Beyond Standard Model

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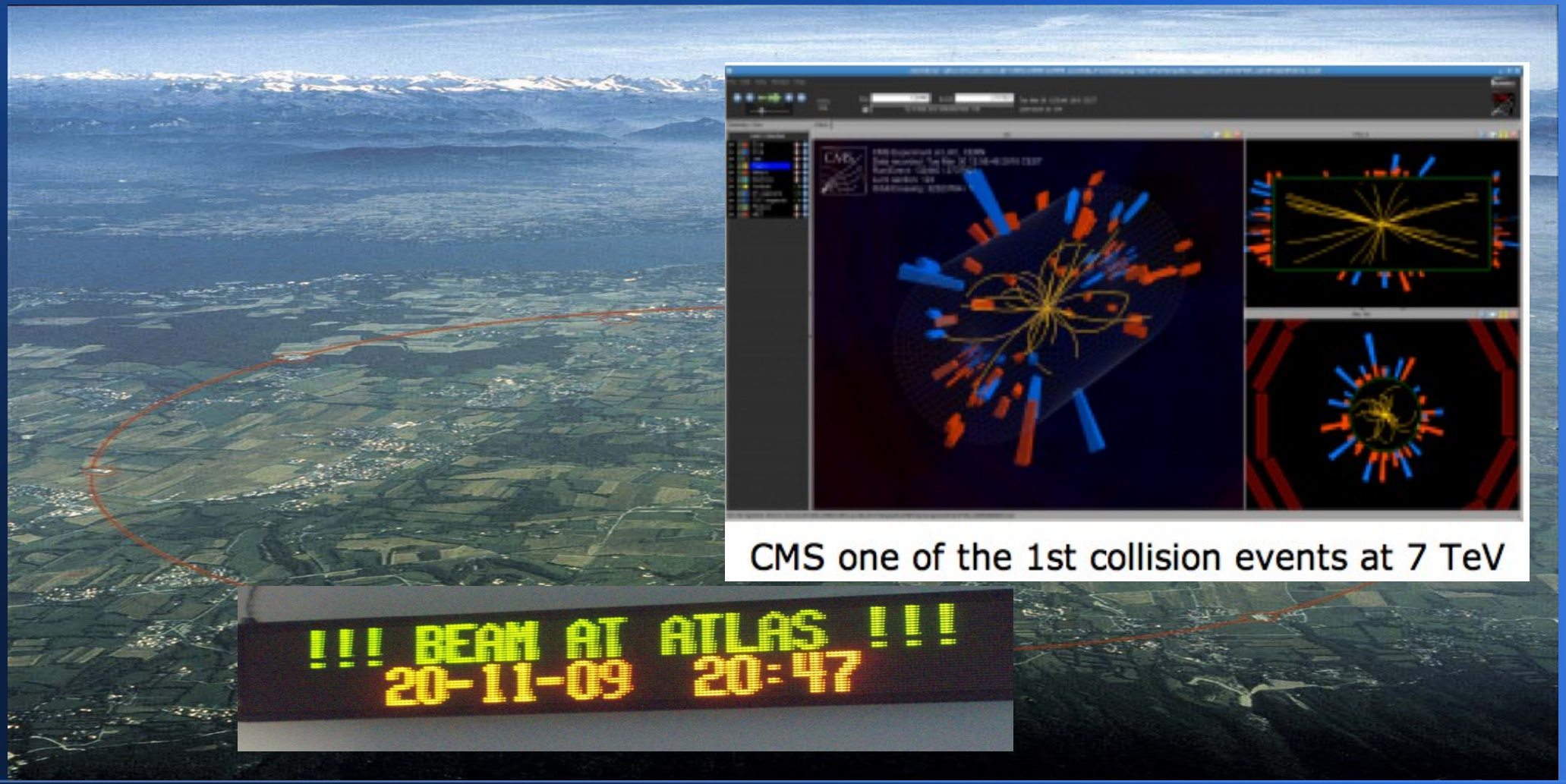
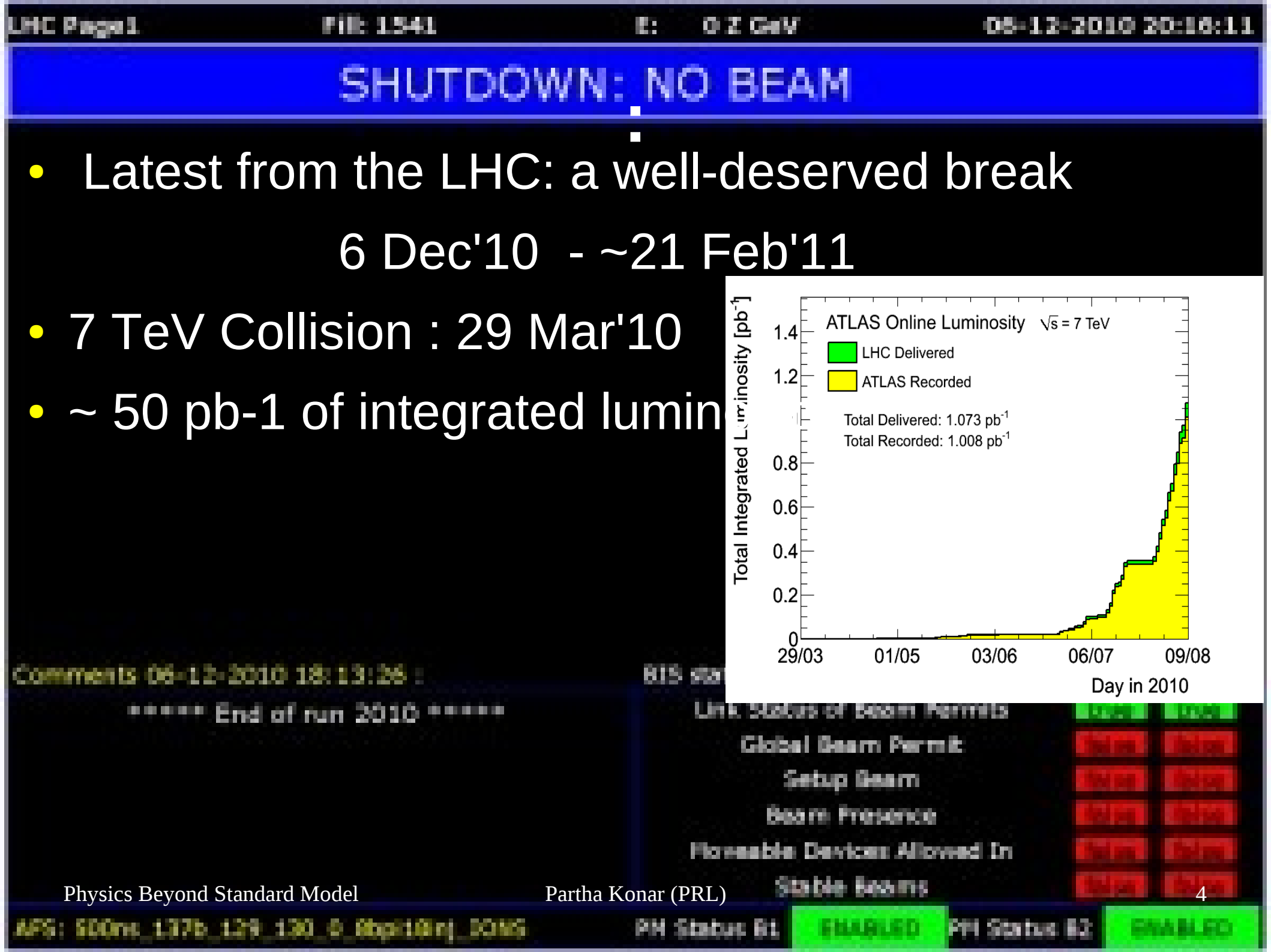
High Energy Physics Symposium 2010
December 13-18, 2010, Jaipur, India

Overview

- Exciting time
- Where are we today?
- Large Hadron Collider
- Look beyond msugra
- Scan and hierarchy study
- Mass determination
- Summary

