Cracking
the dark matter code
@ LHC

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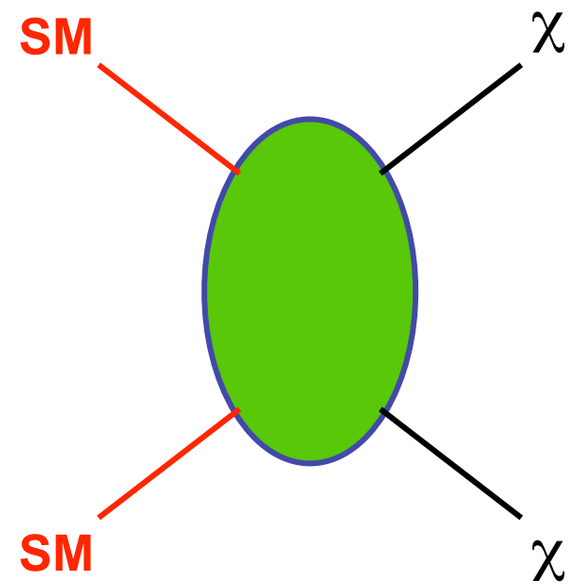
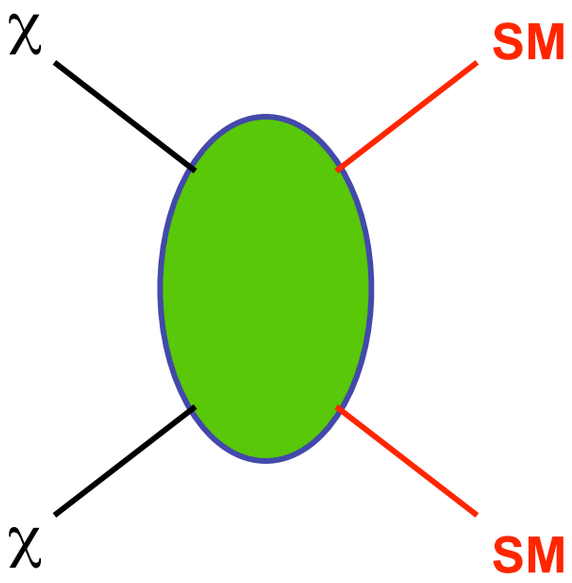
(Korea-CERN fellow)

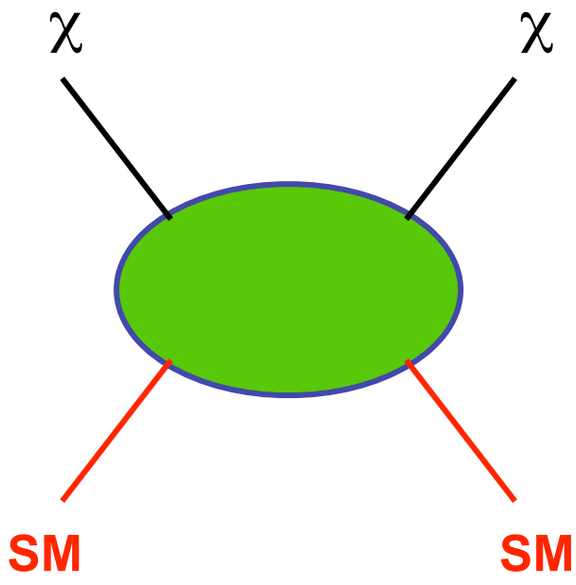
In collaboration with
Won Sang Cho, Doojin Kim, Konstantin Matchev
(arXiv:1206.1546)
and Rakhi Mahbubani (arXiv:1209.XXXX)

Dark matter @ collider



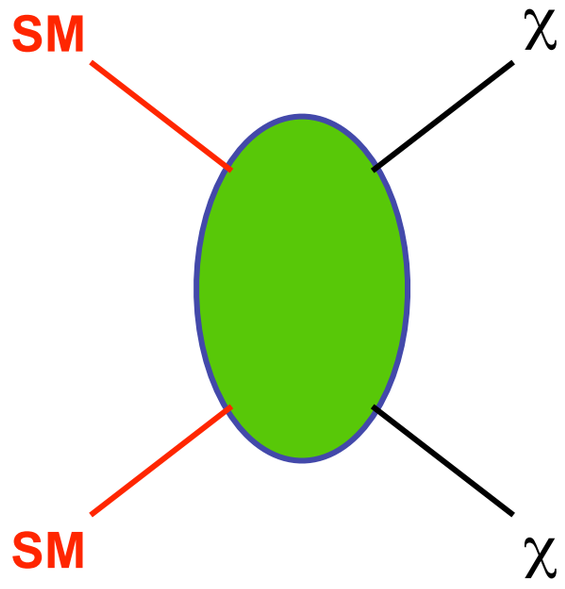


From the above



deep in the earth

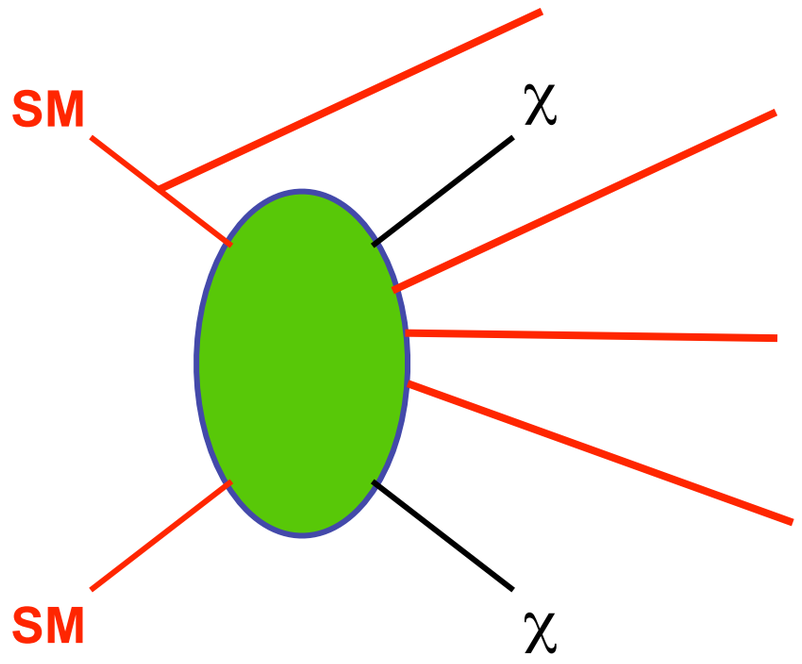
Dark matter @ collider



1. The structure is not simple,
   if we want to look inside.
   - How does an collision
     end up with darkmatters.
   - Assignment of visible particles
     in decaying processes.
     (combinatorics issue)

2. We may be biased based on
   what we want to see.
   - Number of invisible particles.
   - Type of invisible particles.

Dark matter @ collider



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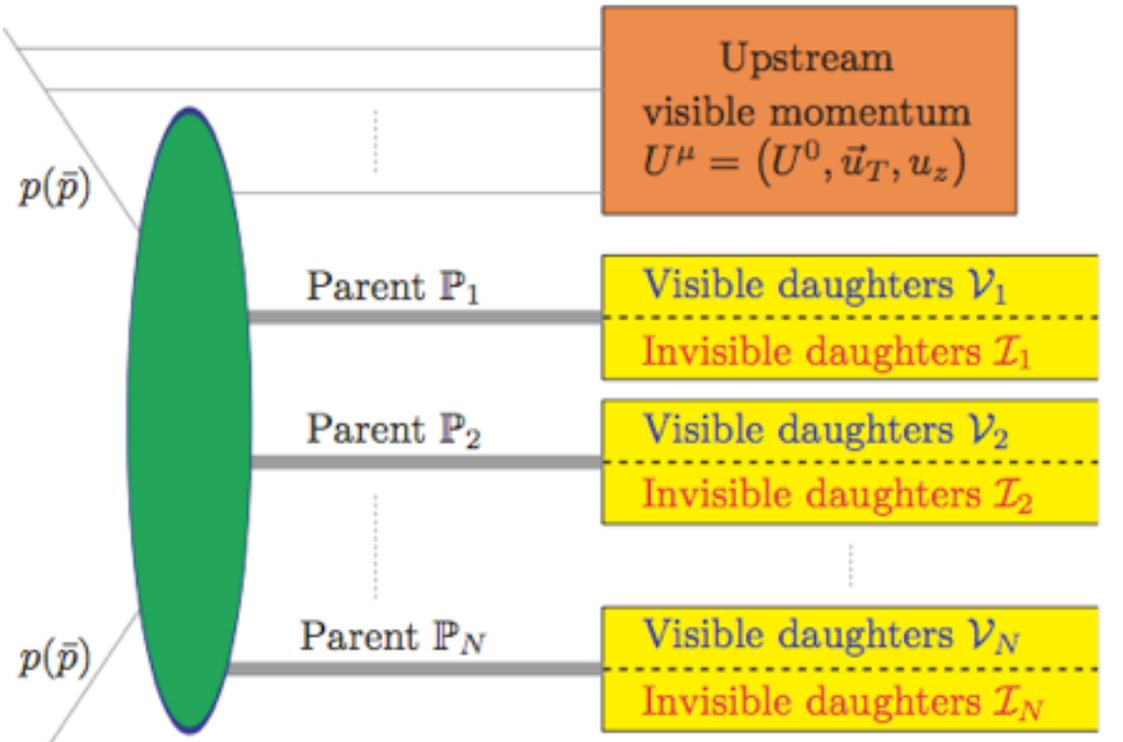

