Heavy Charged Higgs@LHC

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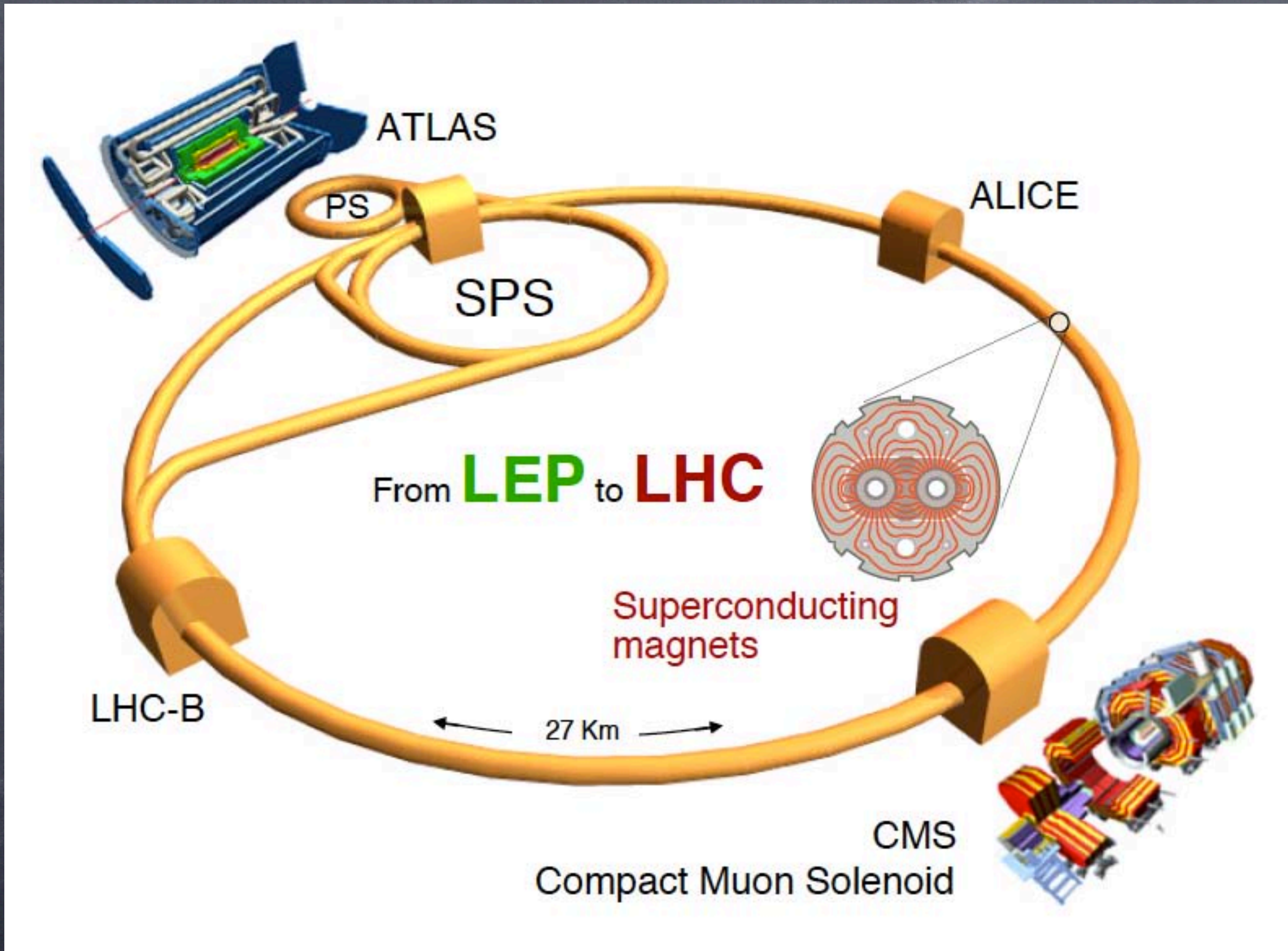
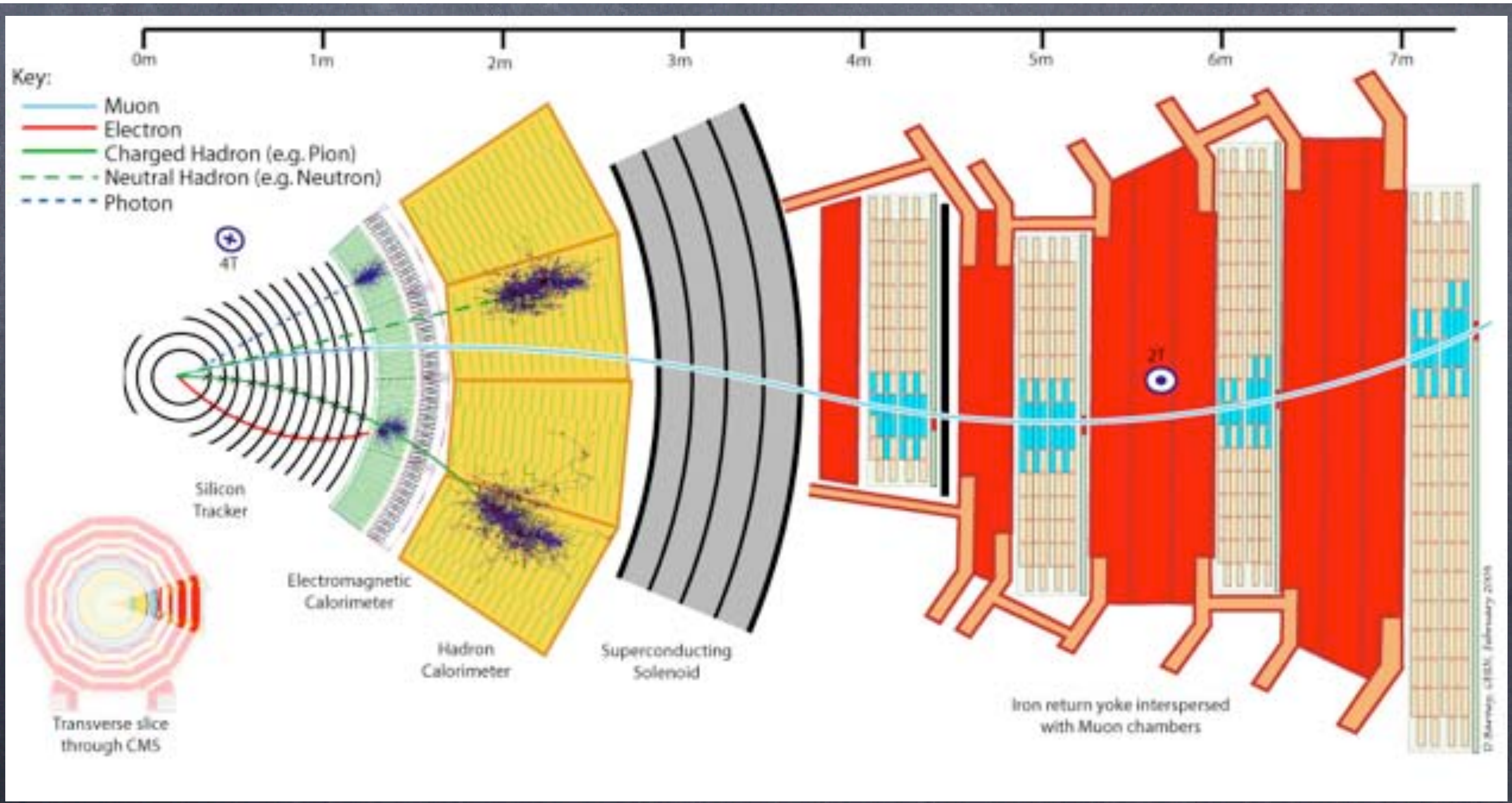
Outline

- 1. Why A Heavy Charged Higgs Boson?
- 2. What is jet/Substructure/top taggers?
- 3. Feasibility at the LHC with a Hybrid-R method
- 4. Conclusions



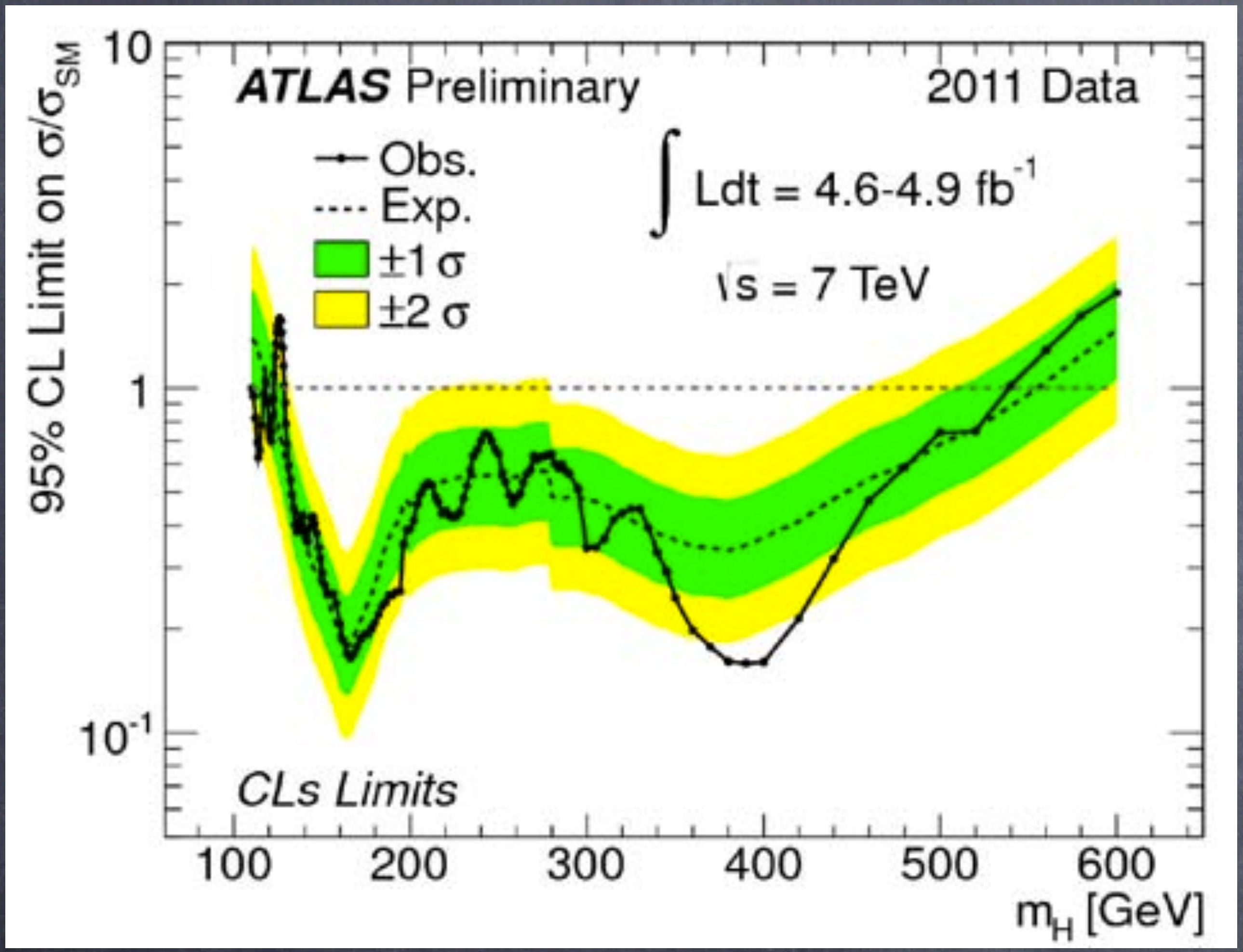
Collecting data 7TeV~5/fb, 8TeV~1/fb

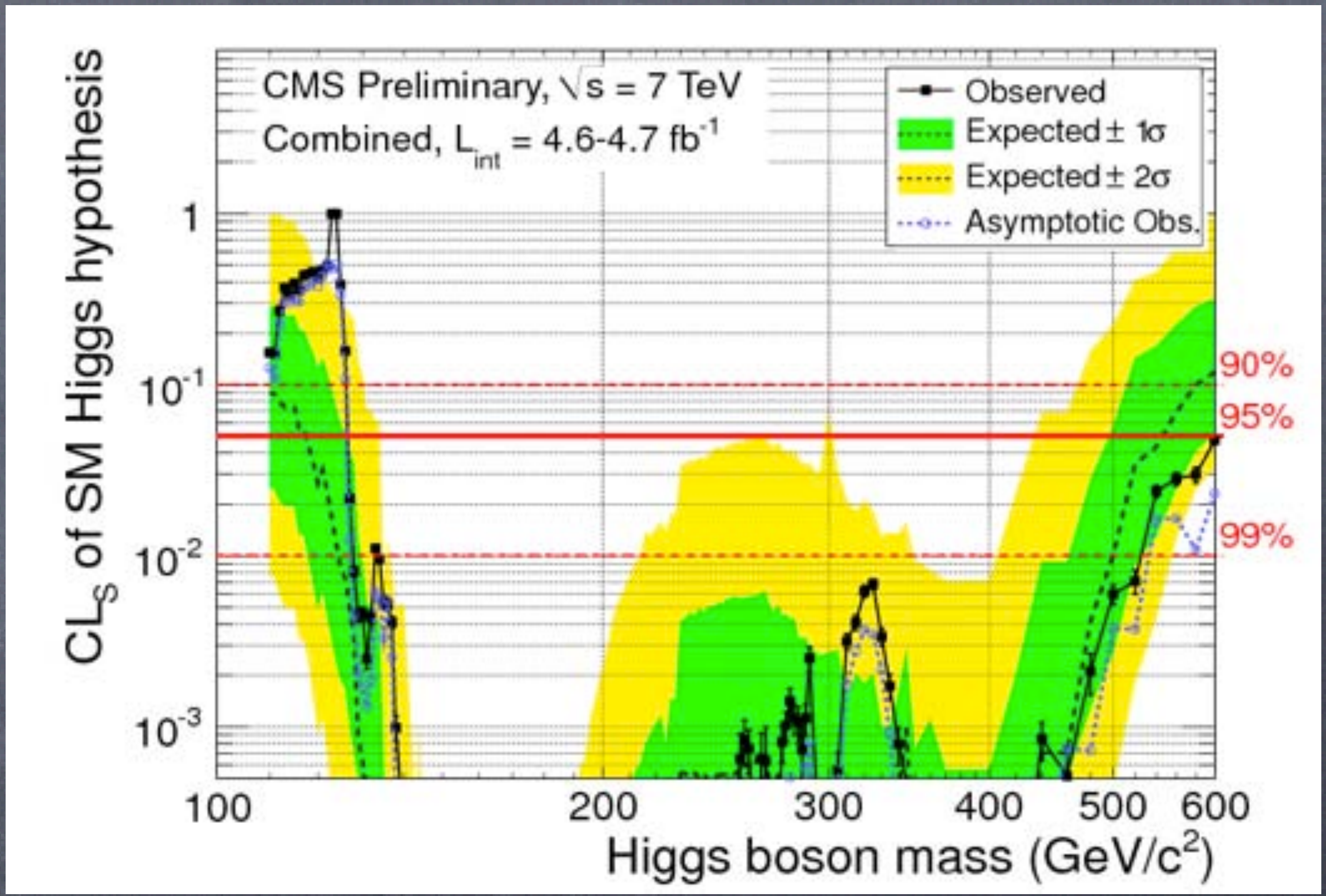
j	Jet	Cluster in EM and hadronic calorimeters (and inner tracker)
γ	Photon	EM cluster without matching track
e	Electron	EM cluster with matching track
μ	Muon	Matching tracks in inner and muon trackers
τ	Tau lepton	Narrow jet with matching track(s)
MET	Missing E_T	pT required to balance all of the above (and more)



CMS Detector as an example

1. Why A Heavy Charged Higgs Boson?



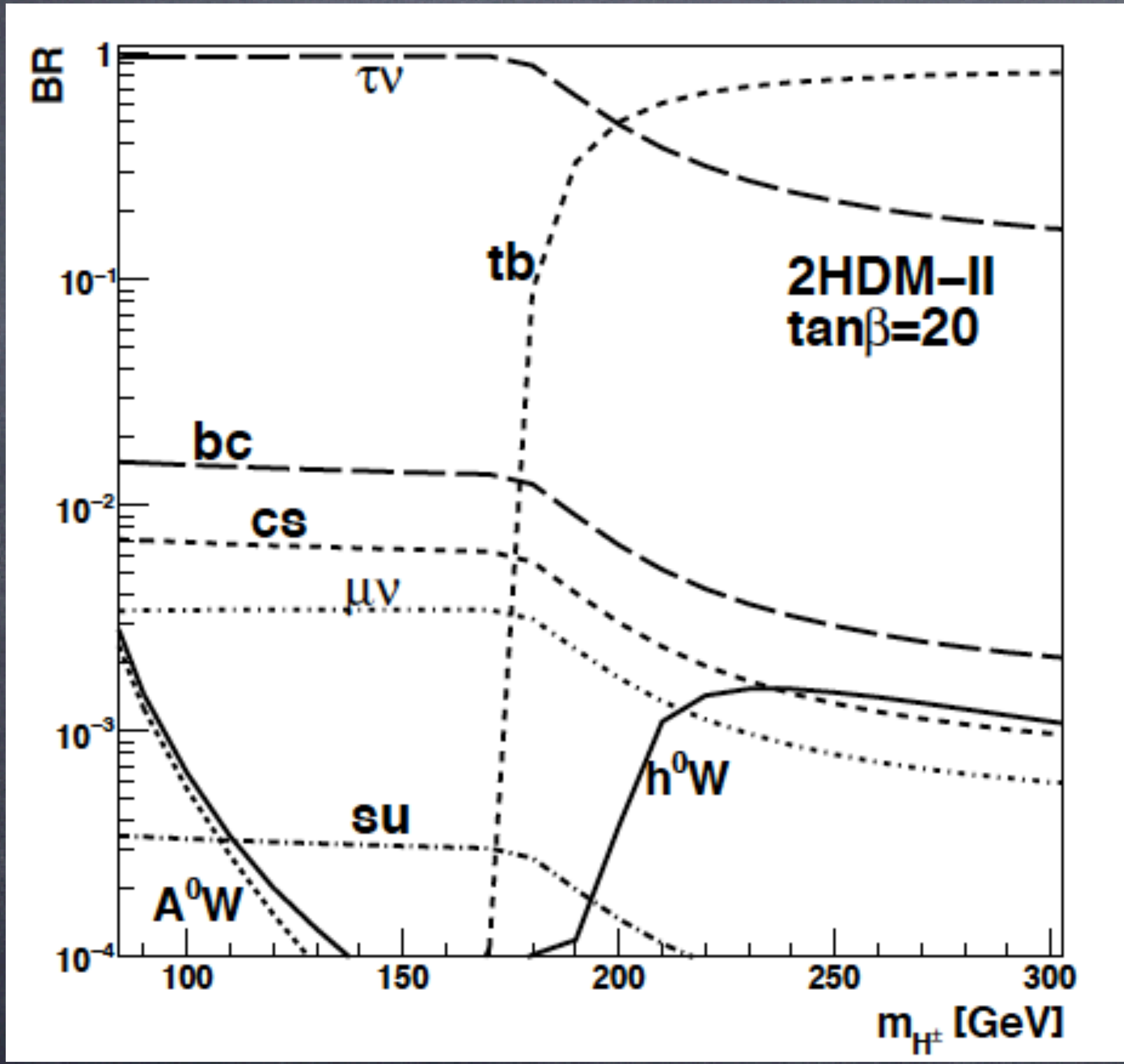


There are evidence for a light Higgs boson around 125 GeV. Whether the Higgs is SM-like? What's is the Higgs Sector?

1. Why Charged Higgs Boson(s)?

- Charge Higgs boson(s) are predictions of most of extension of the SM, i.e. 2HDM, MSSM, mutli-Higgs model, little Higgs models.
- Discovery charged Higgs boson(s) is the herald of New Physics.
- Discovery/Ruling-out of charged Higgs boson(s) is helpful to pinpoint the Higgs sector (EW symmetry breaking).

1. Why Heavy Charged Higgs Boson?



A Heavy Charged Higgs can dominantly decay to t+b (i.e. 2HDM-II) if m>800 GeV

- $H^\pm$ decay modes $M_{H^\pm} < m_t + m_b$, $M_{H^\pm} > m_t + m_b$:
  - $H^\pm \to \tau\nu_\tau$ $\quad H^\pm \to cs$ $\quad H^\pm \to t^* b \to W^\pm \bar{b}b$
  - $H^\pm \to A^0 W^\pm$ $\quad H^\pm \to h^0 W^\pm$ $\quad H^\pm \to tb$

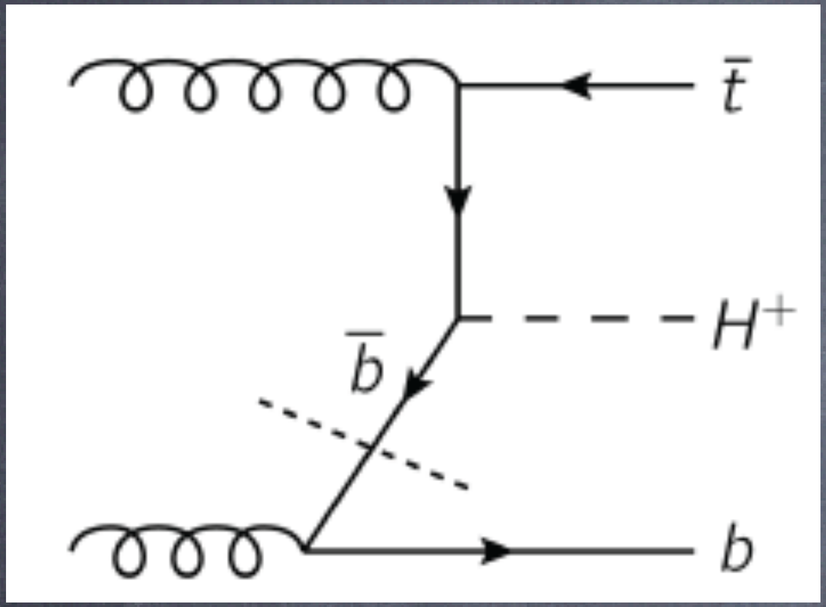
1. Why A Heavy Charged Higgs Boson?

Charged Higgs boson search

- For $m_{H^+} < m_t$, search for $t \to H^+ b$ in top pair decay. Tevatron set a limit for charged Higgs mass up to ~ 160.

