Seeking Clues for the Next Sakata

Matt Strassler

Oct 27, 2011

SAKATA100 at the new KMI

A Very Different World

- In Sakata's day there were many surprising discoveries
  - New charged leptons, new neutrinos, new hadrons

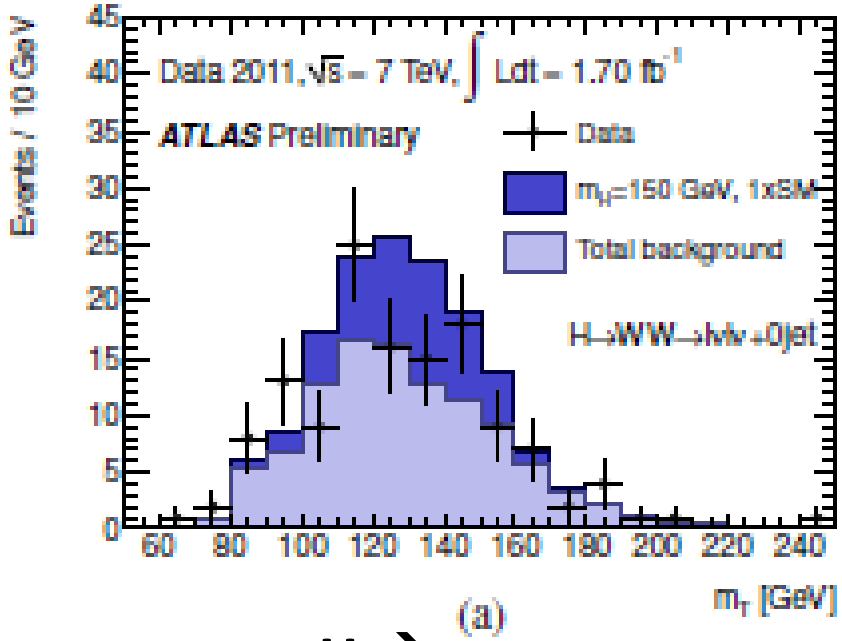
- The back-and-forth between theory and experiment occurred rapidly
  - Sakata took great advantage!

- Problem for next Sakata: We have been living in a different era
  - Great experimental progress in understanding neutrinos
    - Neutrinos are not so easy to use theoretically (seesaw: $\mathbf{m = Y\, M^{-1}\, Y}$)
  - Great observational progress learning about cosmology
    - Dark matter unknown, dark energy confusing, both hard to study
  - Great progress constraining /excluding many speculative ideas
    - Absence of clues is not such a useful clue

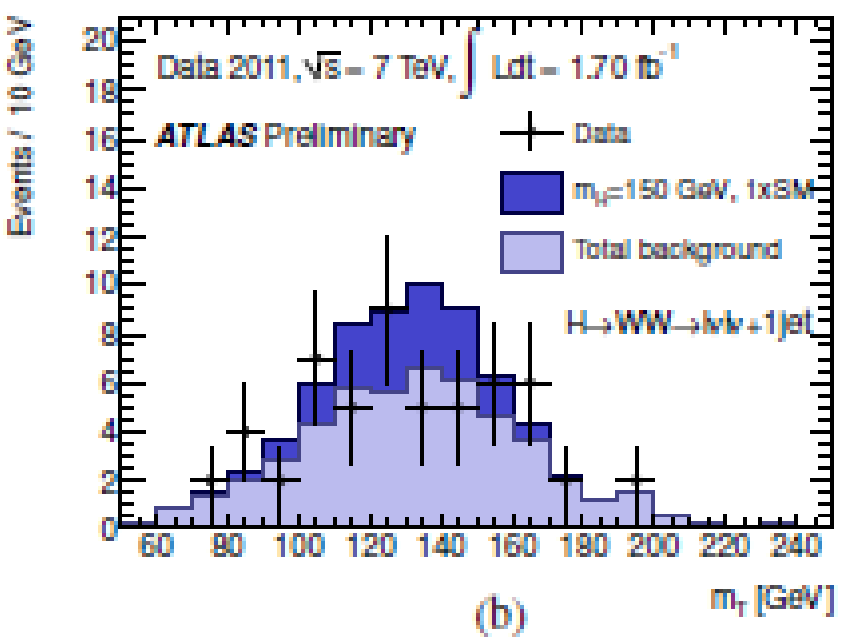
The First (Real) Year of the LHC

- But fortunately the LHC era is well underway
- Summer 2011 has changed what we know about high-energy physics
  - No Standard Model Higgs above 145 (140? 135?) GeV
    - Expt (CMS & ATLAS together) says not 145-450
    - Theory (precision loop calculations) says not above ~400
  - Nothing like popular version of supersymmetry at TeV scale
    - Jets from high-energy quarks + MET from dark matter neutralinos
  - Nothing obvious wrong with quantum field theory up to 3 - 4 TeV

H → W W

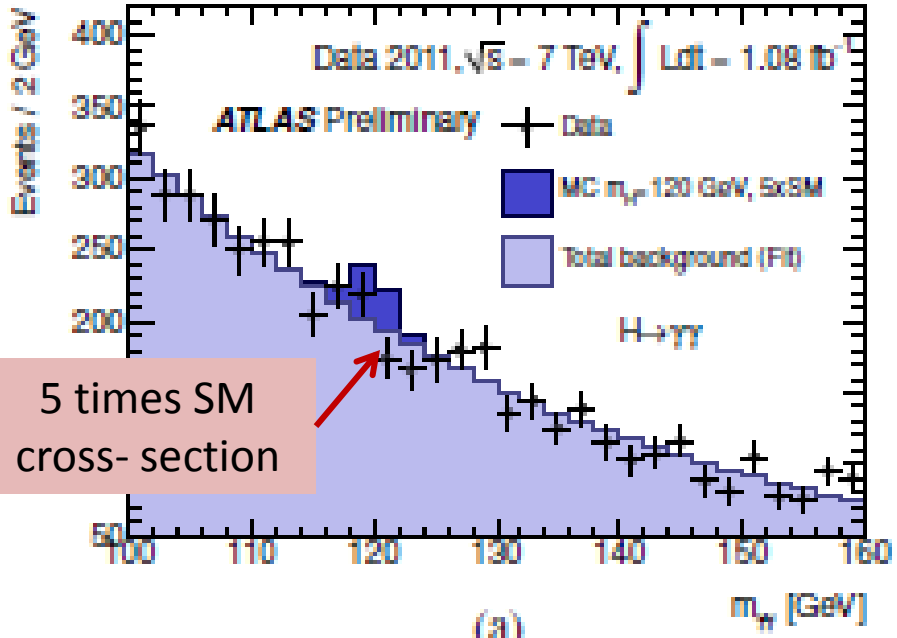


(a)



(b)

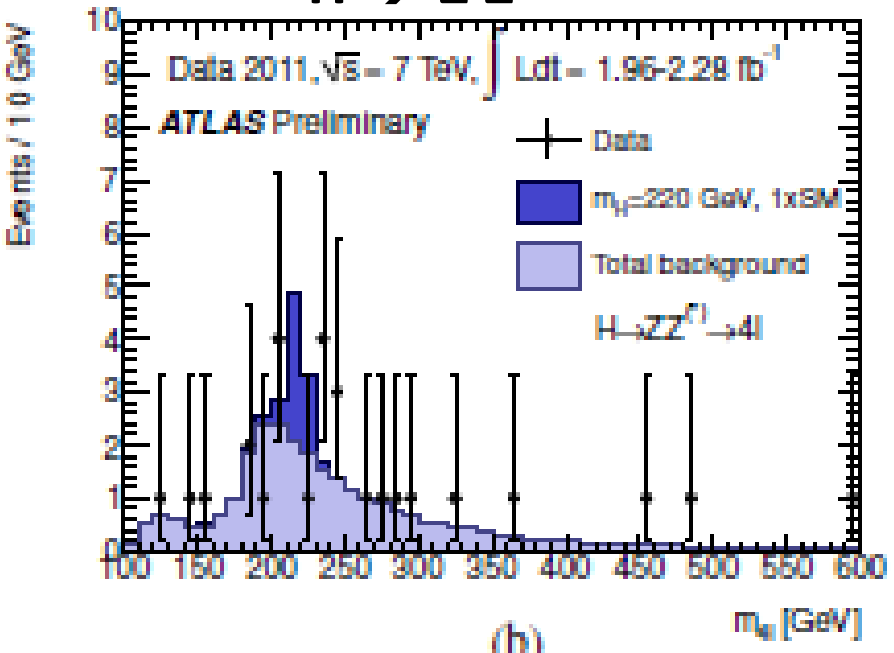
H → γ γ



5 times SM cross- section

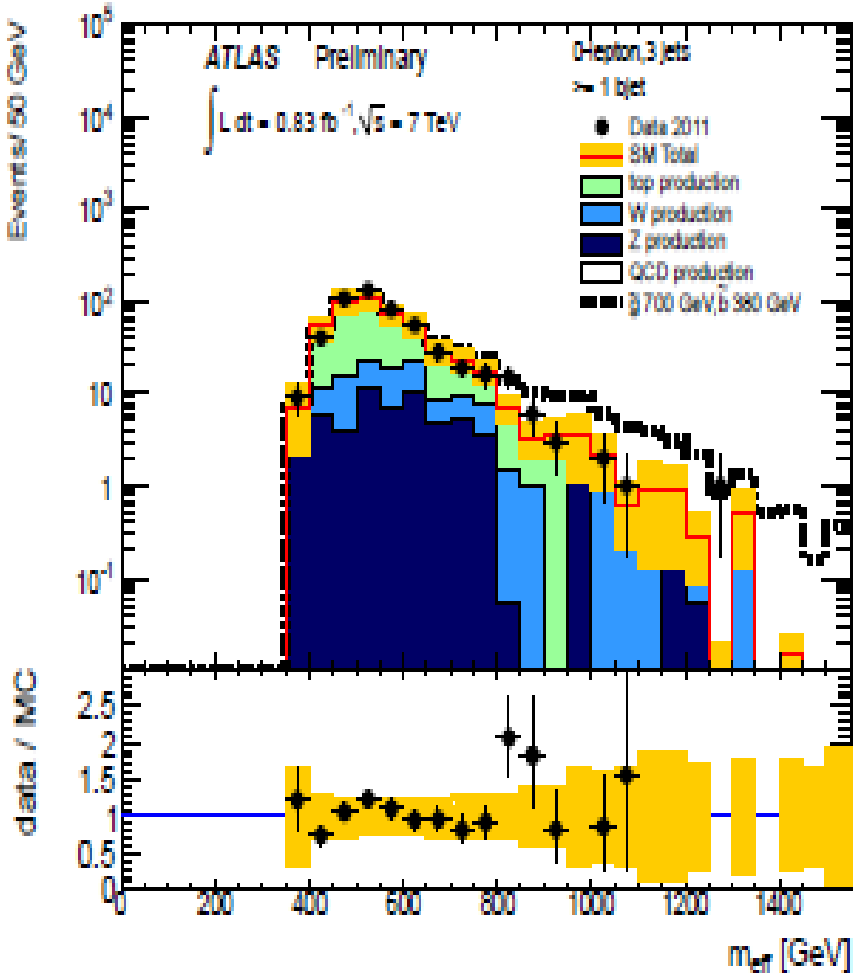
(a)