A. J. Barr, T. J. Khoo, P. Konar, K. Kong, C. G. Lester, K. T. Matchev and MP
arXiv:1105.2977[hep-ph]

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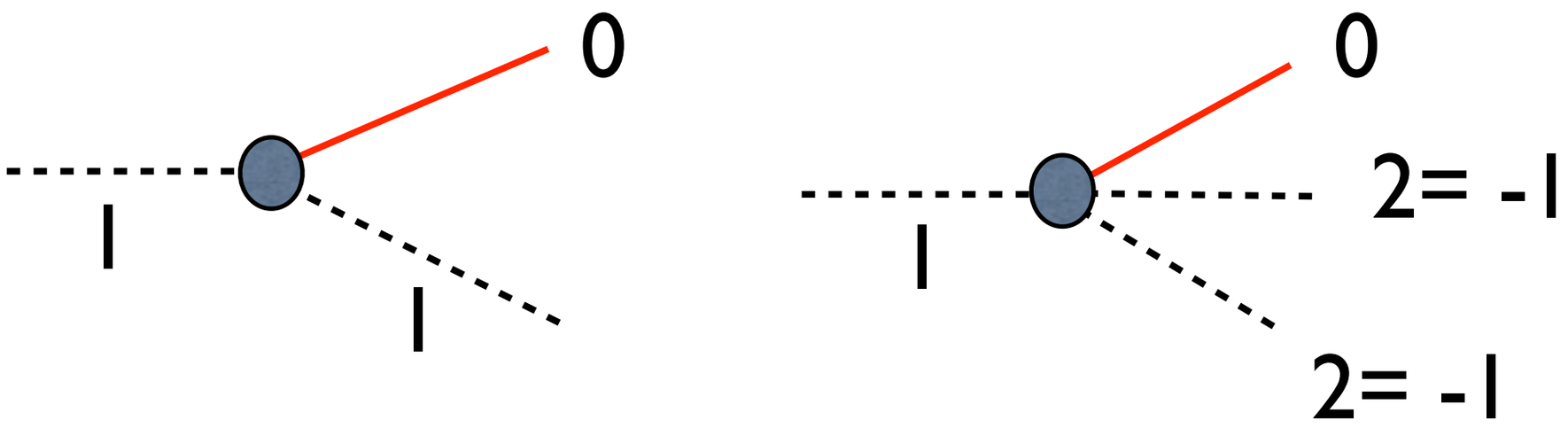
Your favorite model's signature@LHC may NOT BE UNIQUE.

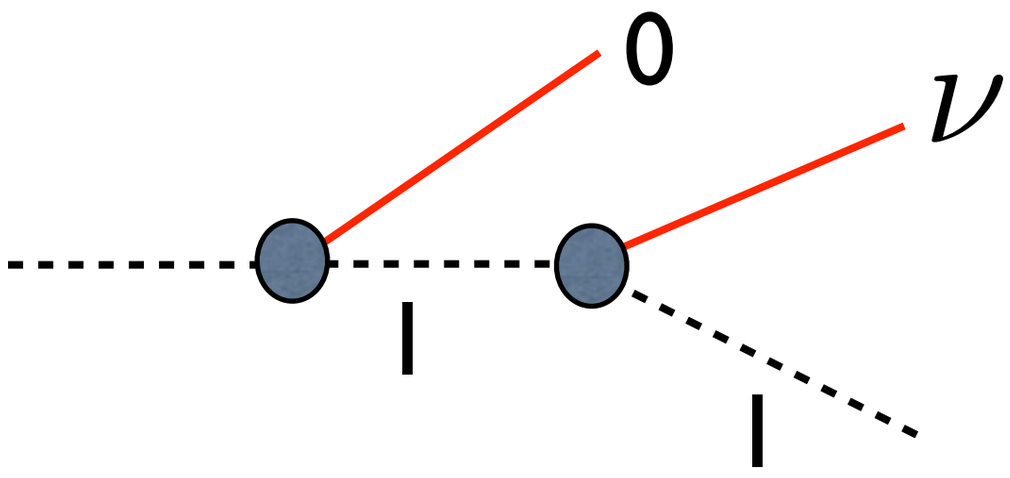
Dark matter (DM) ?

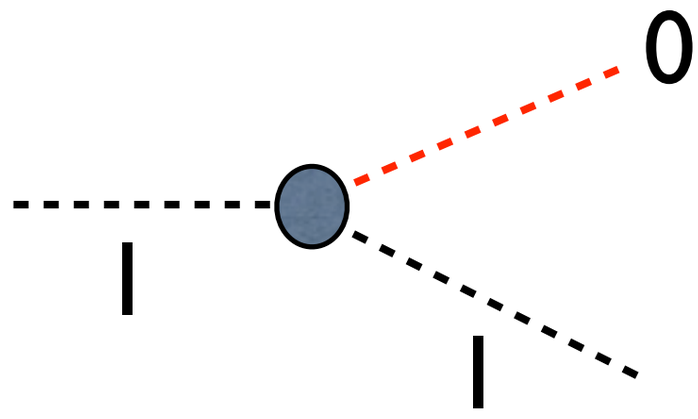
- Maybe, there are more than one DM particle (For example Z3 symmetry)
  - Kaustubh Agashe, Doojin Kim, Devin G. E. Walker, Lijun Zhu (arXiv:1012.4460) : collider study



Dark matter (DM) ?

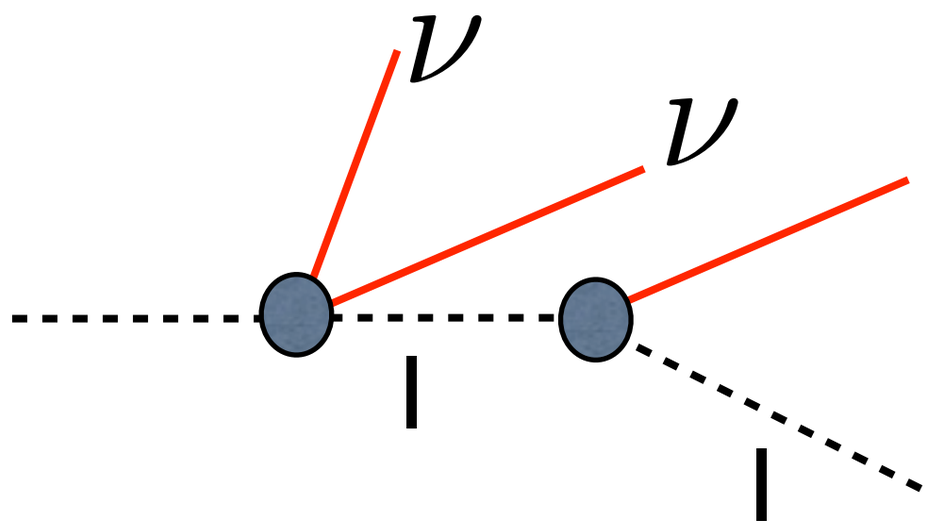
- "Effective" Dark matter at the LHC?
  - NLSP decays invisibly (LSP+neutrino)
  - Soft visible particles, not reconstructed.





Dark matter (DM) ?

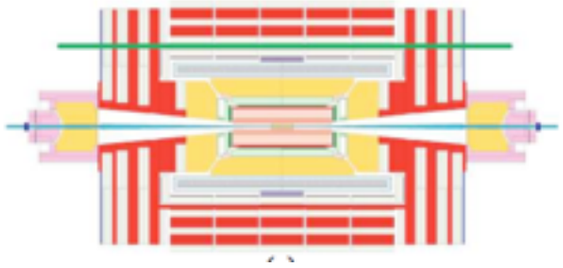
- Undetected guys OR Errors
  - Neutrino(s) from W/ Z

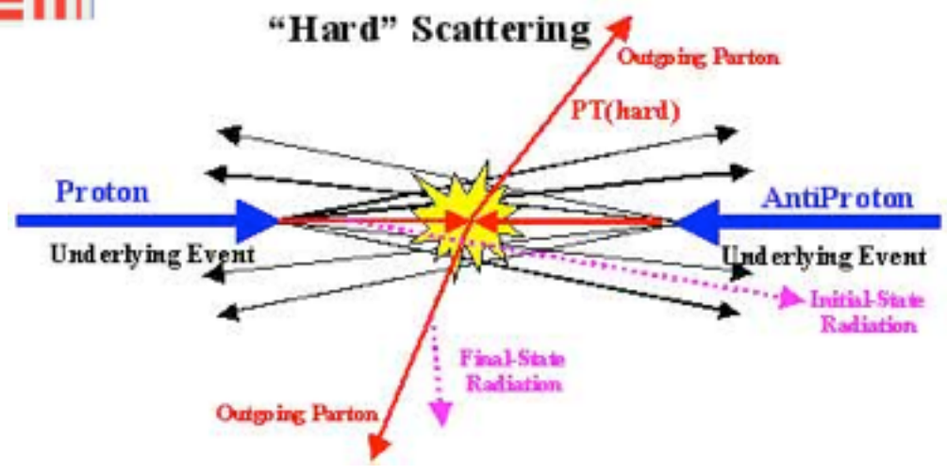


- Errors on the measurement of Missing Transverse Energy (MET)

