Heavy Charged Higgs@LHC

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GUCAS

In collaboration with
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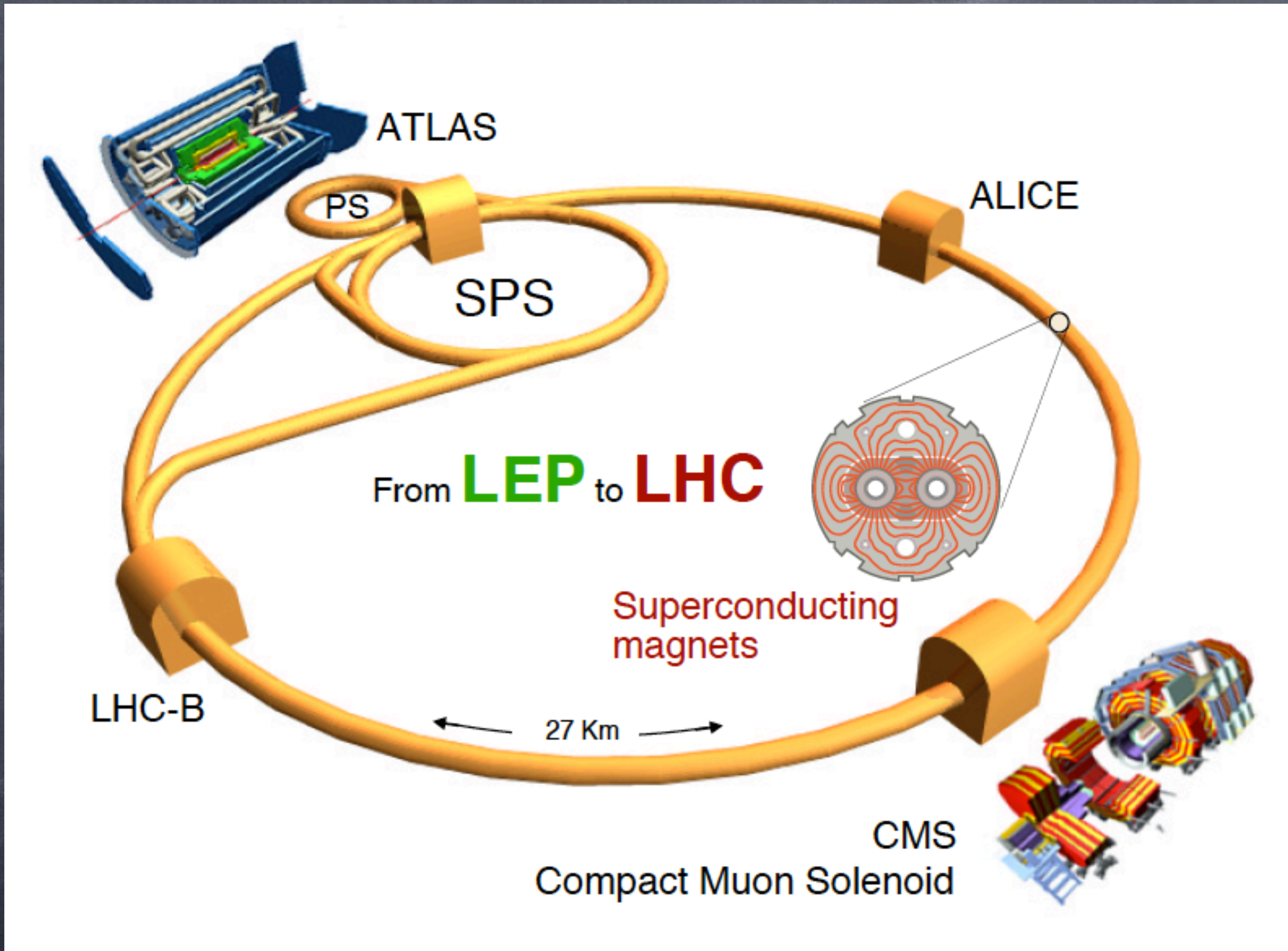
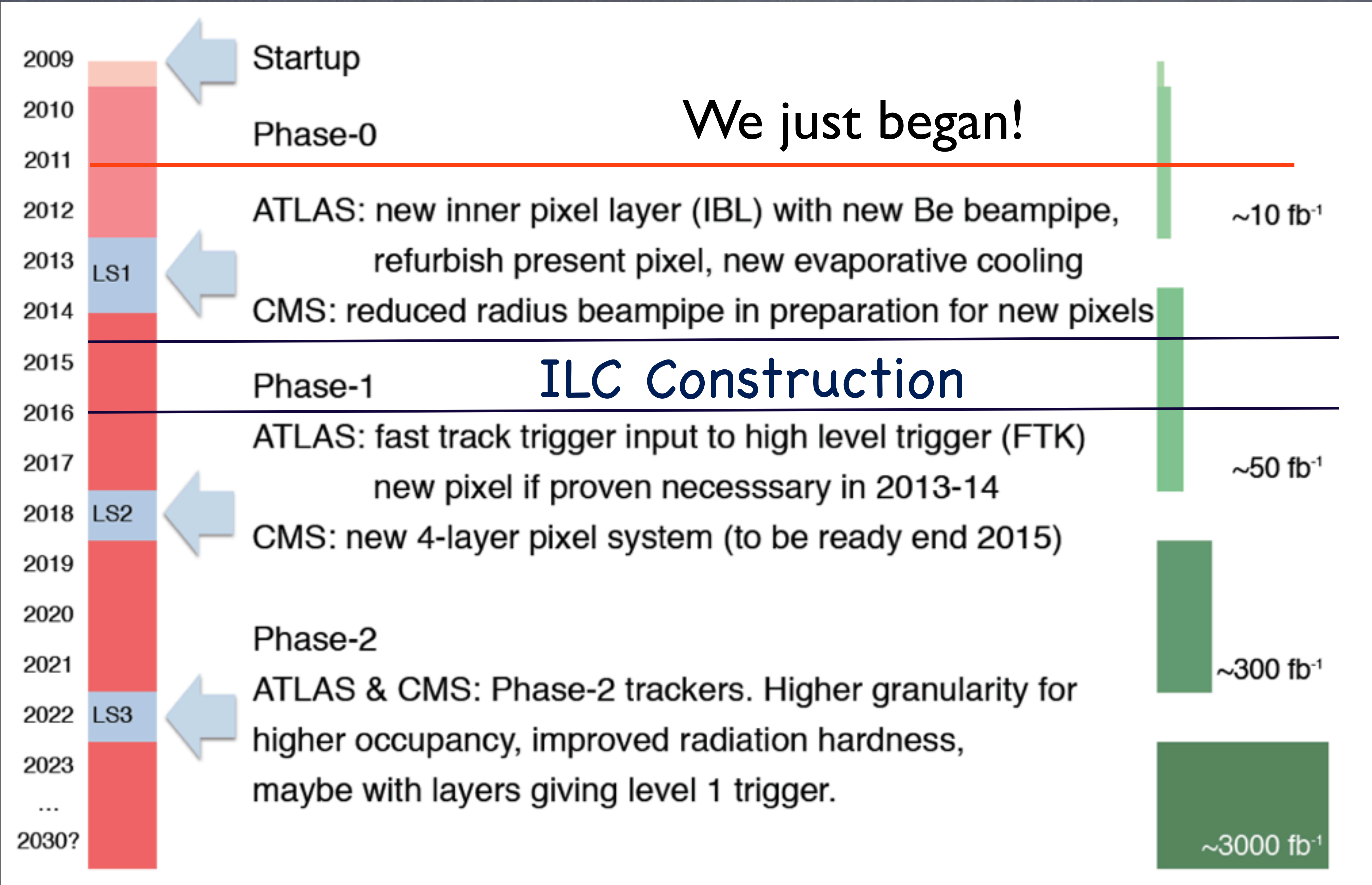
16:30pm, May 17, 2012, USTC, HeFei

Outline

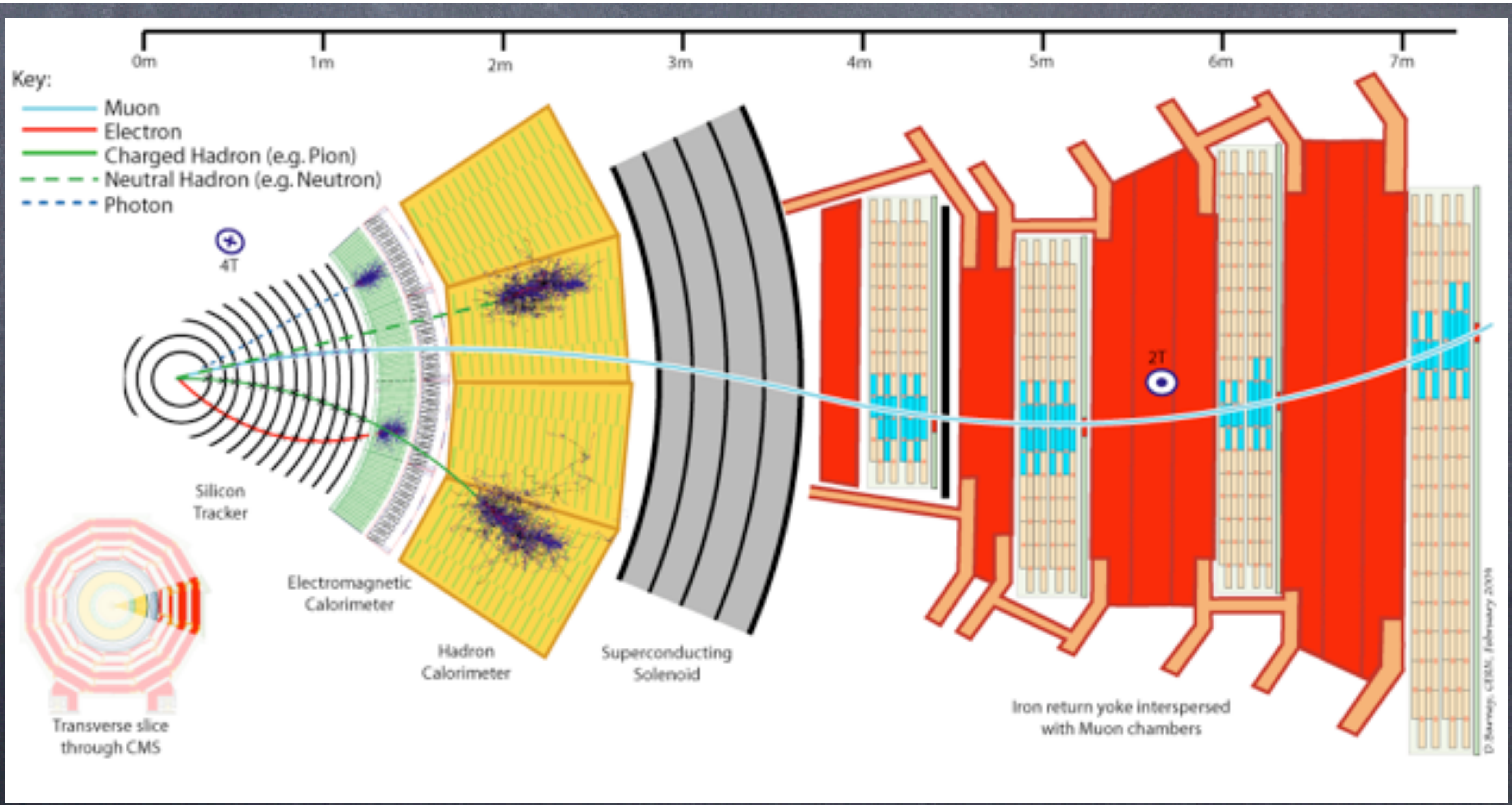
- 1. Why A Heavy Charged Higgs Boson?
- 2. What is jet/Substructure/top taggers?
- 3. Feasibility at the LHC with a Hybrid-R method
- 4. Conclusions



Collecting data 7TeV~5/fb, 8TeV~1.5/fb

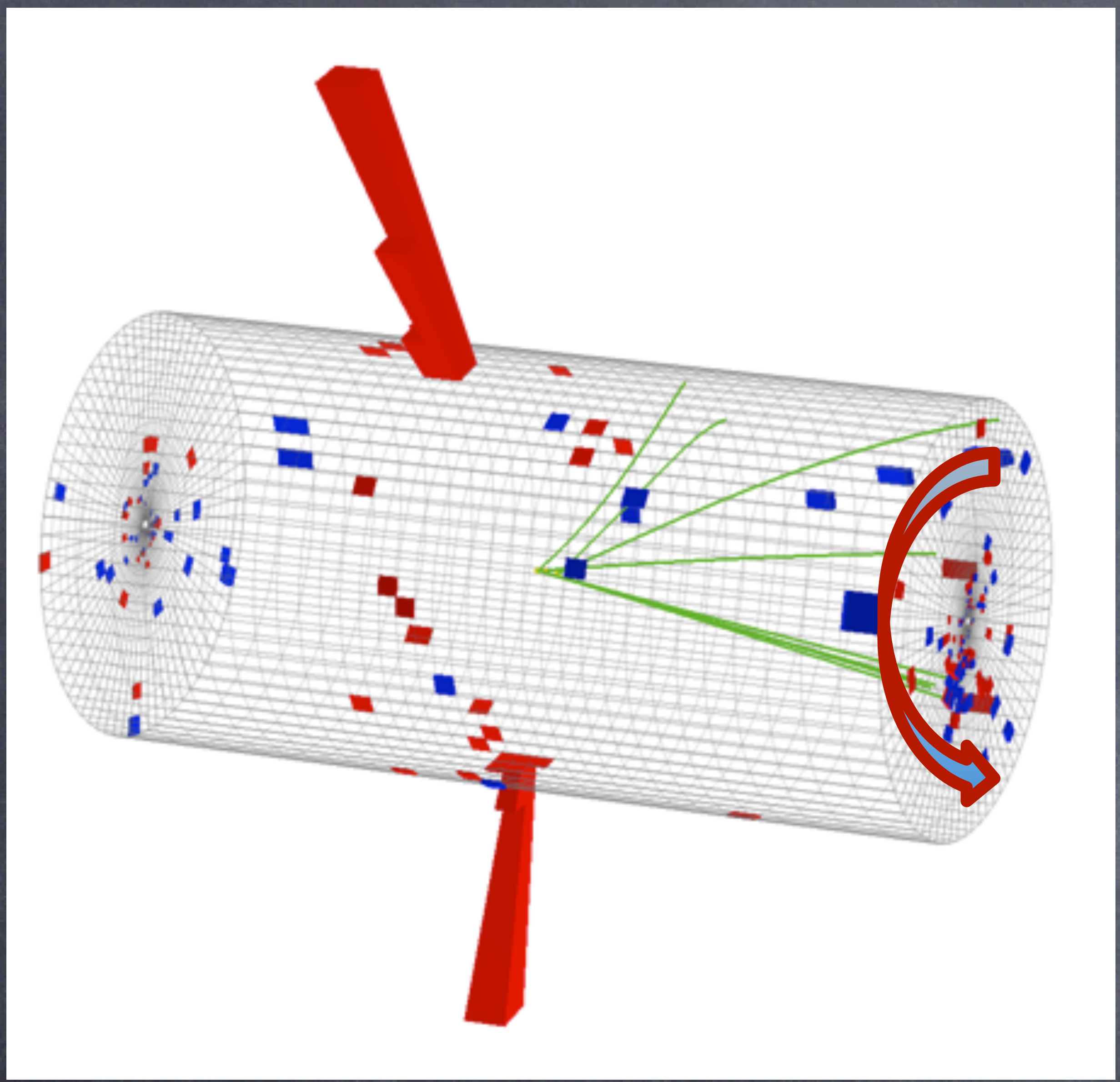

2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
Startup
We just began!
Phase-0
ATLAS: new inner pixel layer (IBL) with new Be beampipe,
refurbish present pixel, new evaporative cooling
CMS: reduced radius beampipe in preparation for new pixels
ILC Construction
Phase-1
ATLAS: fast track trigger input to high level trigger (FTK)
new pixel if proven necesssary in 2013-14
CMS: new 4-layer pixel system (to be ready end 2015)
Phase-2
ATLAS & CMS: Phase-2 trackers. Higher granularity for
higher occupancy, improved radiation hardness,
maybe with layers giving level 1 trigger.
~10 fb-1
~50 fb-1
~300 fb-1
~3000 fb-1

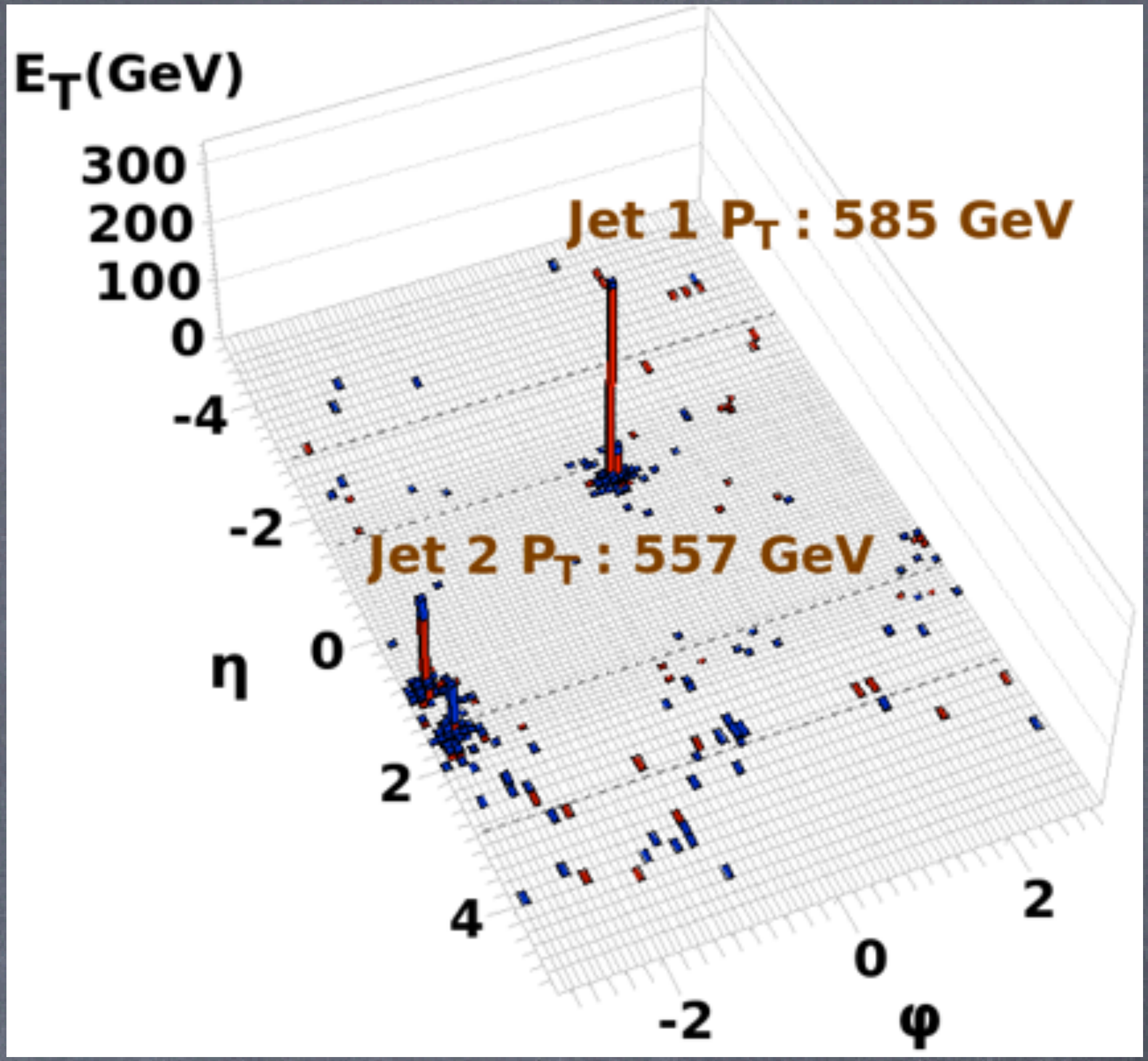
j	Jet	Cluster in EM and hadronic calorimeters (and inner tracker)
γ	Photon	EM cluster without matching track
e	Electron	EM cluster with matching track
μ	Muon	Matching tracks in inner and muon trackers
τ	Tau lepton	Narrow jet with matching track(s)
MET	Missing E_T	pT required to balance all of the above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