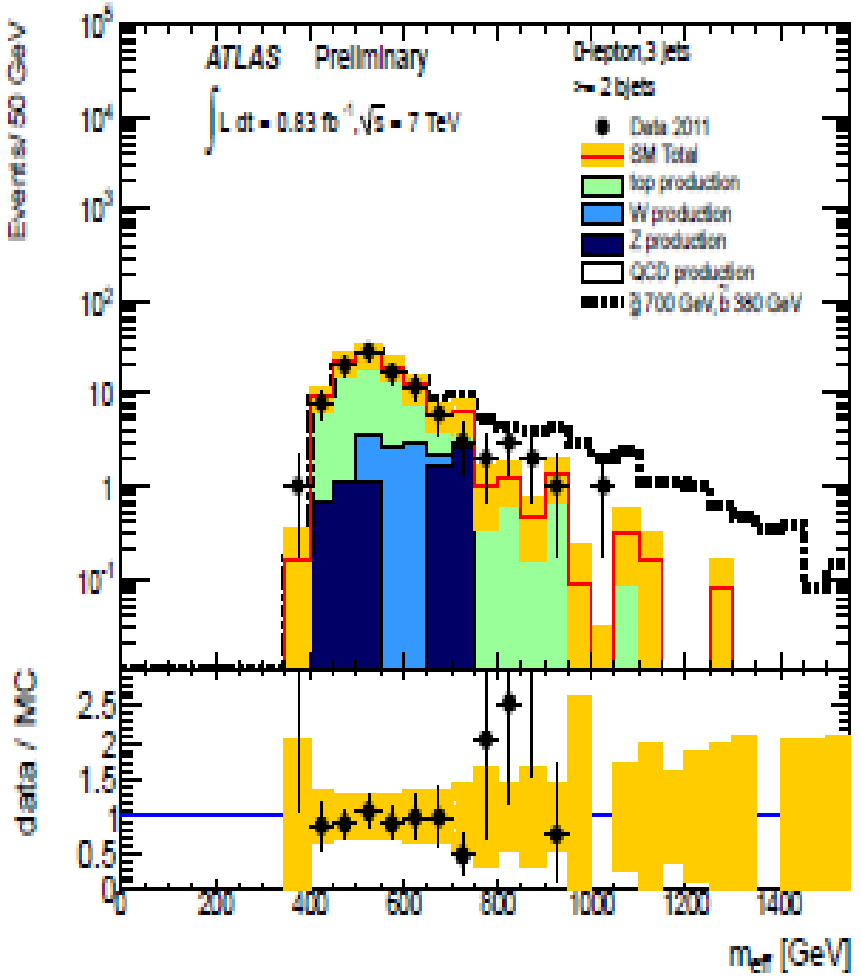
H → Z Z

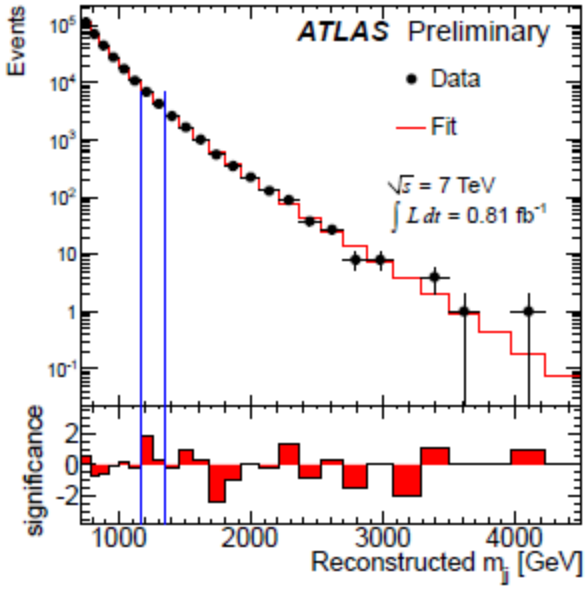


(b)

ATLAS Supersymmetry search (jets + MET with b tags)

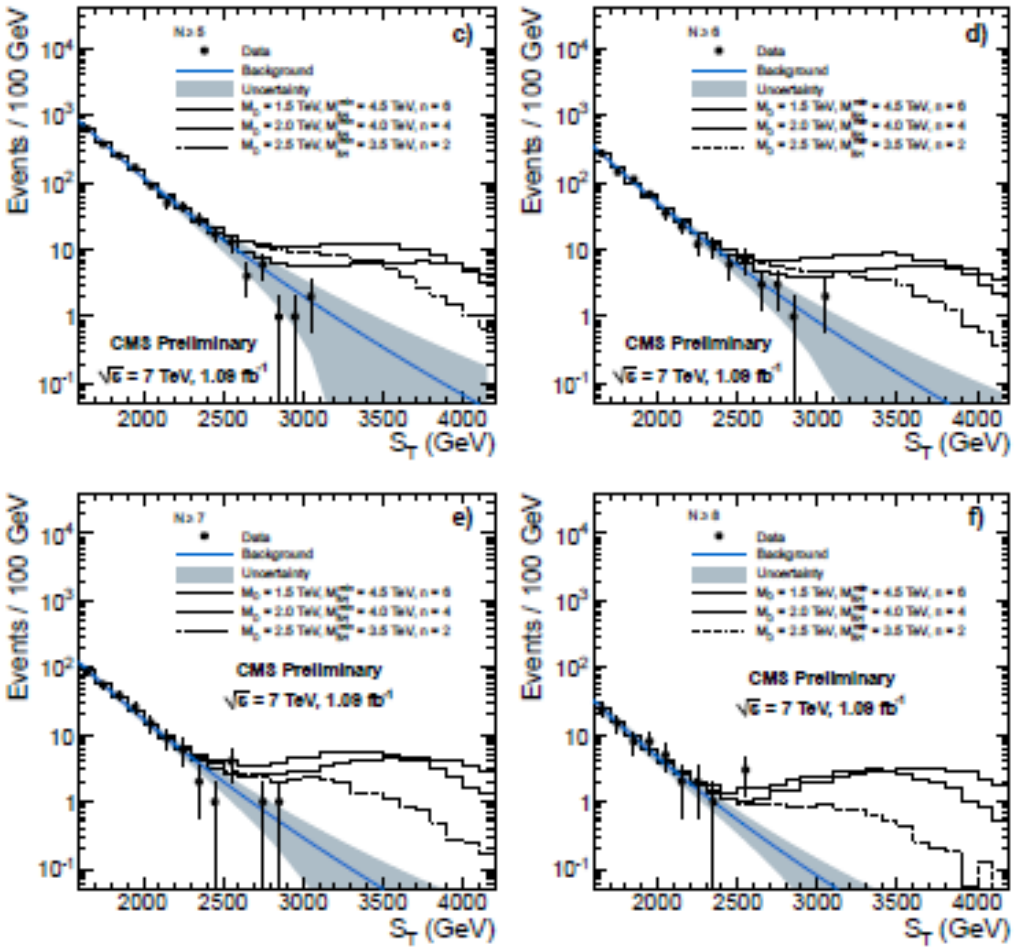






Dijets at ATLAS

No ``Black Holes ‘’at CMS



The First Summer of the LHC

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    - Theory says not well above 300

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      - from high-energy quarks + invisible neutralinos, or similar

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- **Nothing in the data as it has been searched so far**!!

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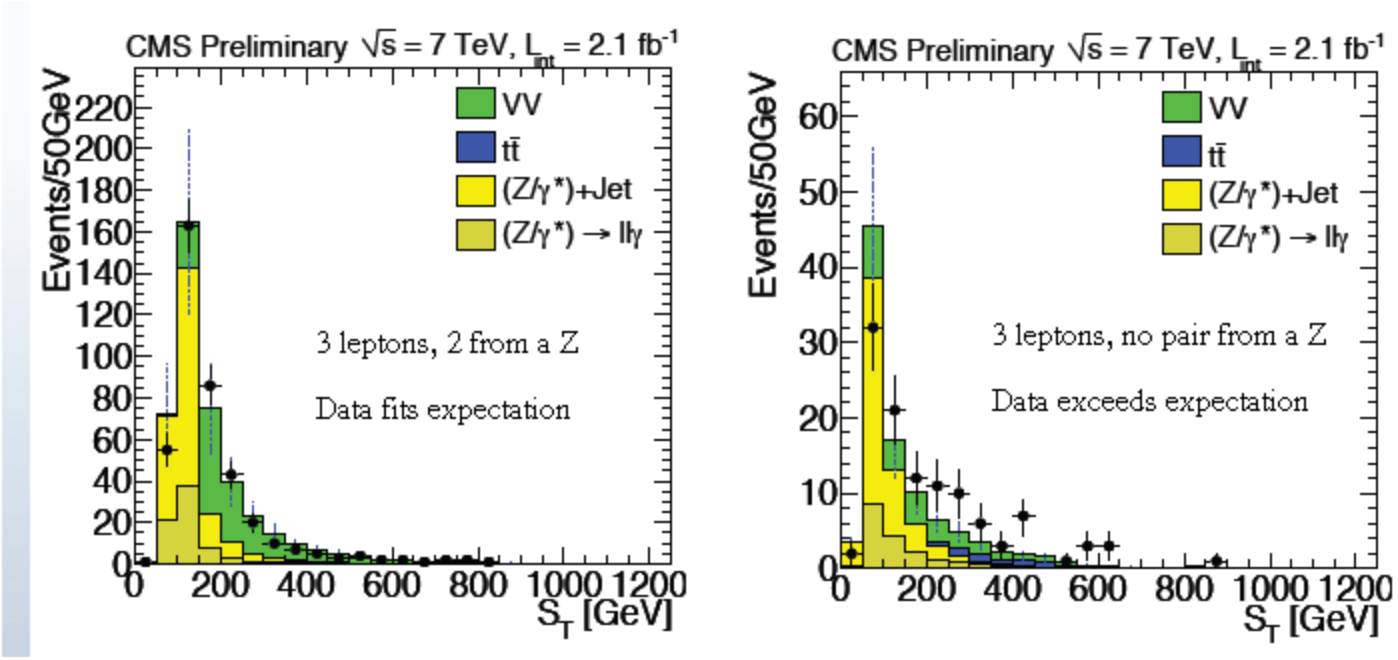
Last Week's News:

- **ing in the data as it has been searched so far**!!

