Title: The Frontier of Fundamental Physics at the LHC

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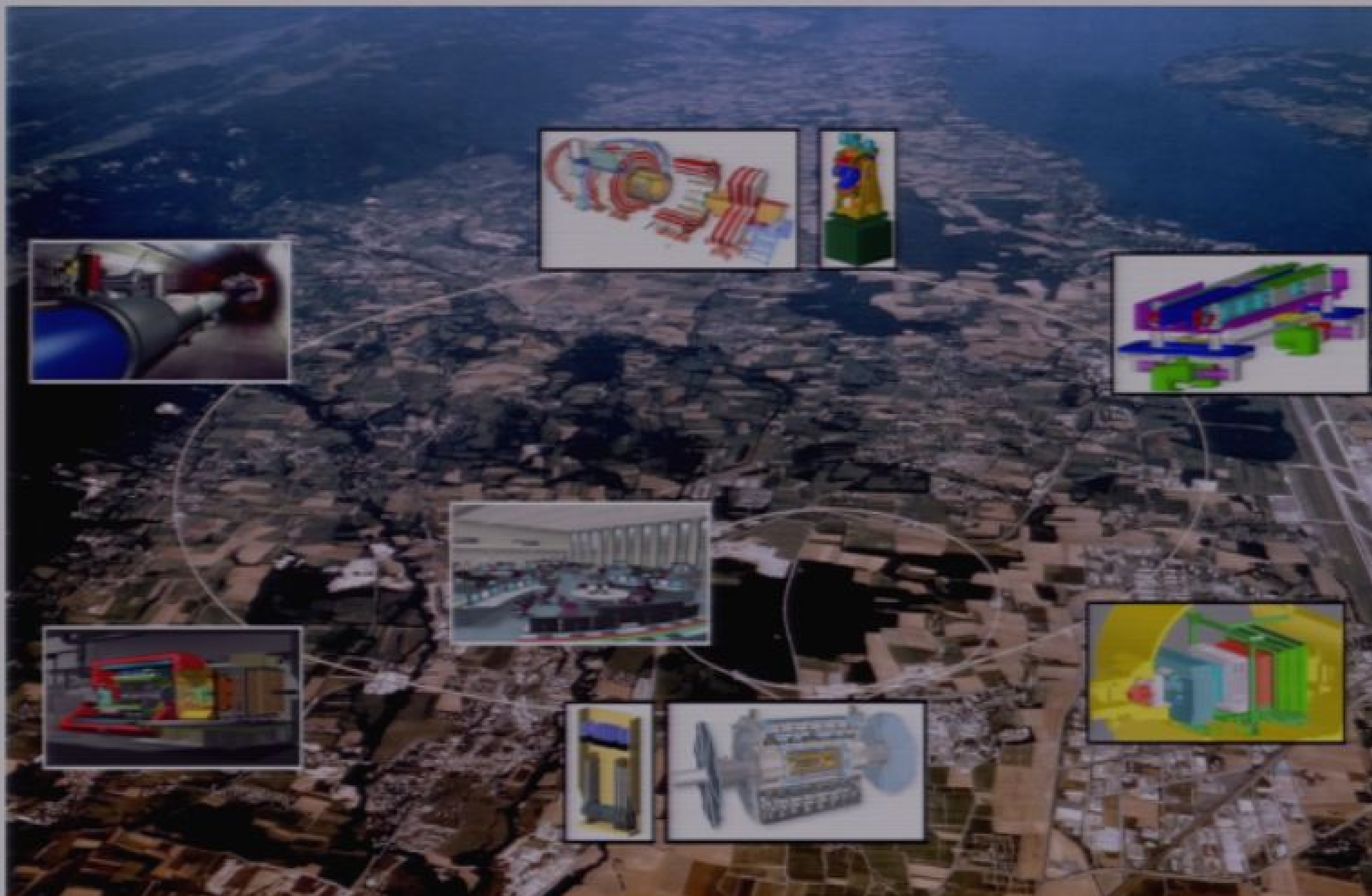
Abstract: The LHC will explore fundamental physics at a new energy frontier. A spectrum of new particles at the TeV scale is expected on two theoretical grounds: explaining dark matter and generating the electroweak scale. Understanding the properties of such particles can clarify the nature of dark matter, the origin of the weak scale, symmetries of nature, and the multiverse. These particles can be discovered by identifying collision events characteristic of new physics in LHC data. Their properties can be measured by characterizing such new physics events in terms of decay modes and basic kinematics. I will describe how this can be accomplished and exciting possibilities for what we may discover.

The Frontier of Fundamental Physics at the LHC

Philip Schuster (SLAC)

The LHC — The Large Hadron Collider



27 km in diameter

14 TeV center of mass proton-proton collider
(2 TeV at Fermilab)

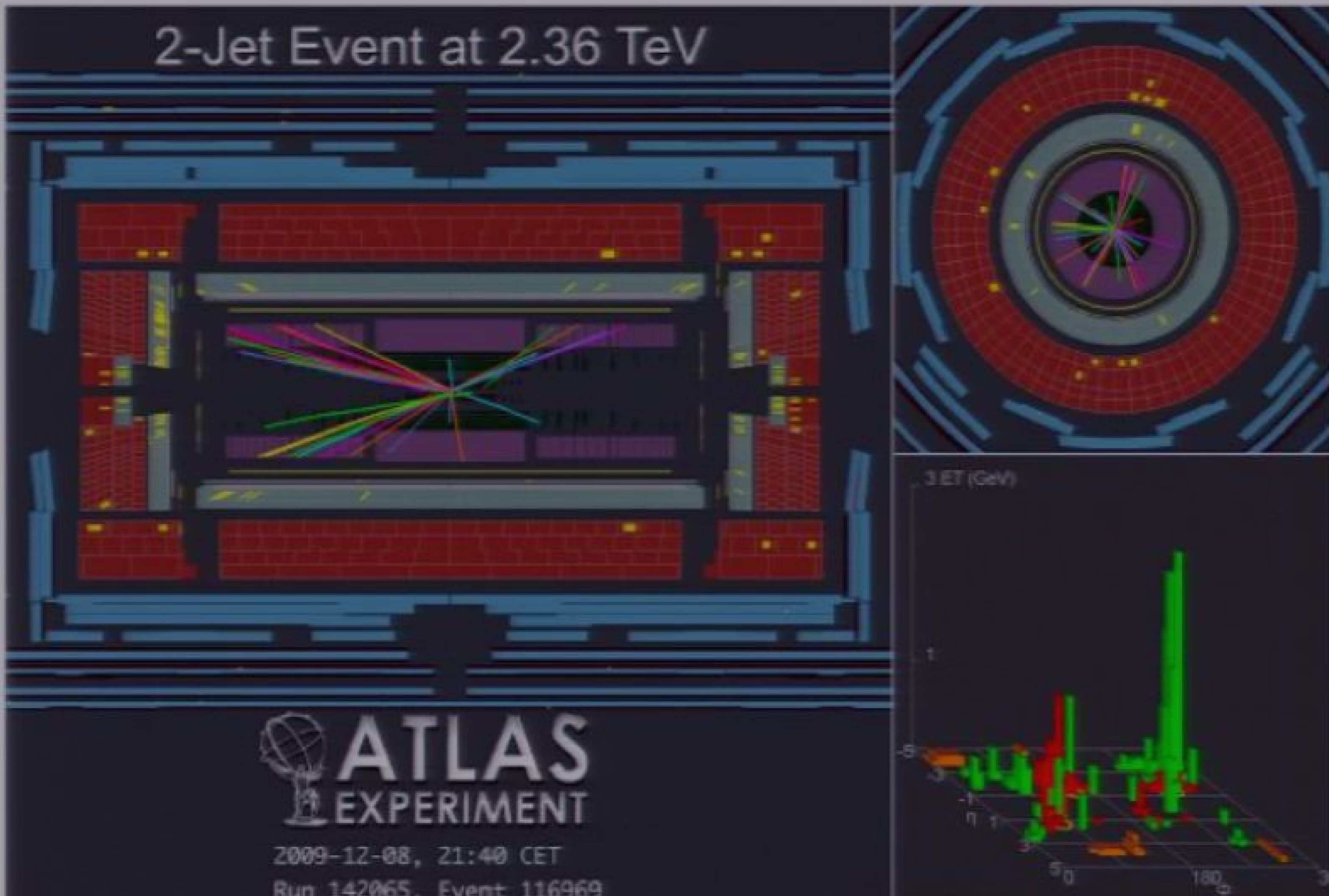
Probing $\sim 10^{-18}$cm

What can we study using the LHC?

- The origin of the weak scale:
  - weak interactions become "strong" at the TeV-scale, so there's either new dynamics, or new states of some kind...
  - A Higgs particle can break electro-weak symmetry, but quantum corrections to its mass are sensitive to the Planck scale — what dynamics is responsible for this hierarchy?
  - Perhaps the weak-scale is fine-tuned. Can we find evidence for that possibility?
- The origin of dark matter:
  - TeV-scale stable particle is a good candidate.
  - Can we find and study it at the LHC?
  - Is dark matter related to the weak-scale, or is it something else entirely?

The unexpected seems likely, so the interesting questions are probably not something we've identified yet!

First LHC Data !!!



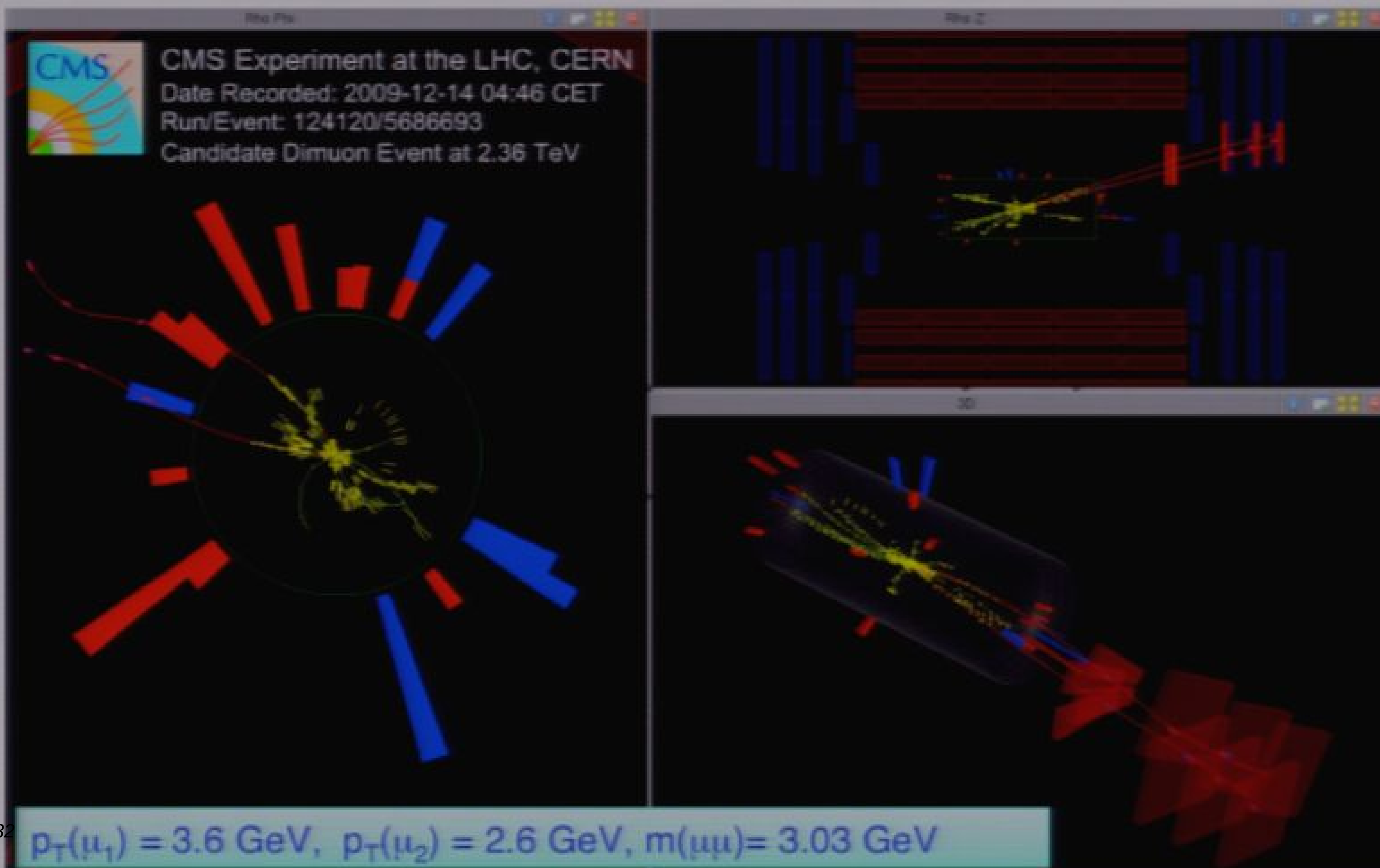
An example of an “event” in early data from ATLAS

A process with two “jets”

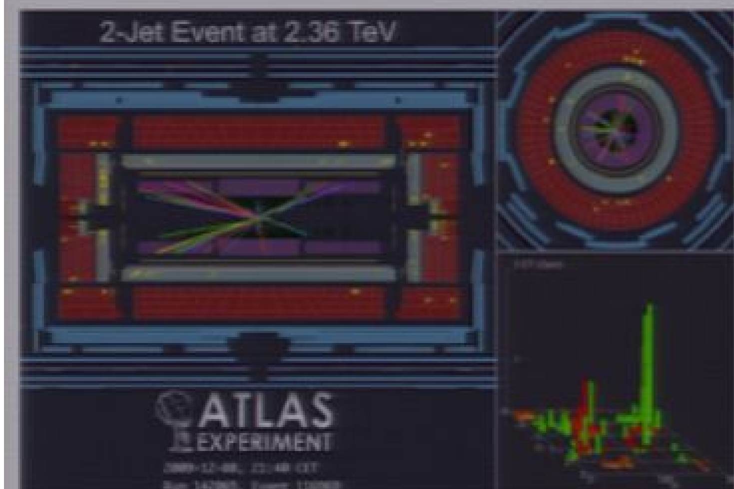
First LHC Data !!!

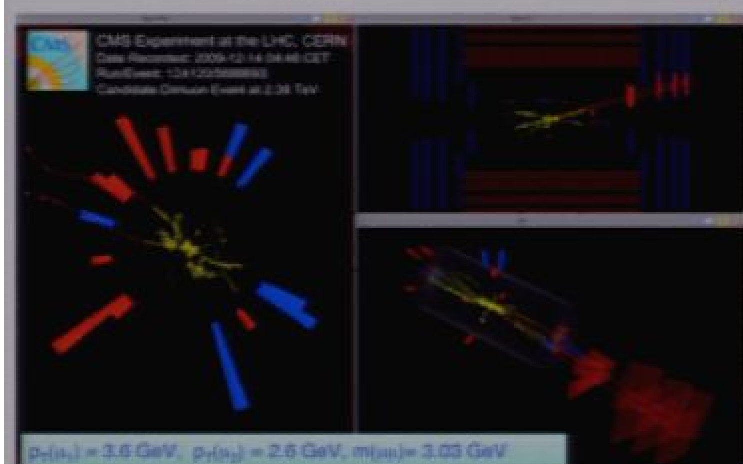
An example of an "event" in early data from CMS

A process with two muons



The Central Challenge





$\Rightarrow$

What new physical principles are being revealed at the TeV scale?

Is nature supersymmetric?

Is the electroweak scale natural?

What is the origin of dark matter?

Is something surprising happening?

Collective Hadron Collider Discovery Experience

$$W/Z$$

No undetermined parameters

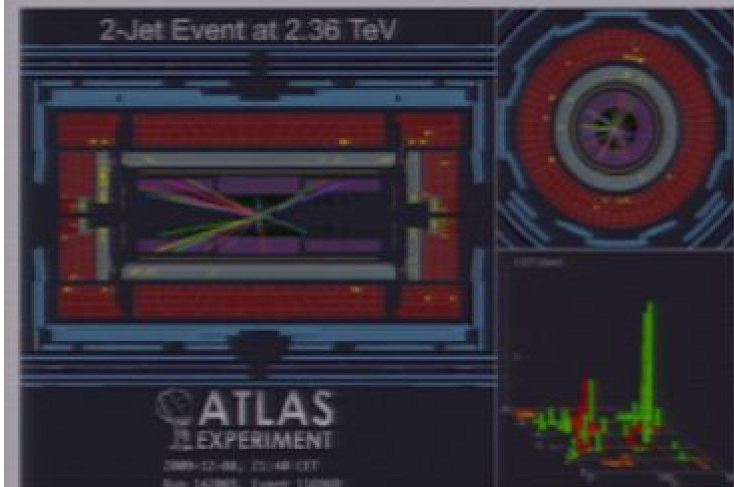
$$t$$

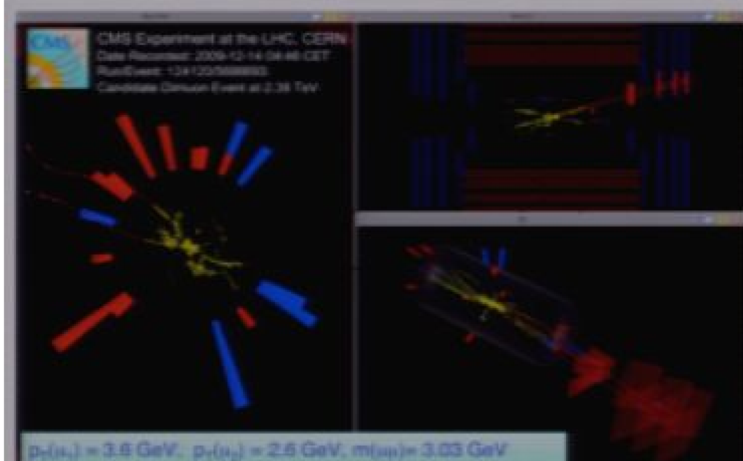
One unknown parameter

(m_t)

In both cases, knew exactly what to look for...

The Central Challenge





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Collective Hadron Collider Discovery Experience

W/Z	t
No undetermined parameters	One unknown parameter (m_t)

In both cases, knew exactly what to look for...

Exploring New Territory

The LHC is so exciting precisely because the answer to the question — what will we see? — has never been more uncertain!

Starting With Evidence For New Physics

A kinematic distribution with an "anomaly" (do you believe it?), and many detailed models that can fit the data —what do we learn?

How do we characterize models and data to inform theoretical investigation?