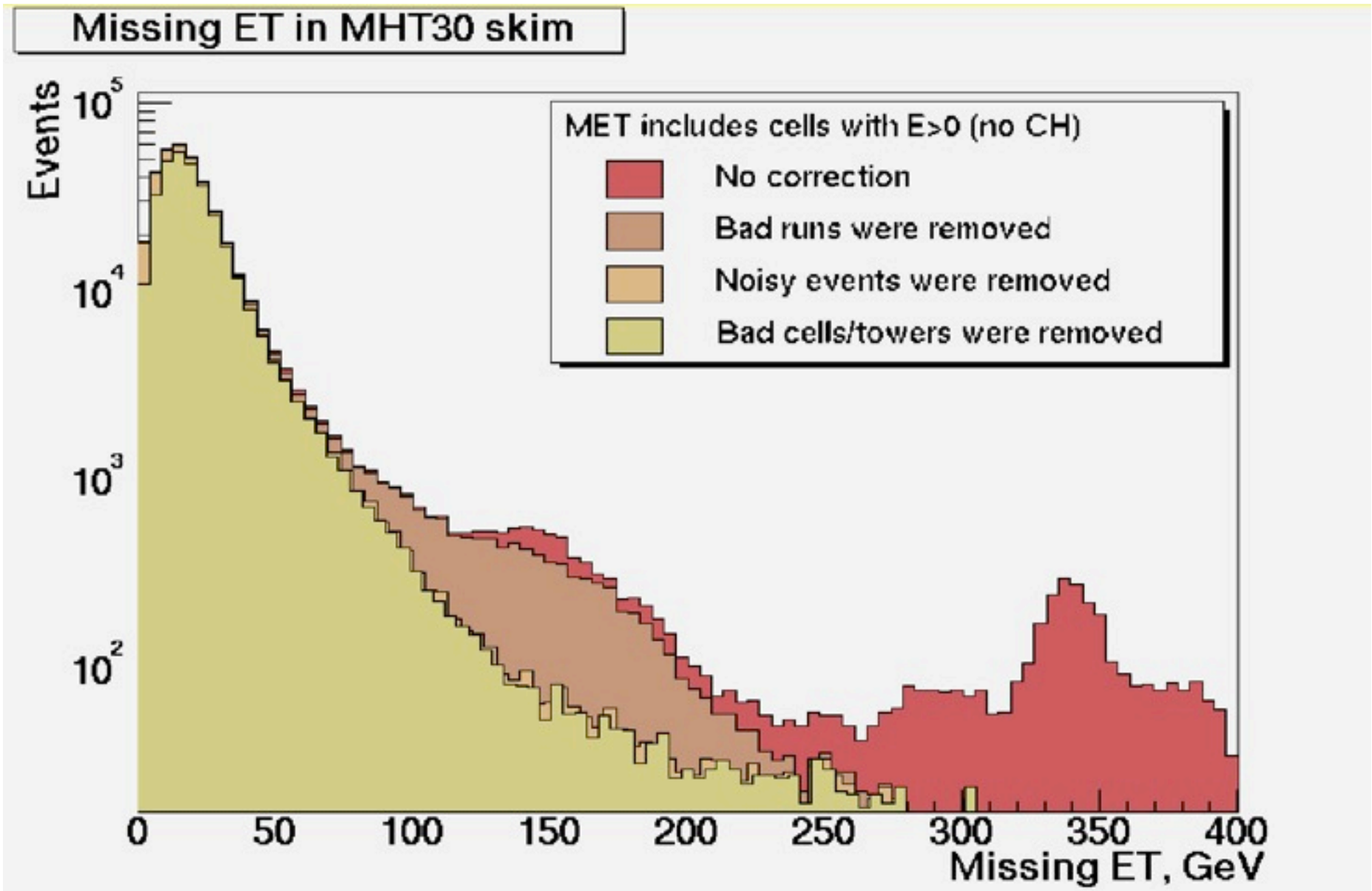
Wrong MET

- momentum mismeasurement
- detector malfunction, spike, dead cell
- cosmic-ray
- beam-halo muon
- underlying events
- etc.

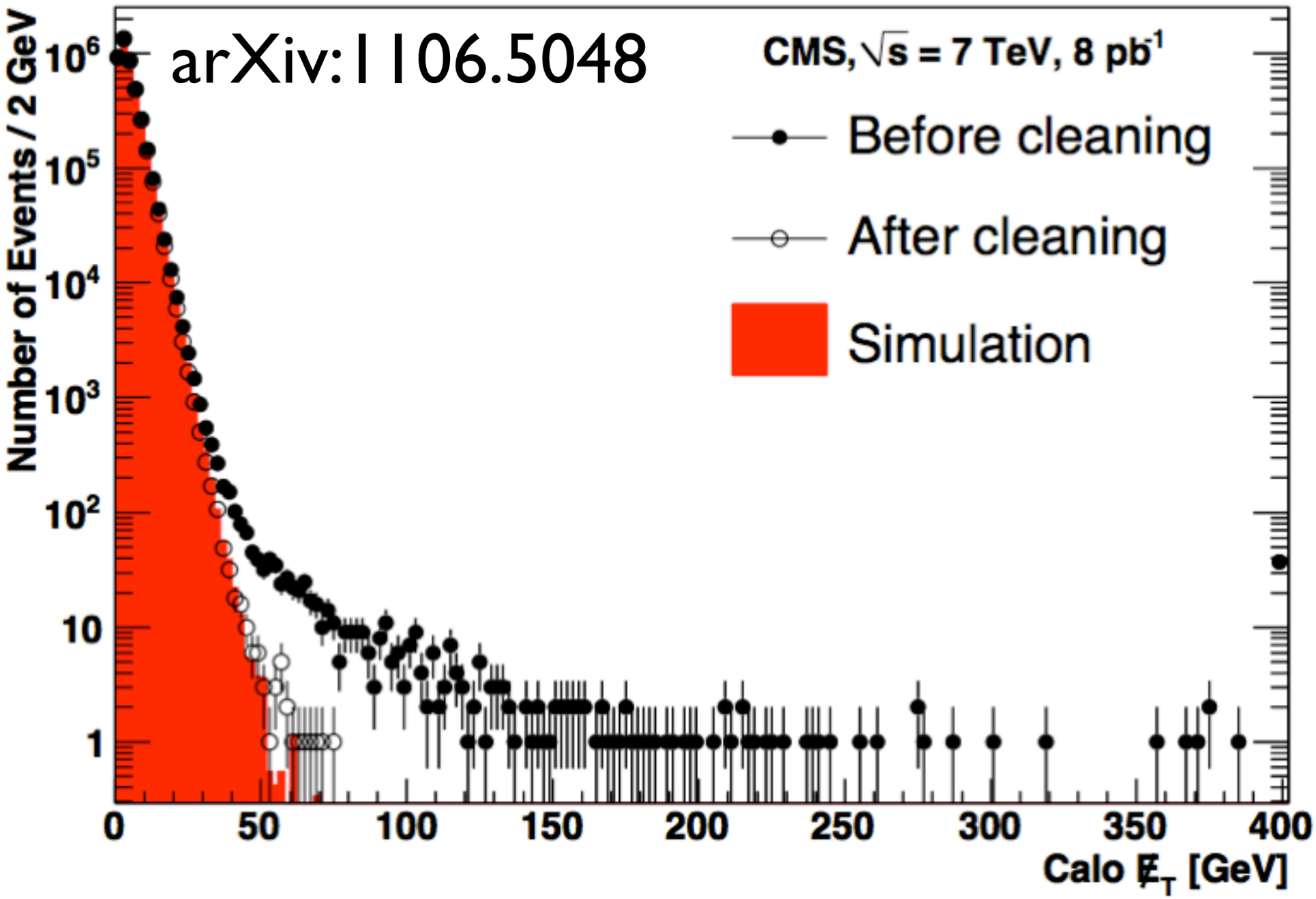




MET Cleaning from Tevatron



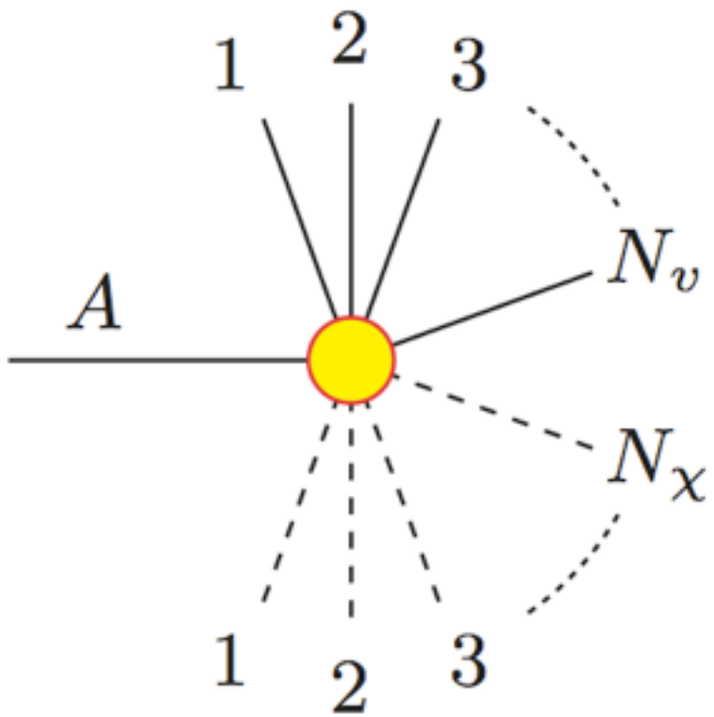
MET in CMS


arXiv:1106.5048
CMS, √s = 7 TeV, 8 pb-1
Before cleaning
After cleaning
Simulation
Number of Events / 2 GeV
10^6
10^5
10^4
10^3
10^2
10
1
0
50
100
150
200
250
300
350
400
Calo E_T [GeV]

Old technique

- "invariant mass distribution of visible particles"