Exciting new era





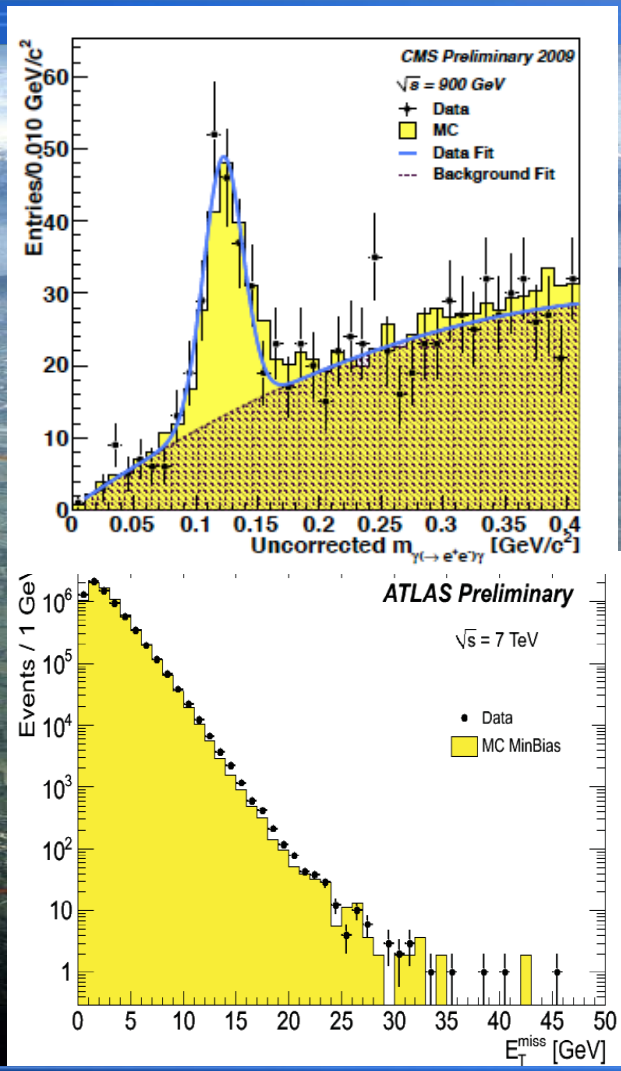
- Latest from the LHC: a well-deserved break

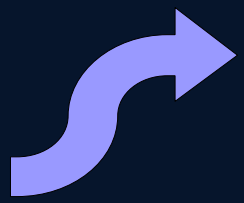
  6 Dec'10 - ~21 Feb'11

- 7 TeV Collision : 29 Mar'10
- ~ 50 pb-1 of integrated lumin

Exciting new era

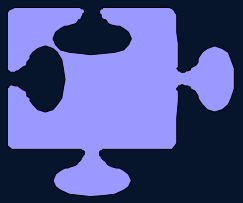
- Both ATLAS and CMS have ~ pb^{-1}
  - More data coming quickly
- Both experiments have W's, Z's, are rediscovering D decays, ψ 's,….
- Detectors working well





A long way

- Tevatron discovered the top quark
- Precision measurements from LEP/Tevatron limit new physics possibilities
  - Many new physics scenarios excluded
- Dark matter and dark energy discovered
  - Informed (inspired?) model building
- Neutrino masses aren't zero
- Calculational tools greatly improved
  - Much better handle on backgrounds
- ….. + many more



Many more questions

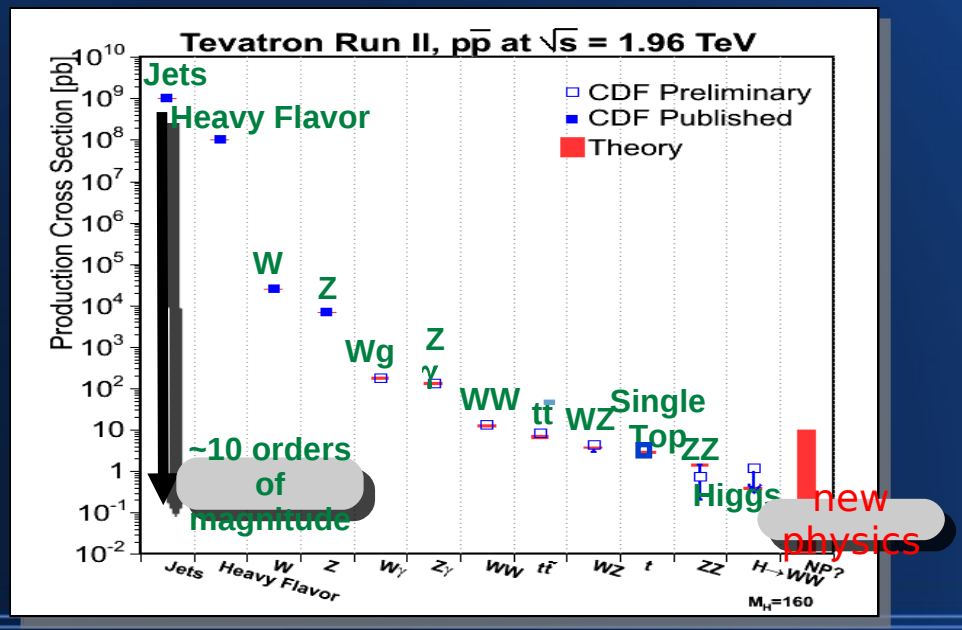
- Physics of the LHC
  - Is there supersymmetry at the TeV scale?
  - What is the source of electroweak symmetry breaking?
  - Are there new Z bosons?
  - Of course there are new questions too
    - Are there extra dimensions?
    - What is the source of dark matter?
    - What do neutrino masses tell us?

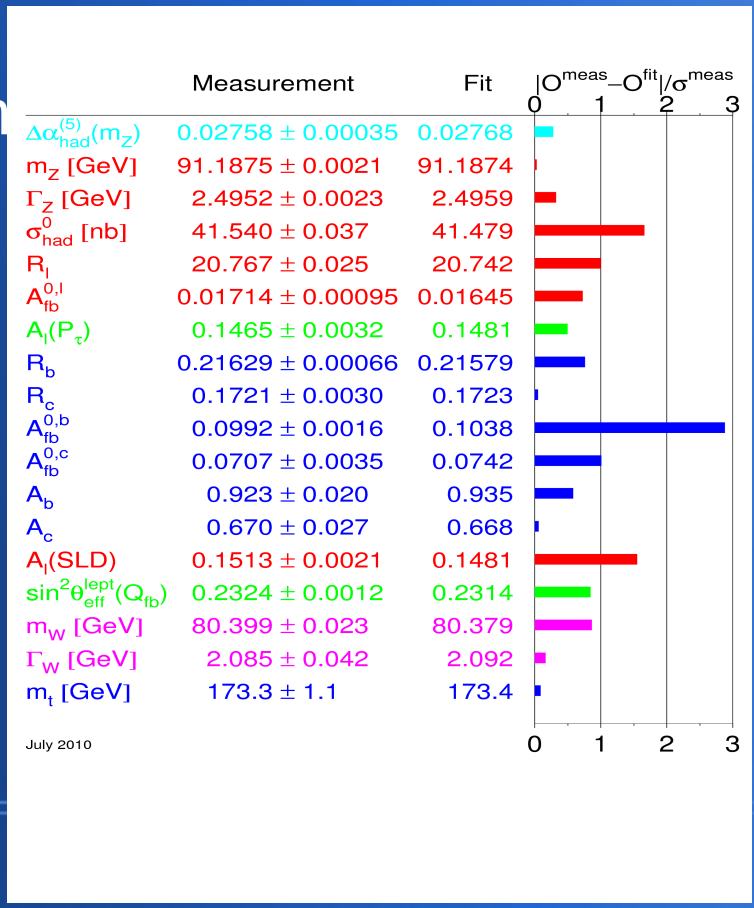
- What's next?
  - Many questions will likely remain even with large data sets from the LH
  - Next year at this time we will be in a very different position