Starting With Evidence For New Physics

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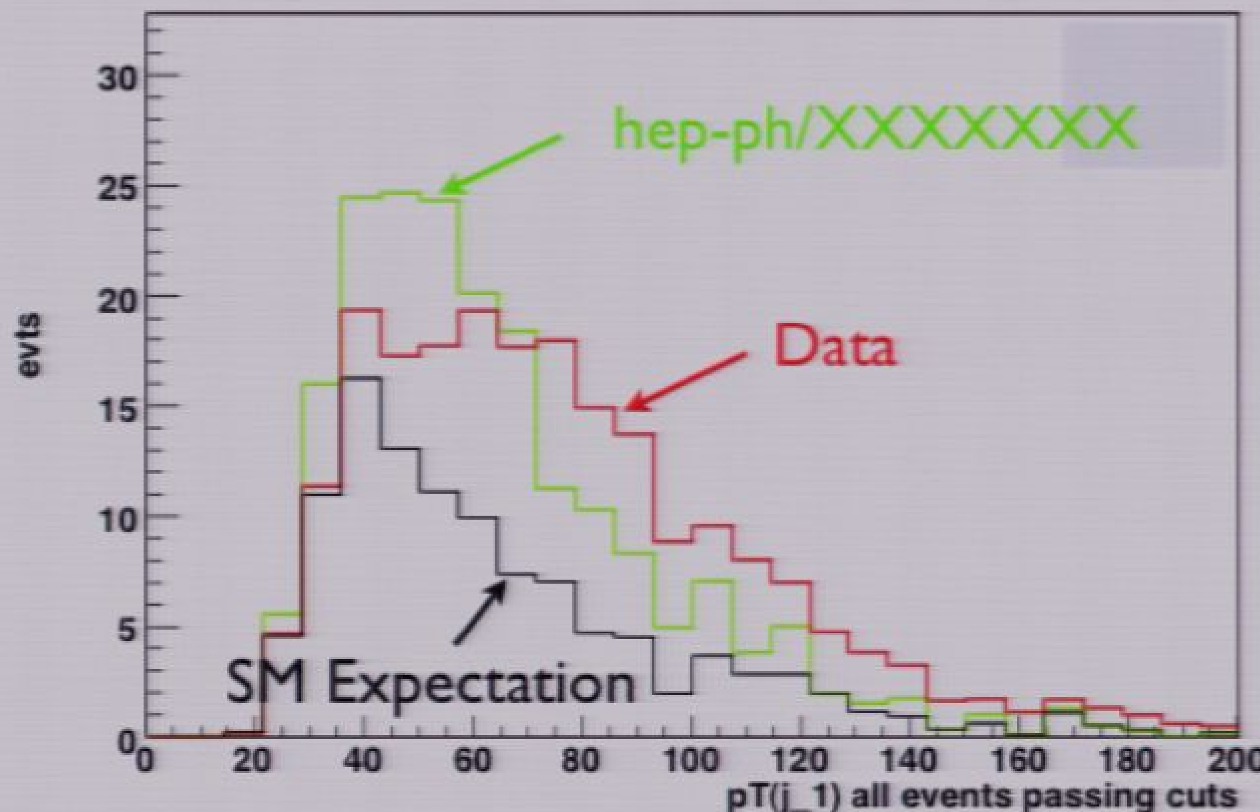


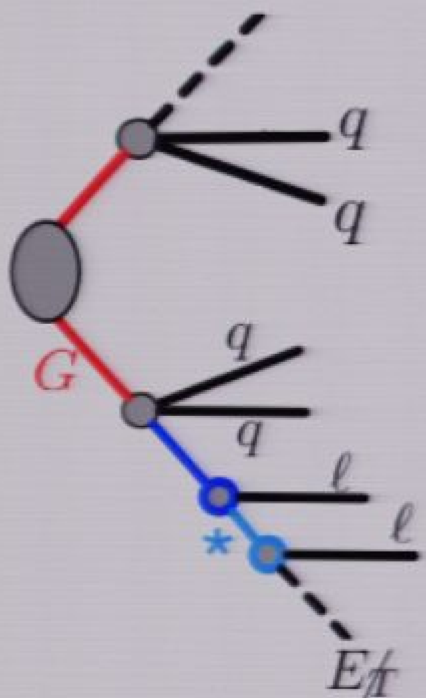
How do we characterize models and data to inform theoretical investigation?

From Data to the New Standard Model at the LHC - Outline

- Exploring the TeV scale with the LHC - Intro
- How will LHC data connect to theory?
  - Spectroscopy and examples
- How can we determine spectroscopy from data?
  - Simplifying field theory at the LHC
    $\rightarrow$ On-Shell Effective Theories (OSET)
- Uses of OSETs at the LHC
  - Applications to searches and beyond in CMS

What will the LHC provide?

Spectroscopy!



Decay Topology: how does a new particle decay into Standard Model particles?

Topology information gives your quantum numbers

Masses of new particles

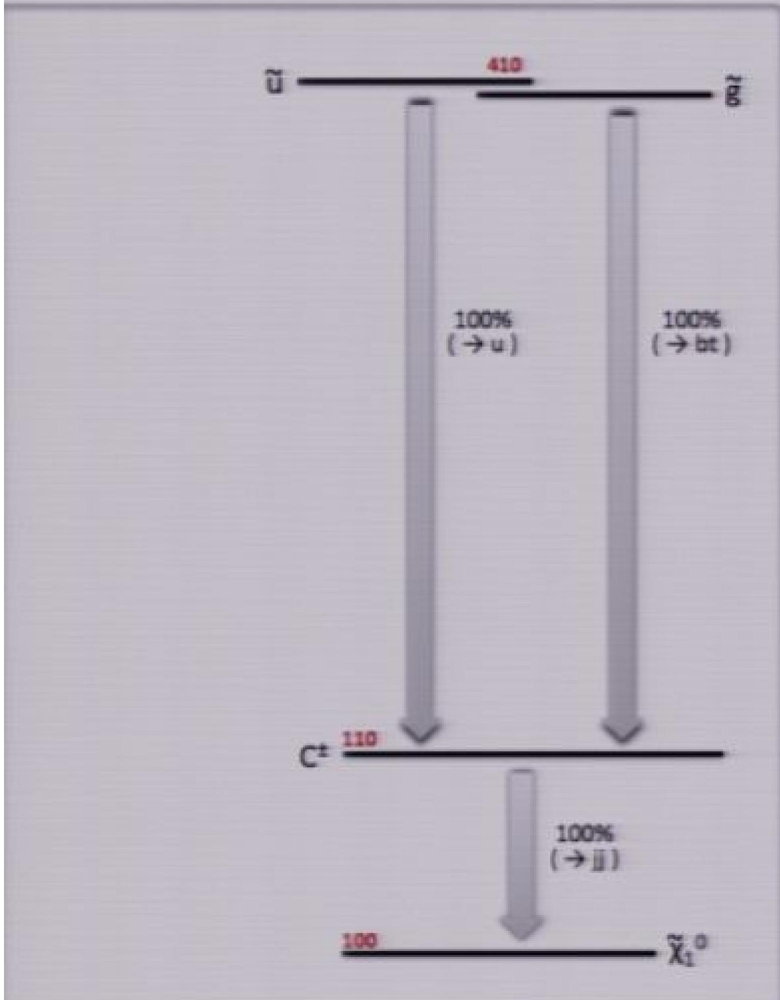
Extremely useful discriminator among the high-scale theories

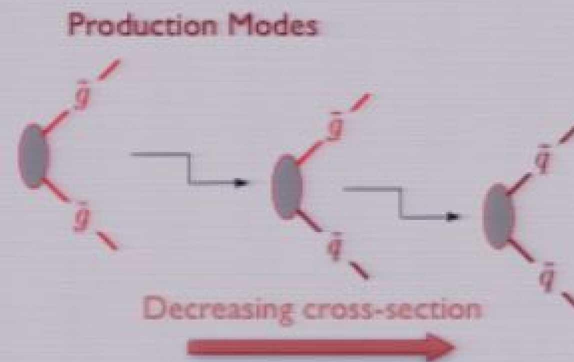
Rates of decay topologies:

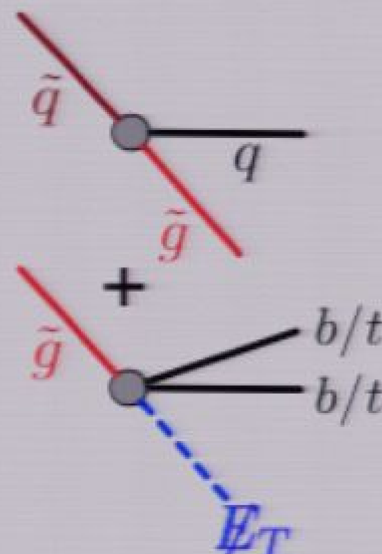
Gives additional information about quantum numbers and probes strength of different couplings in the underlying theory

Theoretical Physics starts here!

Quantitative Spectroscopy is Needed







Far from obvious that this information can be extracted from hadron collider data in a meaningful way!

Spectroscopy and the Underlying Theory

How can spectroscopy connect readily to questions about the underlying theory?

A couple of examples...

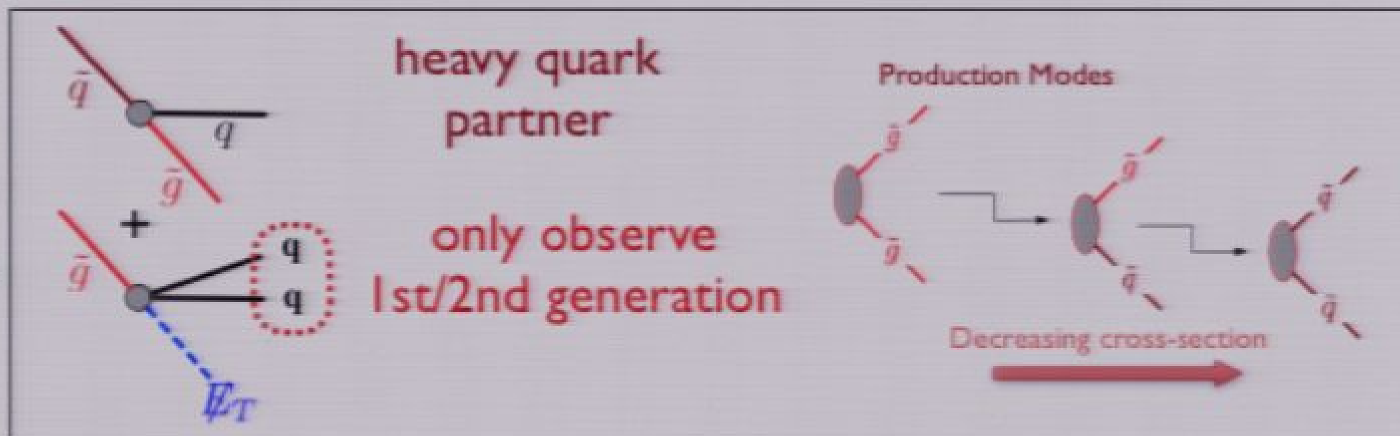
Naturalness?

No evidence for 3rd generation partner

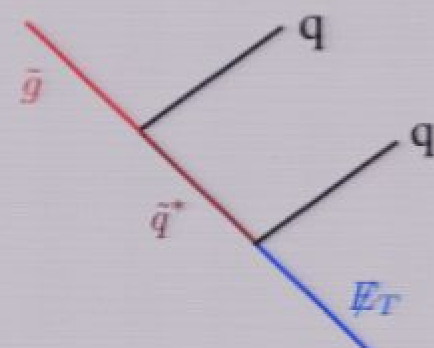
Quark Partner

Gluon Partner

Unknown



New physics with quantum numbers that pair up with Standard Model gauge boson (a good start)

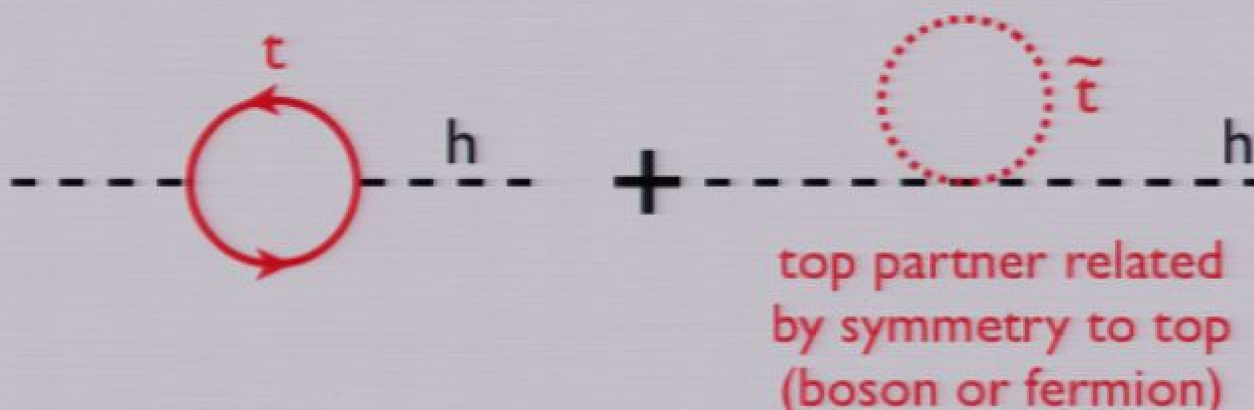


$$\Gamma \sim \frac{\alpha^2}{m_{\tilde{q}}^4}$$

$\Rightarrow$ Lower bound on mass of 3rd generation quark partners

Naturalness?

The top/bottom quark in the Standard Model are naively responsible for the largest UV sensitivity of the Higgs mass



We expect particles with quantum numbers associated with the top/bottom quarks to cancel the UV sensitivity in some fashion

The presence of top/bottom partners relative the other new physics mass scales is key to assessing naturalness

Naturalness?

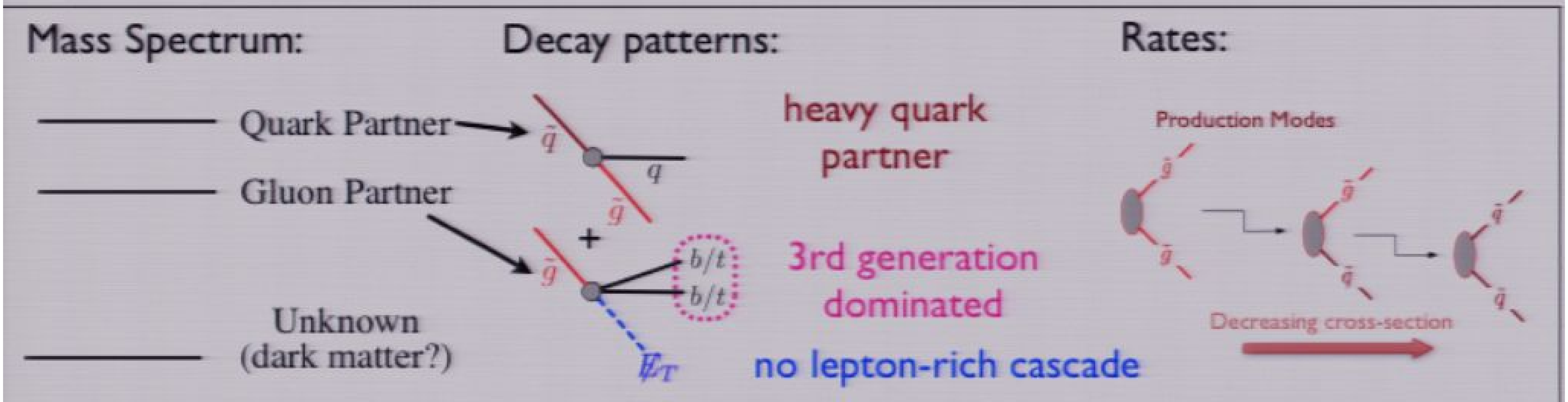
Without dynamics to protect the Higgs (i.e. weak-scale) from quantum corrections, how do we explain the low mass of weak-interactions compared to the Planck scale?

Perhaps there are top/bottom partners, but they are heavy, so there's still some apparent fine-tuning

Do we interpret this as evidence for the multiverse, or some other way of selecting cosmologies with a weak-scale in close proximity to QCD?

What should we look for in this case?

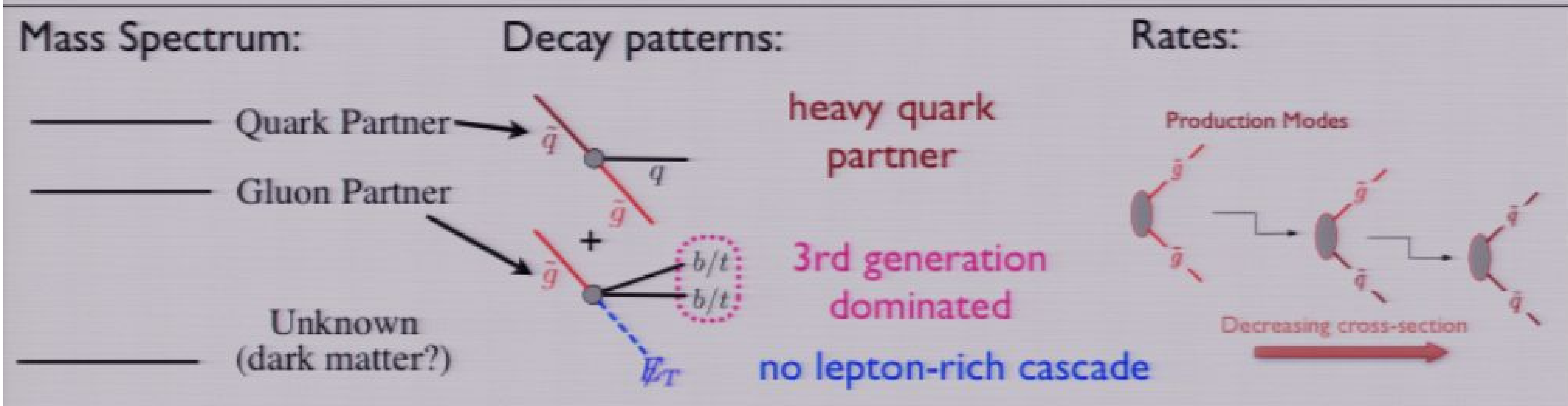
Another example: The Origin of Dark Matter



Spectrum similar to last example, but now there is clear evidence for top/bottom partner particles

Missing energy in the events is evidence for a stable particle: Can this be dark matter?

Example: The Origin of Dark Matter



Dark Matter Candidates:

Heavy (~100's GeV) neutral particles with the same gauge and global quantum numbers as the photon, W or Z bosons, neutrinos, or perhaps the Higgs

Use decay rate information to sort these possibilities out

Example: The Origin of Dark Matter

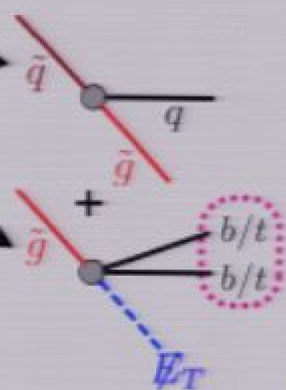
Mass Spectrum:

Quark Partner

Gluon Partner

Unknown (dark matter?)

