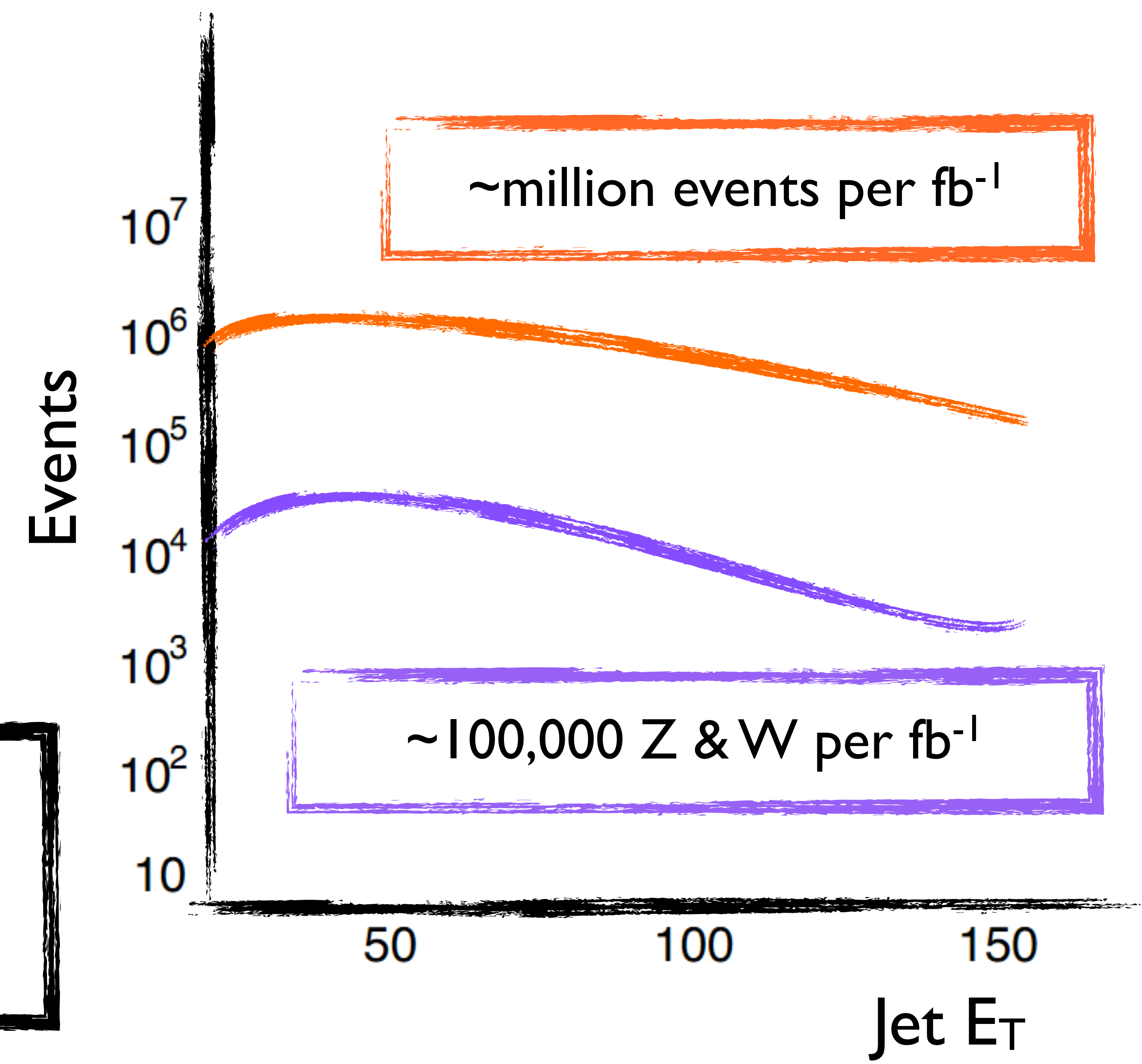
- Monojet = one jet + missing energy (sounds easy!)
  - Select a jet
  - Select for large MET
- in 6.7/fb one jet + missing energy looks like this :



Search Backgrounds

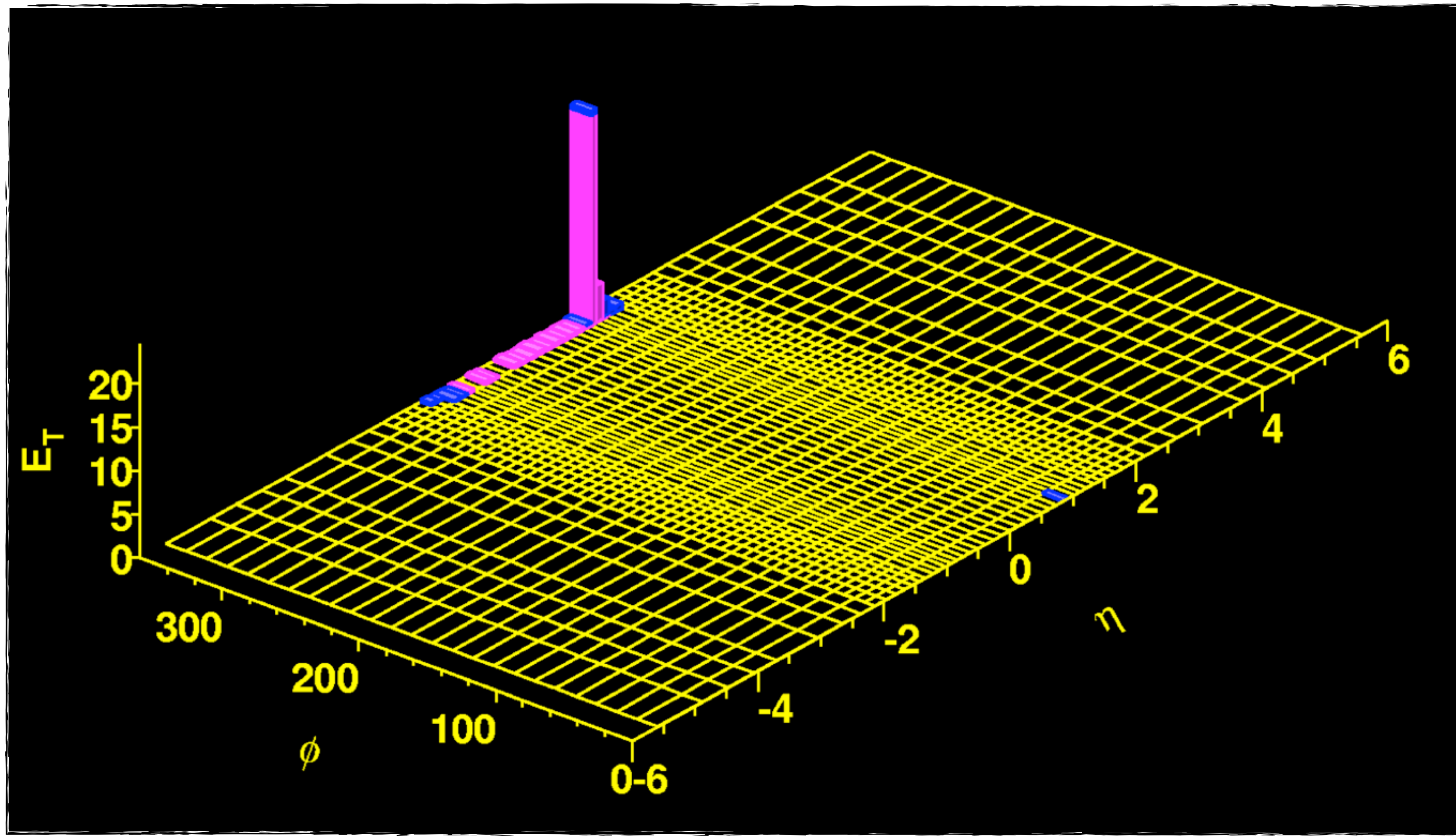
- Monojet = one jet + missing energy (sounds easy!)
  - Select a jet
  - Select for large MET
- in 6.7/fb one jet + missing energy looks like this :
- Much less than total data.

Large backgrounds from QCD & non-collision sources!



Non-Collision Backgrounds

- Cosmic Rays
- Beam Halo



- Beam - detector/gas interactions produce muons that travel through the calorimeter parallel to the beam
- Can generate a false met + monojet signature

Non-Collision Rejection

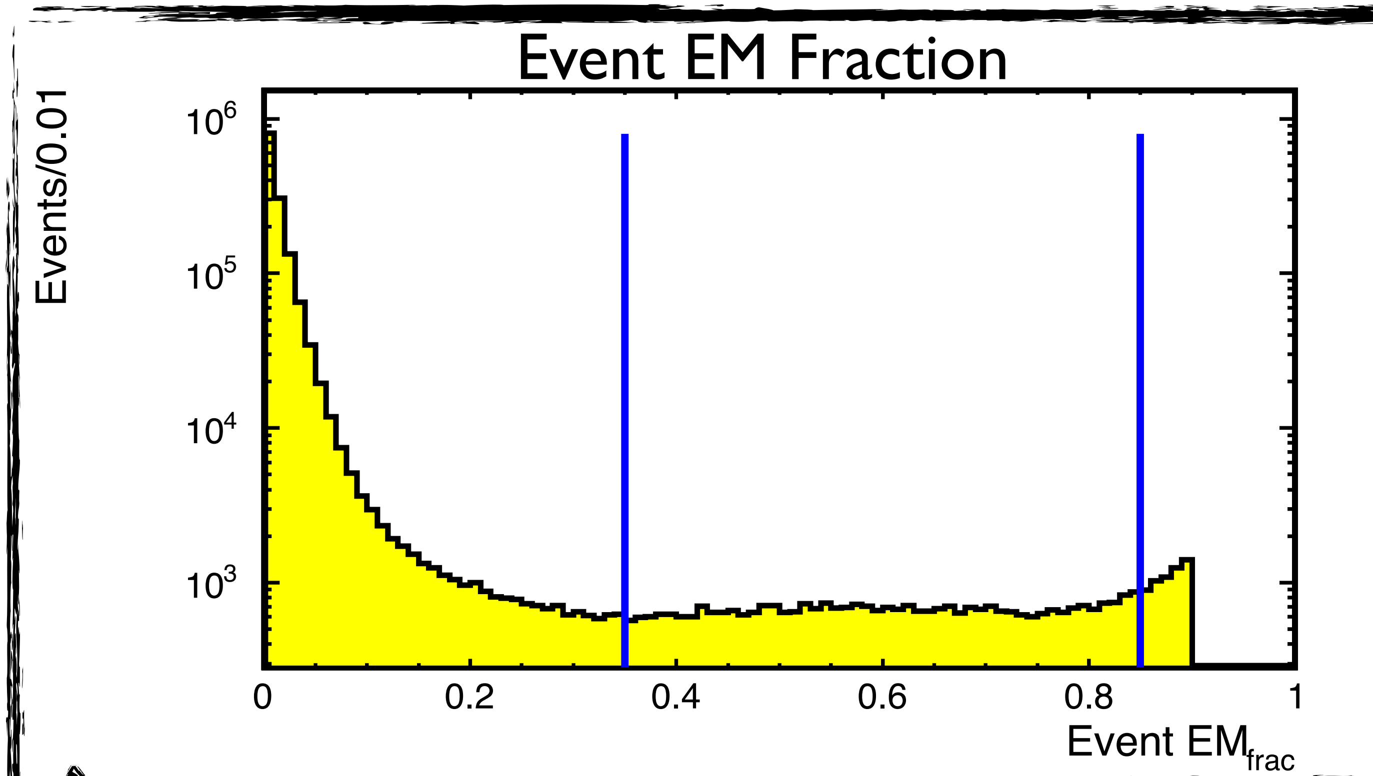
- Major component of non-collision background is beam-halo

- Typically have low electromagnetic (EM) fraction (electron & photon vetoes remove high EM fraction events)

- A cut on the evnt EM_{frac} rejects ~99% of the non-collision background

- Model remnant contribution with events failing the the event EM fraction veto

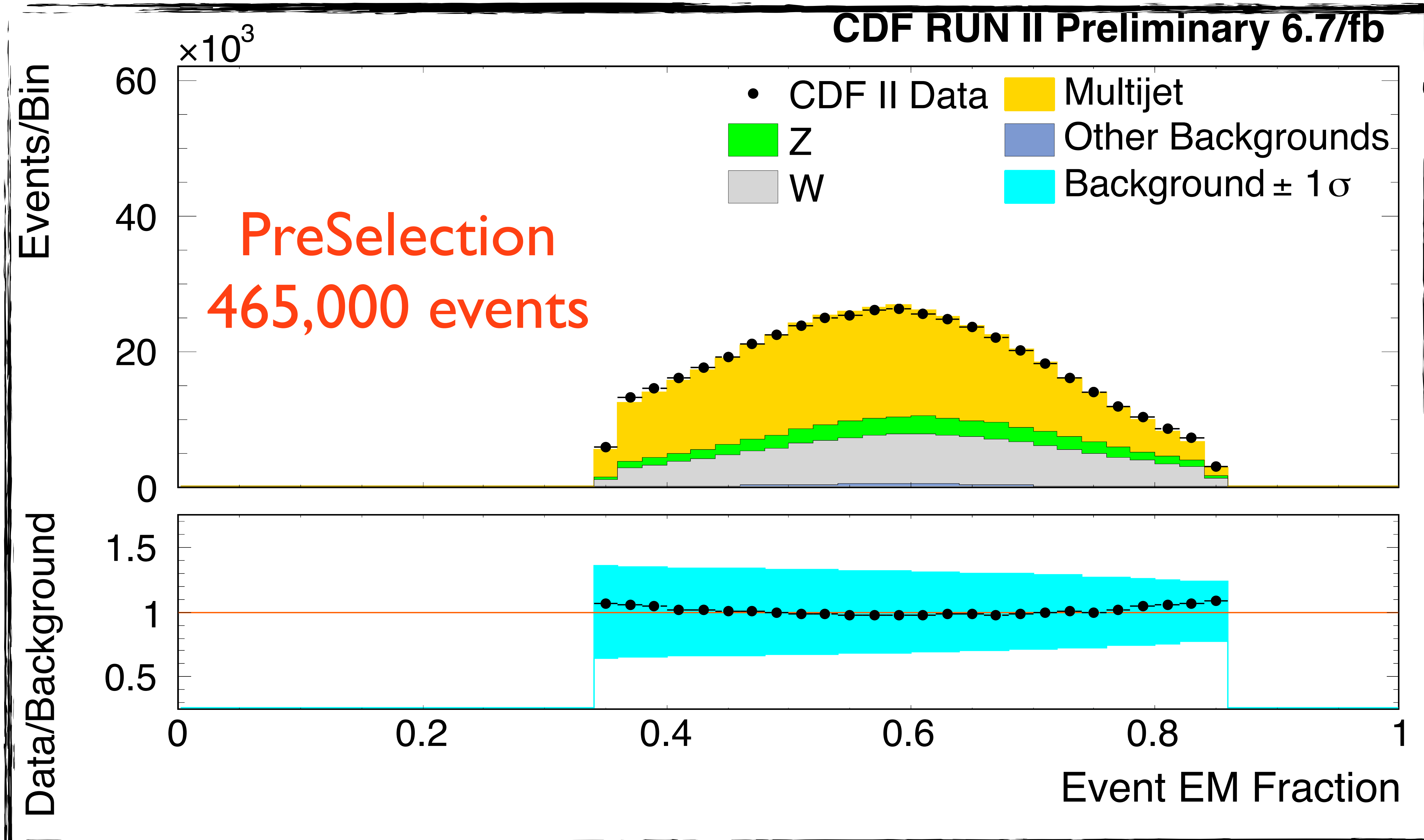
$$\text{Event } EM_{frac} = \frac{\sum_{jets} E_T * EM_{frac}^{jet}}{\sum_{jets} E_T}$$



