Top Quark Forward-Backward Asymmetry, Same-sign Top Quark Pairs, and New Physics

Qing-Hong Cao (曹庆宏)

Peking University

In collaboration with:

Ed Berger, Chuan-Ren Chen, Chong Sheng Li, Gabe Shaughnessy, Jiang-Hao Yu, Hao Zhang

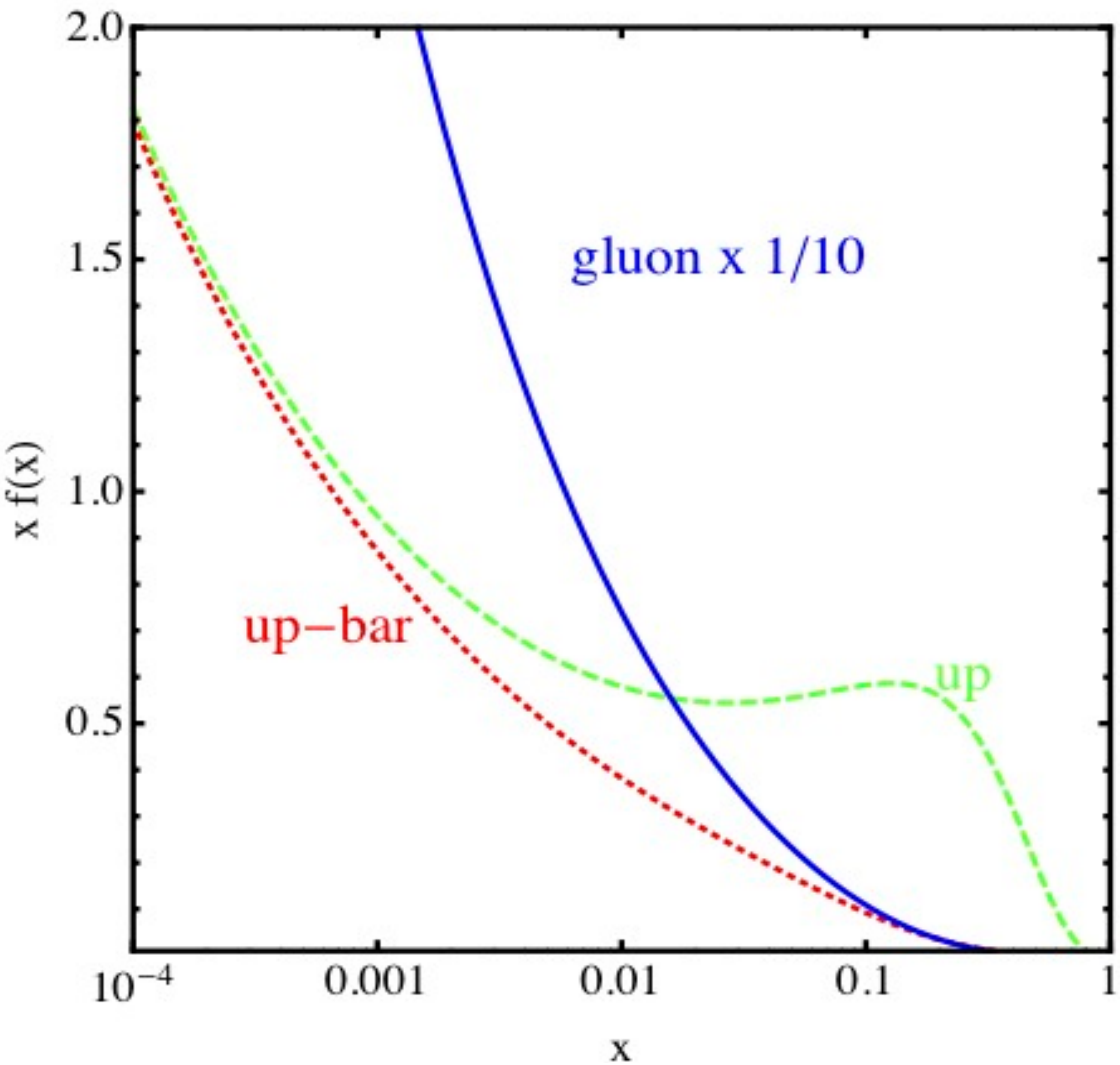
arXiv:1005.2622, Phys Rev Lett **105**,181802 (2010)
arXiv:1009.5379, Phys Lett B **696** (2001) 68
arXiv:1101.5625, Phys Rev Lett **106**, 201801 (2011)
arXiv:1111.3641, to be published in Phys. Rev. Lett.

Dec 9, 2011 @ GUCAS

Why do we study same-sign top pair?
(A not so BAD/GOOD motivation)

★ First years of the LHC 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 Resonances. Production probes the large x region where valence-quarks dominate.

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

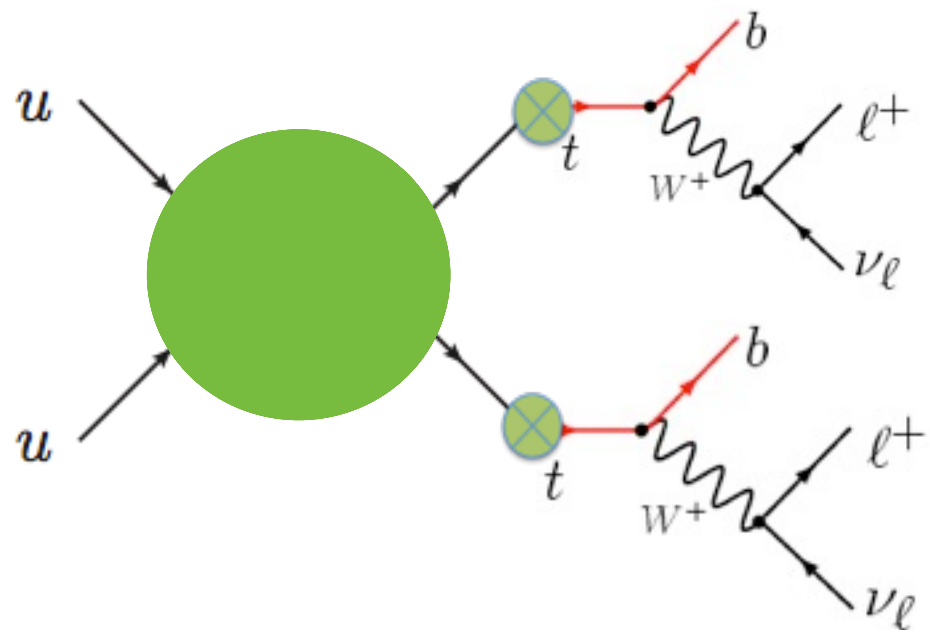
✳ ***Colored*** - large production rate

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

✳ ***Small SM backgrounds***

Why do we study same-sign top pair?
(A not so BAD/GOOD motivation)

