Highlights and Perspectives

Joseph Lykken
Fermilab

23rd Rencontres de Blois, 30.5 – 3.6.2011

- **It was the best of times**

- **It was the worst of times**

- **It was the best of times**

The revolution has started

- **It was the worst of times**

- It was the best of times

The revolution has started

- It was the worst of times

The revolution has started

Vive la revolution

• big changes in particle physics over the next few years

• expect many theorists to lose their heads

• but difficult to predict which of the current BSM factions will prevail – maybe a new dominant figure will emerge out of nowhere

Nostalgia for the Ancien Regime

- we knew what the theory was
- in many cases, the theory made precise predictions
- we could test and over-constrain these predictions

Nostalgia for the Ancien Regime

- LEP etc: EWPT to a part in 10000 and multi-TeV sensitivity to NP (M. Verzocchi)

- B factories: over-constrained UT and multi-TeV sensitivity to NP (A. Golutvin, T. Iijima)

- HERA: parton distributions inside the proton (T. LeCompte)

The Standard Model is not going away

- understood best at high energies, short distances, low temperature, low density

- much that we still need to figure out, including nonperturbative features that are New Physics

- The LHC Era will be a QCD Era

Nonperturbative QCD

- vacuum structure: confinement, chiral symm breaking, topological thingies

- new kinds of bound states: X(3872) first hadron bound state; Y(4260) first hybrid (ccg)

- many challenges for lattice gauge theory

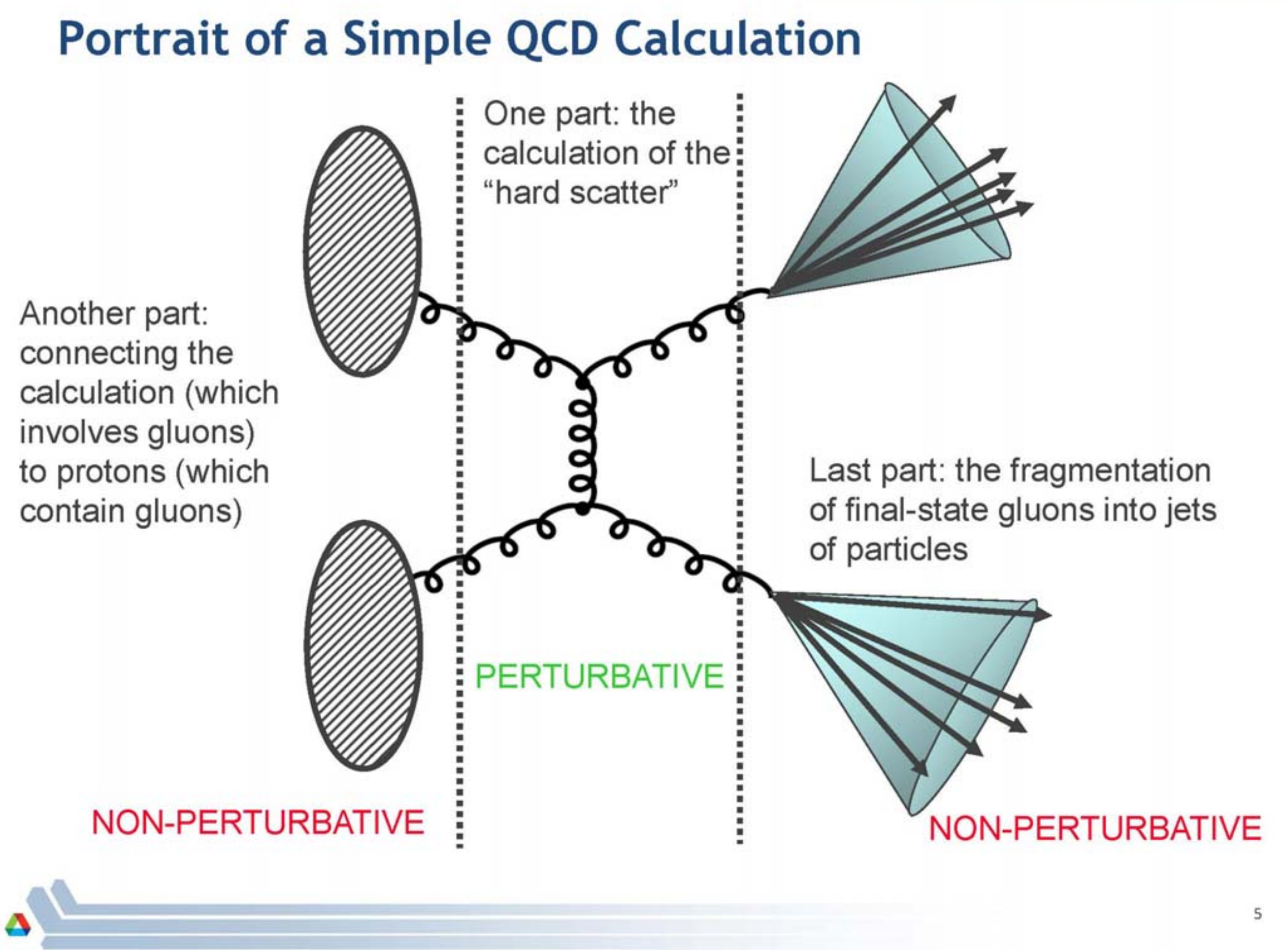
E. Swanson

Heavy ion physics: the Golden Age

QGP, perfect fluid, elliptic flow, jet quenching,
J/psi and upsilon quenching, …

- New emergent physics!   (C. Salgado)
- First discoveries at LHC were in HI (C. Loizides)
- Applied Holography! (Y. Oz)

QCD at LHC is messy at both ends



T. LeCompte

Standard Candles

- an essential part of the LHC discovery program, already pioneered at the Tevatron (Glover, Grannis, LeCompte, Maltoni, Verzocchi)

- requires a big organized effort on both the theory and experiment sides

- with expanded phase space probed by LHC, and with large integrated luminosity (Myers), this should work great

- enable both more data-driven searches and better discrimination of NP look-alikes once you have signal

Tevatron Standard Candles

- precision physics at a hadron collider for top, W, Z, W/Z + jets, b and tau final states

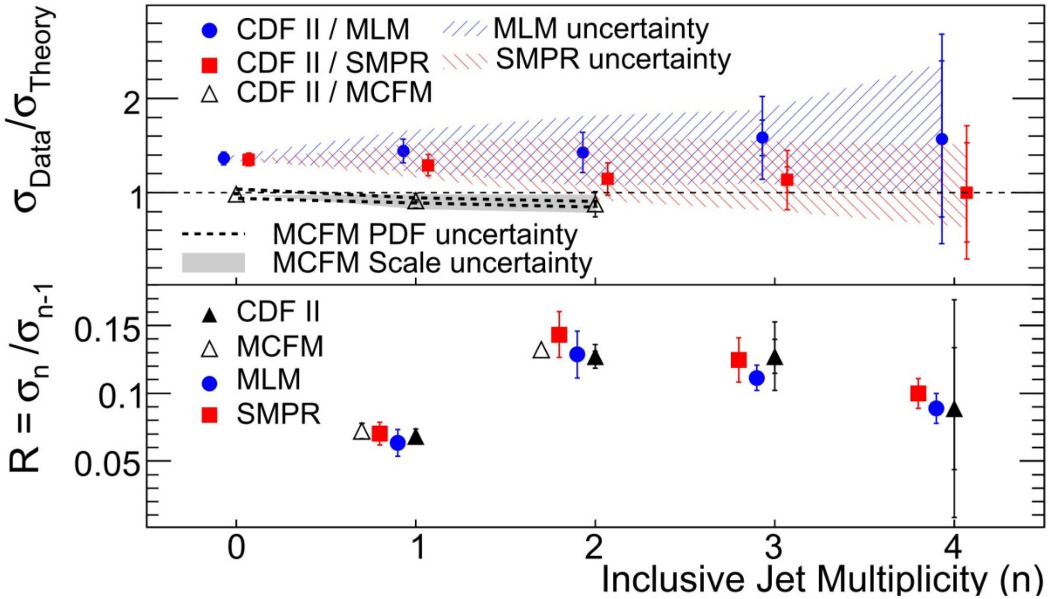
- D0 measured W mass to 5 parts in 10000, better than any single LEP measurement

- D0 measured weak angle more precisely than all LEP experiments combined

P. Grannis, M. Verzocchi, T. LeCompte

Tevatron Standard Candles

W + n-jet rates from CDF



✗ Large uncertainty at LO - increasing with number of jets

✗ Normalisation not good at LO

✓ Normalisation better at NLO

✓ Reduced theory error at NLO

N. Glover

LHC Standard Candles: top

Large cross section at LHC-7: 150 pb for ttbar, 60 pb for single top

PROGRESS IN SM TOP PREDICTIONS

Top pair cross section and distributions:

- Updates of total top pair cross section (NLO QCD + threshold res. (NLL)) *Moch, Uwer; Cacciari et al; Kidonakis, Vogt*
- NNLL extensions at threshold: two slightly different definitions of threshold *Czakon et al.; Beneke et al.; Ahrens et al.*
- Forward-Backward asymmetry from threshold resummation *Almeida et al; Ahrens et al.; Antunano et al.; Kidonakis;*
- Top pair invariant mass very close to production threshold (resonance peak) *Hagiwara et al; Kiyo et al.*
- Partial results towards top pair total rate at NNLO QCD *Czakon; Bonciani et al. ...*

Top pair + jets: top as a background to Higgs searches: $H \rightarrow W^+W^-$ and ttH

- pp → tt+jet *Dittmaier et al.; Melikov, Schulze*
- pp → tt bb *Bredenstein et al.; Bevilacqua et al.*
- pp→ tt jj *Bevilacqua et al.*
- tt(+jet) production including decay at NLO QCD *Melnikov, Schulze*; including weak interference corrections *Bernreuther, Si*
- tt spin correlations revisited *Mahlon, Parke; Bernreuther, Si*

Single-top:

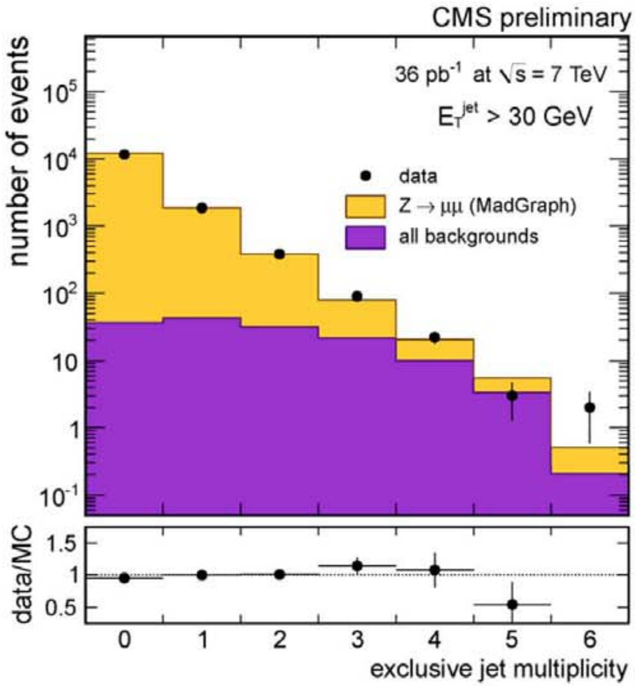
- Single top t-channel production at NLO QCD in 5 and 4 flavor schemes *Campbell, Frederix, FM, Tramontano*
- Single top including decay at NLO QCD *Falgari et al.*

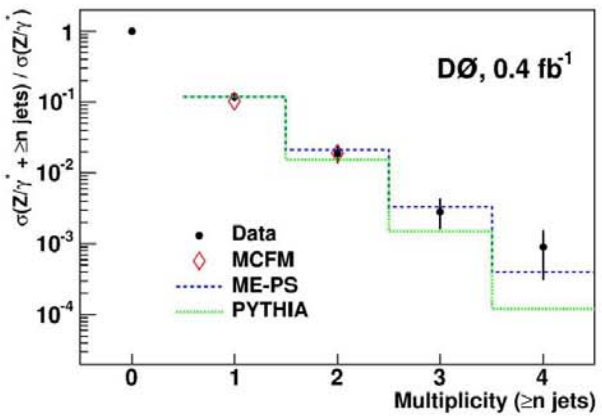
Monte Carlo at NLO:

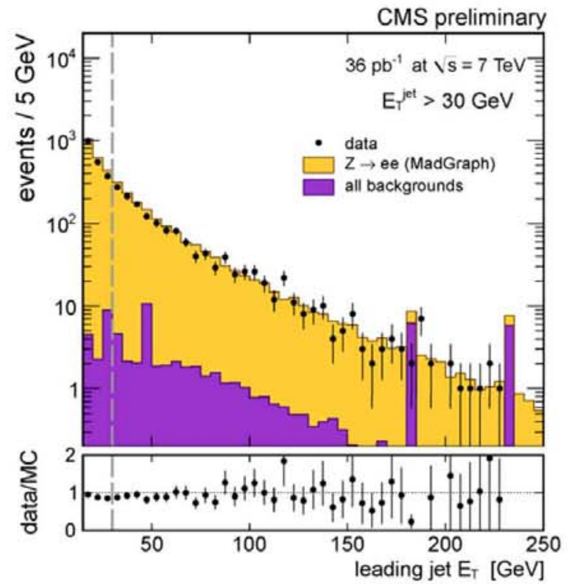
- Wt production at NLO QCD in MC@NLO *Frixione et al.; White et al.*
- tt+1jet in via the POWHEG-Box *Cardos et al..*
- 4F tj in aMC@NLO *Frederix,et al.*

F. Maltoni
M. Narain

LHC Standard Candles: Z + jets



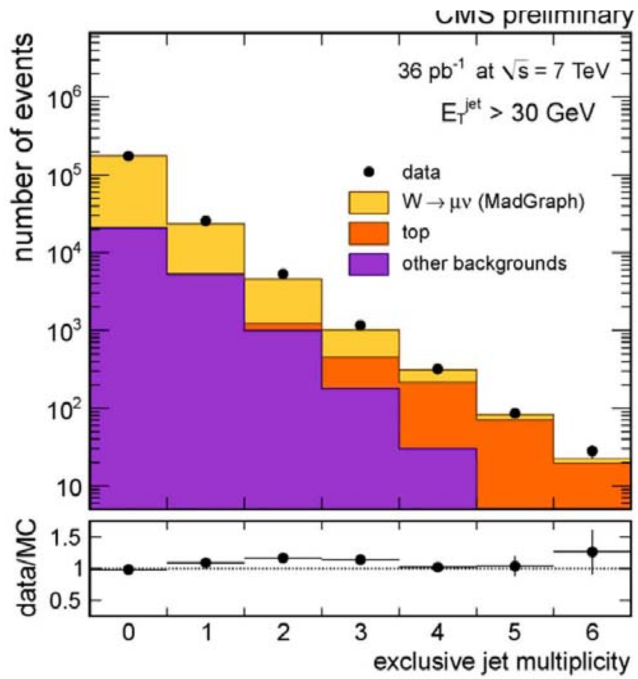


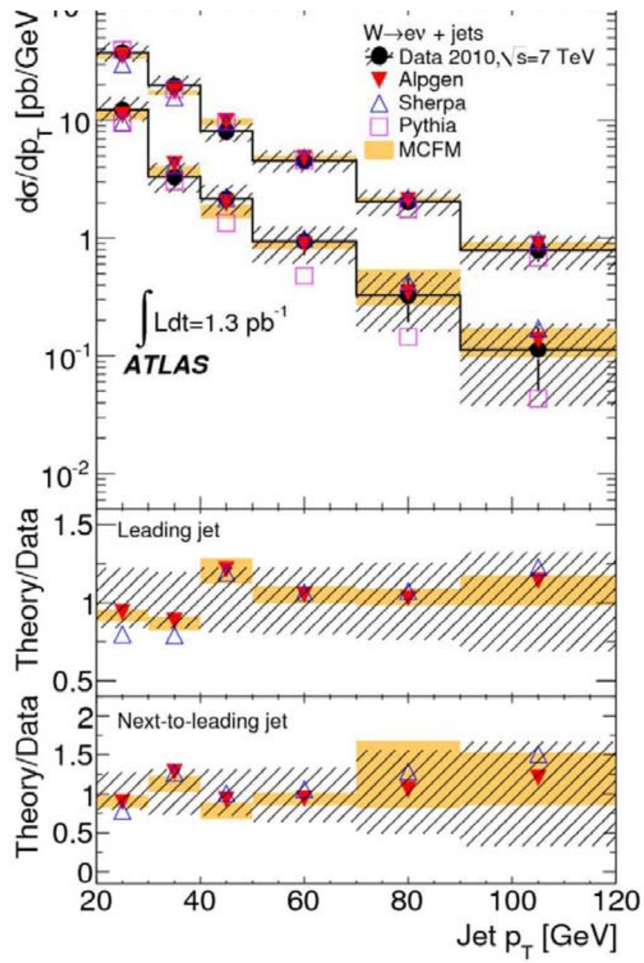


At the LHC, jet multiplicities are higher, and with 3% of the data collected, the range of p_T's accessible is about the same – maybe already a little larger.

T. LeCompte

LHC Standard Candles: W + jets





At the LHC, the top *quark* is a significant background to W+jets. (At the Tevatron, it's the other way around.

