Search for color sextet scalars in early LHC experiments

Edmond L Berger

Argonne National Laboratory

In collaboration with:

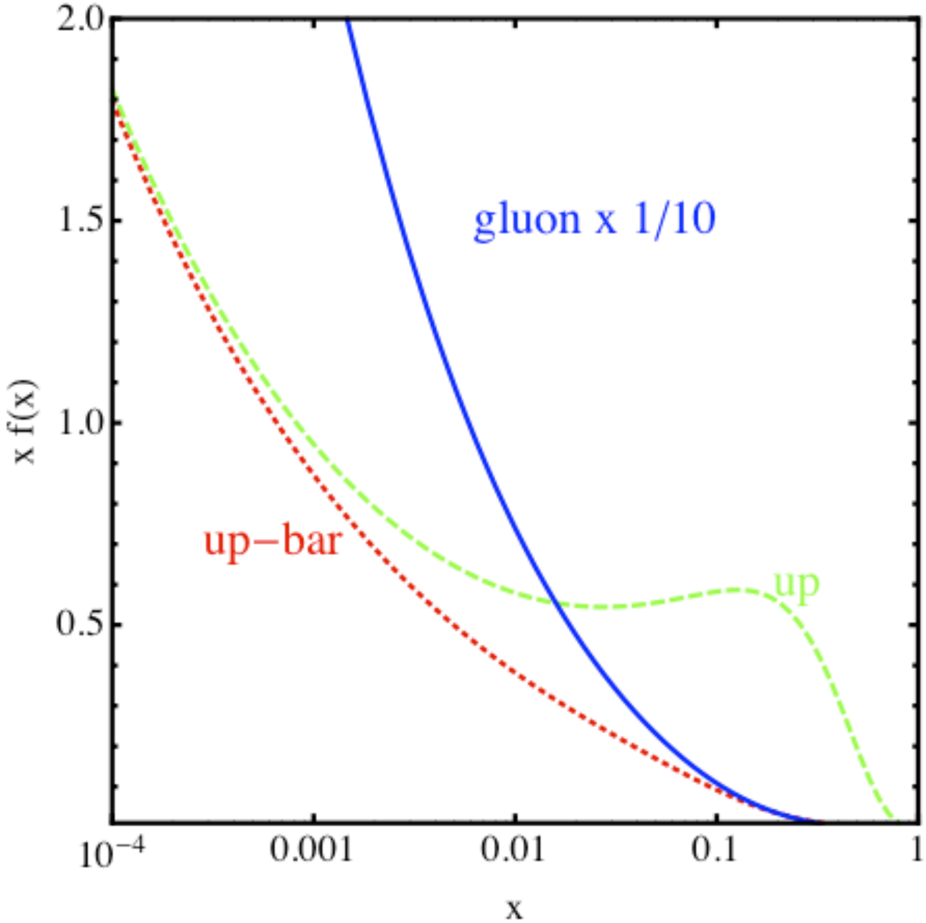
Qing-Hong Cao, Chuan-Ren Chen, Gabe Shaughnessy, Hao Zhang

arXiv:1005.2622

LHC decade

★ First years of the LHC decade will probe a new frontier of physics at the Terascale

DM, SUSY, UED, Exotics, etc.



$$\langle x \rangle \approx m_{\rm NP}/E_{cm}$$

★ Focus here on New Heavy Resonance. Production probes the large x region where valence-quarks dominate.

★ For early discovery at the LHC (7 TeV and $1 fb^{-1}$ luminosity), helps if the NP is **exotic**:

✳ ***Colored*** - large production rate

✳ ***Novel, easily detectable collider signature***
charged leptons, heavy flavor jets, MET, etc

✳ ***Small SM backgrounds***

Sextet scalar and same-sign top pair production

★ Quark-quark initial states can produce sextet and anti-triplet resonances

$$3 \times 3 = 6 + \bar{3}$$

$$3 \times \bar{3} = 1 + 8$$

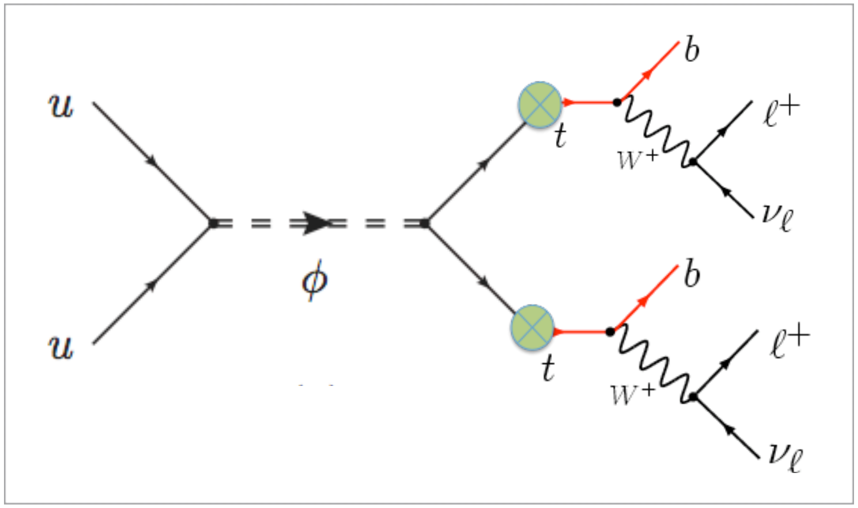
★ Observation of sextet scalar (ϕ) would imply changes in RGE unification equations

★ Couplings (λ_R^{ab}) are not proportional to quark mass; bounds from Tevatron data

$$\mathcal{L} \sim \phi_j^* K_{ab}^j q_a^T C^\dagger \lambda_R^{ab} P_R q_b + h.c.$$

★ K is a Clebsch Gordon factor

★ Same-sign top pair production



✳ large cross section

✳ Signature: same-sign charged lepton pair, b-jets, and large MET

✳ top quark polarization is crucial

We implement full spin correlations in our Monte Carlo simulation

Models

R. N. Mohapatra, Nobuchika Okada, Hai-Bo Yu, arXiv:0709.1486
Chuan-Ren Chen, William Klemm, Vikram Rentala and Kai Wang, arXiv:0811.2105
Jonathan M. Arnold, Maxim Pospelov, Michael Trott, Mark B. Wise, arXiv:0911.2225
Ilia Gogoladze, Yukihiro Mimura, Nobuchika Okada, Qaisar Shafi, arXiv:1001.5260

★ Electroweak quantum numbers

$SU(2)_L$	$U(1)_Y$	$\|Q\| = \|T_3 + Y\|$	couplings to
1	1/3	1/3	QQ, UD
3	1/3	1/3, 2/3, 4/3	QQ
1	2/3	2/3	DD
1	4/3	4/3	UU