- At LHC, the main production mechanism $gb \to tH^-$. Previous studies for charged Higgs search mainly forcus on **300-600GeV**
  $gb \to tH^- \to t\tau\bar{\nu}$
  $gb \to tH^- \to t\bar{t}b \to bqq\tau(\text{hadronic})\nu bb$
  $gb \to tH^- \to t\bar{t}b \to bqqb\ell\nu b$

1. Why A Heavy Charged Higgs Boson?What's New?



$$pp \to tH^- \to t\bar{t}b$$
$$pp \to tH^- b \to t\bar{t}bb$$

Test Field:
the full hadronic channel

Difficulties in previous study:

- Combinatorics is huge
- Lack of powerful observables to suppress background

New Things 800-1500GeV

- Combinatorics can be greatly reduced if the charged Higgs boson is heavy
- Powerful observables can be found after the full reconstruction

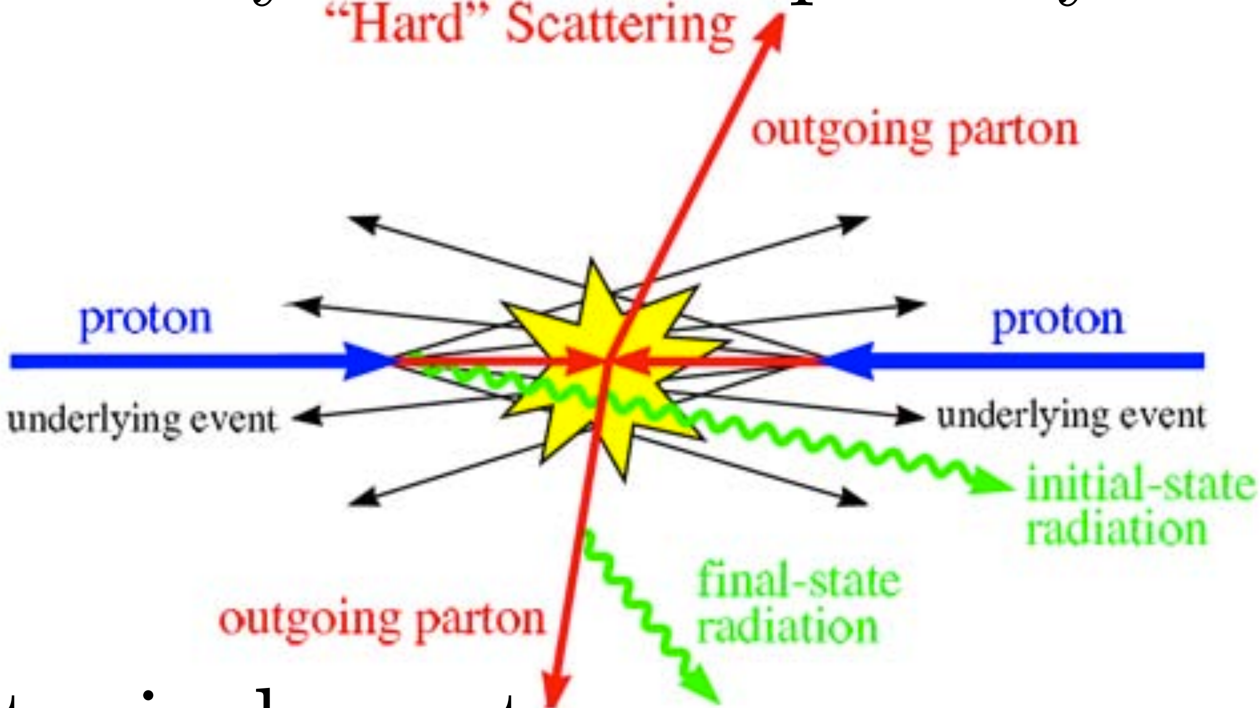
Although there are 7 or more objects in the final states (at parton level for our signals)

- The top from heavy charged Higgs boson decay will be captured by using top tagger(s). A larger cone
- The b quark from heavy charged Higgs boson is more energetic than jets from the associated top quark.
- The rest of jets will be used to reconstruct the associated top quark

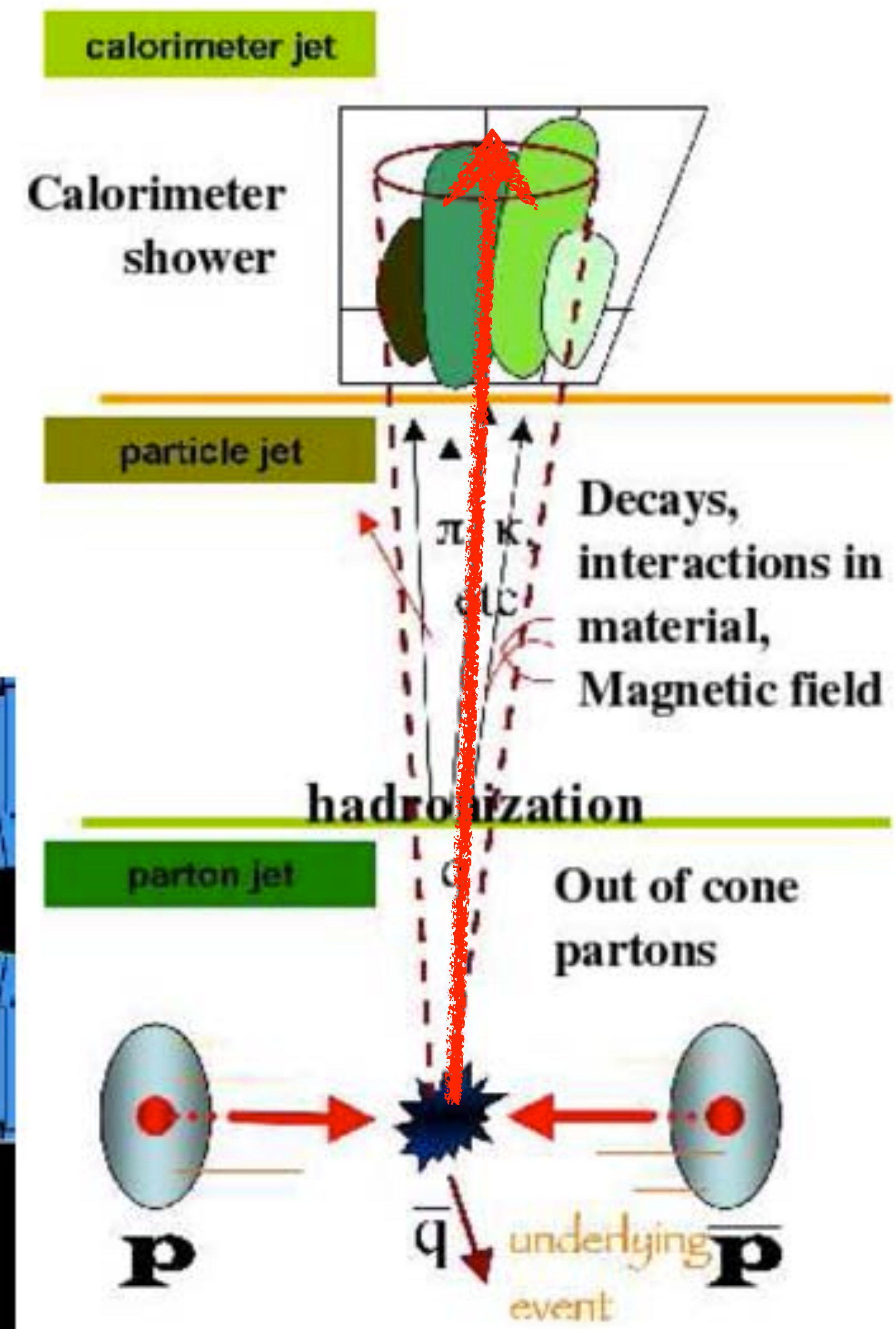
A smaller cone

Combinatoric issue can be overcome and mass bumps can be reconstructed.

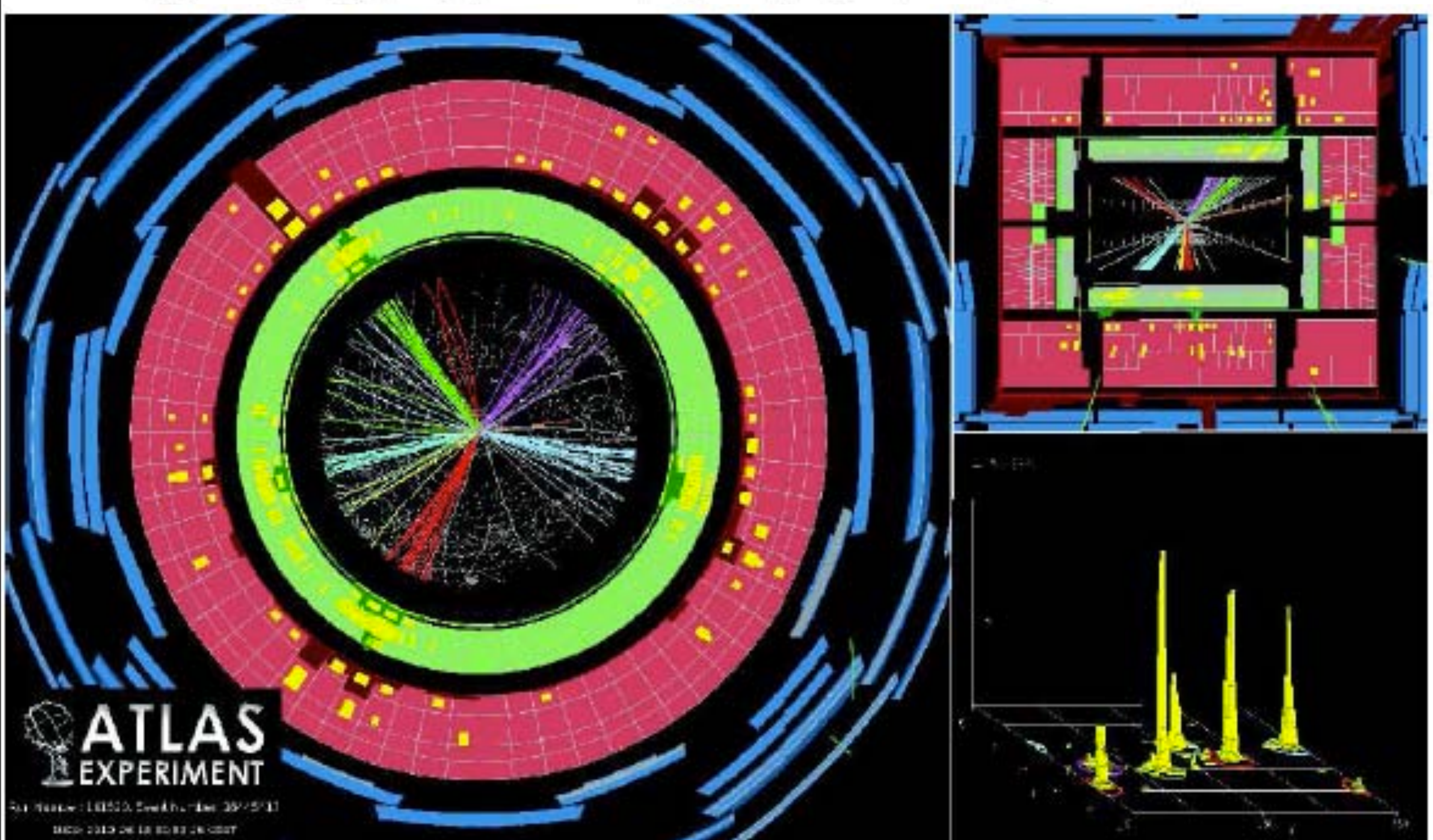
Hardon partons are produced, i.e. by $H^{\pm}$ and top decay



A hard parton's evolution



A typical event



2. What's a Jet??

Towards Jetography: 0906.1833,G.P.Salam

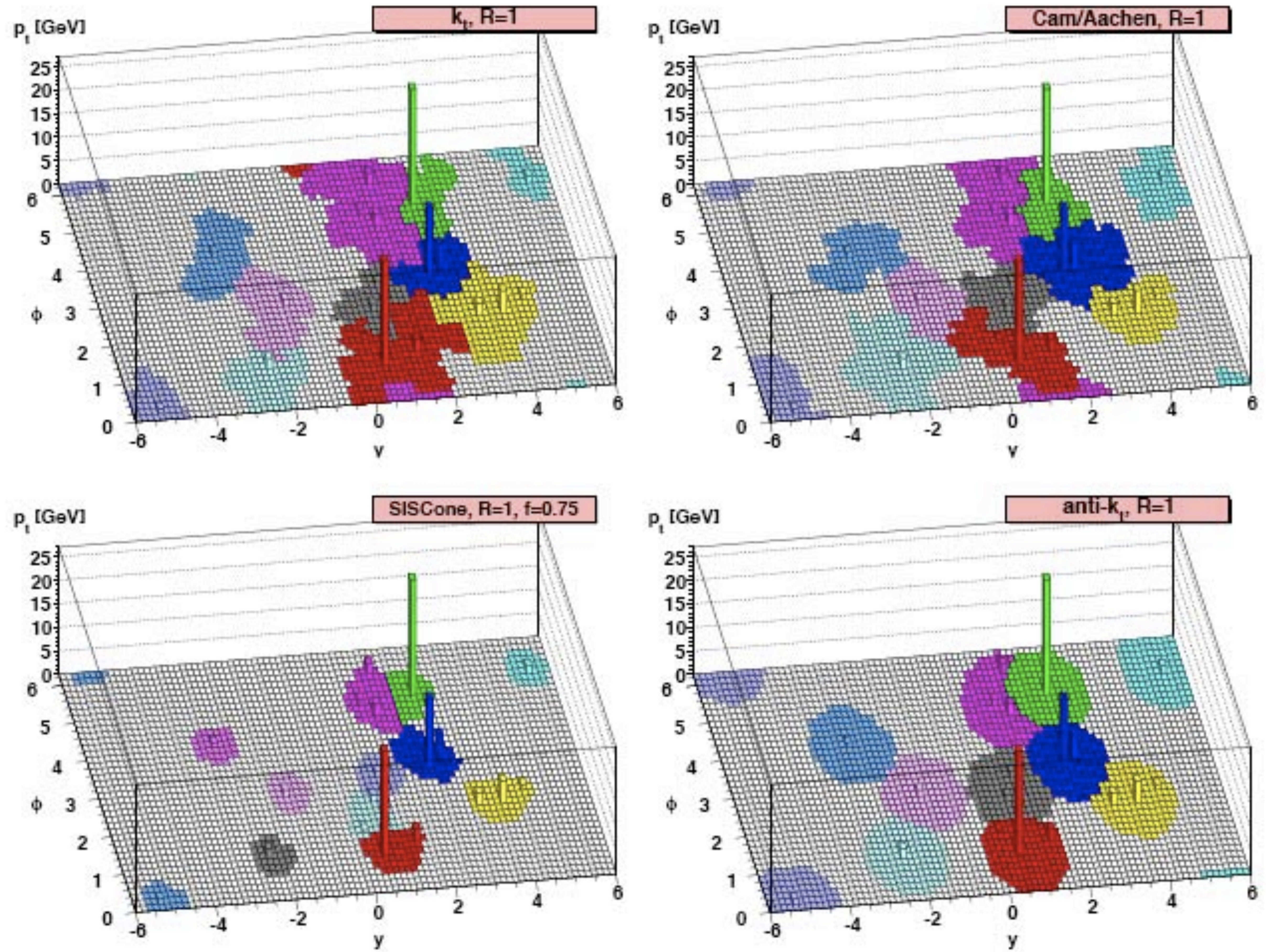
Compute the smallest "distance" d_{ij} or d_{iB} and either cluster i and j together or identify i as a jet

$$d_{ij} = \min\{k_{Ti}^p, k_{Tj}^p\}\Delta R_{ij}/R, \qquad d_{iB} = k_{Ti}^p$$

$$\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$$

Algorithm	p	clusters first	comment
k_T/Durham	> 0	softest	leads to very irregular jets includes a lot of underlying event hard to get jet energy scale right
Cambridge/Aachen	$= 0$	closest	still leads to very irregular jets similar problems to kT algorithm
anti-k_T	< 0	hardest	shape of jet insensitive to soft particles ✓ cone-like jets ✓ may be easier to get jet energy scale right ✓

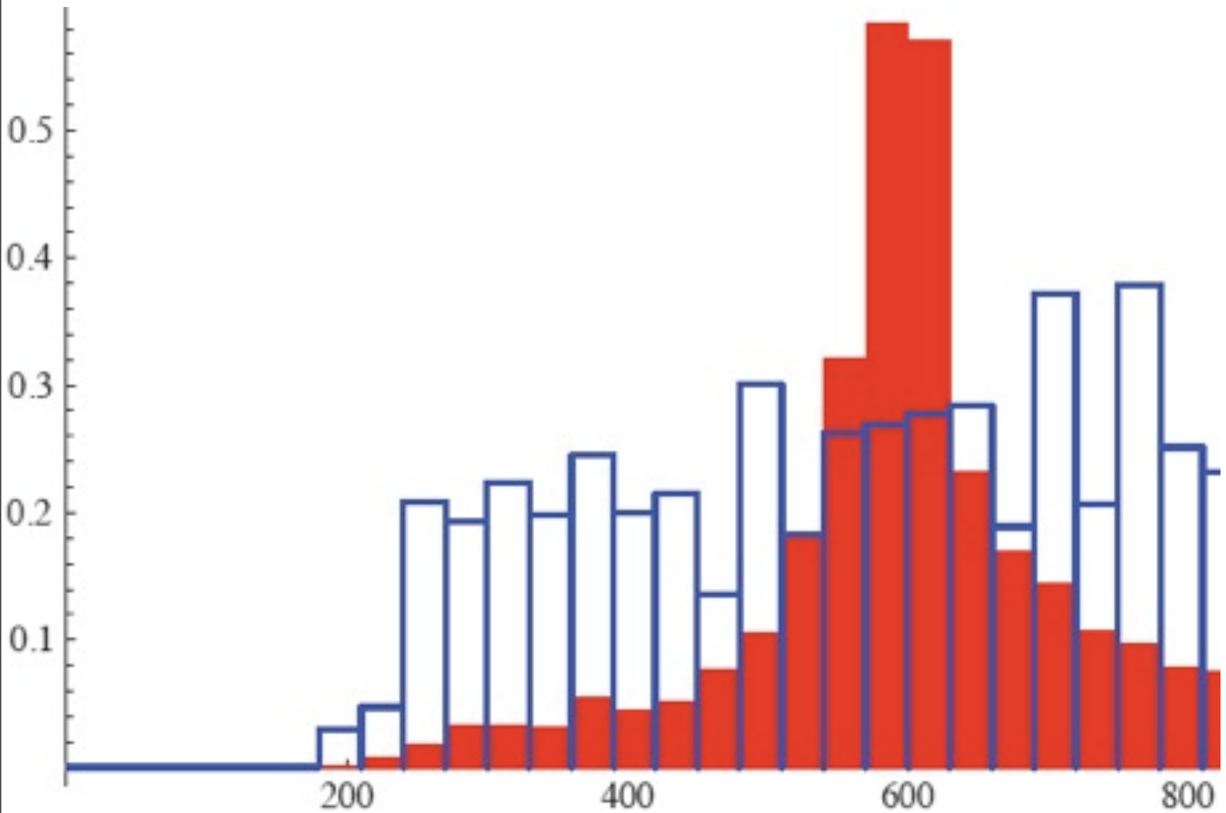
Towards Jetography: 0906.1833,G.P.Salam

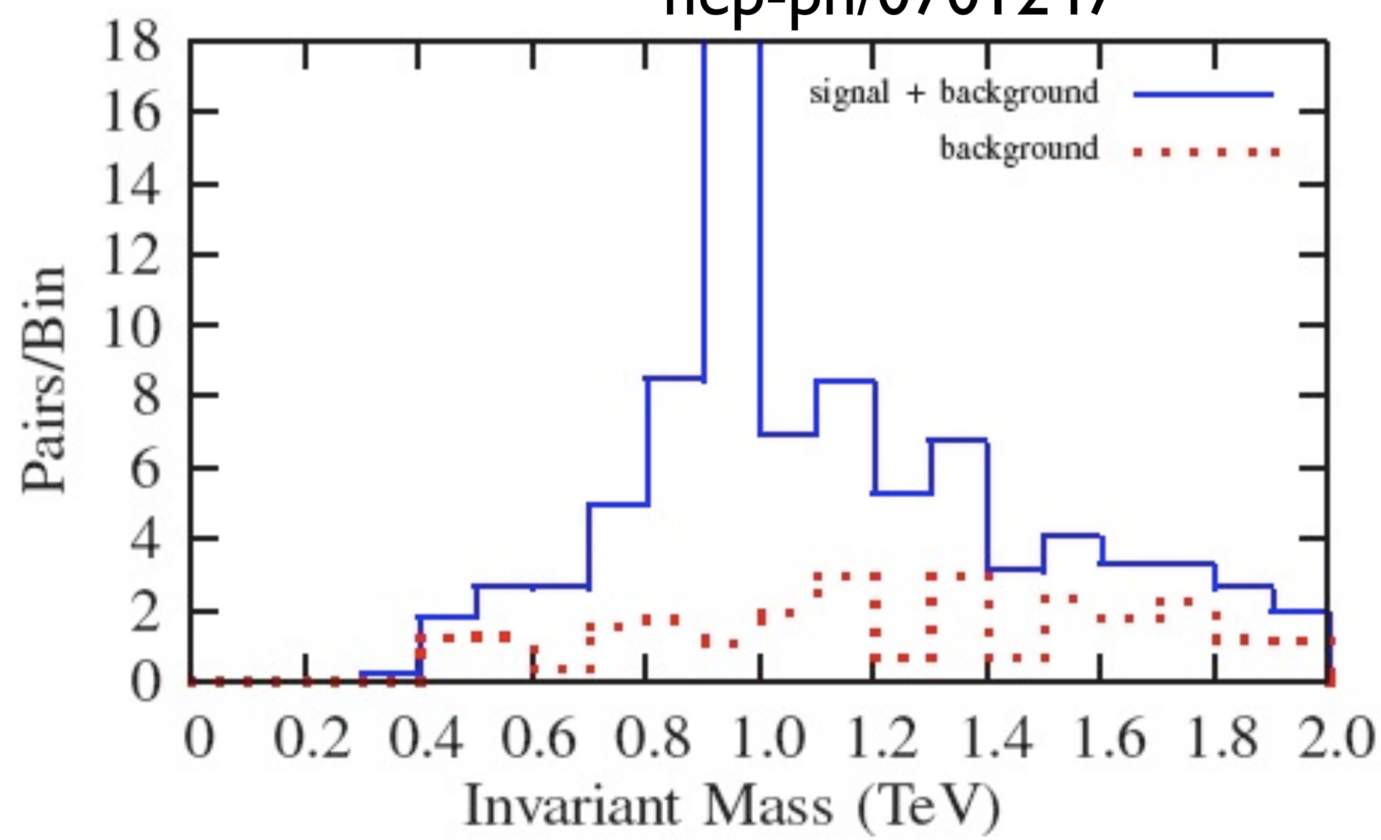


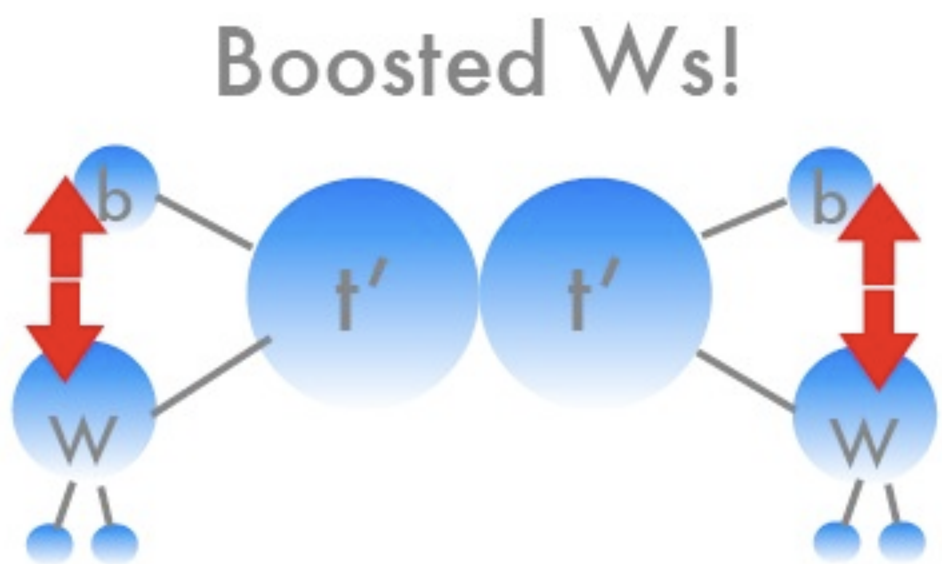
• W-jet method

B. Holdom, hep-ph/0702037

W. Skiba, D. Tucker-Smith
hep-ph/0701247





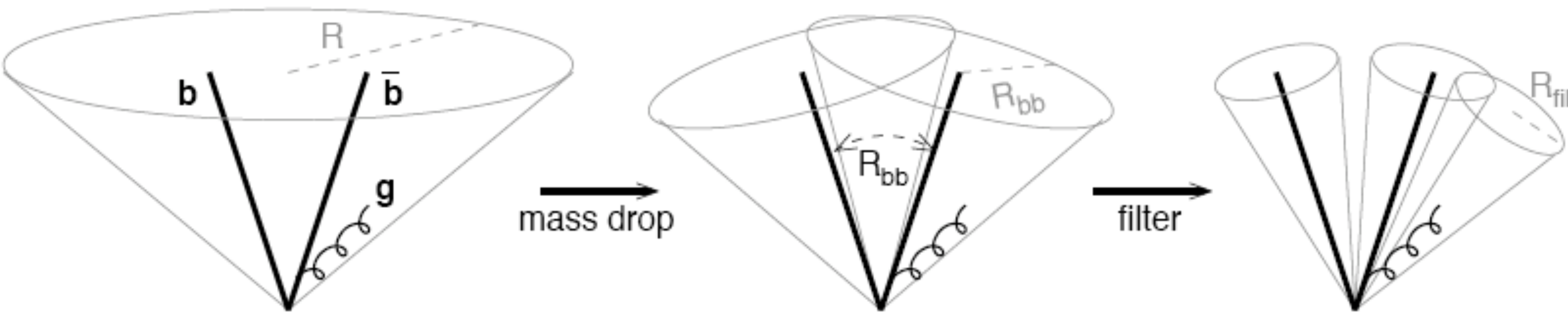


2. Jet mass/sub.

- Sensitive to the cone size of jet finding algorithm
- It is easy to be contaminated by underlying processes pruning
- W must be highly boosted need larger mass of heavy quarks $m_{t'} > 500\text{GeV}$

Jet Substructure study entered into a new era.

