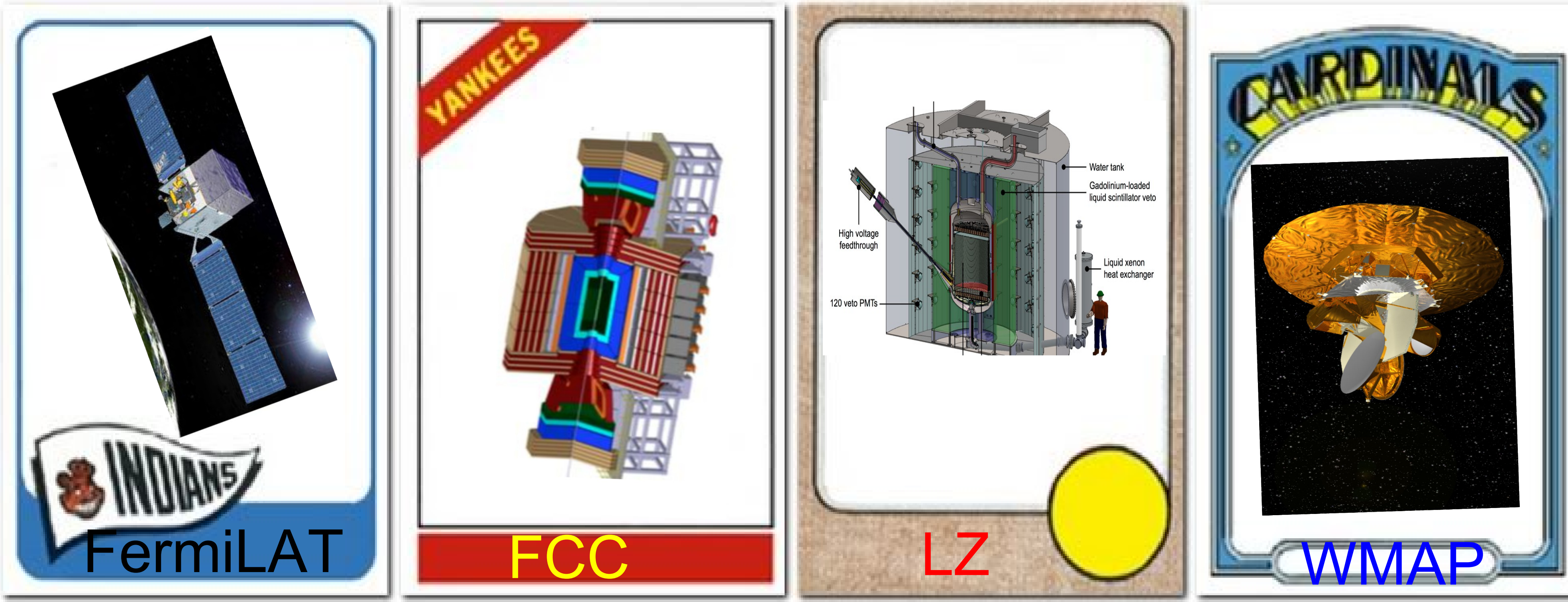


Dark Matter @ FCC

Philip Harris (CERN)*
*Experimentalist

Questions For Consideration

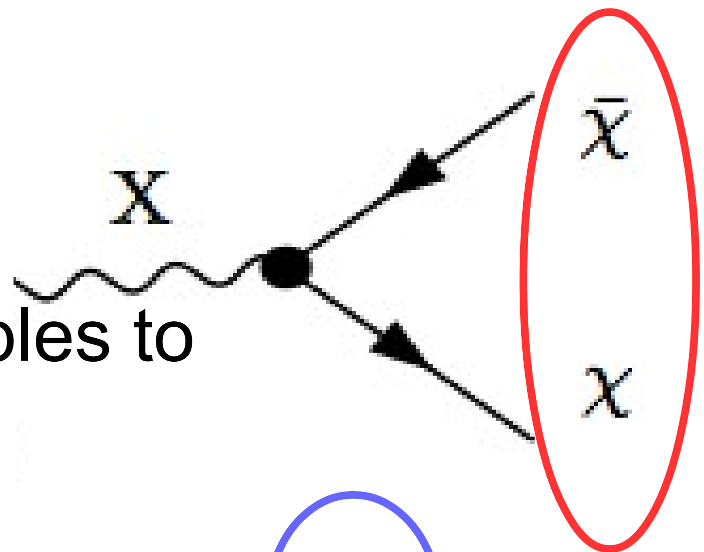
- Whats the place of Dark matter and colliders?
  - What are the modes of detection?
- What's it take to find dark matter in a collider?
  - What are the limitations on the detector?
- What is a collider's place in the world?
  - What other experiments are out there?
  - How can we complement?

Dark Matter and Models

- Dark matter models add at least 2 particles

Either :

mediator that couples to
Dark matter

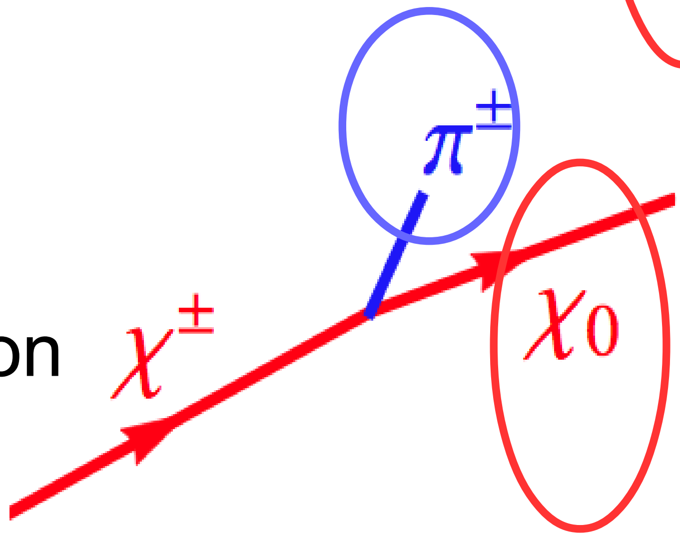


In all cases we tag
Dark matter as

MET signature

Or

additional fermion



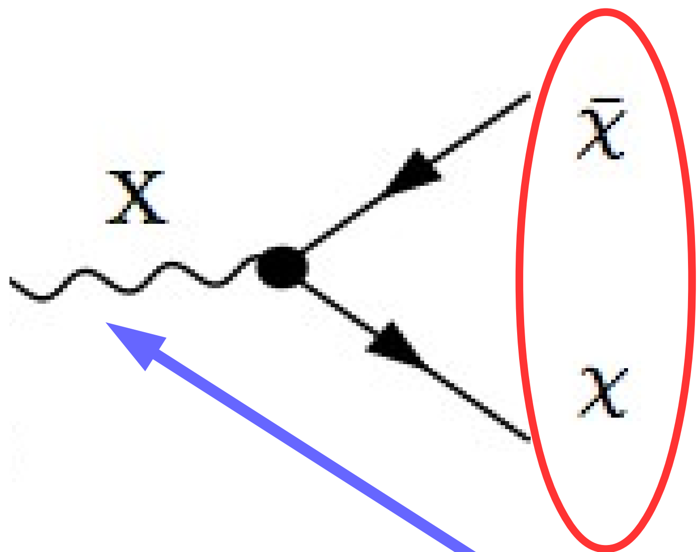
In some cases we find

An additional signature

Dark Matter and Models

- Dark matter models add at least 2 particles

Either :



In all cases we tag Dark matter as

MET signature

Consequently :

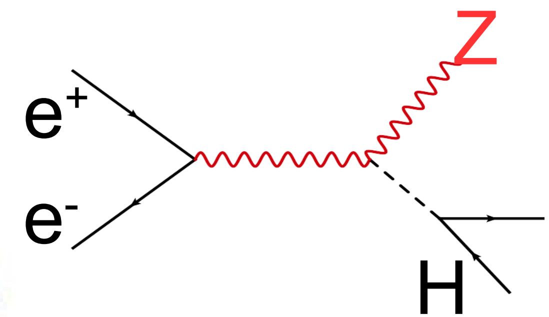
Searching for additional particles

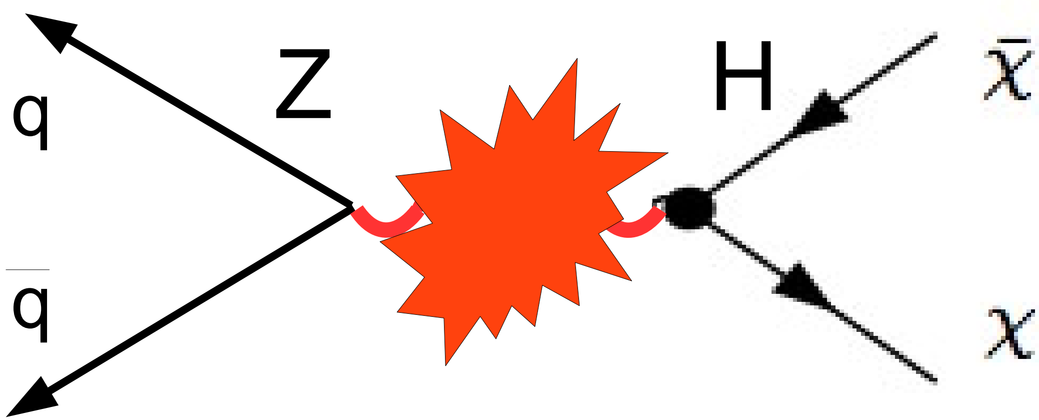
We need to produce the additional particle

Motivates going to higher energies

Exception to 2 particle rule

- It is possible for the Higgs to decay invisibly
  - We need a lot of Higgs to find invisible decay
- Can use an e^+/e^- collider

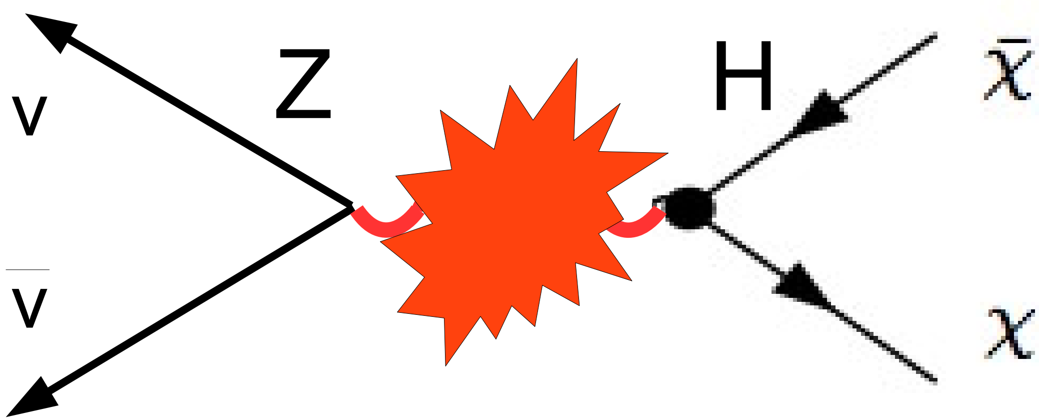




Dijet + Missing Energy above the ZH
Resolve the Z di-jet mass (10 GeV mass resolution)

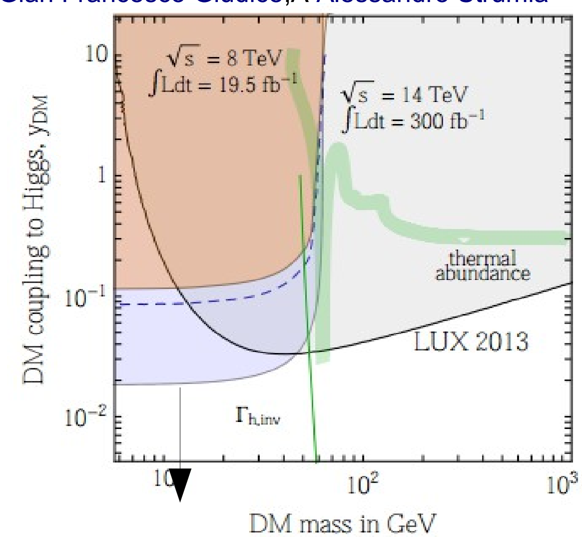
Exception to 2 particle rule

- It is possible for the Higgs to decay invisibly
  - We need a lot of Higgs to find invisible decay
- Can use an e^+/e^- collider



Arxiv/1402.6287

Andrea De Simone, Gian Francesco Giudice,Â Alessandro Strumia



Nothing in your detector

Missing Energy resolution against low pT leptons (<10 GeV)

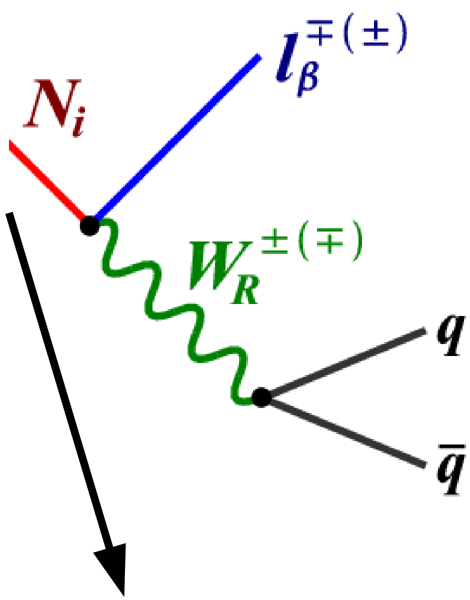
Exception to 2 particle rule

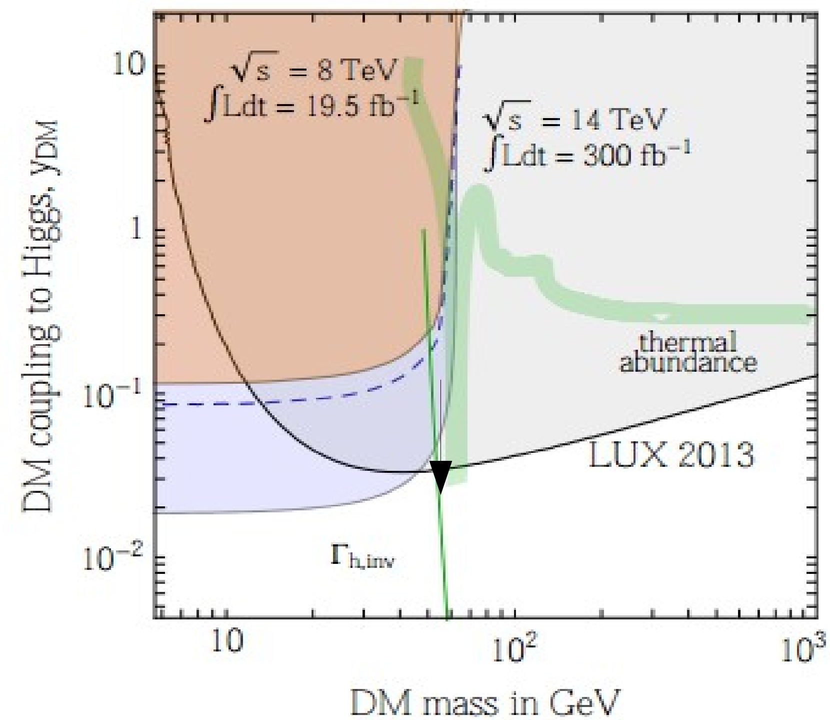
- It is possible for the Higgs to decay invisibly
  - We need a lot of Higgs to find invisible decay
- Can use an e^+/e^- collider

Arxiv/1402.6287

Andrea De Simone, Gian Francesco Giudice,Â Alessandro Strumia

Few models for almost invisible





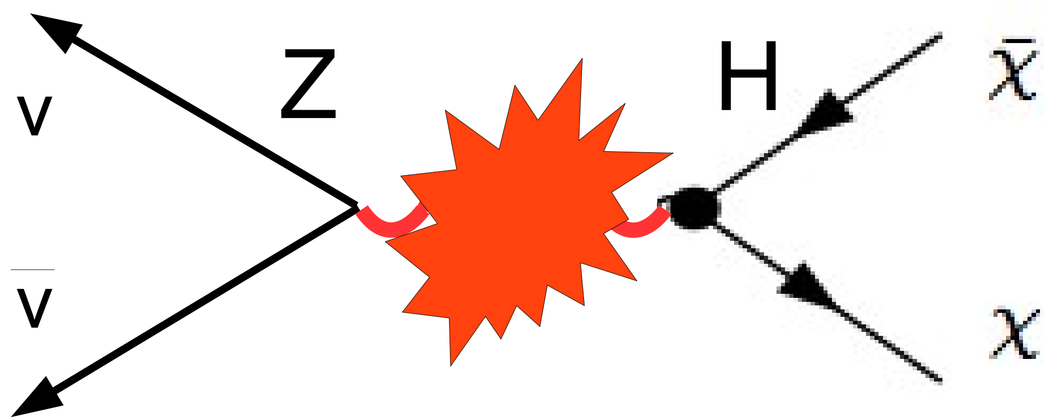
Heavy neutrinos can have a long lifetime
Give clealr signature

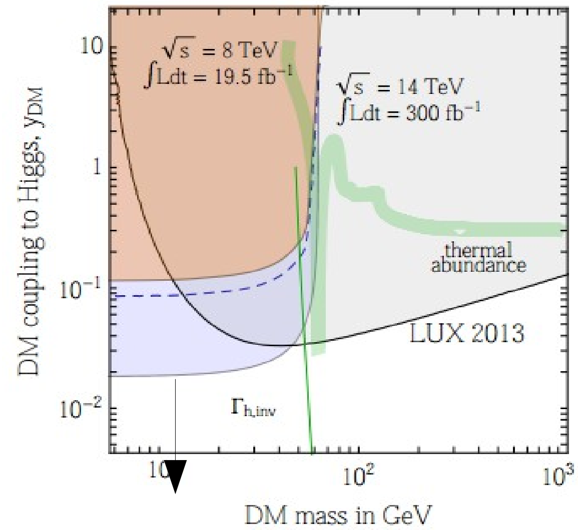
Exception to 2 particle rule

- It is possible for the Higgs to decay invisibly
  - We need a lot of Higgs to find invisible decay
- Can use an e^+/e^- collider

Arxiv/1402.6287

Andrea De Simone, Gian Francesco Giudice,Â Alessandro Strumia



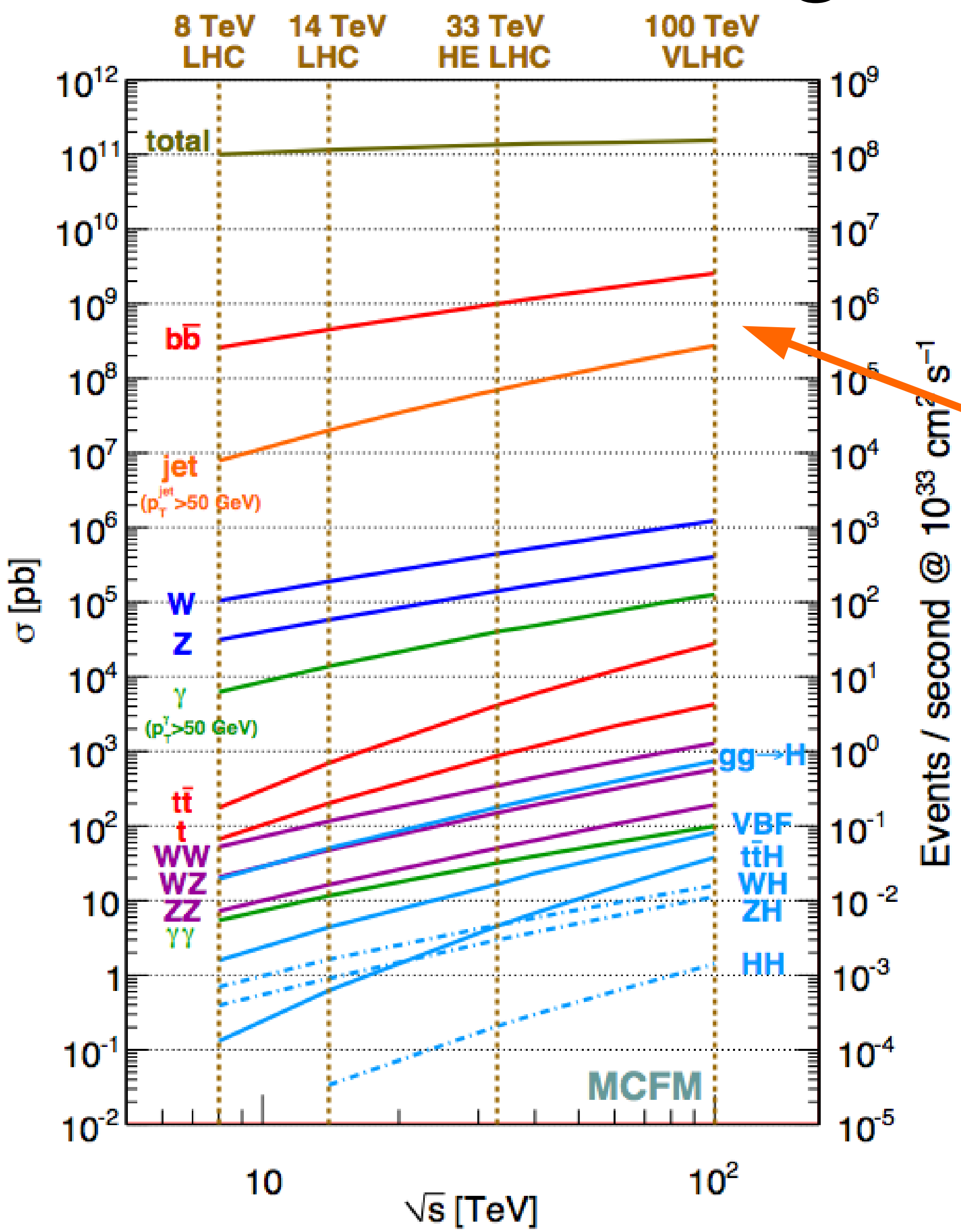


Nothing in your detector

Missing Energy resolution against low pT leptons (<10 GeV)

Going to 100 TeV

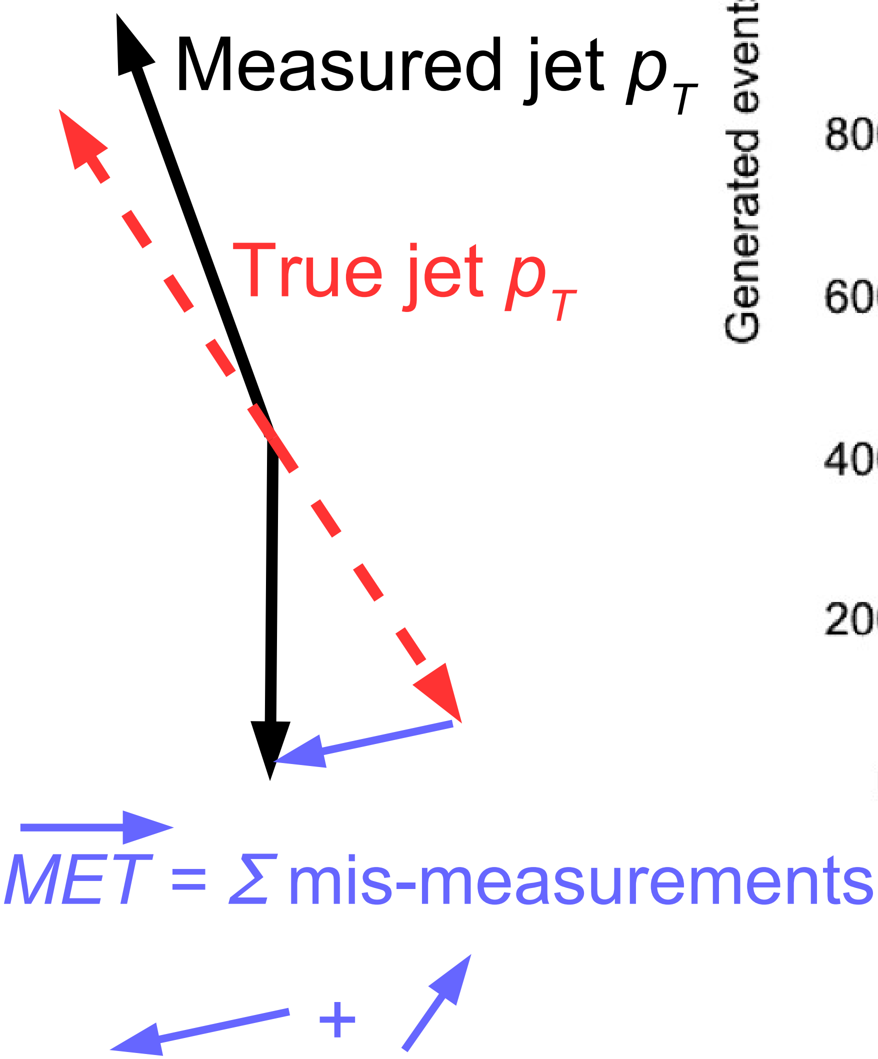
Building a DM analysis

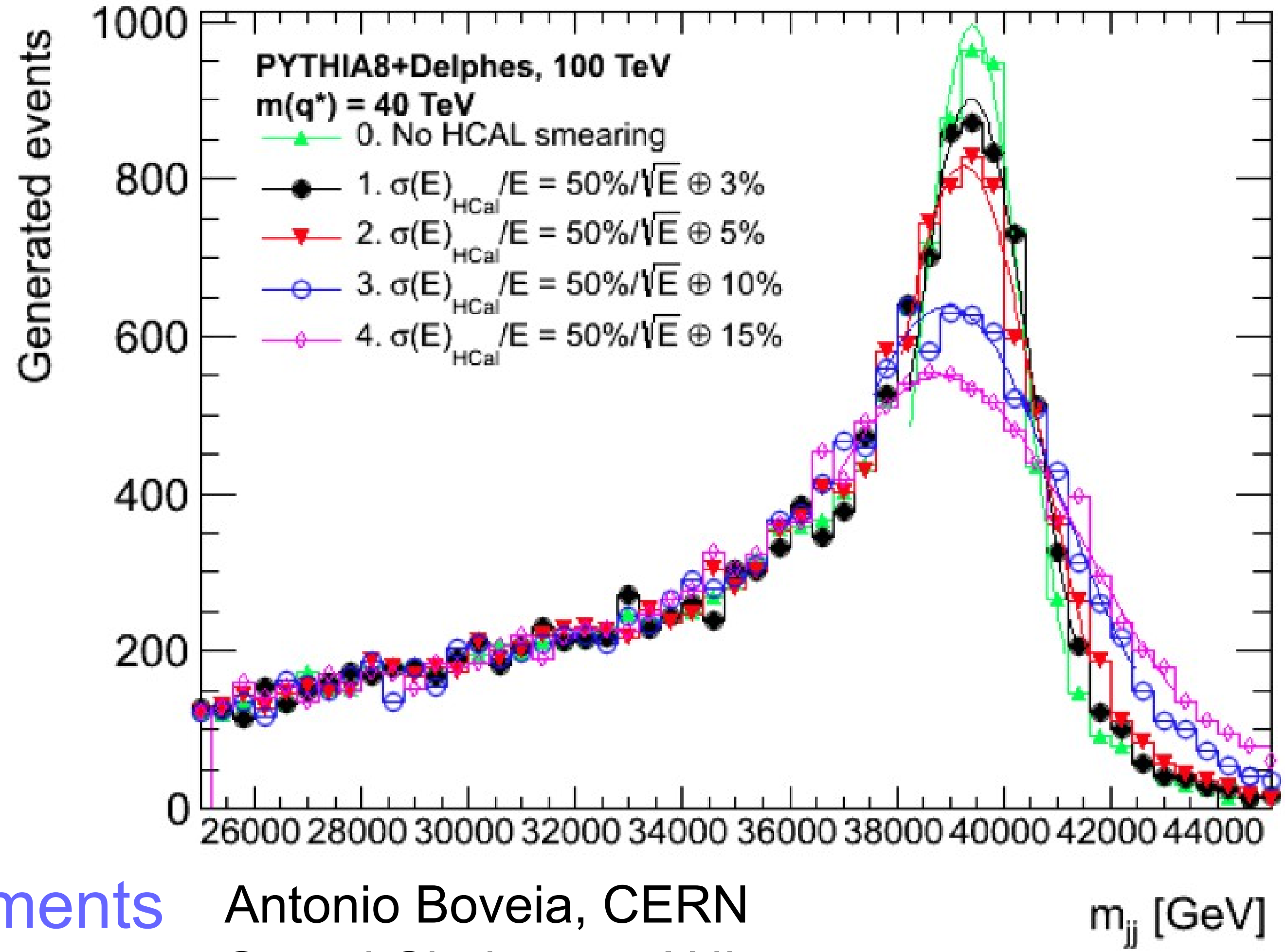


- Step one :
  - Select *MET*
- Base threshold
  - Enough to remove QCD
- What is this threshold?
  - Depends on the *jet resolution*

Shape of 0 *MET* di-jets

- Consider di-jet events

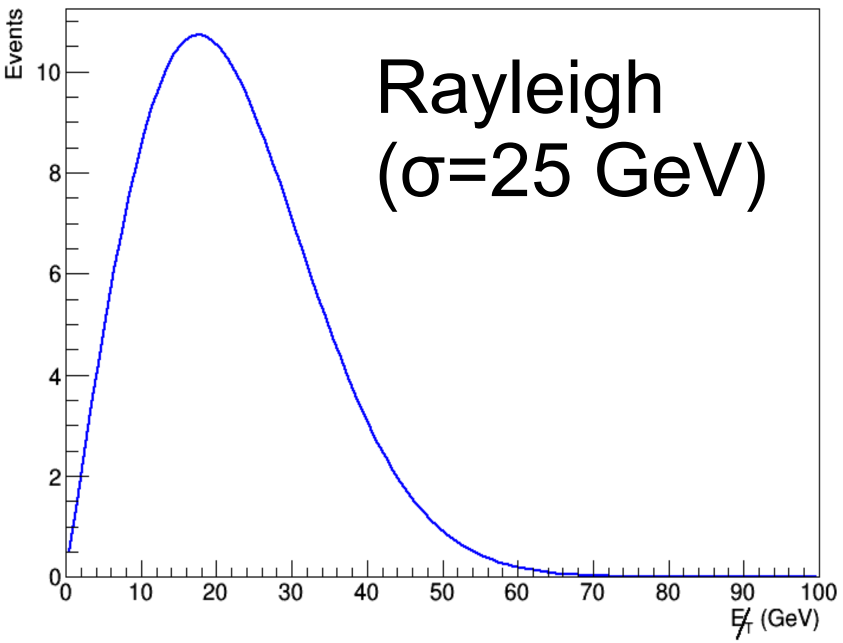




Antonio Boveia, CERN
Sergei Chekanov, ANL
Caterina Doglioni, University of Geneva
Daniel Dylewsky, University of Georgetown
Ana Henriques

Expected QCD Shape

- Compute QCD *MET* by scanning same jet res
  - Using resolution above
- Resulting *MET* shape is a rayleigh distribution
  - Rayleigh : $f(MET)=MET/\sigma^2 \exp(-MET^2/\sigma^2)$
    - Sigma is the jet resolution
- Convolve this with jet p_T spectrum ($d\sigma_J/dp_T=pT^{-5}$)