T. LeCompte

Breakthroughs in pQCD

LHC priority NLO wish list, Les Houches 2005/7*

process	background	status - mostly from Feynman diagram approach
$pp \to VV + 1$ jet	WBF $H \to VV$	WWj (07), ZZj (09)
$pp \to t\bar{t} + b\bar{b}$	$t\bar{t}H$	$q\bar{q} \to t\bar{t}b\bar{b}$ (08), $gg \to t\bar{t}b\bar{b}$ (09)
$pp \to t\bar{t} + 2$ jets	$t\bar{t}H$	$t\bar{t}j$ (07), $t\bar{t}Z$ (08), $t\bar{t}jj$ (10)
$pp \to VV + b\bar{b}$	WBF $H \to VV$, $t\bar{t}H$, NP	
$pp \to VV + 2$ jets	WBF $H \to VV$	WBF $pp \to VVjj$ (07), $pp \to WWjj$ (10)
$pp \to V + 3$ jets	NP	$W + 3$ jets (09), $Z + 3$ jets (10), $W^- + 4$ jets (10)
$pp \to VVV$	SUSY trilepton	ZZZ (07), WWZ (07), WWW (08), ZZW (08)
$pp \to b\bar{b}b\bar{b}$*	Higgs and NP	$b\bar{b}b\bar{b}$ (partial 09)

- ✓ $pp \to H + 2$ jets via gluon fusion (06)
- ✓ $pp \to H + 2$ jets via WBF, electroweak and QCD corrections (07)
- ✓ $pp \to H + 3$ jets via WBF, (07)

Many contributors Badger, Berger, Bern, Bevilacqua, Binoth, Bozzi, Bredenstein, Campanario, Campbell, Ciccolini, Czakon, Denner, Dittmaier, Dixon, Ellis, FebresCordero, Figy, Forde, Gleisberg, Glover, Greiner, Guffanti, Guillet, Hankele, Heinrich, Ita, Kallweit, Karg, Kauer, Kosower, Lazopoulos, Maitre, Mastrolia, Melia, Melnikov, Ossola, Papadopoulos, Petriello, Pittau, Pozzorini, Reiter, Reuter, Rontsch, Sanguinetti, Uwer, Williams, Worek, Zanderighi, Zeppenfeld,

N. Glover

LHC Standard Candles: theory

State of the Art - at a glance

Relative Order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		NNLO	NLO	LO		
α_s^4				NLO	LO	
α_s^5					NLO	LO

LO Automated and under control, even for multiparticle final states

NLO Well understood for $2 \to 1$ and $2 \to 2$ in SM and beyond

NLO $2 \to 3$ SM calculations becoming routine, see Les Houches wish list

NLO Some $2 \to 4$ processes e.g. $pp \to t\bar{t}b\bar{b},\ t\bar{t}jj,\ V+3j,\ WWjj$

NLO Very first $2 \to 5$ LHC cross section in 2010 $pp \to Wjjjj$

NNLO Inclusive and exclusive Drell-Yan and Higgs cross sections

NNLO $e^+e^- \to 3$ jets, but still waiting for $pp \to \text{jets},\ W + \text{jet},\ t\bar{t}, VV$

N. Glover

The Holy Grail: automated NLO event generators

Automating NLO calculations

Real radiation: based on LO event generators

- ✓ Based on Dipole subtraction
  - ✓ SHERPA — Gleisberg, Krauss
  - ✓ AutoDipole — Hasegawa, Moch, Uwer
  - ✓ MadDipole — Frederix, Gehrmann, Greiner
  - ✓ TeVJet — Seymour, Tevlin
  - ✓ Helac/Phegas — Czakon, Papadopoulos, Worek
- ✓ Based on Dipole subtraction
  - ✓ MadFKS — Frederix, Frixione, Maltoni, Stelzer
- ✓ extensive libraries in existing NLO packages
  - ✓ MCFM — Campbell, Ellis
  - ✓ NLOJET++ — Nagy, Trocsanyi

N. Glover

The Holy Grail: automated NLO event generators

Automating NLO calculations

Virtual corrections: implementations

- ✓ semi-numerical form factor decomposition: GOLEM Binoth, Guillet, Heinrich, Pilon, Reiter
- ✓ unitarity and multi-particle cuts: BlackHat Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre
- ✓ reduction at integrand level: CutTools Ossola, Papadopoulos, Pittau
- ✓ generalized D-dimensional unitarity: Rocket Giele, Ellis, Kunszt, Melnikov, Zanderighi
- ✓ generalized D-dimensional unitarity: Samurai Mastrolia, Ossola, Reiter, Tramontano
- ✓ several more packages in progress Lazopoulos; Giele, Kunszt, Winter; Melnikov, Schulze; . . .

Most recently: combine virtual (CutTools) and real (MadFKS) contributions into automated NLO package: MadLoop

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau

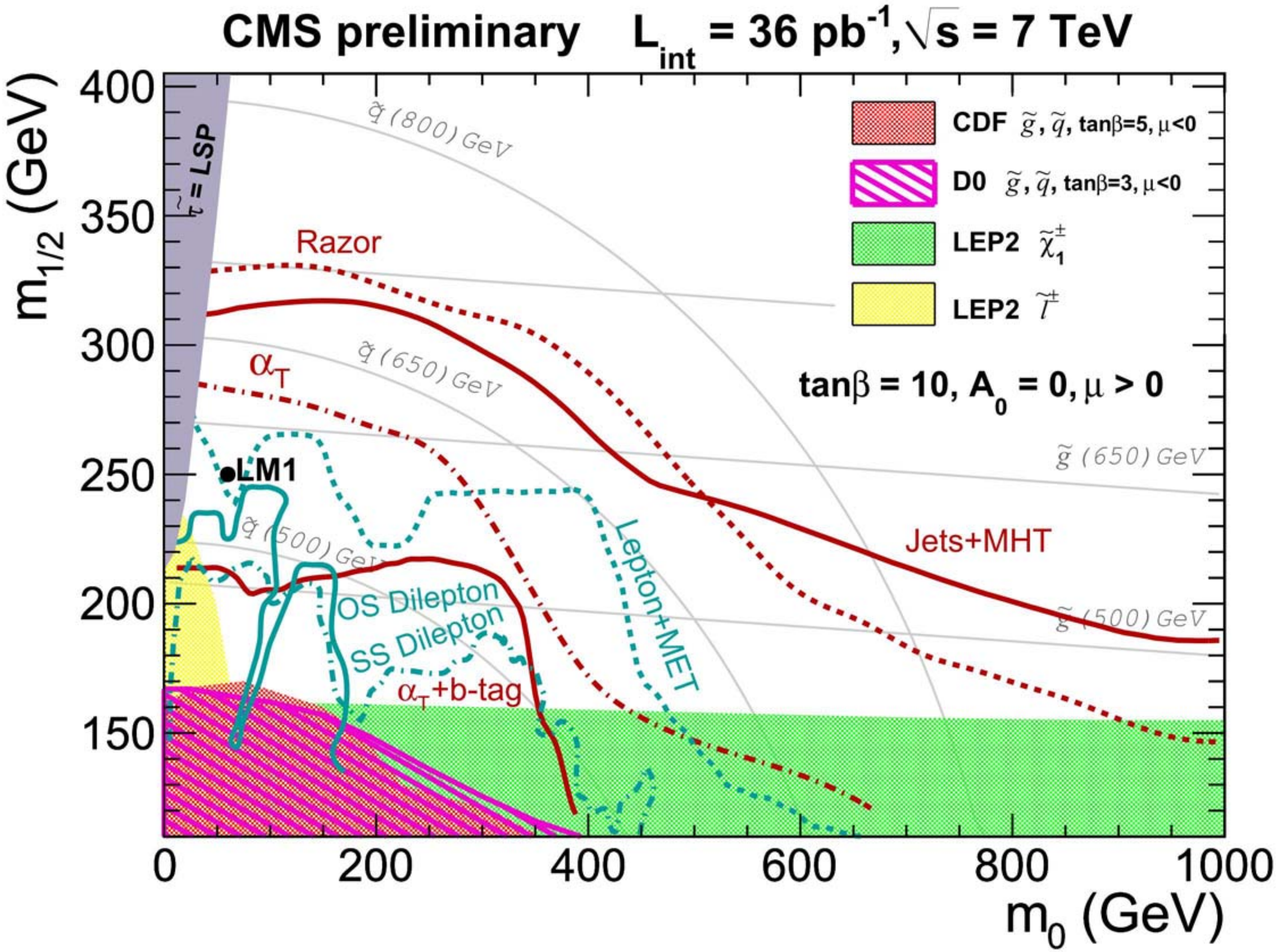
N. Glover

LHC 2011-2012 Discovery Run

O. Buchmuller, A. Taffard,
R. Godbole,
S. Myers

- More than 500 pb-1 in the can already this year
- Experienced analysis teams
- Overlapping analyses for cross-checks
- Wide variety of signature-based searches

