Top physics after Higgs discovery

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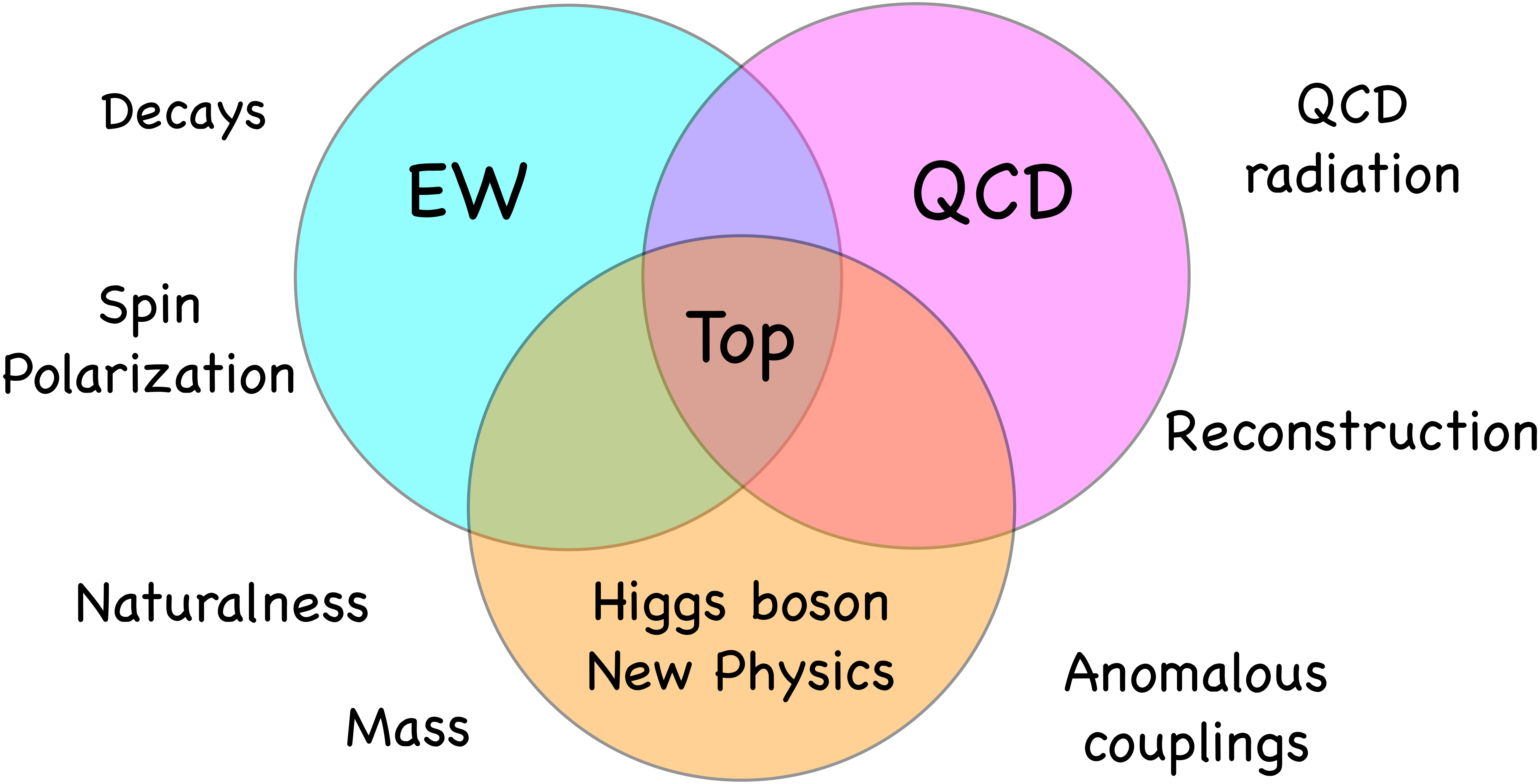


EW

QCD

Top

Higgs boson
New Physics

Decays

Spin
Polarization

Naturalness

Mass

QCD
radiation

Reconstruction

Anomalous
couplings

Interacts over many time scales:

$1/m_t <$	$1/\Gamma_t <$	$1/\Lambda <$	m_t/Λ^2
Production time<	Lifetime <	Hadronization time <	Spin decorrelation time
10^{-27} sec	10^{-25} sec	10^{-24} sec	

The top quark Lagrangian in the SM

Gauge interactions:

$$\mathcal{L} = i\bar{Q}_L \not{D} Q_L + i\bar{t}_R \not{D} t_R + i\bar{b}_R \not{D} b_R$$

with the SM covariant derivative

$$D_\mu = \partial^\mu + i g_s G^a_\mu T^a + i g W^i_\mu T^i + i g' B_\mu Y$$

in terms of the generators and gauge bosons of SU(3) (T^a, G^a_μ, g_s) SU(2) (T^i, W^i_μ, g) and U(1) (Y, B_μ, g') and

$$Z_\mu = \cos\theta_W W^3_\mu - \sin\theta_W B_\mu \quad , \quad A_\mu = \sin\theta_W W^3_\mu + \cos\theta_W B_\mu$$

with the Weinberg angle θ_W

Eventually, the coupling to the Higgs boson field is

$$\mathcal{L}_{\text{Yukawa}} = -y_t \bar{t} t H \quad \text{with} \quad y_t = m_t/v$$

After spontaneous symmetry breaking and rotating into the mass eigenstate basis, the charged current interactions introduce flavor mixing in the SM

$$\mathcal{L}_{W^\pm} = g\, W_\mu^- \sum_{i,j=\mathrm{flavors}} V_{ij} \bar{q}_i \gamma^\mu q_j + \mathrm{h.c.}$$

with the Cabibbo-Kobayashi-Maskawa matrix:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

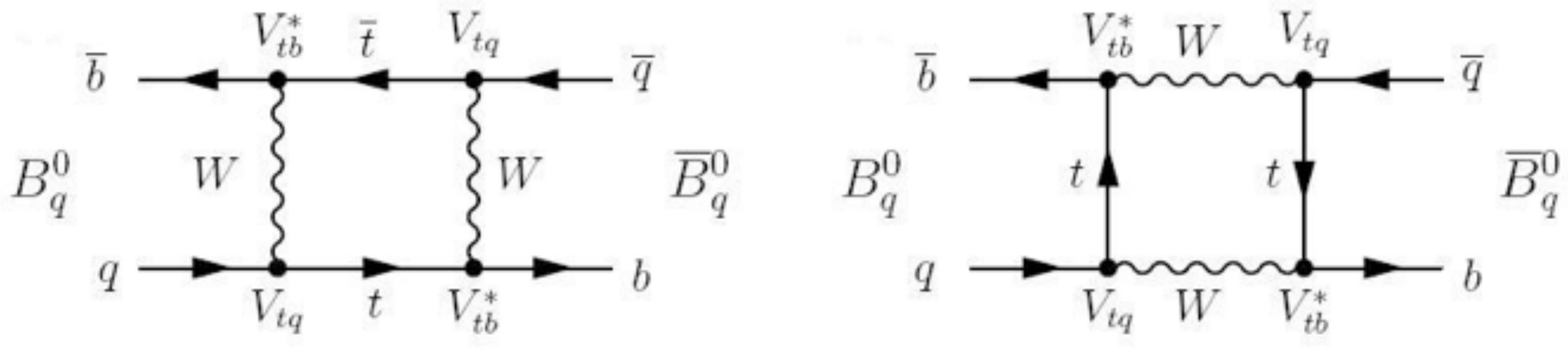
Need 3 generations for CP-violation in SM

$\longrightarrow$ top quark related to origin of CP and possibly baryogenesis

Early indirect evidence for heavy top quark

- After discovering of b-quark existence of top expected
- Indirect evidence from B and K meson mixing - CP phase

Kobayashi-Maskawa



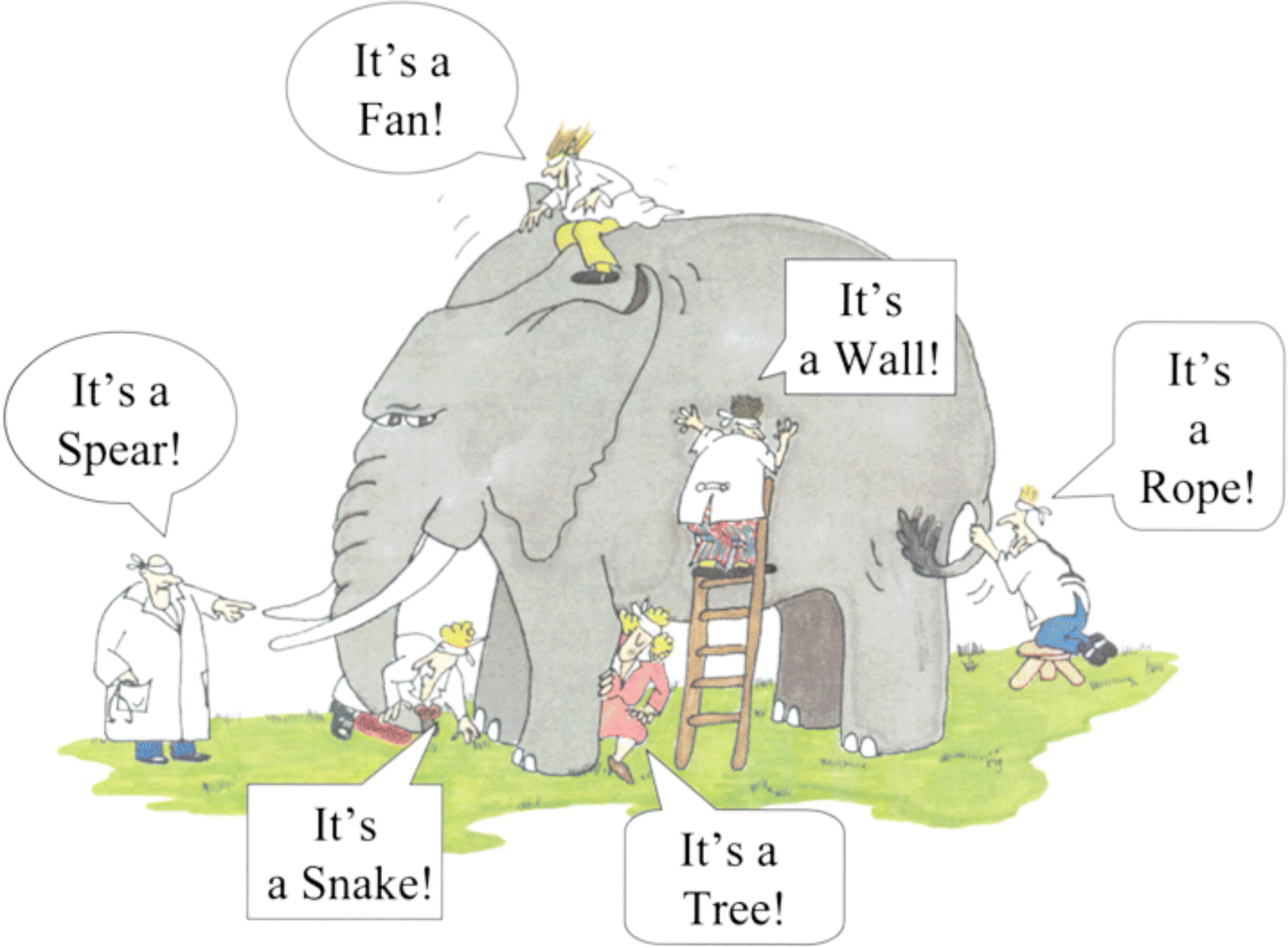
Feynman box diagrams for B mixing.

- Vtb measurement: single top (Tevatron) $V_{tb} = 0.88 \pm 0.07$

unitarity of CKM Mat. $V_{tb} = 0.999135$

- EW precision tests at LEP give constraint of top mass

Measurement of top quark properties

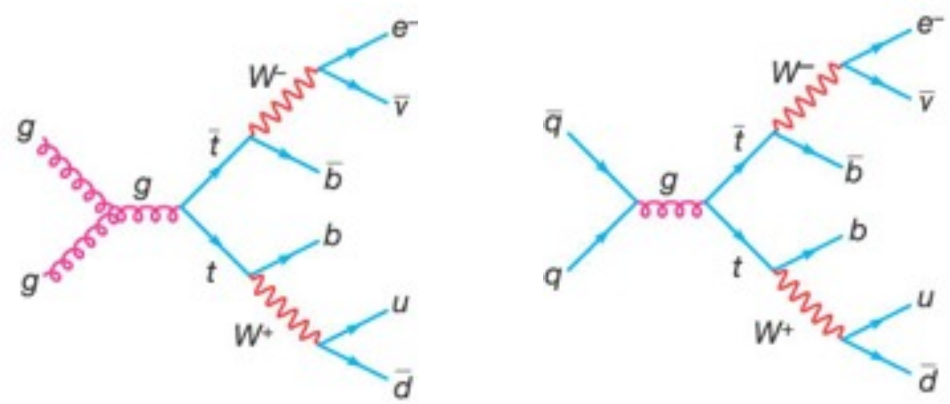


$t\bar{t}$ production cross sections

- $t\bar{t}$ @ NLO [Nason, Dawson, Ellis ('88,'89); Beenakker, Kuijf, van Neerven, Smith]
- $t\bar{t}$ NNLO calculations [Czakon, Fiedler, Ferroglia, Pecjak, Yang; Mitov; Bonciani, Ferroglia, Gehrmann, Maitre, Studerus; Anastasiou, Aybat; Kniehl, Merebashvili, Korner, Rogal; Bonciani, Ferroglia, Gehrmann, Studerus; ...]
- $t\bar{t}$ NNLL resummed [Czakon, Mitov; Kidonakis ('09,'10); Beneke, Falgari, Schwinn; Czakon, Mitov, Sterman; Beneke, Czakon, Falgari; ...]
- $t\bar{t}$ + (H, Z, photon) [Beenakker et al.; Dawson, Reina; Dawson, Reina, Wackeroth; Dawson Rein; Lazopoulos et al.; Peng-Fei et al.]
- $t\bar{t}$ + jet @ NLO [Dittmaier, Uwer, Weinzierl ('07,'09)]
- $t\bar{t}$ + 2jet @ NLO [Bevilacqua, Czakon, Papadopoulos, Worek]
- $t\bar{t}$ including decays @ NLO [Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek]

The dominant production mode:

Top pair production



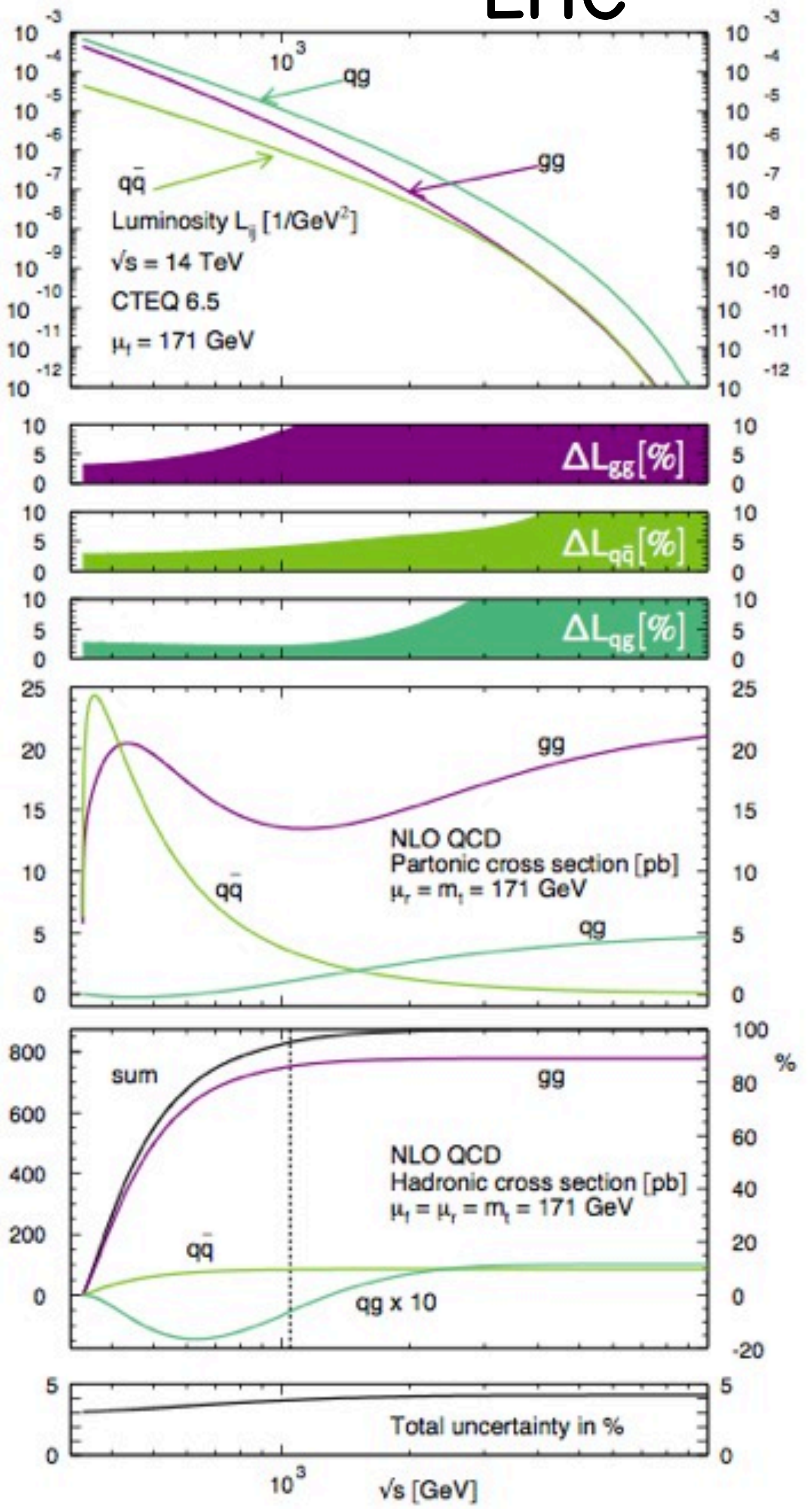
$$\sigma_{pp\to ttX}(s_{\rm had}, m_t{}^2) \; = \sum_{i,j=q,q,g} \int_{4m_t{}^2}^{s_{\rm had}} d\hat{s}\, L_{ij}(\hat{s}, s_{\rm had}, \mu_f^2)\, \hat{\sigma}_{ij\to tt}(\hat{s}, m_t{}^2, \mu_f^2, \mu_r^2)$$

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

[@ NNLO+NNLL, Czakon, Fiedler, Mitov '13]

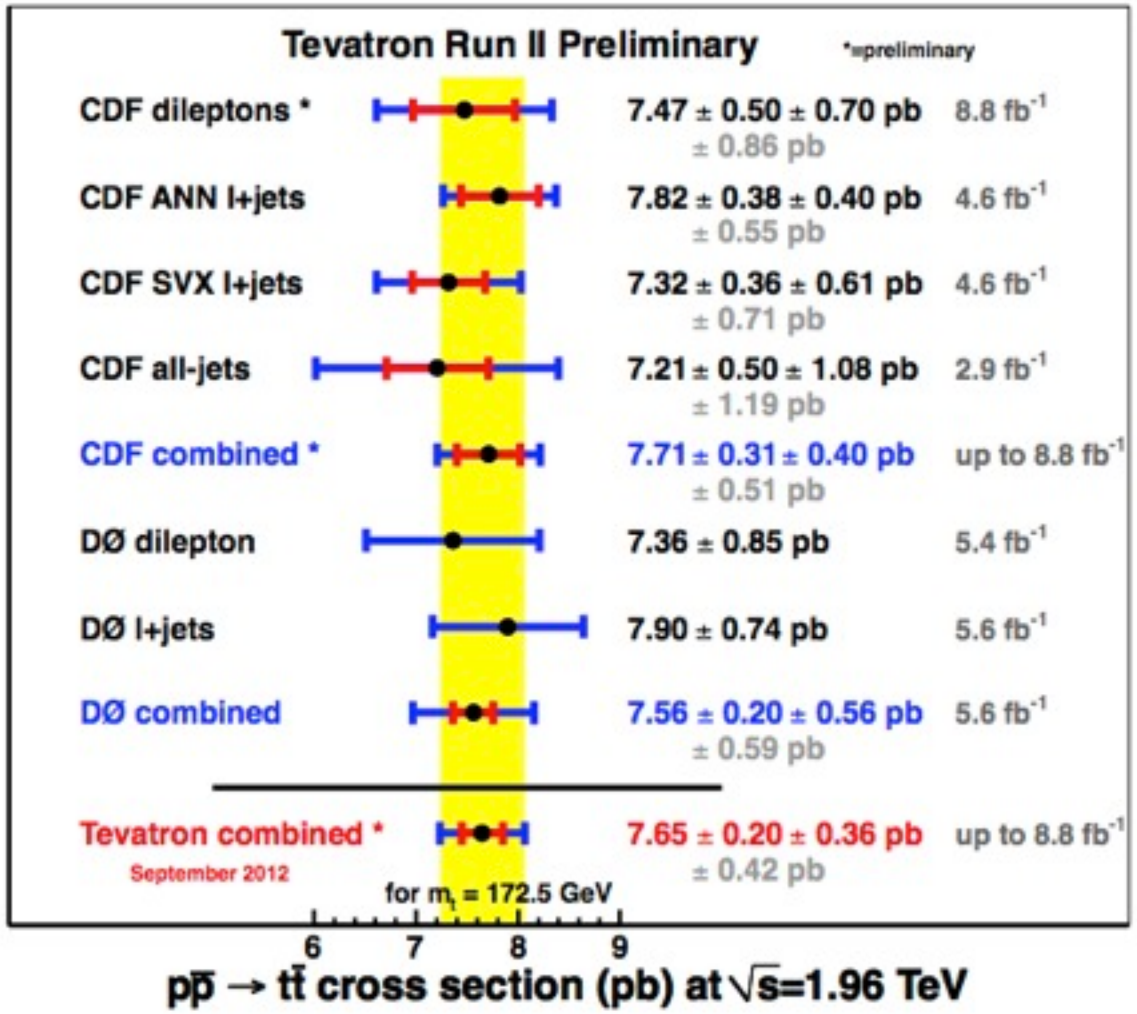
- Cross section roughly same for bbbar at B-factories as ttbar at LHC. LHC surpasses #Events after ~10 years (BABAR 530 ifb).
- Measurements not statistics limited!

LHC

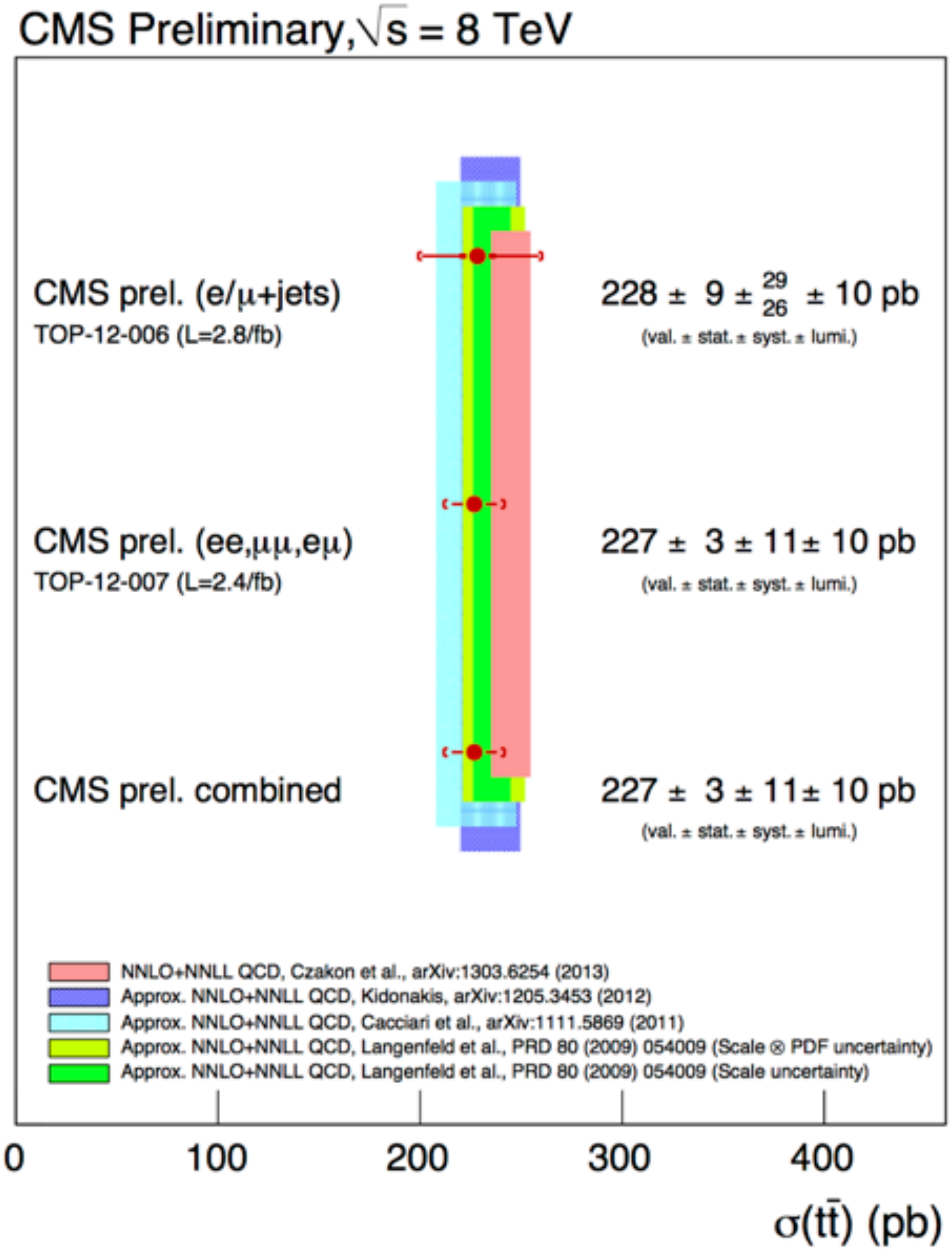


[Moch, Uwer 2008]

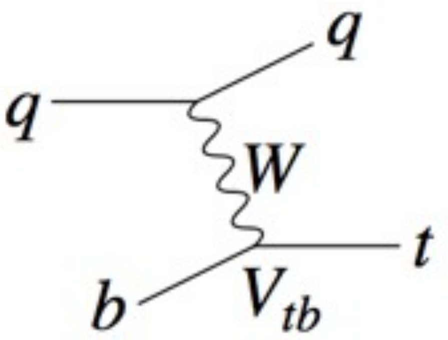
$t\bar{t}$ production cross sections



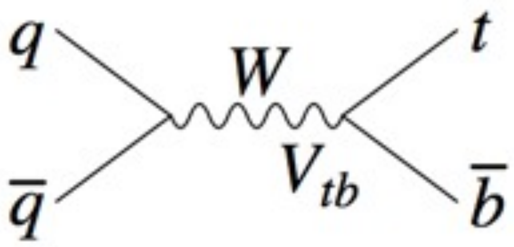
production cross section
in very good agreement
with theory prediction



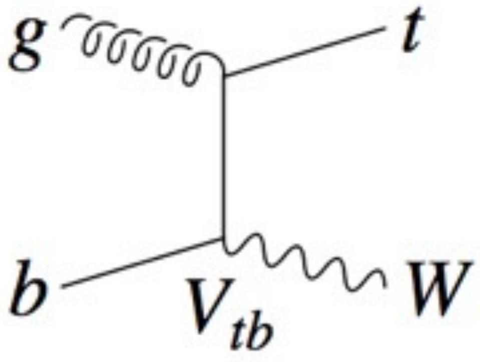
Single top production



t-channel



s-channel



Wt-associated

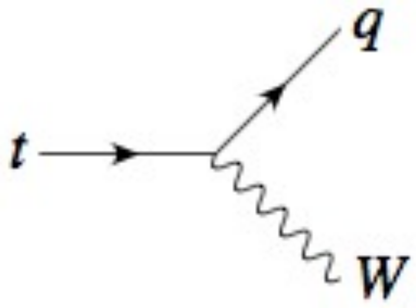
- production modes discriminated by # of tagged b-jets and their kinematics
- Cross sections for top / anti-top [pb]:

	t-channel	s-channel	Wt-channel
LHC	155.9 / 90.7	6.6 / 4.1	33 / 33
Tevatron	1.98	0.88	0.07

- At Tevatron with ~10 ifb per experiment in total 60 000 single top events vs 150 000 pair top events

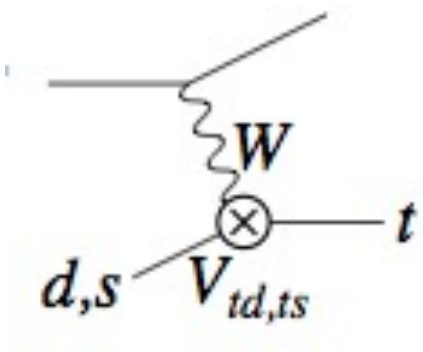
Single top production subleading but useful for measurements

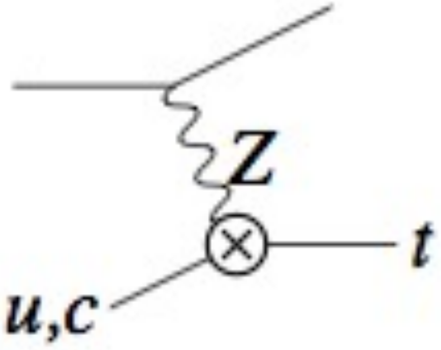
- Vtb



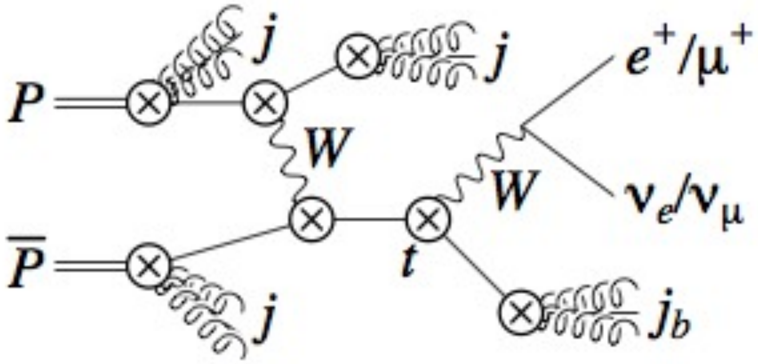
$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^{\mu}\frac{1}{2}(1-\gamma_5)$$

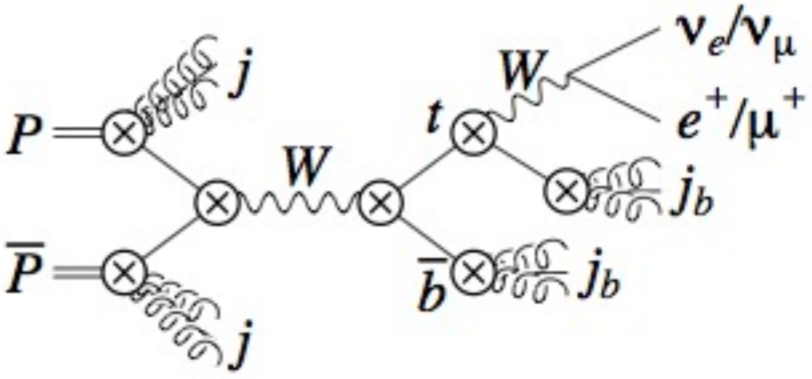
- Anomalous couplings in production



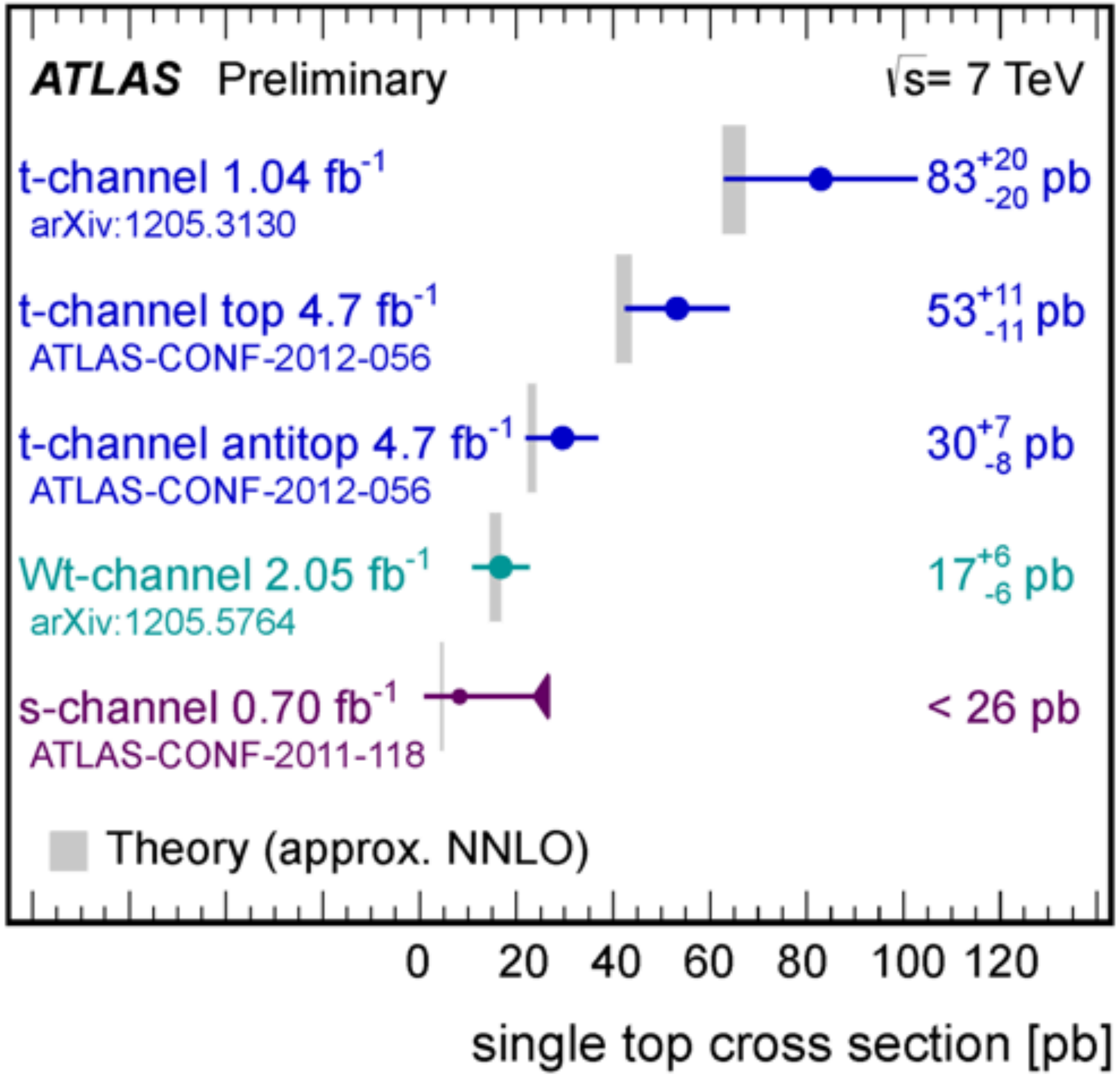


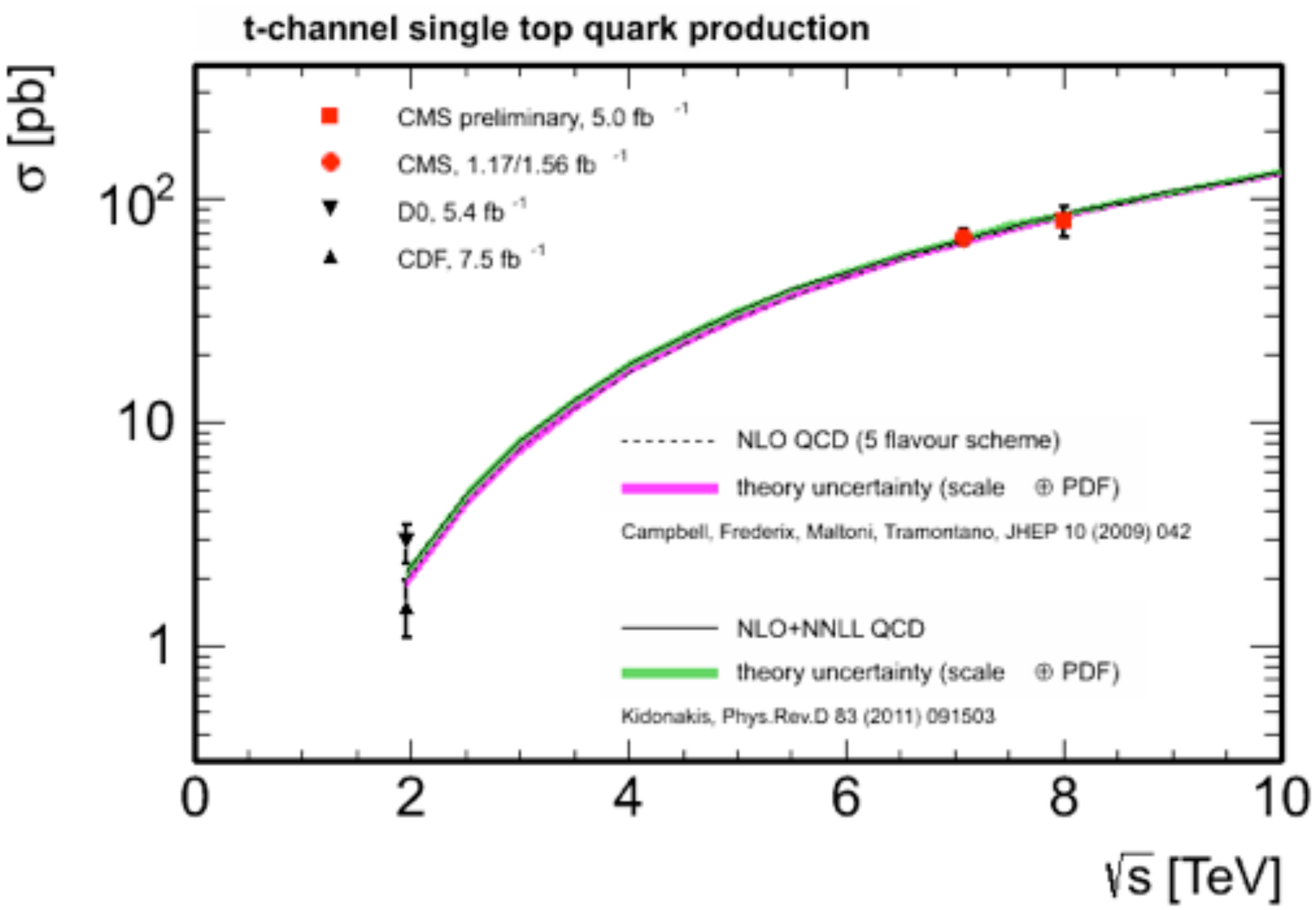
- Perfect factorization through NLO, like DIS and DY





