THEORY OVERVIEW: CHANGING (EXCITING?) TIMES

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Aspen Winter Conference, 2011

Promise

- Large Hadron Collider
  - Explore weak energy scale
  - Nothing replaces studying as high energy as possible!
- Dark Matter Experiments
  - On Ground and in Space
  - Direct and Indirect
- CMB , Dark Energy, Black Holes
- Gravity Waves

Where Are We Now?

- LHC working as well as can be hoped
  - Repeatedly achieving new milestones
  - Experiments working in an unprecedented manner at turn-on
- Dark matter searches constantly improving
  - Searches from different directions
  - Synthesizing information from new regimes

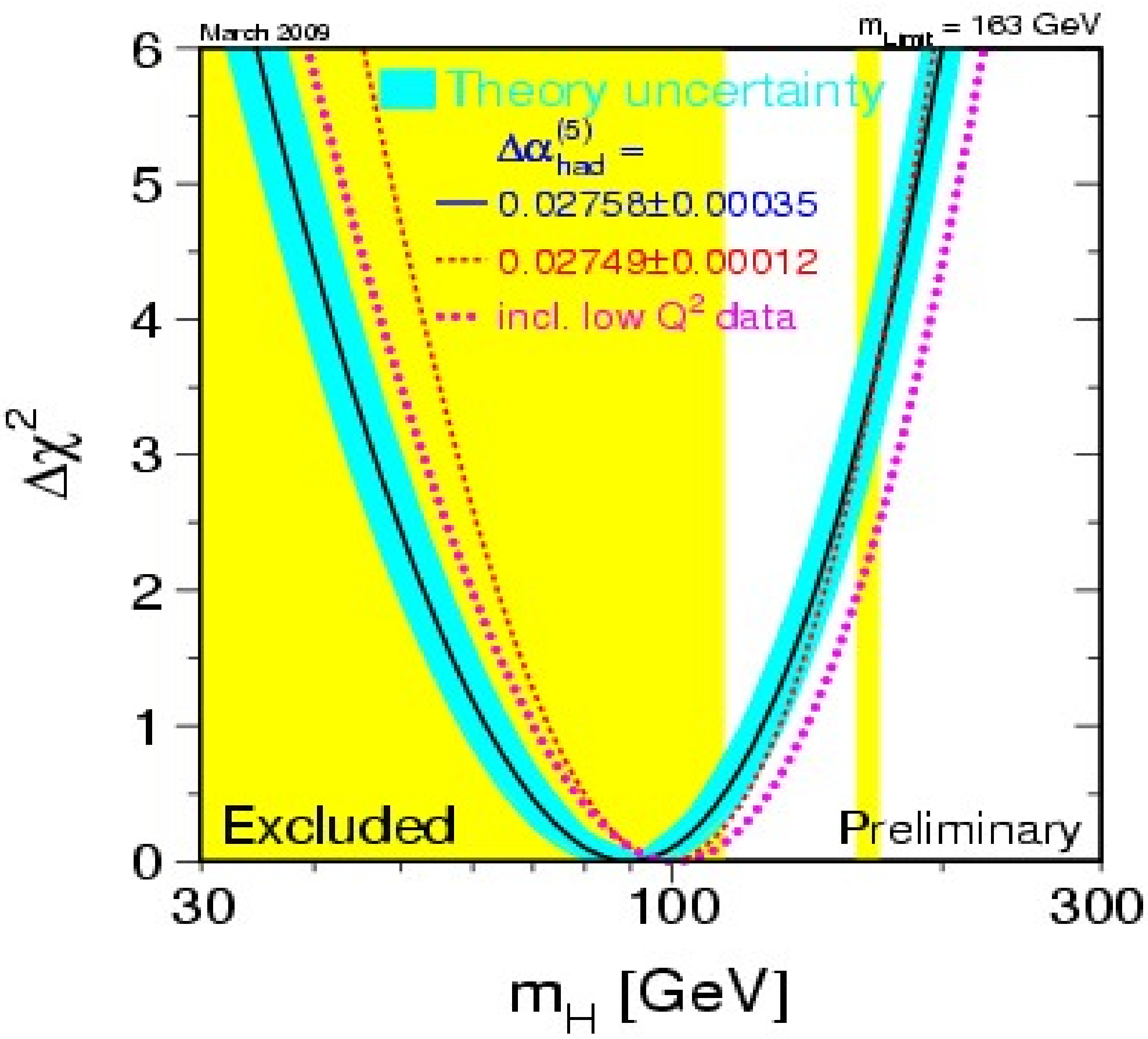
Progress in Last Year

- Dark Matter Searches and Models
- Light Dark Matter
- New Ideas for Dark Matter Candidates
  - Motivated by anomalies
  - Motivated by theoretical insights

Progress in the last year

- Experiment: stuff ruled out—some light Higgs models
  - Light susy, light black holes
- New recognition of early LHC BSM capacity
  - Wide resonances **
  - Long-lived hadrons
- Jet physics
  - General cleaning up of events
    - Precision with jet physics
  - Higgs-> bbbar
  - ISR tagging **
    - Kinematic handle

Higgs Should be Within Reach



Challenge to establish its properties
Measure as much as possible
Can we tell it's a Higgs?
Can we decide if it's part of a more complicated Higgs sector?

More progress

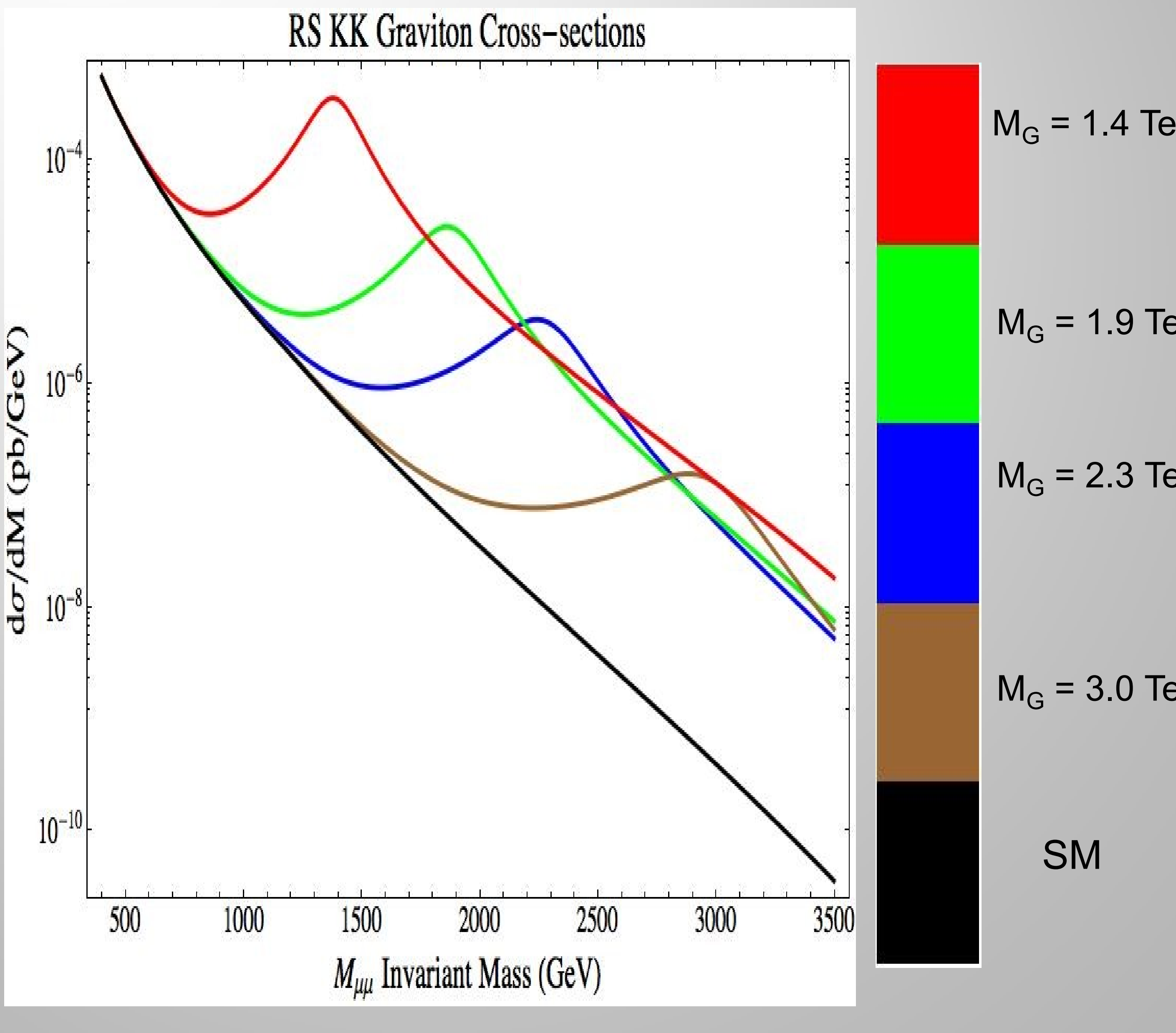
- Dark Matter
  - New classes of models **
  - New “coincidences”
    - $\rho_B \sim \rho_{DM}$
  - Lots of new models
    - Some new signatures
    - Some new challenges