Higgs tagger (BDRS): 0802.2470 J.M. Butterworth,A.R.Davison,M.Rubin,G.P.Salam



Optimized for R =1.2

2. Higgs tagger

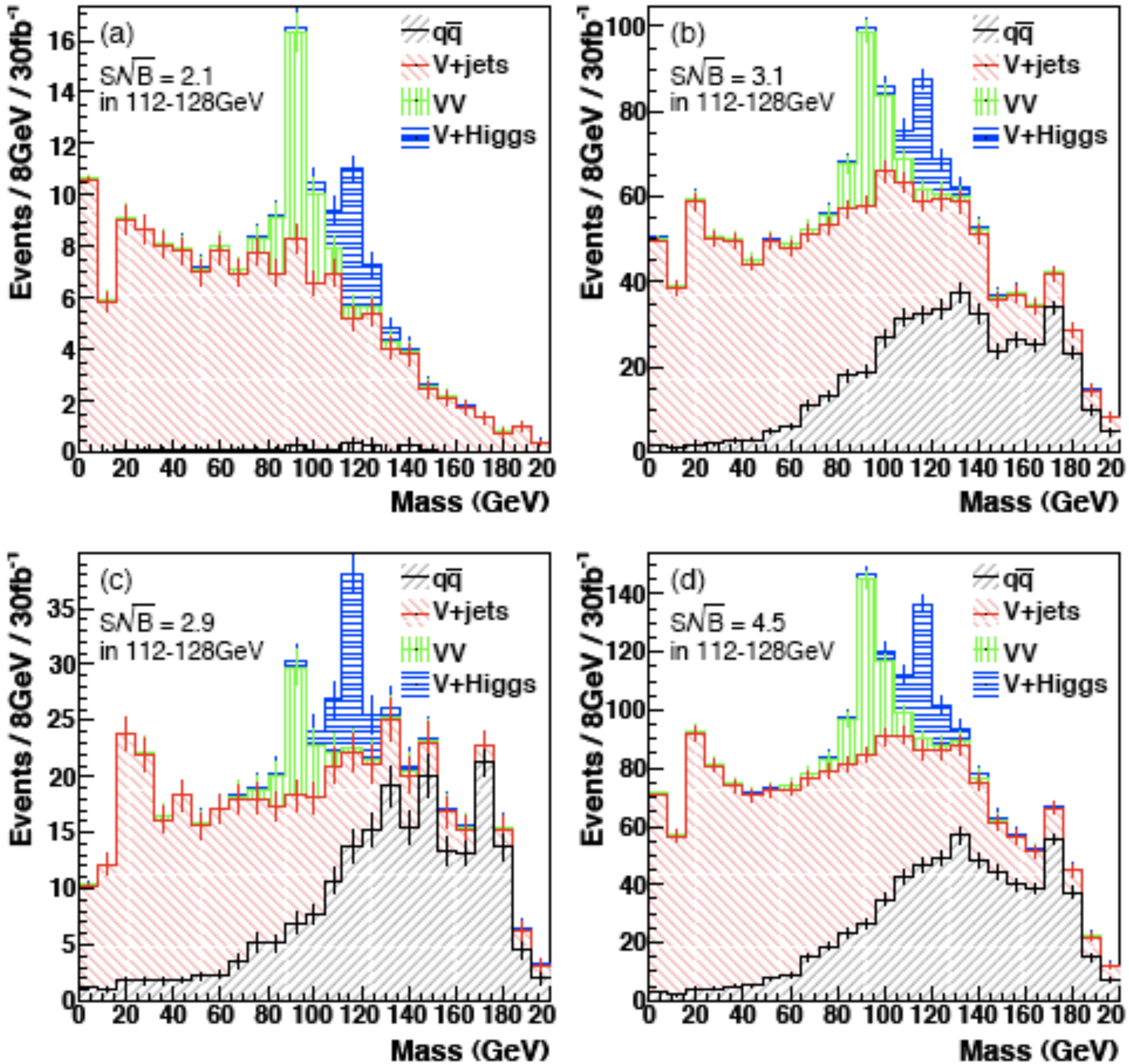
Higgs tagger (BDRS): 0802.2470 J.M. Butterworth,A.R.Davison,M.Rubin,G.P.Salam

A dilepton channel

B Missing Energy Channel ME>200 GeV

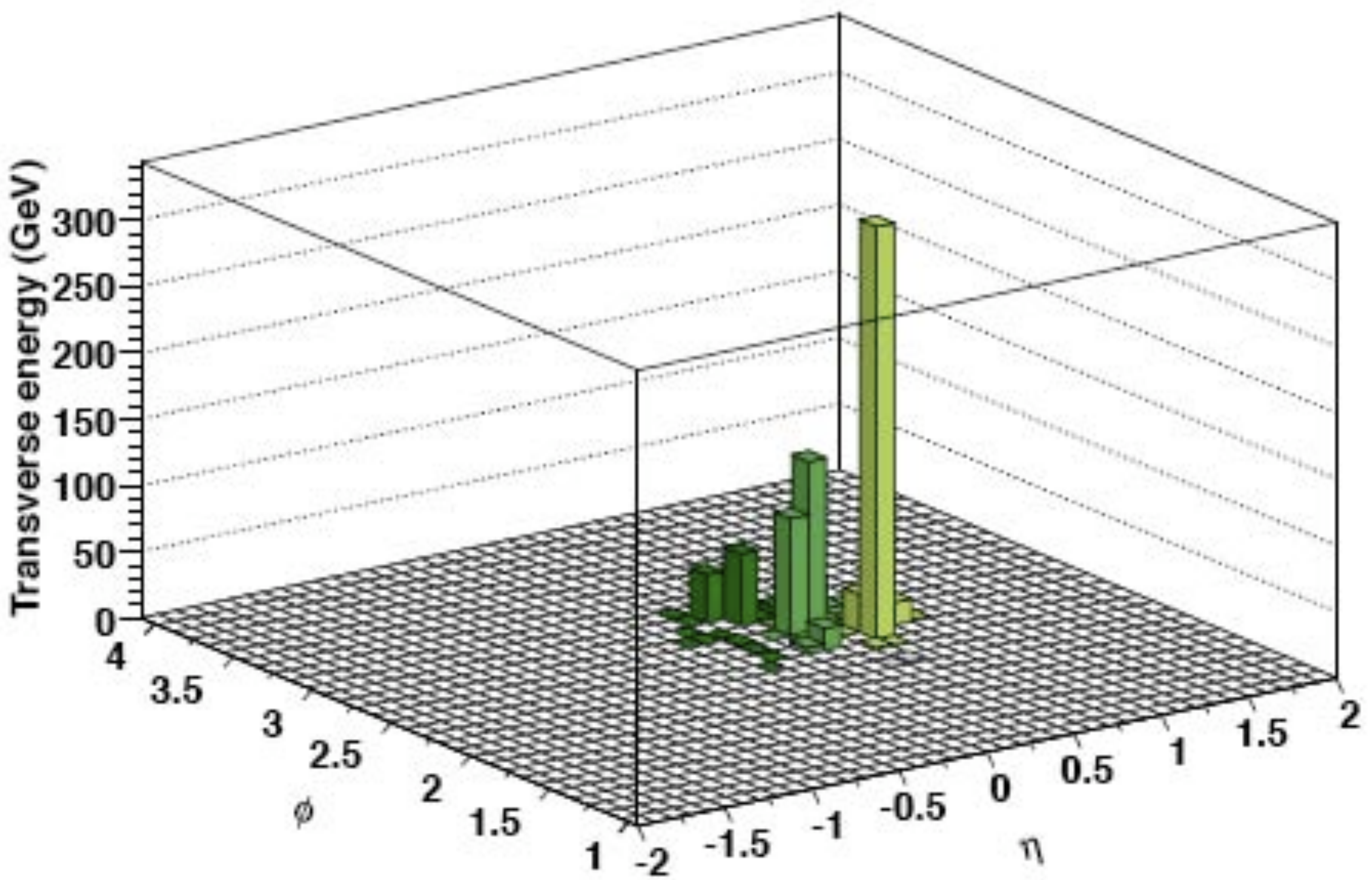
C Semileptonic Channel ME>30GeV, Pt(l)>30 GeV

3 channels Combined



Top quarks can be involved into most new physics processes.

Hadronic Top tagger: 0806.0848,D.E.Kaplan,K.Rehermann,M.D.Schwartz,B.Tweedie



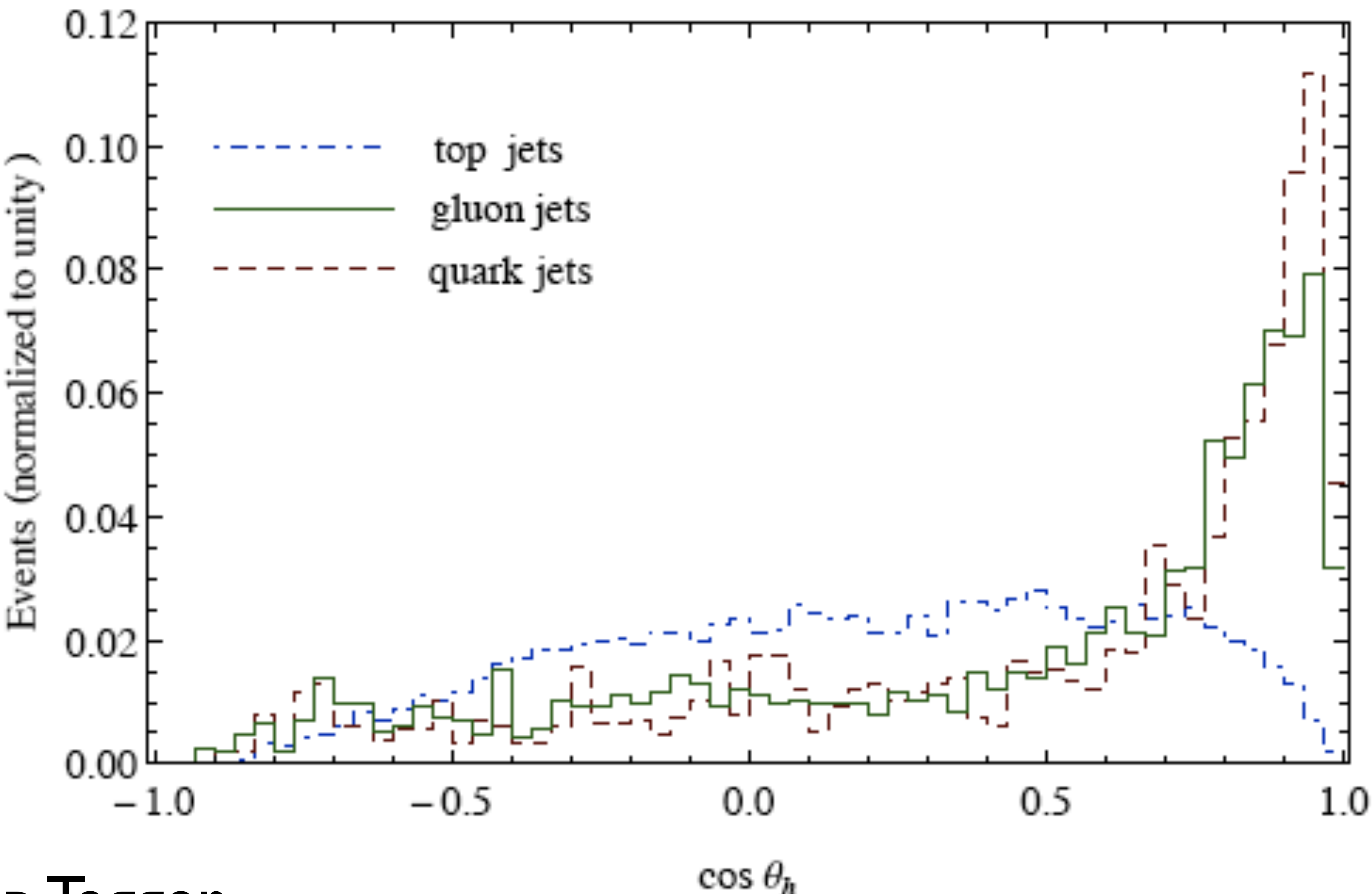
2. Top Tagger

Angle separation: $\sim 2m_t/p_T$

A hadronic top tagger exploits masses of top and W boson and helicity of W inside the top jet

Top tagger: 0806.0848 D.E.Kaplan,K.Rehermann,M.D.Schwartz,B.Tweedie

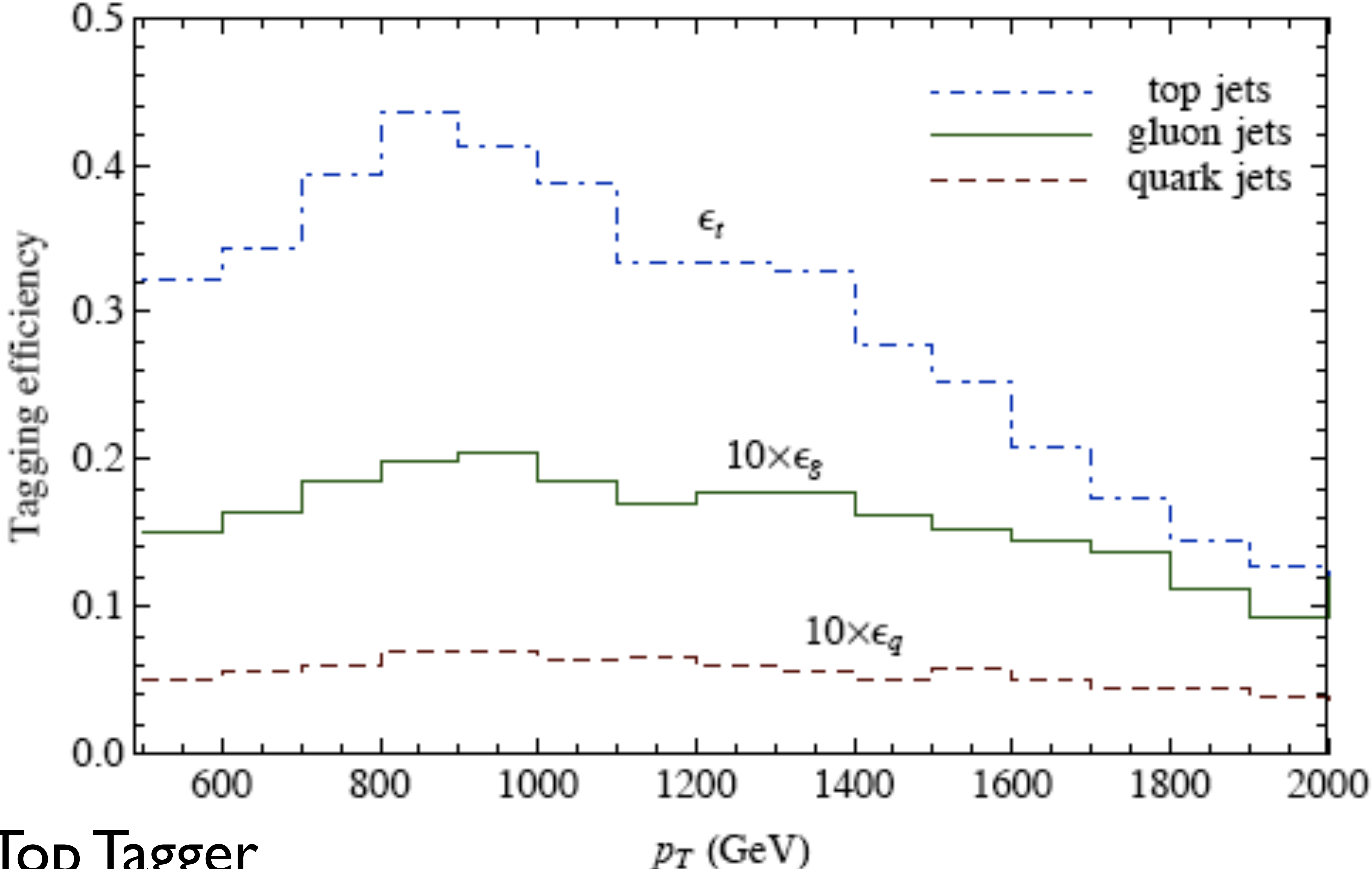
Hadronic w helicty



2. Top Tagger

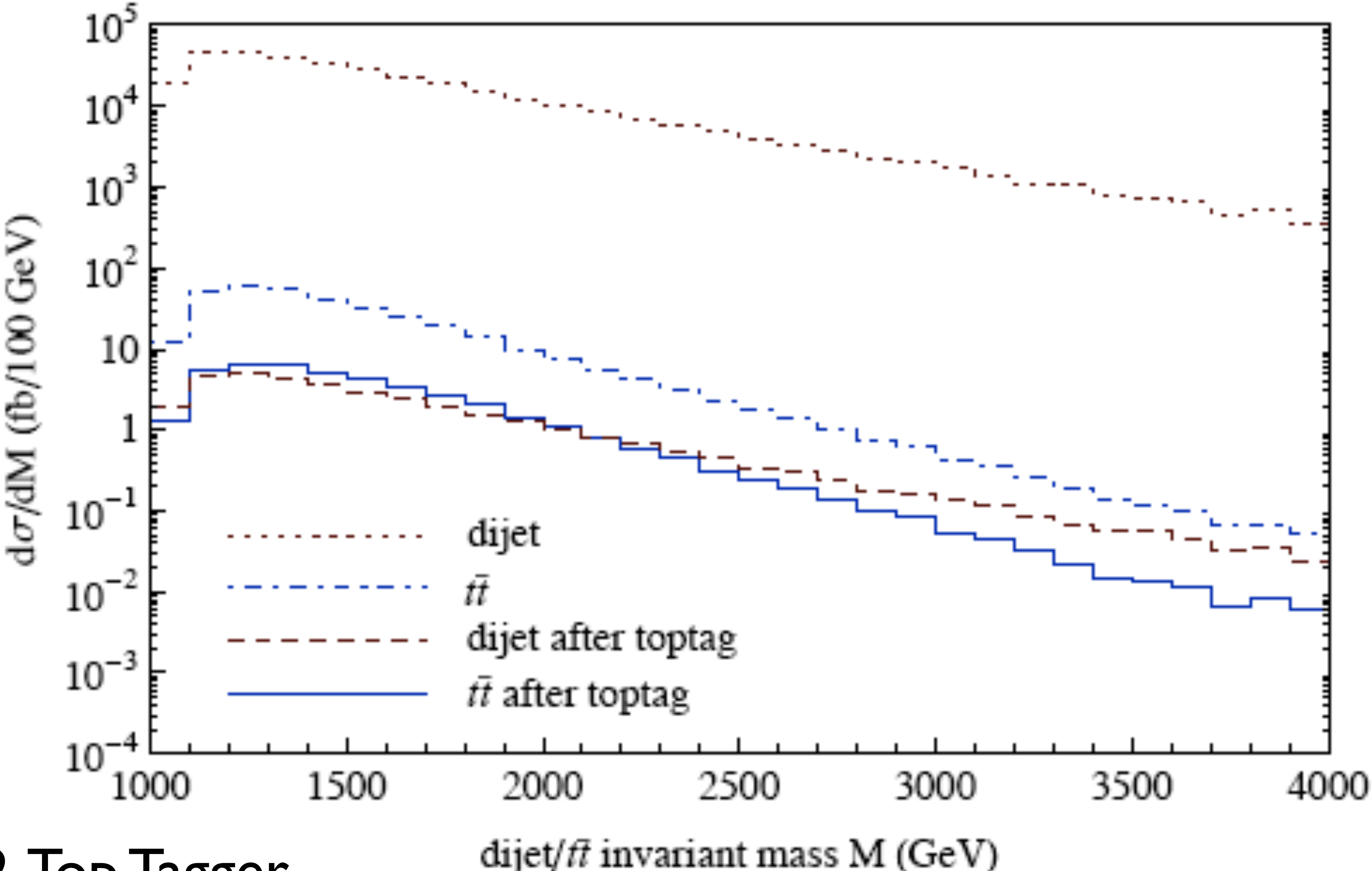
Top tagger: 0806.0848 D.E.Kaplan,K.Rehermann,M.D.Schwartz,B.Tweedie