★ same-sign top pair production

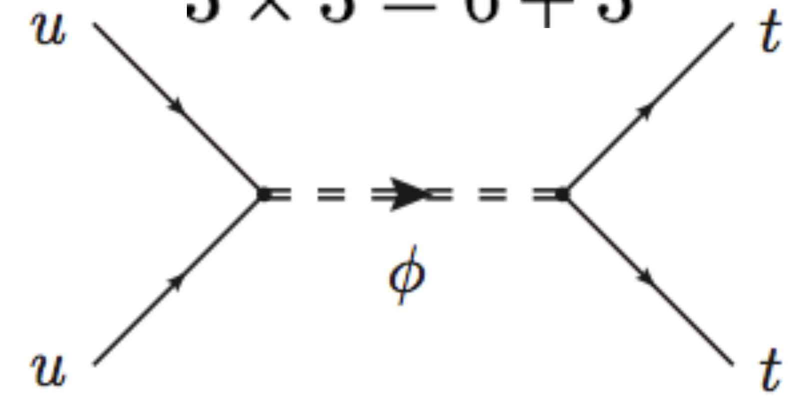


* ✳ Potentially large cross section
* ✳ Signature: same-sign charged lepton pair, b-jets, and large MET
* ✳ top quark polarization can be measured.

★ s-channel resonance

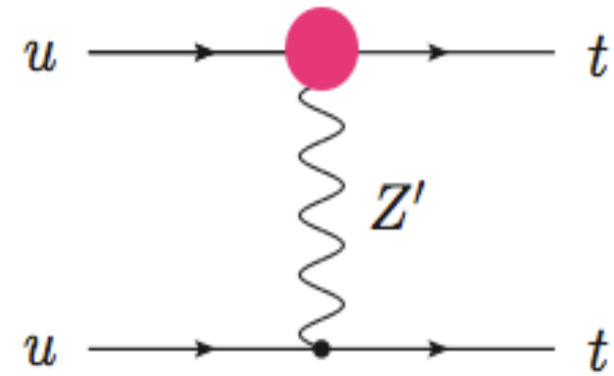
Quark-quark initial states can produce color sextet and anti-triplet resonances