Past Year's Progress I: Wide Resonances

With Brian Shuve,
Randall Kelly

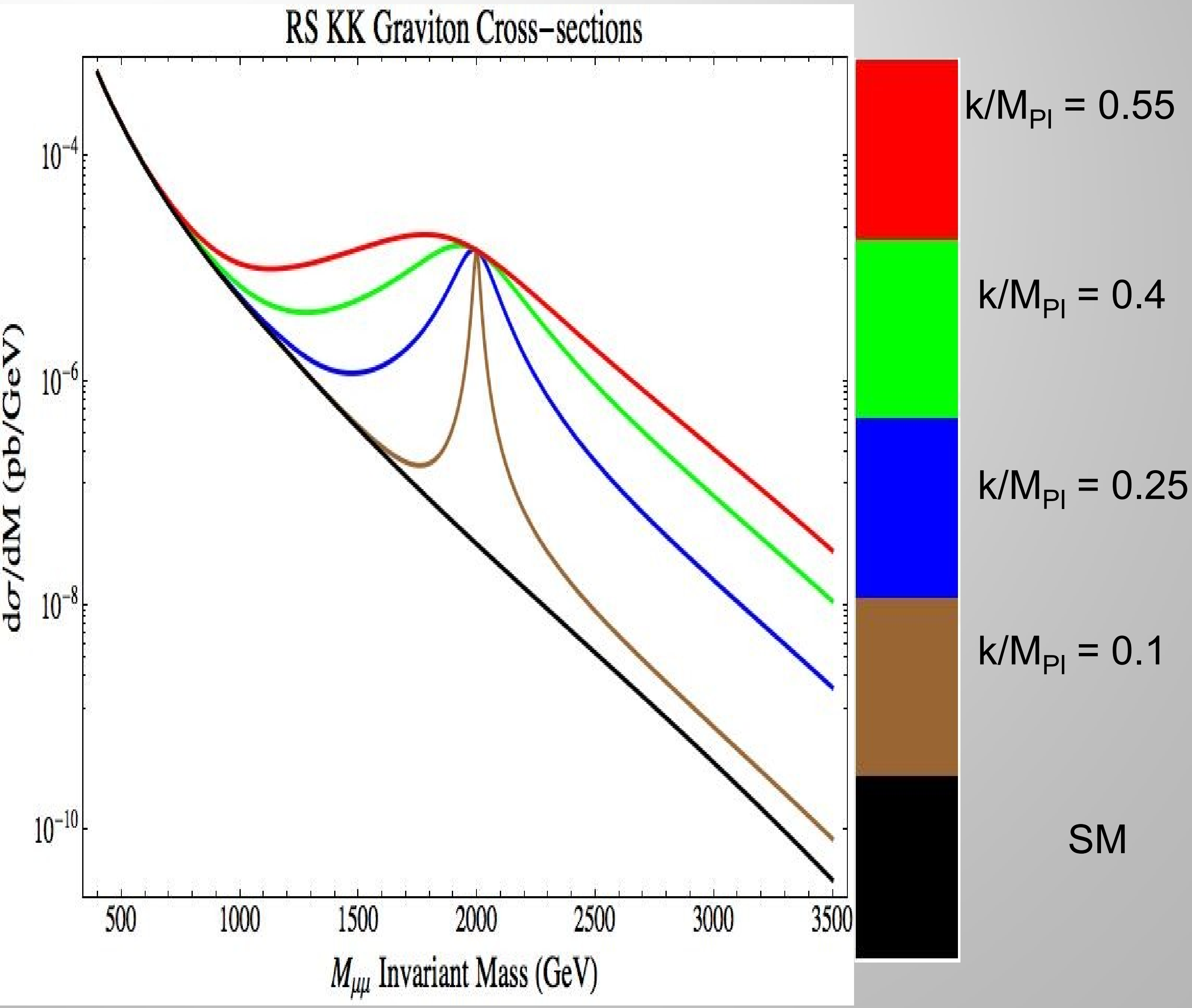
- Resonances will be first and simplest place to look
- Particularly Drell-Yan processes with decays to muons
  - Background well understood
  - Low background at high invariant mass
- Useful for models
  - Z′
  - RS
  - Understanding detector and experiment reach

RS X-sections (varying mass)



k/M_{Pl} = 0.35

RS X-sections (varying k/M_{Pl})



M_G = 2 TeV

On vs Off Resonance

On peak:

$$\hat{\sigma}(M_g^2) \sim \frac{1}{M_g^2}.$$

Off peak-need to integrate against parton distribution
Estimate using narrow width.

$$\frac{1}{(\hat{s} - M_g^2)^2 + M_g^2\Gamma^2} \approx \frac{\pi}{M_g\Gamma}\delta(\hat{s} - M_g^2)$$

$$\sigma \sim \frac{(k/M_{\rm Pl})^2}{s}\frac{d\mathcal{L}}{d\tau}(M_g^2, s).$$

Favors wide states, large k/M, Resonance mass through luminosity

Wide Resonances

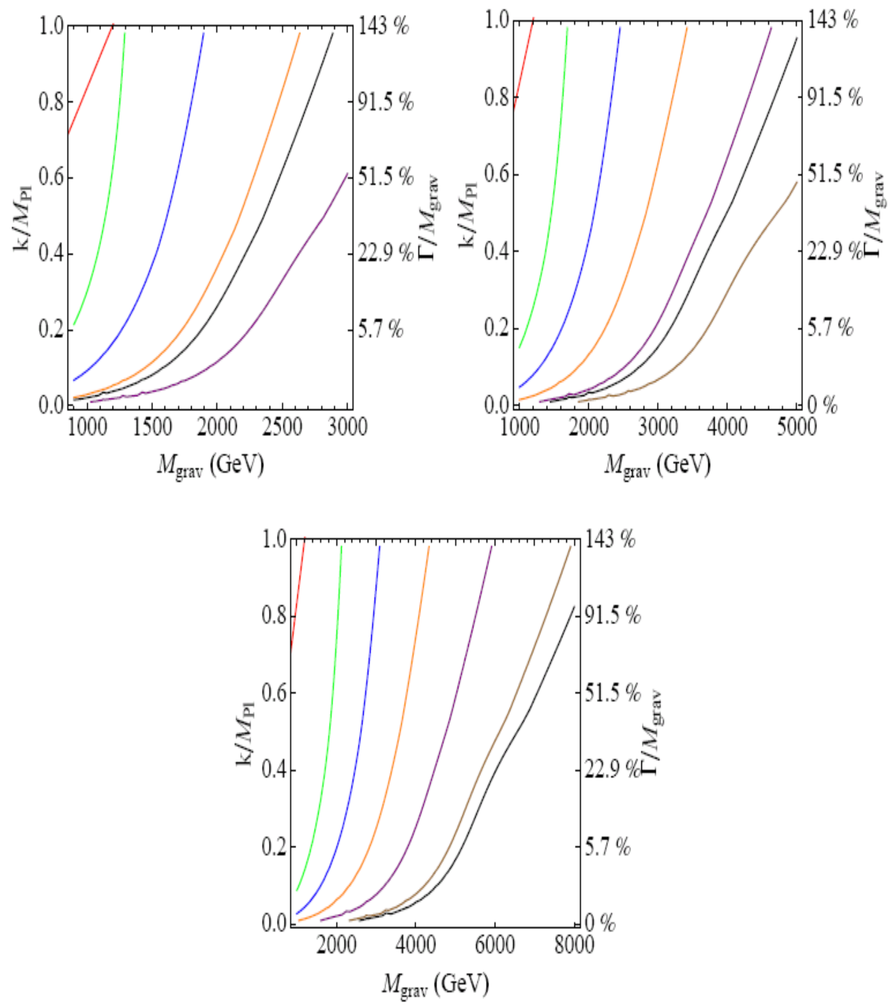


Figure 2: Plots showing contours of constant cross section for the first KK mode of the graviton in RS models as a function of the curvature $k/M_{\rm Pl}$. The width of the corresponding resonance is also shown. The cross sections are shown for $\sqrt{s}$ = 7 TeV (left), 10 TeV (center), and 14 TeV (right). Legend: green is 1 pb, blue is 100 fb, orange is 10 fb, purple is 1 fb, brown is 100 ab. The black curve indicates the cross section for 5 events at certain benchmark luminosities: 1 fb^{-1} at 7 TeV, 10 fb^{-1} at 10 TeV, and 100 fb^{-1} at 14 TeV. The red lines are bounds from