LHC SUSY searches: old reliables and new innovations



New kinematic variables for SUSY discovery

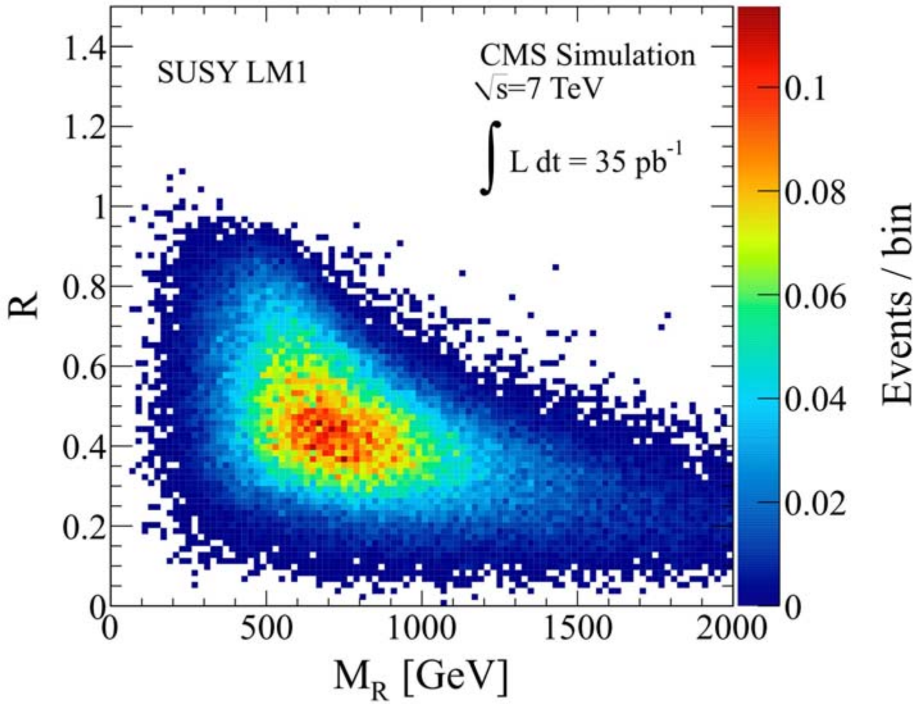
O. Buchmuller

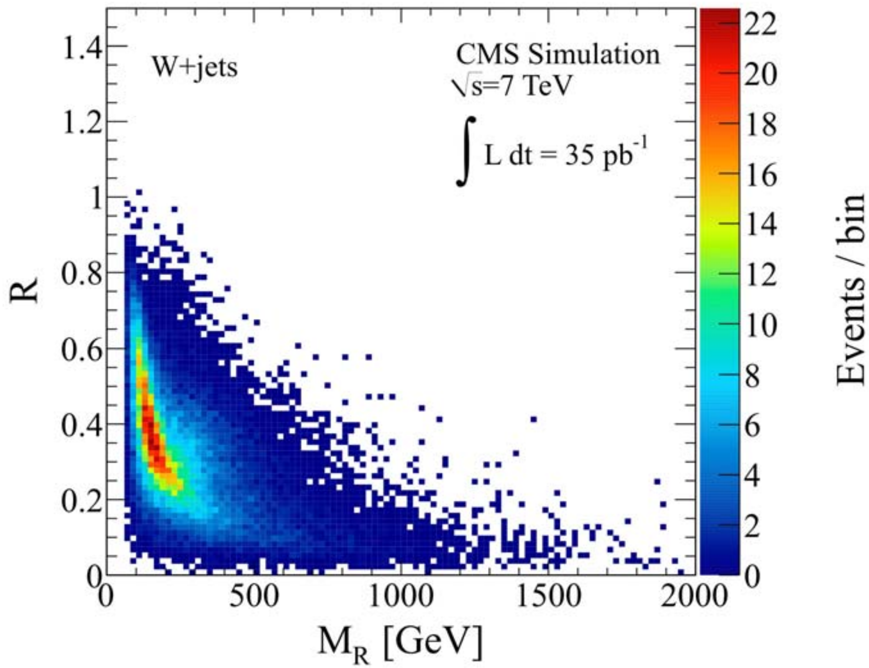
• Inspired by theorists, both ATLAS and CMS developed new inclusive SUSY searches implemented in the 2010 data, based on new kinematic discriminators alpha_T, mT2, and the *razor* variables

• The extra information encoded in these variables can be very efficient for killing backgrounds

• Bonus: once you make a discovery, these and similar variables help tell you what you found