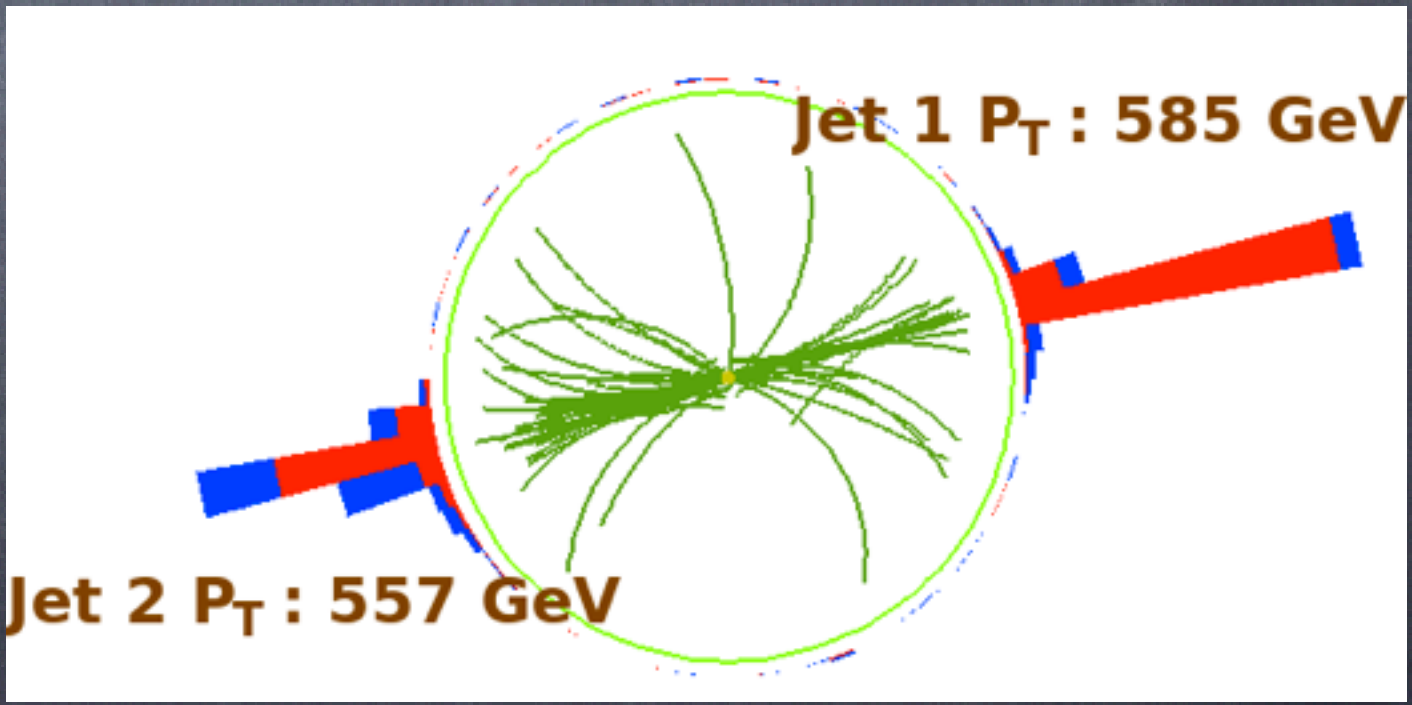


CMS Detector as an example

$|\eta| < 5$



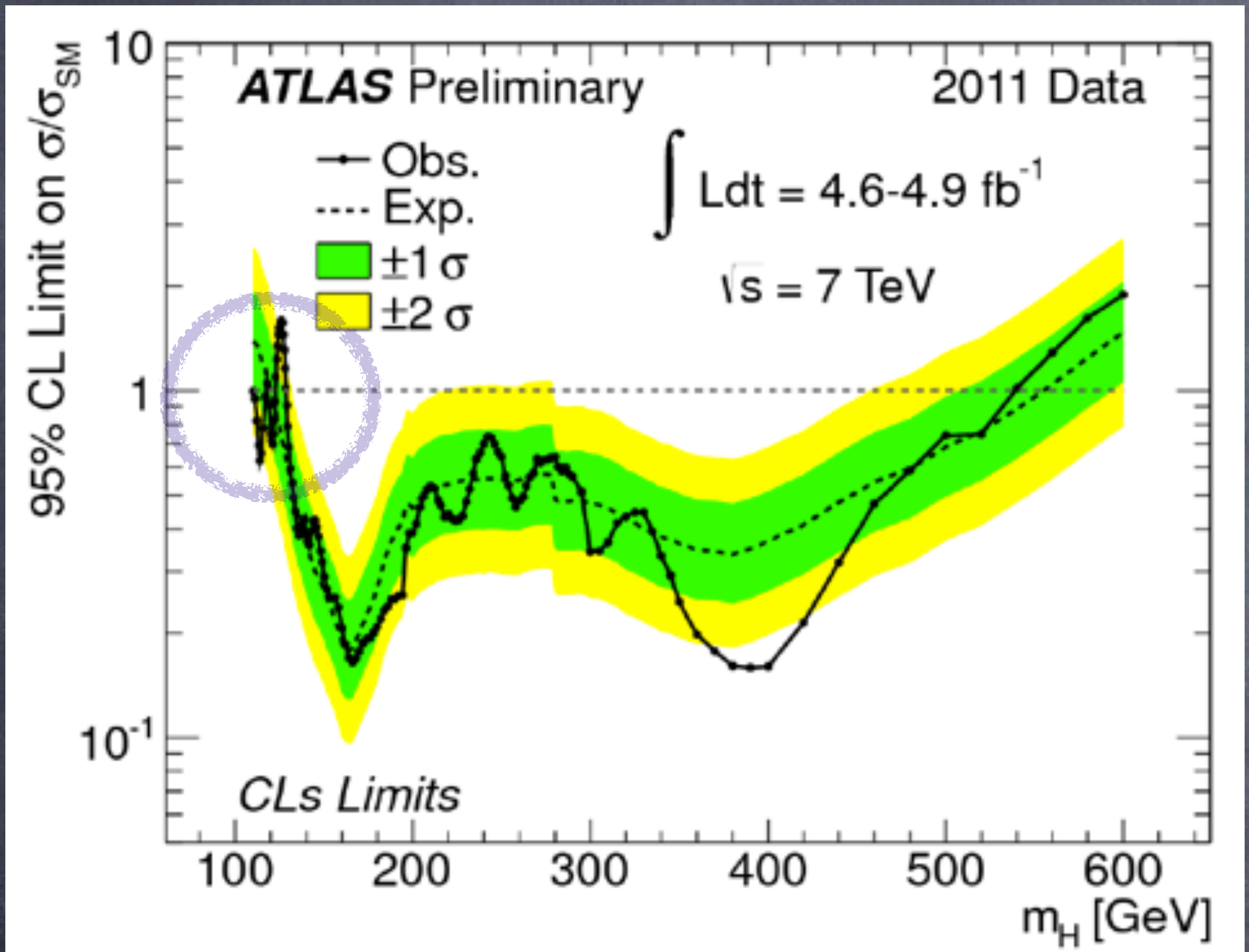


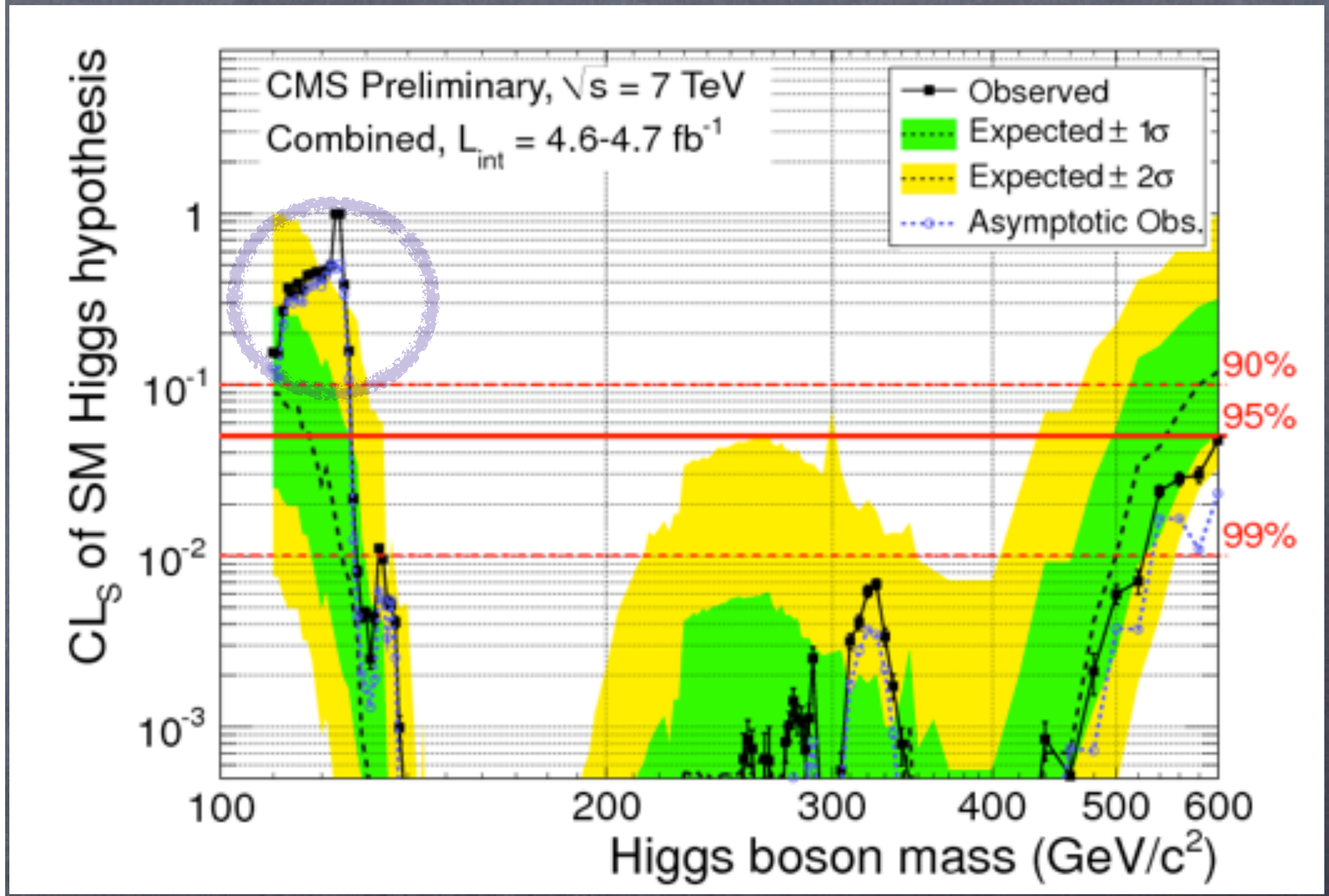


$\delta\eta \times \delta\phi = 0.1 \times 0.1$

A typical display of events @ LHC

1. Why A Heavy Charged Higgs Boson?

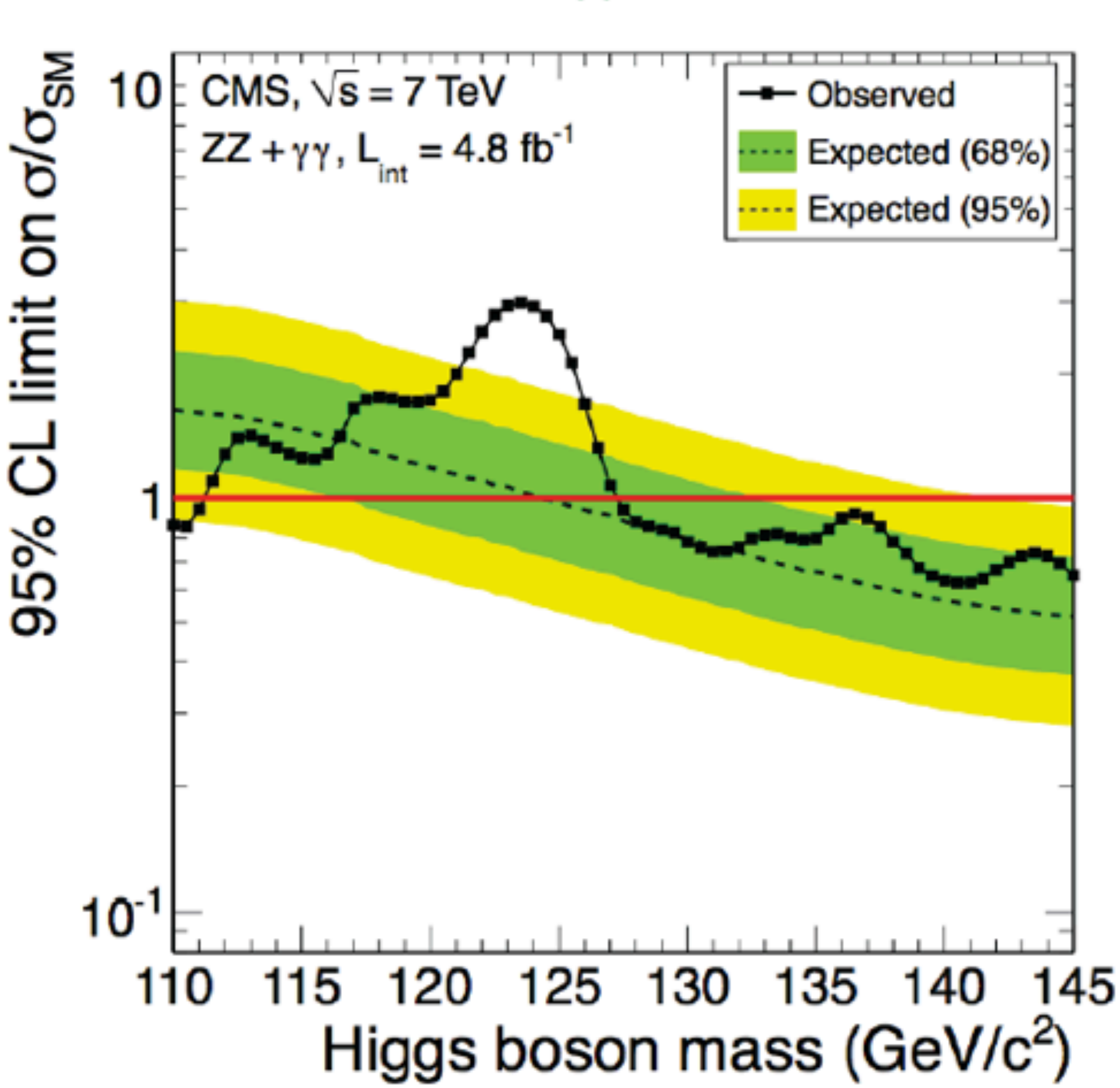




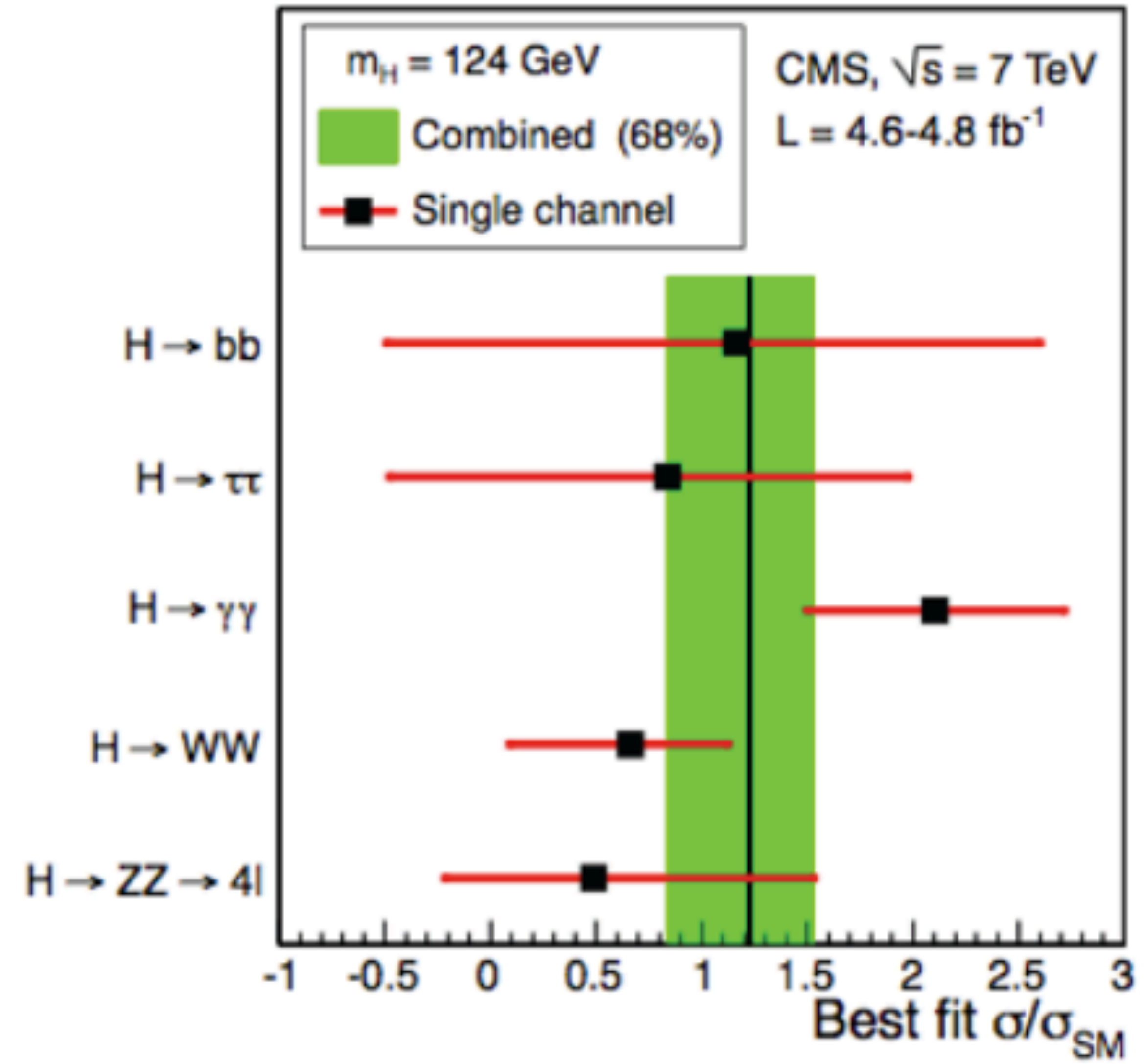
Whether the Higgs is SM-like?

What's is the Higgs Sector?

ZZ+γγ



Highest excess at 124 GeV



- All investigated channels show consistent excess but the observed excess is also consistent with BG only

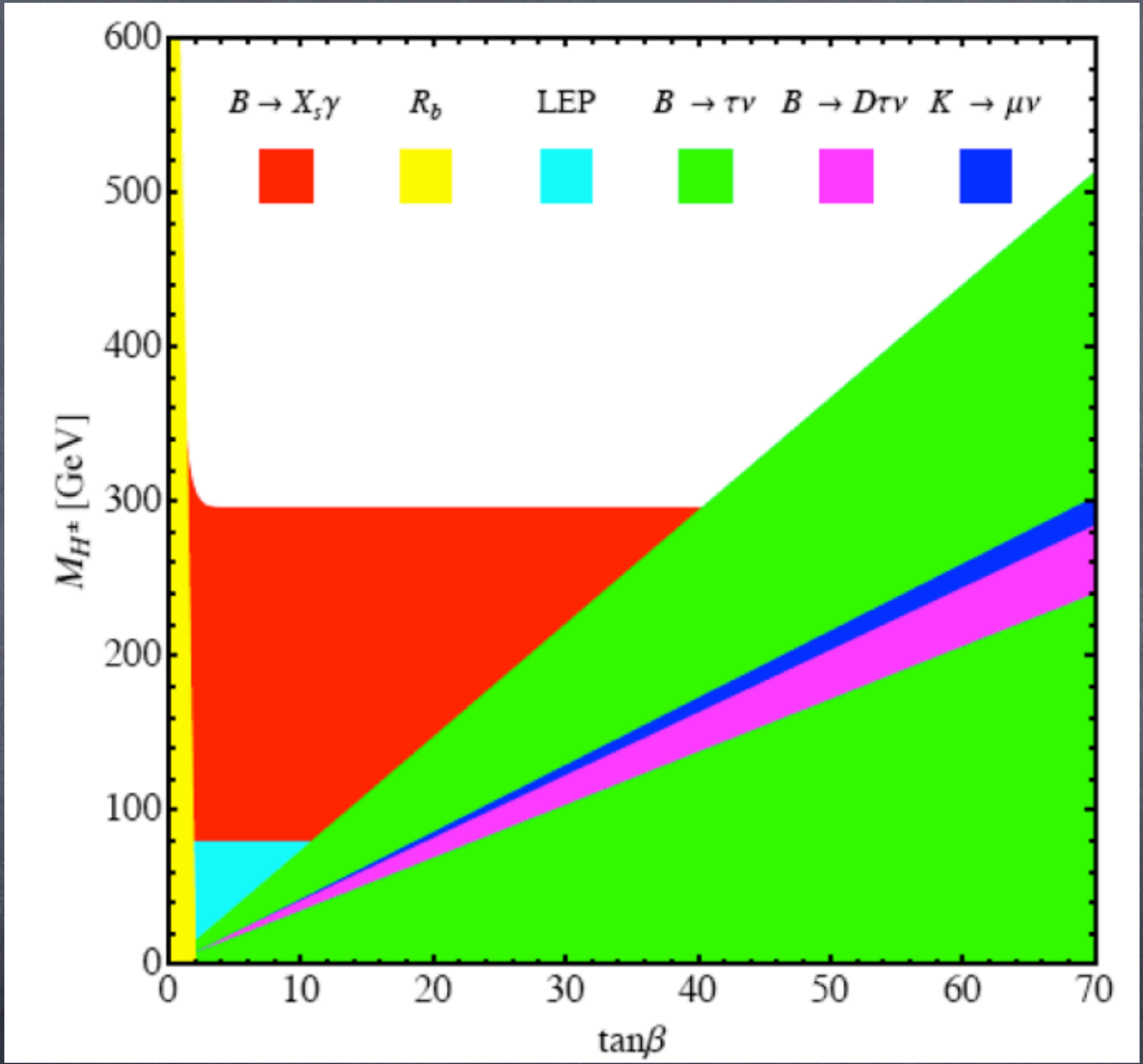
Hints for beyond minimal SM?

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).

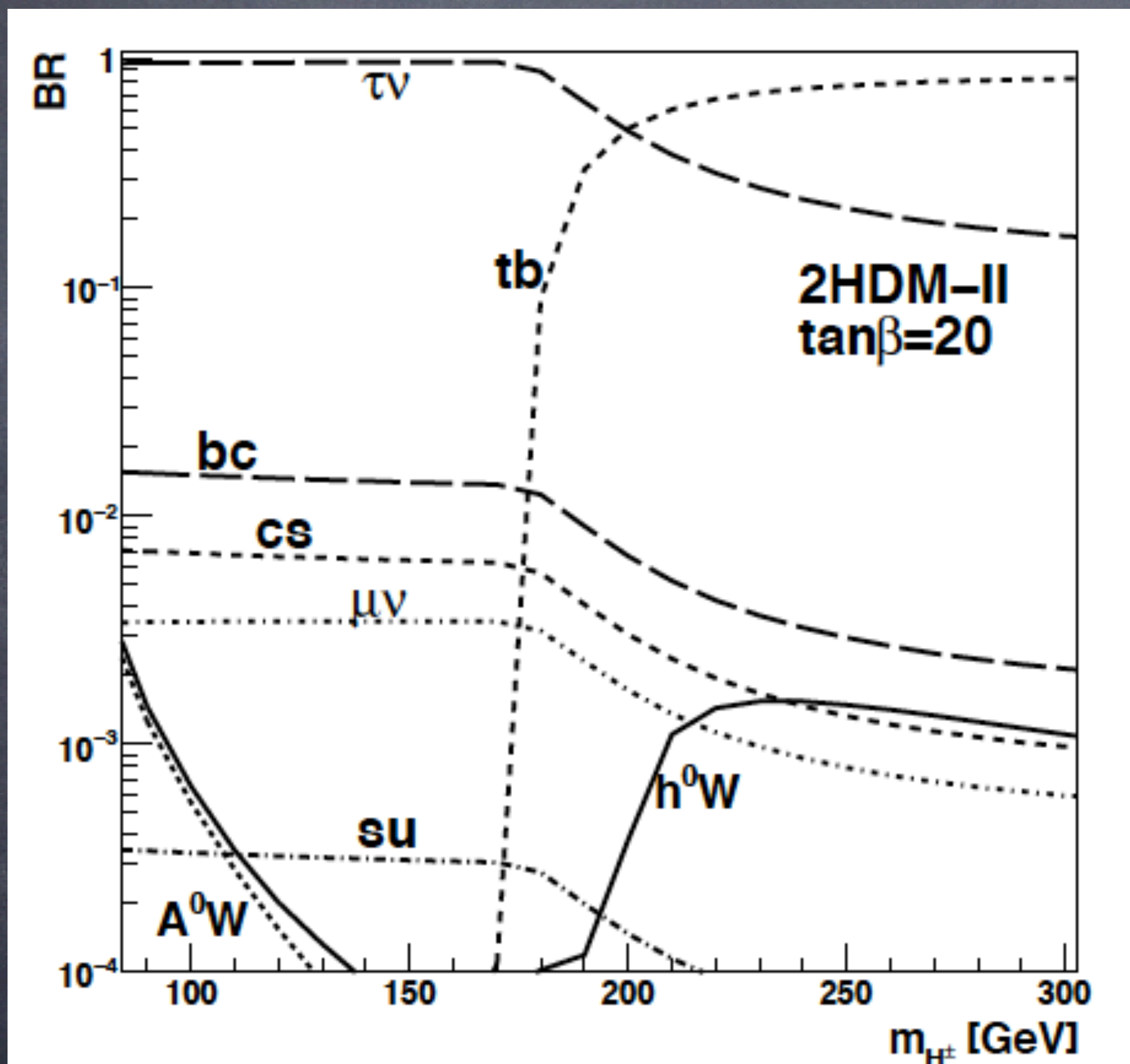
Conferences:

Charged Higgs Discovery at Colliders 2006(08)(10)



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

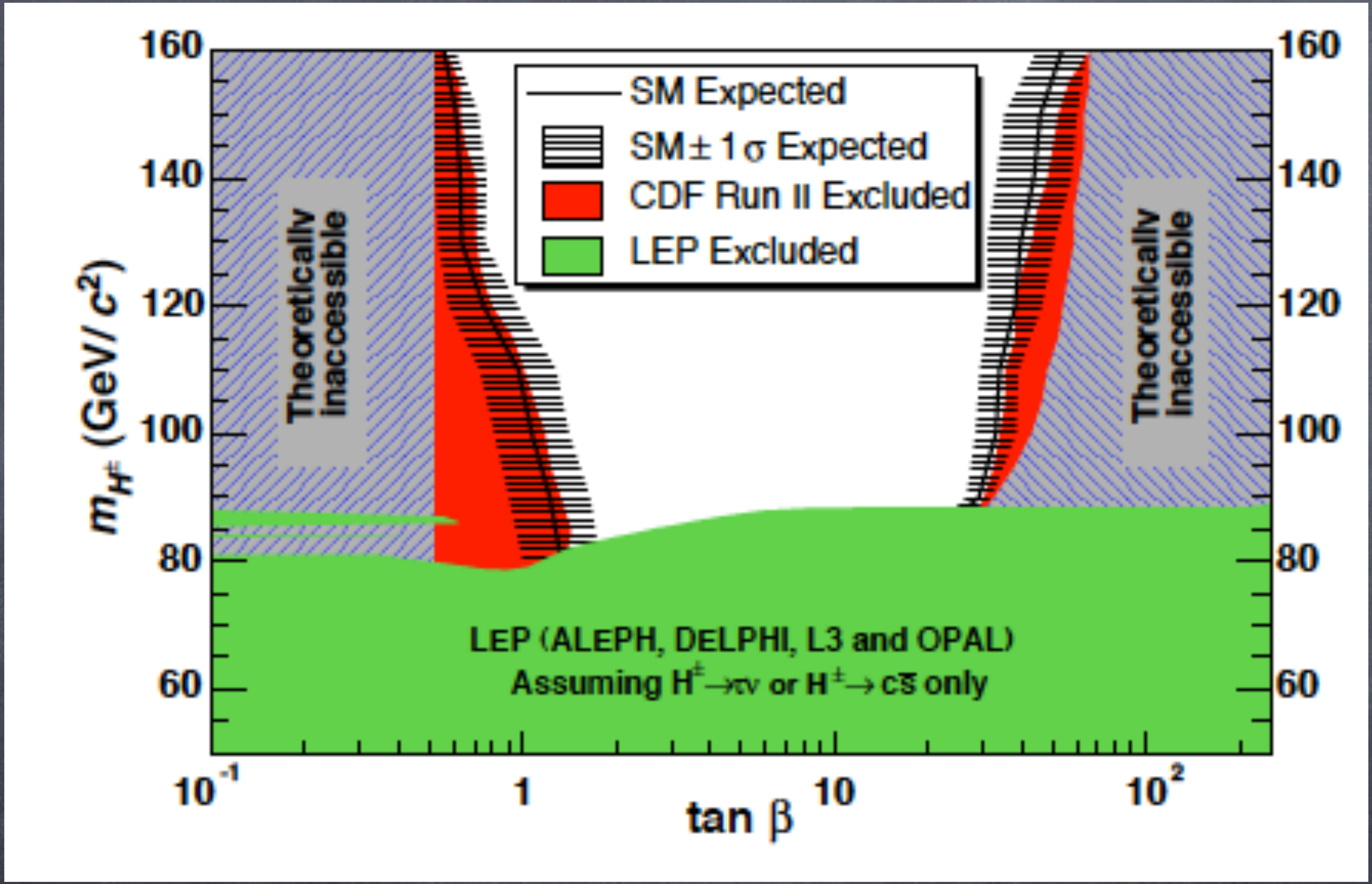
1. Why Heavy Charged Higgs Boson?