[Graphs Z. Sullivan]


ATLAS Preliminary
√s= 7 TeV
t-channel 1.04 fb^{-1}
arXiv:1205.3130
83^{+20}_{-20} pb
t-channel top 4.7 fb^{-1}
ATLAS-CONF-2012-056
53^{+11}_{-11} pb
t-channel antitop 4.7 fb^{-1}
ATLAS-CONF-2012-056
30^{+7}_{-8} pb
Wt-channel 2.05 fb^{-1}
arXiv:1205.5764
17^{+6}_{-6} pb
s-channel 0.70 fb^{-1}
ATLAS-CONF-2011-118
< 26 pb
Theory (approx. NNLO)
0
20
40
60
80
100
120
single top cross section [pb]


t-channel single top quark production
σ [pb]
10^2
10
1
CMS preliminary, 5.0 fb^{-1}
CMS, 1.17/1.56 fb^{-1}
D0, 5.4 fb^{-1}
CDF, 7.5 fb^{-1}
NLO QCD (5 flavour scheme)
theory uncertainty (scale ⊕ PDF)
Campbell, Frederix, Maltoni, Tramontano, JHEP 10 (2009) 042
NLO+NNLL QCD
theory uncertainty (scale ⊕ PDF)
Kidonakis, Phys.Rev.D 83 (2011) 091503
0
2
4
6
8
10
√s [TeV]

Top Quark decays

Decays before hadronizes via EW interaction. Since $m_t > m_W + m_b$

$$\begin{array}{lll} t & \rightarrow & W^+ + b \\ & & \lfloor\!\rightarrow l^+ + \nu \end{array}$$

$$\begin{array}{lll} t & \rightarrow & W^+ + b \\ & & \lfloor\!\rightarrow q + \bar{q} \end{array}$$

with $\Gamma_t \simeq 1.4 \text{ GeV}$

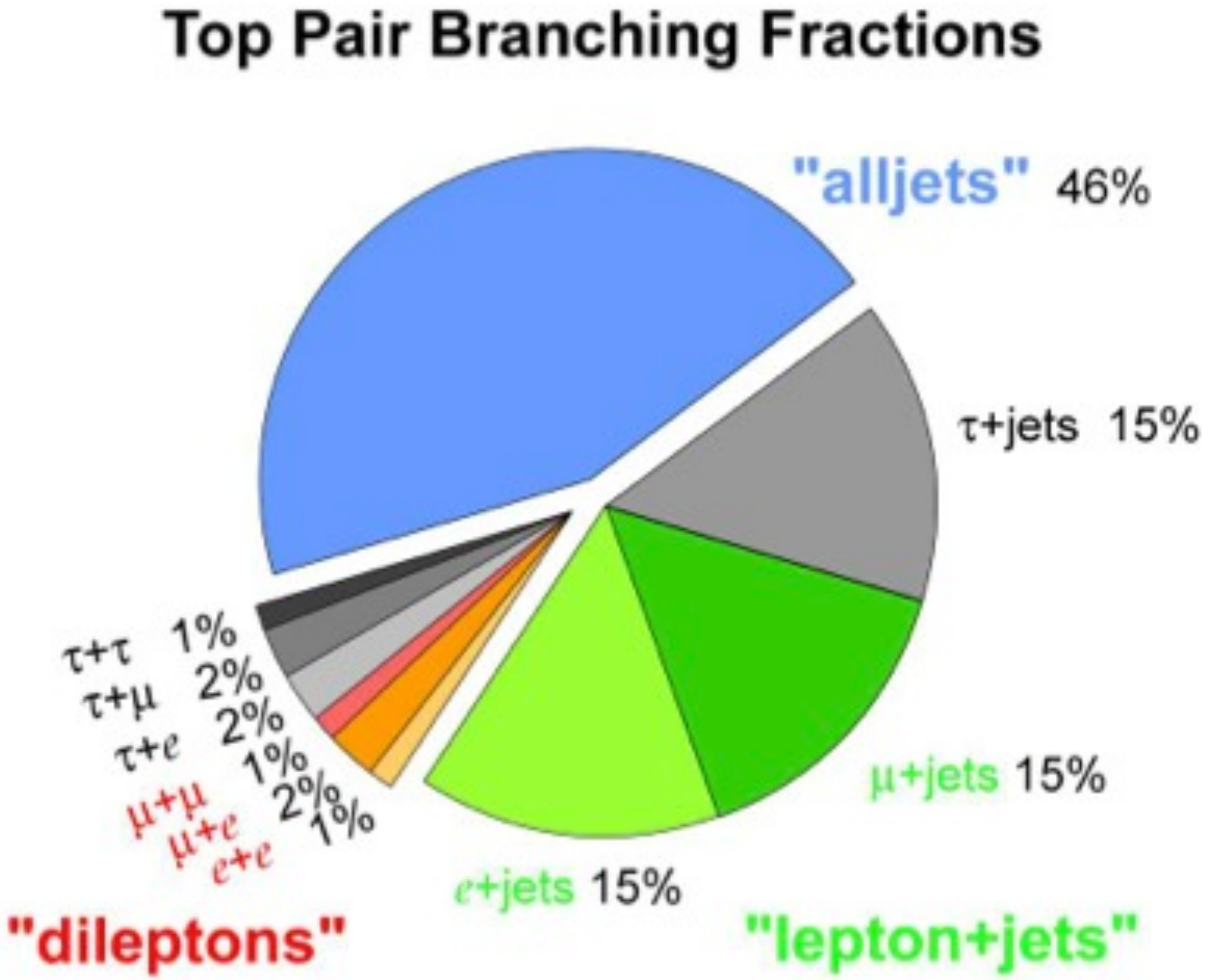
Top decay modes determined by W decay, e.g.

$$\mathrm{BR}(W^+ \to e^+ \bar{\nu}) = \frac{1}{3+3+3} \approx 11\%.$$

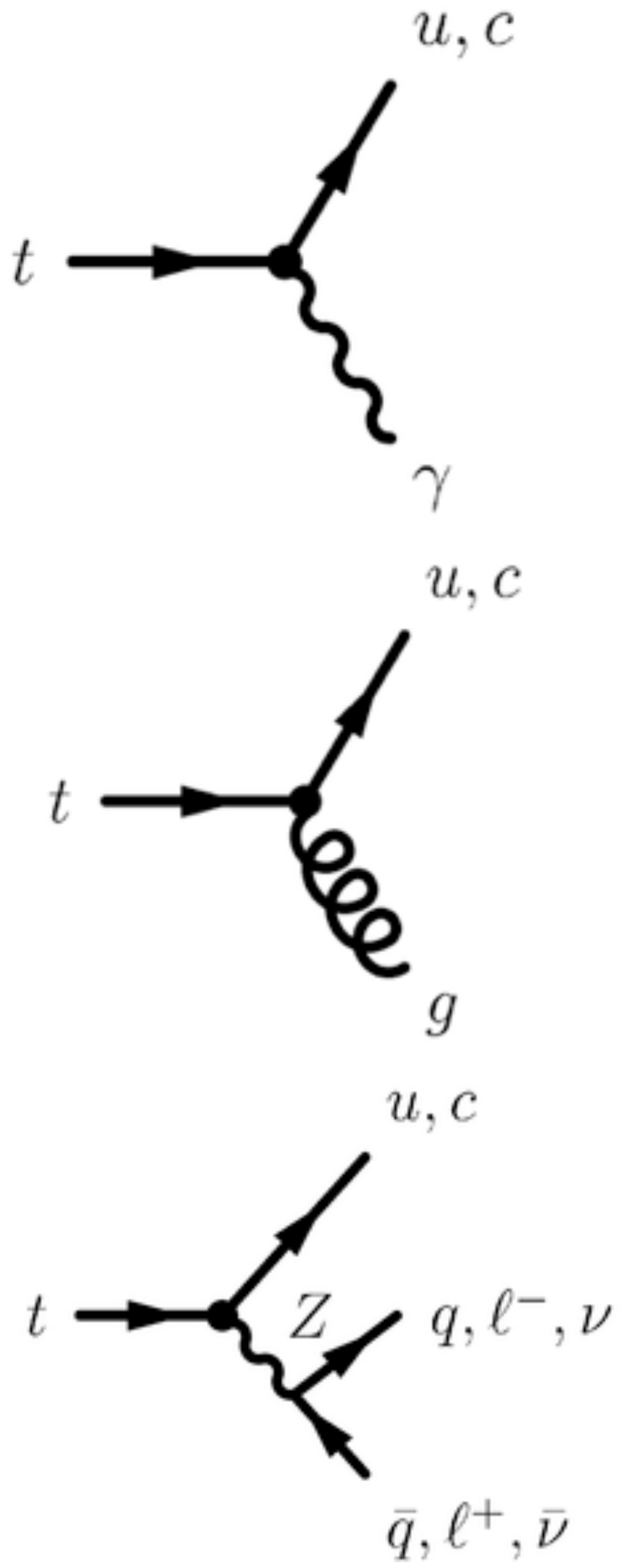
lv

3 x ud

3 x cs



Rare/Anomalous Top Quark decays



FCNC can be loop-induced in the SM and enhanced by New Physics

$$\mathscr{L}_{\rm eff} = g_s \sum_{q=u,c} \frac{\kappa_{qgt}}{\Lambda} t\sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R) q G^a_{\mu\nu} + h.c.,$$

ATLAS study at 7 TeV with 2 ifb

$\kappa_{cgt}/\Lambda < 1.6 \cdot 10^{-2}\,\mathrm{TeV}^{-1}$ $\mathscr{B}(t \to cg) < 2.7 \cdot 10^{-4}$

$\kappa_{ugt}/\Lambda < 6.9 \cdot 10^{-3}\,\mathrm{TeV}^{-1}$ $\mathscr{B}(t \to ug) < 5.7 \cdot 10^{-5}$

from single top prod

converted

No evidence for t -> Zq decay found

➔ $\mathrm{BR}(t \to Zq) < 0.73\%$

Top quark spin and polarization

The decay amplitude for $t(p_t) \to b(p_b) W^+(p_W)$ is given by

$$\mathcal{M}(t \to bW^+) = -\frac{ig}{2\sqrt{s}} V_{tb} \bar{u}(p_b) \gamma^\mu (1-\gamma_5) u(p_t) \epsilon_\mu^{\lambda *}(p_W)$$

and the decay rate for a given W-boson polarization is calculated as:

$$\Gamma = \frac{1}{2m_t} \int dLIPS \overline{\sum} |\mathcal{M}(t \to bW^+)|^2$$

Assuming the top quark is unpolarized, working in its rest frame, the momentum configuration can be parametrized as:

$$p_t = (m_t, 0, 0, 0) \quad p_W = (E_W, 0, p \sin\theta, p\cos\theta) \quad p_b = (E_b, 0, -p\sin\theta, -p\cos\theta)$$

with $E_W = \frac{m_t^2 + M_W^2}{2m_t}$ and $p = \frac{m_t^2 - M_W^2}{2m_t}$, W polarization vectors are

$$\epsilon_0 = \frac{1}{M_W}(p, 0, E_W \sin\theta, E_W \cos\theta) \qquad \epsilon_\pm = \frac{1}{\sqrt{2}}(0, 1, \pm i \cos\theta, \mp \sin\theta)$$

with $m_b = 0$ we get

$$\overline{\sum} |\mathcal{M}(t \to bW^+)|^2 = \frac{g^2}{8} |V_{tb}|^2 Tr \left[(\not{p}_t + m_t) \not{\epsilon}^*_\lambda (1 - \gamma_5) \not{p}_b \not{\epsilon}_\lambda \right]$$

and substituting the explicit polarization vectors one derives

$$\overline{\sum} |\mathcal{M}_0|^2 = \frac{2 G_F m_t^4}{\sqrt{2}} |V_{tb}|^2 (1 - x)$$

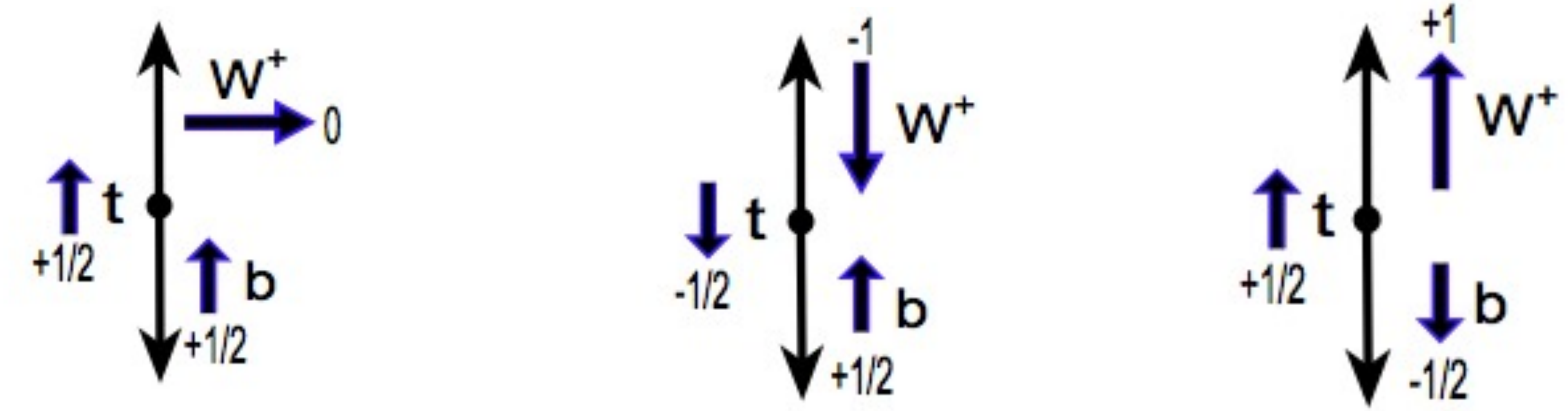
$$\overline{\sum} |\mathcal{M}_-|^2 = \frac{2 G_F m_t^4}{\sqrt{2}} |V_{tb}|^2 2x^2 (1 - x^2)$$

for $x = \frac{M_W}{m_t}$, such that the fraction of longitudinally polarized W is:

$$F_0 = \frac{\Gamma_0}{\Gamma_{\text{tot}}} = \frac{1}{1 + 2x^2} = \frac{m_t^2}{m_t^2 + 2M_W^2} \simeq 0.70$$

Structure of elw. top interactions

For $m_b = 0$ the W coming from $t \to bW^+$ can either be left-handed or longitudinal, never right-handed, because of angular momentum conservation



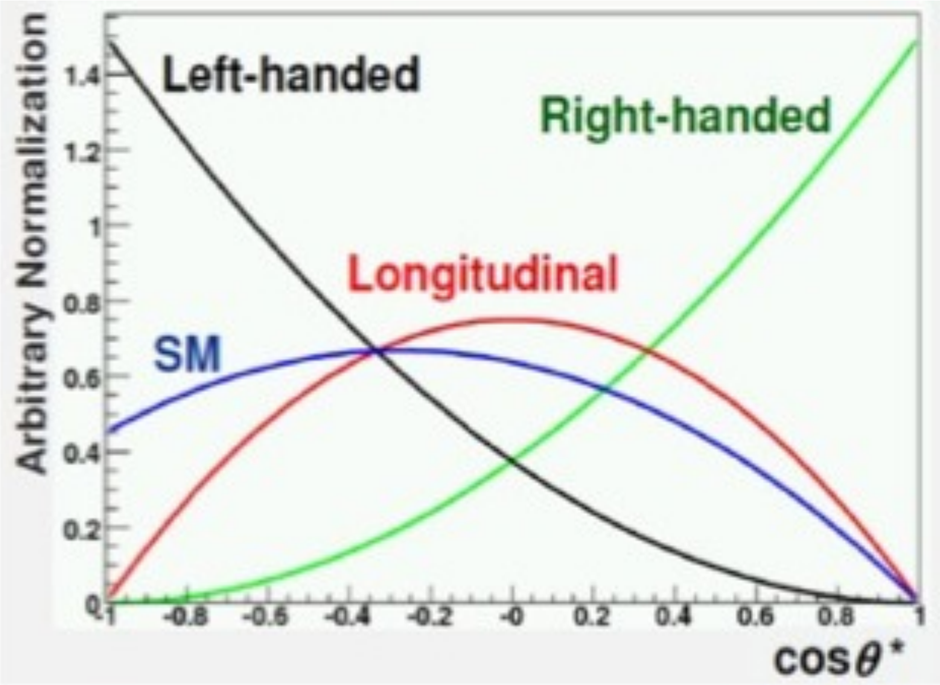
$$F_0 = \frac{m_t^2}{m_t^2 + 2M_W^2} + \mathcal{O}\left(\frac{m_b^2}{m_t^2}\right) \qquad F_- = 1 - F_0 + \mathcal{O}\left(\frac{m_b^2}{m_t^2}\right) \qquad F_+ = \mathcal{O}\left(\frac{m_b^2}{m_t^2}\right)$$

- Probes Weak interactions near EW symmetry breaking scale
- Test of V-A interaction in Standard Model

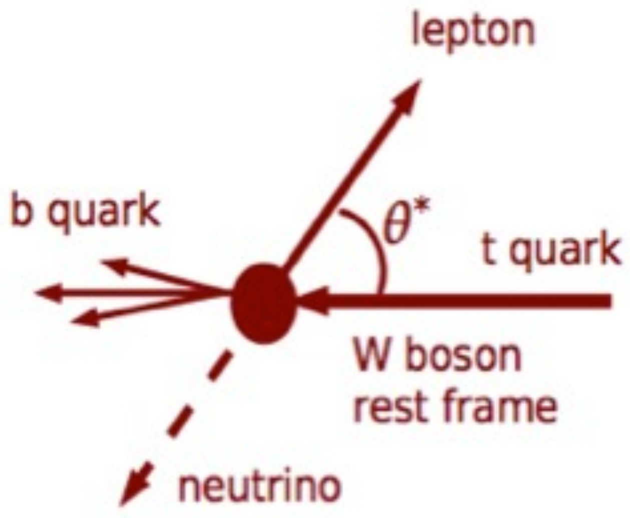
Including second stage decay $W^+ \to l^+ \nu$

allows to use charged lepton to measure W helicity fractions

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = F_0 \frac{3}{4}(1-\cos^2\theta^*) + F_- \frac{3}{8}(1-\cos\theta^*)^2 + F_+ \frac{3}{8}(1+\cos\theta^*)^2$$



(Collins-Soper angle)



or to measure top quark polarization. After summing all W helicities the squared matrix element is

$$\sum |M|^2 \sim \frac{(m_b^2\, p_t \cdot p_l - m_t^2 p_t \cdot p_l + 2p_t \cdot p_l)}{((p_l + p_\nu)^2 - m_W^2)^2}$$

⇨ lepton - top perfectly correlated to check for top polarization

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{l,n}} = \frac{1}{2}(1 + \mathcal{P}_n \cos\theta_{l,n})$$

[Mahlon, Parke 1996]

top completely polarized: $\mathcal{P}_n = \pm 1$

top polarization: Important for many applications

Example: Polarized tops from stop decays $\tilde{t} \to \chi_1^0 t$

[Perelstein, Weiler JHEP]
[Han, Katz, Krohn, Reece JHEP]
[Bhattacherjee, Mandal, Nojiri JHEP]

stop mass terms in MSSM:

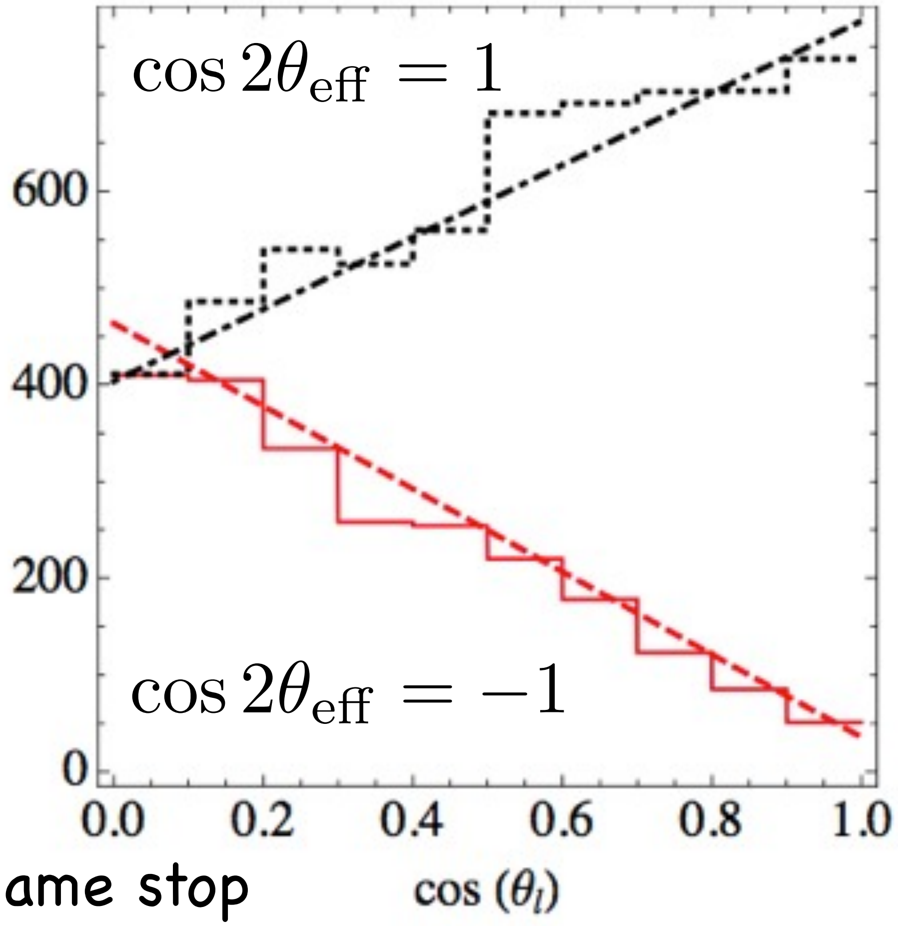
$$\mathcal{L} = \left(\tilde{t}_L^*, \tilde{t}_R^*\right) M^2 \left(\tilde{t}_L, \tilde{t}_R\right)^T$$

mass eigenstates

$$\begin{aligned} \tilde{t}_1 &= \cos\theta_t\, \tilde{t}_L + \sin\theta_t\, \tilde{t}_R\,, \\ \tilde{t}_2 &= -\sin\theta_t\, \tilde{t}_L + \cos\theta_t\, \tilde{t}_R\,, \end{aligned}$$

→ resulting vertex:

$$g_{\rm eff}^{ij} \tilde{t}_i \tilde{\chi}_j^0 \left(\cos\theta_{\rm eff}^{ij}\, P_L + \sin\theta_{\rm eff}^{ij}\, P_R\right) t$$



Maybe can be used to measure stop mixing angle, i.e. composition of mass eigenstates

angle between lepton and neutralino from same stop

Top Quark mass

See talks by Brian and CP

The top quark mass is fundamental parameter of SM and input to electroweak precision measurements

Problem: the top quark mass is not an observable, unlike decay rates or cross sections, but is scheme and scale dependent quantity.
Measurement of mass of colored object by color neutral decay products inherently ambiguous -> Cannot be determined better than $\mathcal{O}(\Lambda_{\rm QCD})$

[Smith, Willenbrock PRL 79]

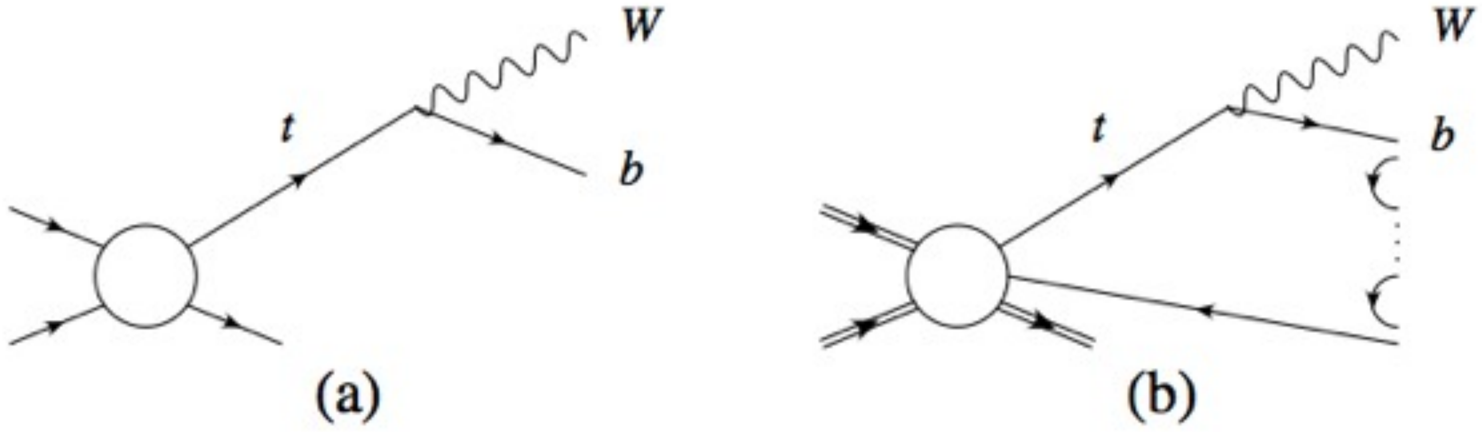
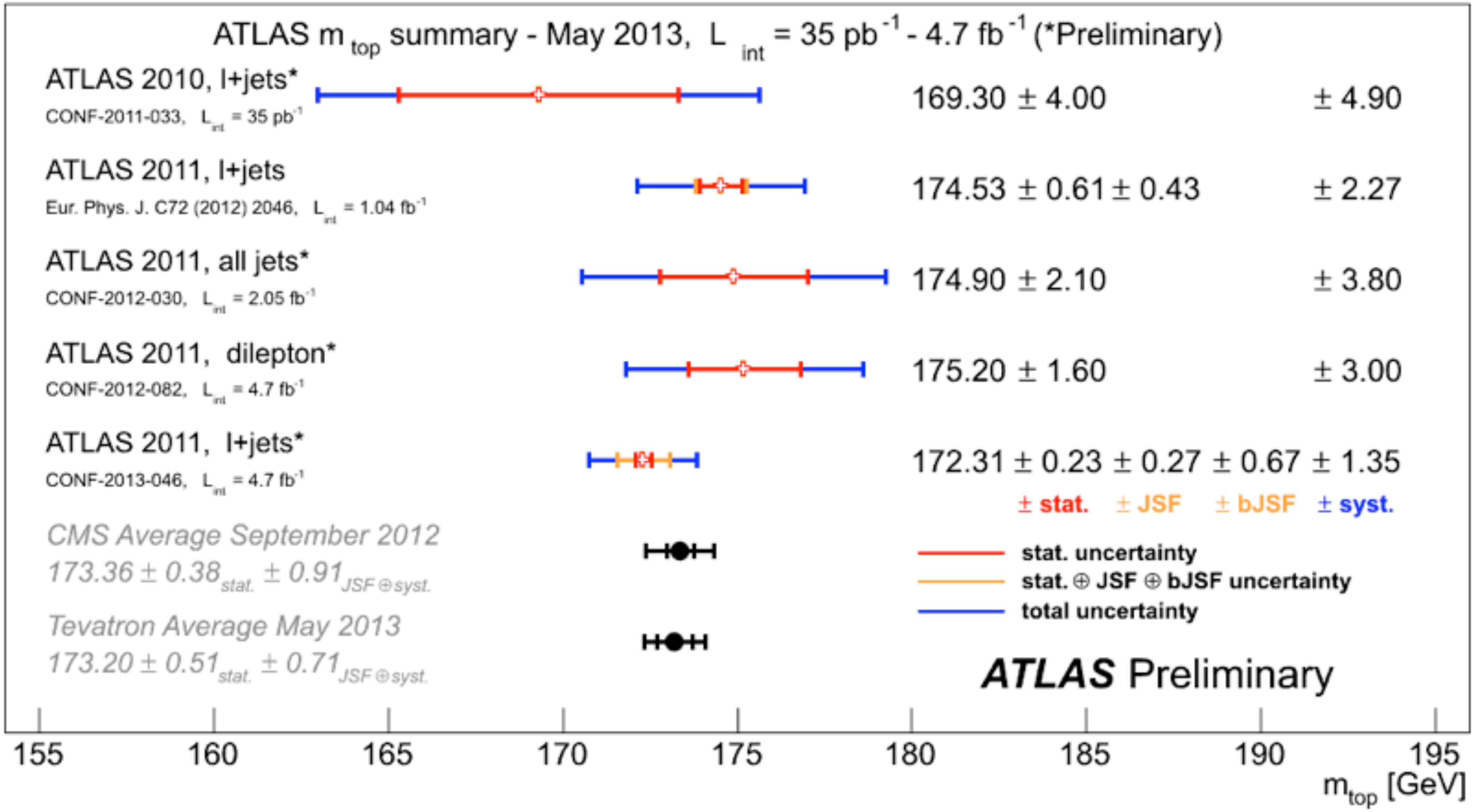


Figure 2: The production and decay of a top quark in (a) perturbation theory, and (b) nonperturbatively.

top quark mass measurements



ATLAS and CMS combined top mass measurement:

m_{top} = 173.3 ± 1.8 GeV [CMS-PAS-TOP-12-001]

Measured mass is the input parameter of the used Monte Carlo

Top reconstruction/tagging

You cant measure what you cant detect

Top physics at LHC systematics limited, not statistics!