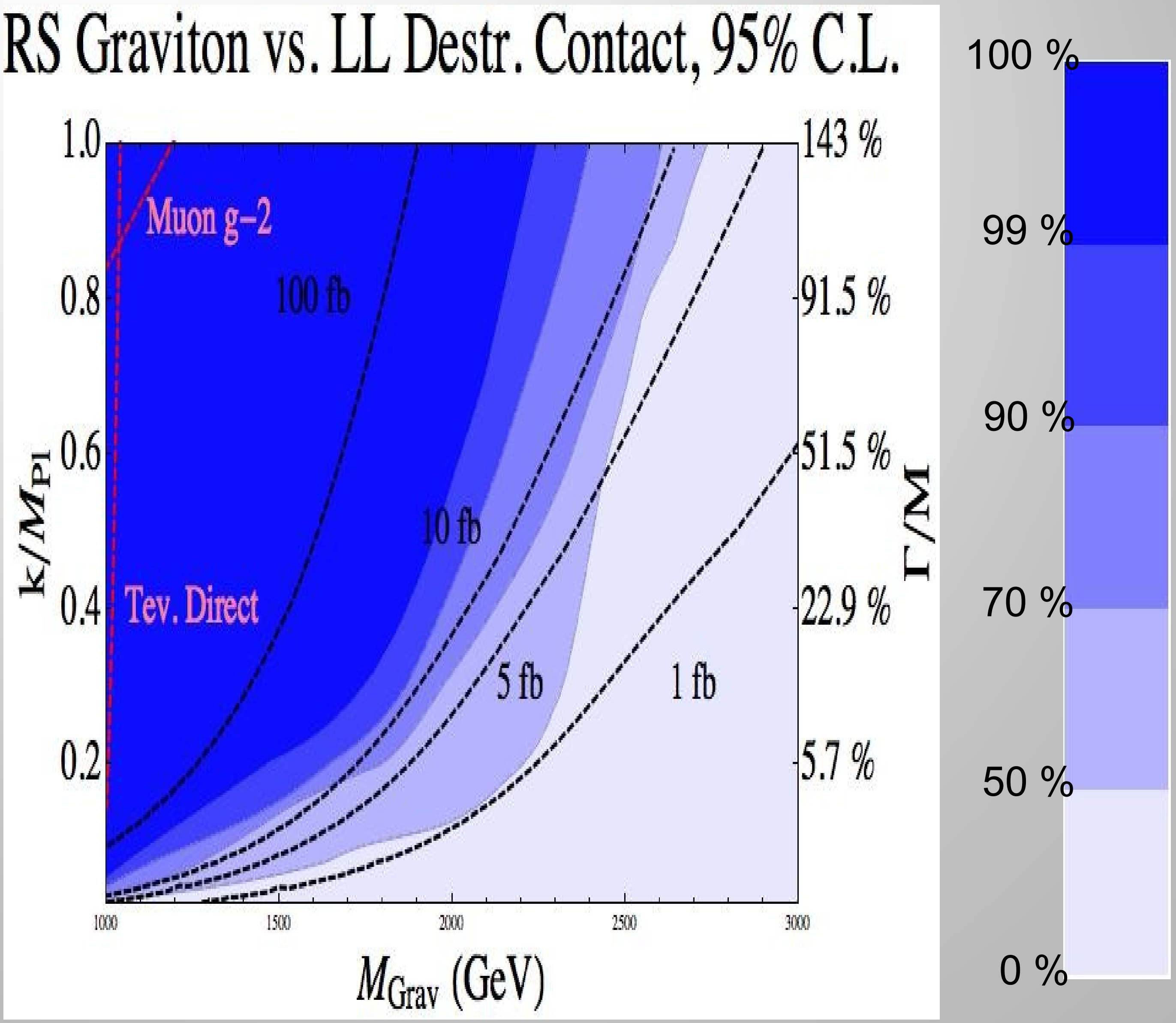
- Understand reach of various LHC parameters
- When does LHC beat Tevatron, even in early run
  - High mass
  - Resonances from glue-glue initial state
  - Wide resonances
- Focus on wide resonances
  - Especially important since large coupling needed for sufficient event rate at low luminosity
- When can we see resonances?
- When can we distinguish them from contact interactions?
- Can we learn about nature of interaction that produced resonance?

Focus

- *Shape* of distribution
- For much of parameter space can distinguish broad resonance from featureless falling distribution (SM or SM +contact)
- Simple: look for “upturn” or absolute rise in rate
- More sophisticated statistical analysis
  - Use both excess events in some bins and absence in others

– Binned maximum likelihood analysis

Results



RS Graviton vs. LL Destr. Contact, 95% C.L.
Muon g−2
Tev. Direct
100 fb
10 fb
5 fb
1 fb
1.0
0.8
0.6
0.4
0.2
κ/M_{Pl}
143 %
91.5 %
51.5 %
22.9 %
5.7 %
Γ/M
1000
1500
2000
2500
3000
M_{Grav} (GeV)
100 %
99 %
90 %
70 %
50 %
0 %

Can we learn more?

- Seems reasonable event rate
- And distinguishable
- We've considered total cross section and distribution with energy so far
- With enough statistics, angular information can also prove valuable

- In particular, can distinguish parity-violating interactions
- SM interactions violate parity whereas new physics does not necessarily

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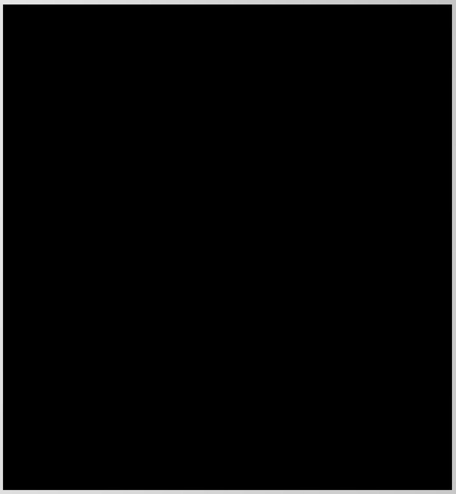
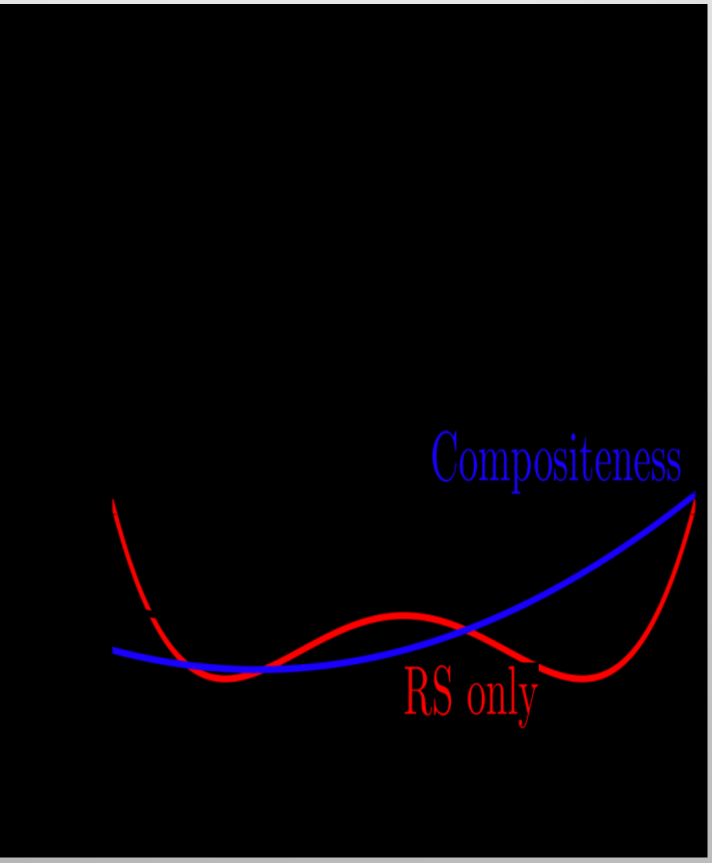
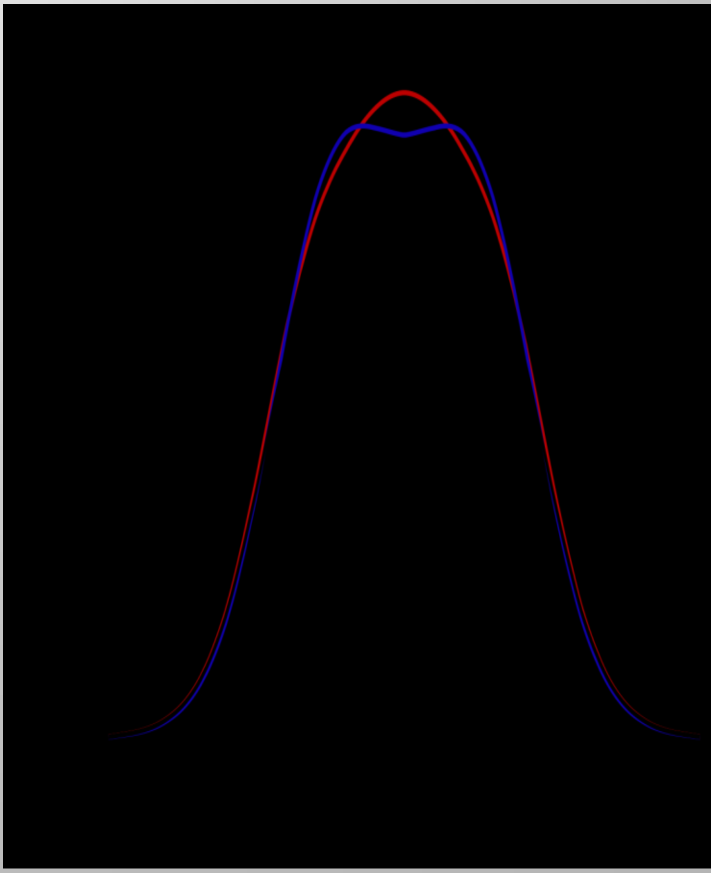
Pseudorapidity distribution