Mt, mw, Hw, tagging efficiency



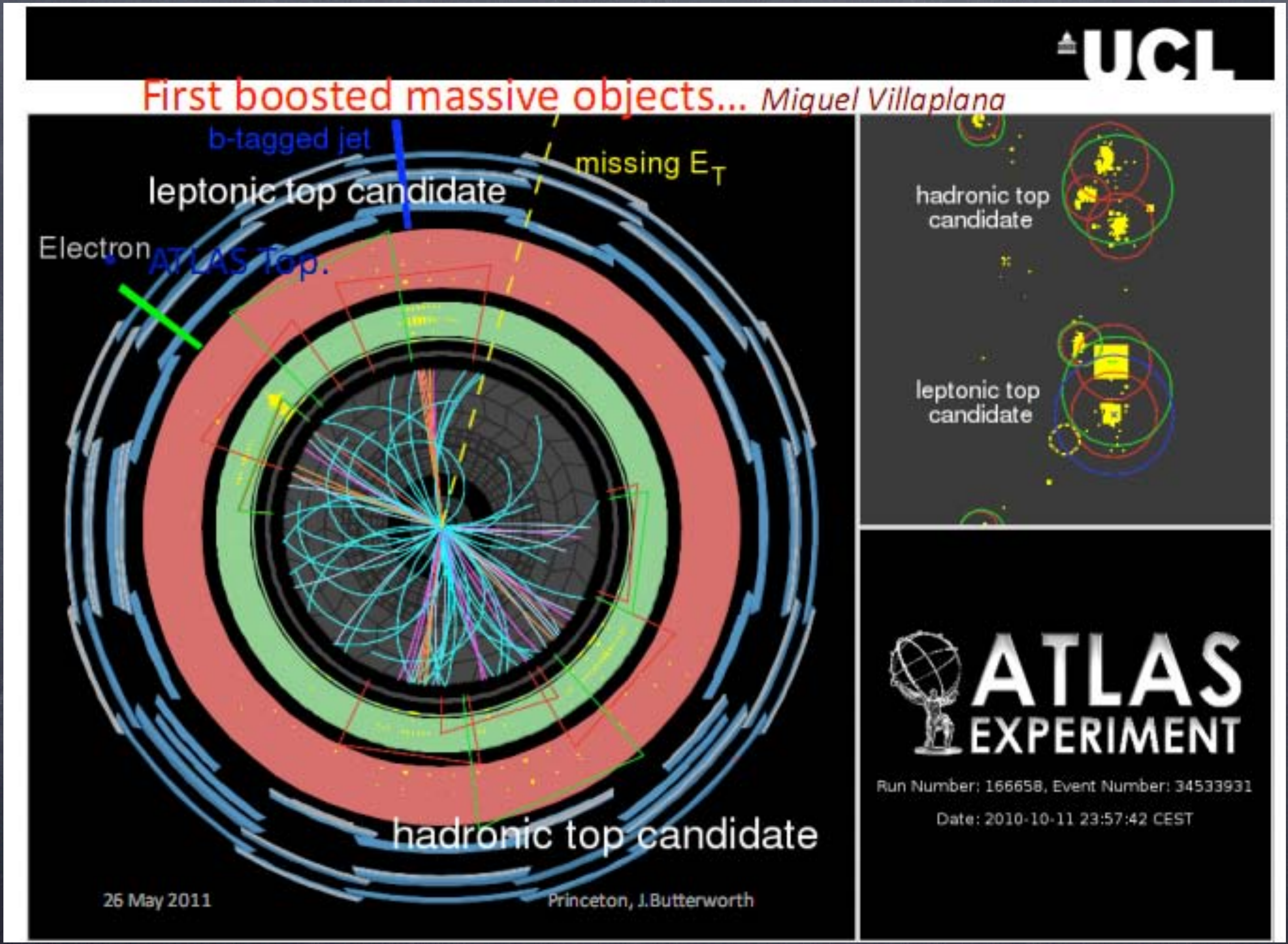
2. Top Tagger

Hadronic Top tagger: 0806.0848 D.E.Kaplan,K.Rehermann,M.D.Schwartz,B.Tweedie



2. Top Tagger

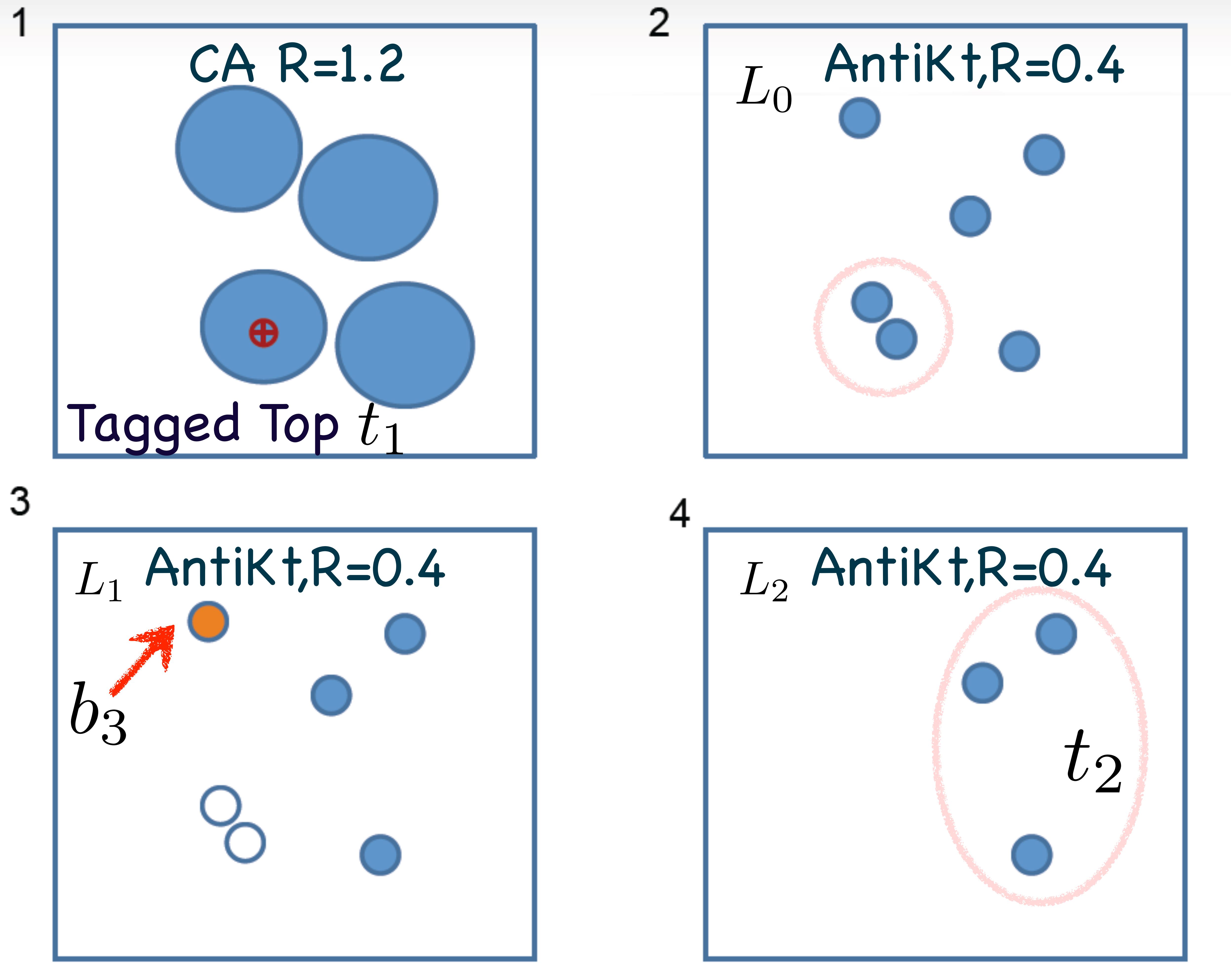
The Hadronic Top tagger indeed work!



Boosted Top event observed at ATLAS

We propose a Hybrid-R method

- CA jet algorithm with a larger cone and top tagger to capture a highly boosted top t_1.
- Recluster the pseudo-jets in the event with a small cone with anti-K_t $R = 0.4$ and get a jet list L_0.
- If small-size jets are within the larger cone of the direction of the tagged top jet, remove them and get a new jet list L_1.
- Identify the most energetic jet in L_1 as the b_3 jet. The rest of unused jets form a jet list L_2.
- There are at least 3 jets in the L_2. Reconstruct the second top and W by
$$\chi^2 = \frac{|m(j_1,j_2) - m_W^{PDG}|^2}{\sigma_W^2} + \frac{|m(j_1,j_2,j_3) - m_t^{PDG}|^2}{\sigma_t^2}$$


1
CA R=1.2
Tagged Top t_1
2
L_0 AntiKt,R=0.4
3
L_1 AntiKt,R=0.4
b_3
4
L_2 AntiKt,R=0.4
t_2

3. Feasibility@LHC

R	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
k_t algorithm	16%	22%	25%	28%	29%	29%	28%	27%
CA algorithm	13%	19%	24%	27%	29%	30%	30%	30%

$$m_{H+} = 1 \text{ TeV}$$

R	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
k_t algorithm	25%	27%	28%	28%	27%	26%	24%	22%
CA algorithm	23%	27%	29%	30%	30%	30%	30%	29%

$$m_{H+} = 1.5 \text{ TeV}$$

Top tagger is better with larger mass when R fixed.

CA algorithm is chosen for hadronic top tagger.

Cone Size shall be optimized for S/B.

3. Feasibility@LHC

$$\mathcal{L} = \mathcal{L}_{SM} + \partial_\mu H^+ \partial^\mu H^- - m_{H^\pm}^2 H^+ H^- + H^+ \bar{t}(Y_L P_L + Y_R P_R) b + h.c. \ .$$

$$Y_L = Y_R = 1$$

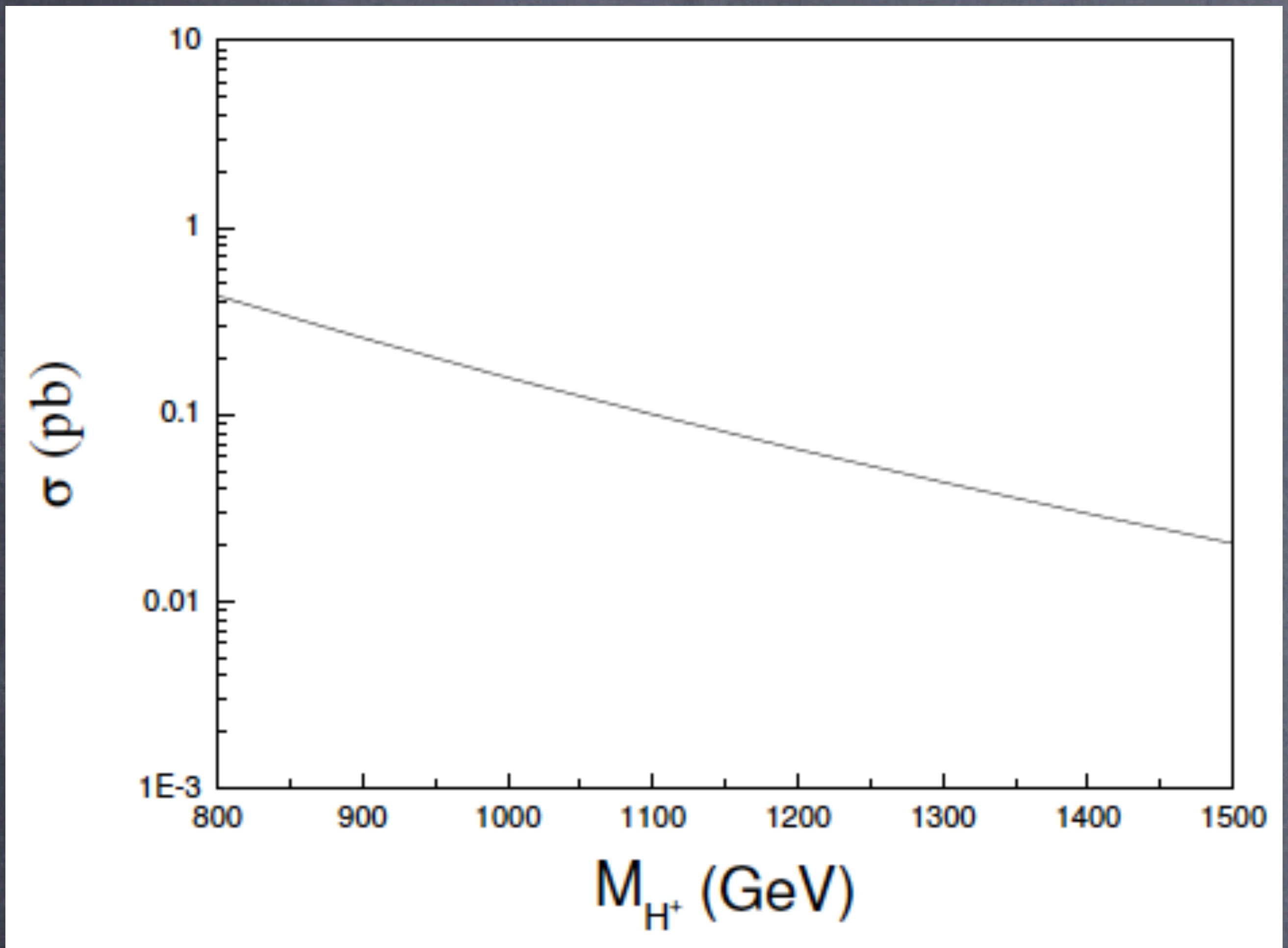
Must be tagged!

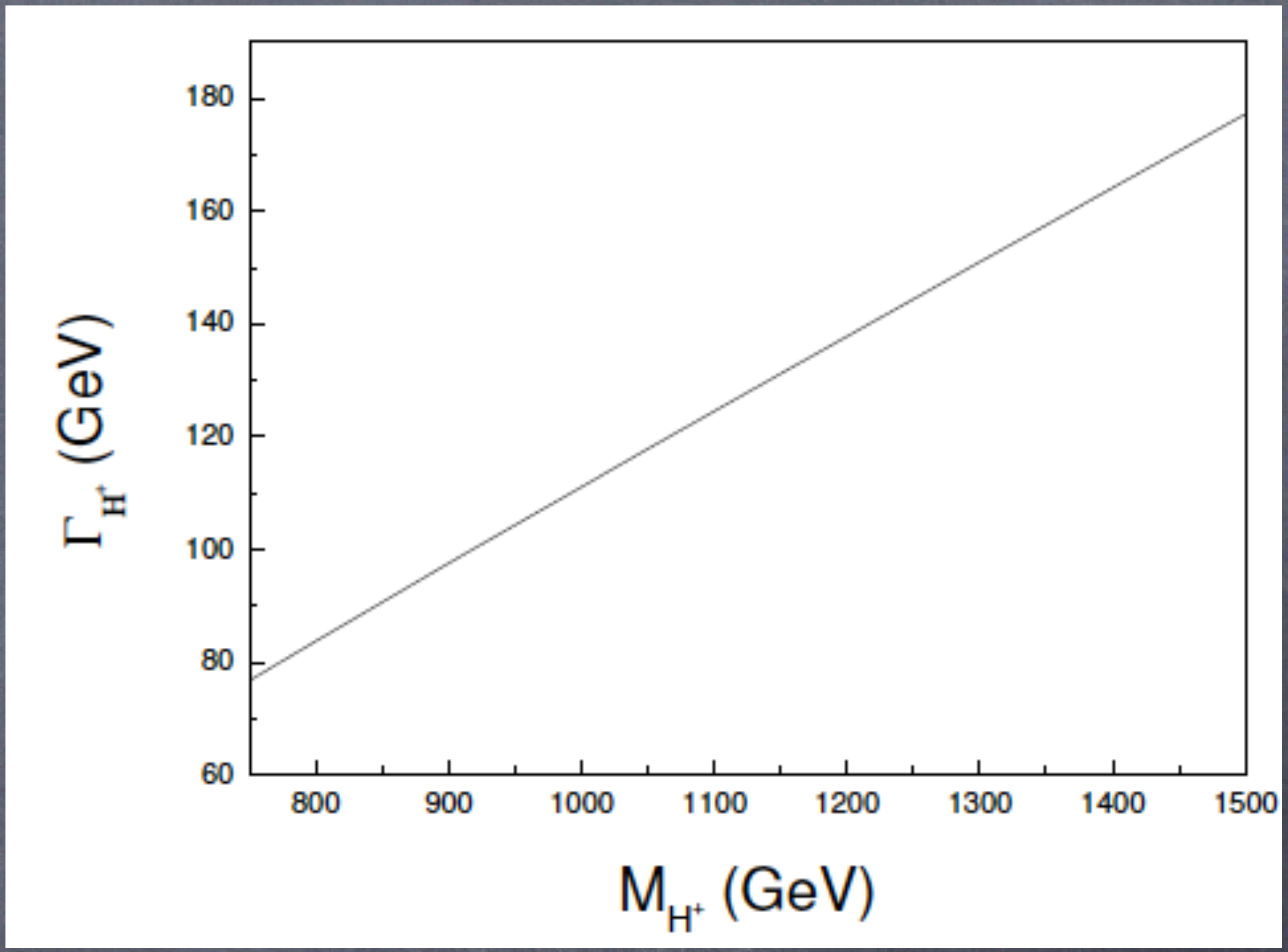
Conventions:

$$pp \to t_2 H^- \to t_2 t_1 b_3$$
$$pp \to t_2 H^- b_4 \to t_2 t_1 b_3 b_4$$

$pp \to Ht^-$ with $s = 14$ TeV
K factor included

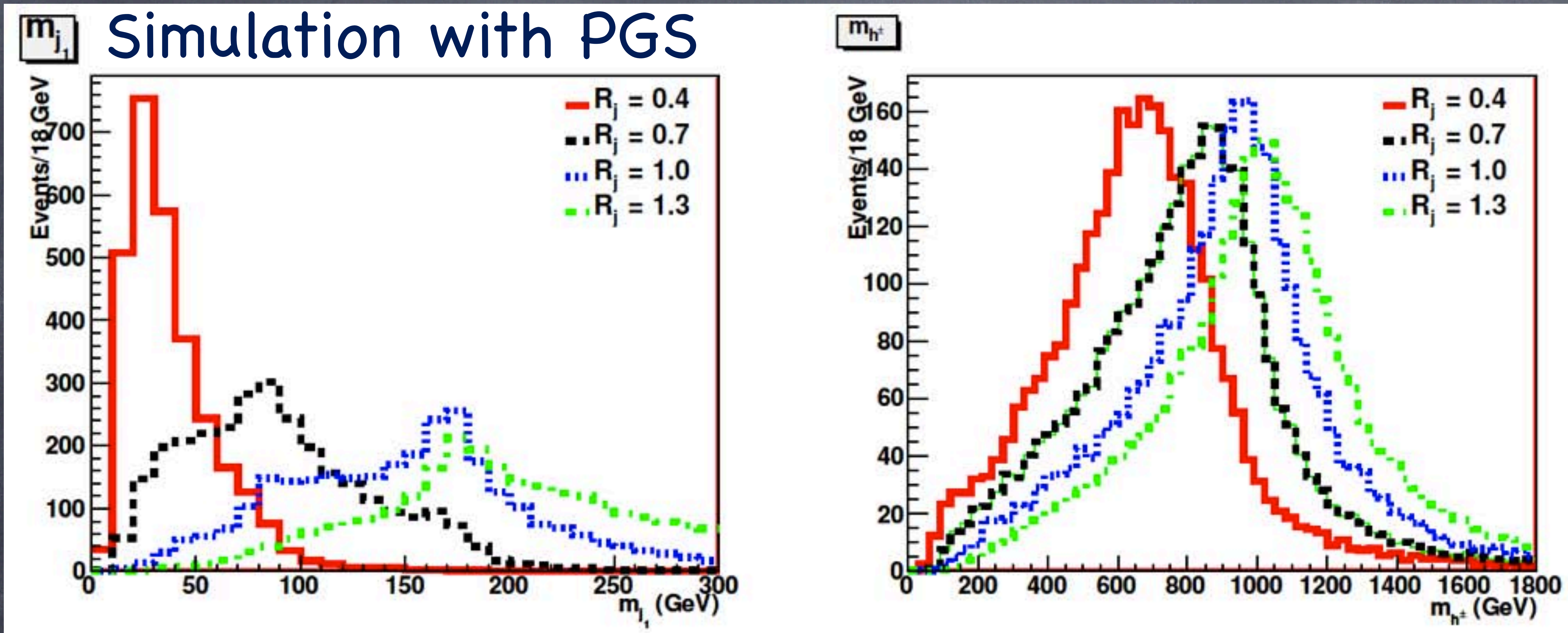
The decay width
$Br(H^+ \to tb) = 100\%$





The cross section is large enough, and the resonance is narrow enough to be resolved by detectors.

3. Feasibility@LHC



- Cone size and algorithm are crucial for the performance of the hadronic top tagger
- Charge Higgs mass bump can be approximately reconstructed.
- The detector effect and the decay width effect can not wash out signal

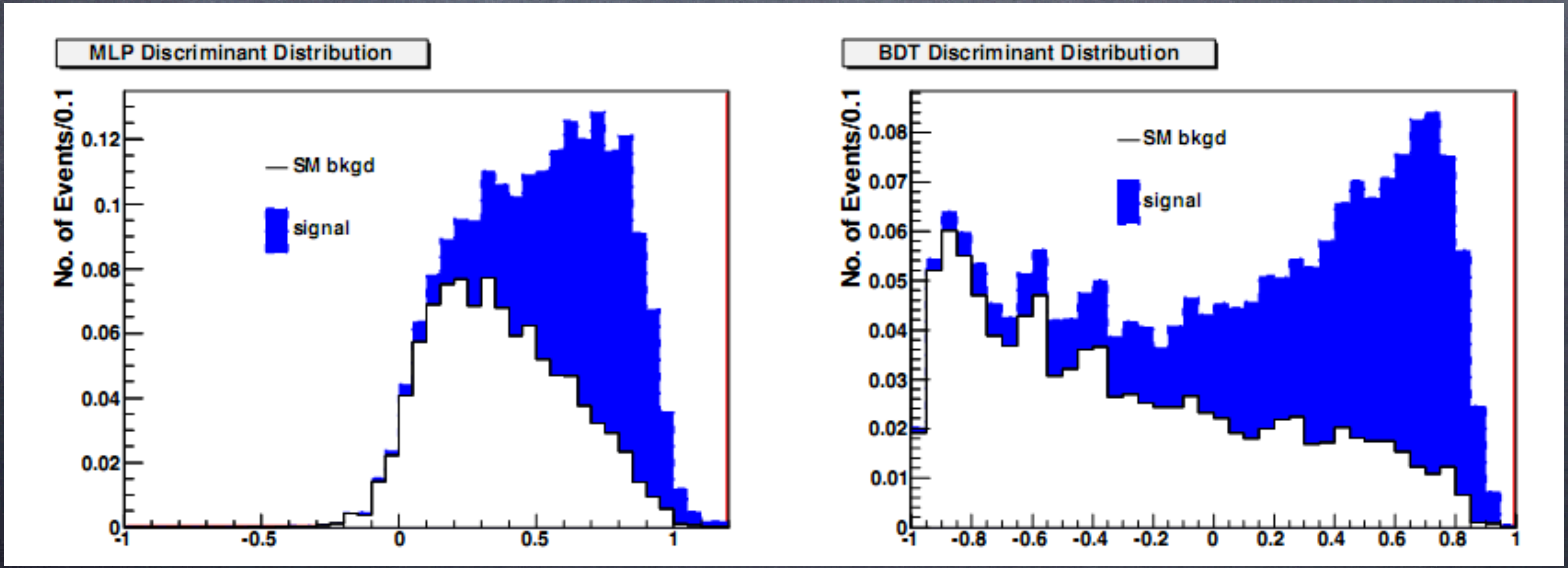
3. Feasibility@LHC

	signal $m_{H^\pm} = 1$ TeV	$t\bar{t}$ + jets	QCD $n_j \geq 4$
Cross Section x Br (pb)	0.053	553	9186.8
After JH tagger & $H_T > 400$GeV	29%	7%	4.8×10^{-3}
Two b-taggings	10%	4.2×10^{-4}	4.8×10^{-7}
The number of jets in jet list L_0, $n_j \geq 6$	10%	3.7×10^{-4}	3.4×10^{-7}
$H_T > 700$GeV & $C > 0.3$	9.6%	2.1×10^{-4}	3.0×10^{-7}
The leading jet $E(j_1) > 350$GeV	8.9%	1.6×10^{-4}	2.5×10^{-7}
The second leading jet $E(j_2) > 250$GeV	7.9%	1.3×10^{-4}	2.2×10^{-7}
$P_t(b_3) > 300$ GeV & $P_t(t_1) > 300$ GeV	5.3%	4.5×10^{-5}	7.7×10^{-8}
$\lvert m_{W_2} - m_W^{\mathrm{PDG}}\rvert < 20$ GeV & $\lvert m_{t_2} - m_t^{\mathrm{PDG}}\rvert < 30$ GeV	3.1%	2.6×10^{-5}	2.3×10^{-8}
$\lvert m_{H^\pm} - m_{H^\pm}^{\mathrm{assumed}}\rvert < 200$ GeV	2.5%	1.5×10^{-5}	1.5×10^{-8}
Events in 100 fb^{-1}	133	830	13.8

A Cuts based method can work but ...