CMS Tri-lepton Events

- Small excess -- not significant, but interesting
- Something to keep an eye on – at this point, nothing more



Plots taken from Richard Grey's talk at last week's Berkeley SUSY Workshop

ST= scalar sum of pT of leptons, jets and missing transverse momentum

Reminder of the LHC and its Experiments

- 3.5 TeV per beam

- Integrated Luminosity
  - ~ 35 pb^{-1} last year per experiment
    - Z cross section is few thousand pb, top cross section 160 pb
    - Higgs/SUSY cross section is 10 pb or lower
  - 1000 pb^{-1} = 1 fb^{-1} March – July, ~2 fb^{-1} by August
    - (most available results are 1 fb^{-1} of data)
  - ~5 fb^{-1} by end October (end of 2011 pp run)

- Pileup: dozens of pp collisions each time two proton bunches cross
- Trigger: thresholds for selecting events to store are rising dramatically

Two Topics

- Flavor Physics: Testing the Predicted Physics of Quarks
  - Standard Model predicts small forward-backward asymmetries
  - Tevatron observes larger top quark forward-backward asymmetry
  - ???

- The Potentially Unexpected: Searching for Hidden Valleys
  - A hidden sector with lightweight particles and a mass gap
  - These can alter expected signals for new physics

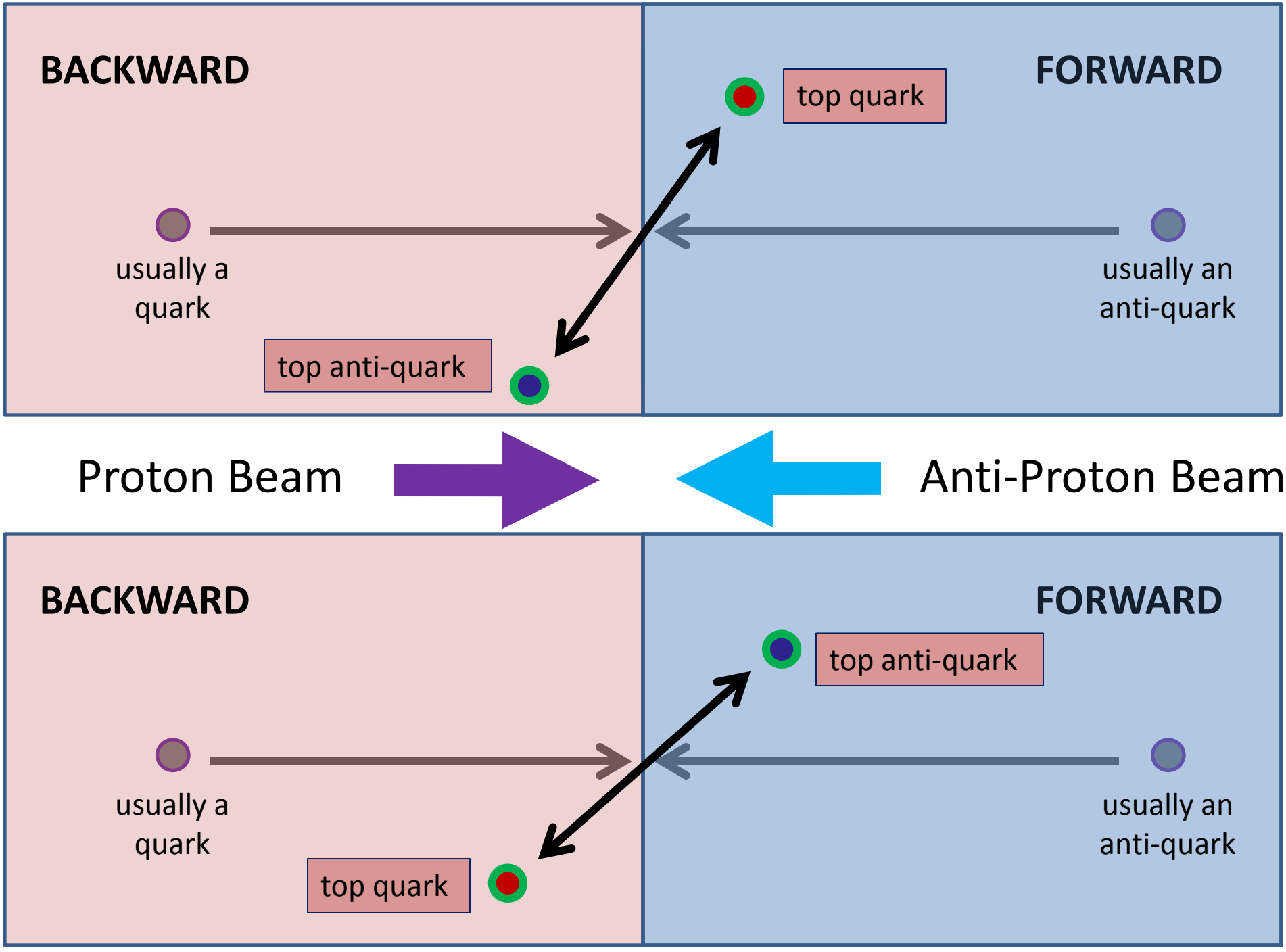
Quark-Antiquark Asymmetries at Tevatron and LHC

Tevatron Top-quark Forward-Backward Asymmetry

- proton + anti-proton → top + anti-top

- Since t t-bar is heavy, high-x process
  - gg → t t-bar small
  - q q-bar → t t-bar ; q comes from p, q-bar from p-bar

- Therefore we may ask
  - Does top quark travel in **forward** direction equally to **backward**?
    - Forward defined relative to p direction


BACKWARD
FORWARD
top quark
usually a quark
usually an anti-quark
top anti-quark
Proton Beam
Anti-Proton Beam
BACKWARD
FORWARD
top anti-quark
usually a quark
usually an anti-quark
top quark

Tevatron Top-quark Forward-Backward Asymmetry

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  - Does top quark travel in **forward** direction equally to **backward**?
    - Forward defined relative to p direction

$$A_{FB} = \frac{N(qy > 0) - N(qy < 0)}{N(qy > 0) + N(qy < 0)},$$

- q q-bar → t t-bar symmetric only at tree-level
  - picks up small asymmetry (6—8 %) at Next-to-Leading-Order (NLO)

- gg → t t-bar symmetric forward to back

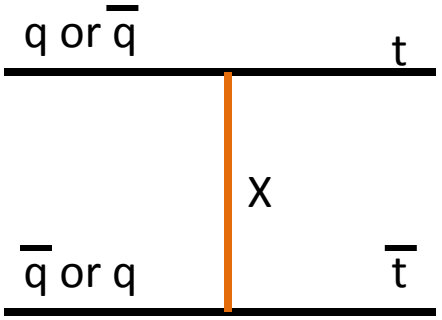
Tevatron Top-quark Forward-Backward Asymmetry

- CDF
  - Asymmetry large, growing with energy
    - Few percent for $m_{tt} < 450$ GeV
    - 47.5 +- 11% for $m_{tt} > 450$ GeV (~ 3 sigma) [t t-bar partonic frame]

- DZero
  - Asymmetry moderate, rather flat in energy
    - About 20% (~ 2.5 sigma) throughout

Motivation to Look at Other Quarks

- Seems very difficult to accommodate this with SM only
- No one has found an experimental or theoretical error or even a subtlety
- Models to explain this asymmetry must introduce particles that couple to light quarks and to top quarks
  - Generally very ugly,
    - but goal here is not to judge beauty but to falsify with data



- Model classes:
  - Affect t_R only [expect no effect on other quarks]
  - Affect t_L only/also [expect effect on b quark]
  - Affect all up-type quarks [expect effect on c (and u) quark]