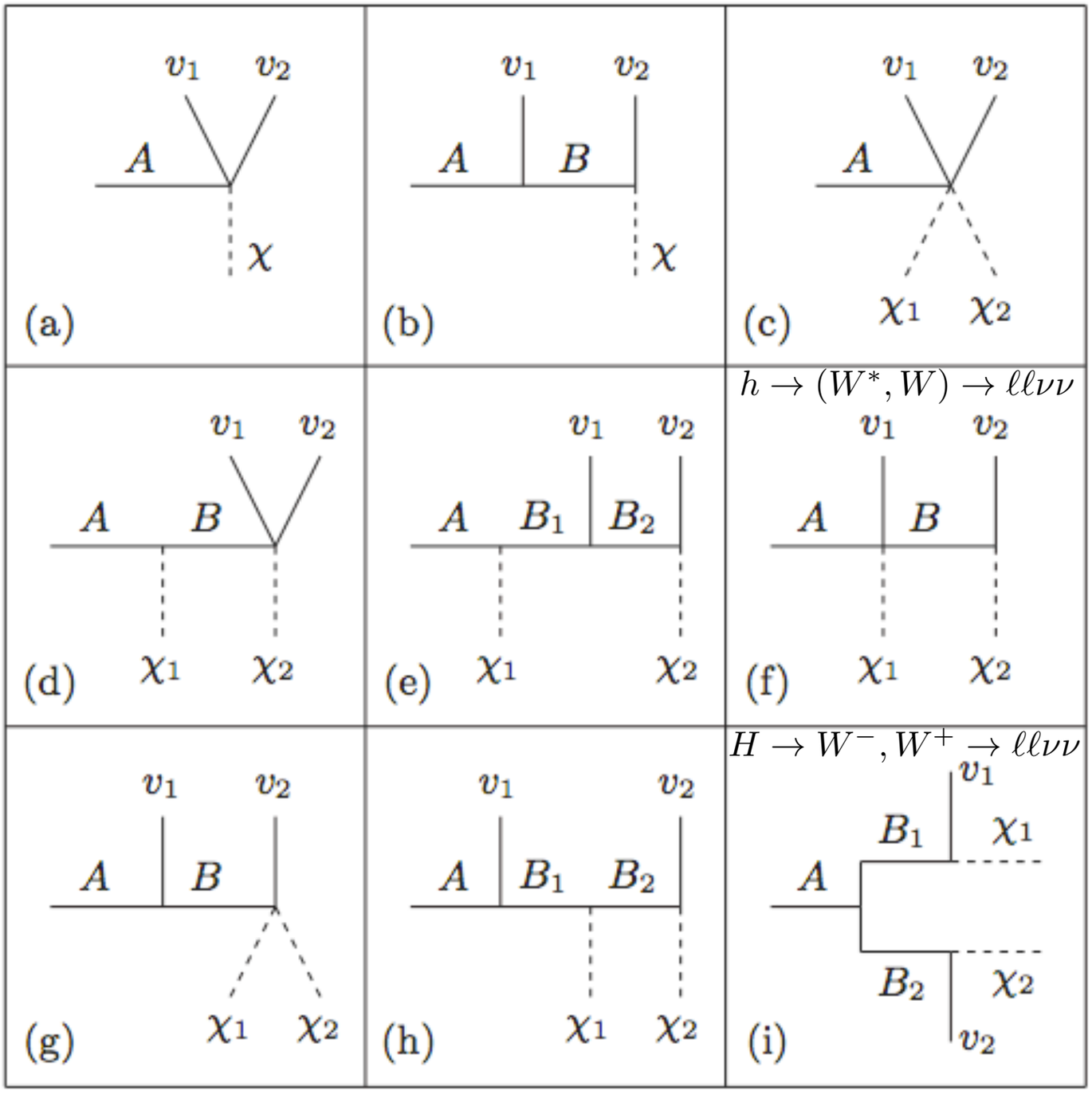
	N_χ				
N_v	1	2	3	4	5
1	1	2	4	8	16
2	2	7	20	55	142
3	4	20	78	270	860
4	8	55	270	1138	4294



Won Sang Cho, Doojin Kim, Konstantin T. Matchev, M.P
arXiv:1206.1546[hep-ph]

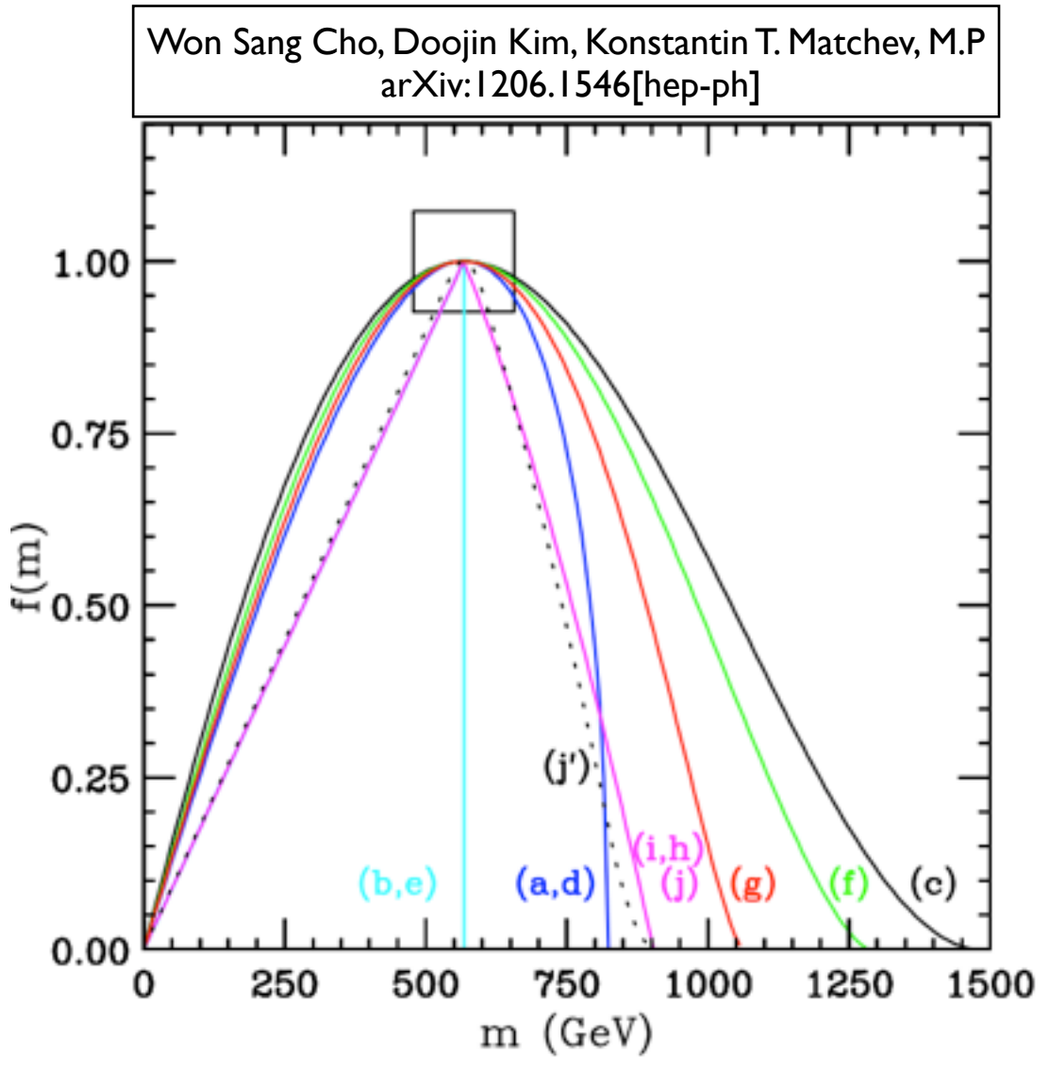
1. It does not rely on MET
2. Various techniques have developed to remove backgrounds.
3. Immune to uncertainties of LHC(PDF)
4. But depends on spins of particles... Require more than simple kinematics.

Example:two visible

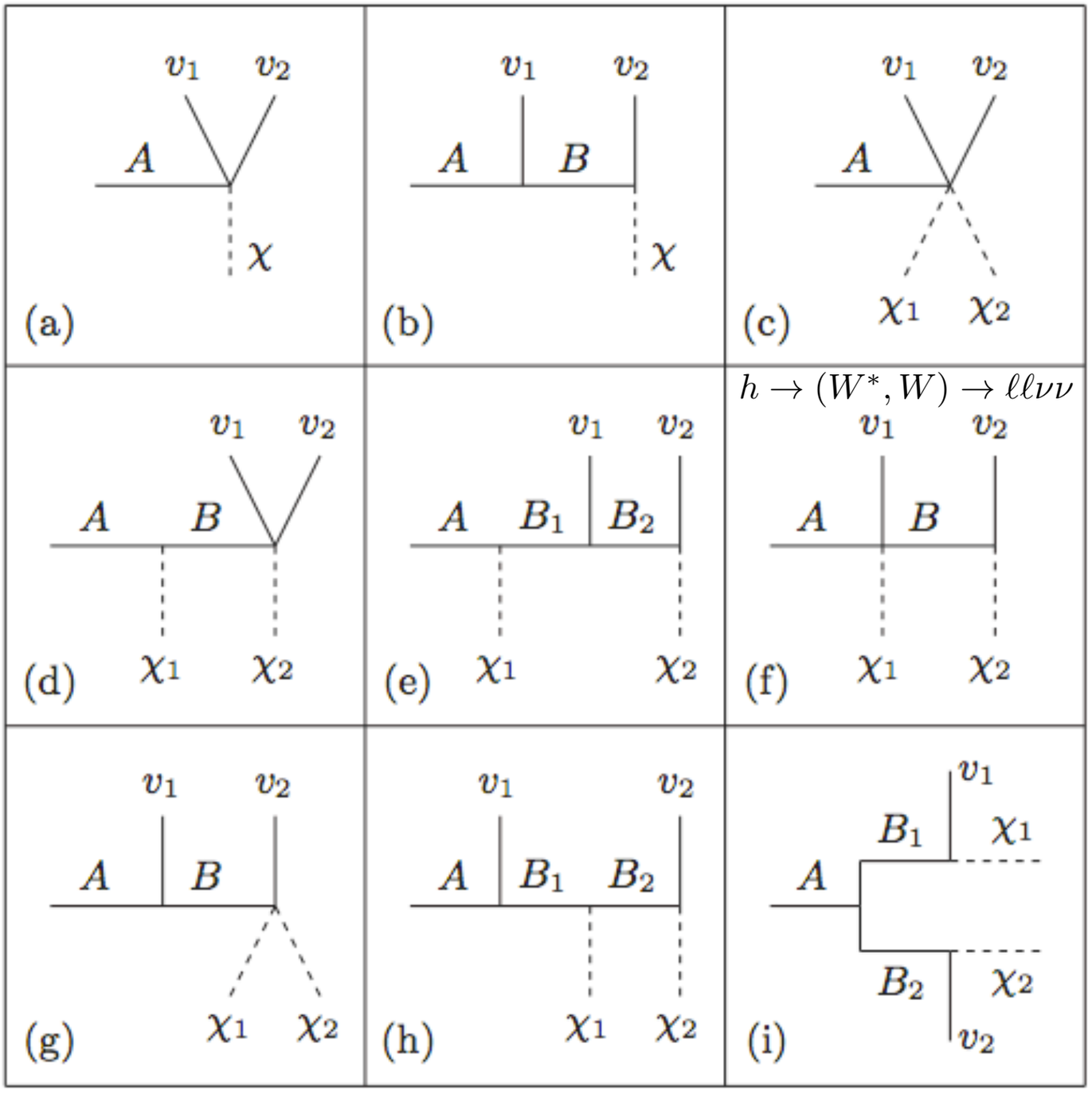


We want to focus on the PEAK location and the curvature (R2) at the PEAK

Won Sang Cho, Doojin Kim, Konstantin T. Matchev, M.P
arXiv:1206.1546[hep-ph]