Top reconstruction/tagging

You cant measure what you cant detect

Leptonic top reconstruction

Using $m_W^2 = (p_l + p_\nu)^2 = m_l^2 + 2(E_l E_\nu - \vec{p}_l \vec{p}_\nu)$ and $E_i = \sqrt{m_i^2 + \vec{p}_i^2}$

with $\vec{p}_i = (p_{T,i}, p_{Z,i})$ and $m_l = 0$ one obtains

$$p_{Z,\nu} = \frac{\kappa p_{Z,l} \pm \sqrt{\vec{p}_l^2(\kappa^2 - p_{T,l}^2 p_{T,\nu}^2)}}{p_{T,l}^2} \qquad \text{with} \qquad \kappa = \frac{m_W^2}{2} + \vec{p}_{T,l} \cdot p_{\vec{T},\nu}$$

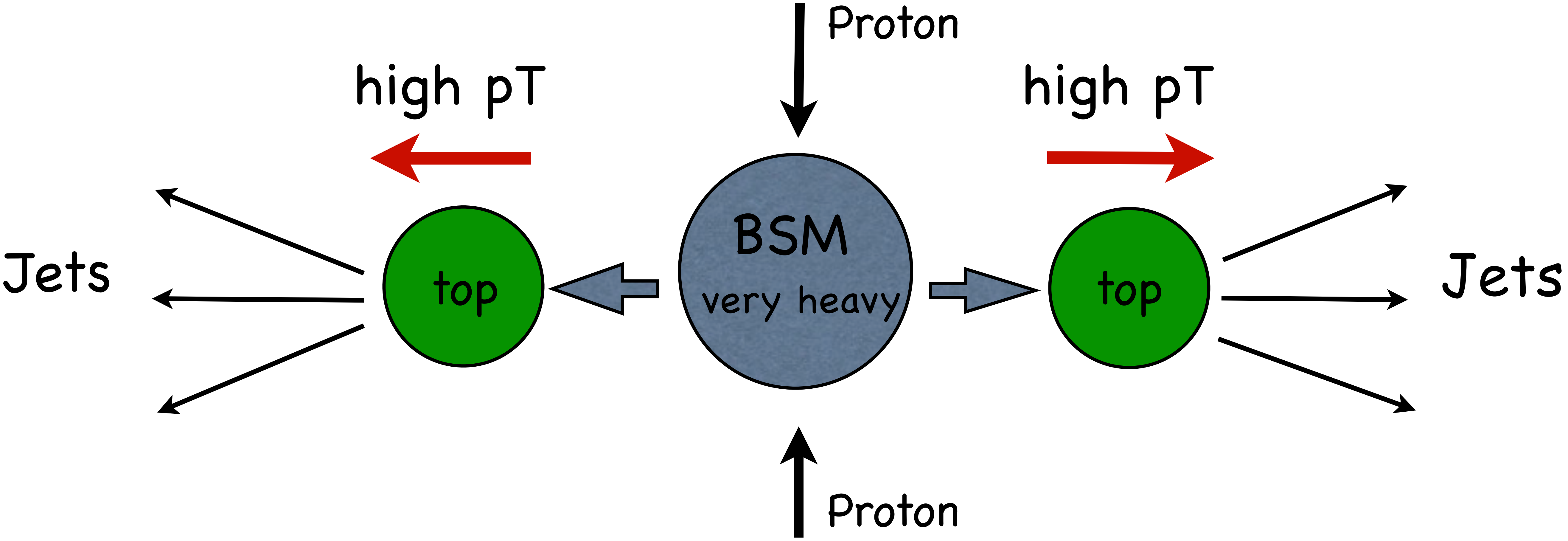
often the solution is chosen which yields the best $m_t^2 = (p_b + p_l + p_\nu)^2$

Hadronic top reconstruction

Often simple χ^2 -fit with $m_W^2 = m_{j_1 j_2}^2$ and $m_t^2 = m_{b,j_1,j_2}^2$

Top reconstruction in boosted final states

In many scenarios where top quarks have to be measured they are produced with large transverse momentum



- Here jet substructure cannot be avoided
- Many reconstruction techniques have been proposed and compared

A brief review of jet physics

At the LHC many sources of radiation:

- Pileup → Can add up to 100 GeV of soft radiation per unit rapidity

[Cacciari, Salam, Sapeta JHEP 1004]

- Underlying Event → $\langle \delta m_j^2 \rangle \simeq \Lambda_{\mathrm{UE}}\, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$ with $\Lambda_{\mathrm{UE}} \sim \mathcal{O}(10)\ \mathrm{GeV}$

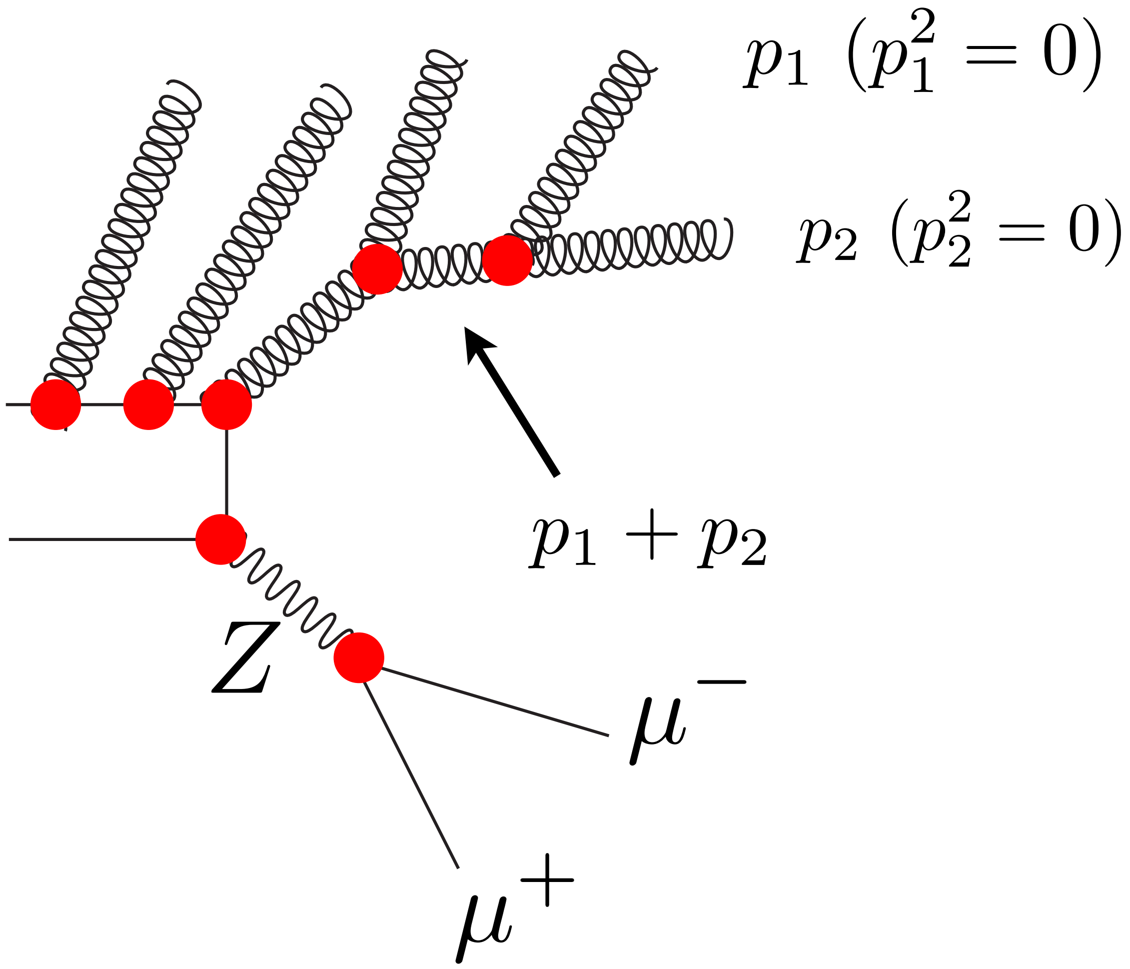
[Dasgupta, Magnea, Salam JHEP 0802]

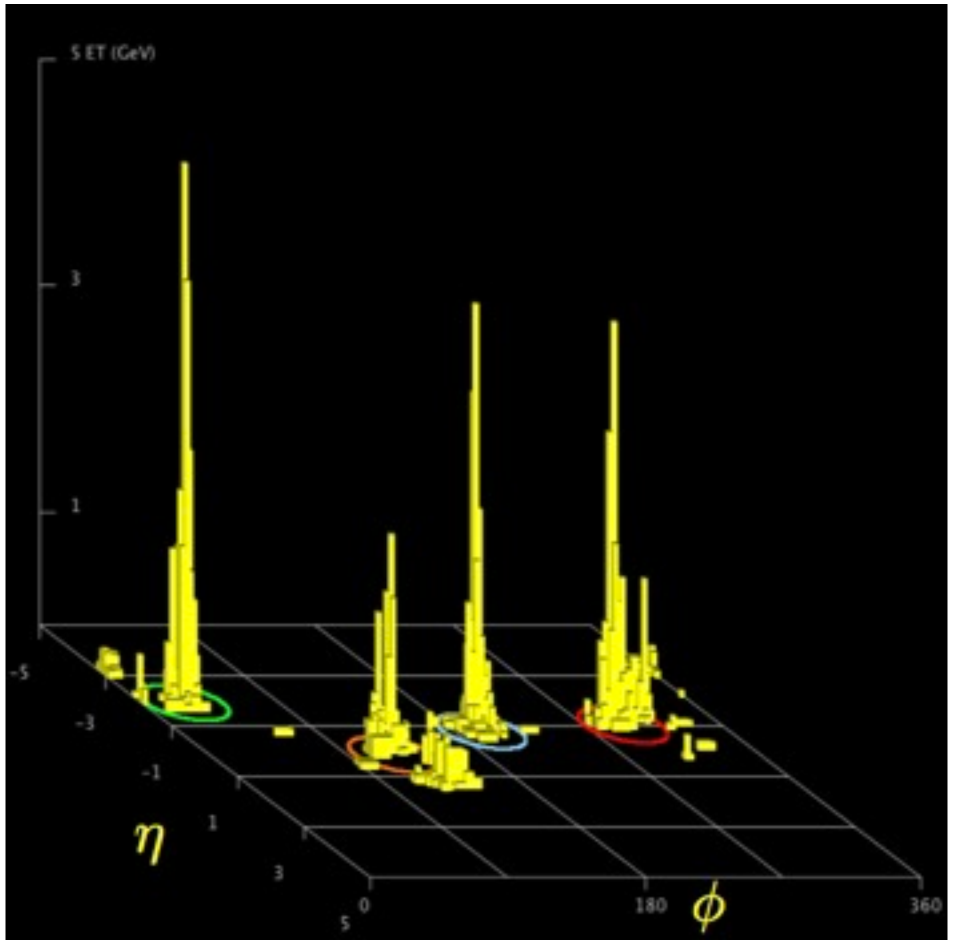
- Initial state radiation (ISR)

- Hard radiation from many resonances in event

→ Need methods to separate final state radiation (FSR) from rest of event

Jets are collimated sprays of hadrons





Probability enhanced in soft and collinear region due to ~ $1/(p_1+p_2)^2$

- If $p_1 \to 0$, then $1/(p_1+p_2)^2 \to \infty$
- If $p_2 \to 0$, then $1/(p_1+p_2)^2 \to \infty$
- If $p_2 \to \lambda p_1$, then $1/(p_1+p_2)^2 \to \infty$

For more detail see also talk by Brian, CP or Dave Soper at CTEQ summer school

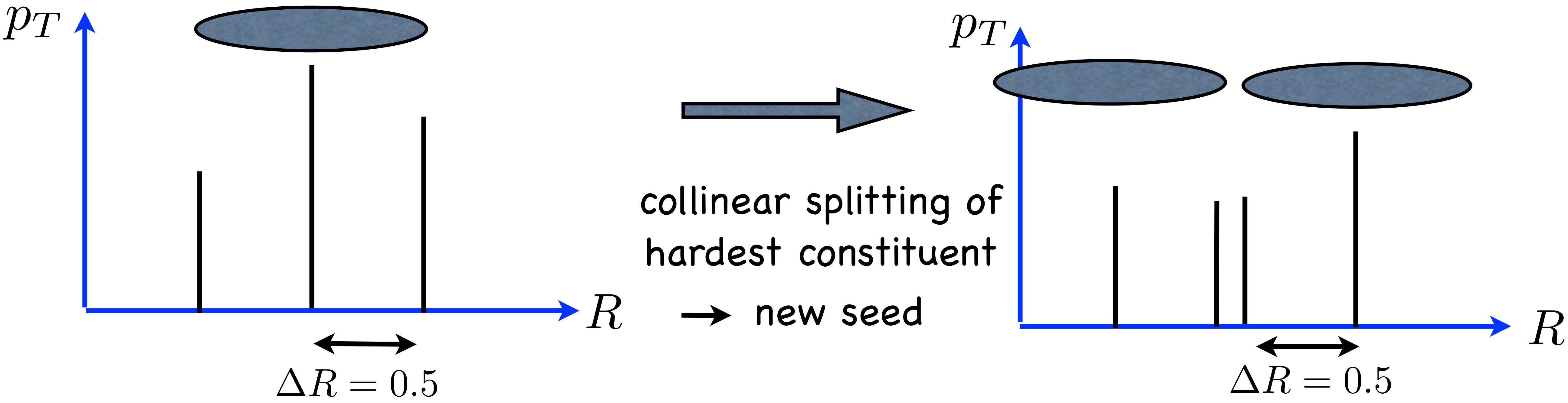
IR safe definition of jets:

Observables must be insensitive to modification of final state
with respect to soft and/or collinear splitting

Seeded cone algorithms are infrared unsafe!

Example: Take the hardest constituent of event as seed for jet cone

Assume 3 constituents in event with cone size R=0.5



collinear splitting of
hardest constituent

→ new seed

1-jet configuration

2-jet configuration

- Sequential recombination, e.g. inclusive kT algorithm

[S.D. Ellis & Soper, '93]
[Catani, Dokshitzer, Seymour Webber '93]

Distance measure

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{Ti}^2$$

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

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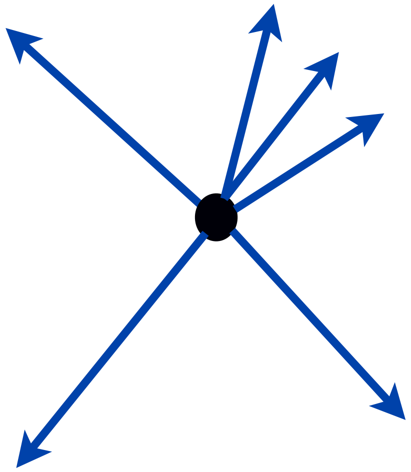

Minimum distance between jets is R

Only number of jets above pt cut is IR safe

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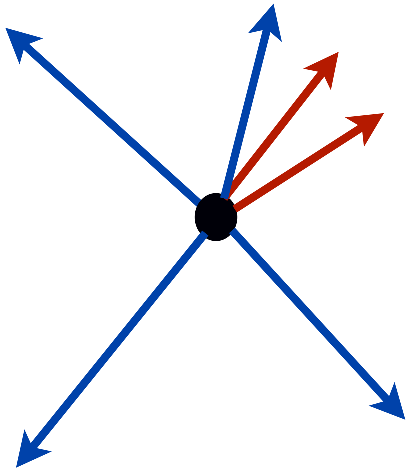

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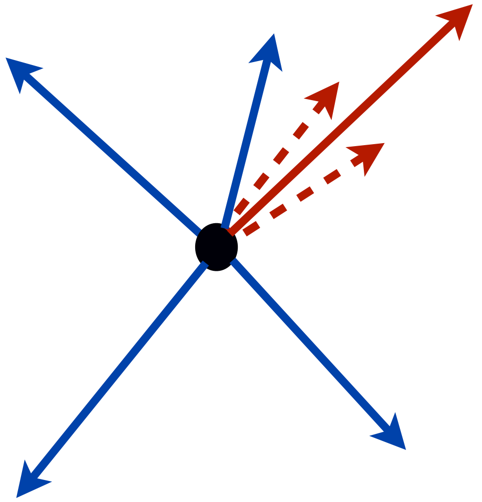

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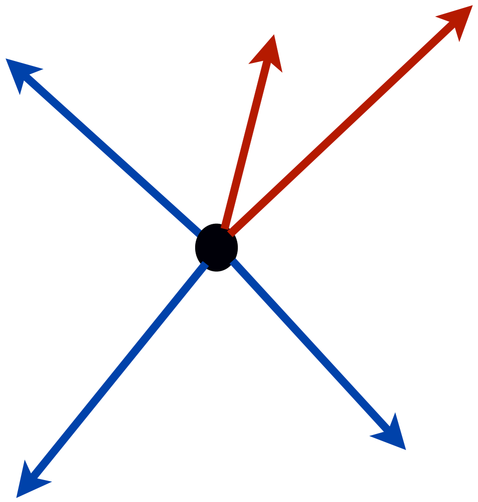

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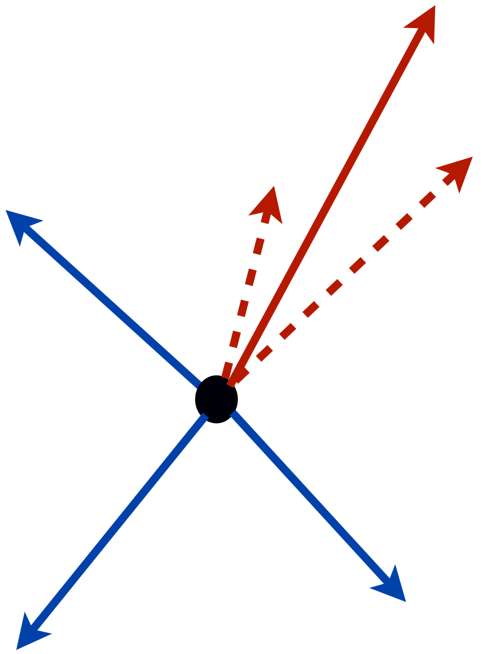

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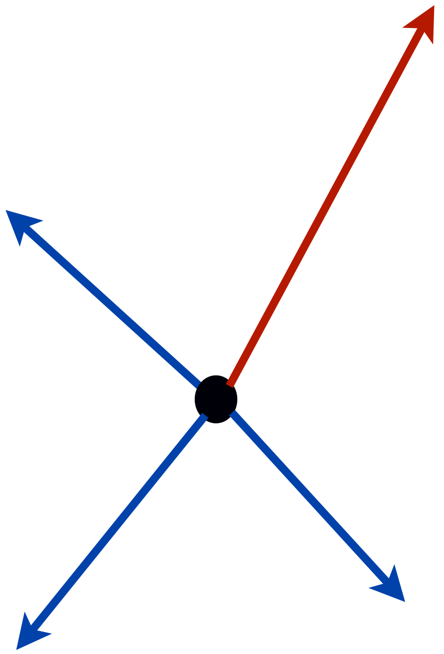

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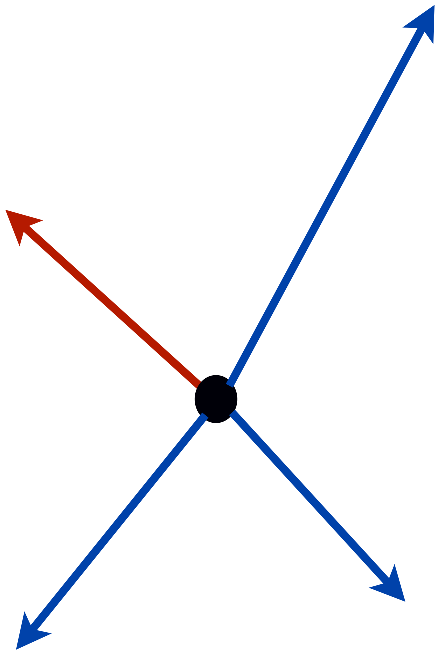

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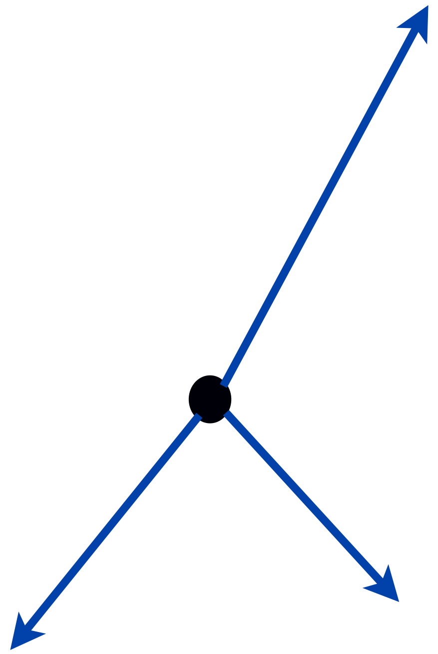

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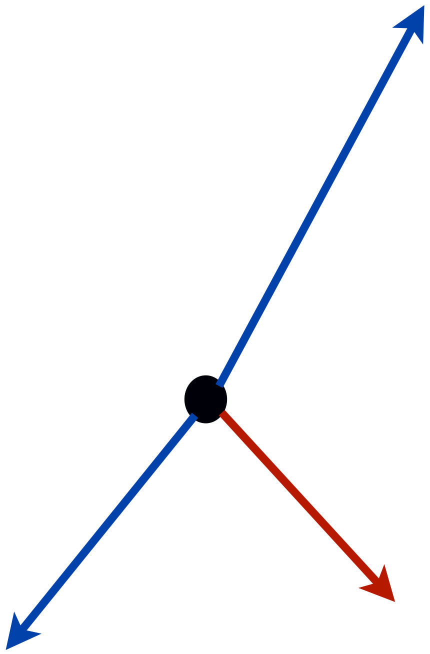

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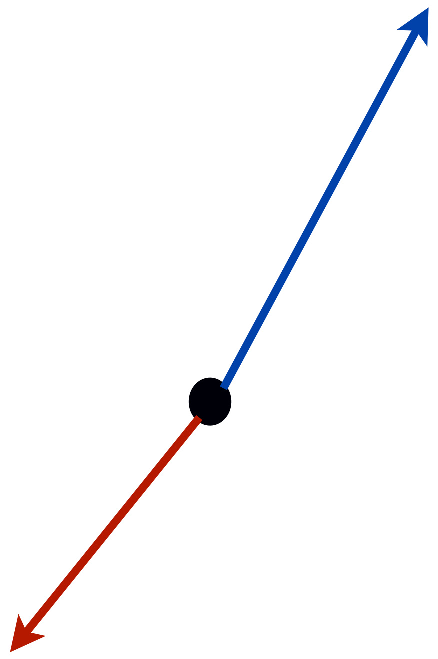

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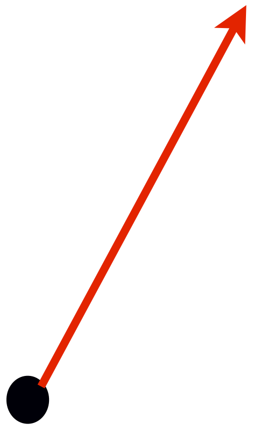

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Found 4 Jets

Minimum distance between jets is R

Only number of jets above pt cut is IR safe

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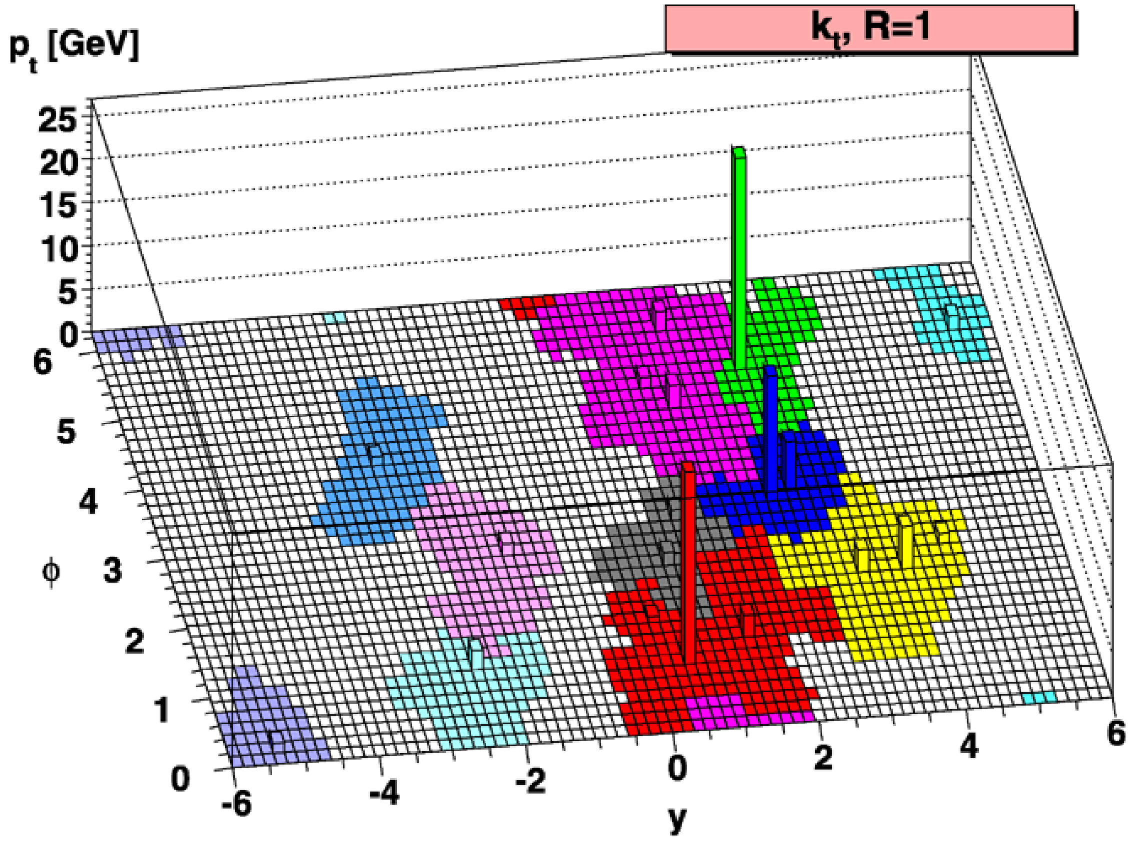
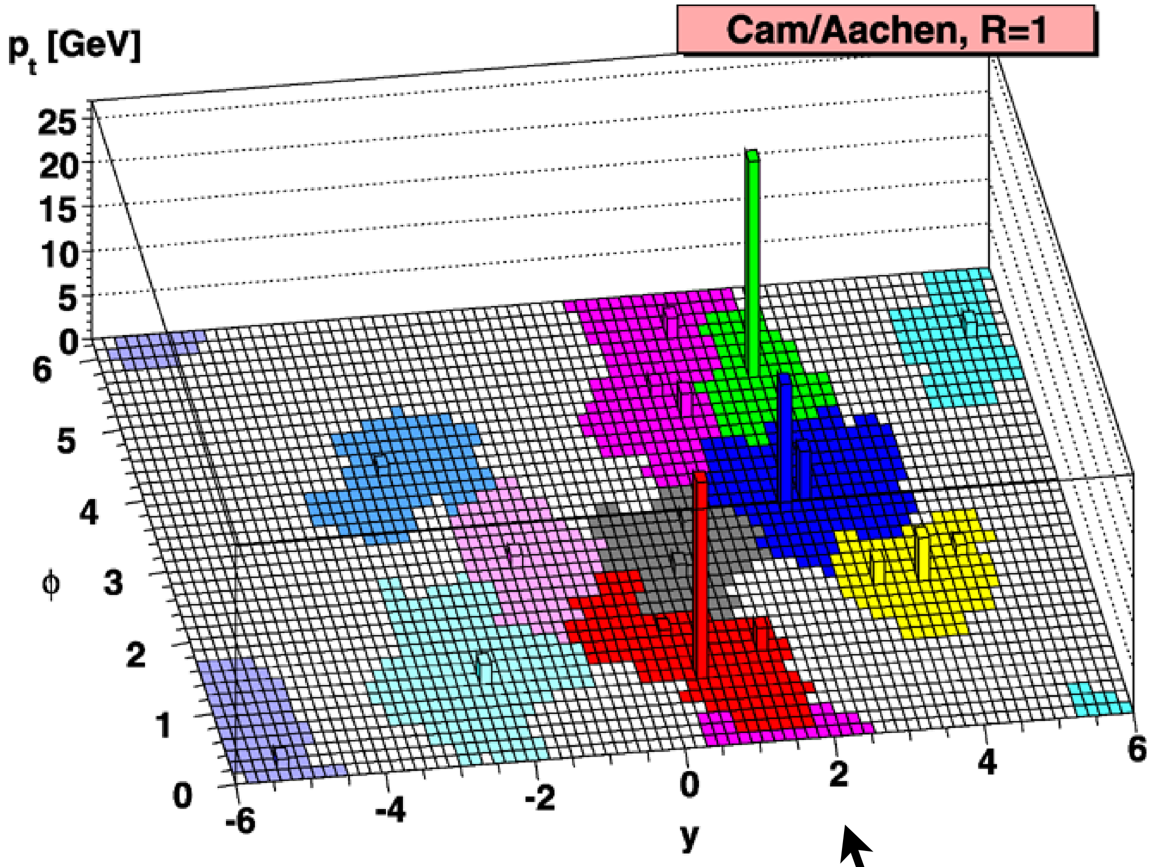
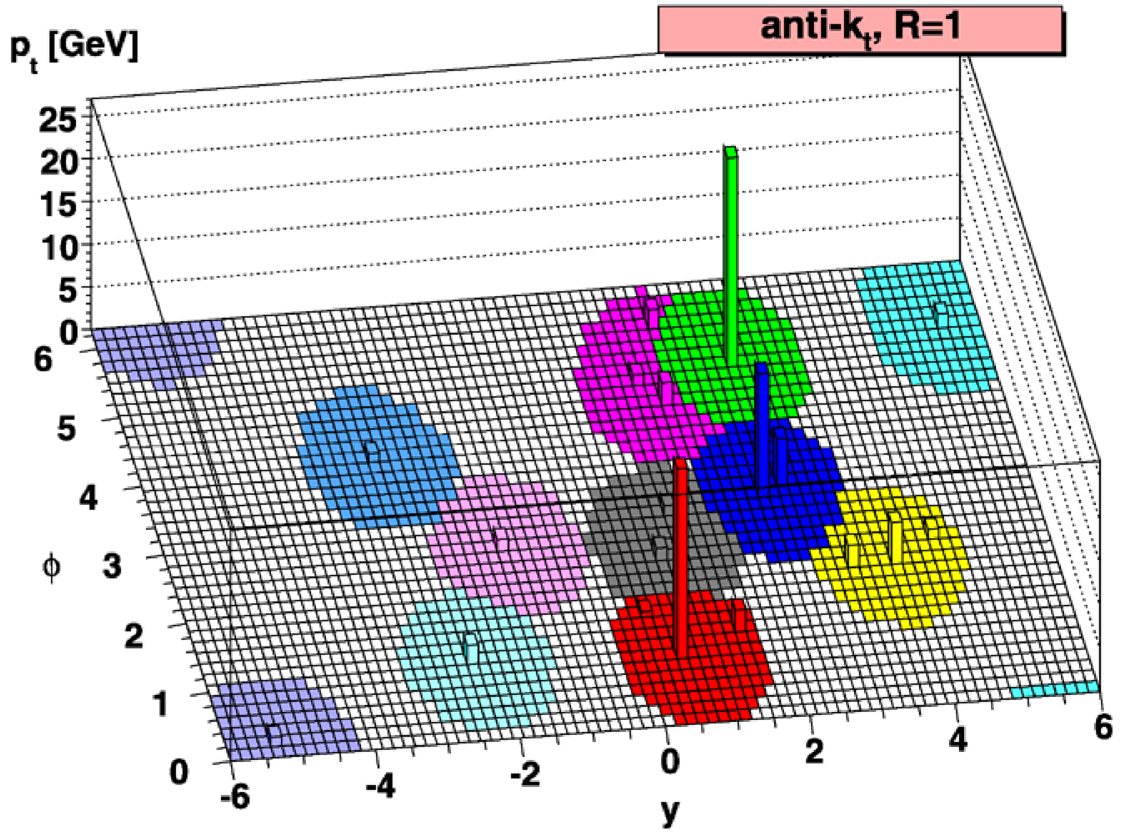
[G. Salam, Towards Jetography]





soft jet
more
circular

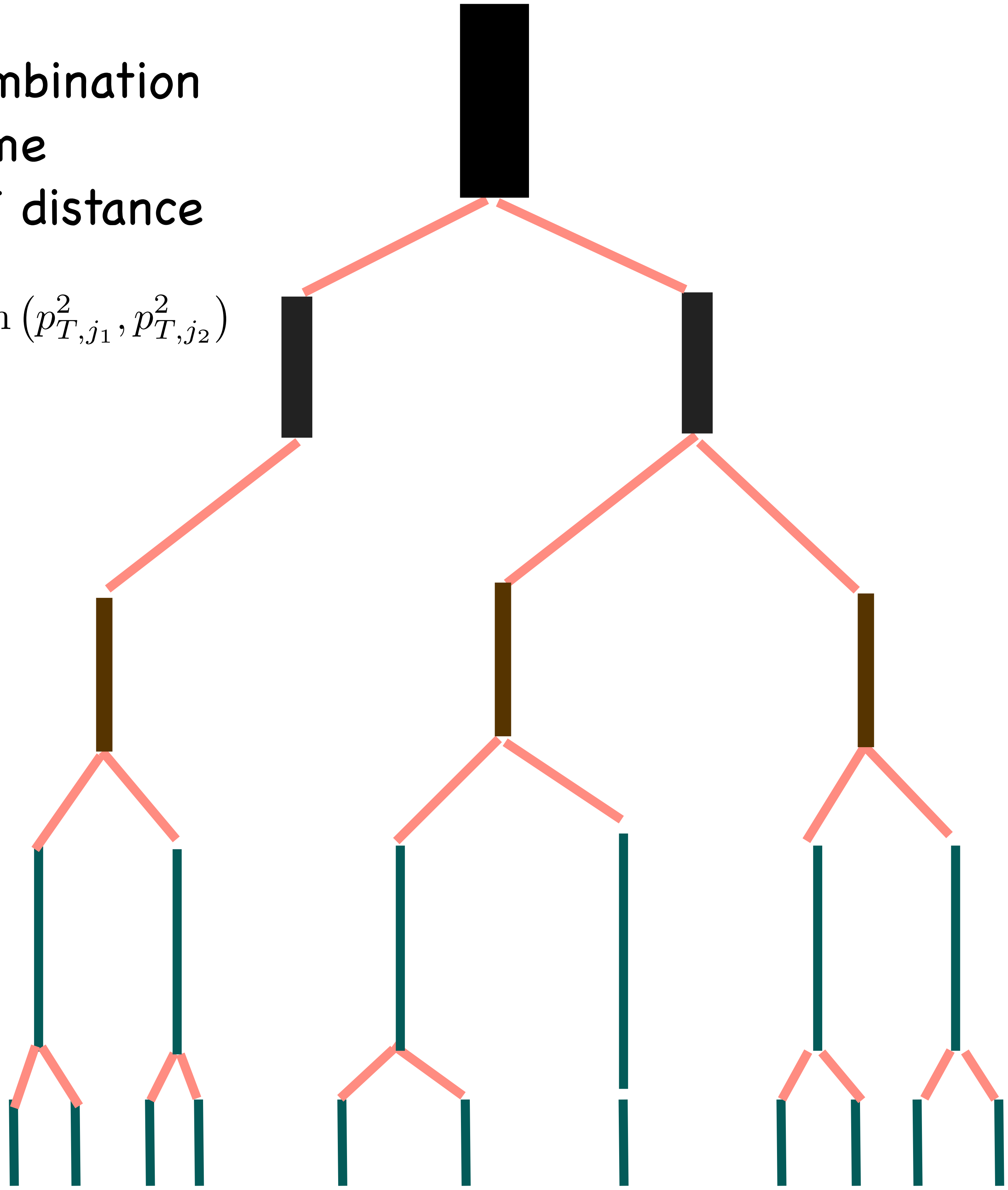
shape independent
of jet pT



hard jet
more
circular

order of recombination
defined by some
metric, e.g. kT distance

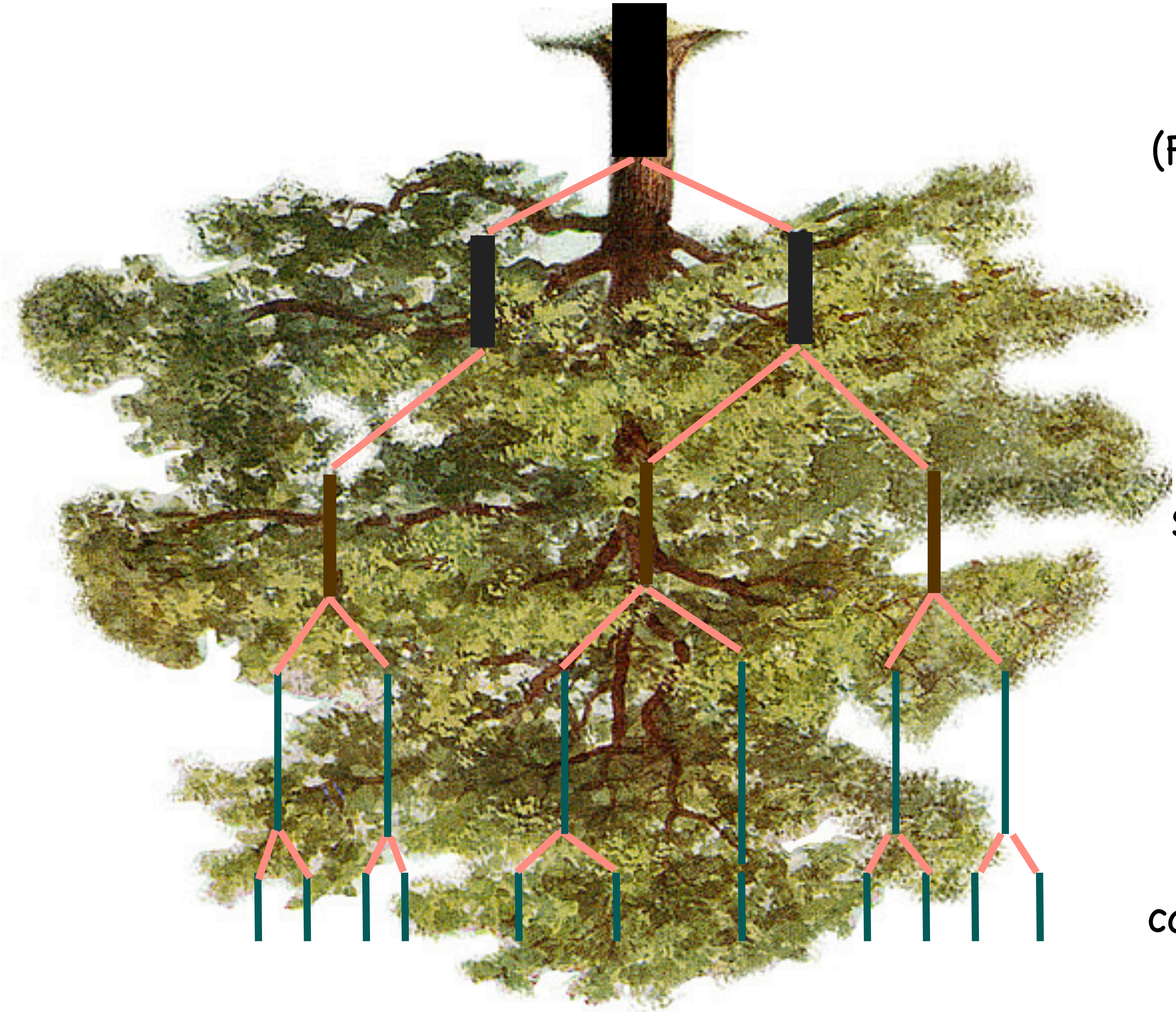
$$d_{j_1 j_2} = \frac{\Delta R^2_{j_1 j_2}}{D^2} \; \min\left(p^2_{T,j_1}, p^2_{T,j_2}\right)$$