Cosmic rays or events with calorimeter deposits out of time with bunch crossings

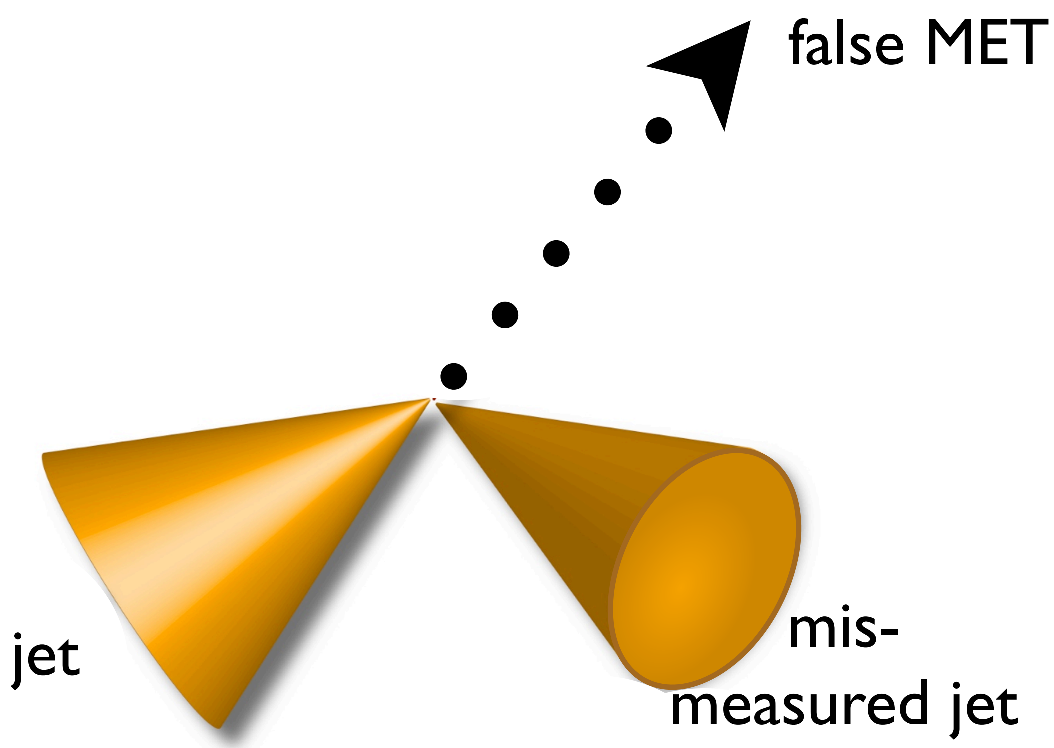
Non-Collision Rejection

- After Veto :



QCD Multijet Rejection

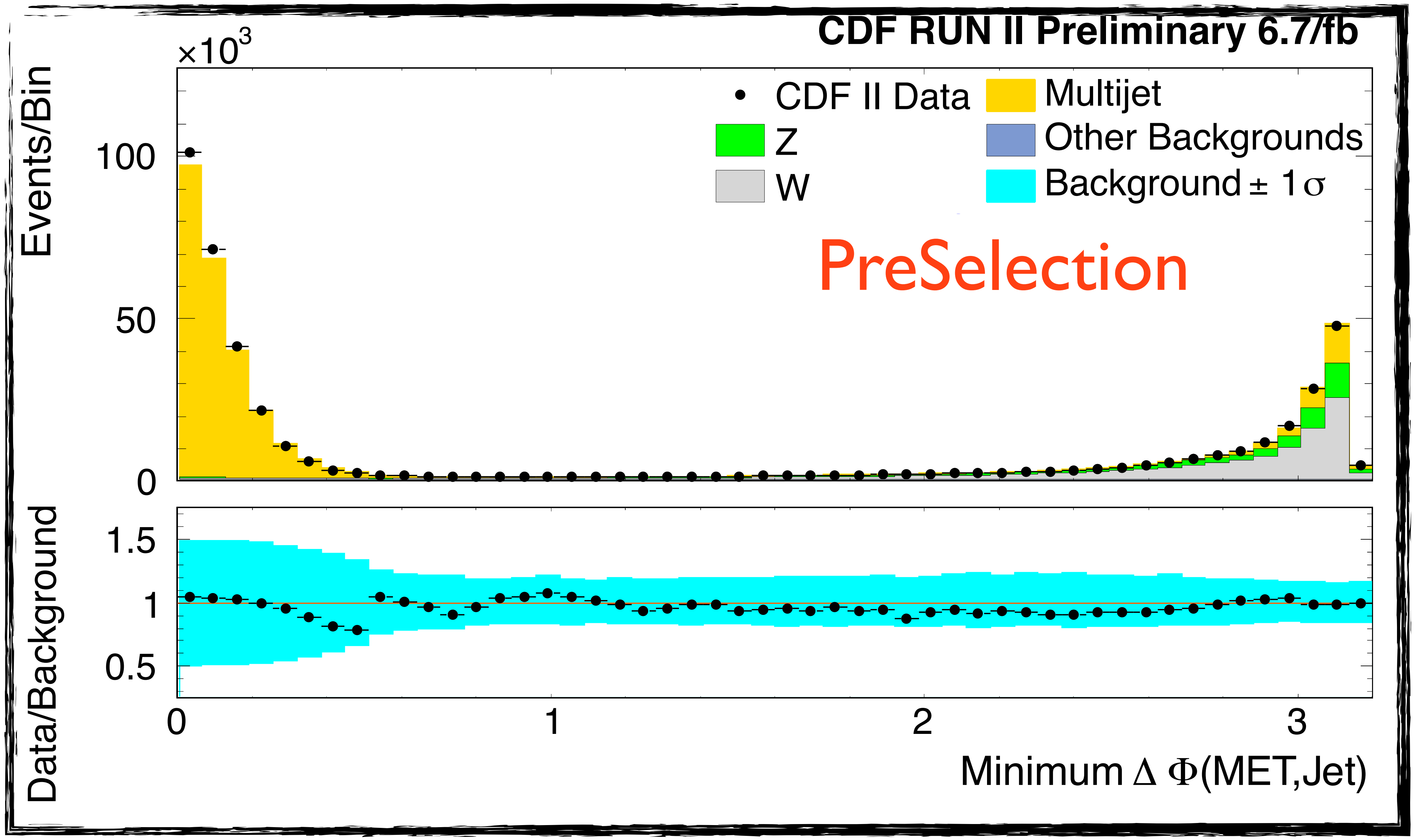
- After non-collision sources, multijet events are the next largest background to a monojet search
- Enter monojet selection due to mis-measurement or mis-reconstruction of 2 or 3 jet events, meaning any model will have large systematic uncertainties and dilute sensitivity to a signal



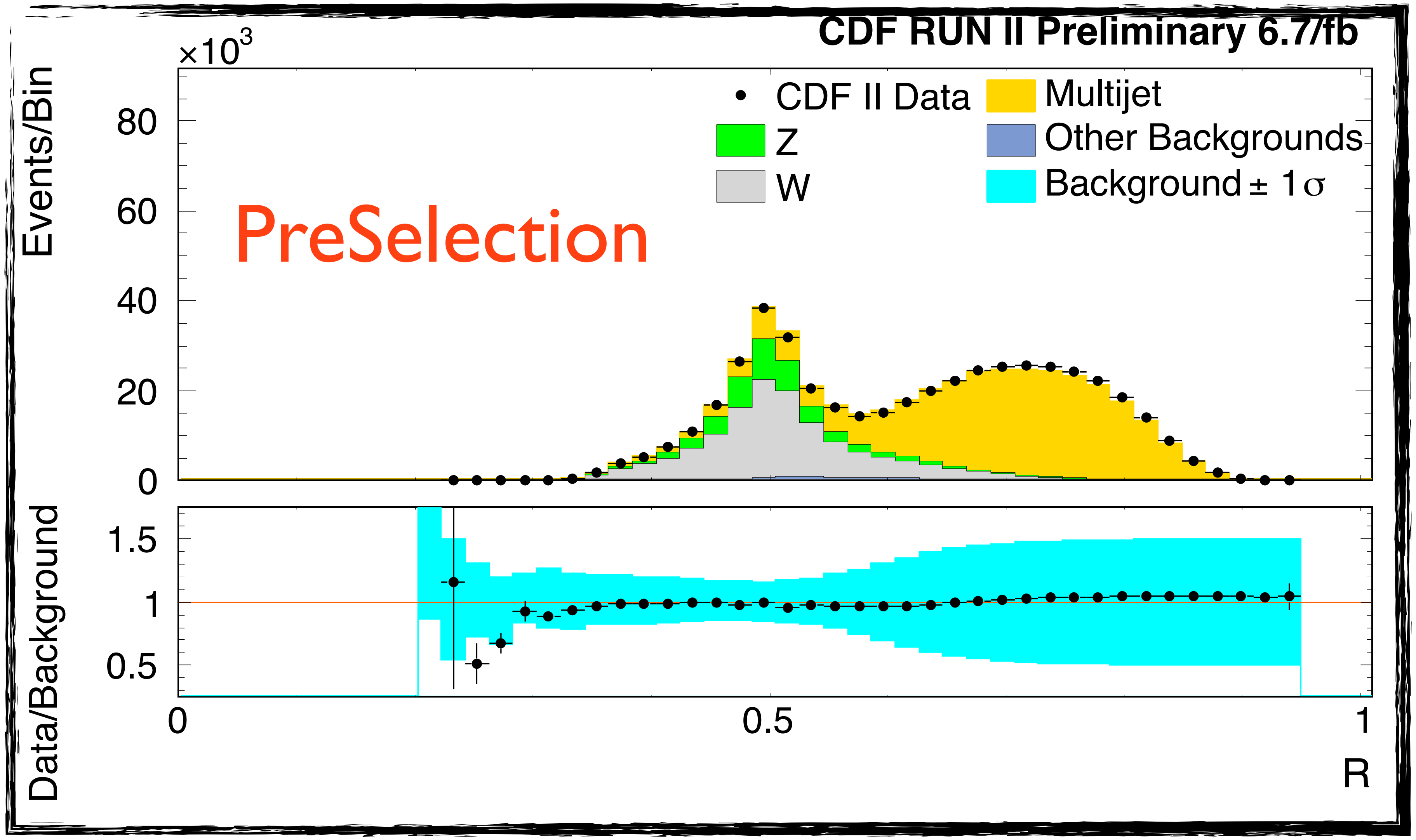
Key Characteristics

- Imbalance in the ratio of jet E_T to missing transverse energy
- Missing transverse energy closely aligned with the jet

QCD Multijet Rejection



QCD Multijet Rejection

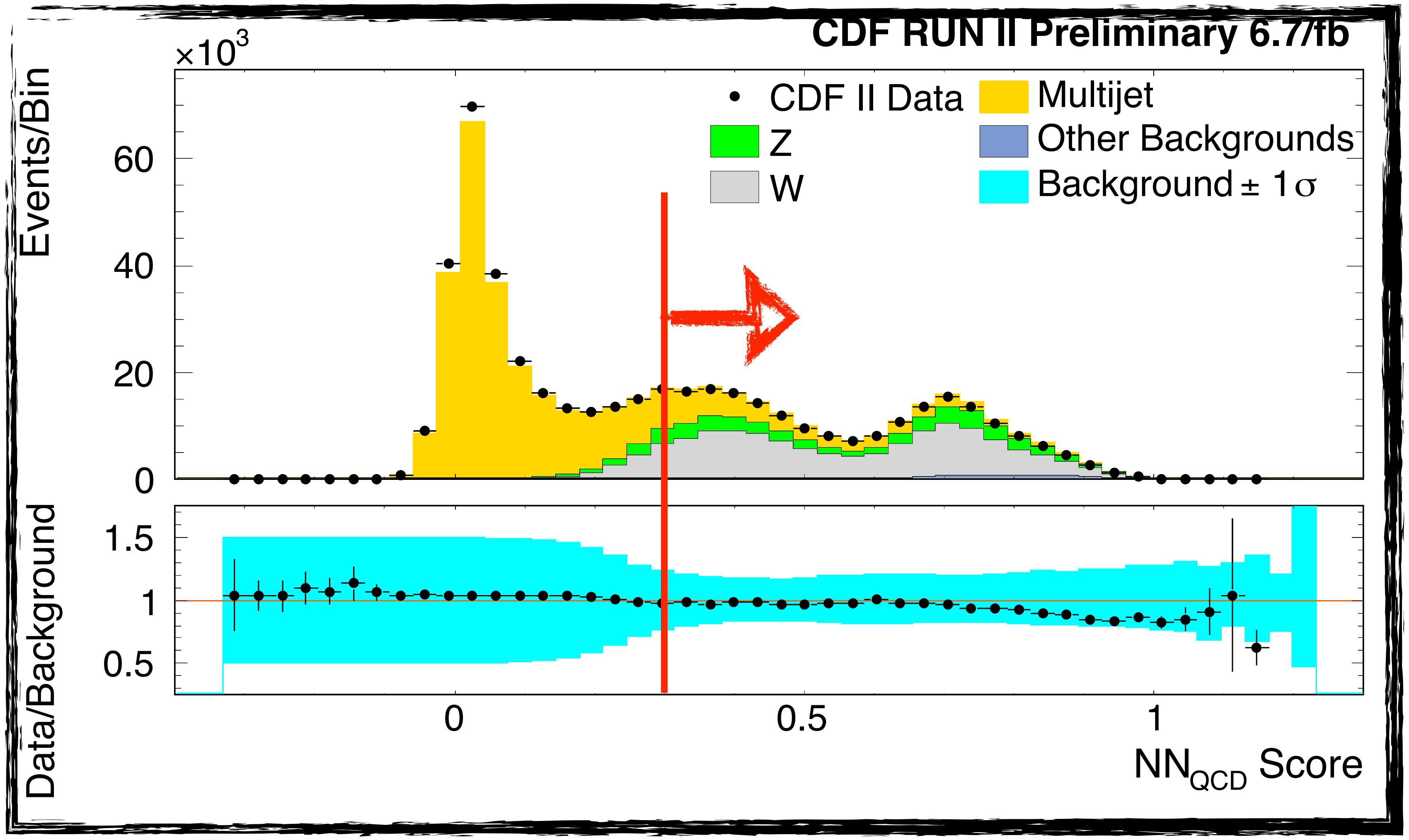


$$R = \frac{\sum_{\text{jets}} |E_T|}{\sum_{\text{jets}} |E_T| + |MET|}$$

Neural Network Multijet Rejection

- Combine quantities that distinguish QCD events from other backgrounds into a single discriminant.

- Train network to separate QCD-data from a combination of simulated Z and W events



Require NNscore > 0.3

~90% Signal efficiency
~80% Multijet rejection

Compared to cuts alone, NN increases signal efficiency by ~10% for the same QCD rate

Multijet Model

- Multijet background is largely instrumental making simulation difficult.

