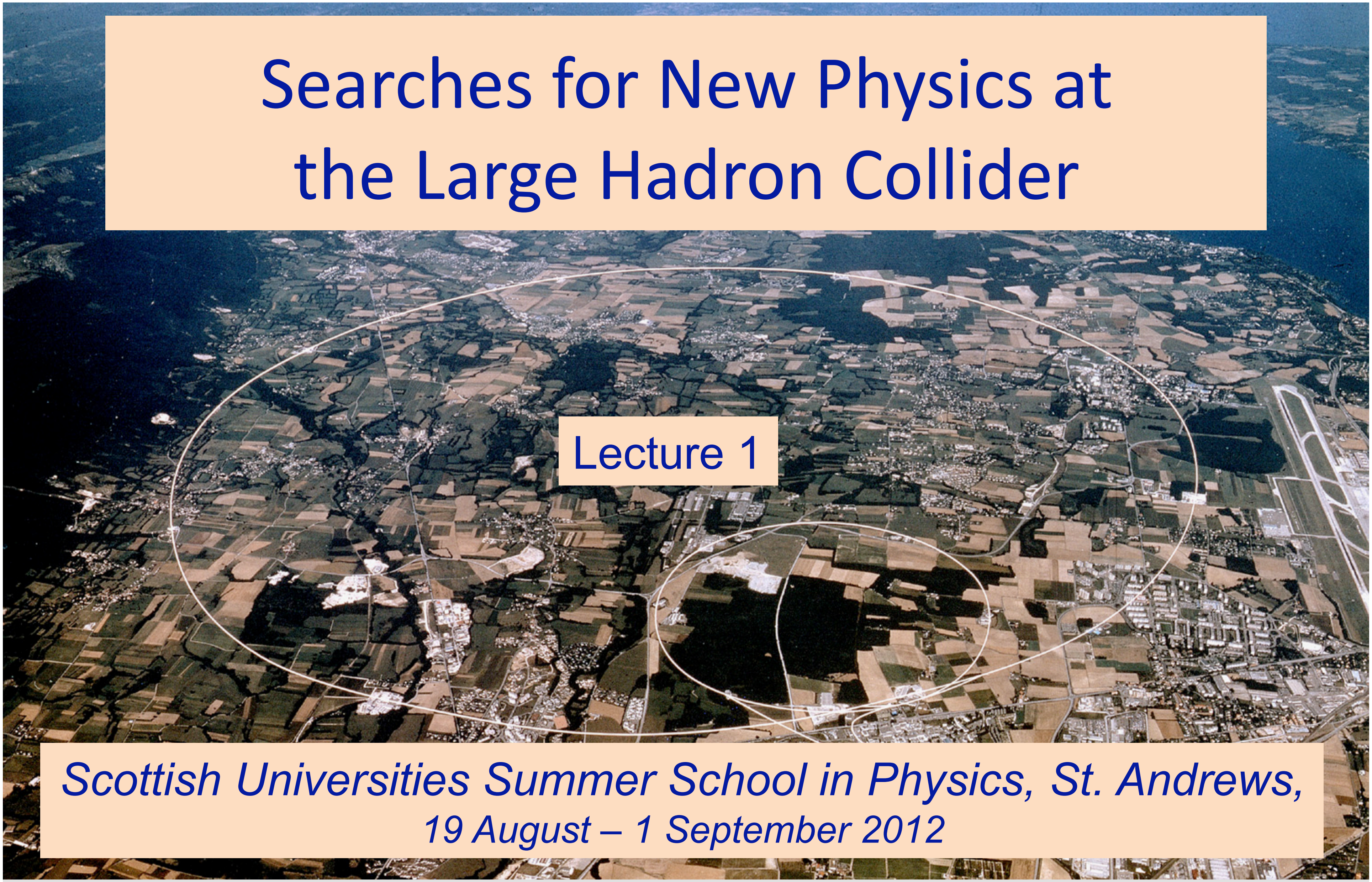


Searches for New Physics at the Large Hadron Collider

Lecture 1

Scottish Universities Summer School in Physics, St. Andrews,
19 August – 1 September 2012

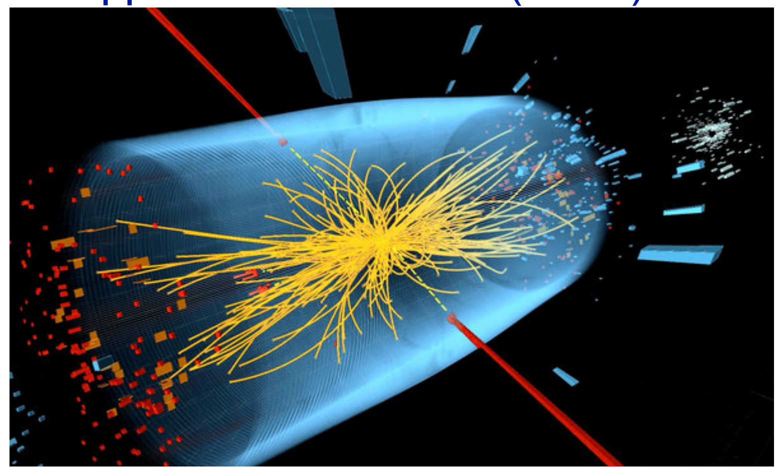
Jeffrey D. Richman
Department of Physics
University of California, Santa Barbara

Introduction

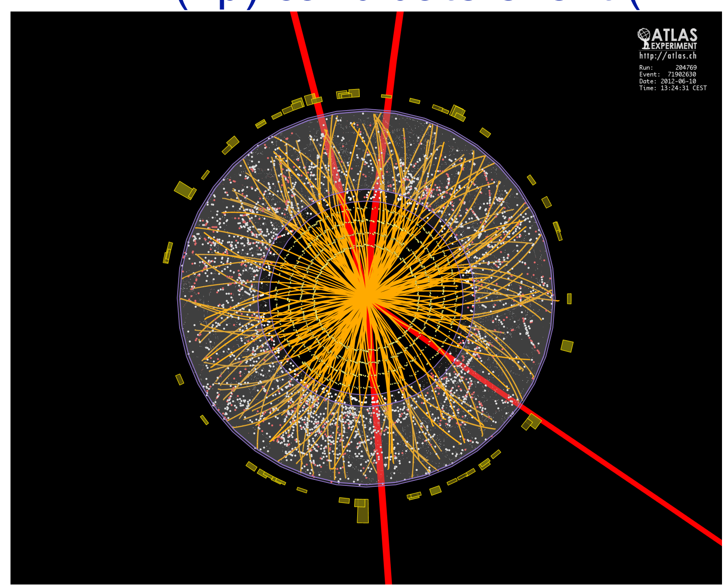
The discovery of a "particle with properties consistent with a Higgs boson" is an historic achievement in physics.

- A special year for the Scottish Universities Summer School in Physics.
- Major step towards understanding how massive particles can be accomodated within the framework of a gauge theory through EW symmetry breaking.

H→γγ candidate event (CMS)



H→ZZ (4μ) candidate event (ATLAS)

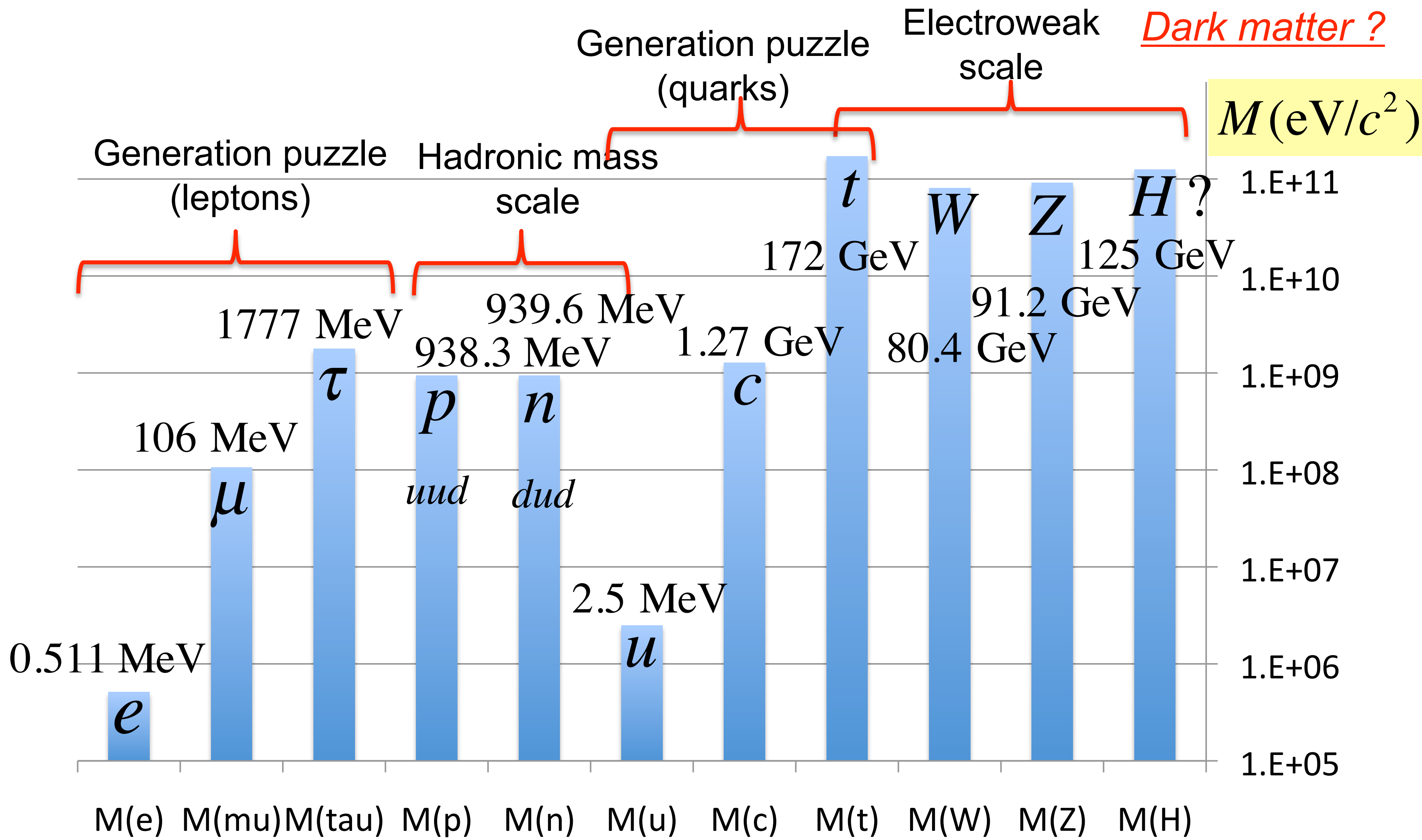


Exploring the TeV energy scale

- We are not just trying to test lots of individual models and theories (SUSY, low scale gravity, large extra dimensions...).
- We are mapping out a critical energy scale of nature.
- We have a responsibility as scientists to fully exploit the extraordinary resource of the LHC. What is the full picture of physics at the TeV energy scale?

credit: Sergio Cittolin/CERN

Key mass scales in physics



$m(\nu) \sim 1\ \mathrm{eV}?$ Si band gap: $\simeq 1.1\ \mathrm{eV}$ $m(\tilde{g}) \sim 1\ \mathrm{TeV}?$ $M_P \approx 10^{19}\ \mathrm{GeV}$

Road map for the TeV scale!

Cross section vs. cm Energy in p + p

$\sigma(pp)$

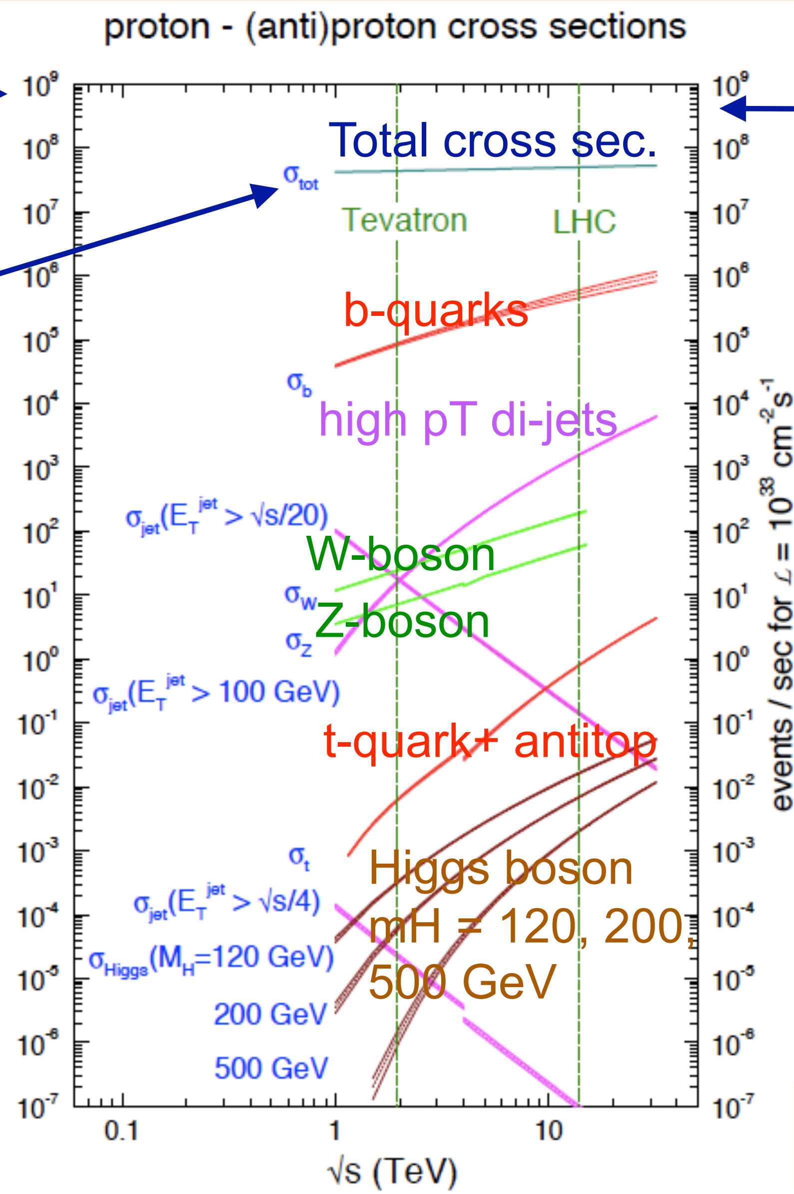
$\sigma_{TOT} \sim 50\ \text{mb}$

1 nb

1 pb

1 fb

Current searches



$$Rate(process\ i) = L_{accel} \cdot \sigma(process\ i)$$

at $L_{accel} = 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$

At the LHC, we are dealing with an **enormous range of cross sections**.

In NP searches, we are often probing the extreme tails of the distributions of SM processes.

$$\sqrt{s} \equiv CM\ \text{energy}$$

Vast range of new physics searches at the LHC

- Searches for supersymmetry
  - R-parity conserving
  - R-parity violating...
- Searches for “exotic” phenomena
  - Resonances
  - Compositeness
  - 4th generation particles
  - Leptoquarks
  - Long-lived particles
  - Black holes
  - Contact interactions

just some of the highest level categories!

A few links/references

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- http://www.phy.pku.edu.cn/~susy2012/index.html
- *A Supersymmetry Primer*, S.P. Martin, arXiv:hep-ph/9709356.
- *Theory and Phenomenology of Sparticles*, M. Drees, R.M. Godbole, and P. Roy, World Scientific Publishers (2004).
- *Supersymmetry in Particle Physics*, I. Aitchison, Cambridge U. Press (2007).
- *Weak Scale Supersymmetry*, H. Baer and X. Tata, Cambridge U. Press (2006).
- *Supersymmetry: Theory, Experiment, Cosmology*, P. Binetruy, Oxford U. Press (2006).
- *Perspectives on LHC Physics*, G. Kane an A. Pierce, World Scientific (2008).

Goals of the lectures

- These lectures are intended to be pedagogical and sometimes even provocative – I will not try to cover all of the possible topics, as in a "review talk."
- I will describe some of the searches I find most interesting and will pick out some of the methodologies that I think are particularly important.
- I encourage questions at any time!
- I have been a CMS SUSY convener and am co-chair of the CMS Exotica Publications Board. The range of physics analyses is overwhelming. Huge opportunities for graduate students and postdocs to contribute and to lead!

Bumps in the road: struggles with the data

- Searching for "New Physics" isn't easy.
- Many examples of problematic searches from the past.
- What can we learn from these *bumps in the road*?
  - There are many ways to do something wrong. There are fewer ways to do everything right!
  - The 1st requirement is a <u>well understood detector!</u>
- But a well designed analysis isn't just "correct"—it is also "<u>robust</u>". The analyzers build in internal <u>cross checks</u> and they try to <u>deeply understand the event sample</u> – the analysis "neighborhood".