Decay patterns:

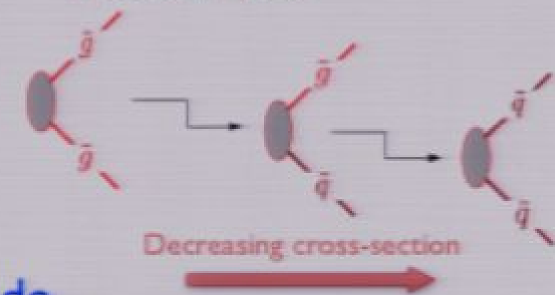


heavy quark partner

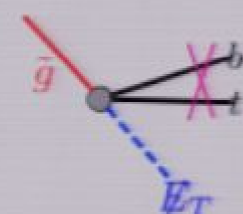
3rd generation dominated

no lepton-rich cascade

Rates:



Only Photon partner light? ⟹ No b/t decay



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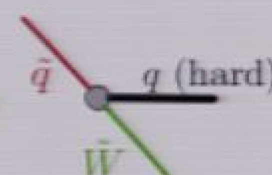
Intermediate charged particle options:

Light W,Z partner? ⟹ direct quark partner decay ($\gtrsim 20\%$)



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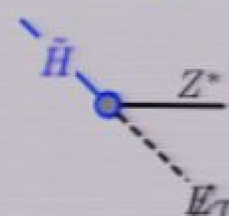
Higgs partner near lighter photon partner ⟹ Striking decay: $Z^* \to \ell^+\ell^-$



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Example: The Origin of Dark Matter

Mass Spectrum:

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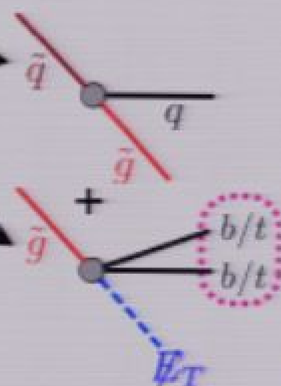

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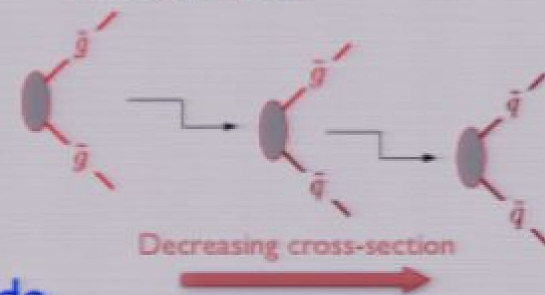


Mass Spectrum:

Quark Partner

Gluon Partner

↑

W, Z, photon, neutrino partners

Higgs partner

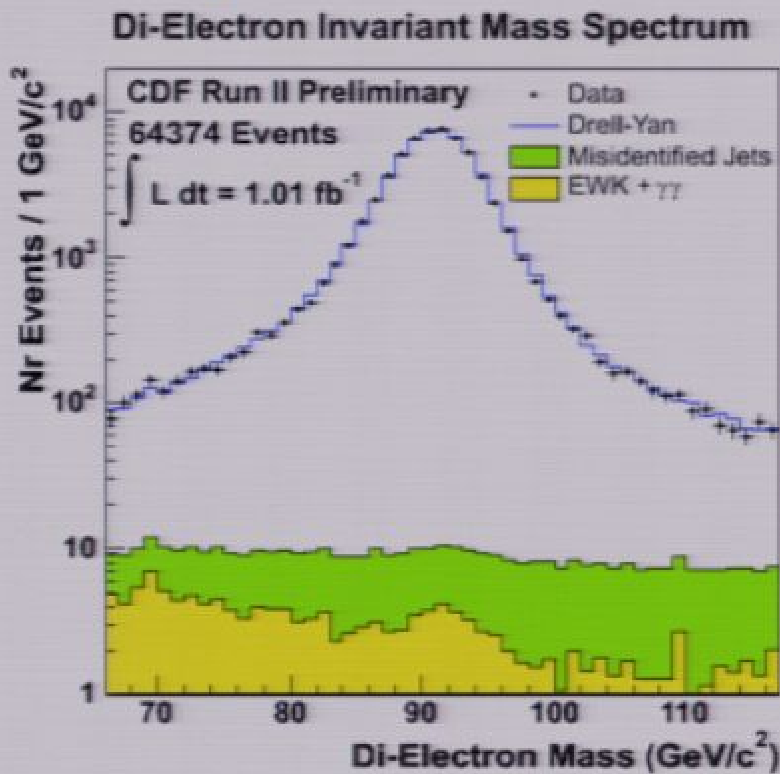
Not consistent with thermal dark matter!

Spectroscopy and the Underlying Theory

Spectroscopy provides the building blocks for theoretical investigation

How do we obtain spectroscopy?

The "easy" case: A resonance

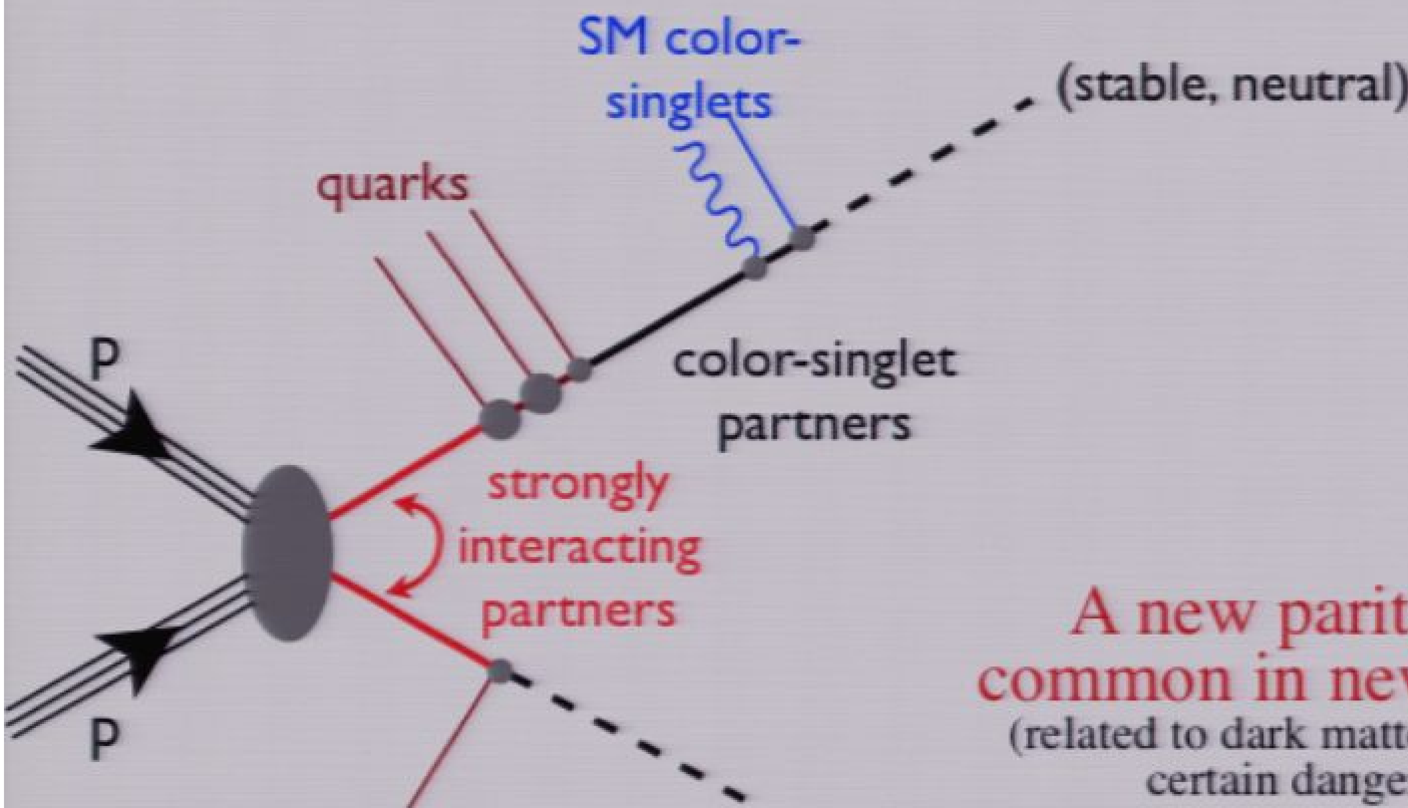


Kinematically reconstruct mass and relative rates of decays

Coupling strengths and spin can be deduced simply

Theory interpretation easier for sharp resonances!

Complicated structure more common



A new parity symmetry is common in new physics models
(related to dark matter and the need to forbid certain dangerous interactions)

New stable particles can (and are expected) to be produced that make direct reconstruction impossible!

Obtaining Spectroscopy

Obtaining spectroscopy is difficult for new physics with stable particles (a large class of theories!)

It is natural to try and fit parameters in models (Lagrangians)

But Lagrangians contain vastly more information than is directly observable

Is it possible to describe how a field theory would look in a hadron collider, but using something simpler?

We want a theory that allows us to turn spectrum pictures into kinematic distributions and vice versa

Removing redundancy

Is it possible to describe how a field theory would look in a hadron collider, but using something simpler?

There is a huge class of field theory models to test (discover)!

Can the large array of field theory possibilities be collapsed into a few classes?

Theory and LHC Data — Through On-Shell Effective Theories

- A little collider physics review

- Shape invariance as a clue for simplifying descriptions of new physics

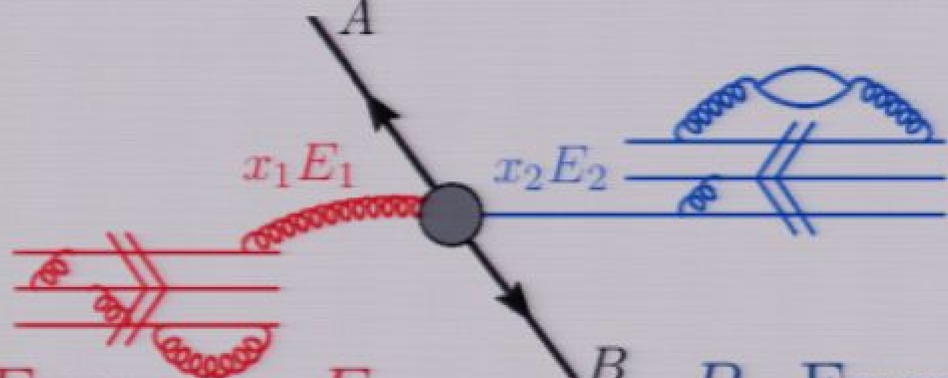
  hep-ph:0703088

- On-Shell Effective Theories

  hep-ph:0703088
  arXiv:0810.3921

The Mechanics of Hard Scattering

Hard Scattering (2 to 2 process)



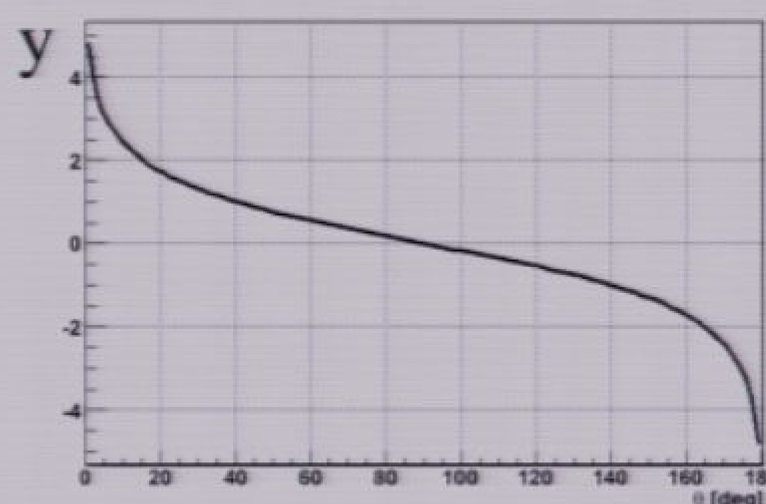
P_1, Energy $= E_1$ P_2, Energy $= E_2$

x_1, x_2: fraction of beam energy carried by each parton (quark or gluon)

Common Collider Variables

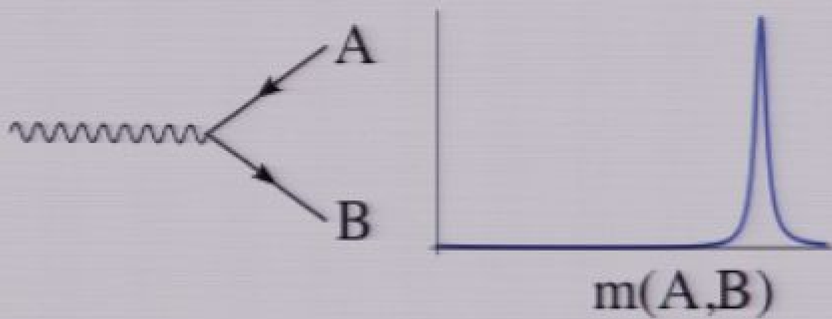
Rapidity: $$y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right)$$

Momentum transverse to the beam: p_T

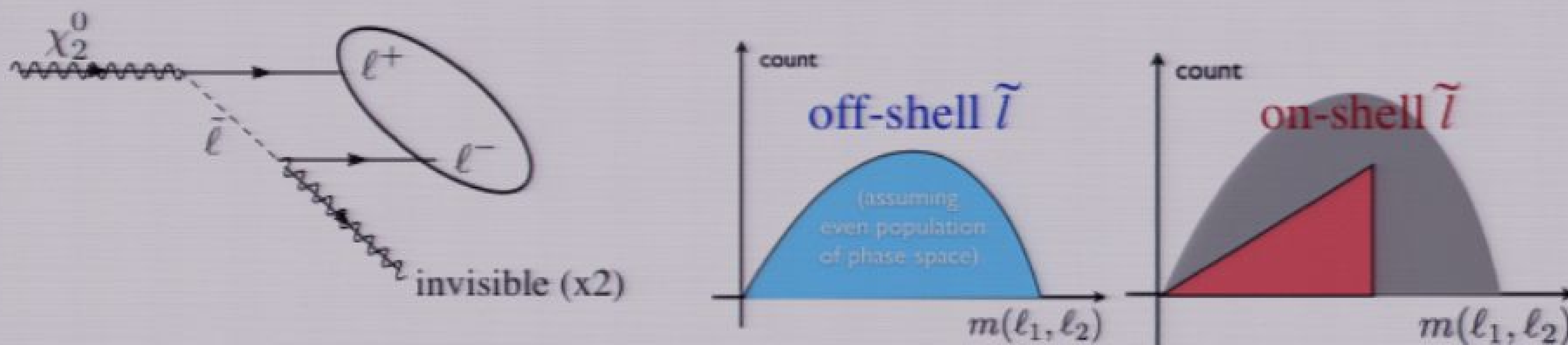


→ reconstruct 4-vectors

Final State Variables: Invariant Mass



pair mass resonances



...many more clever variables, especially for long chains.

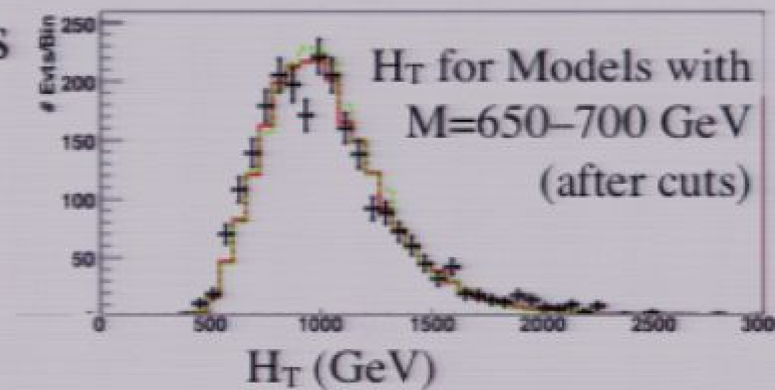
To construct invariants, must pair particles.

To pair, must know decay topology → difficult to use!

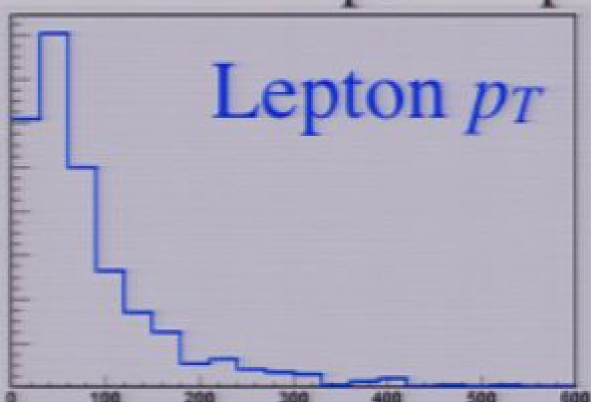
Final State Variables: Transverse Momentum

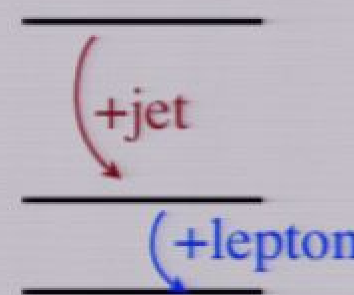
Useful combinations: $H_T = \sum |p_T|, \quad \not{E}_T = \sum \vec{p}_T$

1) H_T bump ~ 1–2 x produced particle mass
(depends on decay chain, LSP mass)



2) Locations of p_T bumps ~ relative mass scales

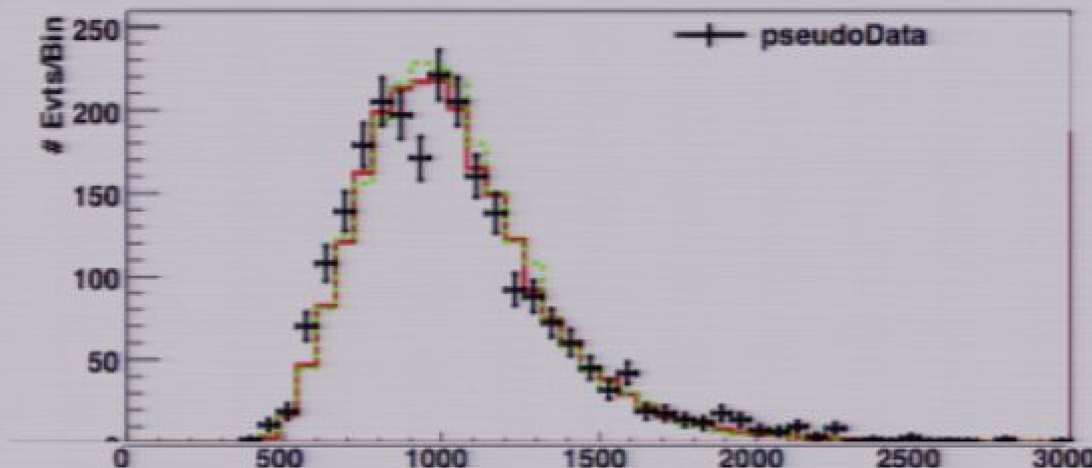




$p_T, H_T, \not{E}_T$ & counts are **search variables** → understood early.
They suffice to build good hypotheses for mass spectra, cascades,
then isolate decay modes for precision mass measurement.

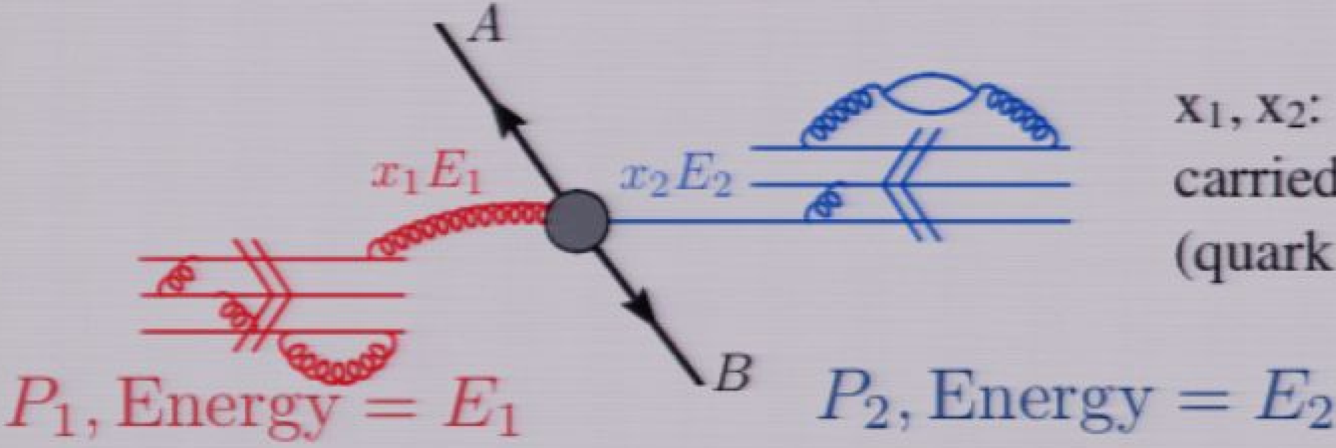
What to describe accurately?