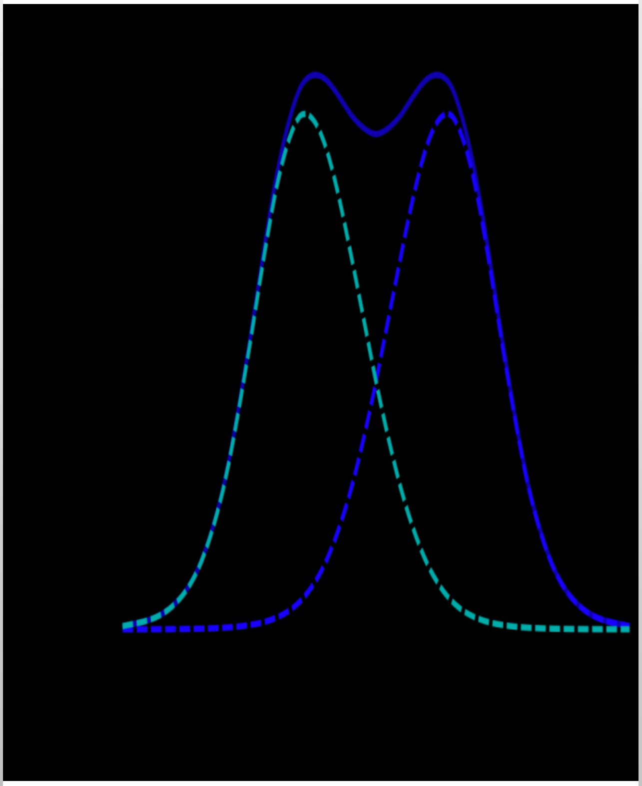


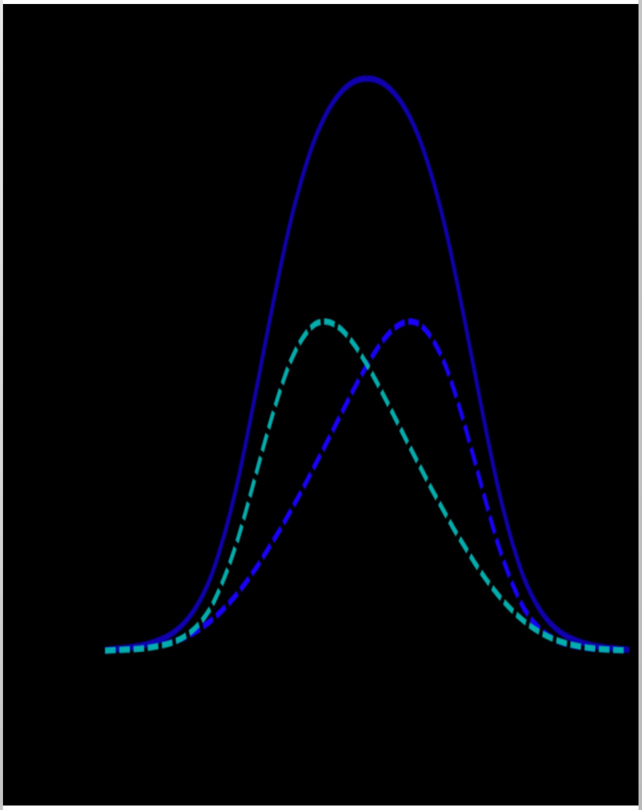


Interpretation

- Muon preferentially forward (wrt quark) due to parity violating SM interactions
- Quark has on average more momentum (larger x) therefore boosted more forward
- Large η, small θ, large cos θ
- Sum curves and get the McD curve
- Wider with less hard invariant mass cut

RS model





Separation of Distributions in Ellipticity

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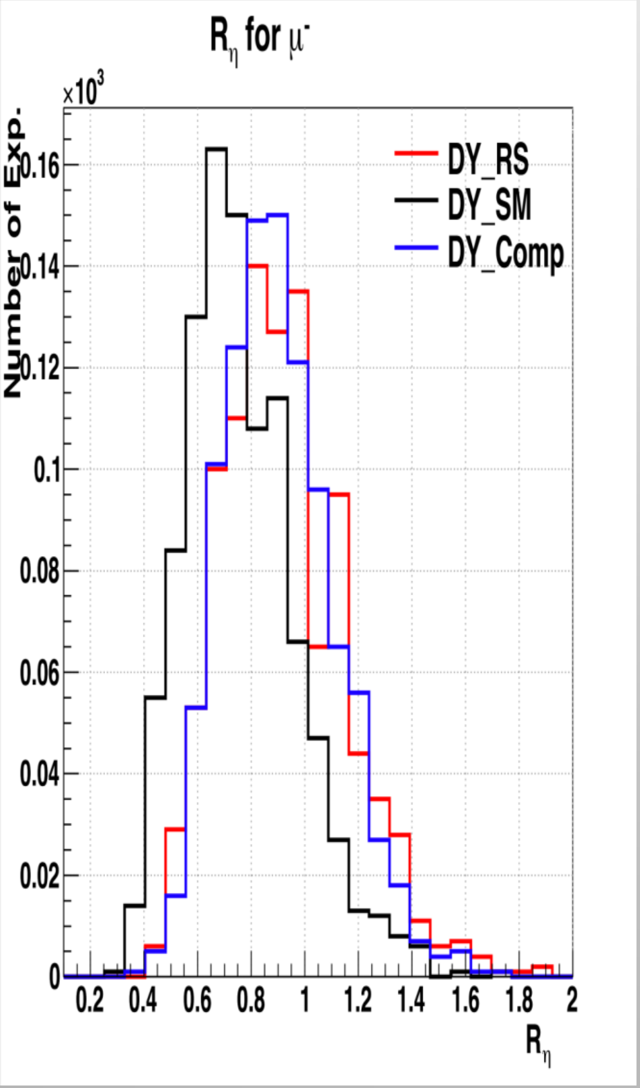

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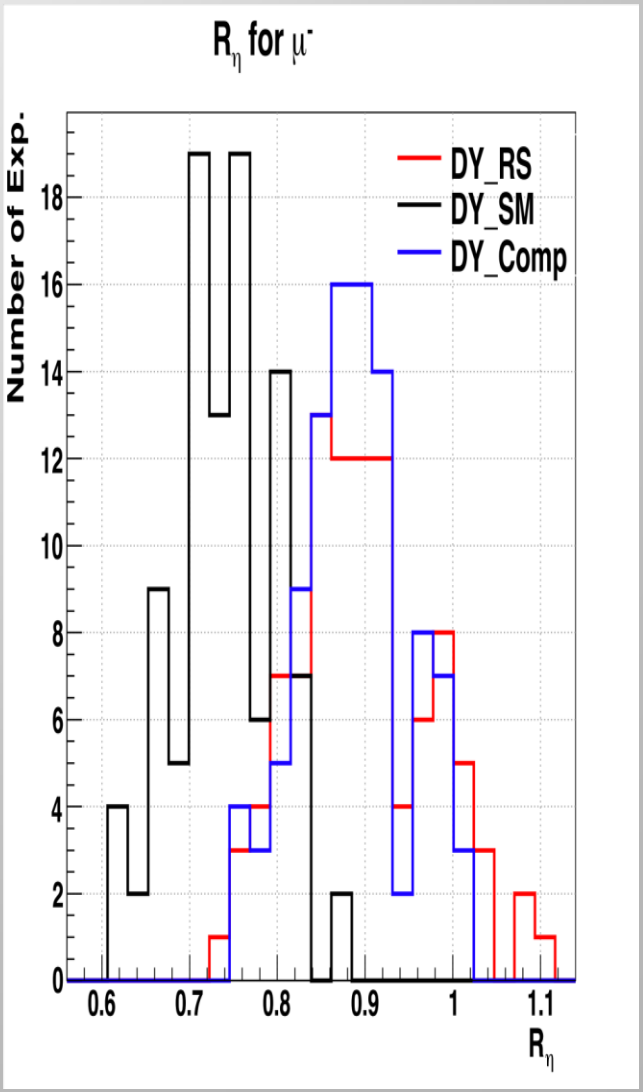