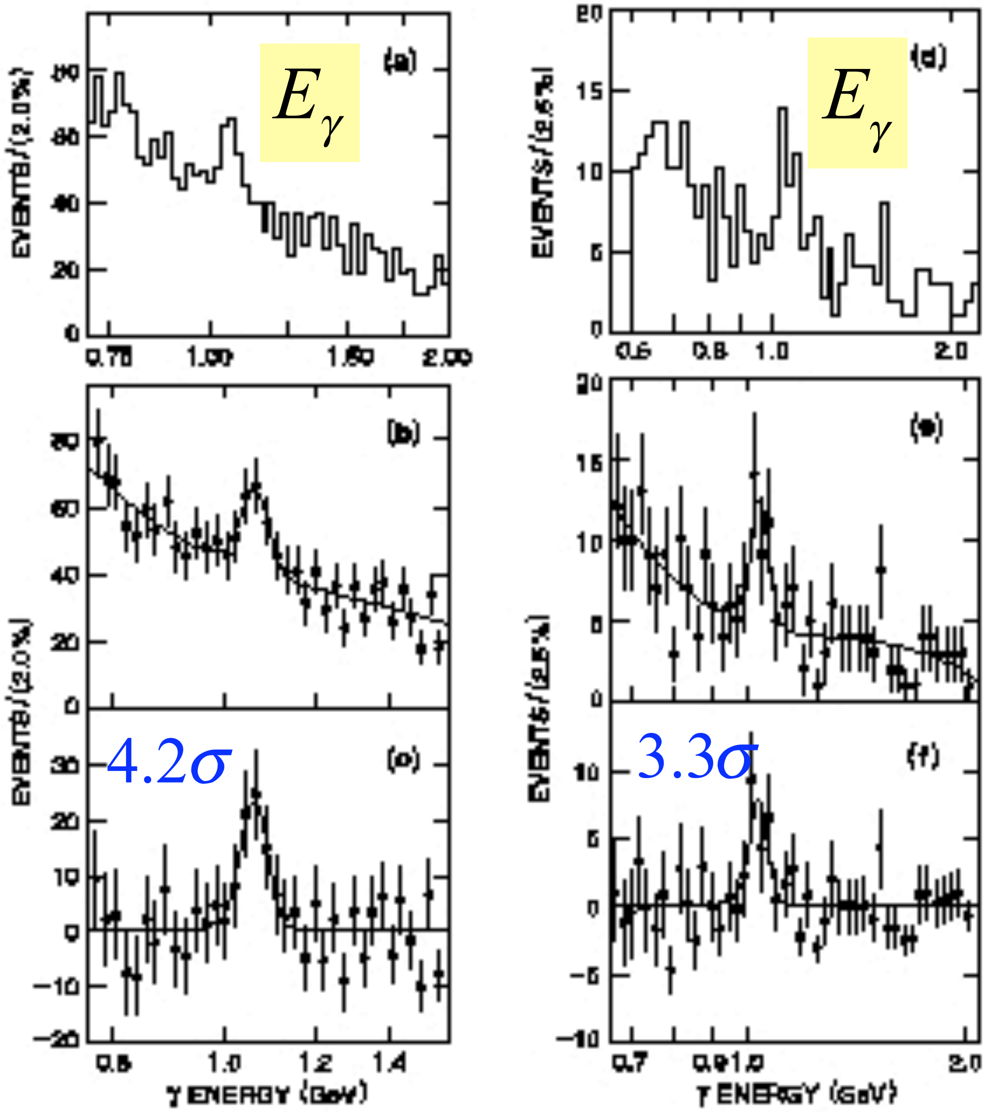
"Evidence for a Narrow Massive State in the Radiative Decays of the Upsilon"

http://slac.stanford.edu/pubs/slacpubs/3250/slac-pub-3380.pdf

http://slac.stanford.edu/pubs/slacpubs/3500/slac-pub-3683.pdf

ς(8.3)→multi-hadrons

ς(8.3)→2 jets



Crystal Ball claimed evidence for the decay

$$e^+e^- \rightarrow \Upsilon(1S) \rightarrow \gamma + X$$

Monochromatic photon corresponds to two-body decay to a new particle:

$$X = \zeta(8.3)$$

$$M(\zeta) = (8322 \pm 8 \pm 24)\ \mathrm{MeV}/c^2$$

$$B(\Upsilon \rightarrow \gamma + \varsigma) \times B(\varsigma \rightarrow \text{hadrons}) = (0.47 \pm 0.11 \pm 0.26)\%$$

...completely absent in subsequent data sample and never published.

Physics Today, March 1985

Zeta revisited: Have we really seen the Higgs?

Much excitement was generated last summer at the XXII International Conference on High Energy Physics in Leipzig by the Crystal Ball collaboration's report of evidence for a curious new particle, the 8.32-GeV "zeta" boson, that might well have been the long-sought-after Higgs particle. In October (PHYSICS TODAY, page 18) we reported that this hint of the Higgs had set in motion considerable activity among particle theorists, because these data were not entirely consistent with the simplest Higgs particle one might have expected.

It now appears, however, that the experimental signal is going away. At the beginning of November the Crystal Ball group reported at the Santa Fe meeting of the APS Division of Particles and Fields that the partial analysis of their 1984 data sample had failed to confirm the zeta signal discovered in their 1983 data. "The potential physics impact of the zeta is so great," the group declares, "that experimenters bear the burden of proof to show that it reproduces in every valid data set."

The Crystal Ball data were taken at the DORIS e^+e^- storage ring at DESY in Hamburg. At Leipzig, the Columbia–Stony Brook CUSB detector group had reported that their preliminary data, taken at the Cornell CESR e^+e^- ring, gave no indication of a new particle near 8.3 GeV. At the November meeting in Santa Fe, the CUSB group reported that additional data had not revealed a zeta signal. Two other detector groups have also joined the search—ARGUS at DORIS and Cleo at CESR. Both groups reported at the

Theoretical interpretation

Ironically, even a branching fraction as small as 1×10^{-3} (saying that one upsilon in a thousand decays radiatively to a zeta) is still an order of magnitude *too large* for the "minimal" version of the Higgs symmetry-breaking mechanism in the standard Glashow–Salam–Weinberg theory. If the zeta were indeed this simplest imagined manifestation of the Higgs mechanism, none of the current experiments would yet have detected its very infrequent appearance in upsilon decay. But Frank Wilczek (then at Princeton) pointed out eight years ago that a fairly conservative elaboration of the Higgs mechanism, well within the standard theory, would greatly increase the decay rate of the upsilon to the Higgs, making it quite compatible with the Crystal Ball data. This "two-doublet Higgs" fixup also relieves the theoretical constraint on the mass of the Higgs particle, which had implied that 8.3 GeV was somewhat too light.

Uh oh, looks like a problem!

Don't worry, everything is fine!

Theorists are very creative. They will often find a way to explain a new signal if we find one!

Volume 147B, number 6 PHYSICS LETTERS 15 November 1984

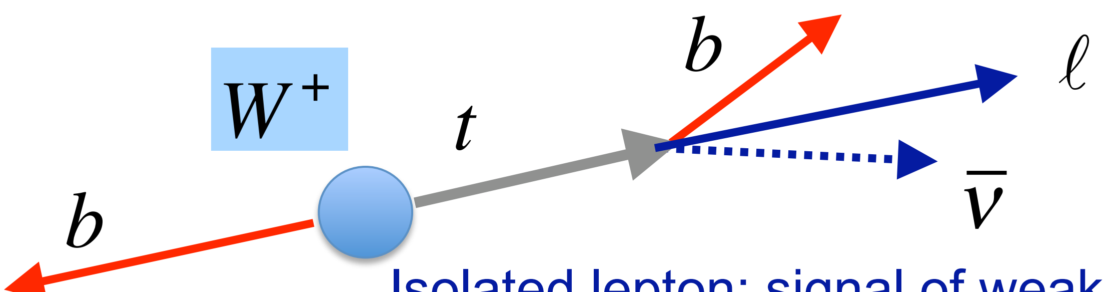
UA1 experiment

ASSOCIATED PRODUCTION OF AN ISOLATED, LARGE-TRANSVERSE-MOMENTUM LEPTON (ELECTRON OR MUON), AND TWO JETS AT THE CERN $p\bar{p}$ COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

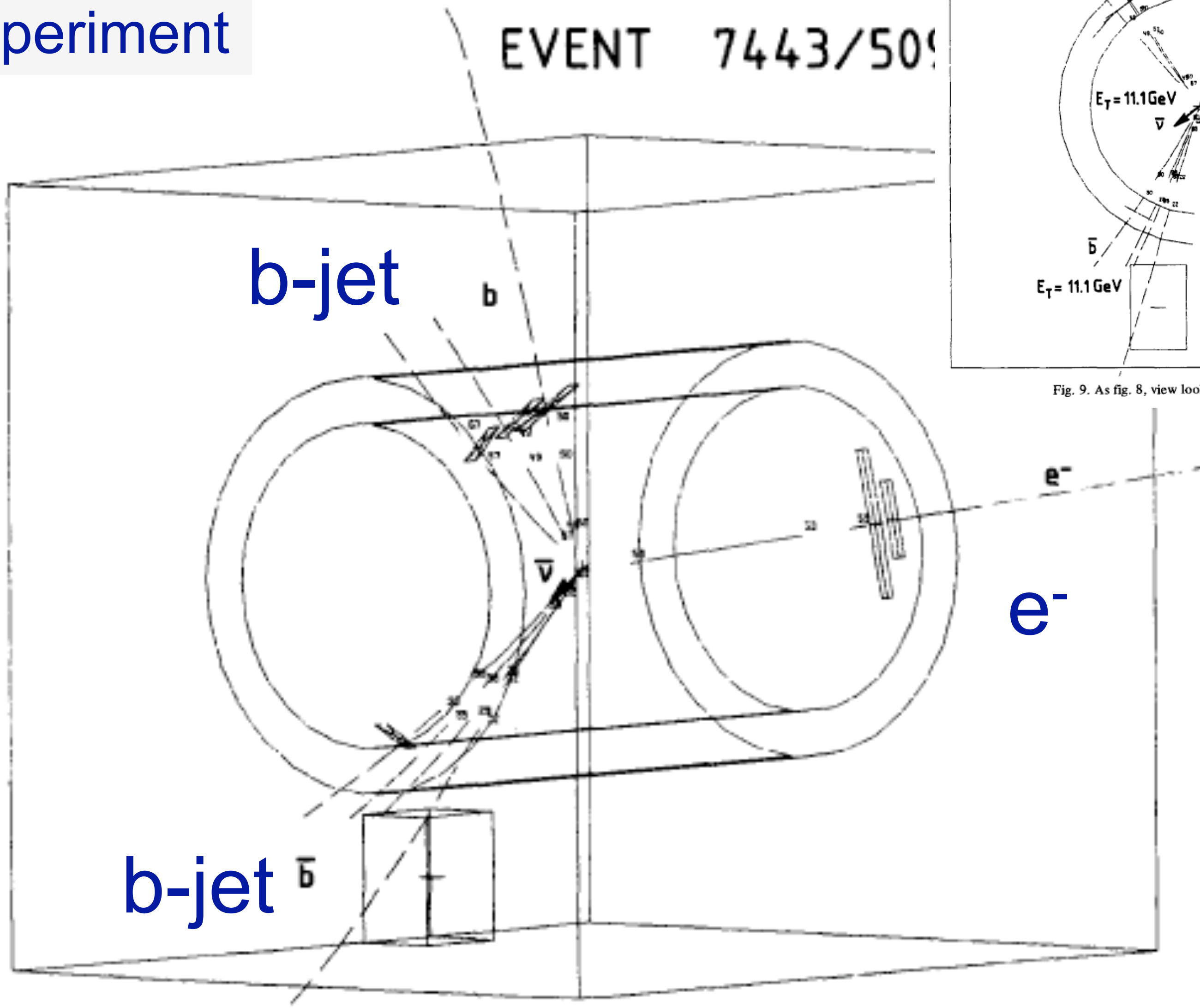
Received 8 October 1984

A clear signal is observed for the production of an isolated large-transverse-momentum lepton in association with two or three centrally produced jets. The two-jet events cluster around the $W^{\pm}$ mass, indicating a novel decay of the Intermediate Vector Boson. The rate and features of these events are not consistent with expectations of known quark decays (charm, bottom). They are, however, in agreement with the process $W \to t\bar{b}$ followed by $t \to b\ell\nu$, where t is the sixth quark (top) of the weak Cabibbo current. If this is indeed so, the bounds on the mass of the top quark are $\boxed{30\ \mathrm{GeV}/c^2 < m_t < 50\ \mathrm{GeV}/c^2}$



Isolated lepton: signal of weak decay of heavy particle.
Arises from large pT kick to lepton from parent mass.

UA1 experiment



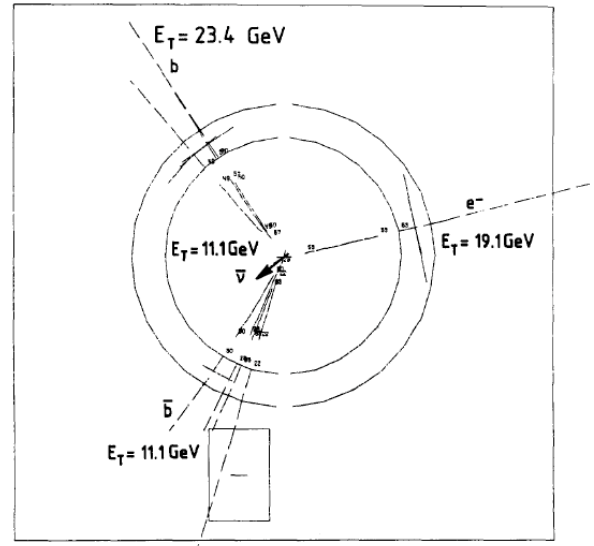


Fig. 9. As fig. 8, view looking along the beam direction.

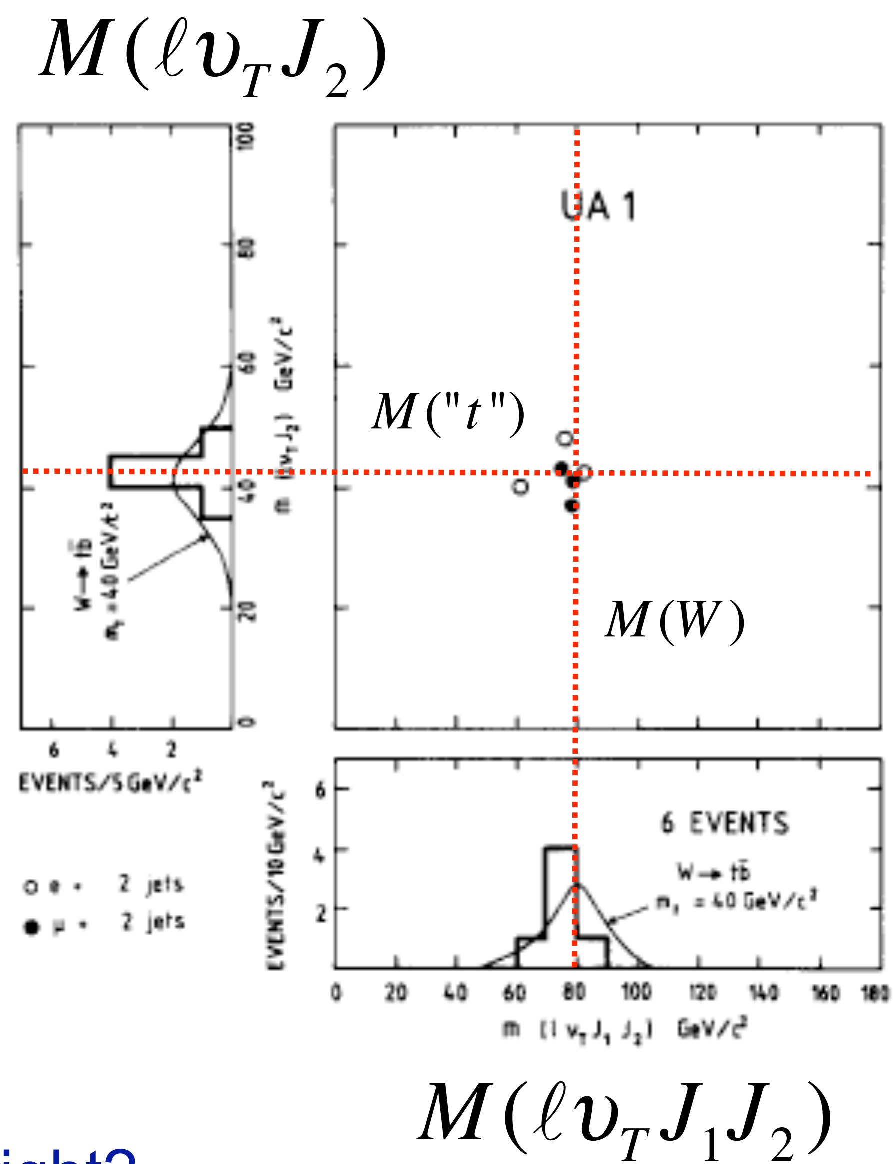
Fig. 8. Graphic display of calorimeter cells ($E_T > 2$ GeV) and charged tracks ($p_T > 1.5$ GeV) observed in the UA1 detector for event 7443/509, a $W^- \rightarrow \bar{t}b$ candidate. The decay products (b, $\bar{b}$, e^- and $\bar{\nu}$) are labelled. General view.

Kinematic distributions can be misleading...

In order to identify the decay mode, we can next evaluate the invariant mass of the lepton, the neutrino, and one of the jets. In fig. 10, we also show the three-body mass distribution $m(\ell\nu_T j_2)$ obtained by selecting the lower-transverse-energy jet. A sharp peak is observed around 40 GeV/c^2. The other solution, based on the other choice of jet, gives a broader spectrum, extending to higher masses (fig. 11). For three events, both choices give consistent mass values. For the other three events, we prefer the low-mass solution since (i) the high mass corresponds to decays strongly suppressed by phase space, and (ii) Monte Carlo simulation shows that, for $W \to t\bar{b}$ events, this is the right choice in the majority of cases. Therefore, we conclude that we have observed a new particle state amongst the

debris of the W decays; this state subsequently decays semileptonically. All jets have invariant masses of less than 10 GeV/c^2, which sets an upper limit to the mass of the underlying partons [‡9].

The decay hypothesis $W \to t\bar{b}$ with $m_t \simeq 40$ GeV/c^2 describes all kinematical distributions [19] very well, as shown in fig. 12. The rate of occurrence of the events, the number of $W \to e\nu$ decays, and the Monte



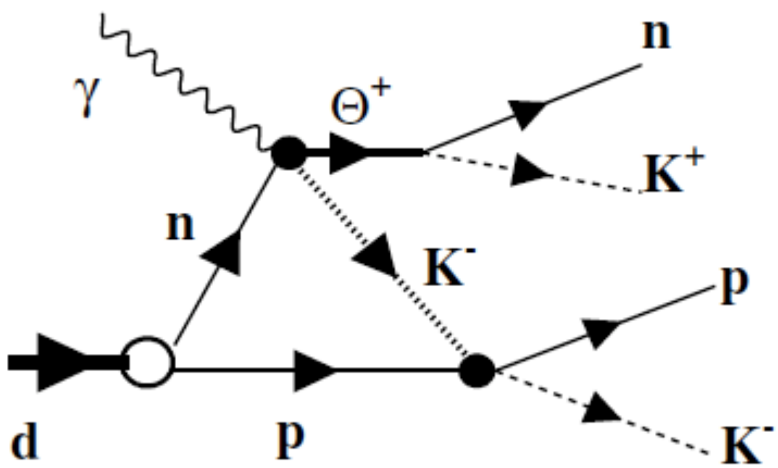
...but this was way back in 1984, right?