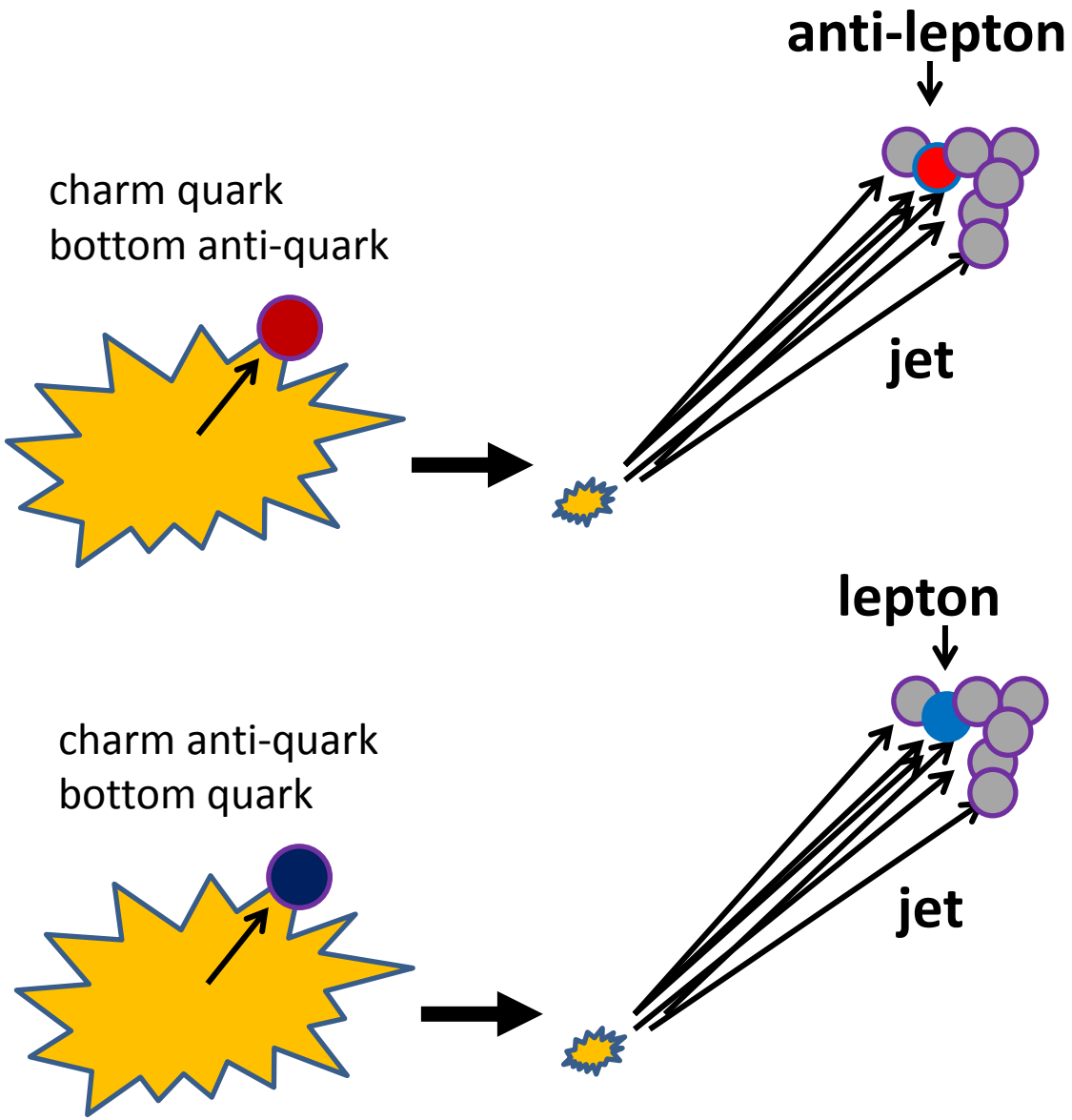
Other quarks at Tevatron?

MJS 2/11; cf Hewett et al. 1/11

- Claim: can measure 25% b and c-quark asymmetries at the 3 sigma level

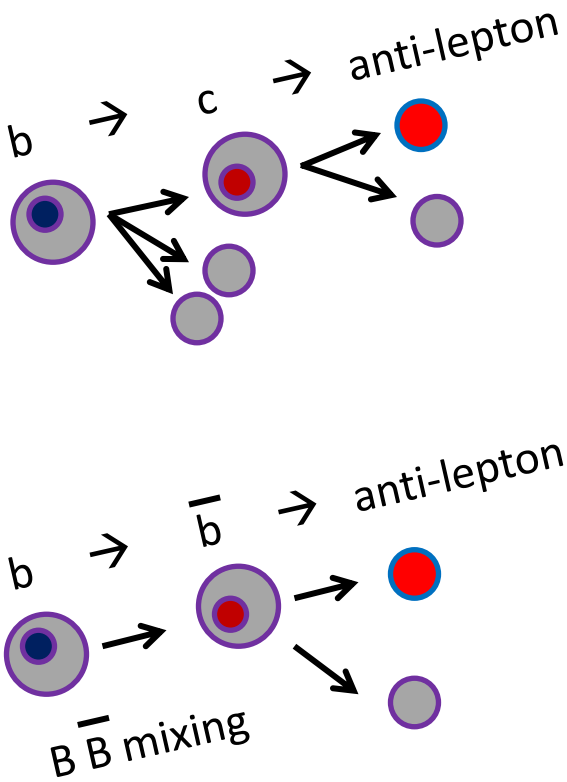
- Method:
  - Select dijets
  - Look for muon inside of jet and look at charge asymmetry of the muon

Dijet Plus Embedded Muon



Dilution Effects

bottom quark can produce an anti-lepton



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- Claim: can measure 25% b and c-quark asymmetries at the 3 sigma level

- Method:
  - Select dijets
  - Look for muon inside of jet
    - Hadronic sources: B meson decay, D meson decay
    - Partonic sources: b, c , b → c, g→ c c-bar, g → b b-bar
  - Look for forward-backward asymmetry of anti-muons (in dijet frame)
  - Combine with backward-forward asymmetry of muons

  - Use b-tagging, muon kinematics to
    - Isolate b asymmetry from c asymmetry
    - Reduce dilution of b asymmetry from B → B-bar, B → D

Dijet Plus Embedded Muon

Jet p_T > 150 GeV [dijet trigger]
M_{jj} > 450 GeV
Muon p_T > 20 GeV , $|\eta| < 2$

Production	Cross-section	
Light quarks and gluons	1.0 pb (0.25 with gg final states)	
One b or c quark or antiquark	0.35 pb	
Charm pairs	0.15 pb	1500 events
Bottom pairs	0.3 pb	3000 events
Total	1.8 pb	18000 events

Despite large b b-bar cross-section, dilution fact or of 3 reduces sensitivity below charm:

b → c → mu with wrong sign
B → B-bar → mu with wrong sign

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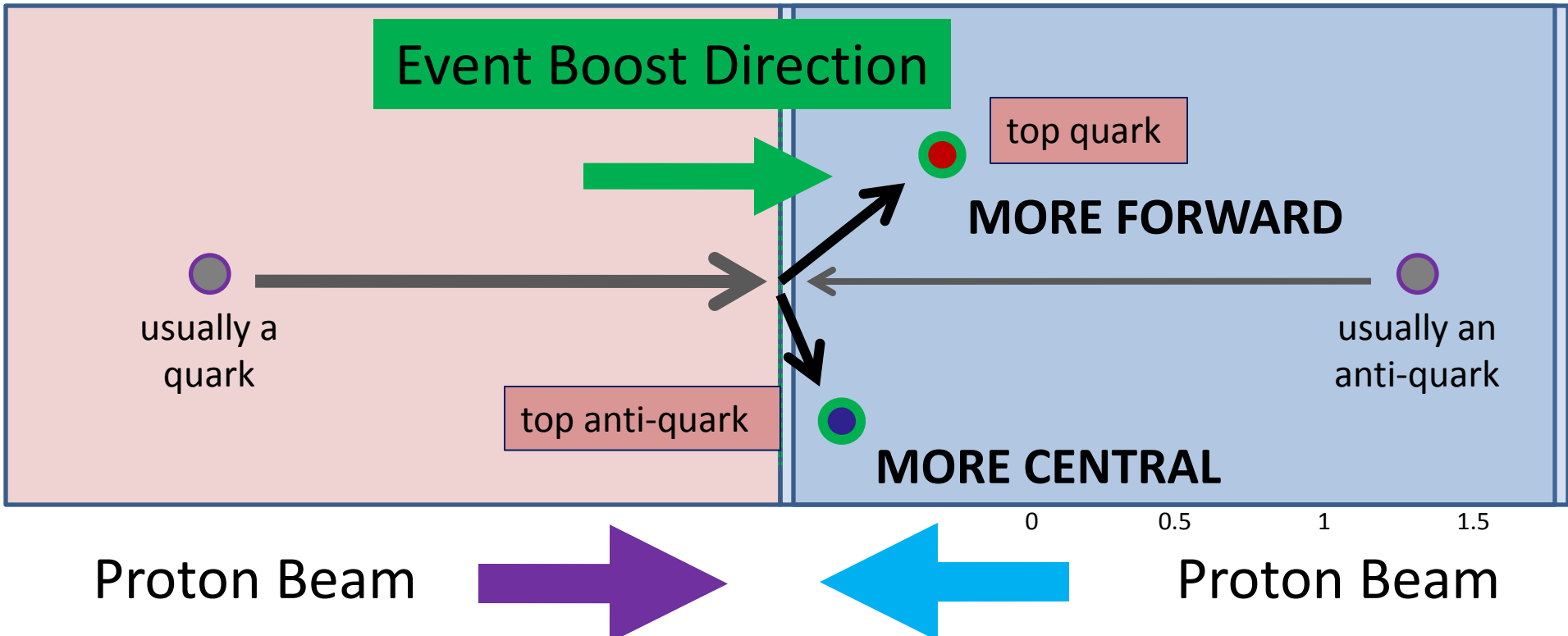
- b-tag muon-free jet
- Higher jet pT cut
- Higher muon pT cut
- Muon relative-pT cut

LHC? Kahawala,Krohn & MJS 8/12

- Cannot measure forward backward asymmetries
- Can measure more-forward/more-central asymmetries
  - Boost direction of the event indicates the q direction statistically

$$A_{FC}^{b\bar{b}} = \frac{N(q\Delta|y| > 0) - N(q\Delta|y| < 0)}{N(q\Delta|y| > 0) + N(q\Delta|y| < 0)},$$



LHC study

Kahawala,Krohn & MJS 8/12

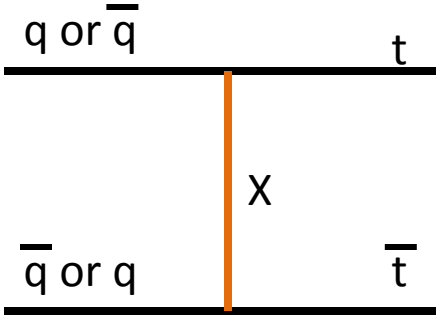
Jet p_T > 150 GeV, 100 GeV
Muon p_T > 25 GeV , $|\eta|$ < 2.4 near one jet
b-tag of other jet [no hope without b-tag, so can't do charm asym]

	Selection	$y_{jj} > 1/2$	$m_{jj} > 450$
$\sigma_{q\bar{q}\to b\bar{b}}$ (pb)	1.1	0.9	0.3
$\sigma_{\bar{q}q\to b\bar{b}}$ (pb)	0.3	0.1	0.0
$\sigma_{gg\to b\bar{b}}$ (pb)	7.1	4.0	0.9
other background	10.0	5.7	1.6
$\sigma_{\rm total}$(pb)	18.6	10.7	2.7
$A_{FC}^{b\bar{b}}(\%)$	0.6	0.9	1.6
significance (σ)	2.5	2.8	2.6

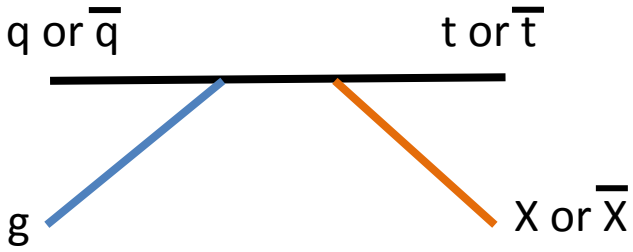
$$y_{jj} = \frac{y(j_1) + y(j_2)}{2}$$

- Numbers for 10 fb^{-1}
- Modeled asymmetry in range observed by Tevatron using suitable axigluon model *only in that limited range* – so probably conservative
- Some improvements possible; vertex location, muon p_T, differential asym
- LHCb ?