- Instead we use a data-driven approach in which we form a binned parameterization (in 6 parameters) of the likelihood that an event is a multijet event :

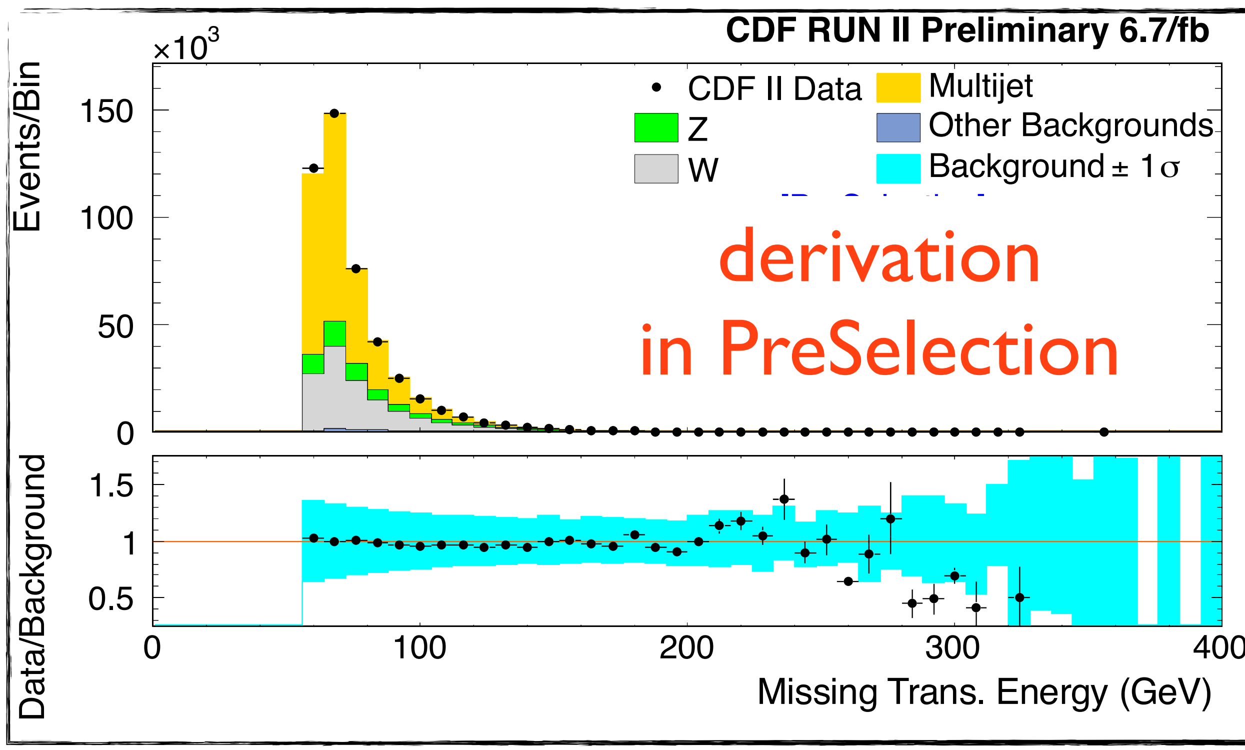
$$\text{Multijet Probability(6 parameters)} = \frac{\text{\# of Data Events - Expected MC Contribution}}{\text{\# of Data Events}}$$

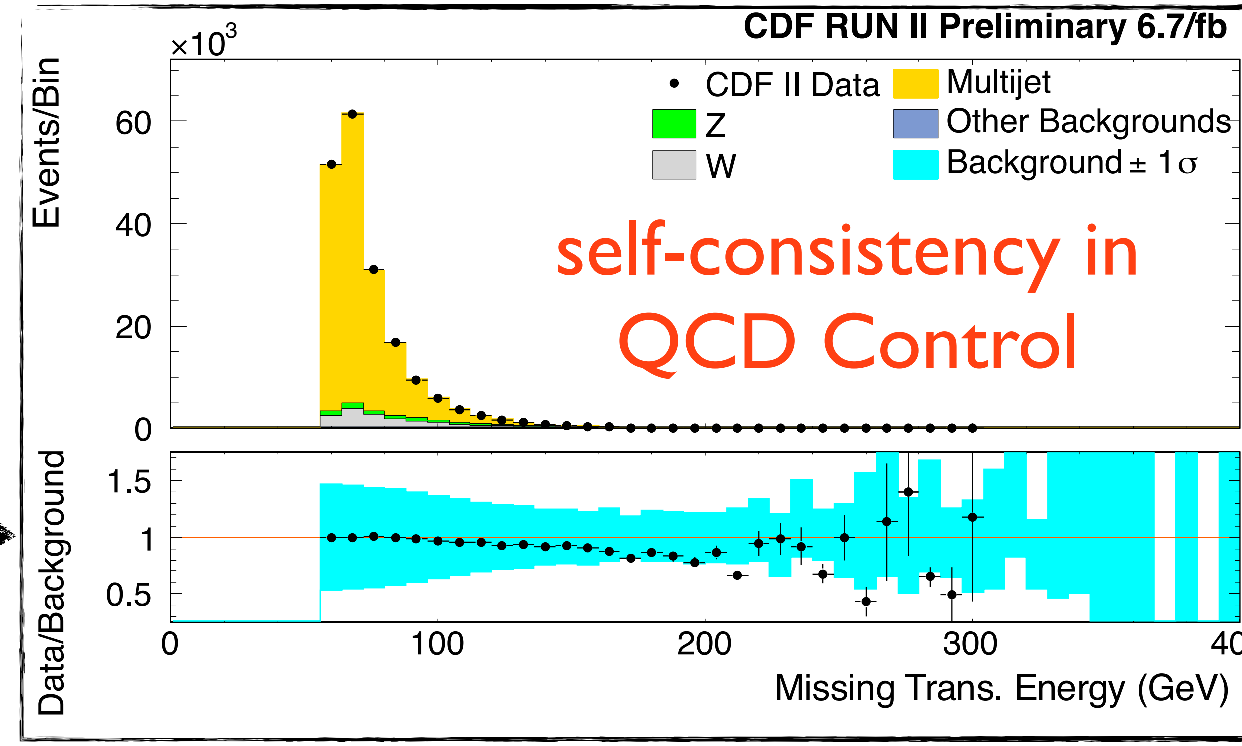
- To estimate the shape of the multijet component of any observed distribution, we weight each contributing event by its multijet probability

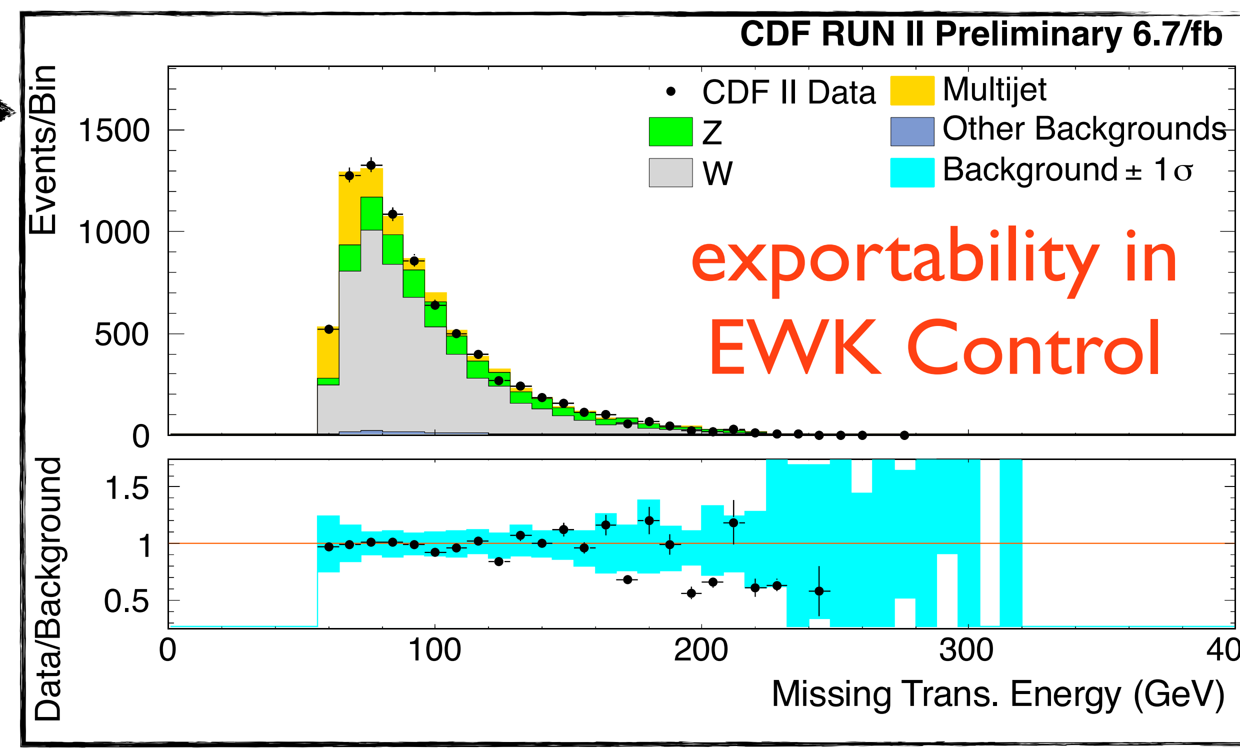
- The normalization of the multijet component is set by sideband fits

Multijet Model

- Multijet probability parameterization is formed in a superset of the QCD control region