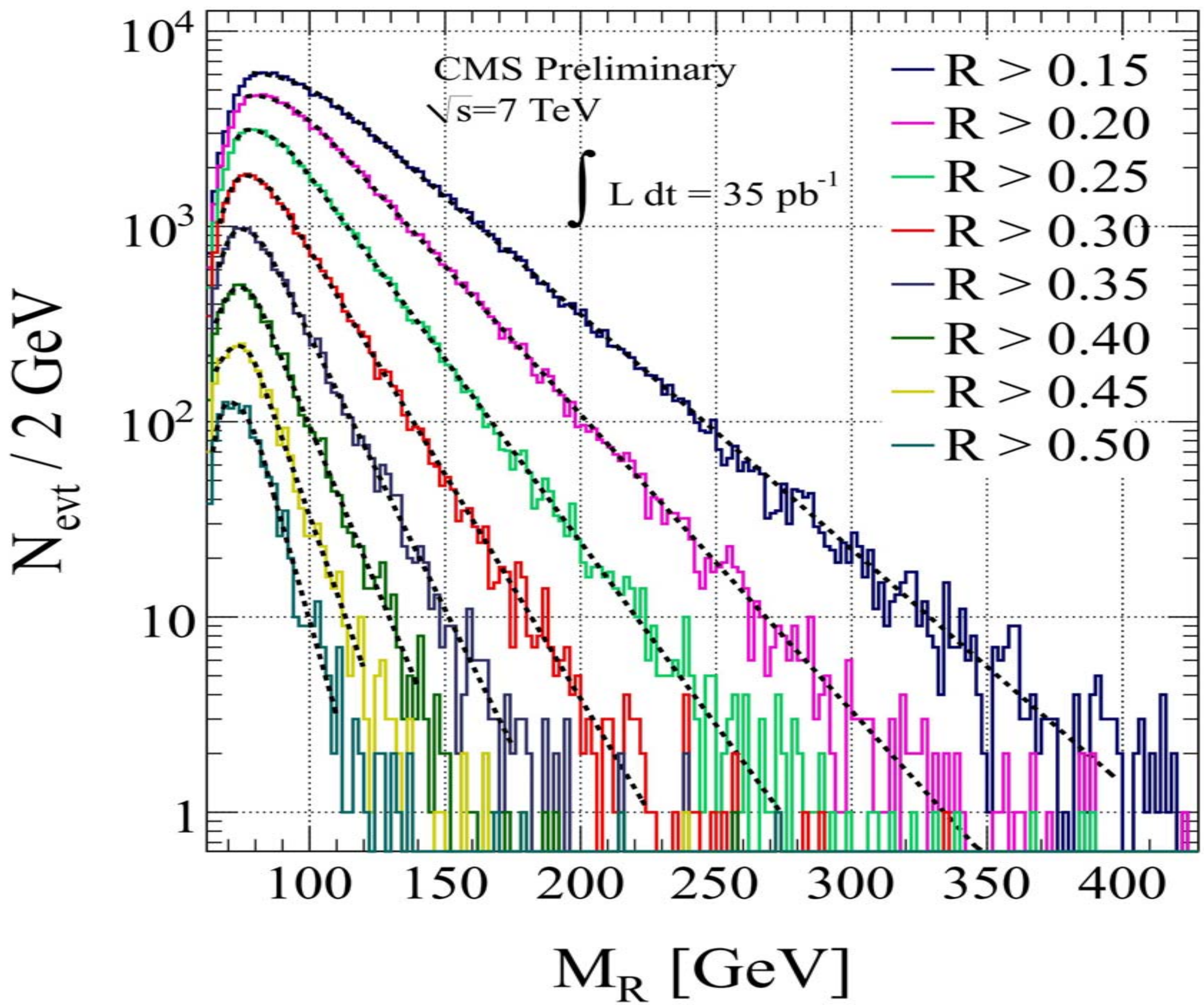
Razor variables



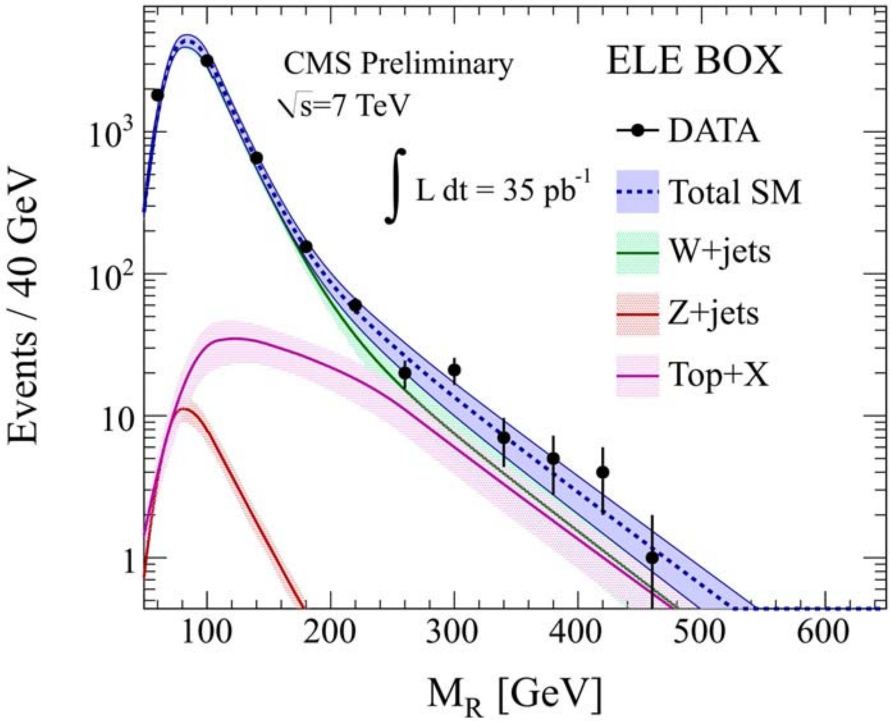


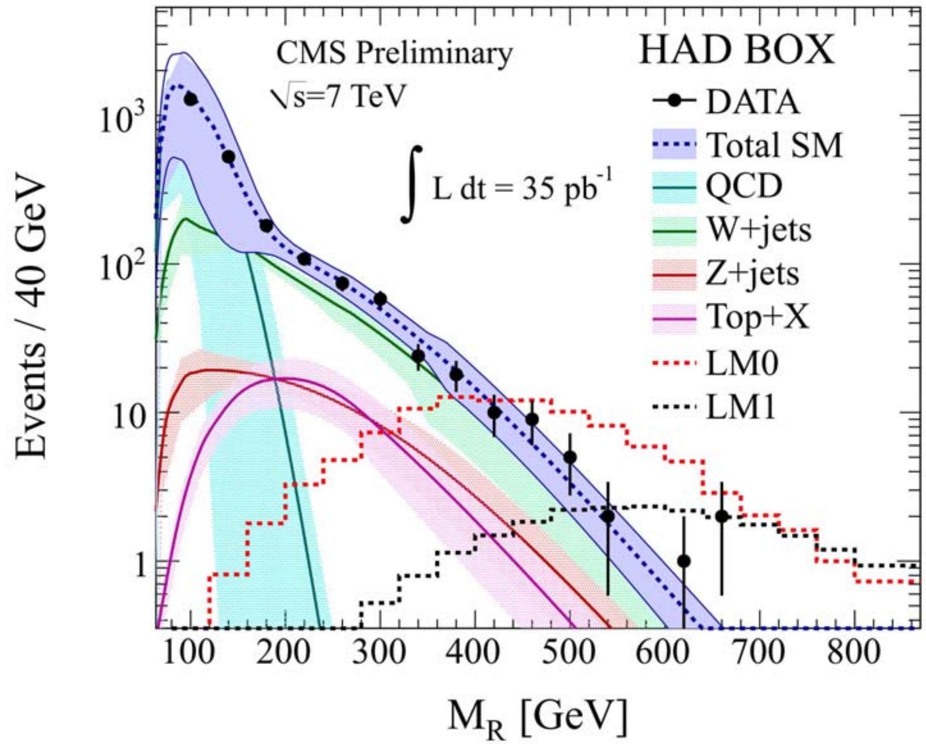
- **Cannot fully reconstruct the kinematics of the production of a pair of heavy particles that each decay to MET + X**
- **R and M_R approximate this kinematics**
- **For a given R threshold, M_R peaks for signal, is exponentially suppressed for QCD, EW, and instrumental backgrounds**

Killing QCD backgrounds to SUSY



Razor analysis for SUSY: control samples





Moving towards searches that are more inclusive and use more data-driven background estimates

Anomalies and Mysteries in the Data

- quark and charged lepton flavor puzzles
- neutrino anomalies
- Tevatron anomalies
- dark matter direct and indirect anomalies
- cosmological mysteries

- **LHCb: Is $S_{\psi\phi}$ large?** Also more info from TeVatron
- **LHCb: How large is $\Delta\Gamma_s$?** Also TeVatron
- **More info on the semileptonic CP asymmetries**
  - Dimuonasymmetry A_{sl}: CDF and D0
  - $a_{sl}^{s,d}$: B-factories, CDF, D0, LHCb?
  - $a_{sl}^{s} - a_{sl}^{d}$: LHCb
- **New data on** $B \to K^{(*)} ll$: B-factories, TeVatron, LHCb Talks by De Nardo
- **New bounds on** $B_s \to \mu\mu$: CDF, LHCb Talks by Mancinelli, Hopkins
- **More data for Charm mixing**: TeVatron, LHCb Talks by Kagan, Zupanc
- ? $\mu \to e\gamma$? Talks by De Gerone, Paradisi

A. Lenz, FPCP2011

Much more to come: $K \to \pi\nu\nu$,... e.g. Talk by DiGregorio

BNL muon g-2 anomaly; new g-2 experiment at Fermilab

quark and charged lepton flavor puzzles

What are neutrinos trying to tell us?

E. Lisi, M. Lindner, S. Pascoli, C. Lunardini

- Reactor neutrino anomaly
- MiniBooNE/LSND short baseline anomaly
- MINOS long baseline anomaly

And this is probably just the beginning

The MINOS muon neutrino/antineutrino anomaly

M. Maltoni, NeuTel

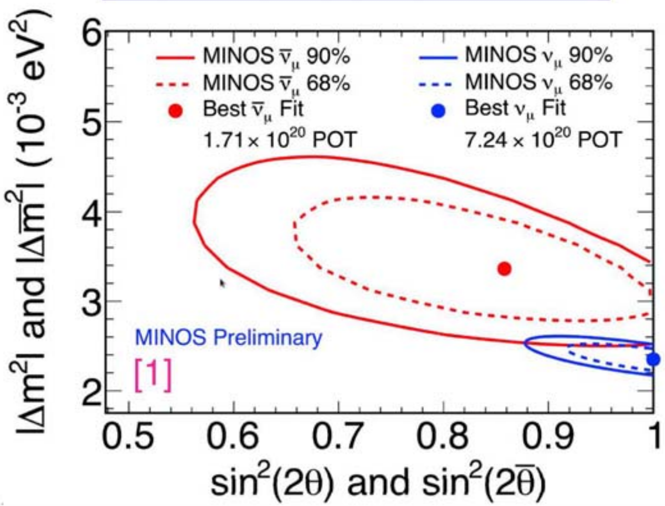
I. CPT violation in three-neutrino models

Minos disappearance: ν_μ vs $\bar{\nu}_\mu$

$$|\Delta\bar{m}^2_{\text{atm}}| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2 \qquad \sin^2(2\bar{\theta}_{23}) = 0.86 \pm 0.11$$ [1]

$$|\Delta m^2_{\text{atm}}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2 \qquad \sin^2(2\theta_{23}) > 0.90\ (90\%\ \text{C.L.})$$ [2]

- in June 2010 Minos presented new data on ν_μ vs $\bar{\nu}_\mu$ disappearance [1];
- some tension appears between neutrino and anti-neutrino results;
- Tension (our fit): $\chi^2_{\text{CPT}} - \chi^2_{\text{\sout{CPT}}} = 5.6\ (2.4\sigma) \Rightarrow$ small but not totally negligible;
- **more data needed before speculations!**
- Still, let's speculate: **IF** confirmed, it could be
  - evidence of CPT violation;
  - or just "conventional" New Physics...
- in either case, how does this relates to other neutrino experiments?



[1] A. Himmel, talk at Fermilab Joint Experimental-Theoretical Seminar, 14/06/2010.

[2] P. Adamson *et al.* [MINOS collaboration], arXiv:1103.0340.

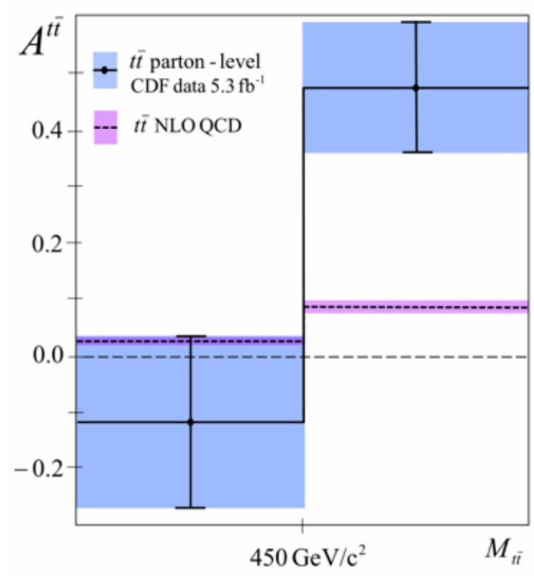
Tevatron ttbar forward-backward asymmetry anomaly

- **Unfold M_{tt} dependence back to parton level**

$A_{FB} = 48 \pm 11_{stat+syst}$ %

5.3 fb^{-1}

$A_{FB}^{Theory} = 9 \pm 1$ %



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+ D0 + CDF dileptons

T. Schwarz, FPCP2011

Tevatron ttbar forward-backward asymmetry anomaly

Two main avenues:

Heavy color-octet gauge bosons

- occur in several models, such as chiral color ("axigluon") extra dim.

Pati,Salam; Frampton,Glashow; Hill et al.; Agashe, Perez, et al. Choudhury et al.; Bai et al.