(Fat)Jet

Subjets

Jet
constituents



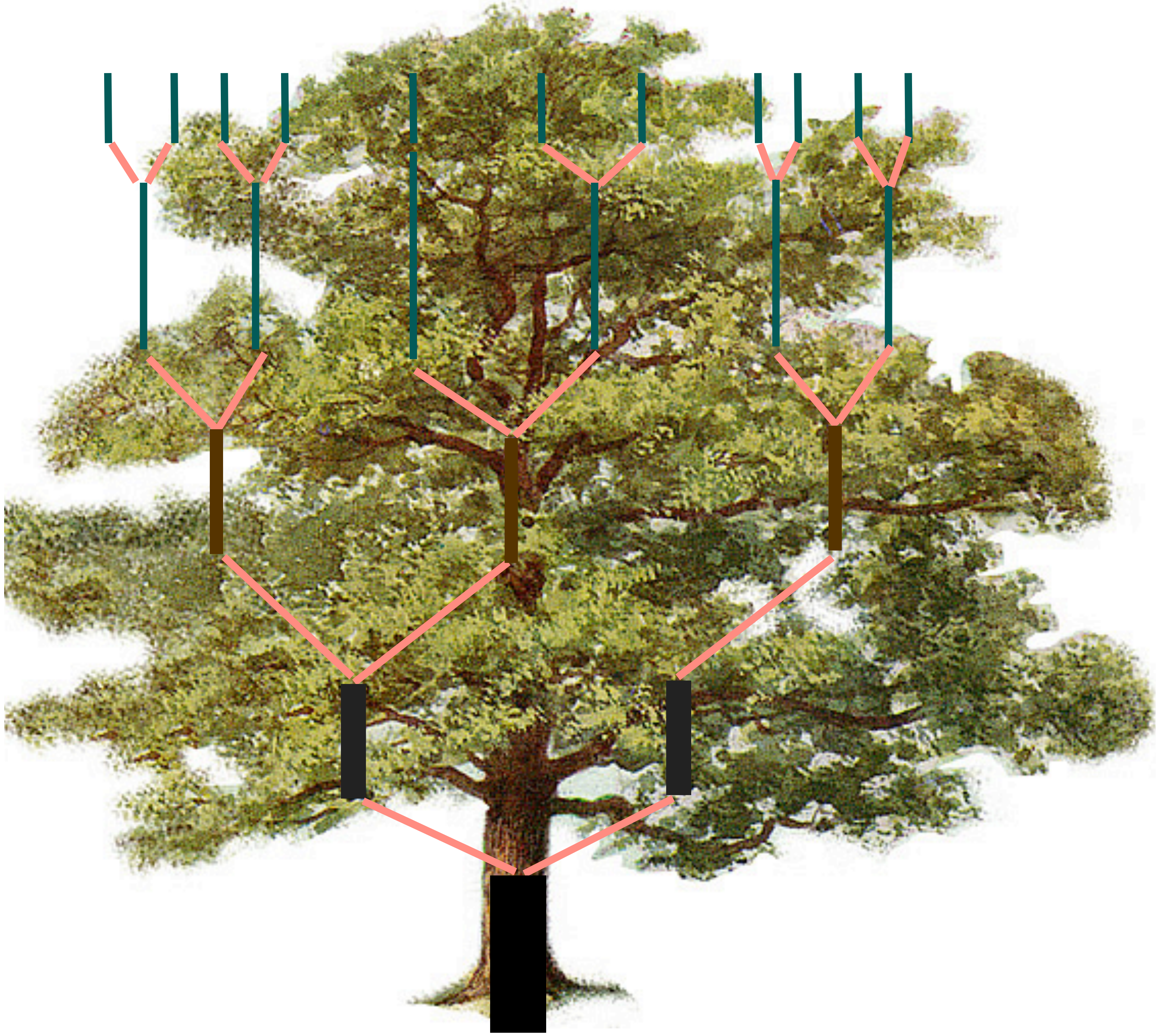
(Fat)Jet

Subjets

Jet
constituents

For jet substructure study reverse cluster history and analyze internal structure

W-boson jet

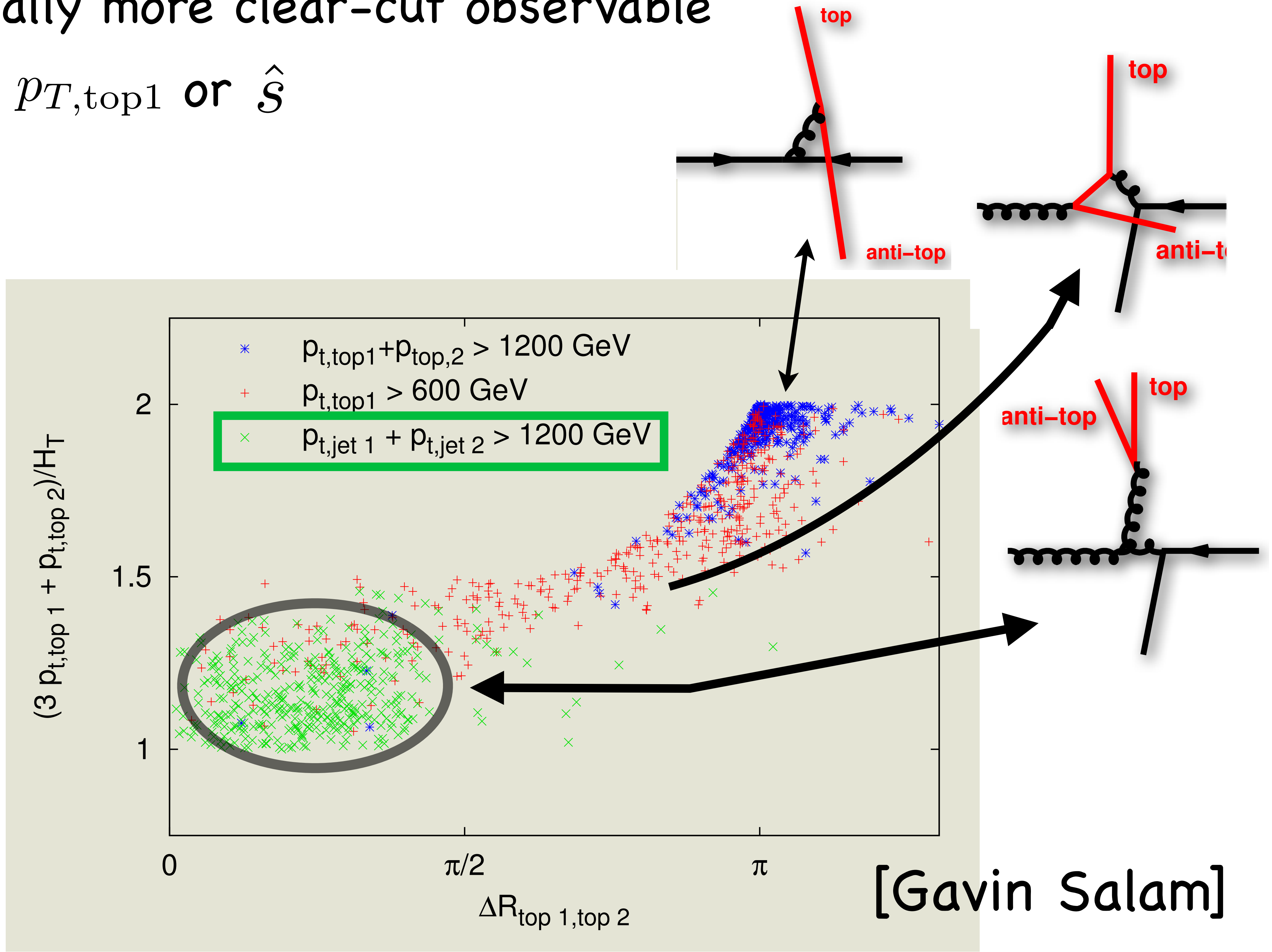


QCD jet

Will choose $m_{t\bar{t}}$ in following for classification

kinematically more clear-cut observable

than say $p_{T,\mathrm{top1}}$ or $\hat{s}$

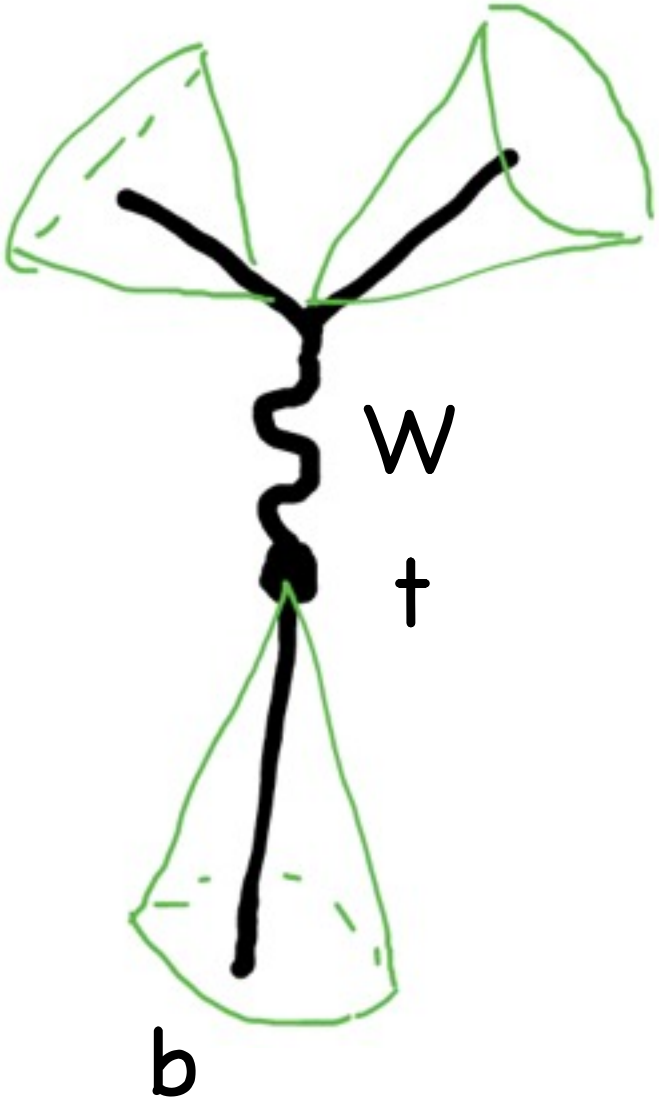


[Gavin Salam]

Different scenarios based on pT vs mass

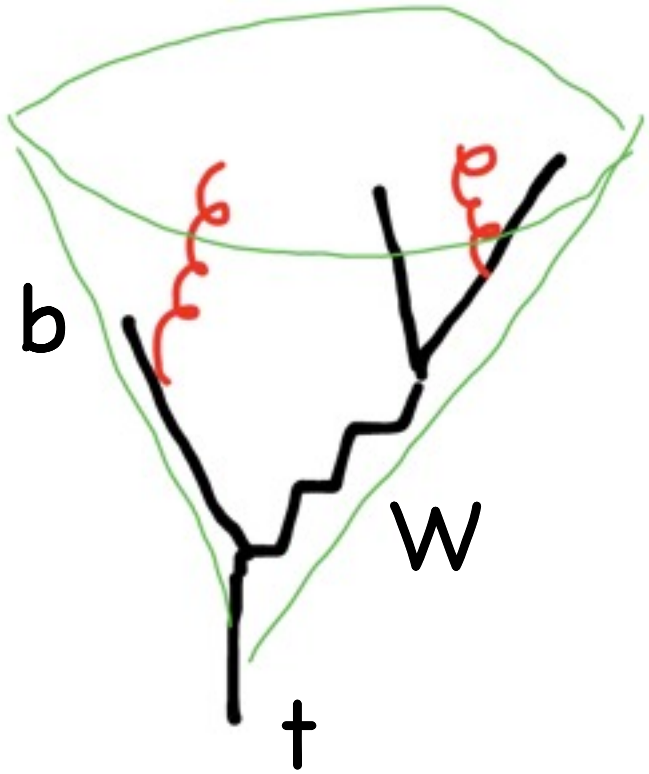
Scenario 1

$$m_{t\bar{t}} \simeq 2\ m_t$$



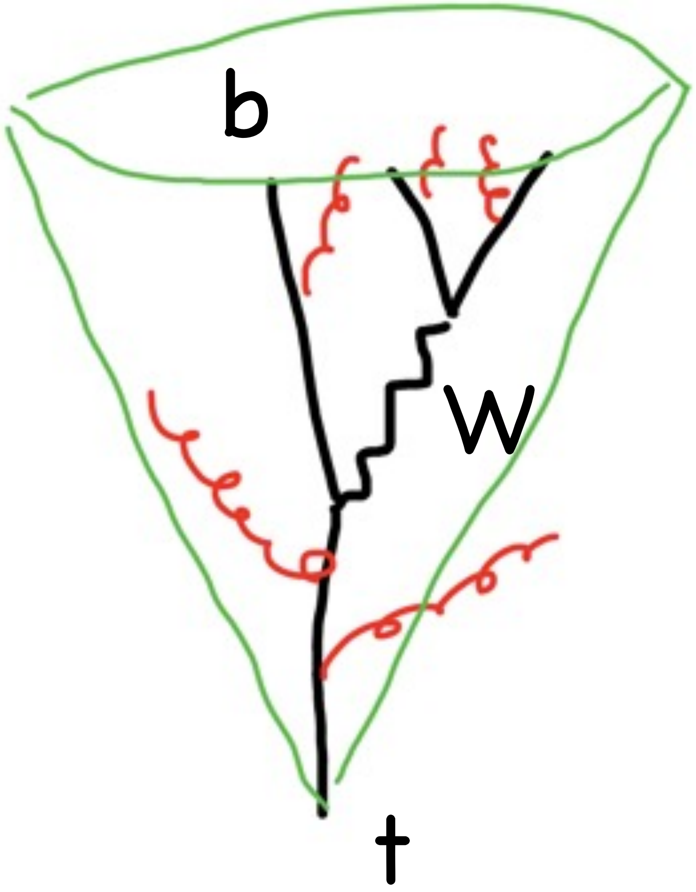
Scenario 2

$$m_{t\bar{t}} > 2\ m_t$$



Scenario 3

$$m_{t\bar{t}} \gg 2\ m_t$$



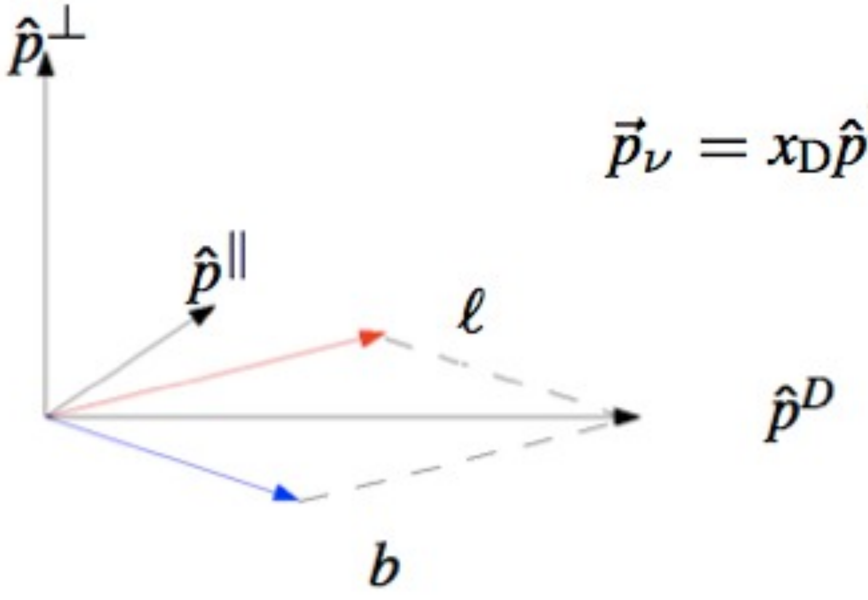
Leptonic top reconstruction in boosted final states

Due to reconstruction of invariant masses in boosted and unboosted case very similar: $m_t^2 = (p_b + p_l + p_\nu)^2$ and $m_W^2 = (p_l + p_\nu)^2$

However, for large boost lepton isolation a problem.
Define mini-isolation criterium [Rehermann, Tweedie JHEP]

$$R_{iso} = \frac{15\ \mathrm{GeV}}{p_{T\mu}} \simeq \frac{3m_B}{p_{T\mu}}$$

In boosted final states it is even possible to "guess" the full neutrino momentum [Plehn, MS, Takeuchi JHEP]



$$\vec{p}_\nu = x_{\mathrm{D}}\hat{p}^{\mathrm{D}} + x_{||}\hat{p}^{||} + x_\perp \hat{p}^\perp$$

2 assumptions:

$x_{||} = 0$ or $x_\perp = 0$

↕

good top momentum reconstruction

Hadronic top reconstruction: Many approaches

top taggers:

y-splitter Top Tagger	[Butterworth, Cox, Forshaw PRD 55 (2002)] [Broijmans ATL-COM-PHYS-2008-001]
energy flow	[Thaler, Wang JHEP 0807]
Johns Hopkins Tagger	[Kaplan, et al. PRL 101 (2008)]
Pruning	[Ellis, Vermilion, Walsh PRD 80 (2009)]
HEP Top Tagger	[Plehn, MS, Takeushi, Zerwas JHEP 1010]
tree-less approach	[Jankowiak, Larkoski JHEP 1106]
Template method	[Almeida et al. PRD 82 (2010)]
N-subjettiness	[Kim PRD 83 (2011)] [Thaler, Van Tilburg JHEP 1103]
Shower deconstruction	[Soper, MS PRD 84; PRD 87]
Qjets	[Ellis, Hornig, Roy, Krohn, Schwartz PRL 108]

Tagger important to purify final state
-> bridge gab between parton and hadron level

Comparison of taggers in BOOST proceedings:

Taggers compared:

- ATLAS
- CMS
- HEP
- JH
- NSubjettiness
- Pruning-Tagger
- Thaler/Wang Tagger
- Trimming-Tagger

Samples used:

fully hadronic tt vs dijet events
in pT slices of 100 GeV

- Herwig 6.5
- Herwig++
- Sherpa incl. matching

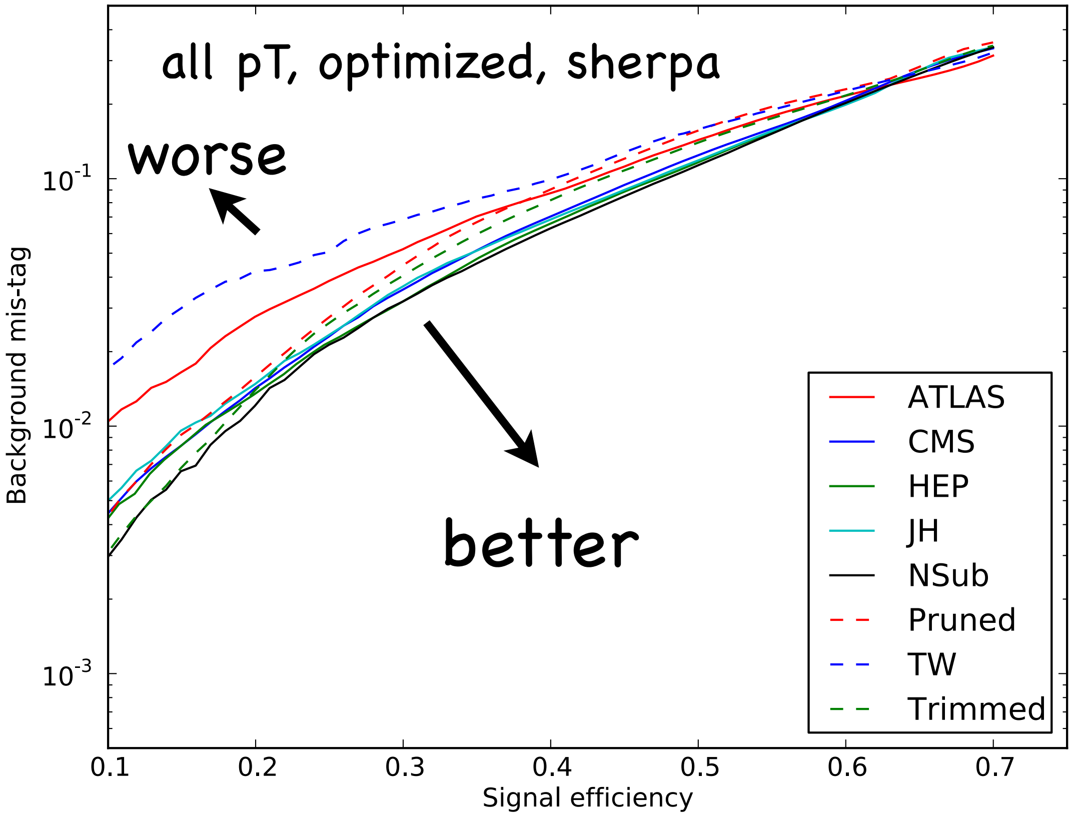
Event selection cuts:

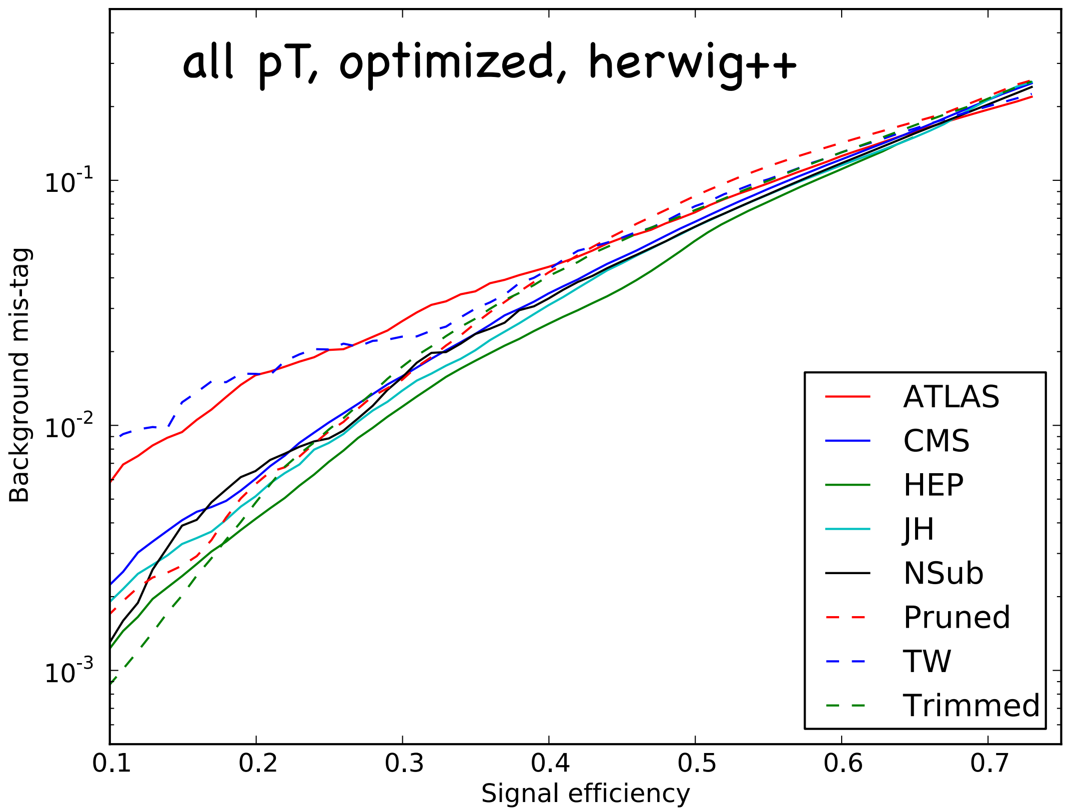
anti-kT jets with R=1.0, pT > 200 GeV

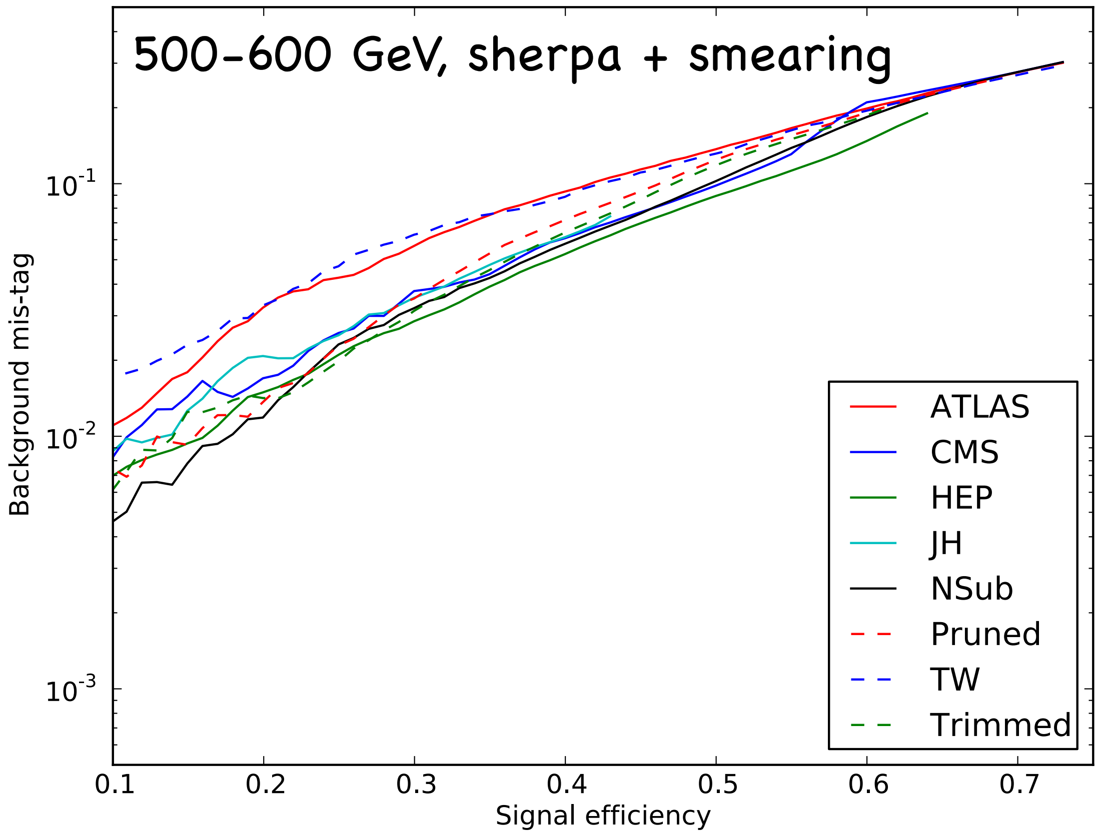
Efficiency:

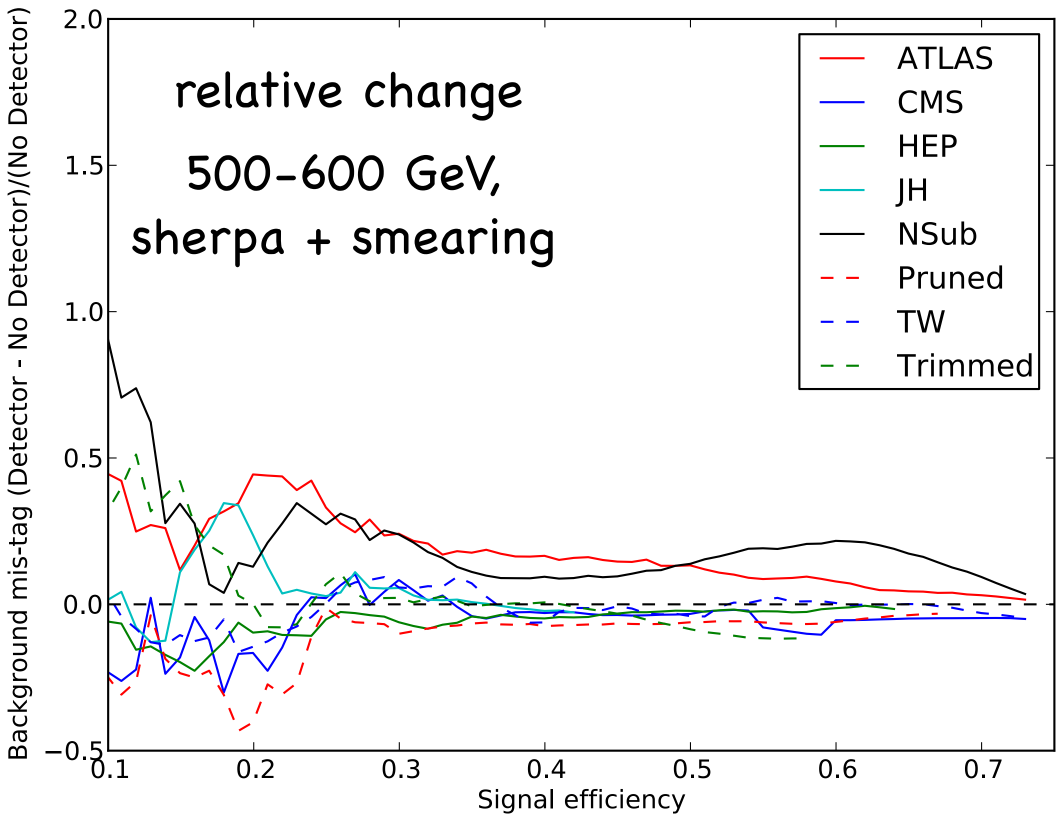
tagged jets / # jets after selection cuts

Comparison of top taggers (BOOST 2012 proceedings)





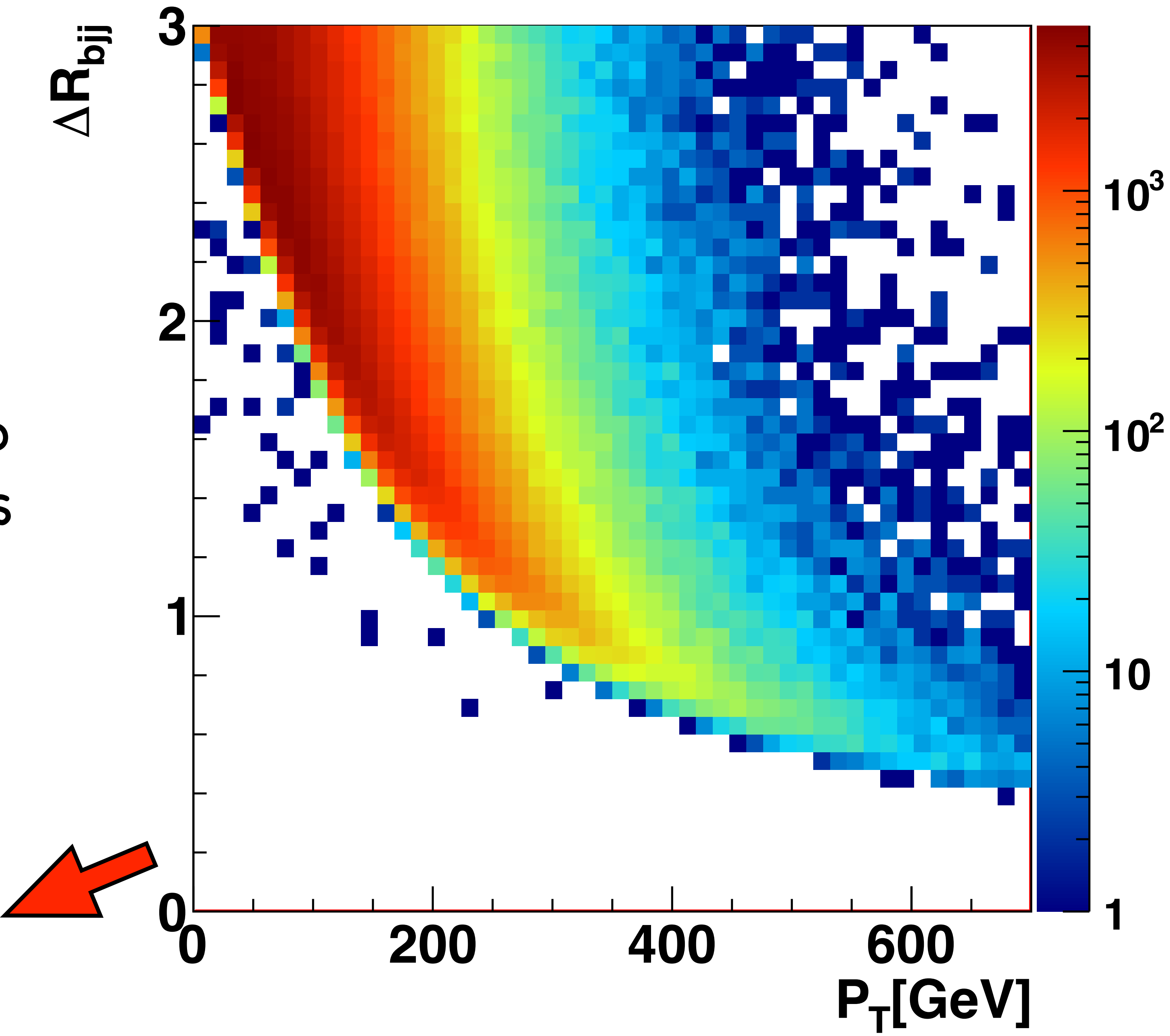




Angular separation of boosted top's decay products in 14 TeV ttbar samples

Maximum distance of top decay products

Need large cone if you want to do top tagging



top transverse momentum

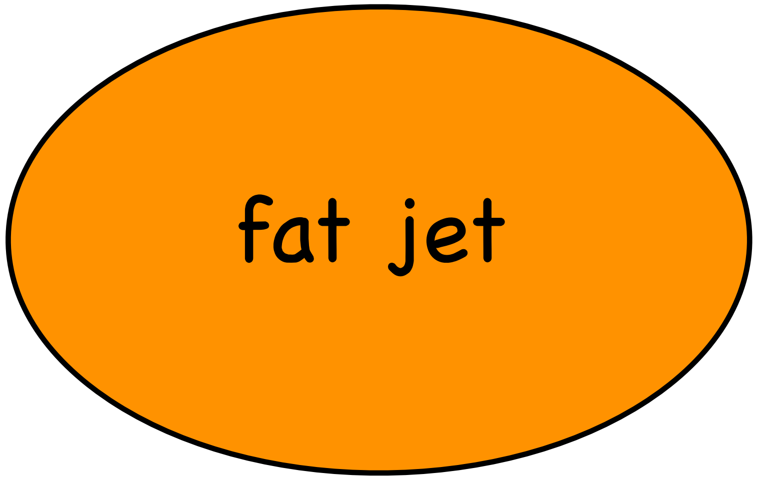
How does the HEPTopTagger work?