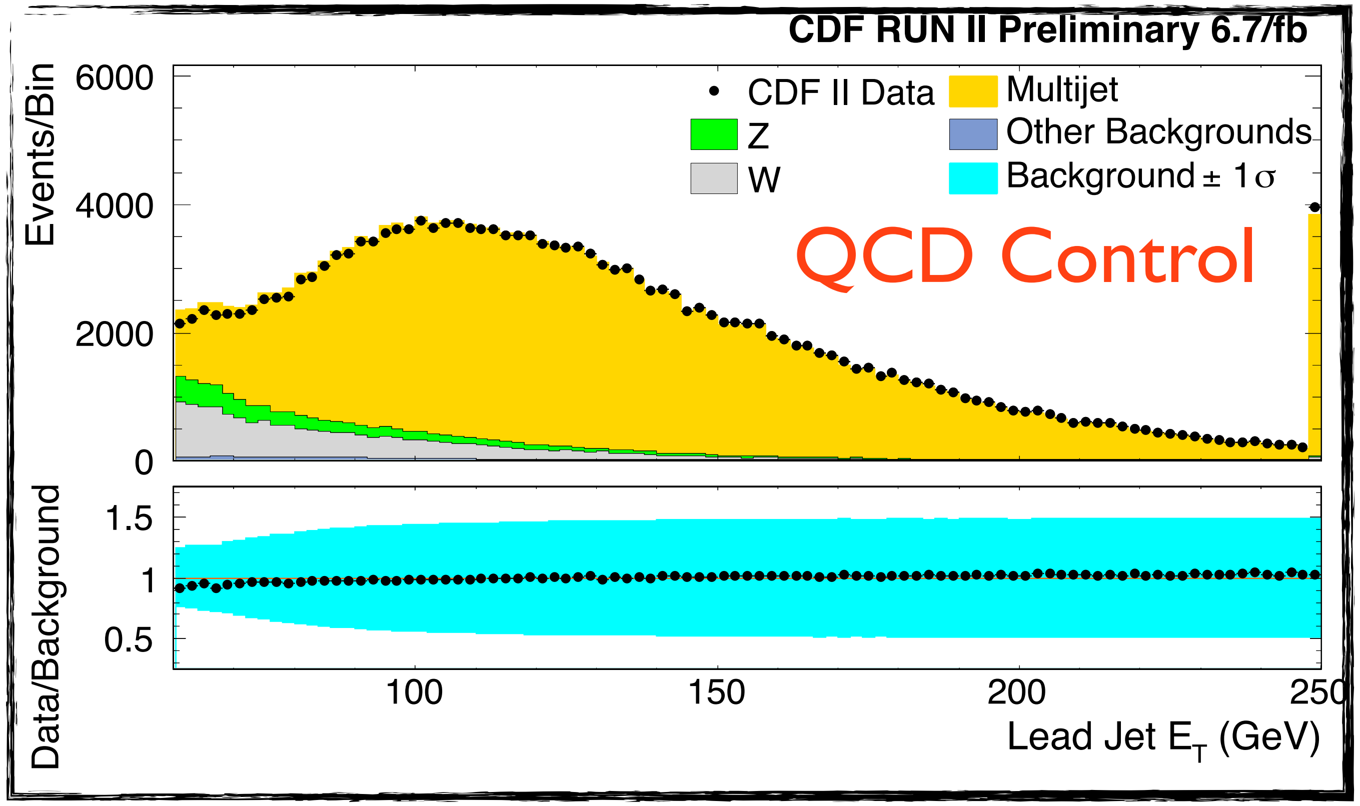


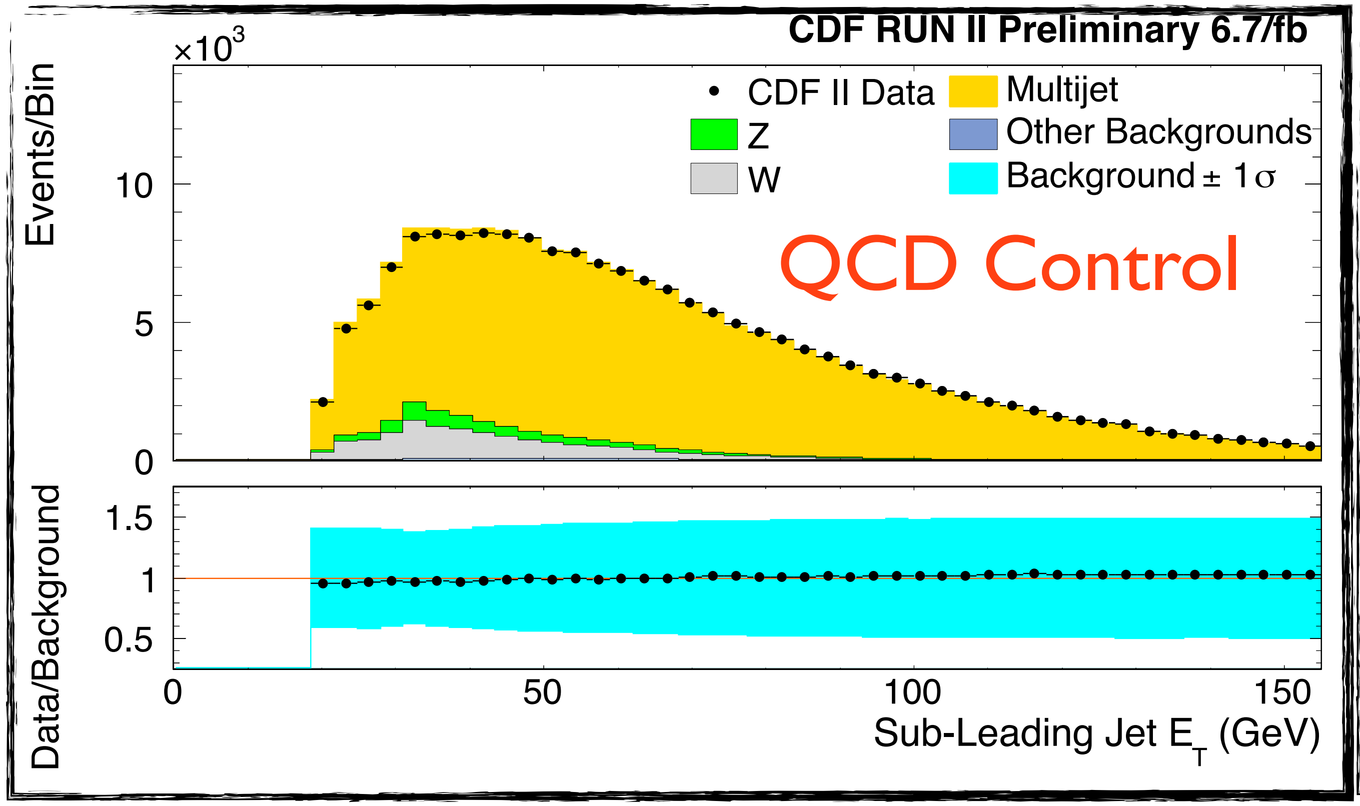


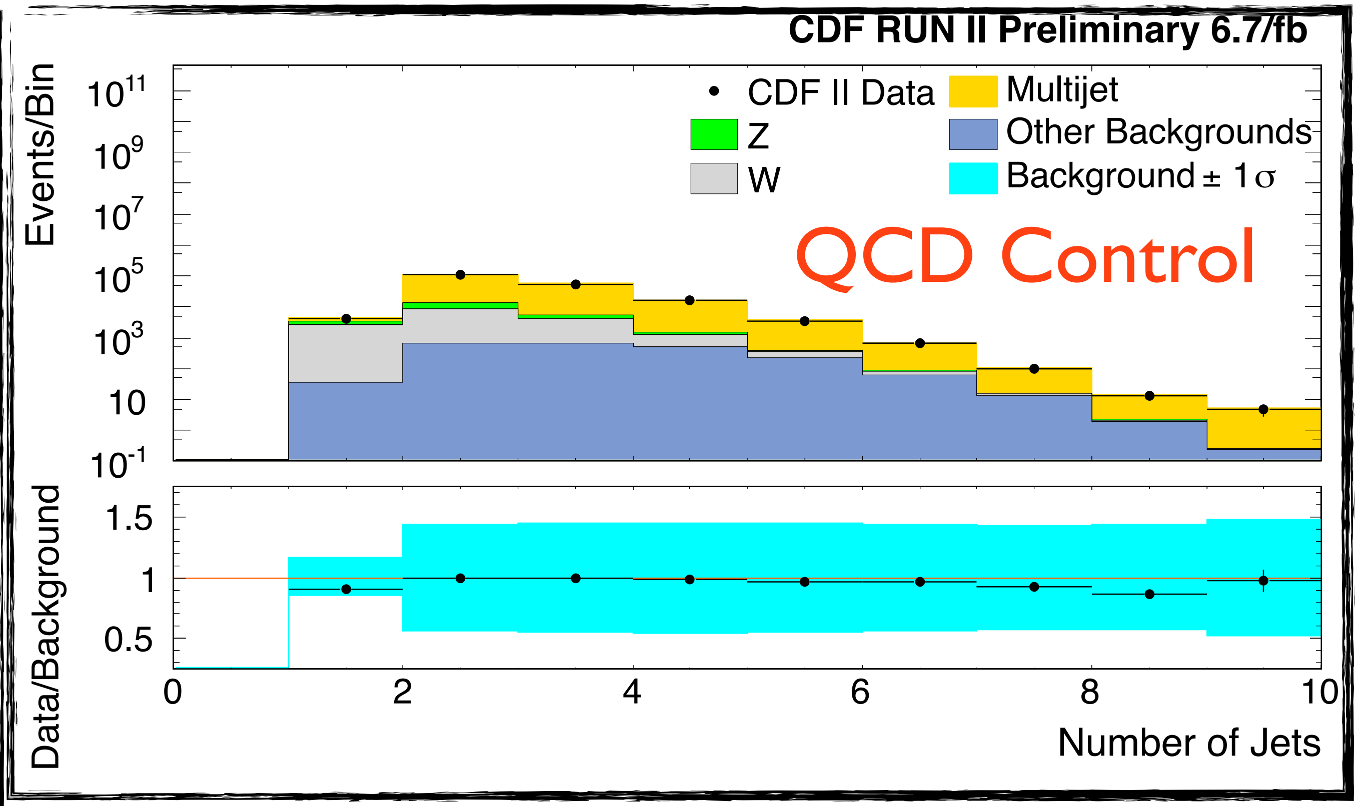


Model Validation (QCD Control)

- Invert cut on NN score or allow for extra jet activity

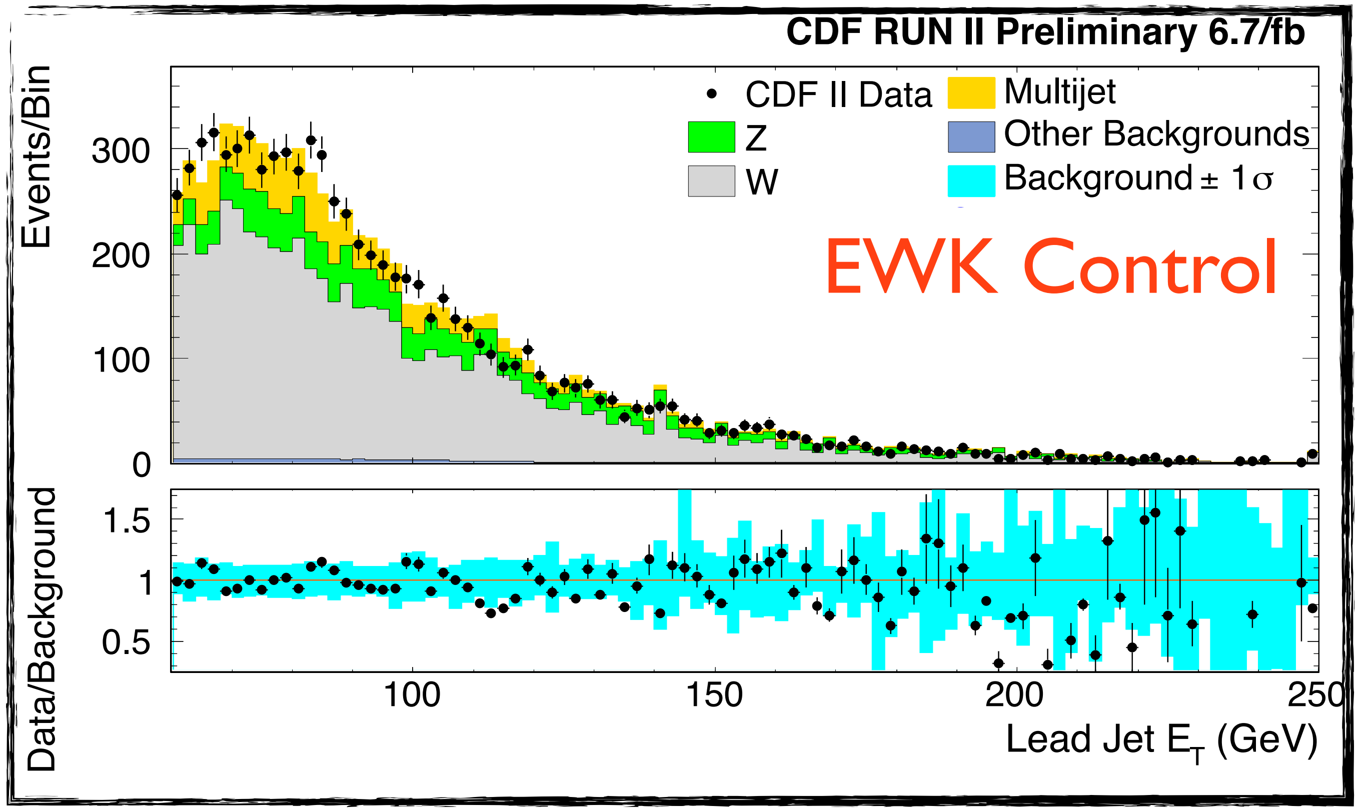


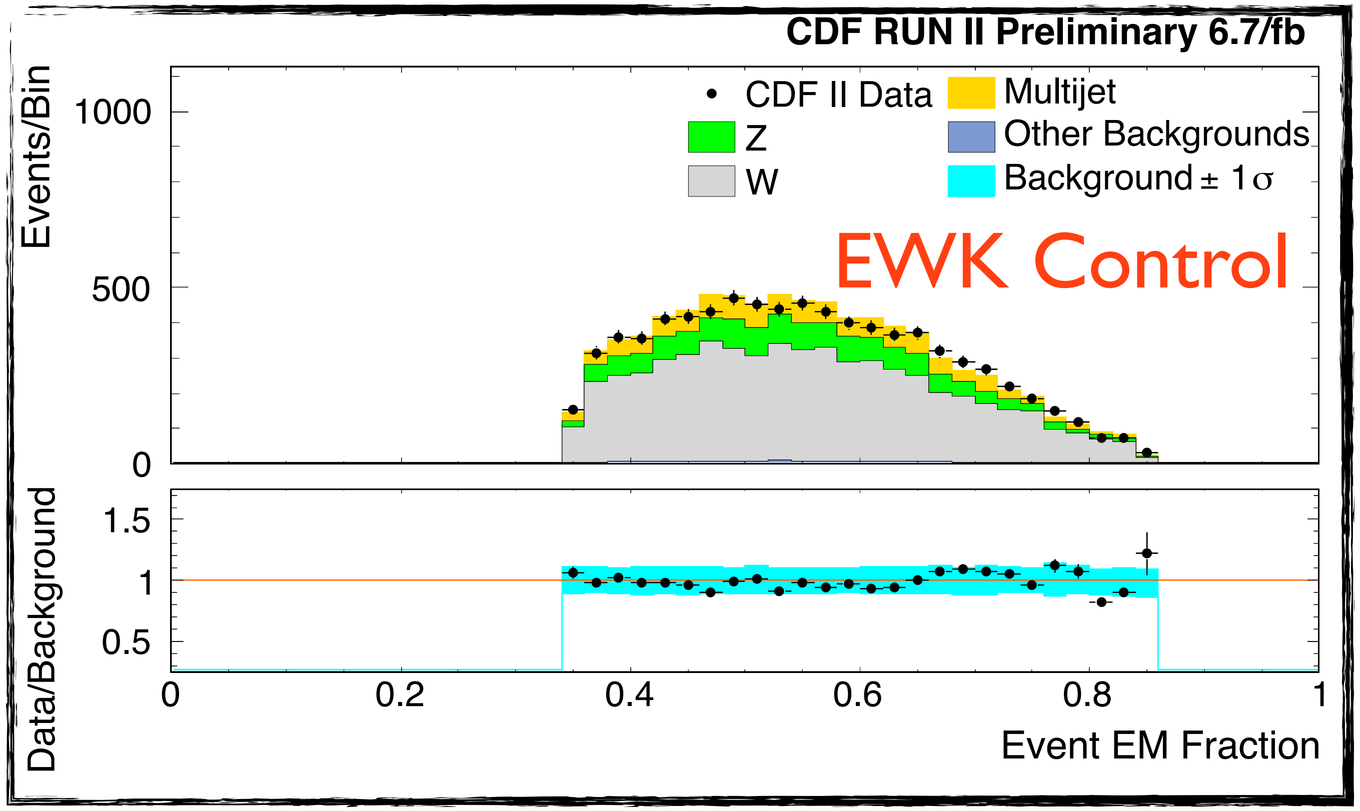


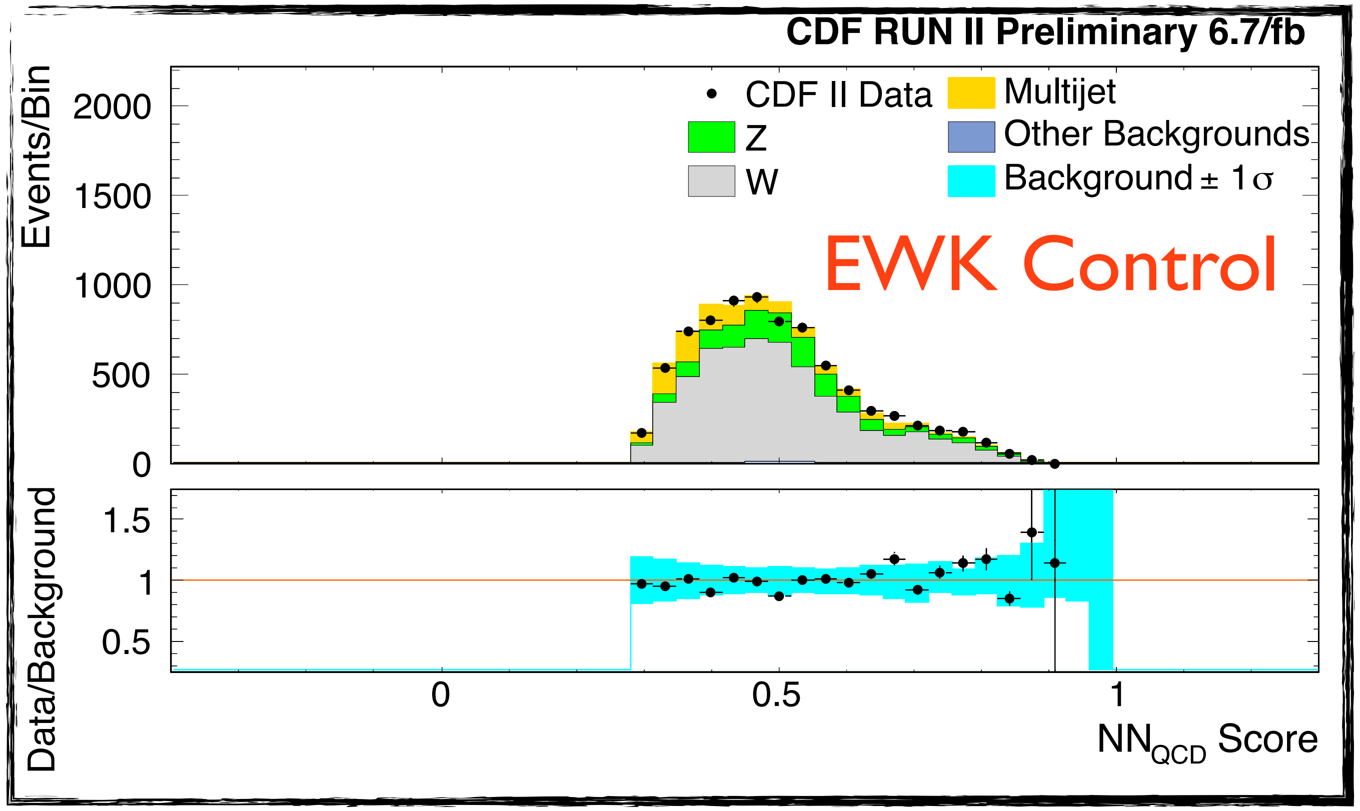


Model Validation (EWK Control)

- Identical to signal region except that we require at least one lepton with transverse momentum of at least 10 GeV/c







Expectations for the Signal Region

- Background total

— CDF Run II Preliminary 6.7 fb^{-1} —

Contribution	Signal Region
non-collision	6 ± 6
Z	22191 ± 2681
W	27892 ± 3735
diboson	412 ± 36
$t\bar{t}$	23 ± 4
single-top	104 ± 14
multijet	3278 ± 1639
total model	53904 ± 6022