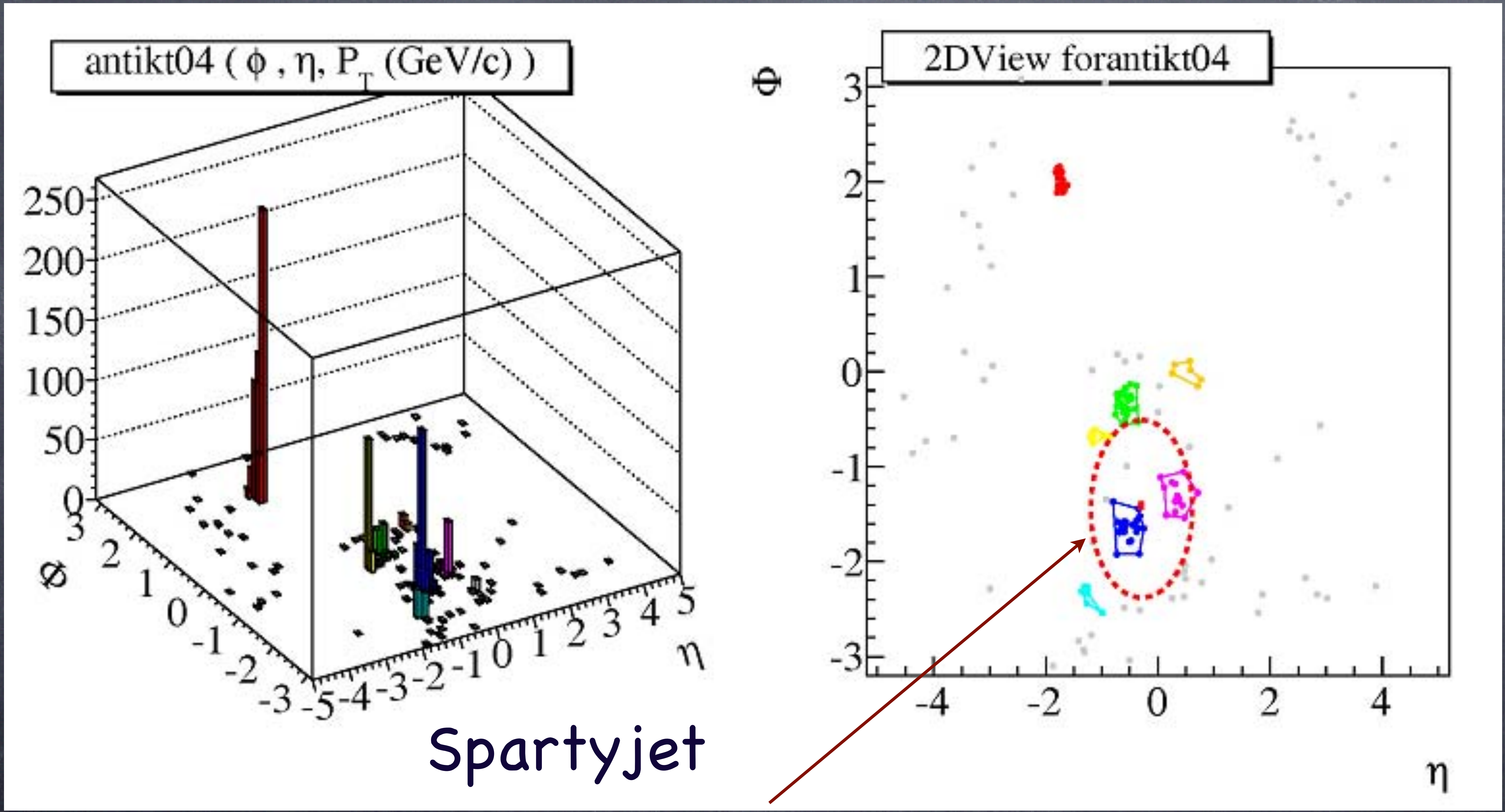
3. Feasibility@LHC

	signal $m_{H^\pm} = 1.0$ TeV	$t\bar{t}$ + jets	QCD $n_j \geq 4$
After simple cuts	2.5%	1.5×10^{-5}	1.5×10^{-8}
After NN cut ($NN > 0.6$)	5.5%	2.0×10^{-5}	3.0×10^{-8}
After BDT cut ($BDT > 0.5$)	5.7%	2.1×10^{-5}	3.2×10^{-8}



Significance can be enhanced 100% or so by TMVA.

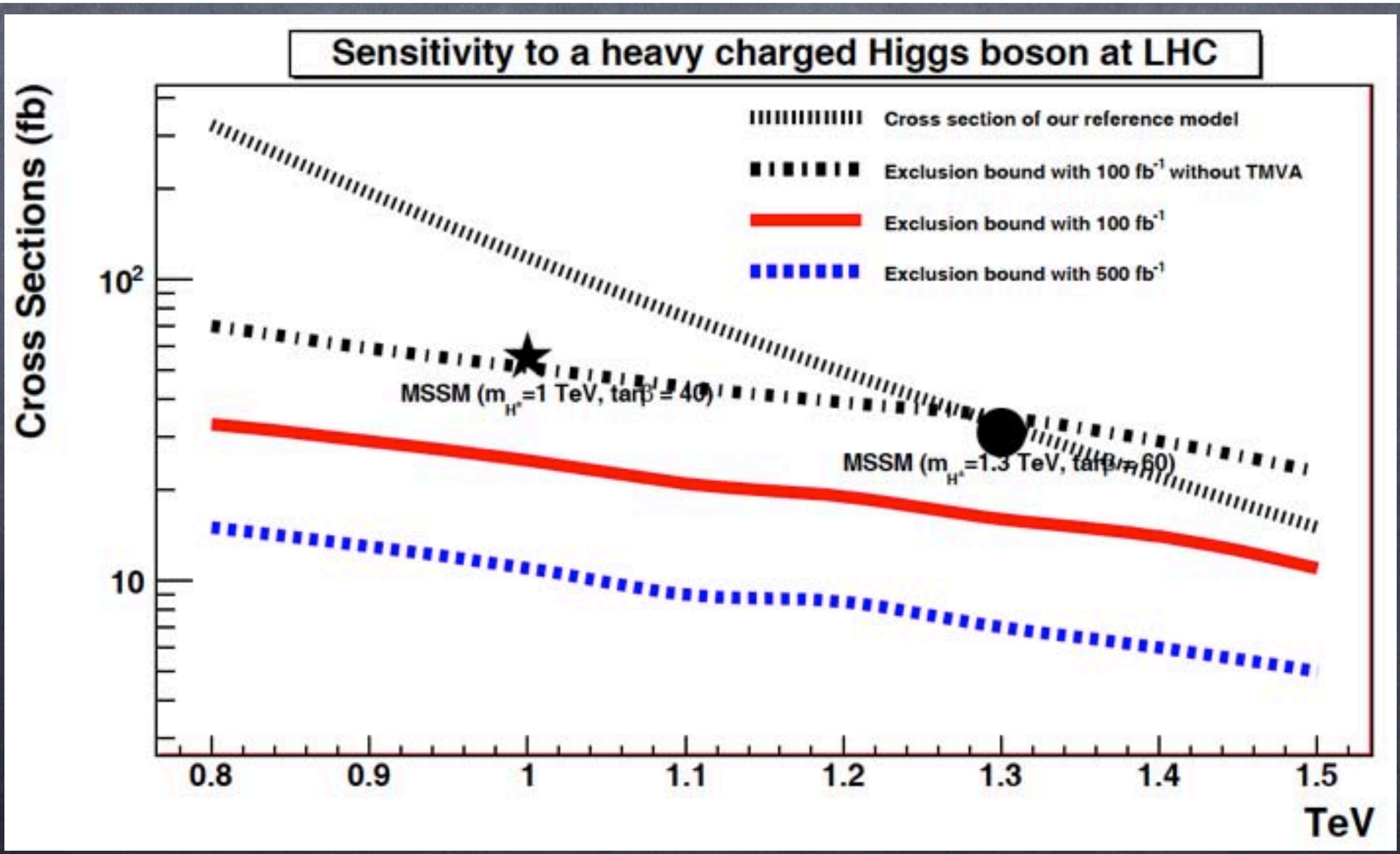
A closer and intuitive look at a signal event.



Conventional top
reconstruction method fails for tagged top

3. Feasibility@LHC

$m_{H^\pm}$ (TeV)	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
σ (fb)	324	192	118	75	49	33	22	15
$\frac{S}{\sqrt{B}}$ (with two b taggings & TMVA)	19.4	13.3	9.5	7.0	5.1	4.0	3.1	2.6
lower bound on $\sigma(fb)$	33	29	25	21	19	16	14	11
$\frac{S}{\sqrt{B}}$ (with two b taggings without TMVA)	9.3	6.5	4.6	3.4	2.5	1.9	1.5	1.3
lower bound on $\sigma(fb)$	70	59	51	44	39	35	29	23

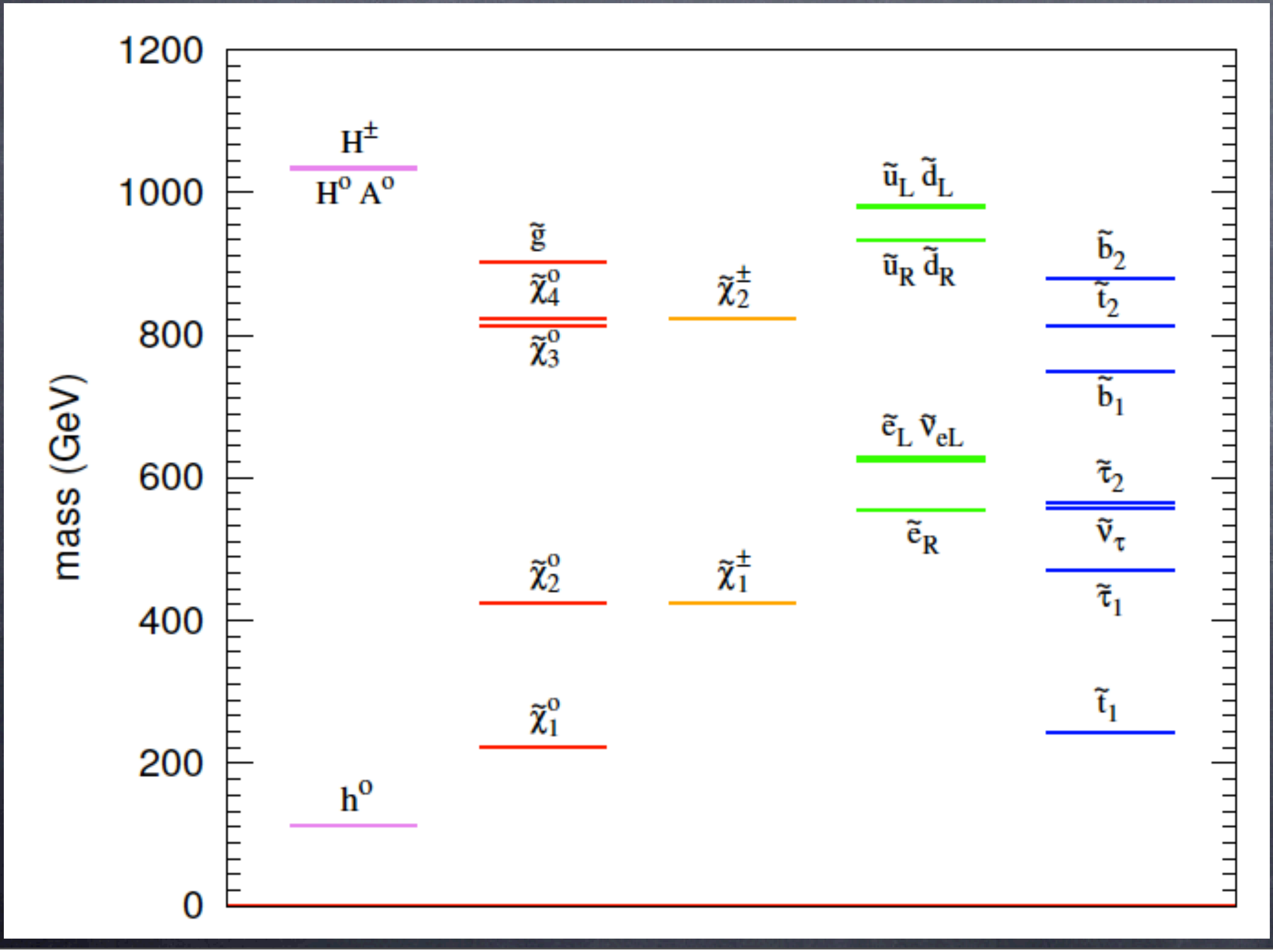


4. Conclusion

- We propose a hybrid-R method to detect heavy charged Higgs boson with hadronic top tagger(s).
- The full hadonic mode is used as a test field and the method does work.
- The heavier the charged Higgs boson, the better performance is our method.
- The heavy charged Higgs (from 0.8 TeV to 1.5 TeV) can be covered with 14 TeV and a 100 fb^{-1} dataset just by using hadronic mode!

Thanks you!