$$Q = Q_L$$
$$U = u_R$$
$$D = d_R$$

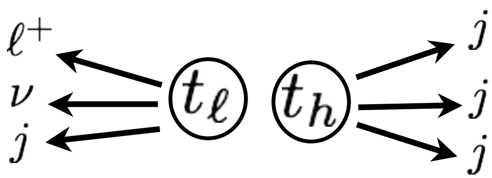
Constraints from the Tevatron

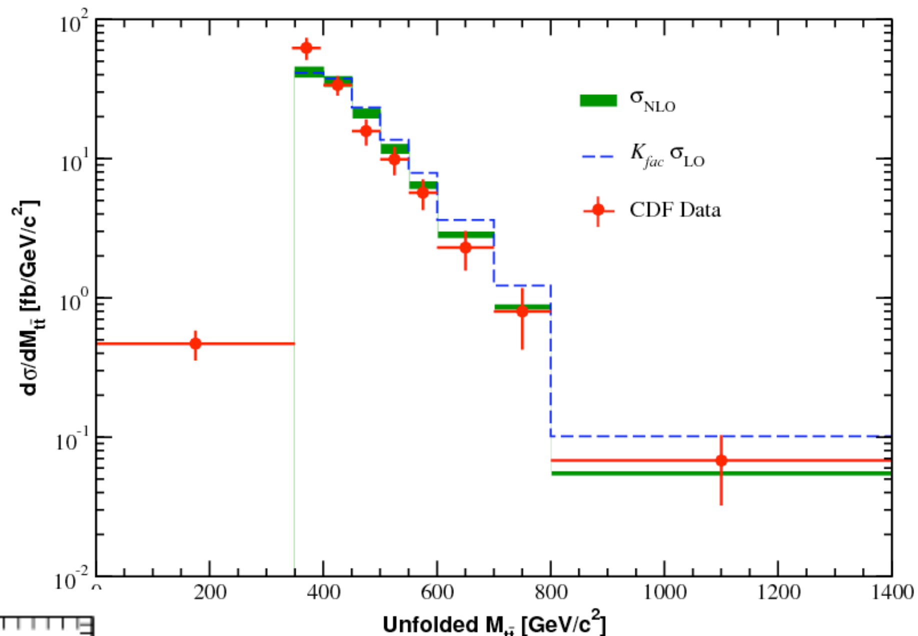
★ Top pair cross section constrained by CDF measurement of

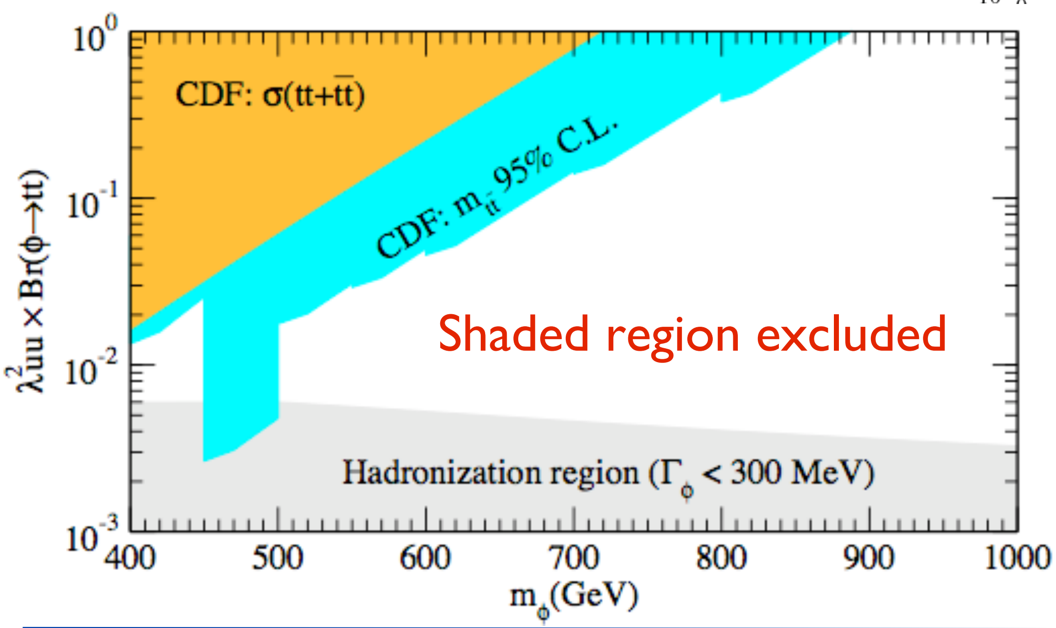
- ✳ Same-sign top pair search

$$\sigma_{tt+\bar{t}\bar{t}} < 0.7 \text{ pb}$$

- ✳ Distribution in $M_{t_\ell t_h}$



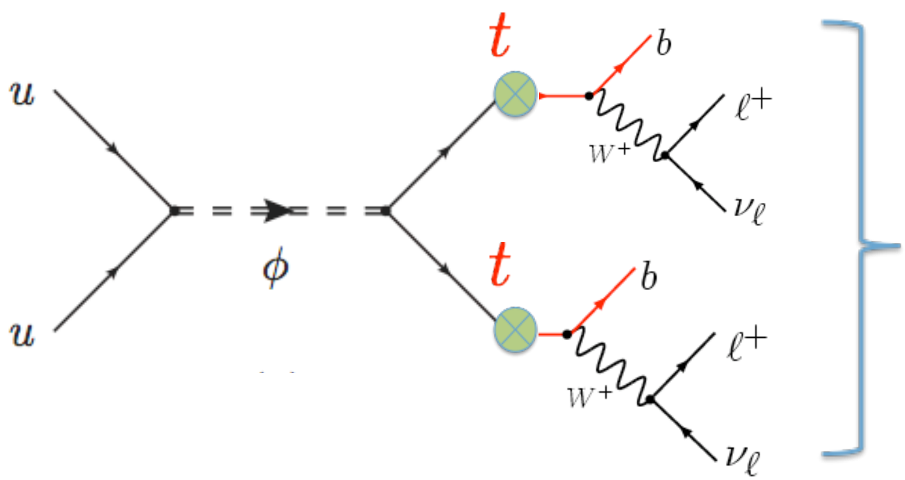




$$\sigma(uu \to \phi \to tt)$$
$$\propto \quad \sigma(uu \to \phi) \times Br(\phi \to tt)$$
$$\propto \quad [\sigma(uu \to \phi)|_{\lambda=1}]$$
$$\times \lambda_{uu}^2 Br(\phi \to tt)$$

Signal and backgrounds

★ Signal topology



same sign di-muons,
2 b-jets and MET

better reconstruction
than for electrons

★ Prominent backgrounds (ALPGEN)

$$pp \to t\bar{t} \to b\bar{b}W^+W^-,\ W^+ \to \ell^+\nu,\ W^- \to jj,\ \bar{b} \to \ell^+$$
$$pp \to W_1^+W_2^+jj,\ W^+ \to \ell^+\nu$$