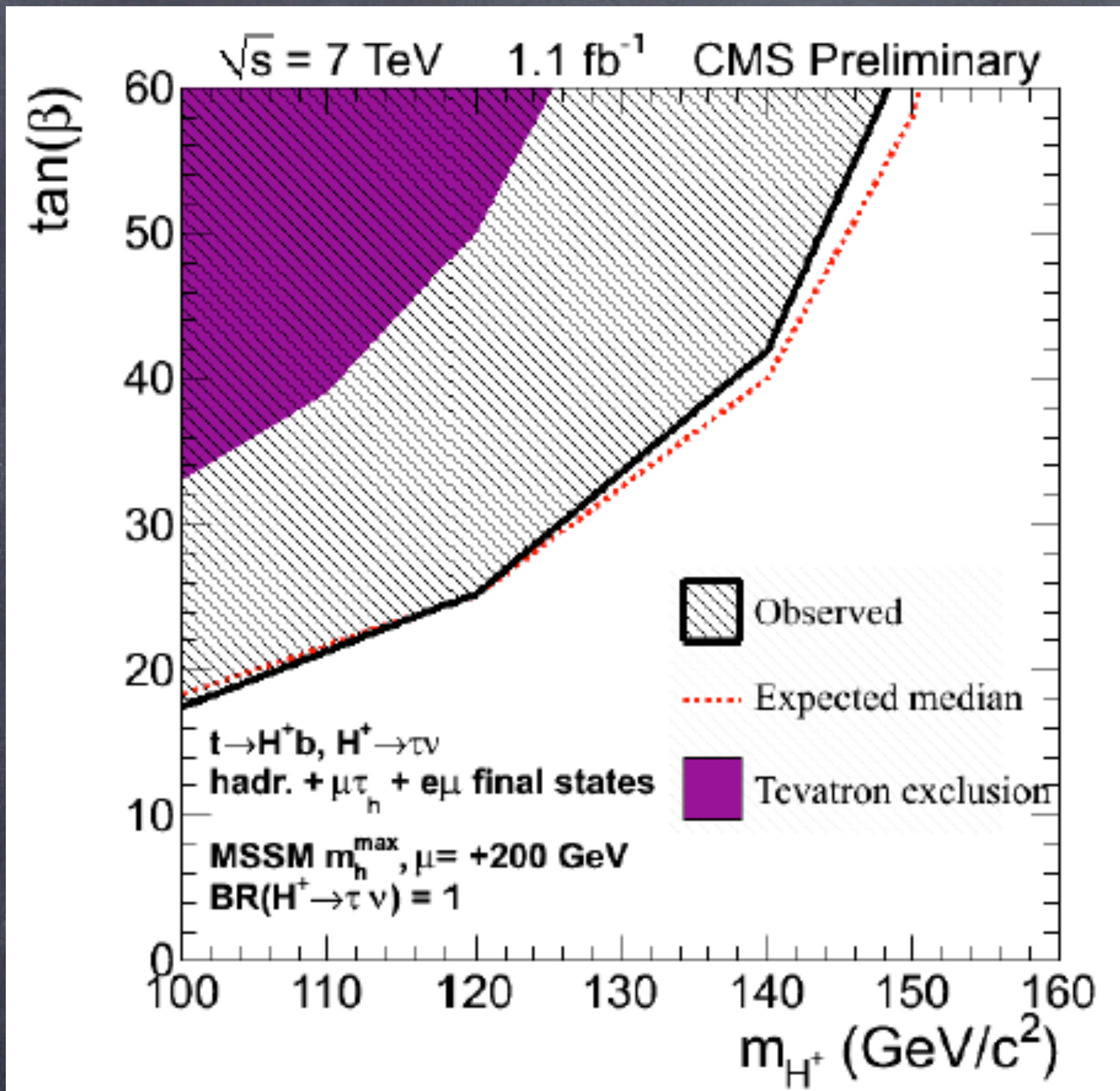
A Heavy Charged Higgs can dominantly decay to t+b (i.e. 2HDM-II) if m>800 GeV

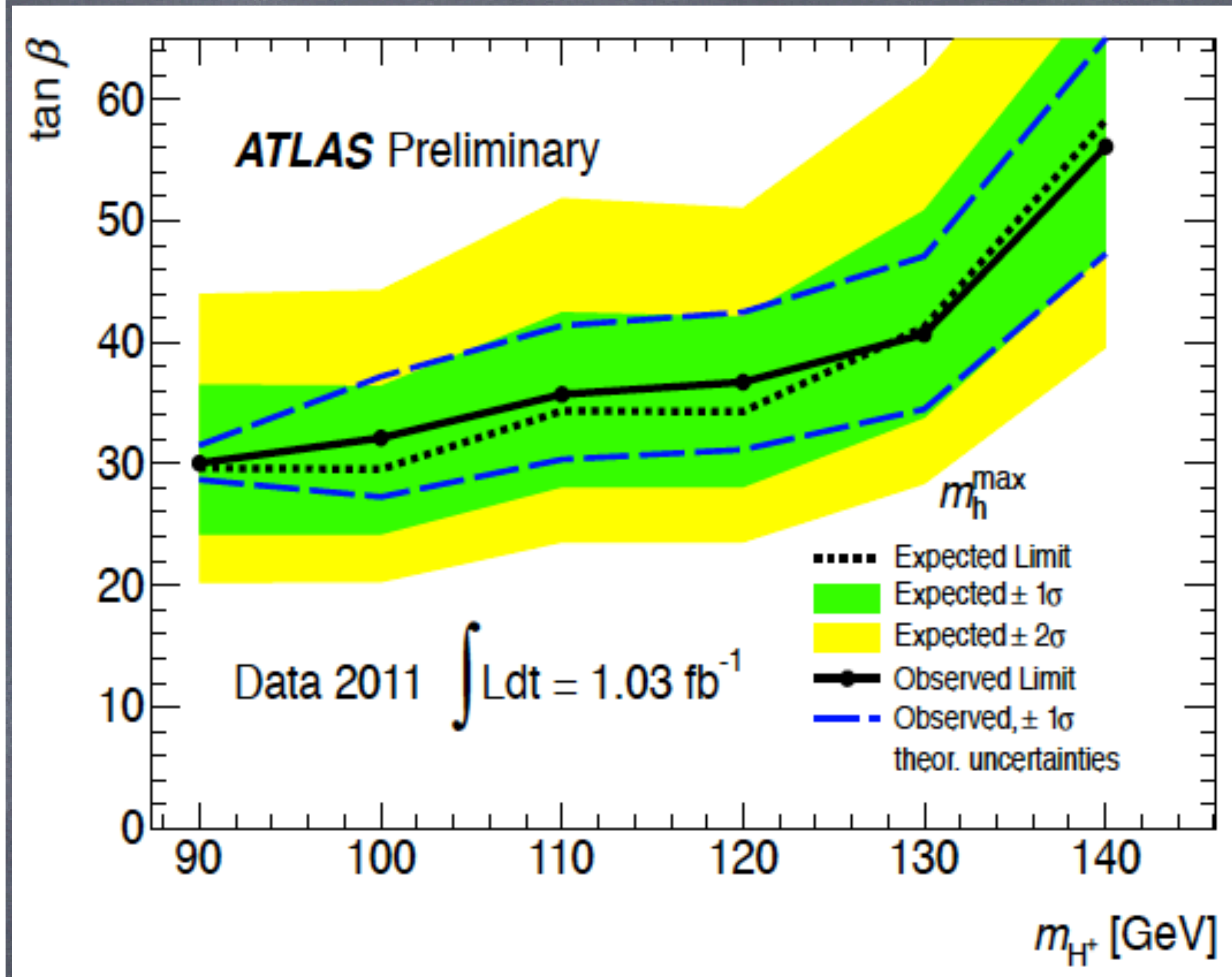
- $H^{\pm}$ decay modes $M_{H^{\pm}} < m_t + m_b$, $M_{H^{\pm}} > m_t + m_b$:
  - $H^{\pm} \to \tau\nu_{\tau}$ $\quad H^{\pm} \to cs$ $\quad H^{\pm} \to t^{*}b \to W^{\pm}\bar{b}b$

    $H^{\pm} \to A^{0}W^{\pm}$ $\quad H^{\pm} \to h^{0}W^{\pm}$ $\quad H^{\pm} \to tb$



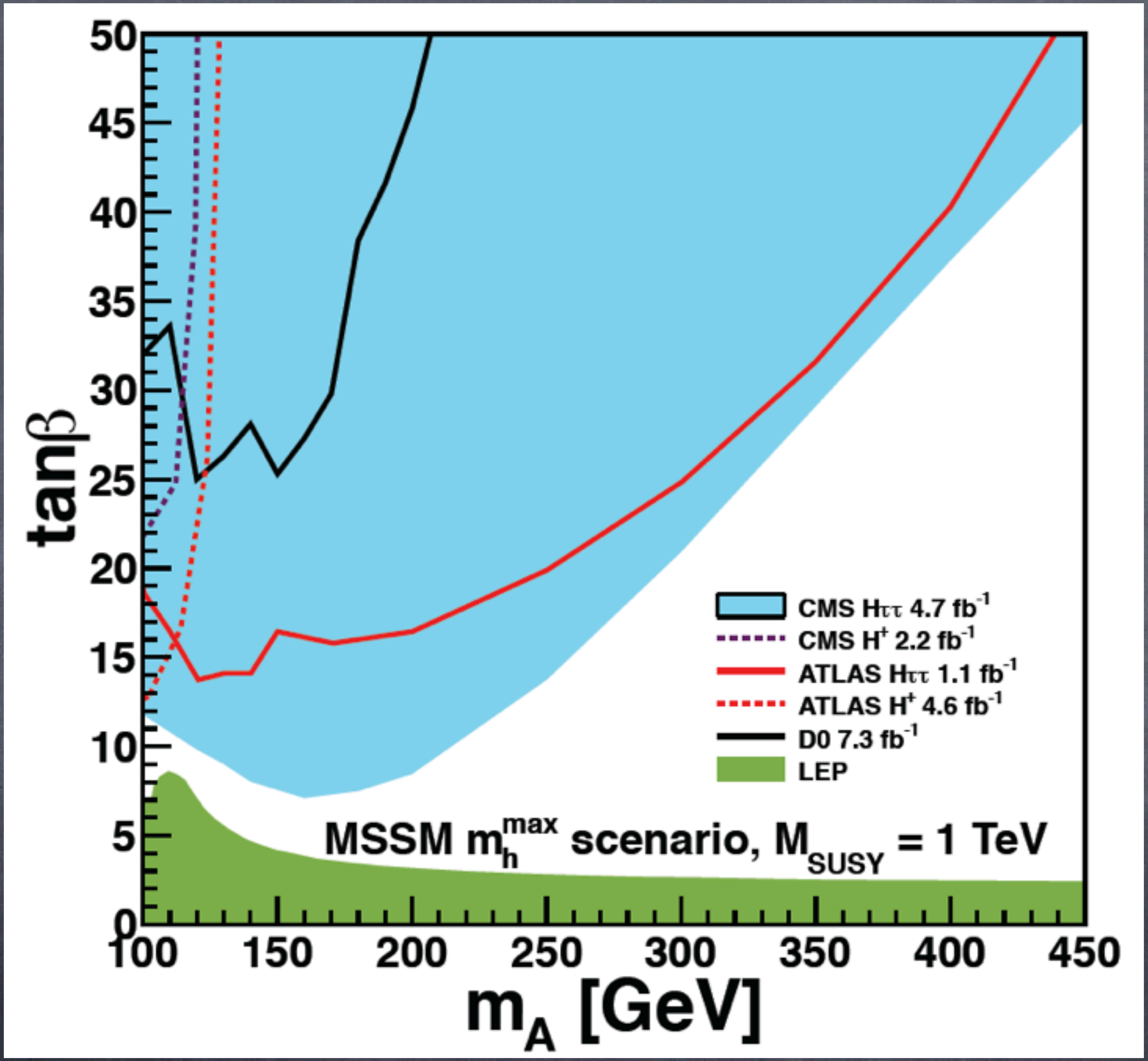
Bound to a charged Higgs boson(2HDM) from direct search from Tevatron&LEP





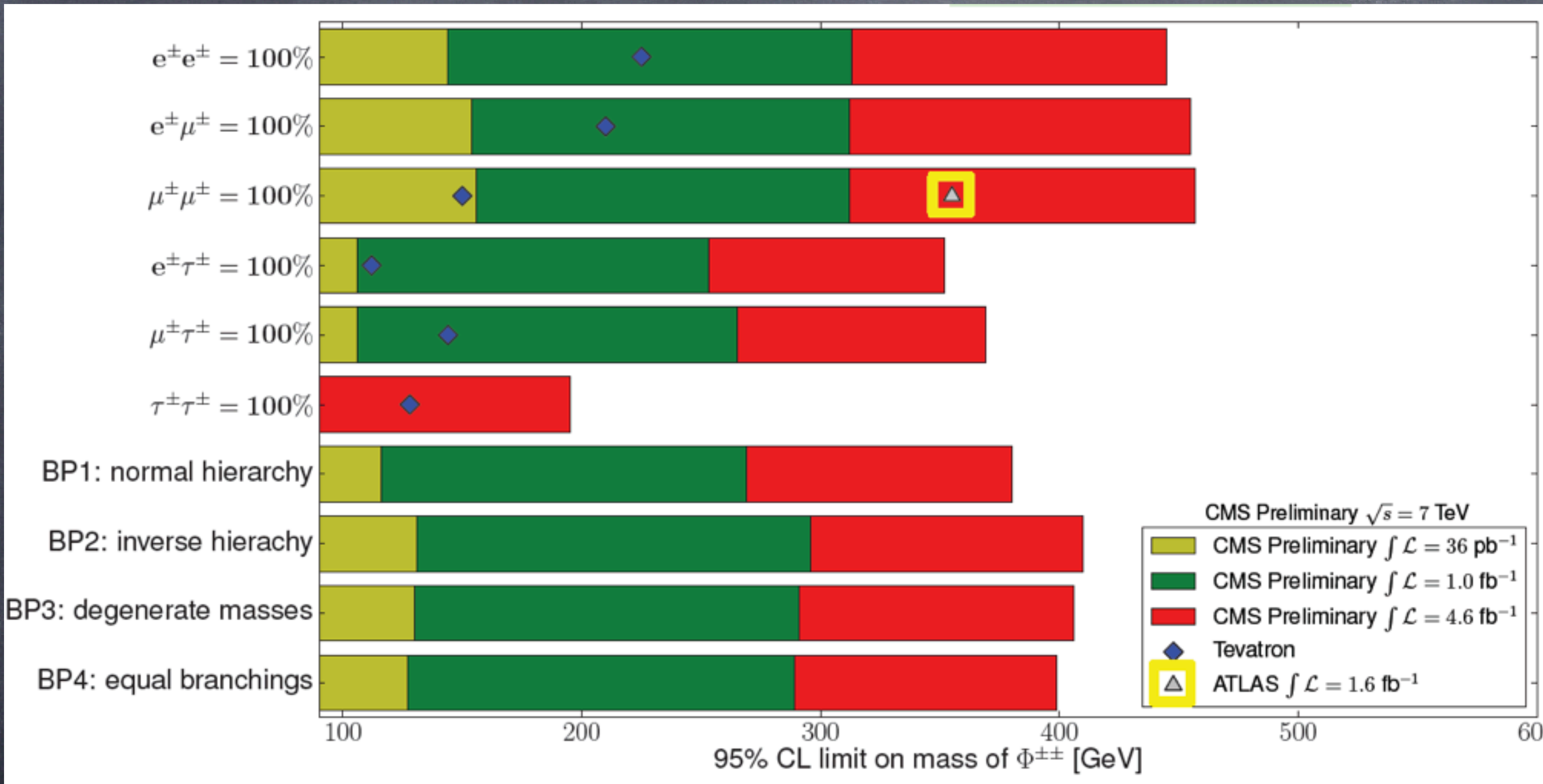
CMS, 1201.4983

ATLAS,1201.5886



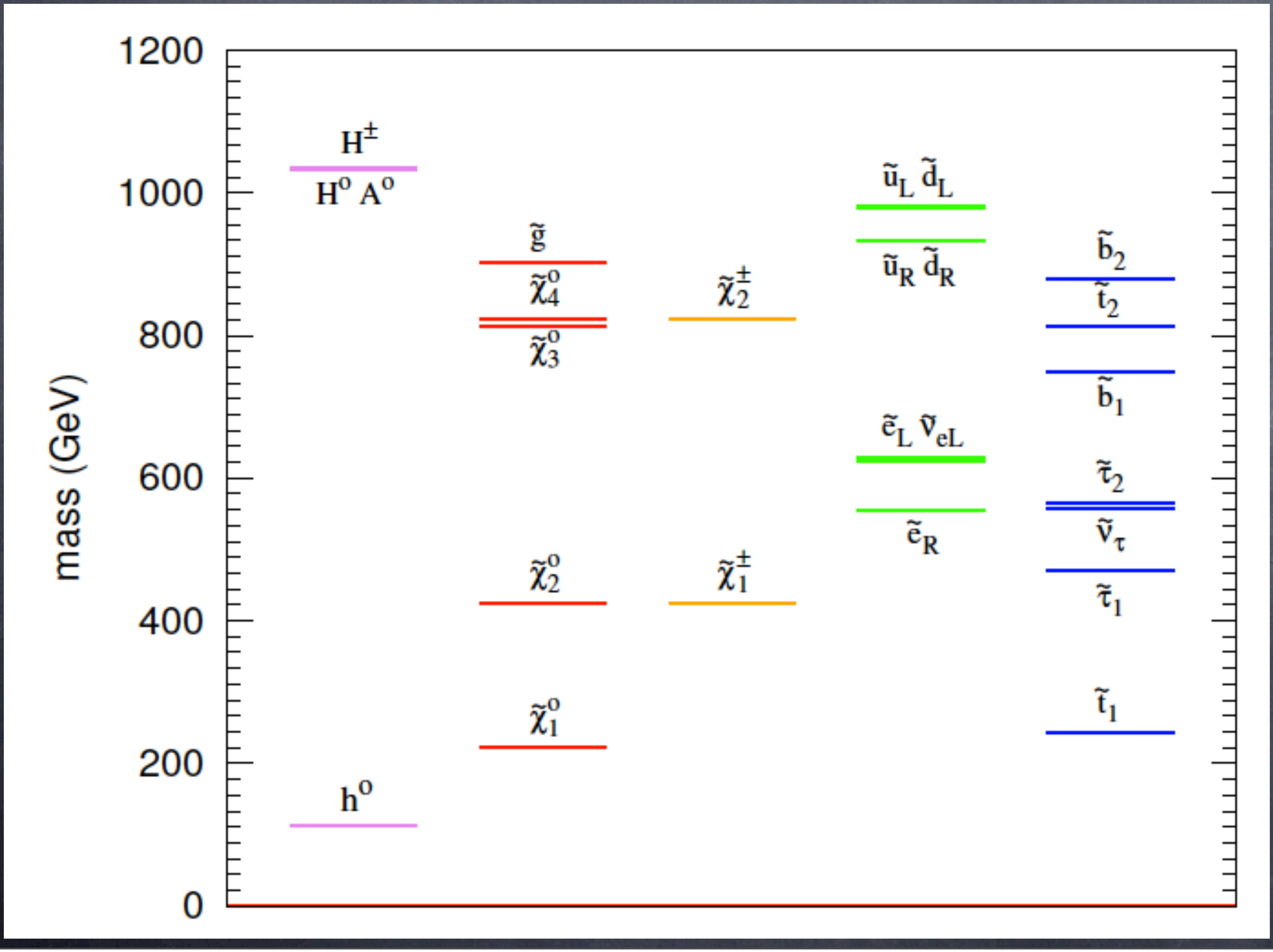
tanβ
m_A [GeV]
CMS Hττ 4.7 fb^{-1}
CMS H$^+$ 2.2 fb^{-1}
ATLAS Hττ 1.1 fb^{-1}
ATLAS H$^+$ 4.6 fb^{-1}
D0 7.3 fb^{-1}
LEP
MSSM m_h^{max} scenario, M_{SUSY} = 1 TeV

1202.4083



Bounds for doubly charged Higgs boson

1. Why A Heavy Charged Higgs Boson?



An example in a nonuniversal MSSM

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

1111.2250

Phys.Rev. D85 (2012) 035005

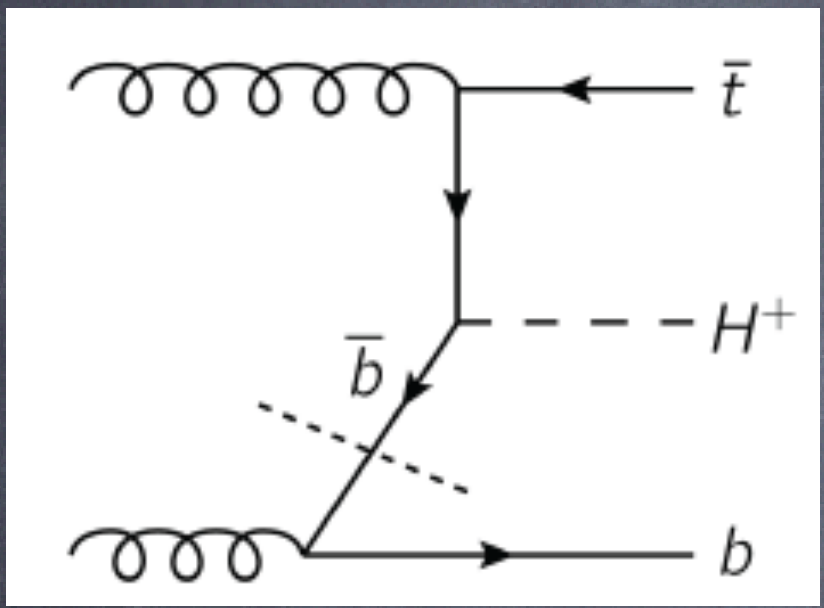
BMP 2

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

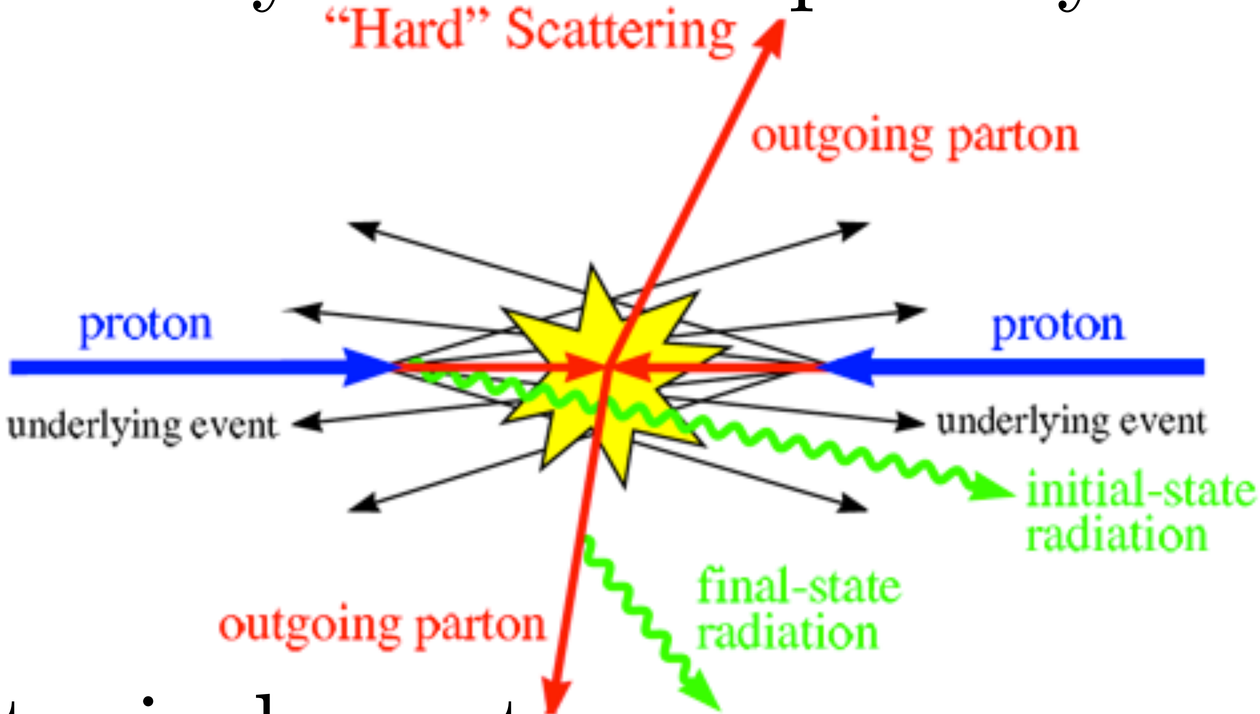
Although there are 7 or more objects in the final states (at parton level for our signals)