[Plehn, Salam, MS, Takeuchi]

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{\mathrm{daughter}_1} < 0.8\, m_{\mathrm{mother}}$ to keep both daughters



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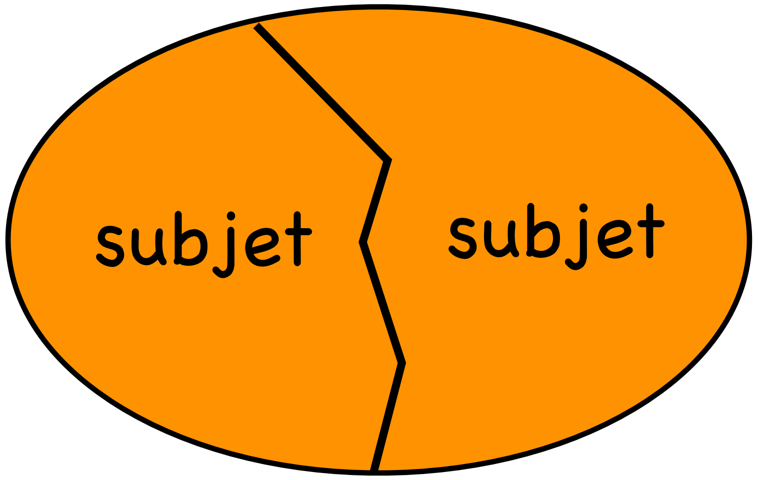

How does the HEPTopTagger work?

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

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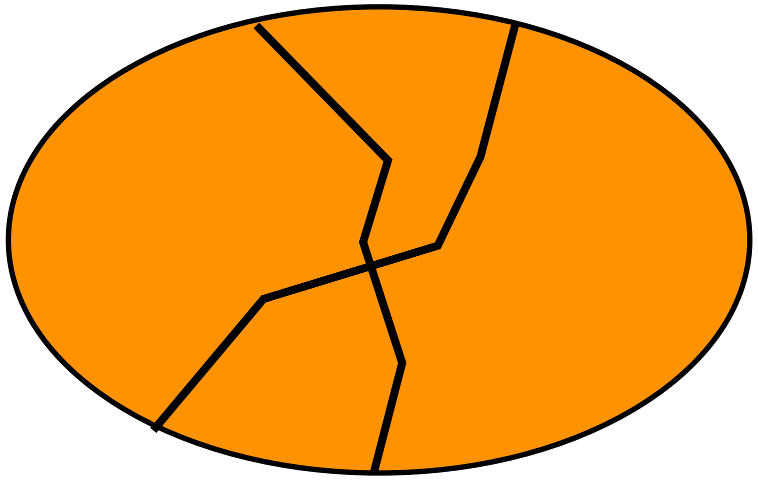

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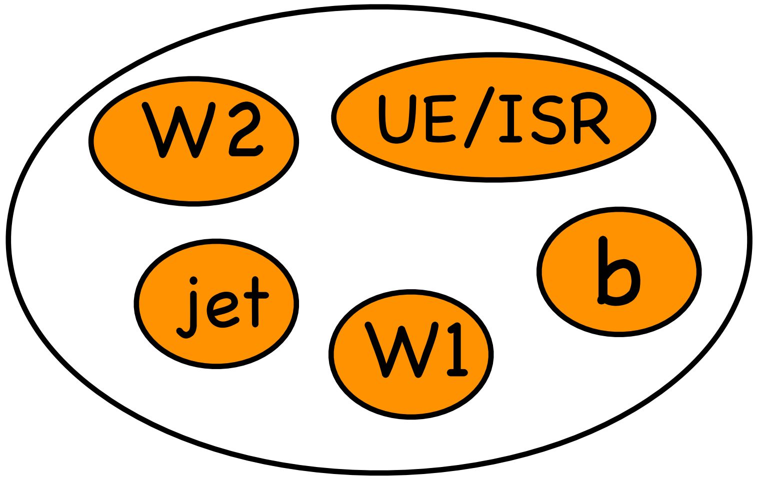

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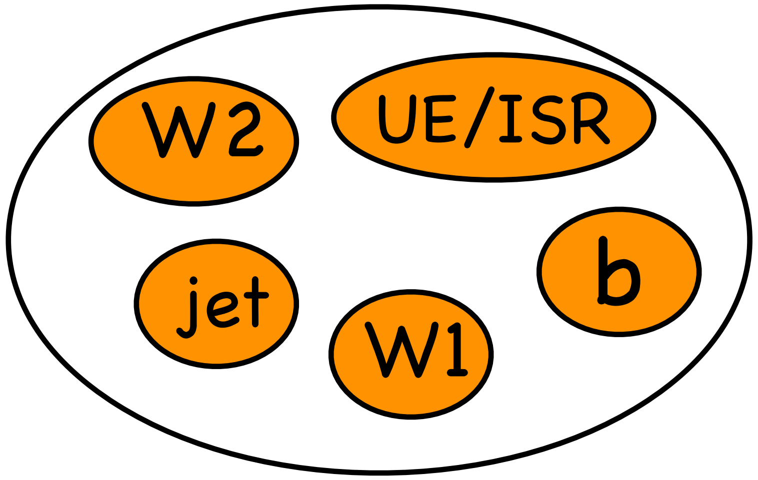
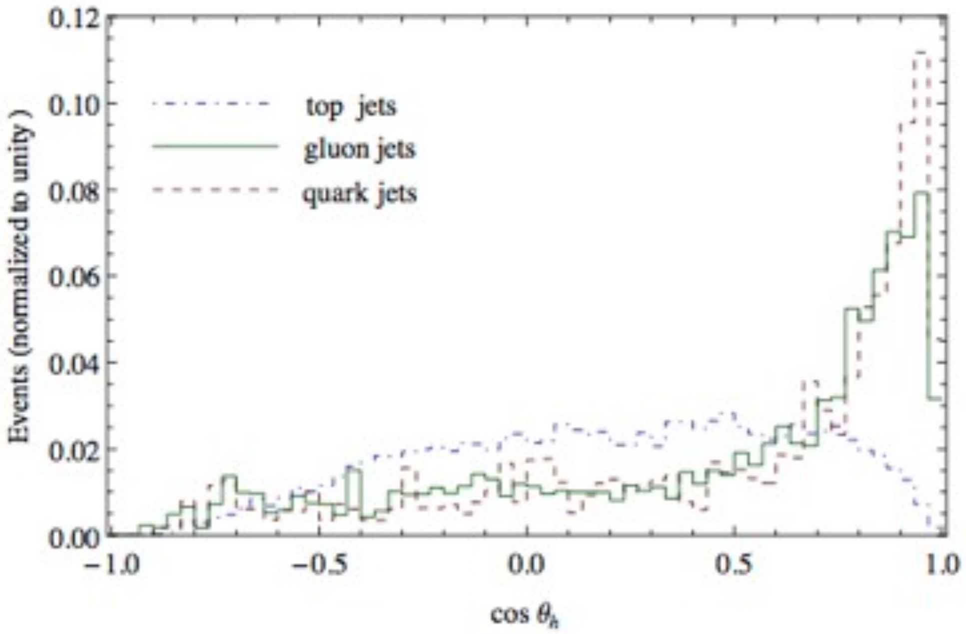


IV.0 Like JH Tagger take, mtop, mW and W helicity angle

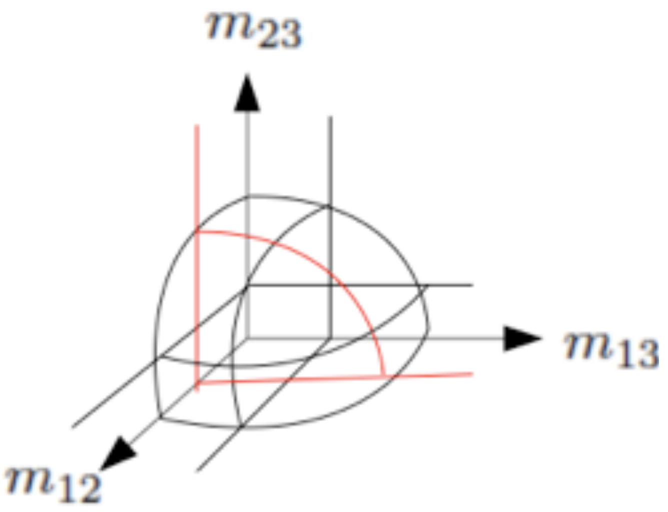
[Kaplan, et al. PRL 101 (2008)]



IV.1 - better - check mass ratios

Cluster top candidate into 3 subjets j_1, j_2, j_3

$$m_t^2 \equiv m_{123}^2 = (p_1+p_2+p_3)^2 = (p_1+p_2)^2 + (p_1+p_3)^2 + (p_2+p_3)^2 = m_{12}^2 + m_{13}^2 + m_{23}^2$$



$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max} \quad \text{and} \quad 0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

$$R_{\min}^2 \left(1 + \left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1 - \left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2 \left(1 + \left(\frac{m_{13}}{m_{12}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$

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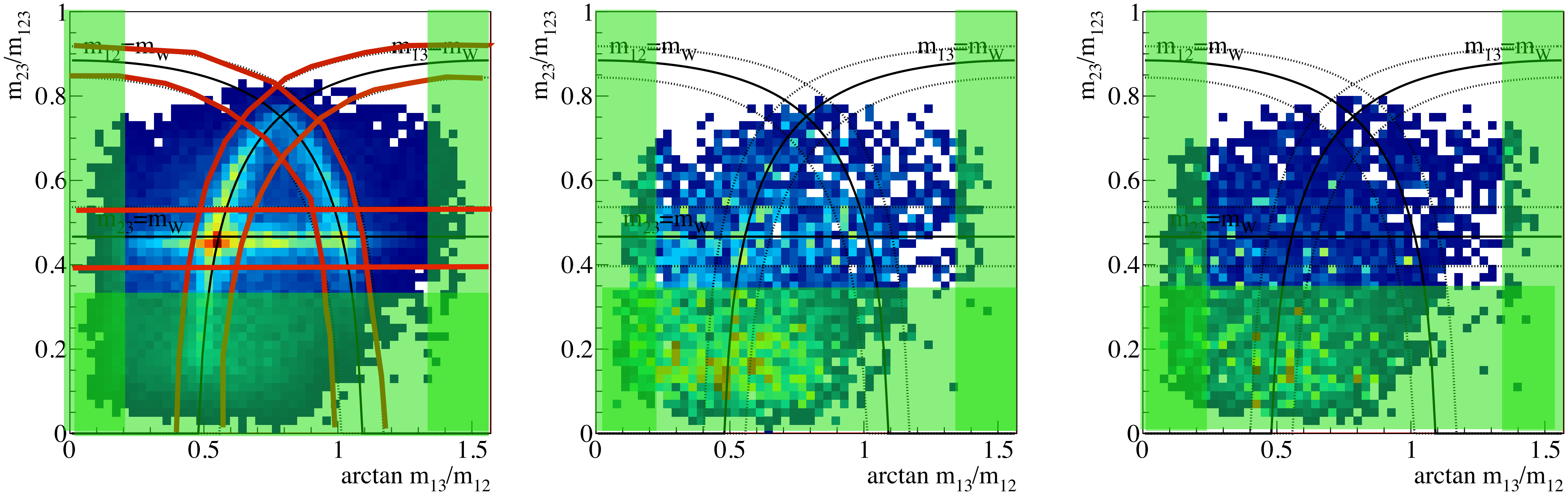
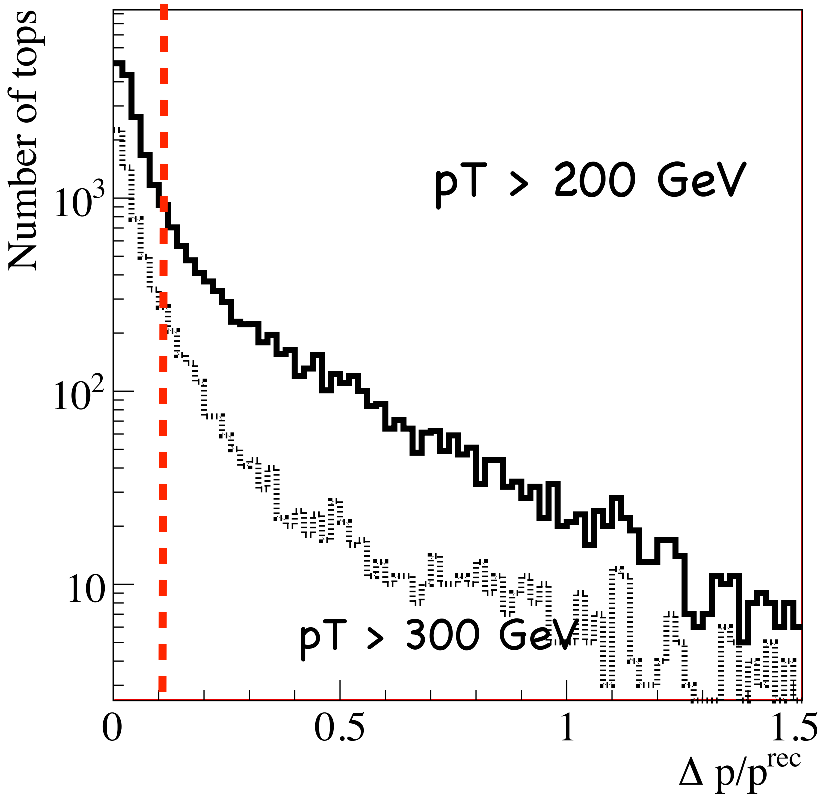
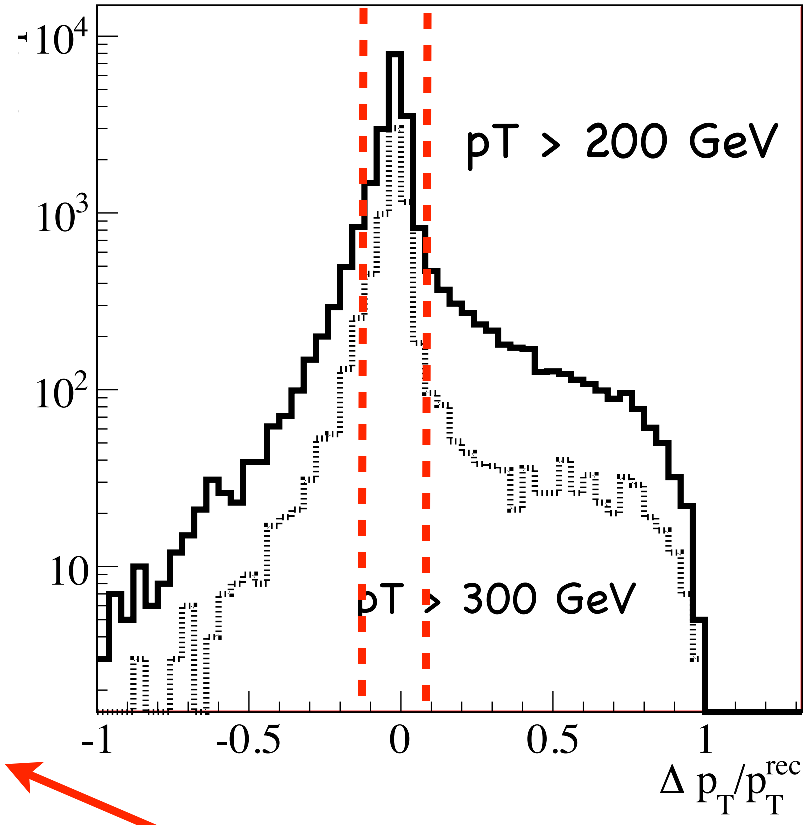
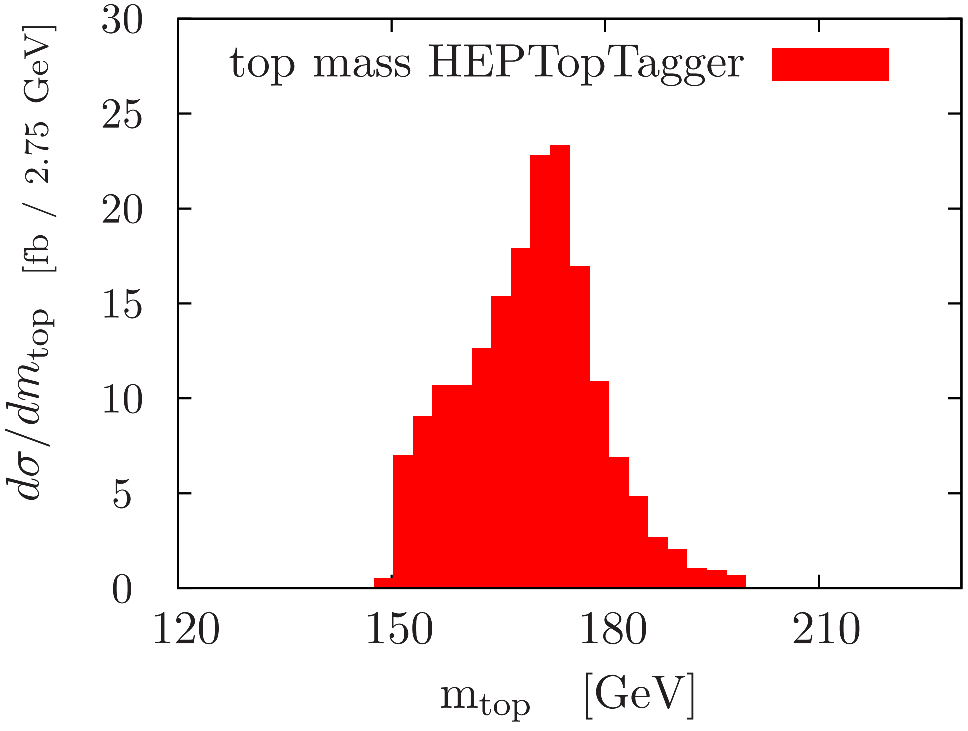
$$R_{\min} = 85\% \times m_W/m_t \qquad R_{\max} = 115\% \times m_W/m_t$$

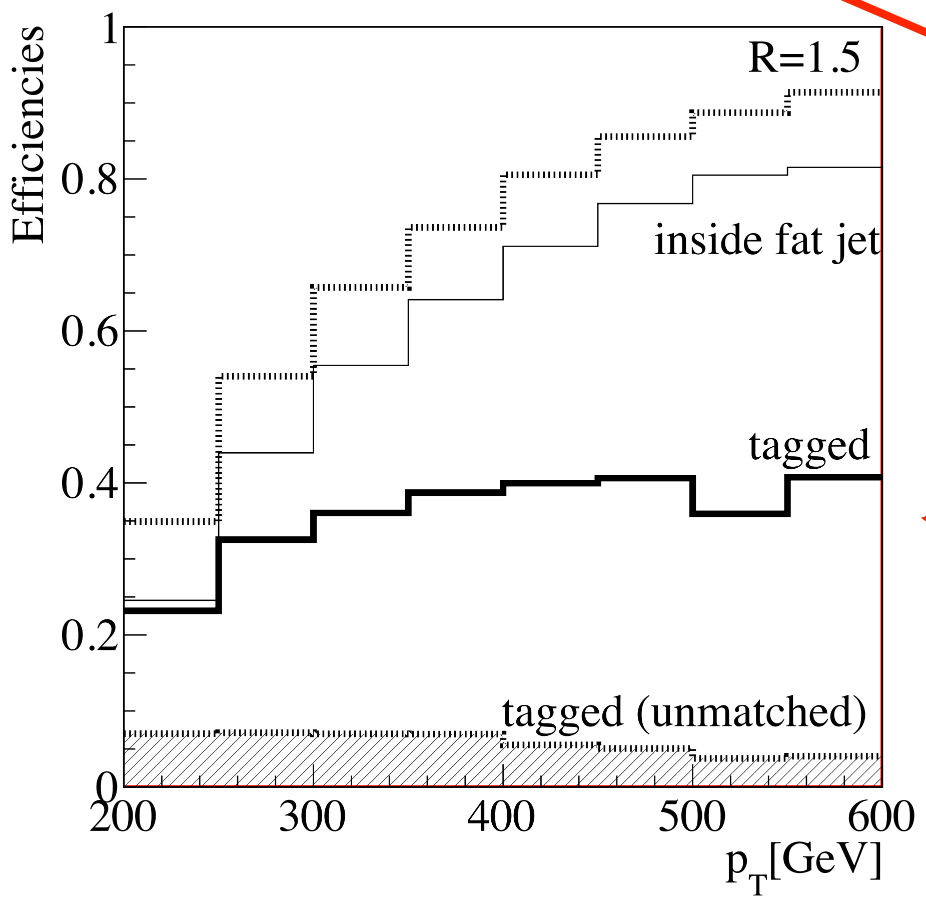


Top quark momentum reconstruction







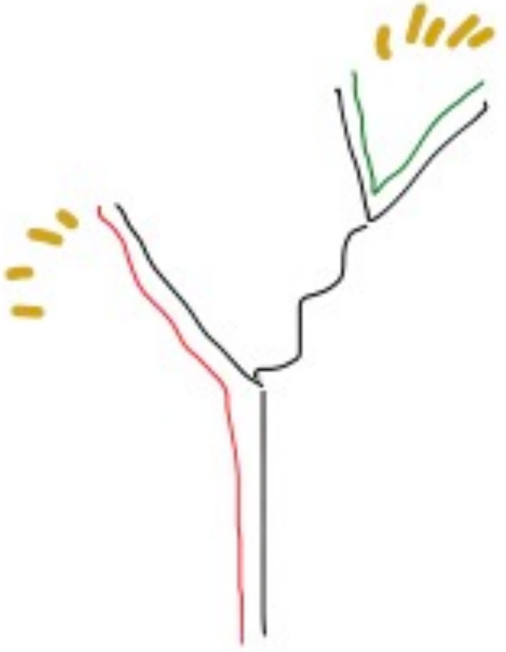


- Great reconstruction of top quark momentum
- 35% tagging efficiency
  2% W+jets fake rate

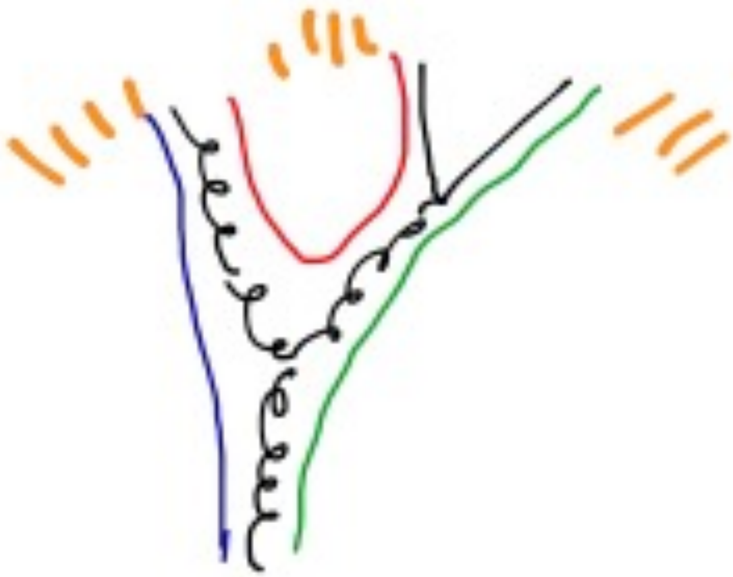
First generation taggers, e.g. Hopkins, CMS, HEP

make use of many properties of the top for reconstruction (top mass, W mass, EW structure of decay)

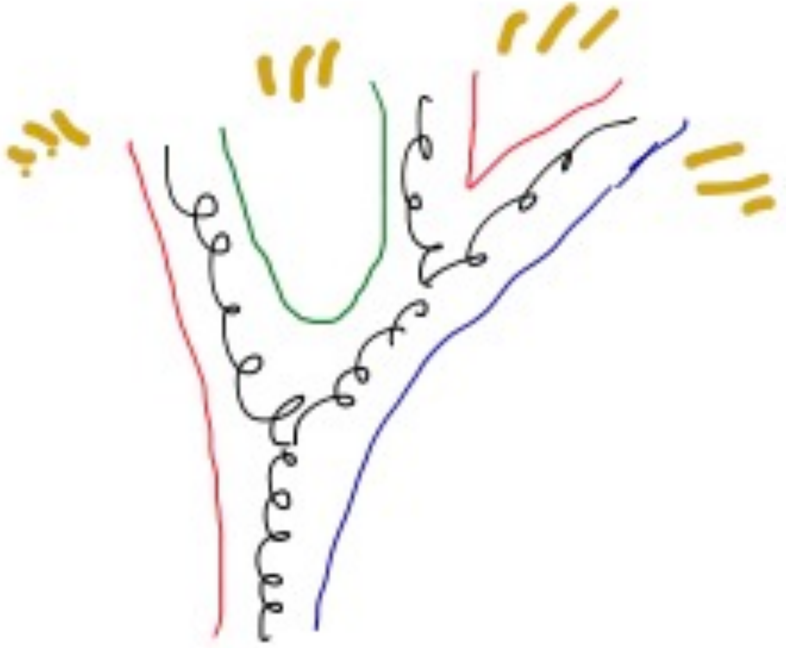
However, QCD radiation pattern are left mostly aside.



top



QCD

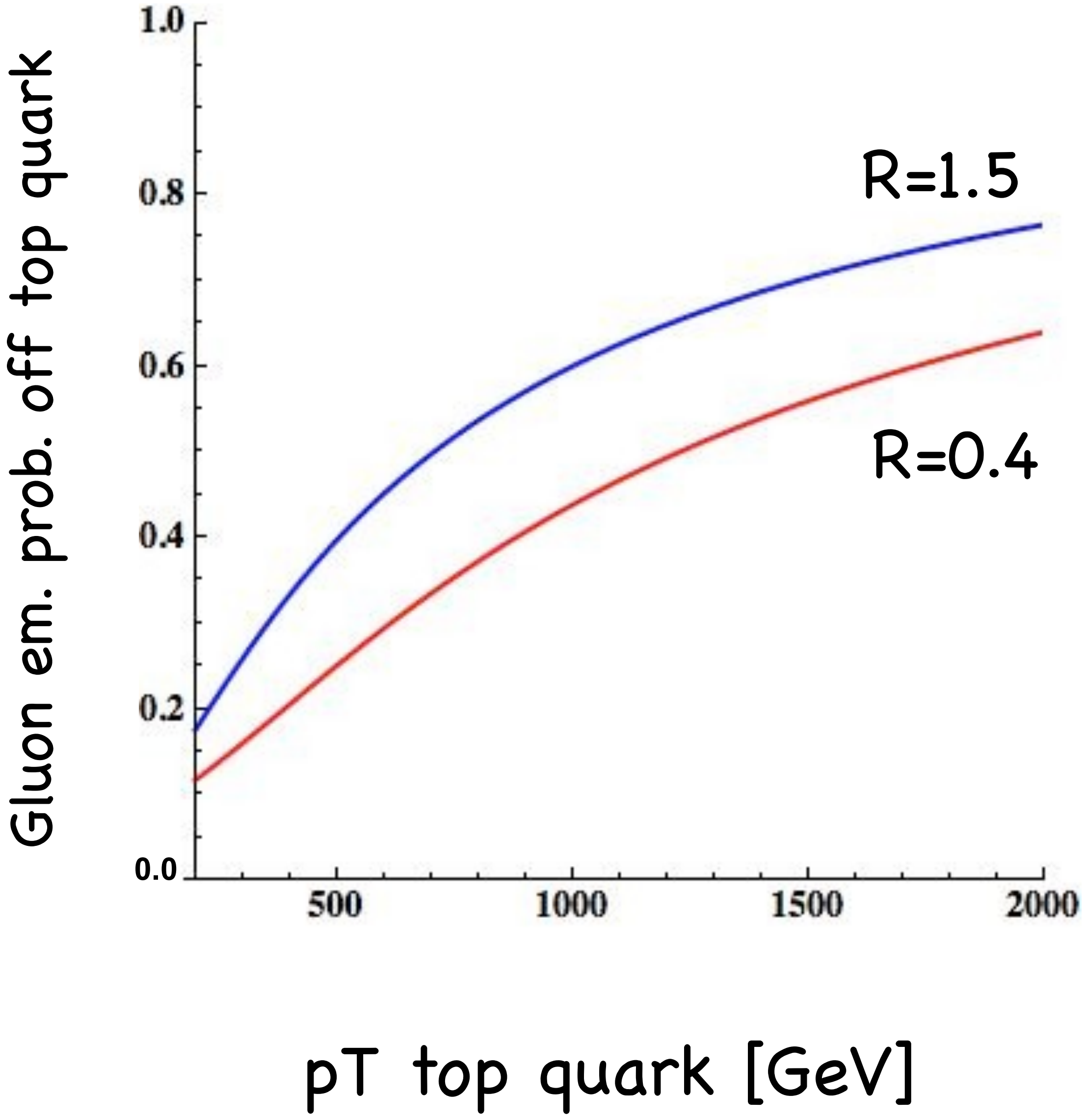


QCD

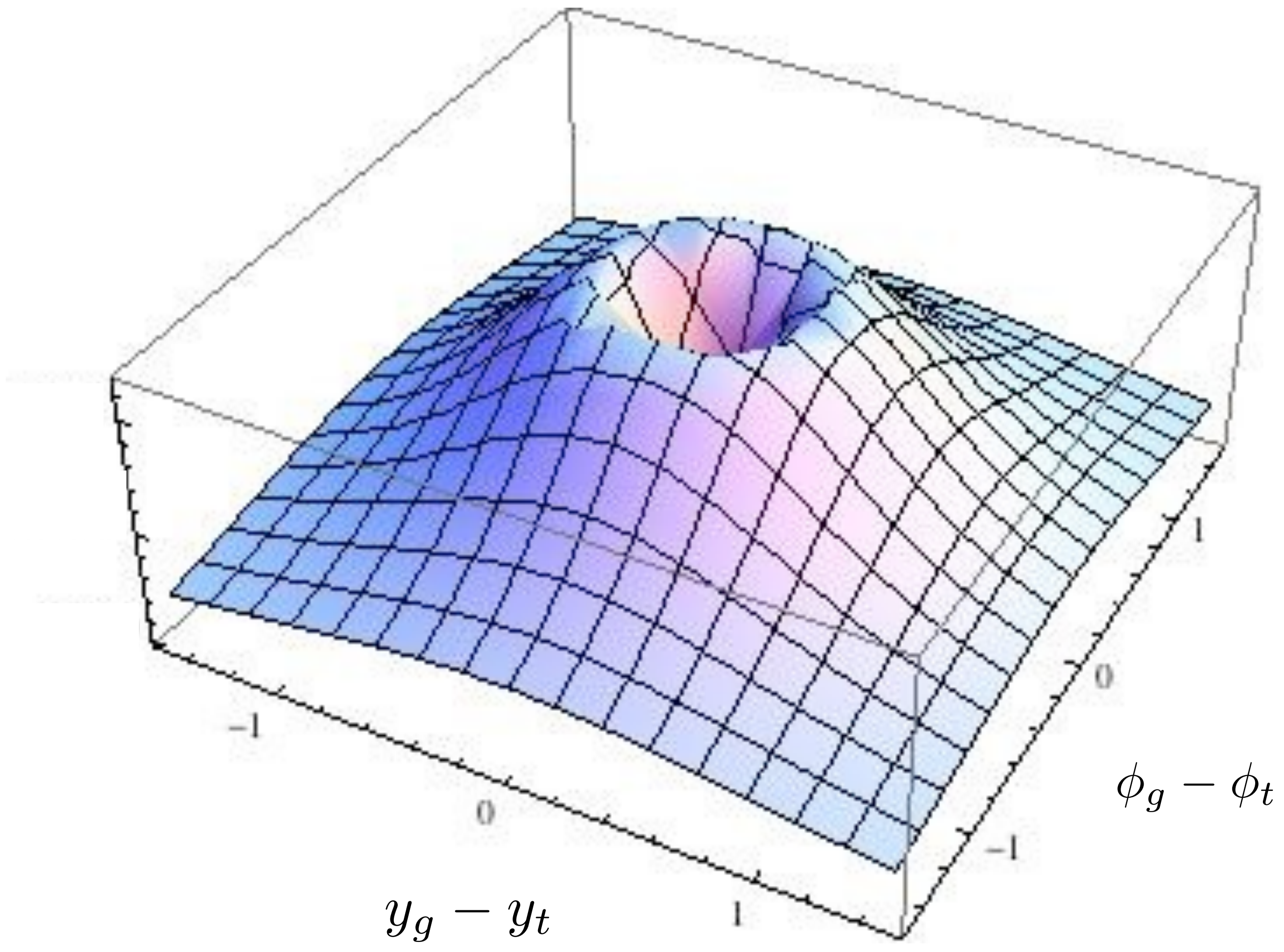
One can be more quantitative...