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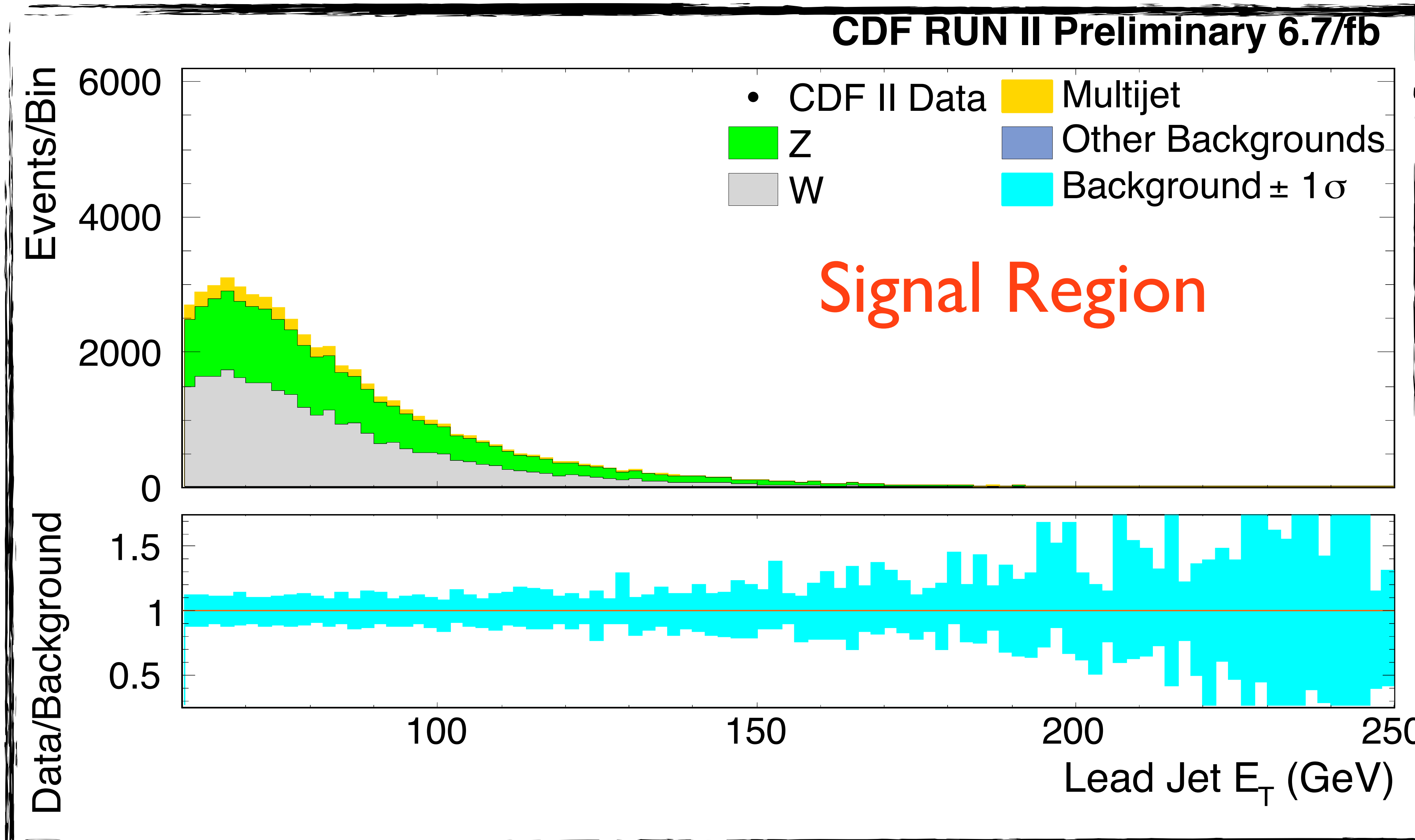
reduced by 4 orders of magnitude!

Expectations for the Signal Region

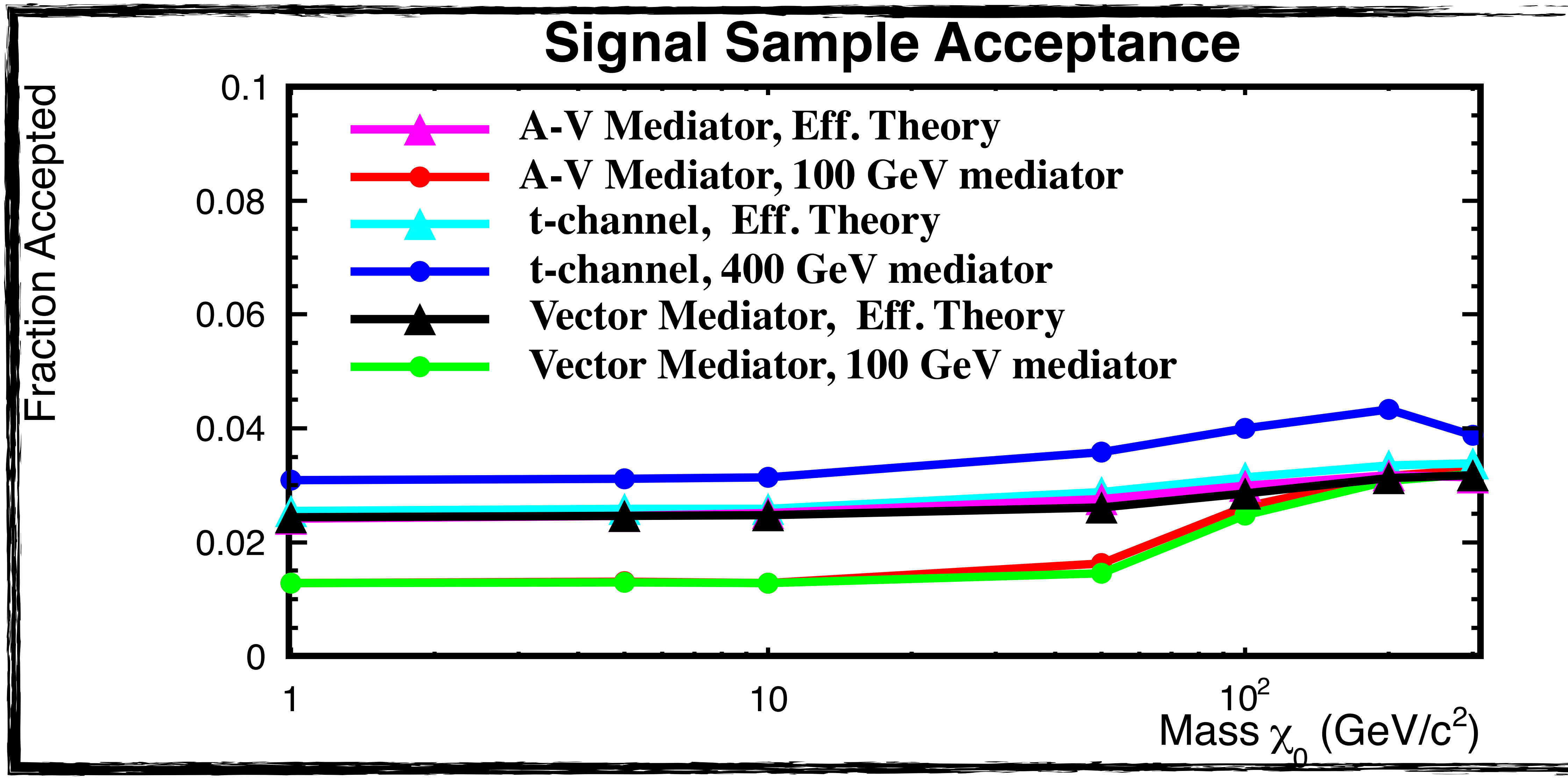
- Background total



over 90% W & Z

Signal Acceptance

- Signal region acceptance is ~1-3%



- Assuming an arbitrary production rate of ~1pb, this would translate into ~100 events in 6.7/fb

Systematic Uncertainties

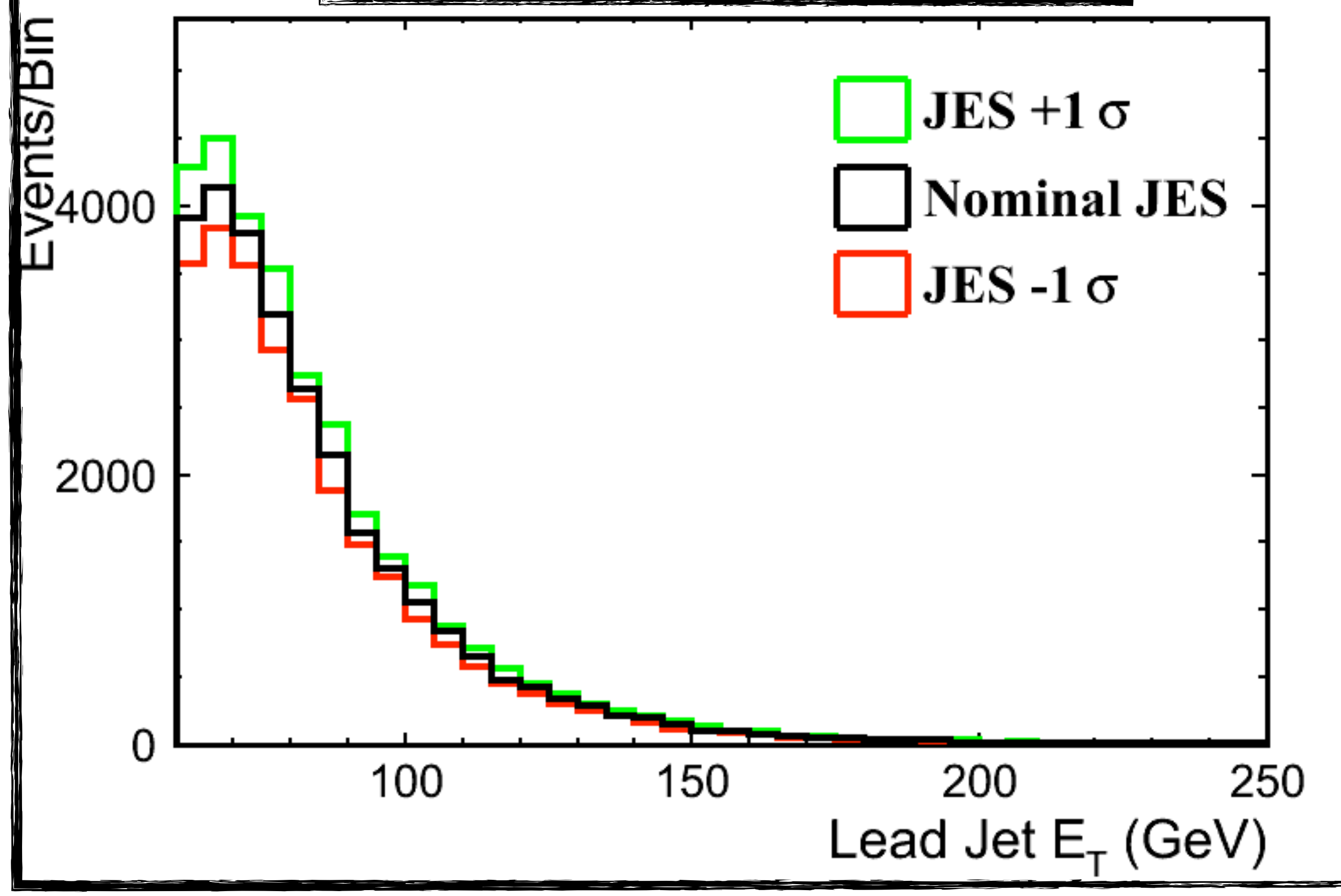
Shape Systematics :

- Jet Energy Scale
- Multijet Background Shape

Rate Systematics :

- luminosity (6%)
- efficiency corrections (~2%)
- theoretical cross-sections (~10%)
- ISR/FSR (~1.4%)
- PDF uncertainties (1-3%)
- Multijet Normalization (50%)

W+jet Template Under JES Variation



Vary kinematic quantities/normalizations under the effect of a systematic and propagate effects through to templates of the lead E_T jet

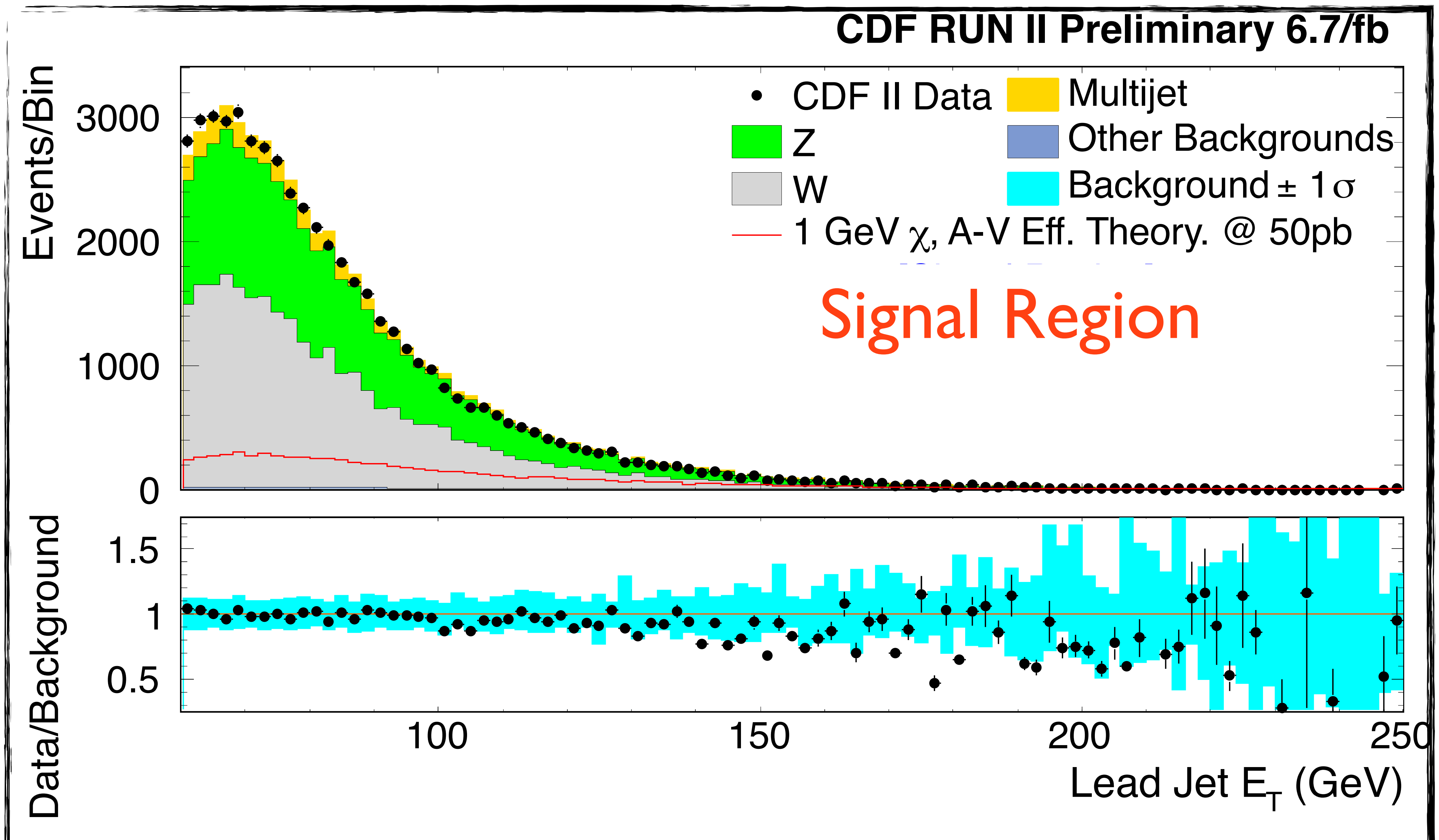
Will use the lead ET jet shape to extract limits on dark matter production rate