- 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

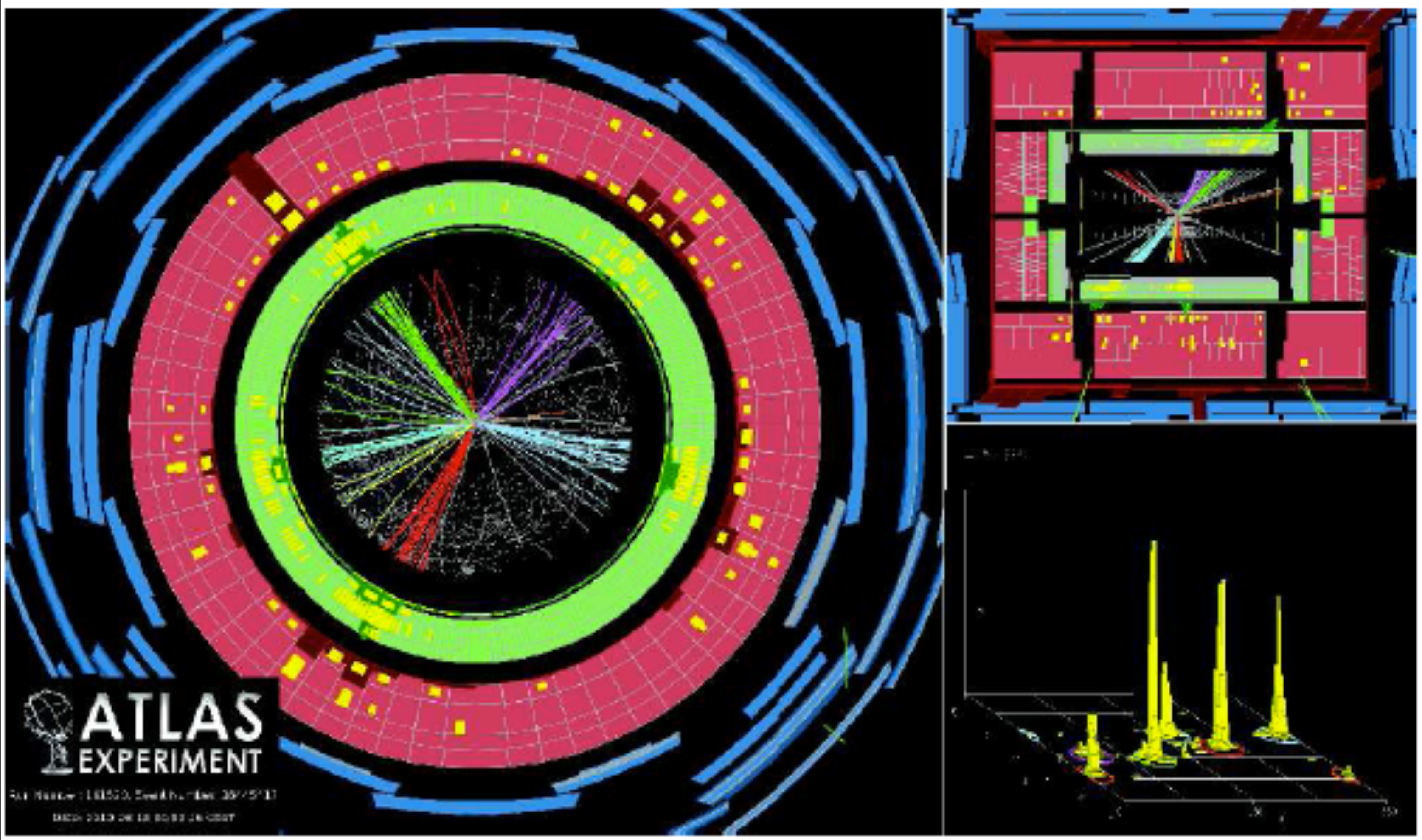
A smaller cone

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

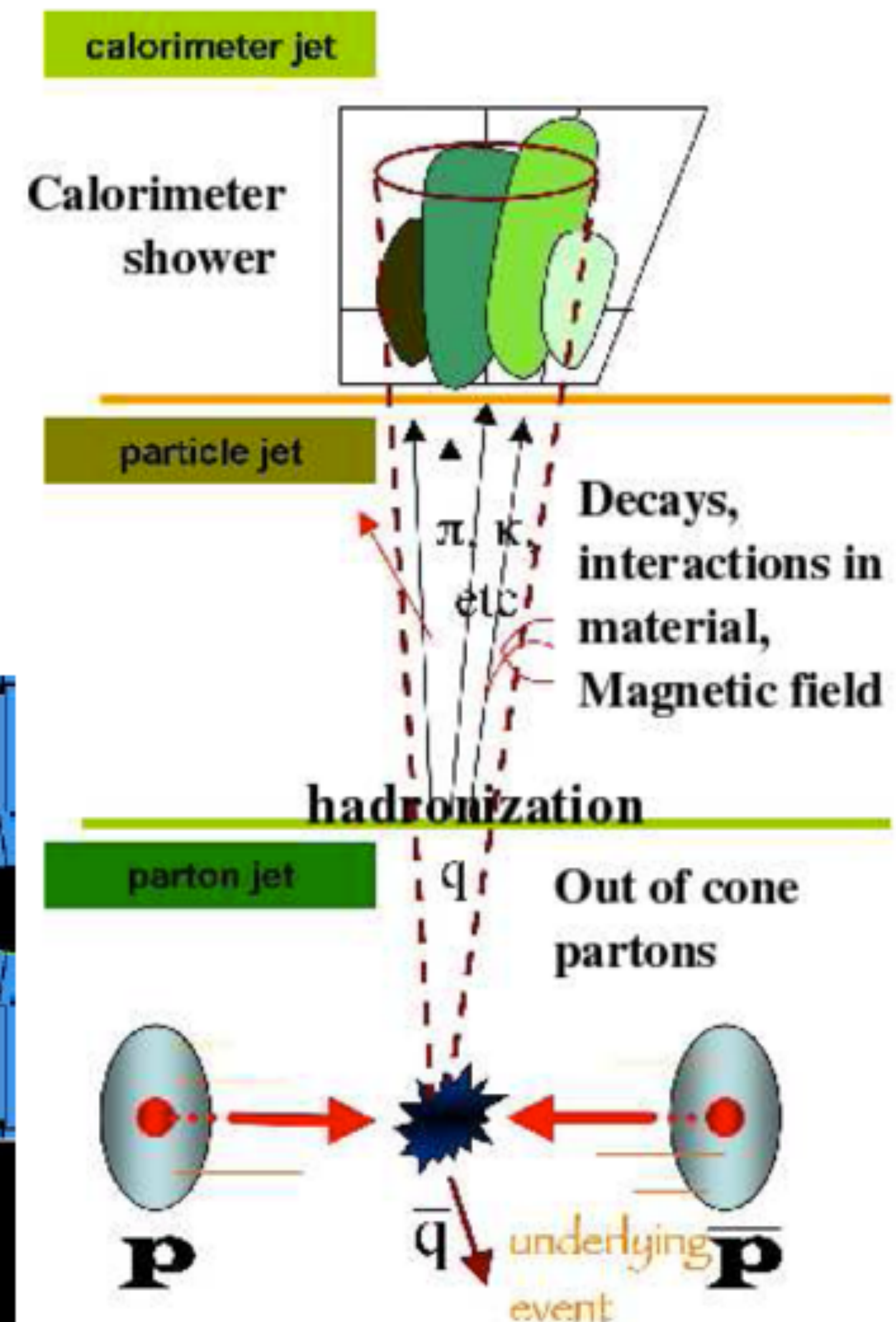
Hardon partons are produced, i.e. by $H^{\pm}$ and top decay



A typical event

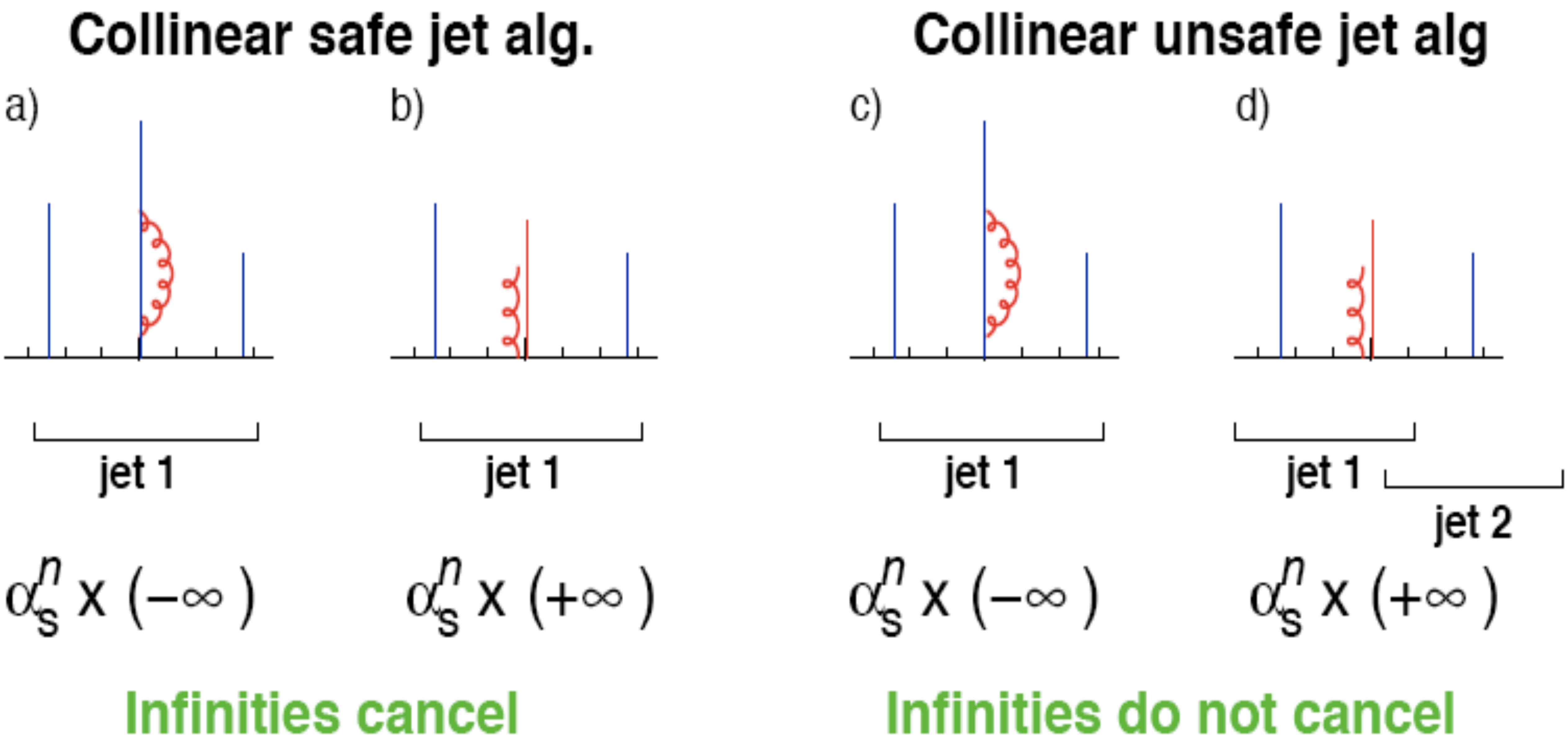


A hard parton's evolution



2. What's a Jet??

Towards Jetography: 0906.1833, G.P. Salam



2. What's a Jet??

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.

2. What's a Jet??

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

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

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

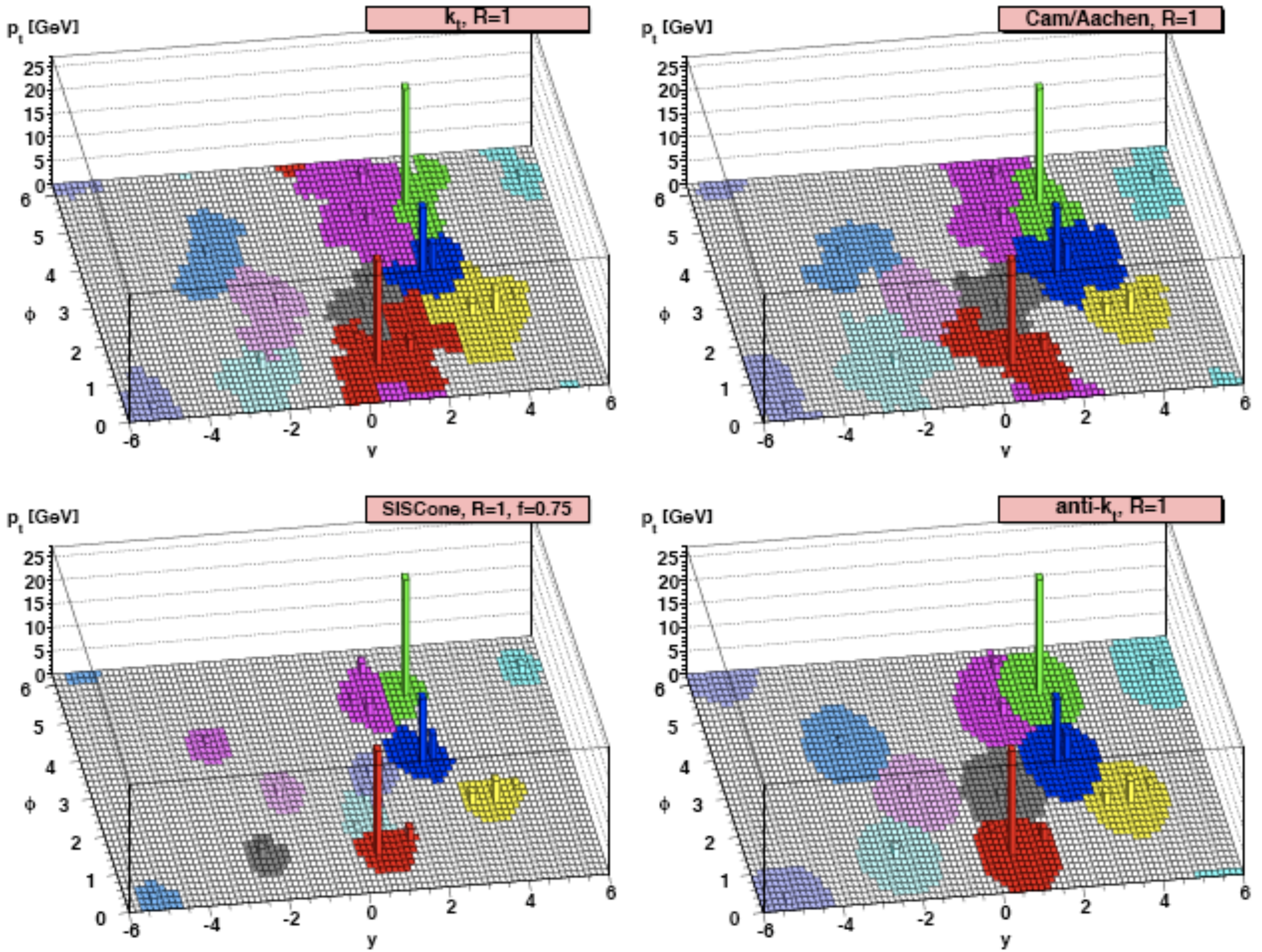
$$\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$$

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 ✓

2. What's a Jet??

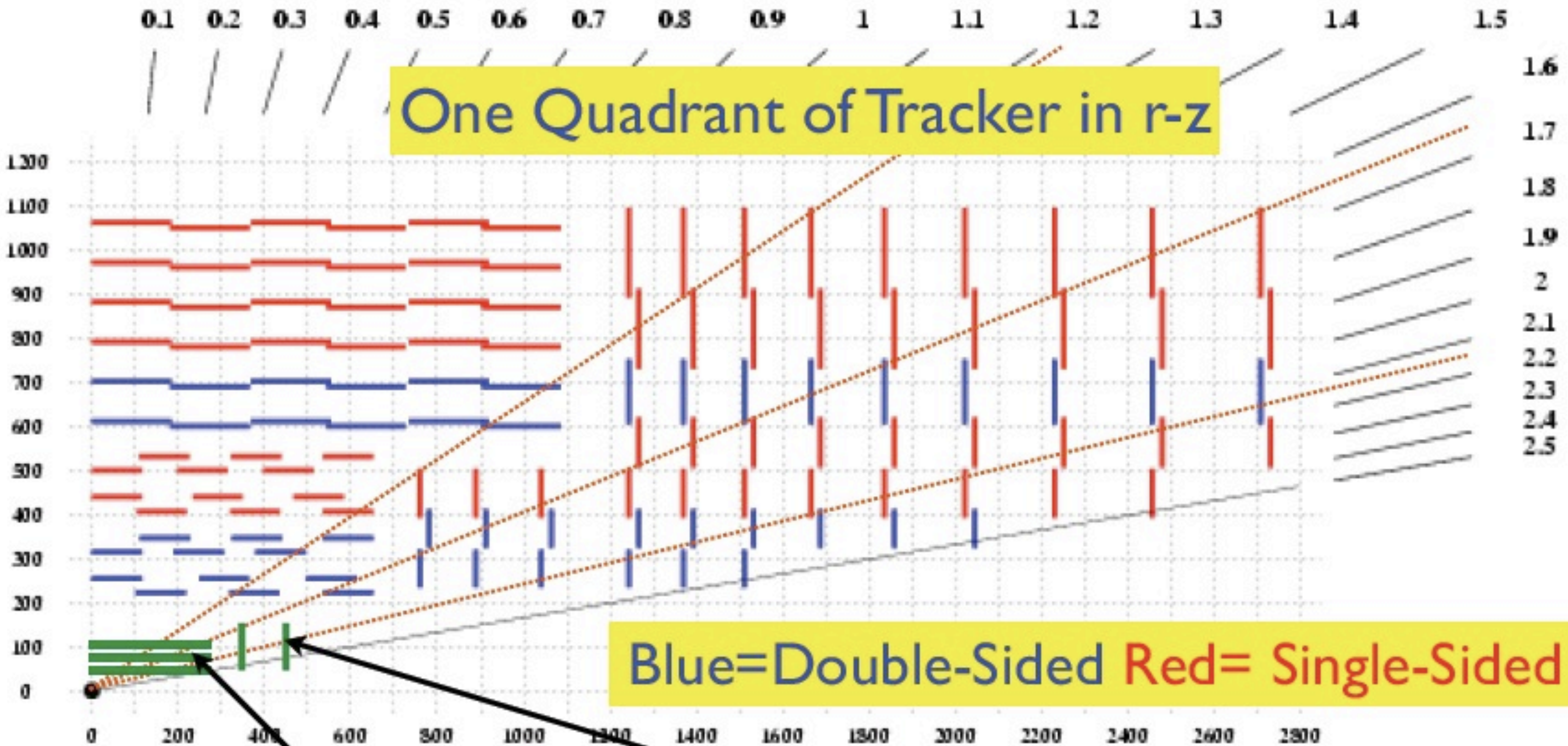
Towards Jetography: 0906.1833,G.P.Salam

2. What's a Jet??



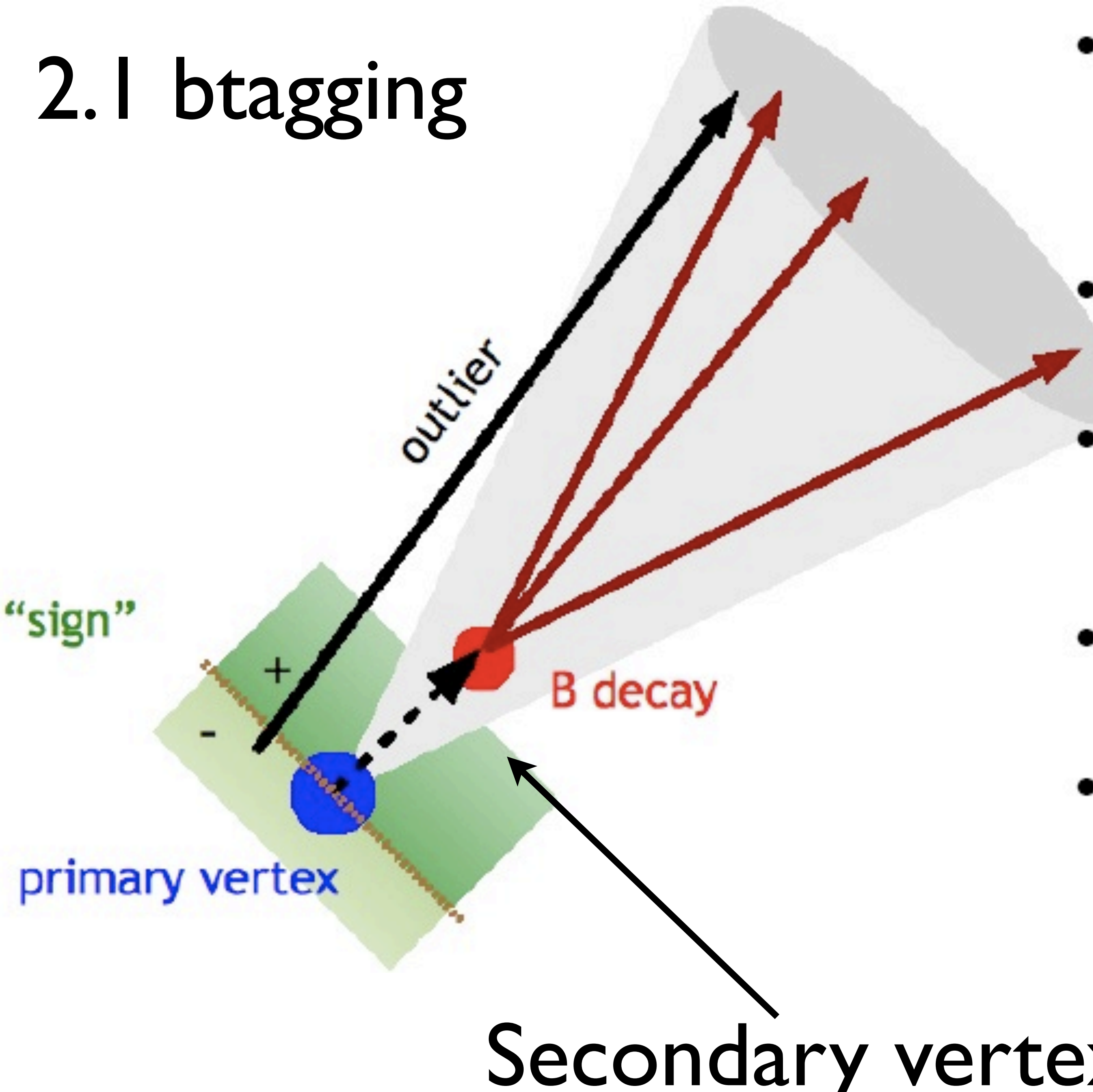
2.1 btagging

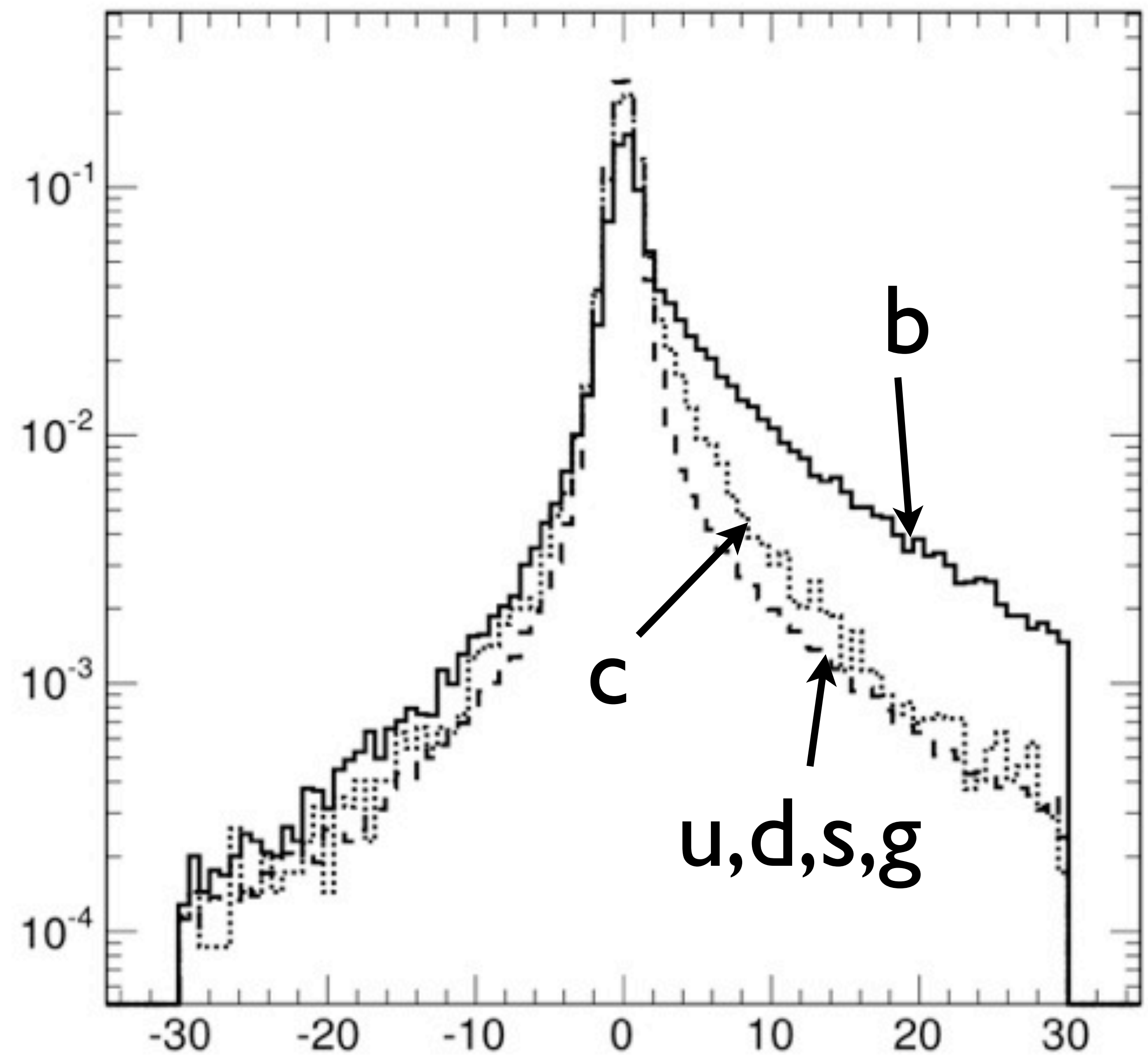
The layout of Si tracker @ CMS $\delta L \sim \mu m$