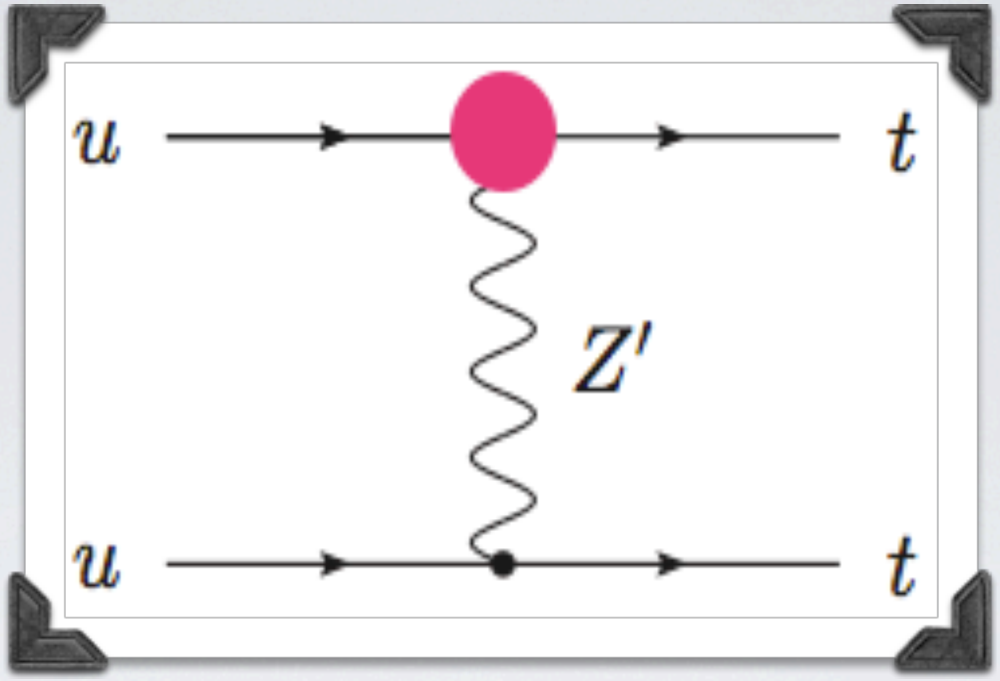
$$3 \times 3 = 6 + \bar{3}$$



★ t-channel process

Flavor changing neutral current Z-prime





Flavor Changing Neutral Z-prime

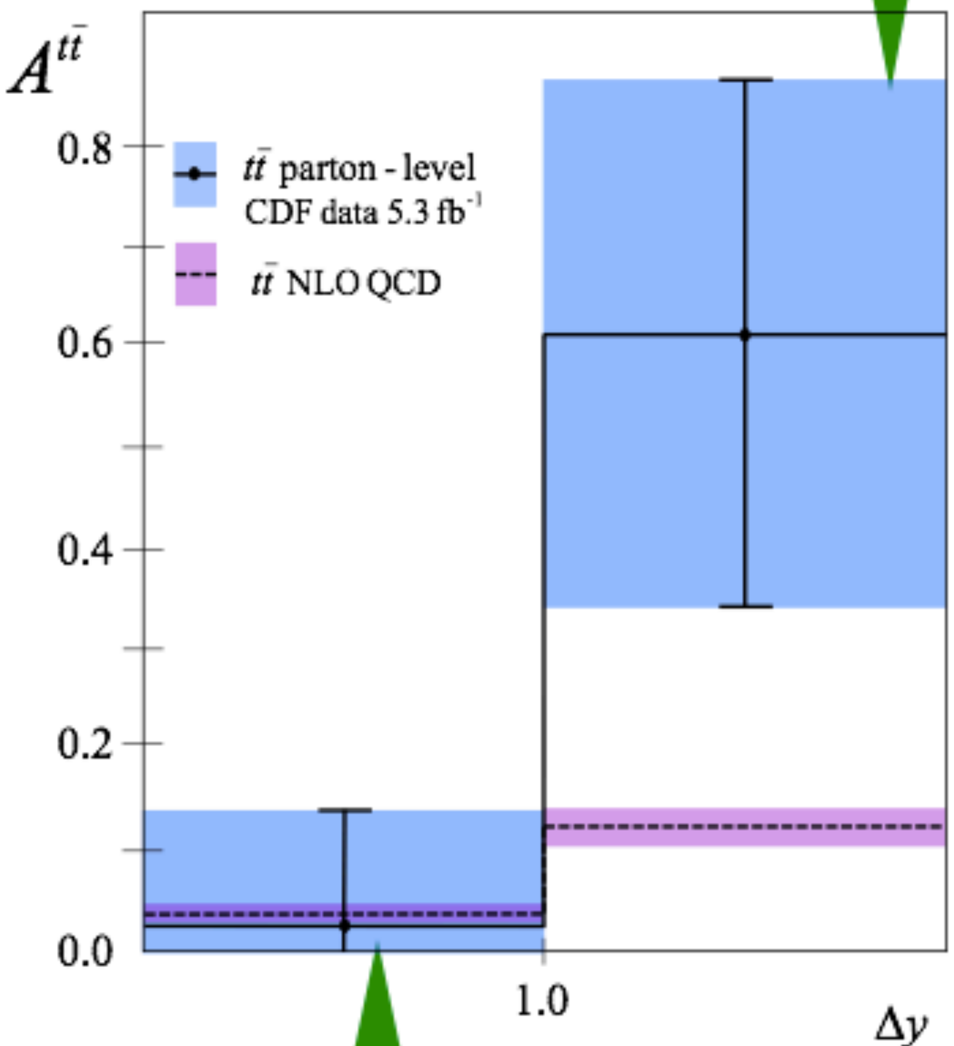
(Motivated by the Top-quark Forward-Backward Asymmetry)

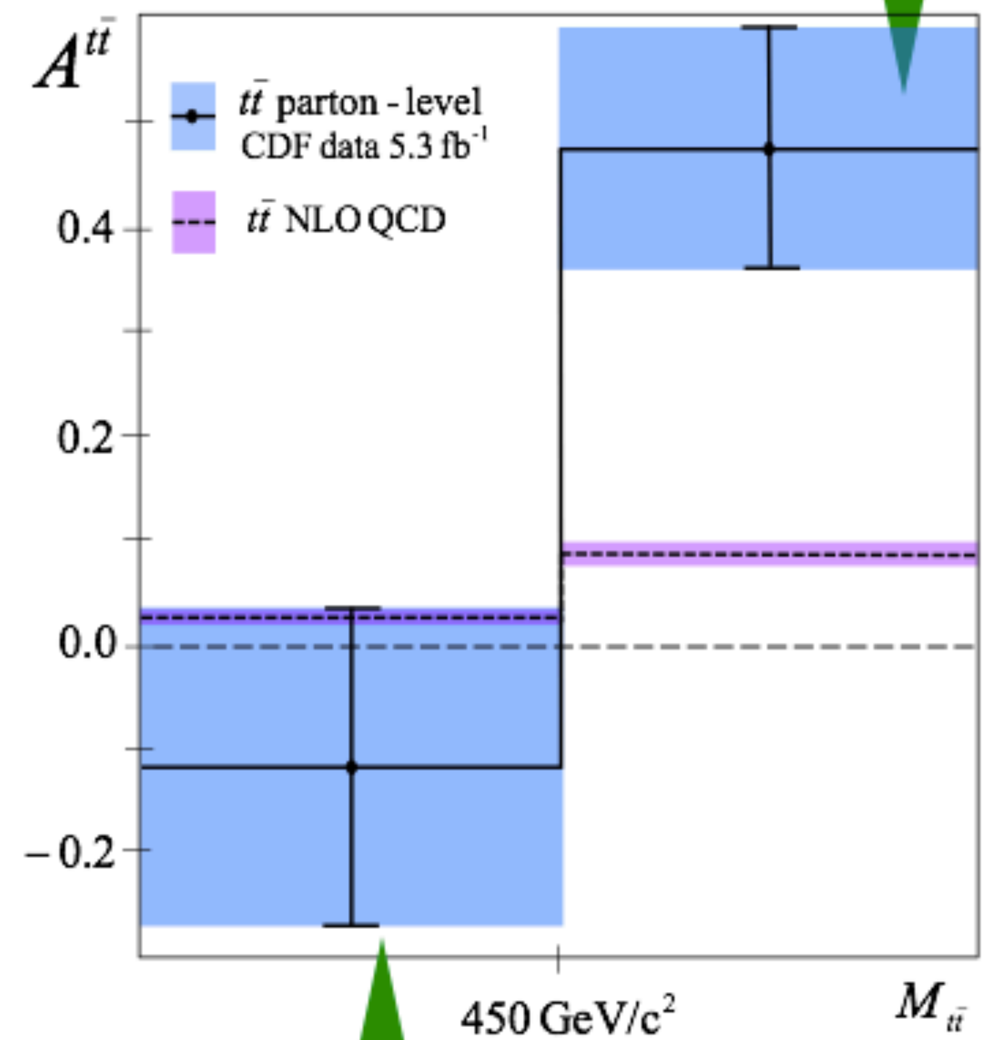
CDF measurement

arXiv:1101.0034 5.3 fb^{-1}

$$A_{FB}^{\mathrm{obs}} = 0.611 \pm 0.256$$
$$A_{FB}^{\mathrm{SM}} = 0.123 \pm 0.018$$

$$A_{FB}^{\mathrm{obs}} = 0.475 \pm 0.112$$
$$A_{FB}^{\mathrm{SM}} = 0.088 \pm 0.013$$