Test Asymmetries With Asymmetries



- Many models to explain top FB asymmetry
  produce other types of asymmetries at LHC
- For example:



- These asymmetries potentially powerful in excluding models
  - Shelton-Zurek model excluded (probably) using total charge asymmetry
    - W'$^{+}$ production > W'$^{-}$ production Craig, Kilic & MJS 2/11
  - Many other models excludable soon with differential charge asymmetries
    - New particle reconstructed-mass plot shows asyms

Knapen, Zhao & MJS in prep

Impact of Hidden Valleys on LHC Searches

Current Main Search Strategies at LHC

- Higgs Boson searches
- SUSY-like
  - High energy jets
  - Large missing transverse momentum
  - Perhaps add something rare (b-tag, lepton, photon)
- Exotic-classes
  - New resonances
    - produced singly or doubly
    - Decaying to 1, 2, or perhaps 3 leptons/photons/jets
- Black Holes
  - Huge energy, large number of jets etc.
- A few other specific cases

Signals Can be Hidden by Hidden Valleys

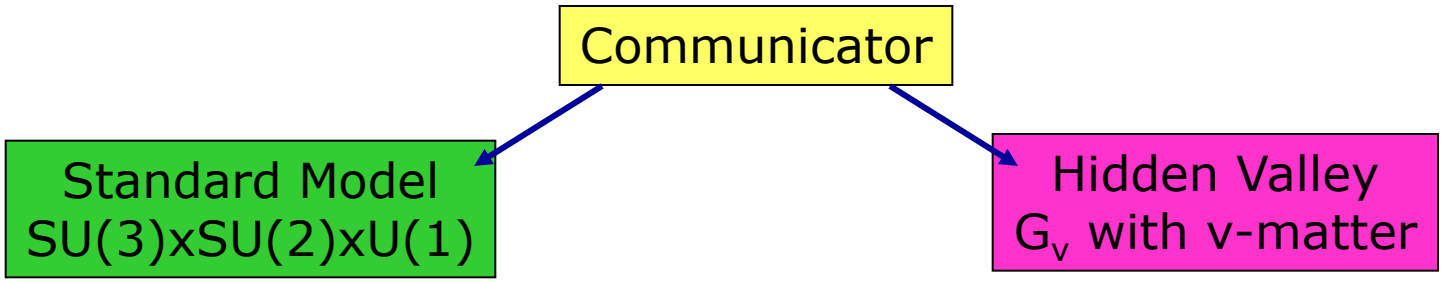
- A hidden sector that produces a visible signal can cause problems
  - Higgs boson can become very hard to find
  - SUSY etc. can be harder to detect
  - Black holes can look very different from expectations
- It can also provide new but exotic opportunities to discover them
- So far very few dedicated analyses searching for this possibility

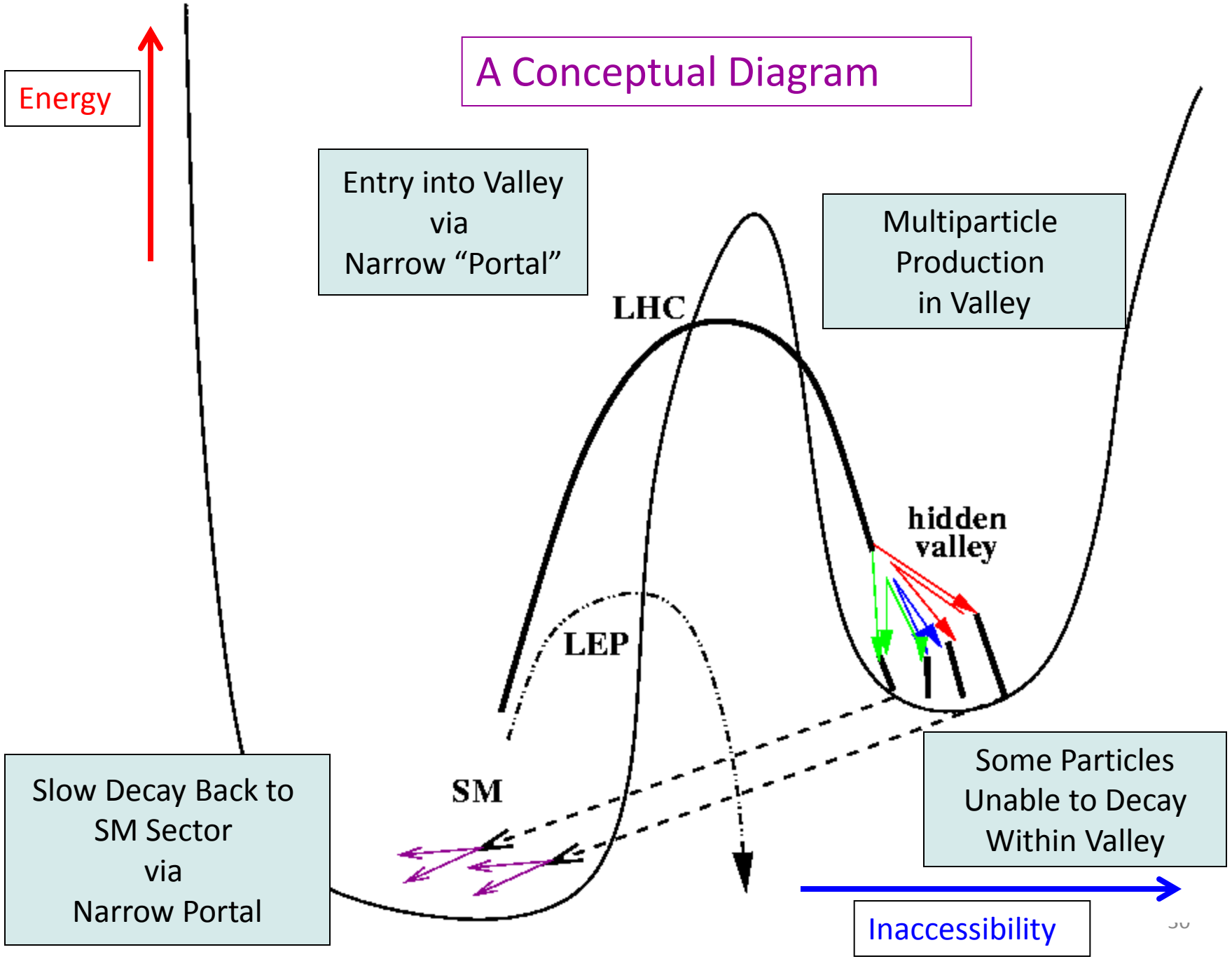
Hidden Valley Scenario (w/ K. Zurek)

hep-ph/0604261

- Not a model, but a scenario:
  - **A Very Large Meta-Class of Models**

Basic minimal structure:

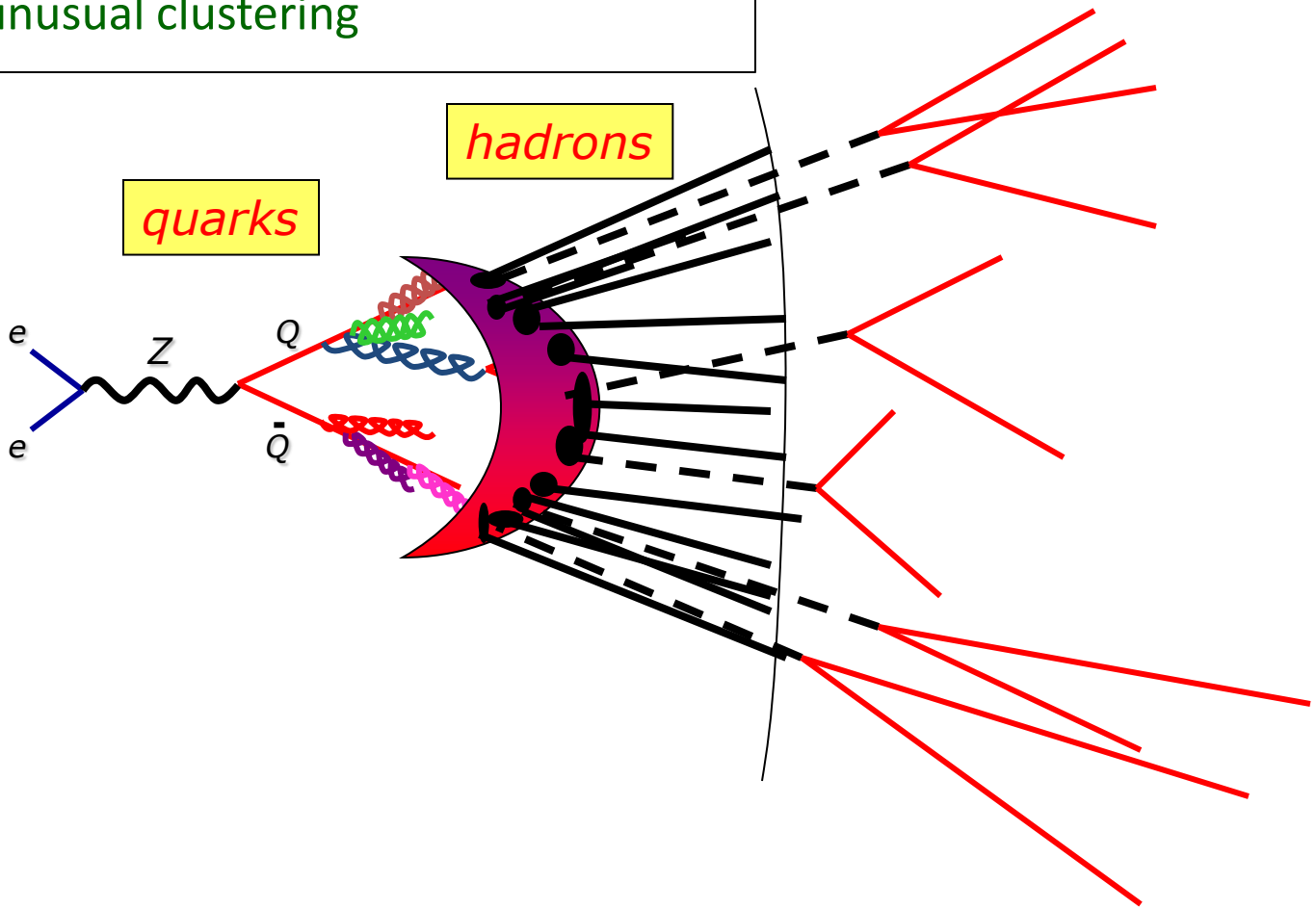



A Conceptual Diagram
Energy
Entry into Valley
via
Narrow "Portal"
Multiparticle
Production
in Valley
LHC
hidden
valley
LEP
SM
Slow Decay Back to
SM Sector
via
Narrow Portal
Some Particles
Unable to Decay
Within Valley
Inaccessibility

