# The Top Forward-Backward Asymmetry

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JS and K. Zurek: `arXiv:1101.5392`
J. Hewitt, JS, M. Spannowsky, M. Takeuchi, T. Tait, `arXiv:1103.xxxx`

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# The top quark

- The top quark is one of the most promising places to search for new physics.
- The top plays a privileged role in theories of EWSB:

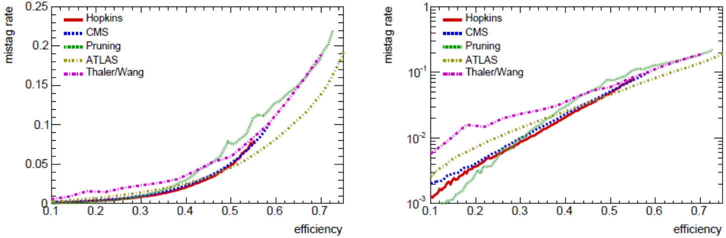
$$\lambda_t \approx 1$$

  - Hierarchy problem + precision electroweak: top partner, dark matter candidate: $t\bar{t}$+MET
- The top also has large couplings to flavor symmetry breaking physics
- Top properties are least well-measured: more room for new physics.

# Tops at the LHC

LHC is the first top factory: new era in top physics

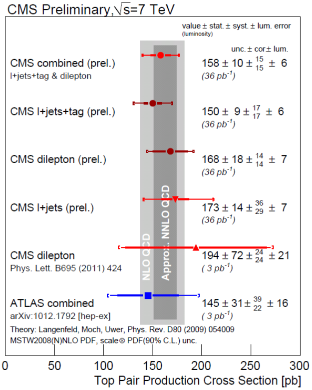
- Will accumulate large samples: unprecedented sensitivity to top properties
- Will inhabit novel kinematic regime: $\sqrt{s} \gg m_t \gg \Lambda_{QCD}$
  - need to develop novel reconstruction strategies: boosted top tagging



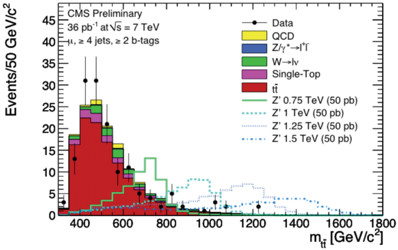

BOOST 2010 proceedings

# Tops at the LHC

LHC is already probing new mass ranges:



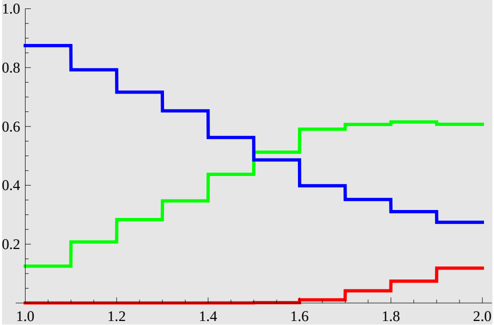

CMS TOP-11-001-PAS




CMS TOP-10-007-PAS

# Tops in intermediate mass range

CM range 1 TeV–2 TeV poses special challenges:




Fraction of tops resolved as three, two, and one partonic objects at $\Delta R < 0.4$, as a function of $\sqrt{s}$ (TeV)

$\Rightarrow$ To fully exploit the potential of first LHC run, need multiple event reconstruction techniques

# Tops in intermediate mass range

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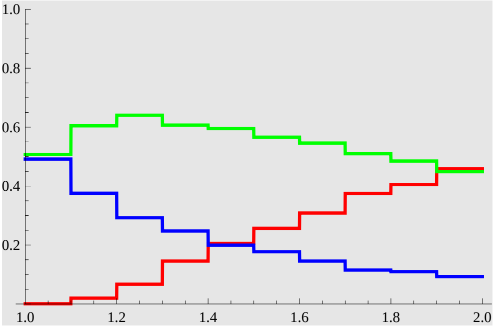
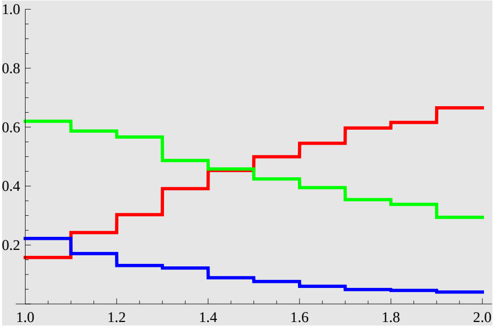