use emission prob. from [Soper, MS PRD 87]

$$\mathcal{P} = 1 - e^{-S_{ttg}}$$



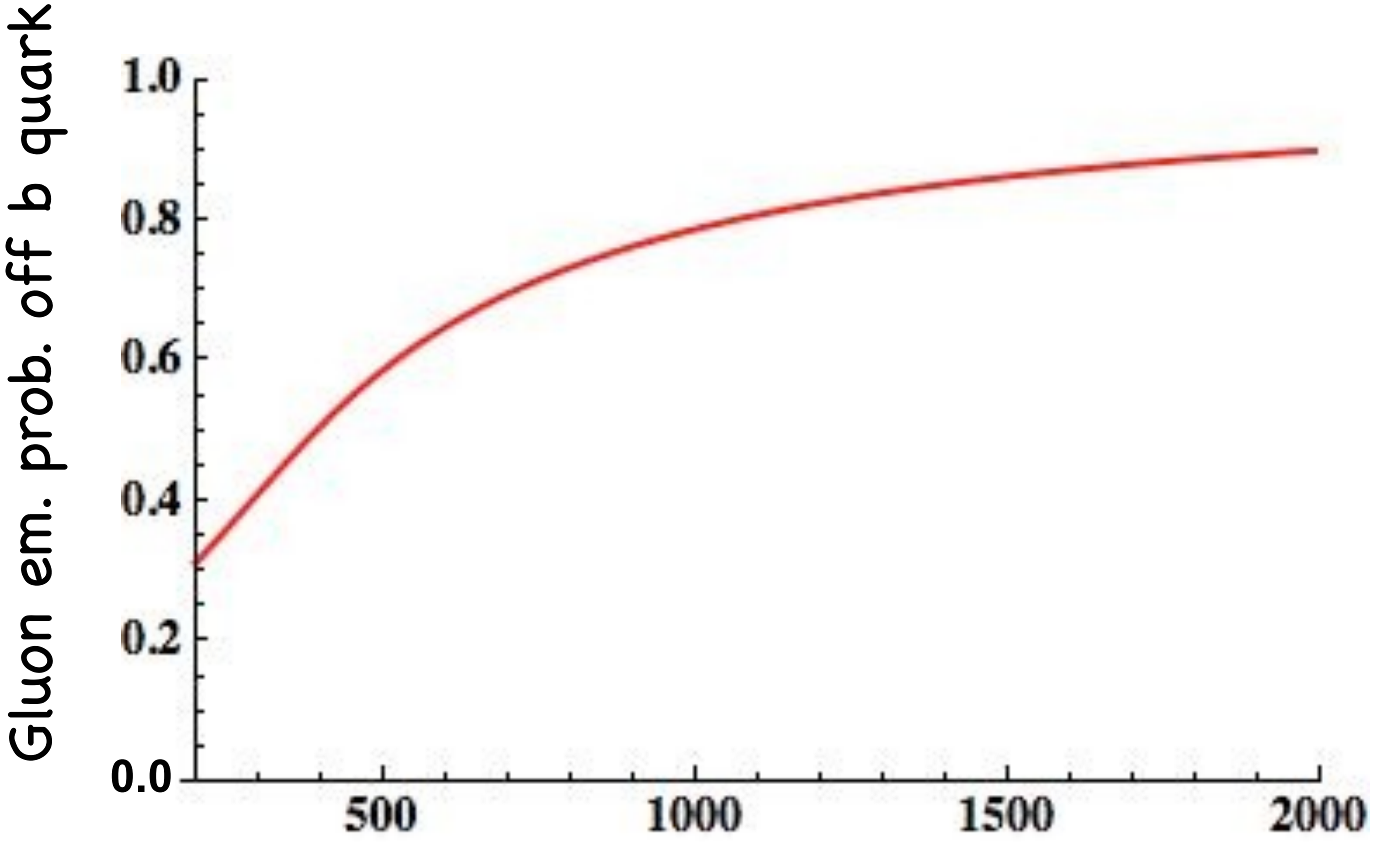
Dead region around top



pT top 500 GeV, pT gluon 20 GeV

Radiation off bottom quark down to hadronization scale

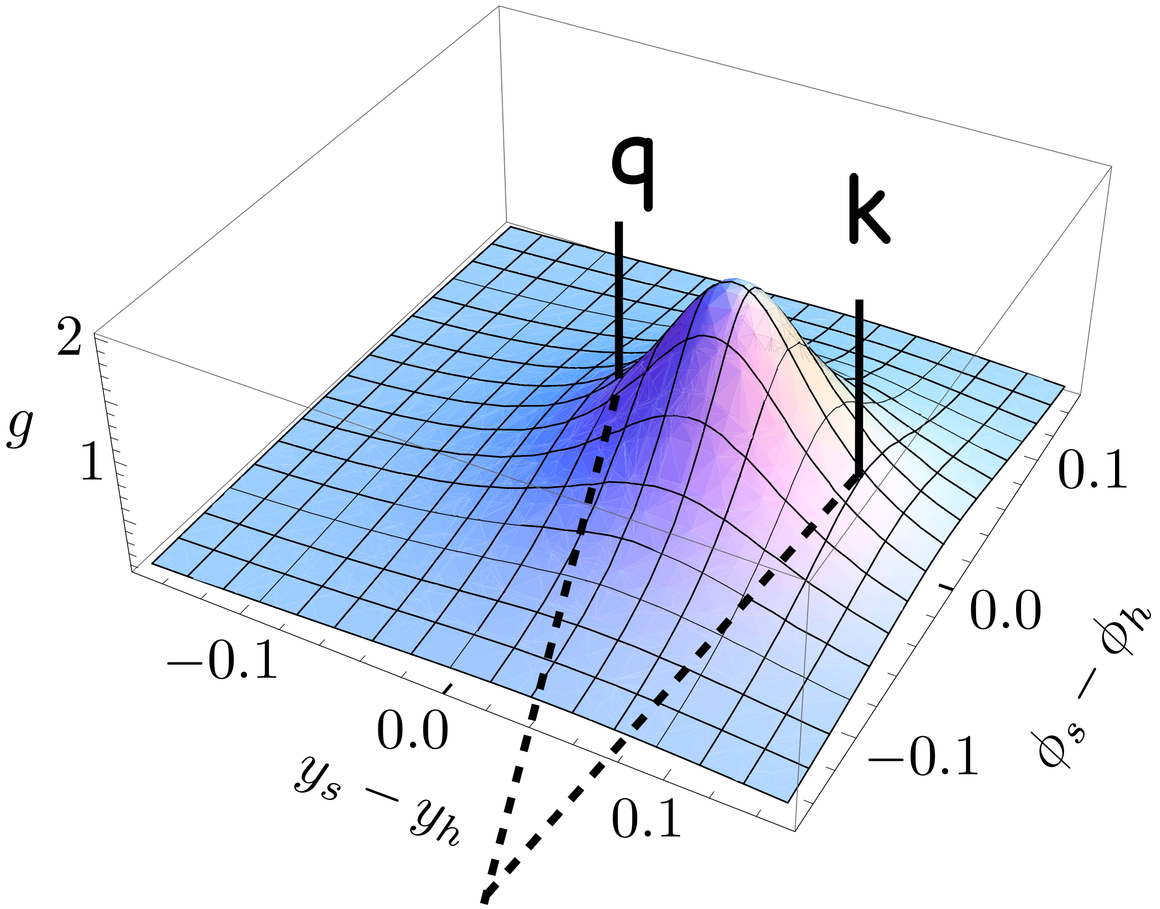
$$\mathcal{P} = 1 - e^{-S_{bbg}}$$



pT top quark [GeV]

pT bottom = pT top / 3

angular distribution for radiation off W decay products

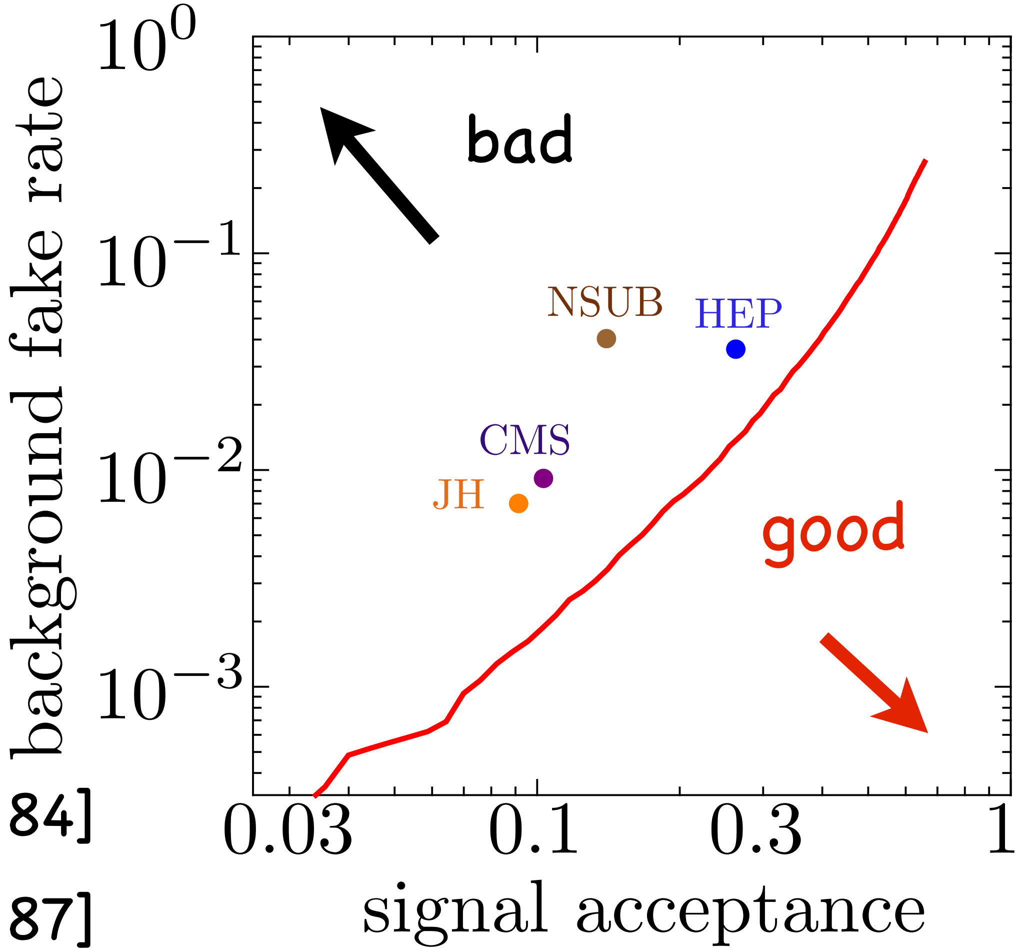


W decay products

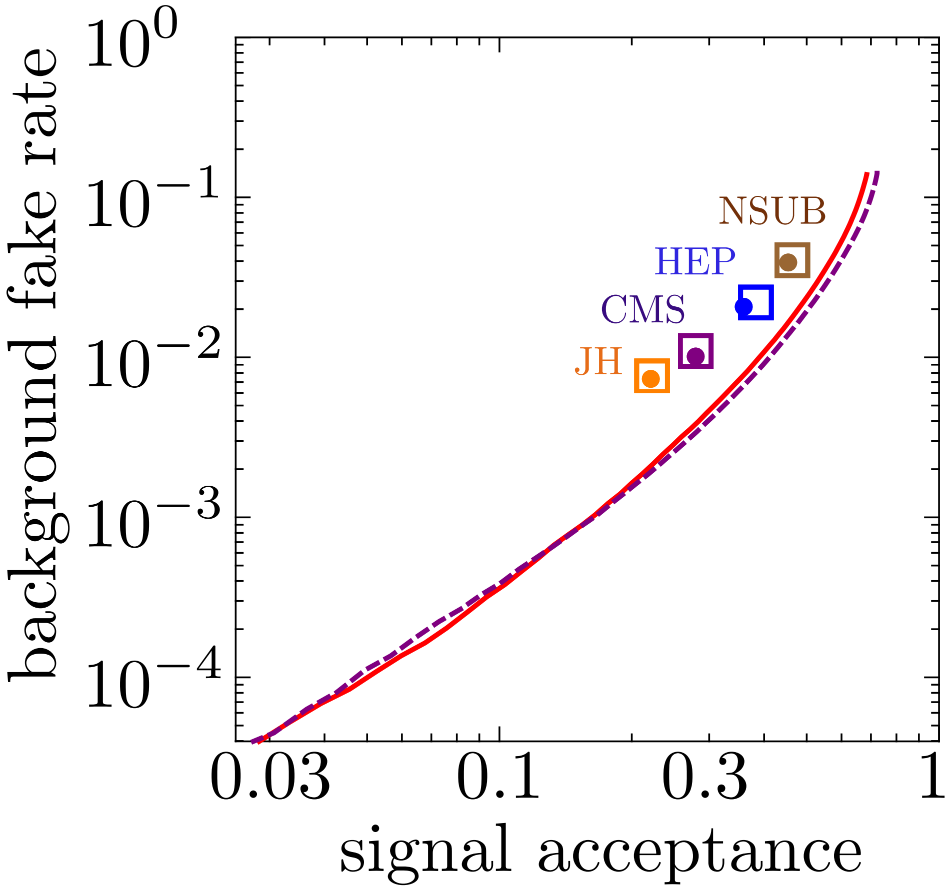
Newer taggers, e.g. based on the method shower deconstruction, make explicitly use of the fact that the top and its decay products have special QCD radiation profile:

Idea: Reverse engineer CKKW [Catani, Krauss, Kuhn, Webber JHEP]

pTj > 200 GeV, R=1.5 CA



pTj > 500 GeV, R=1.2 CA



[Soper, MS PRD 84]

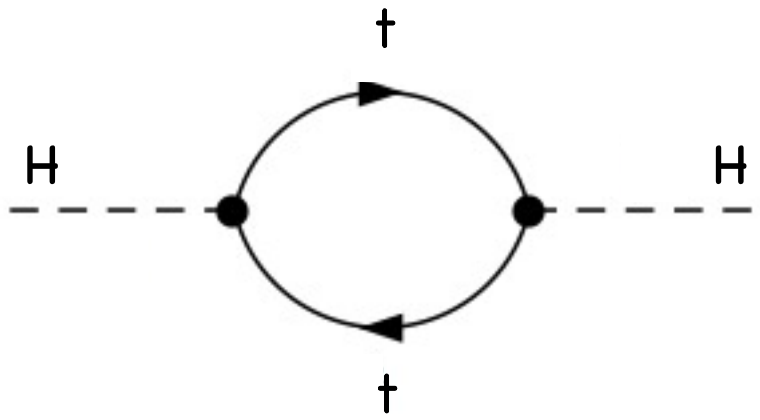
[Soper, MS PRD 87]

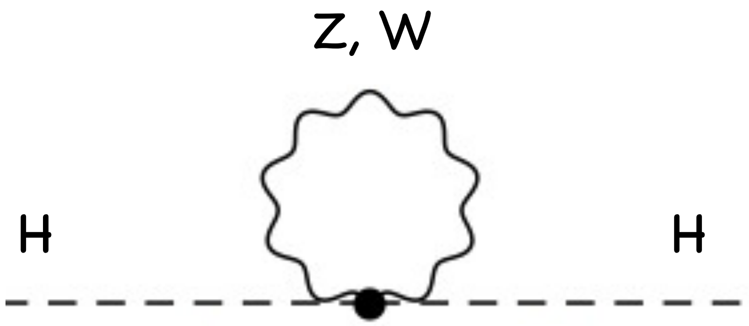
Using the top quark to find new physics

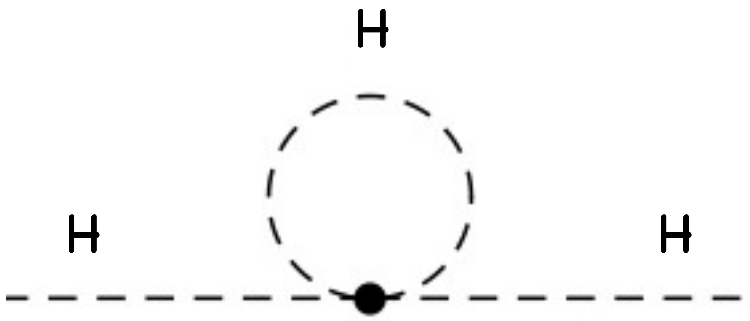
The Standard Model after the 4th of July

The discovery of a Standard-Model-like scalar resonance marked milestone in increasing understanding of nature. And raises questions:

1)







$$m^2_{h,\mathrm{SM}} = \mu^2 + \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m^2_{h,\mathrm{SM}} - 4m_t^2), \quad \mu^2 = -2\lambda v^2$$

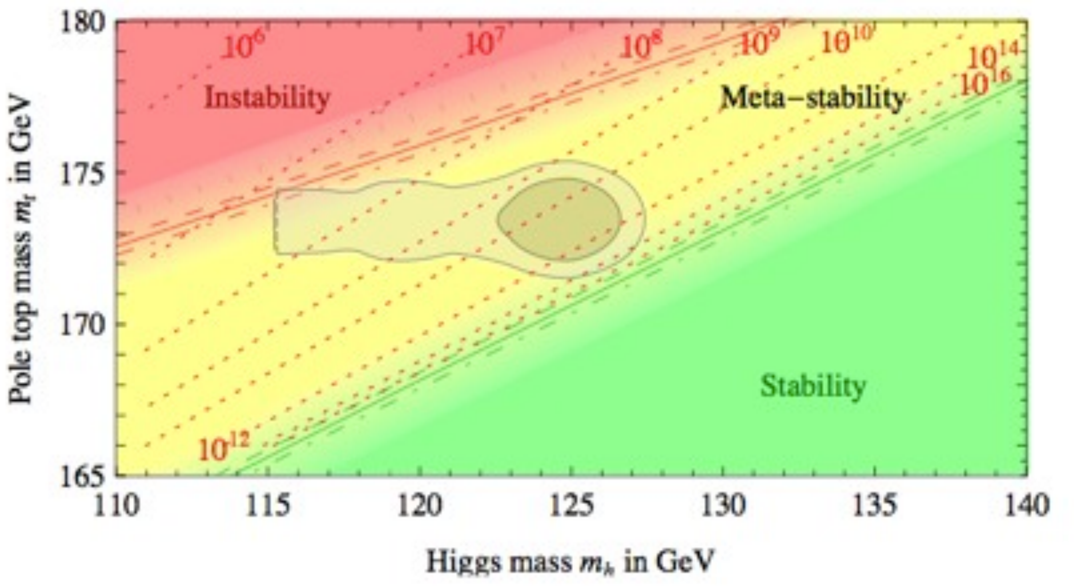
⟶ numerically top loop dominates: $(2m_W^2 + m_Z^2 + m^2_{h,\mathrm{SM}} - 4m_t^2) \simeq -81700$

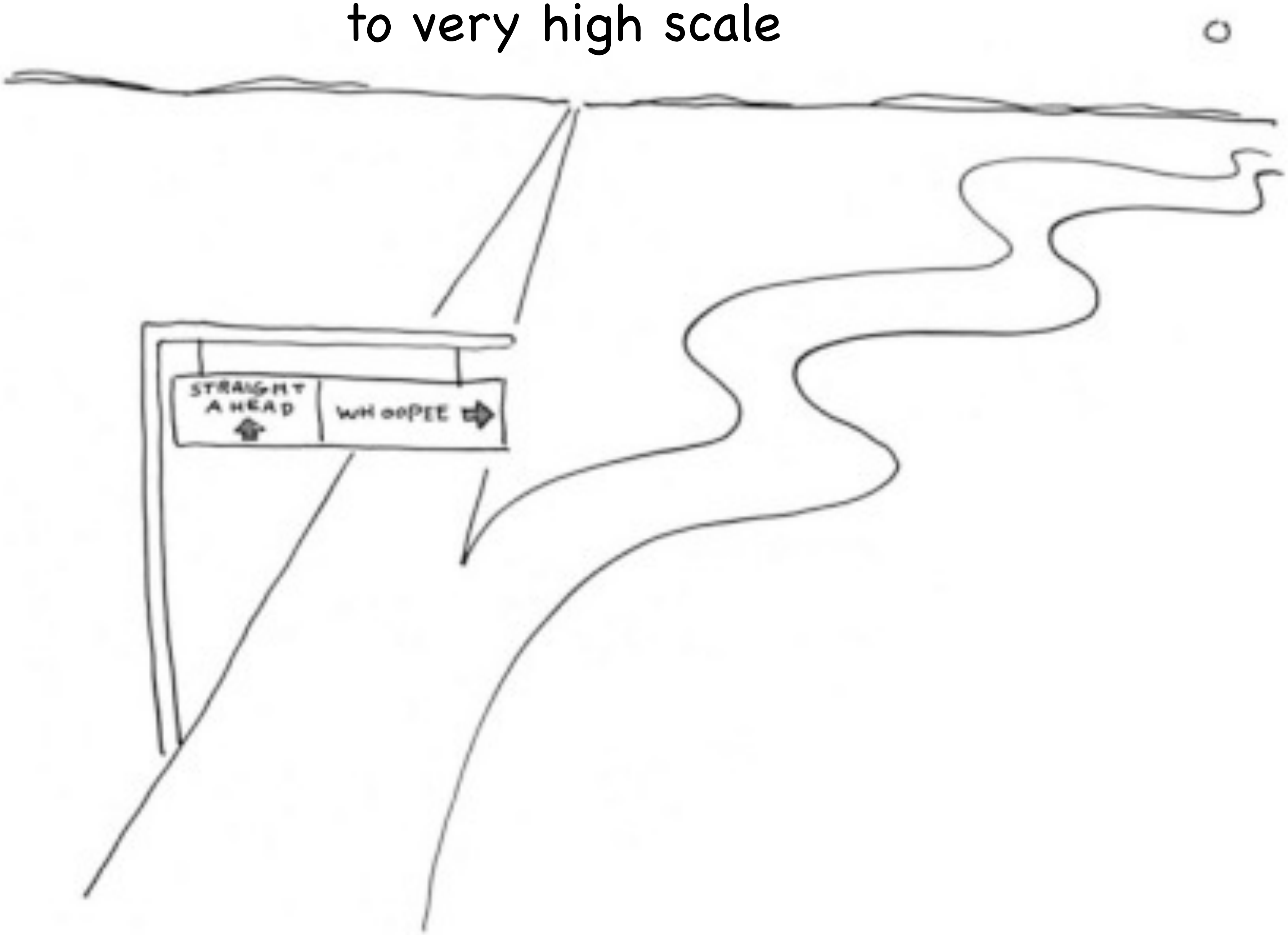
⟶ Up to which scale Λ is SM valid? How to avoid excessive fine-tuning?

2) Is Higgs potential stable?

No definite answer due to large top mass uncertainty

[Elias-Miro et al, PLB 709]





Standard Model is valid to very high scale

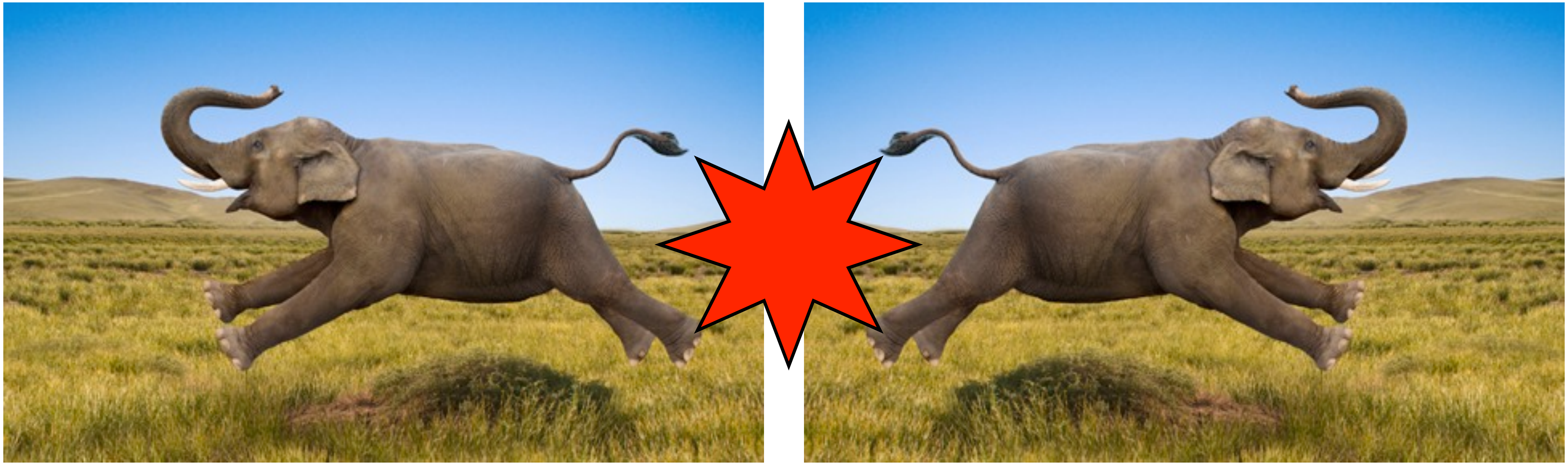
Elementary scalar:

- SUSY restores naturalness
- Coleman-Weinberg potential
- ....

Composite scalar:

- Higgs as Pseudo-Nambu-Goldstone boson
- ....

Energetic tops are often the key

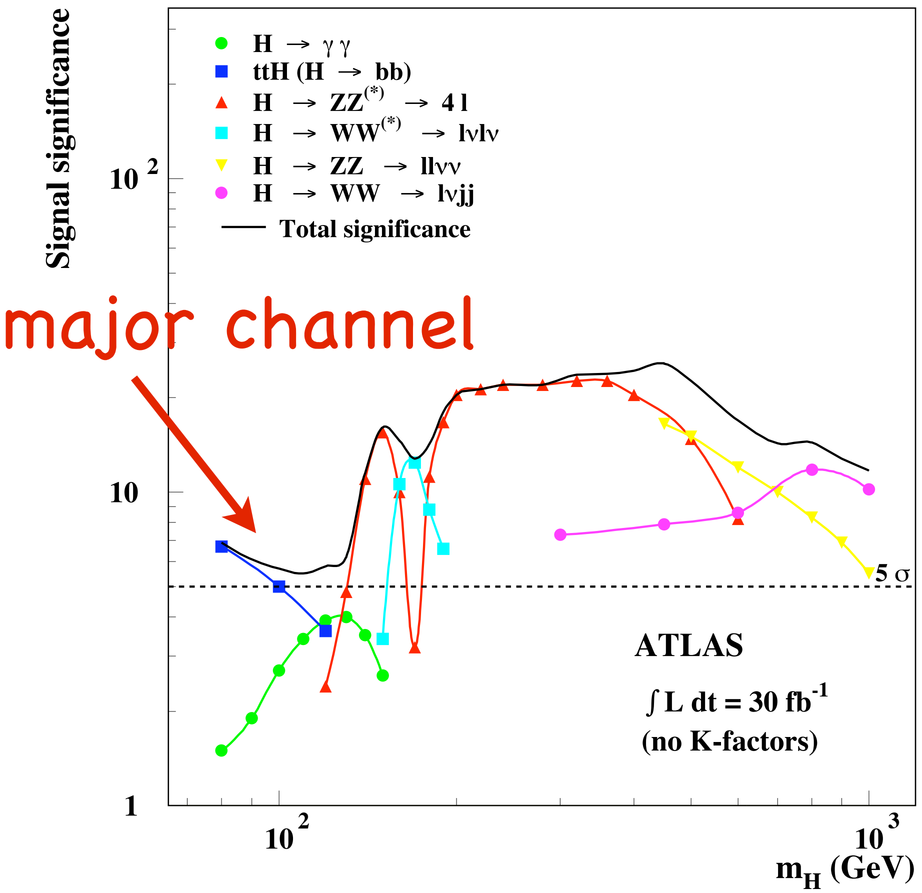


- Almost all signal events are boosted, e.g. heavy Z′ or KK gluon...
- Background drops faster than signal, e.g. tth, top partner
- Couplings require large momentum (mtt), e.g. Afb, top radius

Applications: tth
as busy as it gets in the SM

Motivation:
- sizable cross-section
- Higgs discovery contribution in low mass range
- access to t- and b-Yukawa couplings

High expectations:



tth major channel

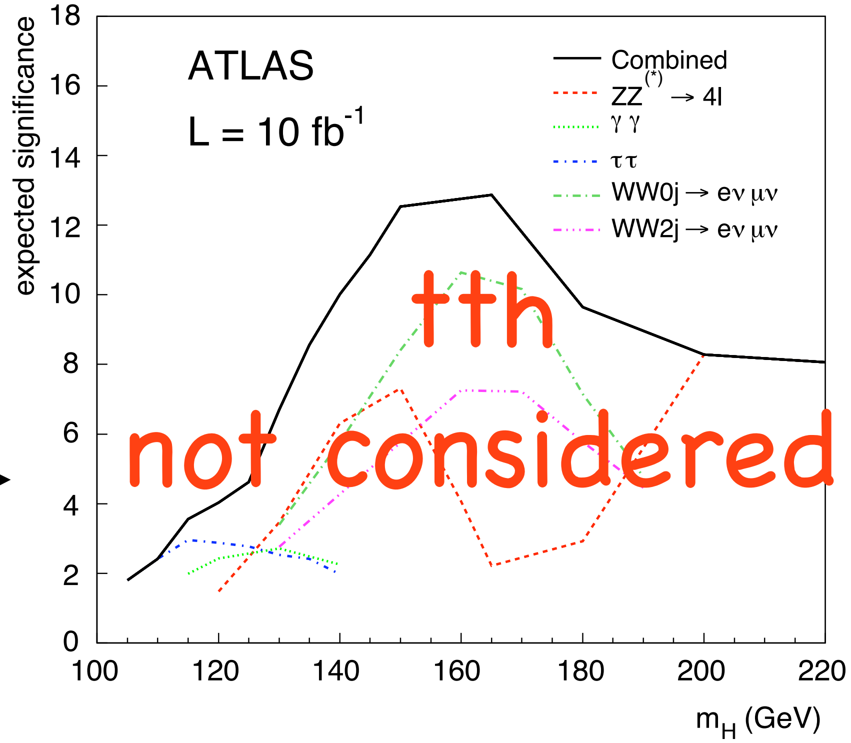
[ATLAS TDR 1999]

Cammin
and
Schumacher
(ATLAS)

$S/B \simeq 1/9$

$S/\sqrt{B} \simeq 2.2$

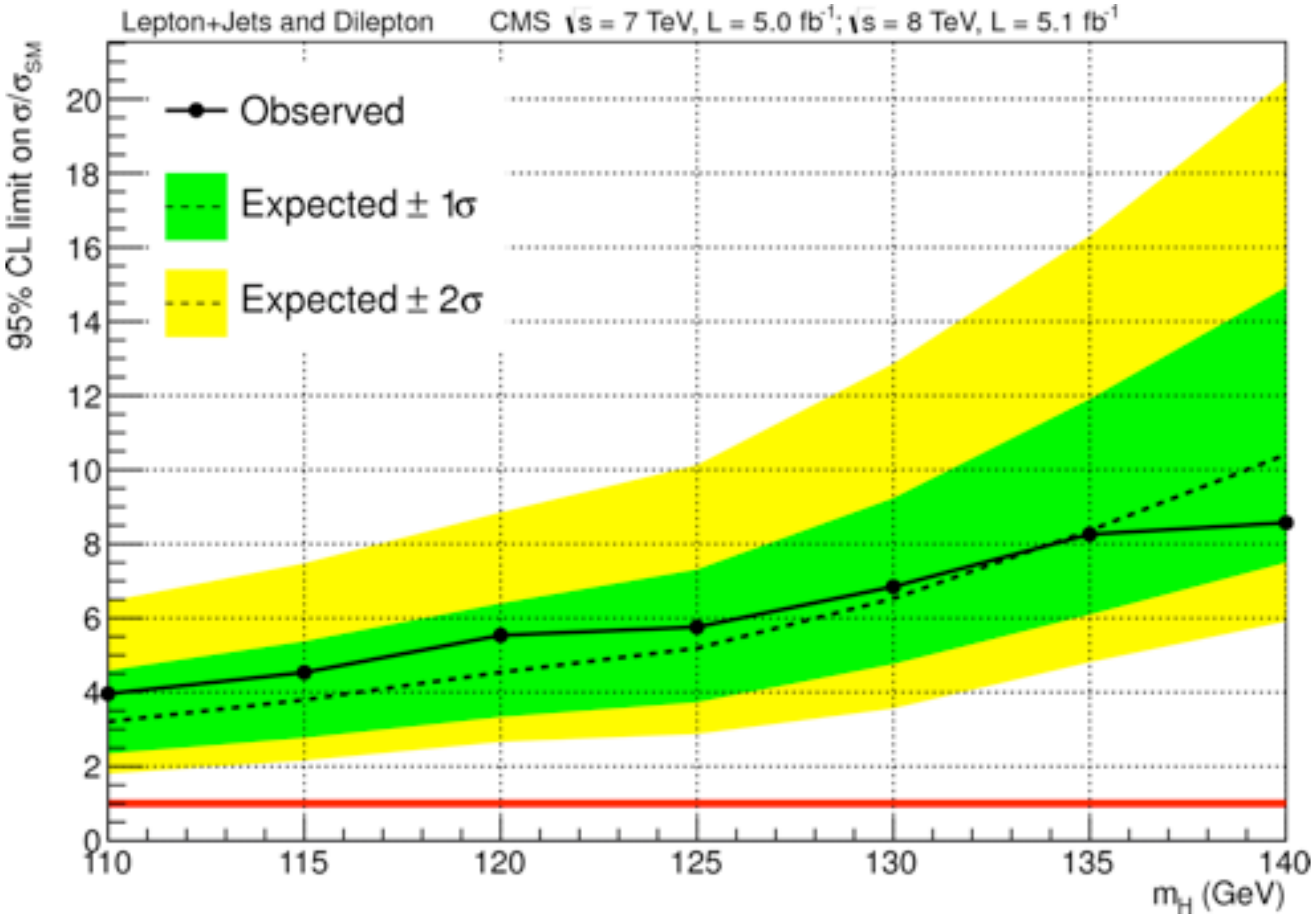
Expected Performance of the
ATLAS Experiment,
CERN-OPEN-2008-020



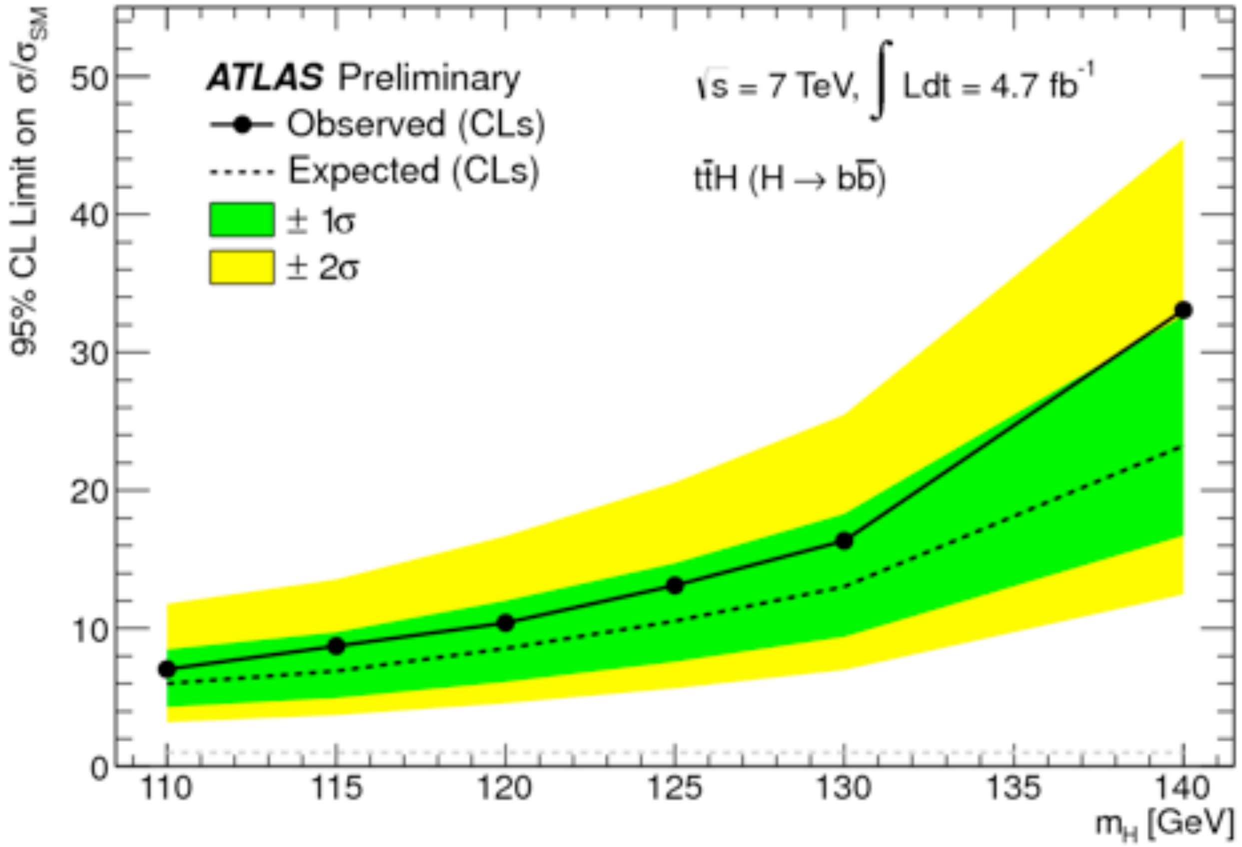
tth
not considered

Present results by CMS and ATLAS

CMS, 7 and 8 TeV each 5 ifb comb.