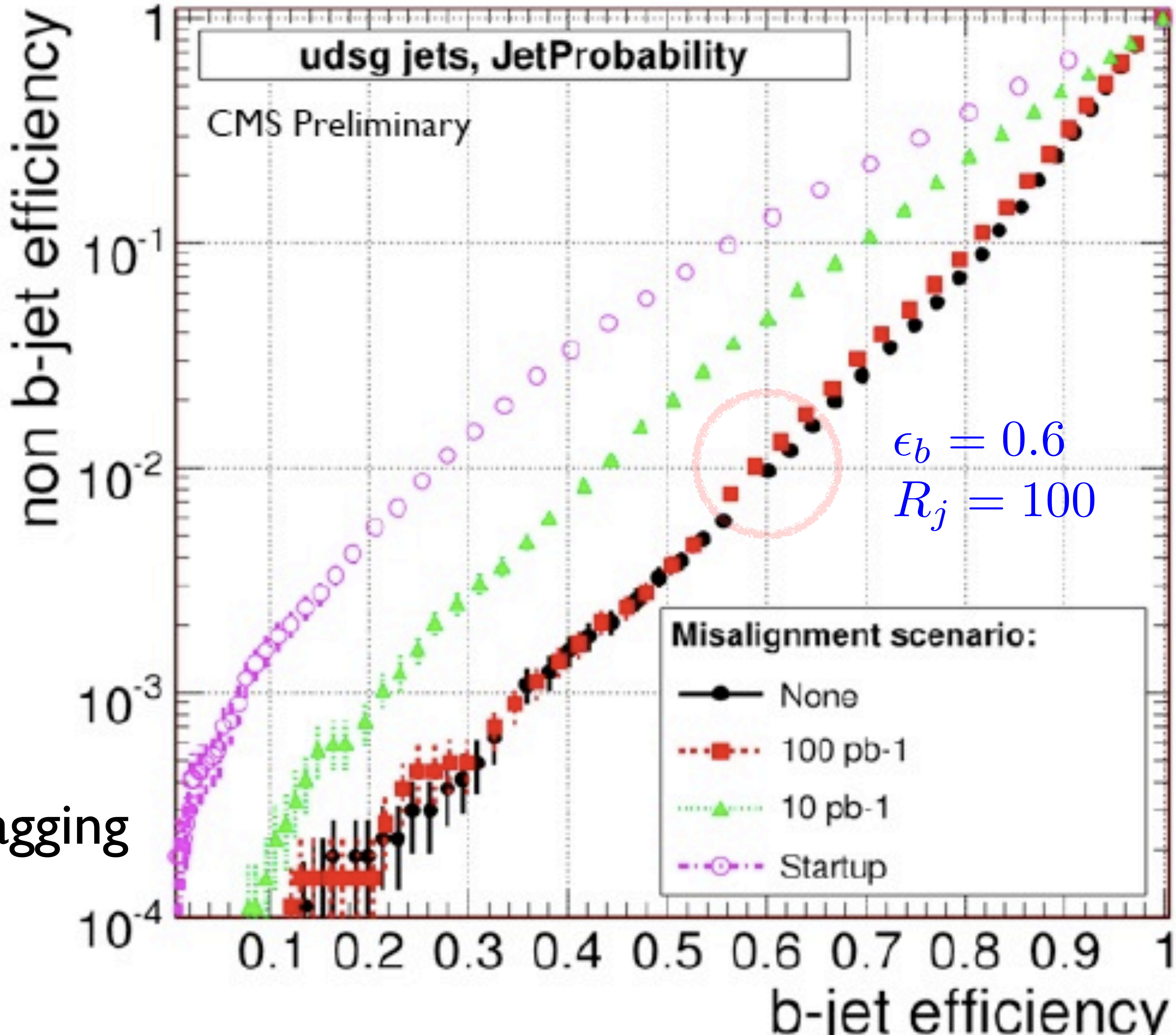
- 3 Barrel Pixel Layers, 2 Forward Pixel Disks
- 4 Inner Barrel Layers (TIB), 6 Outer Layers (TOB)
- 3 Forward Inner Disks (TID), 9 Outer Disks (TEC)

2.1 btagging





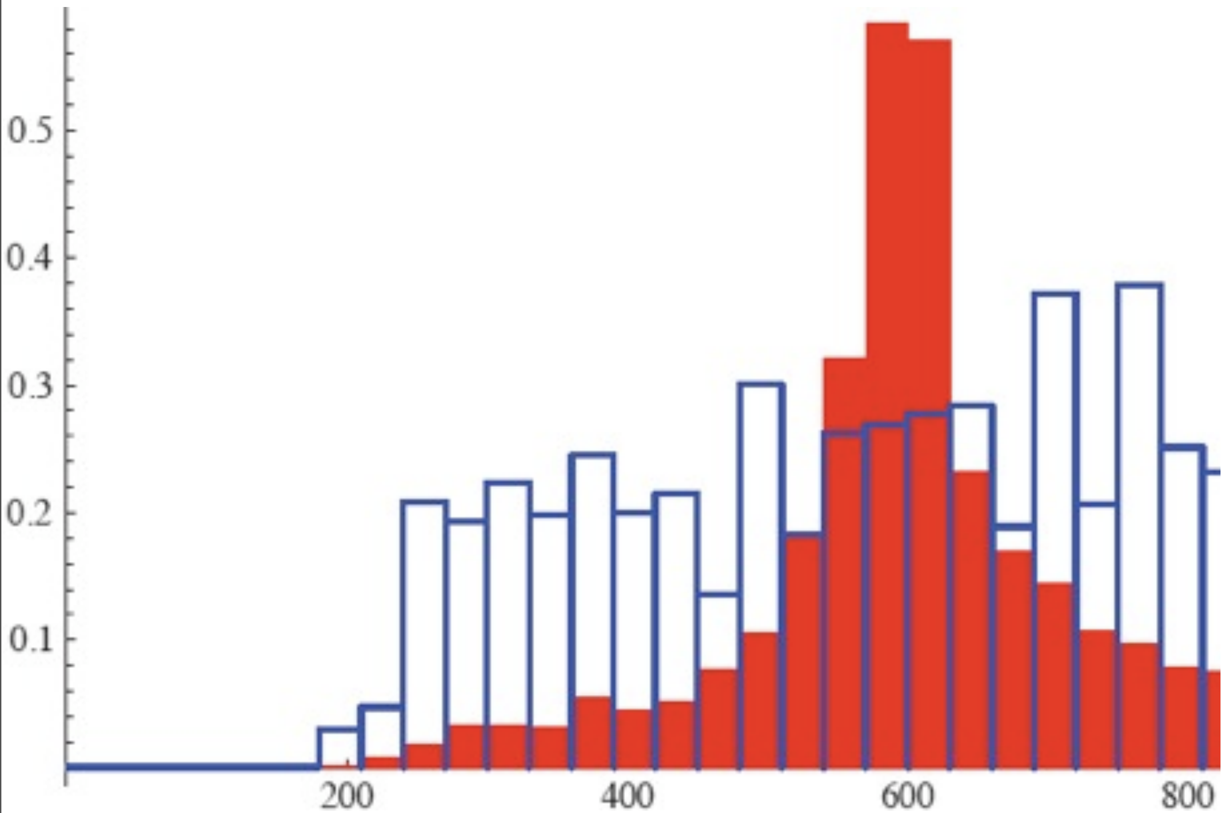
1. Impact parameters
2. Invariant mass of tracks, say to reject Kaon
3. Charge multiplicity,b jet is massive,
   more charged particles can be produced.


udsg jets, JetProbability
CMS Preliminary
non b-jet efficiency
b-jet efficiency
Misalignment scenario:
None
100 pb-1
10 pb-1
Startup
$\epsilon_b = 0.6$
$R_j = 100$

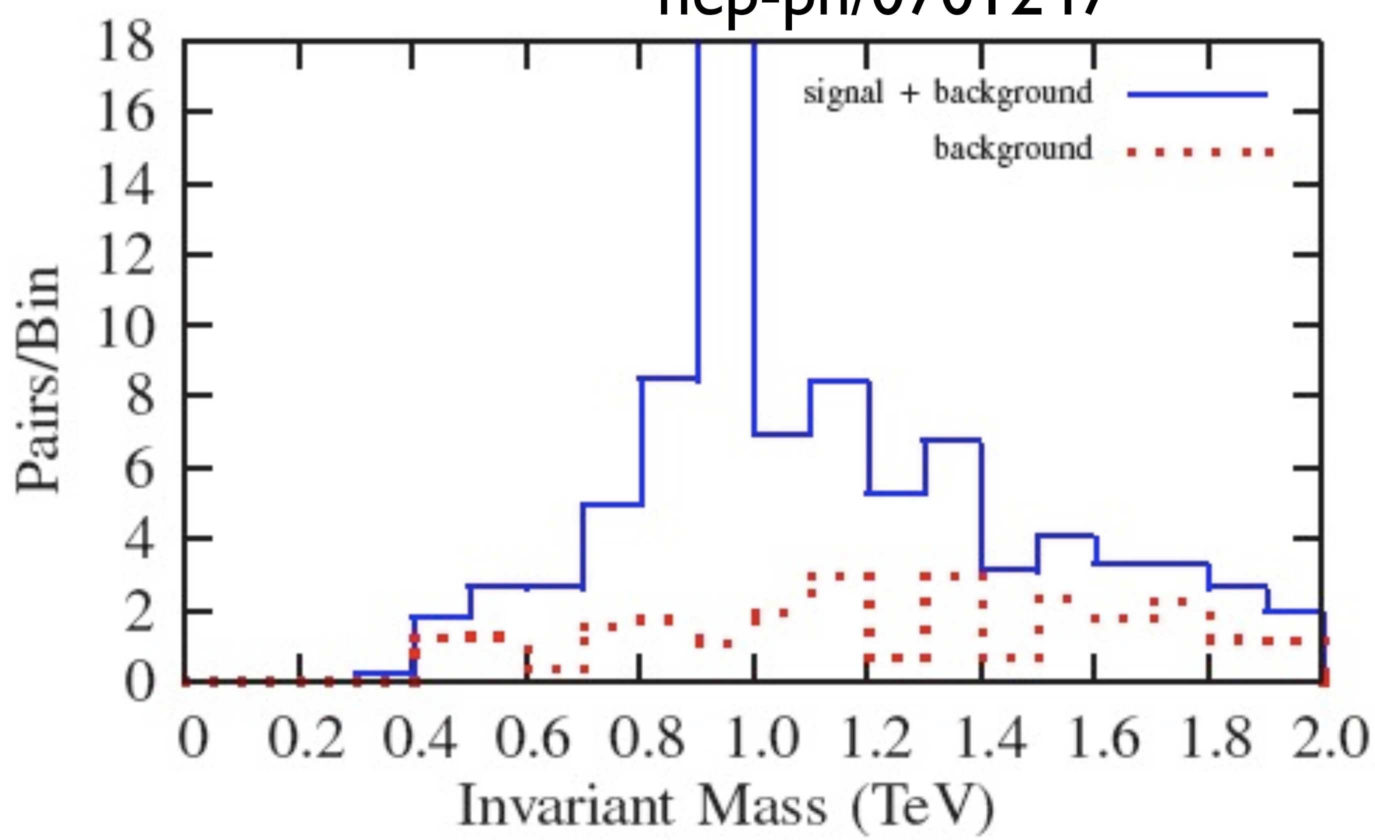
2.1 btagging

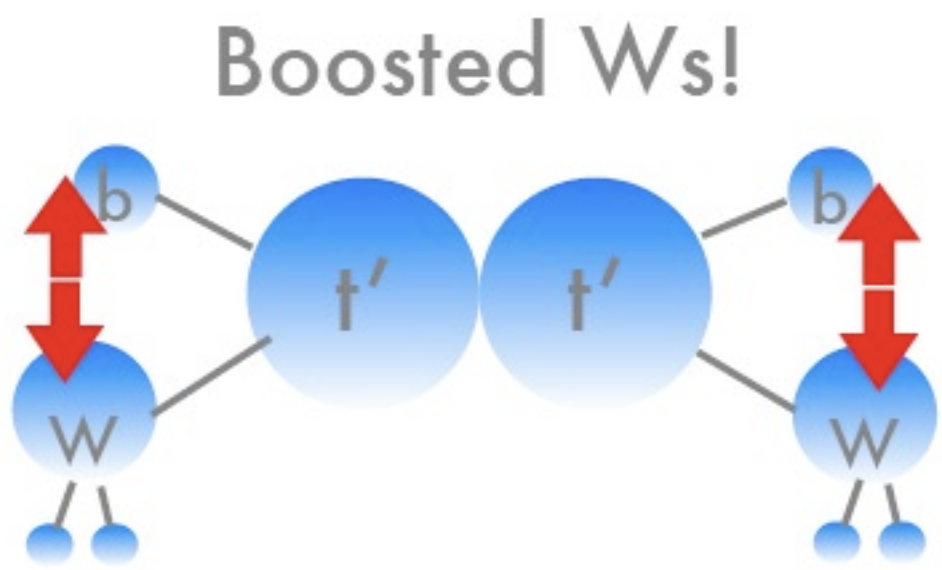
• W-jet method

B. Holdom, hep-ph/0702037



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



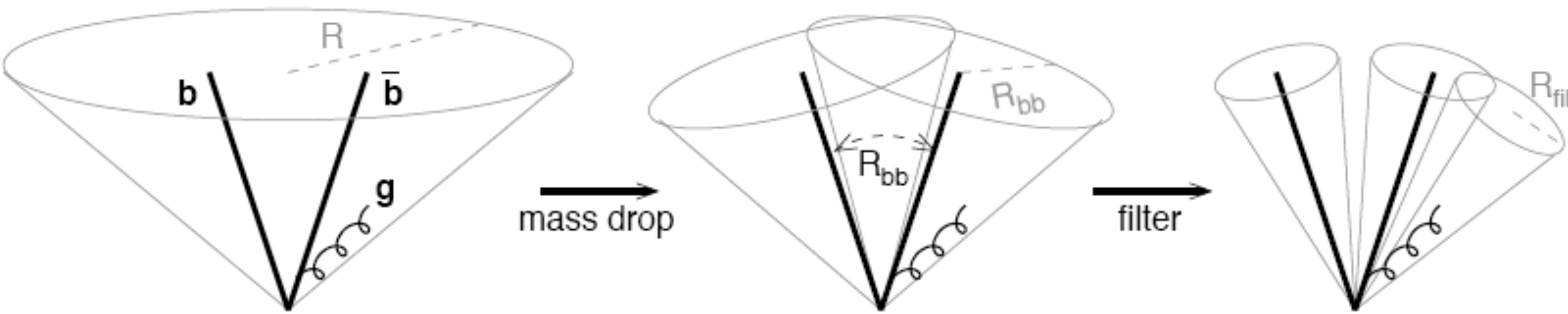


2.2 Jet mass/sub.

- 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 R =1.2

2.2 subjet.

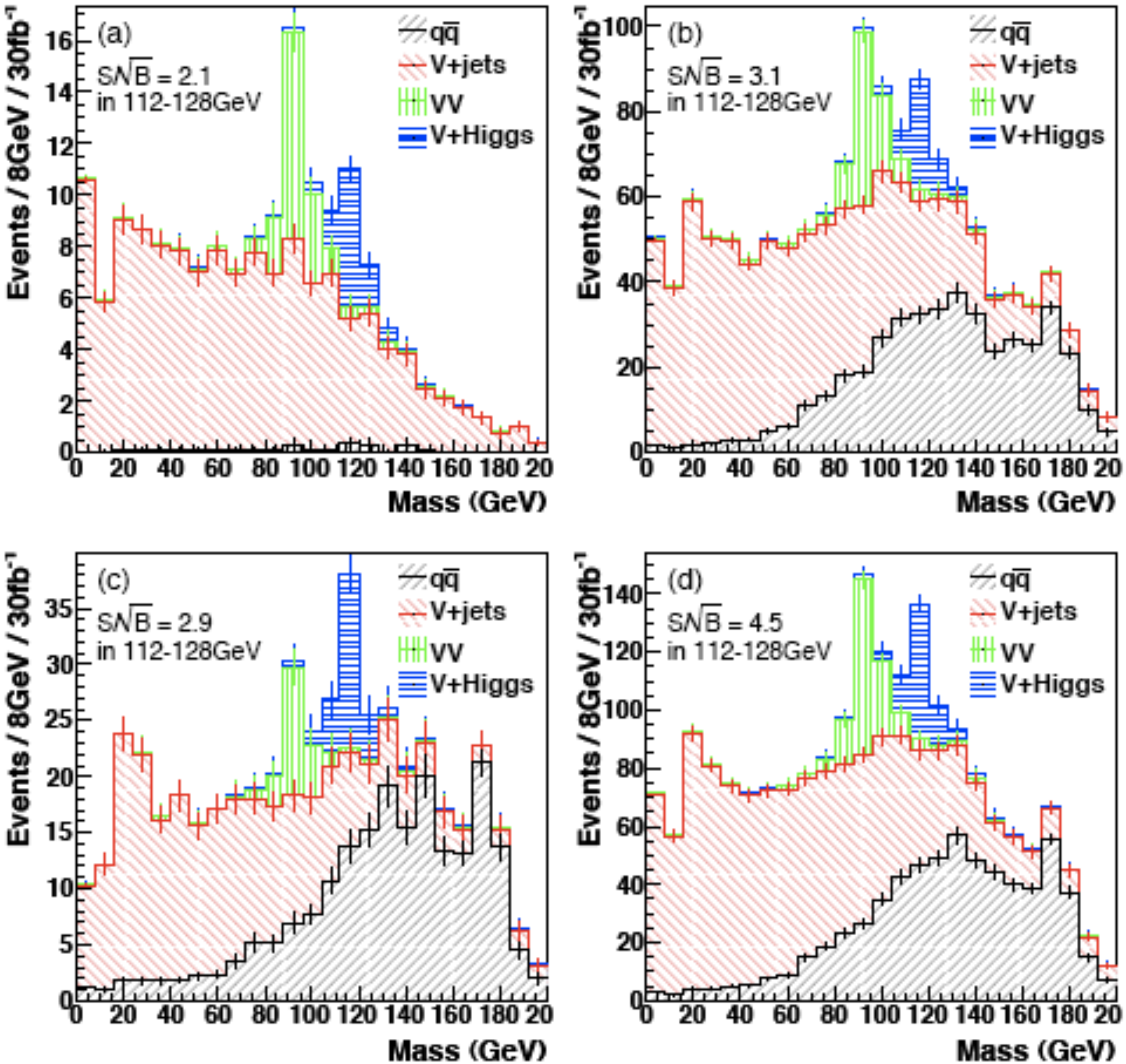
Higgs tagger (BDRS): 0802.2470 J.M. Butterworth,A.R.Davison,M.Rubin,G.P.Salam

A dilepton channel

B Missing Energy Channel ME>200 GeV

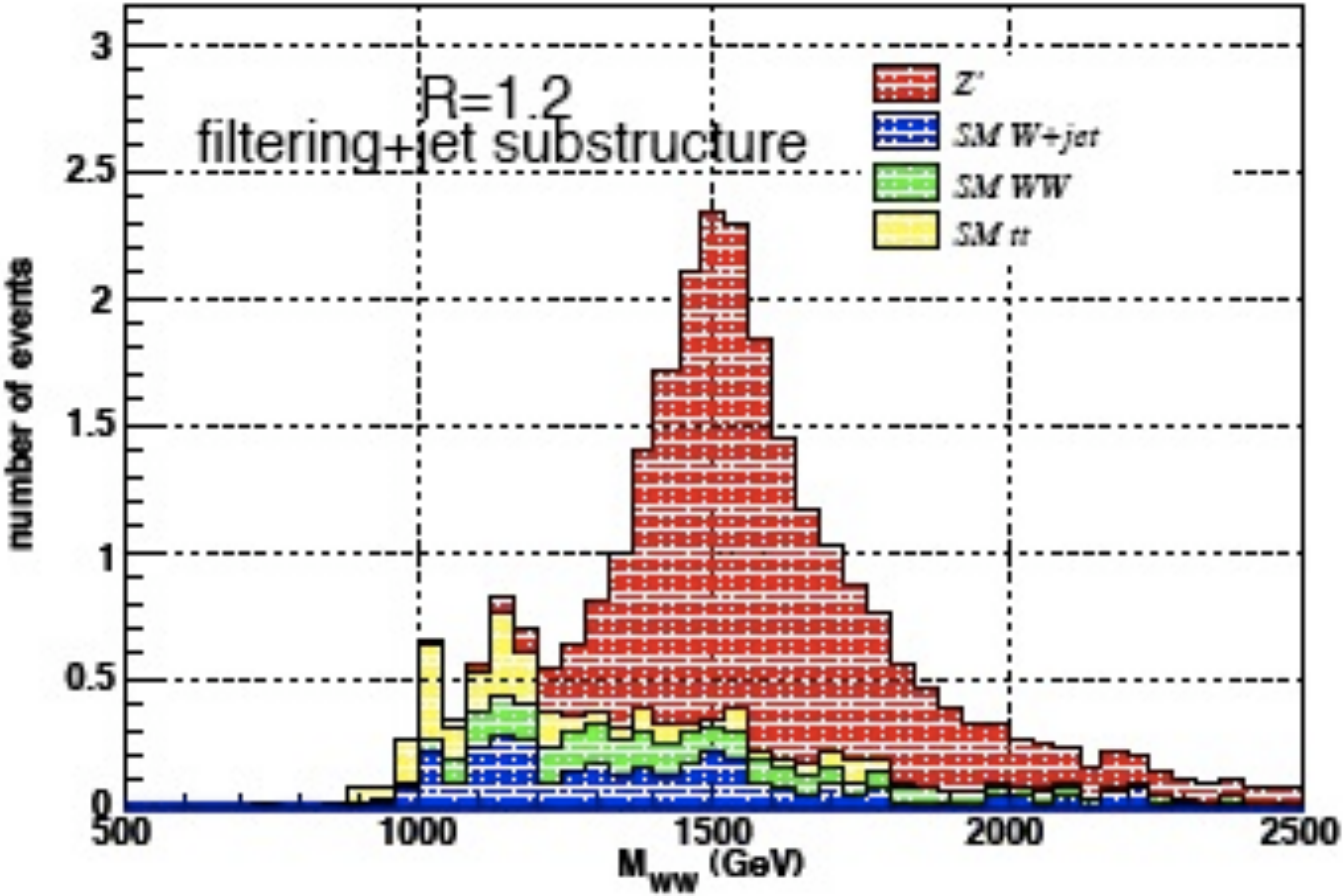
C Semileptonic Channel ME>30GeV, Pt(l)>30 GeV

3 channels Combined



2.2 subjet.

Wtagger: MVA: Boost Decision Tree 2.2 subjet.



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

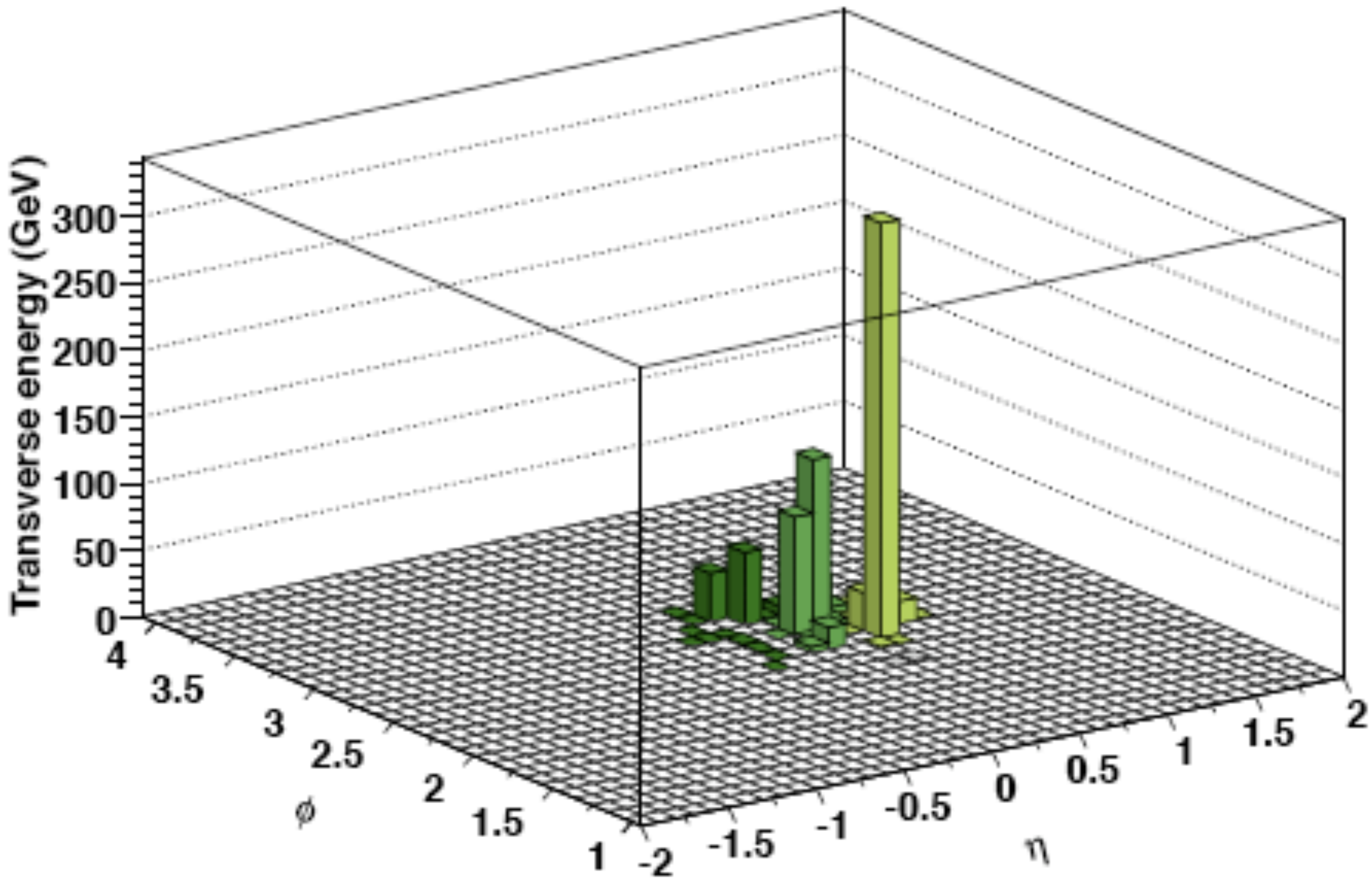
QCD mistag rate

2.2 subjet.