Fraction of tops resolved as three, two, and one partonic objects at $\Delta R < 0.6$, as a function of $\sqrt{s}$ (TeV)

$\Rightarrow$ To fully exploit the potential of first LHC run, need multiple event reconstruction techniques

# Tops in intermediate mass range

CM range 1 TeV–2 TeV poses special challenges:

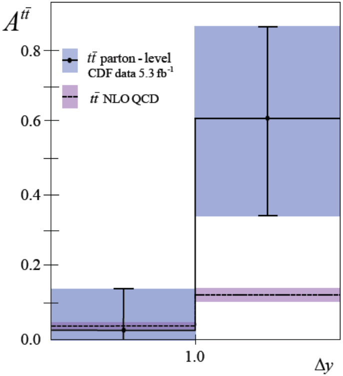


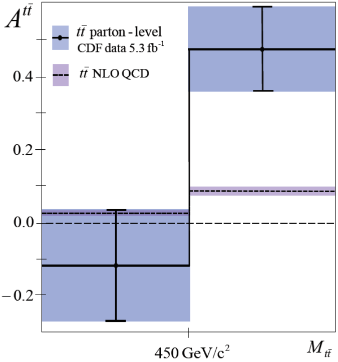

Fraction of tops resolved as three, two, and one partonic objects at $\Delta R < 0.8$, as a function of $\sqrt{s}$ (TeV)

$\Rightarrow$ To fully exploit the potential of first LHC run, need multiple event reconstruction techniques

# Top physics at the Tevatron

- D0, CDF have consistently observed anomalously large values for $A_{FB}^{t}$ at $\gtrsim 2\sigma$ level
- Recent CDF measurements of asymmetry in different kinematic regions:

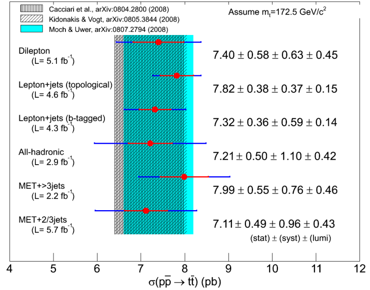


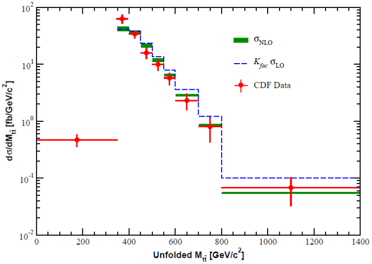

High-mass asymmetry $A_{hi}^{t} = 0.475 \pm 0114$, $3.4\sigma$ from SM (MC@NLO)

# The pair production cross-section

- Other top properties – in particular the top cross-section – are in very good agreement with the SM




CDF measurements of $\sigma(p\bar{p} \to t\bar{t})$

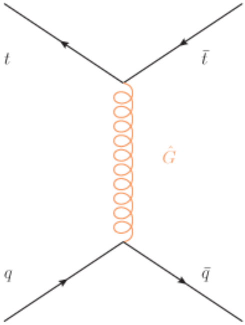



from Cao, McKeen, et al. '10

- Must explain large asymmetry without significant change to cross-section

# Strategies to generate large $A_{FB}^{t}$

- To successfully explain all top measurements, generate asymmetry from interference of new physics with SM
- In particular, must interfere with $q\bar{q} \to t\bar{t}$, which restricts to 2 possibilities:




- *s*-channel exchange of spin 1 octet
  (Frampton, Shu, Wang; Chivukula, Simmons, Yuan; Bai, Hewett, Kaplan, Rizzo)
- asymmetry $\propto -g_A^{u,d} g_A^t$: to get positive asymmetry, require flavor nonuniversal couplings

# Strategies to generate large $A_{FB}^t$

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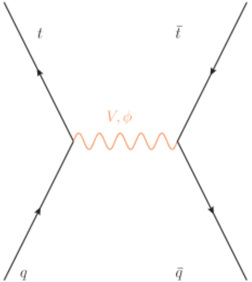