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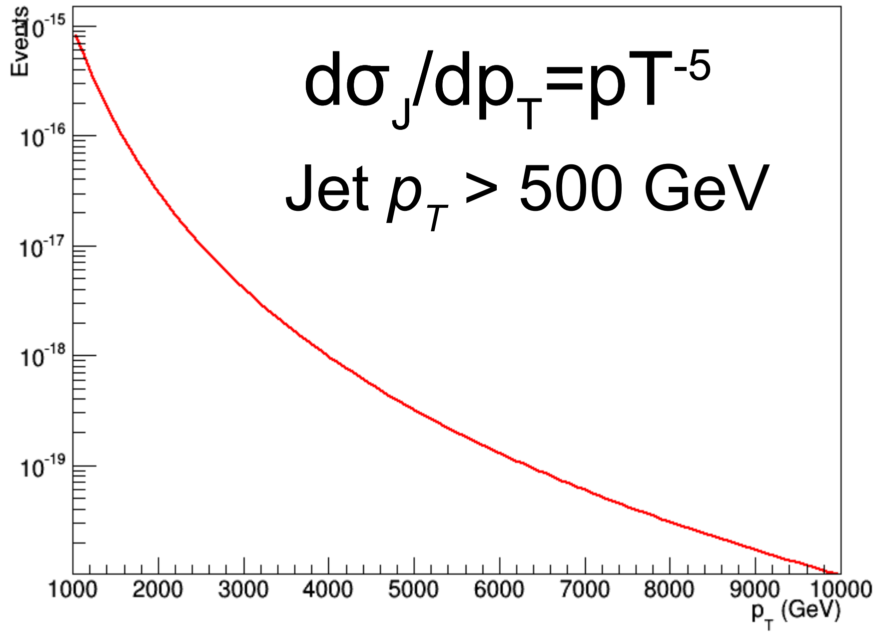
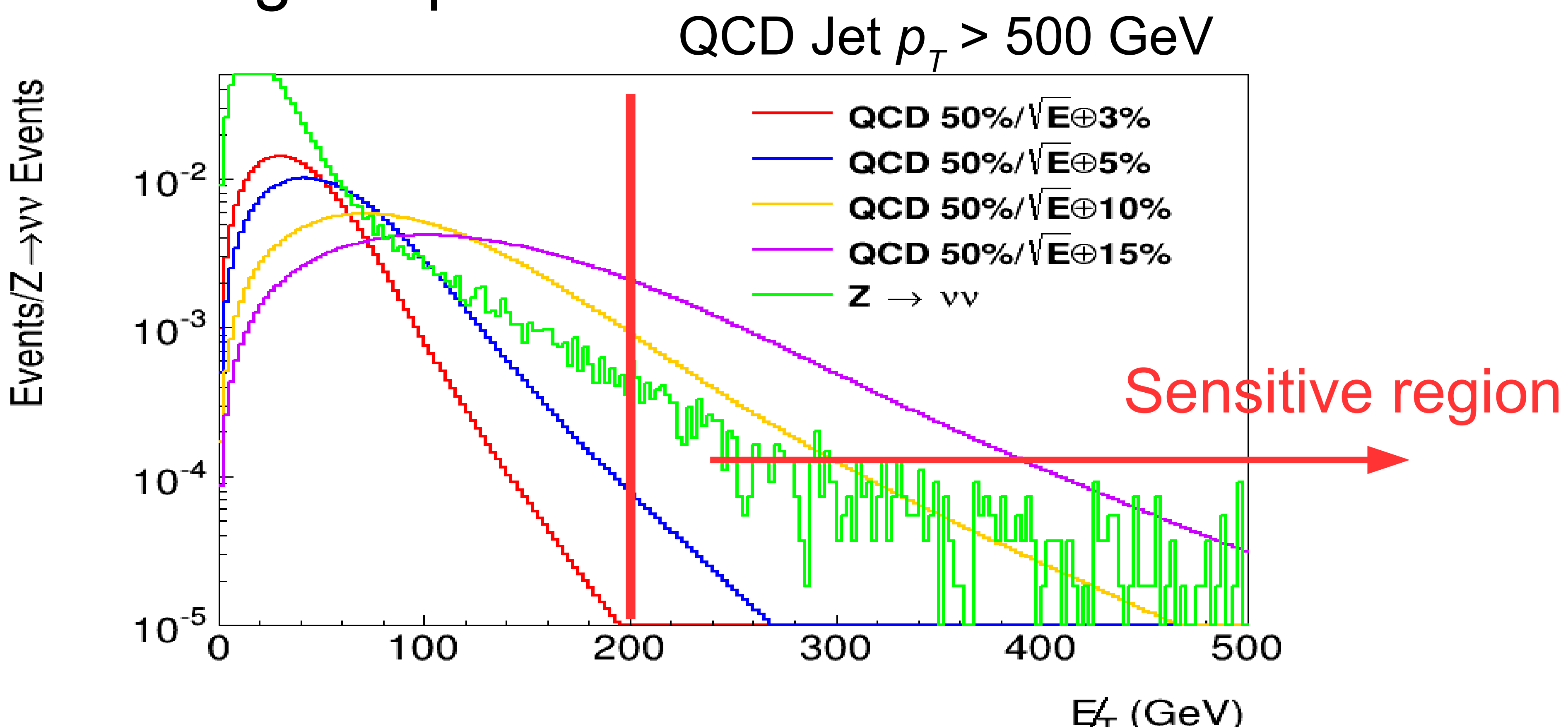


MET Resolution

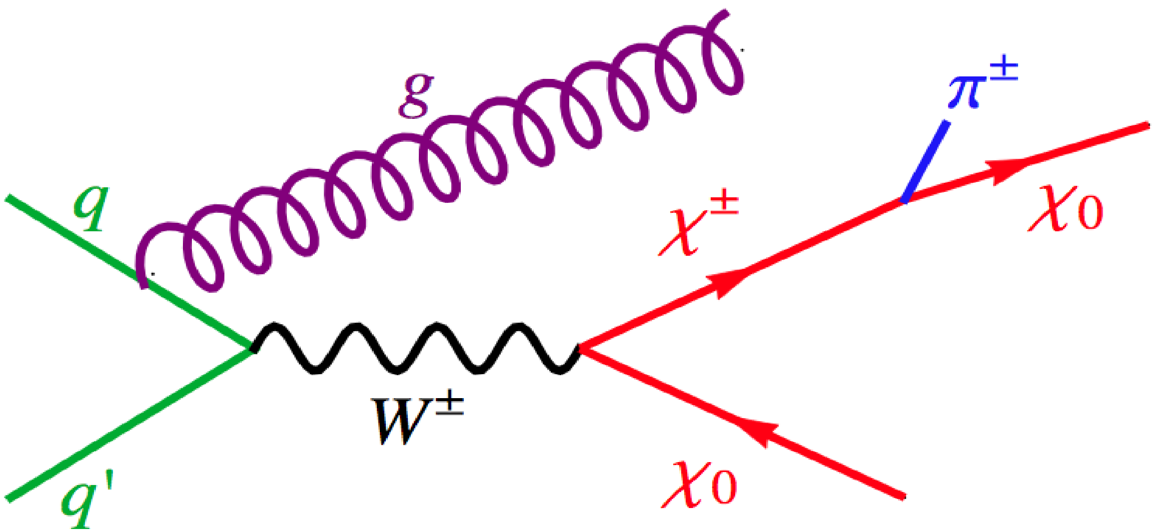
- Resulting shape



Normalizing cross sections to approx. expectation from MCFM
Comparing with Z : derive a clear bound for *MET*

Planned Summer student on jets+*MET* with Caterina/Anotino and Ana Henriques

Disappearing Tracks



M.Low,L.Wang

Arxiv/1404.0682

M.Cirelli,F.Sala,M.Taoso

Arxiv/1407.7058

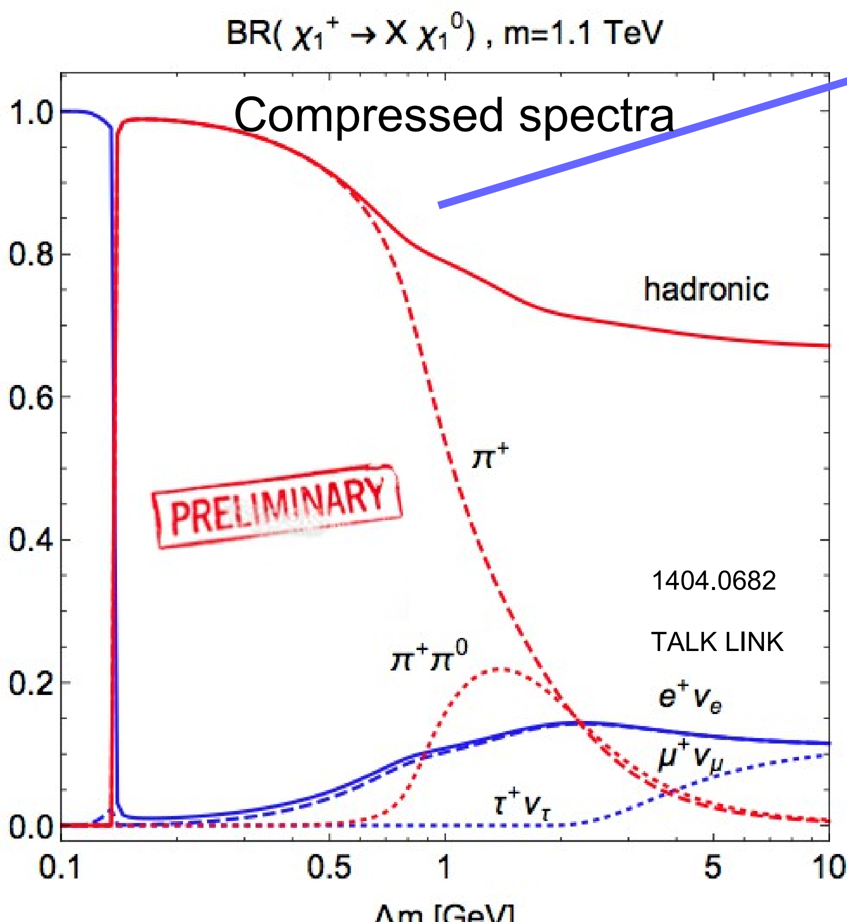
J.Zurita,P.Schwaller,R.Mahbubani

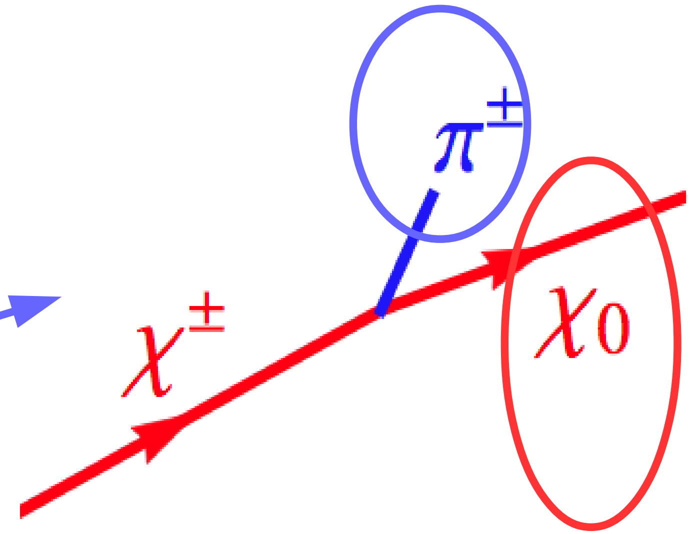
Preliminary

https://indico.cern.ch/event/352868/session/7/contribution/24/material/slides/0.pdf
https://indico.cern.ch/event/352868/session/8/contribution/31/material/slides/0.pdf
https://indico.cern.ch/event/352868/session/7/contribution/26/material/slides/0.pdf

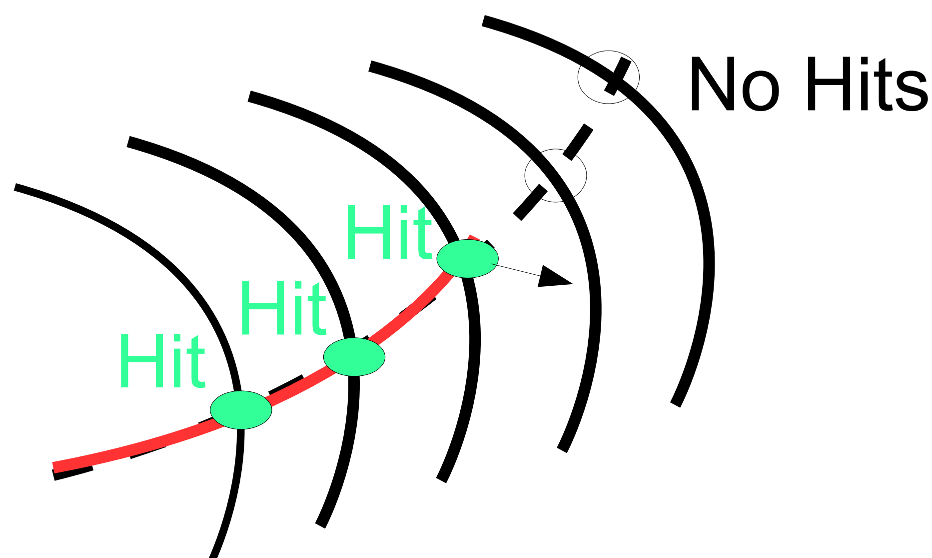
Disappearing Track Search

- Two step analysis
  - Cut on *MET* (gets rid of di-jets)
  - Look for a disappearing track





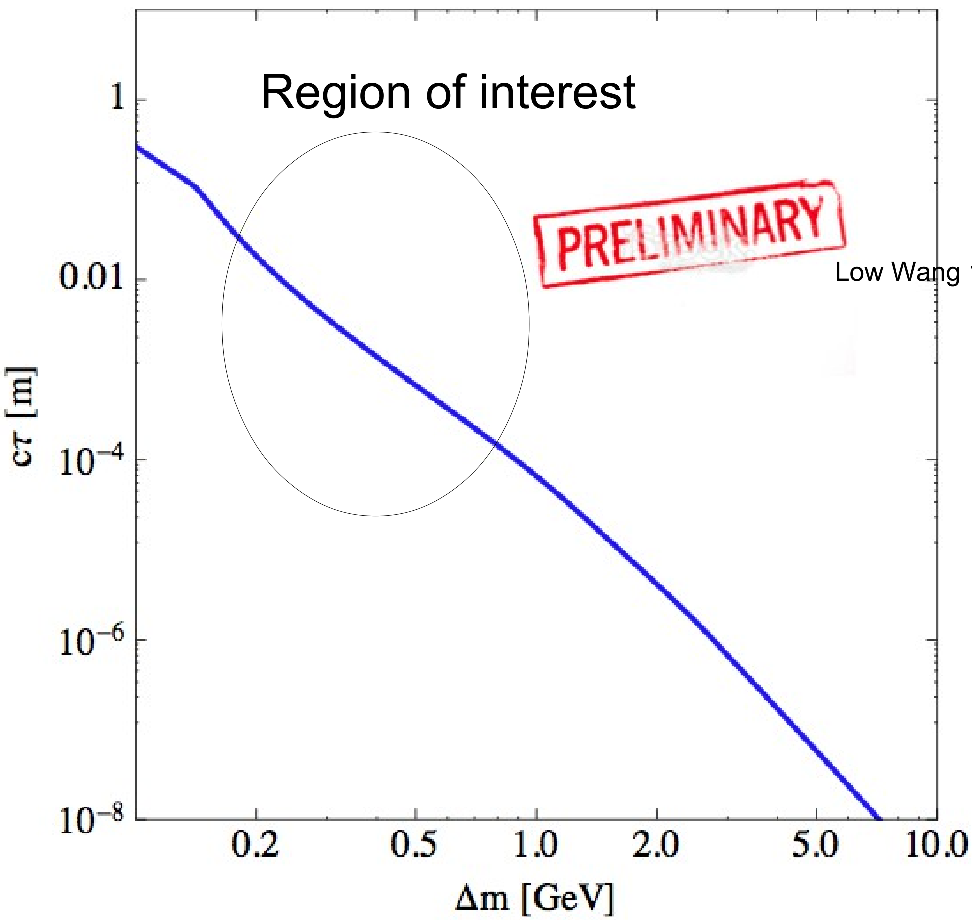
Strategy :
Select one isolated track



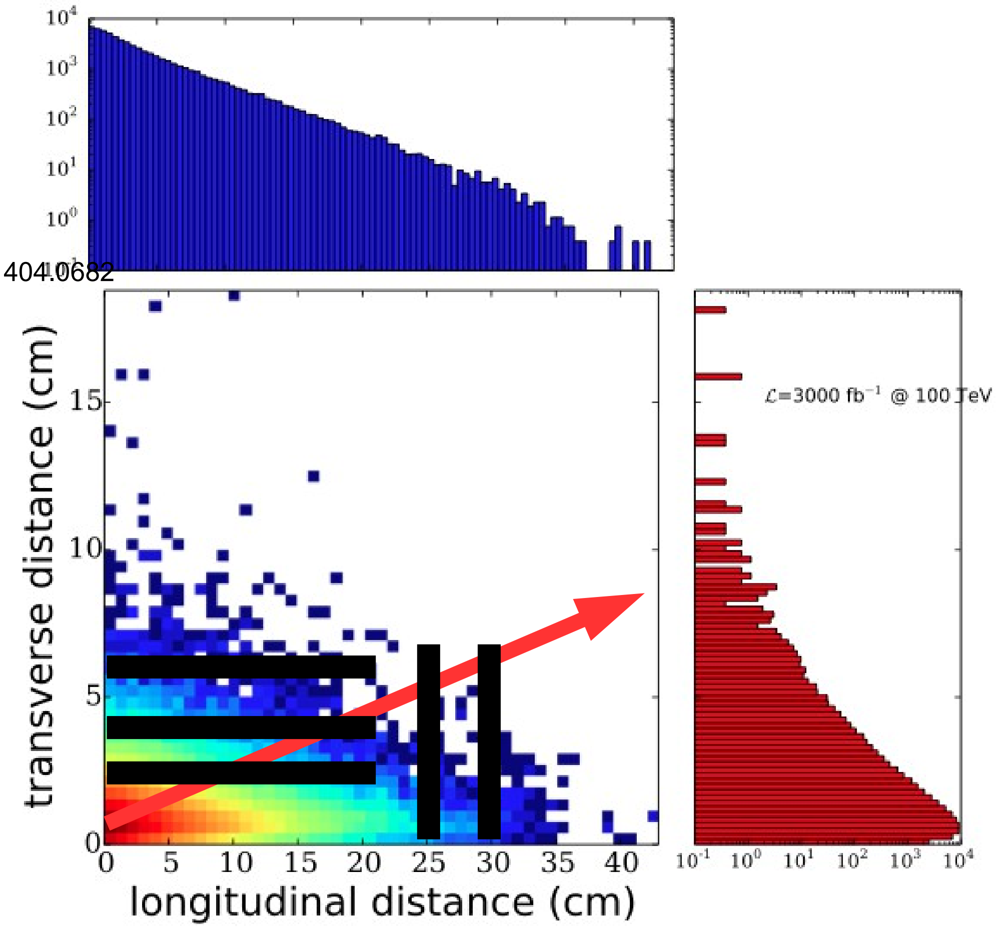
R.Mahbubani, P. Schwaller, J. Zurita Filippo Sala Low Wang 1404.0682

Decay Length in Design

- What is the decay length needed?
  - Expect lifetimes that are on the order of cms



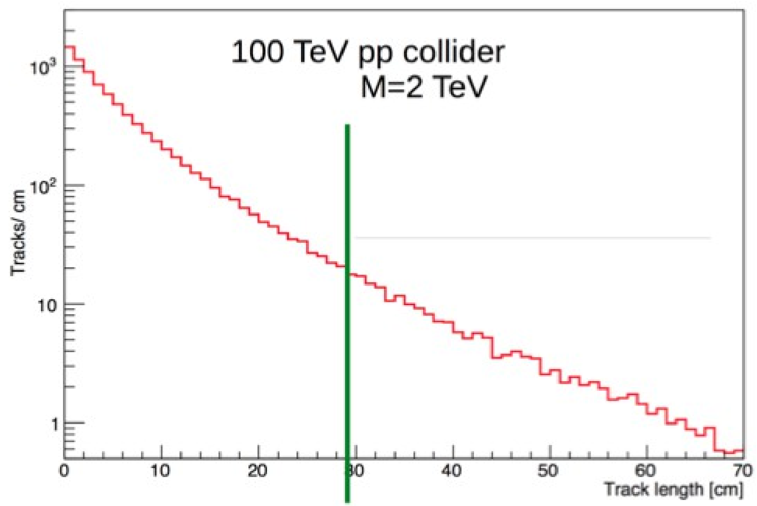
Low Wang 1404.0682

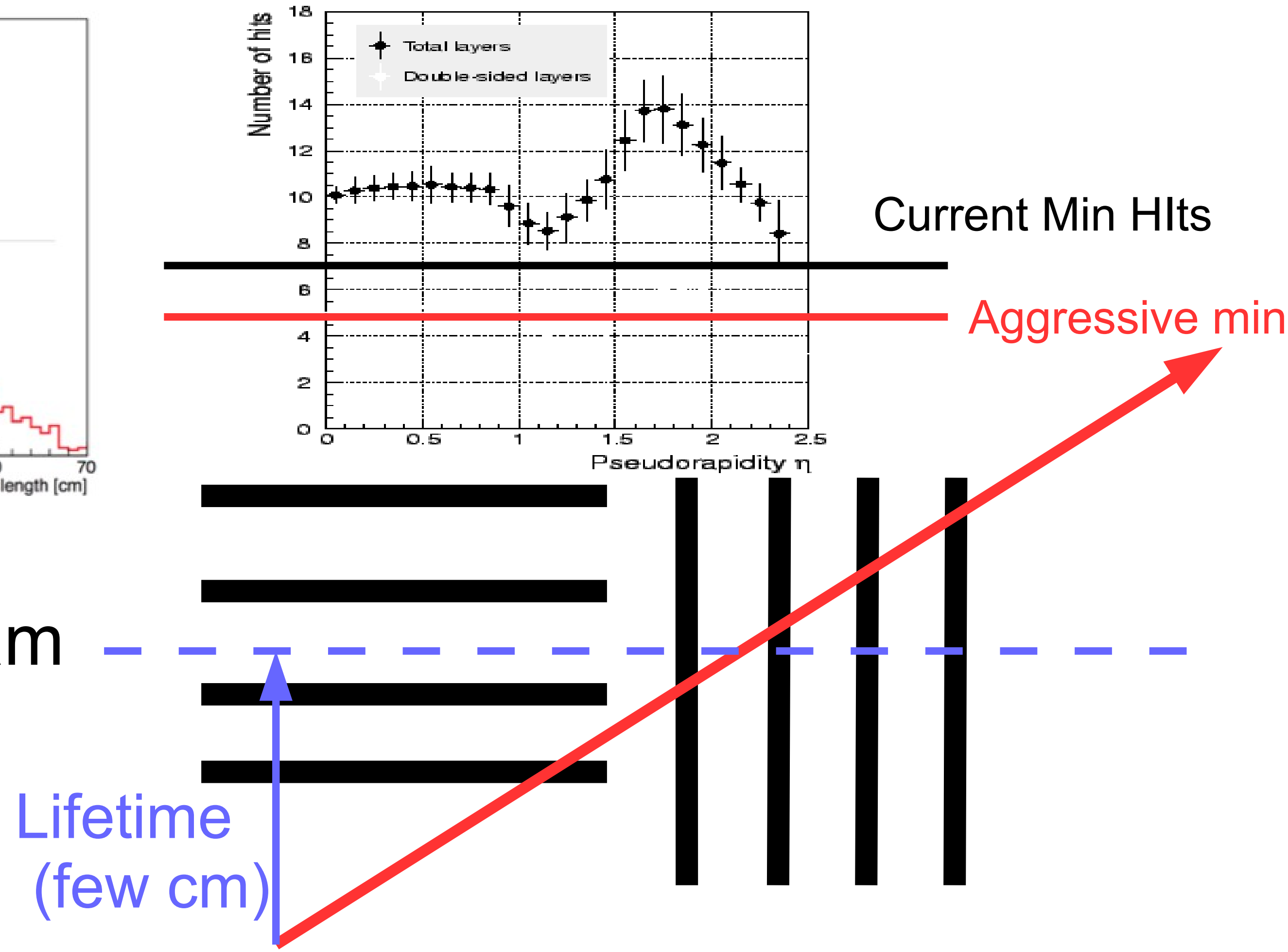


R.Mahbubani, P. Schwaller, J. Zurita Filippo Sala Low Wang 1404.0682

Disappearing tracker

- Need at least 3 hits to reconstruct a track
  - To be robust typically require 5-7 hits





Tracking close to beam drastically enhance signal detection

R.Mahbubani, P. Schwaller, J. Zurita   Filippo Sala   Low Wang 1404.0682

Disappearing tracker

- Need at least 3 hits to reconstruct a track
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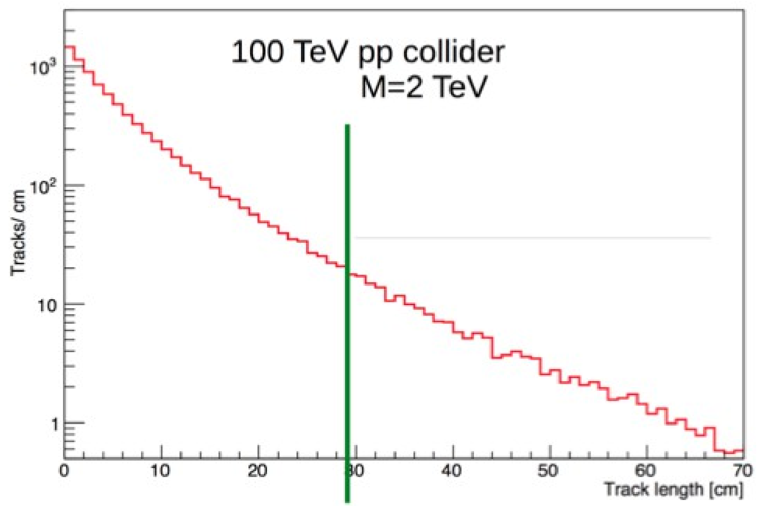