Standard Model

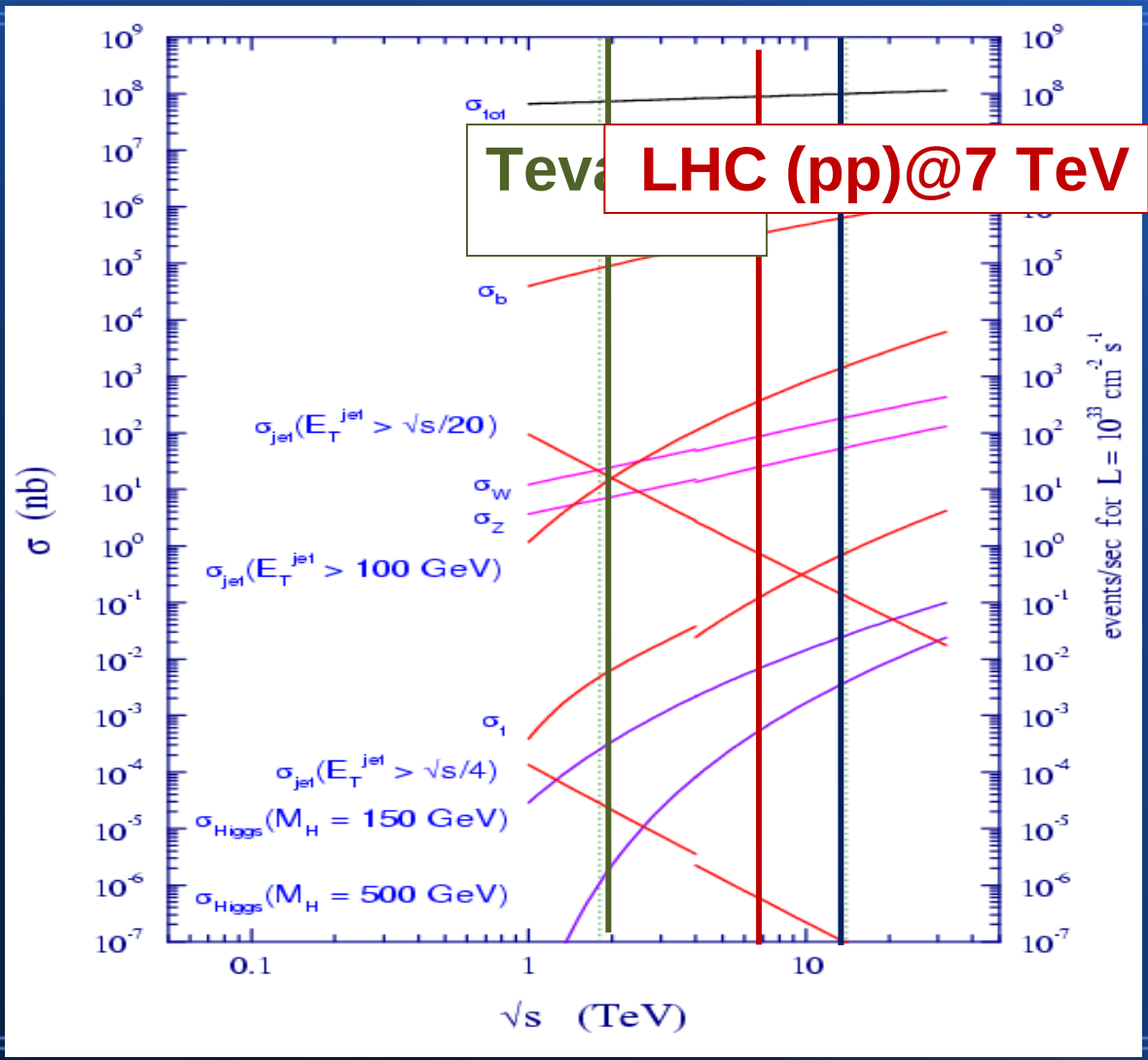
SM is a Non-abelian Gauge Theory

- Standard model provides excellent interpretation of experimental data starting with LEP
- Where is electroweak symmetry breakin





Standard Model



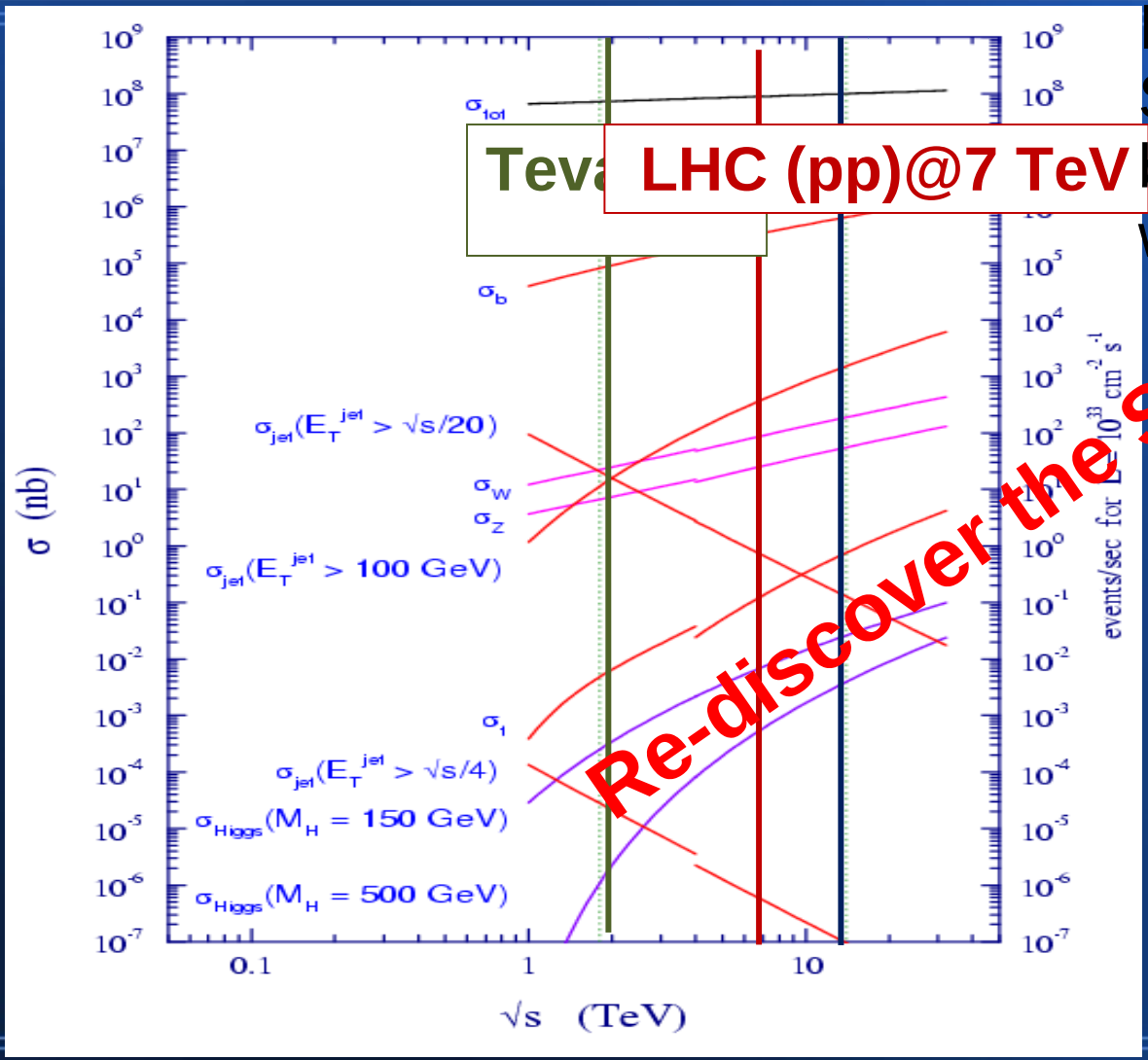
Important to understand not only Standard Model production of *X* but also of *X* + *n* jets where

X = W, Z, tt, WW, H, …

n = 1,2,3,…

- 1 pb^{-1}
  - 5000 $W \to e\nu$, $\mu\ \nu$ $l + E_T^{miss}$
  - 500 $Z \to e^+e^-$, $\mu\ ^+\mu\ ^-$ e/μ ID
- 20 pb^{-1}
  - $t\bar{t}$ jet energy calibration,
  - b tagging, E_T^{miss}
- 100 pb^{-1}
  - 500,000 $W \to e\nu$,$\mu\ \nu$
  - 50,000 $Z \to e^+e^-$, $\mu\ ^+\mu\ ^-$

Standard Model



Re-discover the Standard Model

Important to understand not only Standard Model production of X but also of $X + n$ jets where