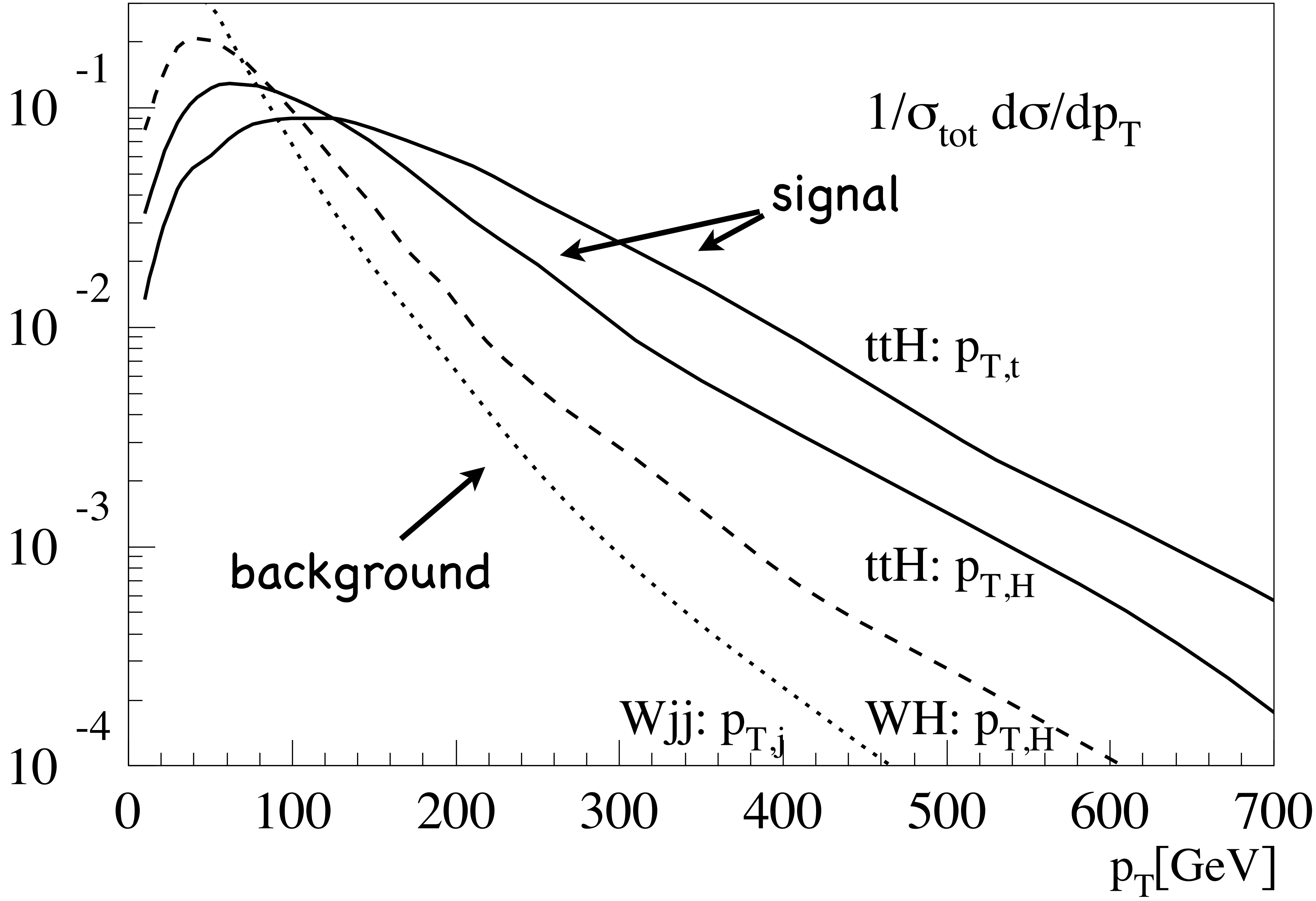
ATLAS, 7 TeV at 4.7 ifb



Both experiments are sensitive at X-times the SM cross section

However, tth coupling measurement will be systematics limited. Low S/B will render measurement notoriously difficult with standard reconstruction techniques.

pT distributions relevant for tth



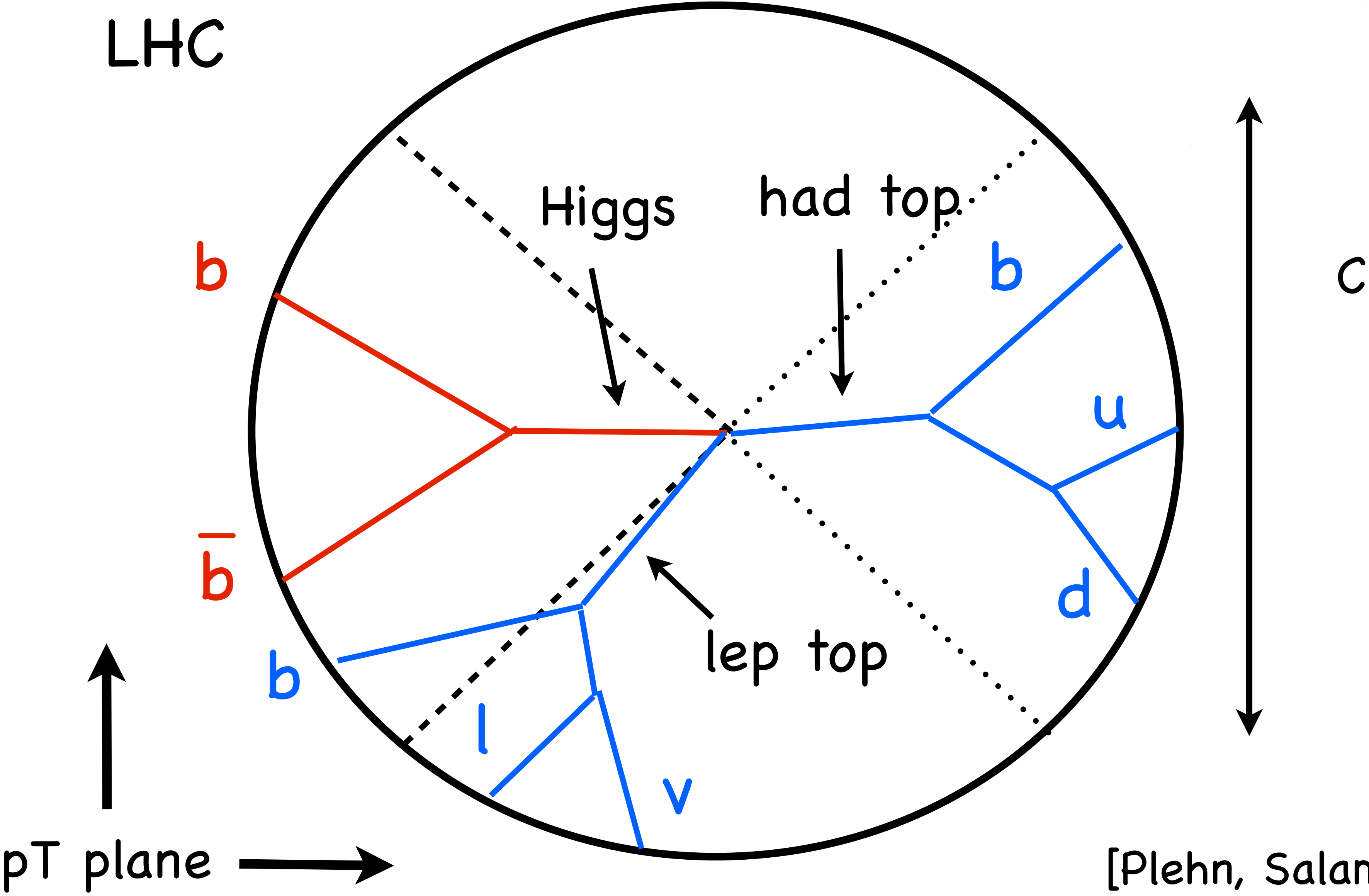
Problems in event reconstruction:

- (b-)jet multiplicity
- reconstruction efficiency

Boost should help

but

need tagger for this environment



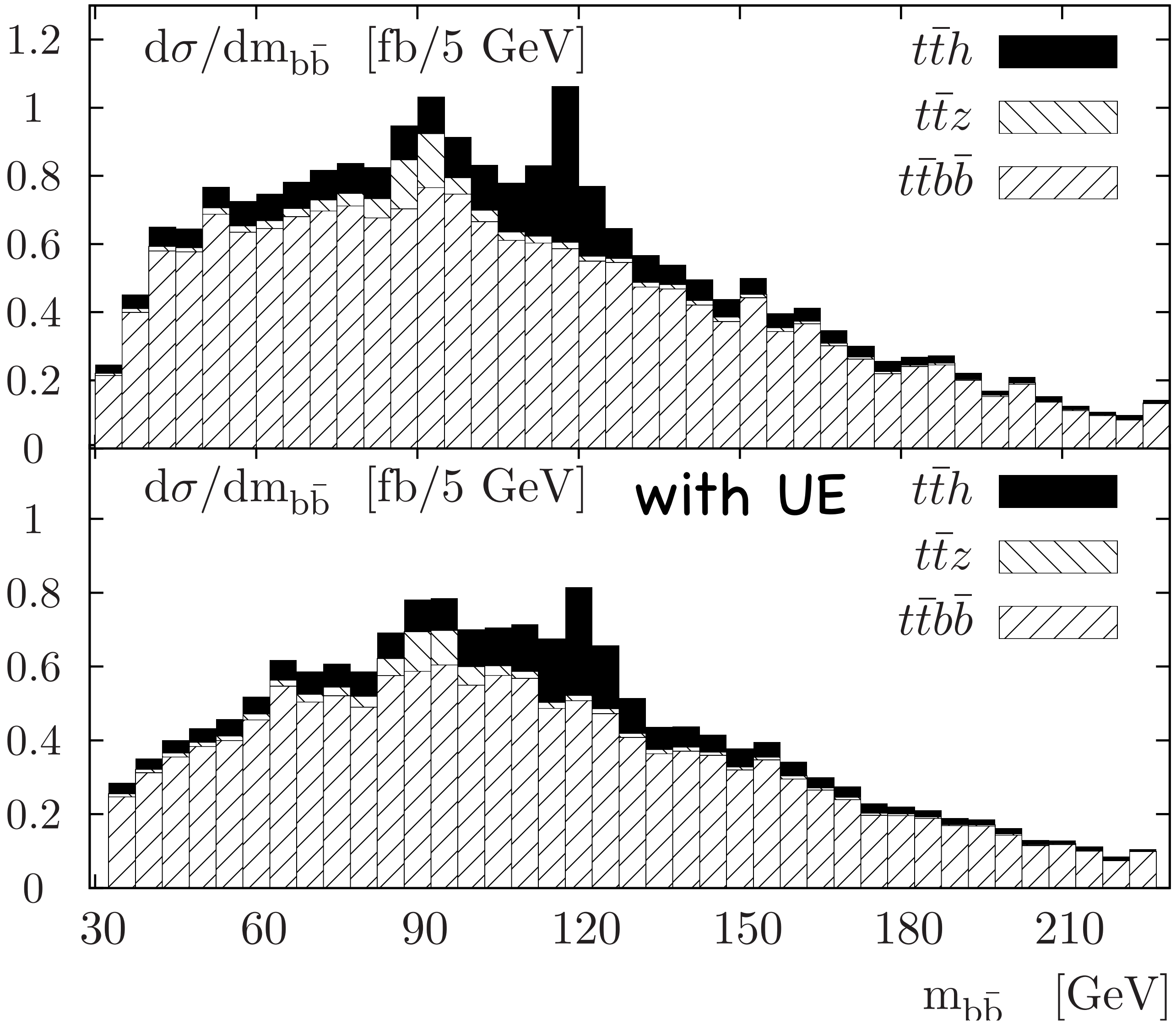
Cambridge/Aachen

jet algorithm

R=1.5

[Plehn, Salam, MS PRL 104 (2010)]

Results for tth



- 5 sigma sign. with 100 1/fb
- Development of Higgs and top tagger for busy final state
- Improvement of S/B from 1/9 to 1/2

⟶ Can use Z peak to calibrate Higgs-top coupling

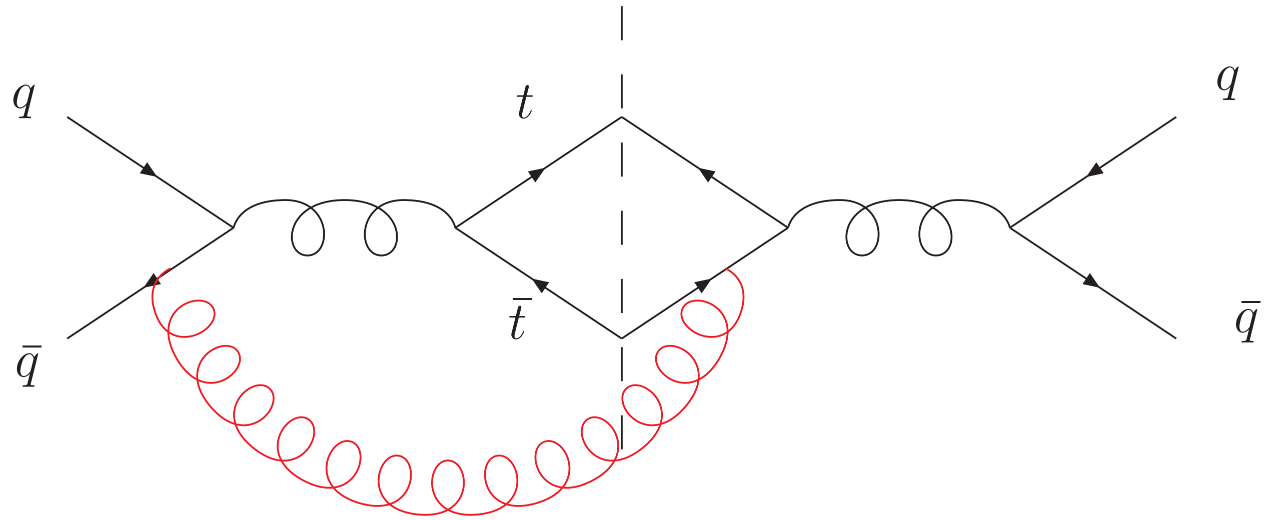
⟶ tth might be a window to Higgs-top coupling

Forward backward asymmetry

D0 and CDF observed anomalously large values of Afb

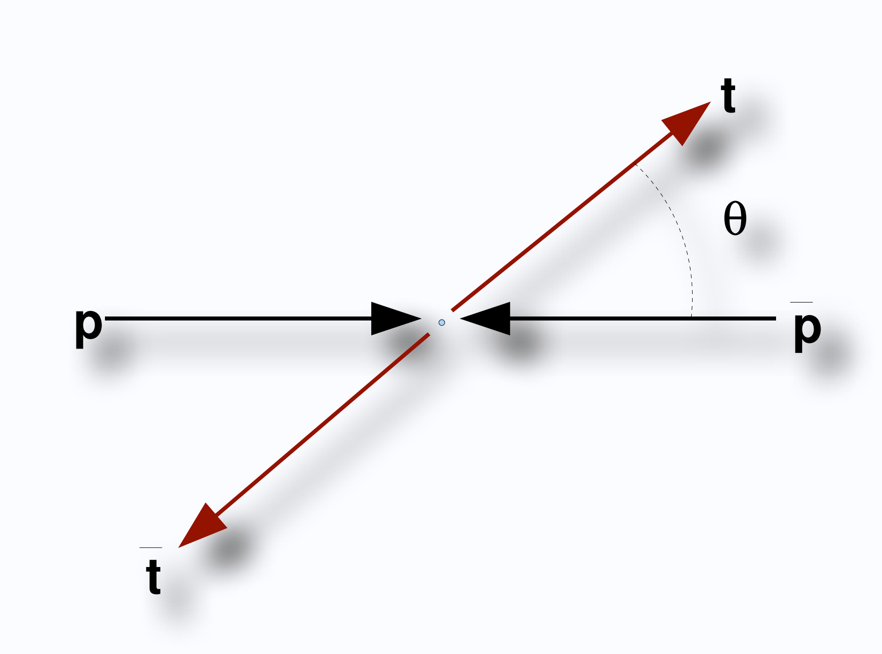
- Charge asymmetry small NLO effect (~6%) [Kühn, Rodrigo]
- NLL threshold resummation reduces theory uncertainty

[Almeida, Sterman, Vogelsang]



$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$



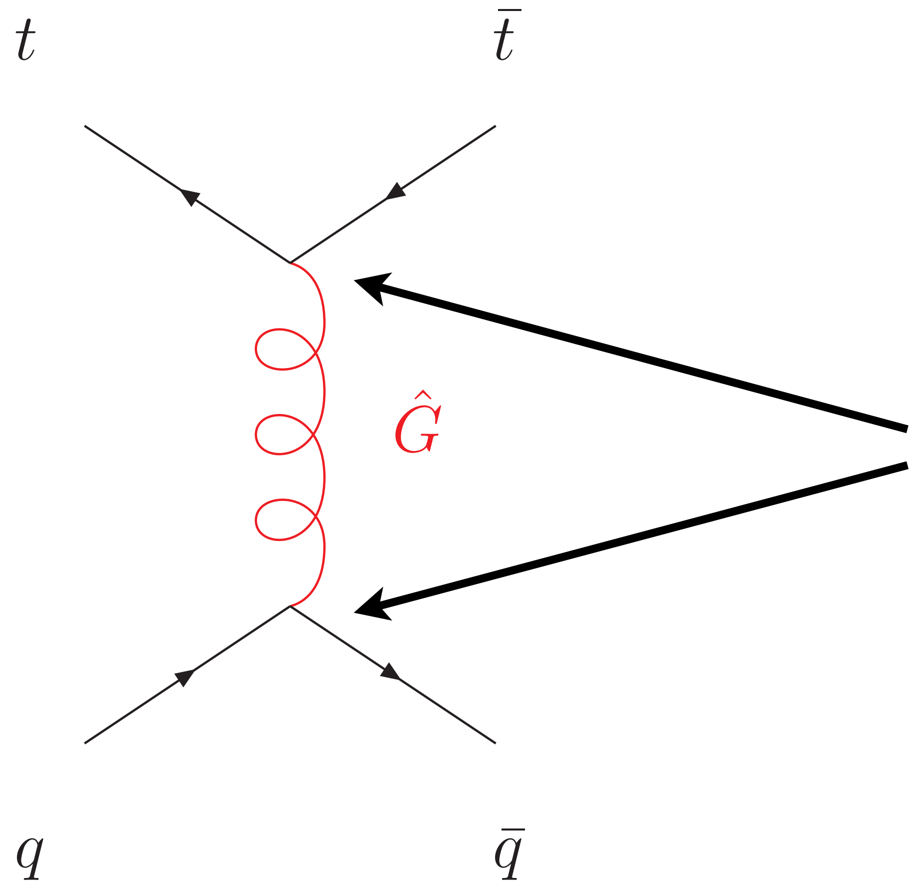
D0: Afb = (8 ± 4(stat) ± 1(syst))%

CDF: (leptonic) A_{FB} = 0.21 ± 0.07(stat) ± 0.02(bkg-shape)

(semileptonic) A_{FB} = 0.150 ± 0.050(stat) ± 0.024(syst)

more pronounced at large invariant mass
(> 450 GeV)

Models to account for asymmetry

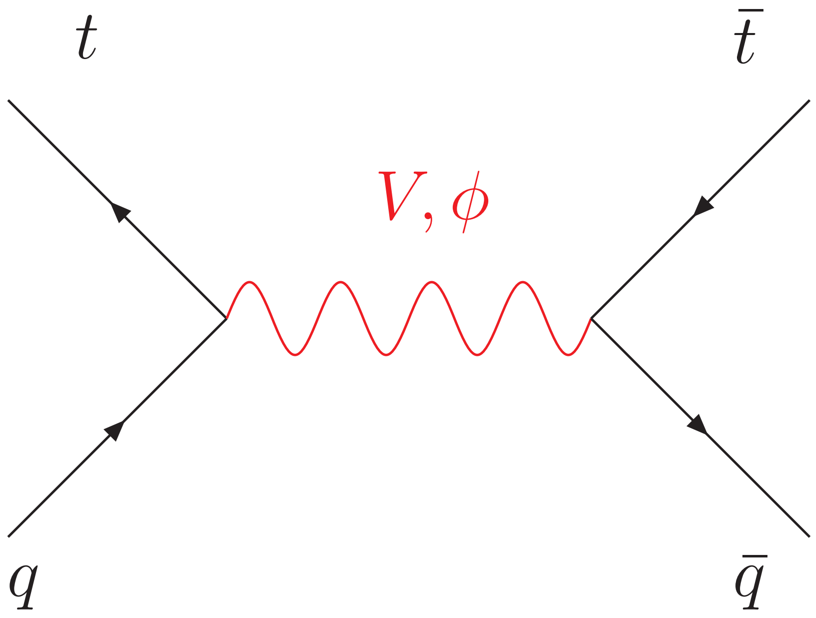


s-channel resonance:

[Frampton, Shu, Wang; Chivukula, Simmons, Yuan; Bai, Hewett, Kaplan, Rizzo]

-gu,d gt to get pos. asymmetry

requires flavor non-universal coupling



t-channel resonance:

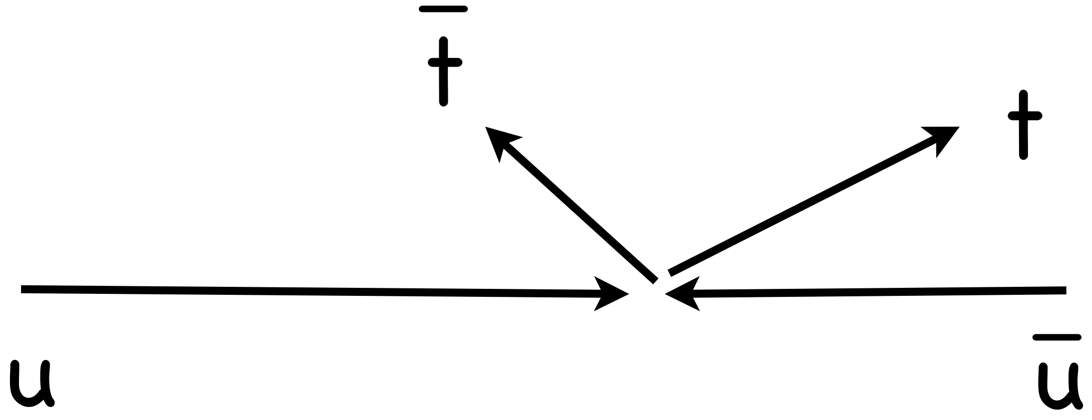
[Jung, Murayama, Pierce et al.; Shu, Tait, Wang; Cheung, Keung, Yuan; Barger, Keung, Yu; Shelton, Zurek; Grinstein, Kagan, Trott, Zupan; Ligeti, Schmaltz, Tavares]

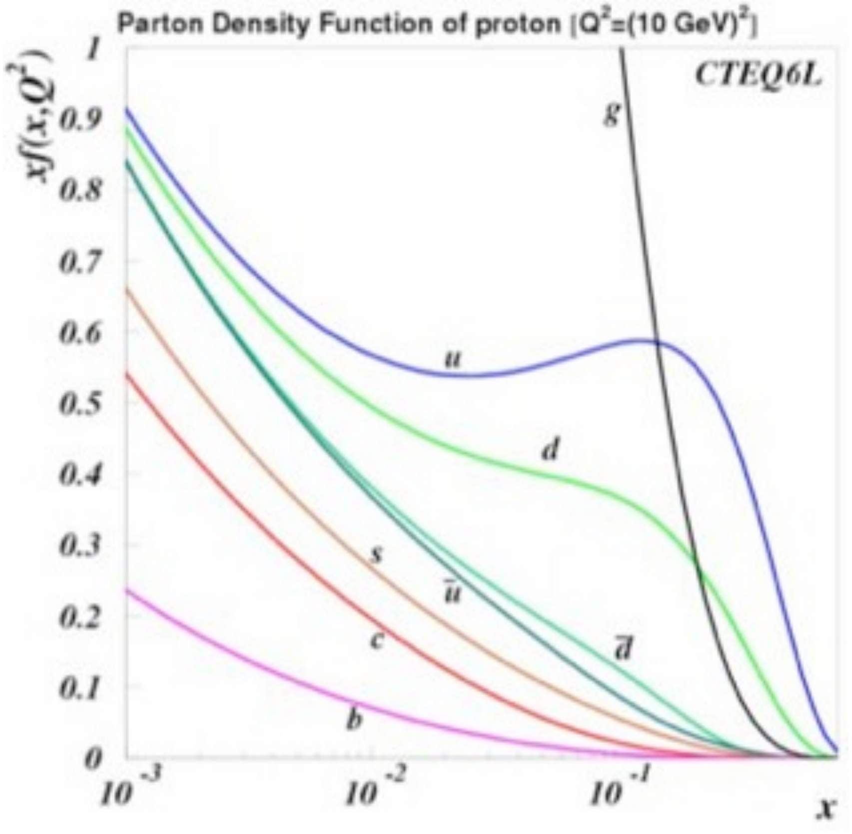
requires flavor off-diagonal coupling

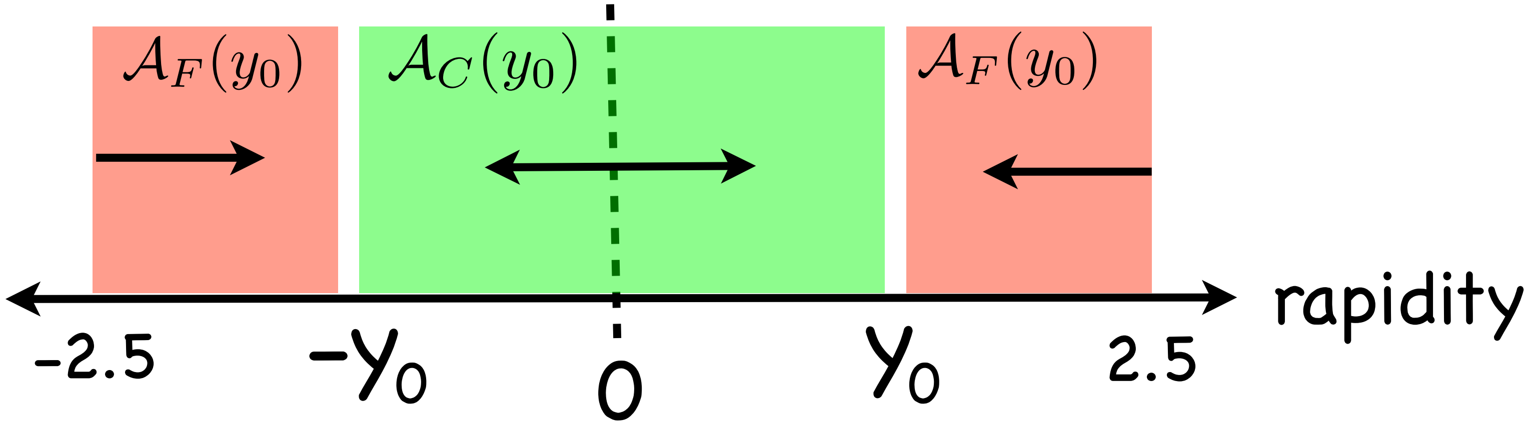
Overview: [Gresham, Kim, Zurek]

We will have to measure asymmetry at the LHC

- Symmetric proton beams
- If CP conserved → FB becomes Charge asymmetry







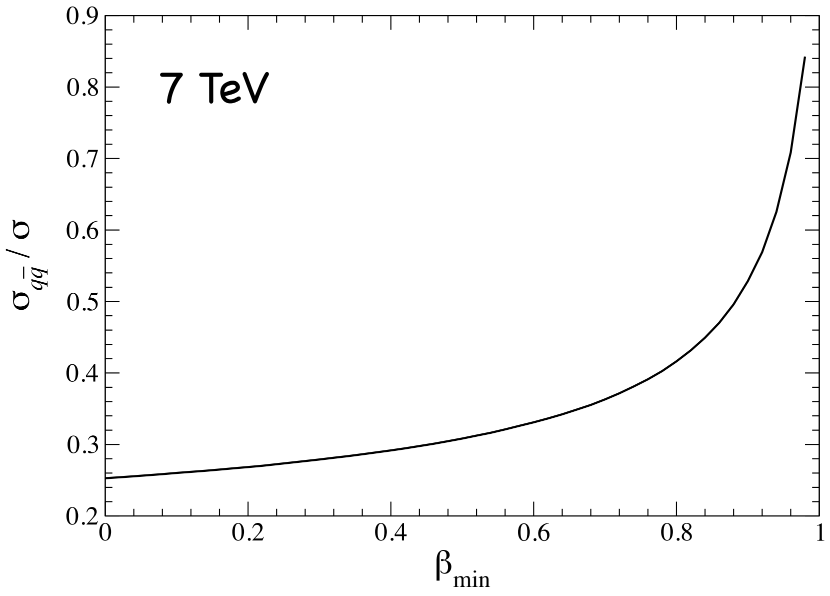
gg dominant prod. mode but symmetric

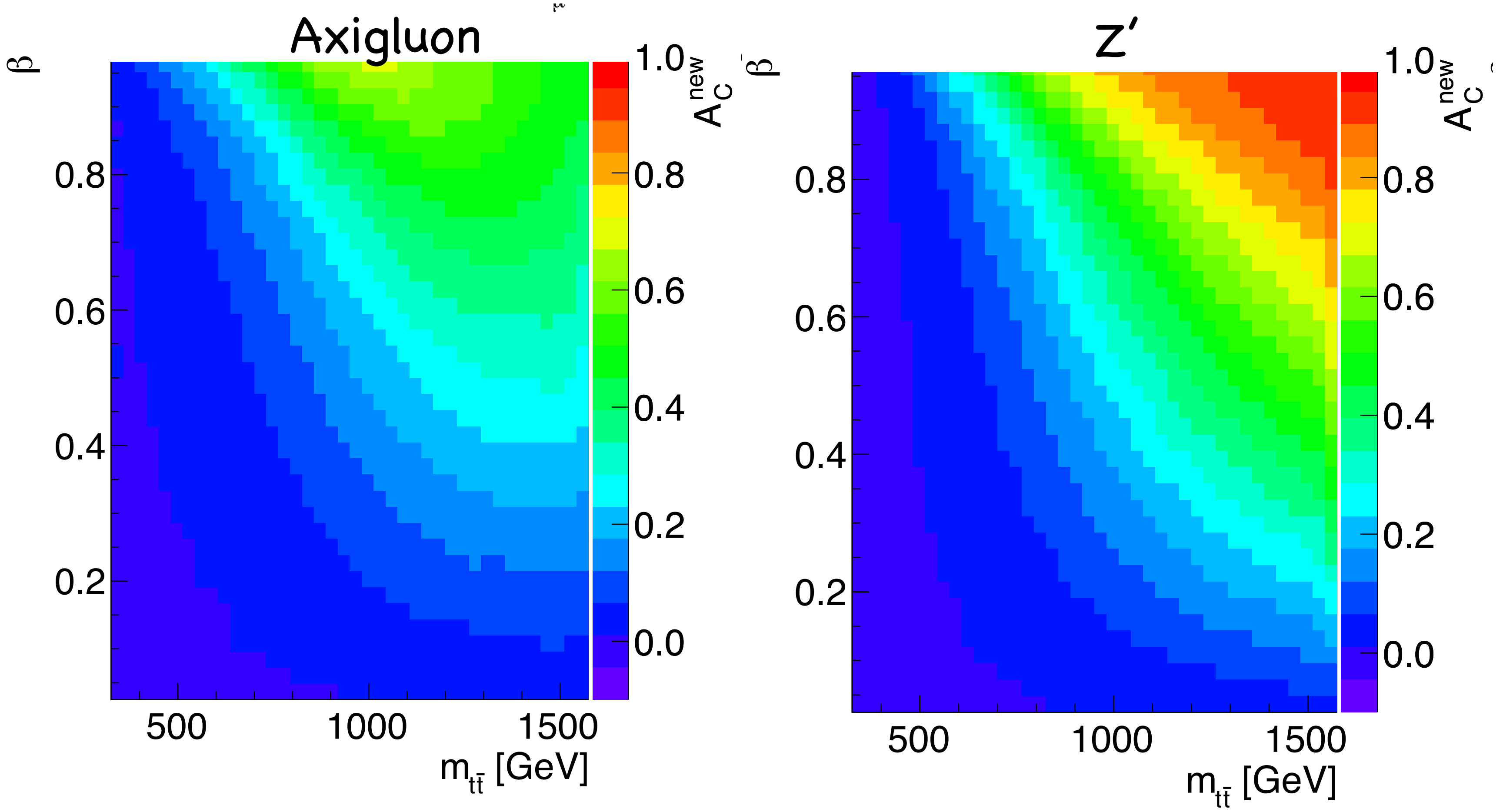
need qq and qg initial state

Study for charge asymmetry @ LHC

[Aguilar-Saavedra, Juste, Rubbo]

$$\beta = \frac{|p_t^z + p_{\bar{t}}^z|}{E_t + E_{\bar{t}}}$$





Event reconstruction: Consider moderately boosted semileptonic tops

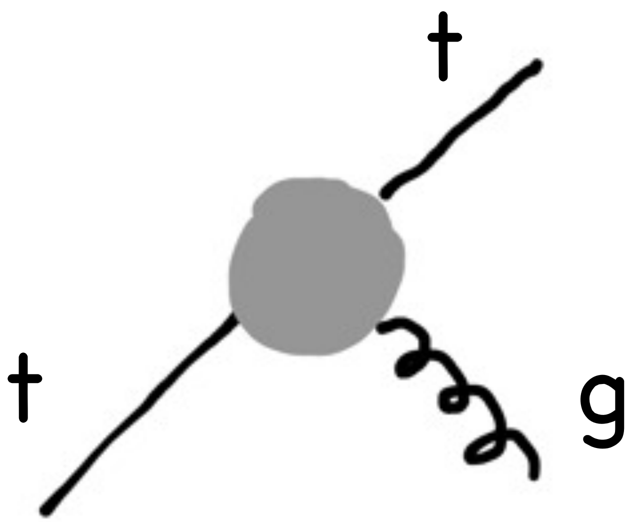
- require isolated lepton with pT > 15 GeV, $y_l = y_{\text{lep. top}}$
- require jet with pT>200 GeV, use HEPTopTagger
- demand b-tag in hadronic top