Example:two visible



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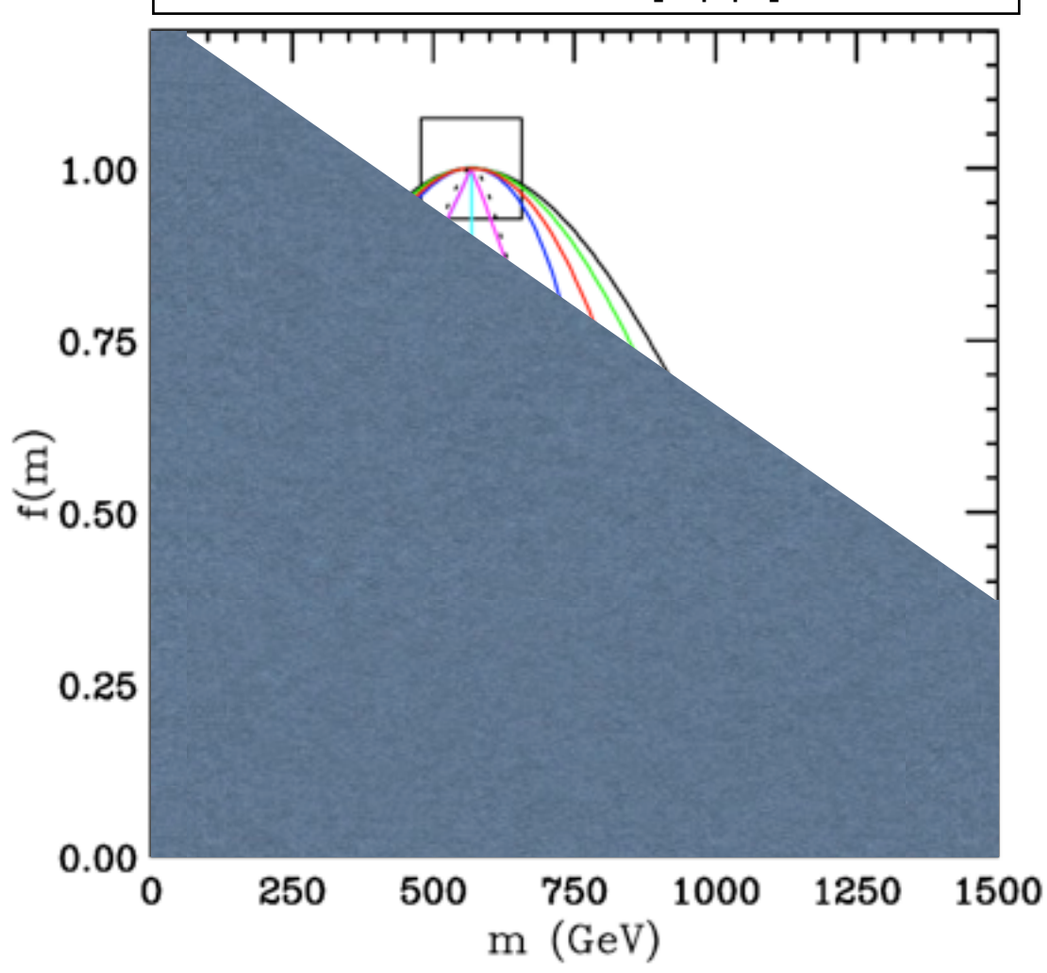
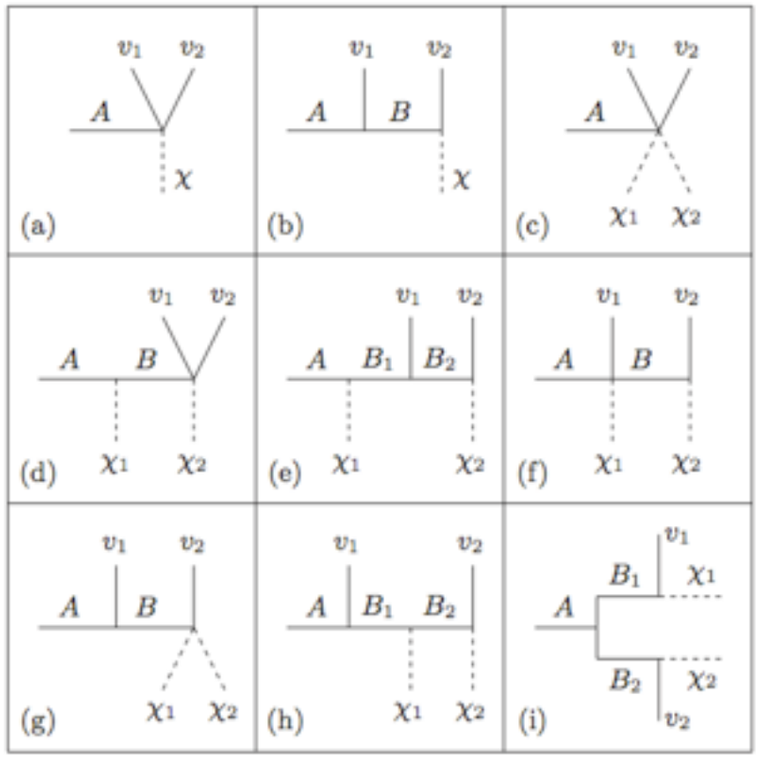
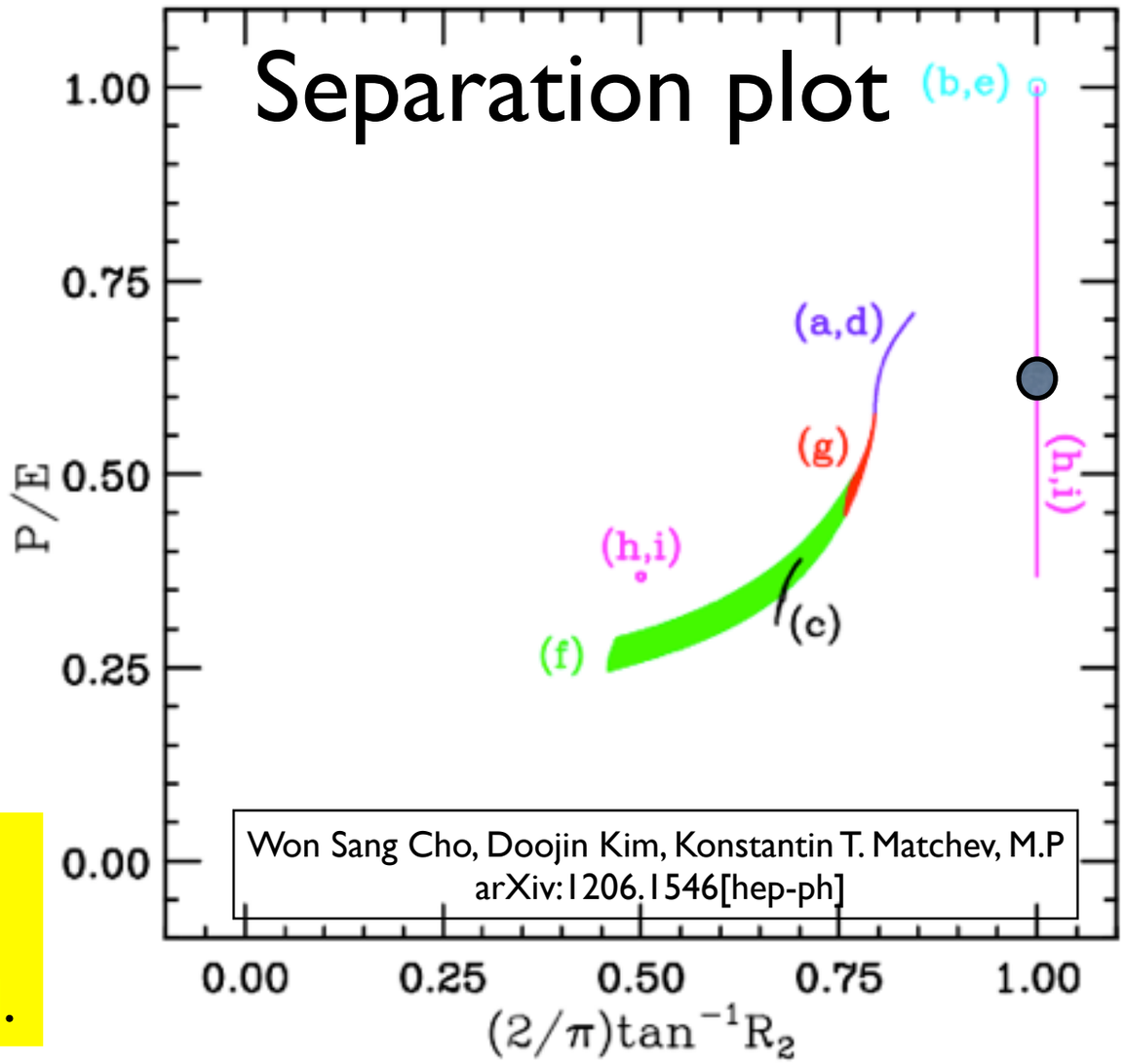


Separating Power





Number of events that
we need to have to discriminate
topology with 97% confidence level.