- *t*-channel exchange of spin 0,1, several color structures possible

  (Jung, Murayama, Pierce *et al.*; Shu, Tait, Wang; Cheung, Keung, Yuan; Barger, Keung, Yu; JS, Zurek; Grinstein, Kagan, Trott, Zupan; Ligeti, Schmaltz, Tavares )
- right magnitude for asymmetry requires large flavor-off-diagonal couplings

# Strategies to generate large $A_{FB}^t$

- To successfully explain all top measurements, generate asymmetry from interference of new physics with SM
- In particular, must interfere with $q\bar{q} \rightarrow t\bar{t}$, which restricts to 2 possibilities:

Both strategies require departure from SM flavor structure. *t*-channel large flavor violation striking. Is it possible to accommodate this flavor structure elsewhere in the SM?

1. MFV: (Grinstein, Kagan, Trott, Zupan; Ligeti, Schmaltz, Tavares)
2. extend Maximally Flavor Violating structure beyond top (JS, Zurek)

# Constructing a maximally flavor-violating model

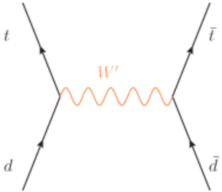
- Connect $A_{FB}^t$-motivated flavor structure to outstanding anomalies in $b$-sector
- Introduce new flavor non-universal $SU(2)_R$ coupling to fermions in the combinations

$$\begin{pmatrix} u_R \\ b_R \end{pmatrix}, \qquad \begin{pmatrix} t_R \\ d_R \end{pmatrix}$$

- Do not couple to $(c_R, s_R)$
- Include small $b$-$s$ mixing $S_{sb}$
- Fix masses and couplings from $A_{FB}^t$, examine consequences for $B$ sector

# Fixing boson masses and couplings

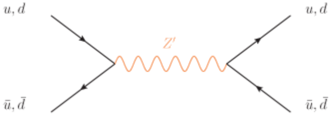
$A^t_{FB}$ generated by $W'$ exchange:




- require $m_{W'} \sim$ 450-600 GeV,
  $\tilde{g} \sim$ 1.5-2

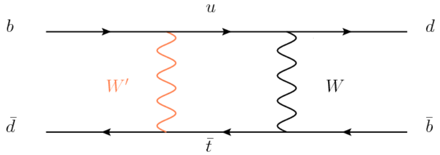
  (Cheung, Keung, Yuan)
- no trouble with dijet constraints (or same sign tops)

- Unlike $W'$, $Z'$ constrained by dijet searches
- Avoiding Tevatron limits (still okay for LHC...) requires $m_{Z'} \gtrsim$ 900 GeV



# Implications for $B$ physics

- New contributions to $B_d^0 - \bar{B}_d^0$ mixing:




- no CKM suppression
- smallness of $m_u$ makes this diagram phenomenologically viable:

$$\mathcal{M}_{RL} = -\frac{g^2 \tilde{g}^2 m_t m_u}{32\pi^2 m_{W'}^4} \mathcal{G}\left(\frac{m_t^2}{m_{W'}^2}, \frac{m_W^2}{m_{W'}^2}\right) \langle(\bar{d}\gamma^\mu \mathcal{P}_R b)(\bar{d}\gamma_\mu \mathcal{P}_L b)\rangle$$

- Order 20% of SM contribution:

$$\frac{\mathcal{M}_{RL}}{\mathcal{M}_{SM}} = -0.2 \left(\frac{\tilde{g}}{2}\right)^2 \left(\frac{450\text{ GeV}}{m_{W'}}\right)^4 \frac{\mathcal{G}(m_{W'}^2)}{\mathcal{G}(450\text{ GeV})}$$

# Implications for $B$ physics

- The magnitude of the box diagram is in the right range to help explain the D0 wrong sign dimuon asymmetry,

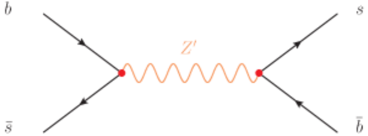
$$
\begin{aligned}
a_{sl}^{b} &\equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \\
&= (-9.57 \pm 2.51 \pm 1.46) \times 10^{-3} \text{ (D0)} \\
&= -2.3^{+0.5}_{-0.6} \times 10^{-4} \text{ (SM)}
\end{aligned}
$$