- The previous distributions are important!



- Want to understand what features of the matrix element affect:
  - transverse momentum distributions and kinematics
  - total production cross-section
- These are in fact **largely** determined by particle masses, and basic properties of pp collision.

The Dynamics of Hard Scattering



x_1, x_2: fraction of beam energy carried by each parton (quark or gluon)

cattering probability)

$$\frac{d\sigma_{inc}}{d\text{Vars}} = \int \underbrace{\frac{dx_1}{x_1}\frac{dx_2}{x_2}}_{=\frac{d\hat{s}}{\hat{s}}d\bar{y}} \underbrace{x_1 f_g(x_1,Q) x_2 f_q(x_2,Q)}_{\text{parton distribution functions}} \underbrace{\frac{d\hat{\sigma}(qg \to AB)}{d\text{Vars}}}_{\text{parton cross-section}}$$

PDF's $\sim (1-x)^p x^{-q}$

parton E_{cm}^2 → $\frac{d\hat{s}}{\hat{s}}$; CM boost → $d\bar{y}$

$\int d\bar{y}$ →parton luminosity

$$\rho(\hat{s}, Q^2) \propto (\hat{s}/S_{tot})^{-q} \qquad (q\text{~}1\text{–}1.5)$$

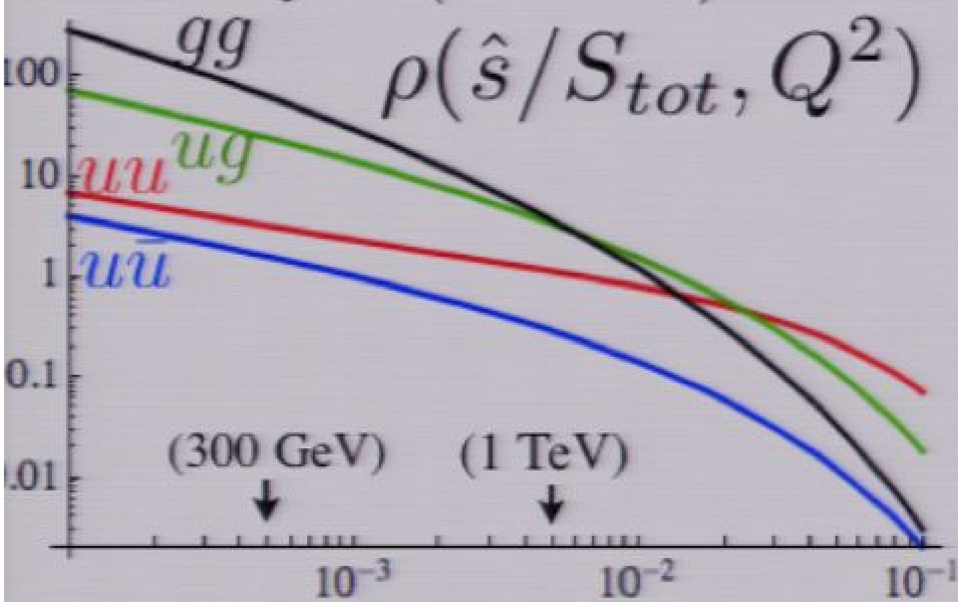
Production Rates and Kinematics

$$\frac{d\sigma_{inc}}{d\text{Vars}} = \int \underbrace{\frac{dx_1}{x_1}\frac{dx_2}{x_2}}_{= \frac{d\hat{s}}{\hat{s}} d\bar{y}} \underbrace{x_1 f_g(x_1, Q) x_2 f_q(x_2, Q)}_{\text{PDF's} \sim (1-x)^p x^{-q}} \underbrace{\frac{d\hat{\sigma}(qg \to AB)}{d\text{Vars}}}_{\text{parton cross-section}}$$

$\int d\bar{y} \rightarrow$ parton luminosity

$$\rho(\hat{s}, Q^2) \propto (\hat{s}/S_{tot})^{-q}$$

$Q^2 = (500 \text{ GeV})^2$



$\tau = \hat{s}/S_{tot}$

Rates:

$$\sigma_{(pp \to XY)} \sim \alpha^2 {S_{tot}}^q / {s_0}^{q+1}$$

Kinematics:

For slowly varying M.E.

$$\langle \hat{s} \rangle \approx \frac{q+1}{q} \sim 1.5 - 2$$

→ semi-relativistic products!

Lightest particles generally dominate production

Shape Invariance in Hadronic Collisions

CM-frame Lorentz invariants: $\hat{s}$ & $\hat{t}$ **or** $\hat{s}$ & p_T^2 **or** $\hat{s}$ & ξ

related by: $\hat{t} = -\frac{1}{2}\left[\hat{s}(1-\xi) - s_0\right]$ $\qquad p_T^2 = \frac{\hat{t}\hat{u} - M^4}{\hat{s}} \Rightarrow dp_T^2 d\hat{s} = \xi d\hat{t} d\hat{s}$

$\xi \sim \beta \cos\theta_{CM}$:"pure angular" variable linearly related to $\hat{t}$ → good variable for M.E. expansion

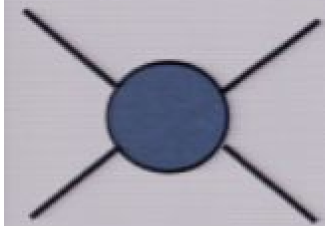
$$s_0^2 \frac{d\sigma}{d\hat{t}d\hat{s}} = \frac{1}{\hat{s}} \frac{s_0^2}{s^2} \rho(\hat{s}, Q^2) |\mathcal{M}|^2$$

$\rho(\hat{s}, s_0) \approx A(\hat{s}/S_{tot})^{-q}$

$$s_0^2 \frac{d\sigma}{dp_T^2} = \frac{1}{\xi} \int_{s_0 + 4p_T^2}^{S_{tot}} d\hat{s}\; s_0^2 \frac{d\sigma}{d\hat{t}d\hat{s}} = \int_{s_0 + 4p_T^2}^{S_{tot}} \frac{1}{\xi} \frac{d\hat{s}}{\hat{s}} \frac{s_0^2}{s^2} \rho(\hat{s}, Q^2) |\mathcal{M}|^2$$

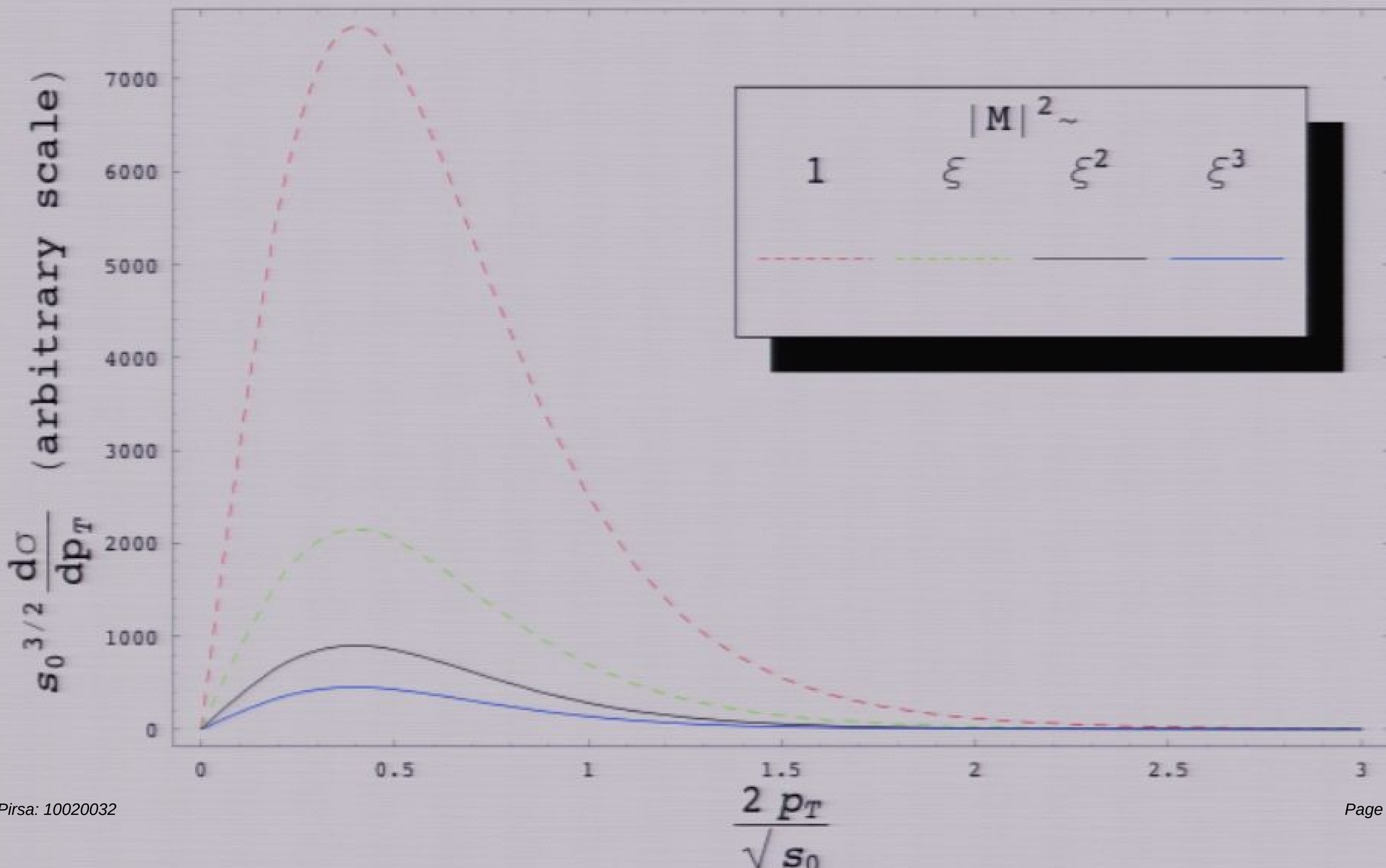
Expand $|\mathcal{M}|^2 = \sum C_{m,n} (\hat{s}/s_0)^m \xi^n$ near threshold (usually dominated by low m, n)

Shape Invariance in Hadronic Collisions



$$\sim |M|^2 \sim \left(\frac{\hat{s}}{s_0}\right)^m \xi^n$$

ξ-Independence of Transverse Shape!



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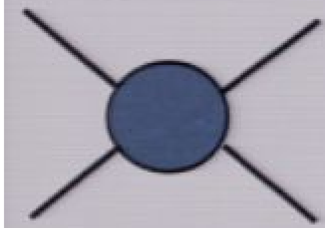

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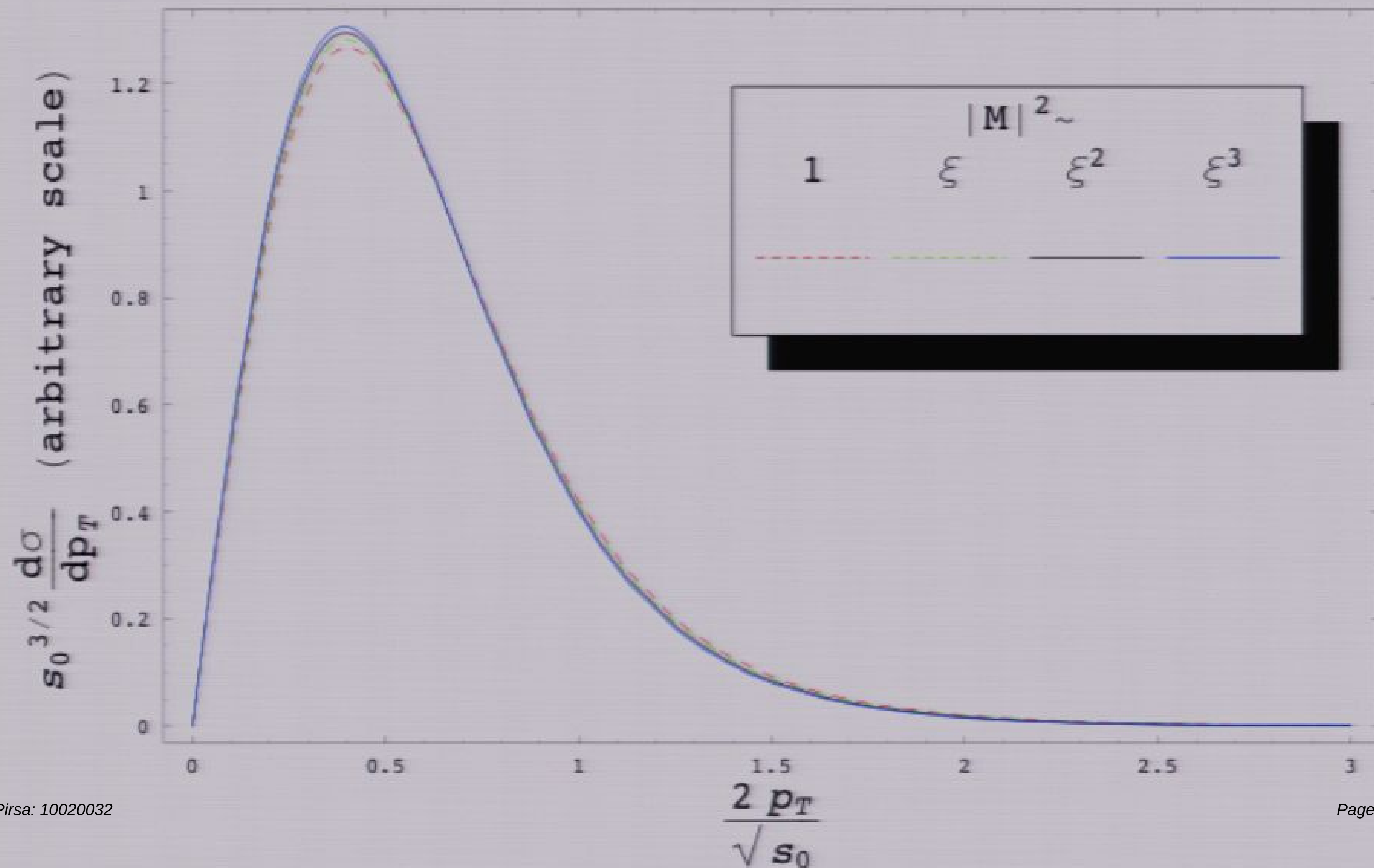

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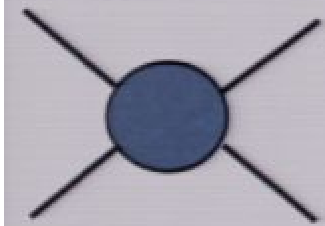

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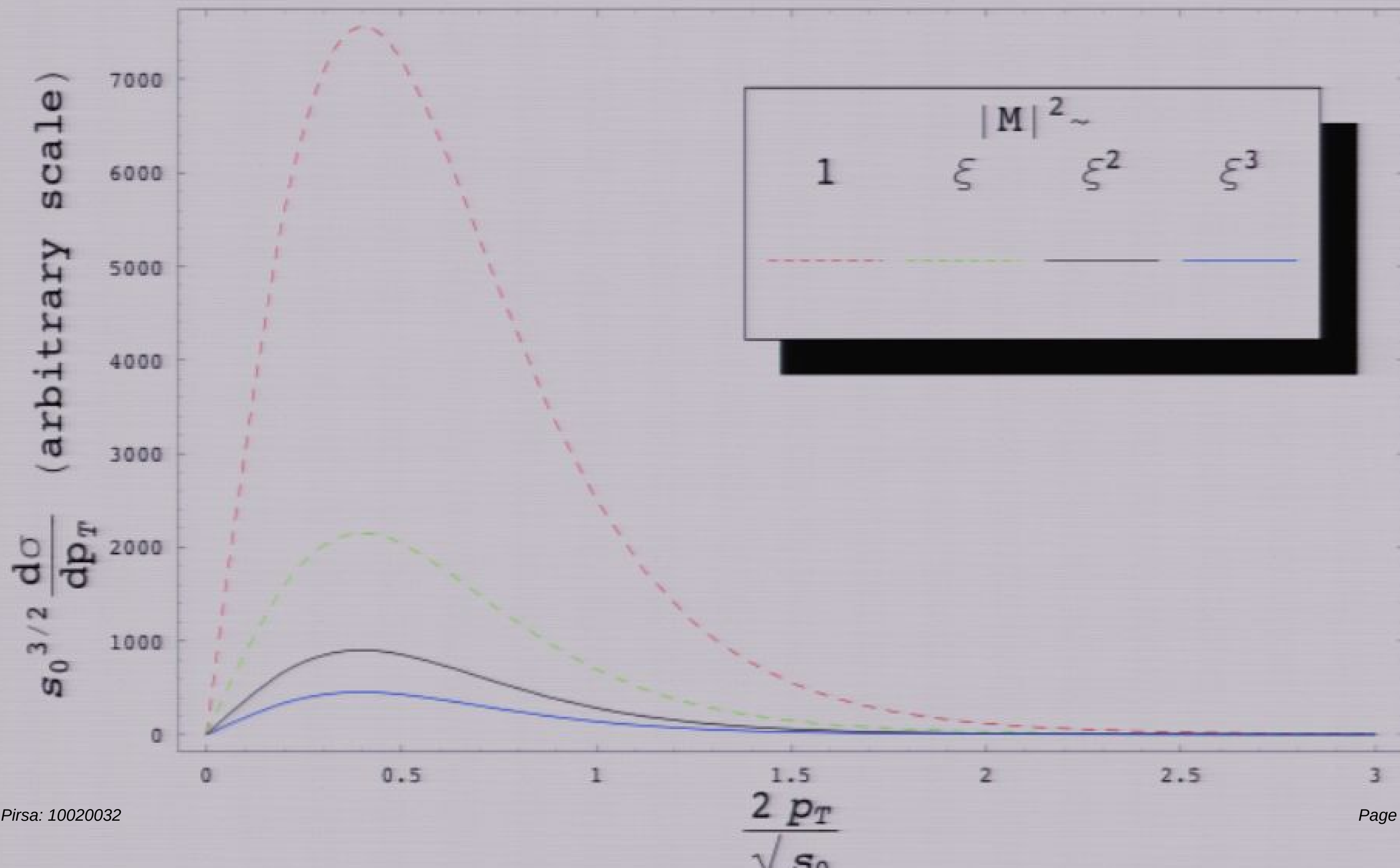
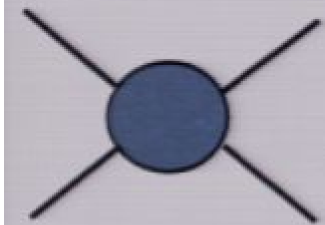
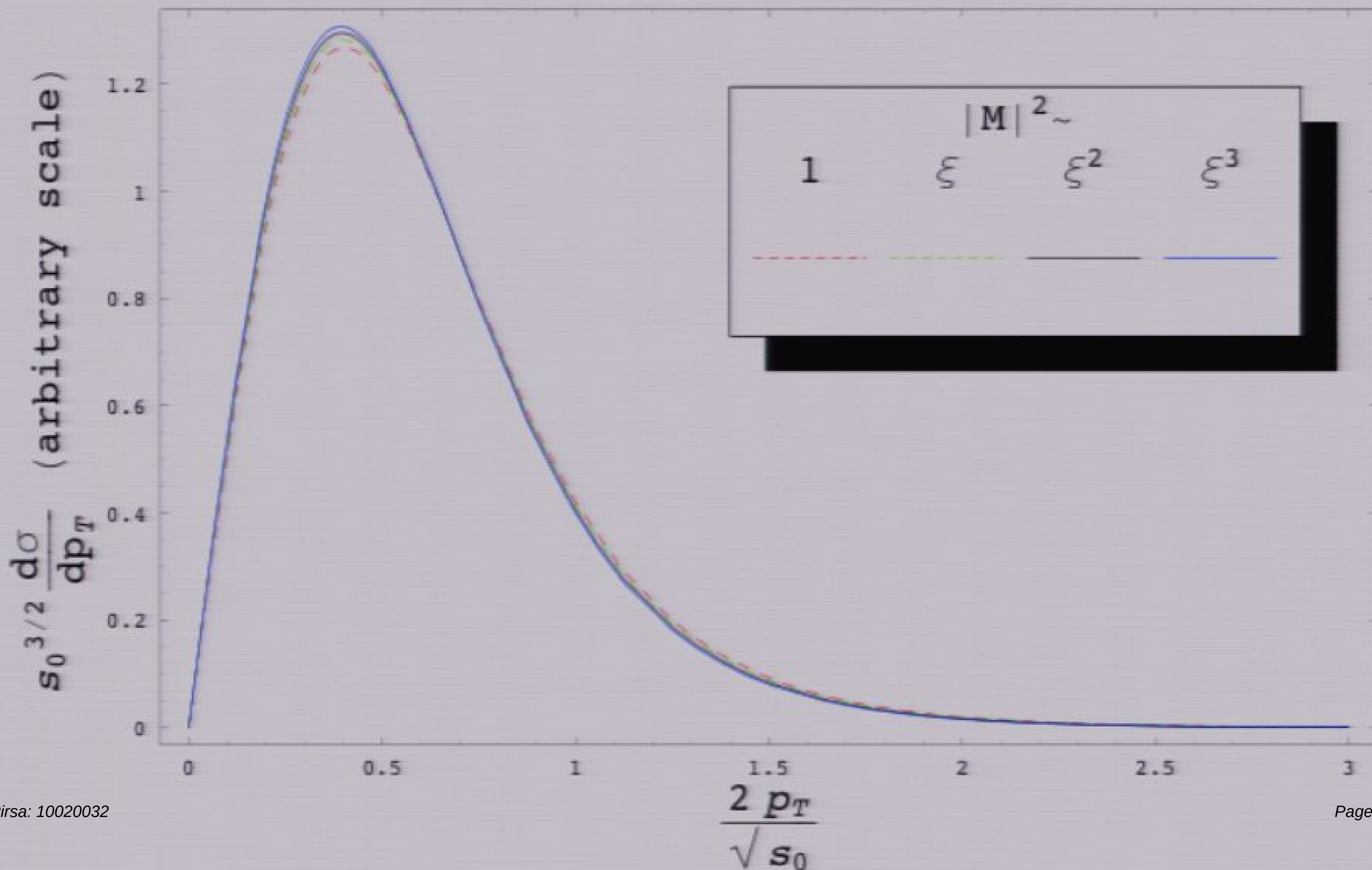