$X = W, Z, tt, WW, H, \ldots$

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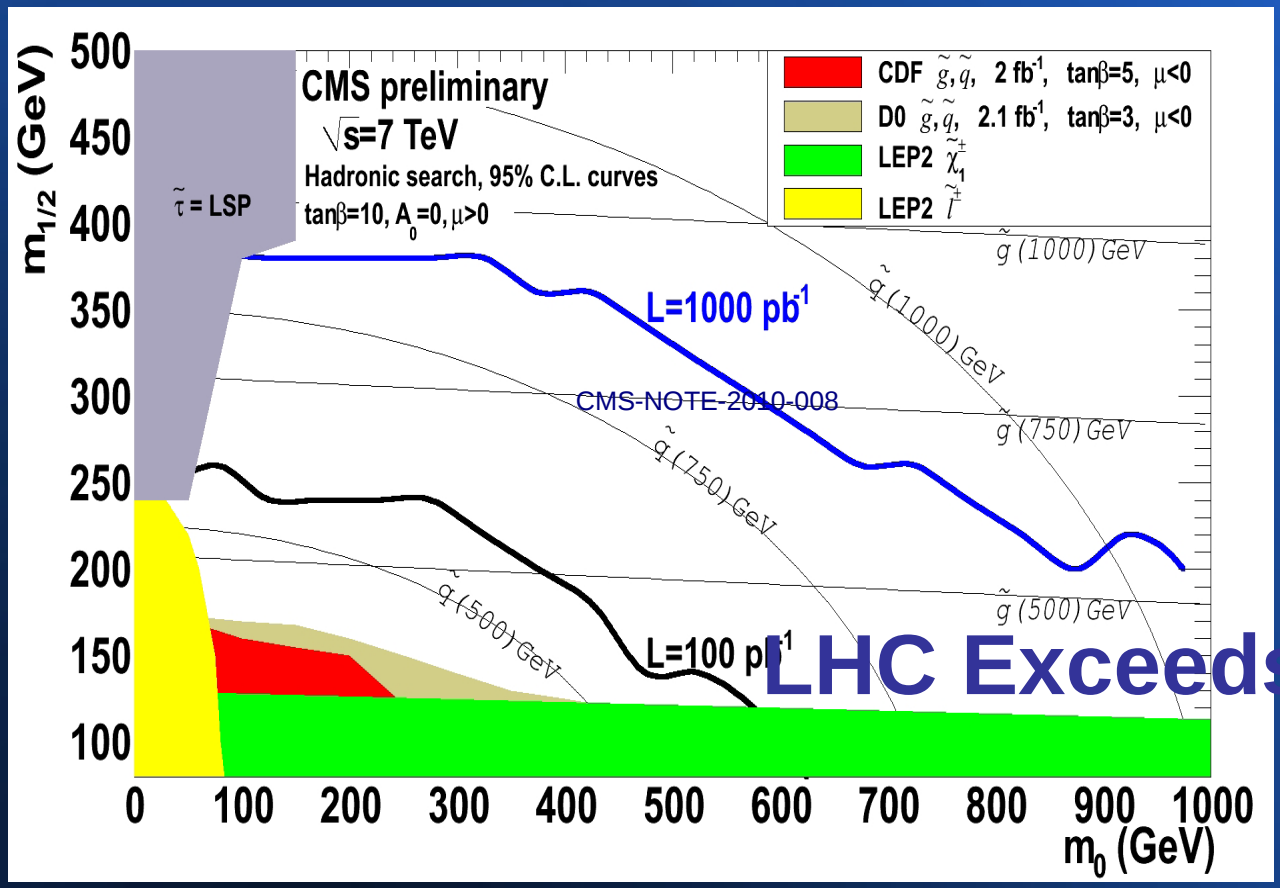
SUSY : jet + missing energy



3 or more jets, ET > 50 GeV

missing ET > 250 GeV

no leptons

LHC Exceeds Tevatron Reach

We should think beyond mSUGRA....

Supersymmetry

- Supersymmetry : Very predictive
- No knowledge on SUY mass spectra

  - SUSY breaking!
- Large no. of parameters
- Specific benchmark points
- Do we miss some interesting signals?
- All SUSY masses as free parameter – Scan??