Analogy: QCD

Production through Z decay

- New lightweight resonances
- Some long-lived resonances
- Multiparticle production with unusual clustering

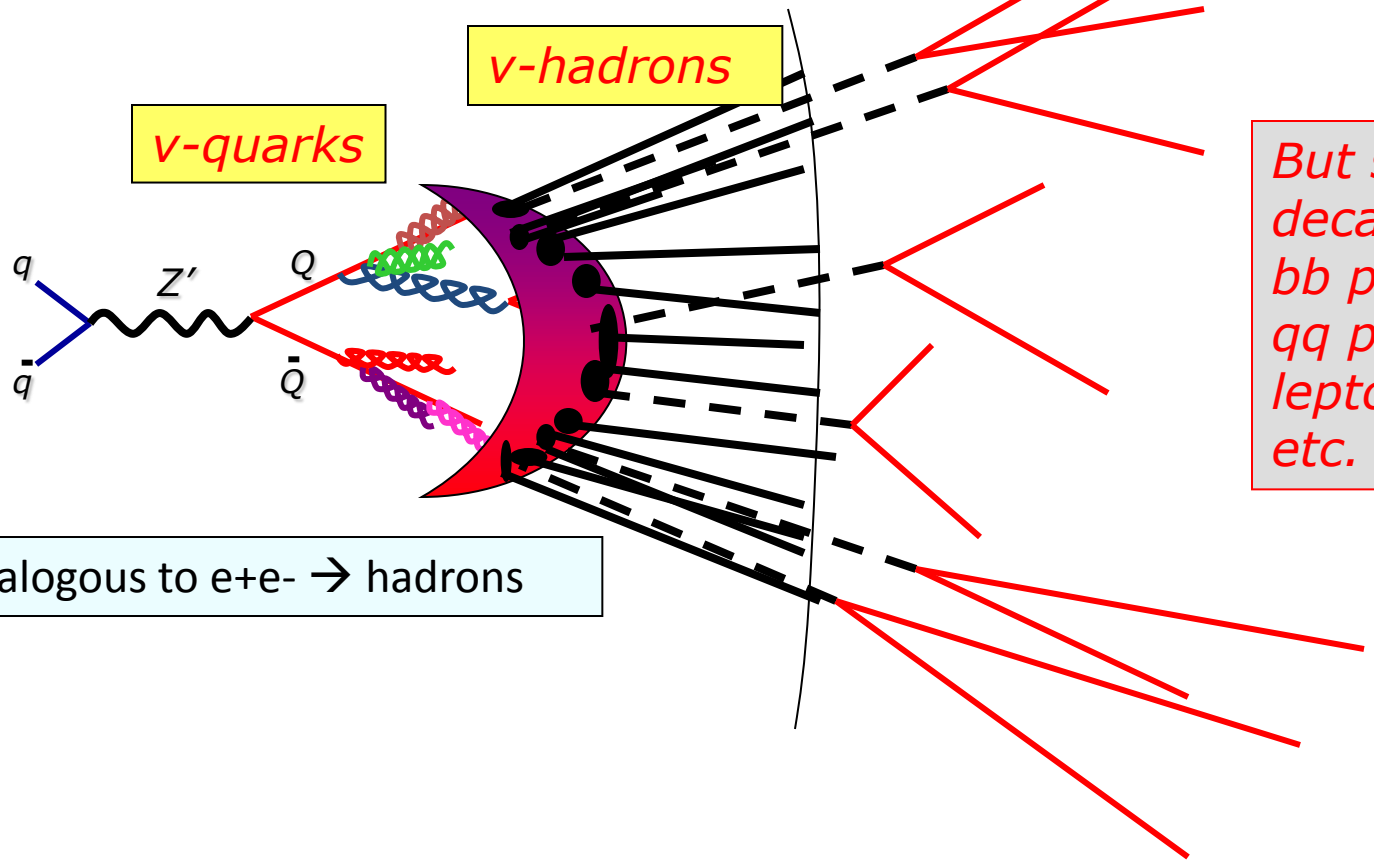


EXAMPLE: Confining Hidden Valley

Production through Resonance Decay

- New neutral lightweight resonances
- Some long-lived resonances
- Multi-particle production with unusual clustering

Some v-hadrons are stable and therefore invisible



But some v-hadrons decay, to bb pairs, qq pairs, lepton pairs, etc.

Analogous to e+e- → hadrons

Common Predictions of HV Scenario

hep-ph/0604261
hep-ph/0605193

- Possible big effect on Higgs
  - H → XX, X decays displaced ➔ new discovery mode
    - *not unique to HV* *Chang Fox Weiner 05 / Carpenter Kaplan Rhee 06*
  - H → XXX, XXXX, etc
    - *not unique to HV*

Higgs can decay in way that causes problems for trigger and for analysis

- Big effect on Supersymmetry, UED, Little Higgs – any theory w/ new global charge

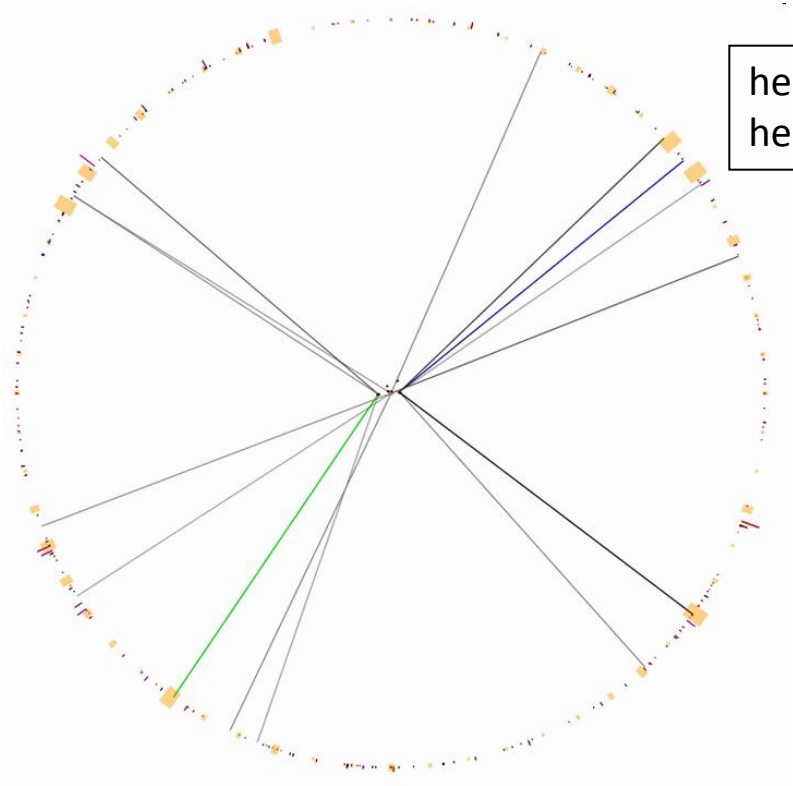
hep-ph/0607160

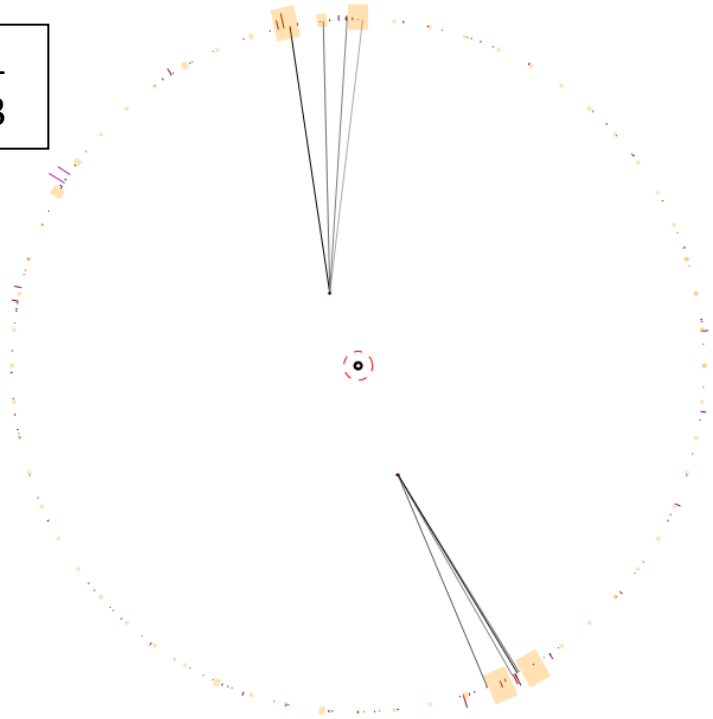
  - LSP (or LKP or LTP) of our sector can decay to the valley LSP/LKP/LTP