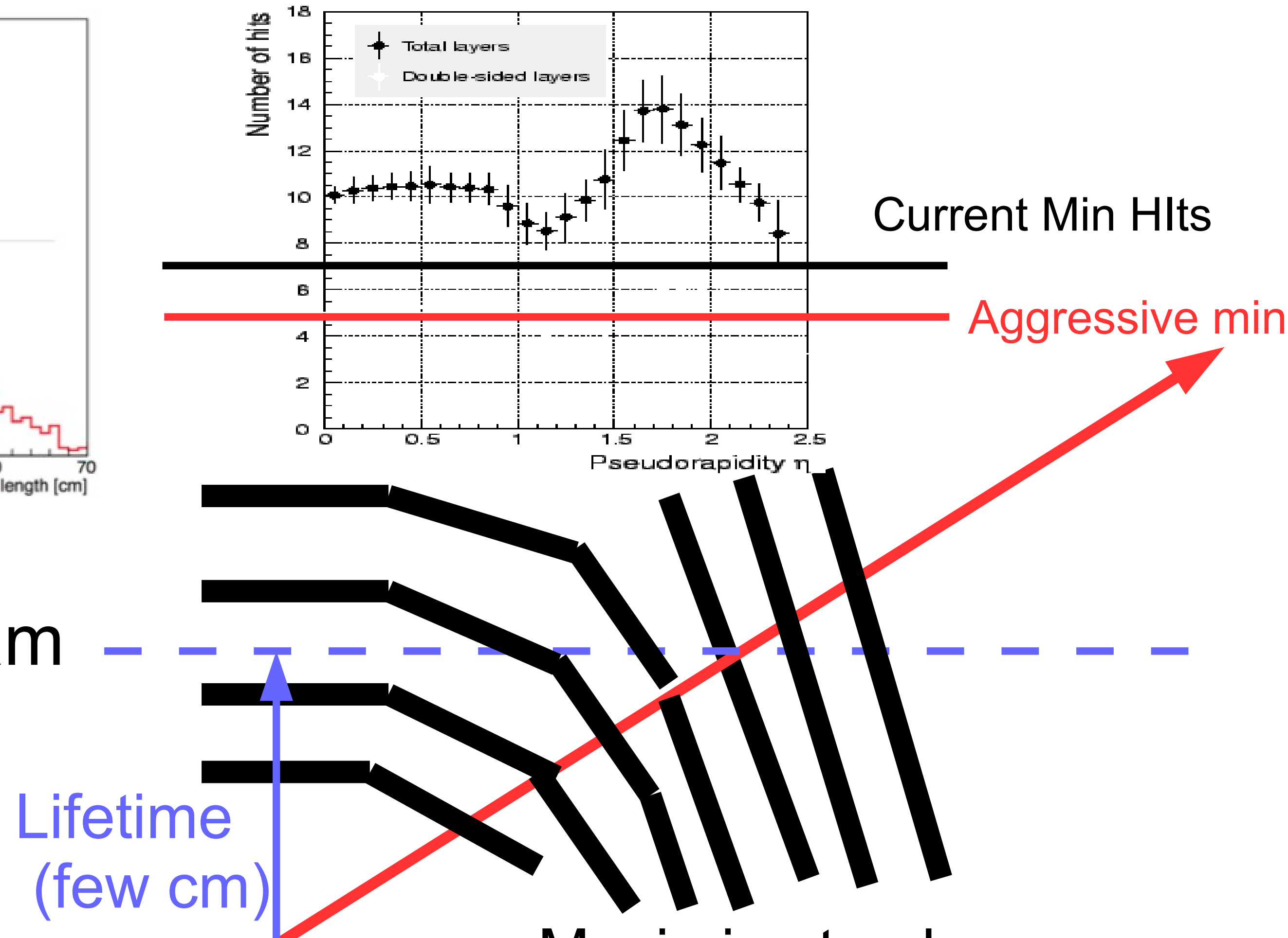

Tracking close to beam drastically enhance signal detection

Maximize track pT/vertexing parameters

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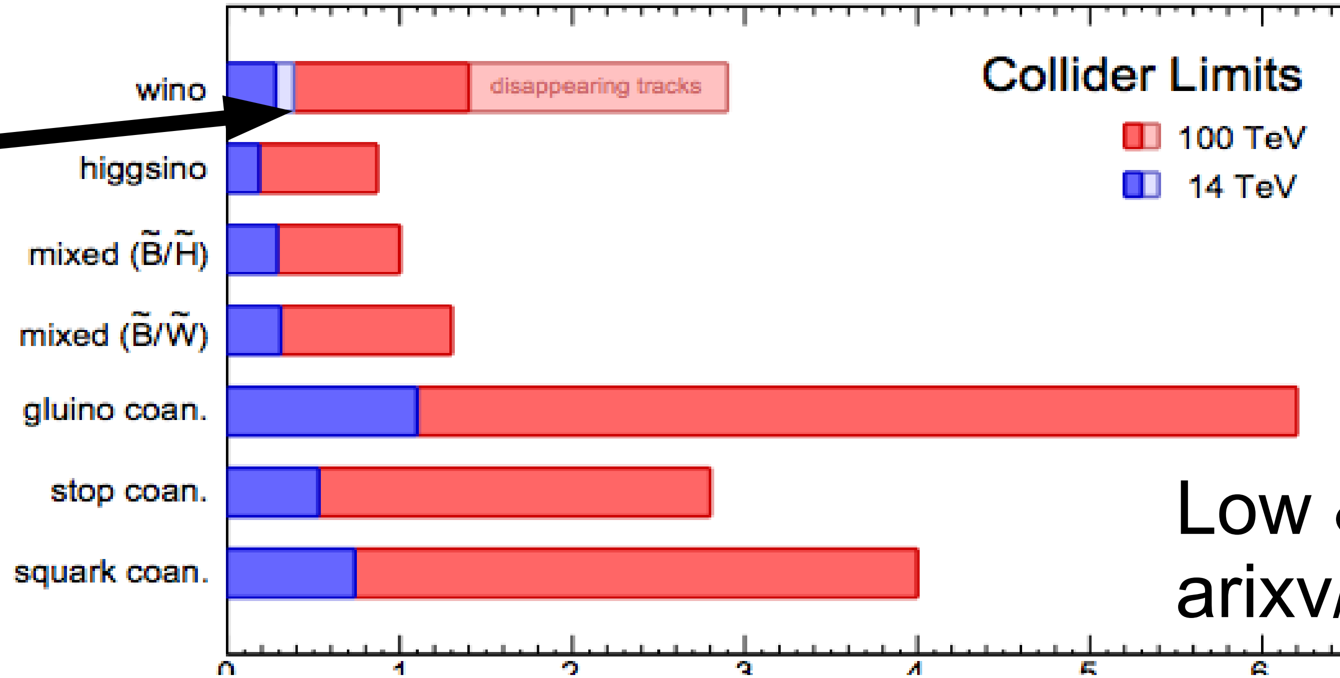
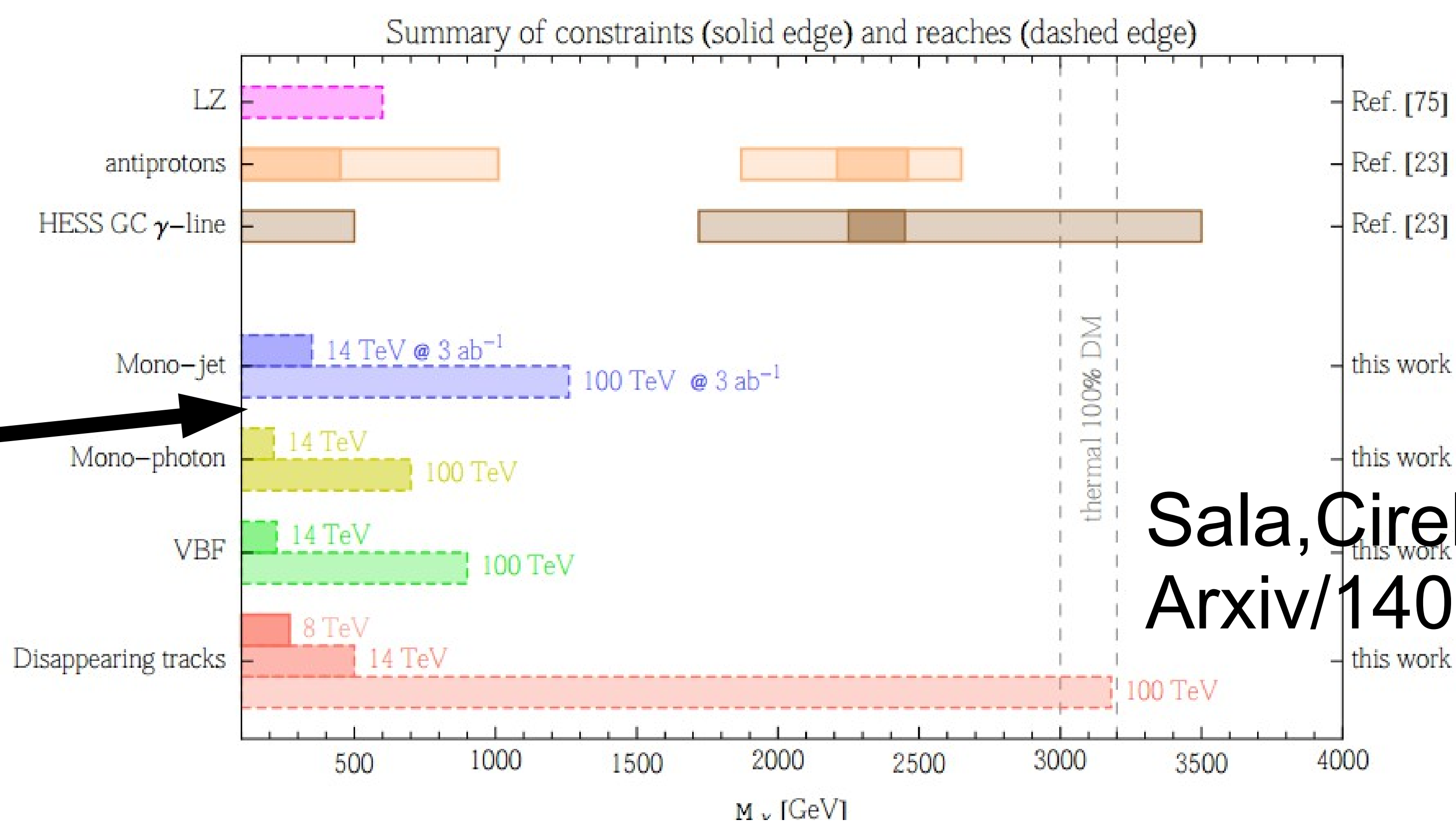
Monojet



Low & Wang
arixv/1404.0682

Monojet



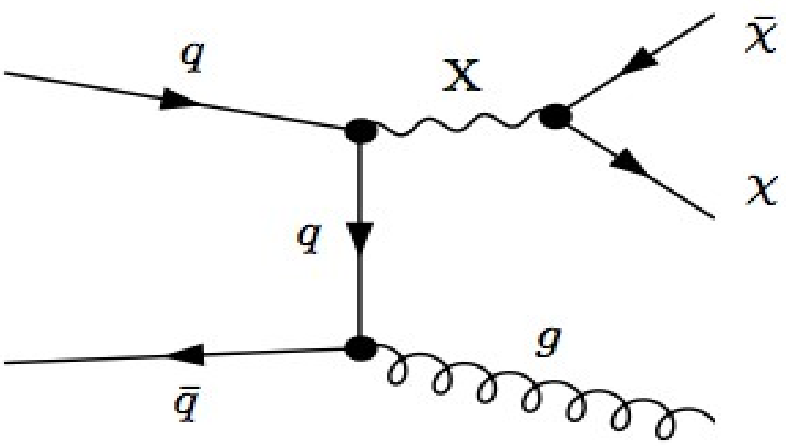
Sala,Cirelli,Taoso
Arxiv/1407.7058

Arxiv/Soon :

P. Harris, V. Khoze, M. Spannowsky, C. Williams

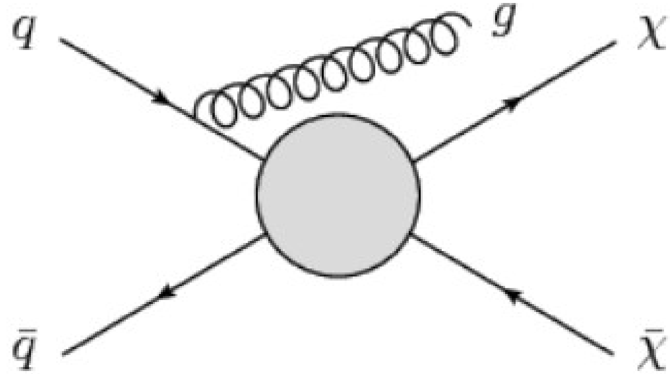
Related Study (not show here):
Arxiv/1503.02931 : Q. Xiang,X. Bi,P. Yin, Z. Yu

Monojet Search

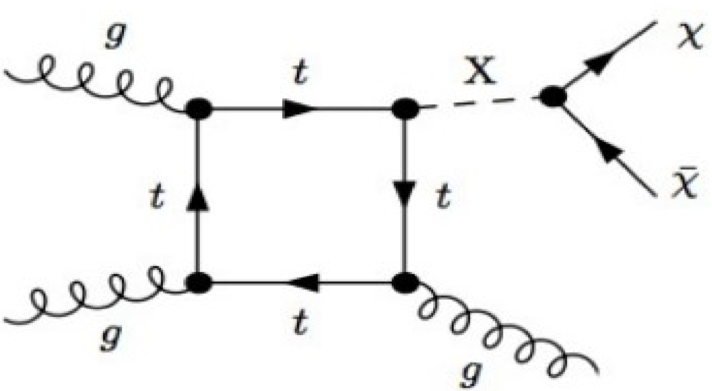


Recent Developments

- Dark matter traditionally classified by
  - EFT
  - Initial state
    - Quark + quark
    - Gluon + gluon
    - ….



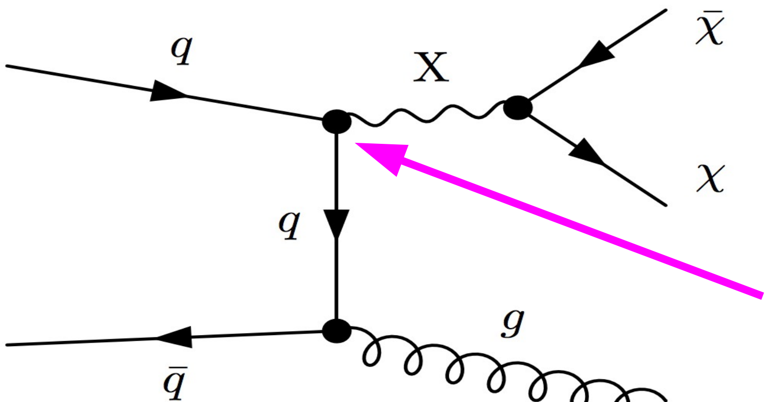
- New idea to classify these as simplified models
  - Scan mediators instead
    - Quark+quark becomes (qq→W'/Z')
    - Gluon+gluon becomes (gg→h/H)
    - ...



What does this mean?

- Two general classes of models
  - Classify by mediator (X)

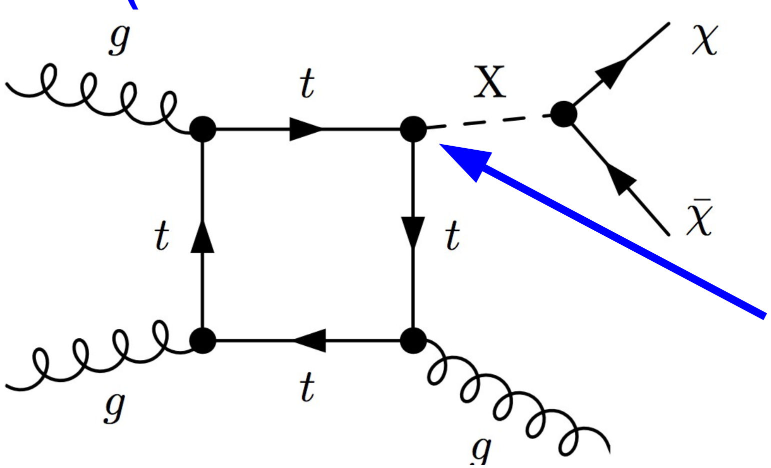
EWK-like (Vector/Axial)



Looks & feels like Z+j

Vec. mediator couples to SM with EWK (flavor universal)

Higgs-like (Scalar/Pseudoscalar)



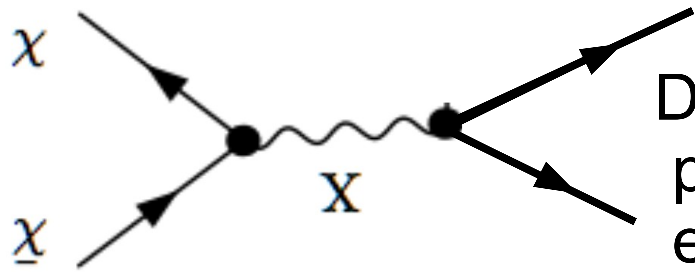
Looks & feels like gluon fusion

Scalar mediator couples to SM with yukawa (α mass)

Collider vs the rest of the world

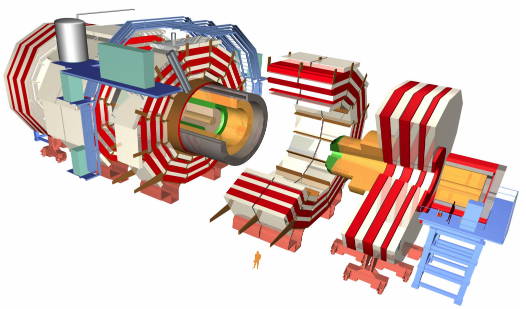
- Simplified models allow us to compare

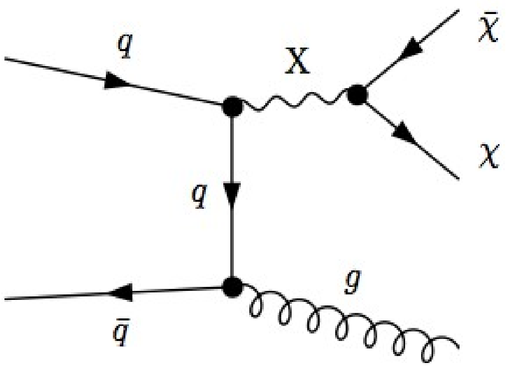
Indirect Detection



Dark matter annihalates produces photons... eventually

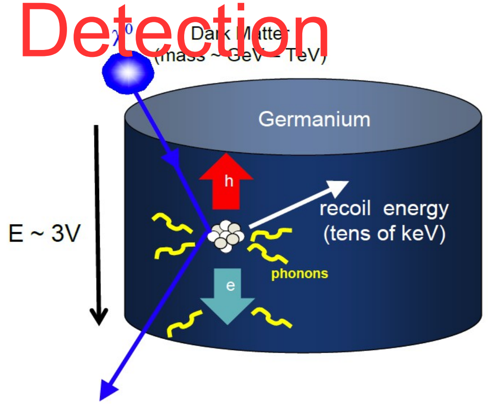
Colliders

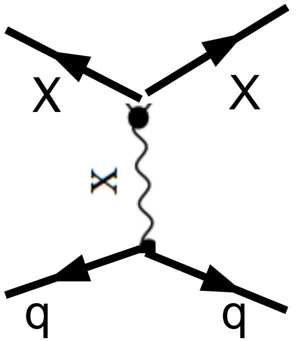




Produce mediator produce dark matter

Direct Detection





Dark matter scatters
Leaves recoiling nucleus

Monojet and Simplified Models

Vector (spin-independent)

$$g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi$$

EWK style coupling
(flavor universal)

Axial (spin-dependent)

$$g_{\mathrm{DM}} Z''_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$

EWK style coupling
(flavor universal)

Scalar

$$g_{\mathrm{DM}} S \,\bar{\chi}\chi$$

Yukawa style coupling
(Mass based coupling)

Pseudoscalar

$$g_{\mathrm{DM}} P \,\bar{\chi}\gamma^5 \chi$$

Yukawa style coupling
(Mass based coupling)

Strategy

- Compare increase in exclusion range w/14 TeV
- As a benchmark :
  - Use CMS monojet analysis @14TeV as benchmark
  - Run this for 1 ab^{-1}
    - Take scalar+j or scalar+jj dark matter as base
      - MCFM for 1 jet and VBF@NLO for 2jet (finite mass in the loop)
  - **Benchmark analysis can futher be optimized**
    - No rescanning done
- Future detector :
  - Use CMS resolution
  - Full analysis @100 TeV
  - Re-scan all the cuts and run the analysis

Monojet vs Disappearing tracks

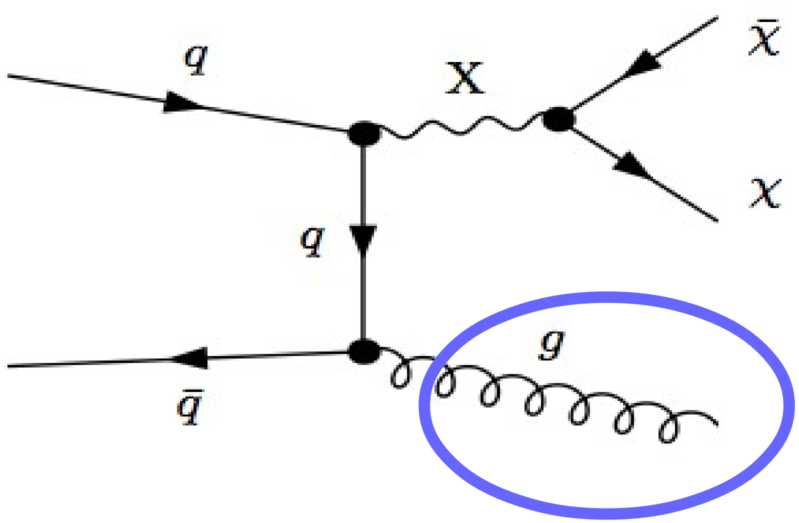
Procedure:

Monojet Analysis

MET > X
Remove QCD → Remove Leptons → Select Jet → Suffer

Select Jet → Find disappearing tracks
Remove all background

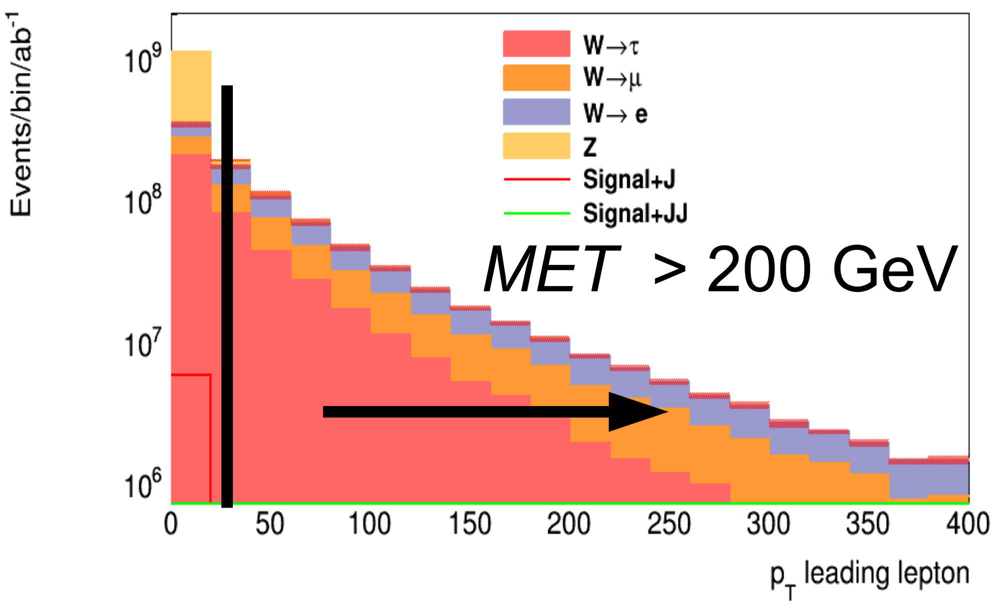
In monojet we can only tag ISR jet



Disappearing track

Next Step : remove leptons

- Standard model backgrounds with real *MET*
  - *W→lv* : Identify events with a lepton if we see it
  - *Z→vv* : No way to tag this without *MET*



Loose id effective lepton veto

Can reduce W by 70%

With ATLAS or CMS we can identify :

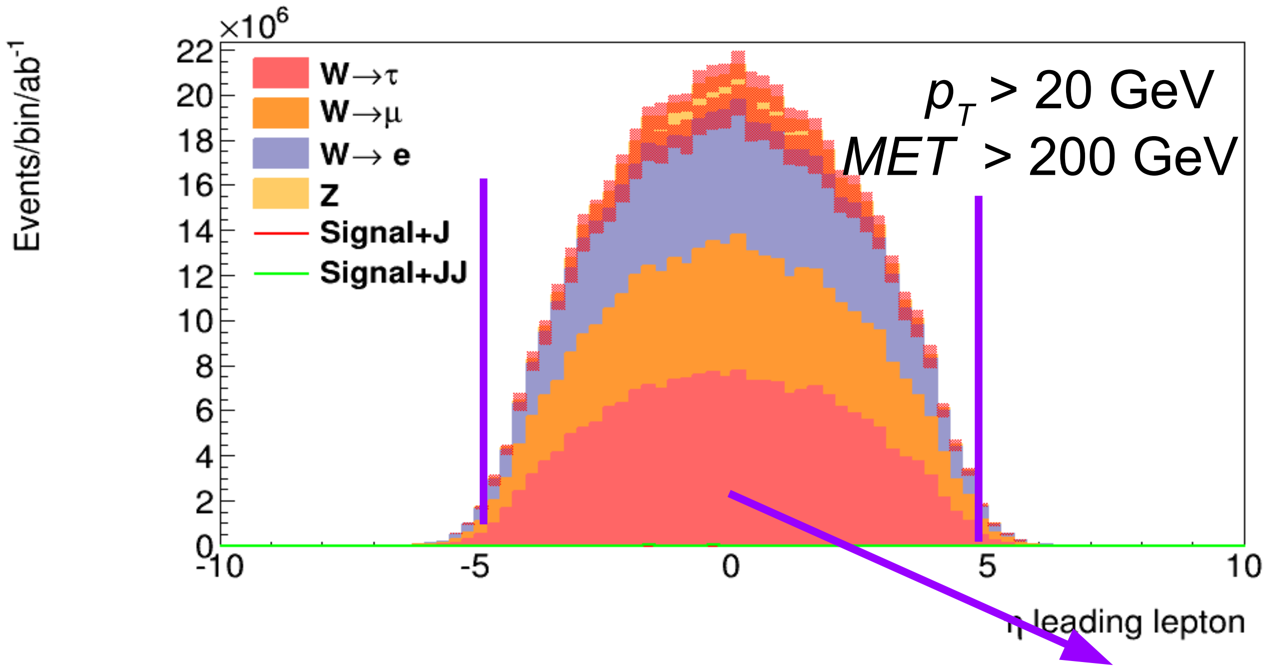
Muons with p_T > 10 GeV 96% Efficiency

Electrons with p_T > 15 GeV 92% Efficiency

Taus with p_T > 15 GeV 85% Efficiency

Arxiv/Soon
PH,V. Khoze,C. Williams,M.Spannowsky

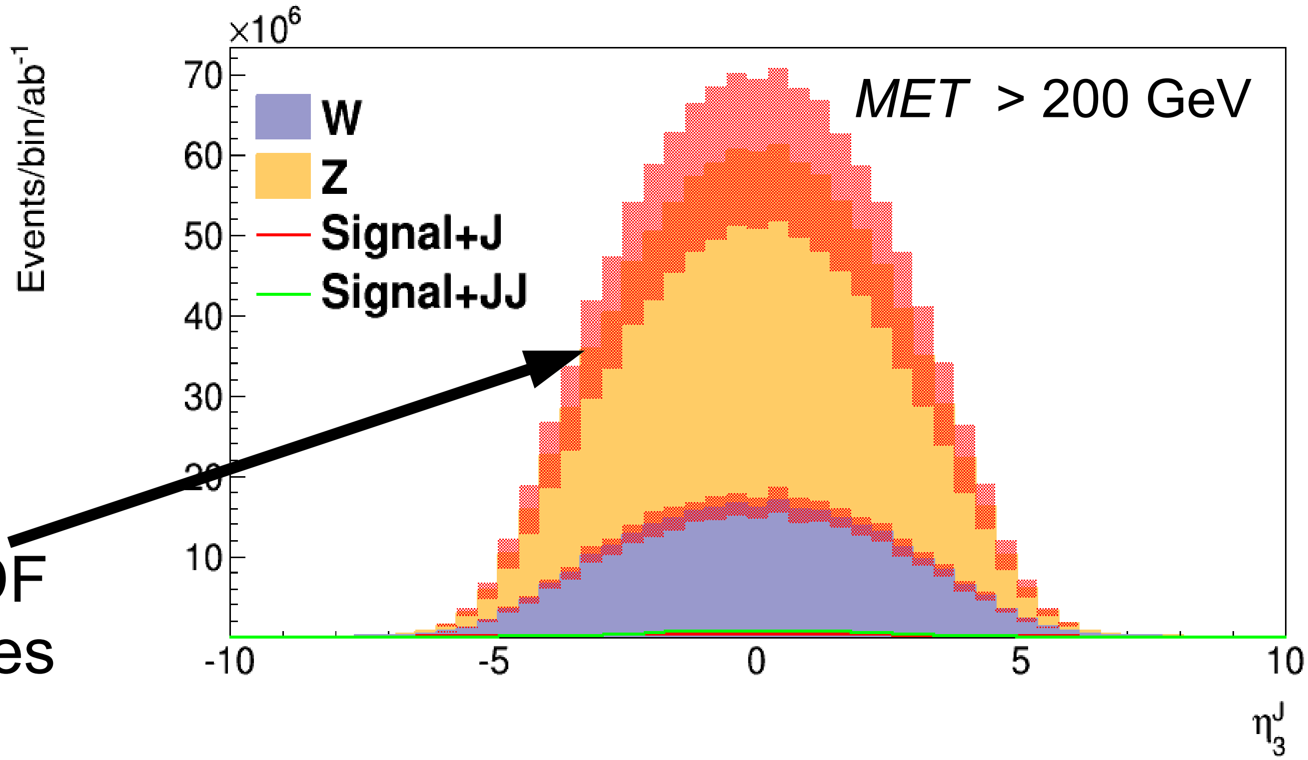
What is the lepton range?



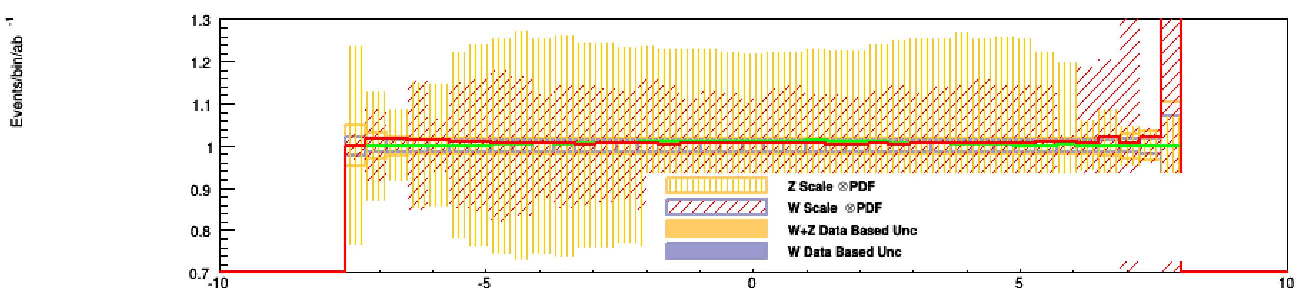
- Leptons range out to an η value of $|\eta| < 5.0$
  - Designing a detector to identify η out to this range
- Samples/Info :
  - NNPDF 3.0 for everything (LO for LO and NLO for..)
  - aMC@NLO NLO 0,1,2 jet for Z+jets (FxFx)
  - aMC@NLO NLO 0,1 jet for W+jets (FxFx)

After Lepton removal

- Next step is to select a jet



Scale & PDF Uncertainties

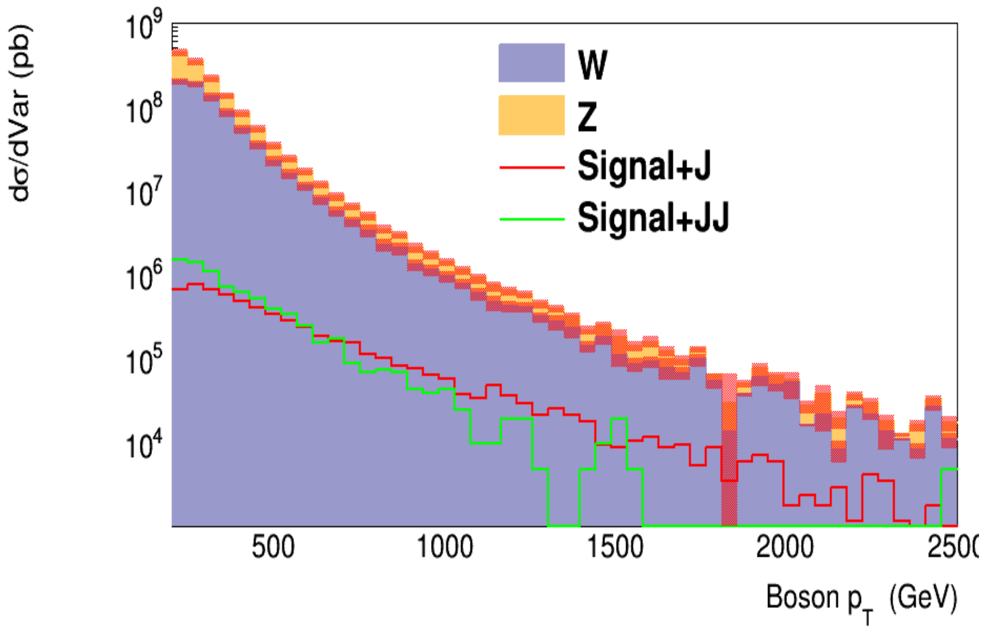


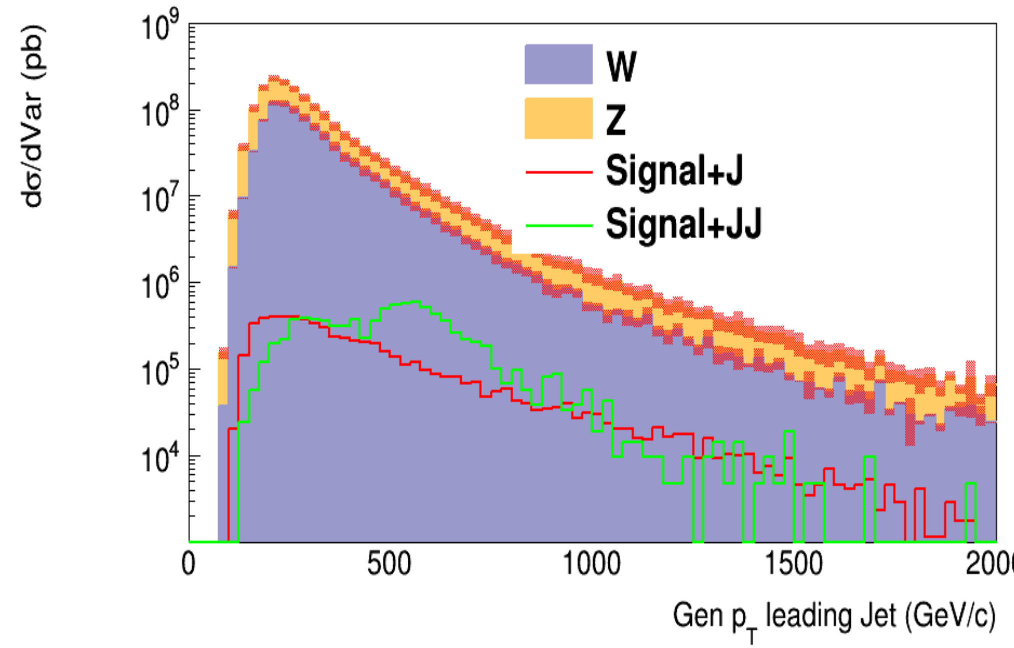
Jets go as far as $|\eta| < 7.0$ in

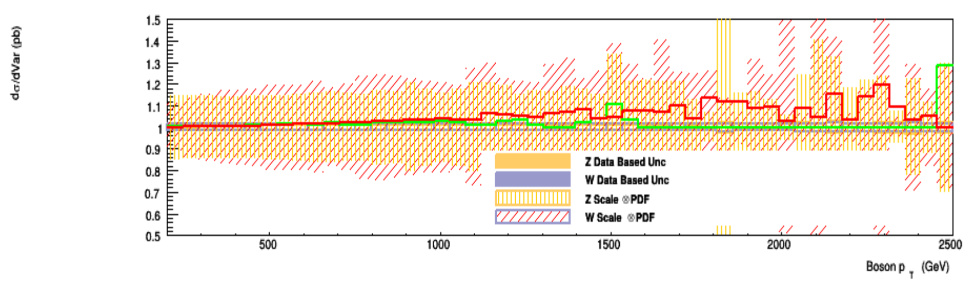
Arxiv/Soon
PH,V. Khoze,C. Williams,M.Spannowsky