- model-independent analysis: Rodrigo,Ferrario

$$\mathcal{L} = g_S\, t^a\, \bar{q}_i (g_V^{q_i} + g_A^{q_i}\, \gamma_5)\, \gamma^\mu\, G_\mu^a\, q_i$$

flavor-non-universal: $g_{V,A}^t \neq g_{V,A}^q$

W. Volgelsang, FPCP 2011

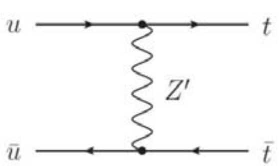
Tevatron ttbar forward-backward asymmetry anomaly

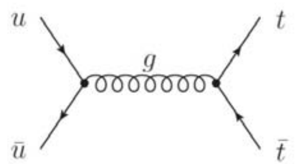
Extra weak gauge bosons

Berger et al.; Fox et al.
Aguilar-Saavedra,Perez-Victoria
Jung,Murayama,Pierce,Wells

$$\mathcal{L} = \frac{1}{\sqrt{2}}\bar{t}\gamma^{\mu}(g_L P_L + g_R P_R)uZ'_{\mu} + \frac{1}{\sqrt{2}}\bar{d}\gamma^{\mu}(\widetilde{g_L}P_L + \widetilde{g_R}P_R)tW'_{\mu}$$

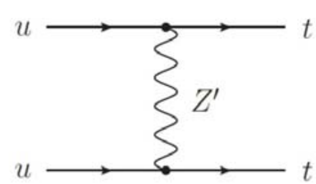
- large flavor-violating couplings
- t-channel avoids large features in $d\sigma/dM_{t\bar{t}}$
- ...and is efficient in generating A_{FB}





$$\mathcal{A}_{int} = \frac{2g_s^2}{9}\frac{(g_L^2 + g_R^2)}{\hat{s}\hat{t}_{Z'}}\left[2\hat{u}_t^2 + 2\hat{s}m_t^2 + \ \ldots\right]$$

- predicts *same-sign* tt pairs. Constraints from Tevatron, copious at LHC.

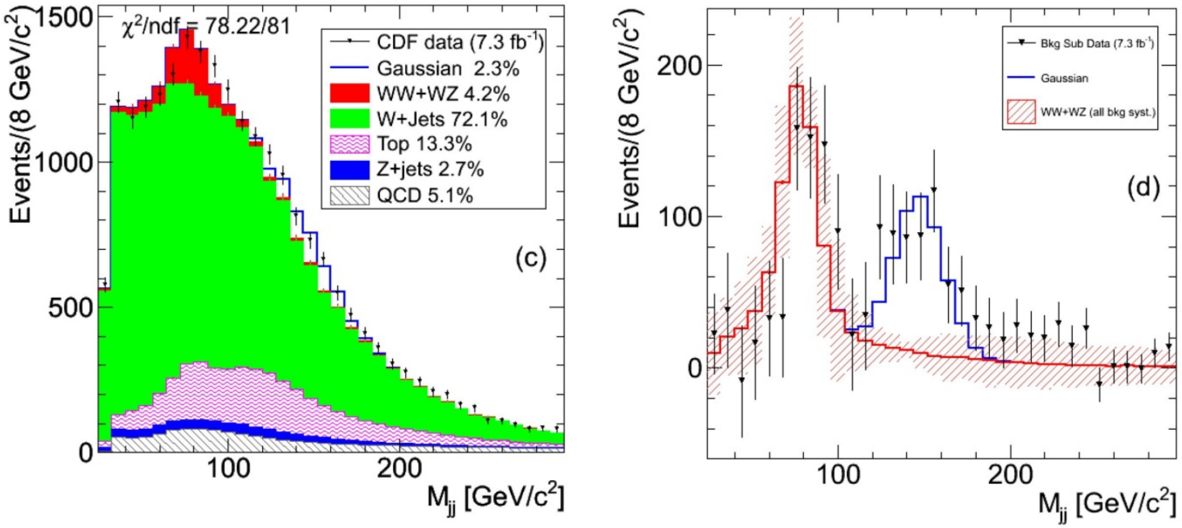


- in some models, helps with CDF Wjj anomaly

W. Volgelsang, FPCP 2011

CDF Wjj anomaly (D word?)

Updated W-jj with $7.3 fb^{-1}$



- Now closer to 5 sigma
- It was not just a statistical fluctuation
- Serious issue for CDF to understand this.
- Larger sample now allows for more detailed studies
  - stay tuned for updates.

G. Punzi

CDF Wjj anomaly

- **You say: it is the JES! -- but you need a 15% error**

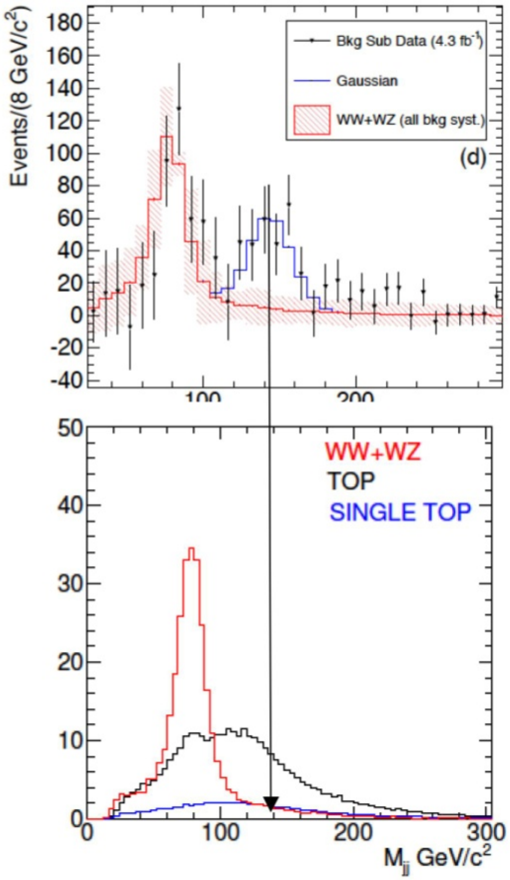
- **You say: it is the Monte Carlo! – but Alpgen, Sherpa, and MCFM NLO give similar results**

- **You say: it is top! …**

CDF Wjj anomaly

Update on W-jj excess

- But, the answer is NO - this cannot possibly be top background
  - There is no significant tagged component
  - Top-enriched control samples show perfect agreement with simulation
  - When using actual detector simulation, the top background does not peak at the right place



FAQ: Maybe it's just statistics - why aren't you showing the full sample anyway ?

G. Punzi

If it is New Physics, then what is it?

- **a leptophobic Z’ (beware of UA2 dijet constraint)**

  M. Buckley, D. Hooper, J. Kopp, E. Neil; F. Yu
  K. Cheung, J. Song; P. Fox et al

- **technicolor: 300 GeV techni-rho decays to 150 GeV techni-pion plus a W**

  E. Eichten, K. Lane, A. Martin

- **scalars related to flavor symmetries, expanded Higgs sector**

  A. Nelson et al; M. Carena et al; G. Segre and B. Kayser

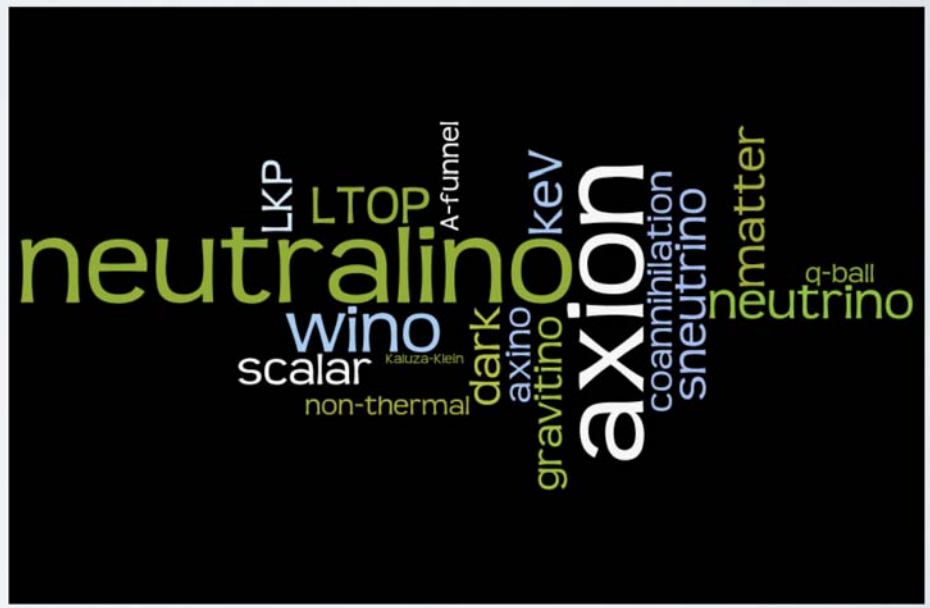
- **radion of a finite extra dimension**

  B. Bhattacherjee and S. Raychaudhuri

THE EVOLUTION OF DARK MATTER THEORY

Pre-2008

Theory driven:
Hierarchy problem (neutralino, WIMP, KKDM),
Strong CP (axion),
etc