1. Why A Heavy Charged Higgs Boson?

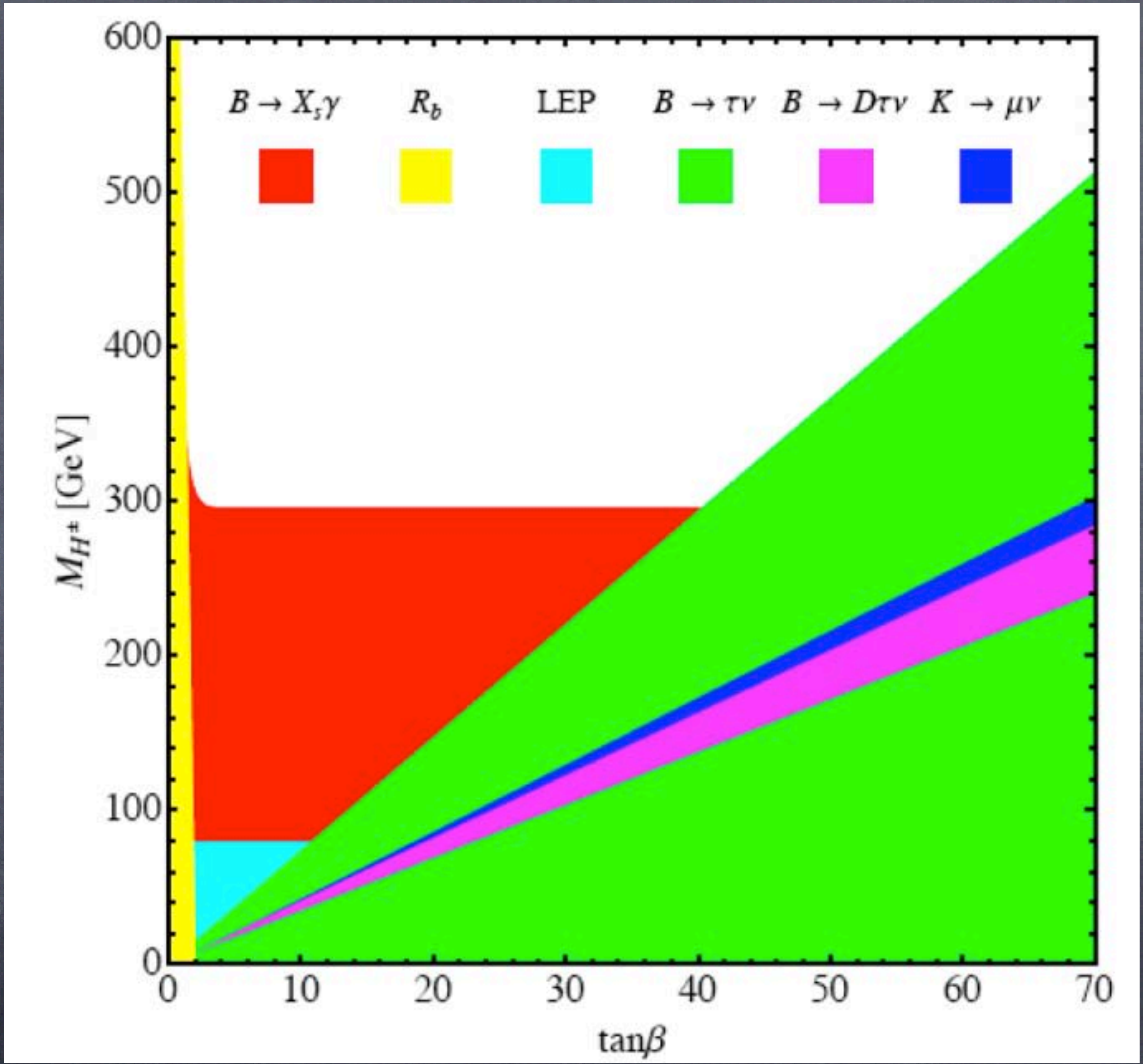


An example in a nonuniversal MSSM

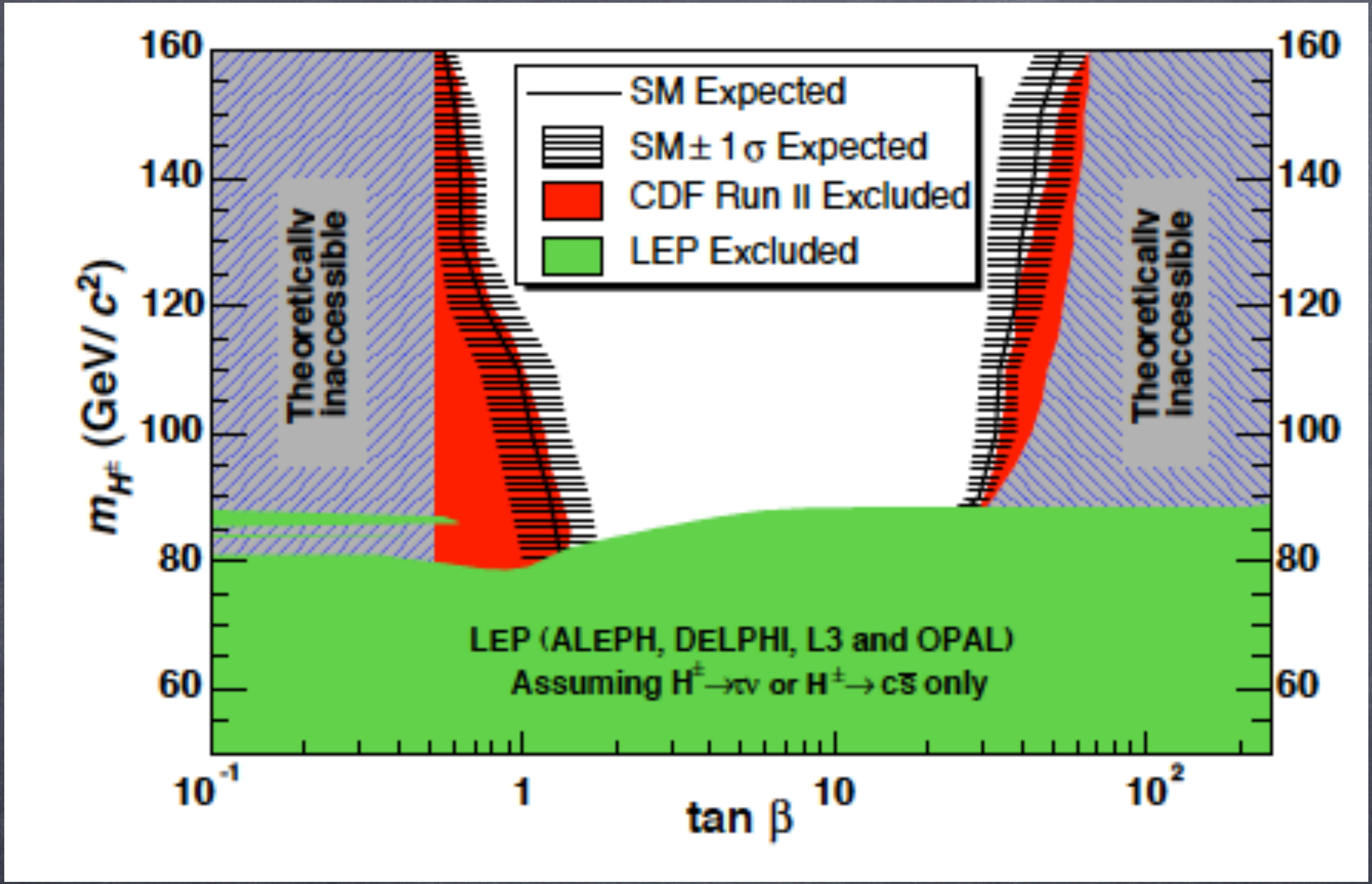
X.J.Bi,Q.S.Yan,P.F.Yin

1111.2250

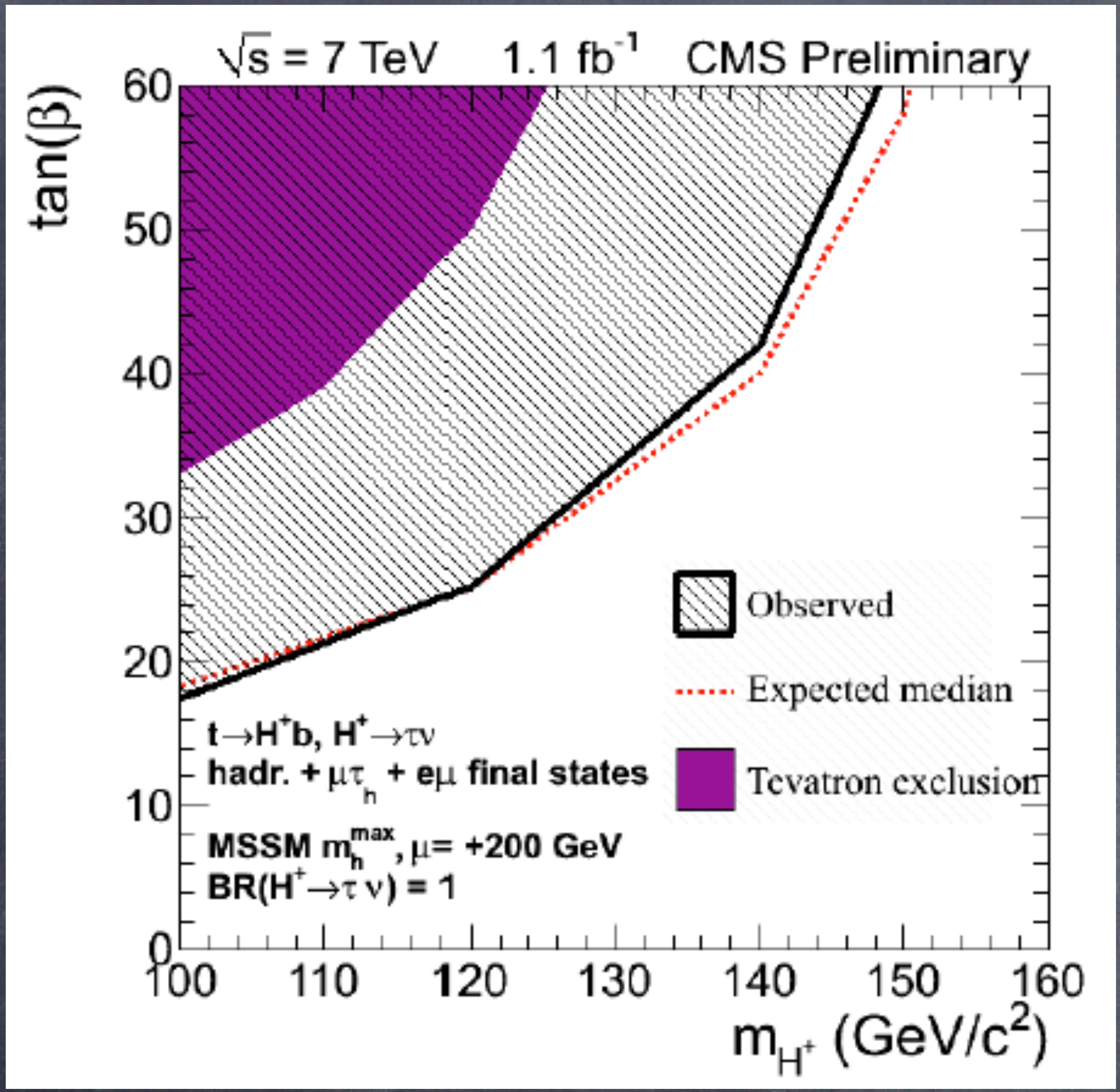
BMP 2

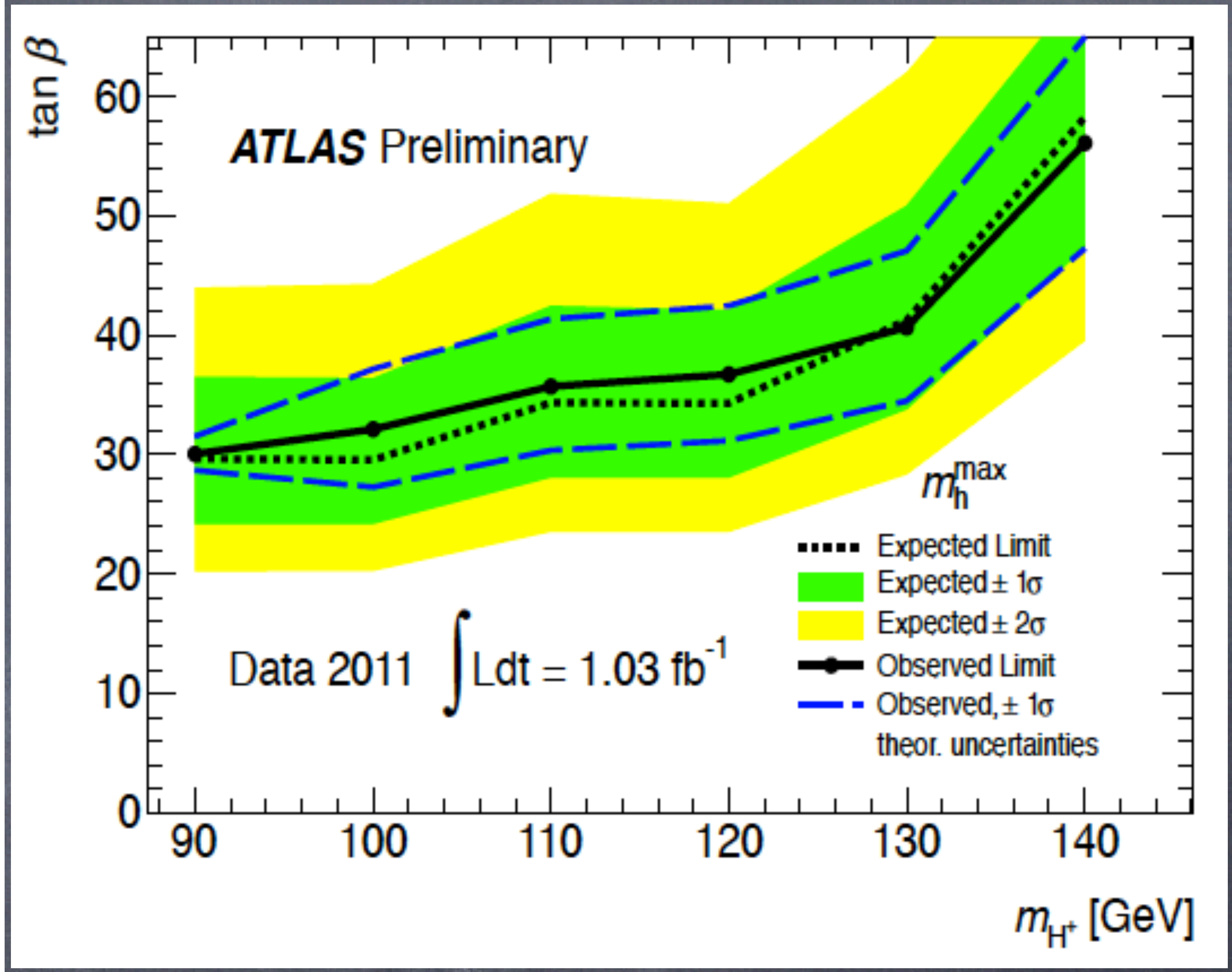


Combined bounds from LEP+B physics,
bench mark model (2HDM),0805.2141,Haisch



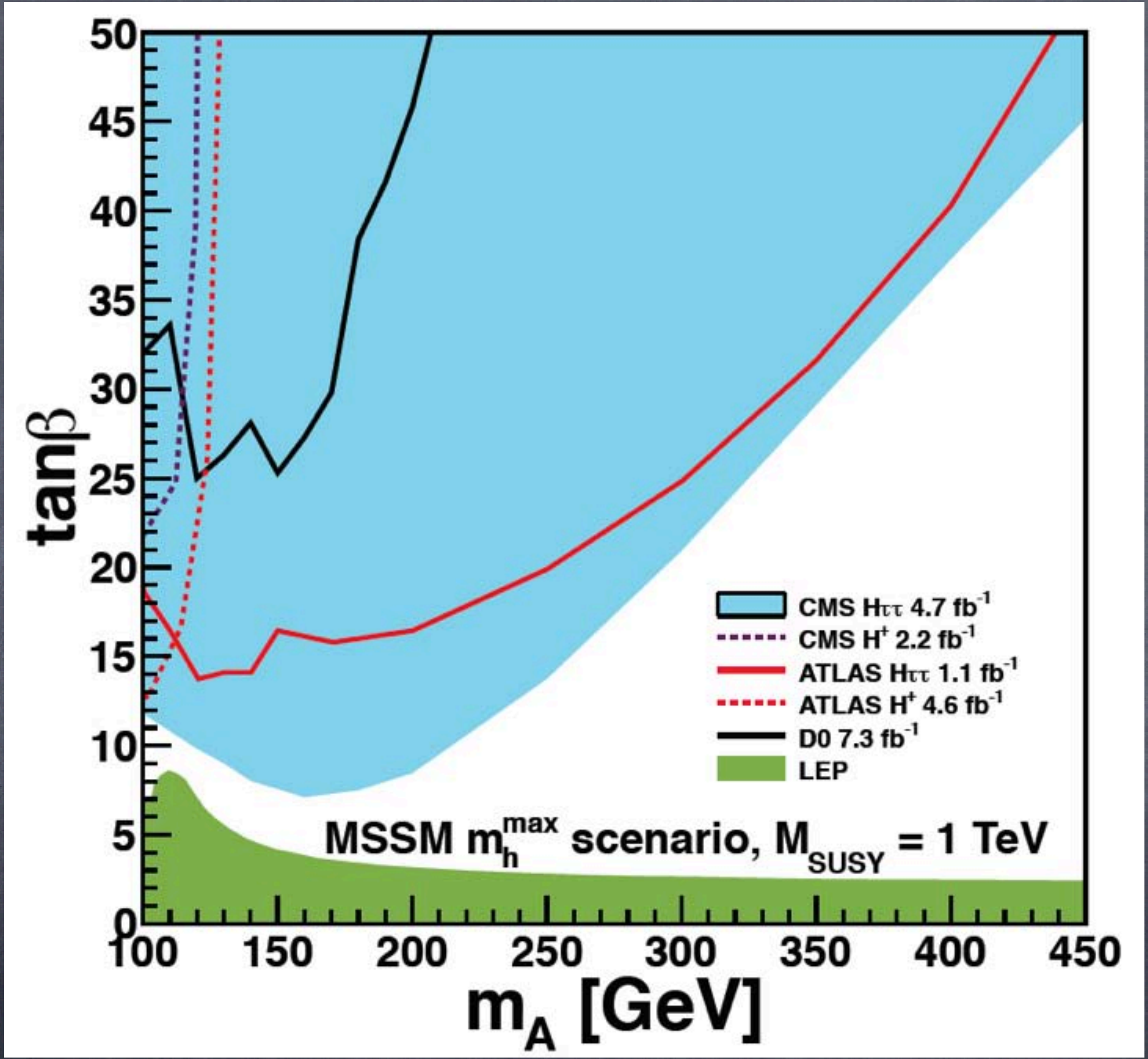
Bound to a charged Higgs boson(2HDM) from direct search from Tevatron&LEP



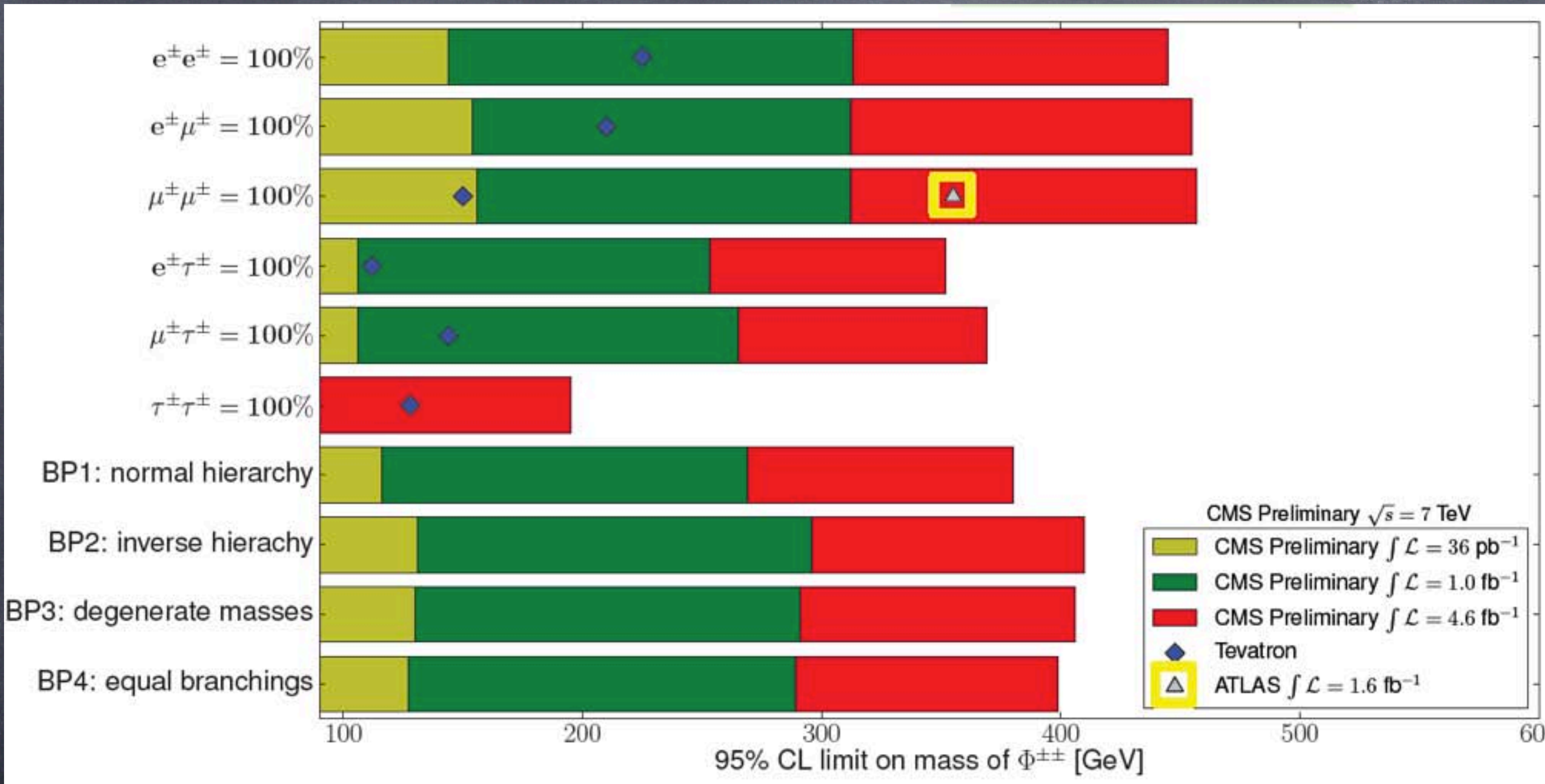


CMS, 1201.4983

ATLAS,1201.5886

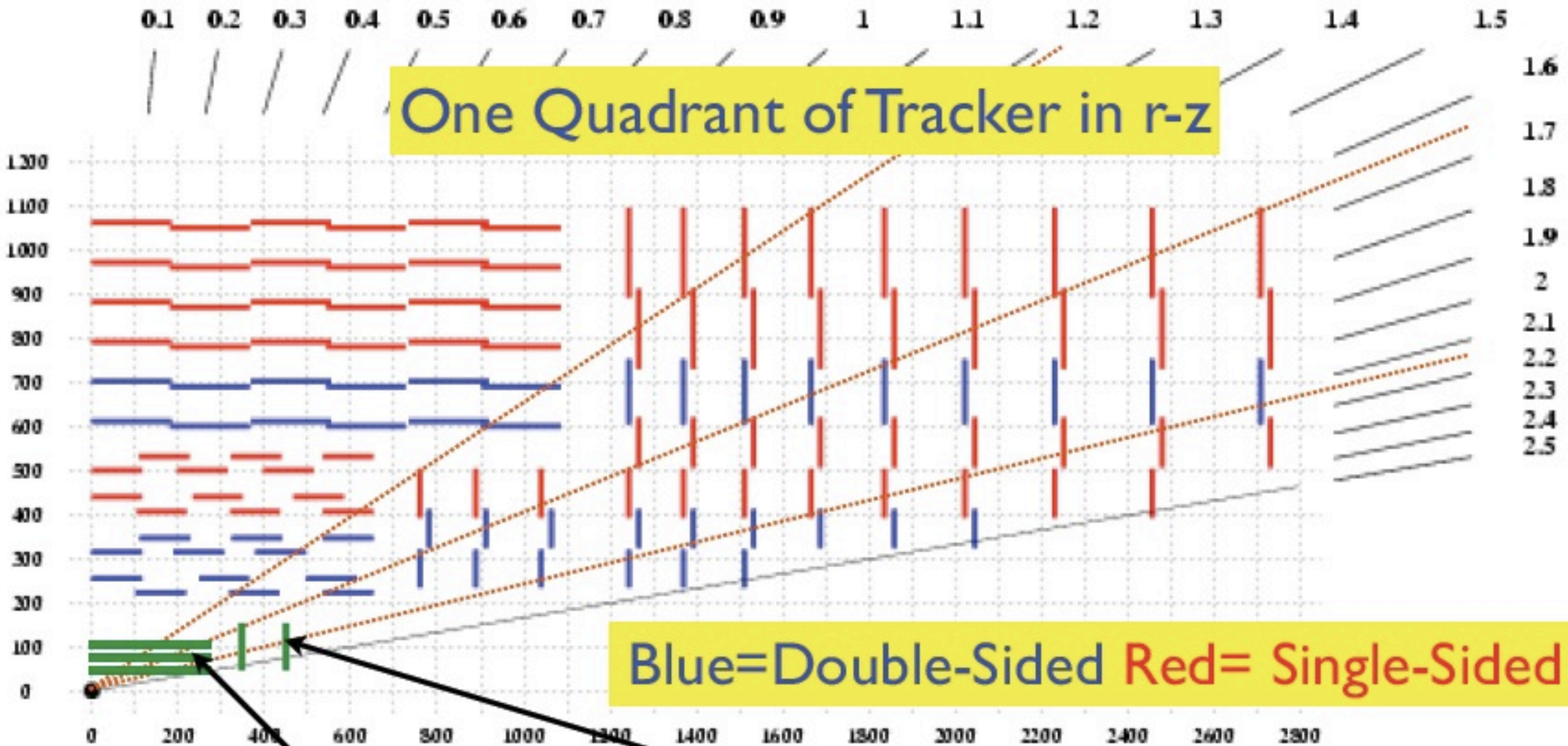

50
45
40
35
30
25
20
15
10
5
0
100
150
200
250
300
350
400
450
tanβ
m_A [GeV]
CMS Hττ 4.7 fb^-1
CMS H^+ 2.2 fb^-1
ATLAS Hττ 1.1 fb^-1
ATLAS H^+ 4.6 fb^-1
D0 7.3 fb^-1
LEP
MSSM m_h^max scenario, M_SUSY = 1 TeV

1202.4083

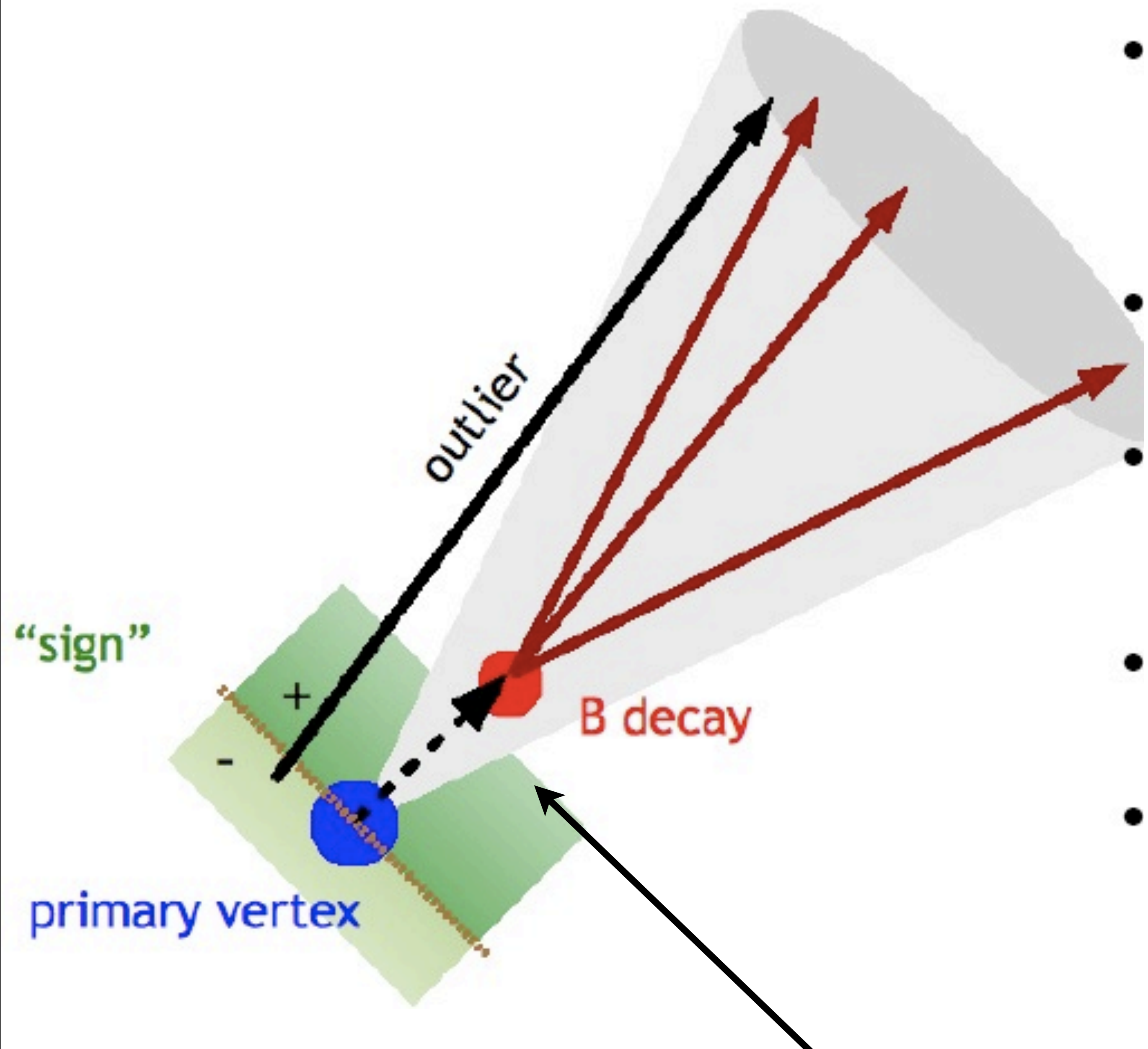


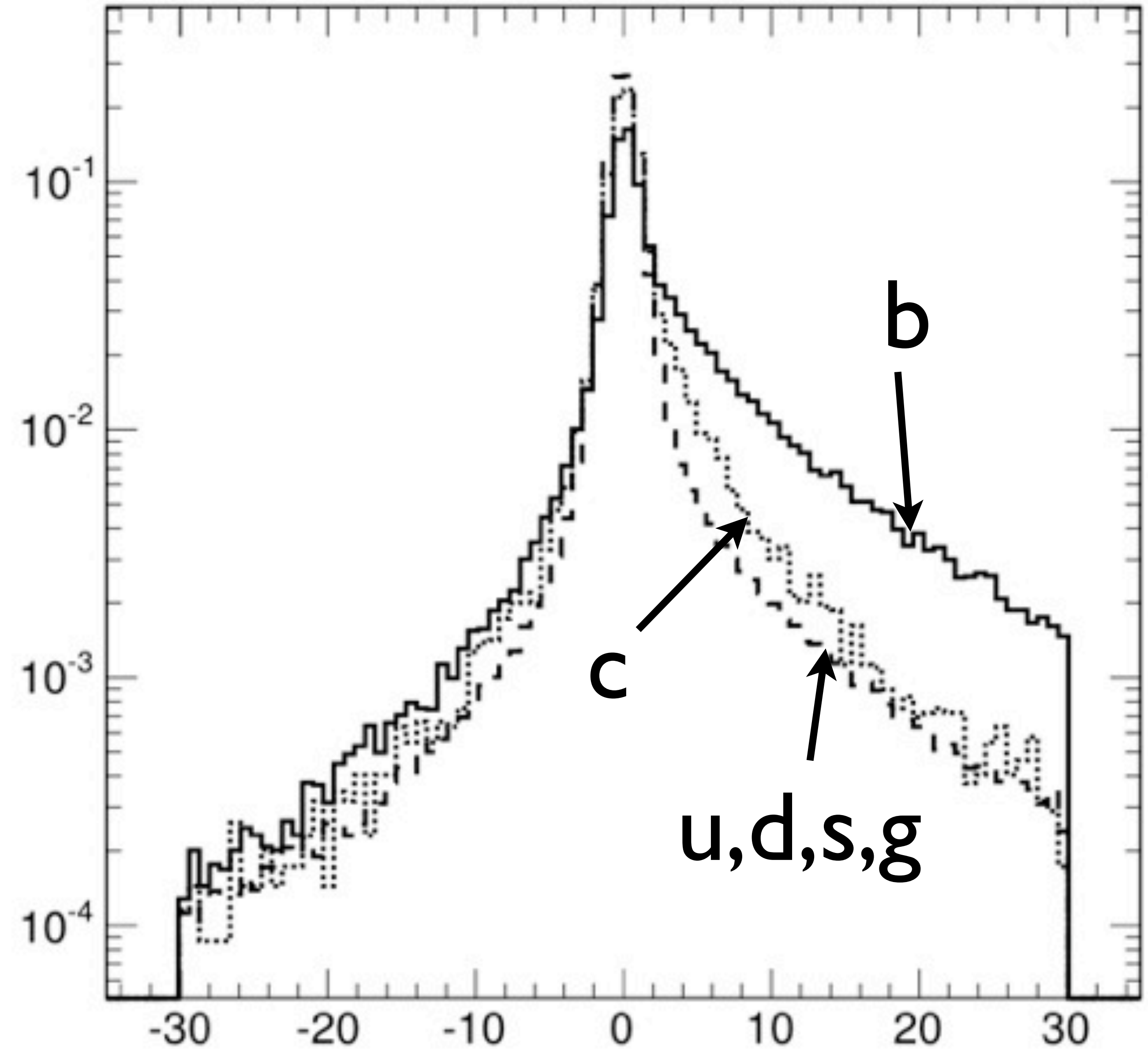
Bounds for doubly charged Higgs boson

The layout of Si tracker @ CMS $\delta L \sim \mu m$



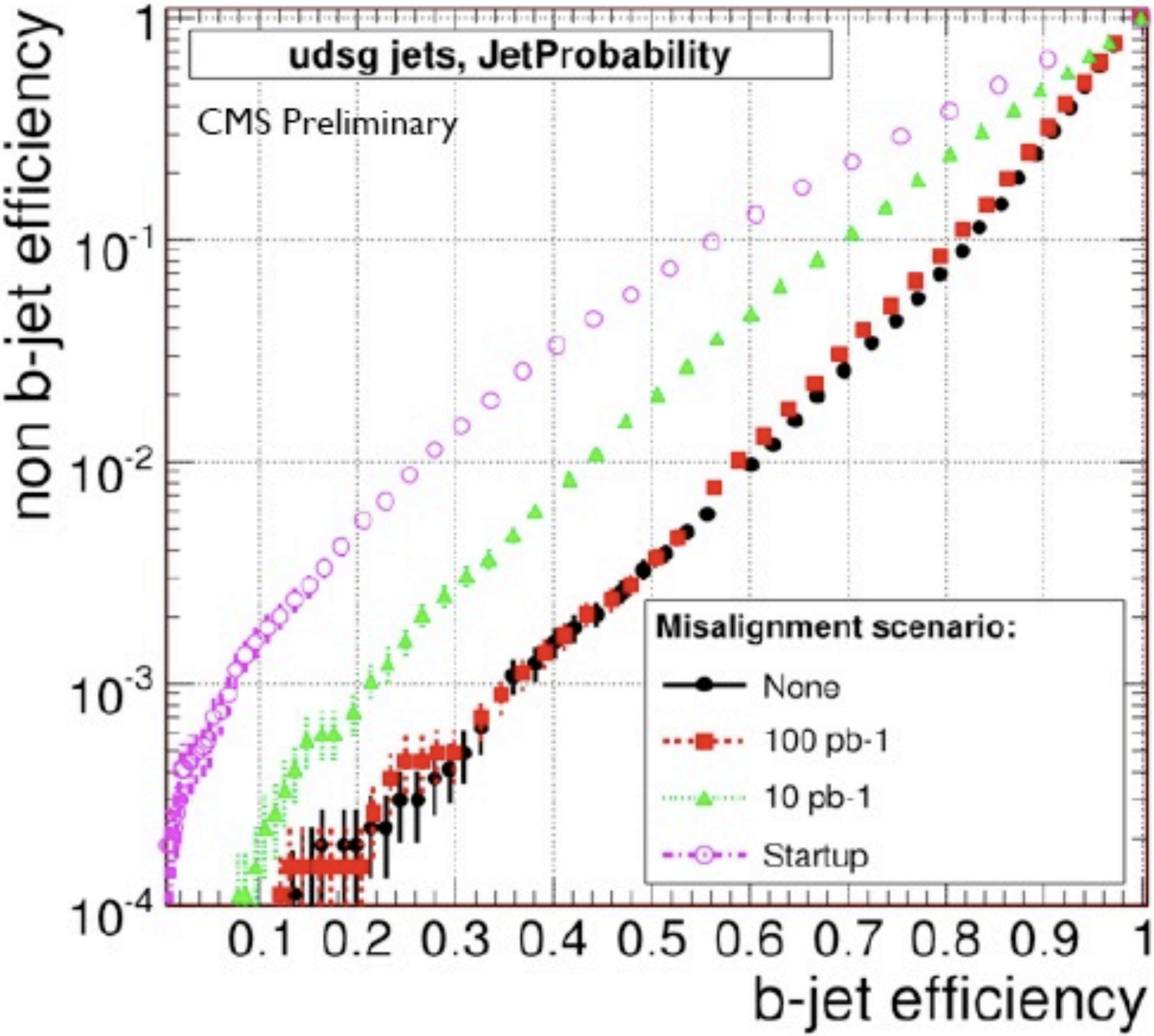
- 3 Barrel Pixel Layers, 2 Forward Pixel Disks
- 4 Inner Barrel Layers (TIB), 6 Outer Layers (TOB)
- 3 Forward Inner Disks (TID), 9 Outer Disks (TEC)