Better at Higher Energy

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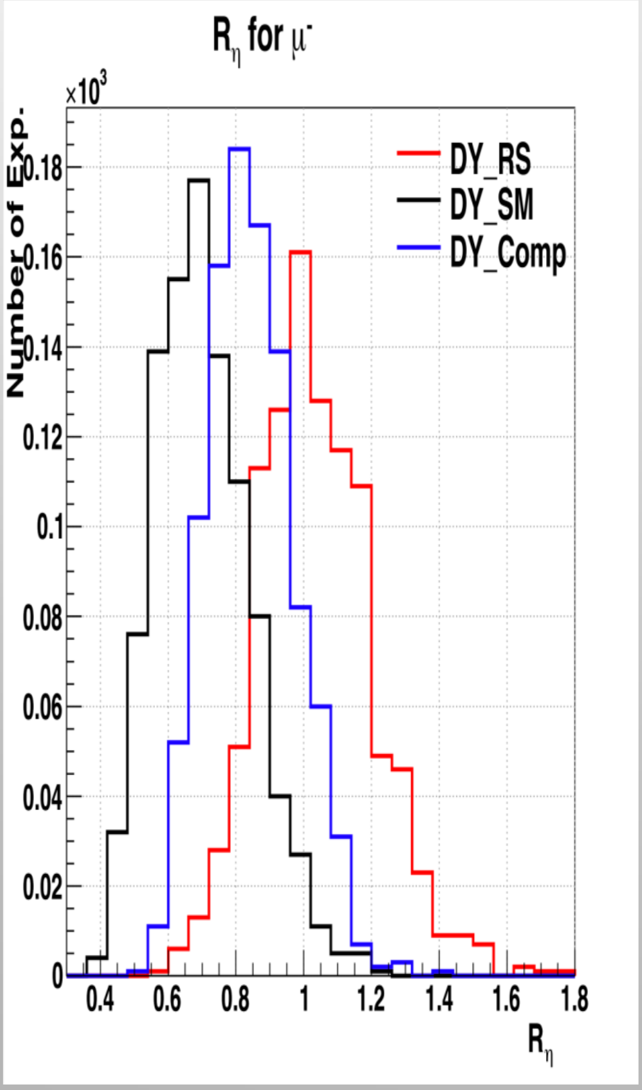
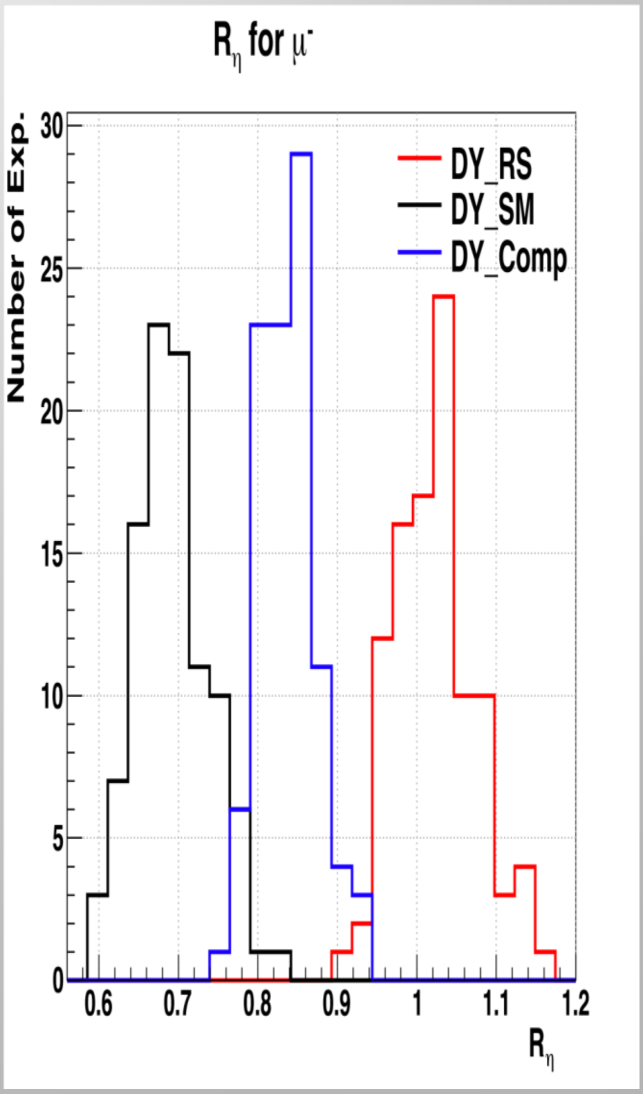




Wide Resonances

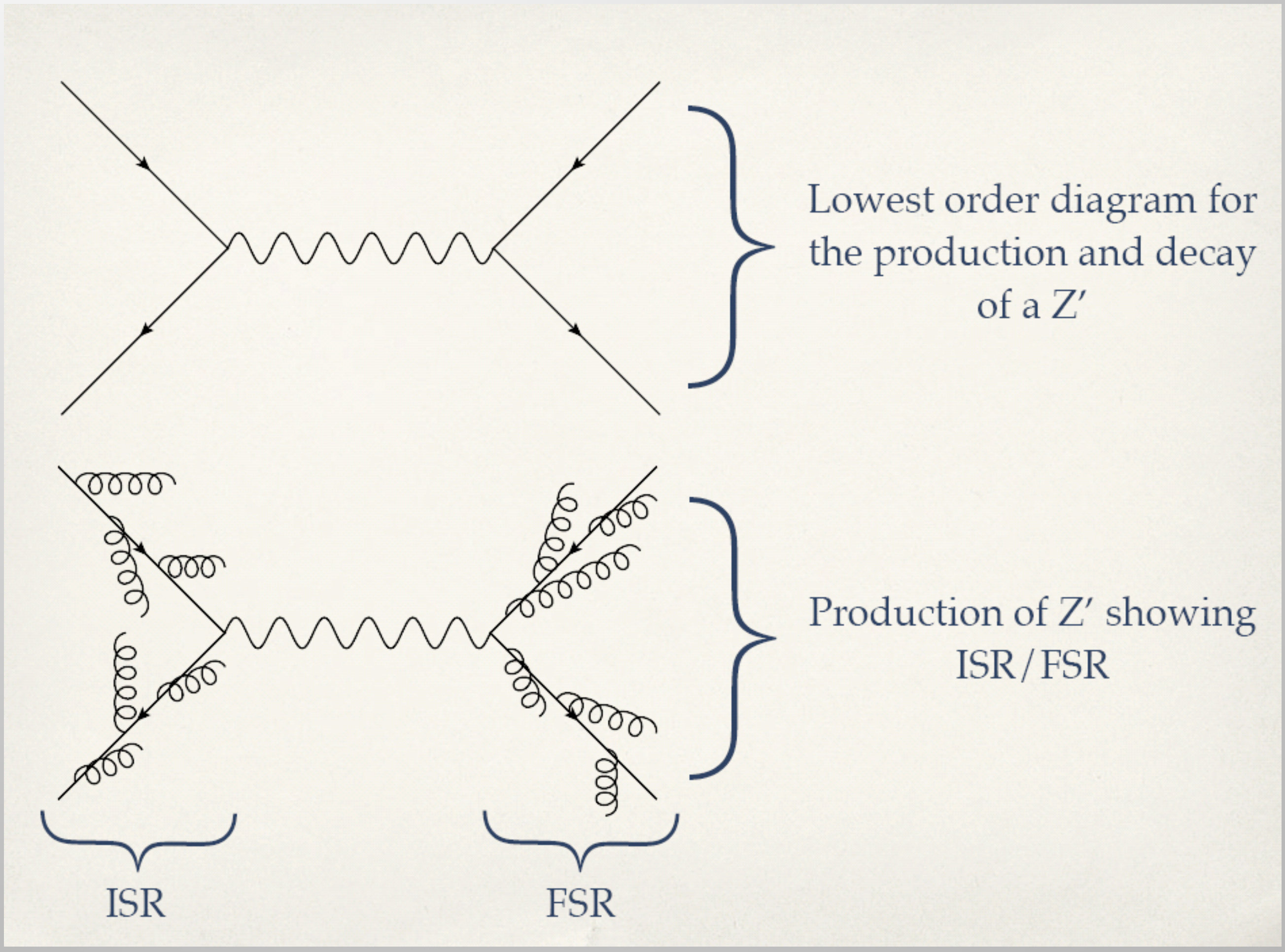
- ✓ Large cross section
- ✓ Distinctive shape wrt energy
- ✓ Distinctive wrt pseudorapidity

- ✓ Very promising

II: Progress Initial State Radiation (ISR) Tagging

- w/Krohn, Wang
- ISR produced due to standard QCD process at proton-proton collider
- Radiation tells us nothing about new physics (or weak interactions)
- Just QCD messiness
- Or???