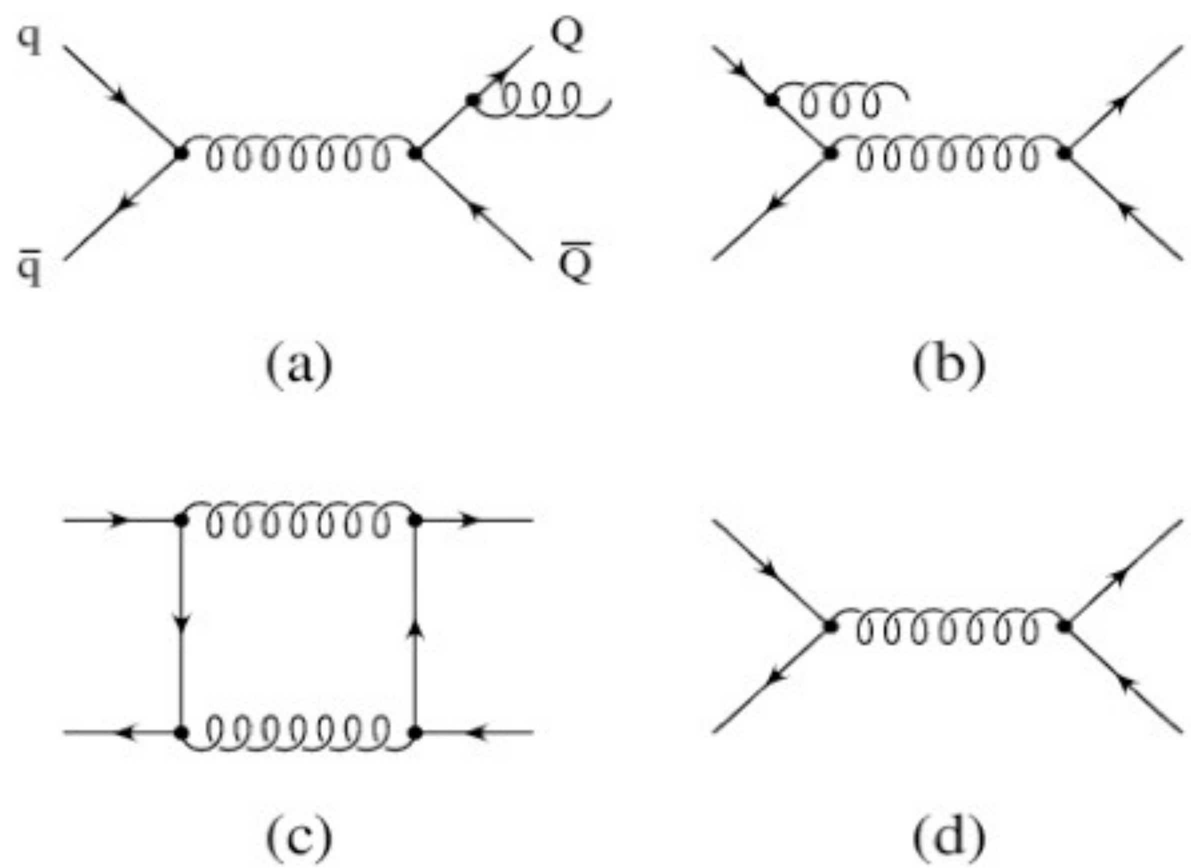
$$A_{FB}^{\mathrm{obs}} = 0.026 \pm 0.118$$
$$A_{FB}^{\mathrm{SM}} = 0.039 \pm 0.006$$

$$A_{FB}^{\mathrm{obs}} = -0.116 \pm 0.153$$
$$A_{FB}^{\mathrm{SM}} = 0.040 \pm 0.006$$

Charge asymmetry

★ A charge asymmetry arises at NLO

Kühn and Rodrigo,1998



Top quarks are produced along the direction of the incoming quark

$$A^{p\bar{p}} = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)} = 0.051(6)$$