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

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



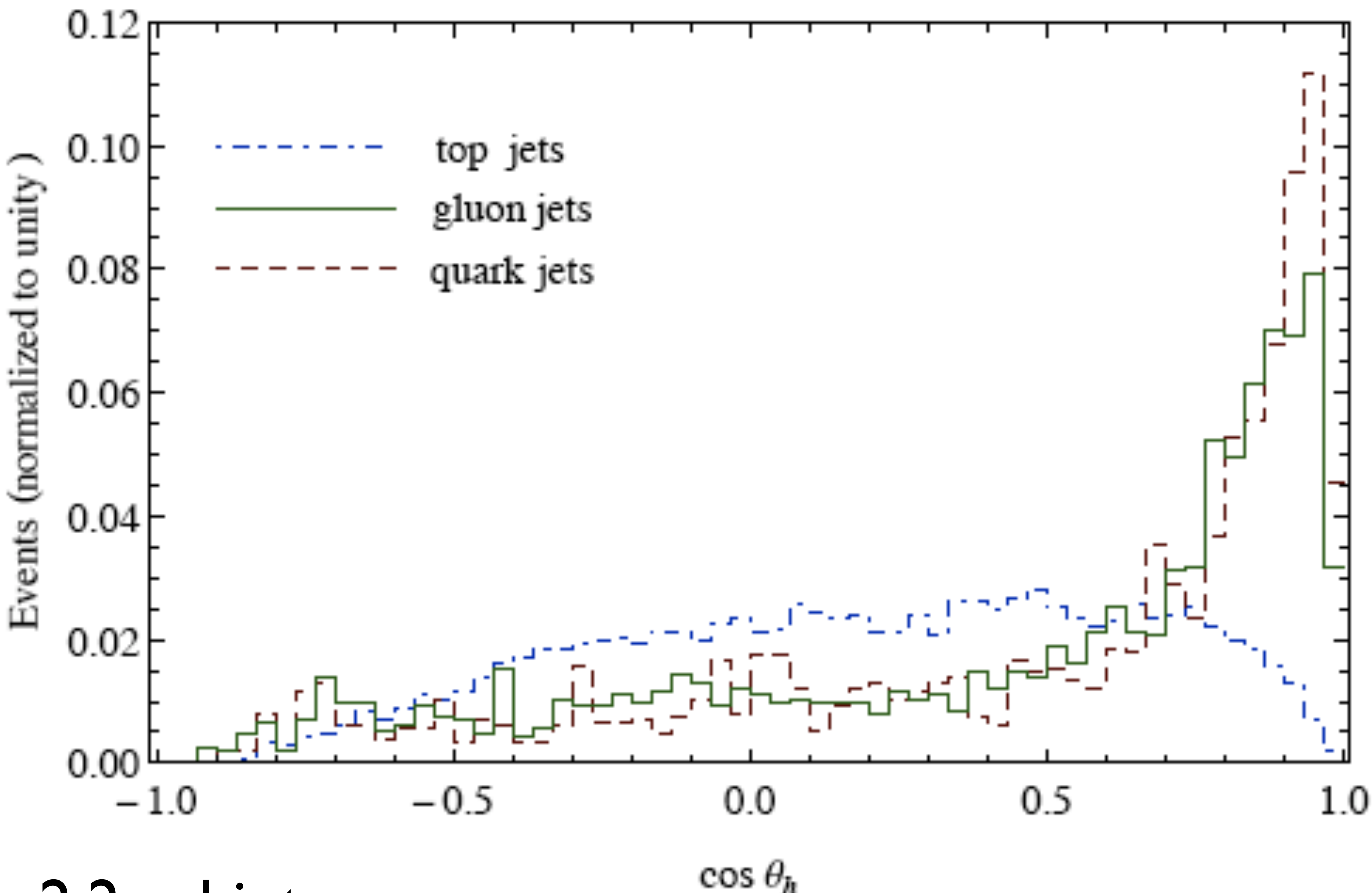
Angle separation: $\sim 2m_t/p_T$

2.2 subjet.

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

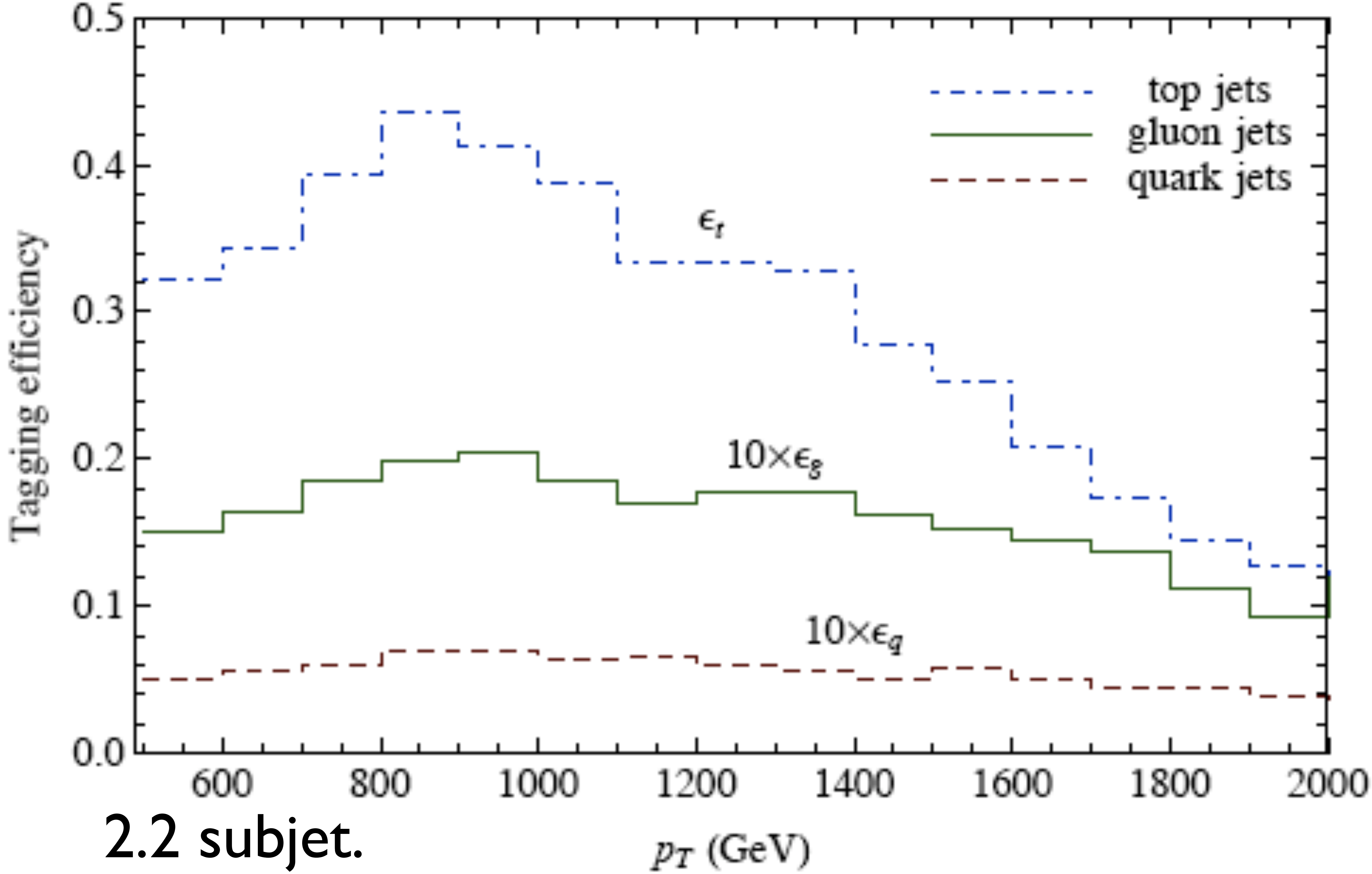
Hadronic w helicty



2.2 subjet.

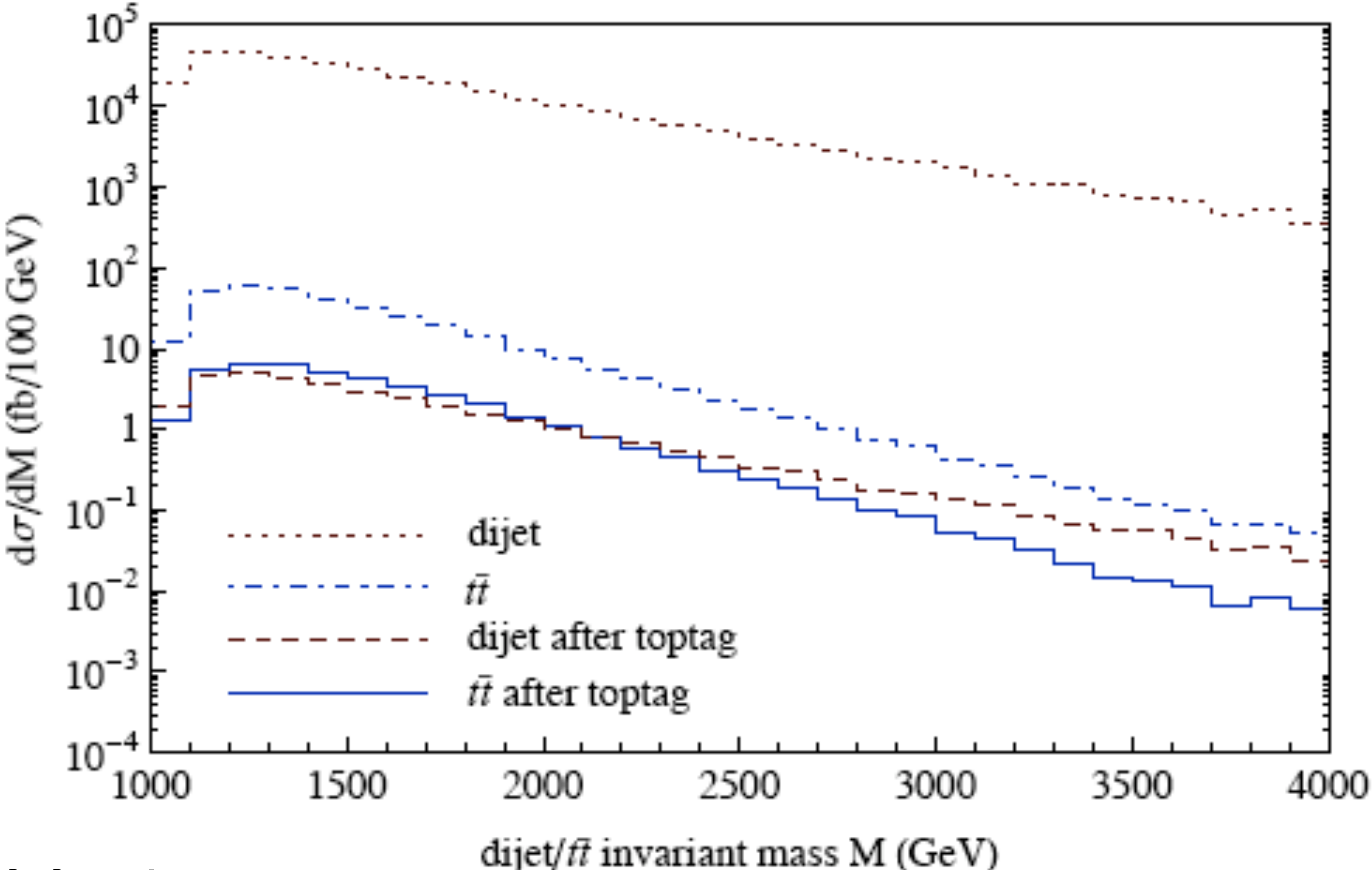
Top tagger: 0806.0848 D.E.Kaplan,K.Rehermann,M.D.Schwartz,B.Tweedie

Mt, mw, Hw, tagging efficiency



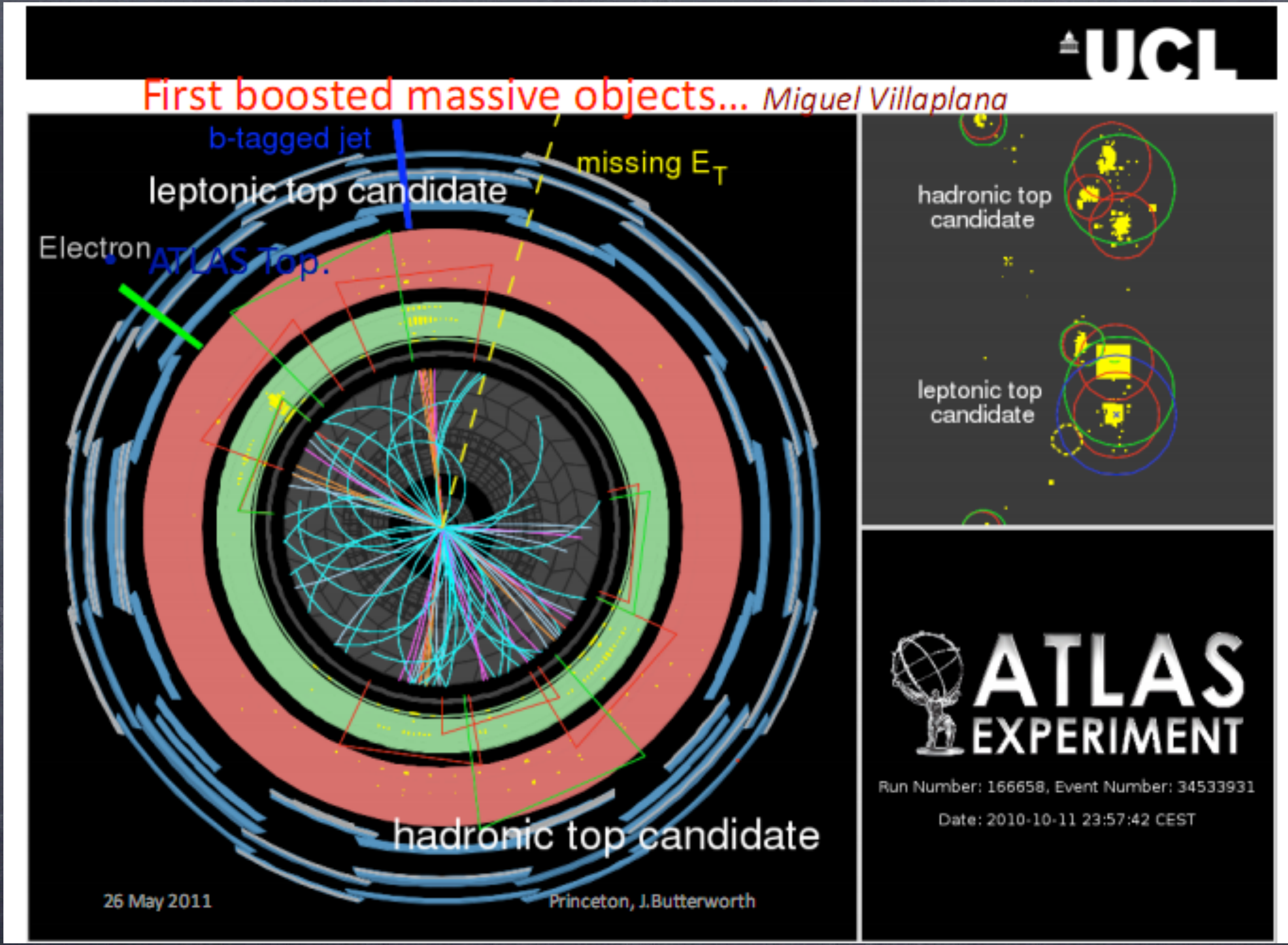
2.2 subjet.

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



2.2 subjet.

The Hadronic Top tagger indeed work!



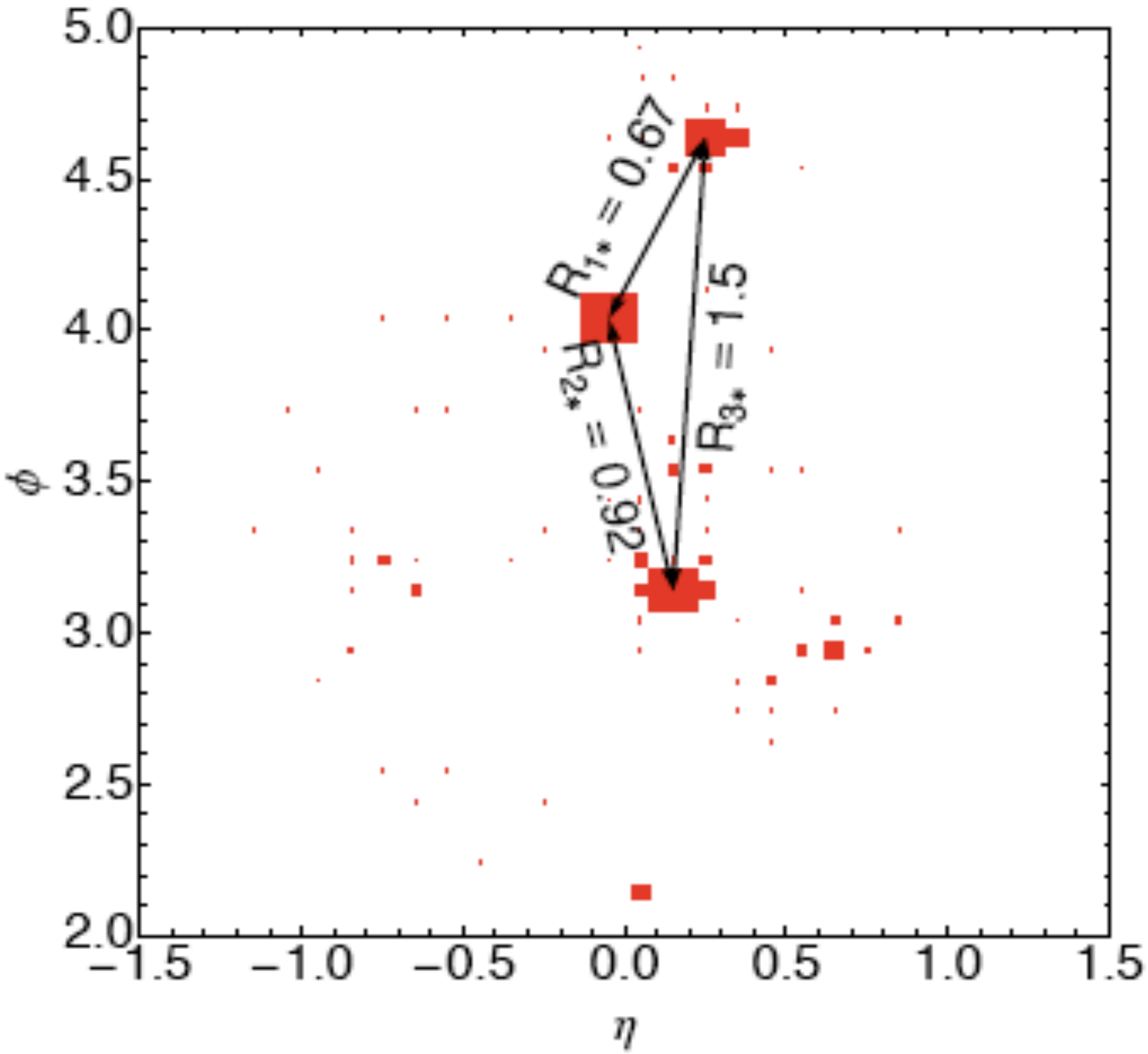
Boosted Top event at ATLAS

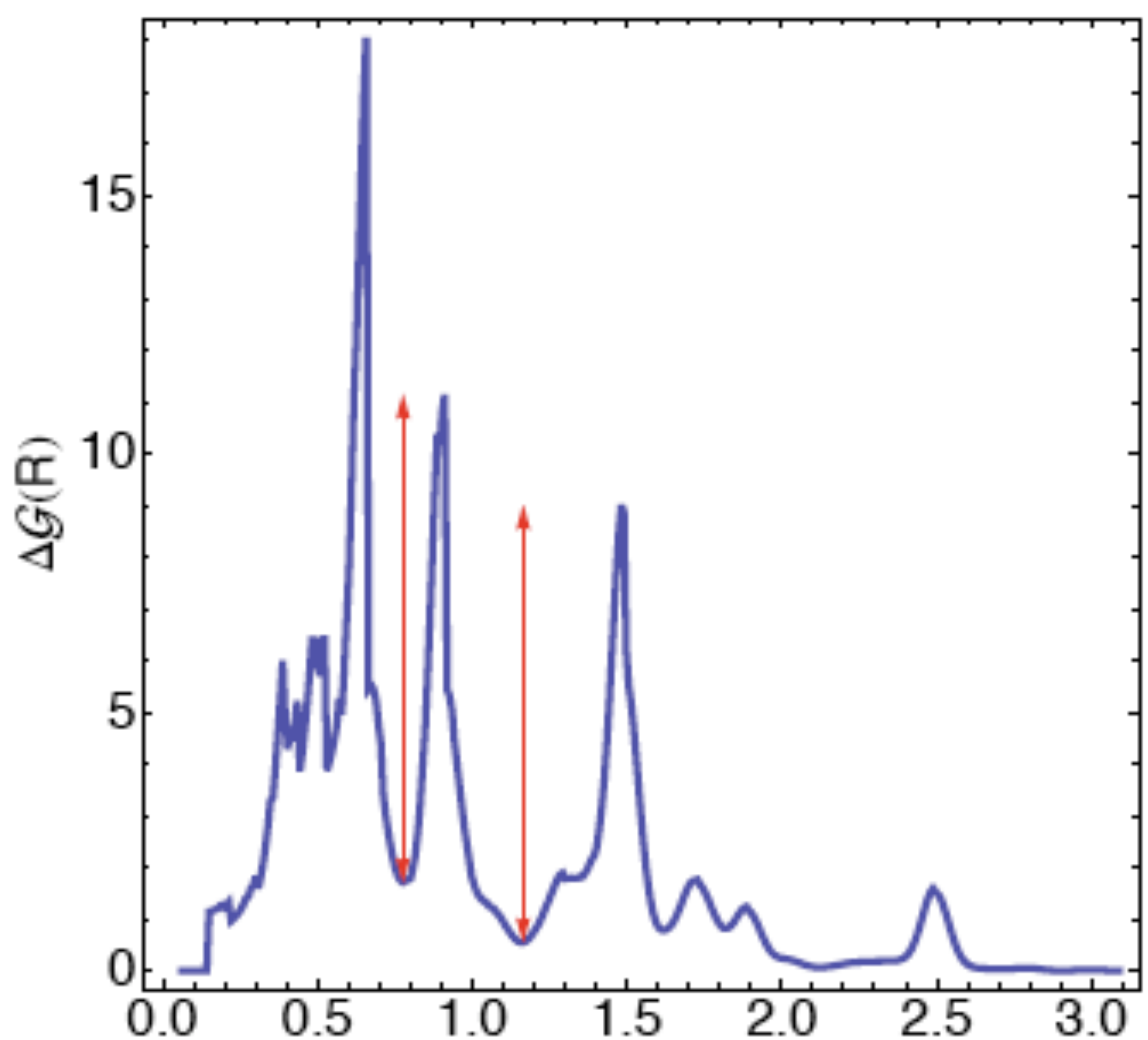
Top Tagging, T. Plehn and M. Spannowsky, 1112.4441