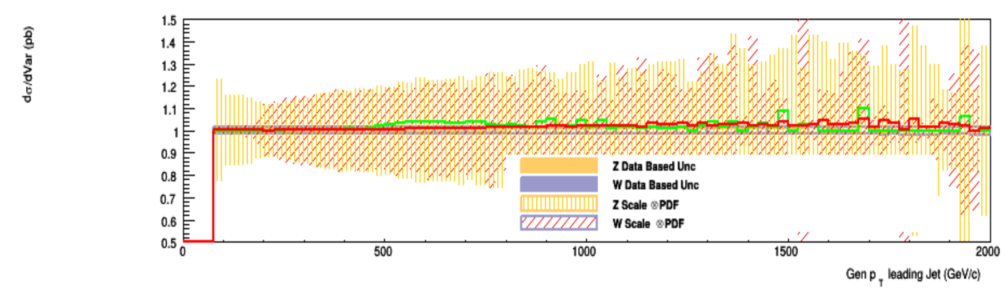
Effect of Jet/*MET* smearing

- Pre detector effects



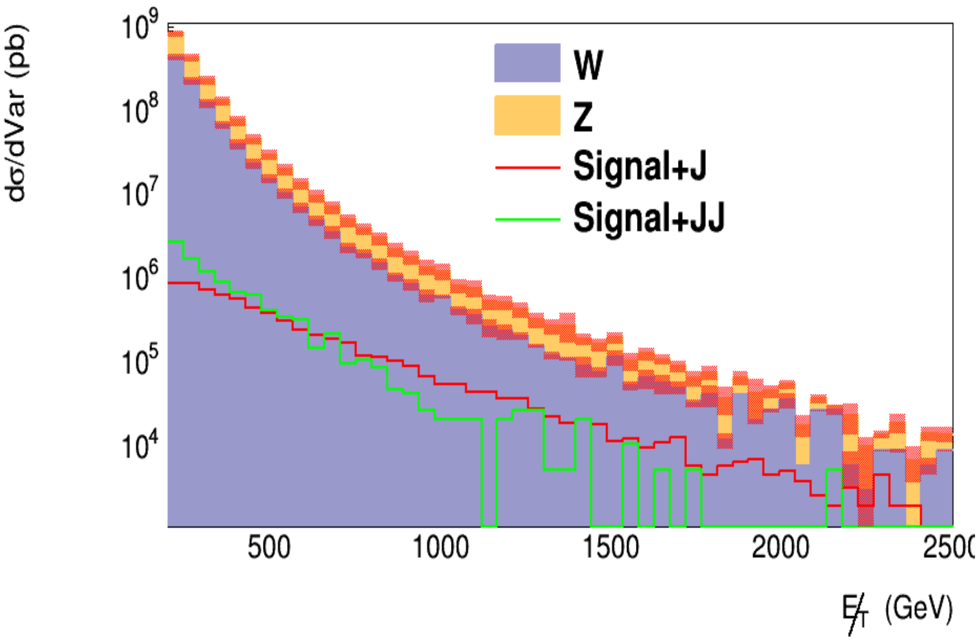


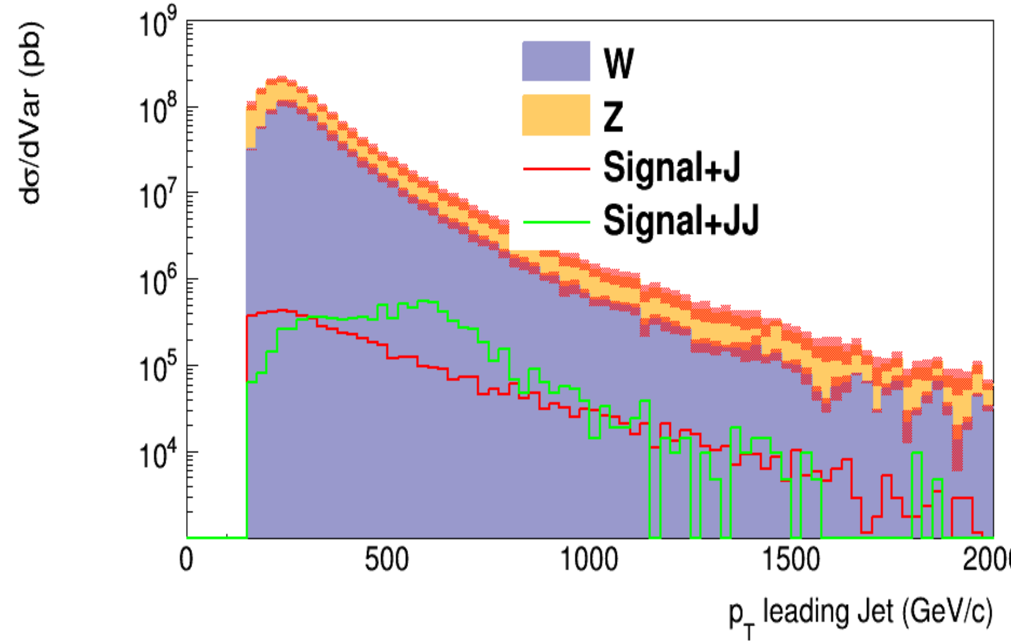


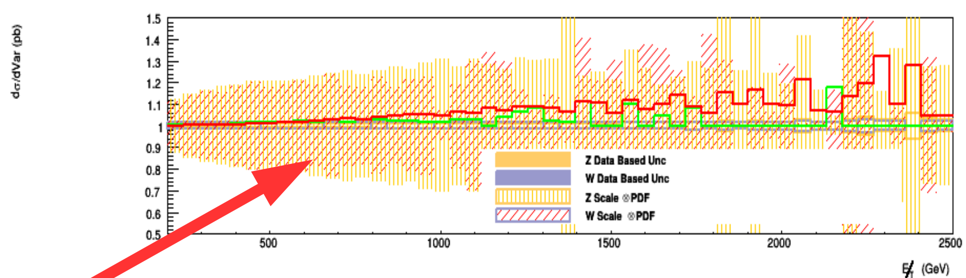


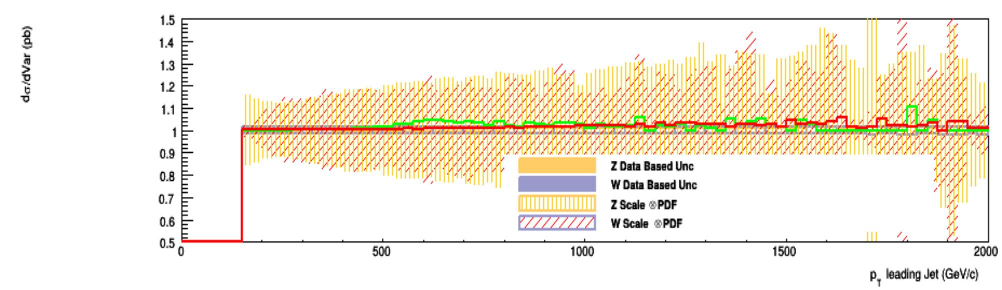
Effect of Jet/*MET* smearing

- Post detector effects







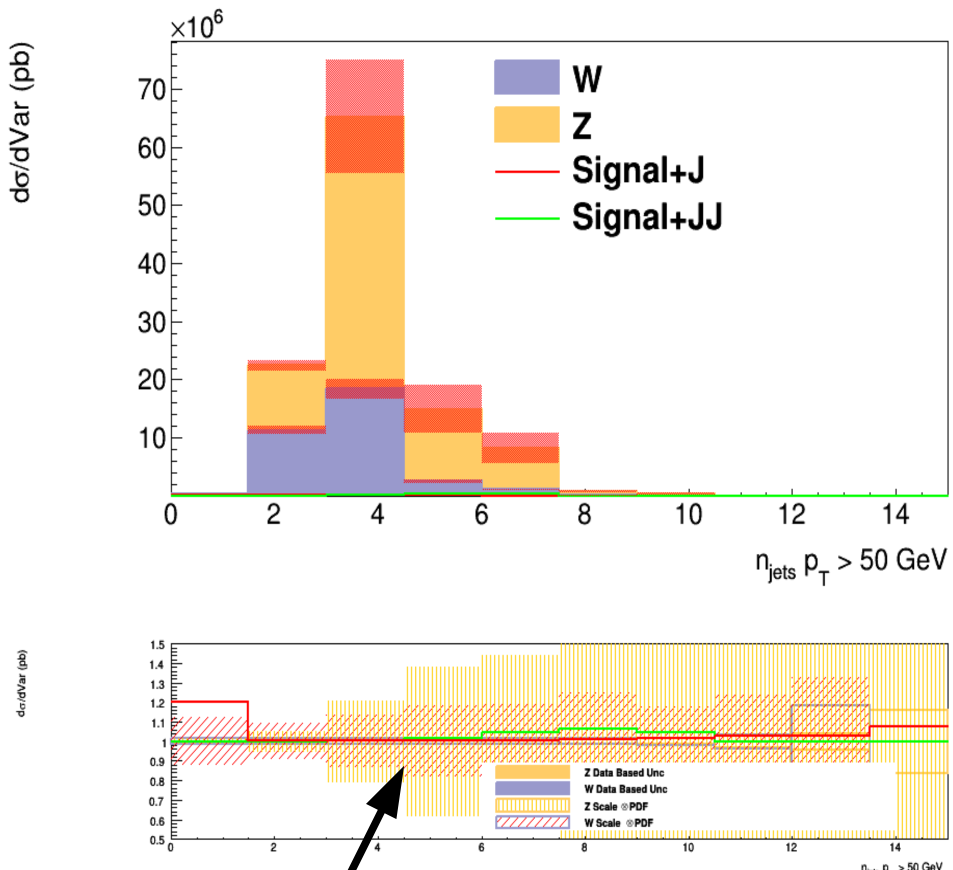


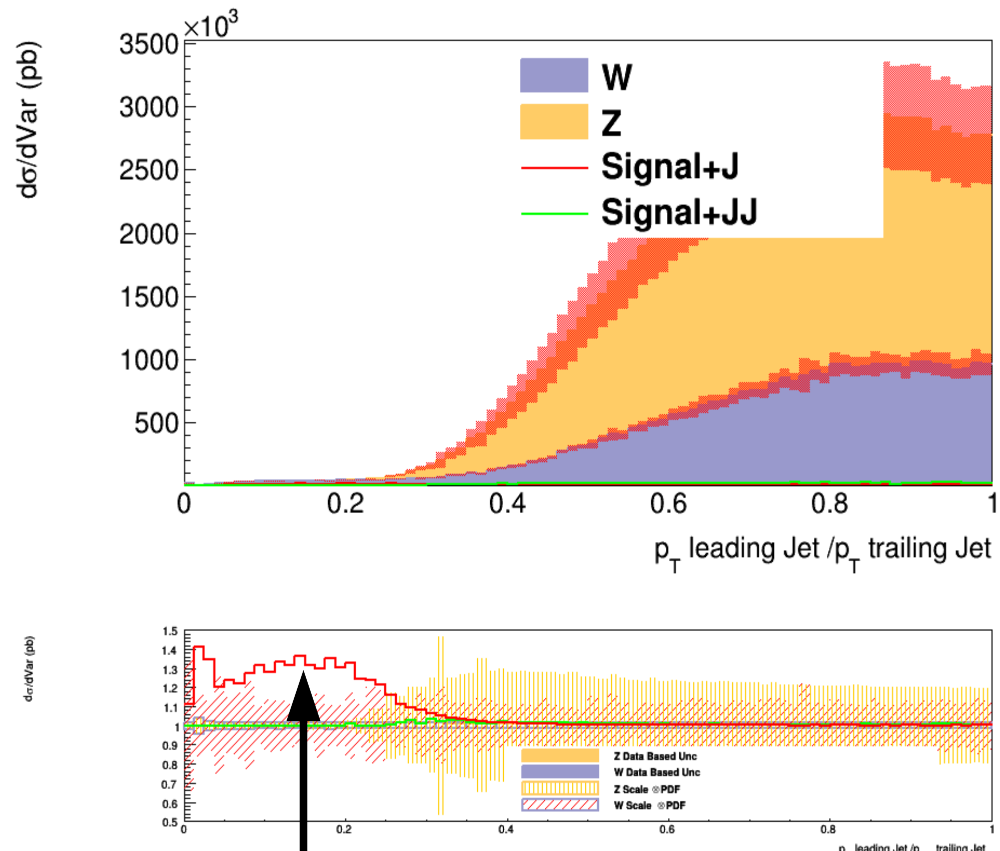
MET resolutions of the scale of LHC

Influence of signal discrimination is minimal

Selecting on Jets

- Monojet is not a monojet any more
    - Cannot trust 1jet MC (2/3 or … important at 100 TeV)



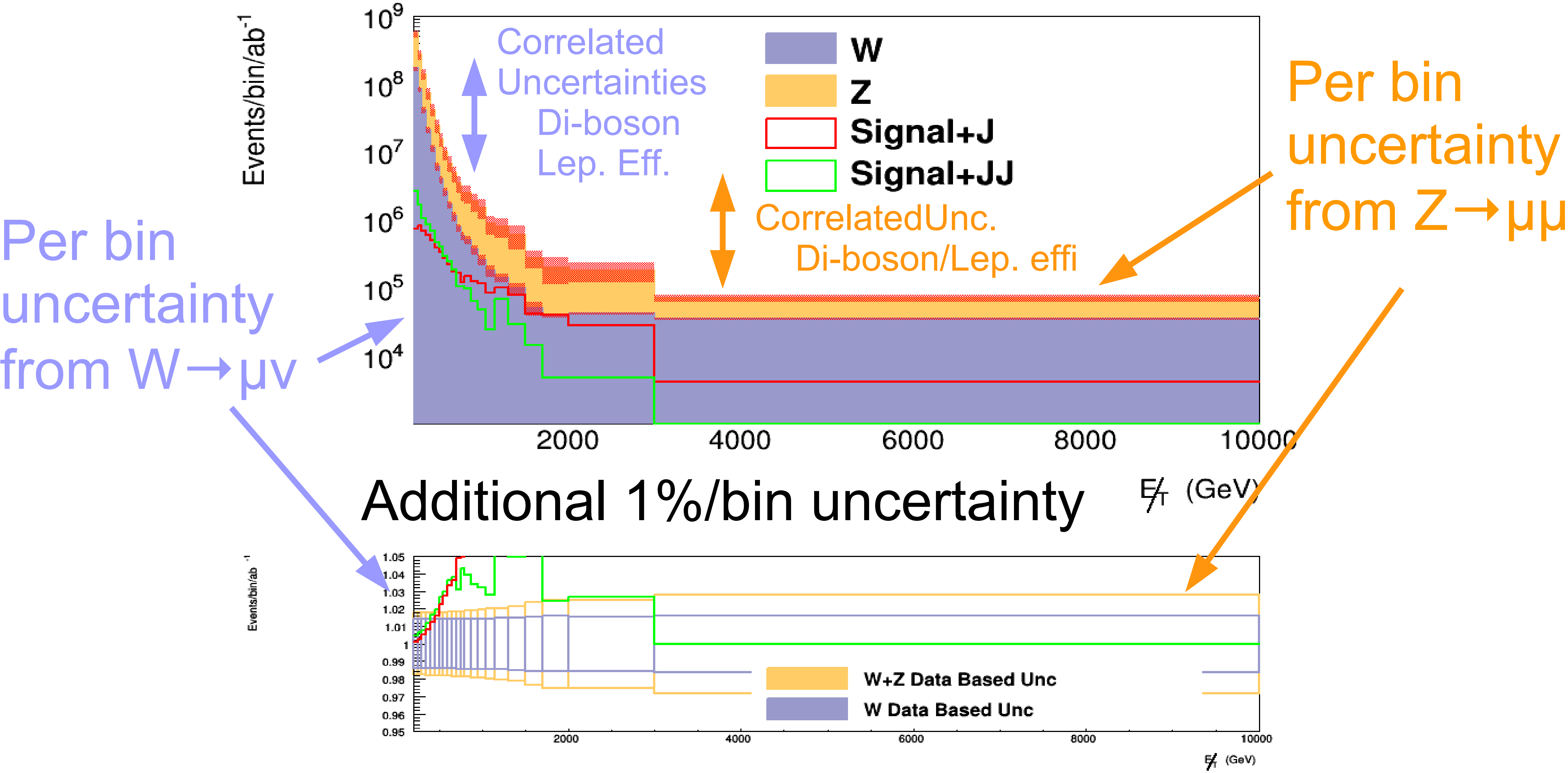


No discrimination in number of jets (also look at the number)

p_T of 2[nd] jet is low wher parton shower used

The Analysis

Perform full shape analysis with binning list below

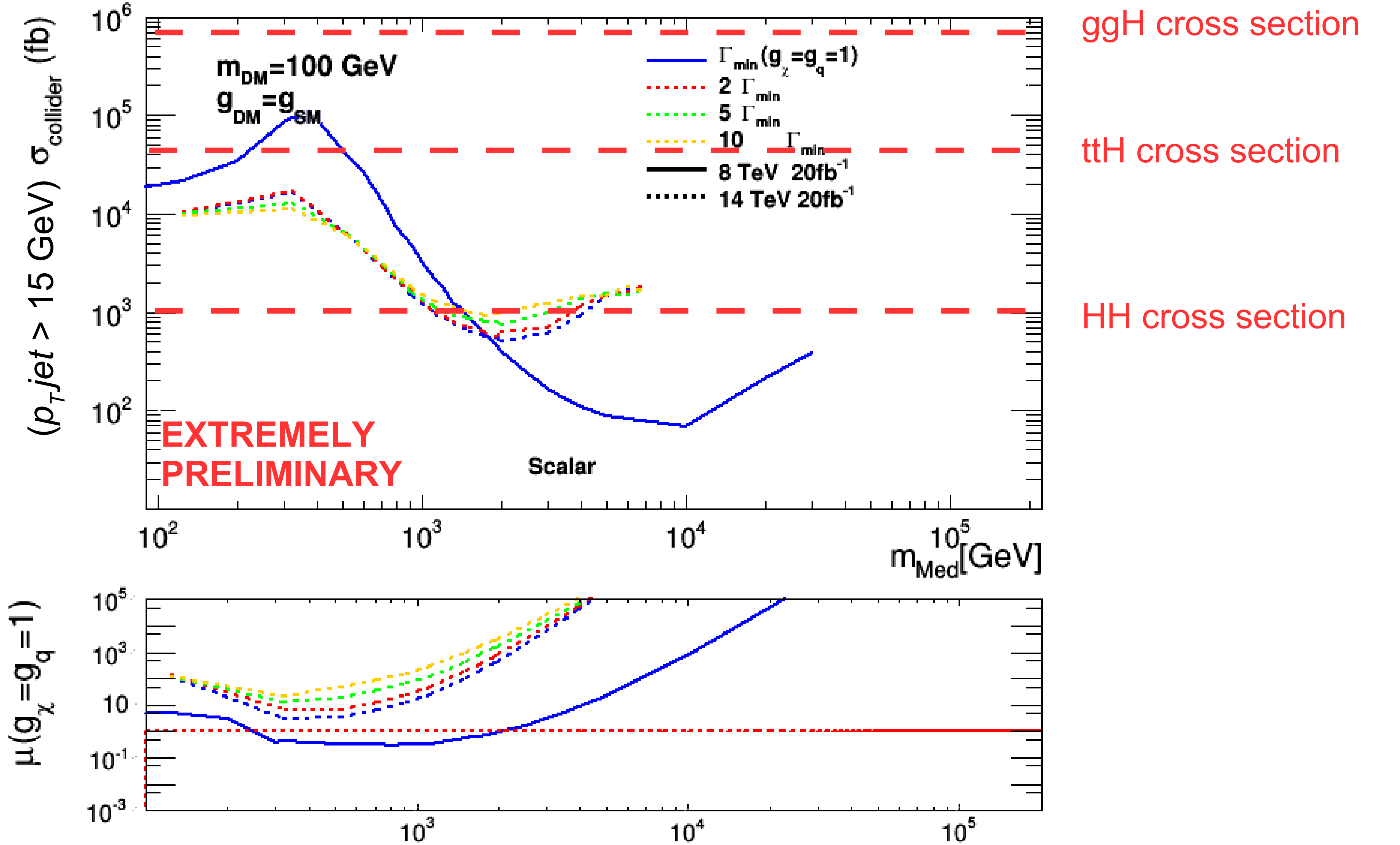


High luminosity Z and W background dominated by : 1% systematic uncertainty

Results

- Inclusive cross section limits

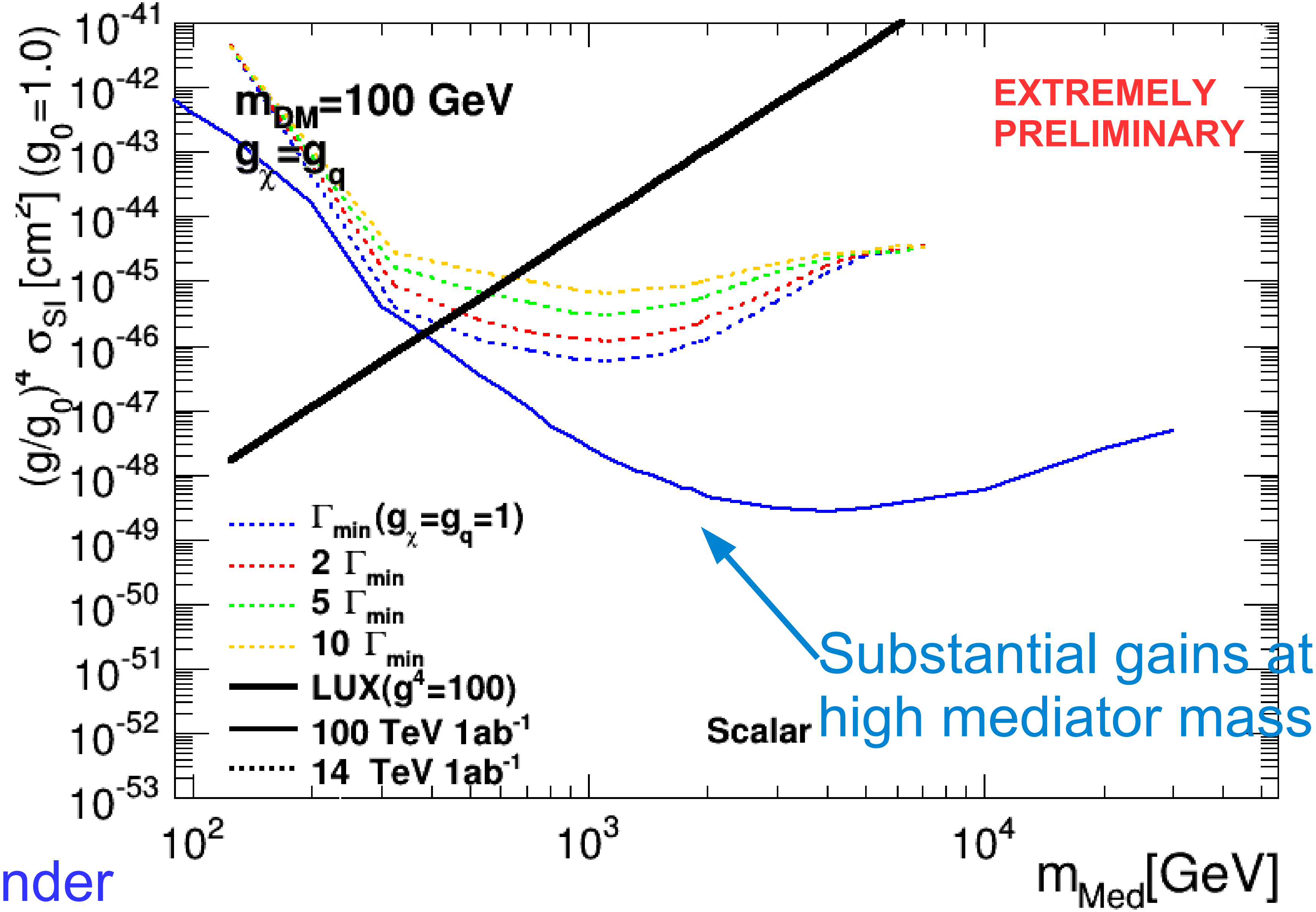
Benchmarks @100 TeV



Note Vector/Axial/Pseudoscalar similar

Results

- Inclusive cross section limits

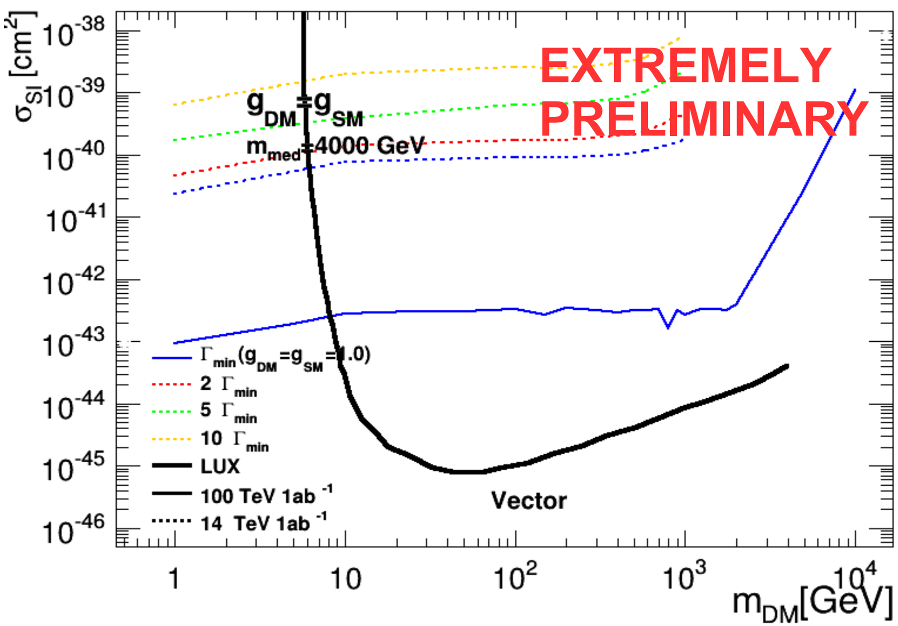


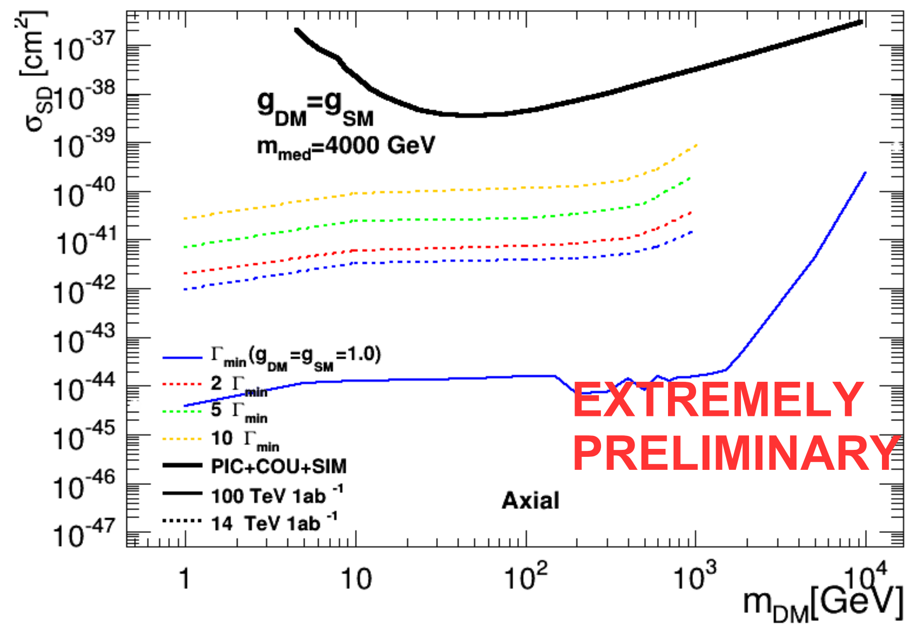
Reminder
(14 TeV needs re-tune)