N. Weiner, PHENO2011

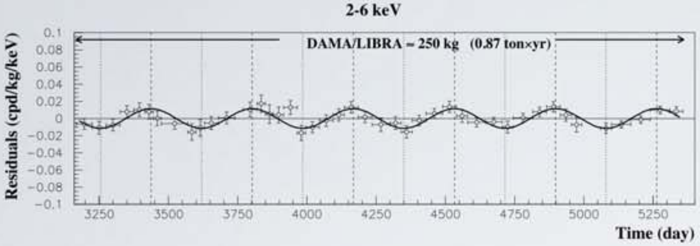
THE EVOLUTION OF DARK MATTER THEORY

2008+

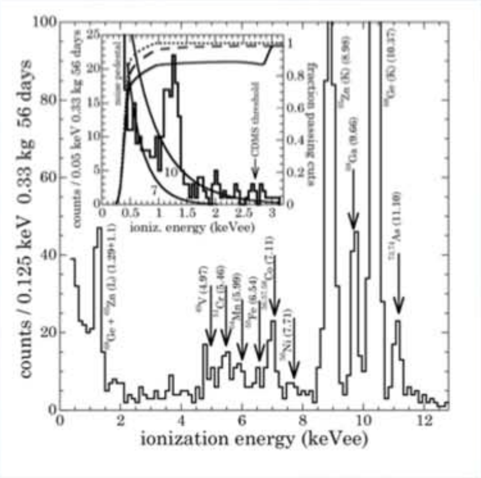
Anomaly driven:
light WIMPs, inelastic
WIMPs, leptophilic WIMPs,
decaying WIMPs, light
mediators, CiDM, quirky
DM, asymmetric DM...

N. Weiner, PHENO2011

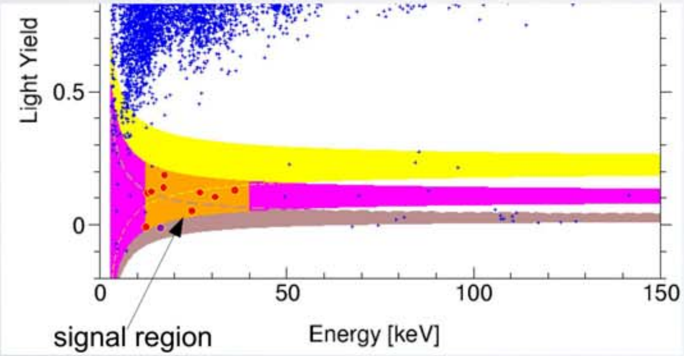
HINTS?



DAMA



CoGeNT

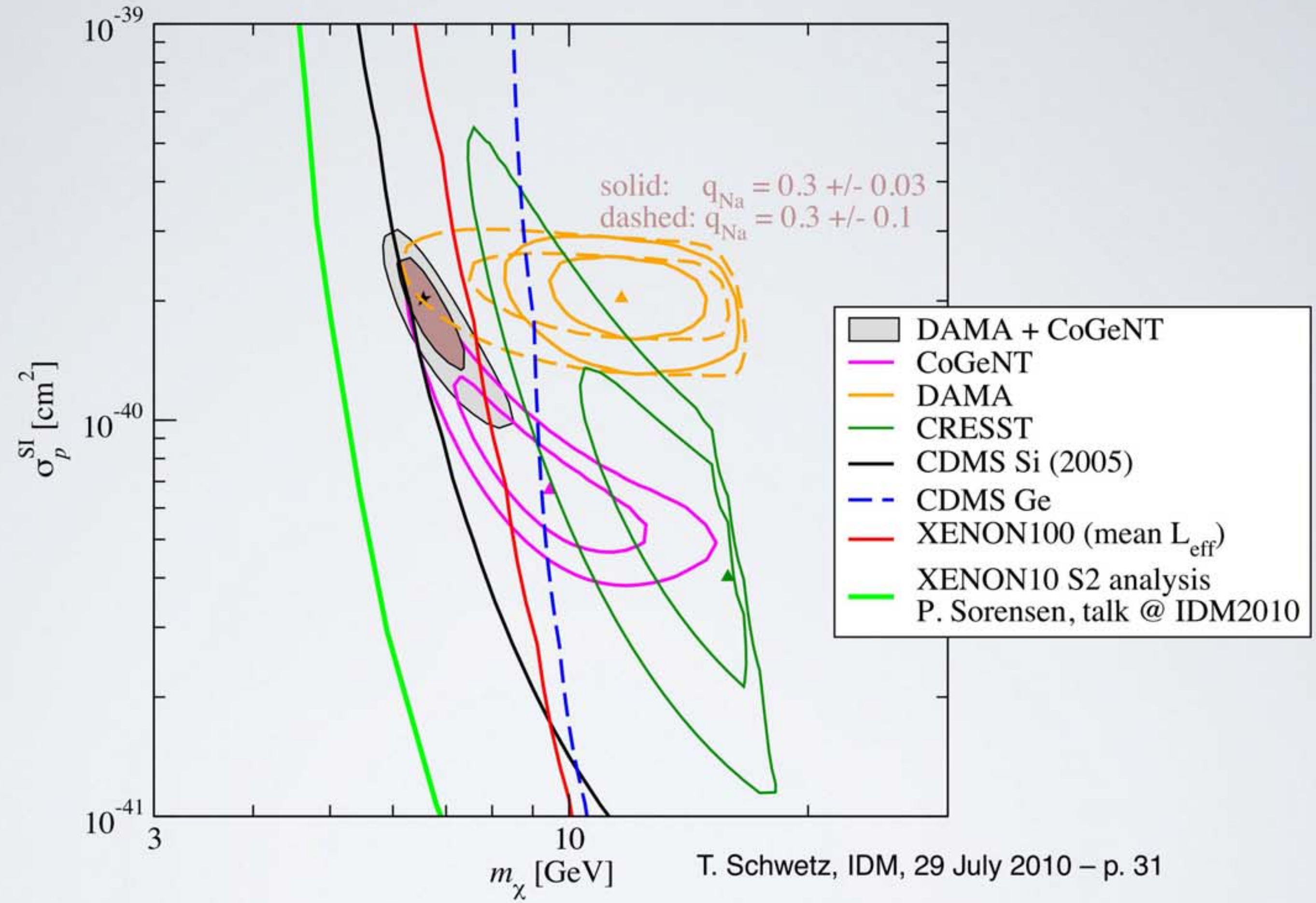


CRESST

N. Weiner, PHENO2011

• The same beast?

N. Weiner, PHENO2011



T. Schwetz, IDM, 29 July 2010 – p. 31

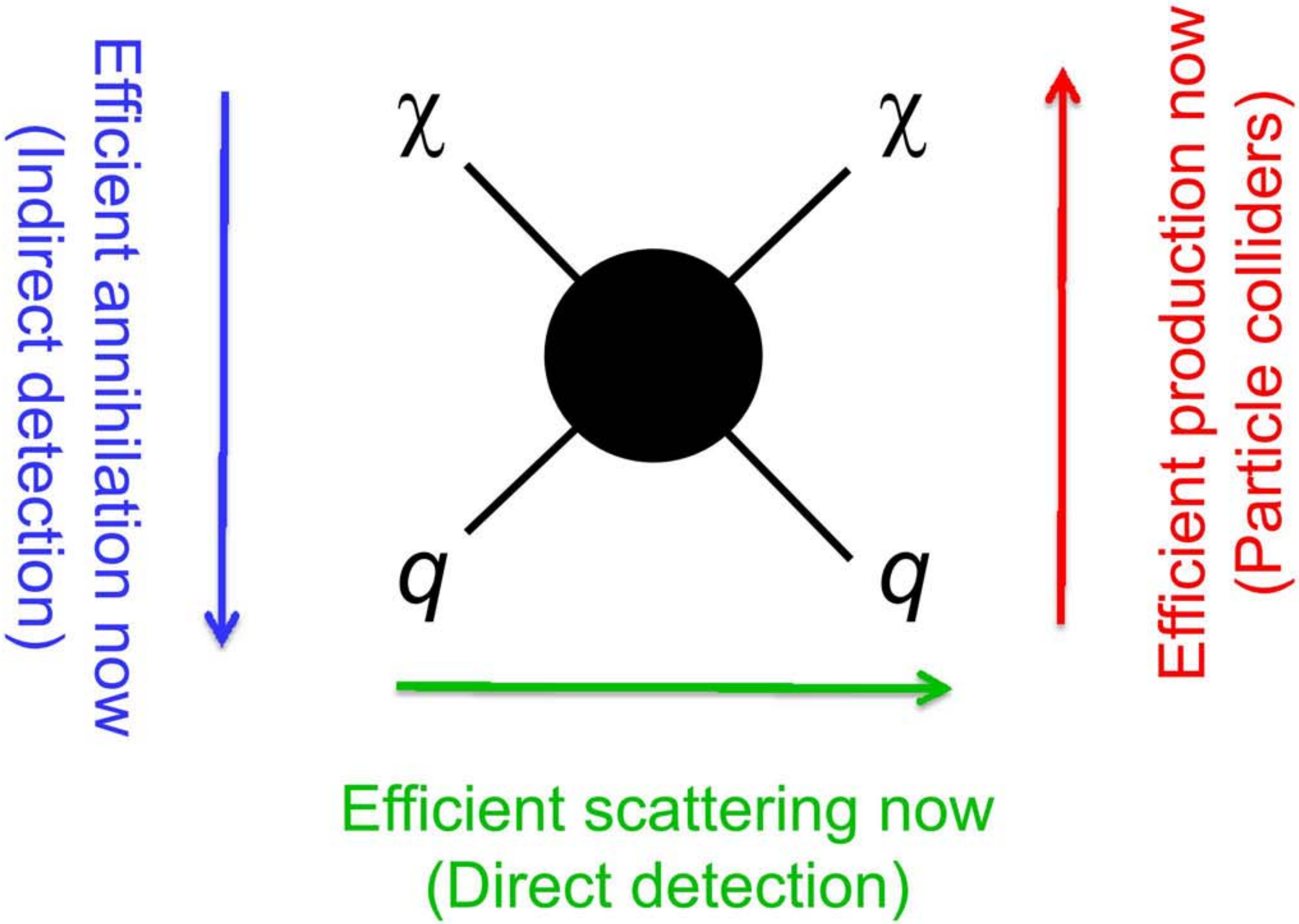
don't *really* line up, but within spitting distance