2.2 Subjet.

1104.1646 M. Jankowiak, A. Larkoski SubJetless

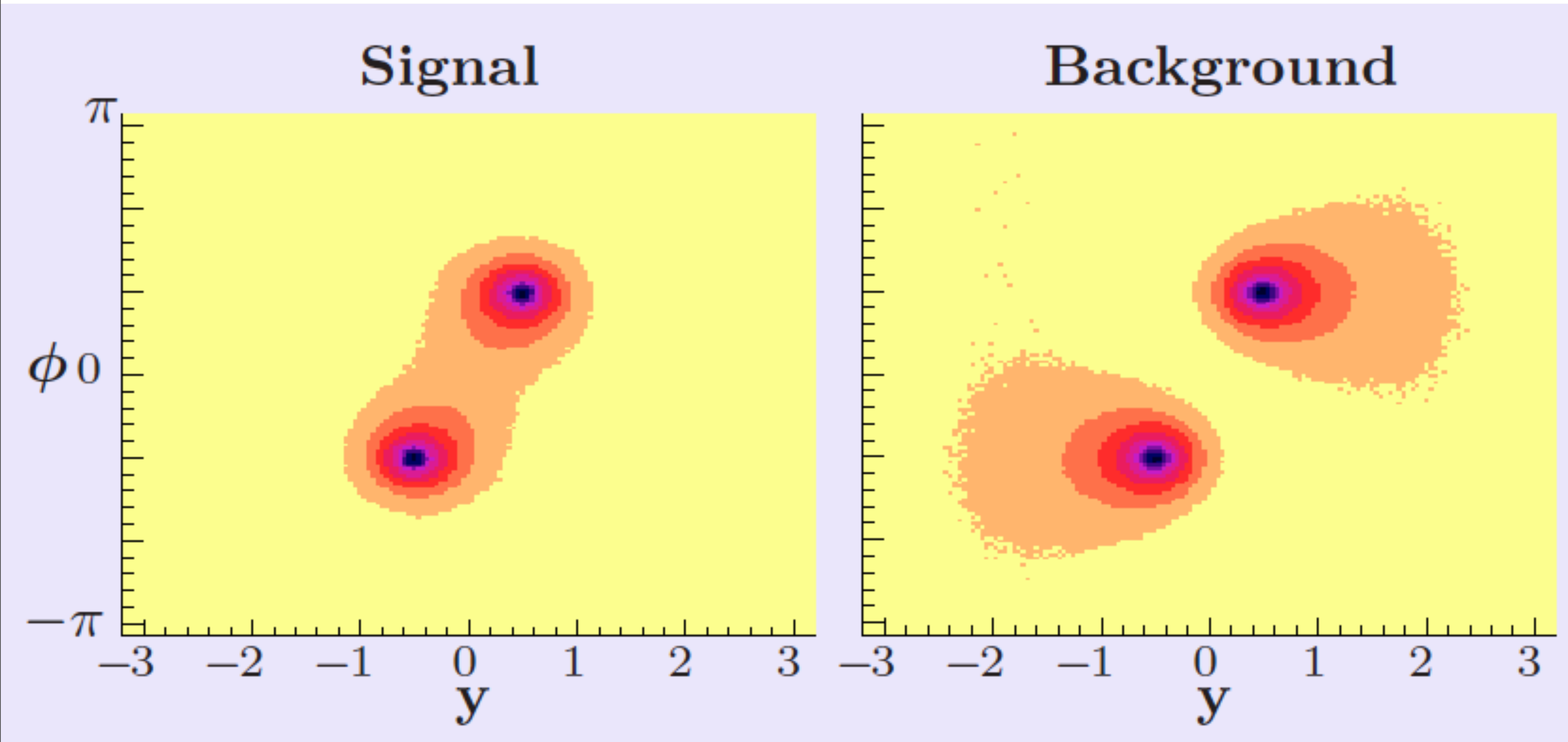
$$\mathcal{G}(R) \equiv \frac{\sum_{i\neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2 \Theta(R - \Delta R_{ij})}{\sum_{i\neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2} \approx \frac{\sum_{i\neq j} p_i \cdot p_j \Theta(R - \Delta R_{ij})}{\sum_{i\neq j} p_i \cdot p_j}$$





Color-Flow

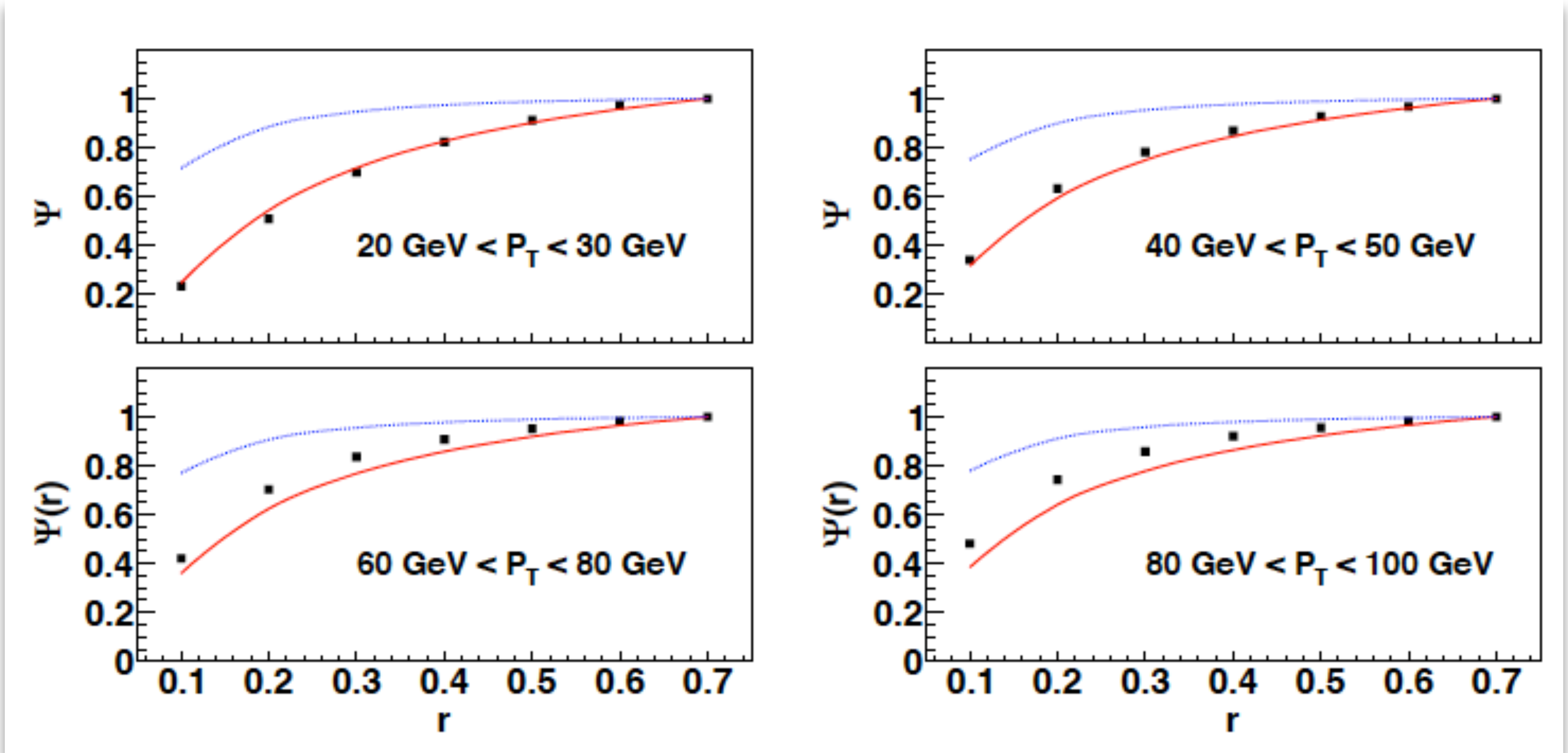
Color Singlet — Color octet



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

2.2 Subjet.

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



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

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

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

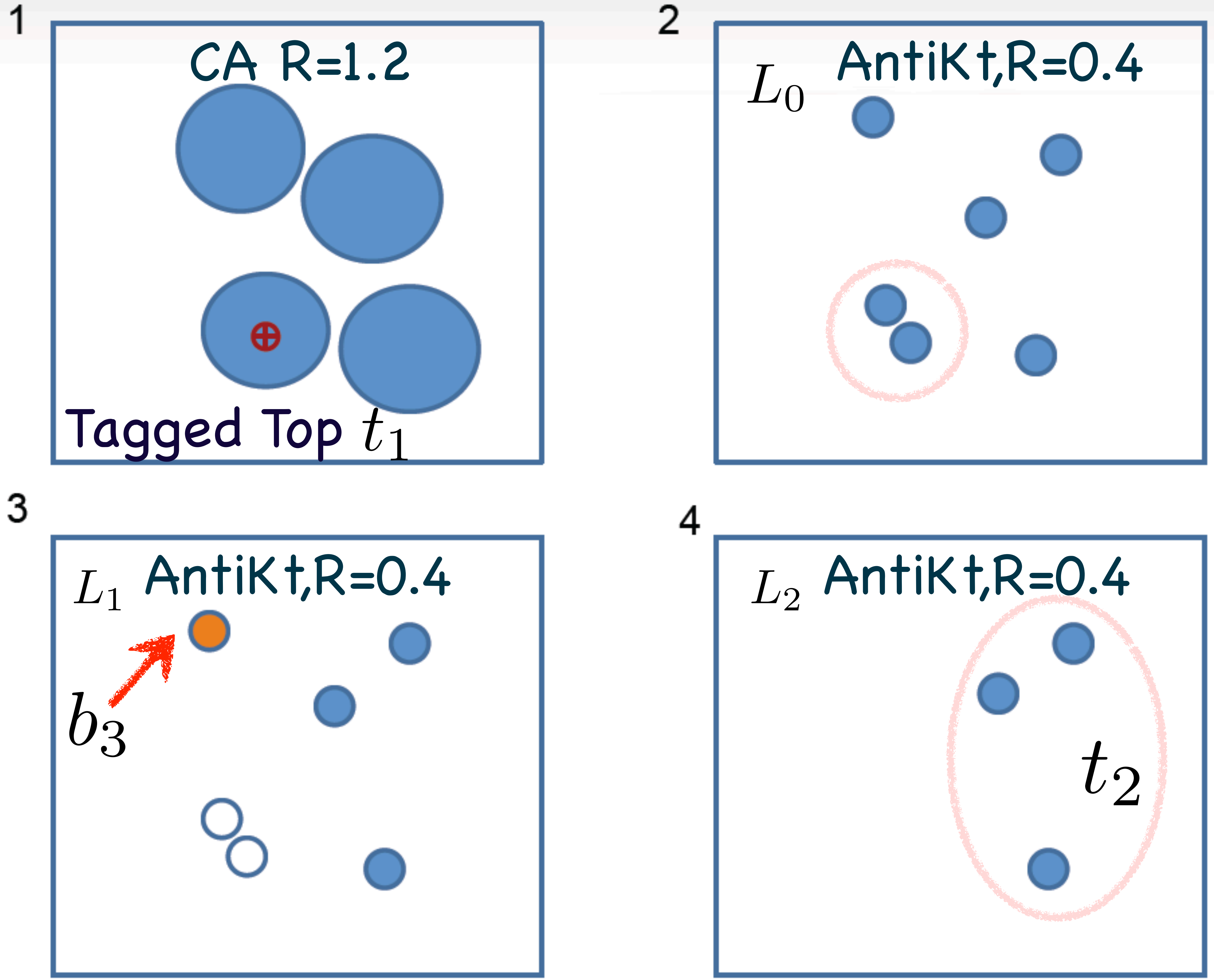
$$\langle \delta m_j^2 \rangle \simeq \Lambda_{\mathrm{UE}} \, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$$

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

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

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

$$Y_L = Y_R = 1$$

Must be tagged!

Conventions:

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

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%

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

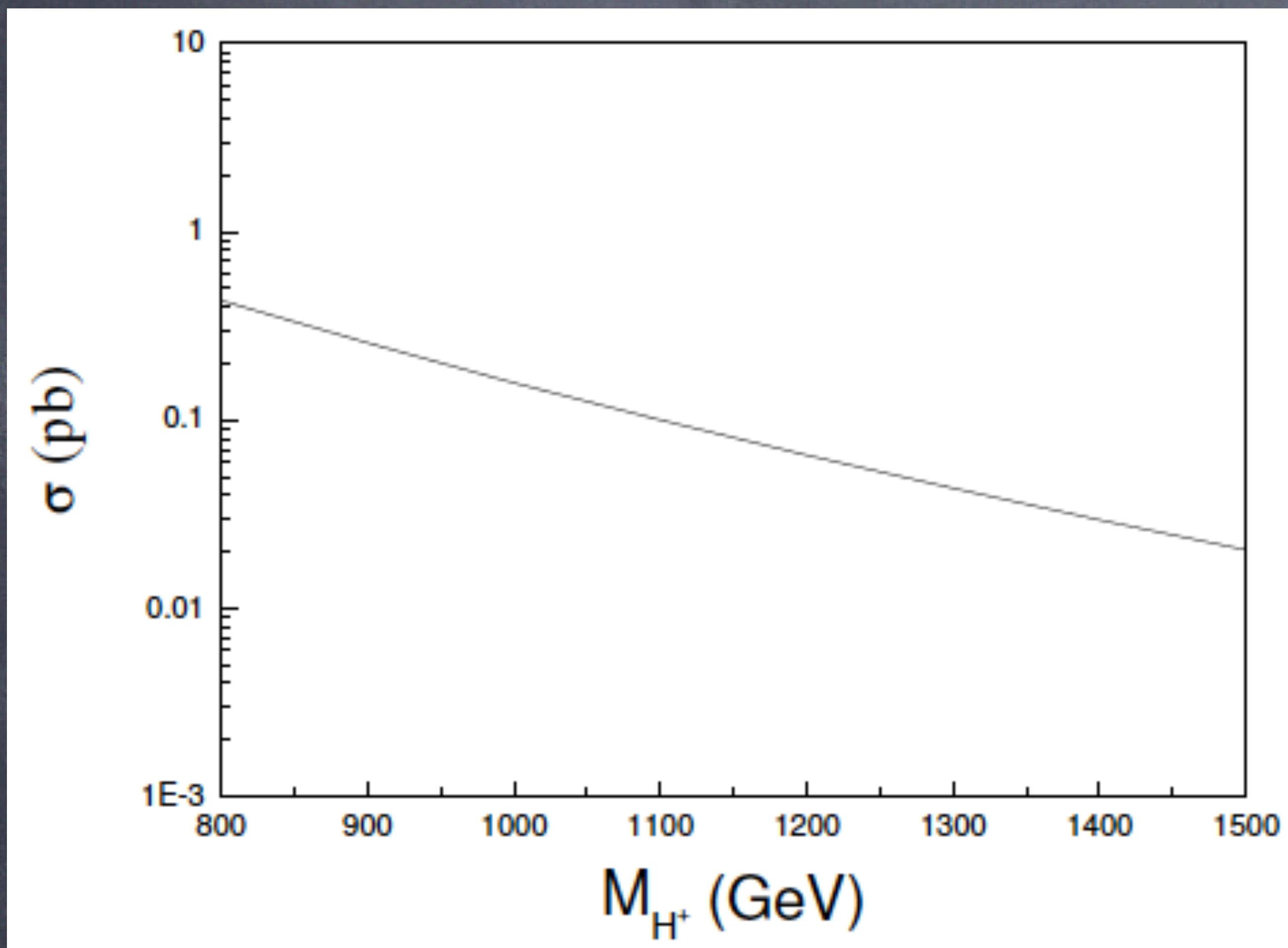
Top tagger is better with larger mass when R fixed.

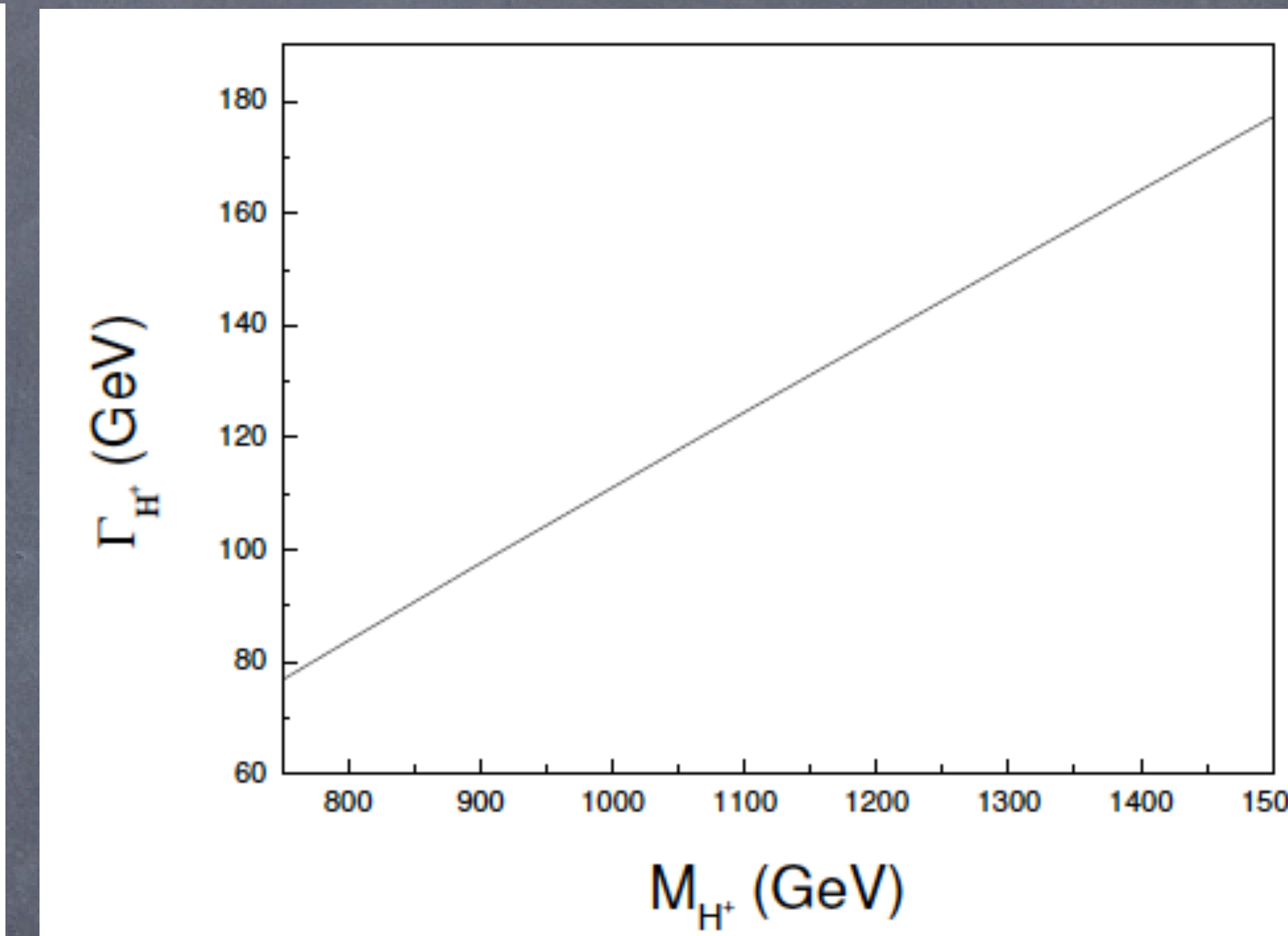
CA algorithm is chosen for hadronic top tagger.

Cone Size shall be optimized for S/B.

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

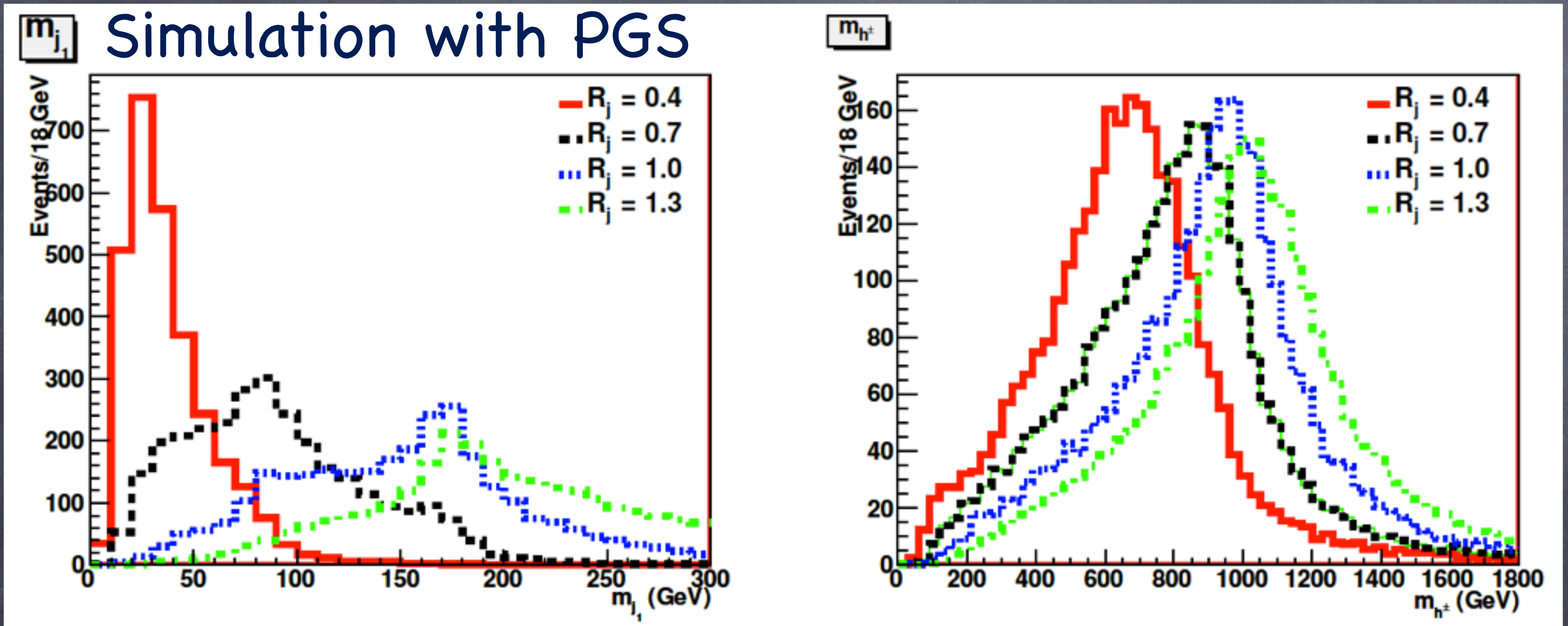
The decay width
$Br(H^+ \to tb) = 100\%$





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

3. Feasibility@LHC



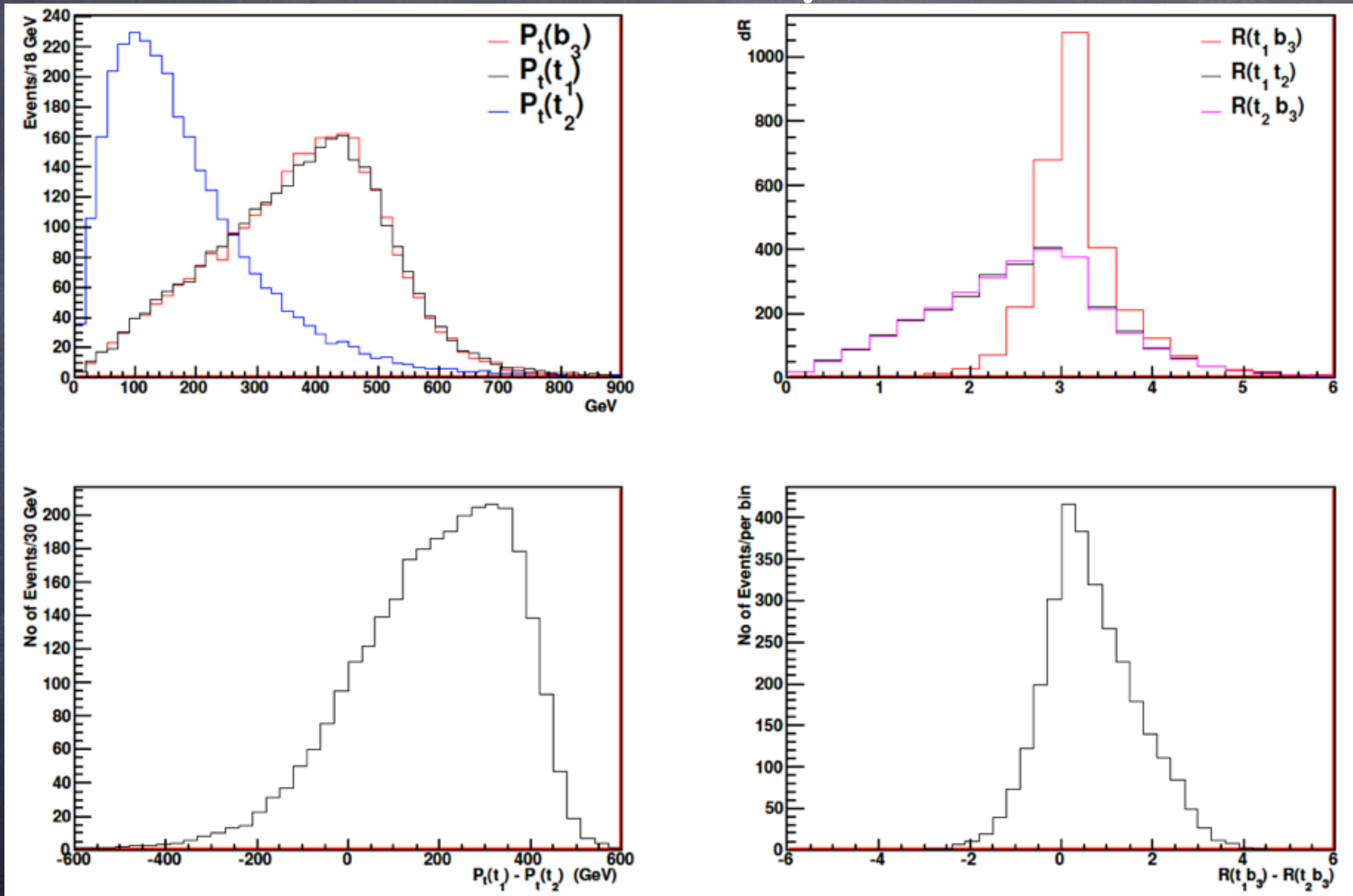
- Cone size and algorithm are crucial for the performance of the hadronic top tagger
- Charge Higgs mass bump can be approximately reconstructed.
- The detector effect and the decay width effect can not wash out signal