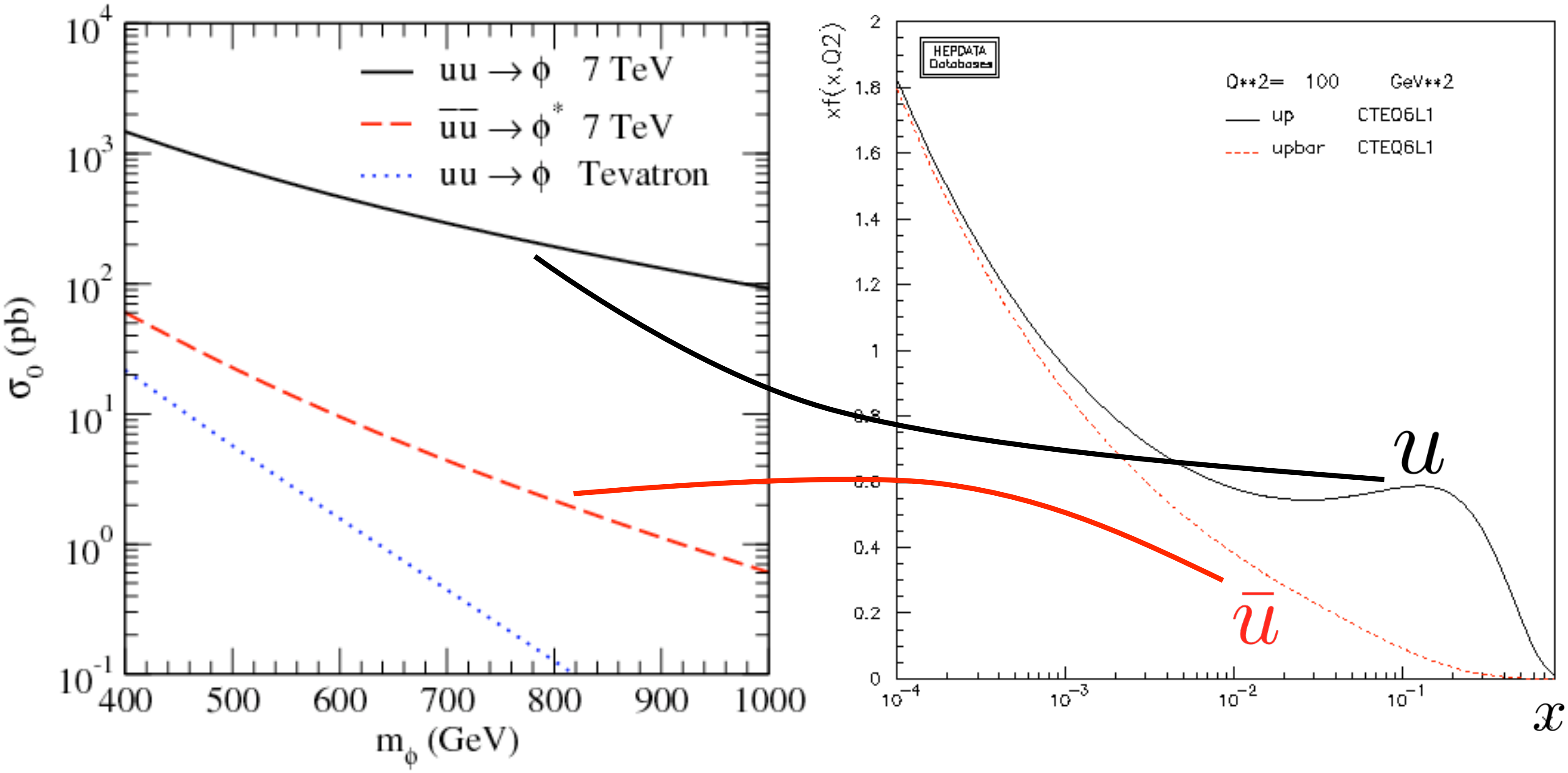
} Dominant backgrounds

$$pp \to W^+W^+W^-,\ W^+ \to \ell^+\nu,\ W^- \to jj$$
$$pp \to ZW^+W^-,\ Z \to \ell^+\ell^-,\ W^+ \to \ell^+\nu,\ W^- \to jj$$

First early hint at LHC

★ More positive di-muons

- ✳ same-sign top pairs contribute an asymmetry in charge multiplicity
- ✳ strong dependence on sextet scalar mass owing to PDF dependence



- ✳ Same-sign charge ratio gives an independent check on scalar mass

Simulation details

★ Acceptance cuts

✳ leptons $p_{T,\ell} \geq 20$ GeV $|\eta_\ell| < 2.0$

✳ jets: $p_{T,j} \geq 50$ GeV $|\eta_j| < 2.5$

✳ separation: $\Delta R_{\ell\ell,\ell j,jj} > 0.4$

★ Energy smearing $$\frac{\delta E}{E} = \frac{a}{\sqrt{E/\mathrm{GeV}}} \oplus b$$

✳ leptons: $a = 10\%,$ $b = 0.7\%$

✳ jets: $a = 50\%,$ $b = 3\%$

★ Tagging rates / Mistag rates

$$\epsilon_{c\to b} = 10\%, \quad \text{for } \mathrm{p_T(c)} > 50 \text{ GeV}$$

$$\epsilon_{u,d,s,g\to b} \approx 1\%$$

Discovery potential

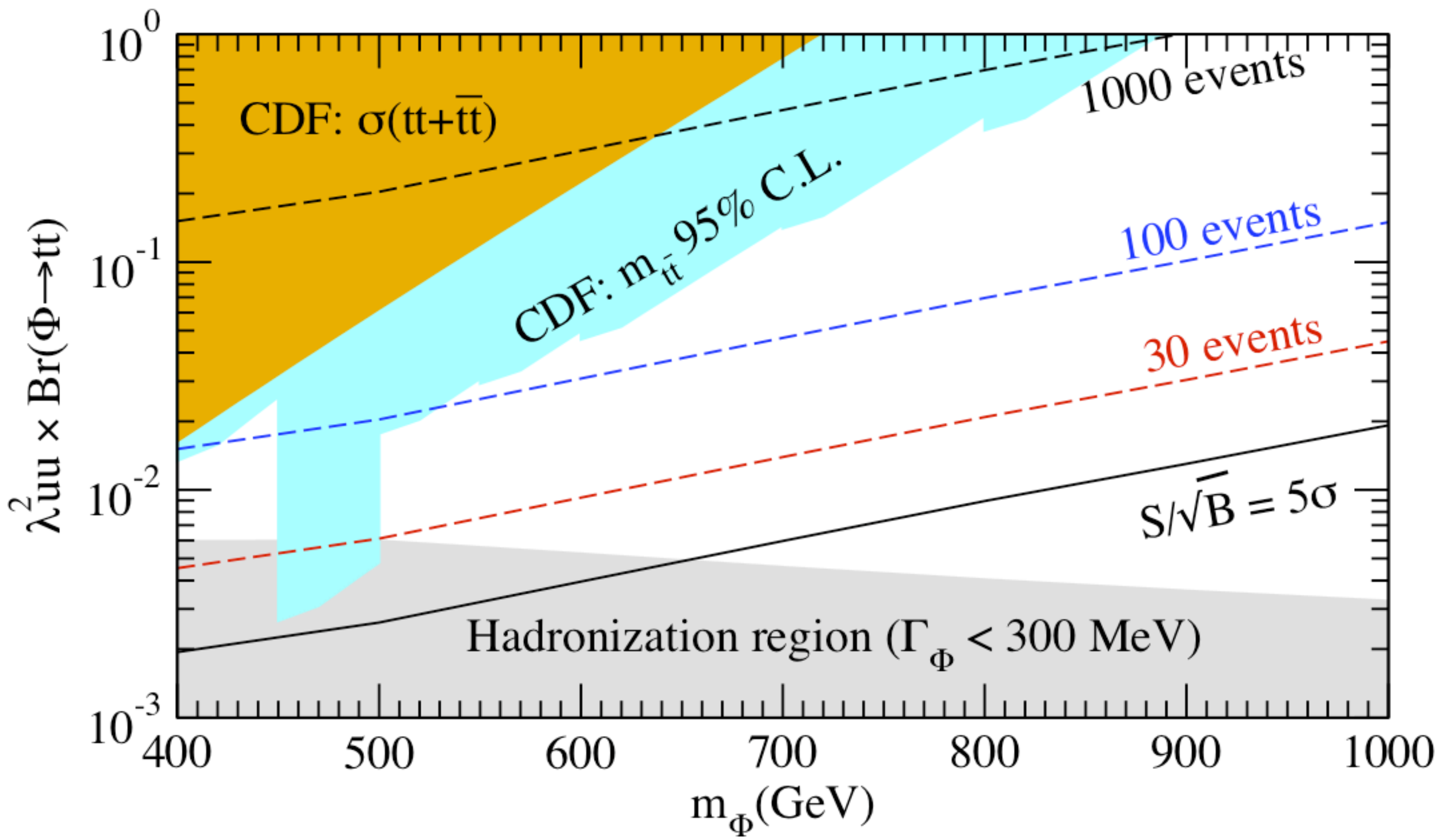
★ Simple cuts to extract signal:

- ✳ Same sign di-muons
- ✳ Two jets with pT>50GeV

✳ Shown are numbers of signal events;

✳ about 4.6 background events

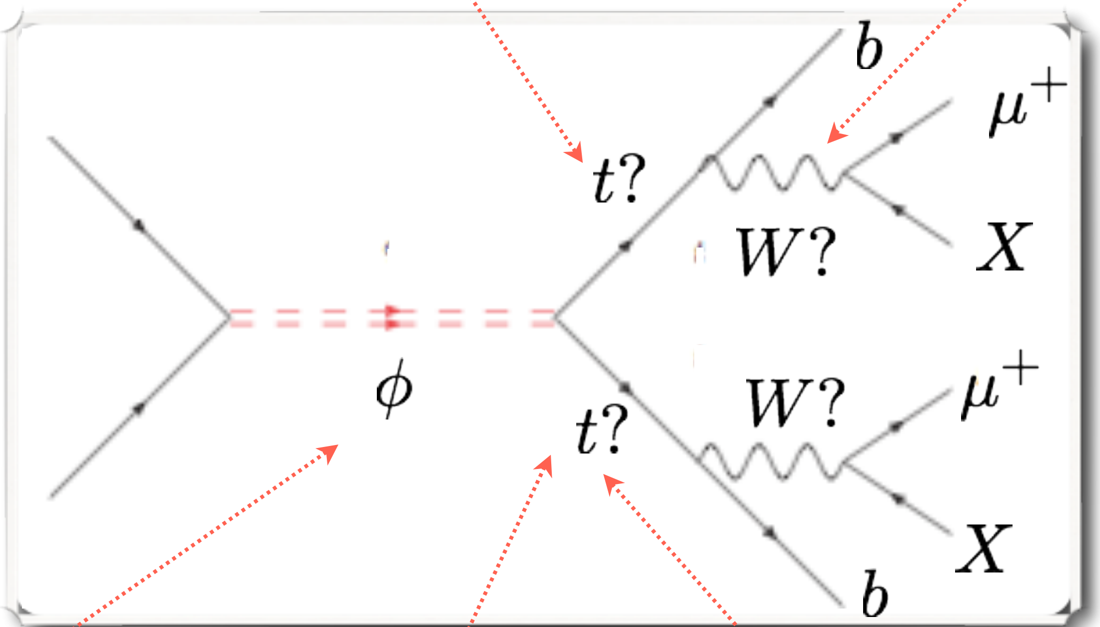
7 TeV $\mathcal{L} = 1\ \mathrm{fb}^{-1}$



Questions to be answered

(2) Does each jet + lepton pair reconstruct a top quark?

(1) Are the muons and missing X from W-boson decays?



Need full event reconstruction

Difficulty:
identical muons and b jets

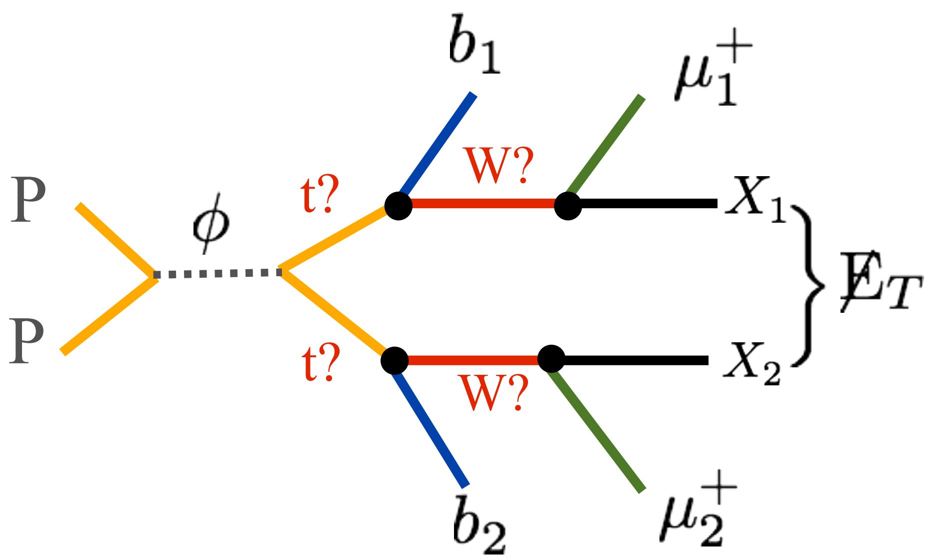
(3) What is the mass of the resonance?

(4) What is top quark polarization?

(5) Are the top quarks from a scalar decay?

Transverse mass and MT2

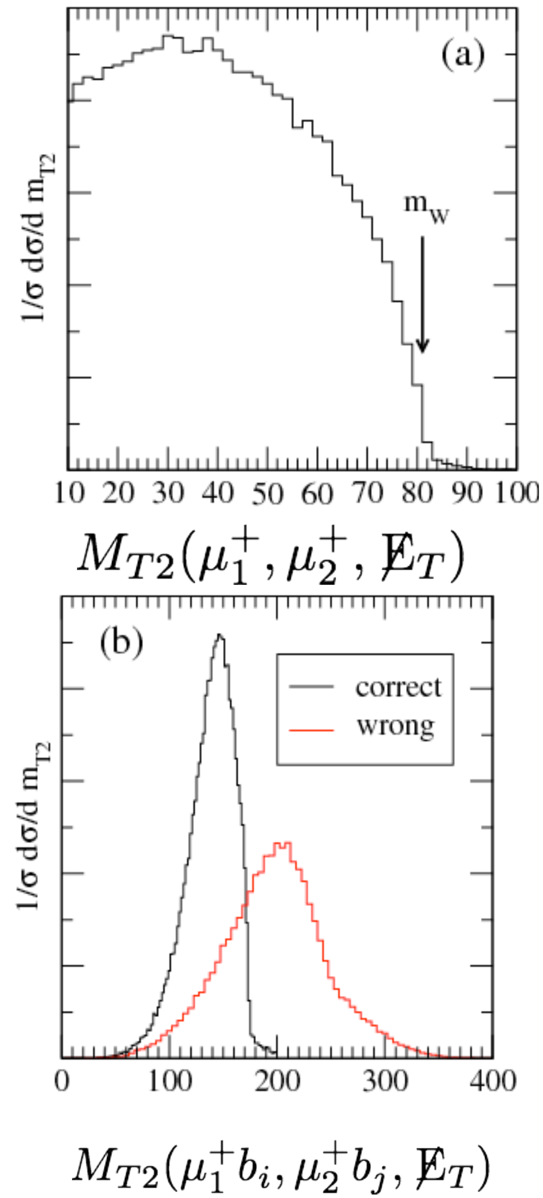
★ MT2 is similar to transverse mass of W-boson, but works for the case of two missing particles in the final state



$$M_{T2}^2(\mu_1^+, \mu_2^+, \not{E}_T) \leq m_W^2$$

$$M_{T2}^2 \equiv \min_{\not{\vec{p}}_{X_1} + \not{\vec{p}}_{X_2} = \not{\vec{p}}_T} \left[\max\left\{ m_T^2(\vec{p}_T^{\,\mu_1^+}, \not{\vec{p}}_{X_1}), m_T^2(\vec{p}_T^{\,\mu_2^+}, \not{\vec{p}}_{X_2}) \right\} \right]$$