Shape Invariance in Hadronic Collisions



$$\sim |M|^2 \sim (\frac{\hat{s}}{s_0})^m \xi^n$$

ξ-Independence of Transverse Shape!



Shape Invariance in Hadronic Collisions

Expand $|\mathcal{M}|^2 = \sum C_{m,n}(\hat{s}/s_0)^m \xi^n$ near threshold (usually dominated by low m, n)

$$s_0^2 \frac{d\sigma}{dp_T^2} = \left(\frac{s_0}{S_{tot}}\right)^{-q} \sum_{m,n} C_{m,n} \int_{s_0+4p_T^2}^{S_{tot}} \frac{d\hat{s}}{\xi \hat{s}} (\hat{s}/s_0)^{m-q-2} \xi^n \quad \hat{s}/s_0 = \frac{1+4p_T^2/s_0}{1-\xi^2}$$

$$= \left(\frac{s_0}{S_{tot}}\right)^{-q} \sum_{m,n} C_{m,n} \underbrace{\int_0^{\approx 1} \frac{2d\xi}{1-\xi^2}(1-\xi^2)^{-m+q+2}\xi^n}_{\text{Euler } B\text{-function}} \times \underbrace{(1+4p_T^2/s_0)^{m-q-2}}_{\text{shape independent of } n}$$

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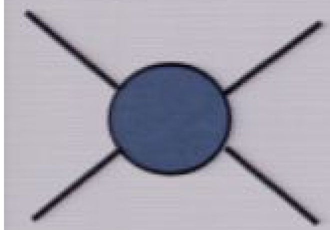

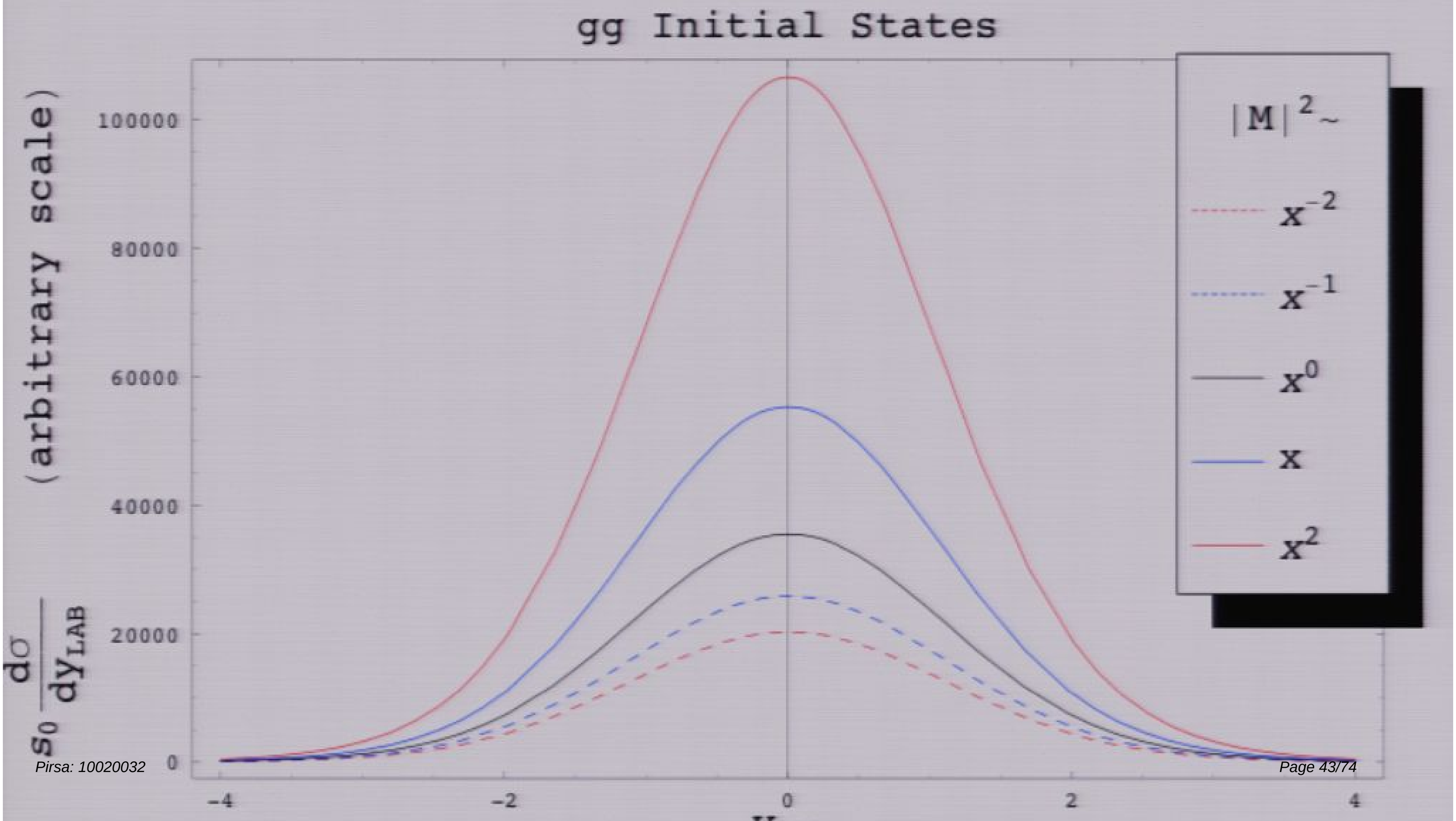

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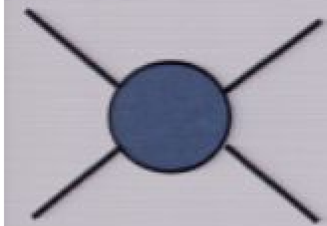

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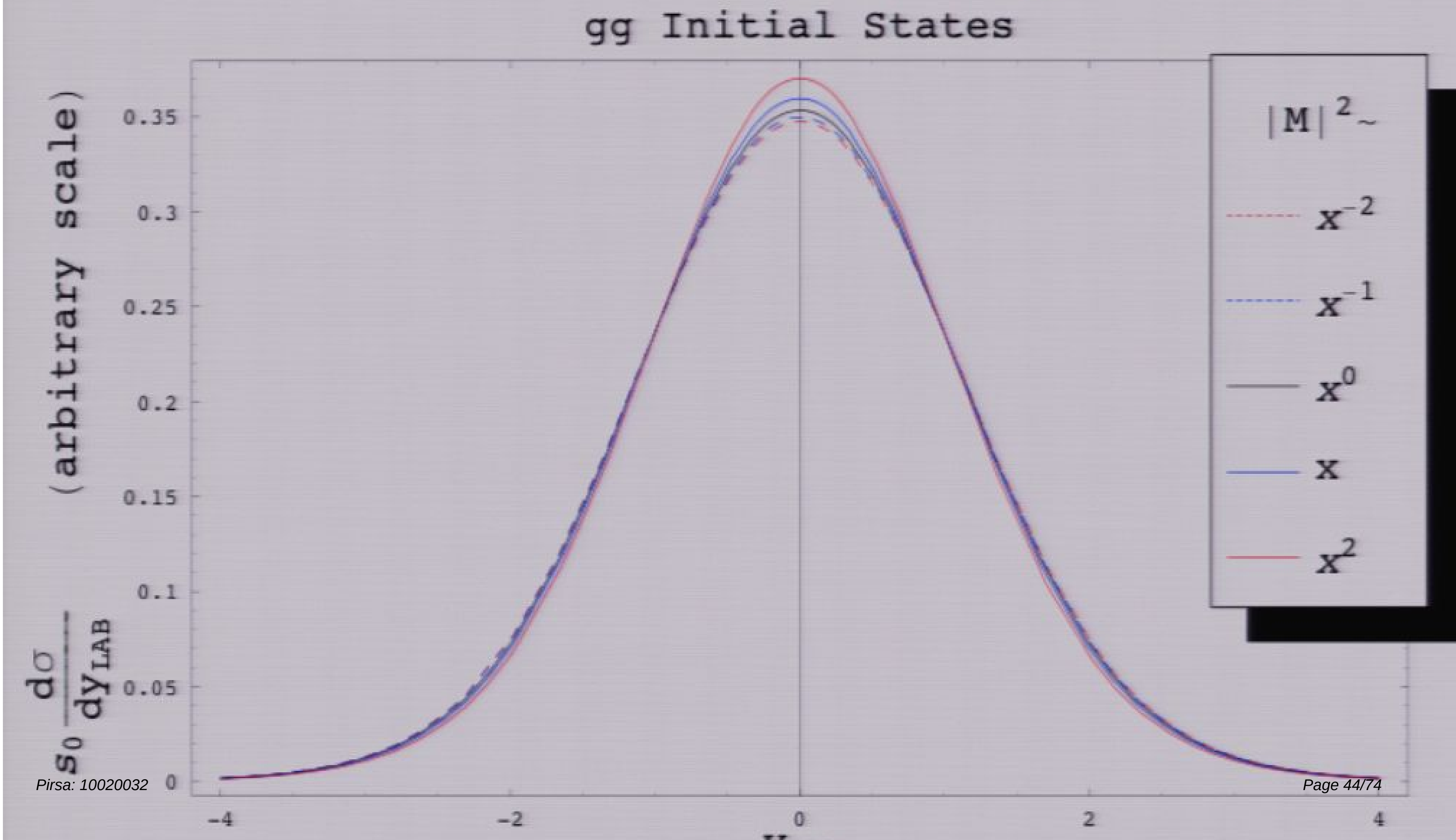
Independence of angular shape!



Shape Invariance in Hadronic Collisions

PDF E_{cm} and y_{cm} homogeneity properties

Inclusive p_T shape invariant under:

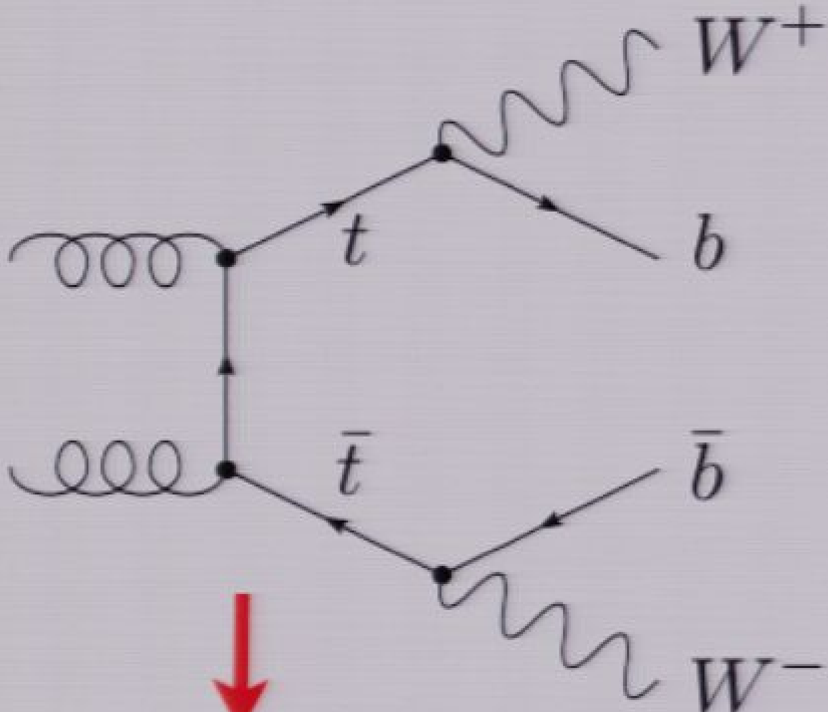
$$|M|^2 \rightarrow |M|^2 \xi^m$$

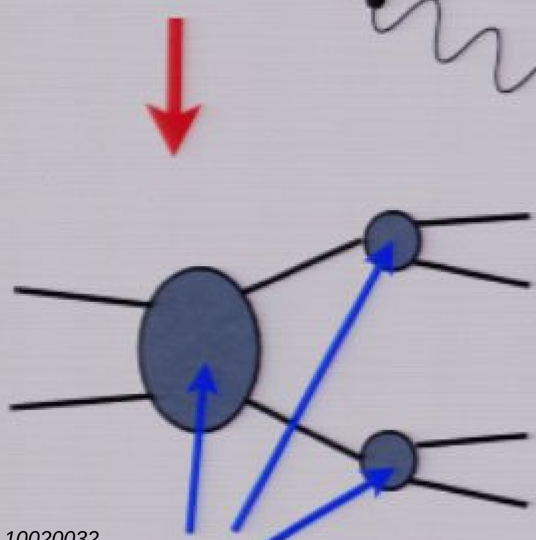
Inclusive y_{lab} shape invariant under:

$$|M|^2 \rightarrow |M|^2 (\frac{\hat{s}}{s_0})^m$$

- Shape invariance: a clear guide to information that ***can be*** stripped out & still do meaningful analysis
  - Important (approximate) ambiguities to be aware of in **any** description of positive signal at LHC
  - Allows predictions, MC generation, *simulation of detector response* w/o full knowledge of model Lagrangian
  - Suggest search/interpretation strategies with **wide reach compared to no. of parameters**

What's an OSET? The Basic Idea:





Simple rules given for these parts

Example: Top Quark

Masses, Rates, and Topology

vs. Amplitudes

Dominant Top Properties:

$\sigma(gg \to t\bar{t})$

$\mathrm{Br}(t \to bW)$

m_t, m_W, m_b

Detailed Top Properties:

$d\sigma/d\hat{t}$ $\quad$ W helicity

t charge

On-Shell Effective Theories: Definition

Production:

$2 \rightarrow 2$

Usually dominates

"Normal" Behavior

$$|\mathcal{M}|^2 = A + B\left(1 - \frac{s_{\text{thresh}}}{s}\right)$$

"Contact" Operator Behavior

or

$$|\mathcal{M}|^2 = A + B\left(\frac{s}{s_{\text{thresh}}} - 1\right)$$

Dominant ξ correction can be included (not usually necessary)

Decay: phase space, with angular correlations as needed

Hadron collider Monte Carlo for simulating events according to OSETs now exists in the Marmoset and MadGraph packages → can be used in LHC experiments

See: hep-ph/0703088 for detail...