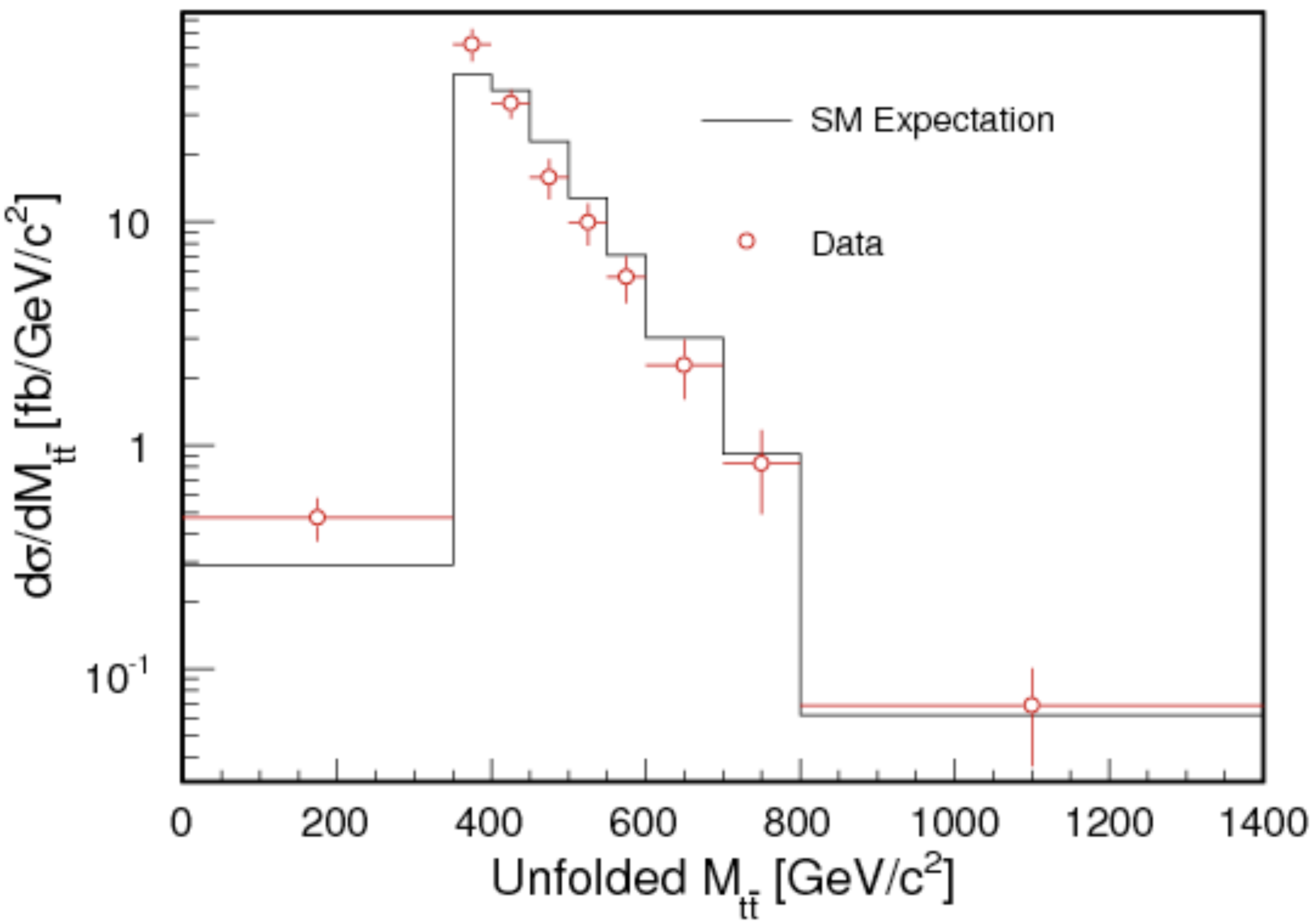
Too small

Needs NP

$$A^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$

Invariant mass spectrum of top quark pair

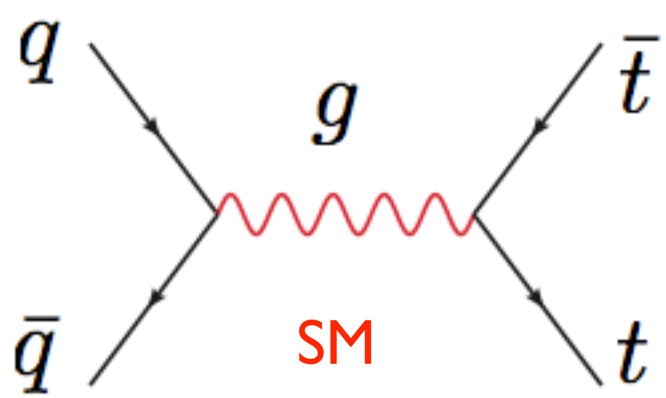
CDF, Phys.Rev.Lett. 102 (2009) 222003



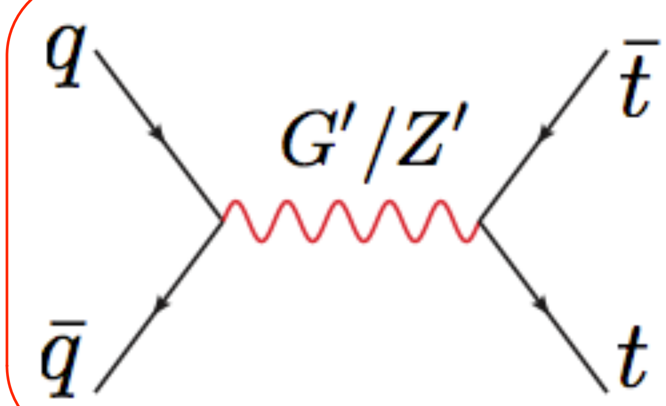
It provides upper bounds on NP resonance.
The large bin (800GeV-1400GeV) is
the most sensitive to a heavy resonance

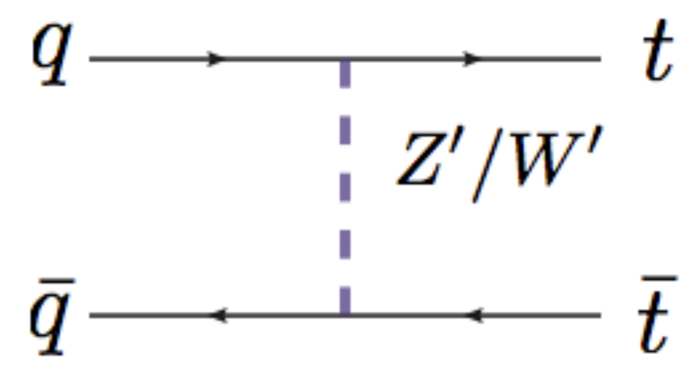
New physics models

★ NP models are divided into two classes



BSM





s-channel: extra octet vector gluon (axigluon is the best)

small couplings to the first two generations: dijet constraints at 7 TeV

large couplings to third generation: to generate large A_{FB}

heavy resonances: ttbar invariant mass spectrum

Very broad width: to interfere with the SM channel

t-channel: Flavor changing interaction

color singlet: Z'-u-t (ϕ-u-t) color sextet or triplet

W'$^+$-d-t (ϕ^+-d-t)

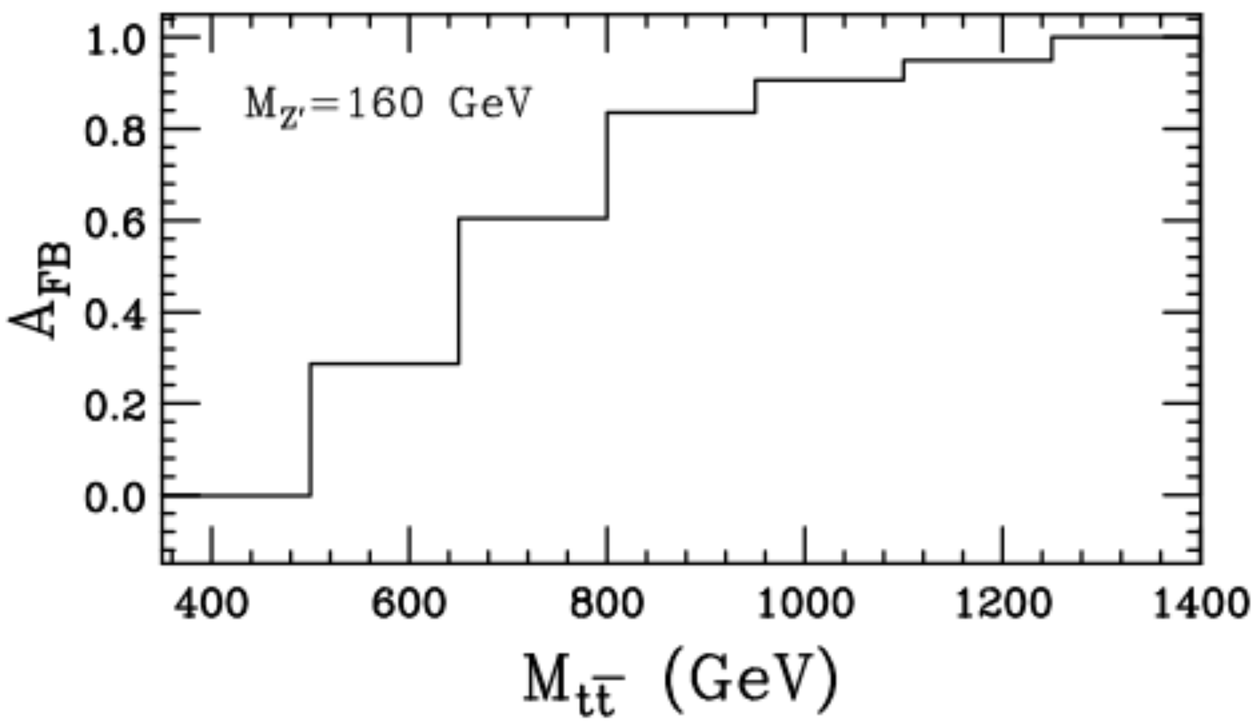
What can one say about the FCNC Z' model at 7 TeV (or at the Tevatron)?