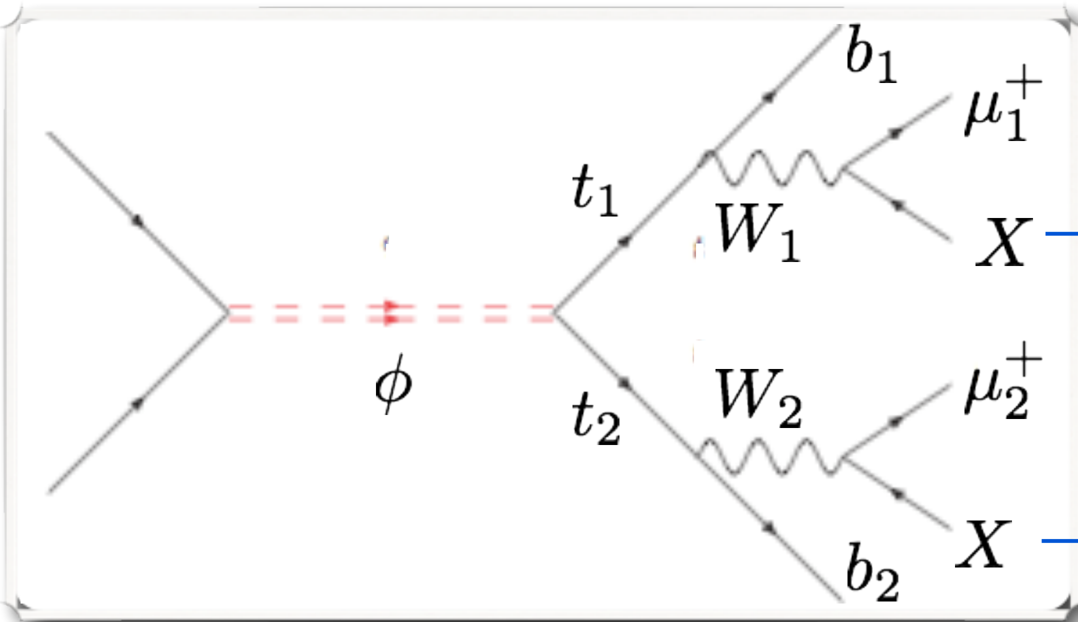
C. G. Lester and D. J. Summers, hep-ph/9906349



Choose smaller MT2 (correct combination found with 95% probability)

Full kinematic reconstruction

★ Four unknowns and four on-shell conditions



6 unknowns
-2 from MET

$$m_{W_1}^2 = (p_{\mu_1} + p_{\nu_1})^2$$
$$m_{W_2}^2 = (p_{\mu_2} + p_{\nu_2})^2$$
$$m_{t_1}^2 = (p_{W_1} + p_{b_1})^2$$
$$m_{t_2}^2 = (p_{W_2} + p_{b_2})^2$$