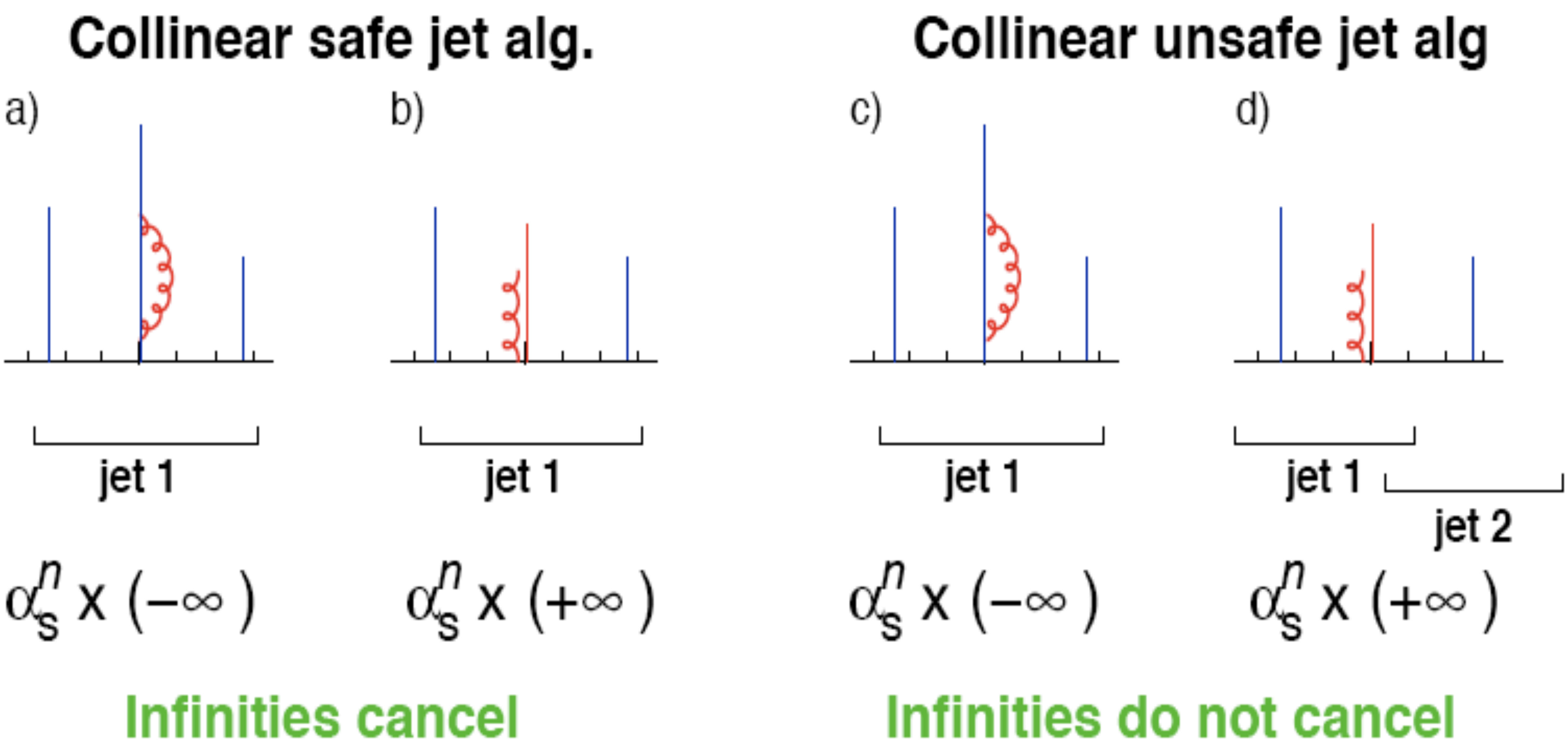
Secondary vertex

1. Impact parameters
2. Invariant mass of tracks, say to reject Kaon
3. Charge multiplicity,b jet is massive,
   more charged particles can be produced.



udsg jets, JetProbability
CMS Preliminary
non b-jet efficiency
b-jet efficiency
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Misalignment scenario:
None
100 pb-1
10 pb-1
Startup

Towards Jetography: 0906.1833, G.P. Salam



Towards Jetography: 0906.1833,G.P.Salam

A

Cone algorithms

Sternman, Weinberg,1977

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 < R^2$$

$$\frac{\sigma_2}{\sigma} = 1 - \frac{32}{3}\frac{\alpha_s}{2\pi}\log\frac{1}{\delta}\log\frac{1}{\epsilon}$$

Intuitive, but not infrared safe.

Towards Jetography: 0906.1833 ,G.P.Salam

B

Sequential recombination jet algorithms

Jade

$$y_{ij} = \frac{2E_iE_j(1-\cos\theta_{ij})}{Q^2}$$

K_t

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

C/A

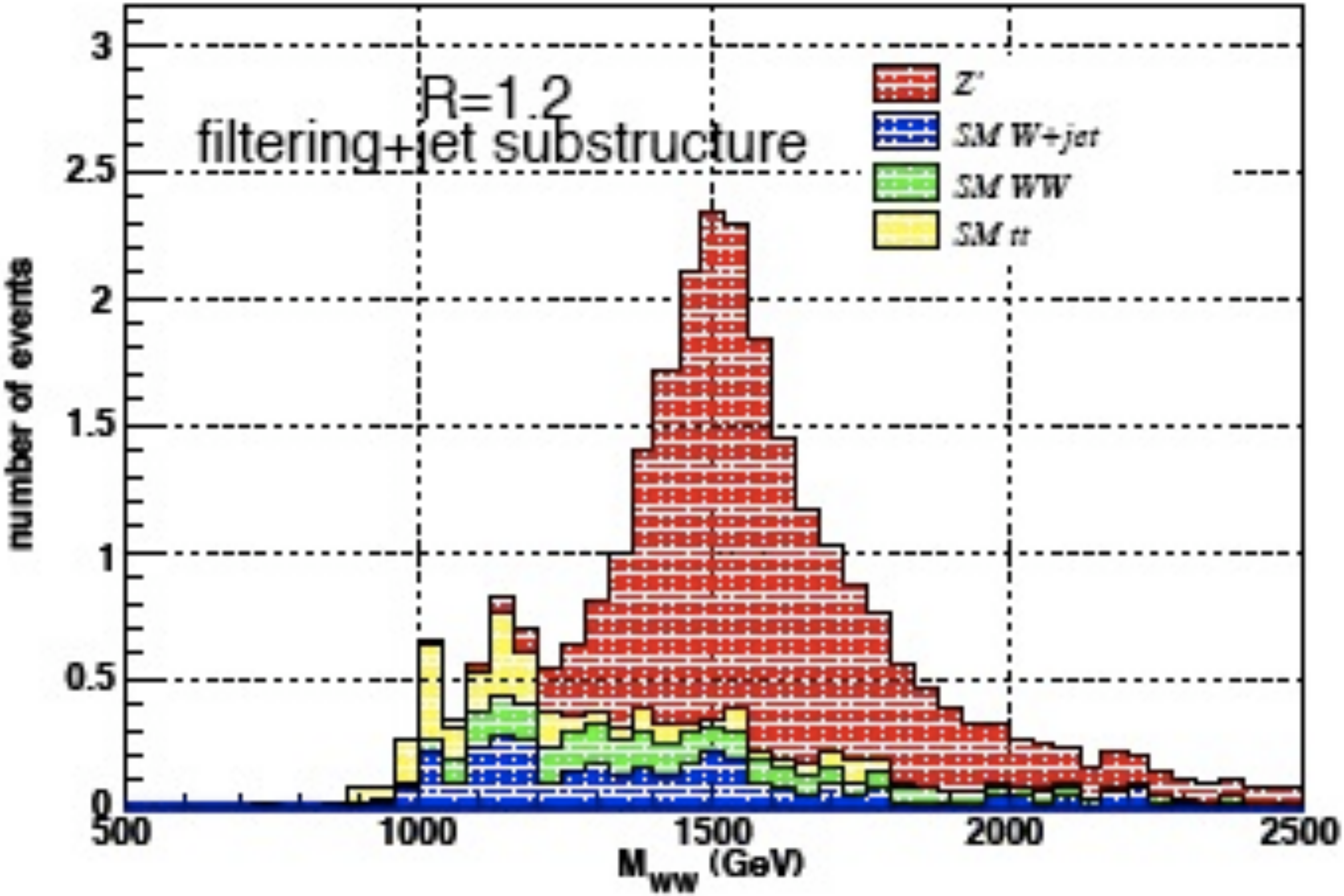
$$v_{ij} = 2(1-\cos\theta_{ij})$$

Anti-K_t

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\frac{\Delta R_{ij}^2}{R^2}$$

P=-1,anti-Kt

Wtagger: MVA: Boost Decision Tree



Yanou Cui, Zhenyu Han, and Matthew D. Schwartz

1012.2077

	$p_T \simeq 500$ GeV	$p_T \simeq 1000$ GeV	$p_T \simeq 1500$ GeV
W	76%	77	72
h	59	61	62

W-Higgs tagger rate

	$p_T \simeq 500$ GeV	$p_T \simeq 1000$ GeV	$p_T \simeq 1500$ GeV
quark $\to W$	6.5%	6.5	5.9
quark $\to h$	6.8	5.6	5.8
gluon $\to W$	10.4	8.3	7.4
gluon $\to h$	10.5	8.8	7.4

QCD mistag rate

A.Katz,M. Son,B.Tweedie,1010.5253

$$\langle m_j^2 \rangle \simeq C_i \, \alpha_s \, p_{T,j}^2 \, \Delta R_{j_1 j_2}^2$$

Gluon jet can be more massive than quark jet

S.D.Ellis,J.Huston,K.Hatakeyama,P.Loch,M.Tonnesmann,Prog.Part.Nucl.Phys.60,484

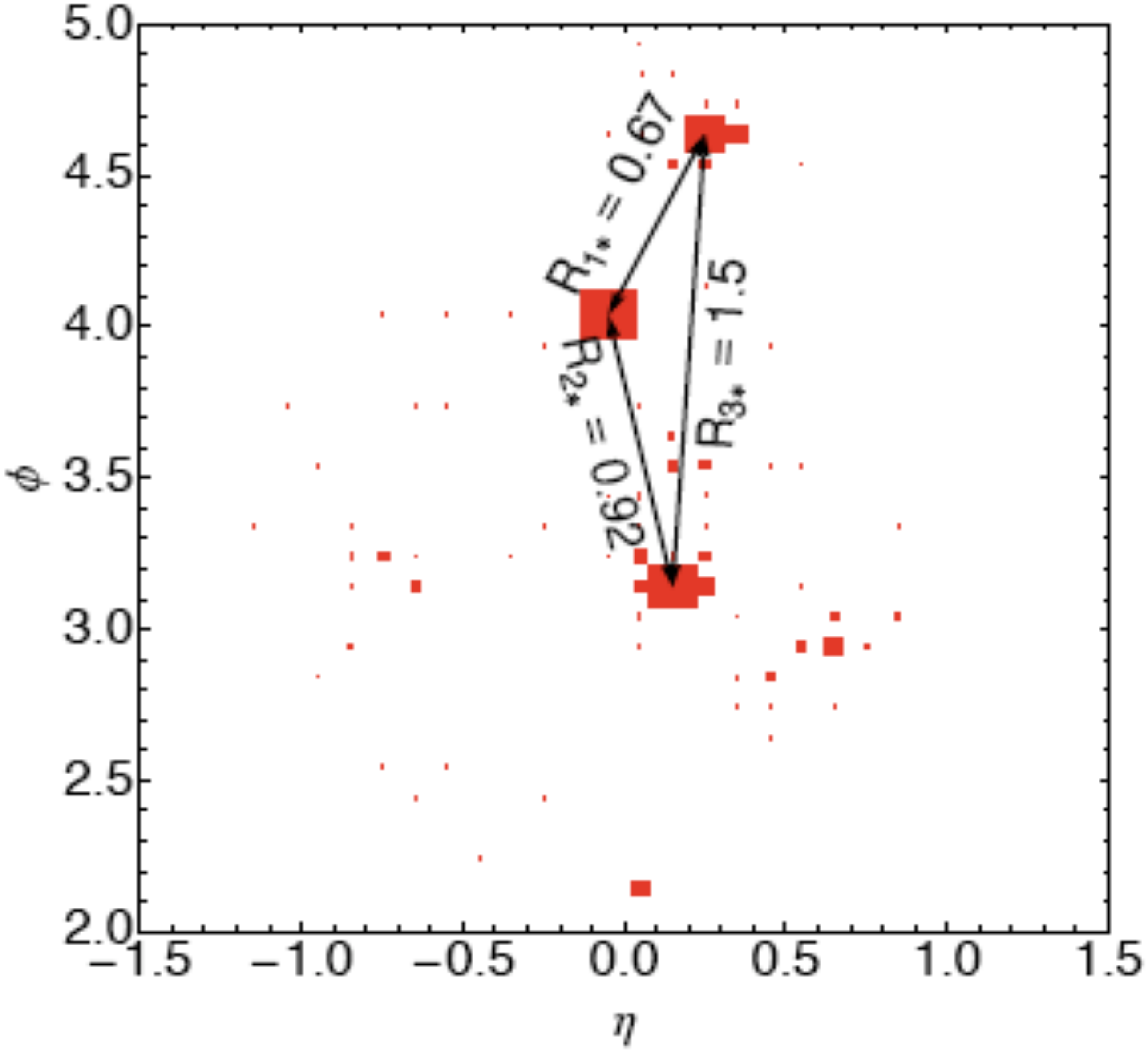
$$\langle \delta m_j^2 \rangle \simeq \Lambda_{\mathrm{UE}} \, p_{T,j} \, \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$$

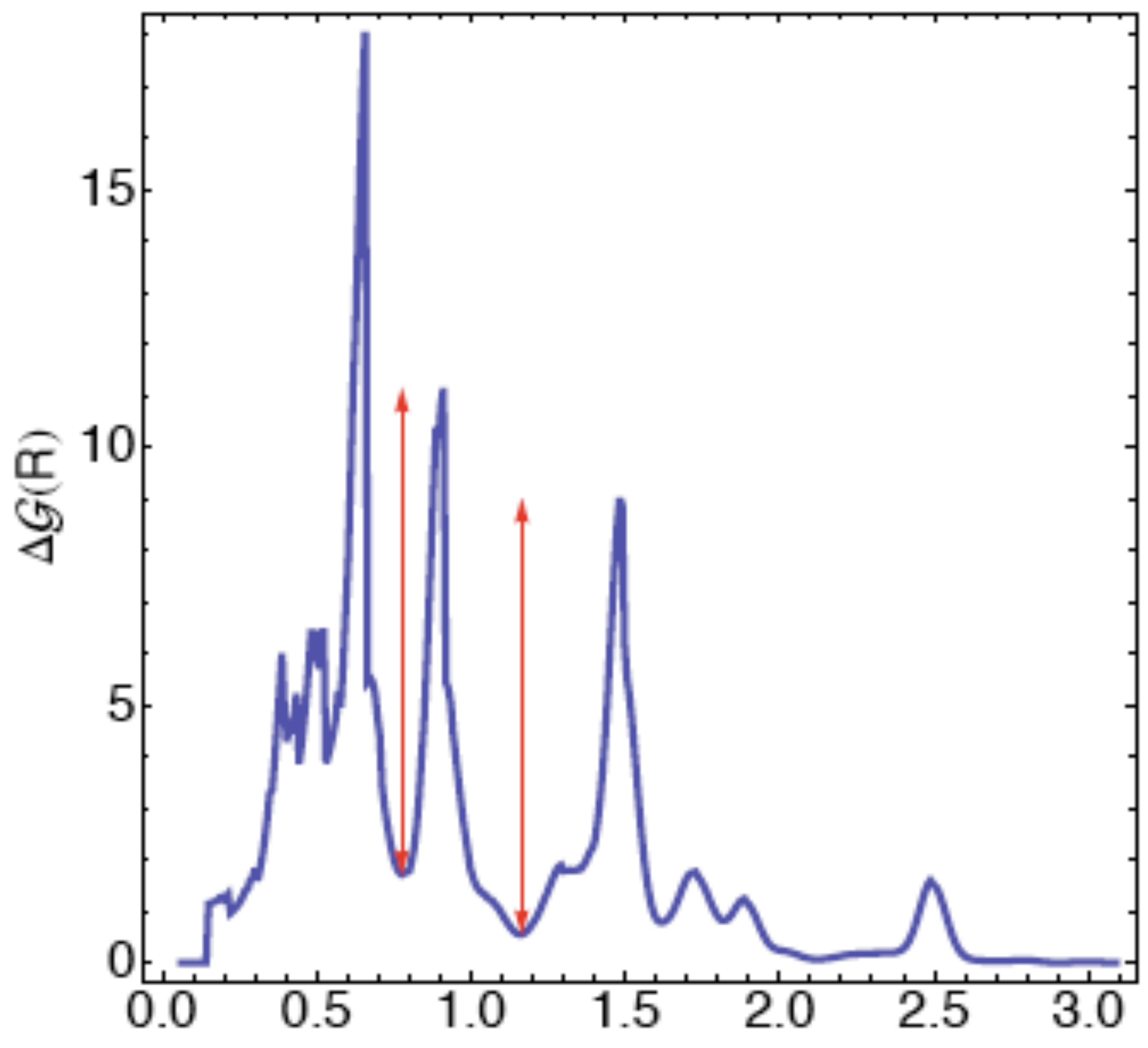
The larger the cone size, the larger the contribution of underlying event.
Pruning should be introduced to remove it.