Note Vector/Axial/Pseudoscalar similar

Comparing with Direct Detection

- Considering first vector and axial mediators

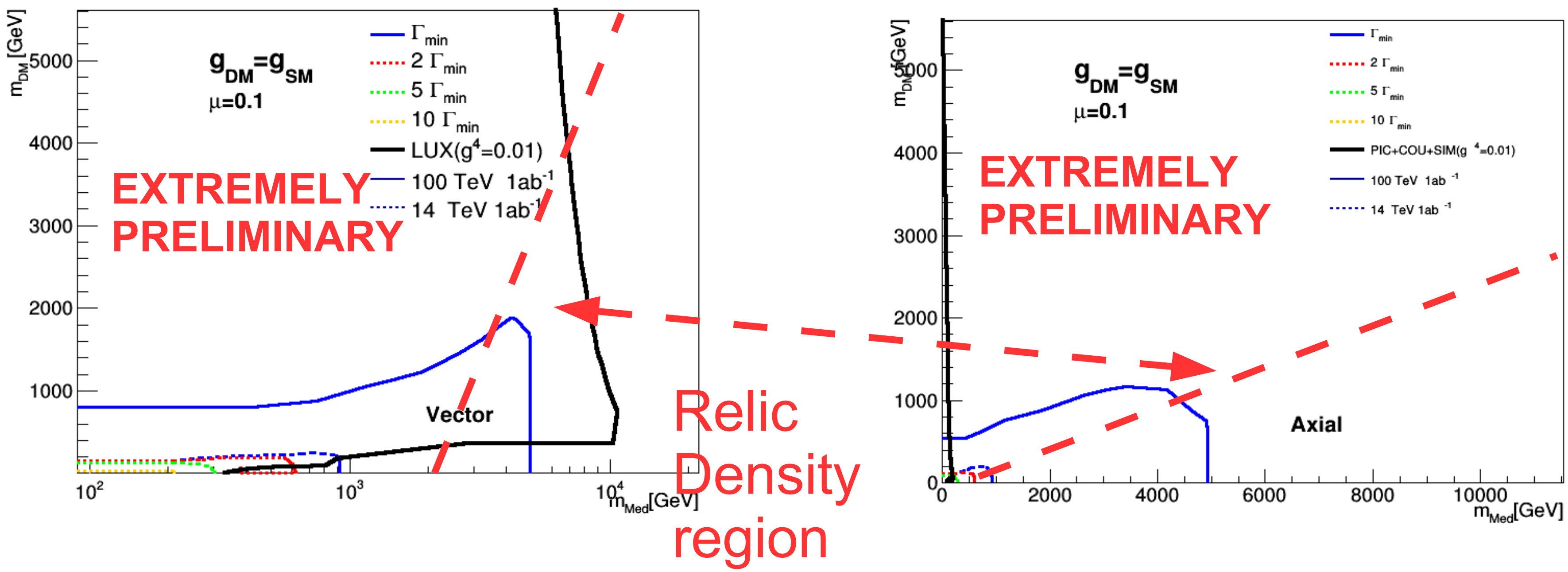




- For vector mediator direct detection still
  - Large improvement is present
  - At high dark matter mass is particularly large

Comparing with Direct Detection

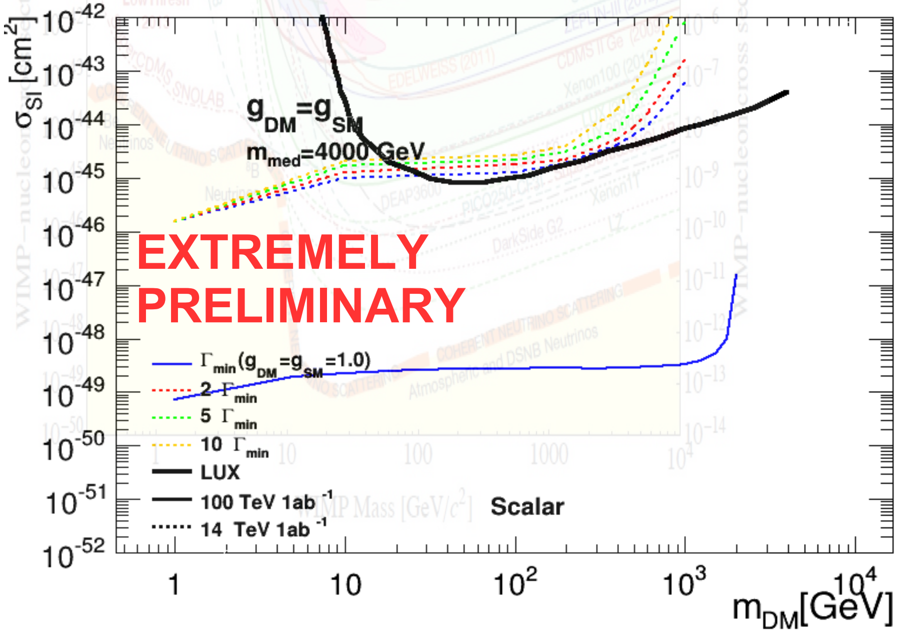
- Considering first vector and axial mediators

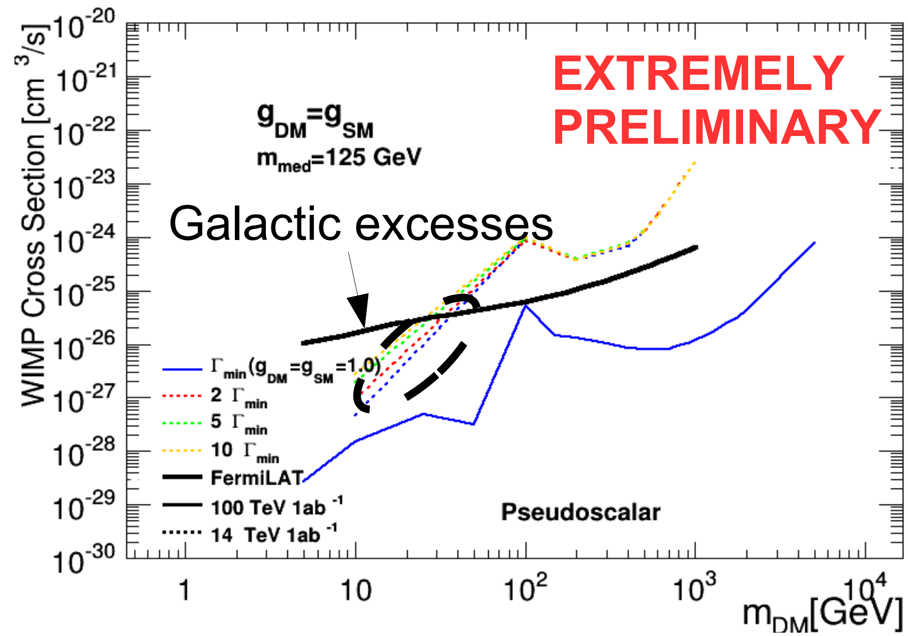


- Some headway into the simplified models
    - Clear coverage up to mediators of 5 TeV
    - Spin-dependent measurements much less sensitive

Comparing with Direct Detection

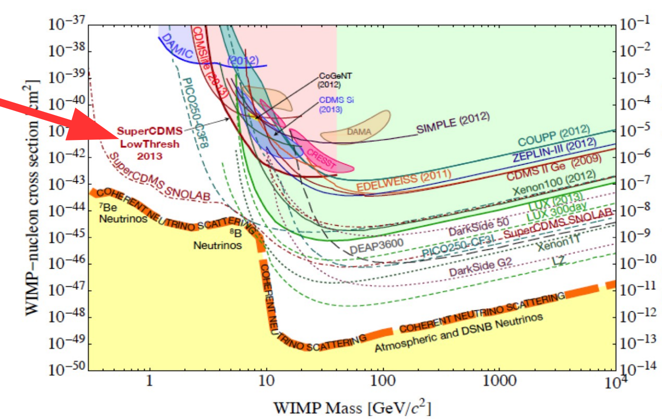
- Considering first vector and axial mediators





Scalar is beyond the neutrino wall

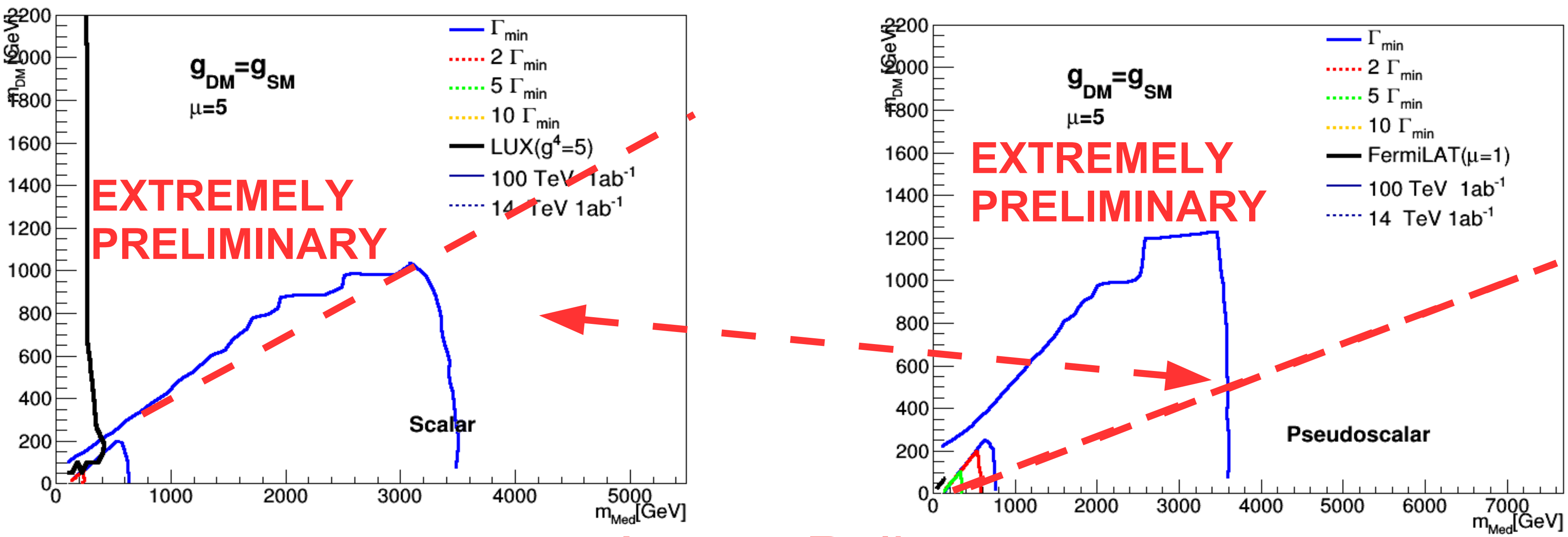
Pseudoscalar well beyond ID bounds



Collider appears to be most sensitive

Comparing with Direct Detection

- Considering first vector and axial mediators

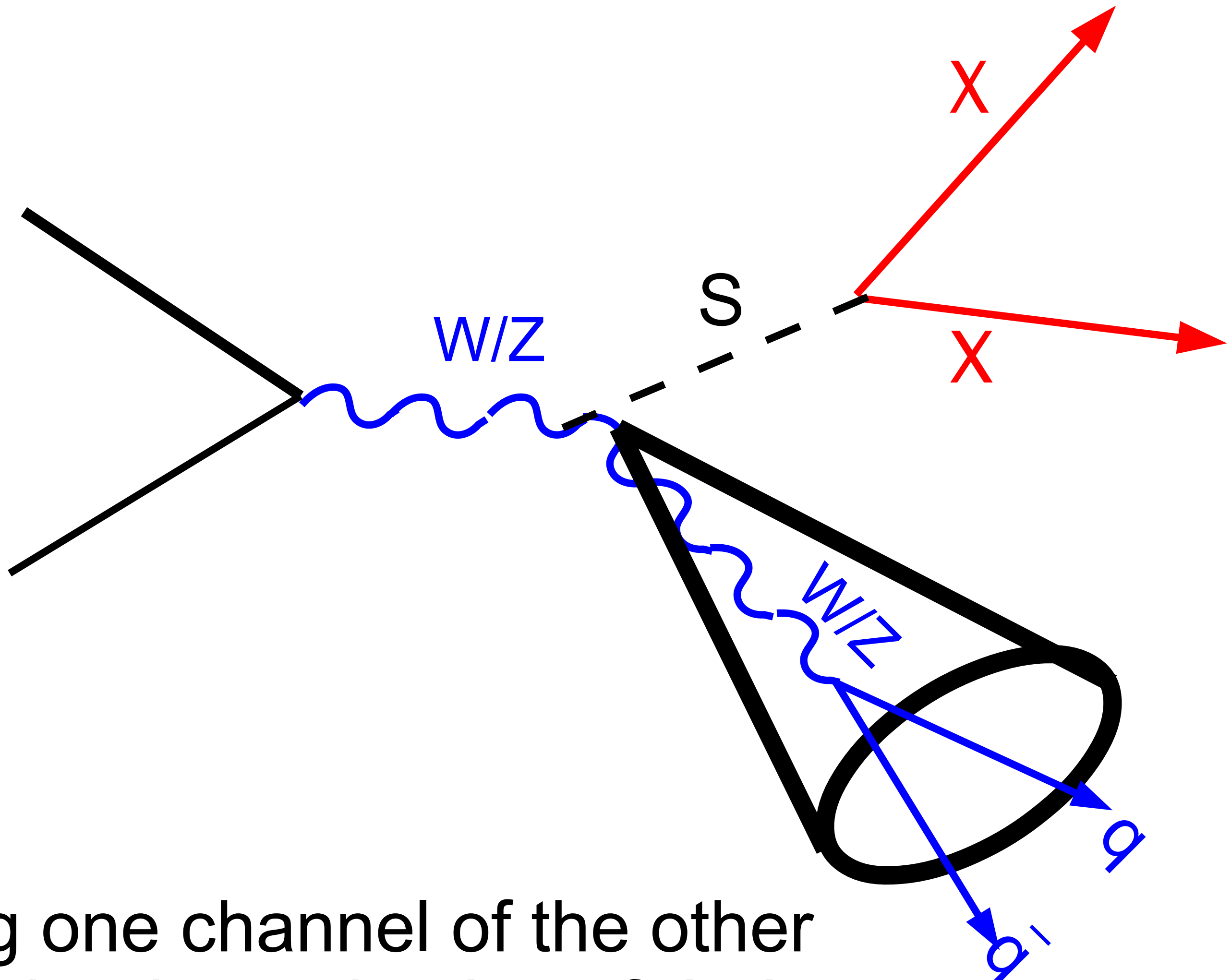


Approx Relic Density region

- Reach for scalar/pseudoscalar similar to V/A
  - Probes mediator in few TeV range with coupling 1

Beyond Ordinary : Monojet

- Mono Ws or Zs and di Top + *MET* critical
  - Both have a boosted final state

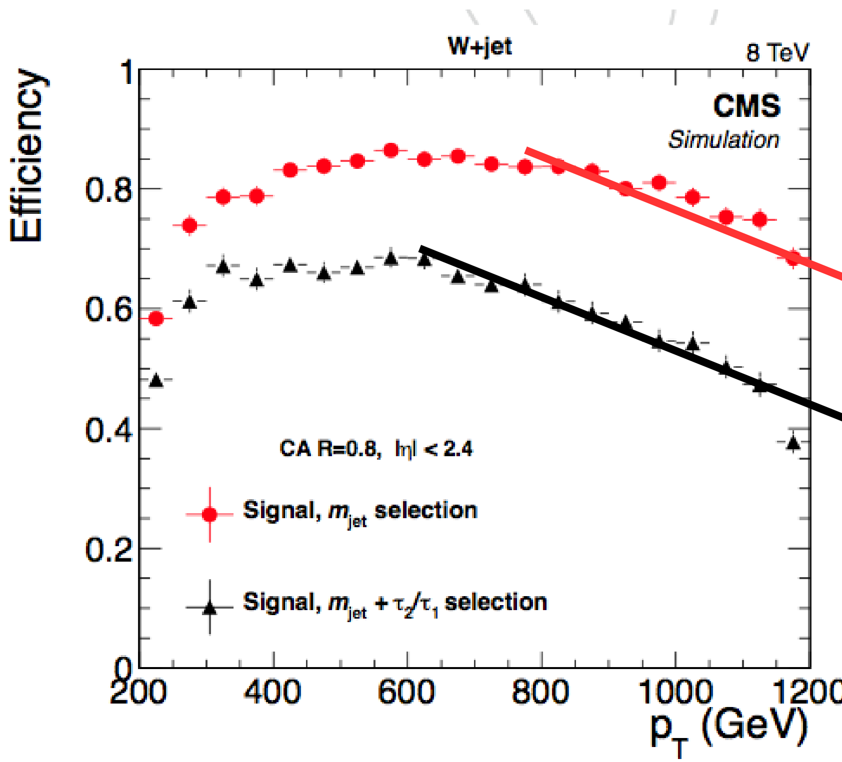


CMS
JME-13-006
JME-14-001

Playing one channel of the other
allows the determination of dark matter properties

V-tagging at High p_T

- Lets recount a story from last year



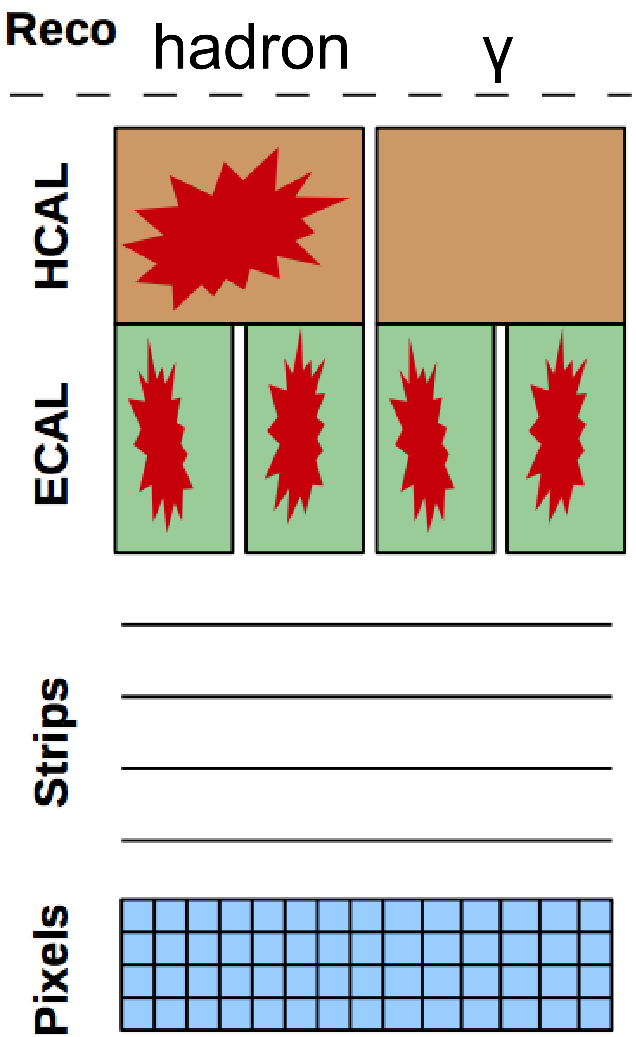
In CMS at 8 TeV
Boosted V Tagging Efficiency
starts to drop down

Effect is substantial at high p_T

Was a major concern from Run II jet reconstruction

What did we do about this?

- First step was to minimize cluster size
  - Utilize the maximal calorimeter granularity



What did we do about this?

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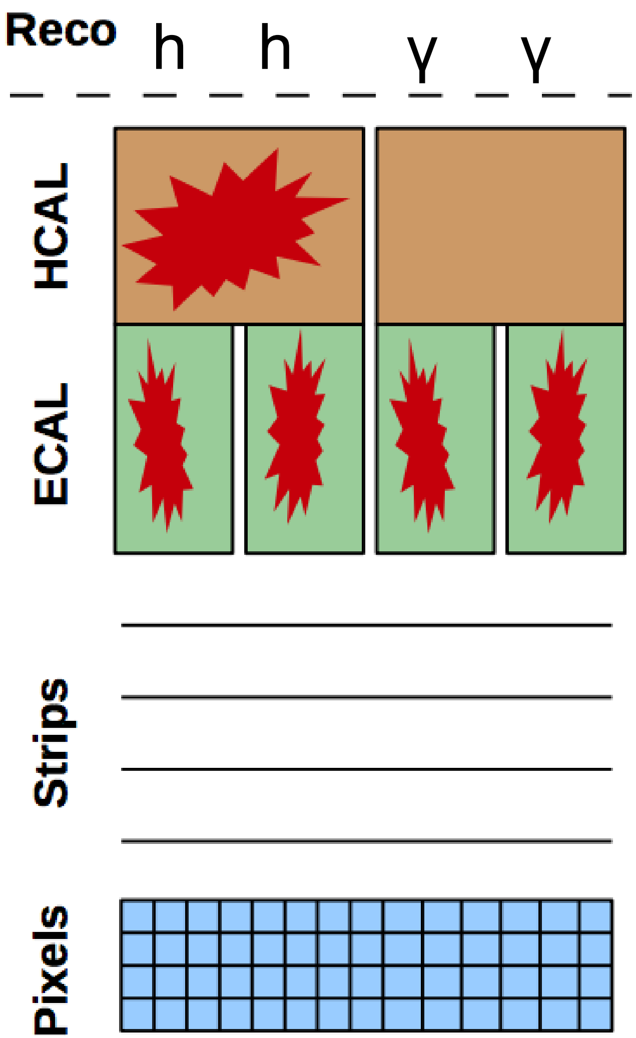
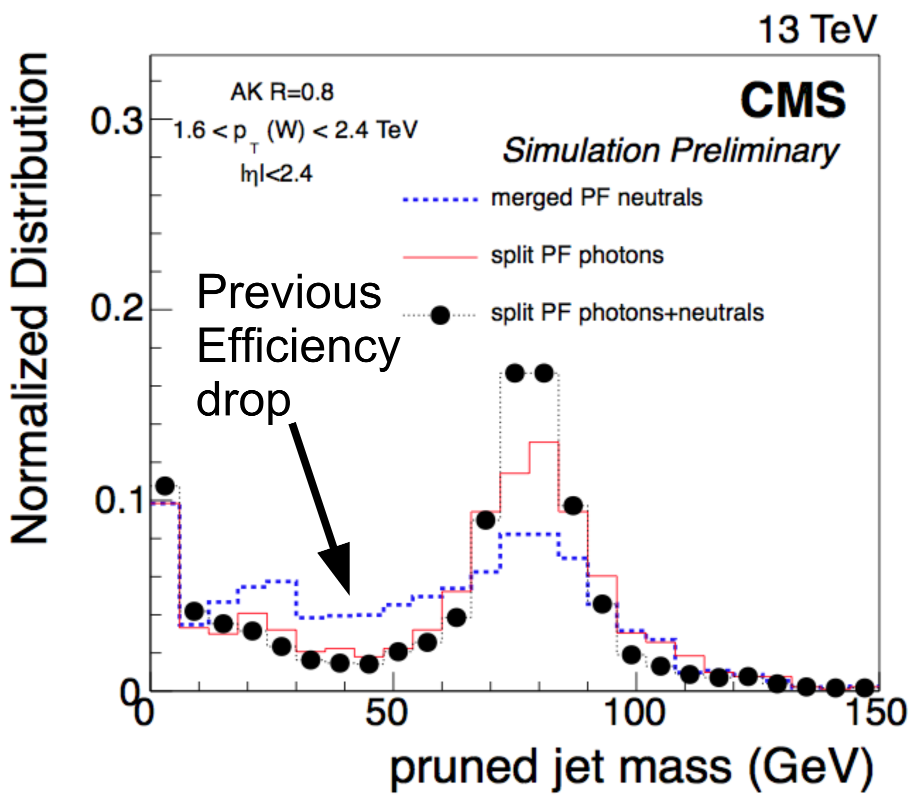


- Assign # of photons by # ecal clusters
- Split hadrons by # ecal clusters



What did we do about this?

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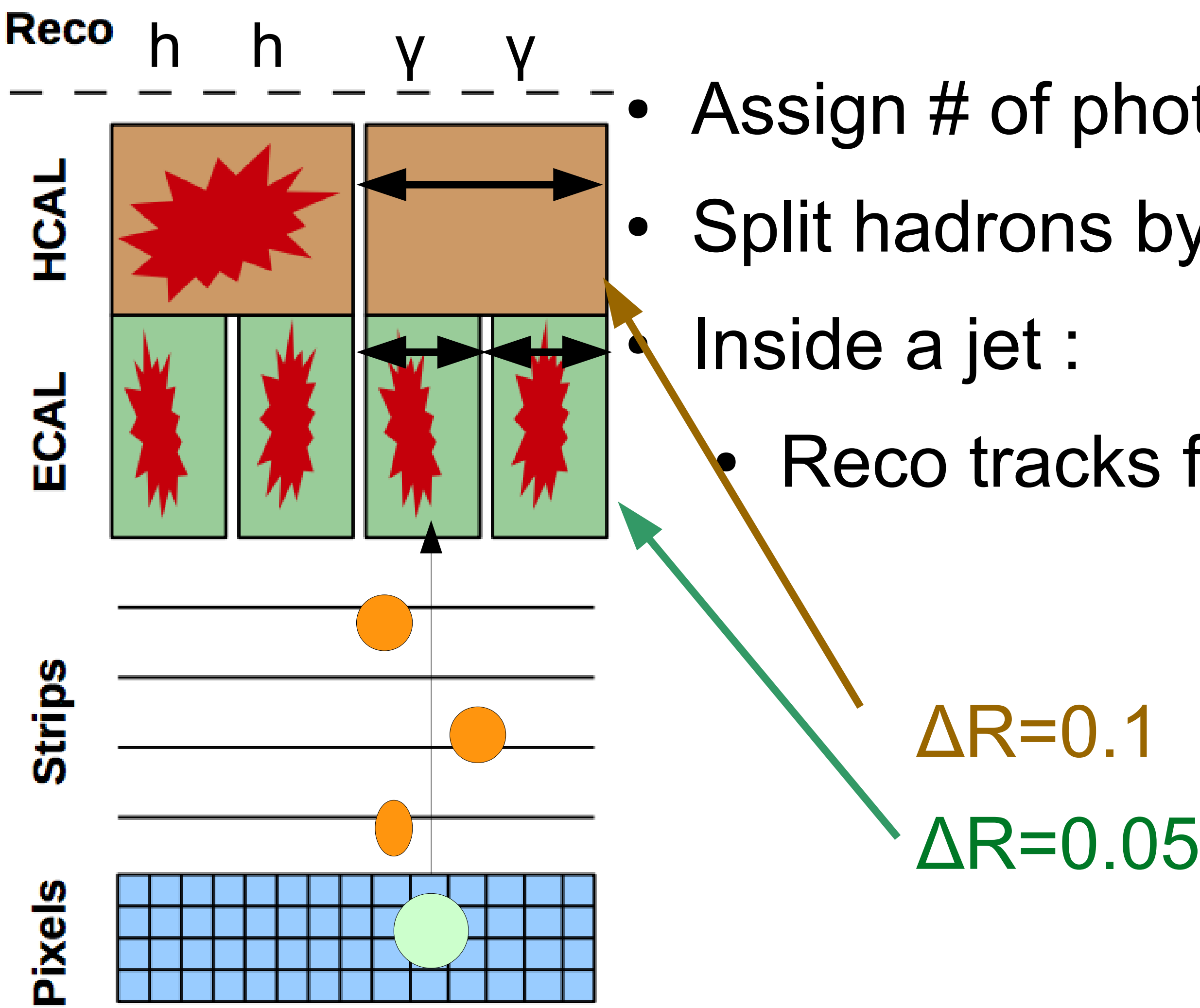
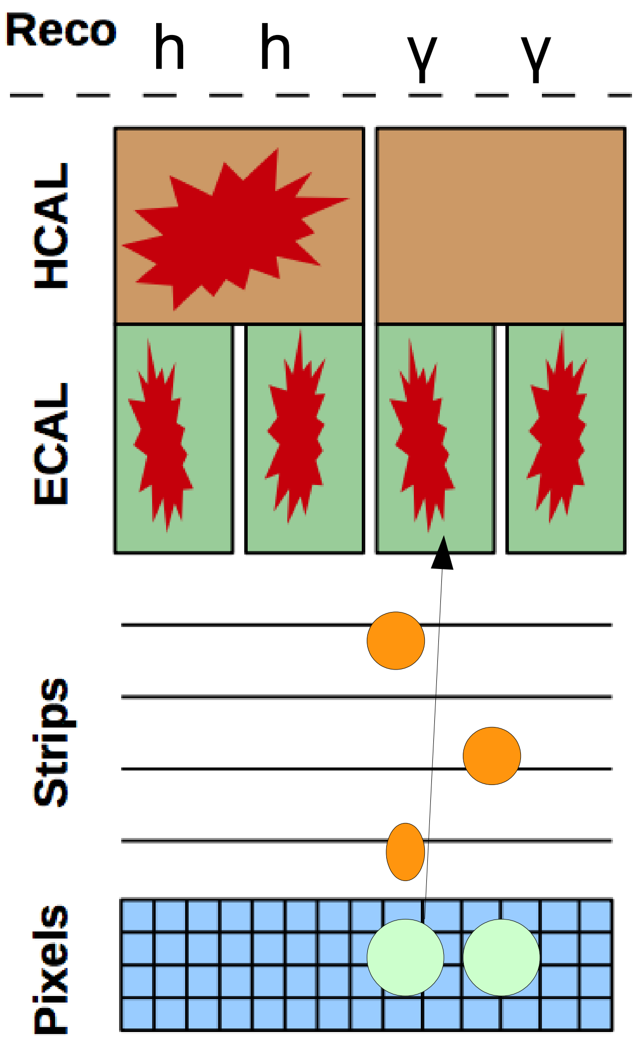


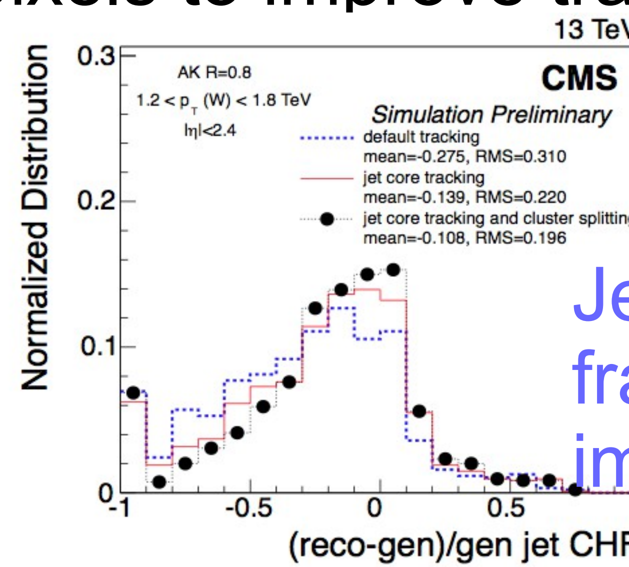
- Assign # of photons by # ecal clusters
- Split hadrons by # ecal clusters
- Inside a jet :
  - Reco tracks from residual hits

What did we do about this?