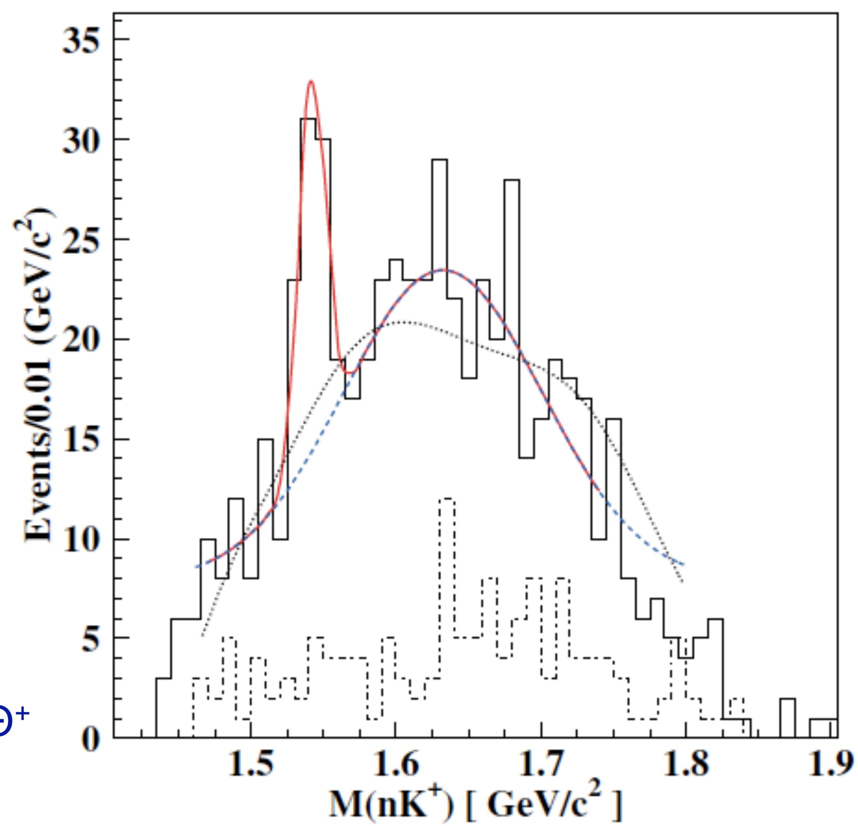
VOLUME 91, NUMBER 25 PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2003

Observation of an Exotic $S = +1$ Baryon in Exclusive Photoproduction from the Deuteron

(CLAS Collaboration)

In an exclusive measurement of the reaction $\gamma d \to K^+ K^- pn$, a narrow peak that can be attributed to an exotic baryon with strangeness $S = +1$ is seen in the $K^+ n$ invariant mass spectrum. The peak is at $1.542 \pm 0.005\ \mathrm{GeV}/c^2$ with a measured width of $0.021\ \mathrm{GeV}/c^2$ FWHM, which is largely determined by experimental mass resolution. The statistical significance of the peak is $(5.2 \pm 0.6)\sigma$. The mass and width of the observed peak are consistent with recent reports of a narrow $S = +1$ baryon by other experimental groups.





See also: K. Hicks, An Experimental Review of the Θ^+ Pentaquark, http://arxiv.org/pdf/hep-ex/0412048.pdf

Experiments confirming the Θ⁺

K. Hicks, *An Experimental Review of the Θ^+ Pentaquark*, arXiv:hep-ex/0412048

Table 1. Published experiments with evidence for the Θ^+ baryon.

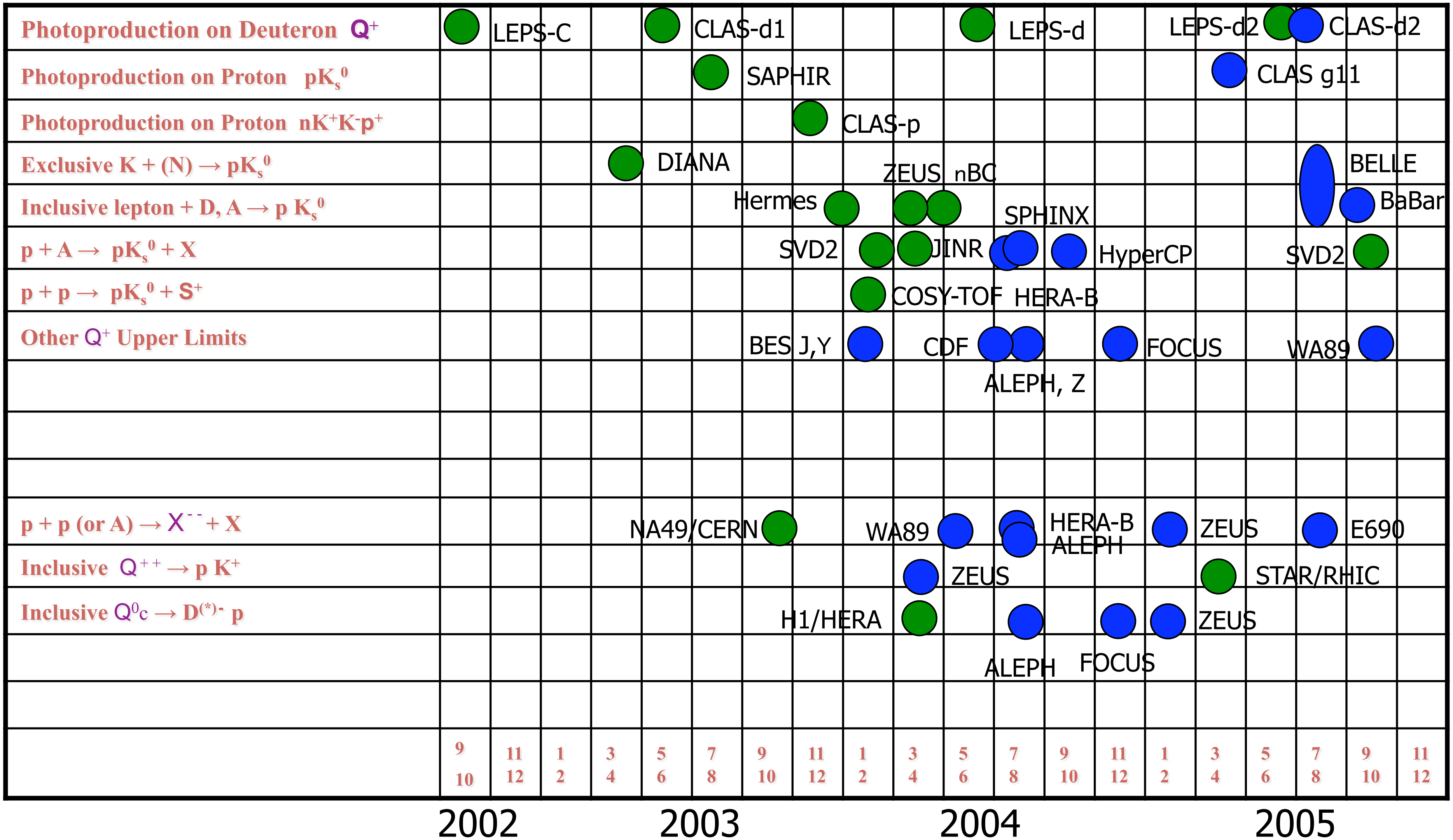
Reference	Group	Reaction	Mass (MeV)	Width (MeV)	σ's*
[8]	LEPS	$\gamma C \to K^+K^-X$	1540 ± 10	< 25	4.6
[9]	DIANA	$K^+Xe \to K^0pX$	1539 ± 2	< 9	4.4
[10]	CLAS	$\gamma d \to K^+K^-p(n)$	1542 ± 5	< 21	$5.2 \pm 0.6^\dagger$
[11]	SAPHIR	$\gamma d \to K^+K^0(n)$	1540 ± 6	< 25	4.8
[12]	ITEP	$\nu A \to K^0pX$	1533 ± 5	< 20	6.7
[13]	CLAS	$\gamma p \to \pi^+K^+K^-(n)$	1555 ± 10	< 26	7.8
[14]	HERMES	$e^+d \to K^0pX$	1526 ± 3	13 ± 9	~ 5
[15]	ZEUS	$e^+p \to e^+K^0pX$	1522 ± 3	8 ± 4	~ 5
[16]	COSY-TOF	$pp \to K^0p\Sigma^+$	1530 ± 5	< 18	4-6
[17]	SVD	$pA \to K^0pX$	1526 ± 5	< 24	5.6

* Gaussian fluctuation of the background, as $N_{peak}/\sqrt{N_{BG}}$. This "naive" significance may underestimate the real probability of a fluctuation by about 1-2 σ.

† Further analysis of the CLAS deuterium data suggest that the significance of the observed peak may not be as large as indicated.

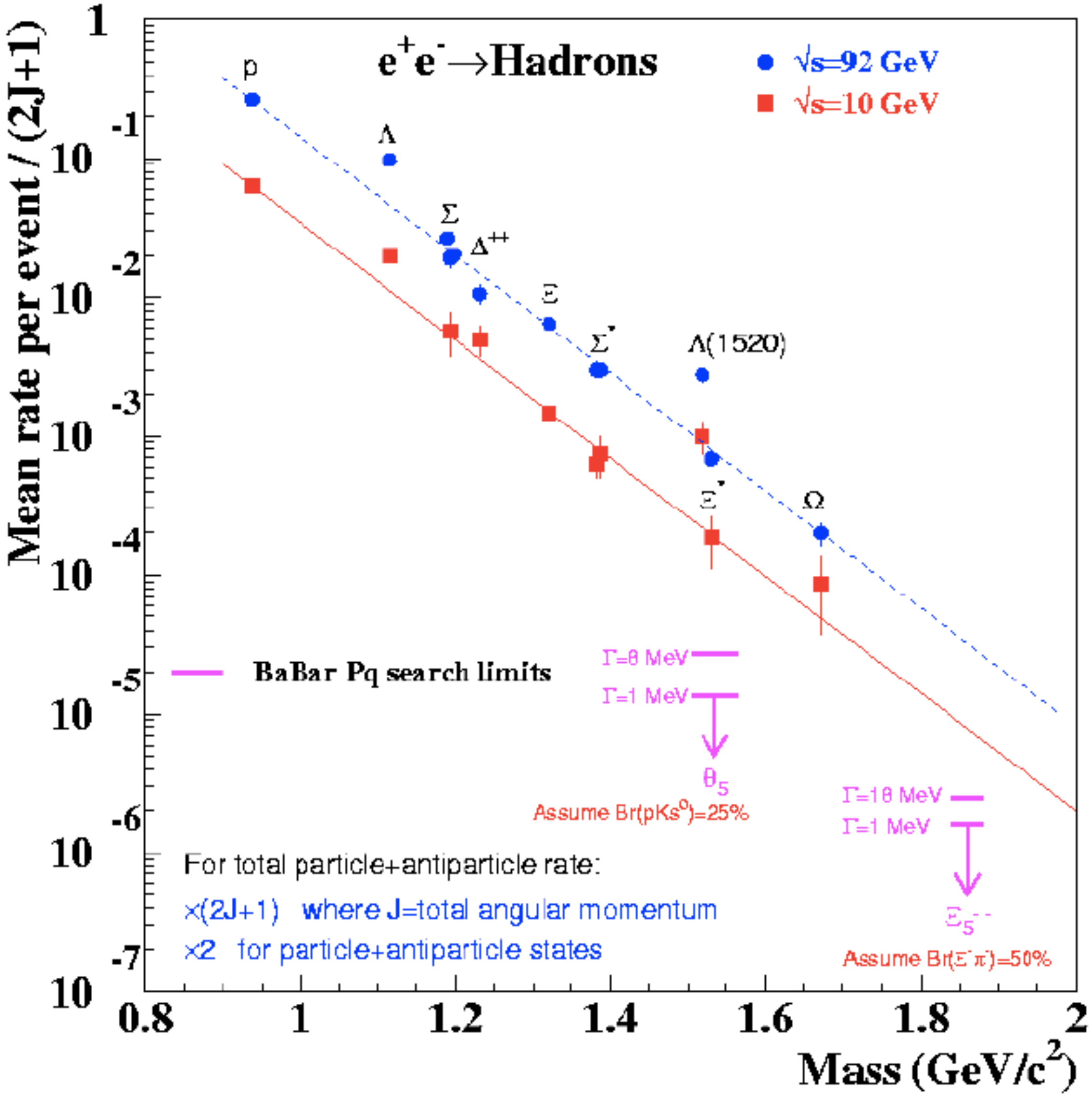
The penta-quark phenomenon: 2002-2005

Slide courtesy of R. Schumacher



From Particles and Nuclei International Conference, Santa Fe, 2005

BaBar pentaquark and baryon searches + LEP baryon searches



What lessons can we learn?

- Yield in signal region can be biased by tuning selection cuts on the data.
- People often stop looking for mistakes when they obtain a “desirable” result.
- Background shape or normalization can be estimated incorrectly.
- Understanding the background in one kinematic region does not necessarily mean that you understand it in another region.
- Shapes used in fit may not adequate to describe the data. (Especially worrisome in multidimensional fits!)
- Trigger efficiencies may not be acccounted for & can bias sig. or backgrounds.
- Systematic errors may be underestimated or incomplete. Assumptions may be wrong!
- Correlations may not taken into account.
- Backgrounds peaking under signal may not correctly determined.
- Signal significance may not be estimated correctly.
- Signal can created artificially as “reflection” of another peaking process.
- Changes in experimental conditions may not fully taken into account.
- Average of many bad measurements might not give a good measurement.
- Bugs in the program!
- Advisor in a hurry. Need to finish thesis! No time to look for more problems.
- A superposition of several of the above effects!

“Strength” of signatures

Not all search signatures are of the same quality.

Weak ⟵⟶ Strong

Excess in tail of an exponentially falling distribution

Broad excess + strong topological features such as leptons or b-tags (SUSY, $H \rightarrow WW$)

Broad mass peak over slowly varying background shape. $W \rightarrow l\nu$

Narrow mass peak ($H \rightarrow \gamma\gamma$)

Narrow mass peak in high resolution channel with additional kinematic checks. ($H \rightarrow ZZ$)

A strong SUSY signature:
same-sign dileptons + b-jets + MET.

A weak SUSY signature:
multiple jets + MET.

The weaker the signature, the more you have to worry about effects on previous page.
But they are always a concern! For example, in precision measurement of “easy” signal.

Perspective on backgrounds

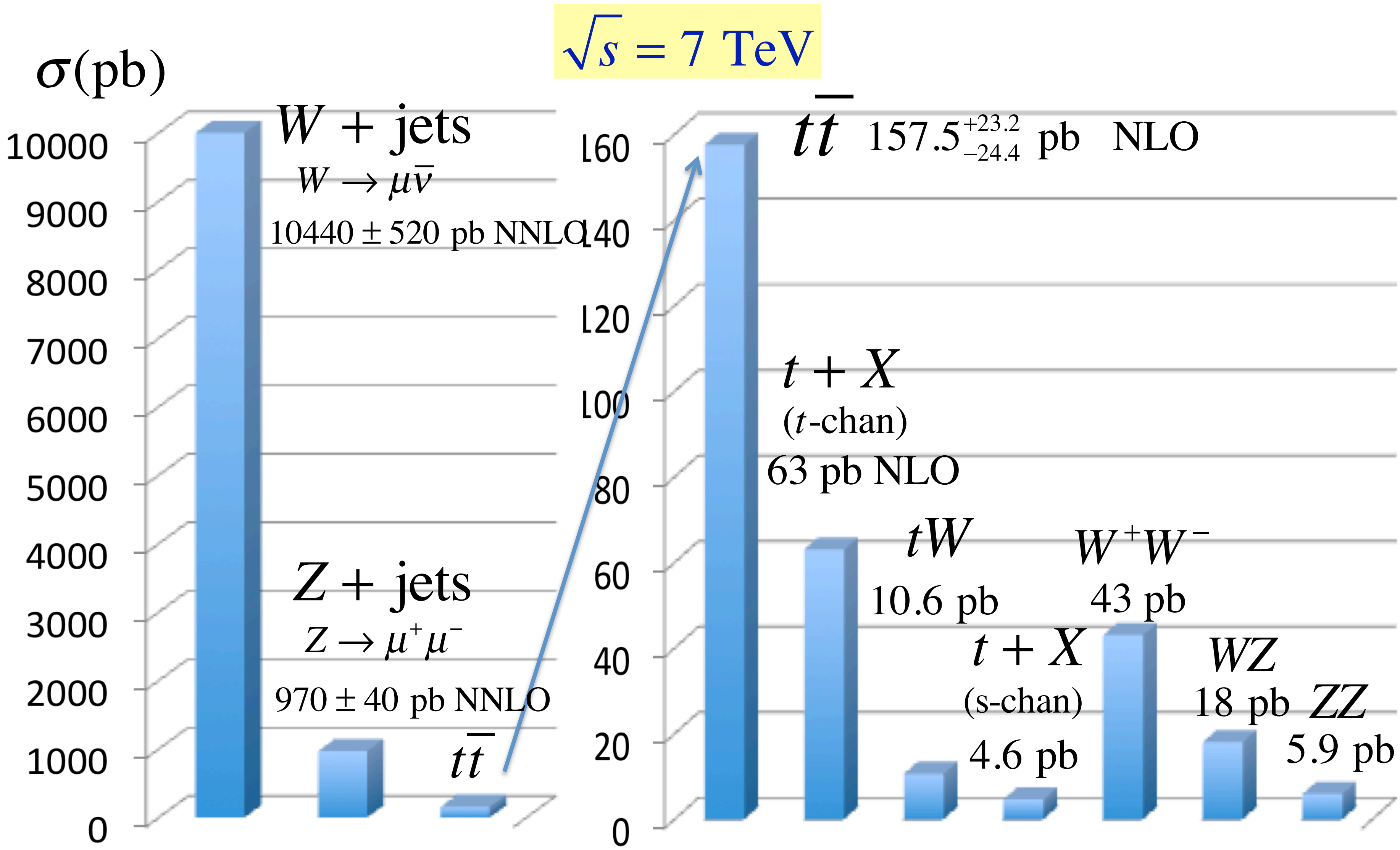
- *The foundation of any search for new physics is a detailed understanding of the SM backgrounds.*
  - If you are performing exp. or thy. studies of SM processes, you are contributing to NP searches!
  - Not just the amount of background, but its uncertainty.
- If the background is *underestimated*, the data may be mistakenly interpreted as evidence for a signal.
- If the background is *overestimated*, the exclusion region will be larger than it deserves to be (and a signal may be missed!). It is not "conservative" to overestimate the background.

MC-based vs. "data-driven" background determination

There is a continuous variation in how much reliance one can place on the MC simulation.