Alternative view of search

Quantitative Searches

Benchmark points / Scanned parameters

$30^9 = 19{,}683{,}000{,}000$

100 GeV - 3TeV by ΔM= 100GeV = 30 points

Mass spectrum of sparticles

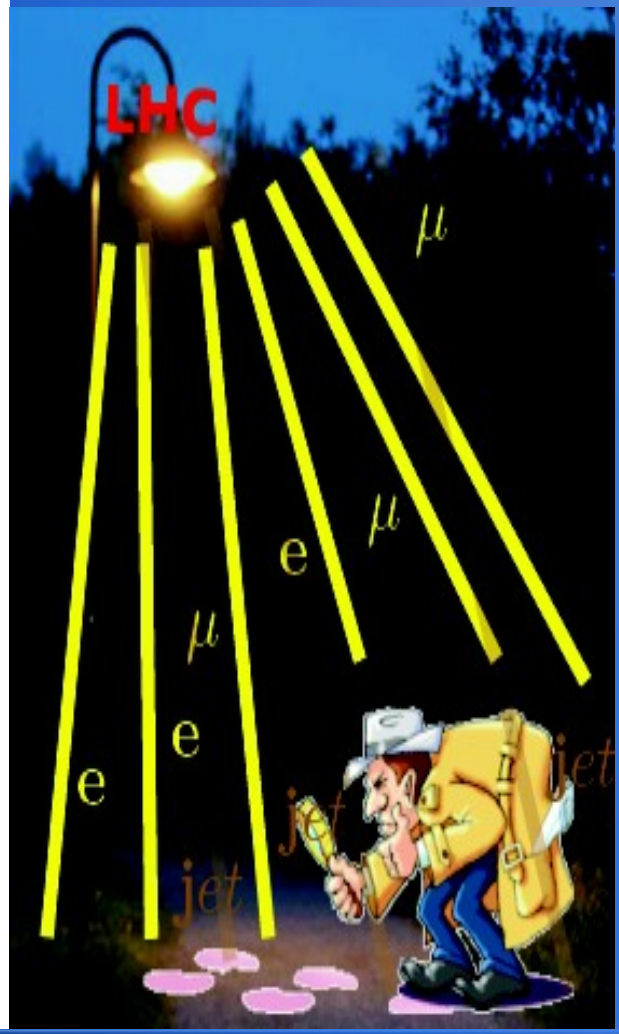
Distributions of kinematic variables

Qualitative Searches

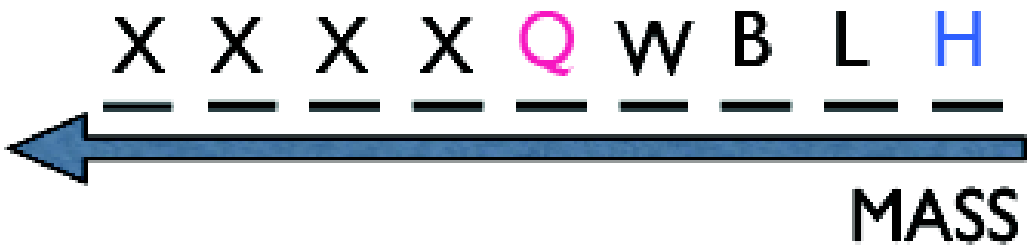
Hierarchical ordering of the sparticles

9! = 362,880

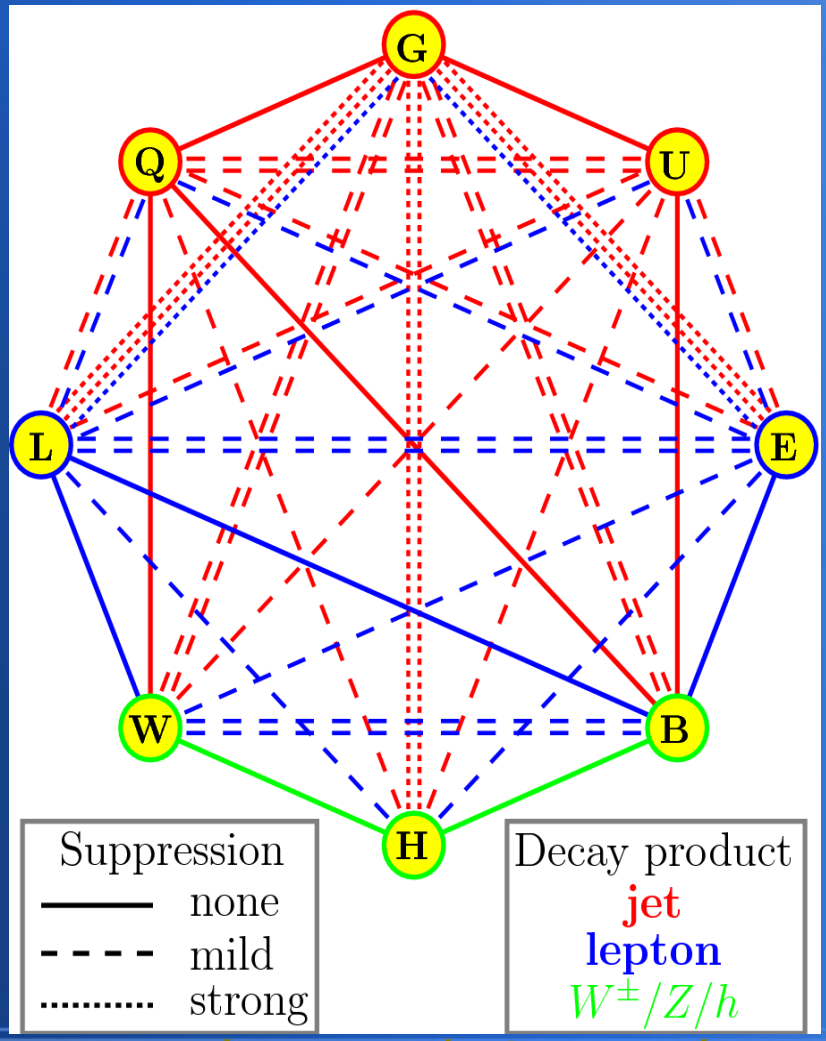
Number/Type of visible particles



Neutral LSP: Example



Decay Mode	Signals			Suppression
	lep	vec	jet	
Q→H	0	0	1	Mixing
Q→L→H	2	0	1	Offshell, Mixing
Q→B→H	0	1	1	-
Q→B→L→H	2	0	1	-
Q→W→H	0	1	1	-
Q→W→L→H	2	0	1	-
Q→W→B→H	0	2	1	Mixing
Q→W→B→L→H	2	1	1	Mixing



PK,Matchev,Park,Sarangi

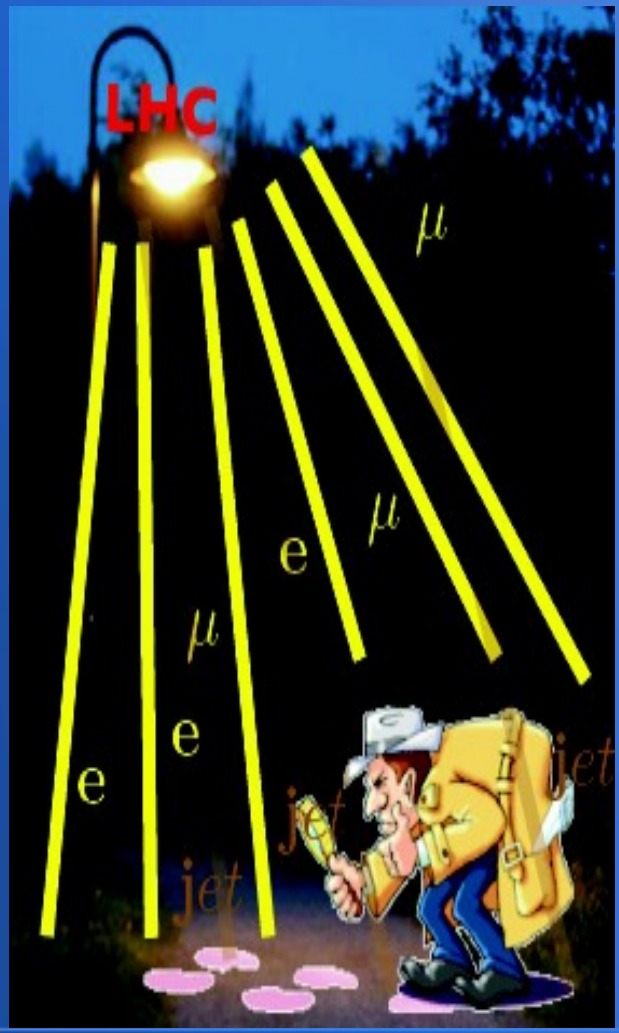
Under the Lamppost

	$n_v = 0$		$n_v = 1$		$n_v = 2$	
n_ℓ	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$
0	79296	26880	12768	3360	1344	672
1	30240	10080	1824	480	192	96
2	19770	6030	1500	180	0	0
3	4656	1296	312	72	6	6
4	1656	396	66	6	0	0

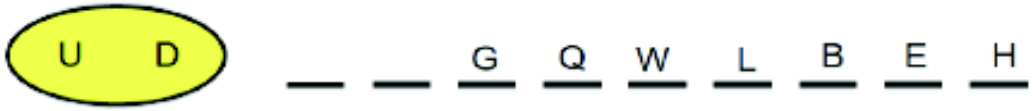
*2= 8~12 leptons!

(R-parity) we can have up to 8 leptons from cascade decay channel + (Up to 2 more leptons from V) , in total, we can have up to 12 leptons.

PK,Matchev,Park,Sarangi



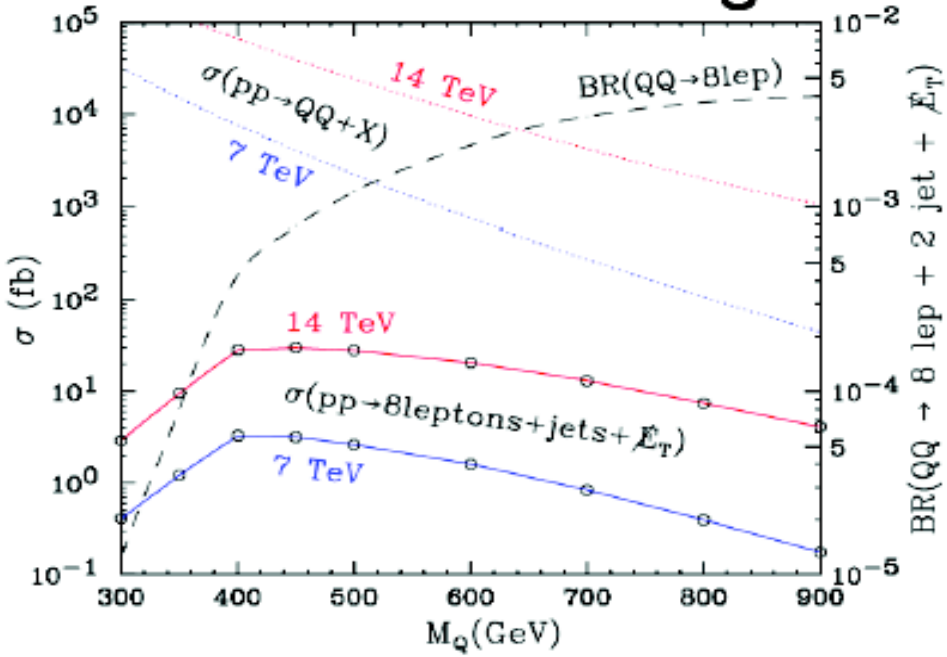
8 lepton events



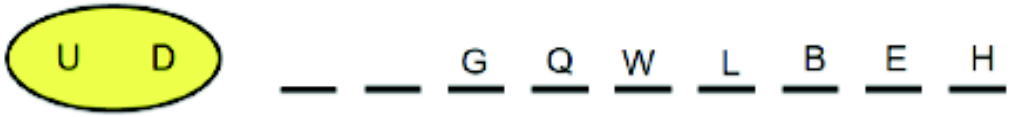
- For the given Q, we scanned the W, L, B, E and H mass terms.