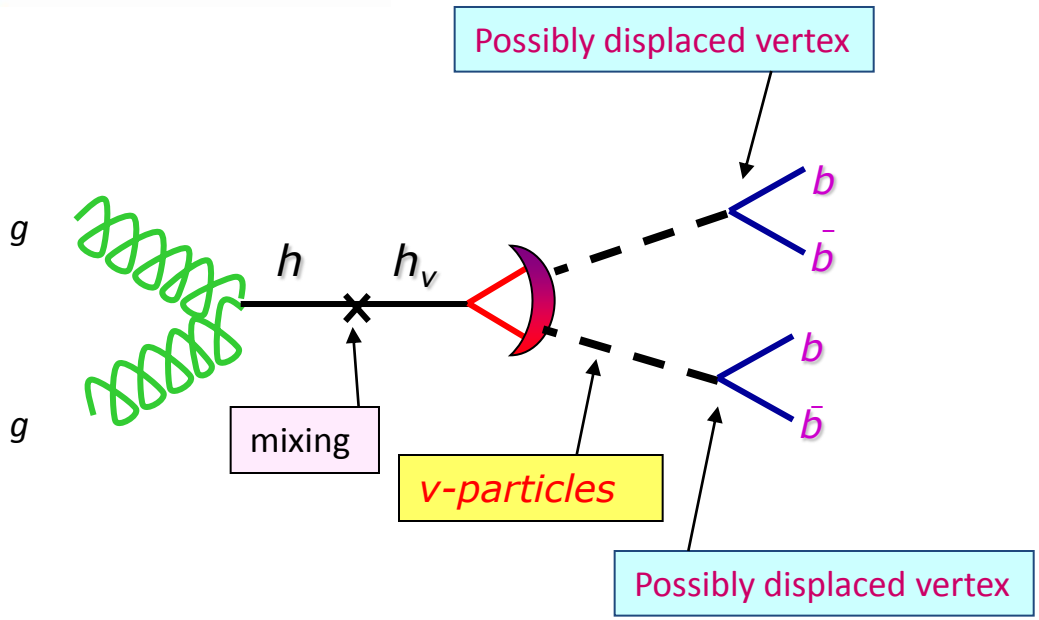
Generalizes well known work from 90s
- *[GMSB, Anomaly, Hidden Sector]*

Classic MET signal of SUSY and similar models can be reduced

hep-ph/0604261
hep-ph/0605193

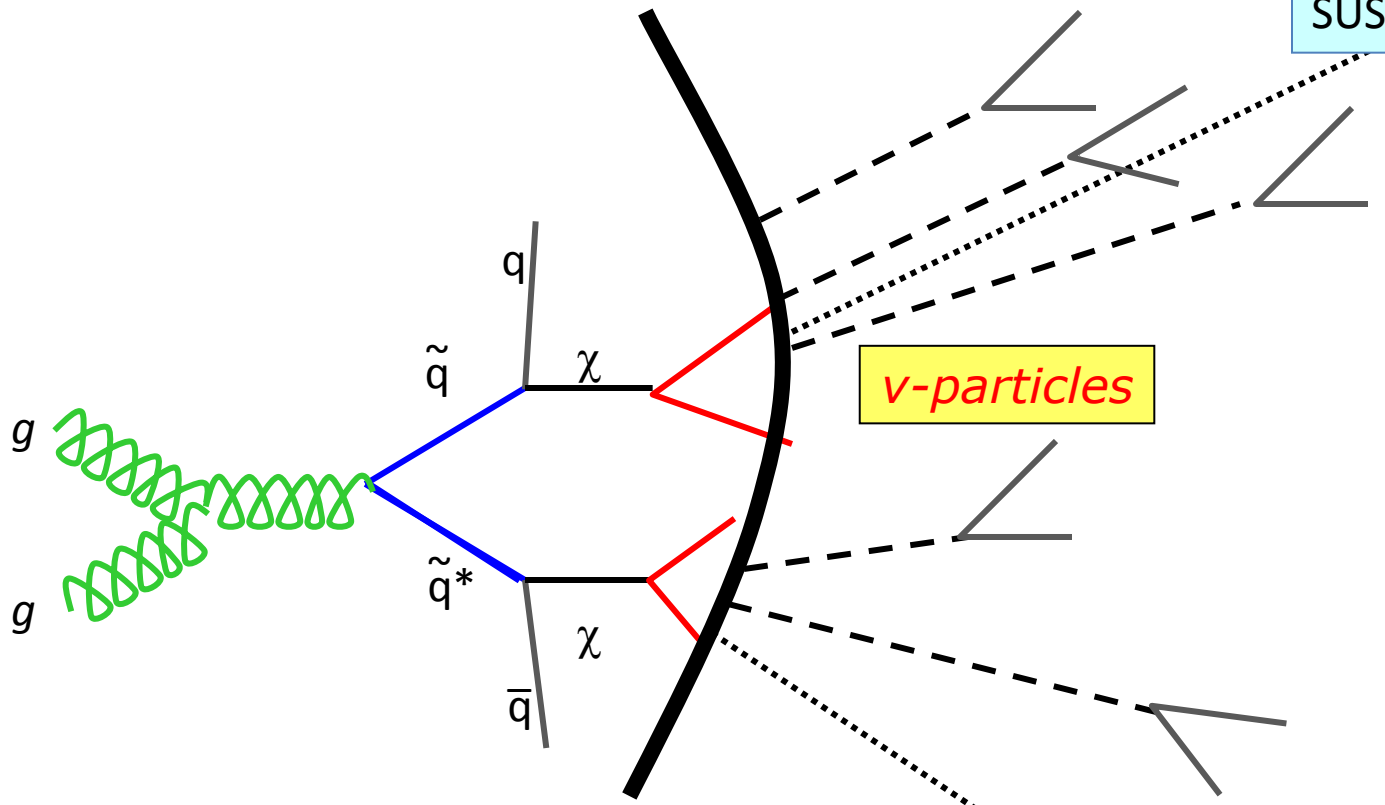






MJS July 06

HV SUSY Scenarios



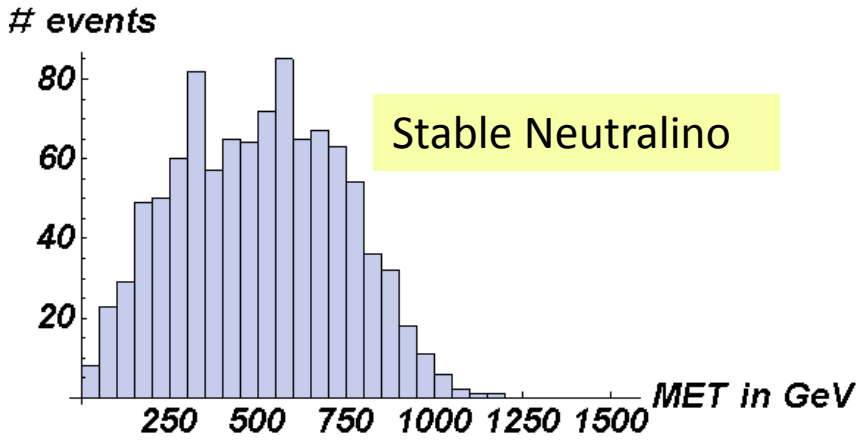
The lightest SUSY v-particle

The lightest SUSY v-particle

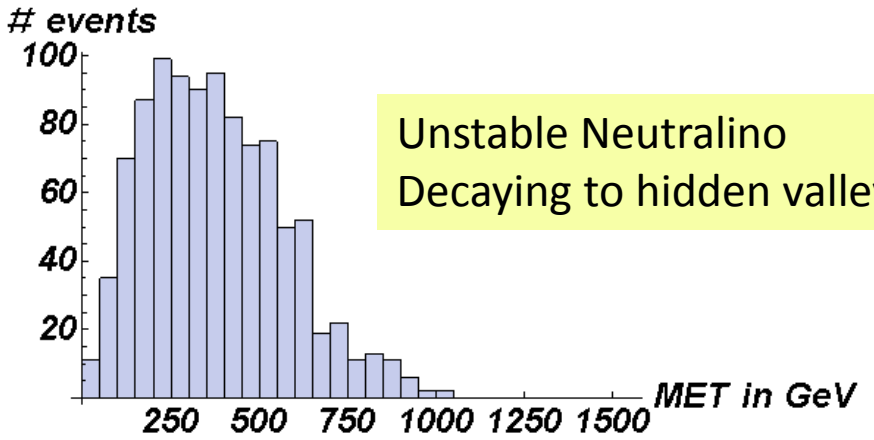
The traditional missing energy signal is replaced with multiple soft jets, reduced missing energy, and possibly multiple displaced vertices

Reduction of Missing Energy Signal

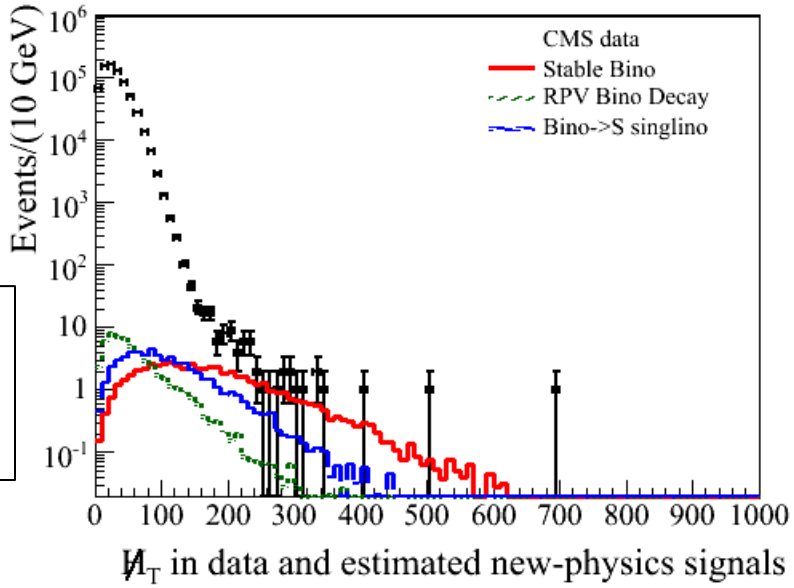
Distribution of Missing Transverse Energy