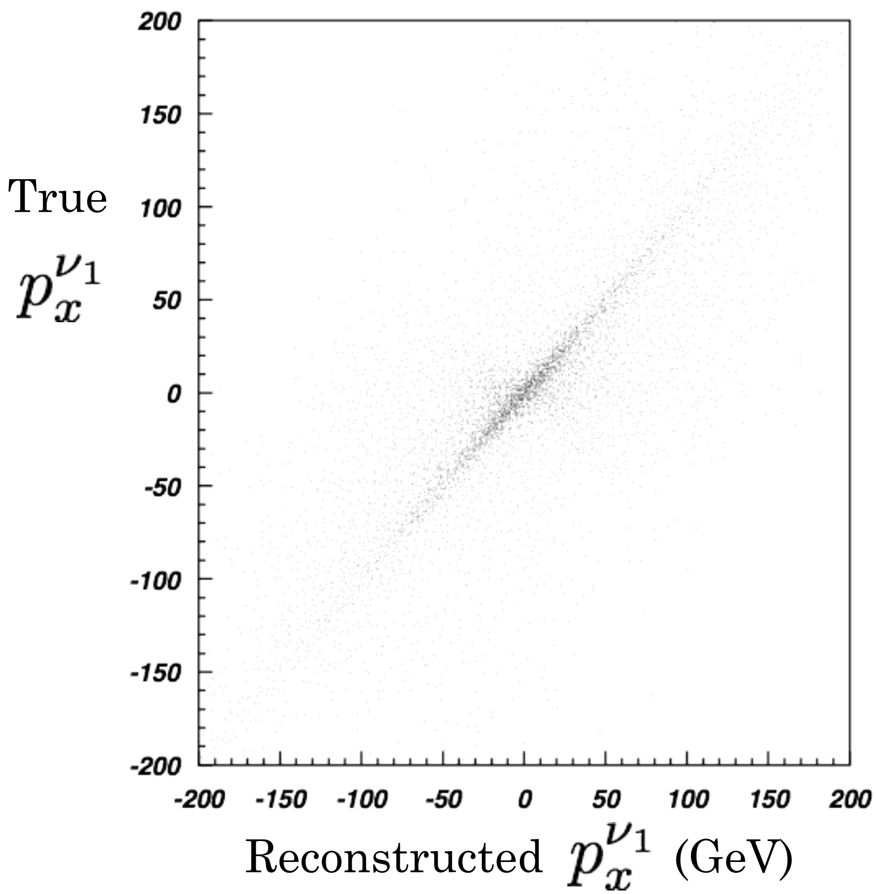
Quartic equation

$$p_x^4(\nu_1) + a\ p_x^3(\nu_1) + b\ p_x^2(\nu_1) + c\ p_x(\nu_1) + d = 0$$

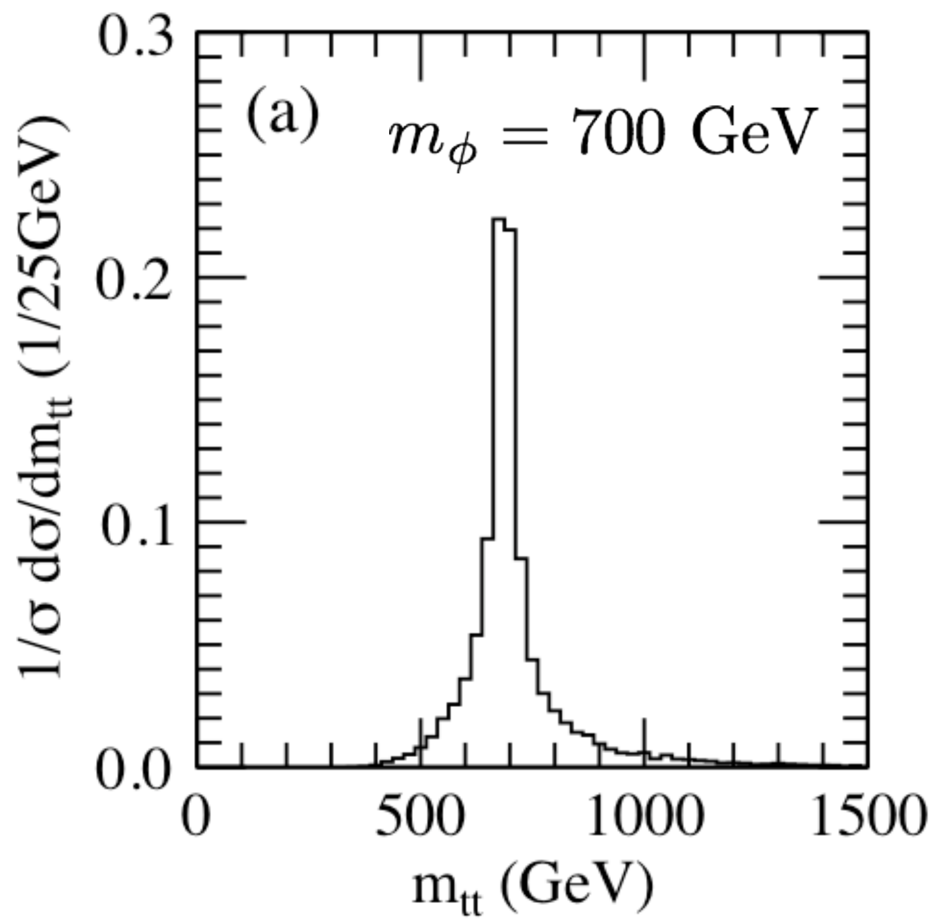
~~Two complex~~, two real solutions

Reconstructed event distribution

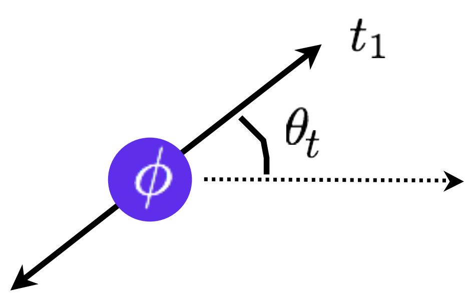
★ Strong correlation between the true $p_x^{\nu_1}$ and reconstructed $p_x^{\nu_1}$

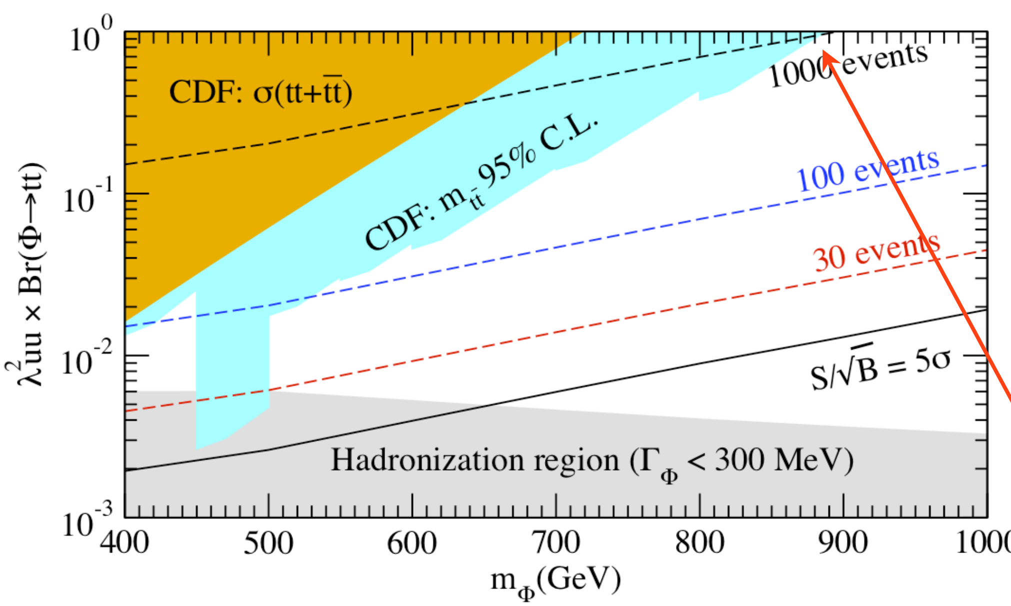


★ The mass of the heavy resonance can be determined:



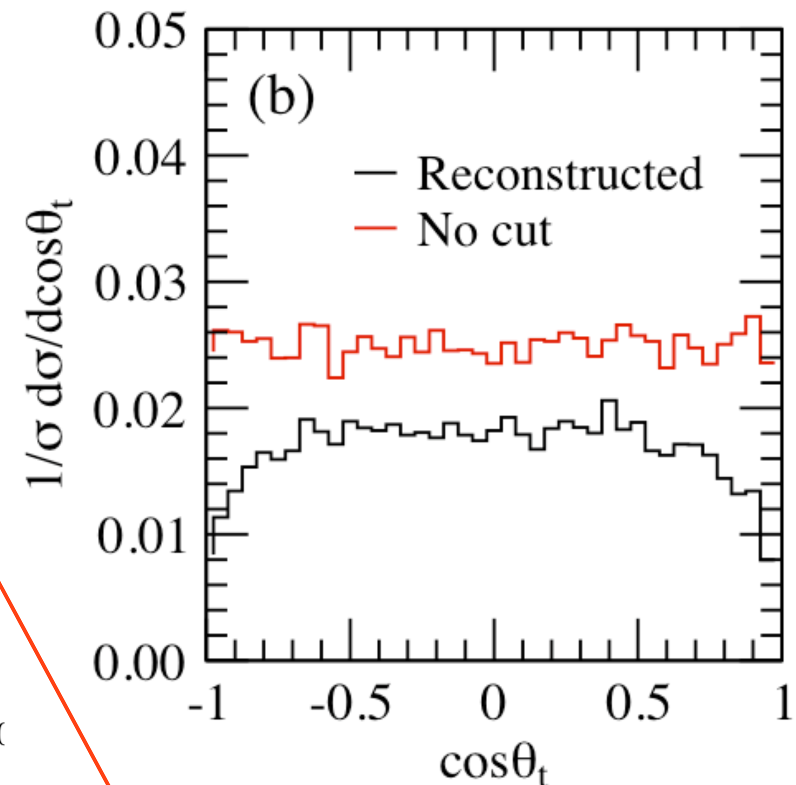
Reconstructed event distribution





★ Can we determine the spin of the heavy resonance?

Not easy !



Not realistic for early LHC!

It requires ~ O(4000) events to verify the flat distribution.

Top quark polarization and resonance spin

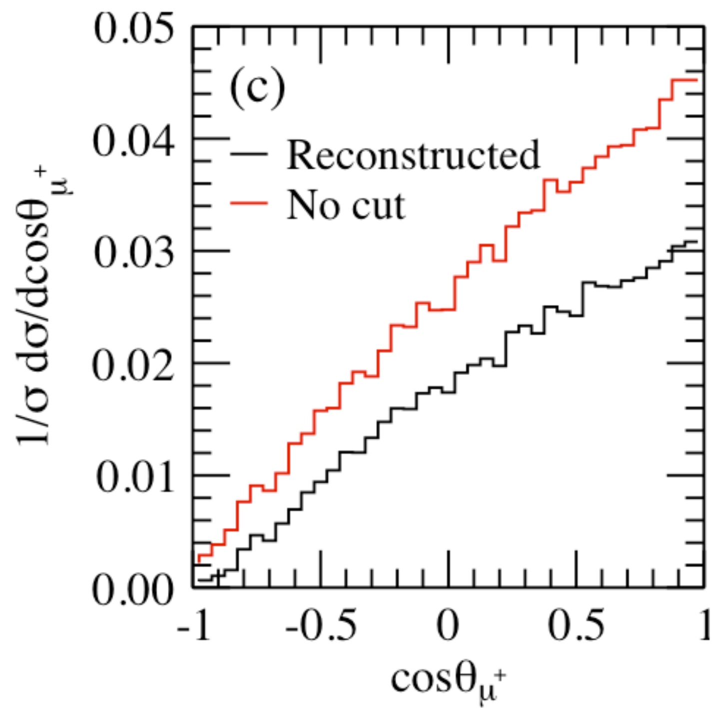
★ Polarization correlates with angle between top quark spin and charged lepton momenta

$$\frac{1}{\Gamma}\frac{d\Gamma(t \to b\ell\nu)}{d\cos\theta} = \frac{1}{2}\left(1 + \frac{N_+ - N_-}{N_+ + N_-}\cos\theta\right)$$