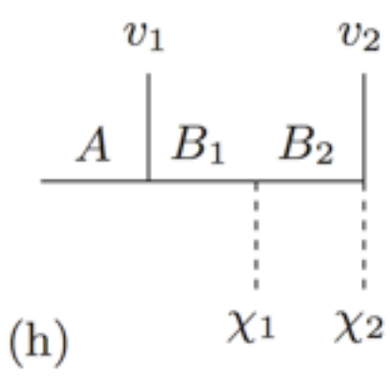
study pt: SUSY Z', arXiv:0906.5009, (Mz', slepton, LSP) = (1.5TeV, 730Gev, 100GeV)

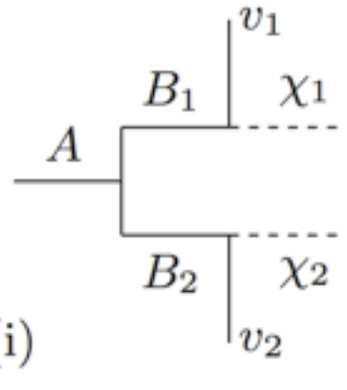
Data	(a,d)	(b,e)	(c)	(f)	(g)	(h,i)
(i)	698	37	96	275	698	∞

Measurement

- Attempt to measure all mass spectra with the shape of the invariant mass distribution.
- Number of mass parameter (Nm)
  Number of independent parameters in the distribution (Np) $N_m \leq N_p$

Topology	(a,d)	(b,e)	(c)	(f,g)	(h,i)
N_m	2	3	3	4	5
N_p	2	1	3	3	2



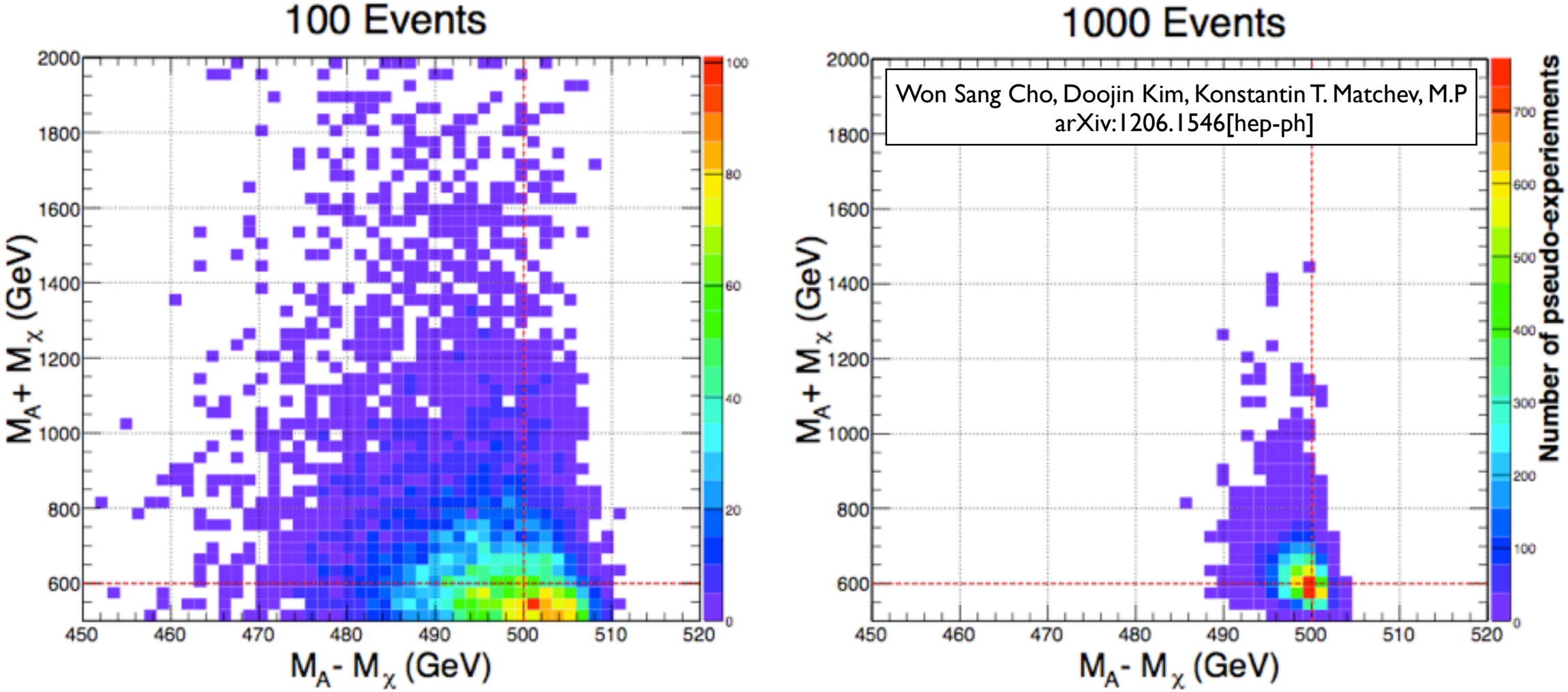


$$f(m) \sim \begin{cases} \eta\, m, & 0 \leq m \leq e^{-\eta} E, \\ m \ln(E/m), & e^{-\eta} E \leq m \leq E, \end{cases}$$

$$\eta \equiv \cosh^{-1}\left(\frac{M_{B_1}^2 + M_{B_2}^2 - M_{\chi_1}^2}{2 M_{B_1} M_{B_2}}\right),$$

for (i) $M_{B_1} = M_{B_2}$ and $M_{\chi_1} = M_{\chi_2}$.