M_C	M_Q	M_W	M_L	M_B	M_E	M_H
400	300	220	190	130	130	130
450	350	280	190	120	120	120
500	400	280	190	120	120	120
550	450	310	200	120	120	120
600	500	350	210	130	120	120
700	600	420	230	150	130	120
800	700	480	250	160	130	120
900	800	500	250	170	130	120
1000	900	510	250	170	130	120

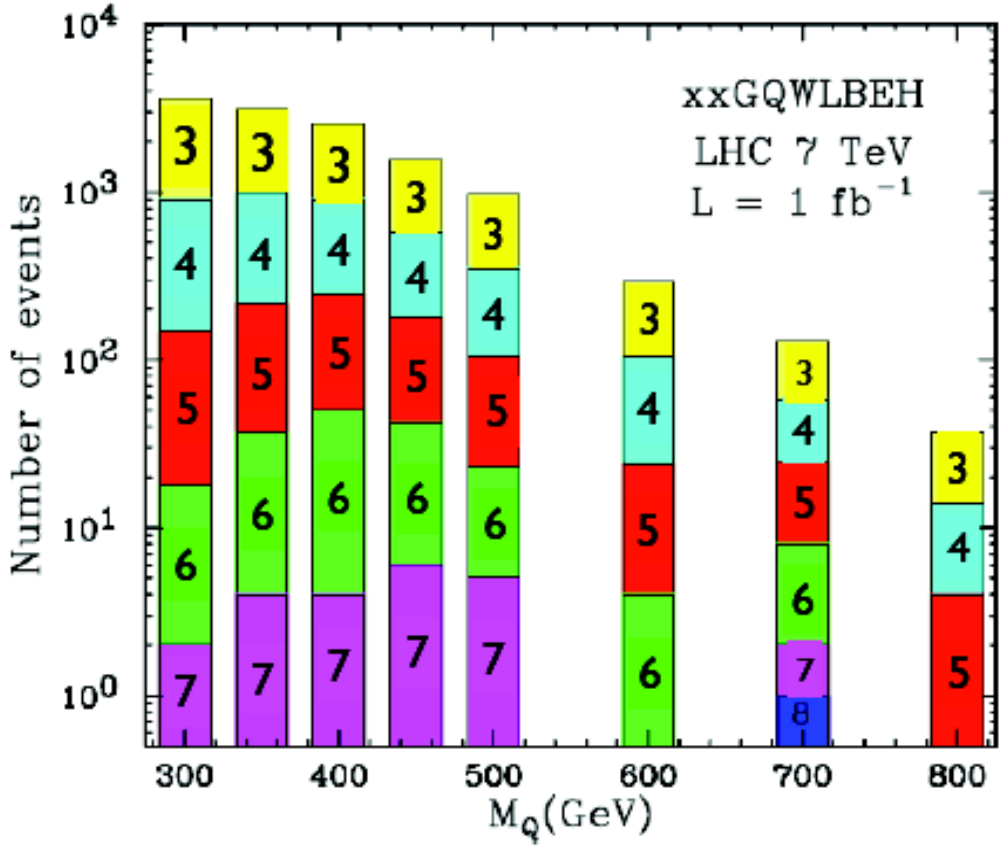
Optimistic, optimistic:
How soon can we get ?



8 lepton events



- Simulation : PYTHIA + PGS
- Count isolated leptons with
  P_T cut : electron 10 GeV
  muon 3 GeV



Suppose we find….

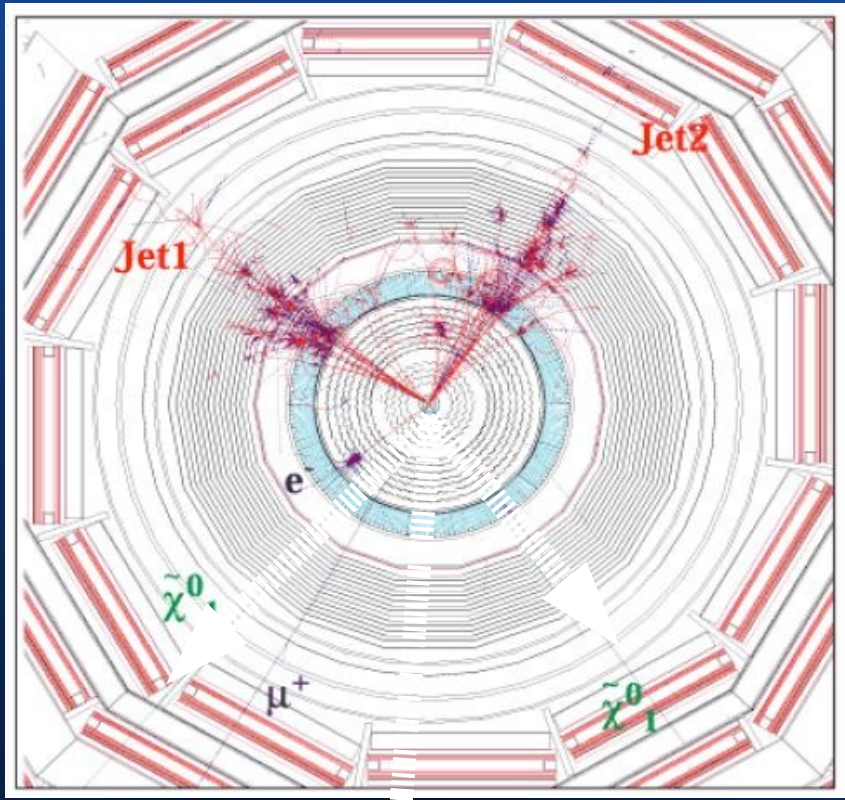
- Missing E_T, tri-leptons, same sign leptons
  - Classic SUSY signatures

    OR may be, being too optimistic...
  - Missing E_T, 8-leptons!!!

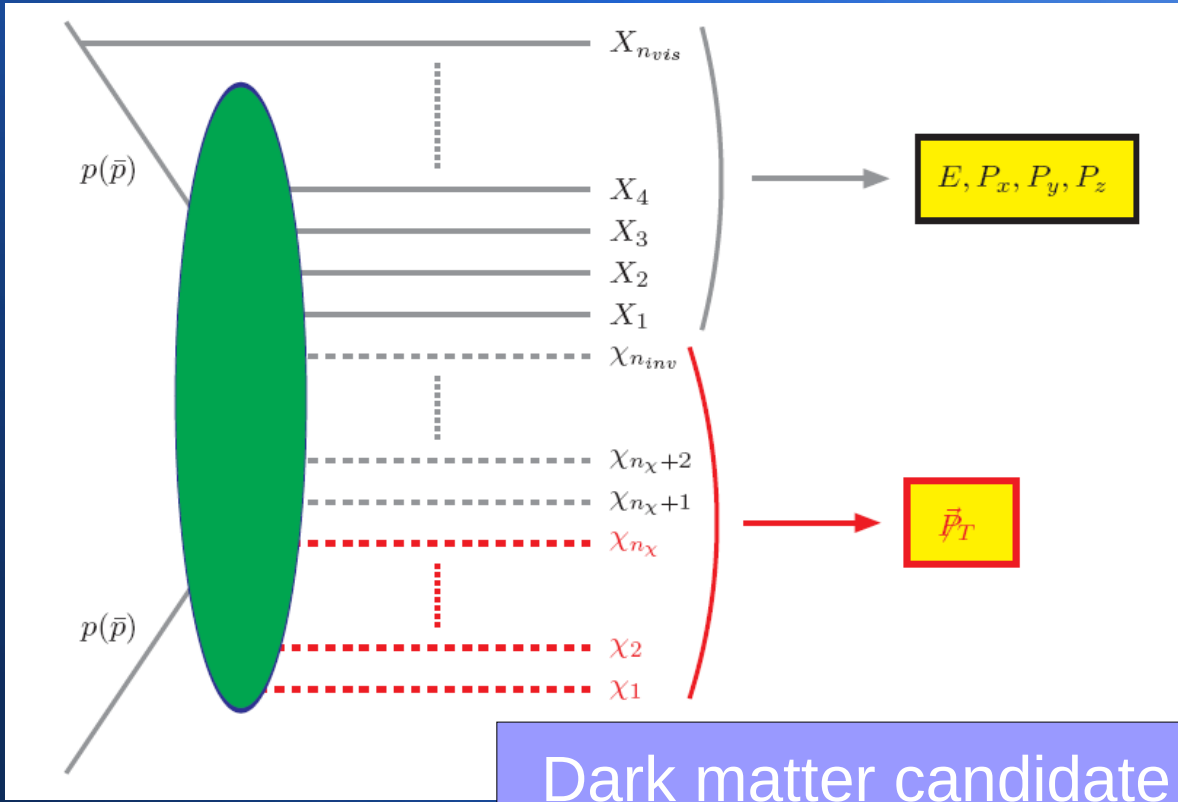
- Have to probe mass spectrum
  - Usual method is using kinematic endpoints, M_{T2}