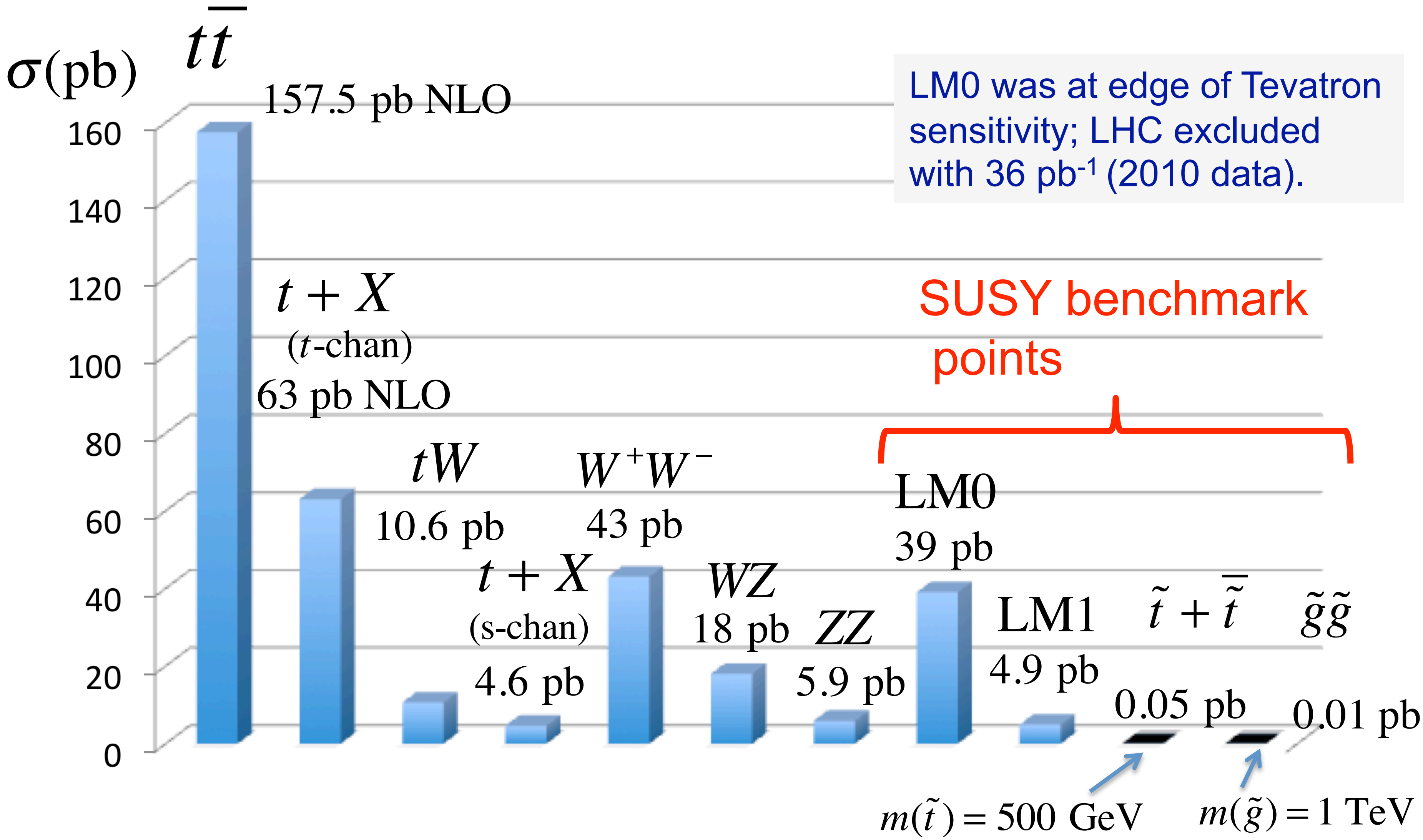
1. Simulate with MC & normalize to cross section. Use predicted background yield in signal region: "Out of the box MC."
2. Simulate background with MC, normalize to a control region, extrapolate MC to signal region.
3. Use control sample in data, together with corrections from MC, to predict background in signal region.
4. Use control samples in data with very minimal input from MC.

Cross Sections for Key SM Processes

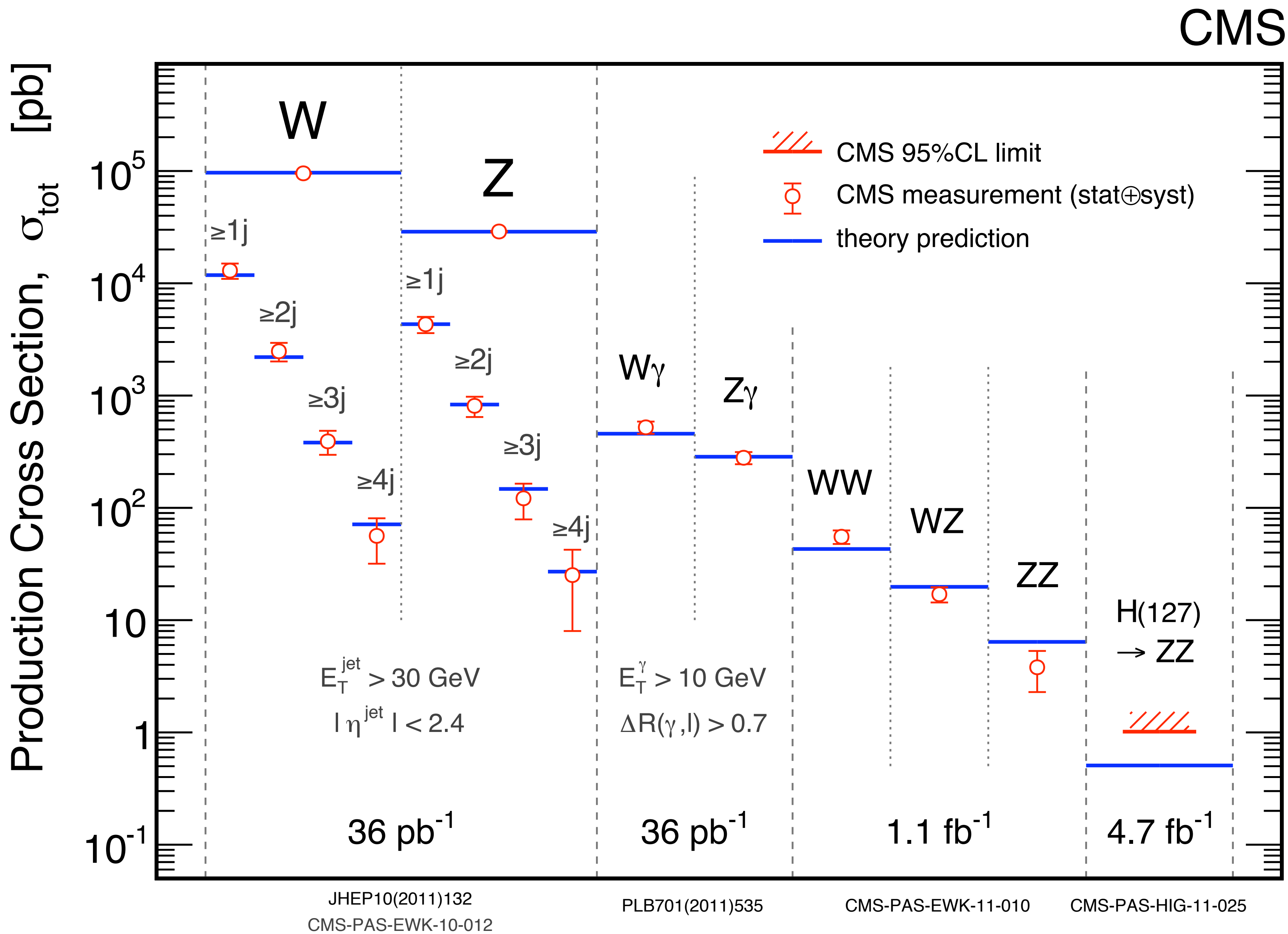


Cross Sections for SM vs. low-mass SUSY benchmark points

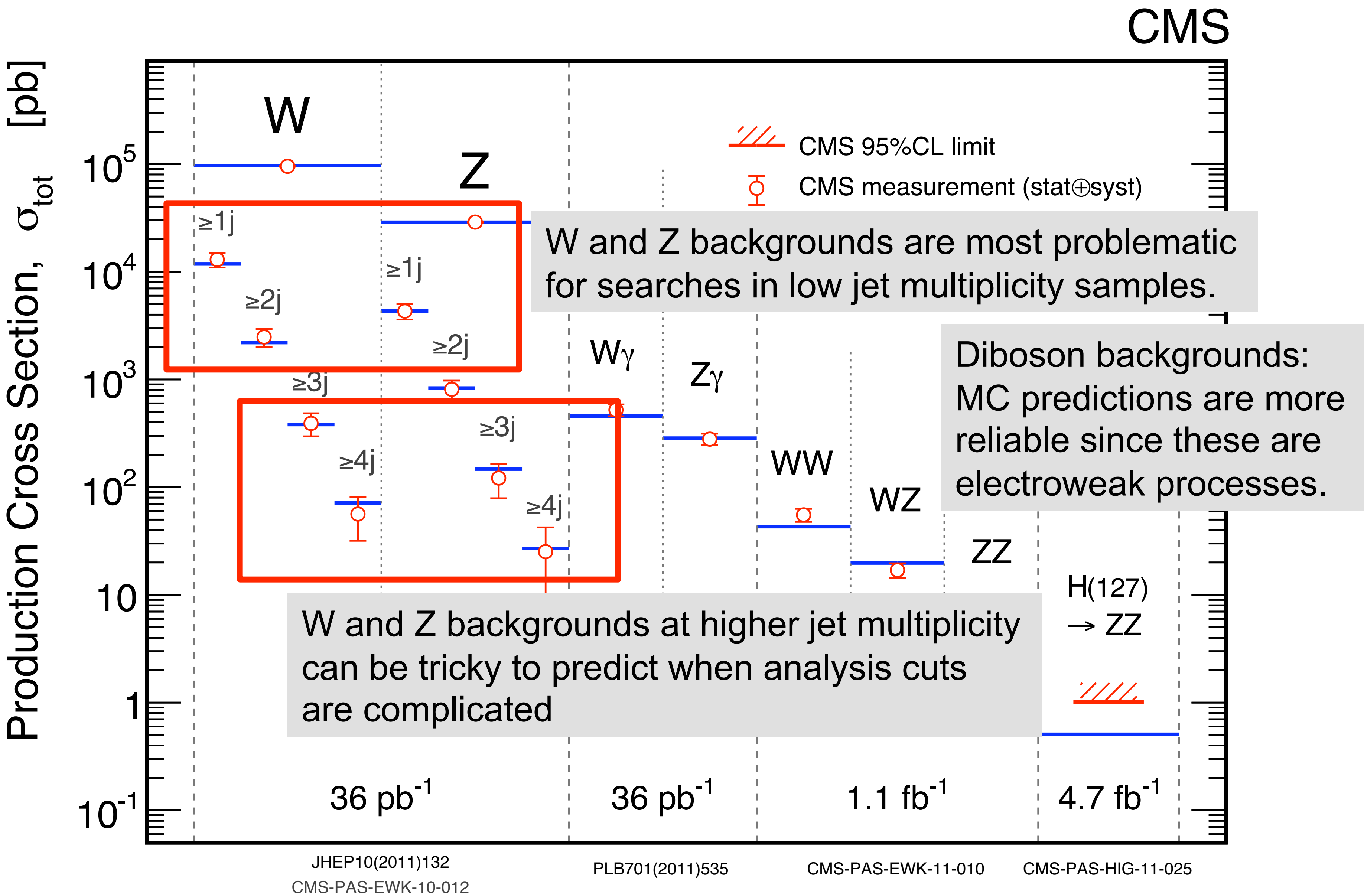
LM0 was at edge of Tevatron sensitivity; LHC excluded with 36 pb^{-1} (2010 data).



W, Z boson cross sections in more detail



Single- and di-boson cross sections



W and Z backgrounds are most problematic for searches in low jet multiplicity samples.

Diboson backgrounds: MC predictions are more reliable since these are electroweak processes.

W and Z backgrounds at higher jet multiplicity can be tricky to predict when analysis cuts are complicated

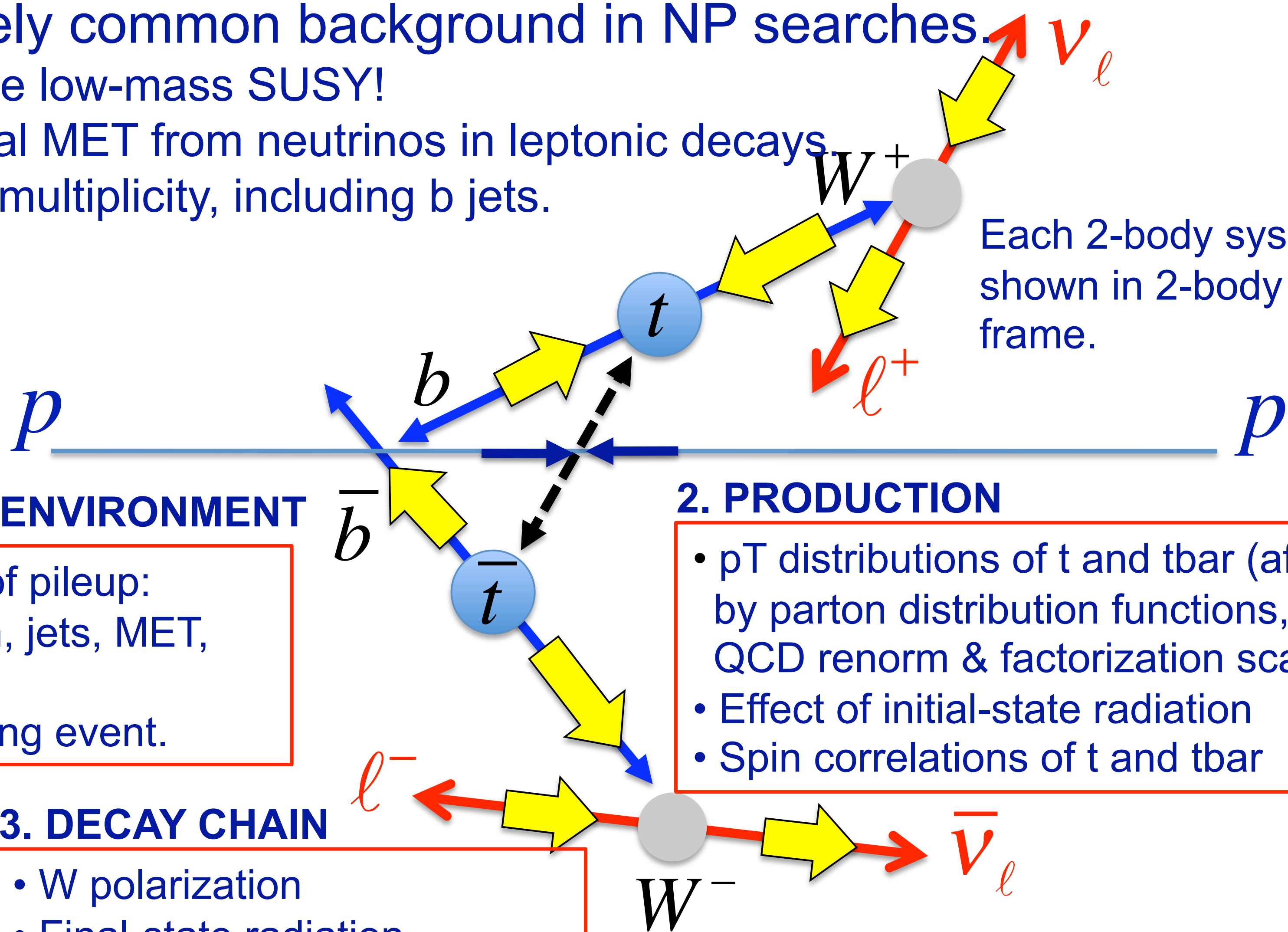
Some questions in background determination

- What aspects of the background really matter? Are these well understood?
- "We know the MC does a great job!" But...has the MC been tested in the same region of phase space as the search?
- Can the MC uncertainties be quantified in a reliable way? The uncertainty that you assign can *directly* determine the signal significance.
- What are the dominant systematic uncertainties? Ideally, these would be controlled using data control samples (e.g., as "nuisance parameters") -- these uncertainties would then effectively become statistical.

Anatomy of a background: ttbar

Extremely common background in NP searches.

- looks like low-mass SUSY!
- large real MET from neutrinos in leptonic decays.
- high jet multiplicity, including b jets.



Each 2-body system shown in 2-body rest frame.

1. EVENT ENVIRONMENT

- Effects of pileup: isolation, jets, MET, vertices
- Underlying event.

2. PRODUCTION

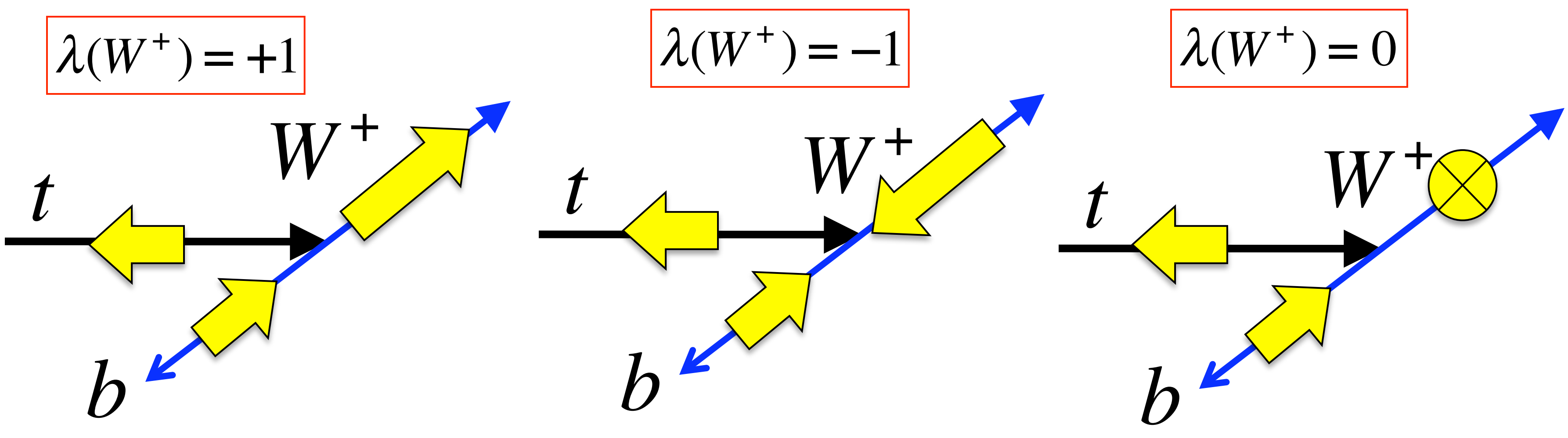
- pT distributions of t and tbar (affected by parton distribution functions, QCD renorm & factorization scales)
- Effect of initial-state radiation
- Spin correlations of t and tbar

3. DECAY CHAIN

- W polarization
- Final-state radiation
- Decay branching fractions

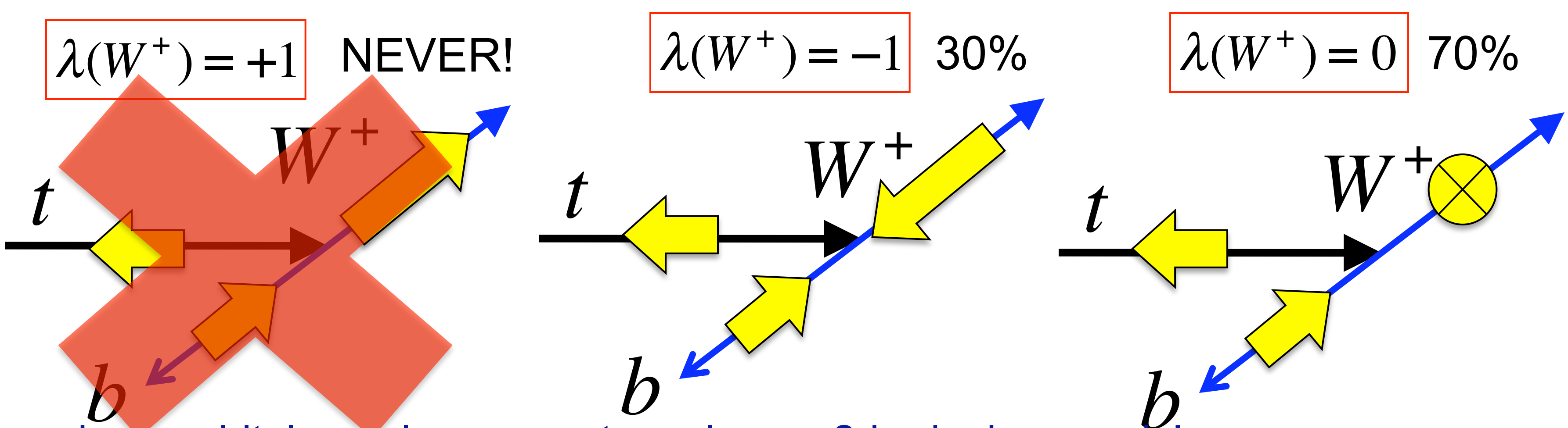
W helicities in top-quark decay

- Knowledge of angular distributions can be helpful in searches.
- Even if you cannot reconstruct an angular distribution in the appropriate Lorentz frame, it can still have a important effect on the observable event kinematics.