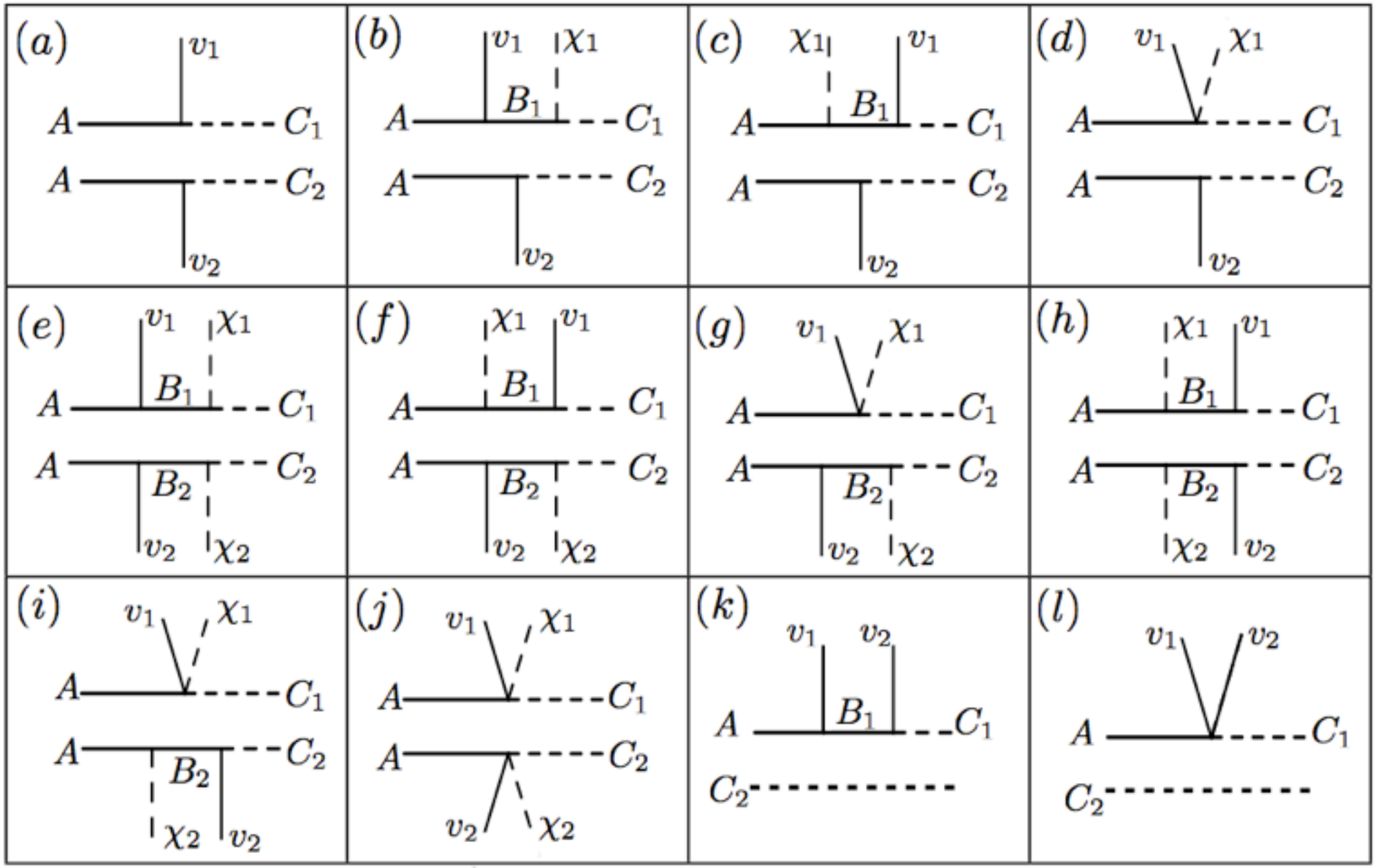
Measurement



Three-body decay chain:
10,000 pseudo experiments

Utilize MET

- Double-legs event-topologies



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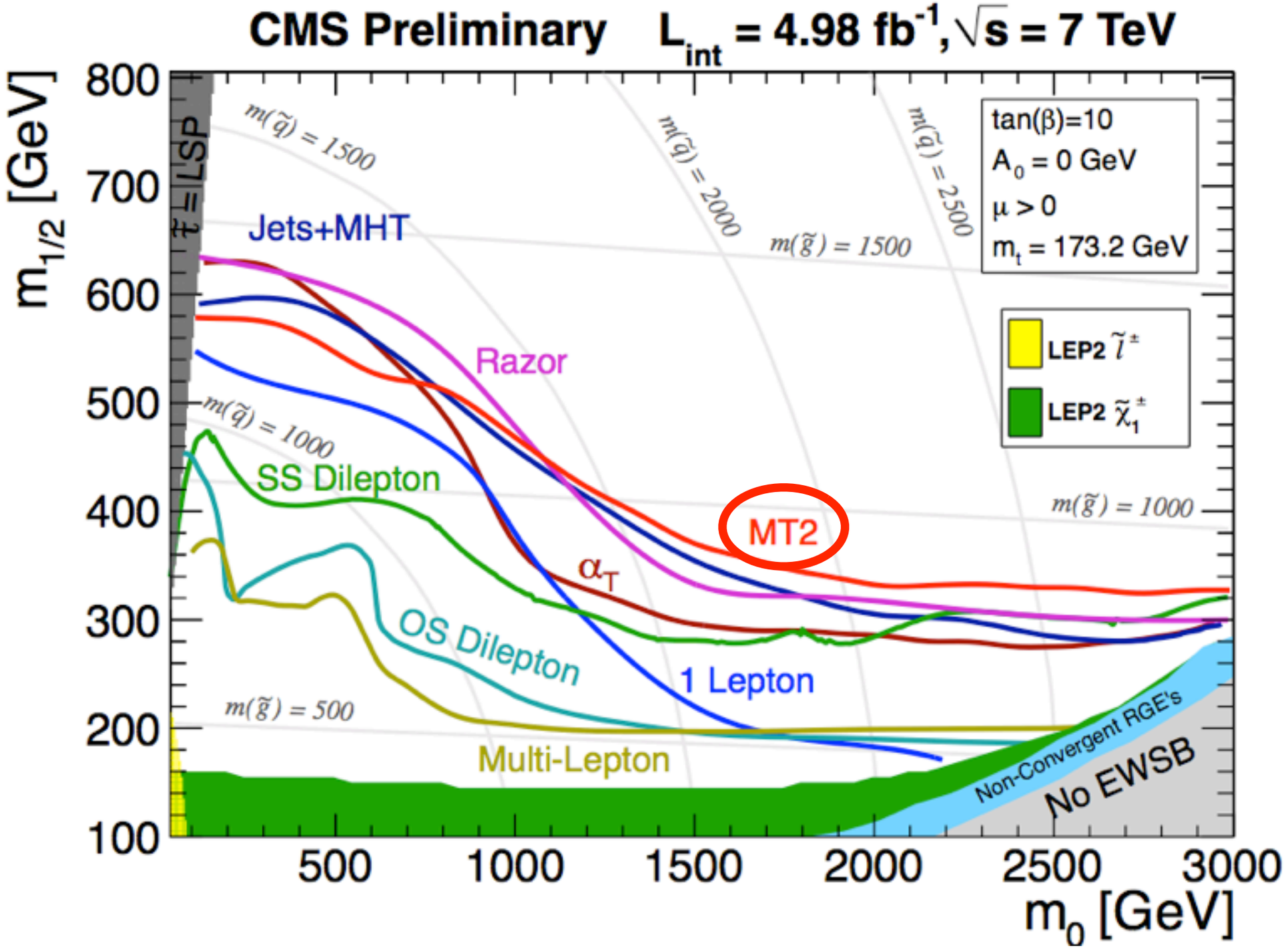
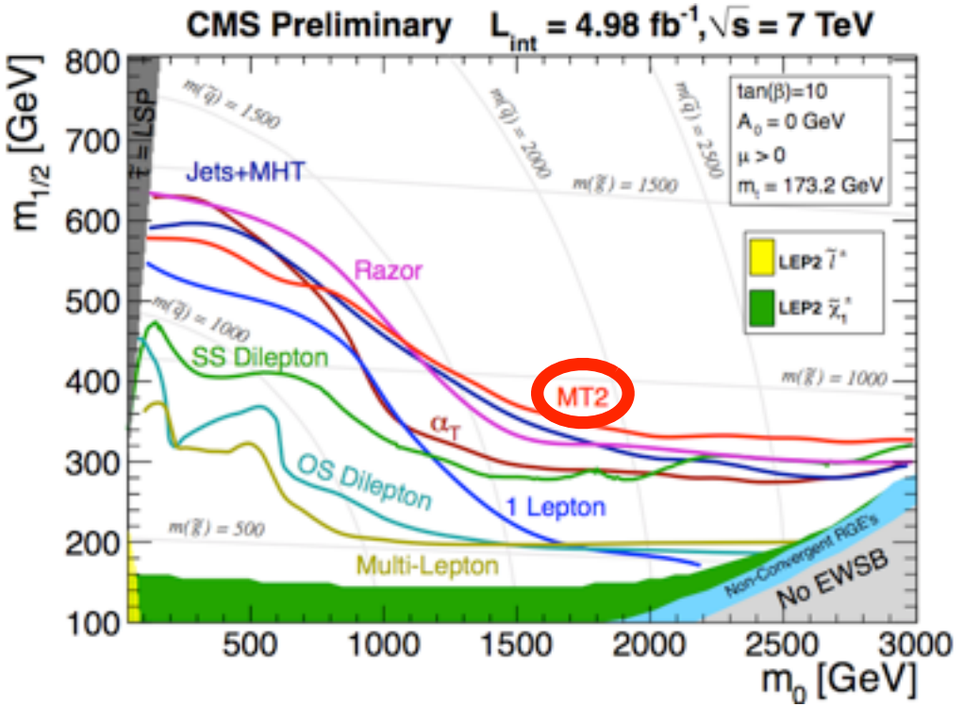
Utilize MET


CMS Preliminary L_int = 4.98 fb^-1, √s = 7 TeV
m_1/2 [GeV]
m_0 [GeV]
800
700
600
500
400
300
200
100
500
1000
1500
2000
2500
3000
τ̃ = LSP
m(q̃) = 1500
m(q̃) = 2000
m(q̃) = 2500
m(g̃) = 1500
m(q̃) = 1000
m(g̃) = 1000
m(g̃) = 500
Jets+MHT
Razor
MT2
α_T
SS Dilepton
OS Dilepton
1 Lepton
Multi-Lepton
tan(β)=10
A_0 = 0 GeV
μ > 0
m_t = 173.2 GeV
LEP2 l̃^±
LEP2 χ̃_1^±
Non-Convergent RGE's
No EWSB

Utilize MET



$$H_T = \sum E_T,$$

$$HET = |-\sum \vec{P}_T|,$$

$$\alpha_T = \frac{E_J^{2nd}}{\sqrt{H_T^2 - HET^2}} = \frac{E_J^{2nd}}{M_T},$$

$$R = \frac{M_T^R}{M_R},$$

$$M_{T2} = \min\left(\max\{M_{T_1}, M_{T_2}\}\right).$$

- alphaT and Razor are good to suppress QCD multi jets corruptions to MET events. (No finite endpoint structure, Some characteristic # to cut backgrounds.)
- MT2 has a finite endpoint for SM backgrounds. (A.Barr arXiv:0907.2713)

Utilize MET

- We investigate ATLAS MT2 variable.
  - Original MT2 had assumptions:
  a) Same mother particles.
  b) Same DM particles at the end of decay chain.
  c) No rigorous studies about additional METs
  (For example, from neutrino)

- a) was removed by Alan J. Barr et.al (arXiv:0908.3779)
  b) was removed by Partha Konar et.al (arXiv:0911.4126)
  c) was studied by C.Lester et.al (hep-ph/0304226)

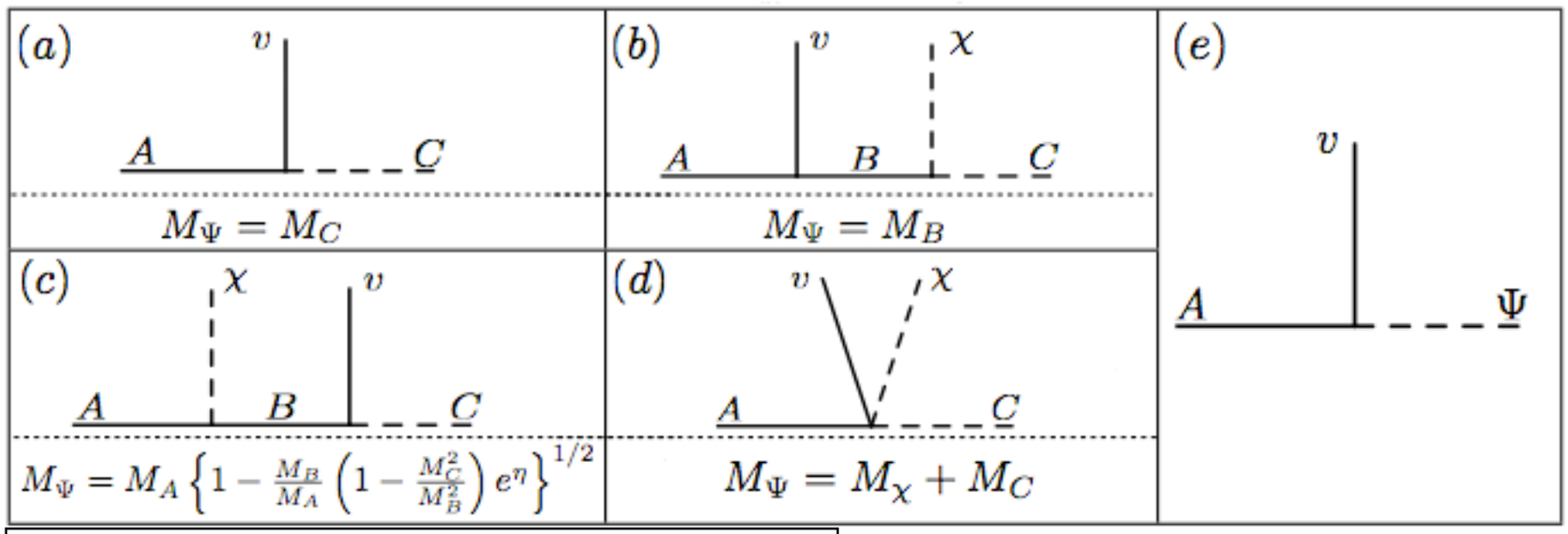
- Need to be revisited with original MT2 variable.
  - Not to be biased by assumptions.
  - Need to understand behavior of variables in various situations.