- Prove couplings have SUSY relations
  - This is another motivation for future collider

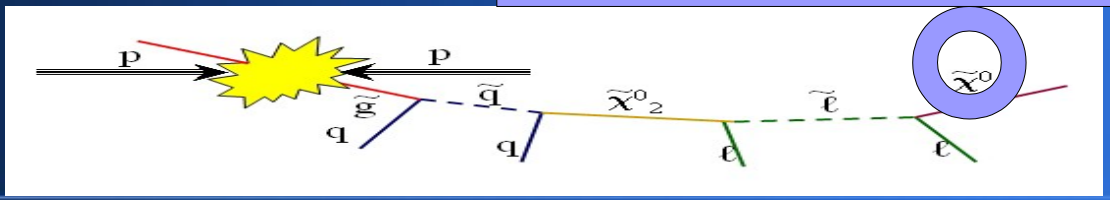
Events@LHC: Different viewpoints



Missing Energy



Dark matter candidate



Mass scale measurement

- Problem: Depend on both M_{SUSY} and M_χ .

→ $M_{\rm eff} = \not{E}_T + \sum_{\rm jets\ j} p_{Tj}$ $H_T \equiv E_T + \not{E}_T$ $E_T \equiv \sum_\alpha E_\alpha \sin\theta_\alpha$

→ $M^{\rm eff}_{\rm susy} = \left(M_{\rm susy} - \frac{M_\chi^2}{M_{\rm susy}} \right)$ function of both M_{SUSY} and M_χ .

→ Cambridge variable $M_{T2}^{max}(M_\chi) = M_{SUSY}$

→ Gator variable $S_{min}(M_\chi) = (2M_{SUSY})^2$

$\hat{s} = \left(E + \sum_{i=1}^{n_{inv}} \sqrt{m_i^2 + \vec{p}_i^{\,2}} \right)^2 - \left(\vec{P} + \sum_{i=1}^{n_{inv}} \vec{p}_i \right)^2$

Find: The *minimum value* of the Mandelstam variable *consistent* with the measured values of the *total energy E, total visible momentum (Px,Py,Pz) and Missing* $\not{E}_T$!

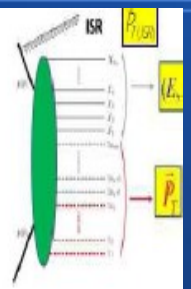
$\sqrt{\hat{s}_{min}} \equiv \hat{s}_{min}^{1/2}(M_{inv}) = \sqrt{E^2 - P_z^2} + \sqrt{\not{P}_T^2 + M_{inv}^2}$

PK,Kong,Matchev

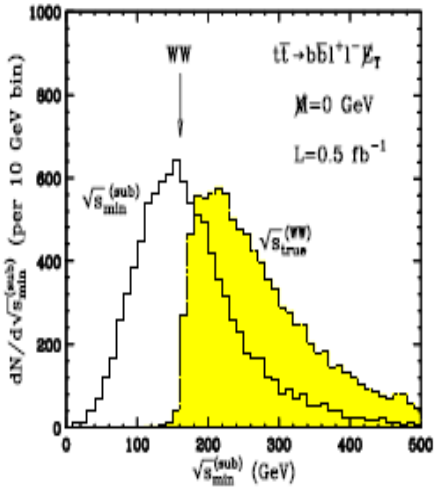
S_min

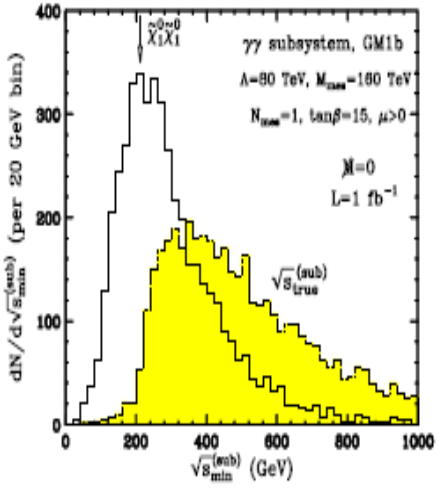
$\sqrt{\hat{s}_{min}}$: Subsystem

- $\sqrt{\hat{s}_{min}} = \sqrt{(\sqrt{E^2 - P_z^2} + \sqrt{P_T^2 + M_{inv}^2})^2 - \vec{P}_{T(ISR)}^2}$



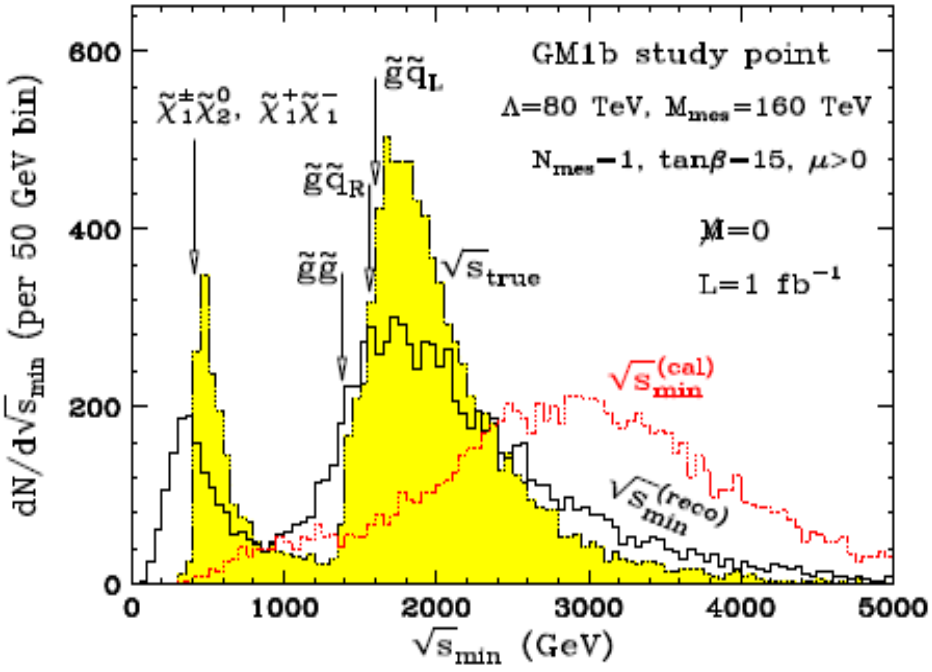
- tt-bar events
  - identify the WW threshold from the 2 lepton subsystem
- GMSB SUSY events
  - identify the N_1N_1 threshold from the 2 photon subsystem





$\sqrt{\hat{s}_{min}}$:Inclusive SUSY production

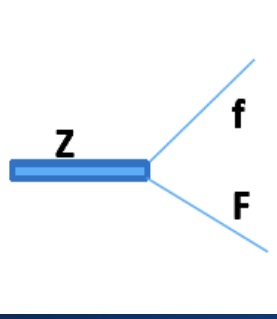
- The peak of $\sqrt{\hat{s}_{min}}$ locate the thresholds for individual dominant production sub-process
- GMSB study-point - GM1b : EW and strong productions

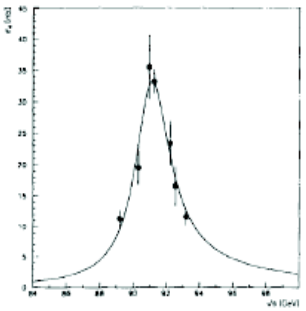


Dark matter at the LHC

The “Standard signals”: Missing transverse energy
+ maybe jets, maybe leptons, maybe photons