- First step was to minimize cluster size
  - Utilize the maximal calorimeter granularity



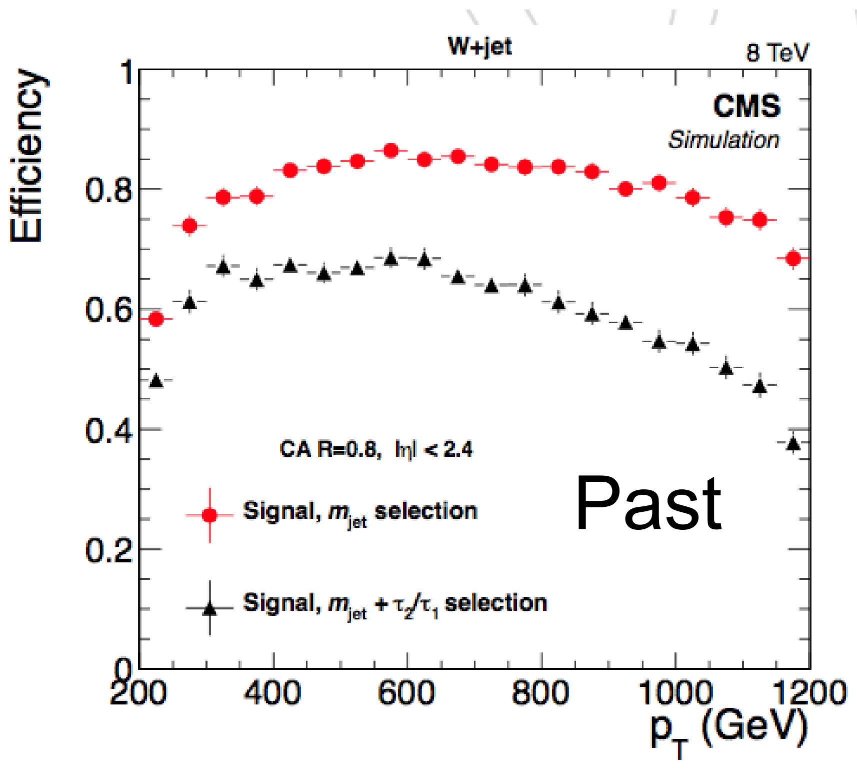
- Assign # of photons by # ecal clusters
- Split hadrons by # ecal clusters
- Inside a jet (jet core tracking) :
  - Reco tracks from residual hits
- Split pixels to improve track resolution

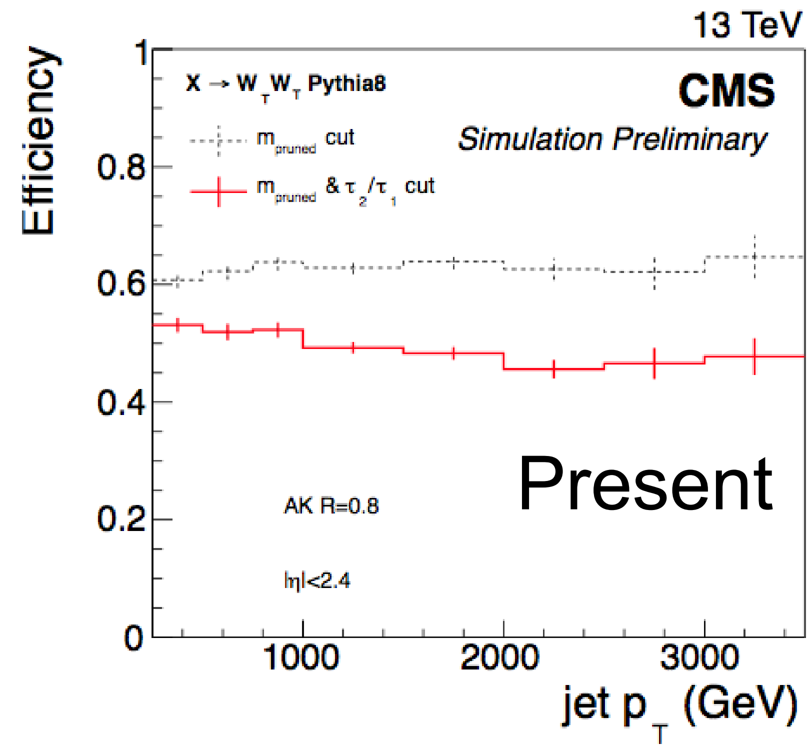


Jet Chaged fraction imporved

V-tagging at High p_T

- Lets recount a story from last year





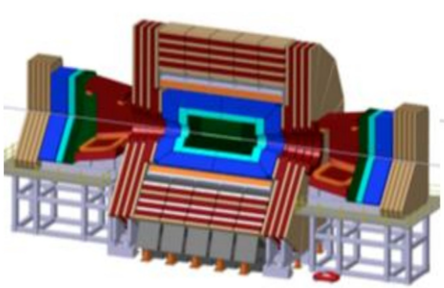
Reconstruction robust up to 4 TeV

Going beyond will be a challenge

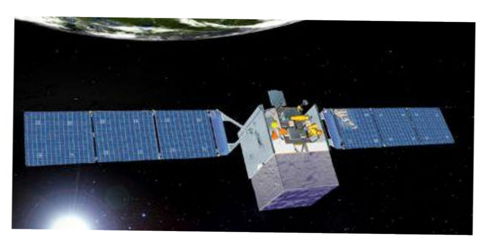
Conclusions

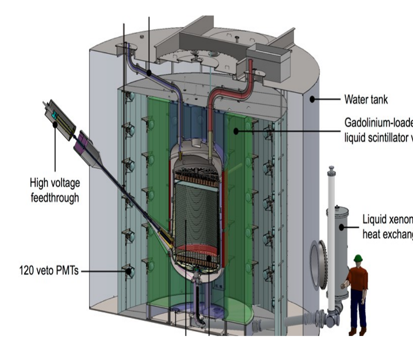
- Detecting dark matter is difficult in some cases
  - Require either a precision detector
  - Suffer from very large backgrounds

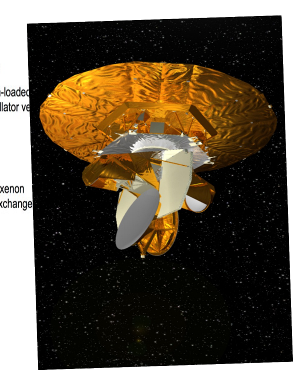
- Collider experiments in the future
  - Can potentially go beyond the neutrino wall
  - Can also extend beyond the cosmic γ rays
    - Need to see how this plays out



VS.







Thanks!

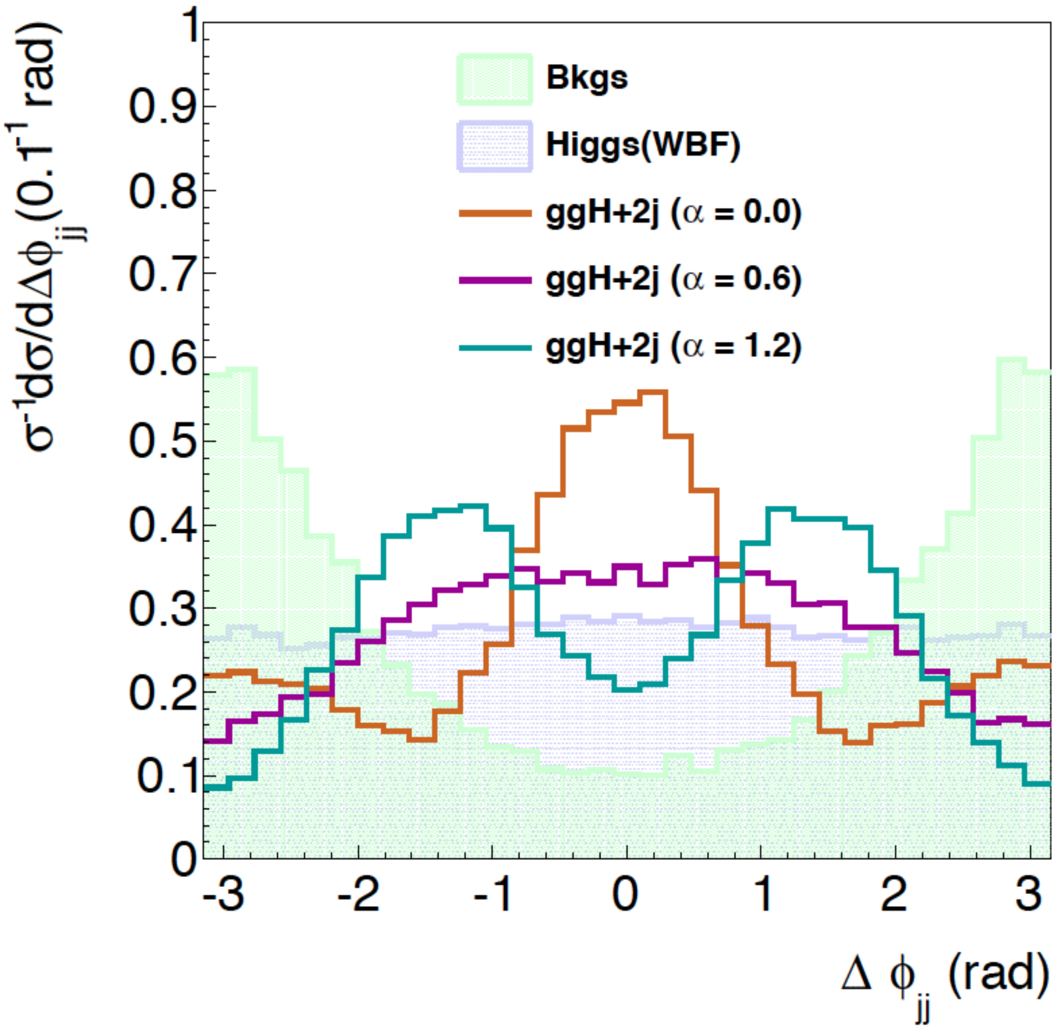
Valya Khoze,Michael Spannowsky,Ciaran Williams
Caterina Dogliani, Antonio Bovea
Filip Mortgaart
Liantao Wang, Matt Low

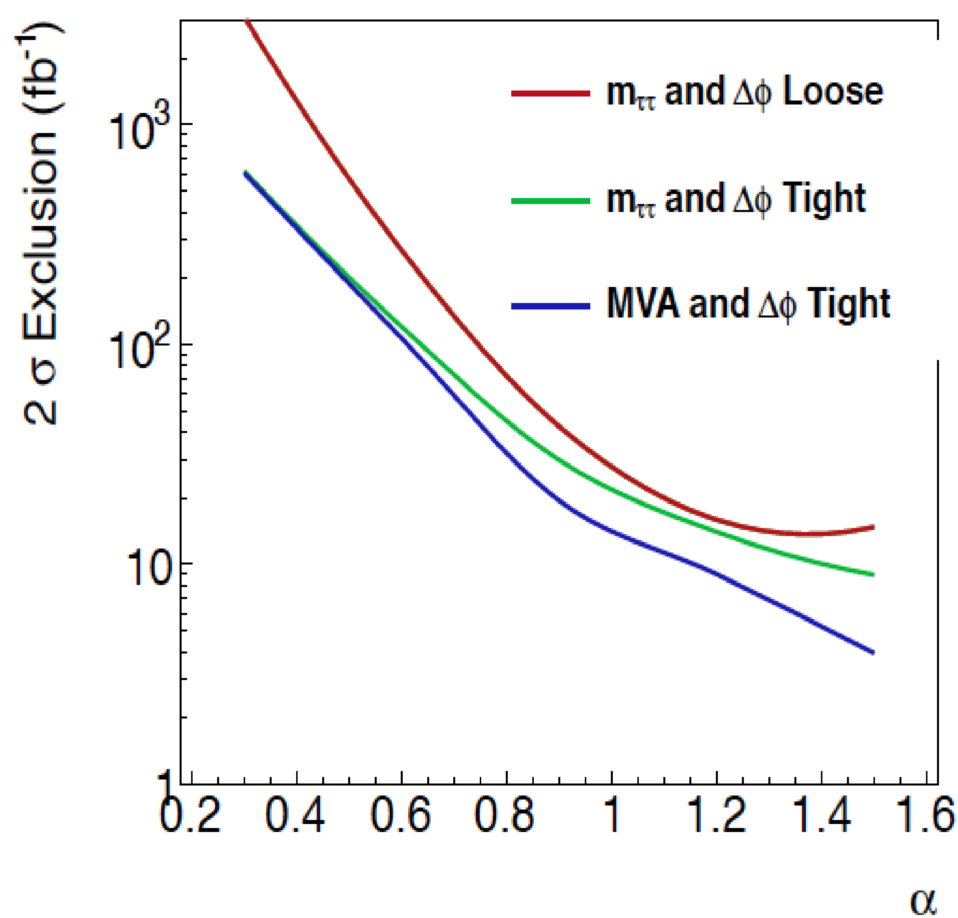
BACKUP

Other Pseudoscalars

- Higgs can be a mix of CP states
  - Can measure this in LHC with $H \to \tau\tau$

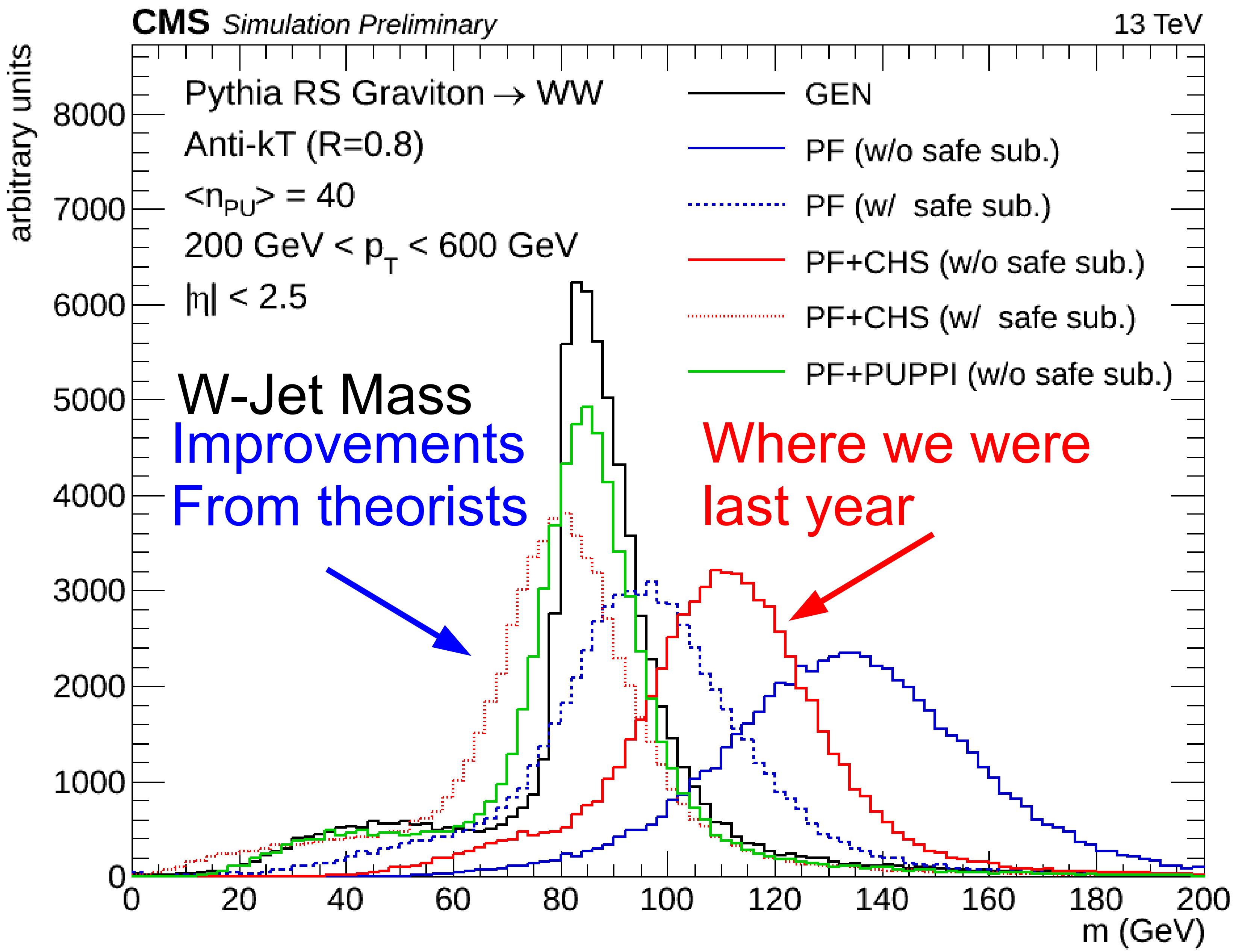
$$\mathcal{L}_{h\bar{f}f} = \cos\alpha\, y_f \bar{\psi}_f \psi_f h + \sin\alpha\, \widetilde{y}_f \bar{\psi}_f i\gamma_5 \psi_f h\,.$$





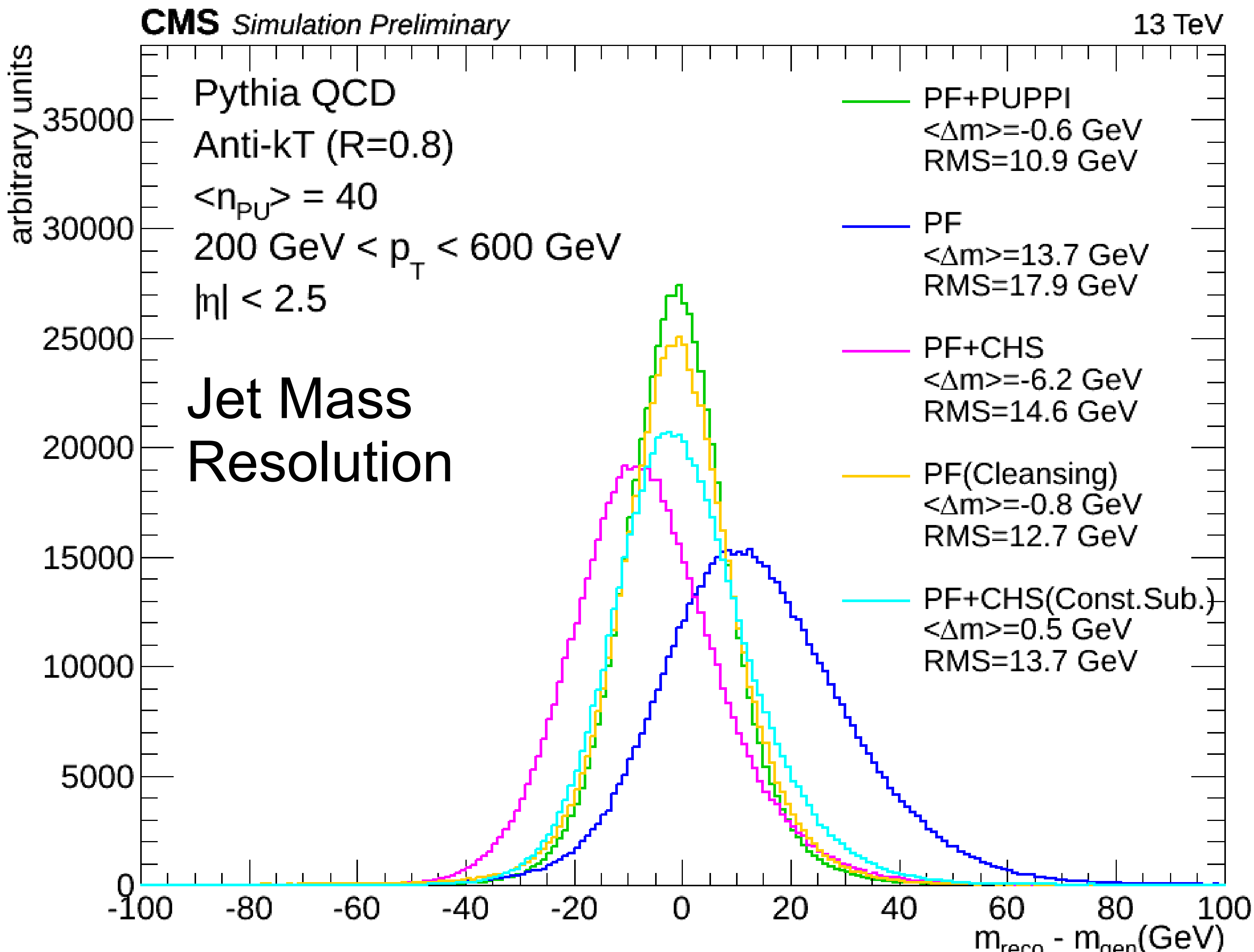
http://arxiv.org/abs/1406.3322

Jets in CMS



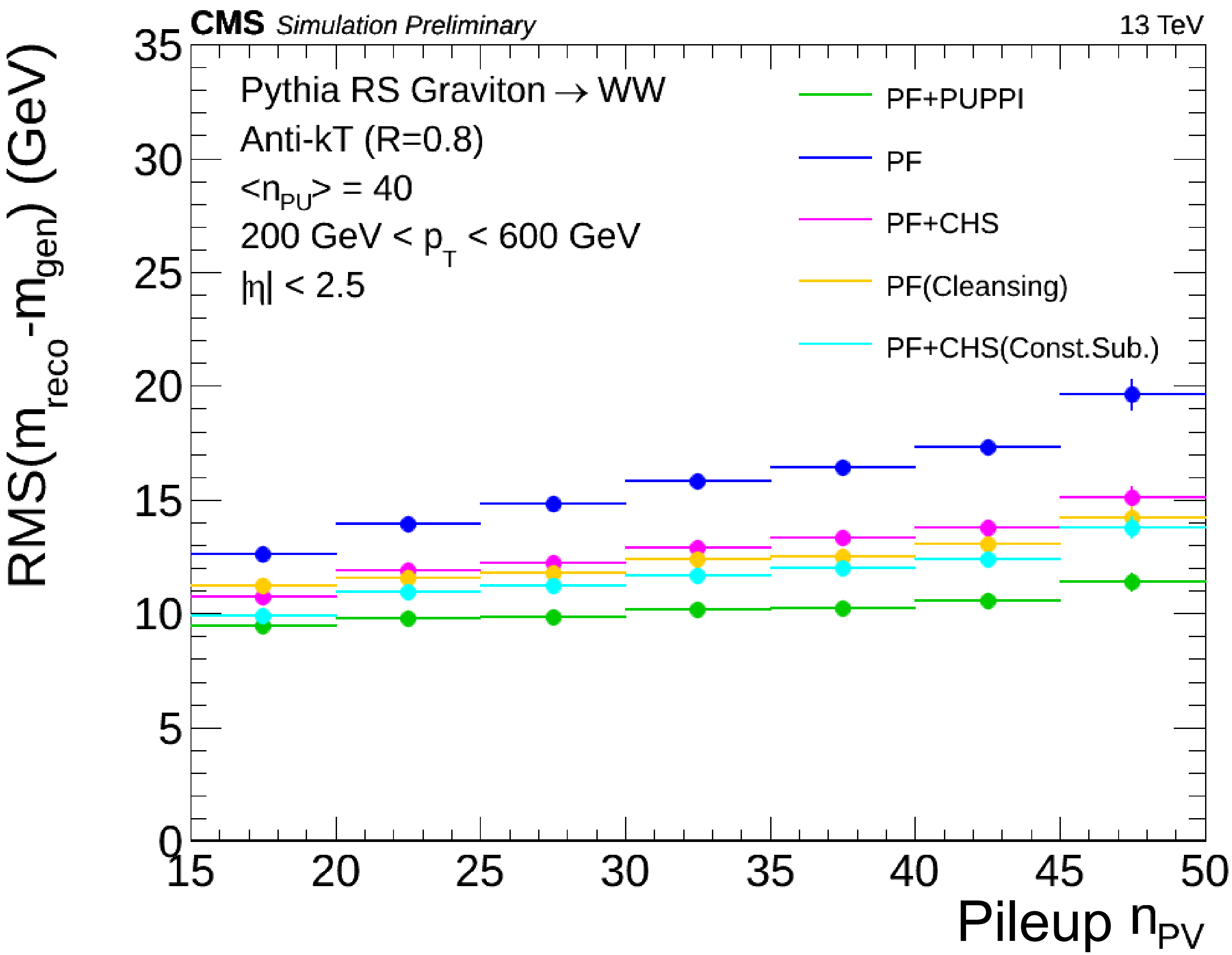
Baseline comparison is state of the art ρ subtraction

Jets in CMS



Mass resolution shows clear improvement (40 PU)

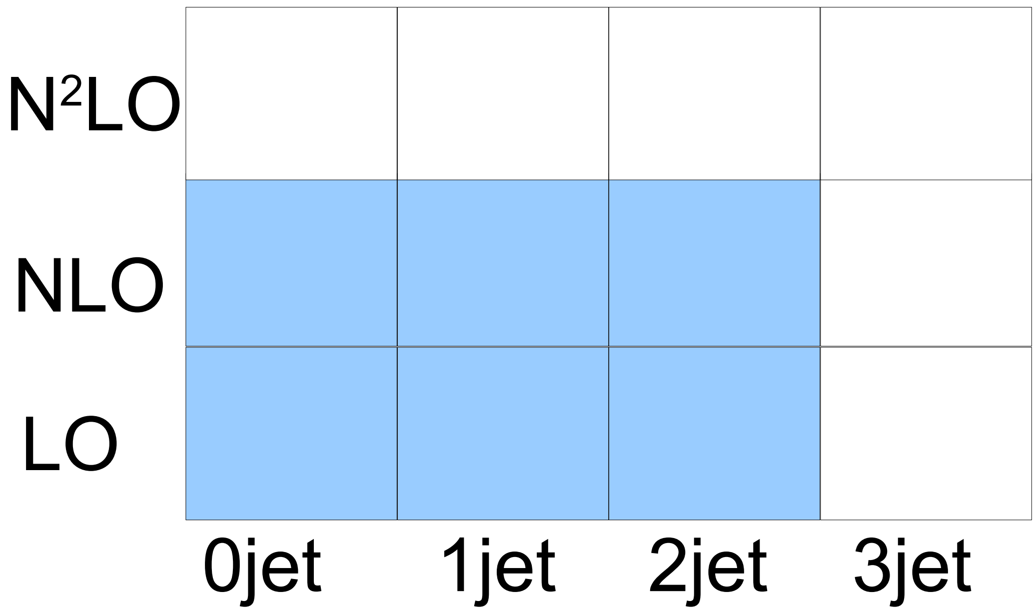
Pileup performance



- Mass resolution is flat against pileup
  - Related trend observed in the data

Main Background : Z→vv

- Generate events with aMC@NLO/MG5
- Generation is NLO 0,1,2 jets



Merging with FxFx (NLO scheme for merging)

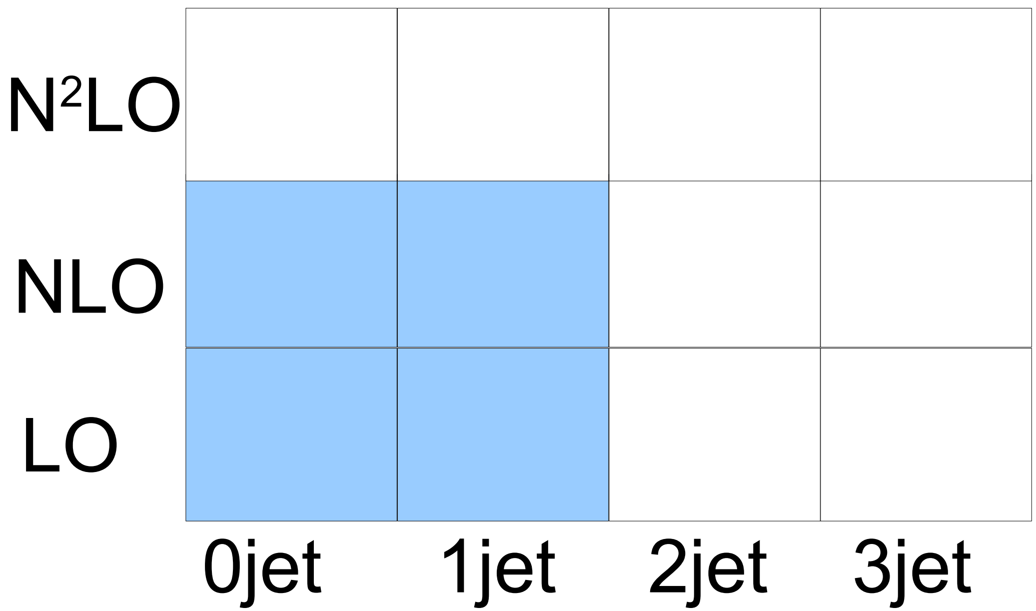
Generation includes Di-boson production

Literally Z→vv + up to two partons

Generate $v_\mu v_\mu$ and multiply by 3

Main Background : lv+0,1j

- Again with aMC@NLO/MG5:
  - pp > l nu, pp > l nu j
- Generation is NLO 0,1jets (2 jets crashed)



Merging with FxFx (NLO scheme for merging)

Semileptonic di-boson production appears included

di-Top do not seem to be included

For the moment ignoring tops (1%)

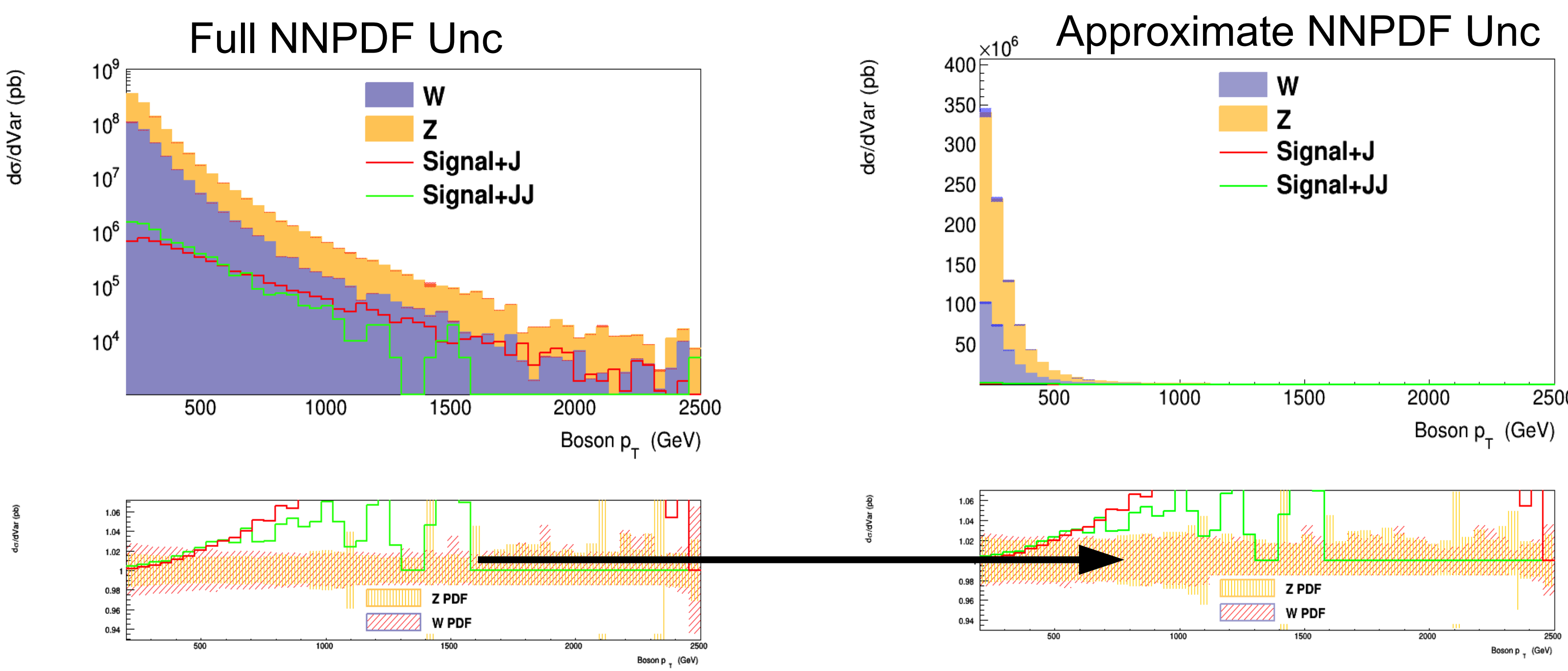
Signal Choice

- For next plots we do :
  - Both 1 and 2 jet generation
    - Done separately
    - Need Ciarian's help me merge this properly