NB: *Not* MSSM (Kuflick, Pierce, Zurek '10)

J. Gunion

EXPERIMENTAL PROBES

Correct relic density → Efficient annihilation then



J. Silk

DARK MATTER IS AN URGENT PROBLEM

DETECTION IN MULTIPLE WINDOWS IS ESSENTIAL

- **Hints from direct detection**
- **strong upper limits in γ rays**
- **may need to go to NMSSM or asymmetric DM**

IF WE DETECT DM, RESURRECTION VIA ASTROPHYSICS

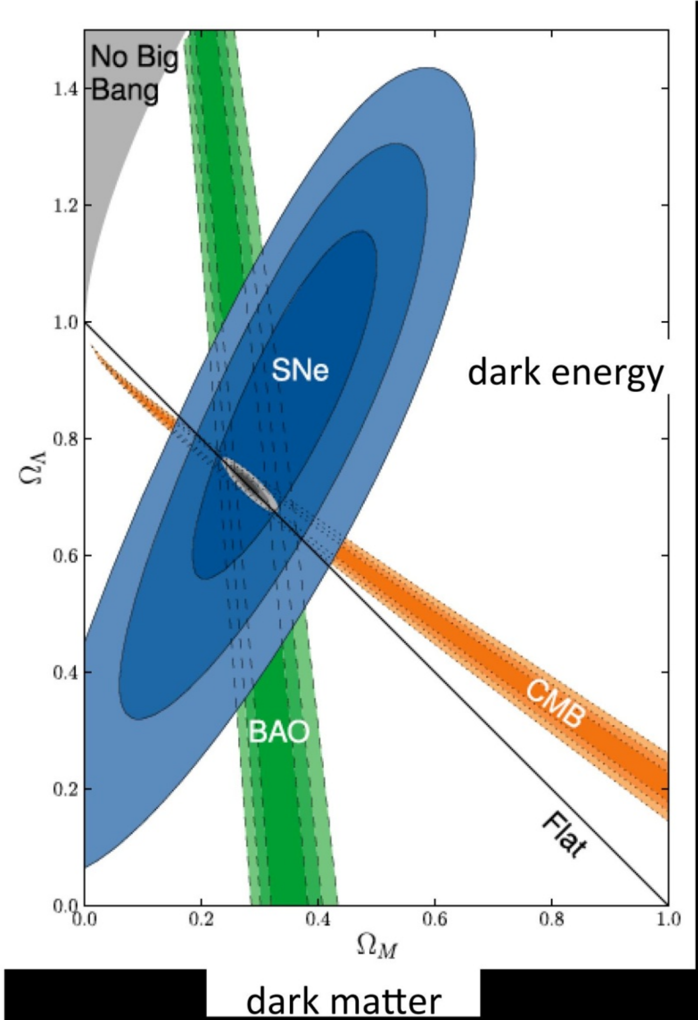
IF WE FAIL, RESURRECTION VIA NEW FUNDAMENTAL PHYSICS

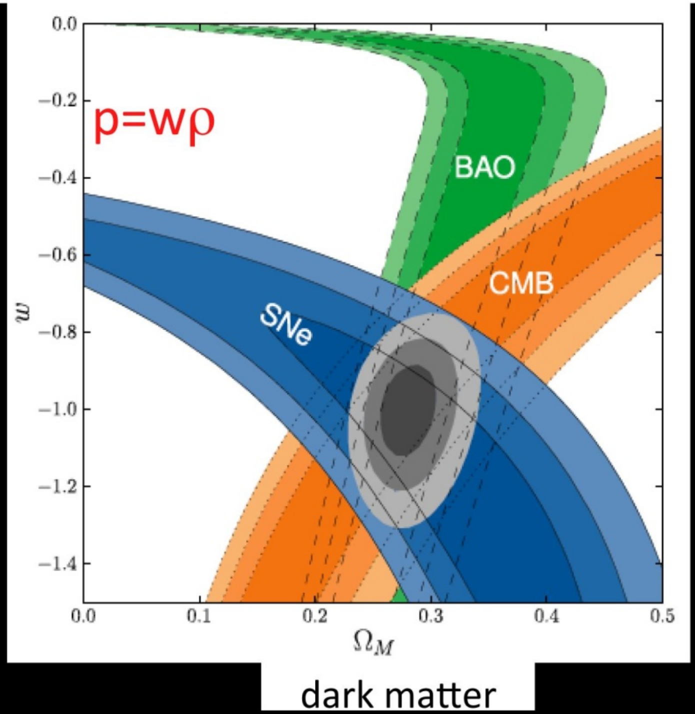
MODIFYING NATURE OF DARK MATTER OR GRAVITY

AS FOR DARK ENERGY: NO SOLUTION IN SIGHT…..

HIGHEST PRIORITY IN EXPERIMENTAL COSMOLOGY,
SO DATA WILL IMPROVE

J. Silk, M. Kowalski





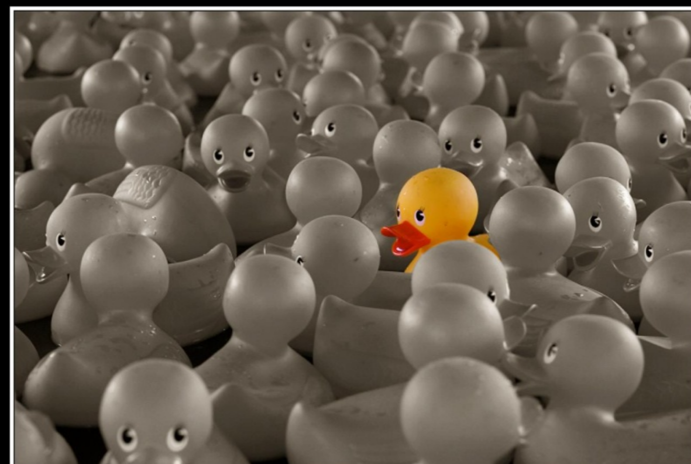
Amanullah et al 2010

Large-scale structure (BAO): DM

CMB fluctuations: DM +DE

Supernovae: DM - DE

Questions such as "why is a certain constant of nature one number rather than another?" may well be answered by "somewhere in the megaverse the constant equals this number: somewhere else it is that number. We live in one tiny pocket where the value of the constant is consistent with our kind of life



Successful scientific theories make *predictions.* The multiverse theory is not provable either by observation, or as an implication of well established physics. It can't make any predictions because it can explain anything at all.

All cosmologists are catholics

- If you believe in inflation, then you believe that there are quantum scalar fields whose vacuum energy acts as an effective cosmological constant that drives accelerated cosmic expansion

- If you believe that dark energy is a cosmological constant, then you believe that the vacuum energy of quantum fields does not drive cosmic expansion, and that something else (as yet unidentified) does

- When you don't have a coherent theoretical framework that relates different phenomena that ought to be related, you are lost

P. Binetruy

Reconciling the two theories: where do they collide?

• issue of vacuum energy (vacuum ↔ quantum theory
absolute energy ↔ expansion ↔ GR)

infamous cosmoloical constant problem

• issue of Lorentz violations

e.g. non-commutativity $[x_\mu, x_\nu] = \frac{i}{\Lambda_{NC}^2}\Theta_{\mu\nu}$ *associated with quantum gravity*

• violations of equivalence principle

T. Montaruli

When in search for the unknown, you don't know what you are going to find.

G. Punzi

New ideas, new frameworks

R. Godbole, A. Pomarol

- The moment of truth is fast approaching for both SUSY and Higgs

- Current anomalies and non-signals may already be hints that we need a major rethink of BSM physics

- There are some genuinely new ideas floating around, like anisotropic scaling (Horava), classicalization (Gomez et al), and monopole condensation (Terning).

- BSM theory may take off in a new direction soon


Thanks to Tran
Thanks to Boaz
Thanks to all the organizers
for an exciting conference in
exceptional surroundings