OSETs and Simplified Models at the LHC

- Use OSETs to create more robust searches for new physics

- Create model-independent searches

- Use OSETs to create Simplified Models for characterizing new physics data

Simplified Searches

- ***Optimize sensitivity*** to general models
- ***Present results*** for general models

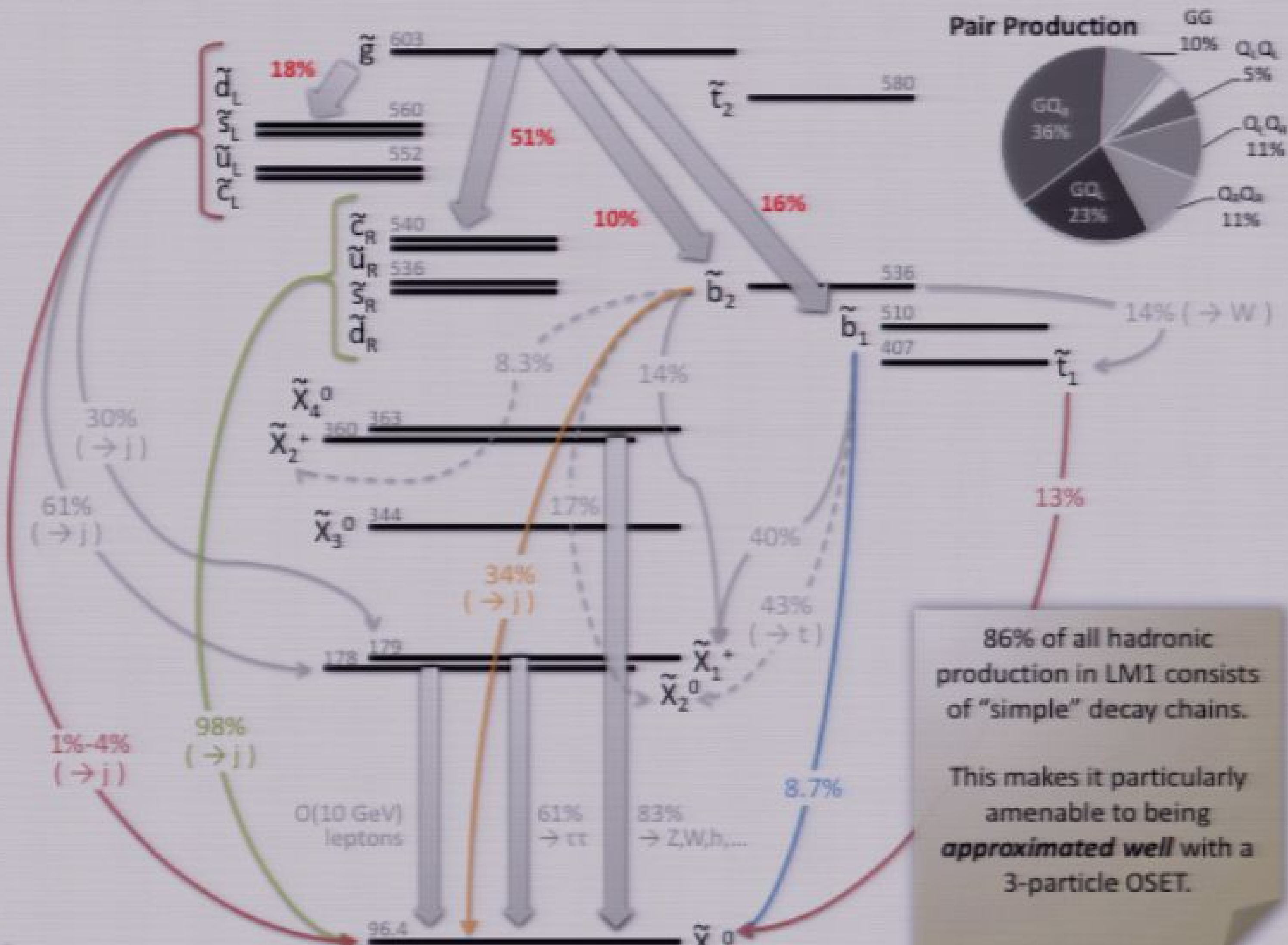
mSUGRA-based (or other models) searches weak on both fronts unless it is clear which topologies a given search is sensitive to.

Solution: design searches around individual topologies sensitive to a wide range of kinematics

(work in progress with UCSB + Vienna CMS groups)

Production modes in a benchmark (LM1):

(after hadronic search cuts: lepton veto, 3 or more jets)



86% of all hadronic production in LM1 consists of "simple" decay chains.

This makes it particularly amenable to being ***approximated well*** with a 3-particle OSET.

S.A. Koay

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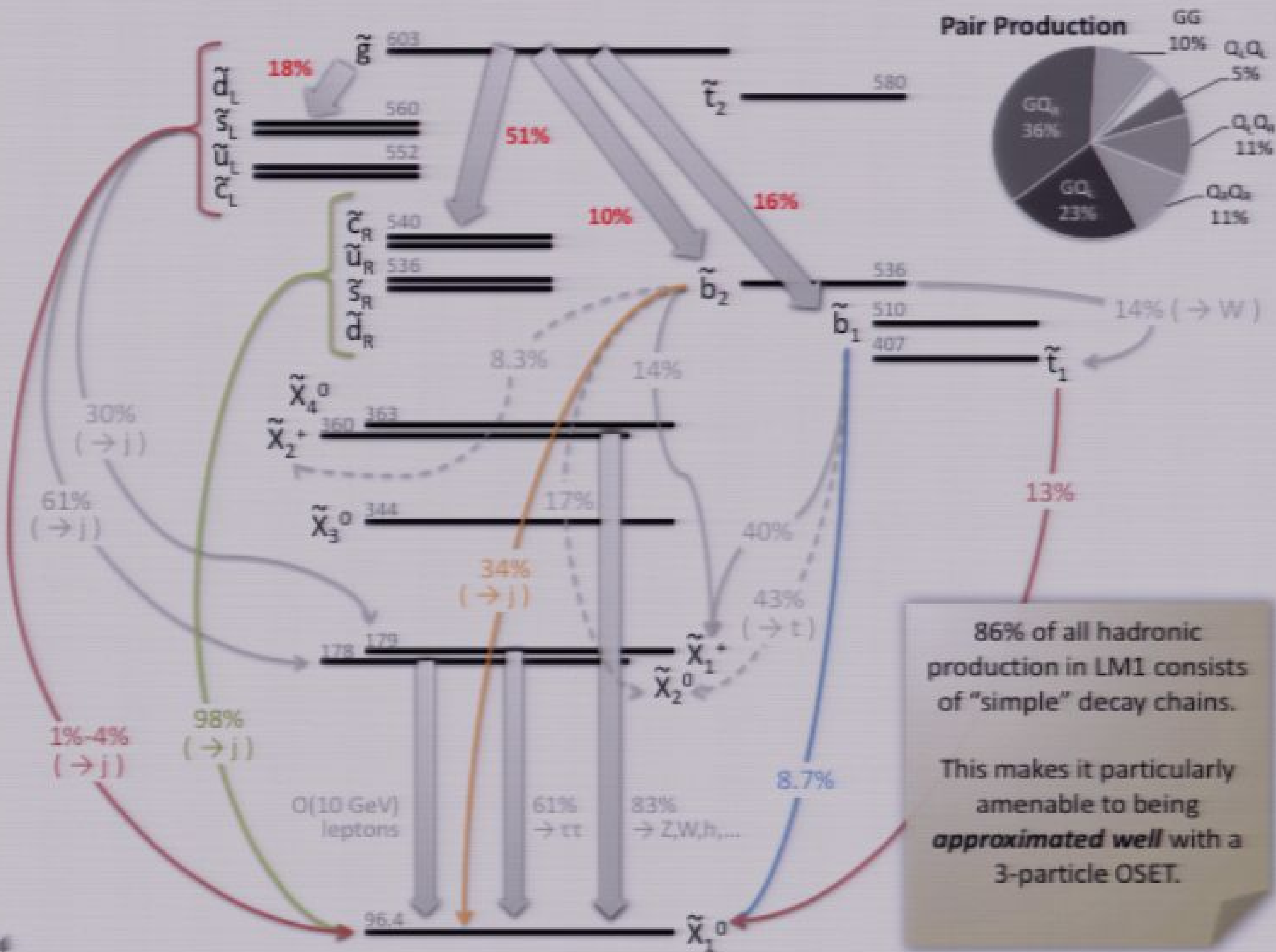
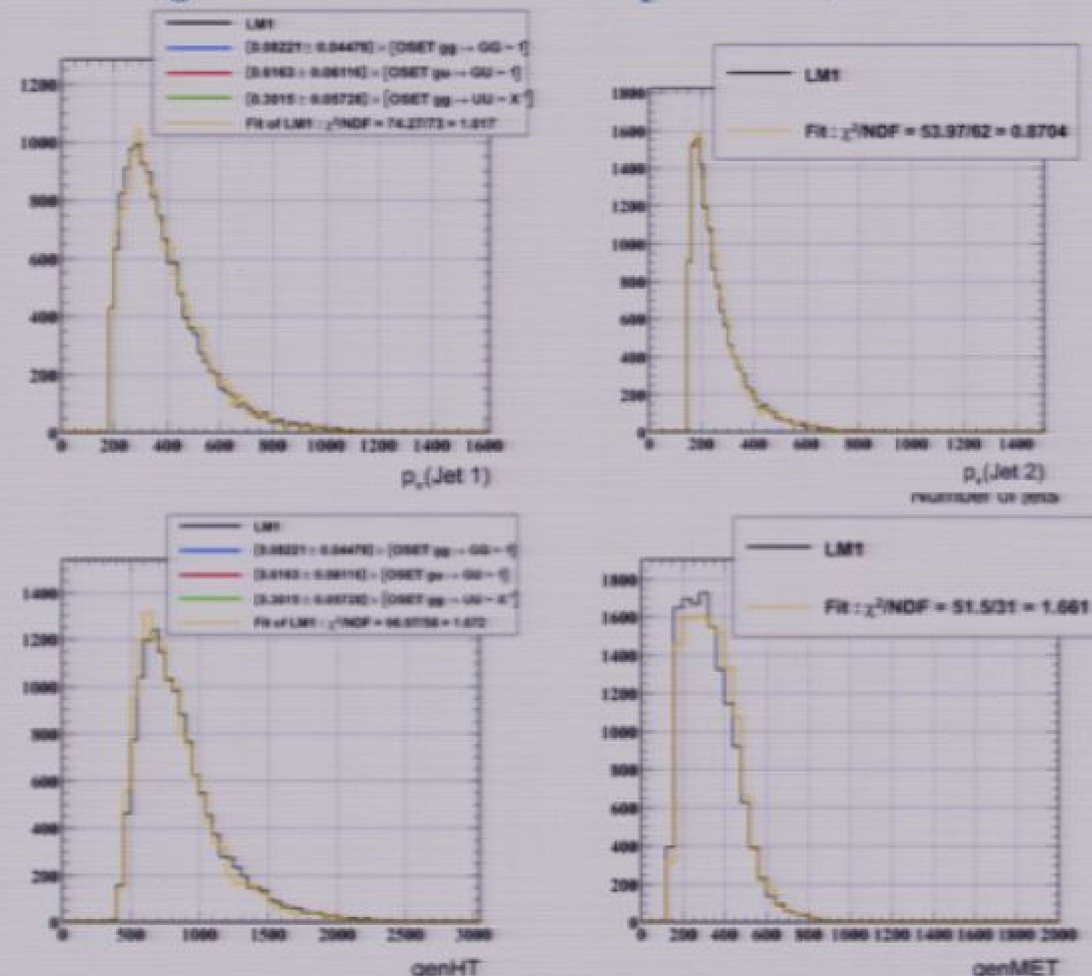


Simple Topology (OSET) Approximation

Fit $\tilde{g}\tilde{g}$, $\tilde{u}\tilde{g}$, and $\tilde{u}\tilde{u}$ production fractions (and masses, by eye) from HT, jet pT

(generator-level comparison)



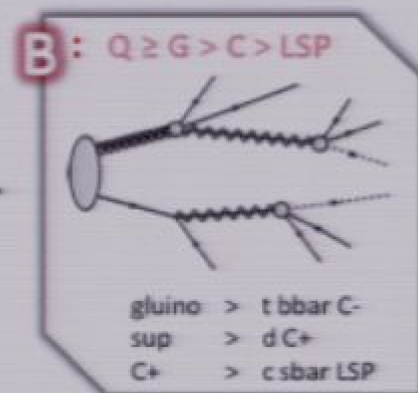
Very good agreement with benchmark!

Topology-Driven Searches

Start with simple OSET approximation to primary/common topologies, and include variations of topology

"Three hard jets"

↔



"~5 hadronic jets"
(Effect of cascade depends on C^+ mass)

↔

Even more/softer jets
(not visible – ignore for now)

Optimize Jet p_T, HT, MET cuts for sensitivity to A/B/C topologies over wide mass range

Use to evaluate and improve robustness of searches, and to present results in a model-independent way

If new physics is seen in search, ***What Next?***

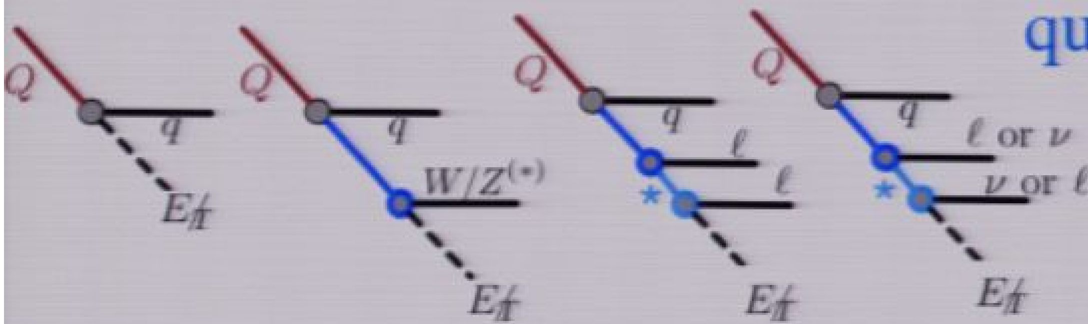
Crude "Simplified Models" are a **<u>general</u>** starting point for analysis.

Example:

- what do they tell us?
- how do we move beyond them?

A schematic overview of a simplified model and an example of its use...

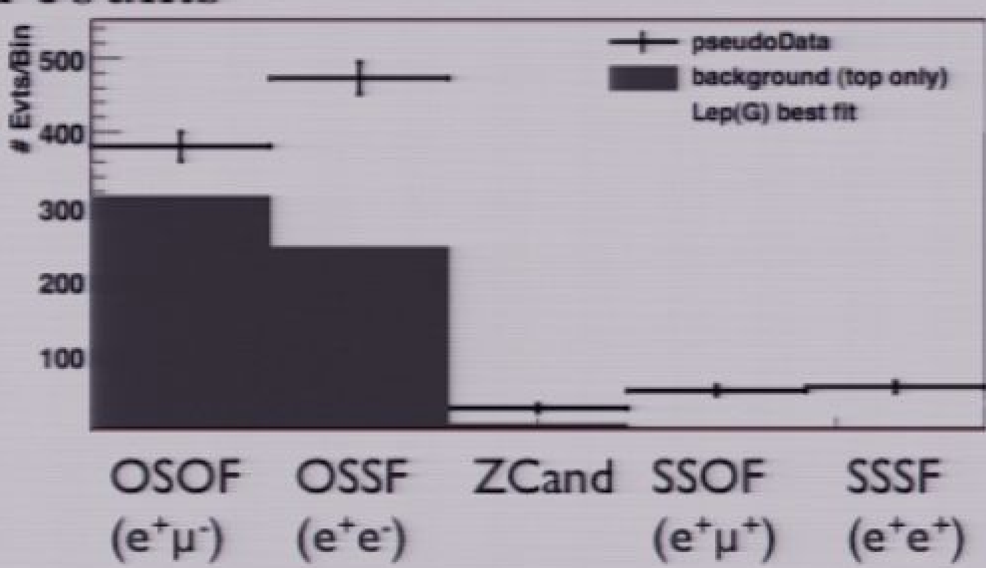
A Simplified Model:



Use 2-3 other models to describe qualitatively different physics

Fit branching fractions, mass, cross-sections to data using simple counting signatures

Example: lepton counts



Example

Simplified model fit is expected to describe data fairly well

Parameters that fit counts, HT, p_T(lepton):

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[redacted]							
Lep(Q) / $B_{\ell\nu}=0$	650-440- – -100	12.8	0.0485	–	0.0	0.9244	0.0270
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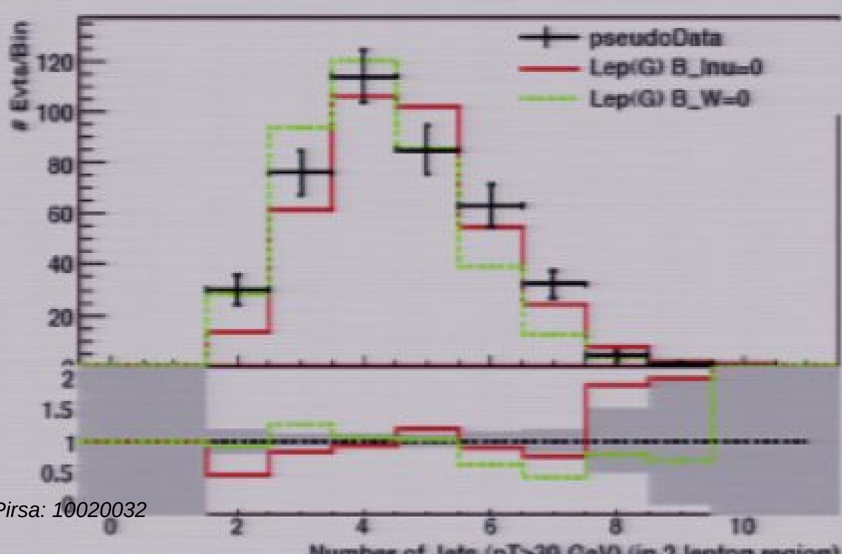
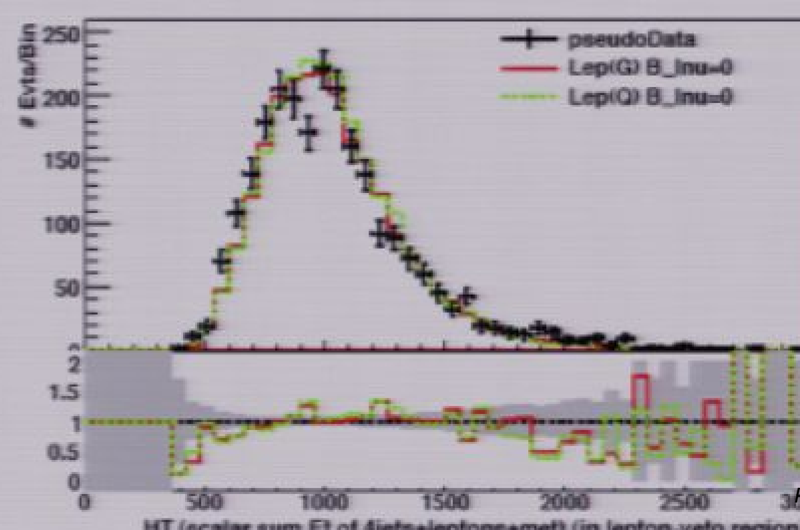
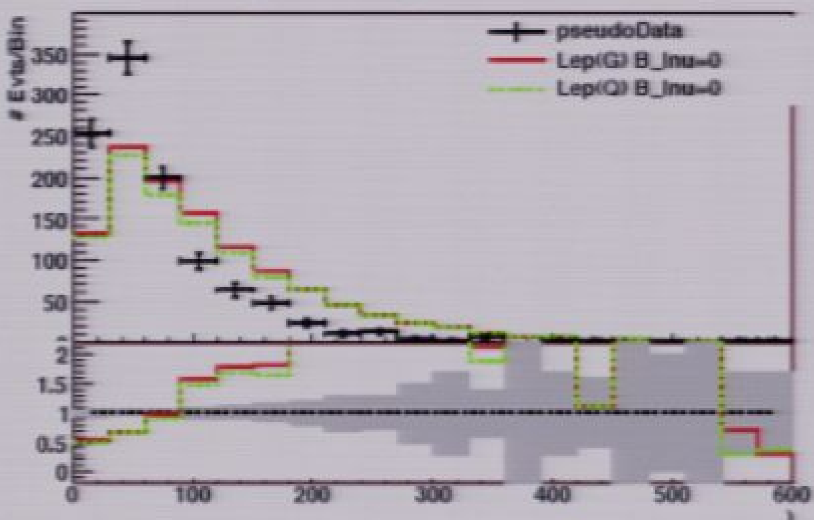