W helicities in top-quark decay

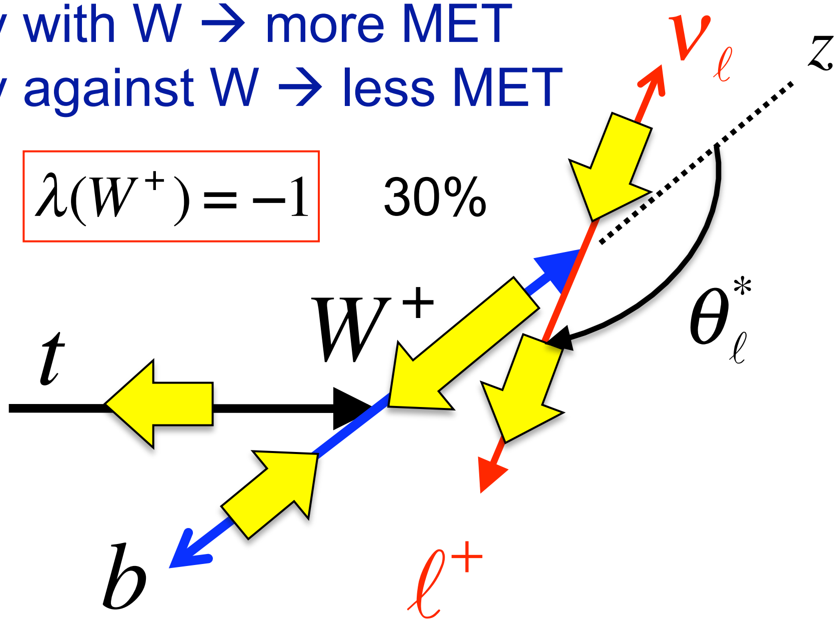
- Knowledge of angular distributions can be enormously helpful in searches.
- Even if you cannot reconstruct an angular distribution in the appropriate Lorentz frame, it can still have a important effect on the observable event kinematics.

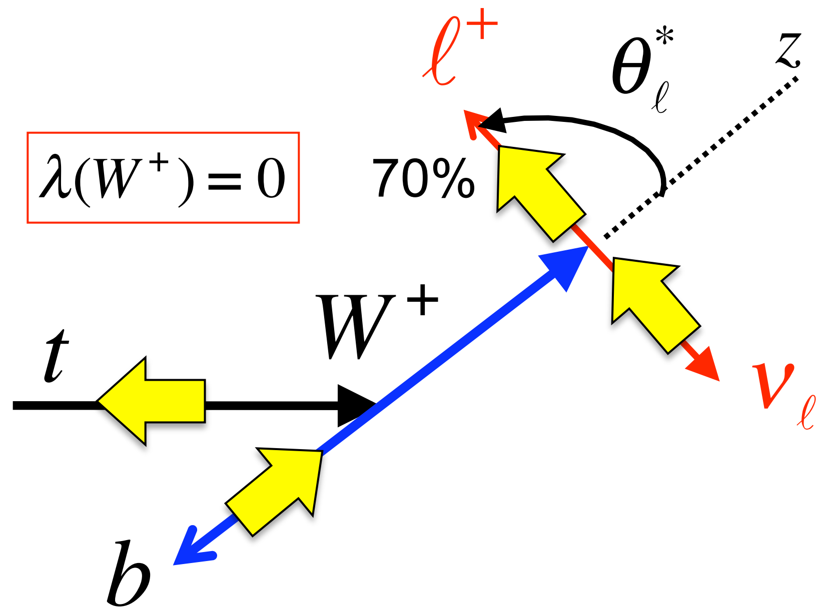


Never have orbital angular momentum along a 2-body decay axis!

Angular distribution for two-body decays

Boost ν with W → more MET
Boost ν against W → less MET





Specify:
(1) spin of decaying particle: for W-boson, this is J=1
(2) spin projection of decaying particle along given axis: for left figure: Jz = -1.
(3) helicities of each of the two daughter particles: λ(ν)=-1/2, λ(l^+)=+1/2.

$$A \propto d^{J=1}_{M=-1,\ 1/2-(-1/2)}(\theta_\ell^*) = \tfrac{1}{2}(1-\cos\theta_\ell^*)$$

$$\frac{dN}{d\cos\theta_\ell^*} \sim (1-\cos\theta_\ell^*)^2$$

$$A \propto d^{J=1}_{M=0,\ 1/2-(-1/2)}(\theta_\ell^*) = \tfrac{1}{\sqrt{2}}\sin\theta_\ell^*$$

$$\frac{dN}{d\cos\theta_\ell^*} \sim \sin^2\theta_\ell^*$$

Help from theorists!

Czarnecki, Korner, Piclum, http://arxiv.org/abs/1005.2625

Helicity fractions of W bosons from top quark decays at NNLO in QCD

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Department of Physics, University of Alberta, Edmonton, Alberta T6G 2G7, Canada and CERN Theory Division, CH-1211 Geneva 23, Switzerland

Jürgen G. Körner†
Institut für Physik, Universität Mainz, 55099 Mainz, Germany

Jan H. Piclum‡
Department of Physics, University of Alberta, Edmonton, Alberta T6G 2G7, Canada
(Dated: May 18, 2010)

Decay rates of unpolarized top quarks into longitudinally and transversally polarized W bosons are calculated to second order in the strong coupling constant α_s. Including the finite bottom quark mass and electroweak effects, the Standard Model predictions for the W boson helicity fractions are $\mathcal{F}_L = 0.687(5)$, $\mathcal{F}_+ = 0.0017(1)$, and $\mathcal{F}_- = 0.311(5)$.

$$\left.\begin{aligned} F(\lambda=0) &= 0.687 \pm 0.005 \\ F(\lambda=-1) &= 0.311 \pm 0.005 \\ F(\lambda=+1) &= 0.0017 \pm 0.001 \end{aligned}\right\}$$

Uncertainties are so small that they could be much larger and not affect most analyses.

Why supersymmetry?

The canonical motivations for TeV scale SUSY:

1. Gauge hierarchy problem: SUSY particles can stabilize the Higgs mass (squared) by cancelling quadratic quantum corrections from SM particles (e.g., top quark loop). Avoids fine tuning: “naturalness”.
2. TeV-scale SUSY can lead to unification of the running coupling constants at a high energy scale.
3. Many SUSY models have a dark-matter candidate, the neutralino, which is in general a linear combination of a neutral gaugino and higgsino.

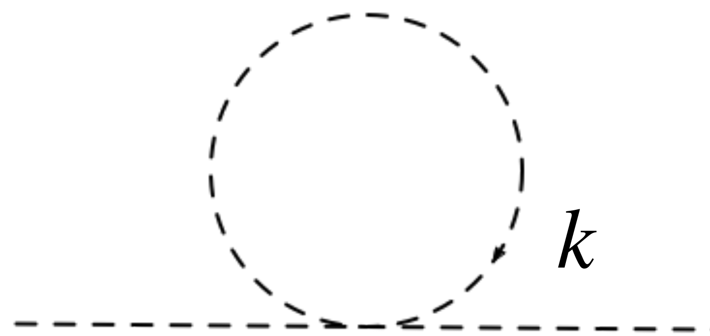
– slepton = scalar lepton; squark = scalar squark

– <particle-name>+ino = spin-1/2 SUSY particle (except “sneutrino”)

Scalar particles and fine tuning

- Fundamental scalar fields have the problem of quadratic divergences to the scalar mass squared. These arise from loop-corrections to the mass, which are generically for spin 0:

$$\delta m^2 = \lambda \int^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^2} \sim \frac{\lambda}{16\pi^2} \int^{\Lambda} dk^2$$



$$m^2 = m_0^2 + \alpha\lambda \frac{\Lambda^2}{16\pi^2}$$

dominant at low m_t

$\lambda \sim m_h^2 / v^2$

In the Standard Model:

$$\delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left[\left(4m_t^2 - 2M_W^2 - M_Z^2 - m_h^2\right) + O\left(\log\frac{\Lambda}{\mu}\right)\right]$$

Field content of the MSSM

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-1-theory.pdf

Field Content of the MSSM					
Super-Multiplets	Boson Fields	Fermionic Partners	SU(3)	SU(2)	U(1)
gluon/gluino	g	$\widetilde{g}$	8	1	0
gauge/	$W^\pm$, W^0	$\widetilde{W}^\pm$, $\widetilde{W}^0$	1	3	0
gaugino	B	$\widetilde{B}$	1	1	0
slepton/	$(\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$	1	2	-1
lepton	$\tilde{e}^-_R$	e^-_R	1	1	-2
squark/	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	1/3
quark	$\widetilde{u}_R$	u_R	3	1	4/3
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/	(H^0_d, H^-_d)	$(\widetilde{H}^0_d, \widetilde{H}^-_d)$	1	2	-1
higgsino	(H^+_u, H^0_u)	$(\widetilde{H}^+_u, \widetilde{H}^0_u)$	1	2	1

MSSM: 124 parameters vs. 18 in SM (including the QCD vacuum angle θ_{QCD}).

MSSM parameter count

Sector of MSSM	Number of parameters
Standard Model parameters	18
1 Higgs parameter, analogous to Higgs mass in SM	1
Gaugino/higgsino sector	5
Gaugino/higgsino sector – CP violating phases	3
Squark and slepton masses	21
Mixing angles to define squark and slepton mass eigenstates	36
CP violating phases	40
Total	124

Scalar SUSY particles and chiral multiplets

- The SM is a chiral theory: the L and R chiral projections of the fields have different interactions (and quantum numbers).
  - L projections are $SU(2)_L$ doublets
  - R projections are $SU(2)_L$ singlets

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad u_R, \quad d_R$$

- Each chiral projection of a SM fermion has SUSY scalar partner (preserving degrees of freedom).

$$e^- \begin{array}{l} \nearrow \; e_L^- \leftrightarrow \tilde{e}_L^- \\ \searrow \; e_R^- \leftrightarrow \tilde{e}_R^- \end{array} \qquad b \begin{array}{l} \nearrow \; b_L \leftrightarrow \tilde{b}_L \\ \searrow \; b_R \leftrightarrow \tilde{b}_R \end{array} \qquad t \begin{array}{l} \nearrow \; t_L \leftrightarrow \tilde{t}_L \\ \searrow \; t_R \leftrightarrow \tilde{t}_R \end{array}$$

partner of the R-handed e^-; has J=0, no helicity.

SUSY spectrum in gauge/higgs sector (MSSM)

Particle	*J*	Degrees of freedom
W^+	1	3
W^-	1	3
Z	1	3
γ	1	2
H	0	1
h	0	1
H^+	0	1
H^-	0	1
A	0	1
Total		16

Particle	*J*	Degrees of freedom
$\tilde{W}^+$	1/2	2
$\tilde{W}^-$	1/2	2
$\tilde{Z}$ | $\tilde{W}^0$	1/2	2
$\tilde{\gamma}$ | $\tilde{B}$	1/2	2
$\tilde{H}$	1/2	2
$\tilde{h}$	1/2	2
$\tilde{H}^+$	1/2	2
$\tilde{H}^-$	1/2	2
Total		16

Mixing

Particle	J	Degrees of freedom
$\tilde{\chi}_1^+$	1/2	2
$\tilde{\chi}_1^-$	1/2	2
$\tilde{\chi}_2^+$	1/2	2
$\tilde{\chi}_2^-$	1/2	2
$\tilde{\chi}_1^0$	1/2	2
$\tilde{\chi}_2^0$	1/2	2
$\tilde{\chi}_3^0$	1/2	2
$\tilde{\chi}_4^0$	1/2	2
Total		16

If lightest neutralino is LSP, then can be dark matter candidate.

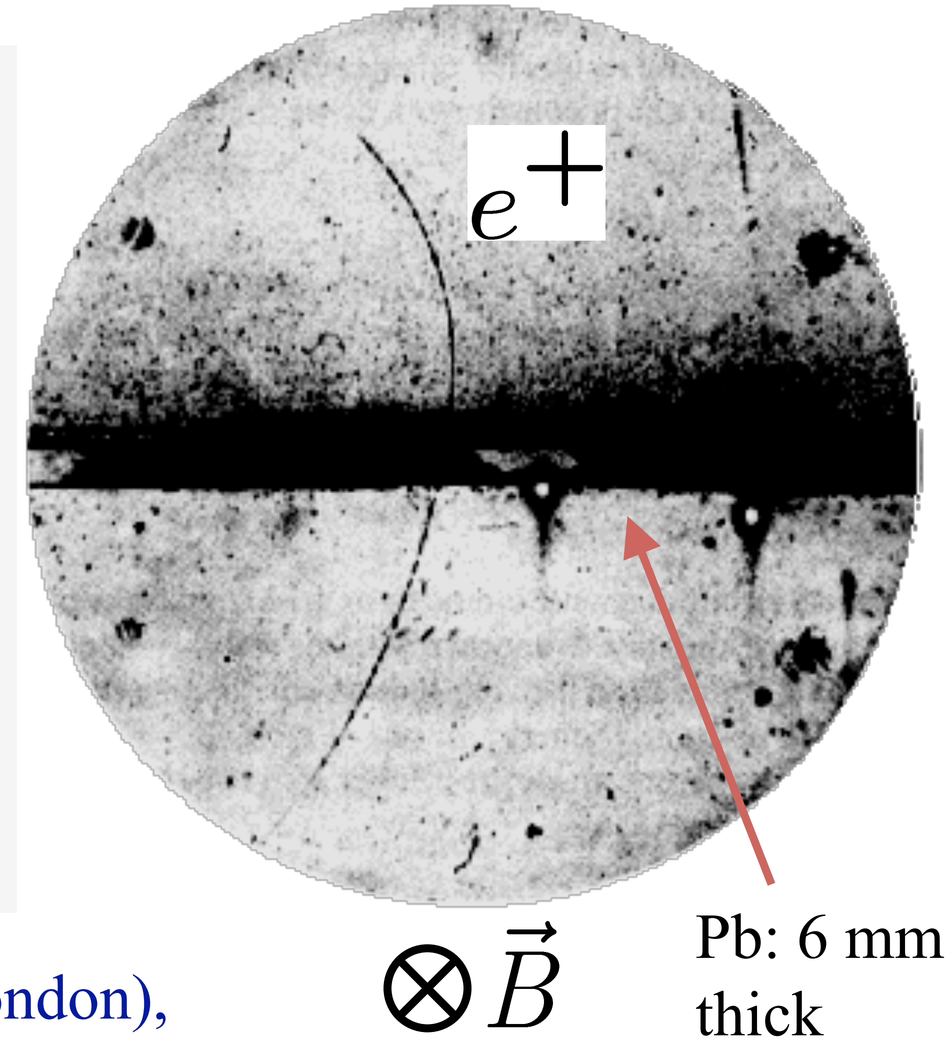
Gauginos = SUSY partners of SM gauge bosons
Higgsinos = SUSY partners of higgs bosons
Neutralinos = mix of neutral gauginos and higgsinos
Charginos = mix of charged gauginos and higgsinos
EWKinos = term that denotes neutralinos or charginos

The gluino ($\tilde{g}$) is special: because of color, it cannot mix with any other particles.

Doubling the particle spectrum is crazy, right?

Doubling the particle spectrum is crazy, right?

- Dirac relativistic wave equation (1928): extra, “negative-energy” solutions.
- Positron interpretation confirmed by C.D. Anderson (cosmic ray experiment) at Caltech.



P.A.M. Dirac, Proc. Roy. Soc. (London), **A117**, 610 (1928); ibid., **A118**, 351 (1928).
C.D. Anderson, Phys. Rev. **43**, 491 (1933).

Collaboration-wide review was easier back then...