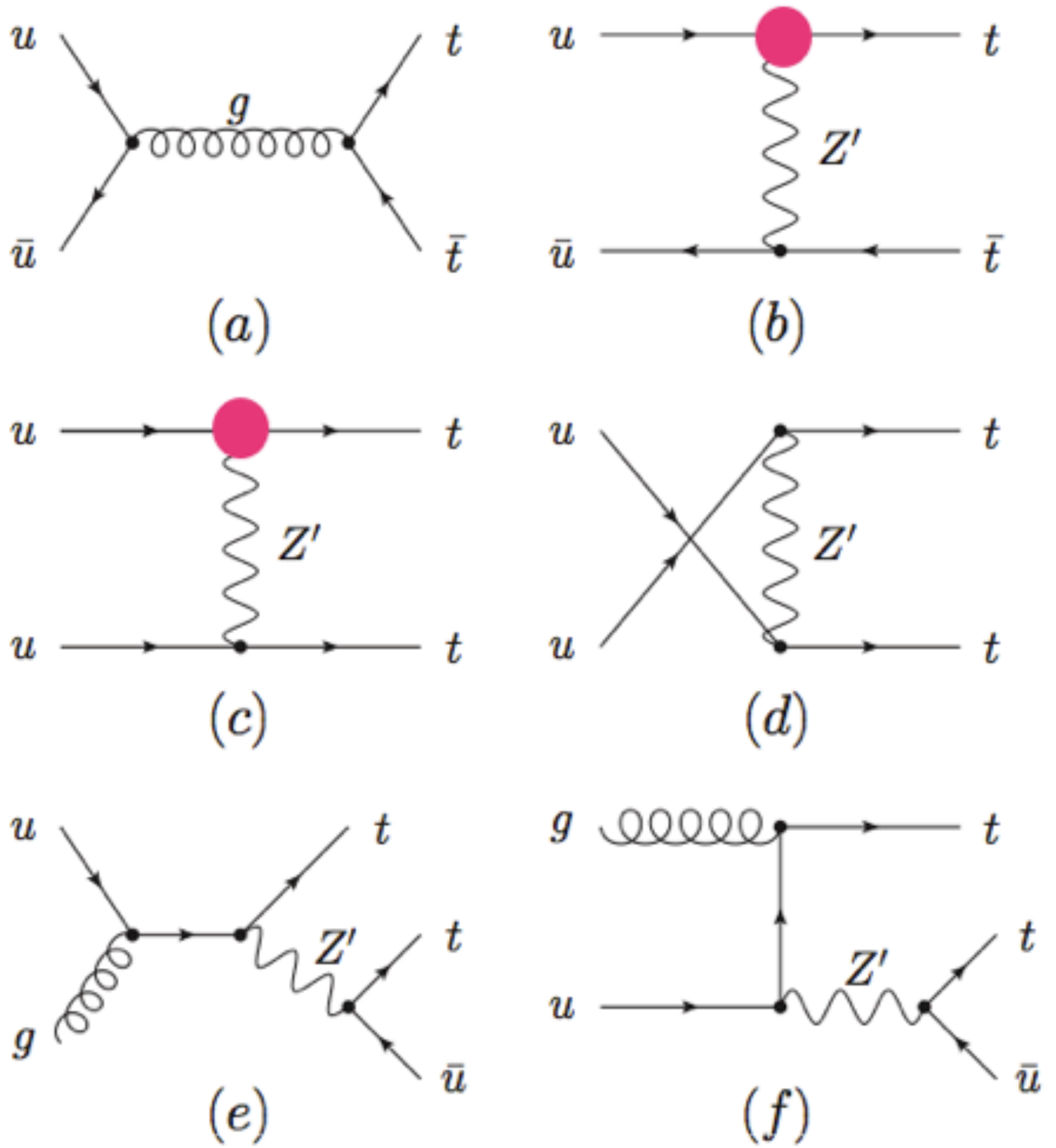
FCNC Z-prime model

$$\mathcal{L} = g_W \bar{u} \gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + h.c.$$

Left-handed coupling is highly constrained by $B_d - \bar{B}_d$ mixing.

Jung et al, Phys.Rev. D81 (2010) 015004





A large FCNC coupling is needed to explain A_{FB} data.