Invariant mass



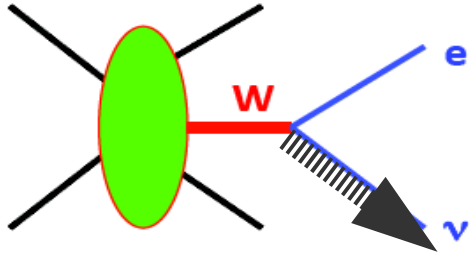


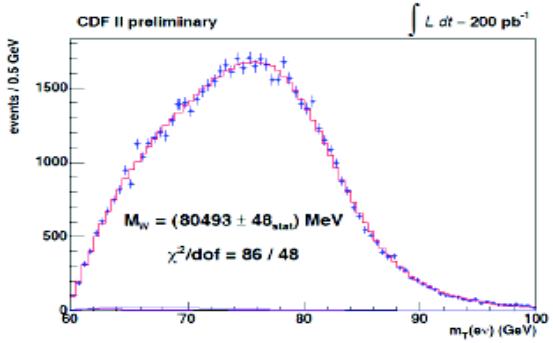
Physics Letters B
Volume 231, Issue 4, 16 November 1989, Pages 539-547

Measurement of the mass and width of the Z^0-particle from multihadronic final states produced in e^+e^- annihilations

Transverse Mass (MT)

$$M_W^2 \geq m_T^2(e,\nu)$$
$$\equiv \left(|\vec{p}_{eT}| + |\vec{p}_{\nu T}|\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\nu T}\right)^2$$

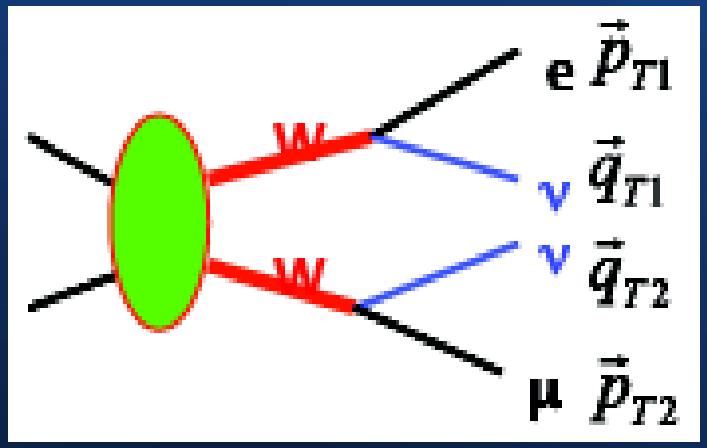




Transversification

Most of the BSM Signatures evolve around that

A pair of semi-invisibly decaying particles



$$\not{E}_T = \vec{q}_{T1} + \vec{q}_{T2} = -\sum \vec{p}_{T(vis_k)}$$

- If $\vec{q}_{T1}$ and $\vec{q}_{T2}$ are obtainable : $M_w \geq \max\{m_T(\vec{p}_{T1},\vec{q}_{T1}), m_T(\vec{p}_{T2},\vec{q}_{T2})\}$
- But since we don't get them, we can do partition !:

$$M_W \geq M_{T2} = \min_{\vec{q}_{T1}+\vec{q}_{T2}=\not{E}_T} [\max\{m_T(\vec{p}_{T1},\vec{q}_{T1}), m_T(\vec{p}_{T2},\vec{q}_{T2})\}]$$

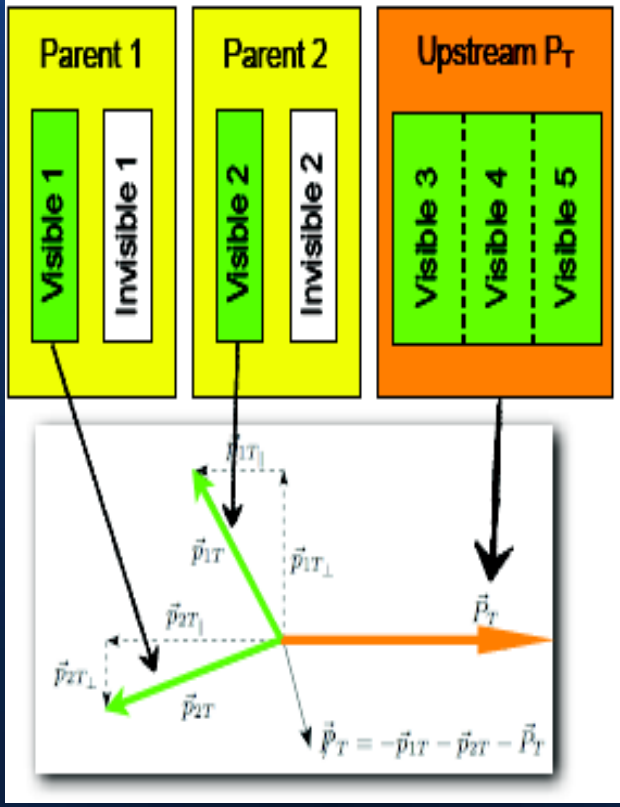
If we don't know the Missing particle mass, we need to guess it's mass to formulate each $m_T(p_T, q_T)$

$m_T(p_T, q_T)$

Barr,Lester,Summers,Stephens

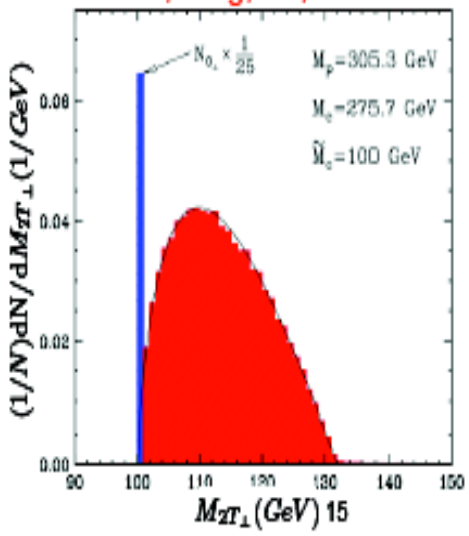
Second Transversification

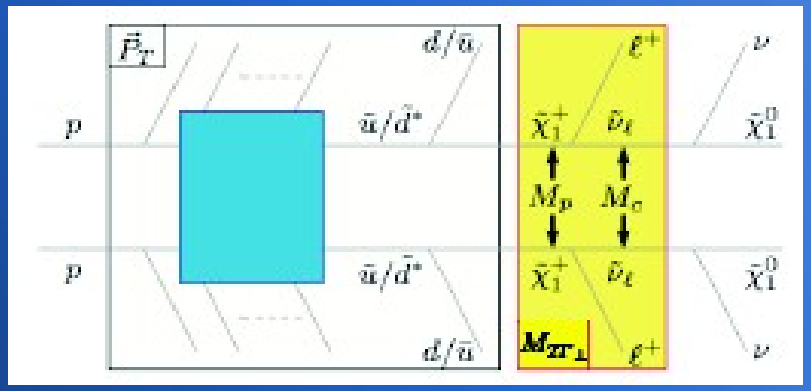
- Having projected on the transverse plane, one can additionally project on the direction of Upstream P_T:



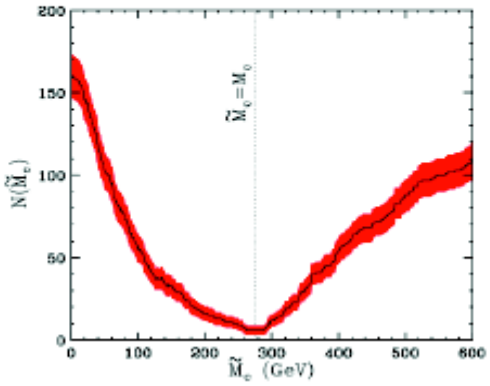
- The endpoints of "perp" distributions are stable against P_T variations

Konar,Kong,KM,Park 2009

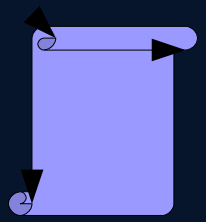




$$N(\tilde{M}_c) = \sum_{\text{all events}} H(M_{2T}(\tilde{M}_c) - M_{2T\perp}^{max}(\tilde{M}_c))$$



PK,Kong,Matchev,Park



Summary

- Exciting time to cross-check the facts
- New physics at TeV energy scale
- Dark Matter motivates new physics
- WIMP – our best bet
- With improved search strategy for BSM
- Tune with latest tricks in studying missing energy events.


Thank You