Example



Lowest order diagram for the production and decay of a Z′
Production of Z′ showing ISR/FSR
ISR
FSR

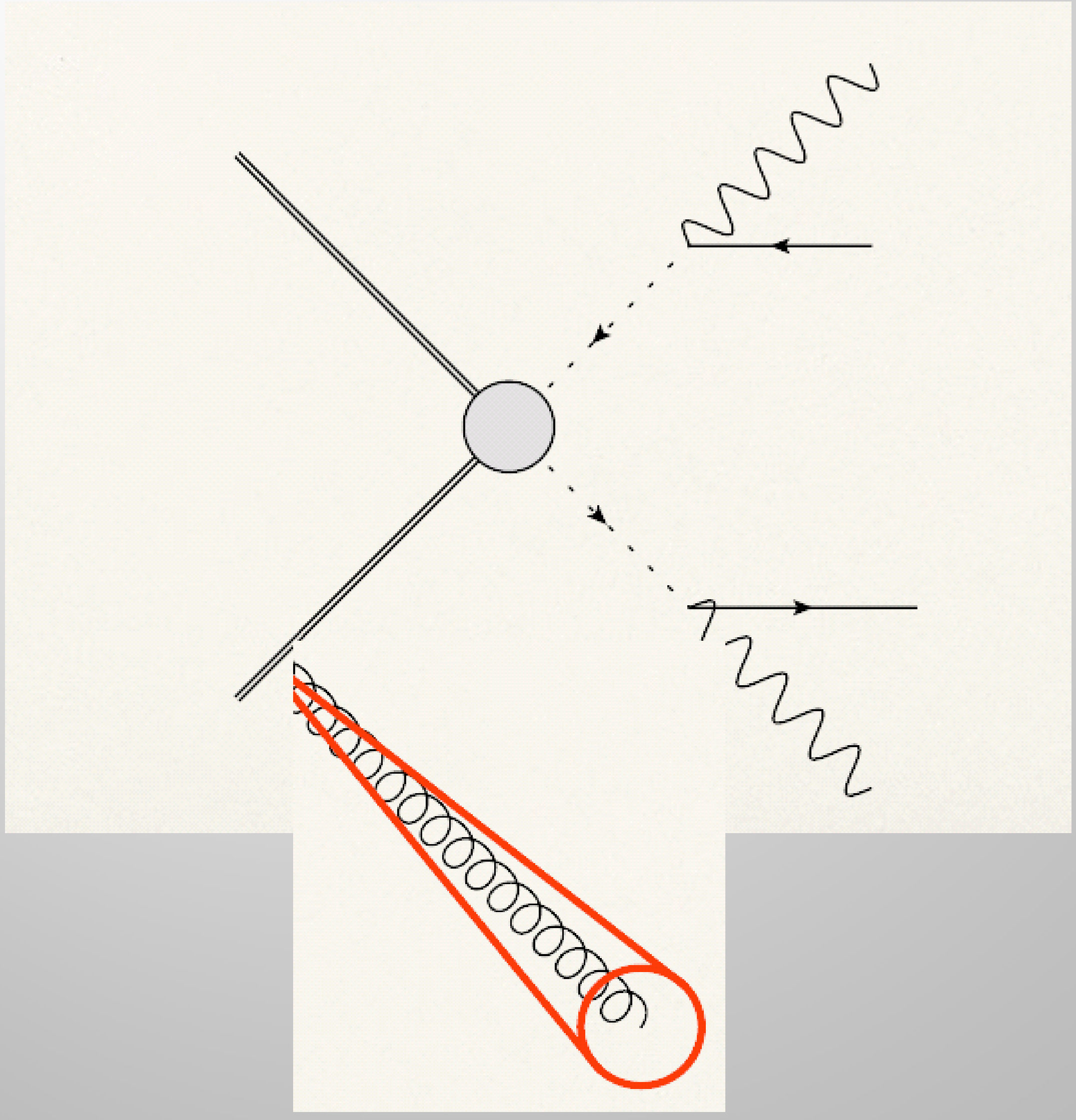
Initial State Radiation

- Seems a nuisance
- More complicated
  - More radiation
  - Initial and final state
  - Additional jets
  - Can contaminate existing jets
  - Or
  - Be their own jet

ISR

- Either way
  - seems like a nuisance
- But we show
- If you can identify it in BSM processes, valuable kinematical information

Example: Disquark production



Can use Identify and Use ISR

- We show
  - Distinctive
  - Carries valuable kinematical information

First step: Identify ISR

Tagging Procedure

- **Tag**
  - Take three hardest jets. Look for those

    1. Distinguished in pT

OR

    2. Distinguished in rapidity

OR

    3. Distinguished in m/pT

- **Check**
  - Require the candidate ISR jet

    1. Not be central

AND

    2. Remain somewhat isolated in rapidity

  - And, require that the implicit FSR jets be

    1. Close in pT

$$\frac{\max(p_{Ti}, p_{Tj})}{\min(p_{Ti}, p_{Tj})} > 2 \;\forall\; j \neq i$$

$$|y_i| > 1.$$

$$|y_i - y_j| > 1.5 \;\forall\; j \neq i$$

$$|y_i - y_j| > 0.5 \;\forall\; j \neq i$$

$$\frac{p_{Tj}}{p_{Tk}} < \rho + \frac{1/2}{1-\alpha}$$

$$\alpha = \frac{\min(p_{Ti}, \not{E}_T)}{\max(p_{Ti}, \not{E}_T)}$$

$$\frac{\max(\Delta_i, \Delta_j)}{\min(\Delta_i, \Delta_j)} > 1.5 \;\forall\; j \neq i$$

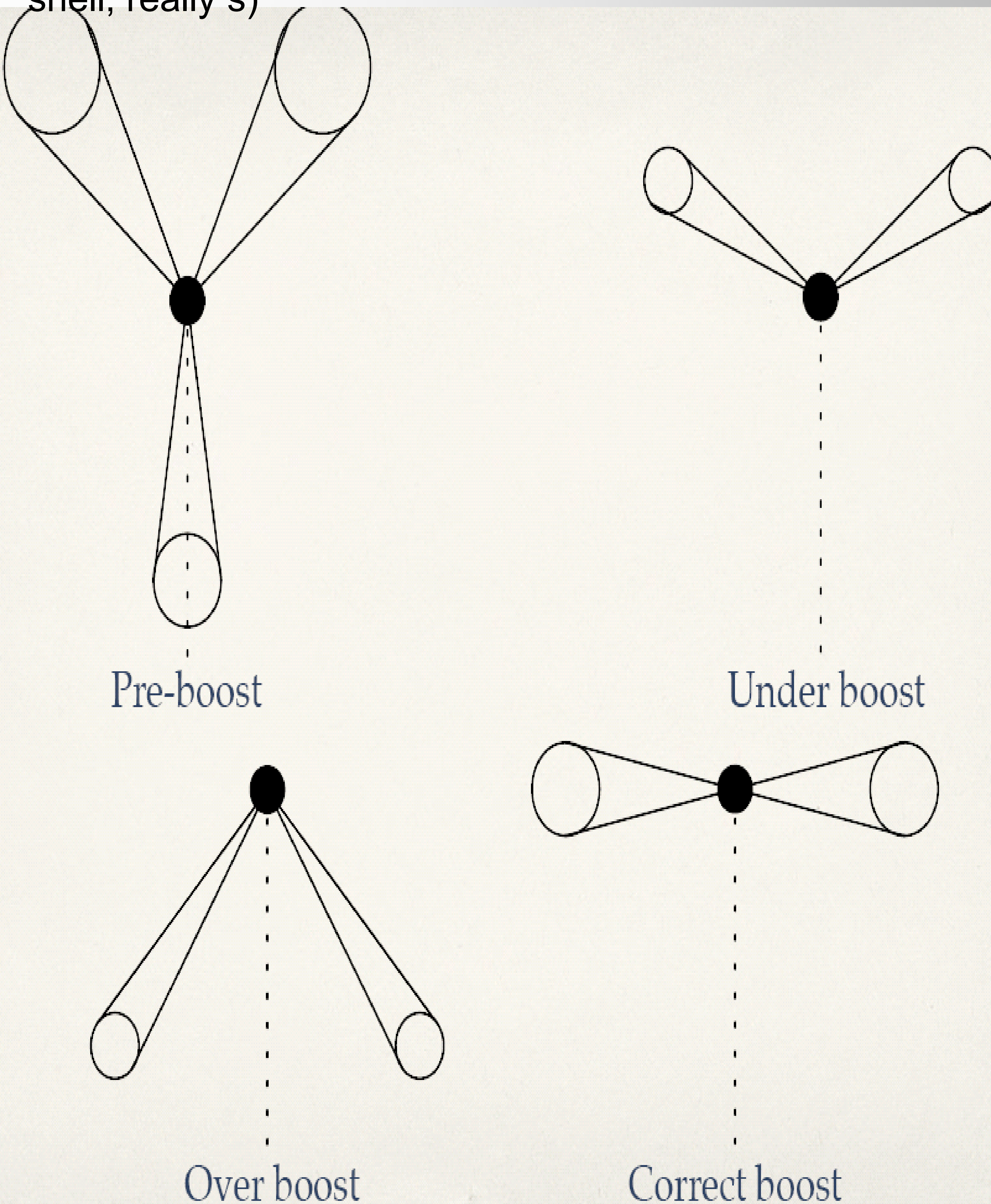
Finally, the implicit FSR jets must be somewhat central: $|y_j| < 2 \;\forall\; j \neq i$

Works very well

Spectrum		Efficiencies [%]	
$m_{\tilde{q}}/m_{\tilde{g}}$	$m_{\rm LSP}$	Trigger	Mistag
500 GeV	100 GeV	42	15
500 GeV	450 GeV	42	12
1 TeV	100 GeV	41	11
1 TeV	950 GeV	41	9
500 GeV	100 GeV	13	22
500 GeV	400 GeV	15	10
1 TeV	100 GeV	12	25
1 TeV	900 GeV	16	8