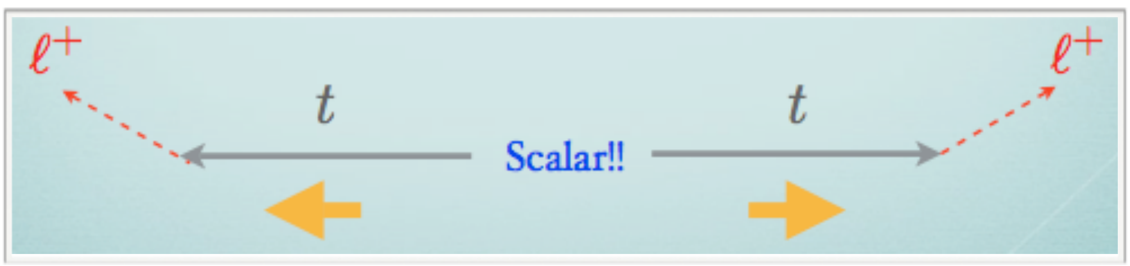
✳ Charged lepton typically follows top quark spin

✳ Right-handed top quark yields $\frac{1}{2}(1+\cos\theta)$

✳ Roughly 30 events required to distinguish from unpolarized case



Polarization of the top quarks can be determined to be right-handed



Are the top quarks from a scalar decay? Yes !

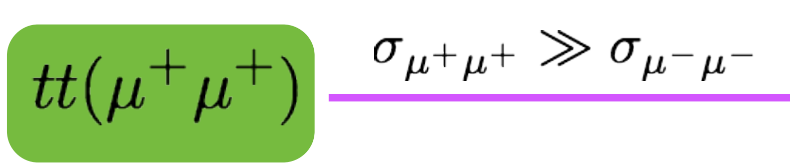
Summary

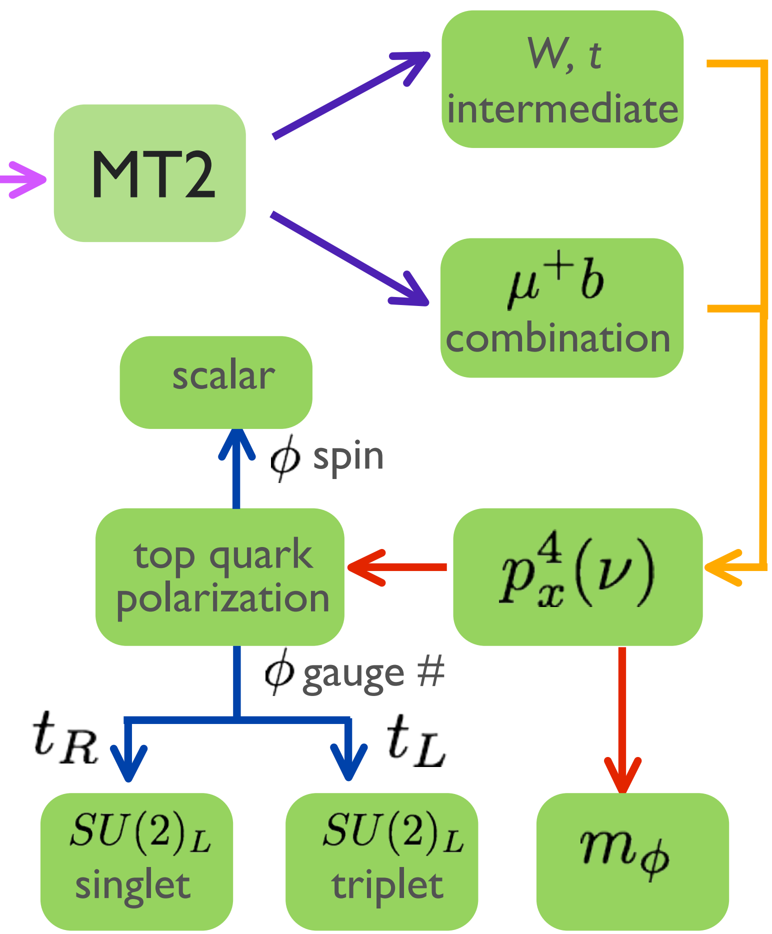
★ Color sextet scalar may be a long shot but offers good discovery potential at 7 TeV

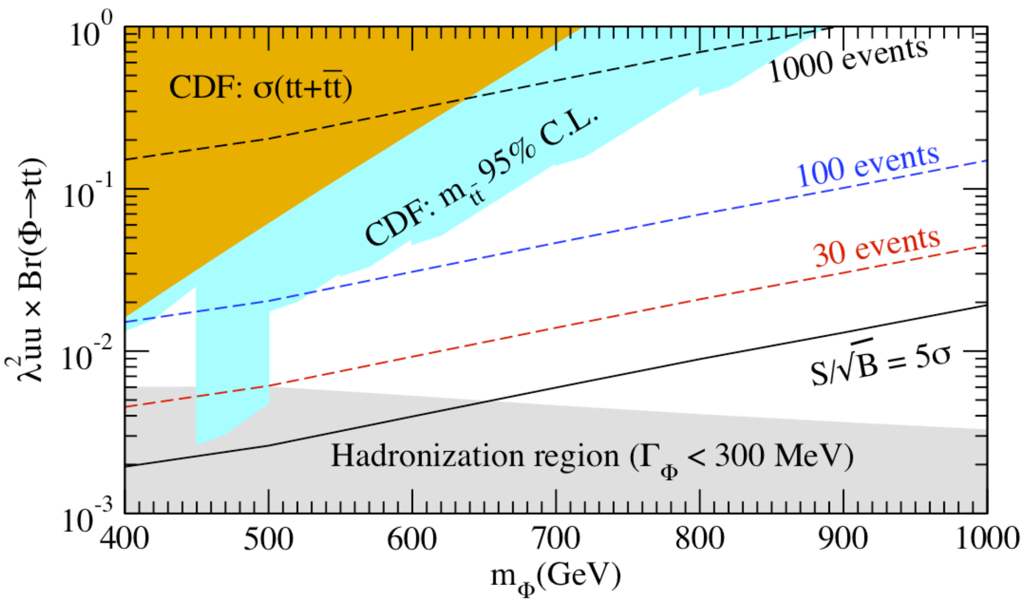
✳ Enhanced cross section relative to EW scale new physics; 30 events sufficient