M. Dasgupta, L.Magnea, G.P. Salam, JHEP0802,055

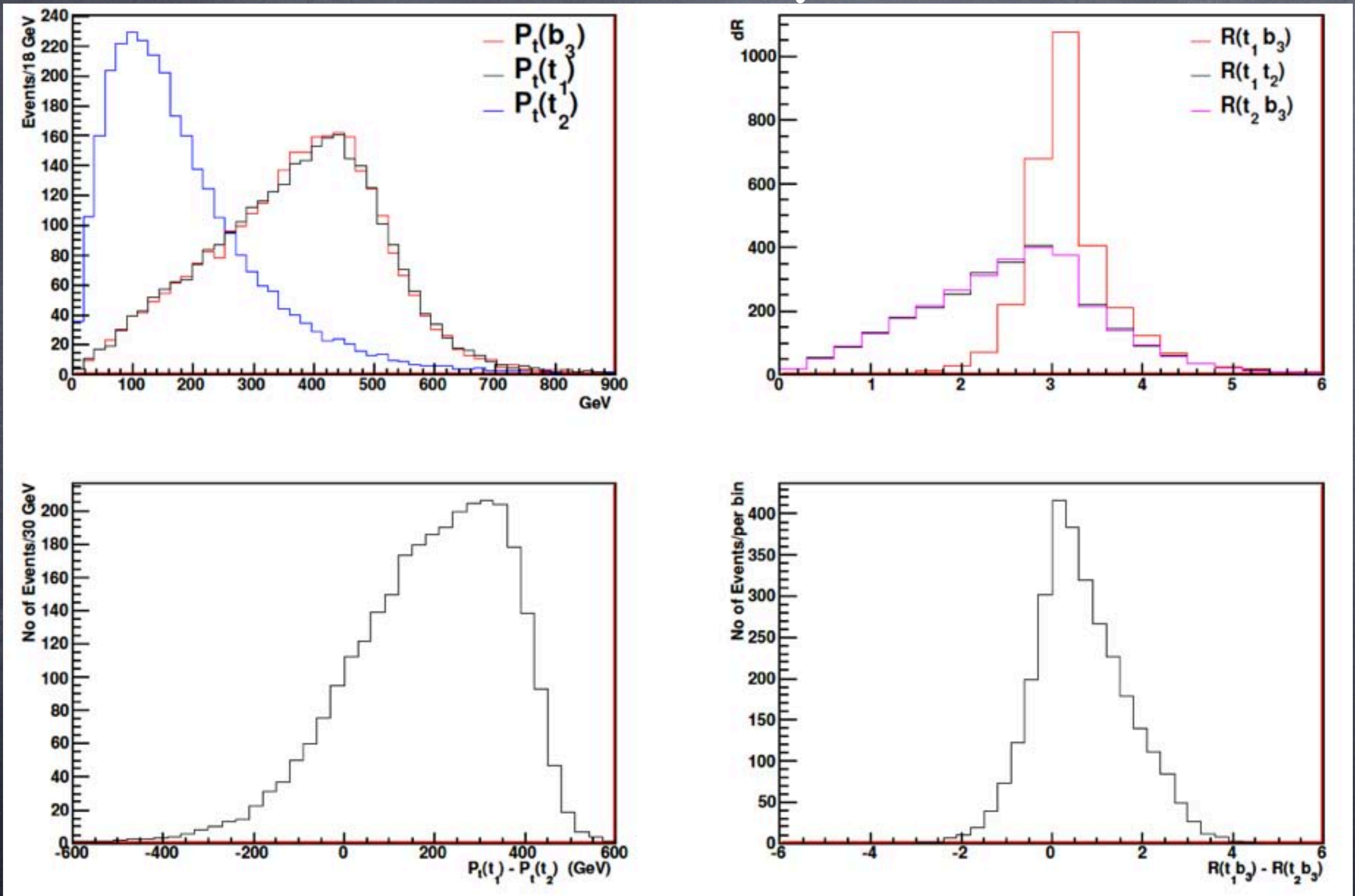
1104.1646 M. Jankowiak, A. Larkoski   Jetless

$$\mathcal{G}(R) \equiv \frac{\sum_{i\neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2 \Theta(R - \Delta R_{ij})}{\sum_{i\neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2} \approx \frac{\sum_{i\neq j} p_i \cdot p_j \Theta(R - \Delta R_{ij})}{\sum_{i\neq j} p_i \cdot p_j}$$





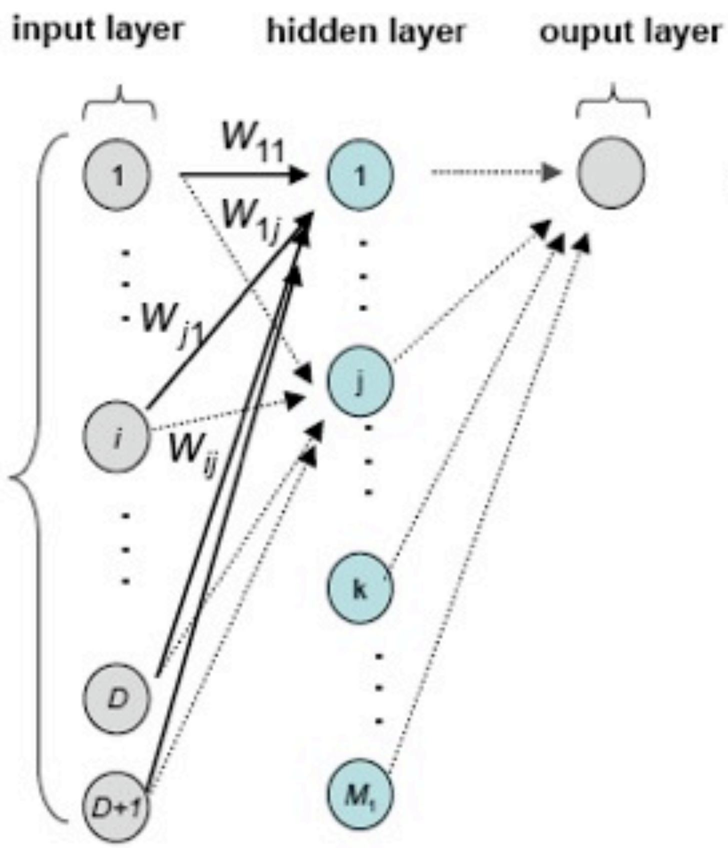
3. Feasibility@LHC



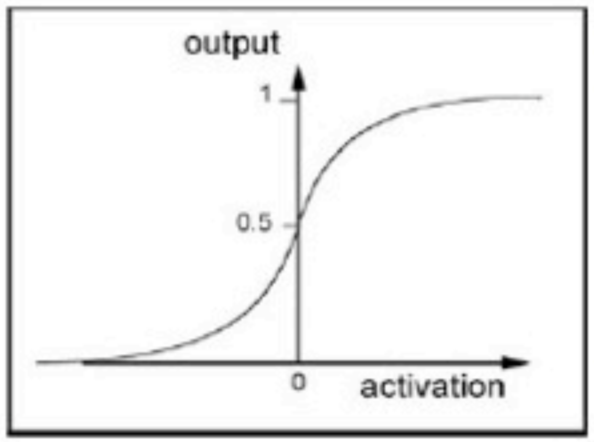
A Show Case $m_{H+} = 1$ TeV why we use those cuts?

Neural Network Discrimination

D_{var} discriminating input variables as input + 1 offset



output: $$y(x) = \sum_{i}^{M} w_{0i} A\left(w_{i0} + \sum_{j=1}^{D} w_{ij} \cdot x_j \right)$$



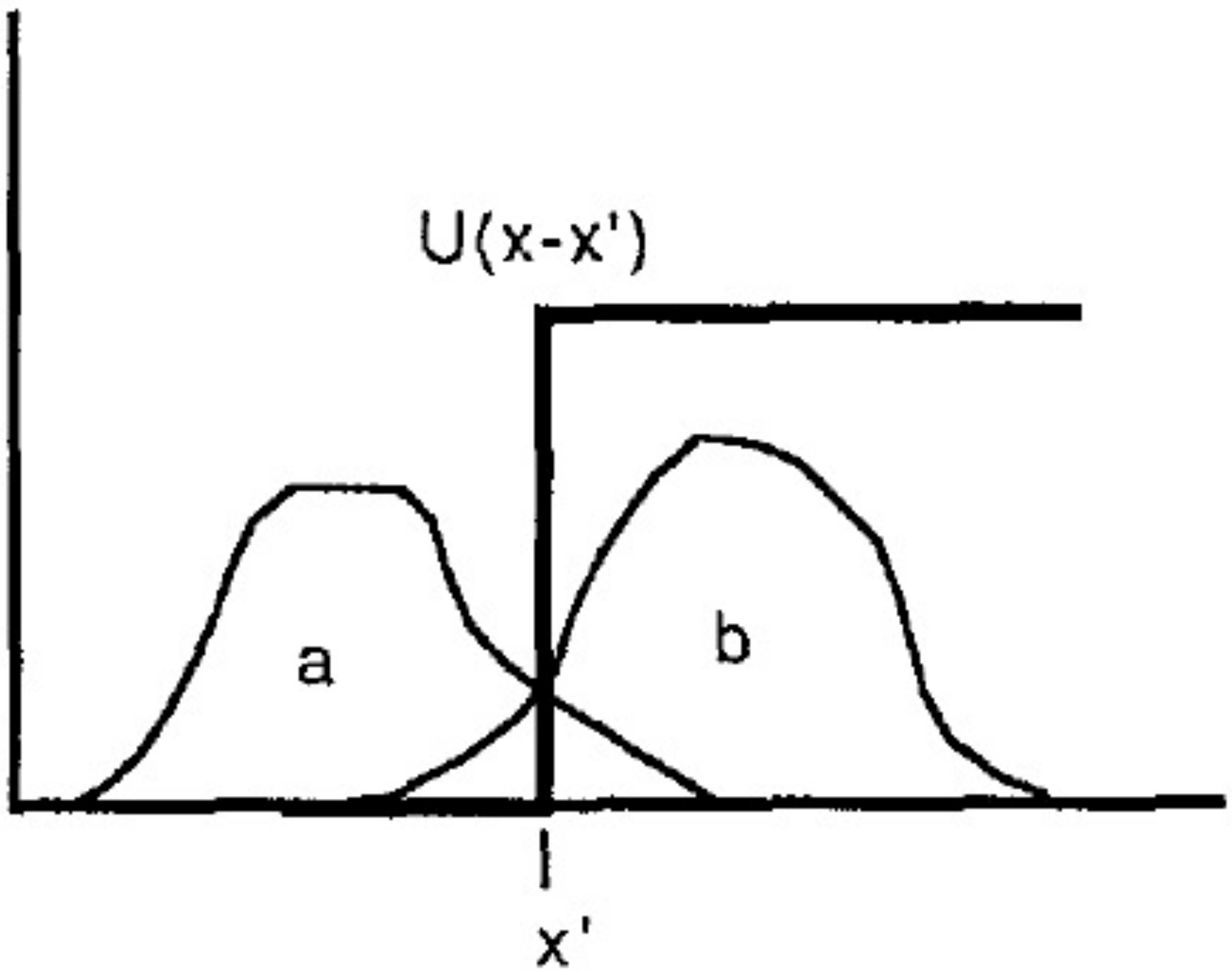
"Activation" function e.g. sigmoid:

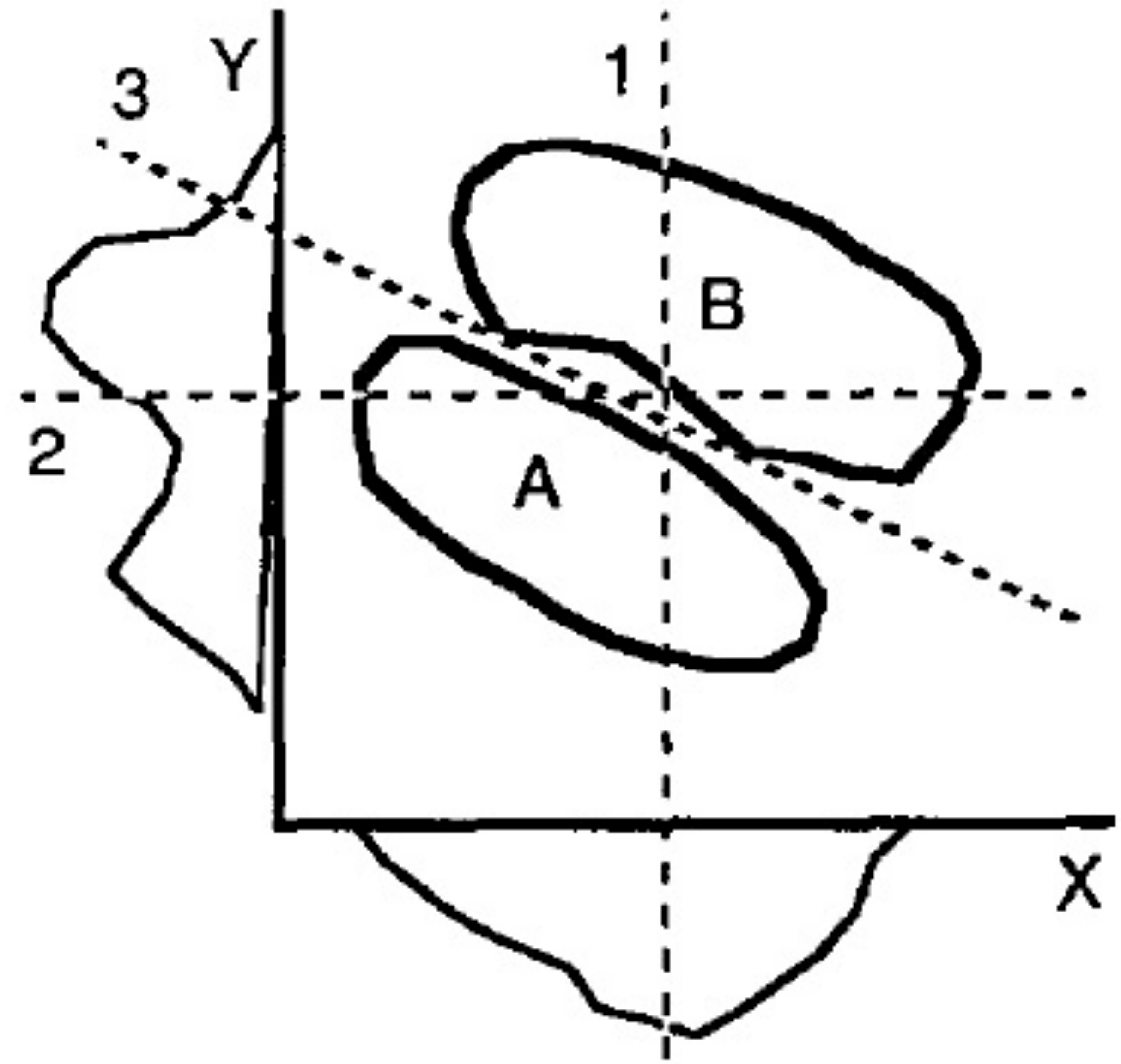
$$A(x) = \left(1 + e^{-x}\right)^{-1}$$

or tanh

nodes→neurons
links(weights)→synapses → Neural network: try to simulate reactions of a brain to certain stimulus (input data)

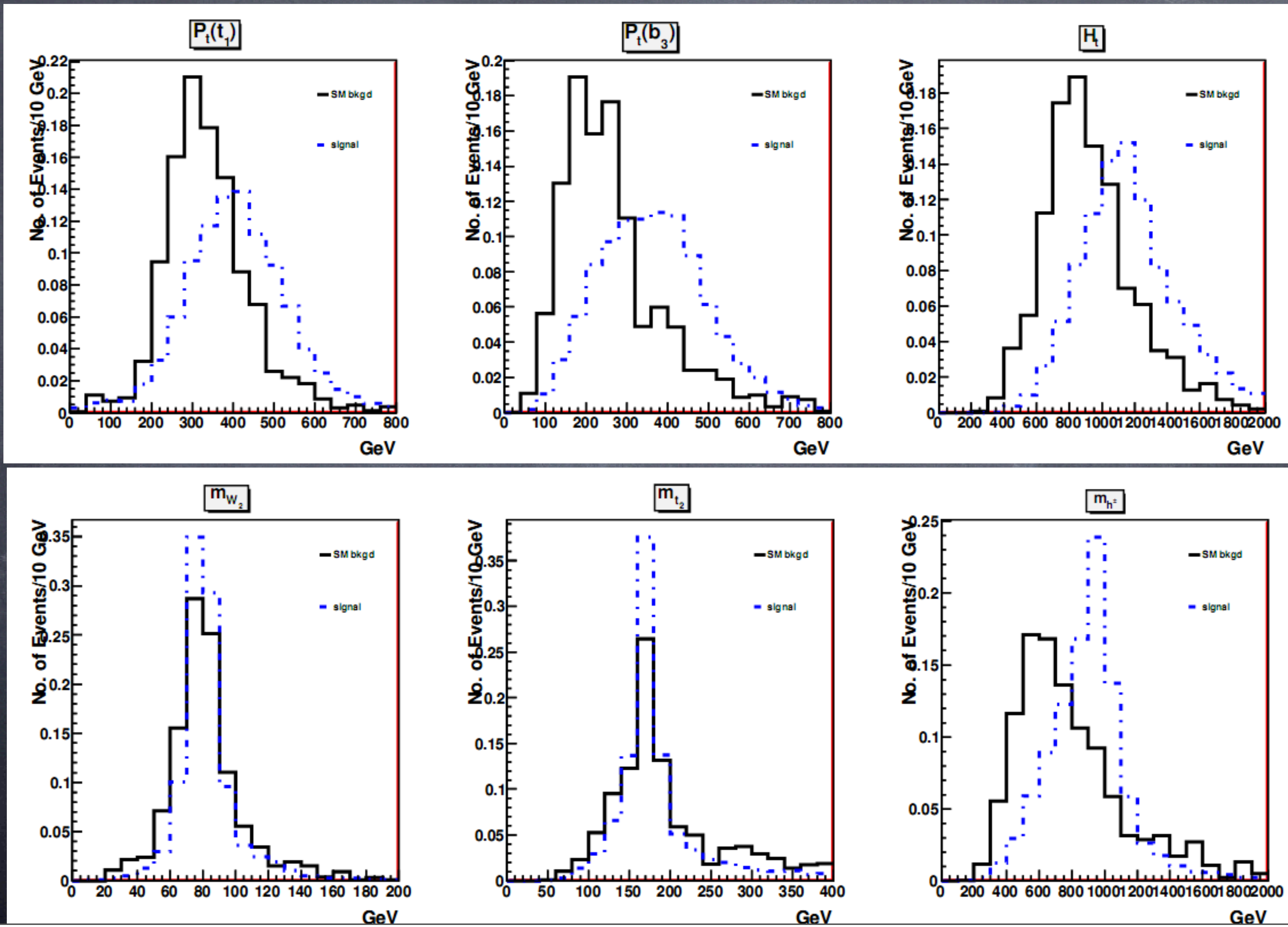
Considering the small number of signal compared with huge background we resort to the heavy machine gun: MVA





Why MultiVariate Analysis? To improve sensitivity of analysis when luminosity is limited and to reduce luminosity when budget fixed.

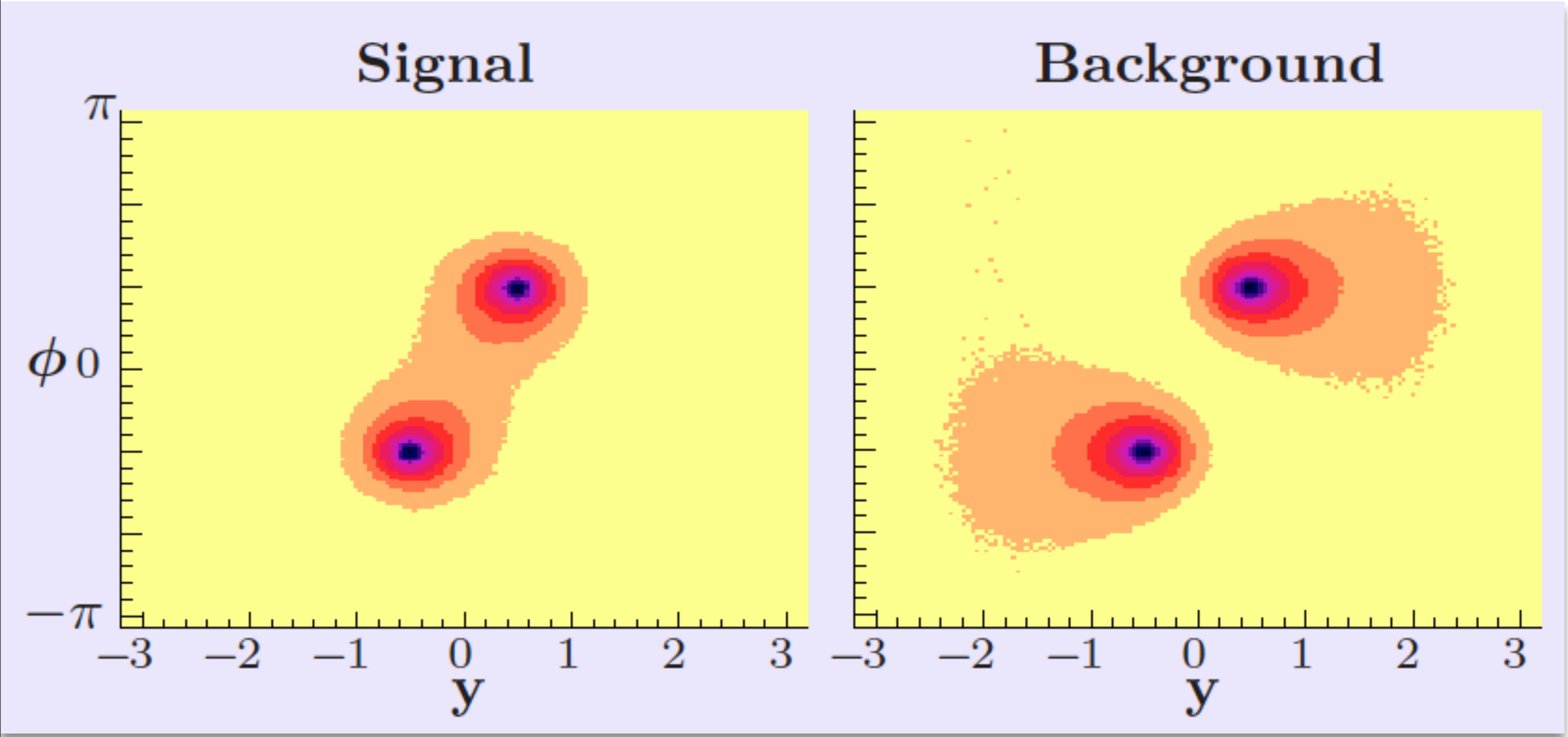
3. Feasibility@LHC



Color-Flow

Color Singlet

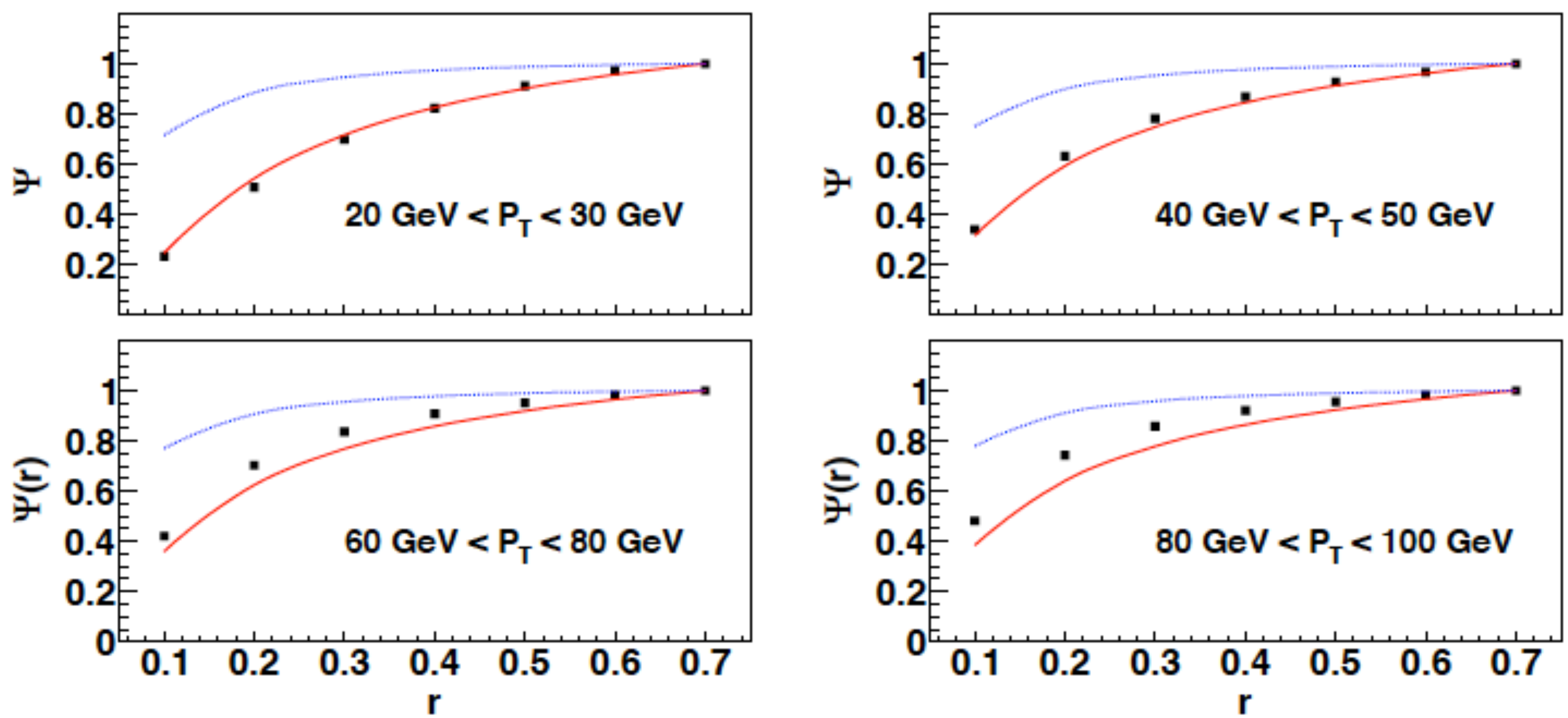
Color octet



J. Gallicchio, M. Schwartz,1001.5027
M.Janowiak,A.Hook,J.Wacker,1102.1012

$$\Psi(r) = \sum_f \int \frac{dP_T}{P_T} \frac{d\sigma_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\text{fi}}^2, R, r)$$

$$\times \left[\sum_f \int \frac{dP_T}{P_T} \frac{d\sigma_f}{dP_T} \bar{J}_f^E(1, P_T, \nu_{\text{fi}}^2, R, R) \right]^{-1}$$



H.N.Li, Z.Li,C.P.Yuan,1107.4535