Differential cross section

$$\frac{d\sigma}{d\cos\theta} = \mathcal{A}_{SM} + \mathcal{A}_{INT} + \mathcal{A}_{NPS} \qquad f_L = 0$$

$$\mathcal{A}_{SM} = \frac{2g_s^4}{9}\left(2 - \beta^2 + \beta^2\cos^2\theta\right)$$

$$\mathcal{A}_{INT} = \frac{\beta g_s^2 g_w^2}{72\pi\hat{s}} \frac{f_R^2}{\hat{s}(\hat{t} - m_{Z'}^2)}\left[2(\hat{u} - m_t^2)^2 + 2\hat{s}m_t^2 + \frac{m_t^2}{m_{Z'}^2}((\hat{t} - m_t^2)^2 + \hat{s}m_t^2)\right]$$

$$\mathcal{A}_{NPS} = \frac{\beta g_w^4}{128\pi\hat{s}} \frac{f_R^4}{(\hat{t} - m_{Z'}^2)^2}\left[4(\hat{u} - m_t^2)^2 + \frac{m_t^4}{m_{Z'}^4}(4\hat{s}m_{Z'}^2 + (\hat{t} - m_{Z'}^2)^2)\right]$$

$$\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

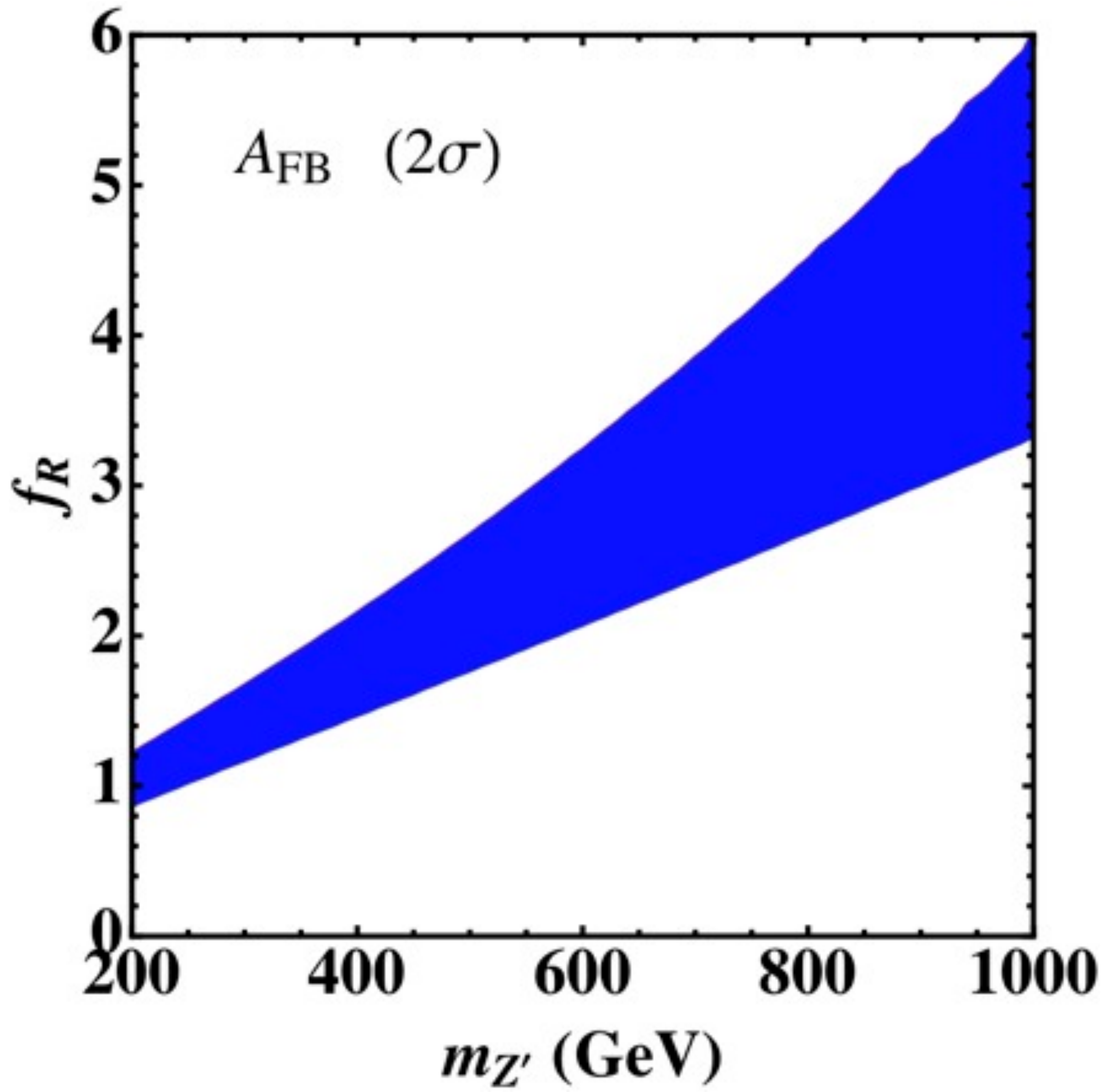
★ INT contribution is negative because $\hat{t} < 0$