Example

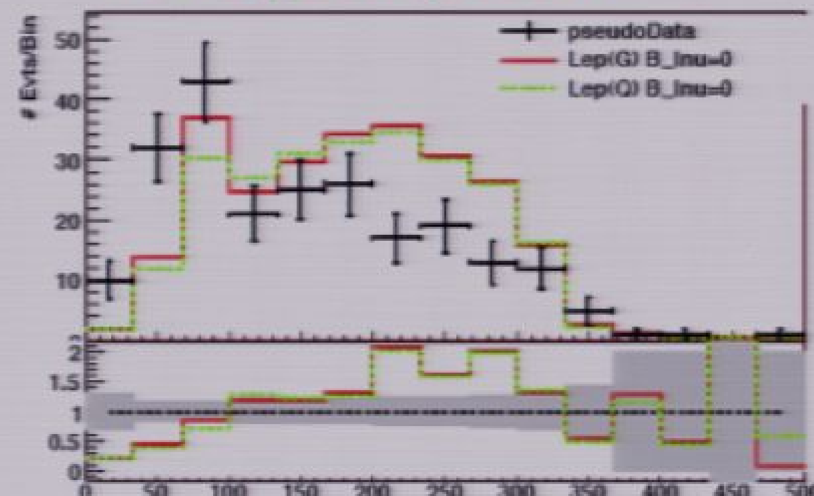
Deviations are typically indicative of additional structure

(1-lepton plots)



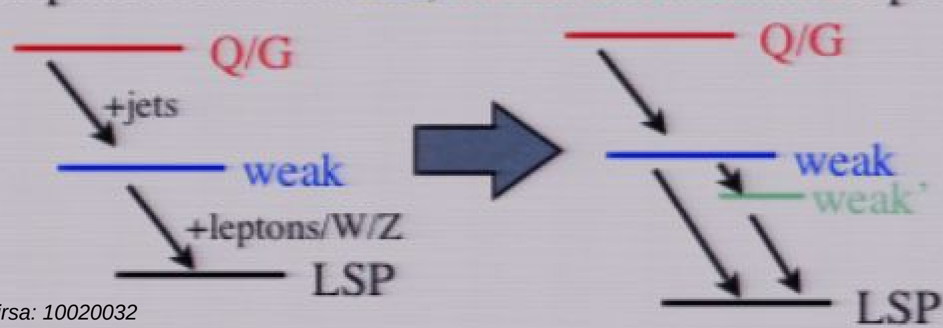
Lepton p_T

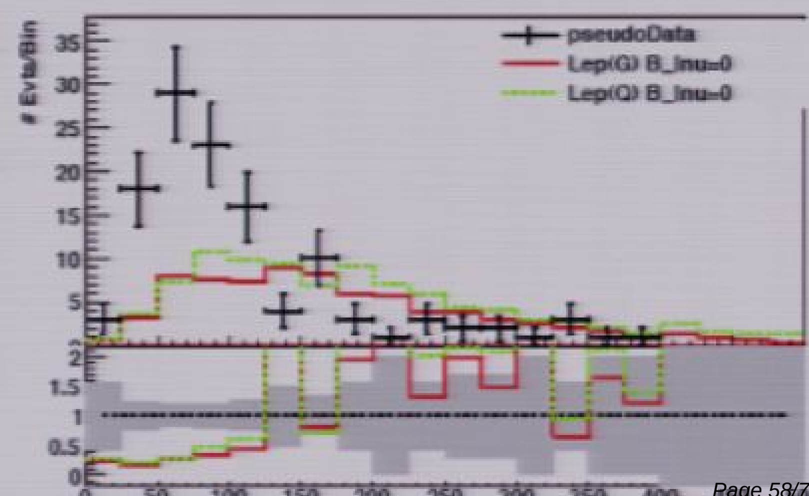
(2-lepton plots)



OSSF (e^+e^-) invariant mass

Cannot reproduce the data with these models (or with tops). Robustly demonstrating this is hard, but provides STRONG EVIDENCE for more complex source of soft, flavor-uncorrelated leptons.





Opposite-flavor ($e\mu$) invariant mass

Example

- Data consistent with quark and/or gluon partner production
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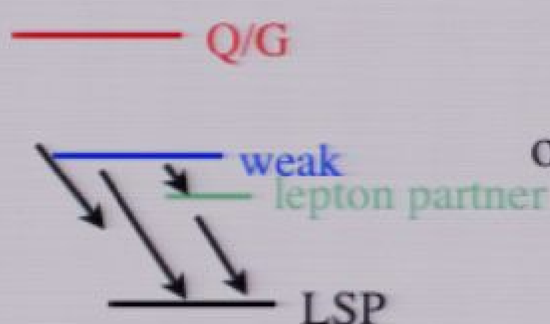
- Large rate of single-lepton cascade (+ precise numbers)
- To reproduce the 2-lepton counts: on-shell lepton partner and **W/Z partners**.



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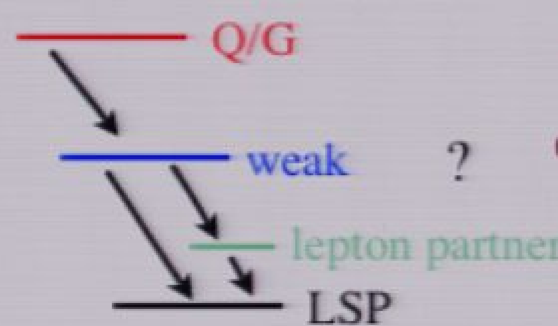

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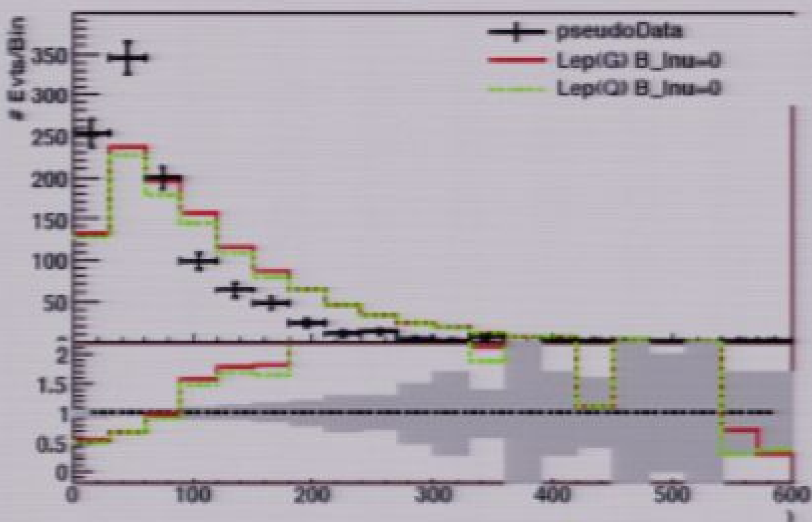
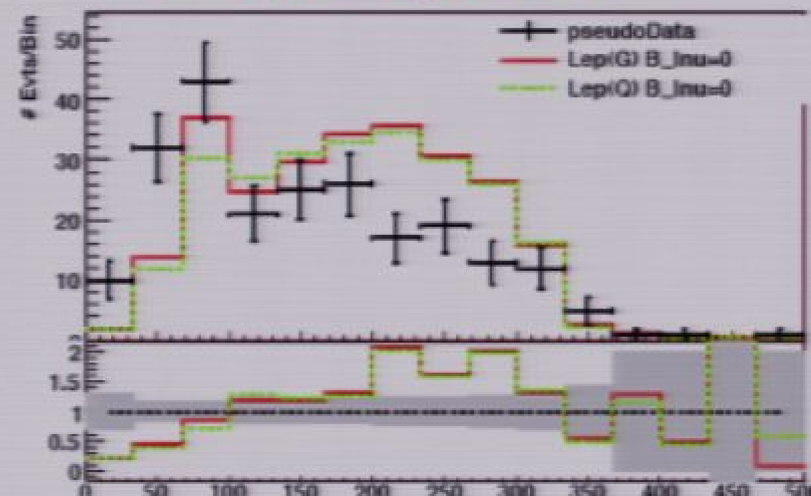


Lepton p_T

(2-lepton plots)



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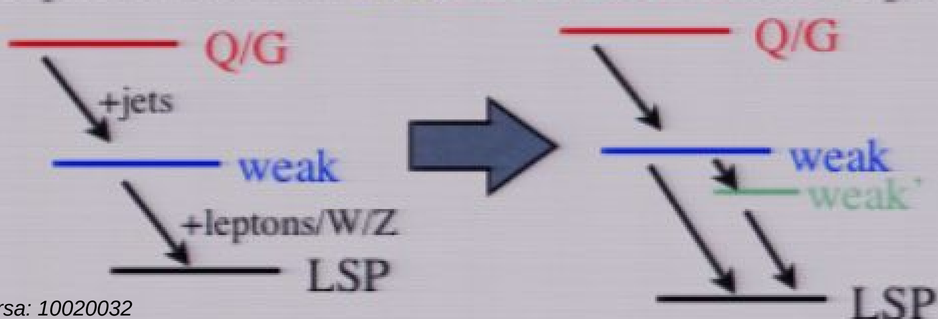

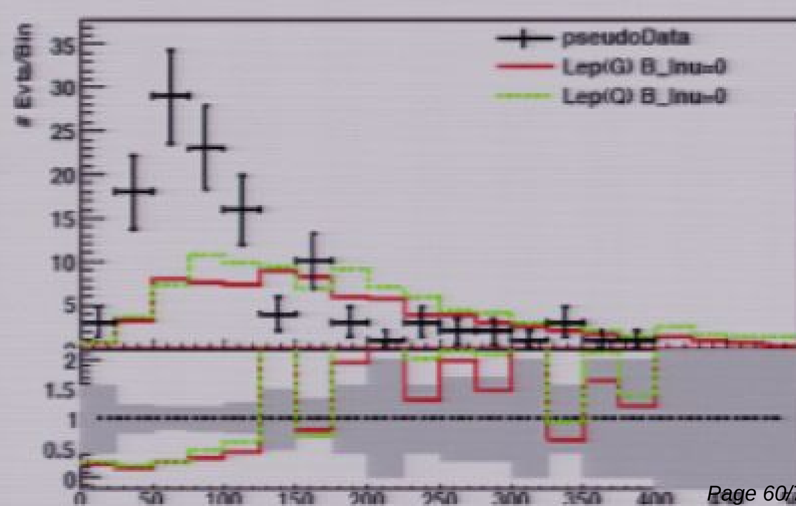

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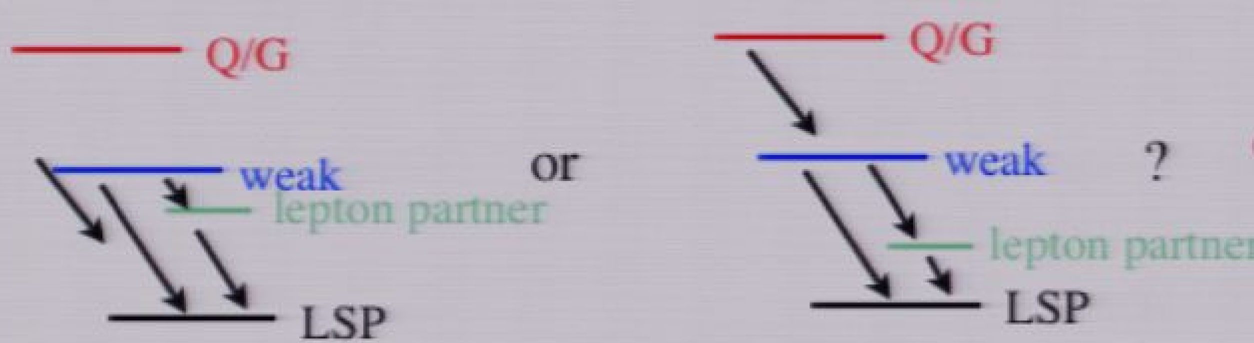

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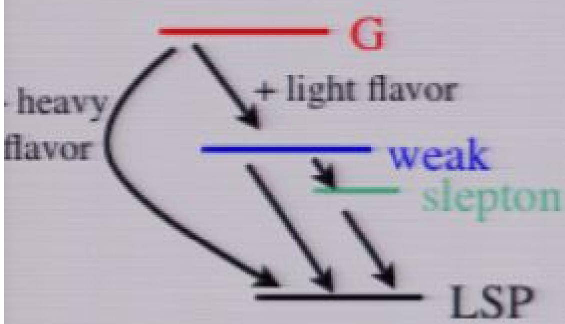

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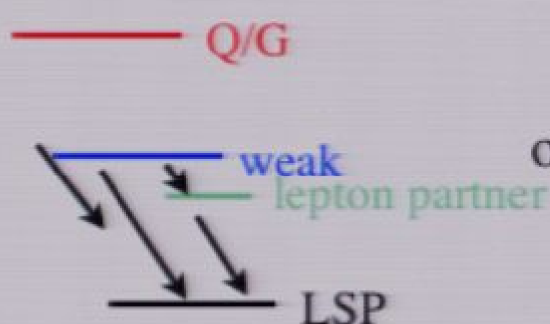

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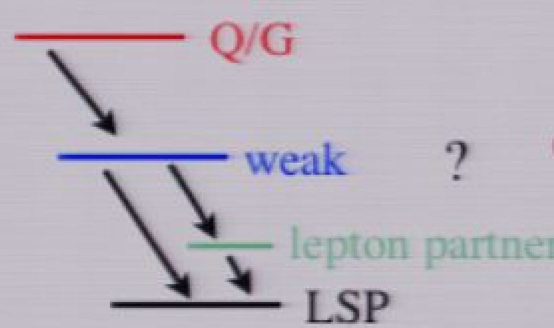

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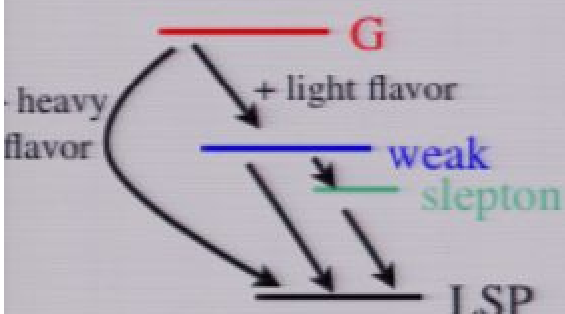

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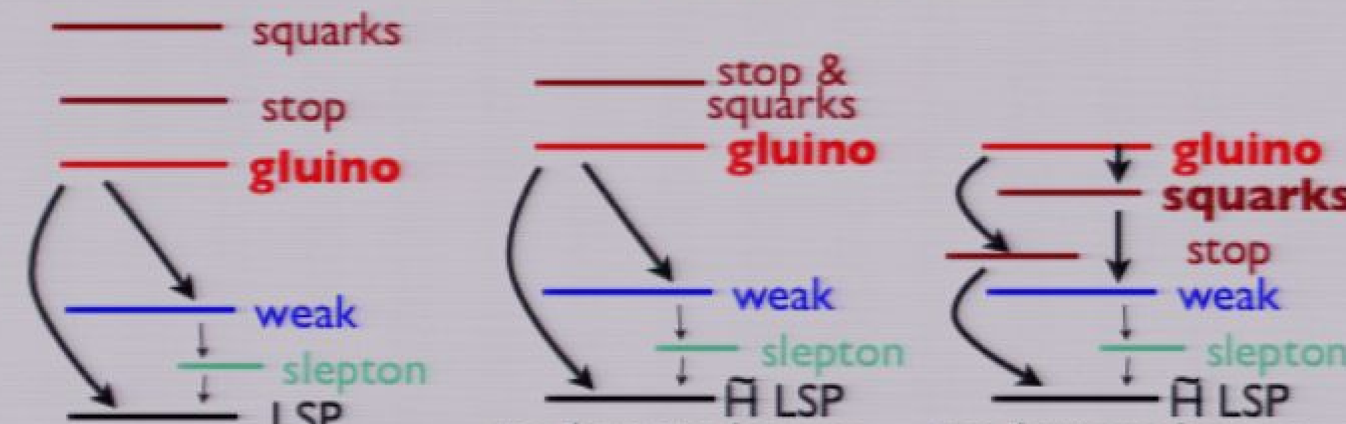
three SUSY motivated ideas



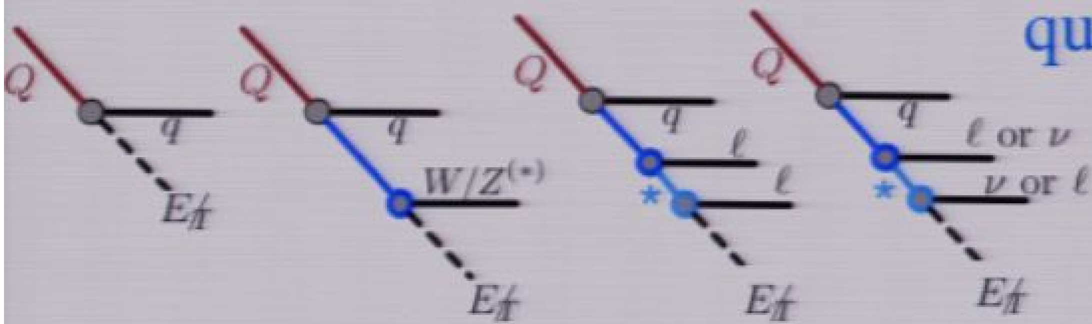
top dominates because stop is lighter

top dominates because it has biggest coupling

top dominates because stop is lighter

A Simplified Model:

Use 2-3 other models to describe qualitatively different physics



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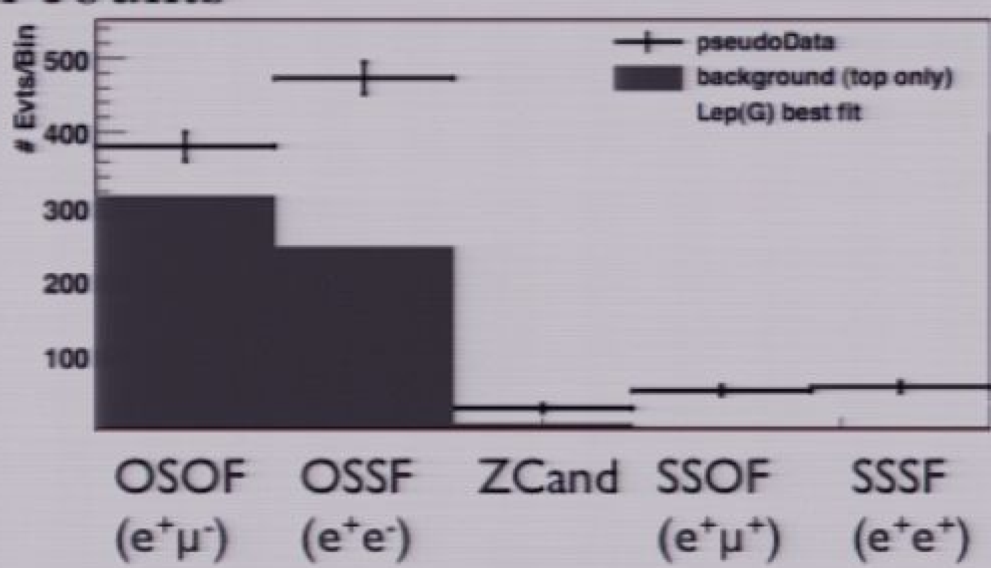