✳ Naturally large same-sign dilepton rates allow background rejection

★ Search strategy

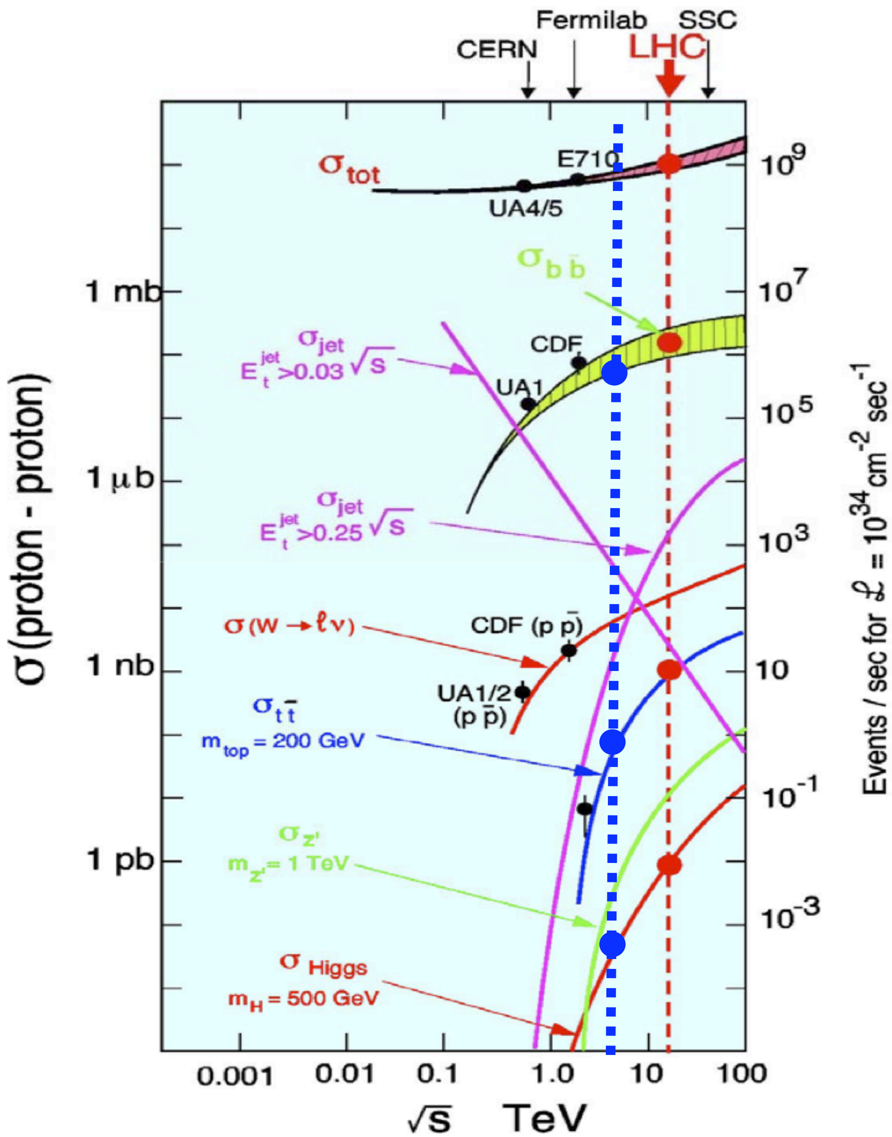






Backup Slides

LHC decade



★ Rate for $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}s^{-1}$

- Inelastic proton-proton reactions: $10^9/s$
- bottom quark pairs: $5 \times 10^6/s$
- top quark pairs: $10/s$
- $W \to \ell\nu$ $150/s$
- $Z \to \ell\ell$ $15/s$
- Higgs boson (150GeV): $0.2/s$
- Gluino, Squarks (1TeV): $0.03/s$

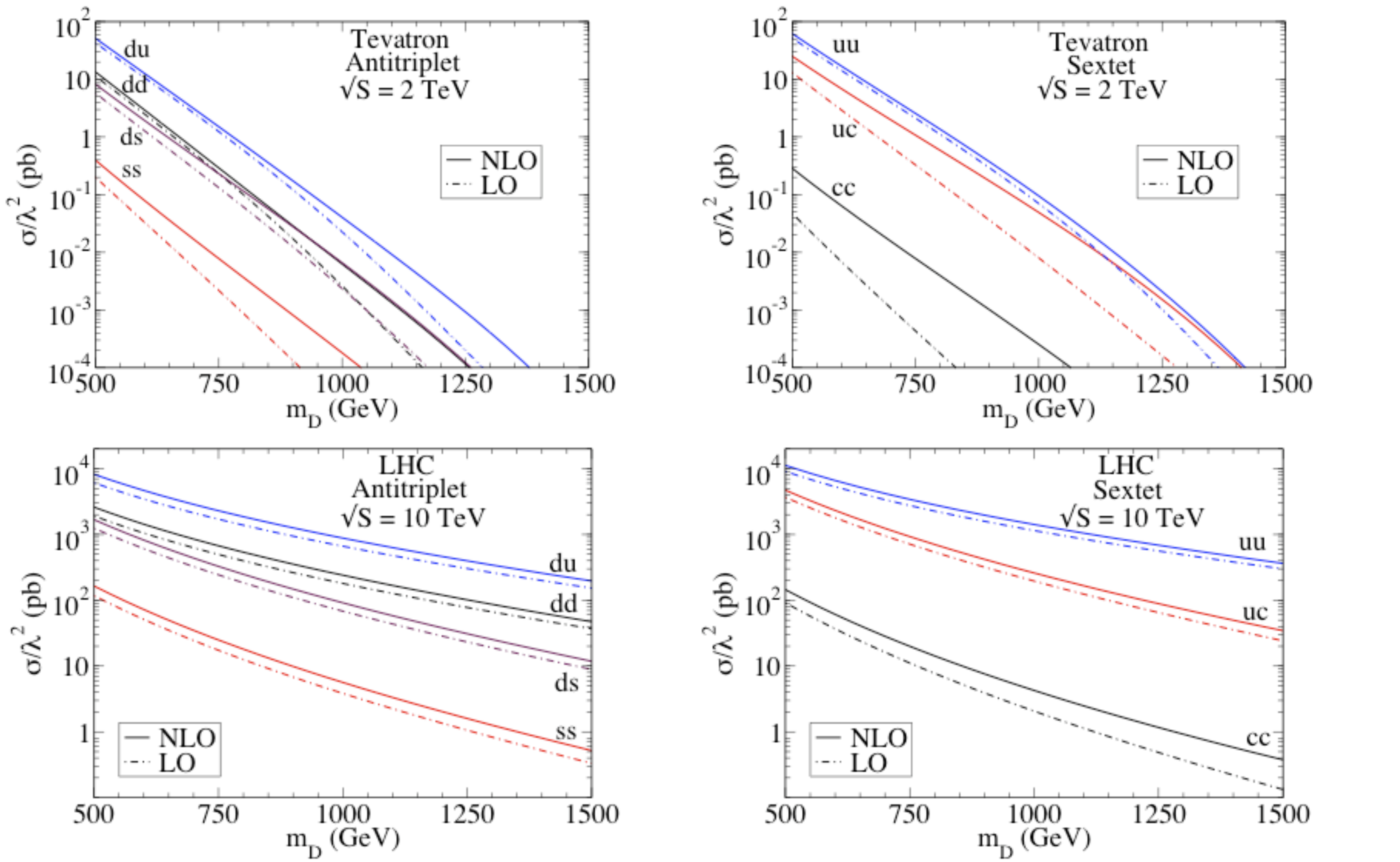
(1) LHC is a factory for SM and new TeV scale physics.

(2) What new physics may be observable at 7 TeV? And how?

Production cross sections at NLO

★ NLO QCD corrections for single color sextet scalar production are available

Han, Lewis, McElmurry, 0909.2666



Top quark polarization

★ Among the top quark decay products, the charged lepton is maximally correlated with top quark spin.

$$\frac{1}{\Gamma}\frac{d\Gamma(t\to b\ell\nu)}{d\cos\theta}=\frac{1}{2}\left(1+\frac{N_+ - N_-}{N_+ + N_-}\cos\theta\right)$$

★ θ is the angle, in the top quark rest frame, between the direction of the charged lepton and the spin of the top quark. In the helicity basis, top quark spin is along its direction of motion.