  $3.2\sigma$ discrepant with the standard model

- Dimuon asymmetry receives contributions from both $B_d^0$ and $B_s^0$: $a_{sl}^b = 0.51 a_{sl}^b + 0.49 a_{sl}^s$
- To explain with new physics contributions to mixing: 20% contribution to $B_d^0$ mixing, 60% contribution to $B_s^0$ (Ligeti, Papucci, Perez, Zupan)

# $b$-$s$ mixing

- New contributions to $B_s^0$-$\bar{B}_s^0$ mixing can be generated via small mixing $S_{sb}$ between $b_R$ and $s_R$ :




$$\frac{S_{sb}^2 \tilde{g}^2}{m_{Z'}^2} (\bar{b}_R \gamma^\mu s_R)(\bar{b}_R \gamma_\mu s_R)$$

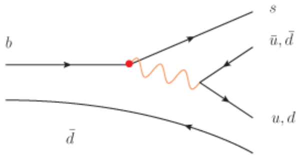
- D0 dimuon asymmetry requires $|S_{sb}| \simeq 10^{-2.5}$; this also fixes the phase

- No problems with kaon mixing: $\text{CKM}_{L,R}$-suppressed box diagram below experimental uncertainty

- No problems with $B_s \to \mu^+ \mu^-$

# $b$-$s$ mixing

- Interesting contributions to rare $B_d^0$ decays:




- SM contributions to $b \to s\bar{q}q$-dominated decays are loop-suppressed: sensitive to new physics
- With $|S_{sb}| \simeq 10^{-2.5}$, $m_{Z'} \simeq$ TeV, $\tilde{g} \sim 1$, find $Z'$ contribution is of the correct order of magnitude to contribute to penguin-dominated modes: predictions

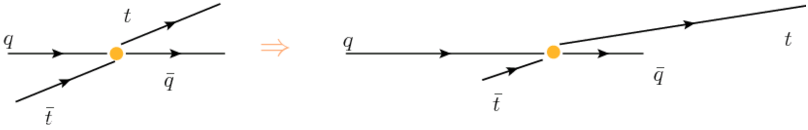
# But are any of these anomalies really new physics?

Fortunately, LHC has the potential to assess this, whether immediately or in the long term

# Top asymmetries at the LHC

- Symmetric initial state – and *gg* dominance – limit but do not eliminate LHC sensitivity to $A_{FB}^{t}$

(Kuhn, Rodrigo; Antunano, Kuhn, Rodrigo)




- typical valence-sea kinematics translate a positive forward-backward partonic charge asymmetry into a positive forward-central charge asymmetry:

$$\mathcal{A}_F(y_0) = \frac{N_t(y_0 < |y| < y_m) - N_{\bar{t}}(y_0 < |y| < y_m)}{N_t(y_0 < |y| < y_m) + N_{\bar{t}}(y_0 < |y| < y_m)}$$

Xiao, Wang, Zhou, Zhu; Hewett, JS, Spannowsky, Tait, Takeuchi

# Top asymmetries at the LHC

- Sensitivity to underlying asymmetry is greatest for high $p_T$ tops:
  - The asymmetry (SM or BSM) is enhanced at high invariant mass
  - The symmetric $gg \to t\bar{t}$ falls off faster than $gq, q\bar{q} \to t\bar{t}$
- Event reconstruction strategy: consider moderately boosted, semileptonic tops
  - require isolated lepton with $p_T > 15$ GeV and $|y| < 2.5$.
  - require hadronic top to pass HEPTopTagger (Plehn, Salam, Spannowsky; Plehn, Spannowsky, Takeuchi, Zerwas): requires $p_{T,t} > 200$ GeV.
  - Demand $b$ tag inside hadronic top
- After these cuts main $W+$ jets background is negligible.