- Scalar DM with med mass at 925 GeV
  - Dark matter mass of 10 GeV for MCFM
  - From VBFNLO decay scalar to S→ZZ→νννν
    - Fastest way to do something invisible without hacking
  - For the full scan we just use MCFM for now

PDF Choice

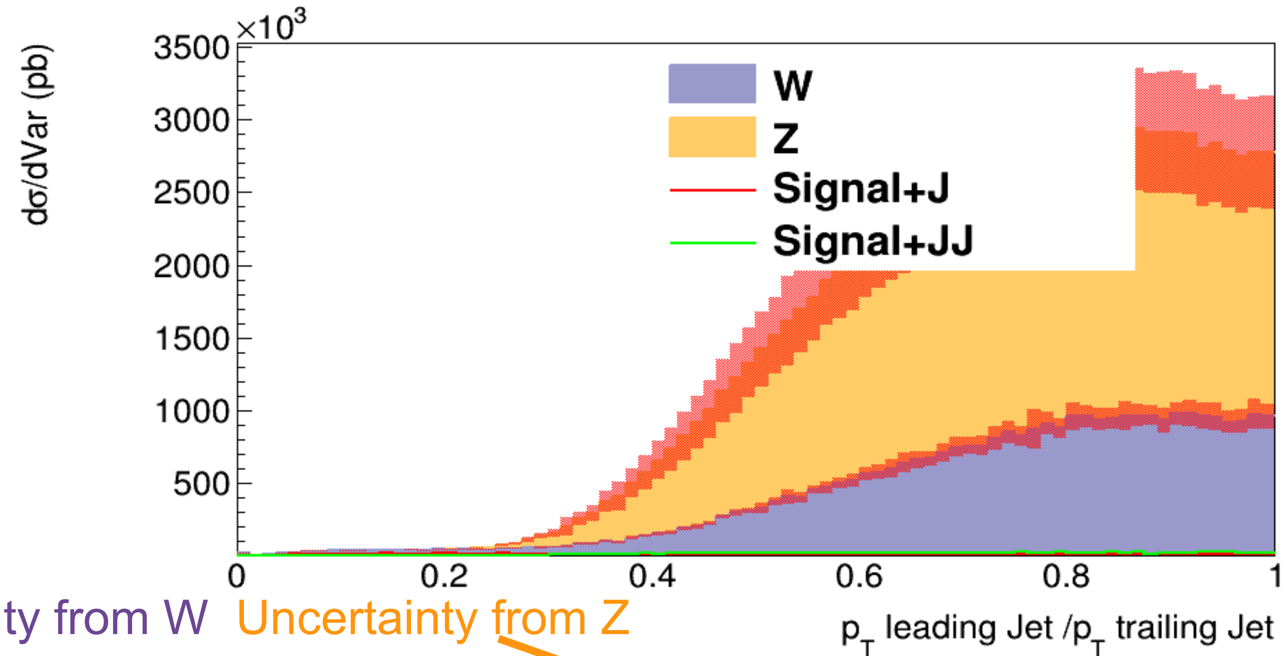
- For the analysis we use NNPDF 3.0
  - Newest pdf expected to be the most robust
  - No issues with MCFM/VBFNLO/aMCNLO



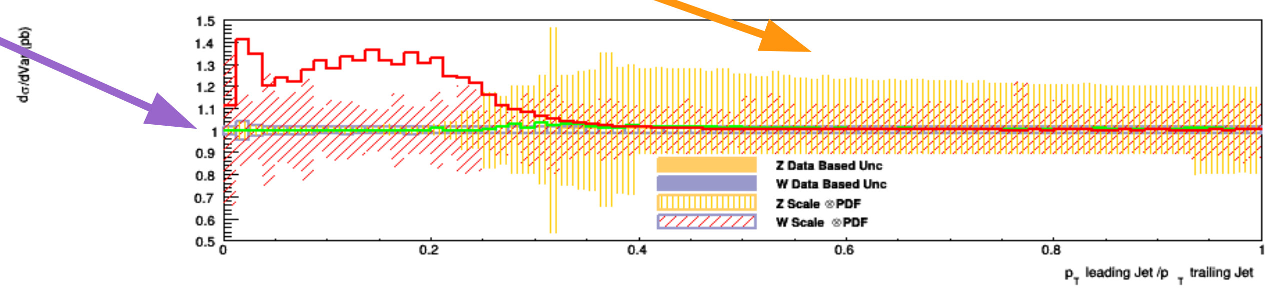
Approximate NNPDF unc by computing RMS/event taking weight=1±2RMS
1RMS underestimates uncertainty (we only show pdf unc in this plot)

Scale Unc

- Add full scale uncertainty and pdf in quadrature



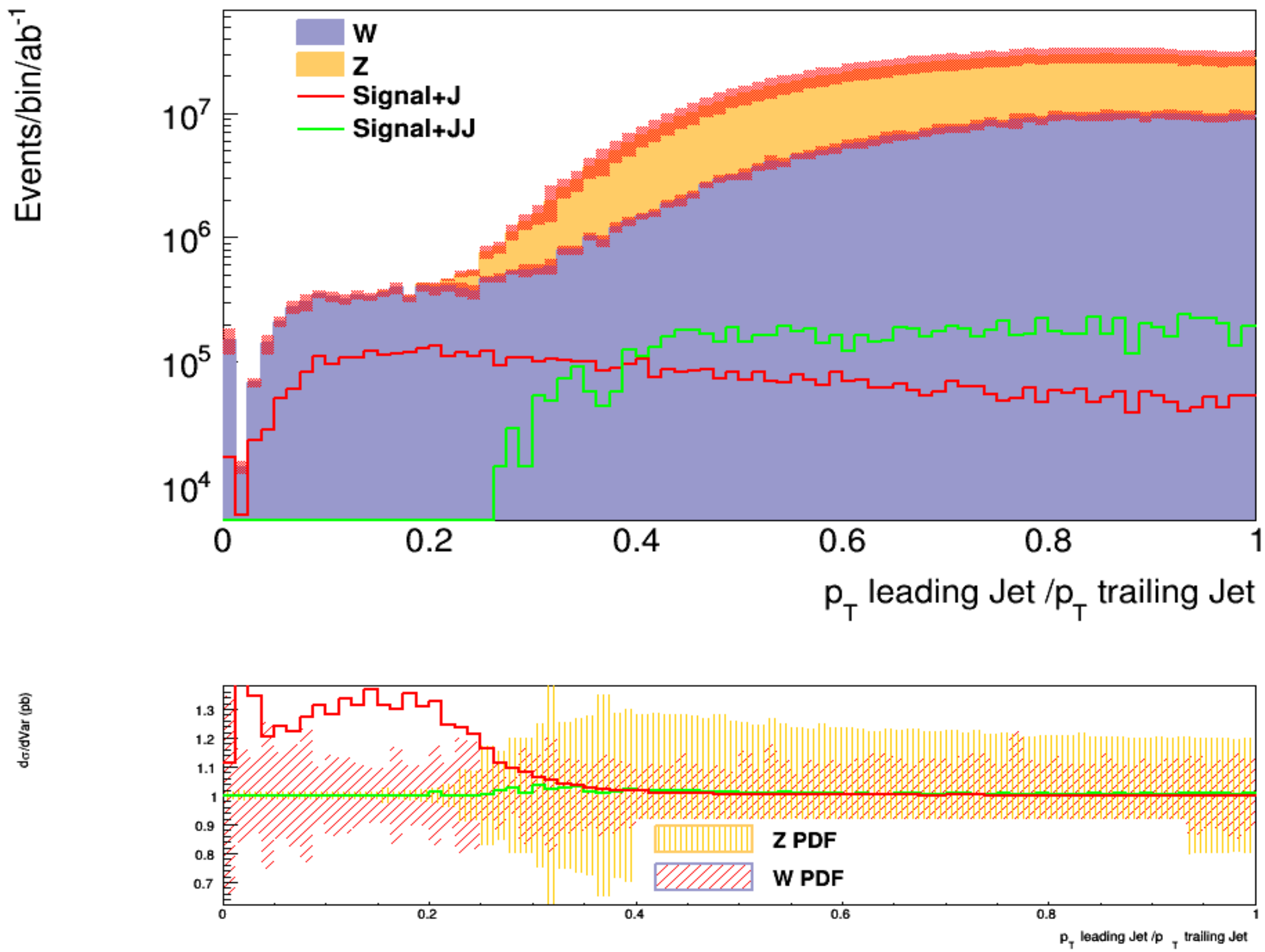
Scale uncertainty from W Uncertainty from Z



This is the full plot with all features

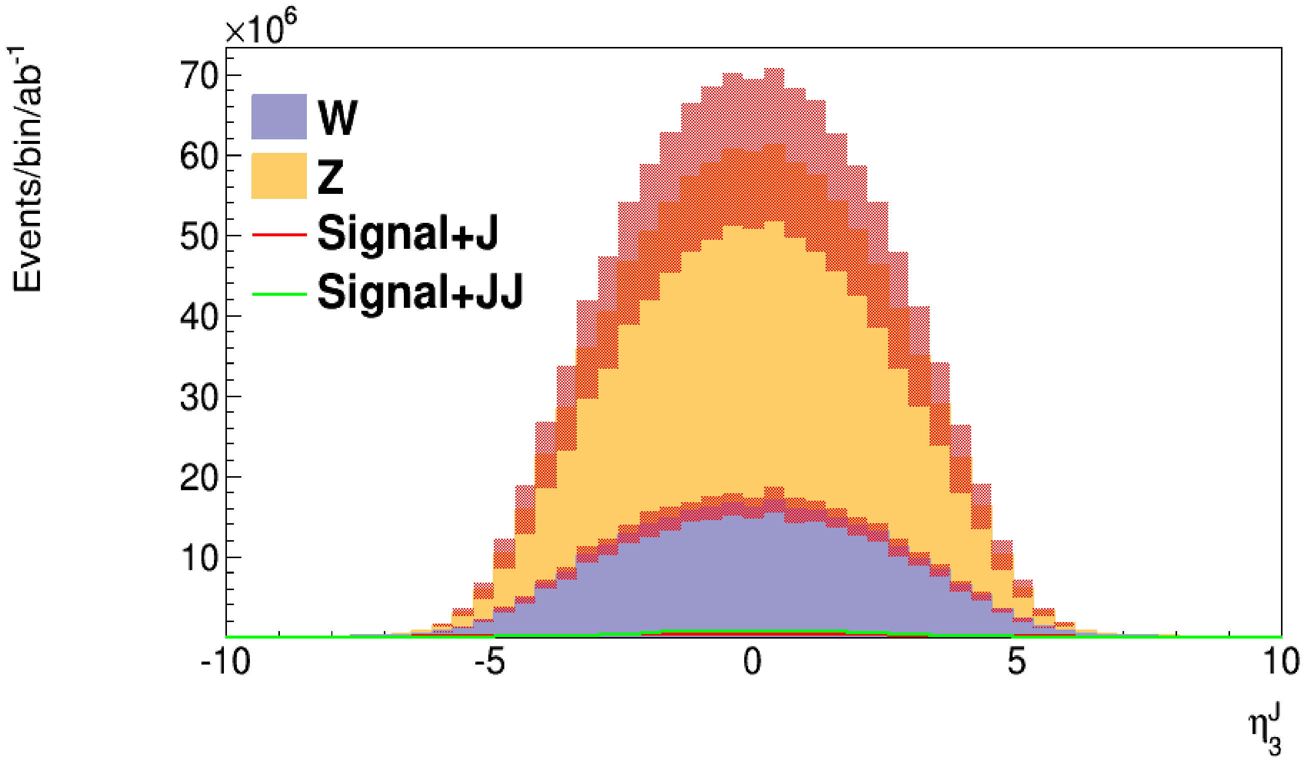
Scale Unc

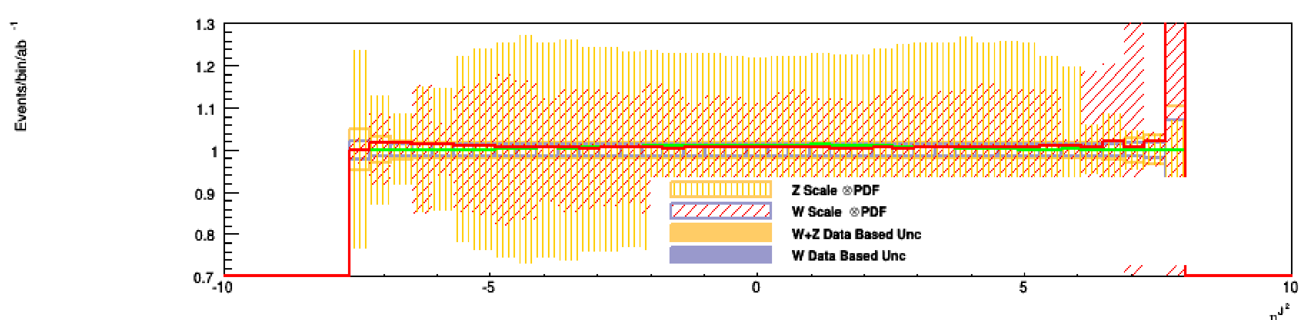
- Add full scale uncertainty and pdf in quadrature



Jet Acceptance

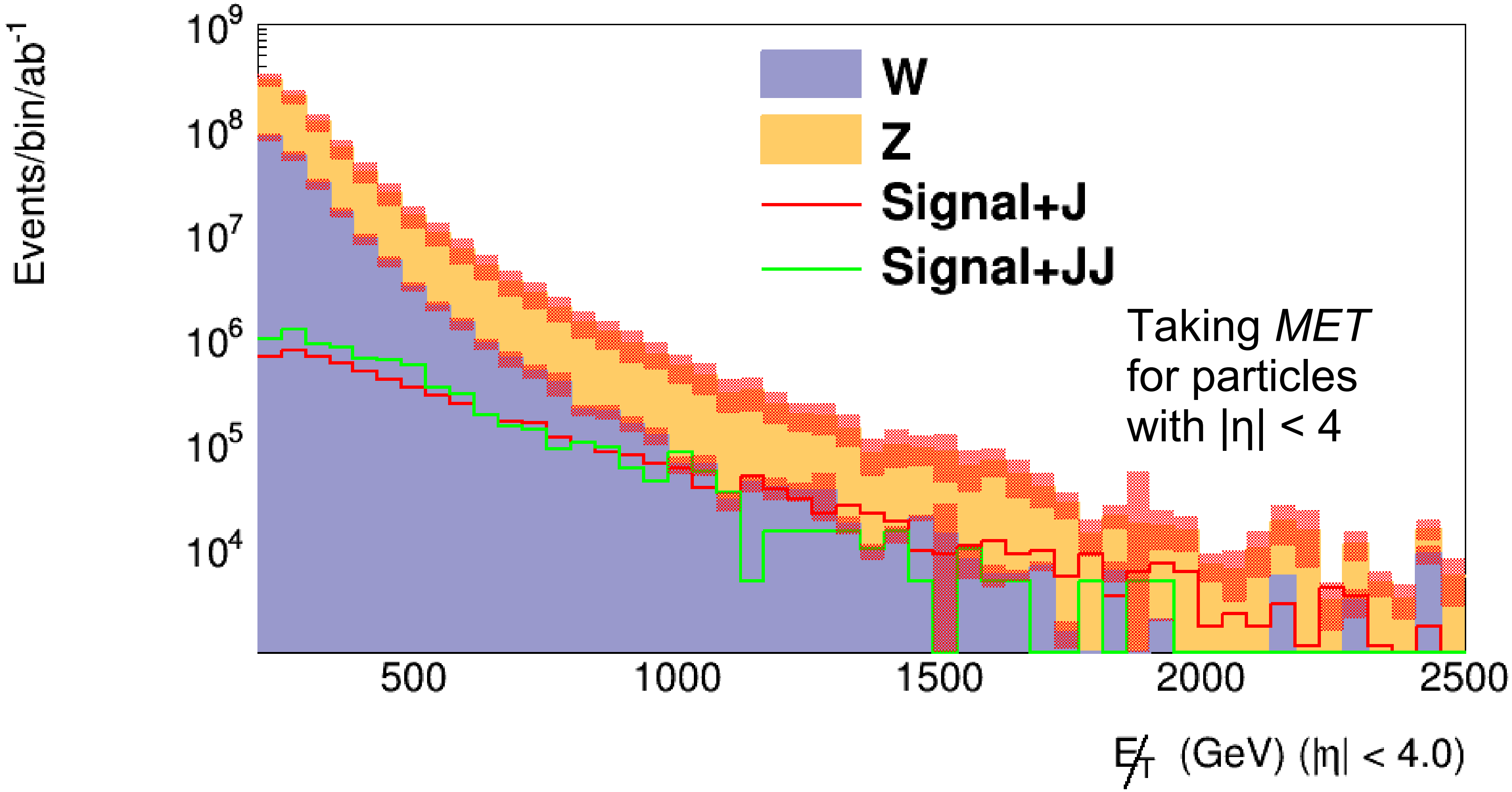
- Jets can range as far as $|\eta| < 7.0$

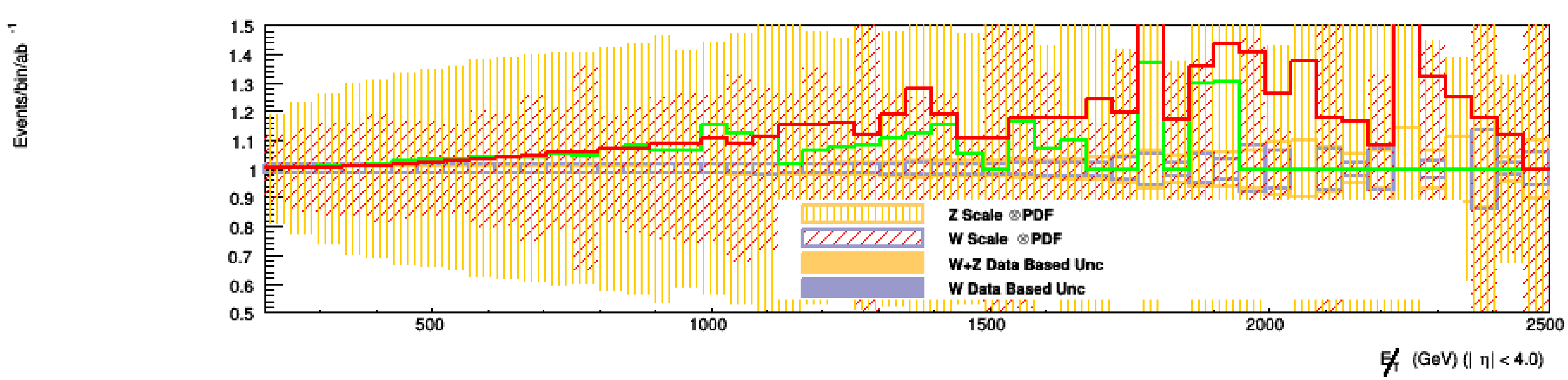




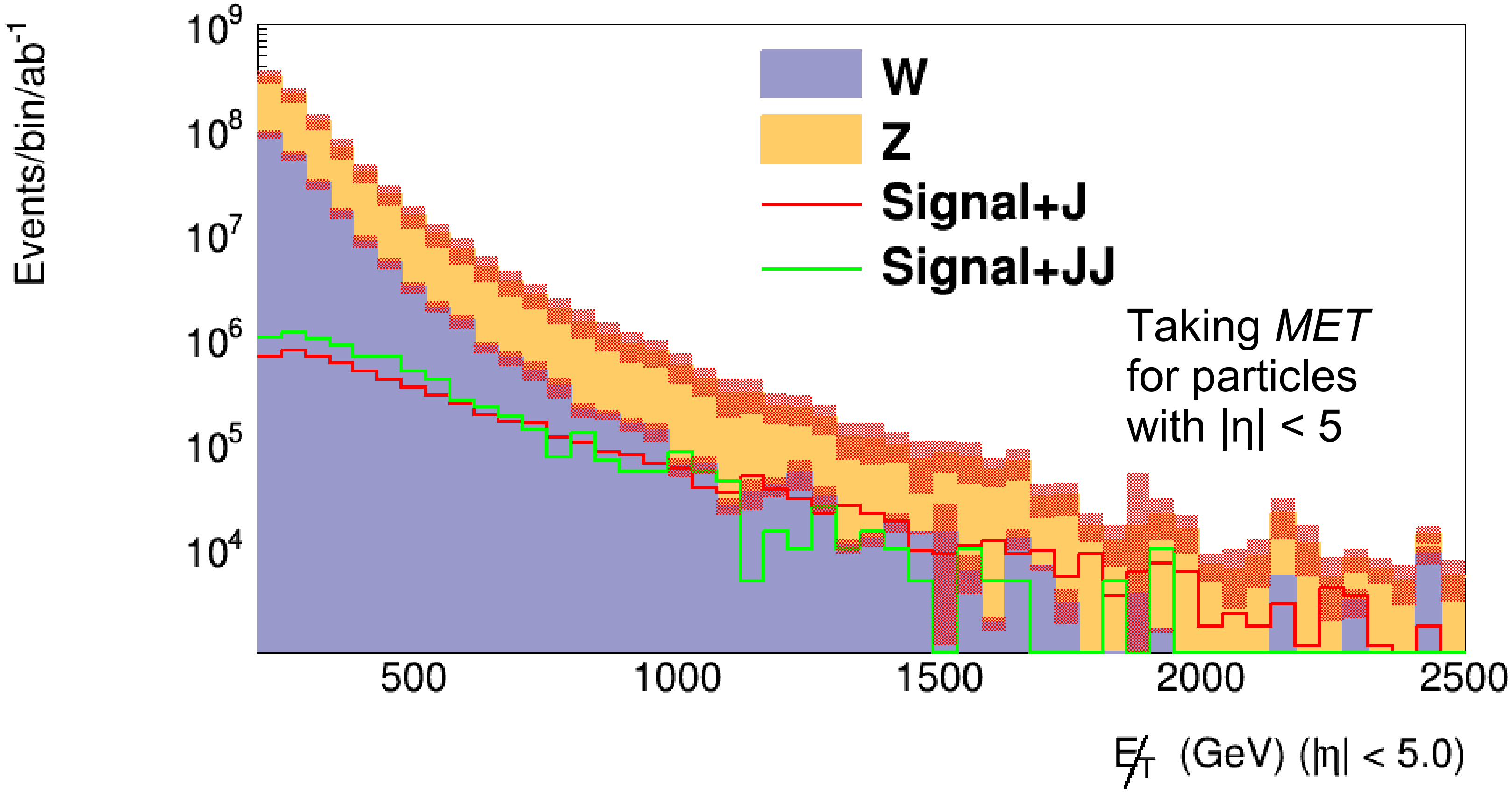
Extended detector acceptance should be considered