Signal Region Data

- No excess over background expectation

observe 52,633

expect 54,000 ± 6,000

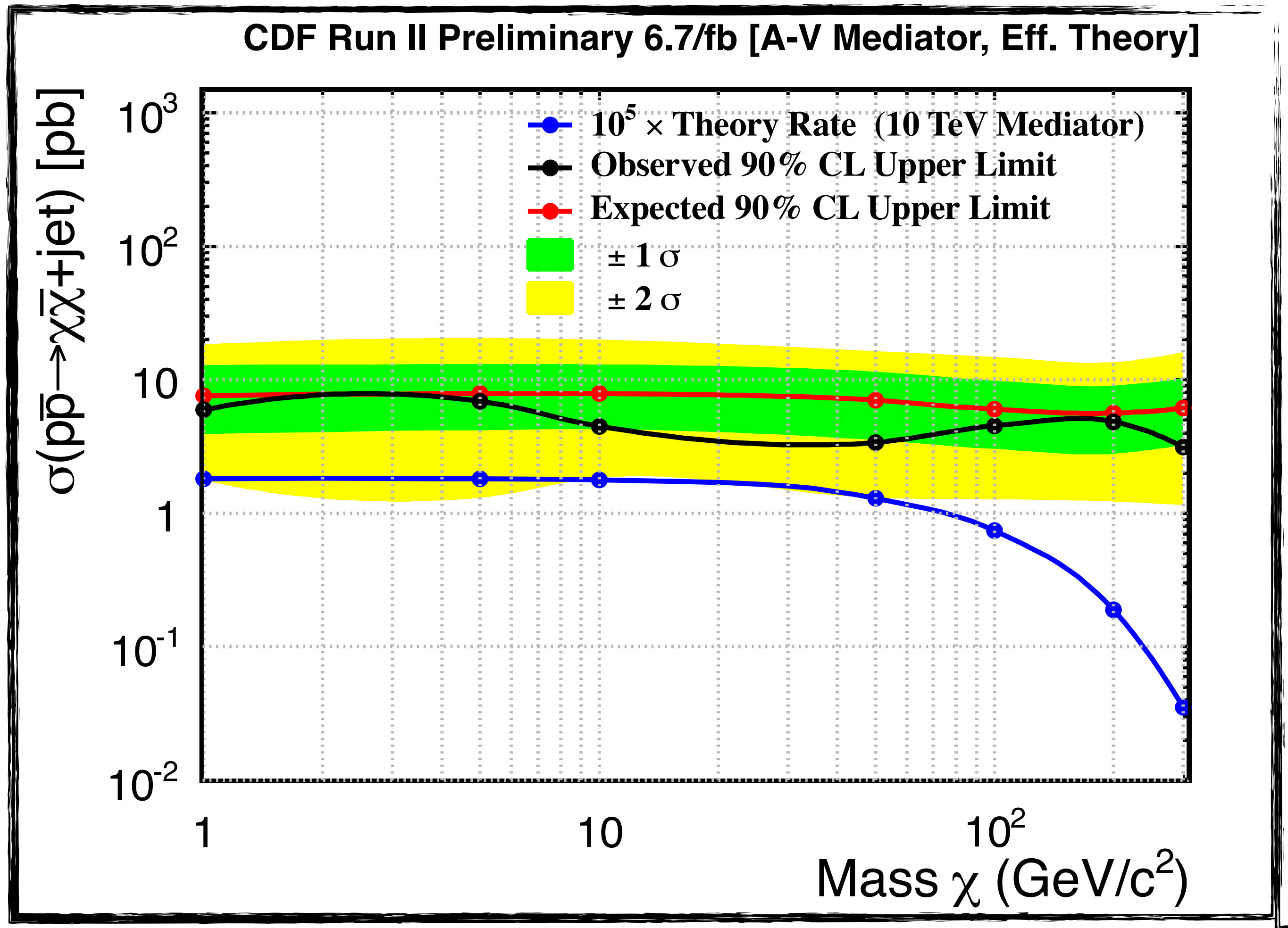


Limit Setting

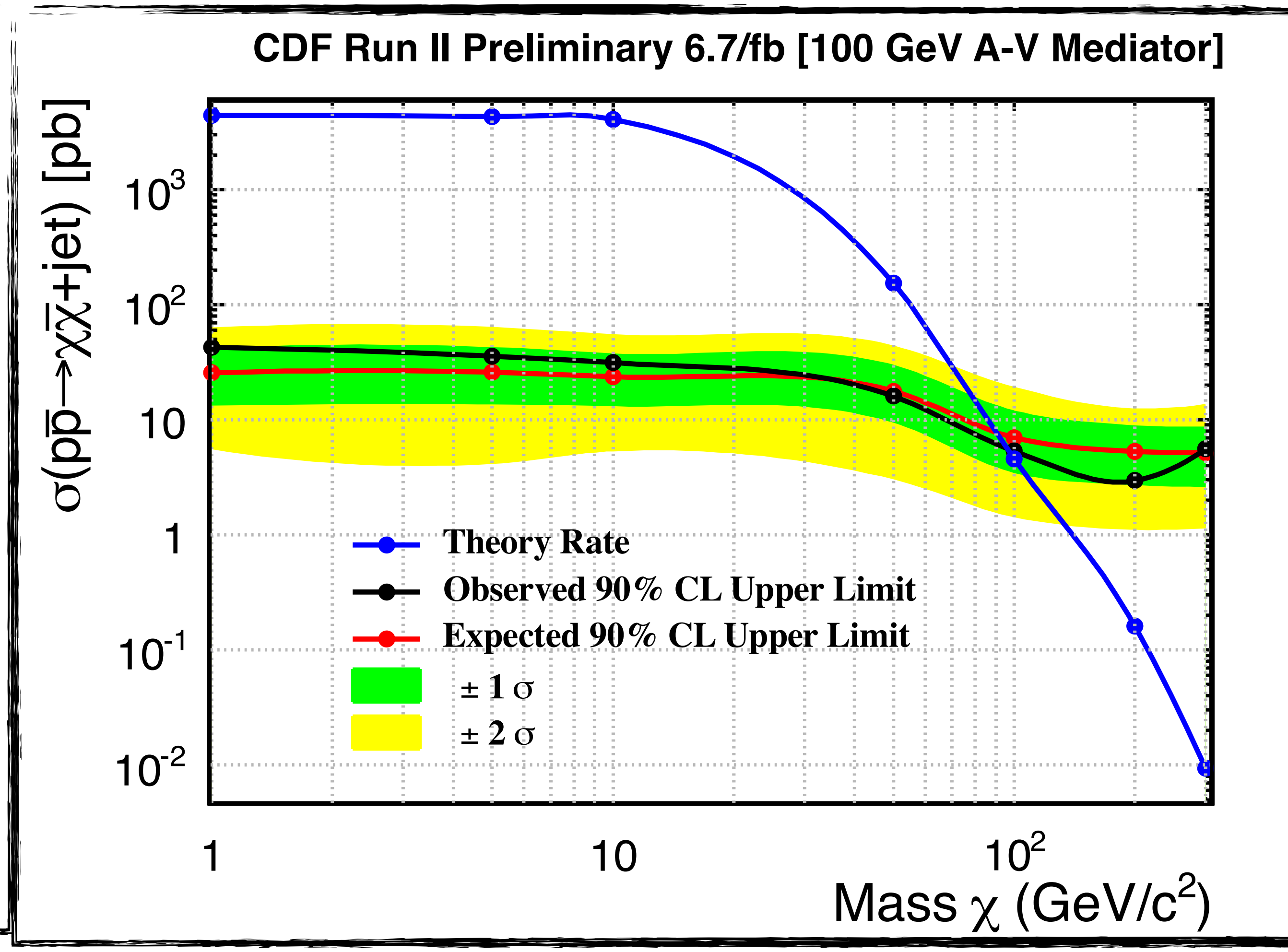
- Extract limits on the dark matter production rate using a Bayesian method
- Compute 90% CL upper limits for a series of background-only pseudo-experiments
    - Obtain median and ±1 and ±2 σ expectation on the upper limit
- Incorporate relevant systematics through their effect on the binned lead Jet E_T distributions for signal & backgrounds