# Top asymmetries at the LHC

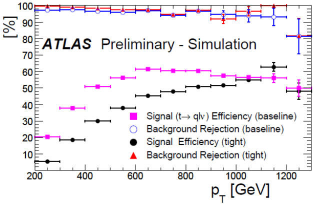
- Optimal separation of forward and central regions with $y_0 = 1.5$
- Standard model asymmetry:
  - is small: $\mathcal{A}_F^{SM} = 0.0149 \pm 0.0046$ (MC@NLO, statistical error only)
  - can measure at $5\sigma$ in $60\,\mathrm{fb}^{-1}$ at 14 TeV
- flavor-violating $Z'$ model:
  - larger asymmetry: $\mathcal{A}_F^{Z'} \approx 0.09$
  - can measure at $5\sigma$ in $10\,\mathrm{fb}^{-1}$ at 14 TeV
- in $10\,\mathrm{fb}^{-1}$ at 7 TeV: can see large BSM asymmetry at $2.8\sigma$

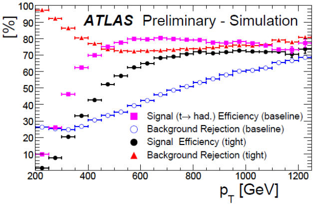
# Signals for the early LHC

- Even if $\mathcal{A}_{\mathcal{F}}$ cannot be measured in first LHC run, $d\sigma/dm_{t\bar{t}}$ certainly can.
- The Tevatron anomaly points to new physics with appreciable couplings well within kinematic reach of LHC 7
- Estimate search reach in $t\bar{t}$ production cross-section using top reconstruction techniques adapted to intermediate $\sqrt{s}$ range

# Semileptonic top tagging via ATLAS

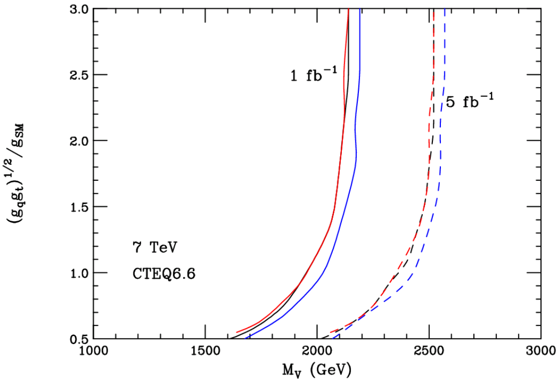
- Dominant contribution to reach comes from semileptonic tops: less background
- We use the (monojet) semi-leptonic top tagging procedure detailed in ATL-PHYS-PUB-2010-2008.




- Augmenting search with other modes and techniques can and will improve sensitivity

# Limits on $t\bar{t}$ resonances

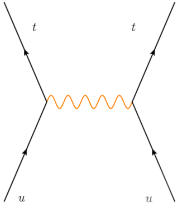


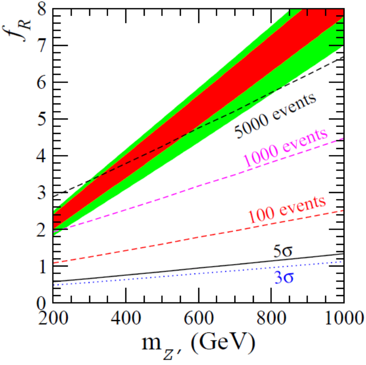

Limits on axial vector and vector color octet resonances; with all-hadronic channel (estimate)

ATLAS semileptonic tagging efficiencies; HEPTopTagger hadronic tagging efficiencies

# Early LHC searches in other channels

- LHC also has good reach for *t*-channel models in the early run
- Same-sign tops: Very low standard model background enables stringent limits (Jung, Murayama, Pierce *et al.*; Berger, Cao, Chen, *et al.*)

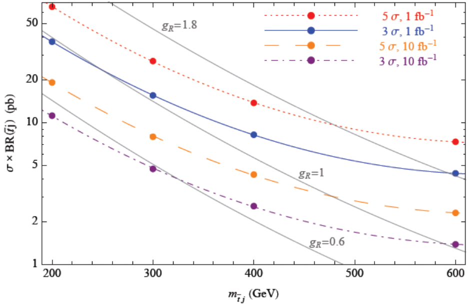



From Berger *et al.*: LHC dimuon event rate contours at 1 fb$^{-1}$

# Early LHC searches in other channels

- If the $t$-channel mediator is not self-conjugate, then search reach provided by single top processes: $qg \to tX$
- search reach from reconstructed $tj$ resonances:



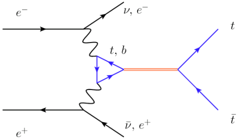

From Gresham, Kim, Zurek: LHC reach in $tj$ for a $W'$

- if $t$-mediator couples to both $u$, $d$, $ud \to tq$ yields a charge asymmetry which can give constraints with $< 1\ fb^{-1}$