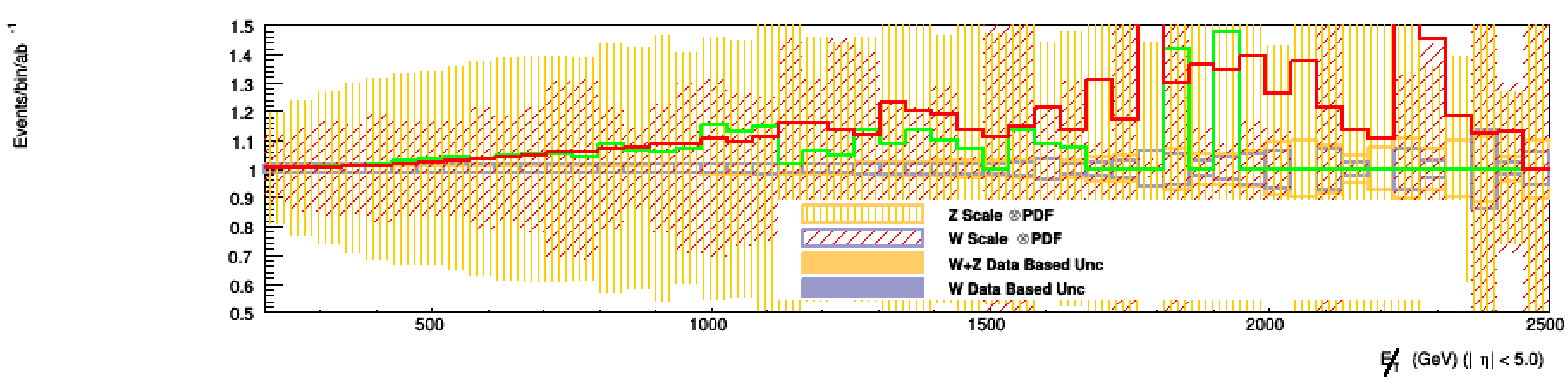
MET vs Particle acceptance



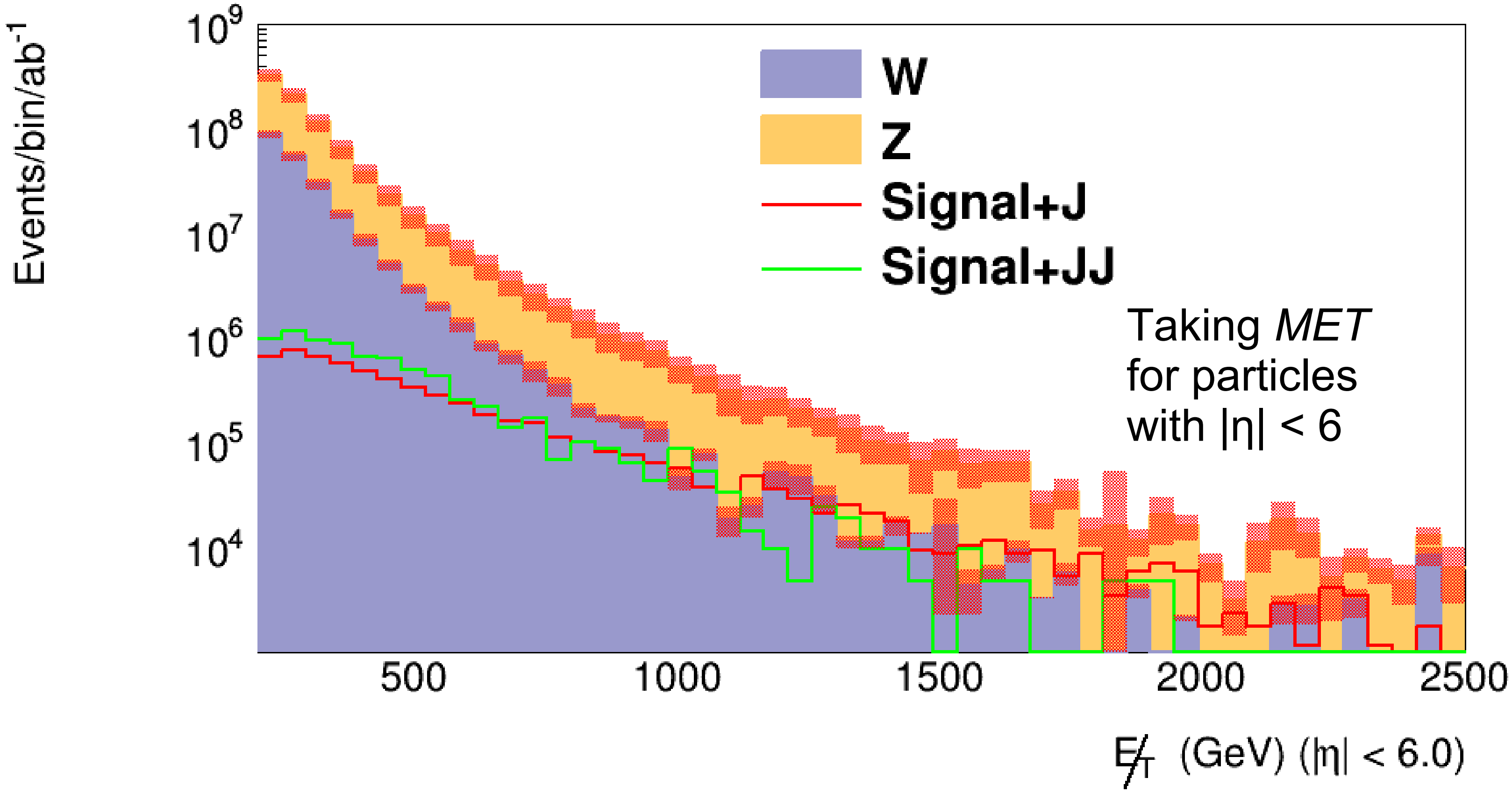


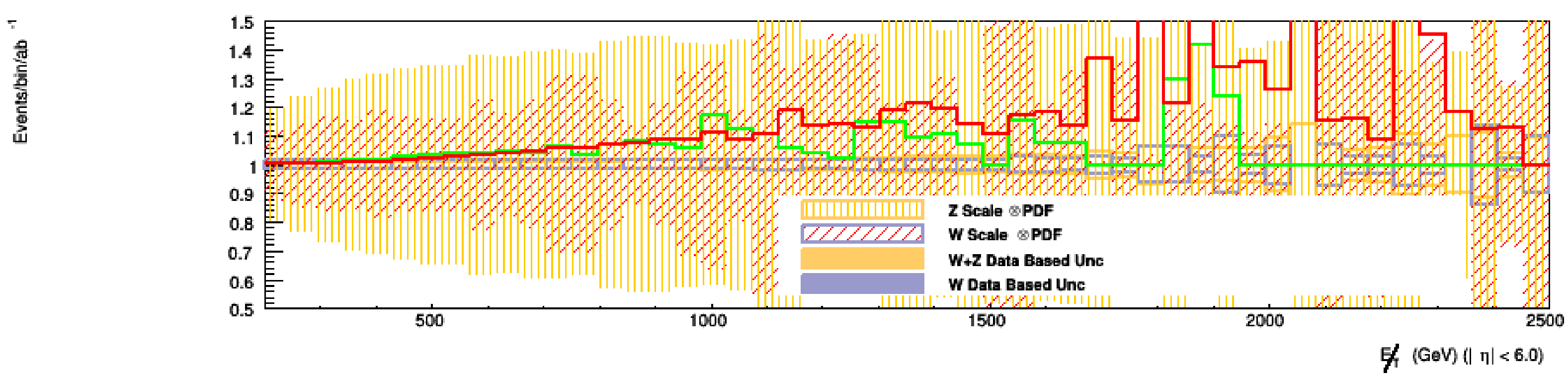
MET vs Particle acceptance



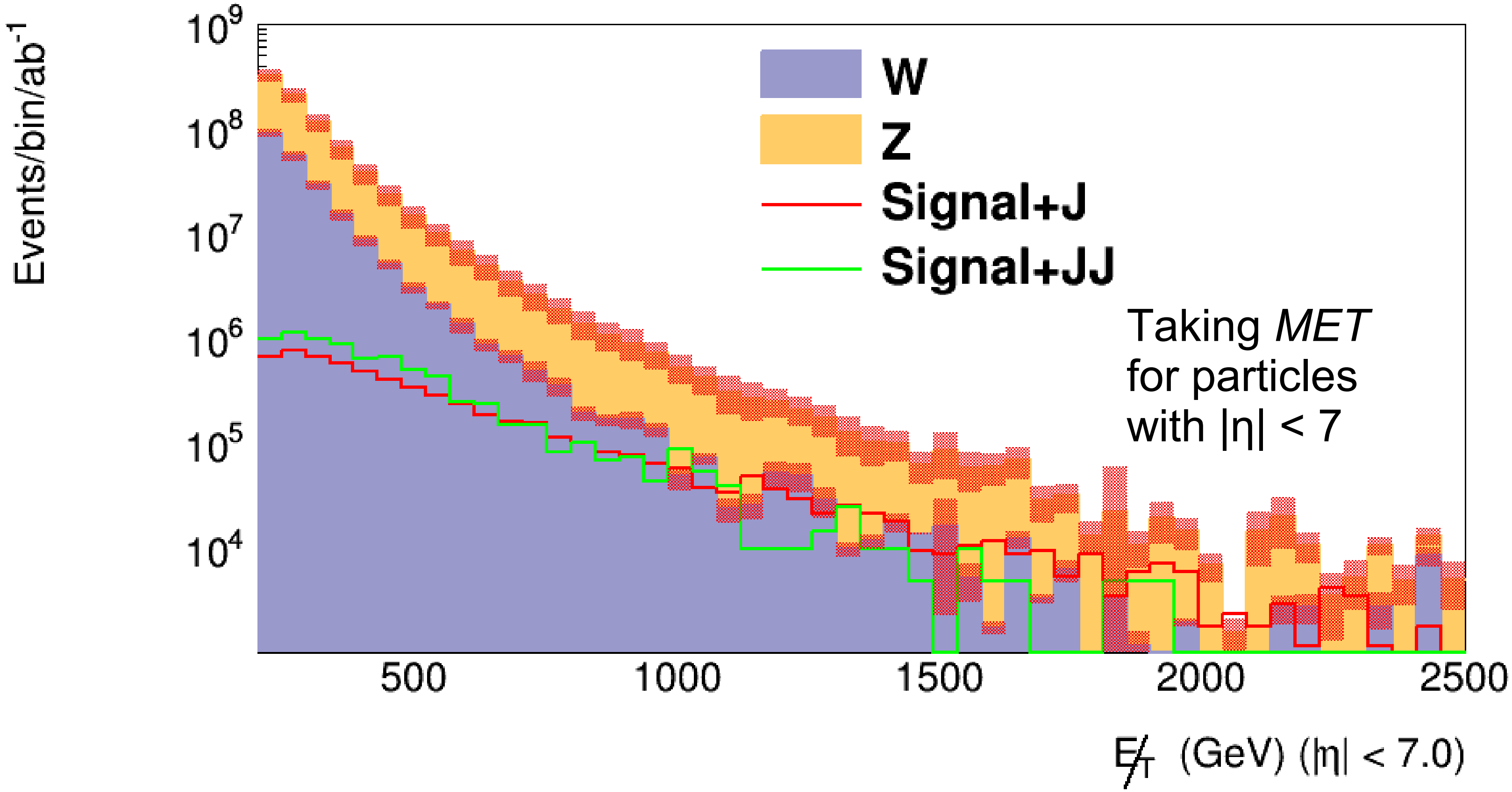


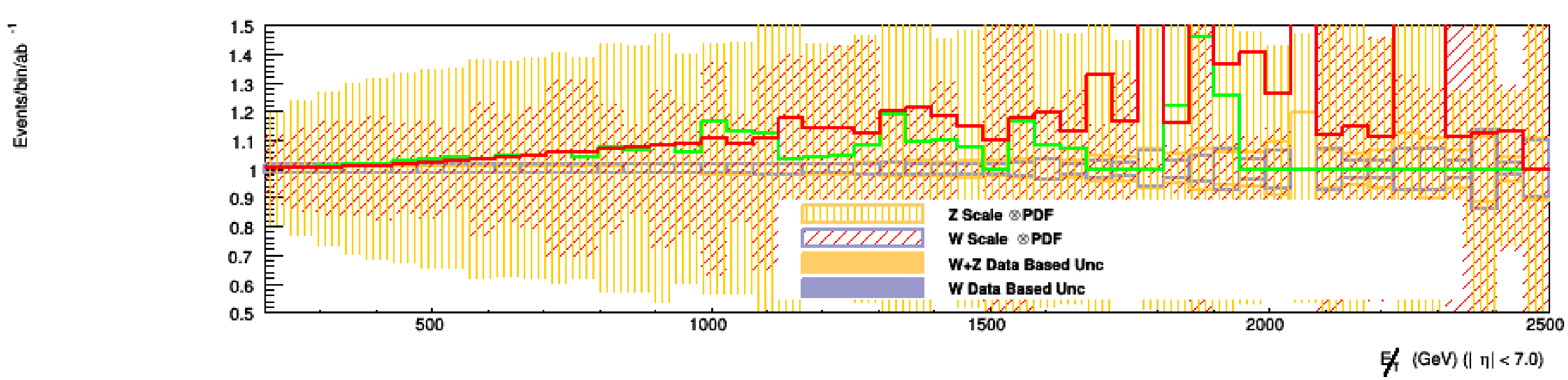
MET vs Particle acceptance





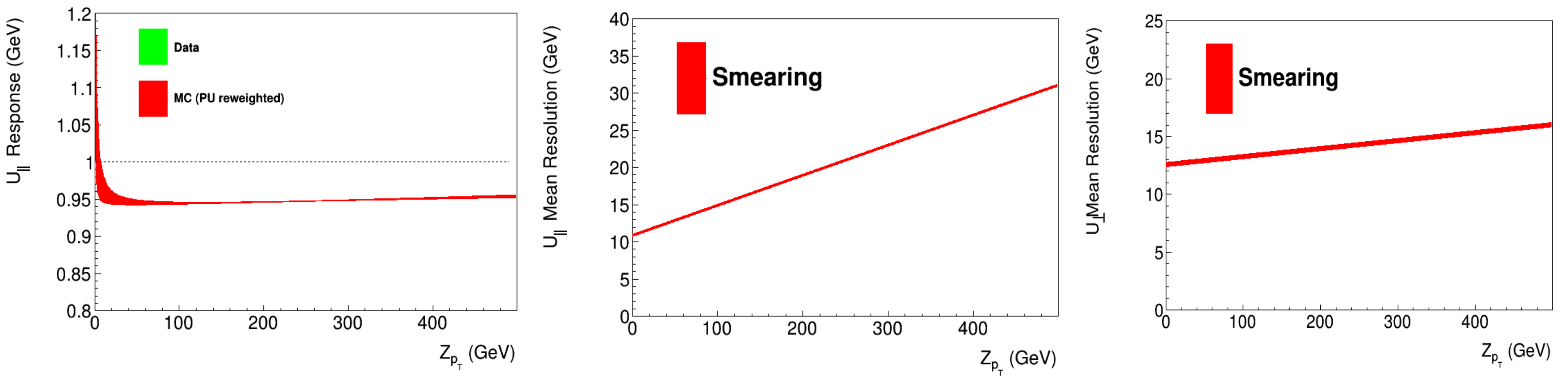
MET vs Particle acceptance





MET smearing

- Procedure :
  - Smear top 3 leading jets
  - Remove them
  - Smear remaining hadronic recoil



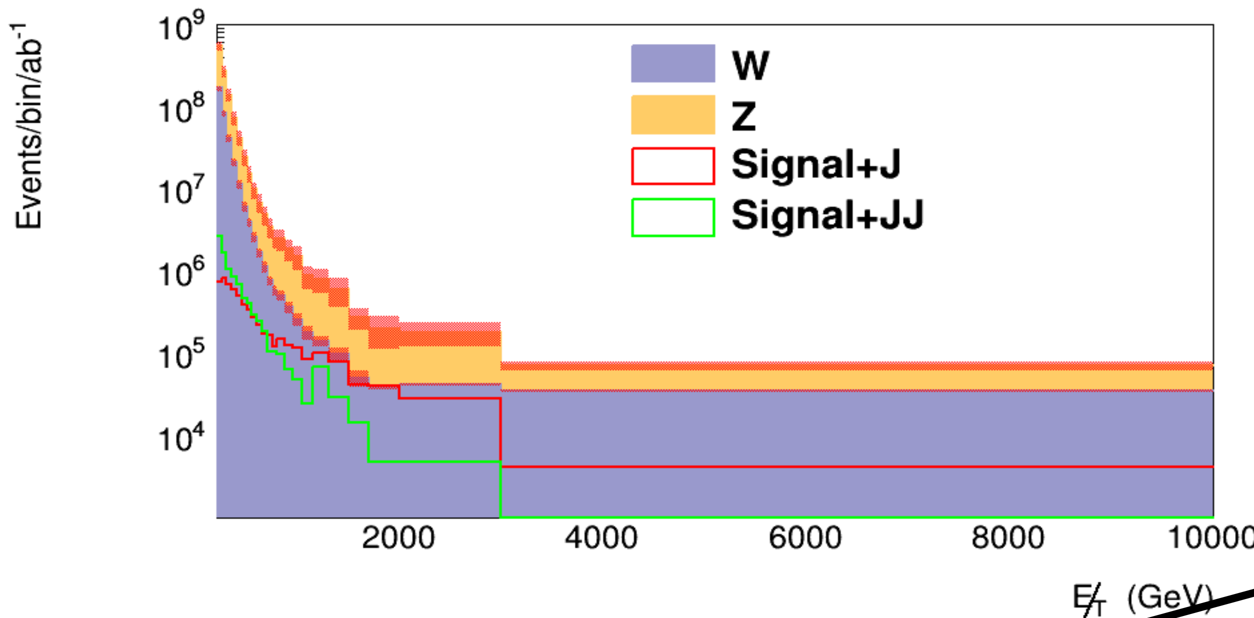
Smearing performed with double gaussian given mean

Allows for propagation into the tails

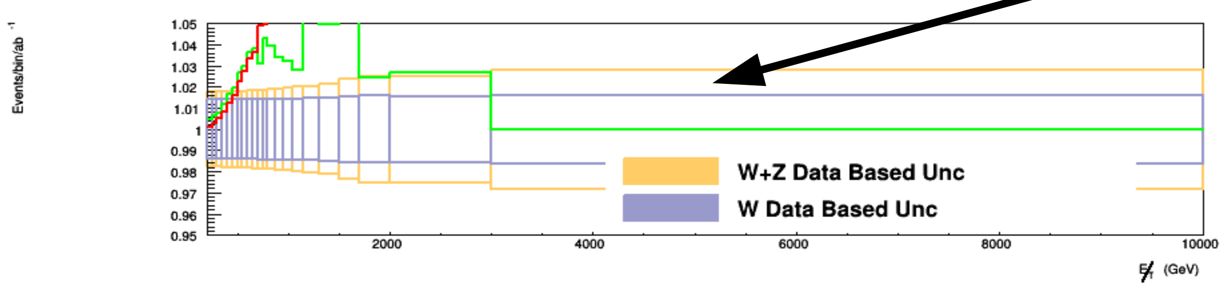
Known to be the most robust approach to model *MET*

Building the Analysis

- Analysis : fit *MET* spectrum
  - Use bin by bin uncertainties from Z→μμ for Z→νν
  - Assume 1:1 ratio for W→μν control region use bbb unc.



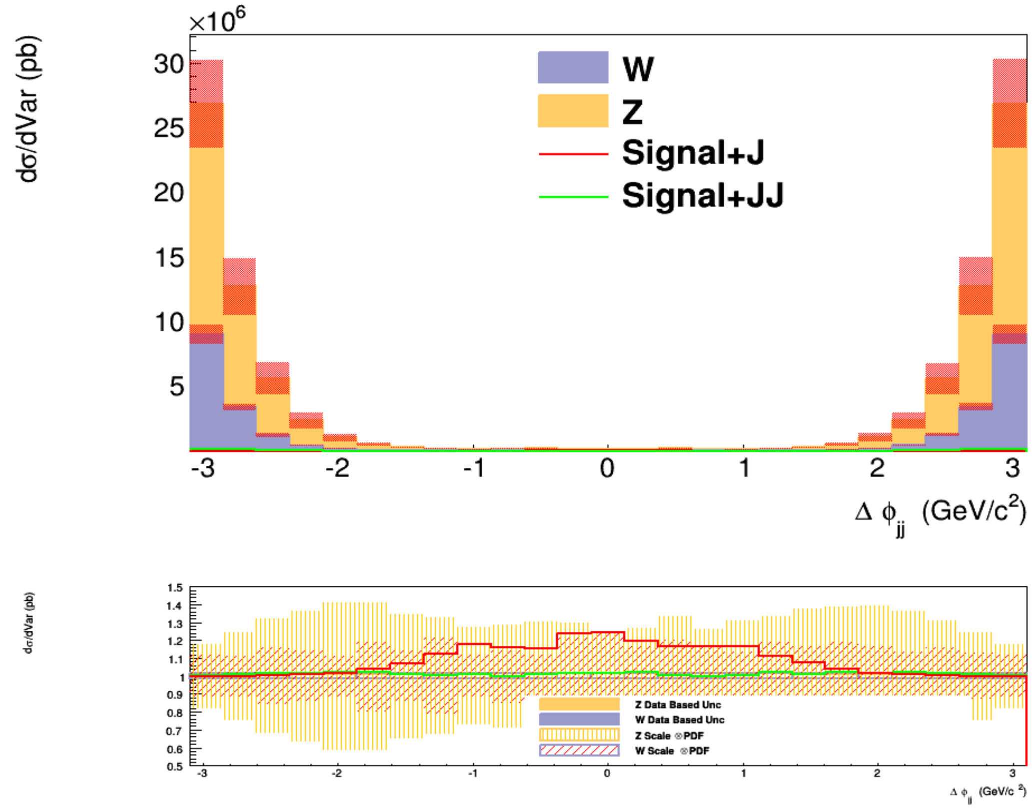
Uncertainty Band With 1ab^{-1} is damn small



However CMS current Precision is similar

Input variables for Scan

- Scan :
  - Leading jet pt/eta
  - Njets
  - Njets50 (pT > 50)
  - $\Delta\varphi_{jj}$
  - $\Delta\varphi_{met\text{-}j}$
  - 3^{rd} jet p_T
  - Trailing jet pt/eta (for signal+2jets)
  - Mjj (for signal+jets)



Take a look at plots in dropbox to view the plots of everything

Systematic Uncertainties

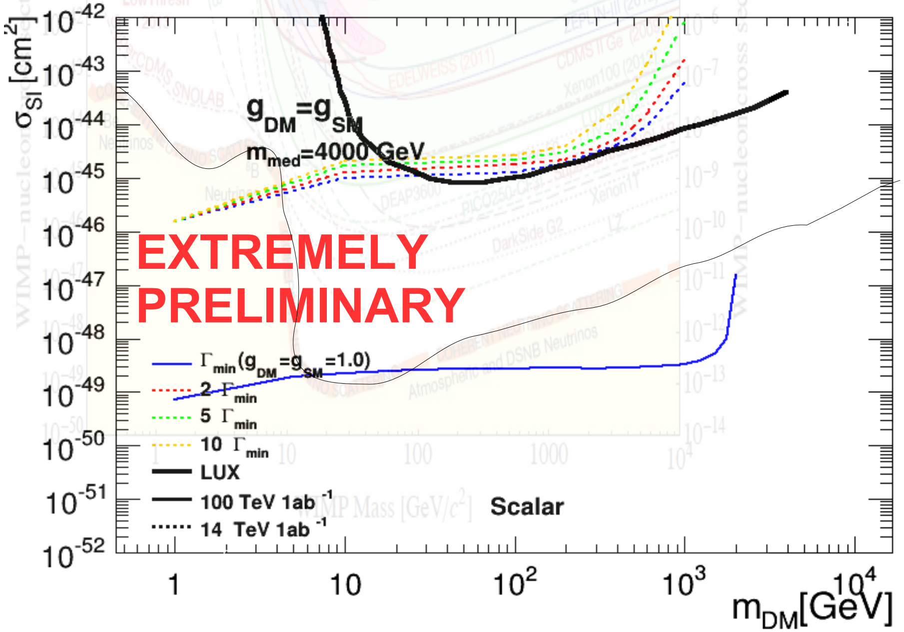
- W template:
  - 15% τ veto (3% on tau id efficiency) 2.5% overall
  - 1% for top and di-boson
  - 1% per-bin uncertainty
  - Staistical uncertainty/bin on W form W(lv) control
- Z template :
  - 1% for muon efficiency (0.5% id eff)
  - 1% for di-boson contribution
  - 1% per-bin uncertainty
  - Statistical uncertainty/bin on Z from Zμμ control

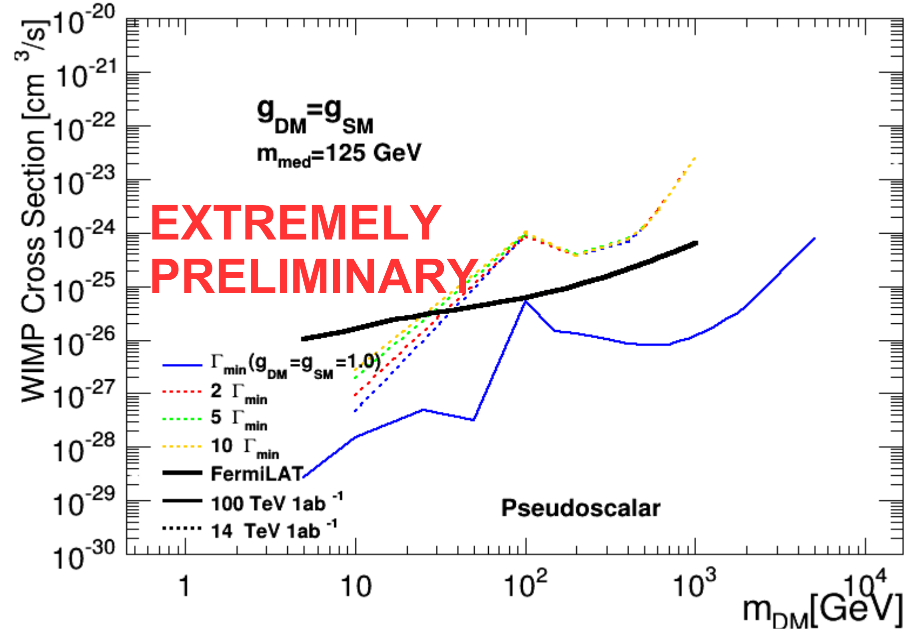
Signal Strategy

- Run full shape analysis for 100 TeV and $1ab^{-1}$
  - Generate limits with and w/o $\Delta\varphi_{jj}$
  - For (p)scalar now using non-yukawa DM coupling
    - As a cross check save yukawa coupling cross section
- Run old papers 14 TeV analysis with $1ab^{-1}$
  - No improvements to the analysis
  - Keep total lumi the same for good measure
  - For 14 TeV use the old samples with yukawa DM
    - Rescale the samples by cross section to non-yukawa

Comparing with Direct Detection

- Considering first vector and axial mediators

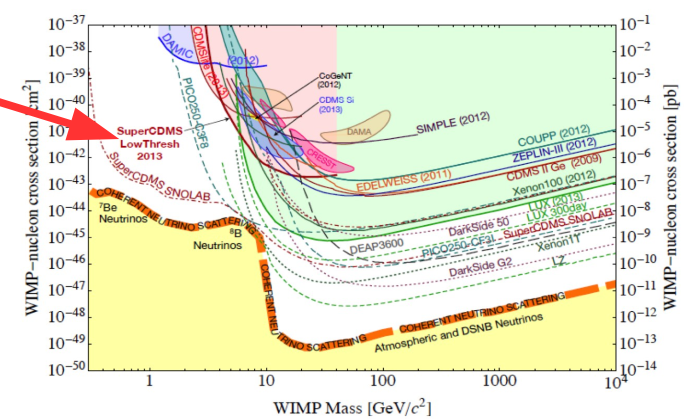




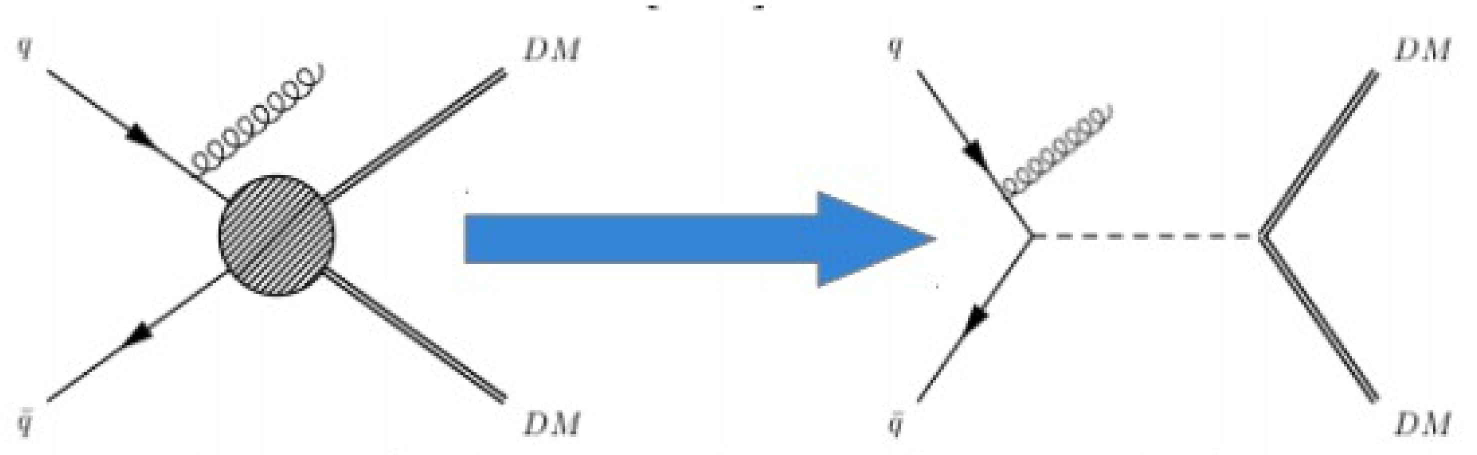
Scalar is beyond the neutrino wall

Pseudoscalar well beyond ID bounds

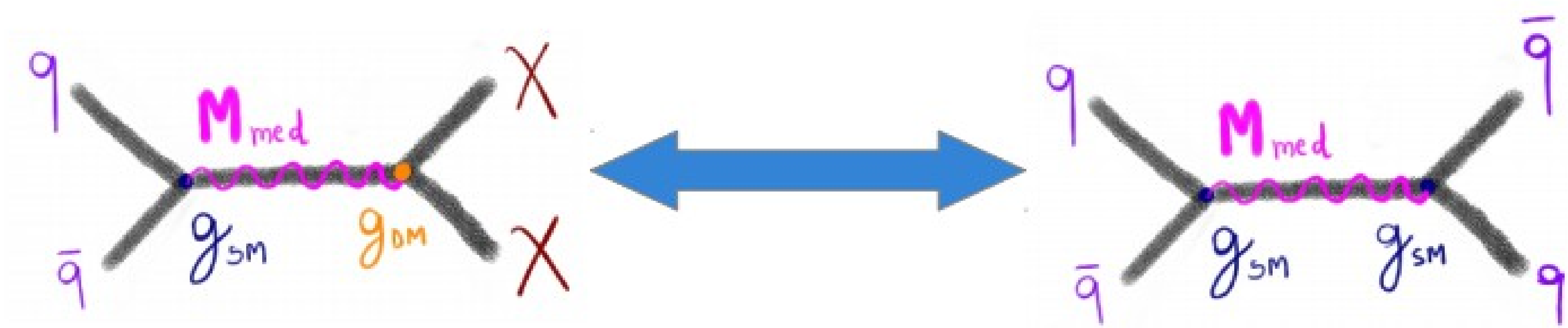
Collider appears to be most sensitive



CMS: arXiv:1408.3583 MET+X searches



Dijet searches



SELECTION AND OBSERVABLES IN MET+X/DIJET SEARCHES

MET+X selection

Signal region:

>1 high-pT jet

pT/MET cut ("monojet")

Lepton veto

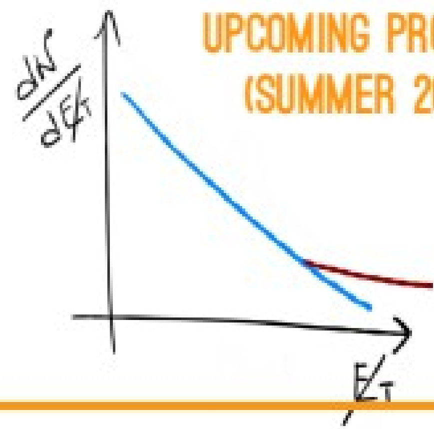
Control regions:

Lepton selection (W/Z CR)

Jet selection: same as CR

MET+X observable

Missing transverse momentum



UPCOMING PROJECT (SUMMER 2015)

Dijet selection

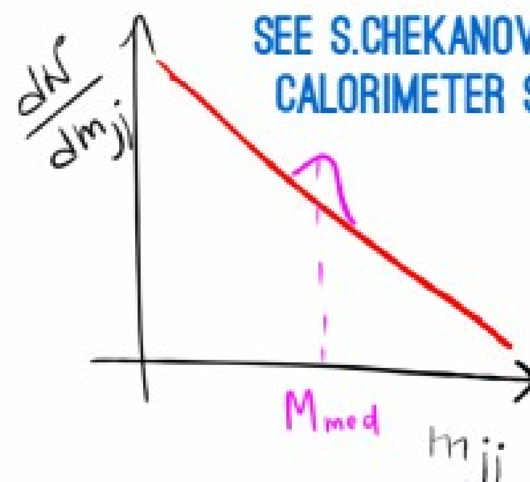
2 high-pT jets

y (j1,j2) < 2.8

y*=1/2*(y1-y2)<0.6

Dijet observable

Dijet invariant mass



SEE S.CHEKANOV'S TALK, CALORIMETER SESSION

Both search signatures are only loosely tied to models

Both observables are **tied** to **calorimeter performance**

CERN Summer Student project 2015:

Consider two different mediator decays
→ different experimental signatures (dijets/jet(s)+MET)

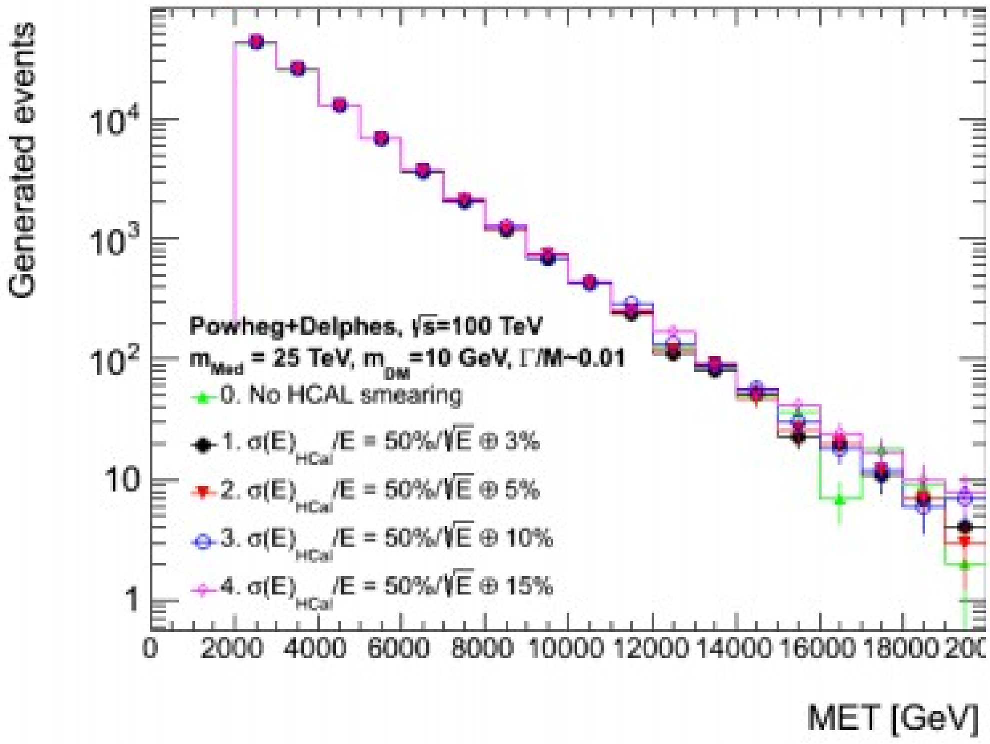
Choose a benchmark point (in coupling/width plane)
where sensitivity is similar at particle level

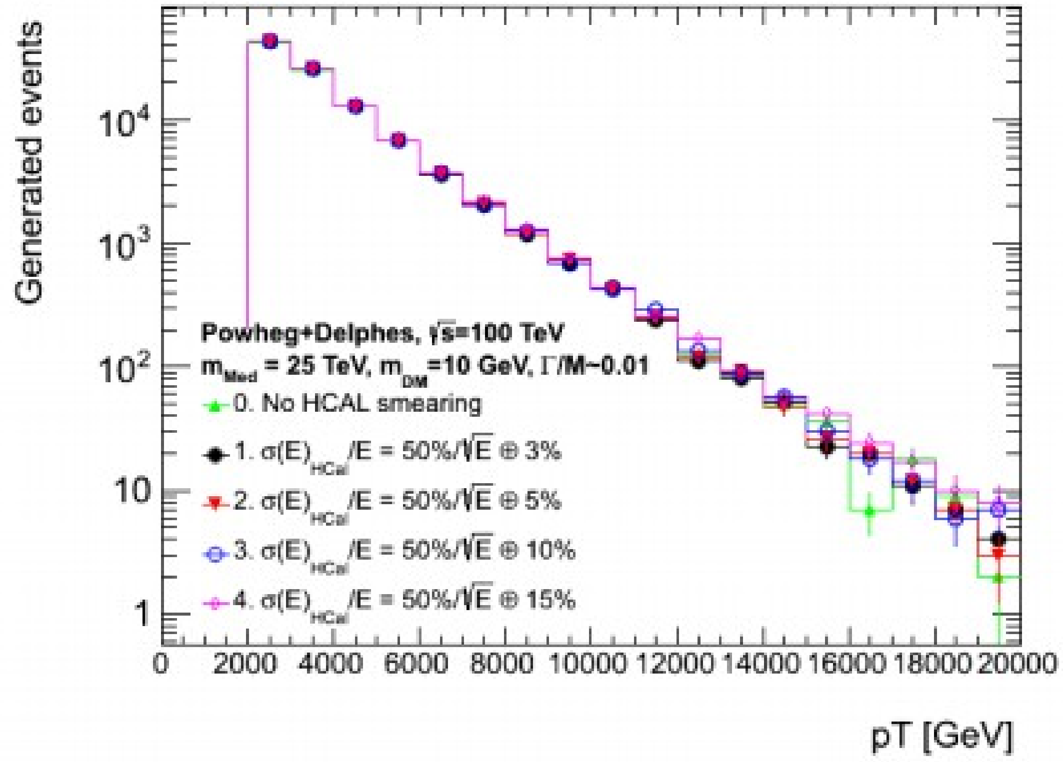
Use FCC software (HepSim/MadAnalysis) to implement different calorimeter configurations and study discovery reach:
which search is privileged in which scenario?

Checking the kinematic of a **signal sample** at **parton level**:

(based on choices of Run-2 benchmarks within [ATLAS/CMS Dark Matter Forum])

more statistics needed, investigate lower MET signals





For effect of additional PS jets: http://arxiv.org/pdf/1310.4491v2.pdf