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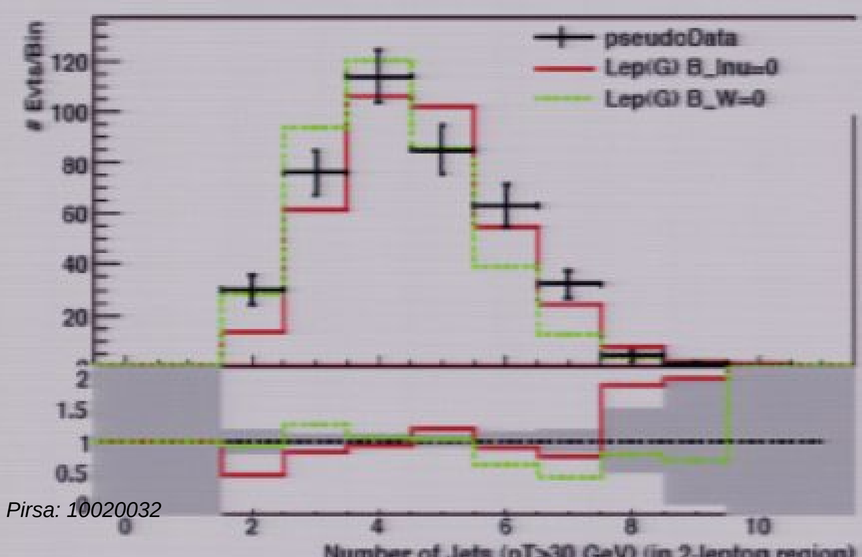

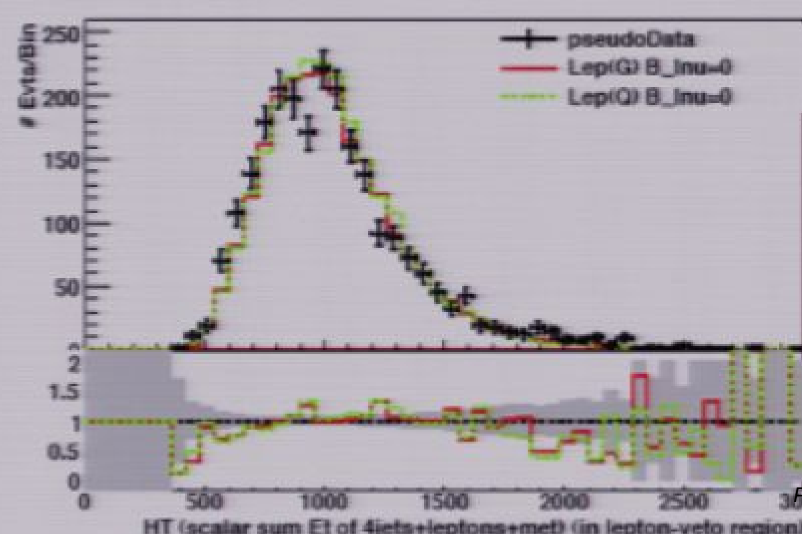

OSETs and Simplified Models — Example

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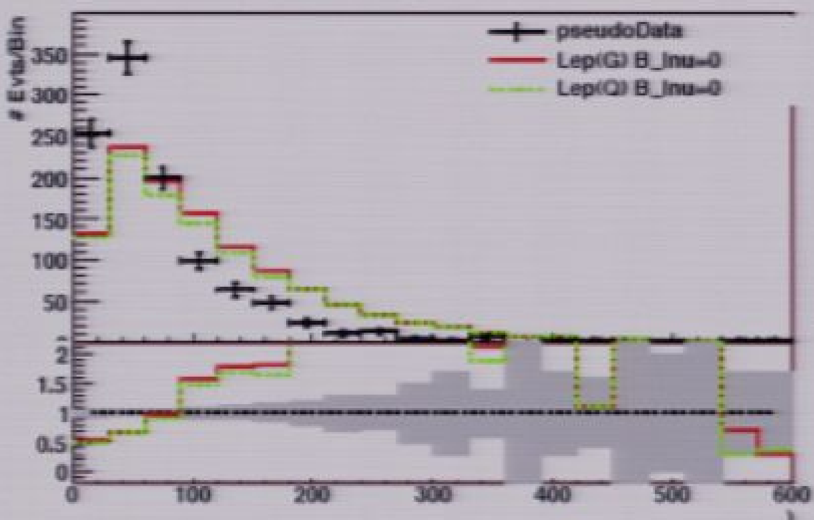

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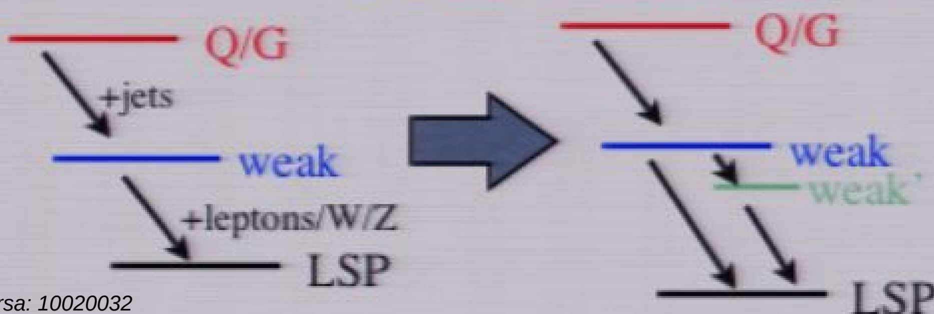
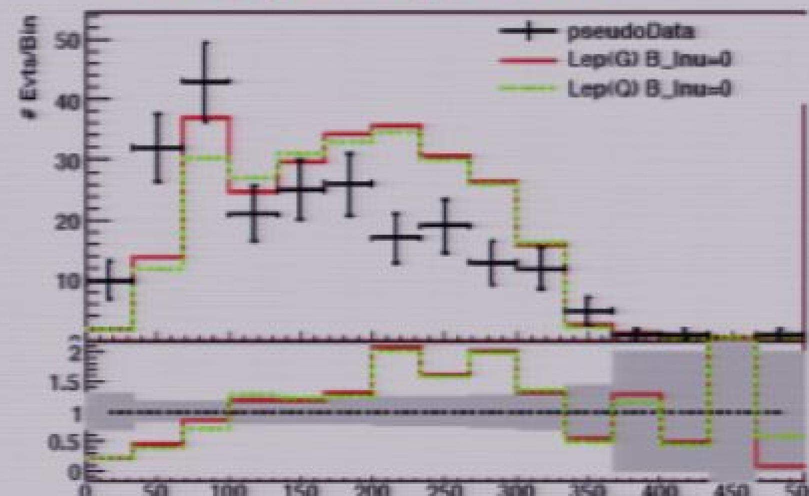


(2-lepton plots)



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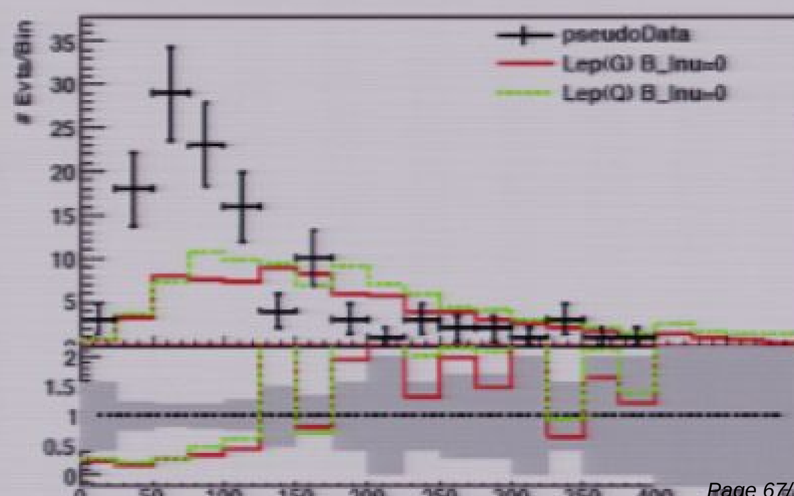

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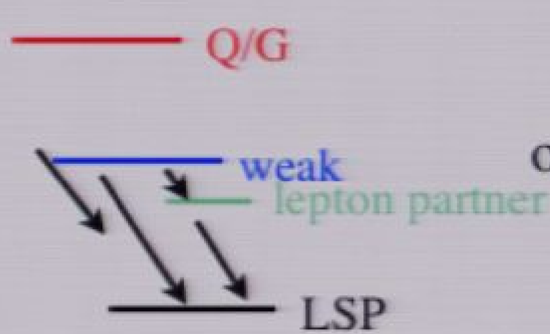

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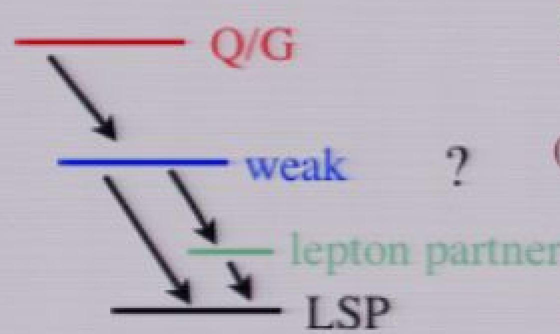

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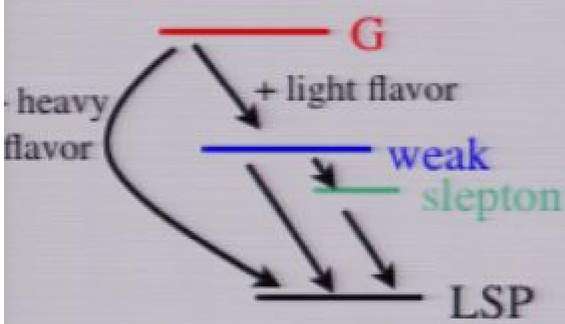

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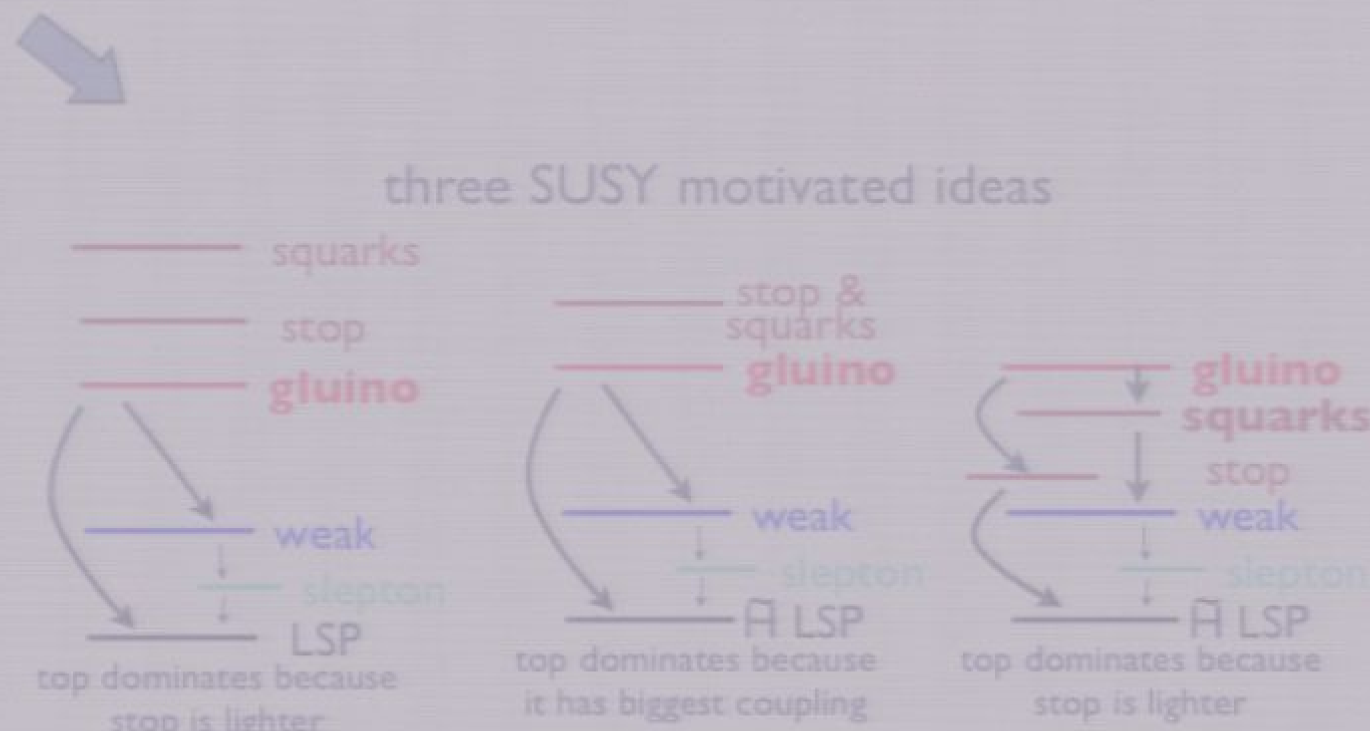

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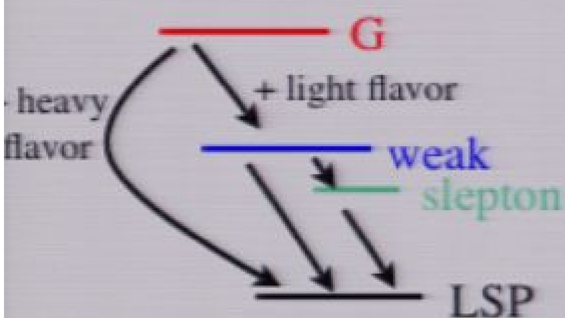

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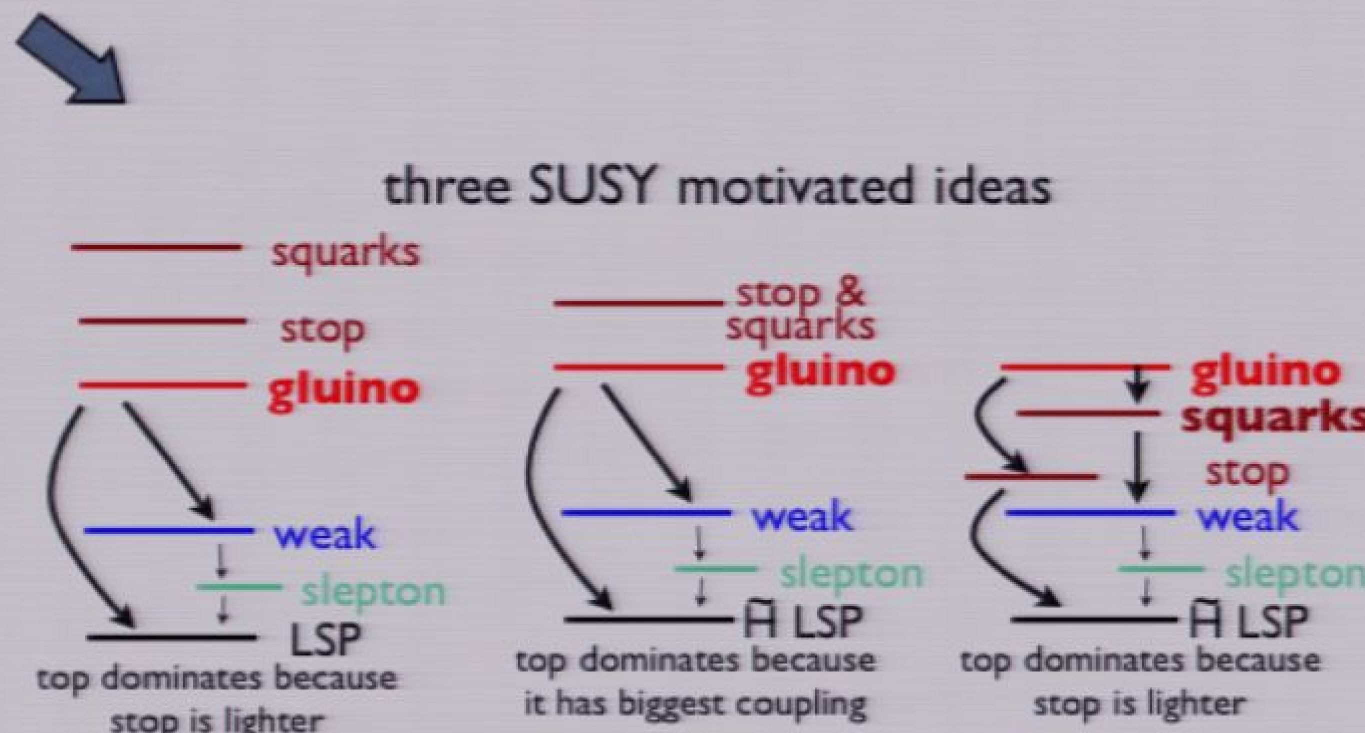


Conclusion and Outlook for the LHC – I

The LHC can provide spectroscopy
(spectroscopy directly links to interesting theory)

Spectroscopy is most readily encapsulated in simplified descriptions of new physics (OSETs)

Conclusion and Outlook for the LHC – II

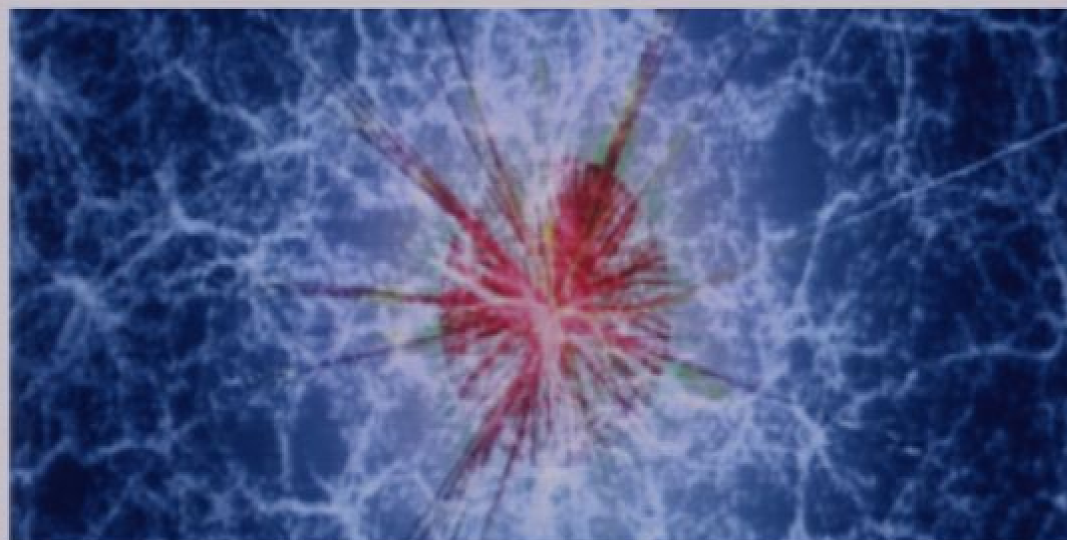
The exploration of the TeV-scale will start this year!

As new physics is discovered, unless it's fairly simple, characterizing its spectroscopy will take ~years

This will require very close theory-experimental collaboration

Out of this process will emerge the next set of exciting theoretical puzzles!

Thanks!



Thanks!


No Signal
VGA-1