(Craig, Kilic, Strassler)

# Implications for the ILC?

- If new physics responsible for $A^t_{FB}$, not obviously an advantageous scenario for the ILC. NP is likely:
  - heavy: $m \gtrsim 500$ GeV
  - leptophobic
  - not obviously related to EWSB.
- Anything coupling to $t\bar{t}$ will be produced at a linear collider at some level through effective gauge boson scattering:




...but rates may be low and CM energy key

- New indirect effects on top production would require study

# Conclusions

- If anomaly in $A^t_{FB}$ persists, it indicates new flavor structures
- The CDF observations of $A^t_{FB}$ suggest new physics well within reach of early LHC
  - All models proposed to date will be tested with early LHC data
  - LHC has reduced sensitivity to $A^t_{FB}$: with current approaches $2-3\sigma$ sensitivity to a large BSM effect in 7 TeV run
- LHC will be able to measure the SM $A^t_{FB}$ at 14 TeV
- Meanwhile Tevatron can make additional measurements which could clarify the picture (stay tuned!)

# Backup: boson masses and symmetry breaking

- Achieving a large $m_{W'} - m_{Z'}$ mass splitting:
  - $U(1)$ mixing requires extreme values of couplings
  - higher-dimensional Higgs representations:

$$\frac{m_{W'}^2}{m_{Z'}^2} = \frac{1/2(T(T+1) - T_3^2)}{T_3^2}$$

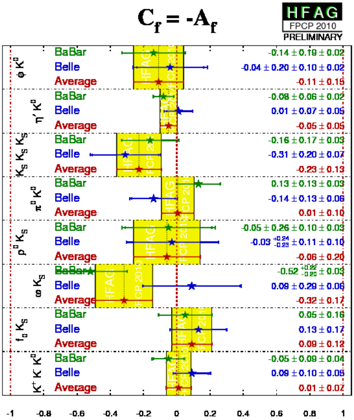
- Working model:

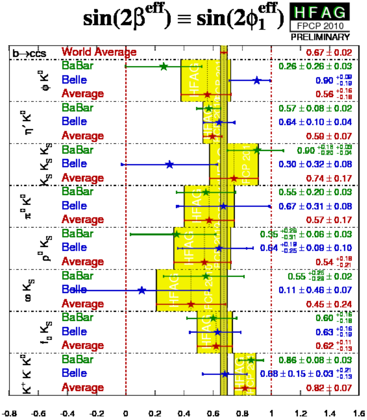
$$SU(2)_R \times U(1)' \times SU(2)_L \to SU(2)_L \times U(1)_Y$$

  with dominant source of $SU(2)_R \times U(1)'$-breaking in a dimension $d \geq 3$ of $SU(2)_R$.

- $Z'$-$Y$ mixing shifts fermion couplings to $Z$ and opens rare decay modes, but mixings suppressed by $m_Z^2/m_{Z'}^2$ and $g_1/\tilde{g}$, and are not dangerous

# Backup: penguins




HFAG Summer 2010 world averages for hadronic $b \to s$ penguin modes

# Backup: ATLAS top tagger

- Baseline selection cuts: $\geq 3$ hard jets, isolated hard lepton, $p_{Tj1} > 250$ GeV
- Hadronic top candidate:
  - $m_j > 100$ GeV
  - Energy sharing variable $z_{ij} = \frac{d_{ij}}{d_{ij}+m_j^2} > 0.08$ (Brooijmans; Thaler, Wang)
  - Smallest $j$-$j$ invariant mass of 3 $k_T$-clustered subjets: $Q_W > 30$ GeV
- Leptonic top candidate: principal variables (some cuts differ for $e$, $\mu$)
  - lepton-jet separation: $R_{\ell j} < 1$
  - lepton-jet invariant mass: $Q_W > 50$ GeV
  - "mini-isolation": $I_{tk} = \sum_{cone} p_{Ti}/p_{T\ell}$ (Rehermann, Tweedie)
  - lepton-jet energy sharing $x_\ell = \frac{E_\ell}{E_\ell+E_j} > 0.35$
- Reconstruct neutrino with $W$ mass constraint; require $MET > 60$ GeV if $m_{TW} < 40$ GeV