The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

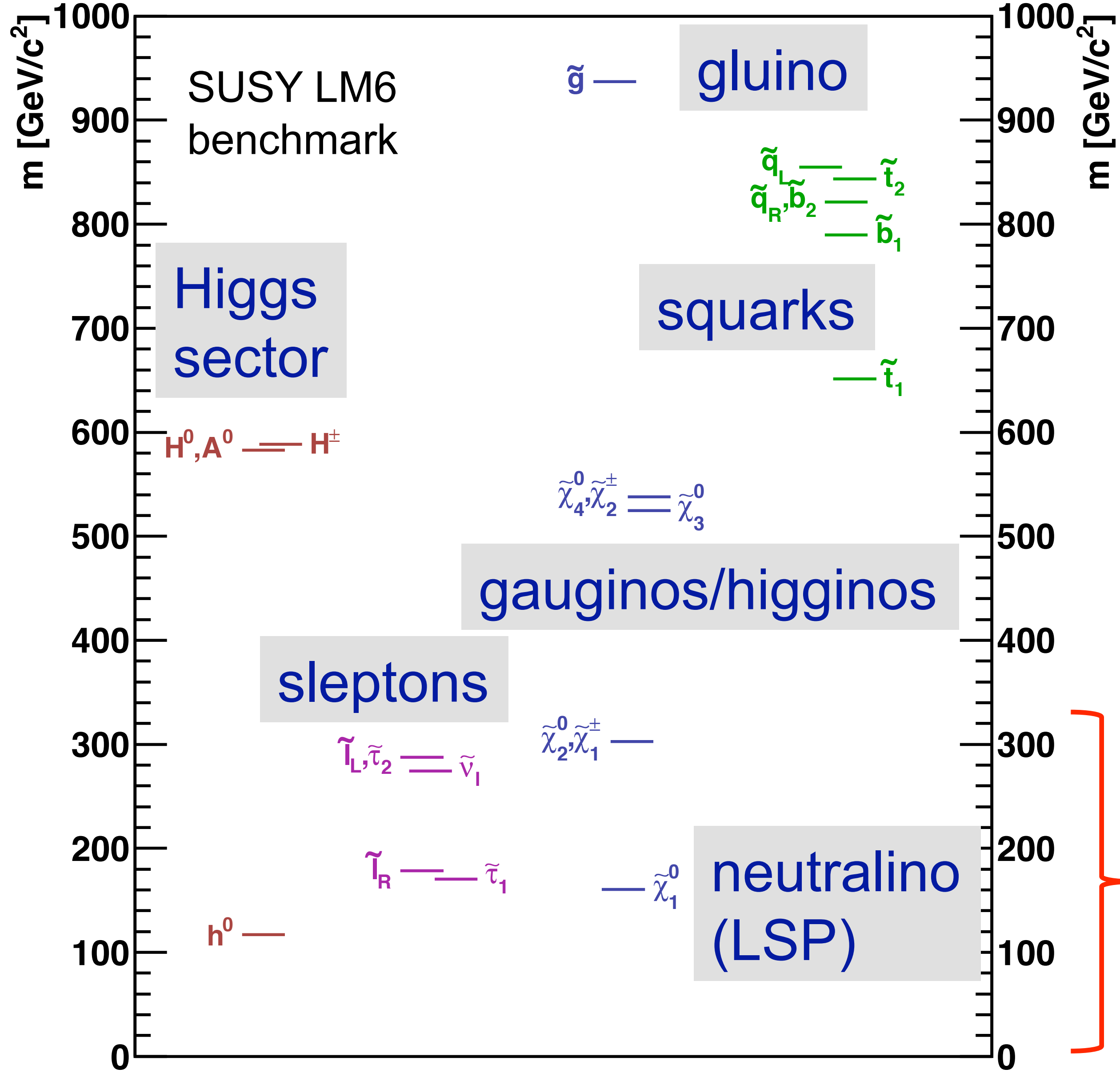
Editor

ON August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron. Later study of the electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no chance at all that two such tracks should line up in this way. We also discarded as completely untenable the assumption of an electron of 20

SUSY breaking

- SUSY, if it exists, is clearly a broken symmetry because partners with masses equal to the SM particles would already have been found.
- SUSY breaking is an complex subject with various scenarios; occurs in "hidden sector"; transmitted to MSSM particles via...
  - gravity mediation → heavy gravitino ($\tilde{G}$), couplings ≈gravity
  - gauge mediation → very light gravitino (eV range); is LSP!
- Whatever the breaking mechanism, SUSY particles still have the same SM gauge couplings as their ordinary SM partners. <u>Key point when thinking about decay modes. Your intuition for the SUSY Particle Date Book is good!</u>

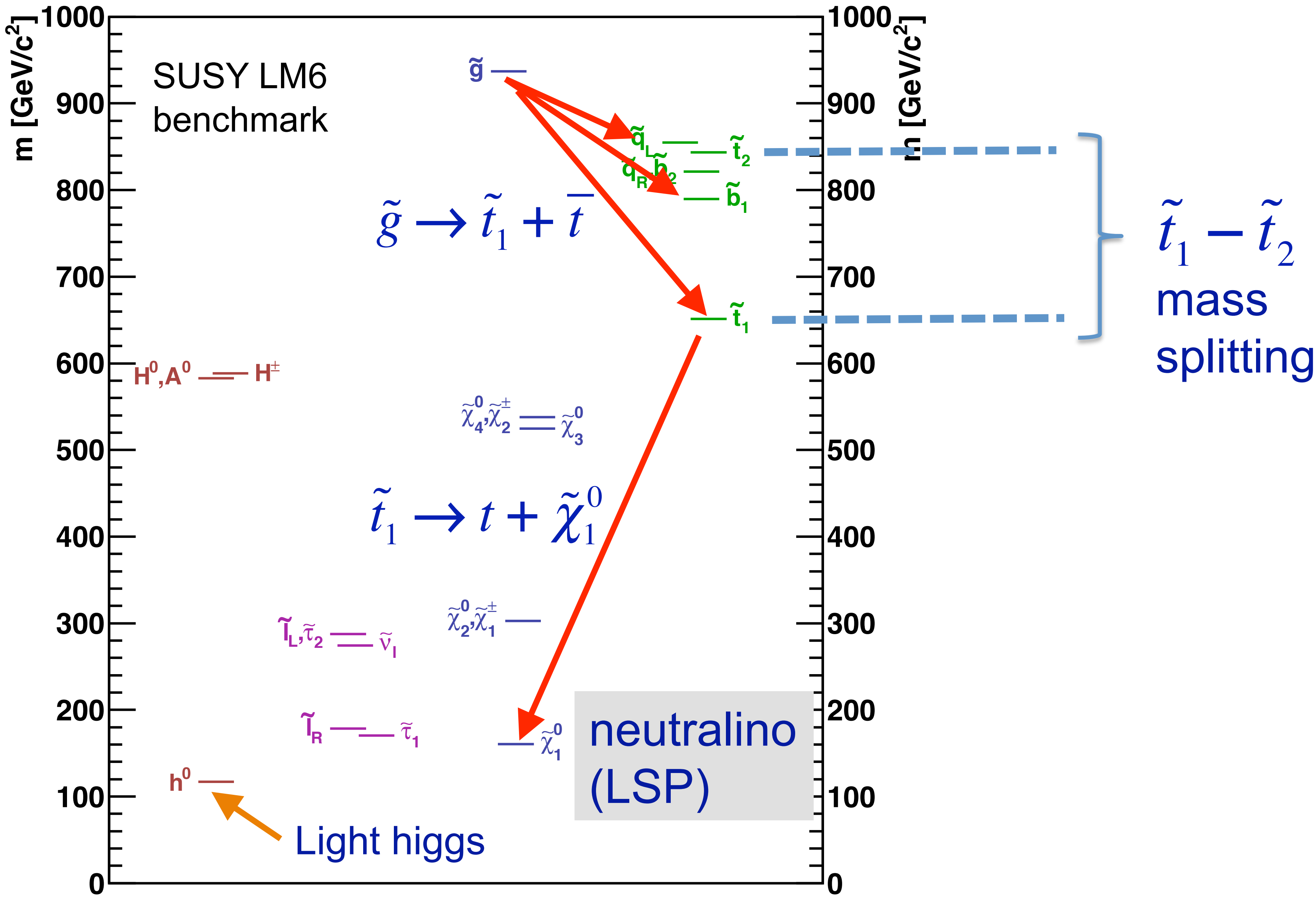
Example spectrum of a (cMSSM) SUSY model



Direct production via strong processes

Direct production via electroweak processes

Example spectrum of a (cMSSM) SUSY model



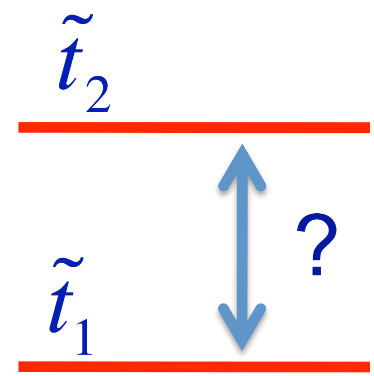
Possible large scalar top ("stop") mixing

- In the case of stop, large mixing may arise between the L- and R-handed SUSY partners, resulting in a large splitting between the mass eigenstates. Diagonalize mass matrix:

$$\begin{pmatrix} m_{Q_3}^2 + m_t^2 + t_L m_Z & m_t(A_0 - \mu\cot\beta) \\ m_t(A_0 - \mu\cot\beta) & m_{U_3}^2 + m_t^2 + t_R m_Z^2 \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_t & -\sin\theta_t \\ \sin\theta_t & \cos\theta_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$t_L = \left(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W\right)\cos 2\beta \qquad t_R = \tfrac{2}{3}\sin^2\theta_W \cos 2\beta$$



May be the lightest squark!

R-parity and its consequences

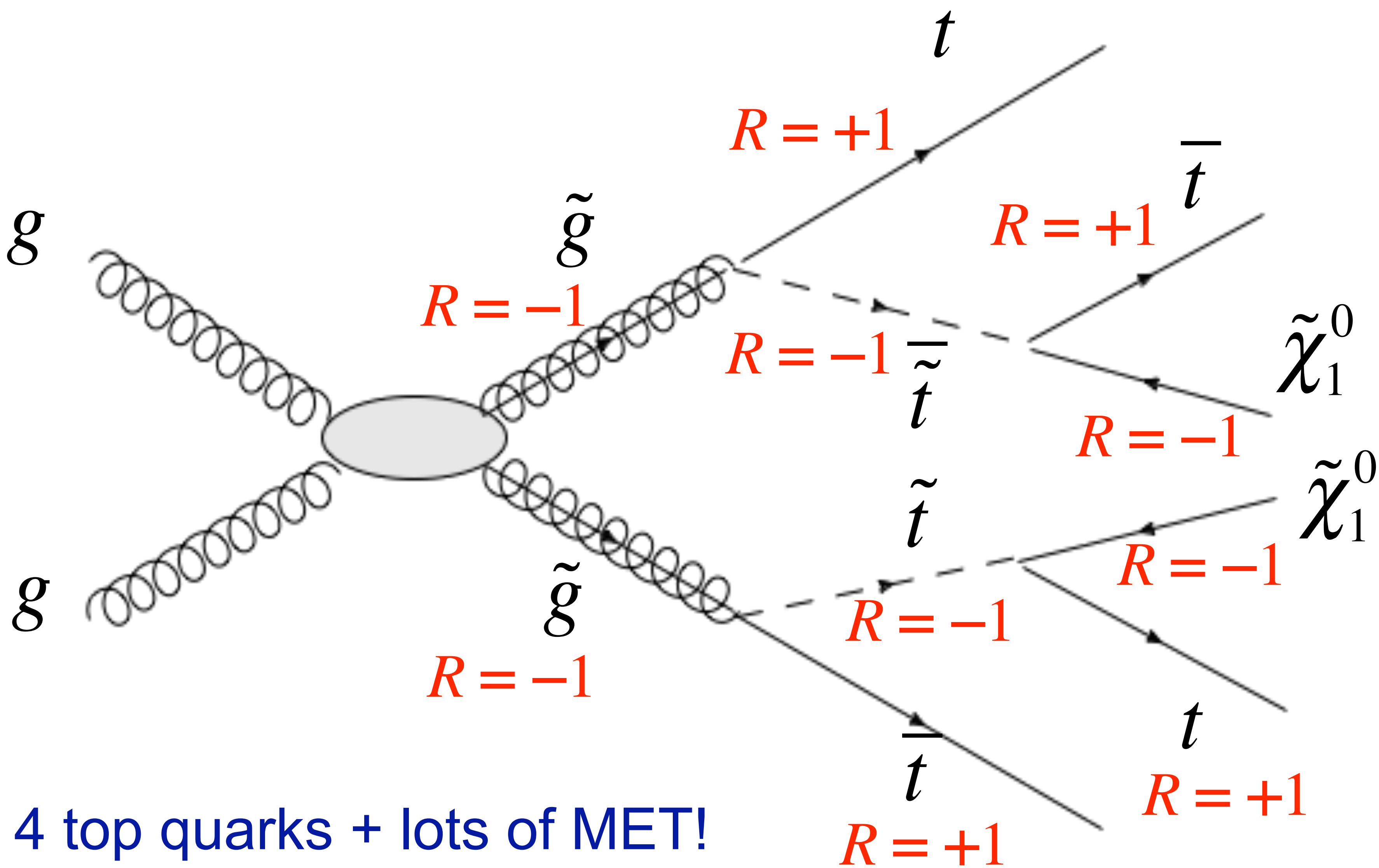
- MSSM has *B-L* symmetry, which leads to a multiplicatively conserved quantum number

$$R = (-1)^{3(B-L)+2S}$$ R-parity

	quark	lepton	gauge boson	Higgs boson	squark	slepton	gaugino/ Higgsino
3(B-L)+2S	3(1/3 - 0) +2(1/2) = 2	3(0 - 1) +2(1/2) = -2	3(0 – 0) +2 (1) = 2	3(0 – 0) +2(0) = 0	3(1/3 - 0) +2(0) = 1	3(0 – 1) +2(0) = -3	3(0 – 0) +2(1/2) = 1
R	1	1	1	1	-1	-1	-1

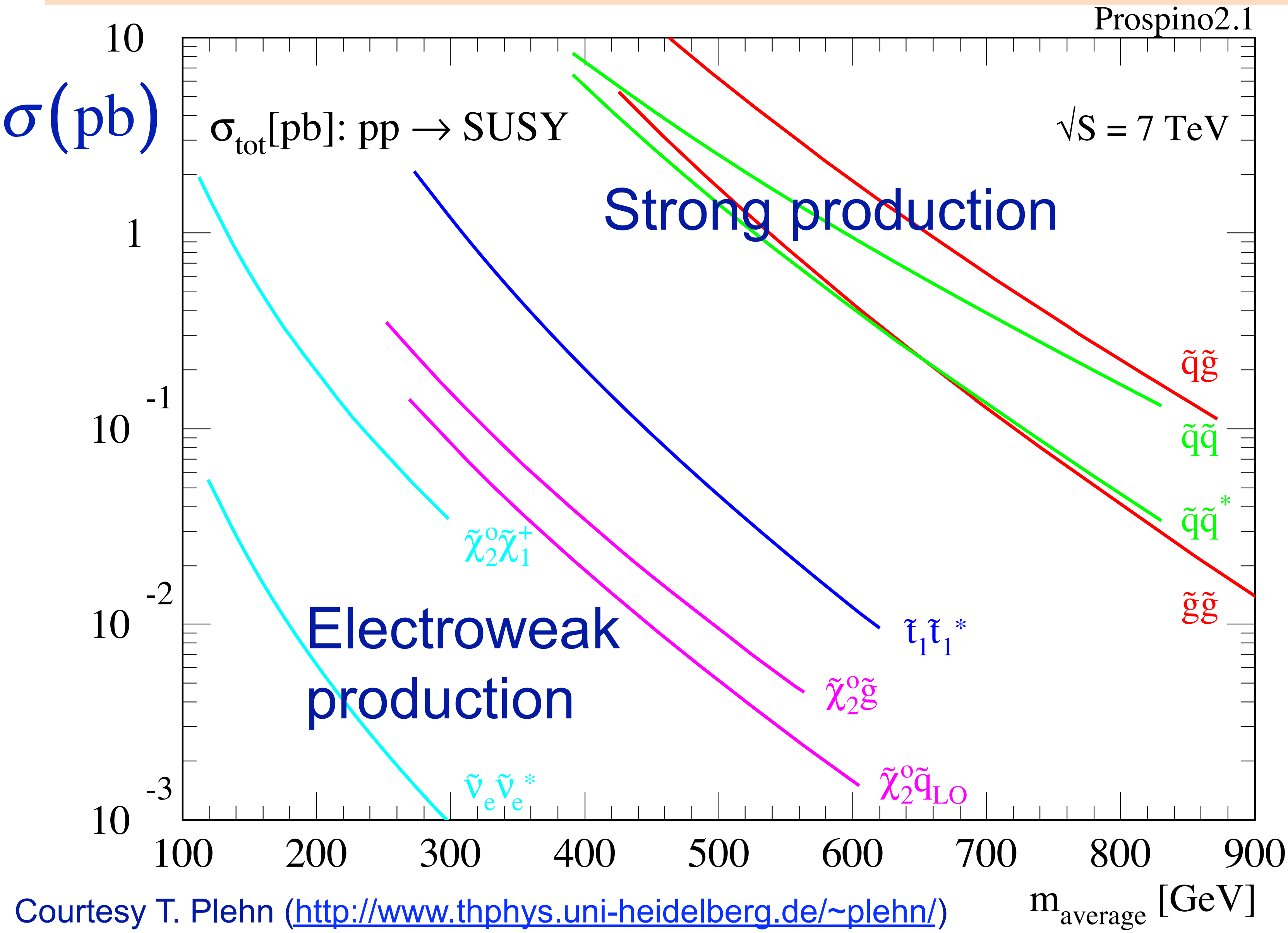
  - Starting from SM particles, SUSY particles must be produced in pairs.
  - The decay chain of a SUSY particle must end with just a single LSP, which in many scenarios is $\tilde{\chi}_1^0$.

Gluino pair production and decay to light stop



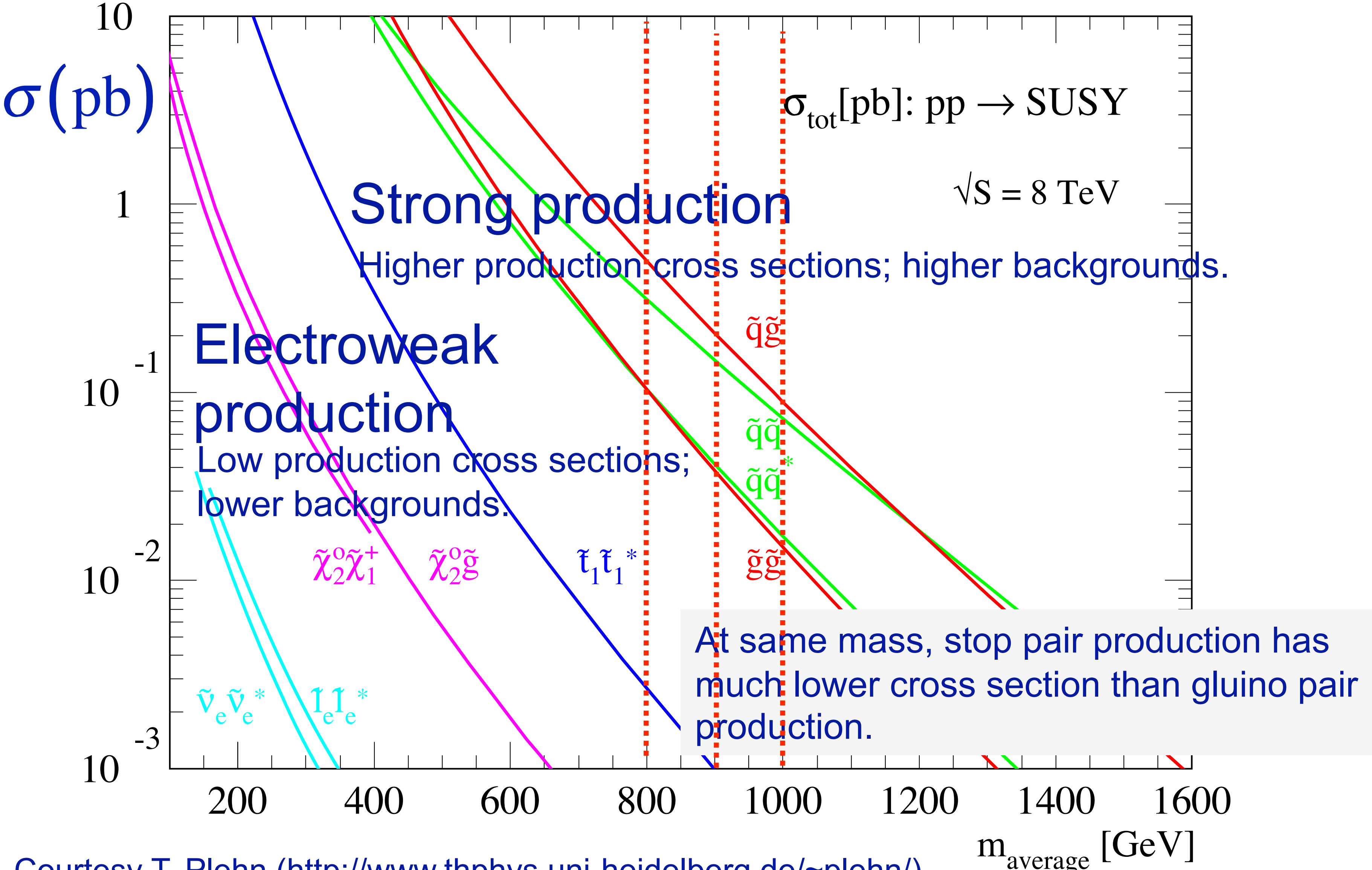
4 top quarks + lots of MET!