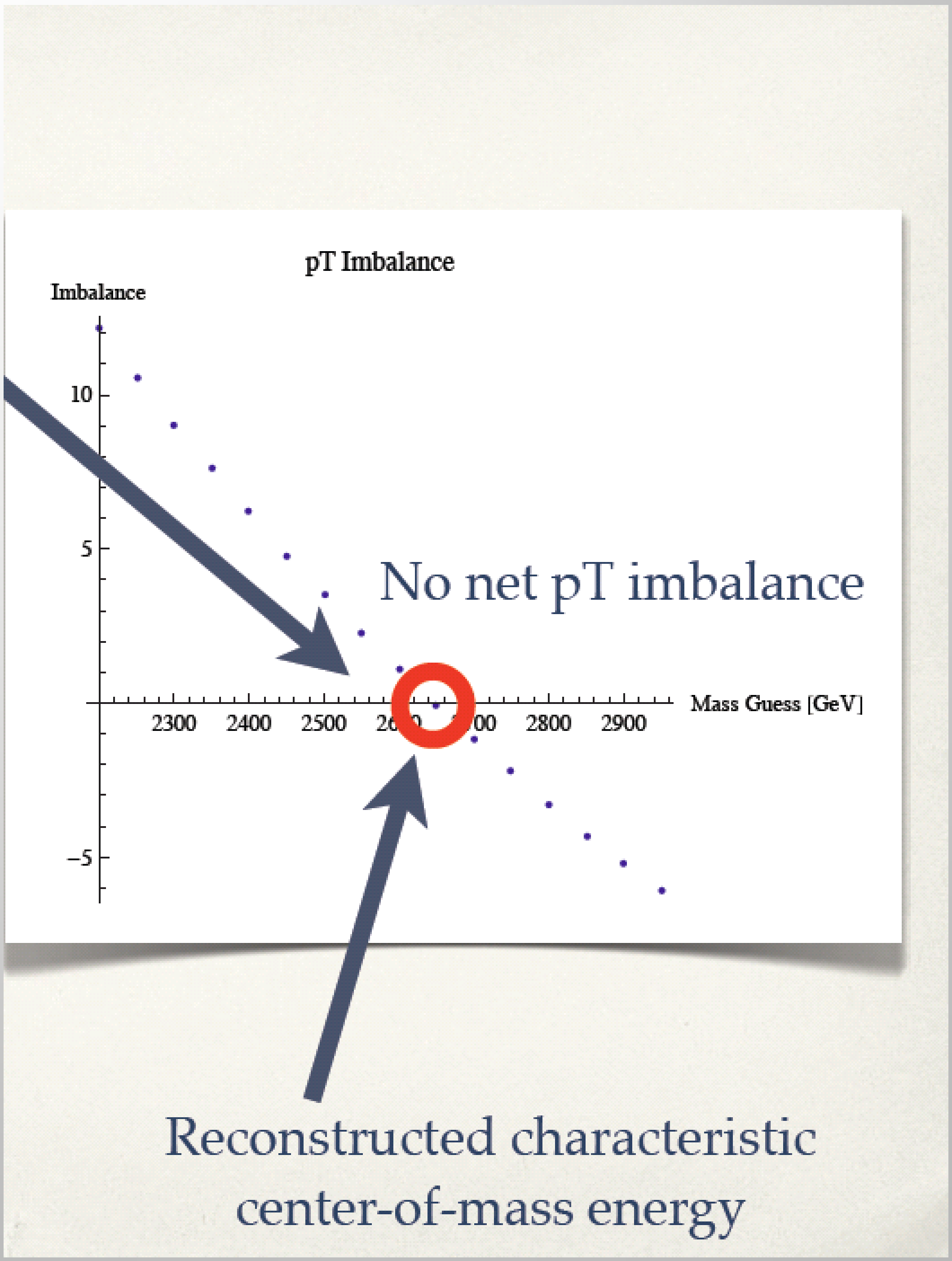
And not yet optimized

Next step: use kinematics to find **mass of squark** that gives correct boost to balance transverse momentum (assumes near on-shell, really s)



Determining mass by boost

- Boost along longitudinal direction to get visible momentum in new frame
- Boost along transverse direction parallel to ISR jet to compensate for ISR
  - Requires assumption of system's mass
  - Assume squarks nearly onshell at production
- Measure projection of visible momentum along ISR direction
  - Correct boost there should be no net projection



We determine mass at 20% level!
Independent lyof LSP mass, decay chain

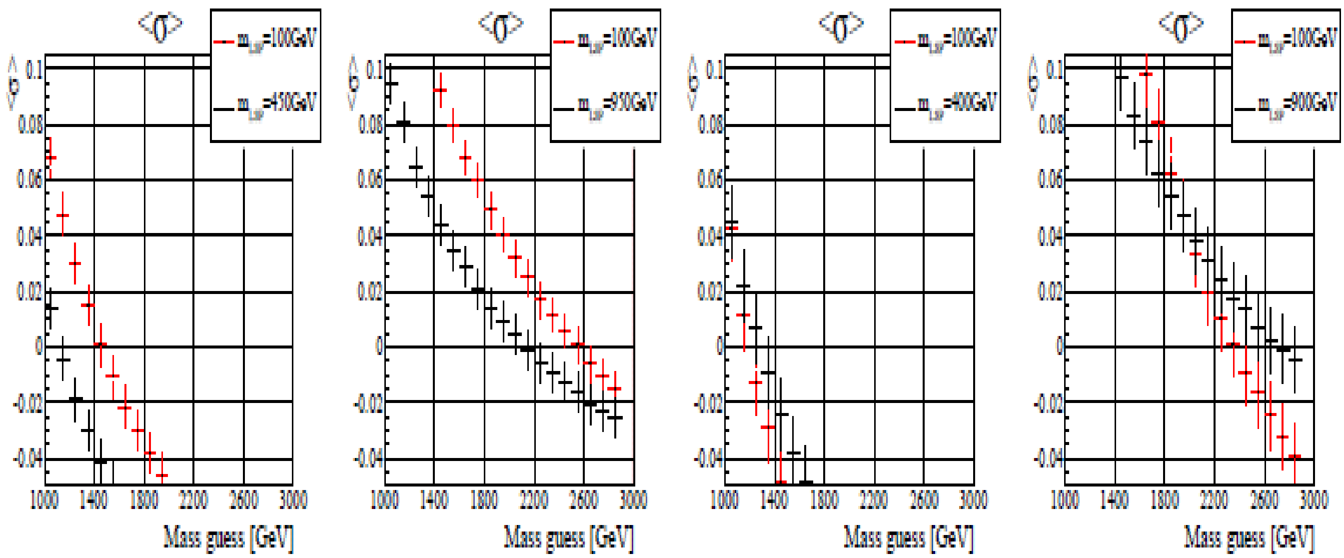
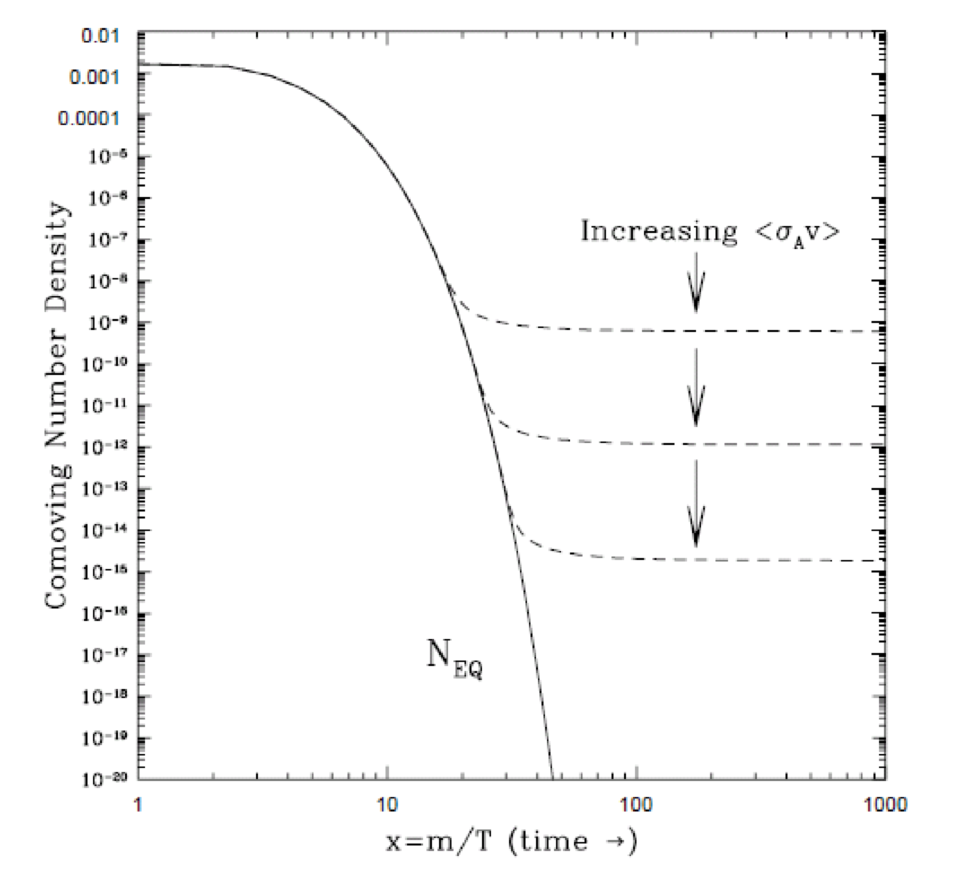


FIG. 1. The average sign of the FSR projection along the transverse ISR direction for, proceeding left to right, di-squark production using $m_{\tilde{q}} = 500$ GeV, $m_{\tilde{q}} = 1$ TeV, and then di-gluino production with $m_{\tilde{g}} = 500$ GeV, $m_{\tilde{g}} = 1$ TeV, with the LSP mass indicated in the legends. The position at which the points intersect $\langle\sigma\rangle = 0$ is what we would identify as $m_{\rm BSM}$, i.e. it where the FSR momenta are balanced because the boost is 'correct'. We see that it is in general close to $2m_{\tilde{q}/\tilde{g}}$. Note that the errors indicated are just the statistical errors associated with our Monte Carlo sample sizes.