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}
$\lvert m_{W_2} - m_W^{PDG}\rvert < 20$ GeV & $\lvert m_{t_2} - m_t^{PDG}\rvert < 30$ GeV	3.1%	2.6×10^{-5}	2.3×10^{-8}
$\lvert m_{H^\pm} - m_{H^\pm}^{assumed}\rvert < 200$ GeV	2.5%	1.5×10^{-5}	1.5×10^{-8}
Events in 100 fb^{-1}	133	830	13.8

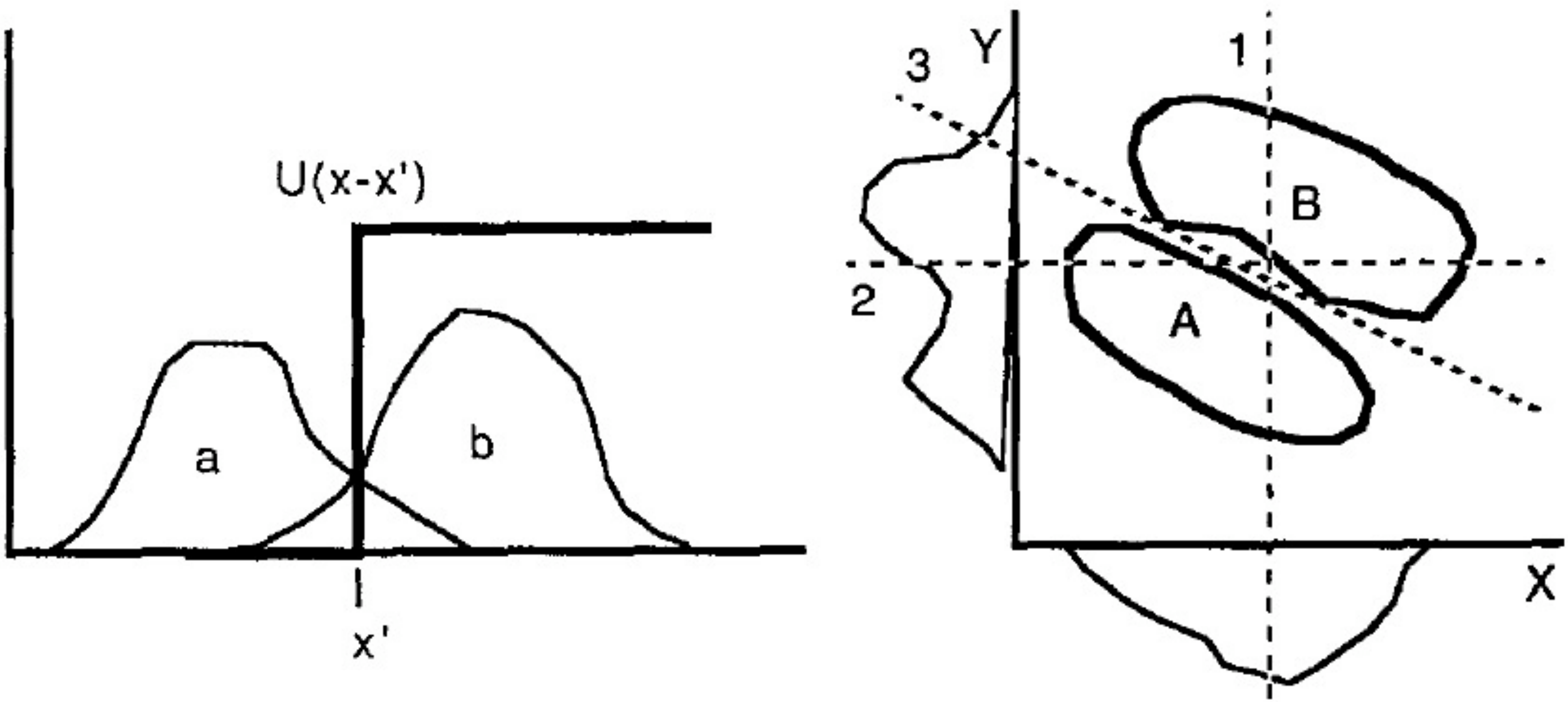
A Cuts based method can work but …

3. Feasibility@LHC



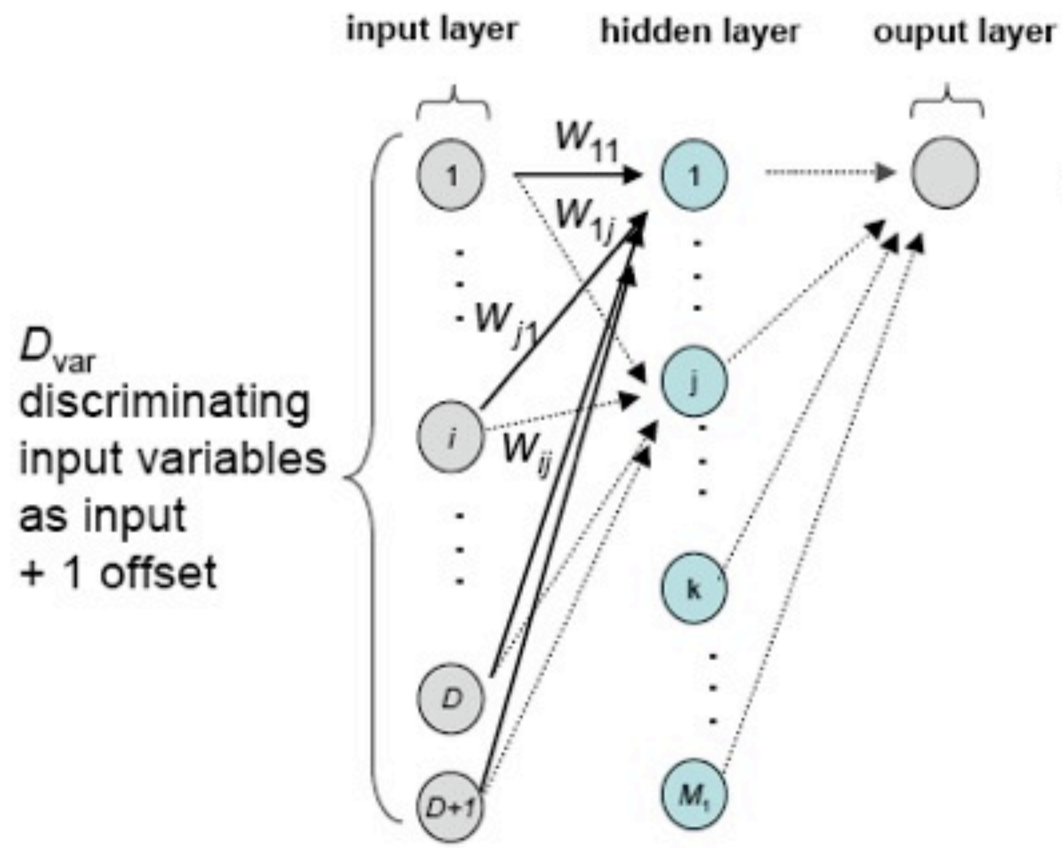
A Show Case $m_{H+} = 1$ TeV why we use those cuts?

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



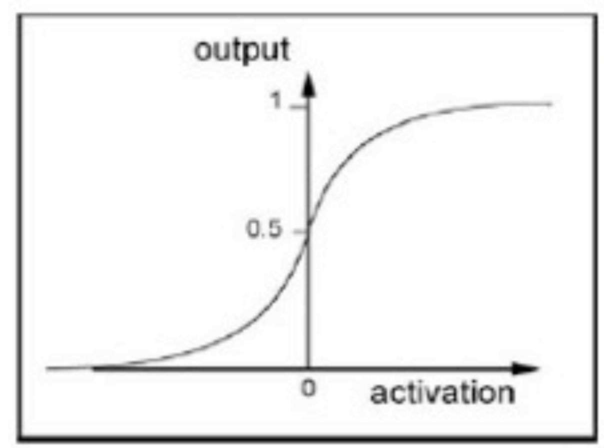
Why MultiVariate Analysis? To improve sensitivity of analysis when luminosity is limited and to reduce luminosity when budget fixed.

Neural Network Discrimination



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:

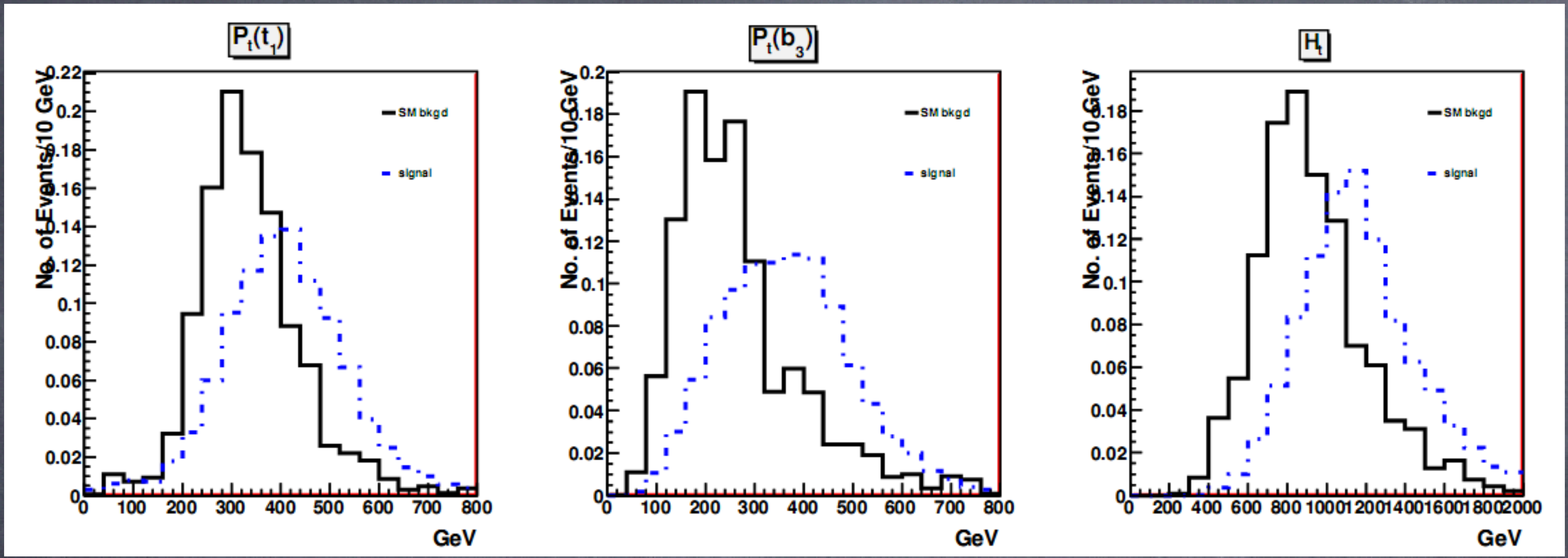
$$A(x) = \left(1 + e^{-x}\right)^{-1}$$

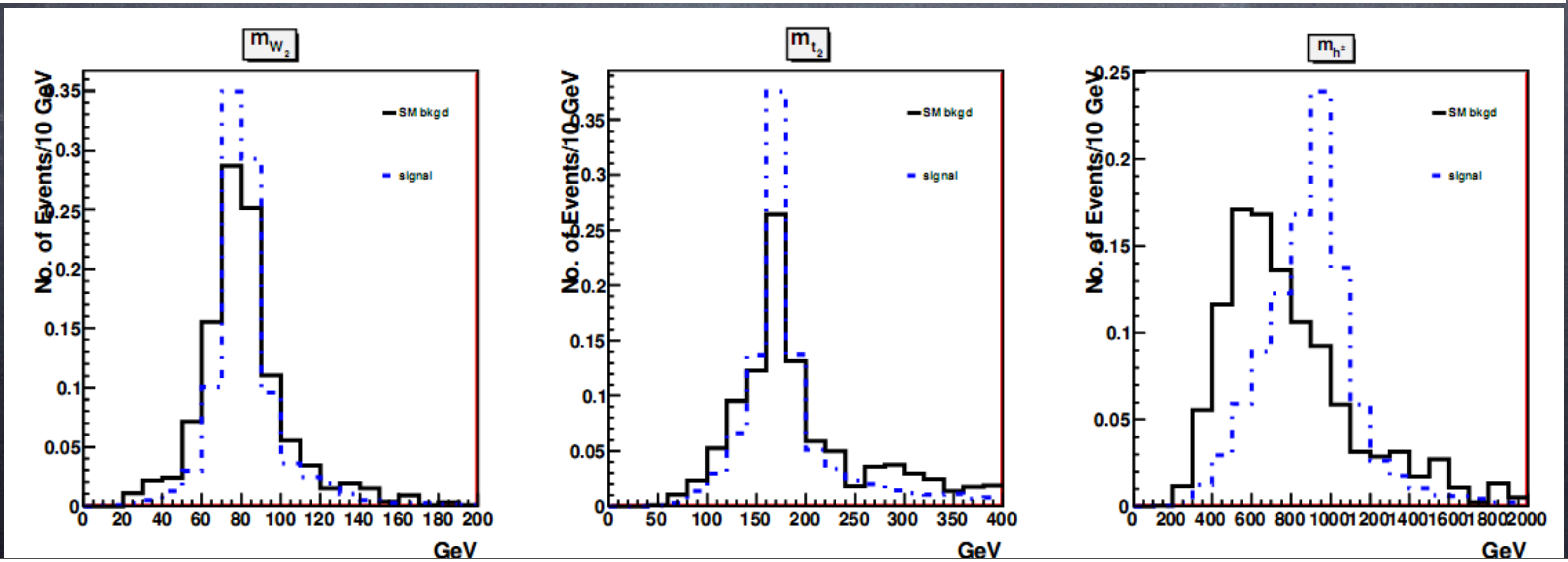
or tanh

nodes→neurons
links(weights)→synapses

→ Neural network: try to simulate reactions of a brain to certain stimulus (input data)

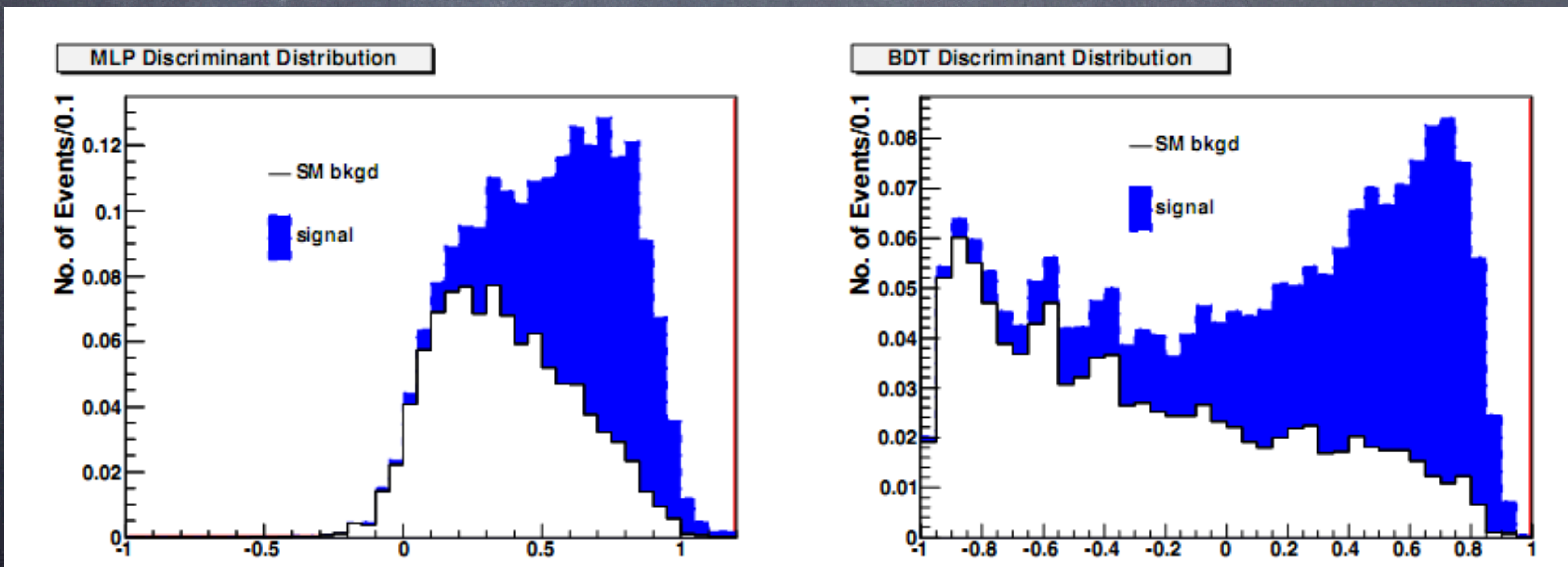
3. Feasibility@LHC





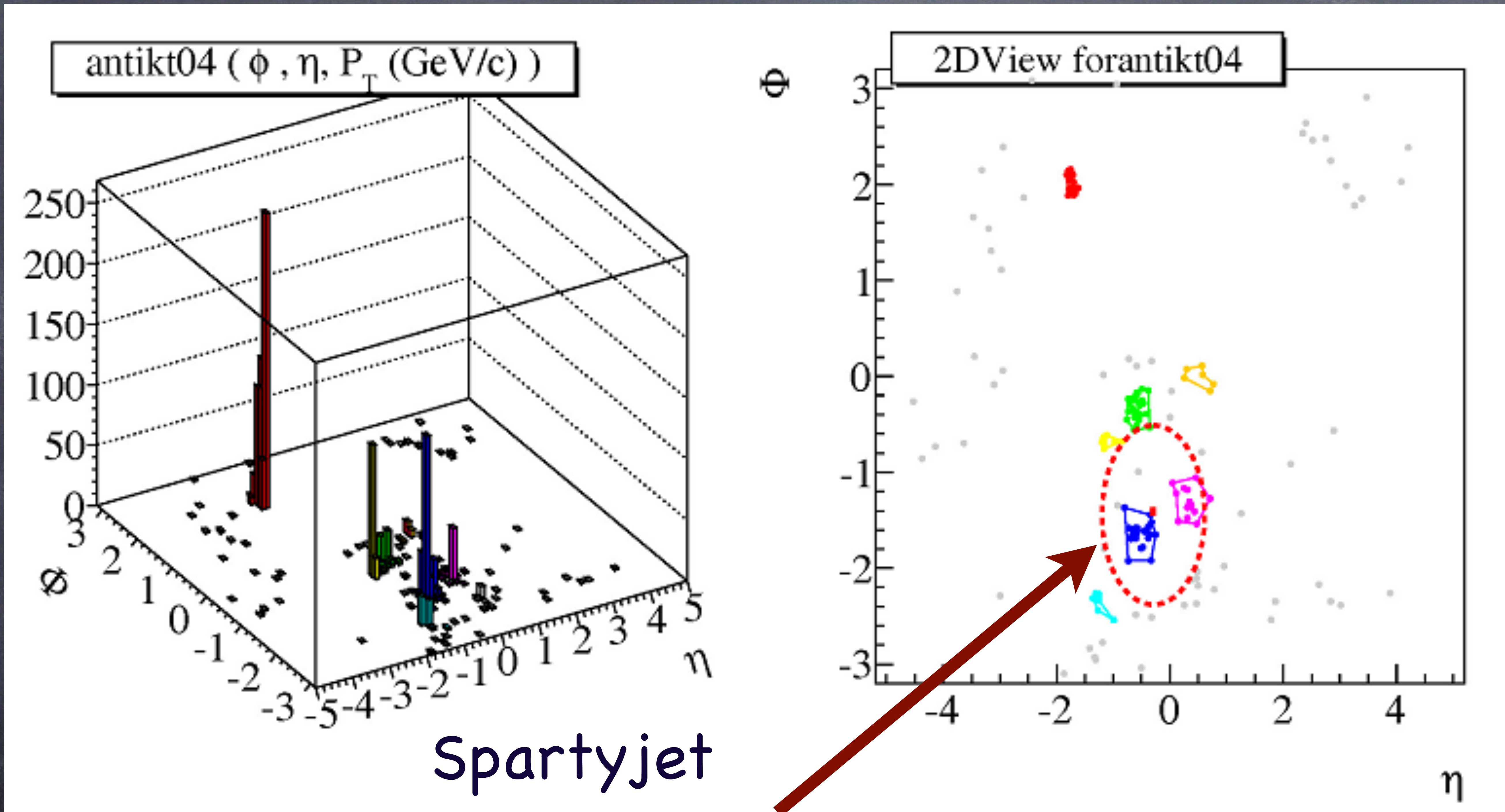
3. Feasibility@LHC

	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.

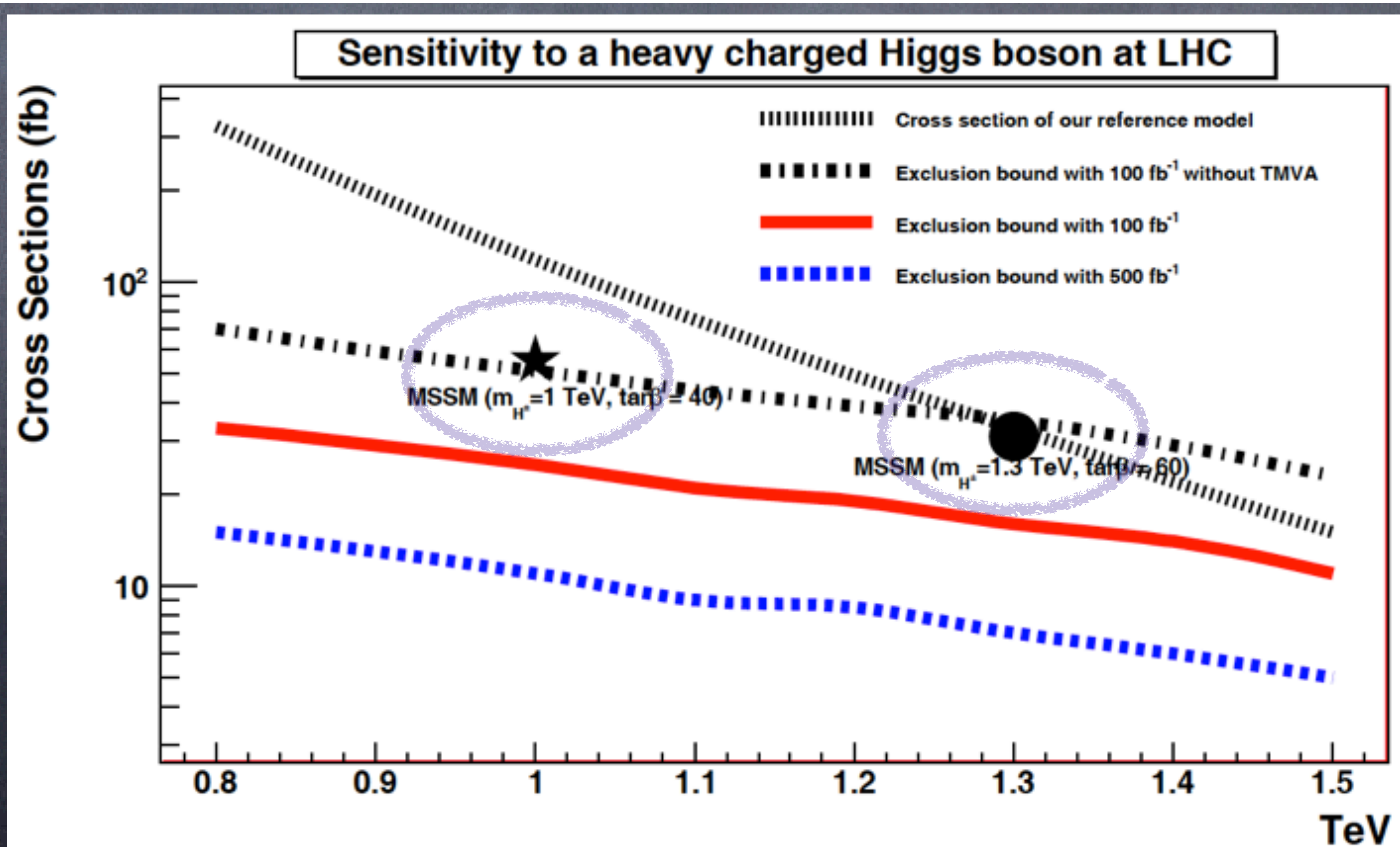
A closer and intuitive look at a signal event.



Conventional top reconstruction method fails for tagging 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!