SUSY particle production at √s=7 TeV



Courtesy T. Plehn (http://www.thphys.uni-heidelberg.de/~plehn/)

SUSY particle production at √s=8 TeV



Courtesy T. Plehn (http://www.thphys.uni-heidelberg.de/~plehn/)

Missing transverse momentum

- In searches for R-parity conserving SUSY models, the measurement of the missing momentum in the direction transverse to the beam is often the most critical aspect of the search.

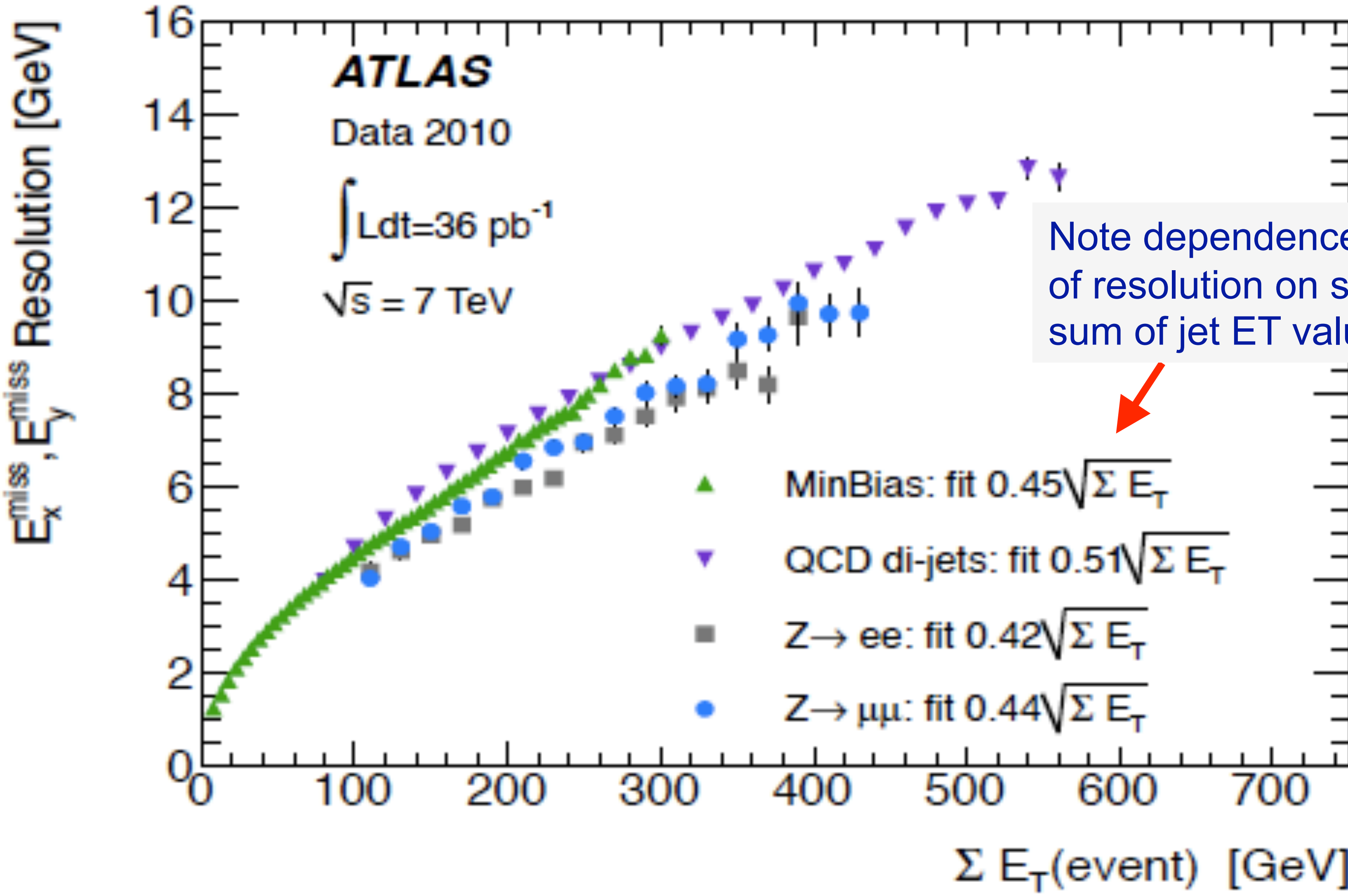
$$\vec{p}_T^{\,\text{miss}} = -\left[\sum_{i=\text{ calo cells, tracks}} \vec{p}_T^{\,i} \right] \qquad \vec{p}_T^{\,\text{miss, jets}} = -\left[\sum_{i=\text{ jets above pT threshold}} \vec{p}_T^{\,i} \right]$$

details are crucial and are different for ATLAS and CMS

- Sources of MET
  - fake MET: jet mismeasurements, losses due to cracks in the detector, detector noise and backgrounds
  - real MET: from undetected particles: neutrinos from $W \to l\nu$ and $Z \to \nu\nu$ decay.

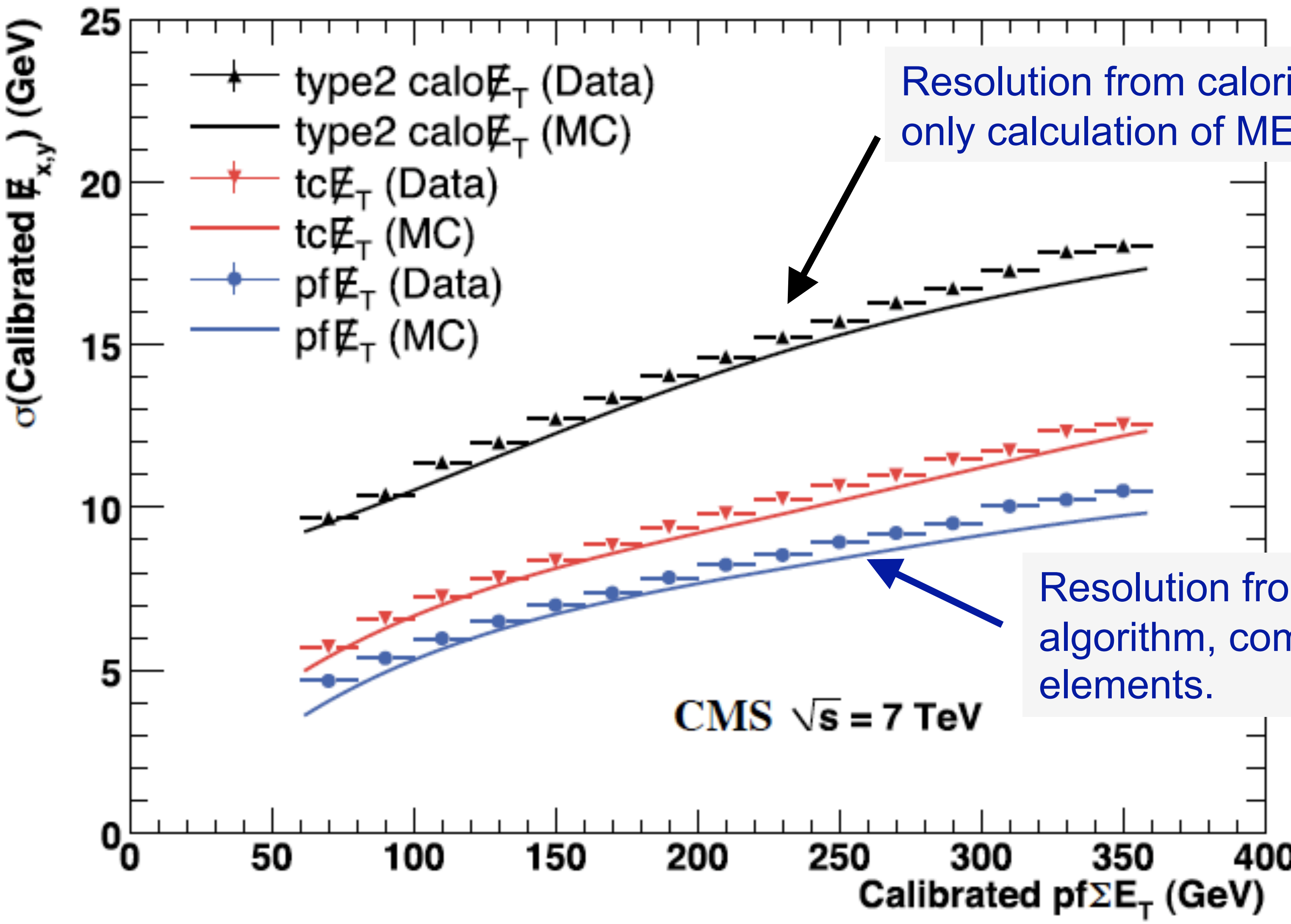
ATLAS MET resolution

ATLAS, arXiv:1108.5602



Note dependence of resolution on scalar sum of jet ET values.

CMS MET resolution



Resolution from calorimeter only calculation of MET

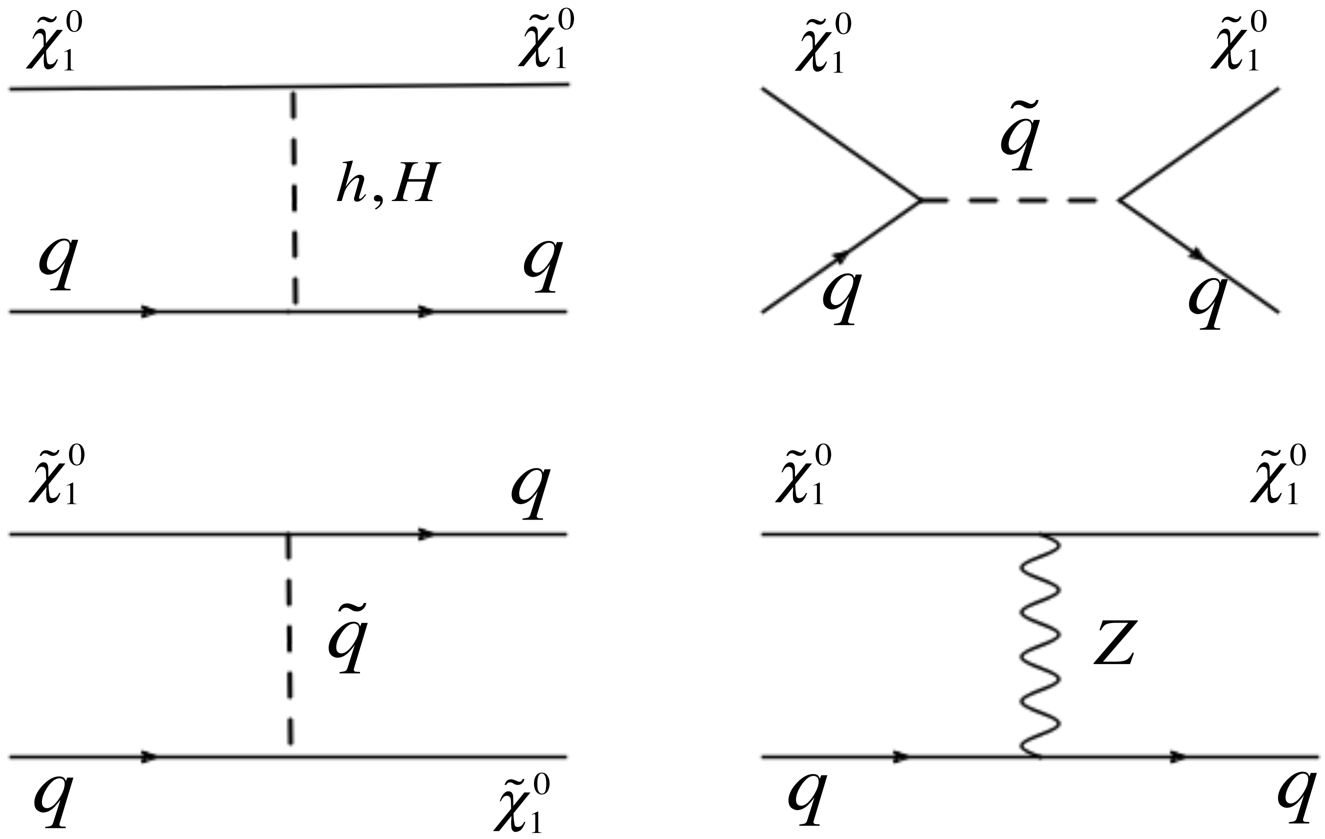
Resolution from particle flow algorithm, combining all detector elements.

Looking for Dark Matter or Gravitons/Large Extra Dimensions: Monojet Searches

ATLAS: monojet https://cdsweb.cern.ch/record/1460396 monophoton http://cdsweb.cern.ch/record/1460397
CMS: monojet http://arxiv.org/abs/1206.5663 monophoton http://arxiv.org/abs/1204.0821

- Search for (pair) production of the LSP. Also a search for gravitons in models of large extra dimensions!
- Y. Bai, P.J. Fox, and R. Harnik, *The Tevatron at the Frontier of Dark Matter Direct Detection*, JHEP 12, 048 (2012), doi:10.1103, arXiv:1005.3797.
- J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T.M. Tait et al., *Constraints on Dark Matter from Colliders,* Phys. Rev. D82 (2010), 116010, arXiv:1008.1783.
- N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Phys. Lett. B 429, 263 (1998).

Interactions of neutralinos with matter

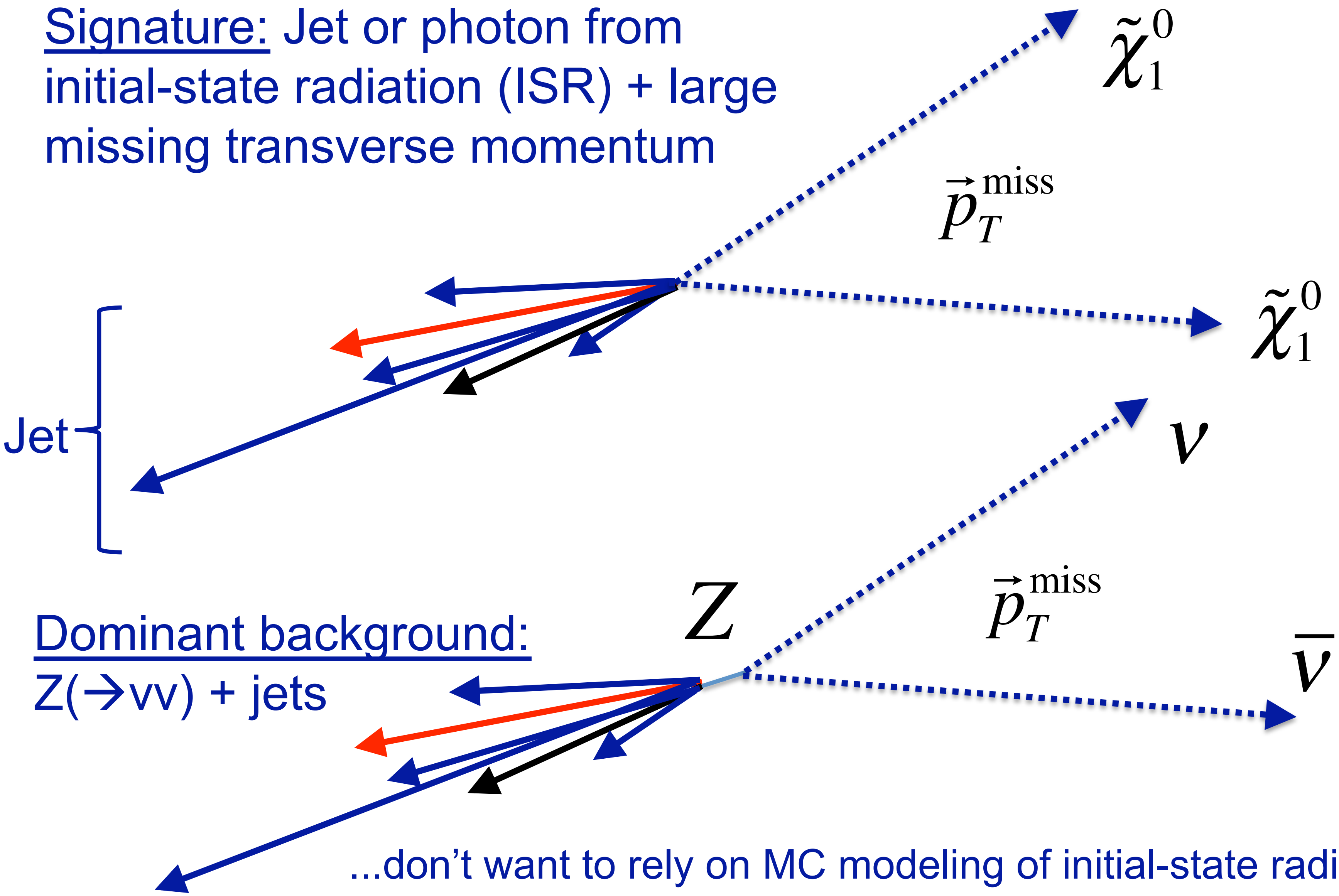


- Above: direct dark matter detection processes: doesn't have to be SUSY!
- Use crossing to get $q + \bar{q} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0$
- How to see $q + \bar{q} \rightarrow$ invisible? (The dark matter problem!)