Stable Neutralino



Unstable Neutralino
Decaying to hidden valley



Black is CMS data

Red is MSUGRA model

Hidden Valley between Blue and Green curves

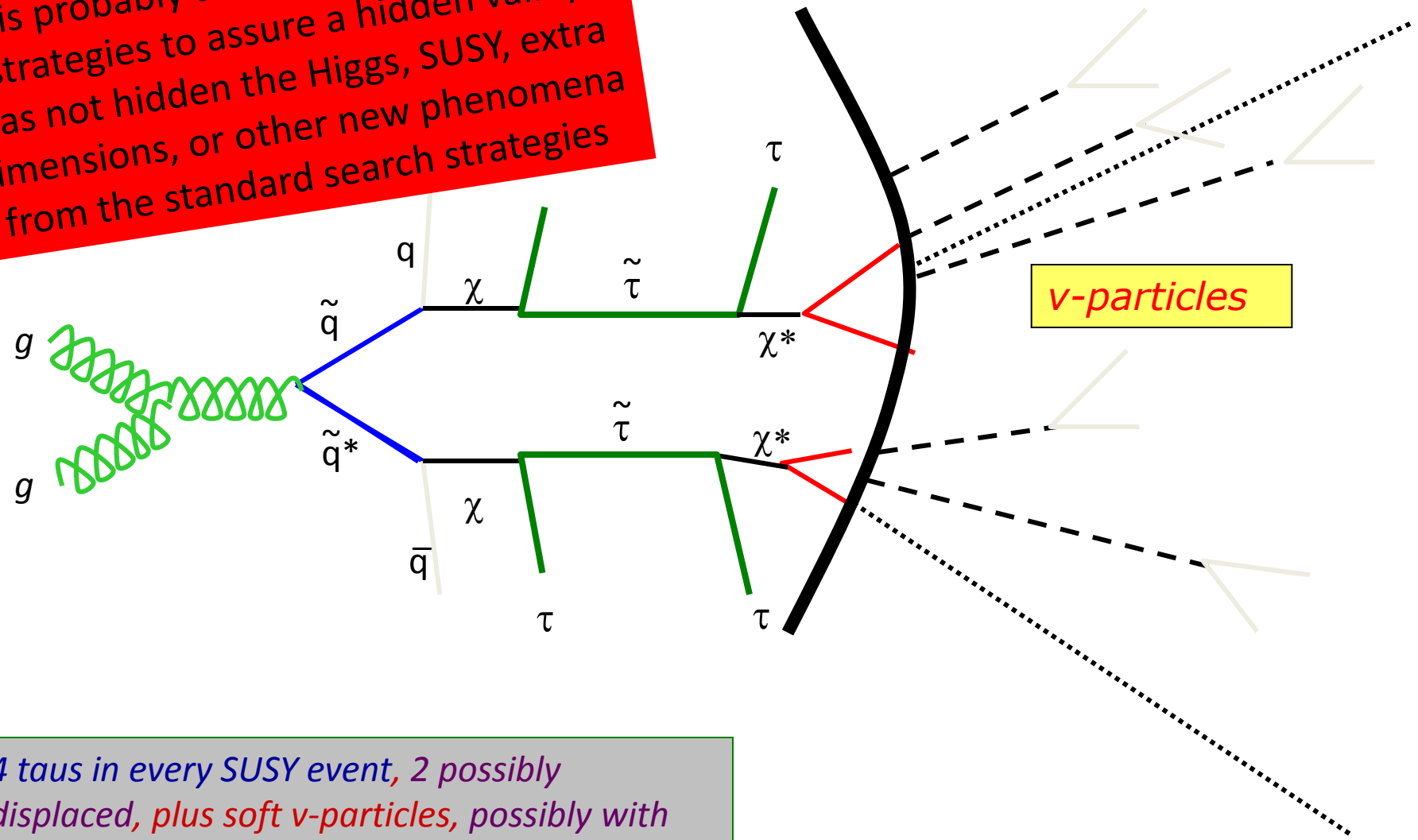
Need for Additional Search Strategies at LHC

Lisanti, Schuster, MJS &, Toro

Many other examples…

MJS July 06

It is probably time to broaden search strategies to assure a hidden valley has not hidden the Higgs, SUSY, extra dimensions, or other new phenomena from the standard search strategies



4 taus in every SUSY event, 2 possibly displaced, plus soft v-particles, possibly with displaced decays

Summary

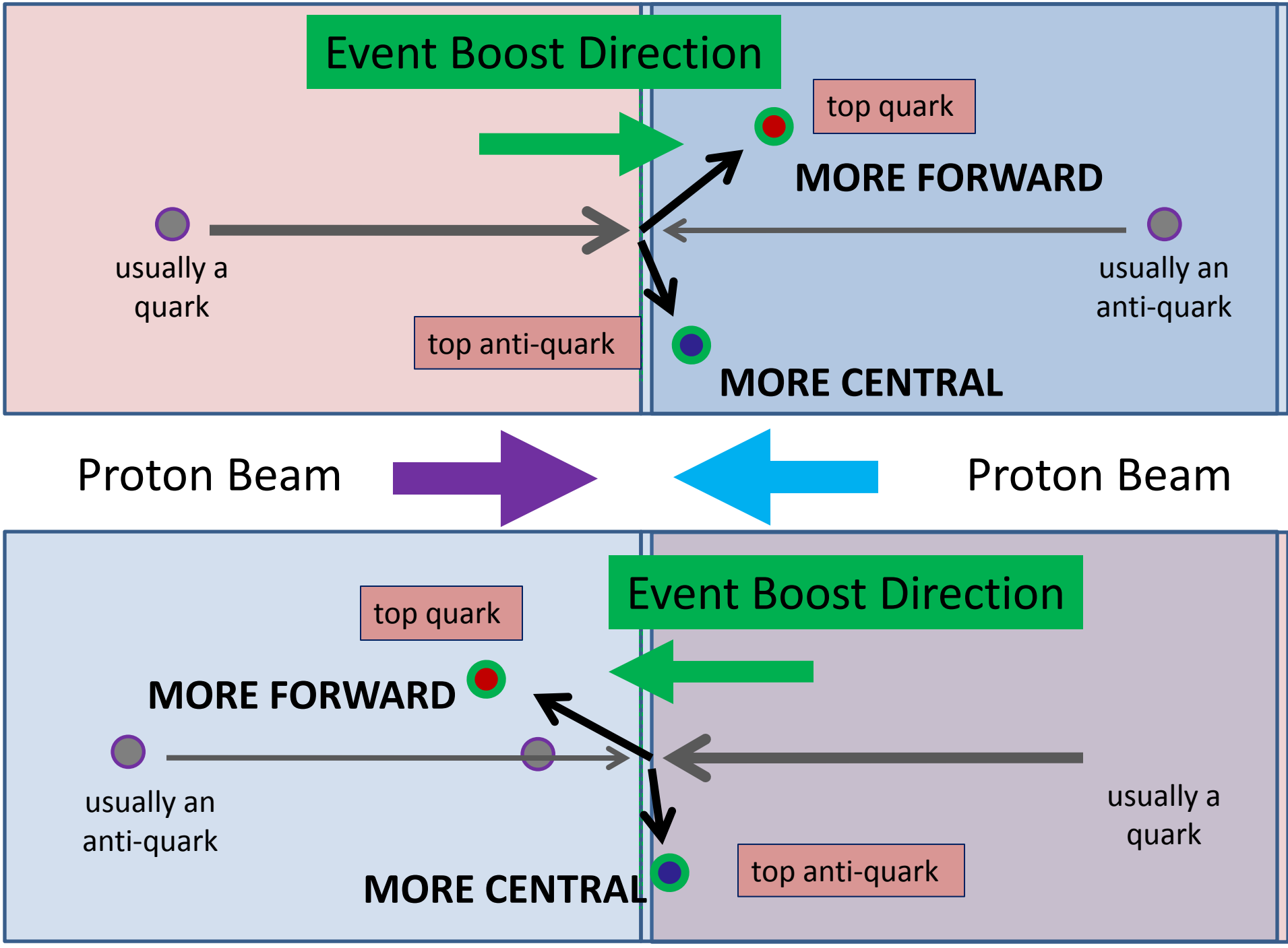
- Exciting new era with great potential for a quick-minded brilliant theorist

- Surprising top forward-backward asymmetry
  - Important to measure this for other quarks – seems possible
  - Models to explain it can generate large charge asymmetries at LHC

- Remember signals can hide in presence of hidden valley
  - **Current trigger not likely to fire on many exotic Higgs decay modes**
  - Missing Transverse Momentum signals often reduced
  - Since obvious searches have not seen anything, soon need to start looking seriously for this wide range of possibilities

- Looking forward to broader and deeper analysis of LHC data!

Additional Slides

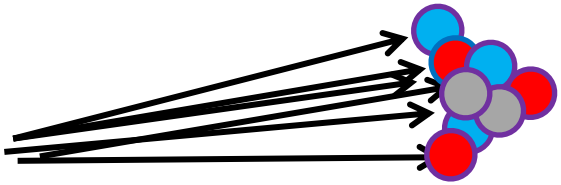

Event Boost Direction
top quark
MORE FORWARD
usually a quark
usually an anti-quark
top anti-quark
MORE CENTRAL
Proton Beam
Proton Beam
top quark
Event Boost Direction
MORE FORWARD
usually an anti-quark
usually a quark
top anti-quark
MORE CENTRAL

Recent Hidden Valleys in Literature

- Unparticles [conformal hidden sector] Georgi 07– no mass gap
  - Mainly invisible

- But many papers (07) break conformal invariance and generate mass gap
  - Hidden sector now becomes hidden valley
    - Cannot use conformal methods (though many papers did)
  - Correct physics is either invisible or hidden-valley-like (MJS 2008)

- Hidden dark-matter sectors to explain PAMELA [Arkani-Hamed et al. 09]
  - Lepton-jets (clustered boosted resonances decaying to leptons)
  - Can affect Higgs/SUSY decays



HV Higgs Scenarios

- H → X X, X decays to
  - Mostly b quarks, occasional taus
  - Mostly quarks, occasional leptons
  - Mostly gluons, occasional photons

  Will the trigger even fire under current conditions?!

- H → XXXX ; triggering?!!?!?

- H → X X, X decays with displaced vertex
  - Trigger a serious impediment
  - ATLAS: long-lived particle search (trigger on muon 40 GeV)
  - CMS: X → displaced leptons only sensitive to m_H >200 GeV
    - due to trigger efficiency