Progress III: New Dark Matter Models

- w/Matt Buckley

WIMP "Miracle"



$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq 0.1 \left(\frac{3 \times 10^{-26}\, \mathrm{cm}^3\, \mathrm{sec}^{-1}}{\langle \sigma_A v \rangle} \right)$$

$$\sigma_{\mathrm{weak}} \simeq \frac{\alpha^2}{m_{\mathrm{weak}}^2}$$

Is WIMP the right Miracle?

- $\rho_X \sim 5\rho_B$
- Why should dark matter and ordinary matter energy densities be at all comparable?
- Could just be independently generated—baryogesis somehow and weak miracle
- Could be related: Asymmetric Dark Matter
  - $n_B \sim 5n_X$
- Could be more generally related; naturalness not quite so inflexible
  - Weak scale dark matter still natural
    - Thermal suppression
    - Bleeding excess number density through in eqm lepton violation below sphaeleron scale

All Sorts of Miracles Possible

- Asymmetric Dark Matter
  - Make B, Transfer B to X, $n_B \sim n_X$, light DM
  - Zurek,Luty,Kaplan
- Hylogenesis
  - Make B, X together $n_B \sim n_X$, light DM
  - Morrissey, Tulin, Hall, March-Russell
- Darkogenesis, Dark Genesis
  - Make X, Transfer X to B $n_B \sim n_X$, light DM
  - Shelton, Zurek
- Xogenesis
  - Make X, Transfer X to B, $n_B < n_X$, weak scale DM
  - Buckley, LR
- Xogenesis'
  - Make X, B, $n_B < n_X$, weak scale DM
  - Cui, Kahawala,LR, Shuve

Light Dark Matter

Weak Scale Dark Matter

Idea

- Asymmetry in dark matter
- Transfer asymmetry to normal matter
- Here we assume dark matter asymmetry produced in early universe
- Question is when we have operators violating B or L and X simulatneously will be get correct matter density
- Question is whether number densities work out for a given mass
- Perhaps most natural mass is weak scale mass

Light Dark Matter: "Relativistic Solution"

- Chemical equilibrium between B or L and X

$$\mu_X/\mu_B = \mathcal{O}(1)$$

- Net asymmetry

$$n_i = g_i f(m_i/T) T^2 R(T)^3 \mu_i$$

- Ratio chemical potential~ratio number density~ratio energy density

$$\mu_X/\mu_B \sim \mathcal{O}(1)$$

$$m_X/m_{\text{proton}} \sim \Omega_{DM}/\Omega_B$$

Weak Scale (or Heavy) Dark Matter "Nonrelativistic Solution"

- More generally

$$n_i = g_i f(m_i/T) T^2 R(T)^3 \mu_i$$

$$f(x) = \frac{1}{4\pi^2} \int_0^\infty \frac{y^2 dy}{\cosh^2\left(\frac{1}{2}\sqrt{y^2 + x^2}\right)}$$

- N … or
  n

Nonrelativistic Solution

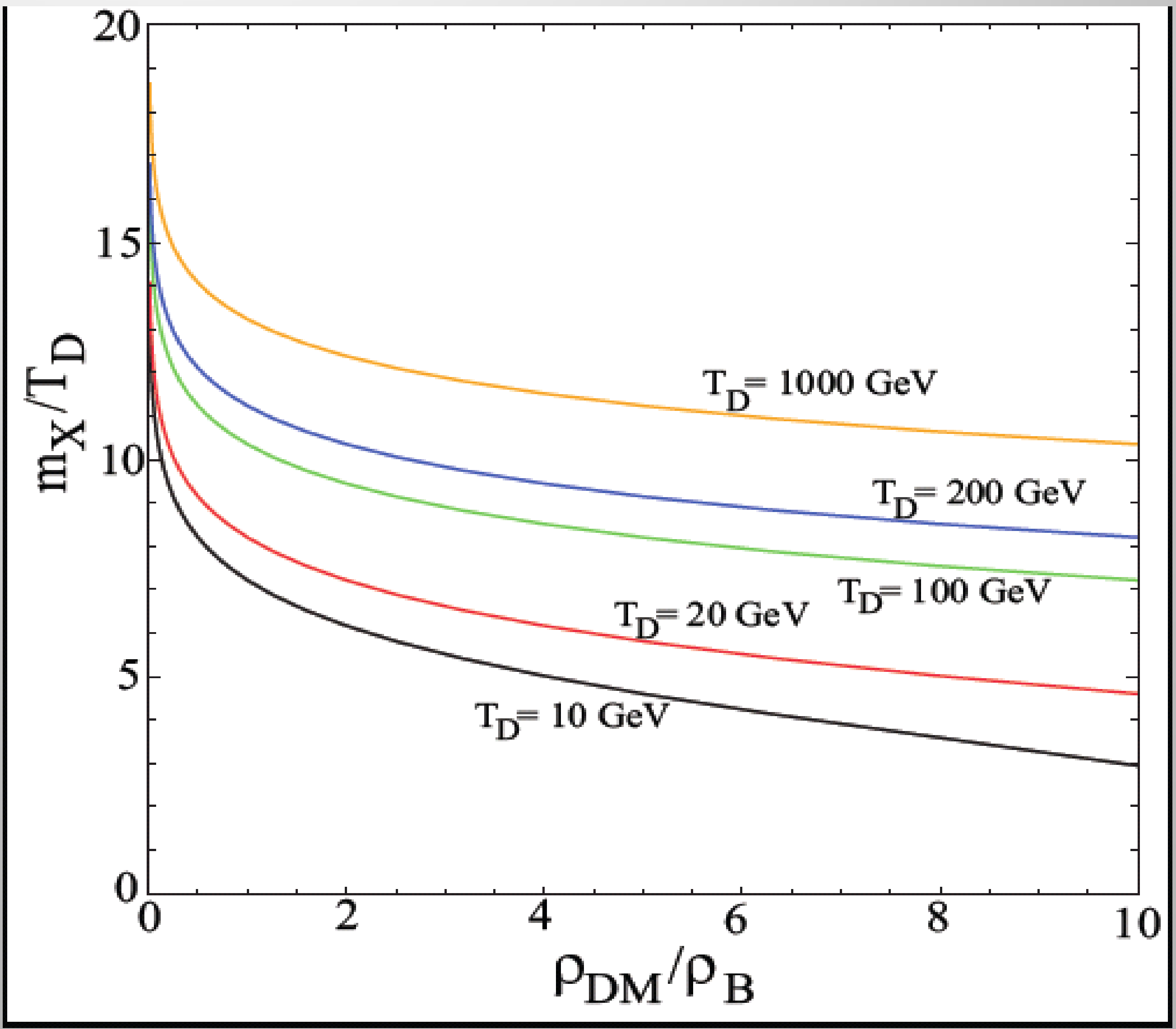
- Need to solve

$$f(m_X/T_D) = \mathcal{O}(1) f(0) \frac{\rho_{\mathrm{DM}}}{\rho_B} \frac{m_{\mathrm{proton}}}{m_X}$$

- Number density of X less than B
- Chemical, but no longer thermal equilibrium
- Allows for different masses

Naturalness allows hierarchy of order 10

- Right ratio of densities found for wide range of m/T
- Usually need m/T~10, which is quite reasonable
- Expect comparable densities over the whole range



Xogenesis New Class of Models

- New "miracle"-New models
  - Transfer asymmetry from dark matter to matter
  - Create both at same time
    - Can be weak scale
    - Can be light
- Different bounds
- Different tests
- Lighter more accessible
- Challenges for future-
  - Models
  - Searches

For the Future

- Open mind
- Open data sets
- Multiple data sets
  - Complementarity
- Optimize and exploit what we have
- Think about experiments, theory in parallel
  - Individually and as a community

What to Do?

- Anticipate
  - As much as we can…
- Model building is good!
  - Simple best
  - But not if not realized in nature
- Truly tragic if LHC misses something that is there
  - Even unrelated to hierarchy
    - Vector representations
    - Light particles
- Jet physics
  - Many advances
  - Asking different questions
  - Helping with both SM, BSM physics

What to Do?

- Celebrate experiments working
- Make sure we do everything we can with existing experiments
- Think about what experiments true implications will be
- Think about what is most necessary for future
  - Soon?