Searching for dark matter at the LHC

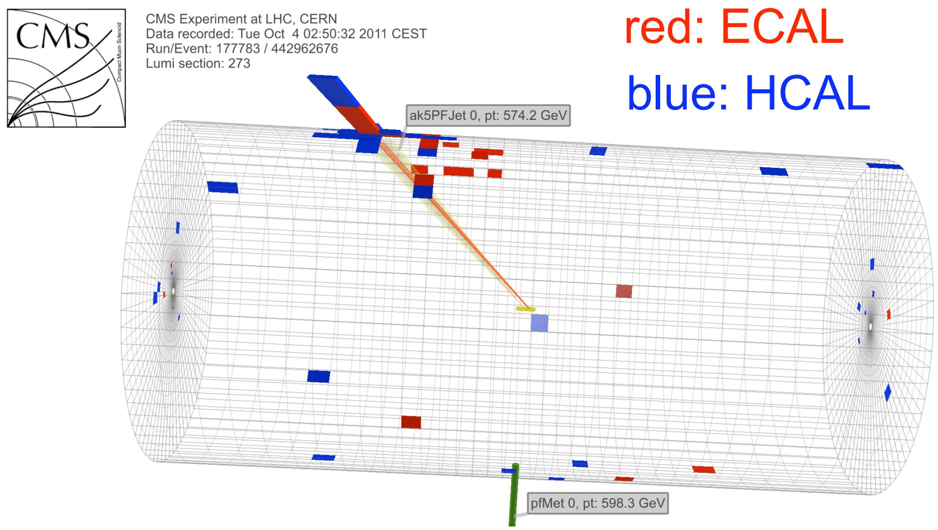
<u>Signature:</u> Jet or photon from initial-state radiation (ISR) + large missing transverse momentum

<u>Dominant background:</u>
Z(→νν) + jets



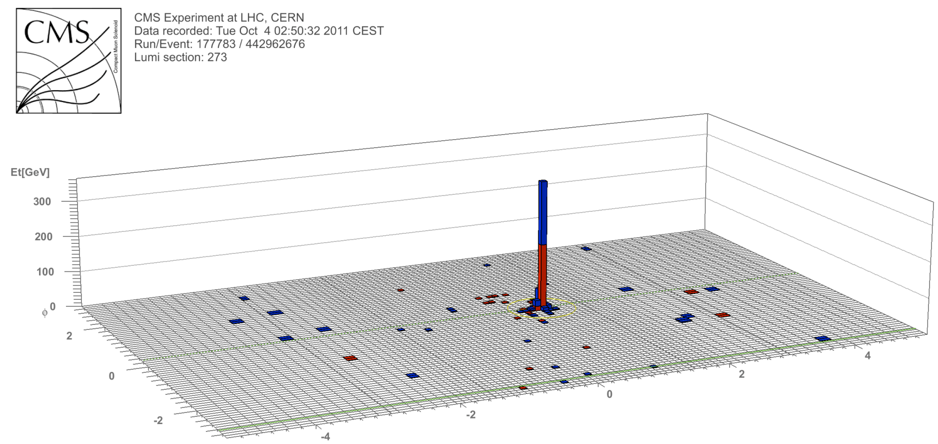
...don't want to rely on MC modeling of initial-state radiation

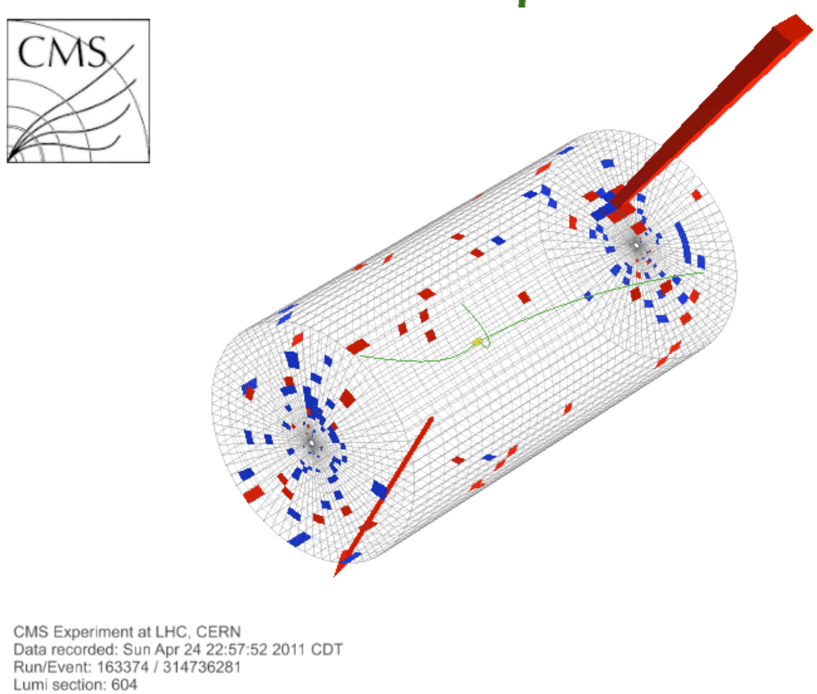
Mono-jet and mono-photon events



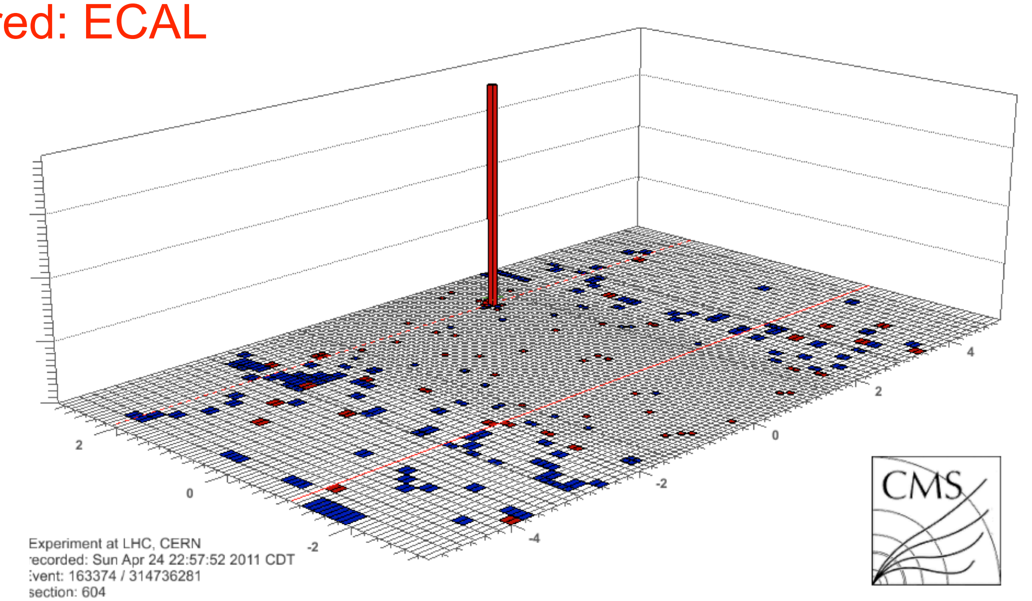
red: ECAL

blue: HCAL



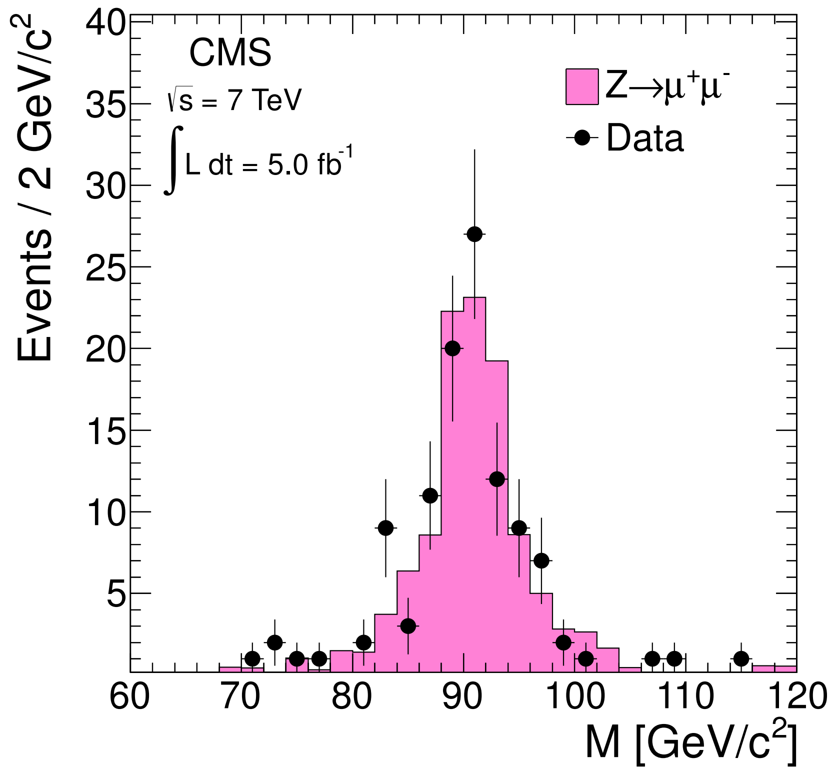


red: ECAL



Measurement of backgrounds

- Rather than directly using MC prediction to model Z→νν, <u>much safer</u> to use control sample with Z→μ+μ- + jets/photons events.
- Automatically models the ISR jet/photon distributions! Correct for lepton efficiencies and relative branching fraction.
  - B(Z→νν)/B(μμ)=5.942 ±0.019
  - Size of control sample is limitation!
  - In some SUSY analyses, this uncertainty is a problem.
- Similar procedure for W+jets



How are the backgrounds rejected in the low jet multiplicity sample?

$Z \to \nu\bar{\nu} + \text{jets}$

(a)

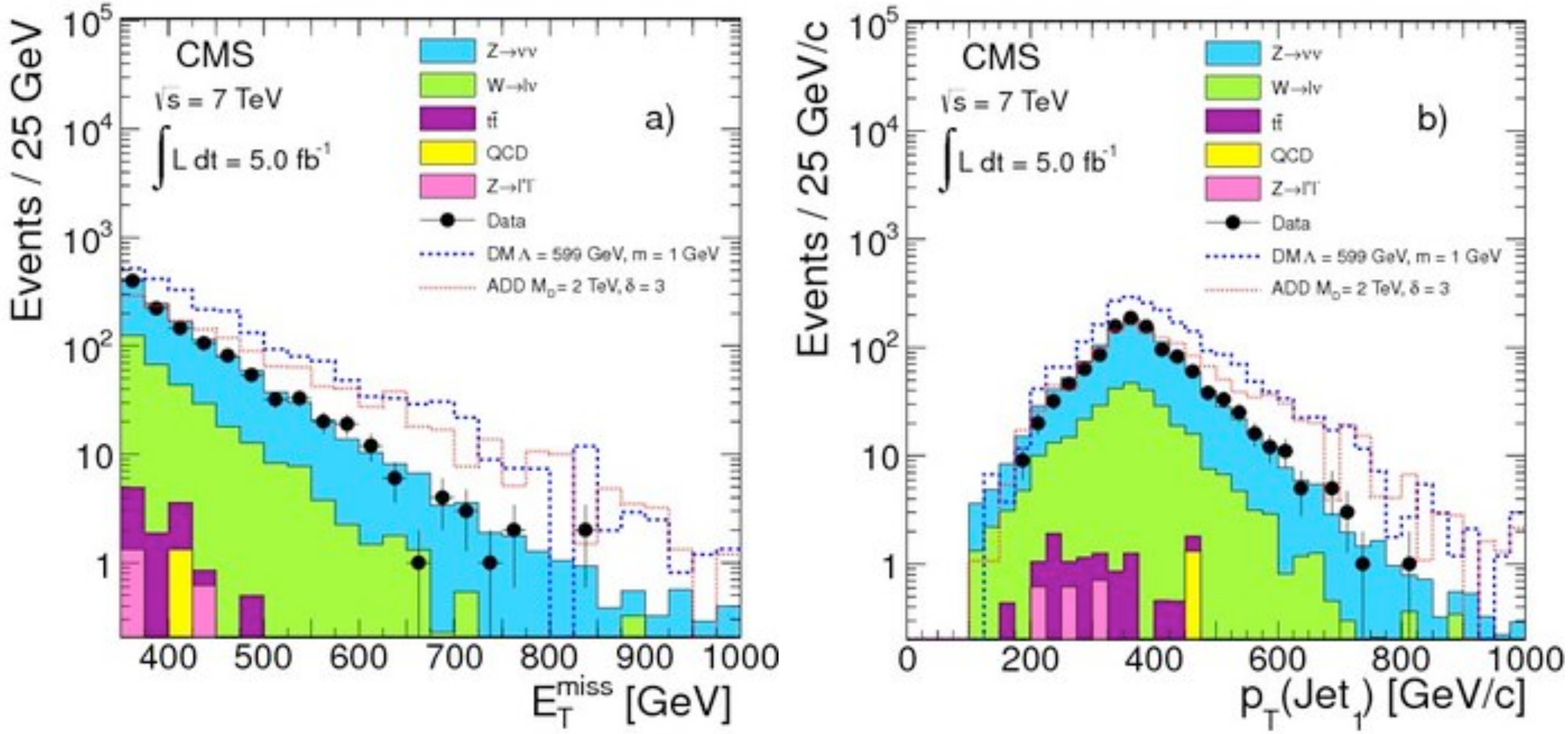
Requirement	$Z(\nu\nu)$ +jets	$W(e\nu, \mu\nu, \tau\nu)$ +jets	$Z(\ell\ell)$ +jets	$t\bar{t}$	Single t	QCD Multijet
$E_T^{miss} > 200$ GeV/c	$(324 \pm 1) \times 10^2$	$(591 \pm 1) \times 10^2$	5255 ± 47	$(133 \pm 1) \times 10^2$	1165 ± 7	$(160 \pm 1) \times 10^2$
$p_T(j_1) > 110$ GeV/c	$(302 \pm 1) \times 10^2$	$(557 \pm 1) \times 10^2$	4908 ± 45	$(119 \pm 1) \times 10^2$	1035 ± 6	$(158 \pm 1) \times 10^2$
$N_{jet}(p_T > 30\,\text{GeV}/c) \leq 2$	$(227 \pm 1) \times 10^2$	$(397 \pm 1) \times 10^2$	3453 ± 38	1587 ± 20	274 ± 3	5296 ± 14
$\Delta\phi(\text{jet}_1, \text{jet}_2) < 2.5$	$(211 \pm 1) \times 10^2$	$(354 \pm 1) \times 10^2$	3139 ± 36	1344 ± 19	237 ± 3	62 ± 5
Lepton Removal	$(198 \pm 1) \times 10^2$	$(97 \pm 1) \times 10^2$	81 ± 6	214 ± 7	35 ± 1	2 ± 1
$E_T^{miss} > 250$ GeV/c	7306 ± 23	2951 ± 19	22 ± 3	70 ± 4	10 ± 0.5	2 ± 1
$E_T^{miss} > 300$ GeV/c	2932 ± 14	967 ± 11	6 ± 1.7	23 ± 2	3 ± 0.2	1 ± 0.7
$E_T^{miss} > 350$ GeV/c	1308 ± 9	362 ± 7	2 ± 0.9	9 ± 1.6	1 ± 0.2	1 ± 0.7
$E_T^{miss} > 400$ GeV/c	628 ± 7	148 ± 4	1 ± 0.4	3 ± 0.8	0.4 ± 0.1	1 ± 0.7

dominant backgrounds by far

Big QCD rejection: Δφ(j1,j2)<2.5

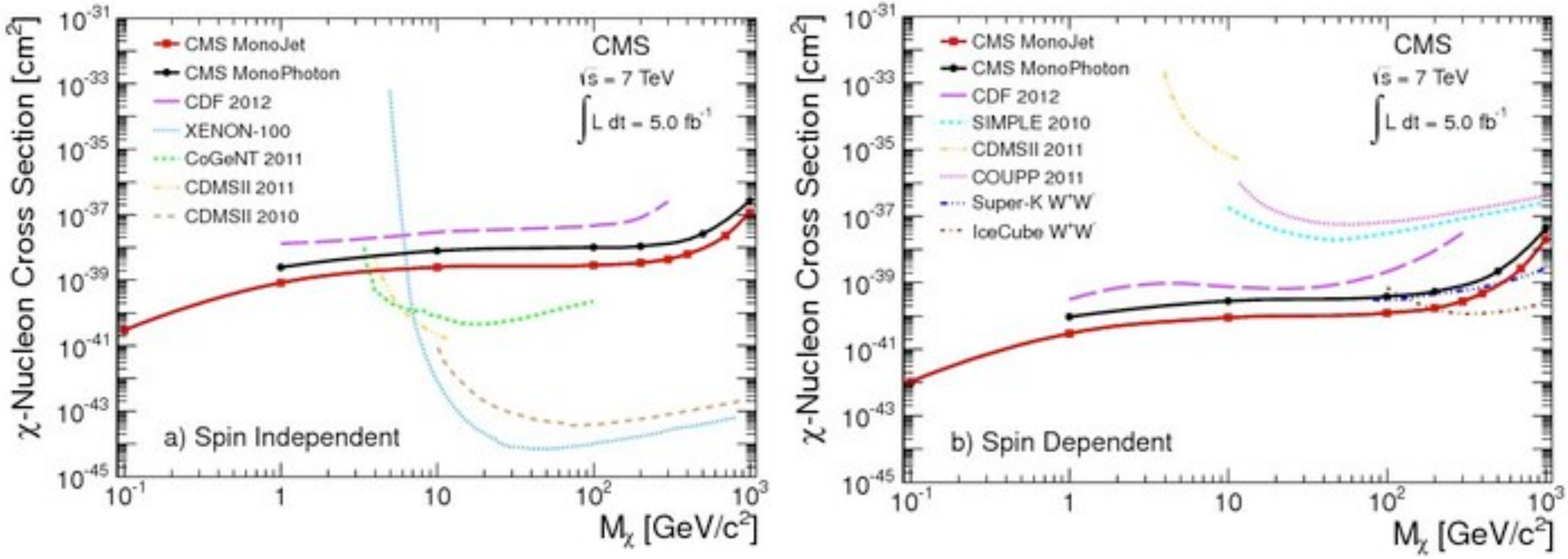
- Z+jets : "irreducible"; suppressed with tighter MET cuts
- Z+jets, W+jets, ttbar: lepton vetos, MET
- QCD: angle between jets

Results from search for SUSY in monojet events



In the dominant background (Z+jets), the MET=E_T^{miss} is almost entirely real, not from the detector resolution. Usually a good thing: less worry about detailed modeling of MET resolution!

Dark matter exclusion plots from monojet and monophoton searches



- Spin-independent interaction model: excludes additional parameter space for very light dark matter mass (<3.5 GeV).
- Spin-dependent interaction model: sensitivity well beyond the results from the direct detection experiments.

Lecture 1 Summary

- Most searches for new physics require a deep understanding of SM background processes.
- The size of the excluded region or the significance of any excess is strongly affected by the background and its uncertainty.
- There are strong motivations for SUSY – but I don't "believe in it".
- Many SUSY models have striking phenomenological signatures, but the cross sections for high mass particles can be low.
- Missing energy signature is critical for searches.

End of Lecture 1