Results

- 90% CL upper limits for Axial Vector mediated DM production



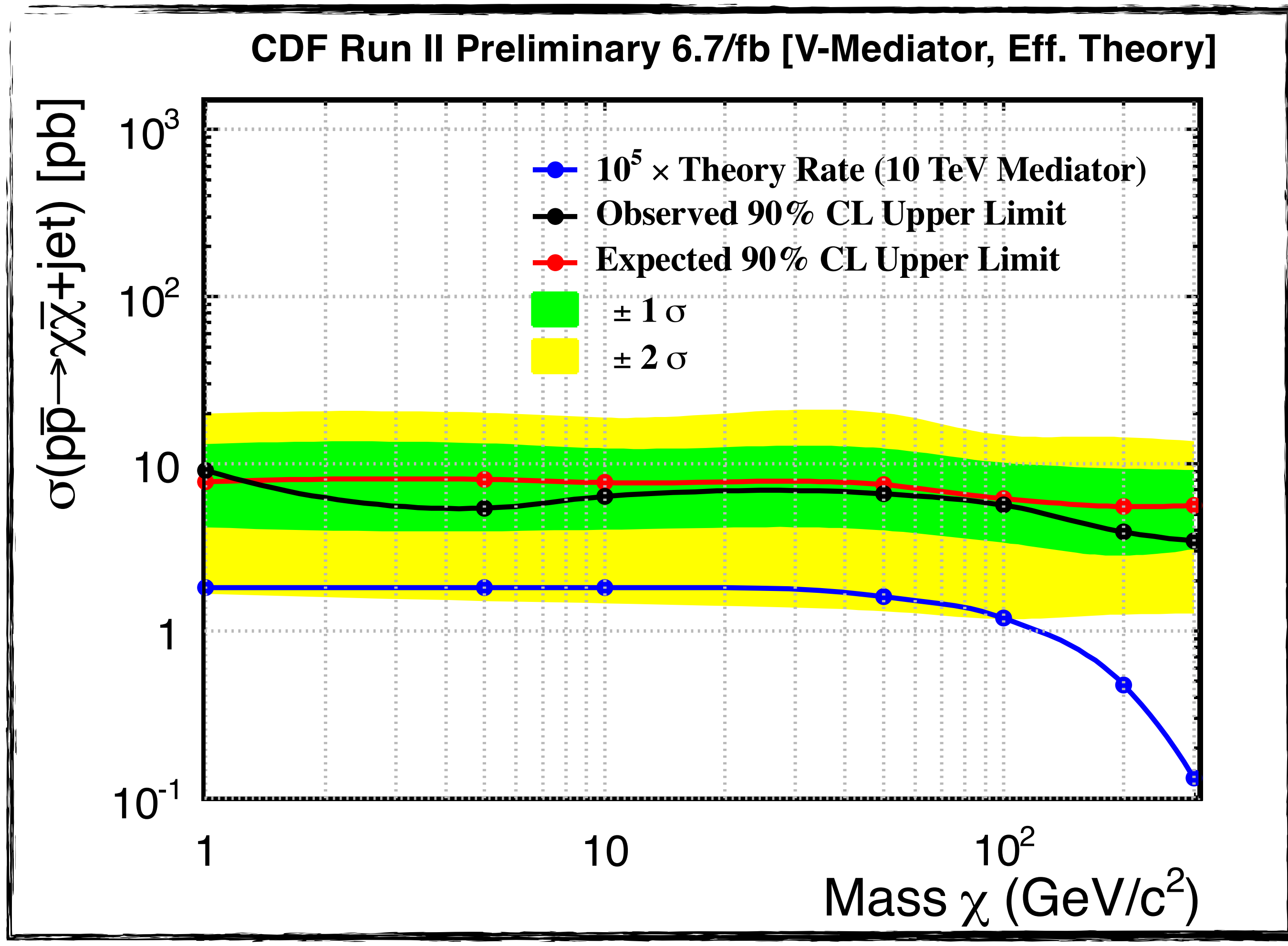
Effective Theory



Light Mediator

Results

- 90% CL upper limits for Vector mediated DM production



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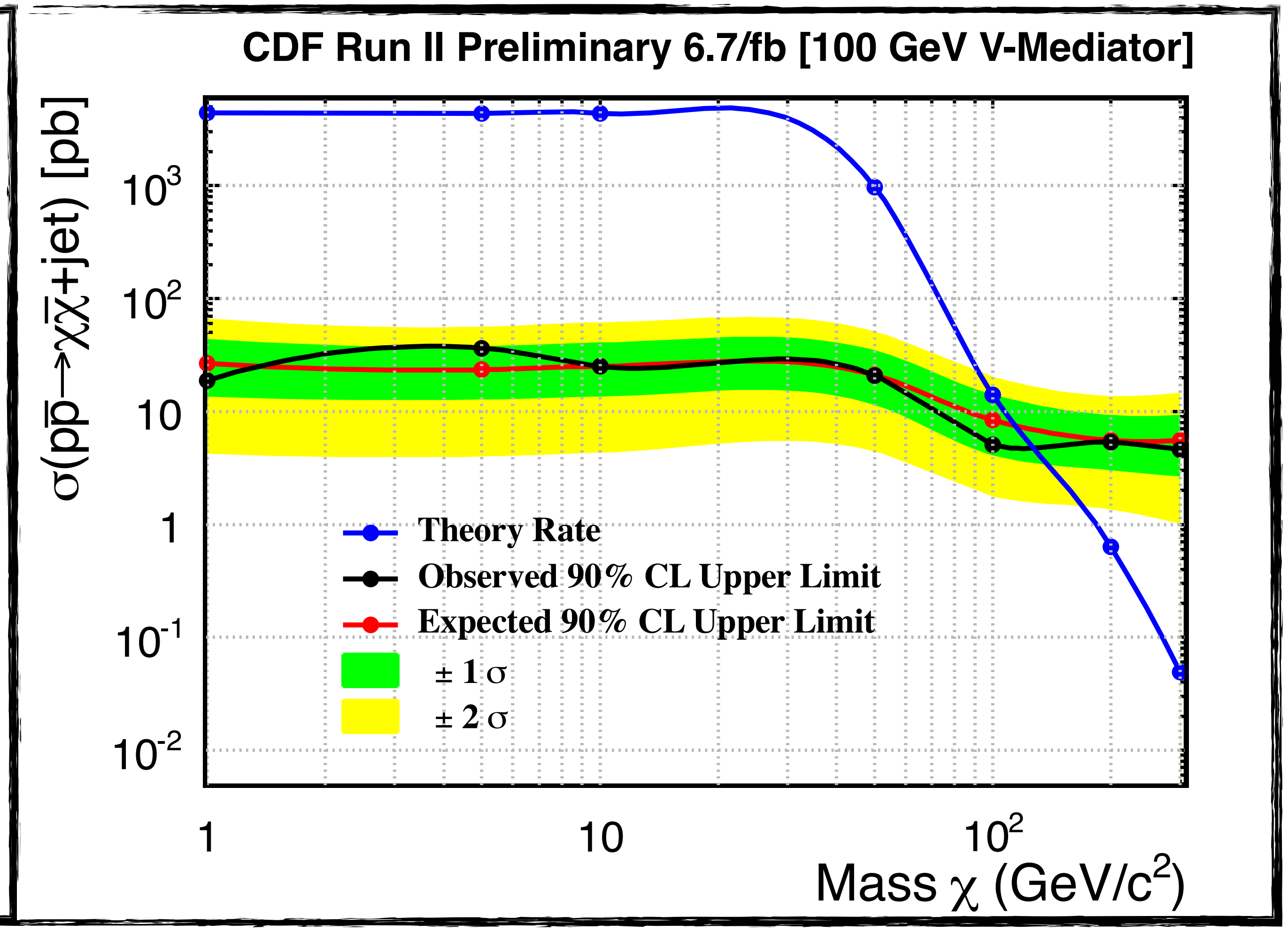
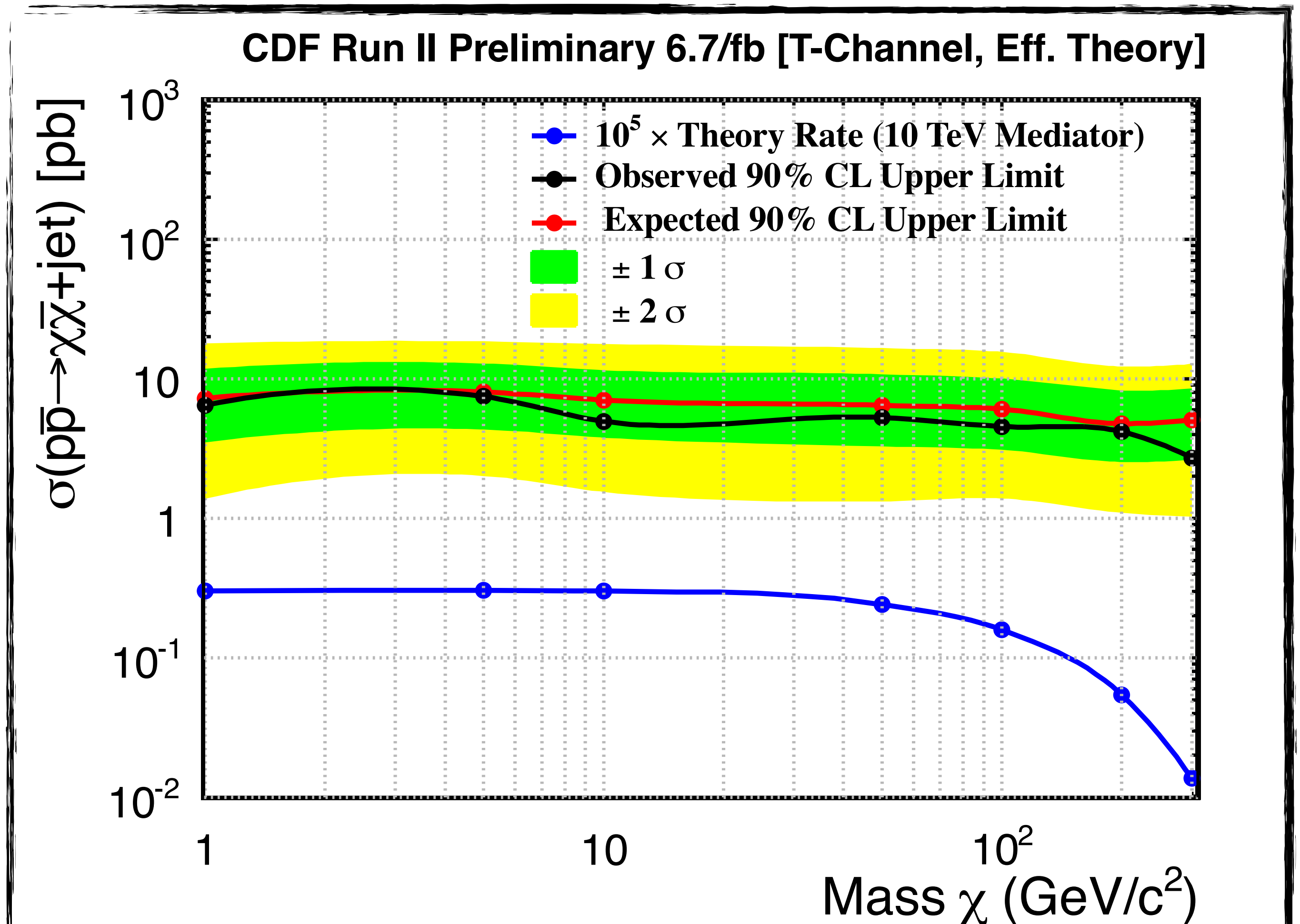


Light Mediator

Results

- 90% CL upper limits for t-channel mediator exchange



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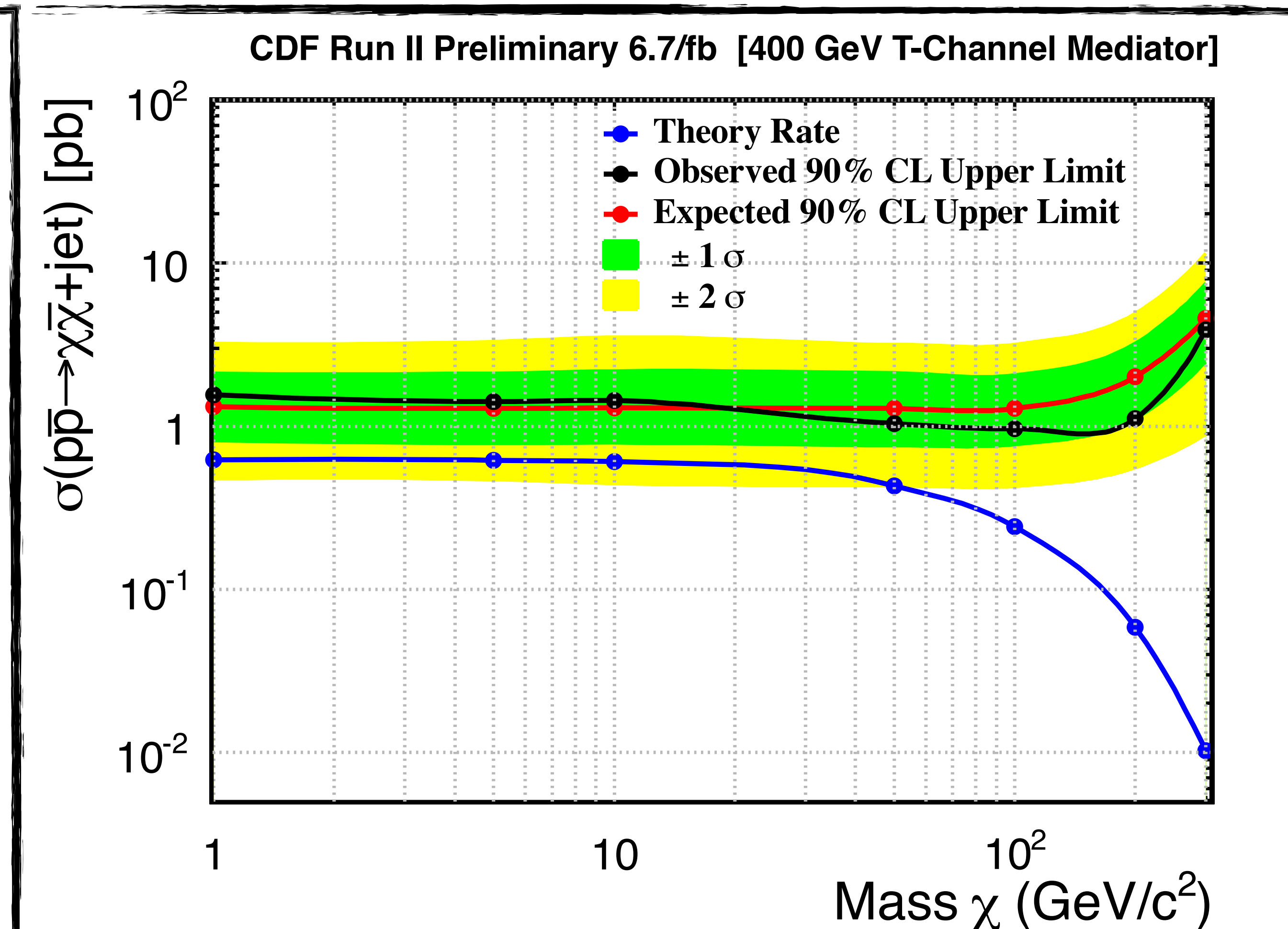
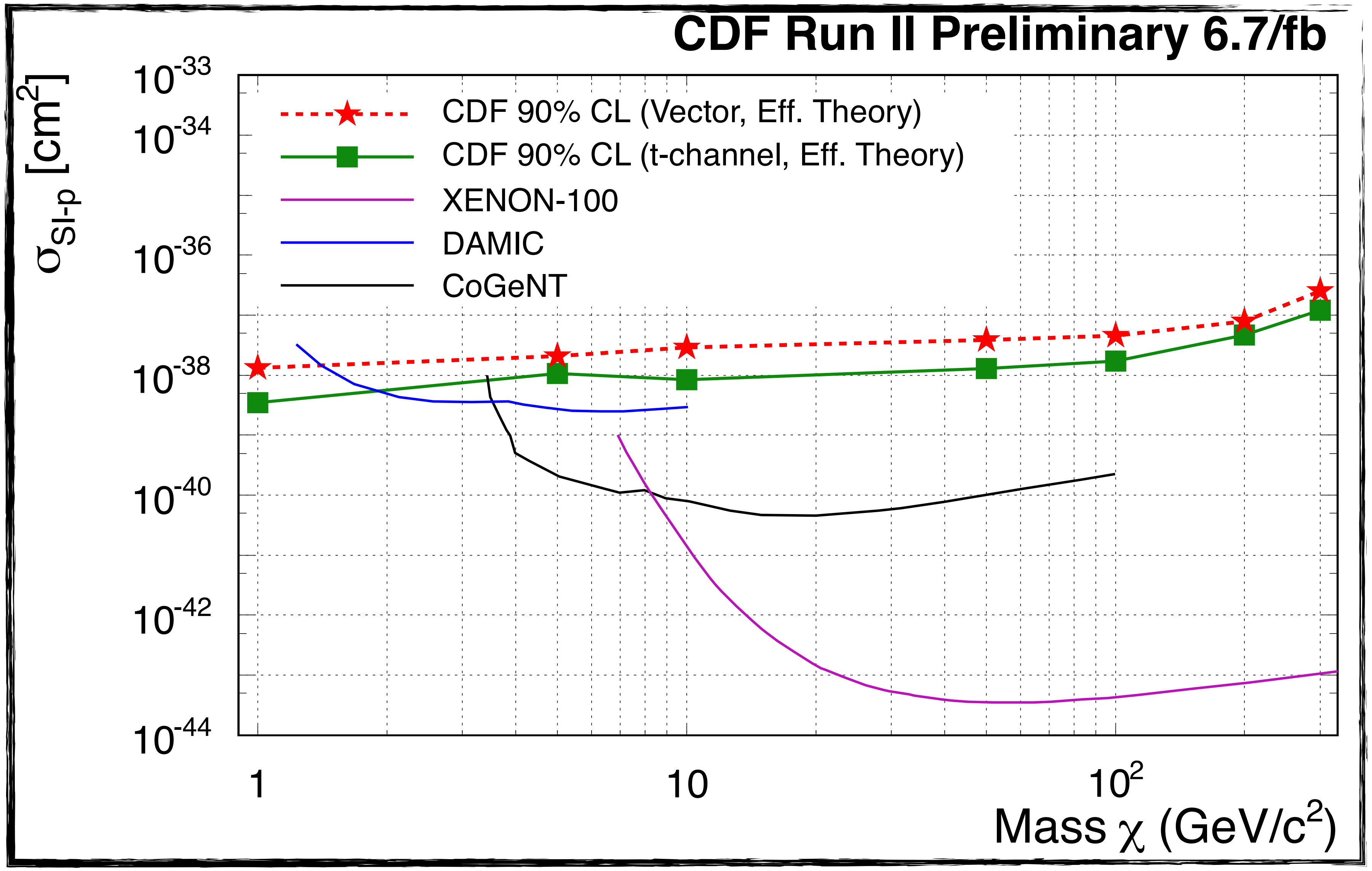


Light Mediator

- We have set limits on $\sigma[p\bar{p} \rightarrow X\bar{X} + jet]$ of ~1-40 pb

Comparison to Direct Detection

- Translation to Spin-Independent bounds on DM-nucleon scattering

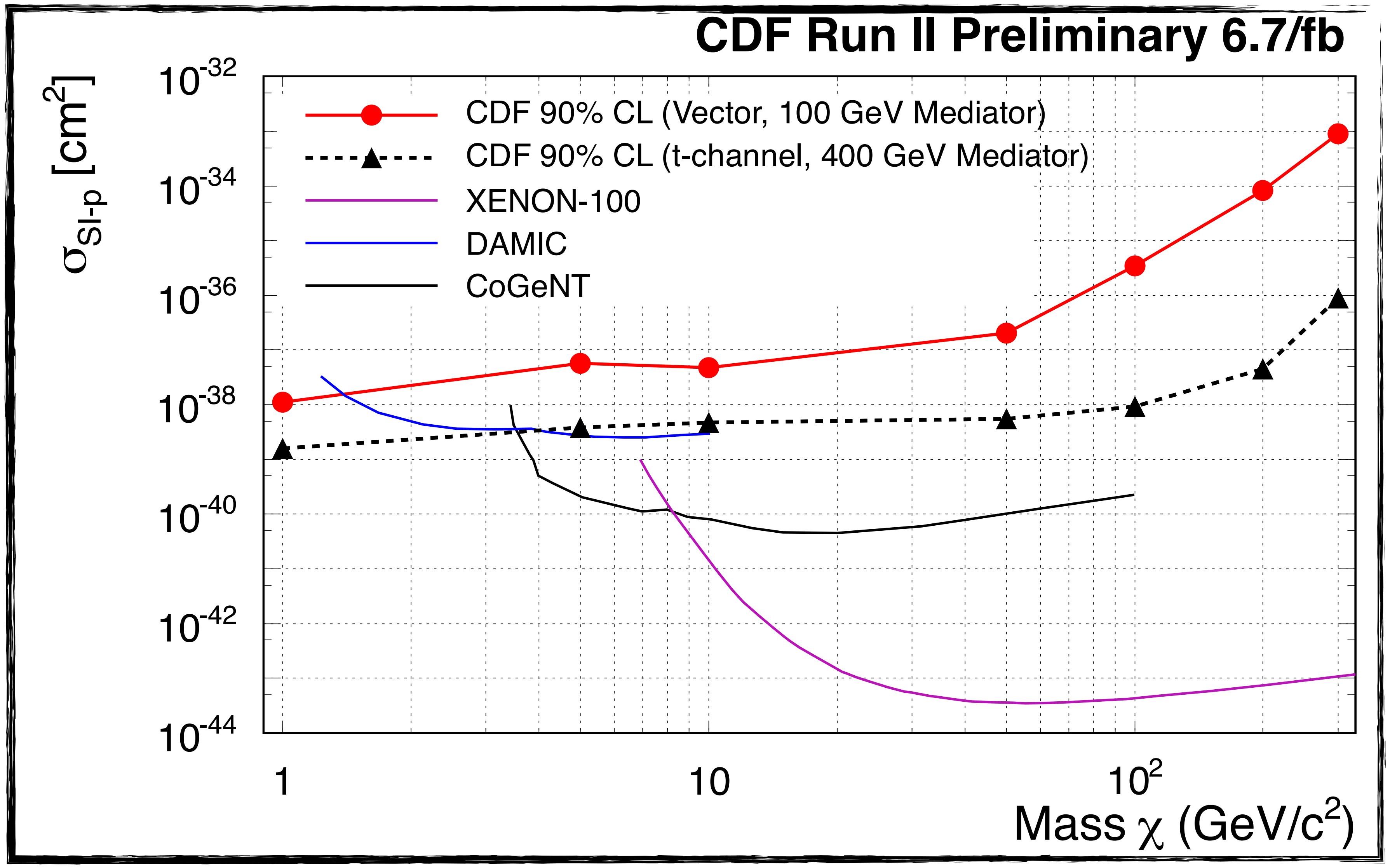


Effective Theory

(CoGeNT), Phys. Rev. Lett. 106, 131301 (2011), astro-ph.CO/1002.4703
(DAMIC) 2011, astro-ph.IM/1105.5191
(XENON100), Phys. Rev. Lett. 105, 131302 (2010), astro-ph.CO/1005.0380