MT2

- Various contributions from all over the world.
  - Cambridge: Parents of MT2
  - Oxford: In detail study of MT2
  - ATLAS: Analyses
  - KAIST : Realization of "kink" feature of MT2, MAOS
  - KEK: Various in-depth phenomenological studies of MT2
  - U.C.Davis : New interpretation of MT2 as kinematical bound
  - U.Florida : Generalizations, link to CMS
  - CMS: Analyses
  - Cornell : TTbar di-leptonic analysis@LHC
  - ETHZ : CMS MT2 analysis
  - CDF : Top quark measurement@Tevatron
  - D0
  - Even more vivid contributions.
- Now, MT2 is one of the standard variables in MET channels.

“effective MET”

- Replace a decay process with “effective” one: Giacomo Polesello, Daniel R. Tovey(arXiv:0910.0174) for the ATLAS MCT (contransverse mass)



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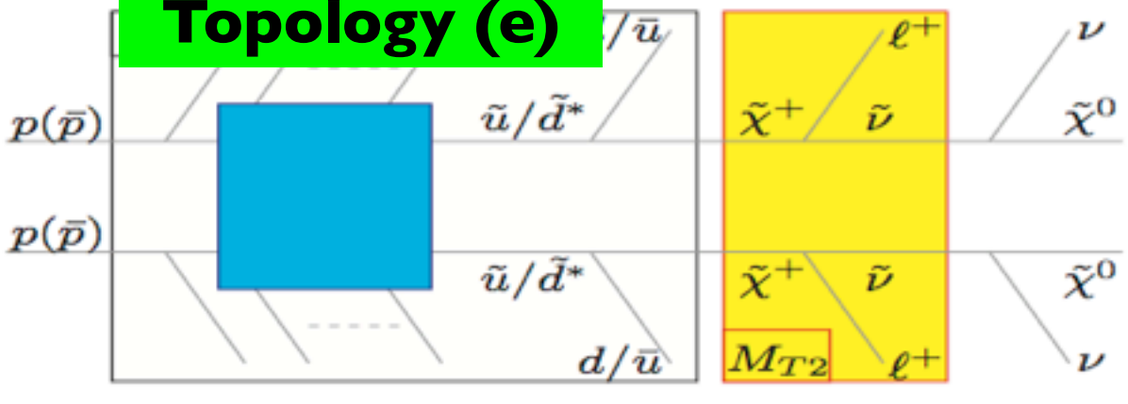
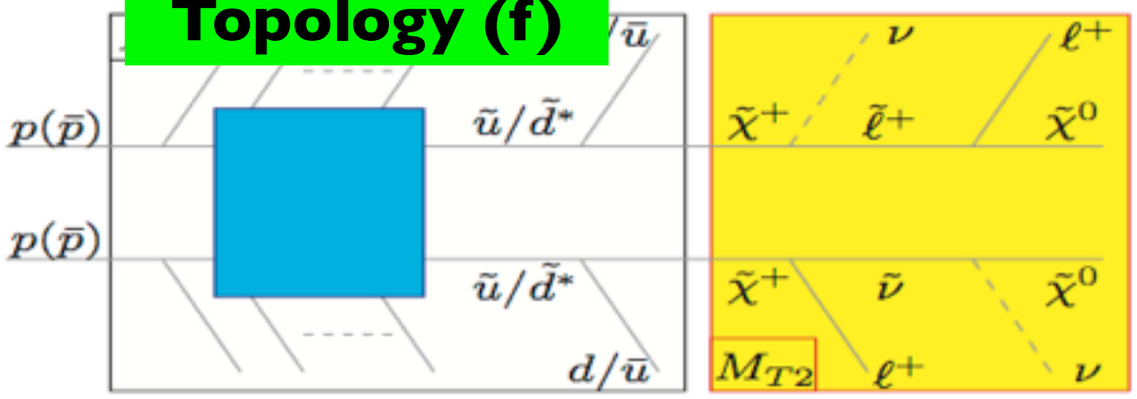
- Replace the original diagram with simple one who can give the same maximum configuration for the visible transverse momentum.

Application

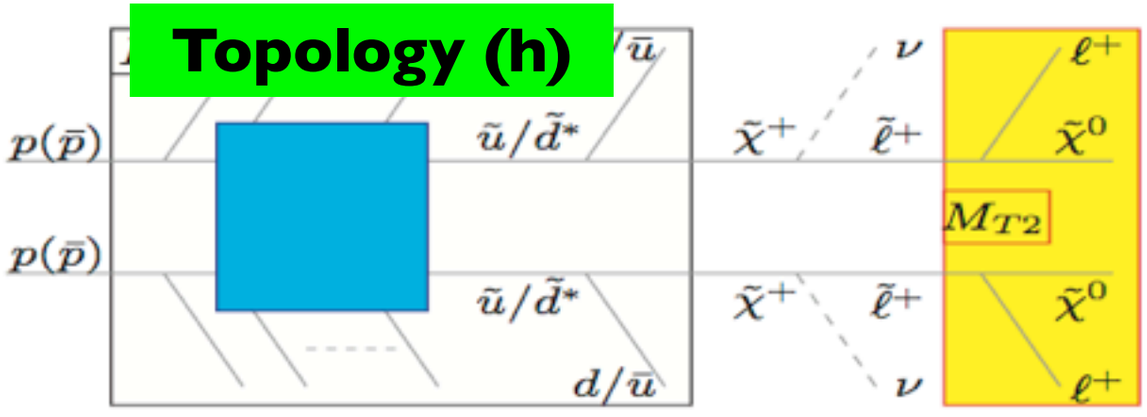
Topology (e)



Topology (f)



Topology (h)



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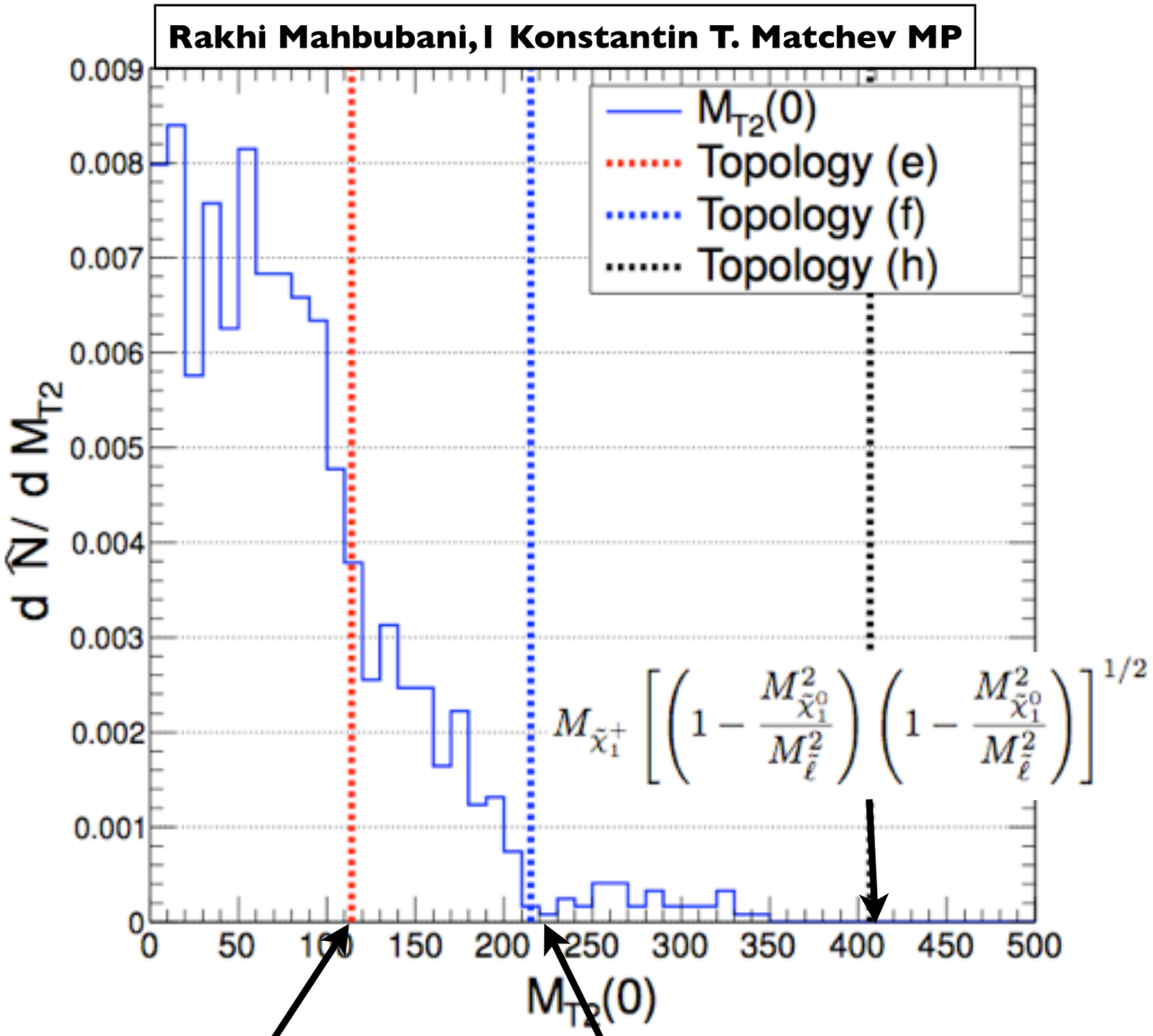

Conclusion

- Identifying the decay topologies based on the invariant mass distribution.
- Interpreting "original" MT2 to be unbiased and still to get useful information on the mass spectra.
- "Effective event topology" can be applied to various transverse variables which has the maximum configuration for the endpoints.

Back up

- Dependency on spin structure of invariant mass distribution:
  (i) antler topology
  VSF (e.g. MSSM) v.s. VFV (e.g. MUED) with S-channel vector (gamma/Z)

Lisa Edelhäuser, Konstantin T. Matchev arxiv:1205.2054