→ W+jets negligible

[Hewett, Sheldon, MS, Takeuchi, Tait]

14 TeV:
- 5σ for SM after 60 ifb
- 5σ for BSM after 2 ifb

Anomalous top gluon couplings



Top-compositeness can induce magnetic moment and radius

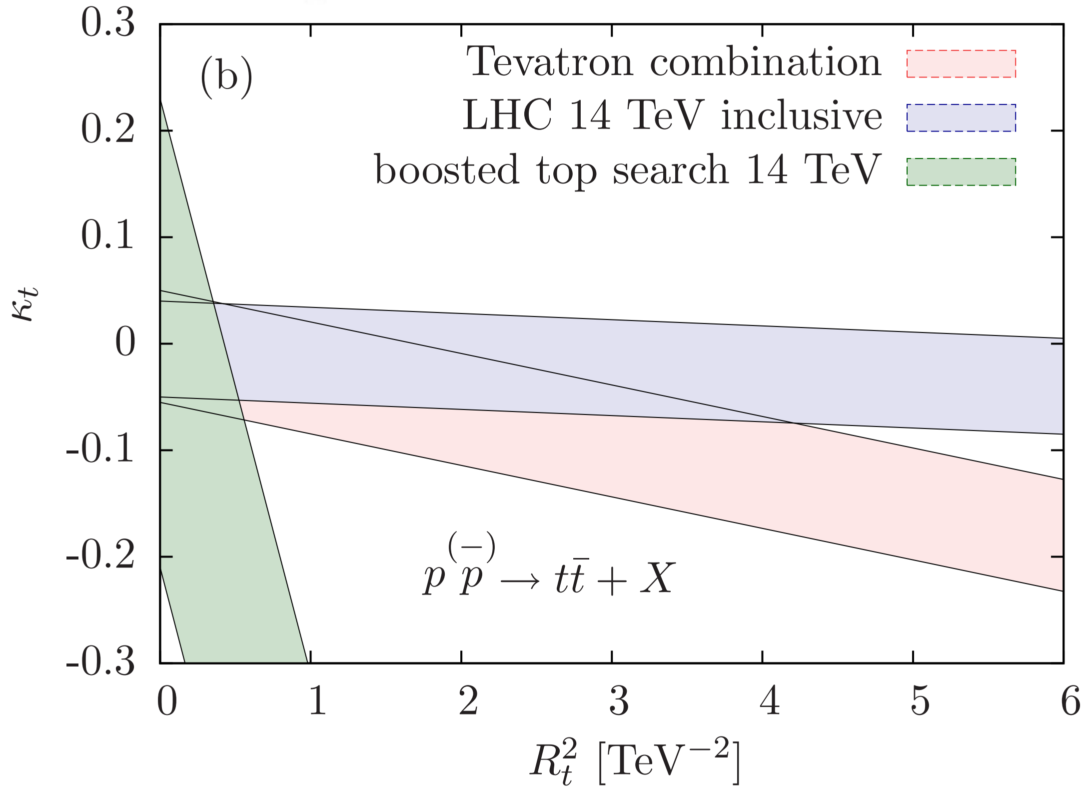
Effect of non-pointlike top structure via

$$\mathcal{L}_R = -g_s \frac{R_t^2}{6} \, \bar{t} \gamma^\mu \, \mathcal{G}_{\mu\nu} \, D^\nu \, t + \text{h.c.},$$

$$\mathcal{L}_\kappa = g_s \, \frac{\kappa_t}{4 m_t} \, \bar{t} \sigma^{\mu\nu} \, \mathcal{G}_{\mu\nu} \, t \,,$$

gluon-fusion induced top production does not depend on R_t at leading order

Use large $m_{t\bar{t}}$ to increase quark contribution in production



	R_t	$\lvert\kappa_t\rvert$
Tevatron ⊕ LHC[7 TeV]	2.9 TeV^{-1} $\sim 0.57 \times 10^{-16}$ cm	0.17
Tevatron ⊕ LHC[14 TeV]	2.1 TeV^{-1} $\sim 0.41 \times 10^{-16}$ cm	0.07
LHC[14 TeV]: inclusive ⊕ boosted top	0.7 TeV^{-1} $\sim 0.14 \times 10^{-16}$ cm	0.05

Combination of Tevatron, incl. LHC and boosted LHC gives good measurement

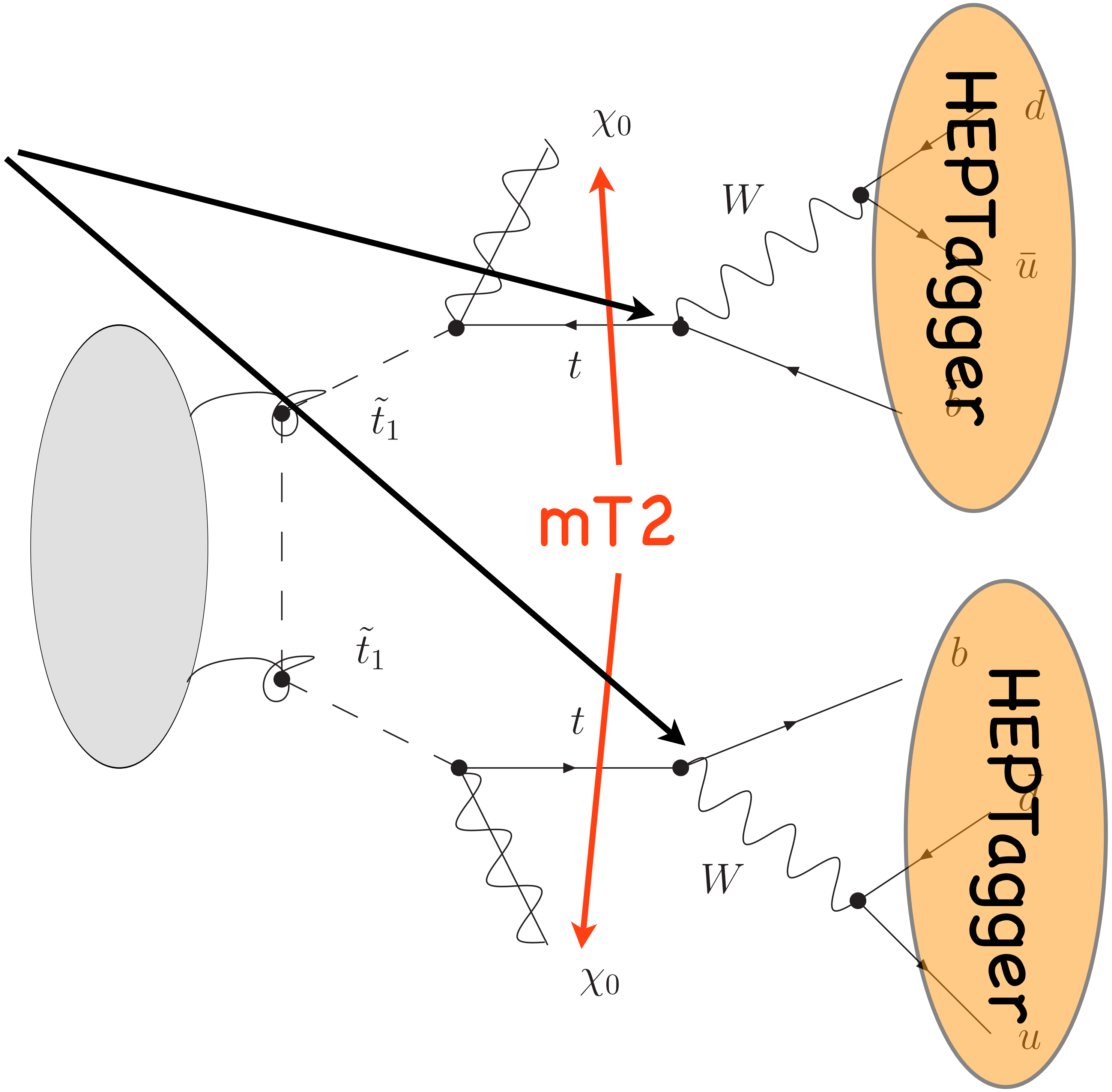
[Englert, Freytas, Spira, Zerwas]

stop reconstruction using all hadronic top quarks

[Plehn, MS, Takeuchi, Zerwas JHEP 1010]

Strategy:

- Use purely hadronic top decay mode
- Use HEPTagger in hadronic final state -> 2 tagged tops
- Separation of ISR and hard process improves mT2
- stop reconstructable over wide range



mT2 as an observable to look for stops

Consider the decay: $\tilde{t} \rightarrow \chi_1^0 t$

One can express the invariant stop mass squared by:

$$m_{\tilde{t}}^2 = m_t^2 + m_{\chi_1^0}^2 + 2\left[E_T^t E_T^{\chi_1^0}\cosh(\Delta y) - \mathbf{p}_T^t \cdot \mathbf{p}_T^{\chi_1^0}\right]$$

Of the invisible LSP only the transverse component could be inferred. Thus use transverse mass:

$$m_T^2(\mathbf{p}_T^t, \mathbf{p}_T^{\chi_1^0}; m_{\chi_1^0}) = m_t^2 + m_{\chi_1^0}^2 + 2\left(E_T^t E_T^{\chi_1^0} - \mathbf{p}_T^t \cdot \mathbf{p}_T^{\chi_1^0}\right)$$

where $m_T^2 \leq m_{\tilde{t}}^2$ ➡ If $p^{\chi_1^0}$ known m_T lower bound for stop mass (see also W mass measurement)

However, in R-parity conserved SUSY mostly squark-pair production, thus two stops decay.
Since only sum of two LSP momenta known, the best one can do is to evaluate

$$\min_{\not{\mathbf{q}}_T^{(1)}+\not{\mathbf{q}}_T^{(2)}=\not{\mathbf{p}}_T}\left[\max\left\{m_T^2(\mathbf{p}_T^{\mathbf{t}}\;\;,\not{\mathbf{q}}_T^{(1)};m_{\chi_1^0}),\ m_T^2(\mathbf{p}_T^{\mathbf{t}}\;\;,\not{\mathbf{q}}_T^{(2)};m_{\chi_1^0})\right\}\right]\le m_T$$

with the dummy vectors $\not{\mathbf{q}}_T^{(1)}$ and $\not{\mathbf{q}}_T^{(2)}$

$$m_{T2}^2(\chi)\ \equiv\ \min_{\not{\mathbf{q}}_T^{(1)}+\not{\mathbf{q}}_T^{(2)}=\not{\mathbf{p}}_T}\left[\max\left\{m_T^2(\mathbf{p}_T^{\mathbf{t}}\;\;,\not{\mathbf{q}}_T^{(1)};\chi),\ m_T^2(\mathbf{p}_T^{\mathbf{t}}\;\;,\not{\mathbf{q}}_T^{(2)};\chi)\right\}\right]$$

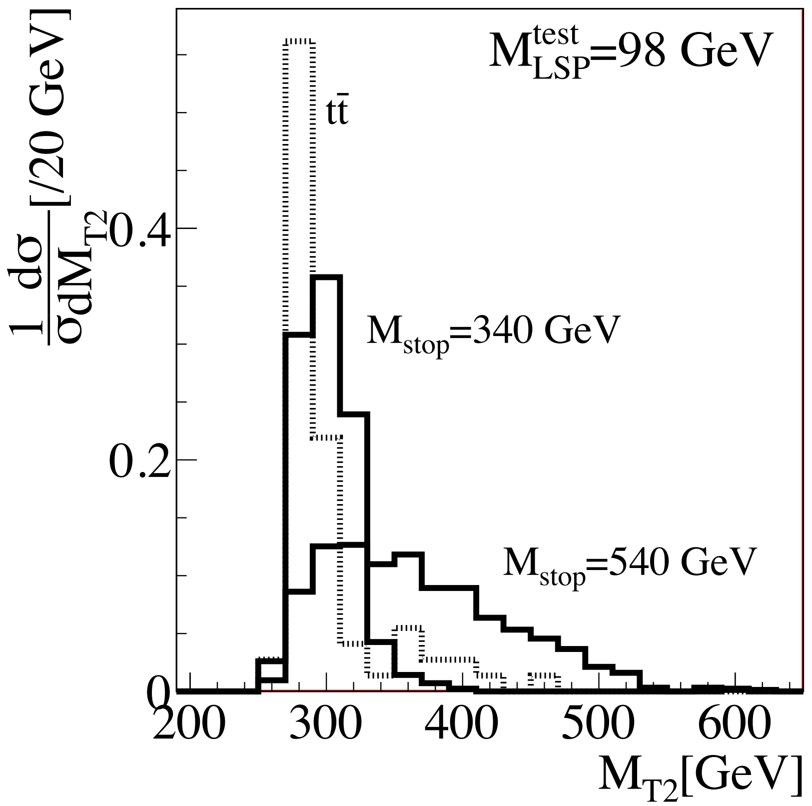
Final definition of mT2. If neutralino mass not known replace by χ

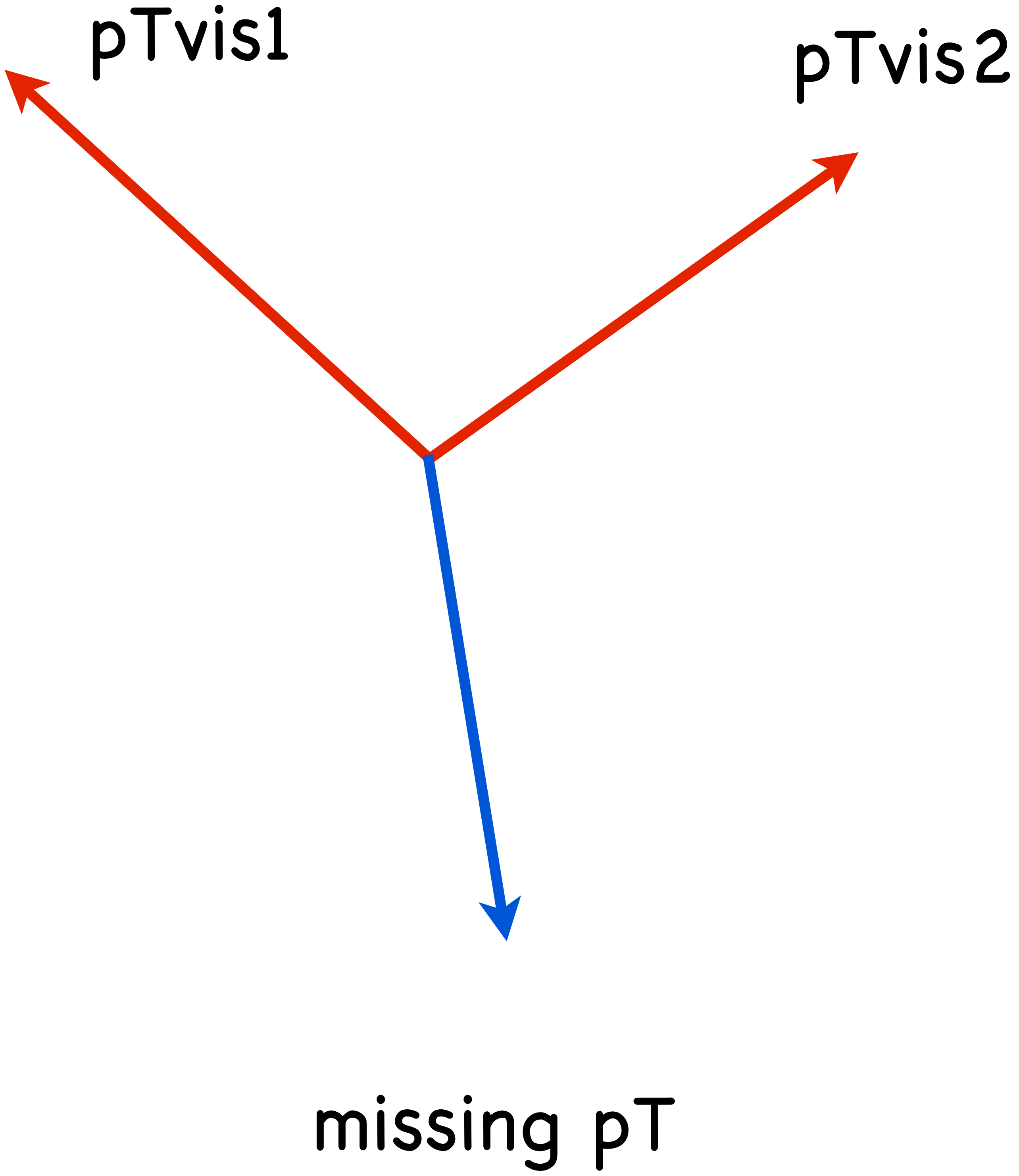
mT2 is kinematic endpoint variable:

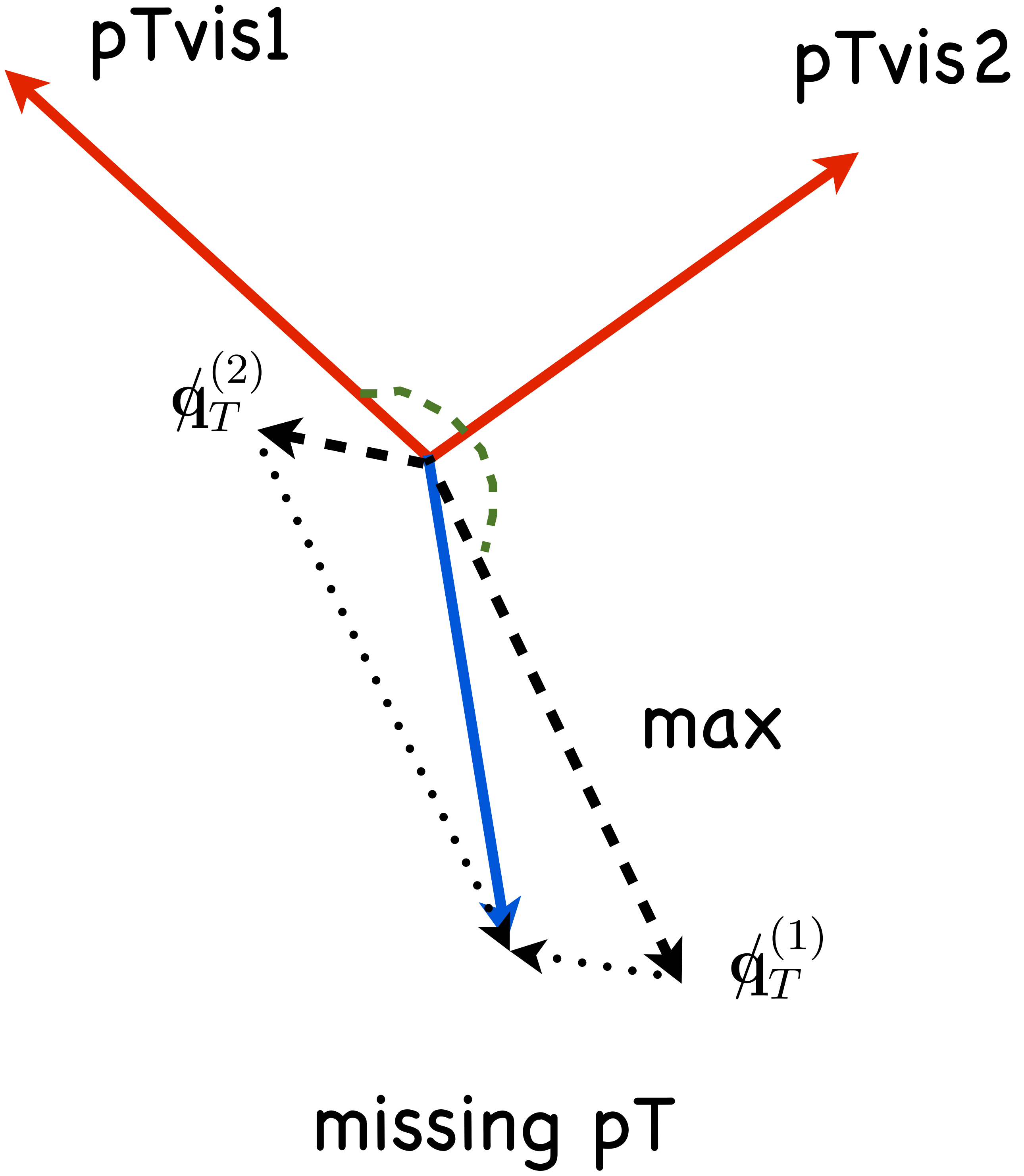
$$m_t+m_{\chi_1^0}\le m_{T2}(m_{\chi_1^0})\le m_{\tilde{t}}$$

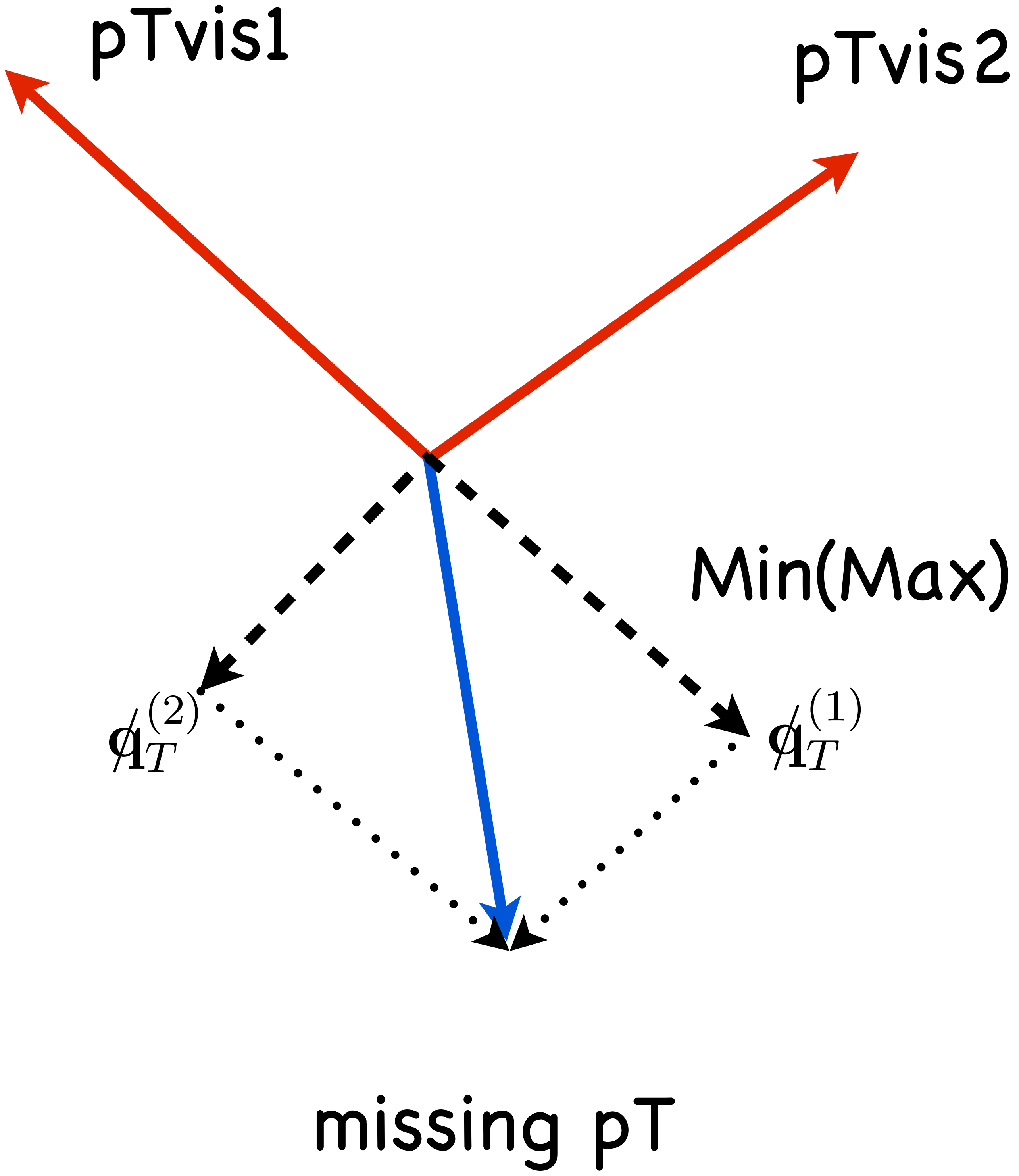
$$m_t+\chi\le m_{T2}(\chi)$$

$$\max_{\text{many events}}\left[m_{T2}(\chi)\right]=m_t$$



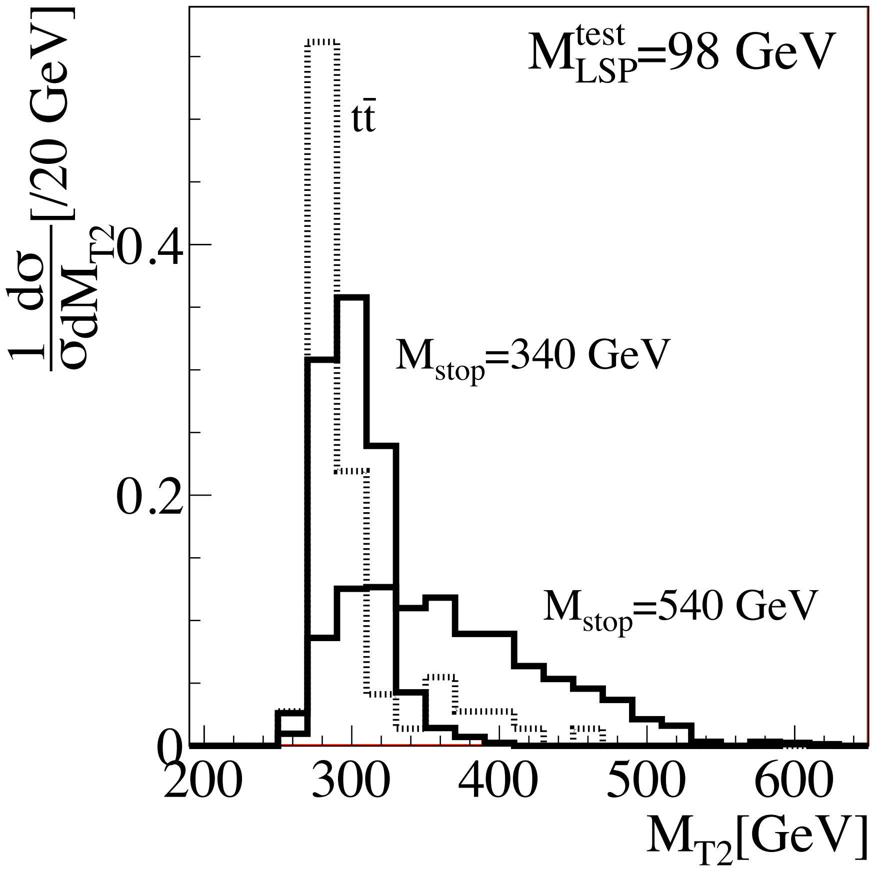

pTvis1
pTvis2
missing pT


pTvis1
pTvis2
$\not{q}_T^{(2)}$
max
$\not{q}_T^{(1)}$
missing pT


pTvis1
pTvis2
Min(Max)
$\not{q}_T^{(2)}$
$\not{q}_T^{(1)}$
missing pT

cuts: [Plehn, MS, Takeuchi, Zerwas JHEP 1010]

2 fat jets: $p_{T,j} > 200/200$ GeV
lepton veto
$\not{p}_T > 150$ GeV
2 tagged tops: $p_T^{\text{rec}} > 200/200$ GeV
b tag for 1st tagged top
$m_{T2} > 250$ GeV

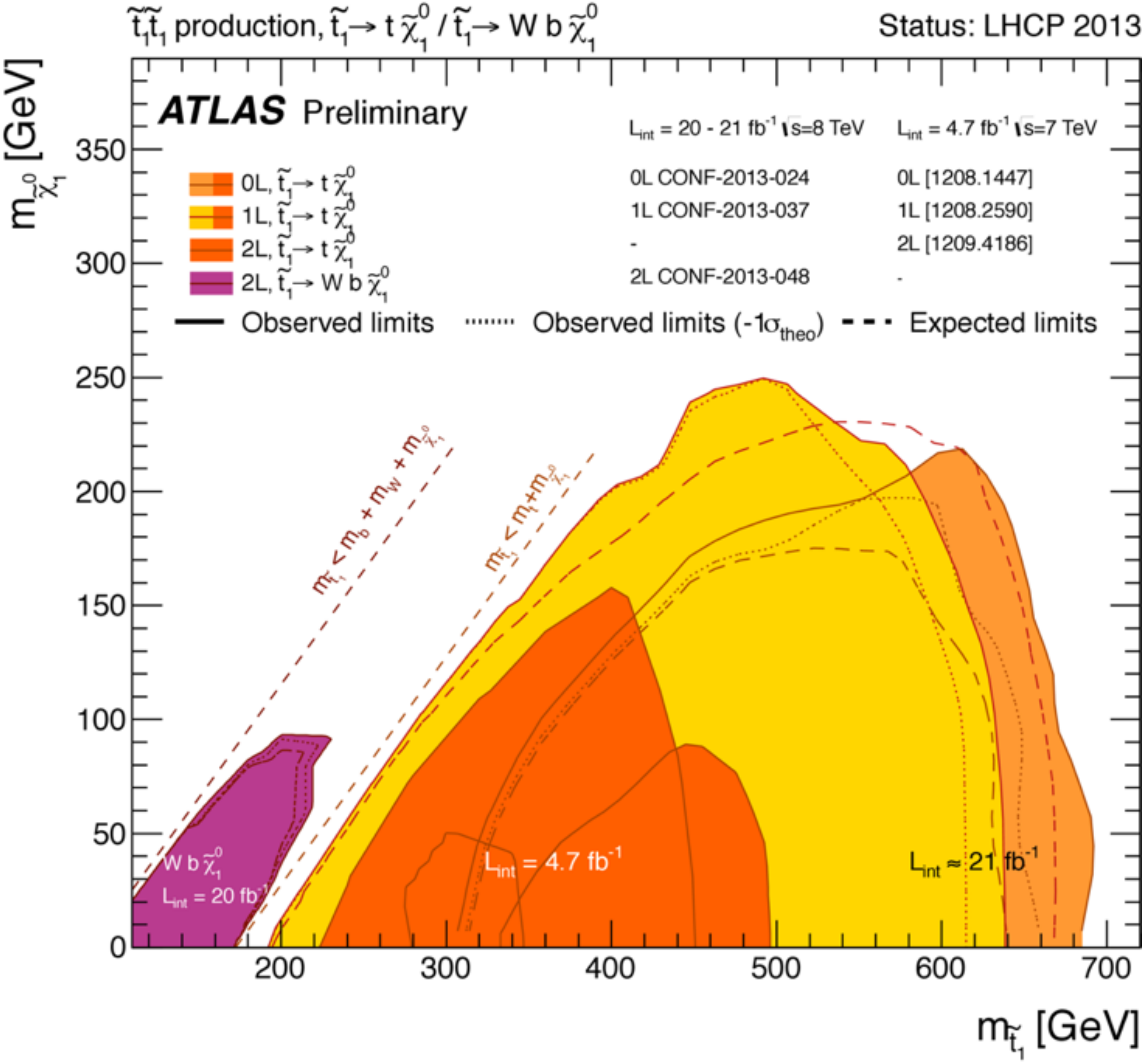


$$m_{T2}^2(\chi) \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{p}_T} \left[\max\left\{m_T^2(\mathbf{p}_T^{\mathbf{t}^{(1)}}, \not{q}_T^{(1)};\chi),\ m_T^2(\mathbf{p}_T^{\mathbf{t}^{(2)}}, \not{q}_T^{(2)};\chi)\right\}\right]$$

	$\tilde{t}_1\tilde{t}_1^*$						$t\bar{t}$	QCD	W+jets	Z+jets	S/B	$S/\sqrt{B}_{10\ \text{fb}^{-1}}$
$m_{\tilde{t}}$[GeV]	340	390	440	490	540	640					340	
$p_{T,j} > 200$ GeV, ℓ veto	728	447	292	187	124	46	87850	$2.4 \cdot 10^7$	$1.6 \cdot 10^5$	n/a	$3.0 \cdot 10^{-5}$	
$\not{p}_T > 150$ GeV	283	234	184	133	93	35	2245	$2.4 \cdot 10^5$	1710	2240	$1.2 \cdot 10^{-3}$	
first top tag	100	91	75	57	42	15	743	7590	90	114	$1.2 \cdot 10^{-2}$	
second top tag	15	12.4	11	8.4	6.3	2.3	32	129	5.7	1.4	$8.3 \cdot 10^{-2}$	
b tag	8.7	7.4	6.3	5.0	3.8	1.4	19	2.6	$\lesssim 0.2$	$\lesssim 0.05$	0.40	5.9
$m_{T2} > 250$ GeV	4.3	5.0	4.9	4.2	3.2	1.2	4.2	$\lesssim 0.6$	$\lesssim 0.1$	$\lesssim 0.03$	0.88	6.1

Tagger + mT2 go well together

340 - 540 GeV stop: $S/B \sim 1$ $S/\sqrt{B}_{10\ \text{fb}^{-1}} \simeq 6$


$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$
Status: LHCP 2013
ATLAS Preliminary
L_{int} = 20 - 21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
0L CONF-2013-024
0L [1208.1447]
1L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
1L CONF-2013-037
1L [1208.2590]
2L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
-
2L [1209.4186]
2L, $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$
2L CONF-2013-048
-
Observed limits
Observed limits ($-1\sigma_{theo}$)
Expected limits
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$W\,b\,\tilde{\chi}_1^0$
L_{int} = 20 fb^{-1}
L_{int} = 4.7 fb^{-1}
L_{int} ≈ 21 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
0
50
100
150
200
250
300
350
200
300
400
500
600
700
$m_{\tilde{t}_1}$ [GeV]

Prospects in top physics for the ILC

- Better precision - less noise!
- Likely not to be systematics limited
- Potentially off-shell contributions in $e^+e^- \to \bar{t}t$ from heavy resonances
- Improved measurement of all kinds of couplings: anomalous couplings, tth, hh, hbb, ... (need at least 500 GeV)
- Improved direct measurement of mass and width
- Polarized beams can enrich tops of specific polarization
- Study QCD radiation, event shapes, jet substructure

Summary

- The top quark is the new elephant in the room

(much weaker, prepared to give up, .e.g Split SUSY....)

- In pre-Higgs times we had the EW scale as target range for new physics (top mass, W and Z, Unitarization).

  If not ~ 200 GeV say 3 TeV for composite models

  → Now we dont really!

  → Last guiding principle: Naturalness

  → Top partner search!

- Top affects Higgs most and is participating in all interactions

- If Higgs looks SM-like in 3 years from now, its the top to be looked into