Comparison to Direct Detection

- Translation to Spin-Independent bounds on DM-nucleon scattering



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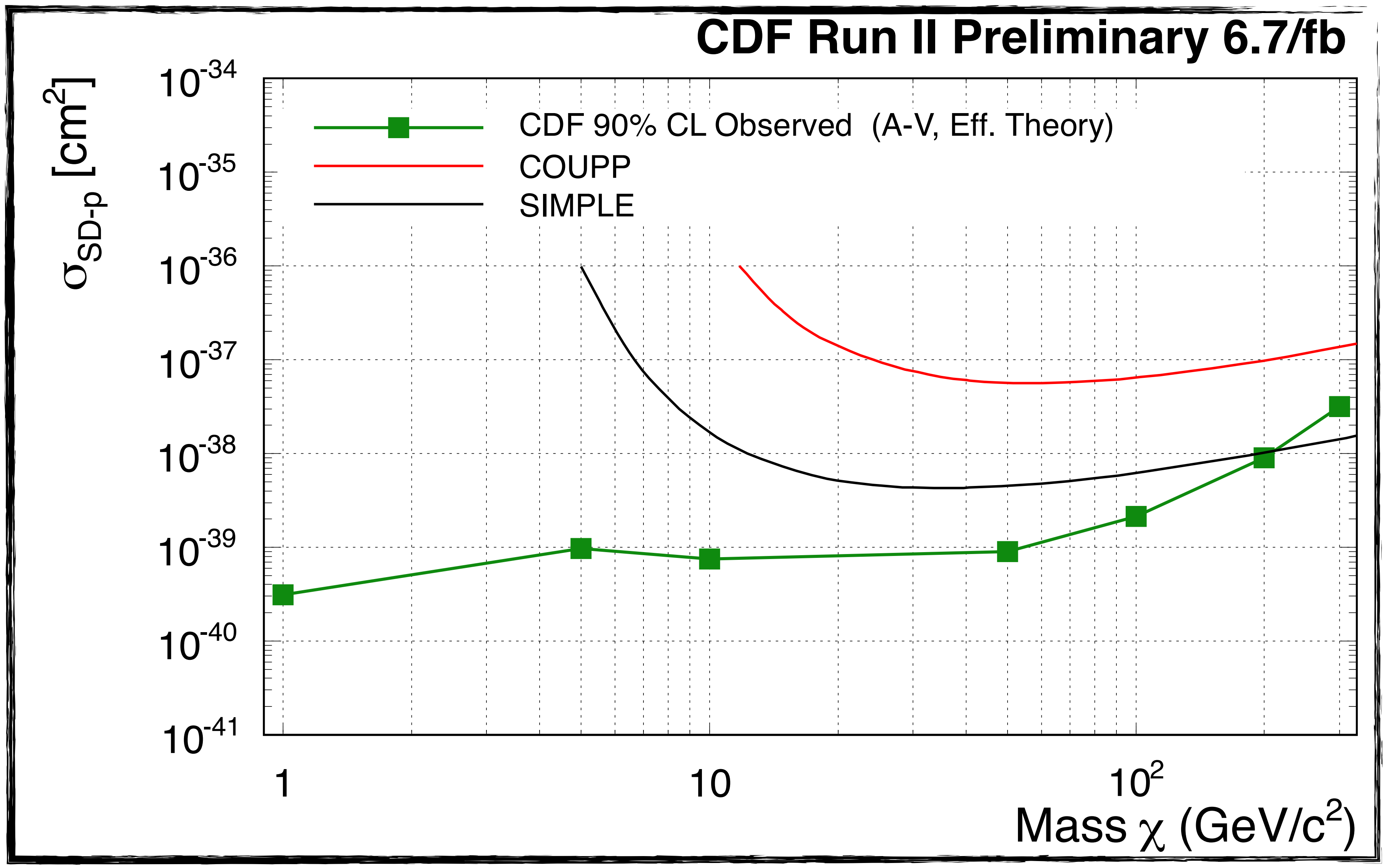
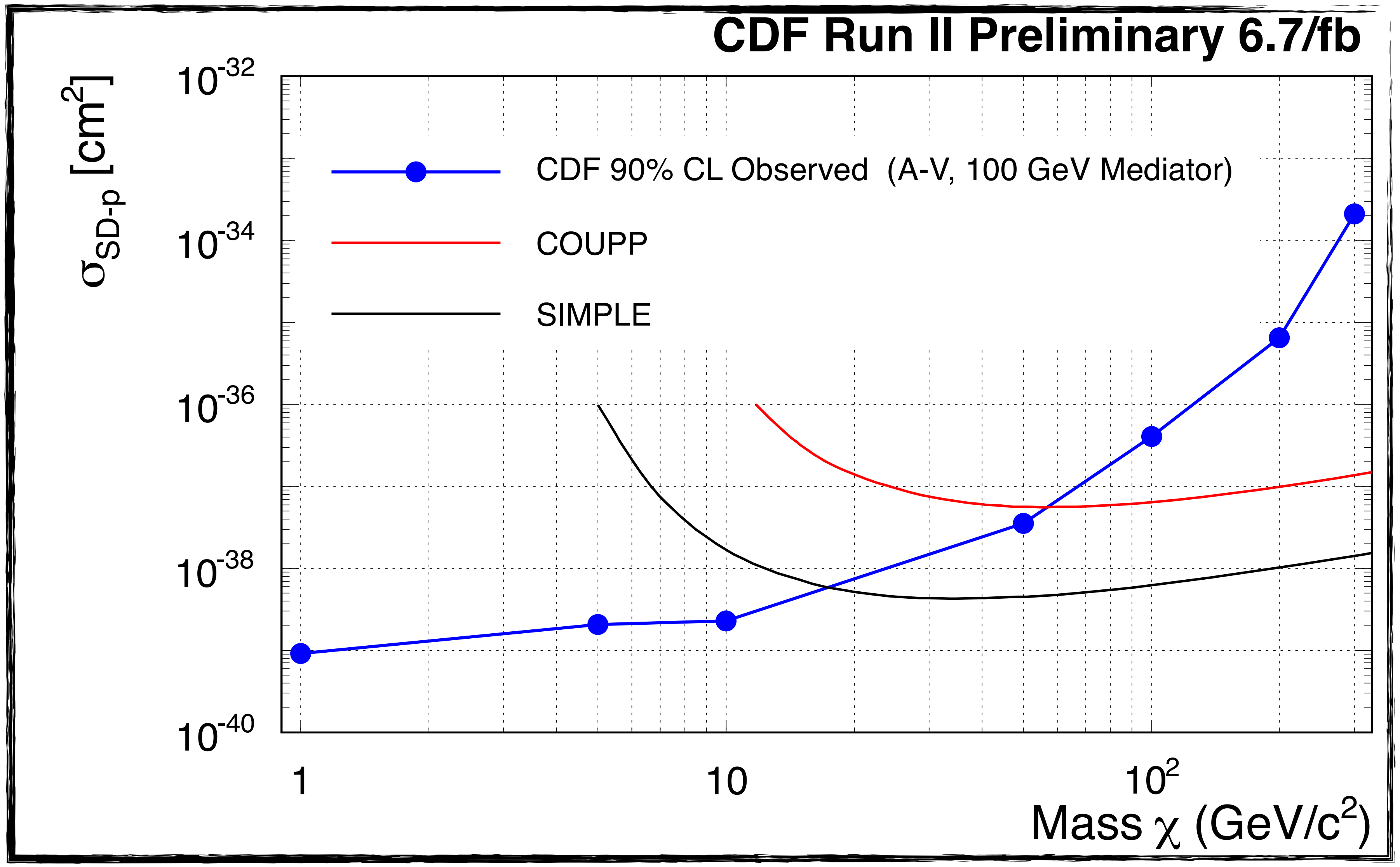


Effective Theory

(SIMPLE) 2011, astro-ph.CO/1106.3014
(COUPP) Phys. Rev. Lett. 106, 021303 (2011), astro-ph.CO/1008.3518

Comparison to Direct Detection

- Translation to Spin-dependent bounds on DM-nucleon scattering



Light Mediator

(SIMPLE) 2011, astro-ph.CO/1106.3014
(COUPP) Phys. Rev. Lett. 106, 021303 (2011), astro-ph.CO/1008.3518

Prospects

- Expect ~20% improvement with update to full CDF Run II dataset
- Dedicated ATLAS and CMS searches should be able to set strong limits and push to higher dark matter mass
- Stay tuned...

In Conclusion,

- Performed a search for dark matter production in the monojet + missing E_T signature
- No sign of dark matter above standard model backgrounds
- Set 90% CL upper limits on dark matter rate
- Translated limits into bounds on dark matter - nucleon scattering cross section.
- CDF is competitive with recent direct detection searches, and are stronger for some models & dark matter masses

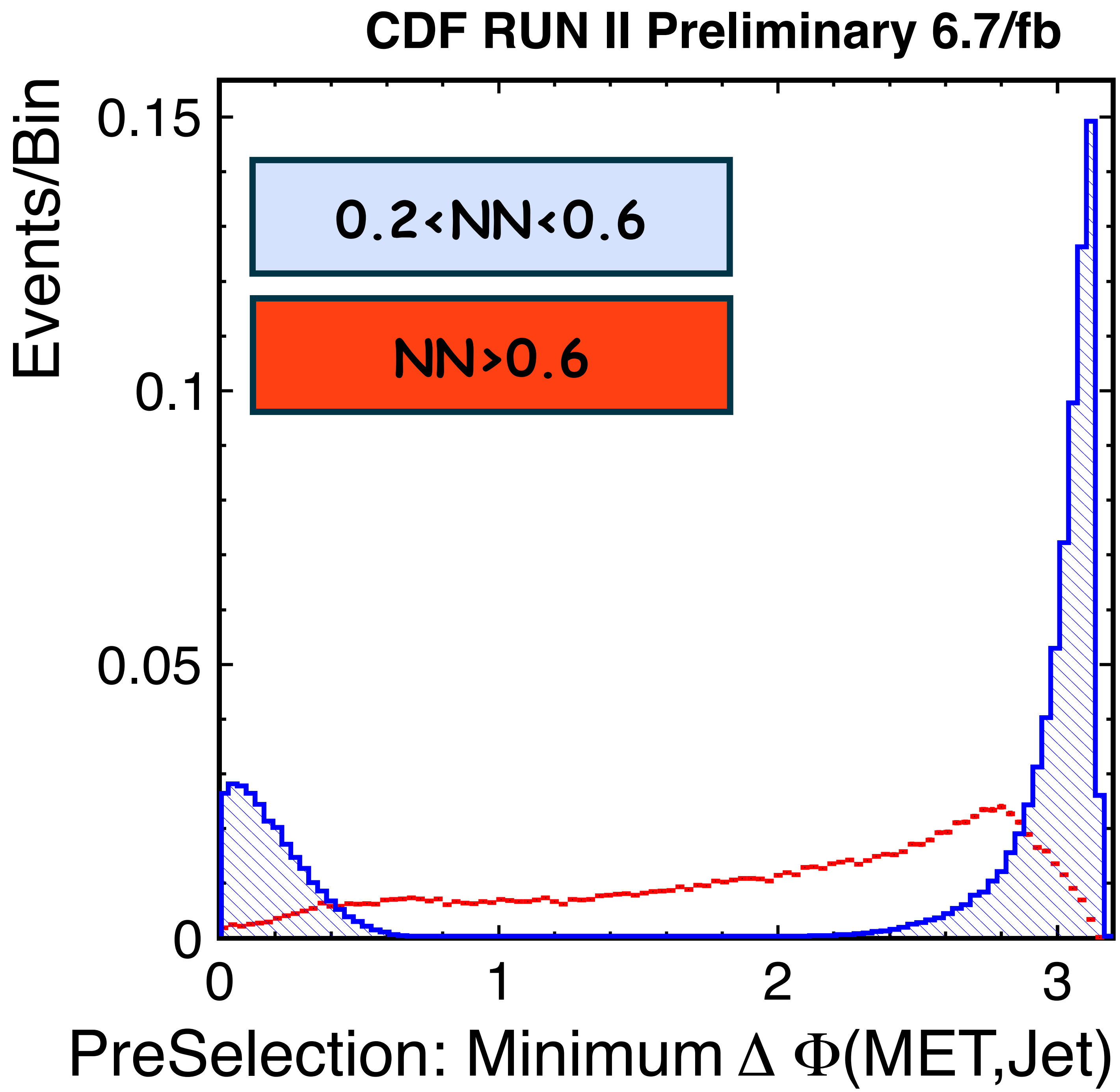
Thanks!

BACKUP

Multijet Matrix

Parameter	binning
Magnitude of TrkMET_{10}	[0,1,10,20, $\geq$ 200]
Minimum $\Delta\Phi(\vec{\not\!\!E}_T$,any jet)	[0,0.5,0.8,2,3,3.1,3.14]
Number of Jets	[1,2,$\geq$ 3]
$\not\!\!E_T$	[60,70,$\geq$ 200]
$\not\!\!E_T$ significance	[0,7.5,15.1]
R	[0,0.45,0.5,0.55,1]

NN Multijet Rejection



NN Multijet Rejection

TMVA Rank	Variable
1	$\Delta\varphi(\text{jet,Met})_{min}$
2	R
3	$\Delta\varphi$(lead Jet,Met)
4	MET
5	lead jet Et
6	Number of Jets
7	$\Delta\varphi(\text{TrkMET}_{10},\text{Met})$
8	TrkMET_{10}
9	$\Delta\varphi(\text{TrkMET}_{10},\text{Lead Jet})$
10	EM_{event}^{frac}
11	lead jet η