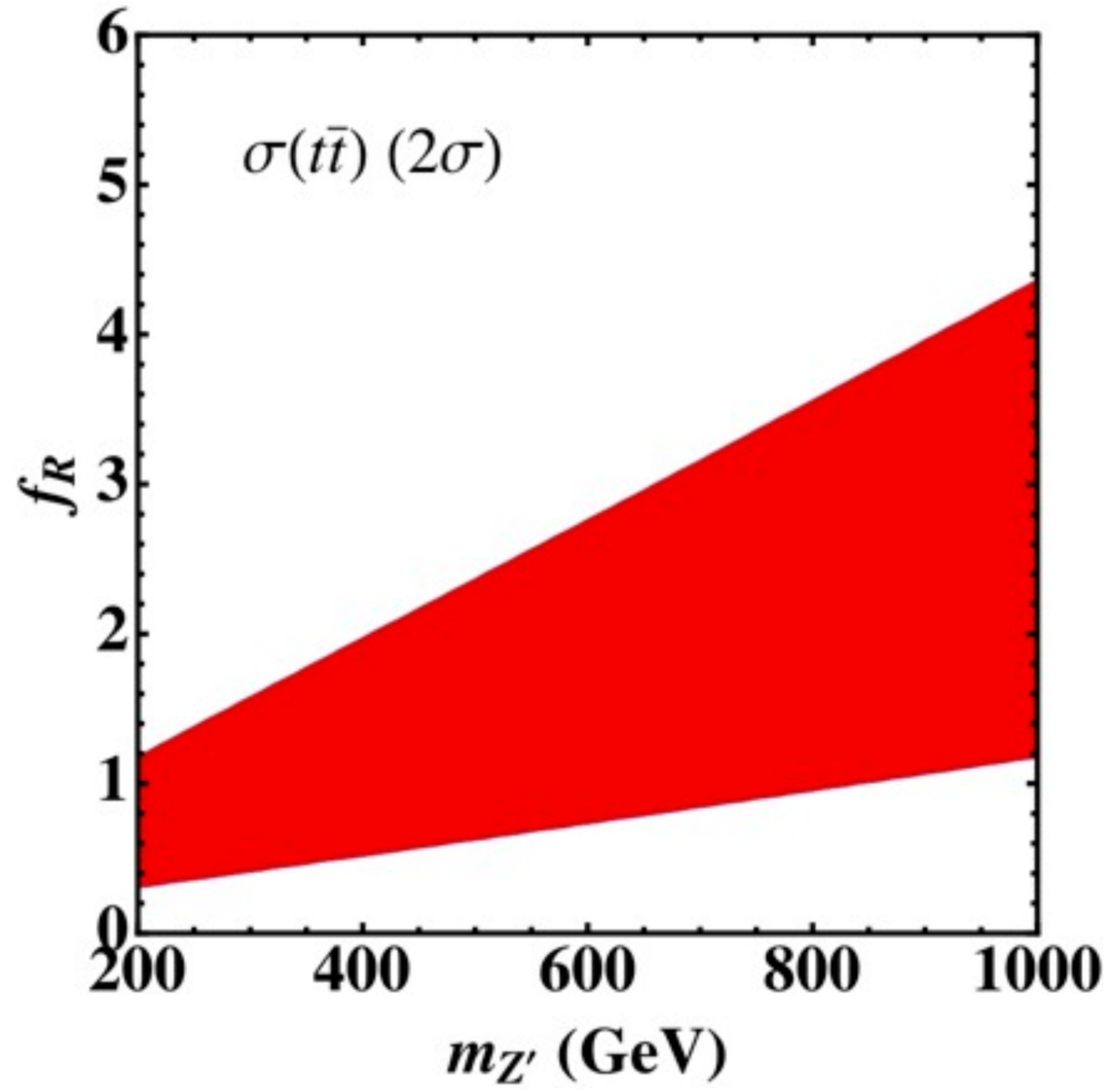
★ NPS contribution is positive

★ For heavy Z', one needs a large f_R such that NPS contribution dominates over INT contribution to produce positive A_{FB}.

Determination of f_R

A_{FB} requires large couplings while $\sigma(t\bar{t})$ prefers small couplings.

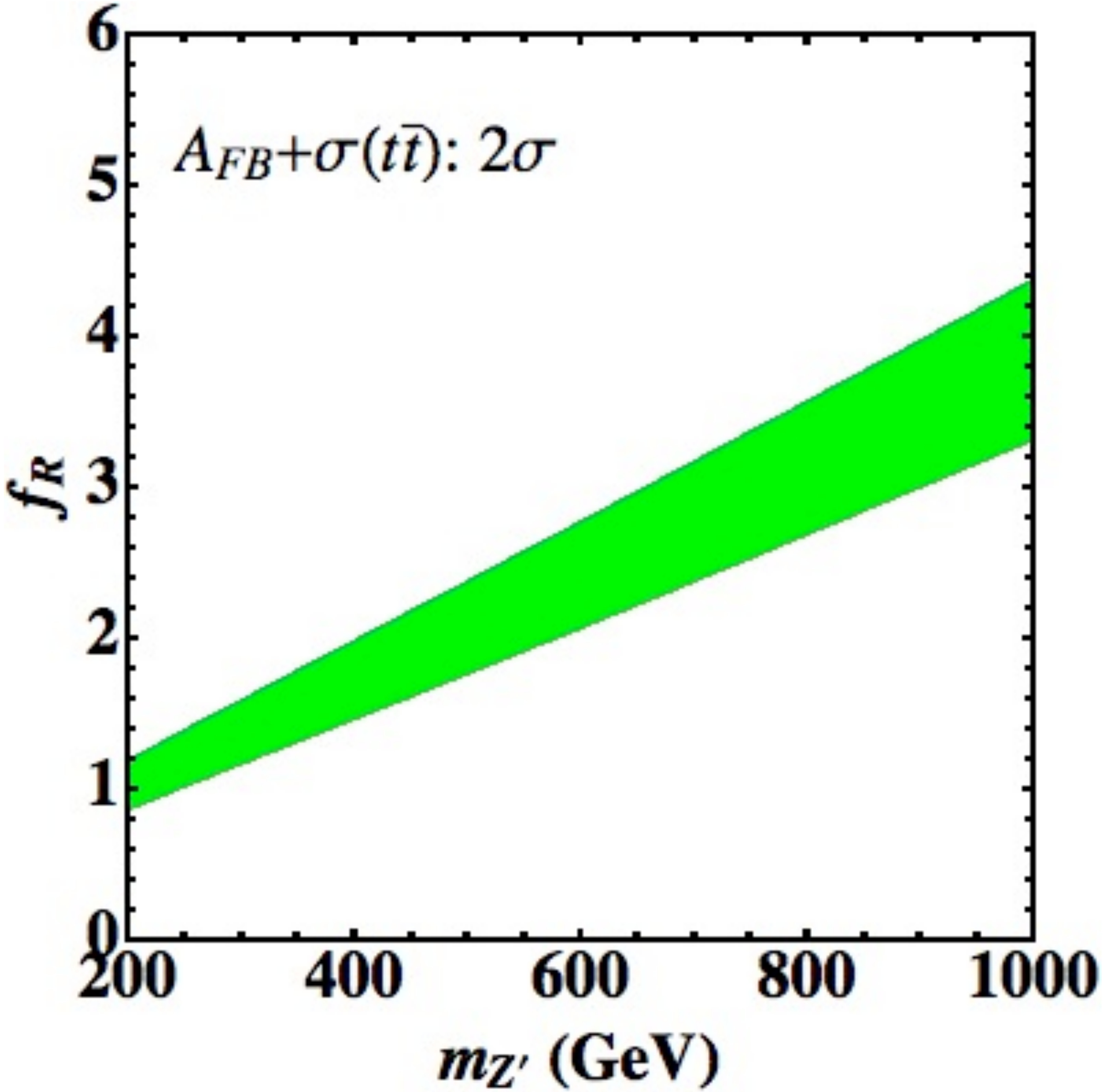




$A_{FB} = 0.475 \pm 0.114$ for $m_{t\bar{t}} \geq 450$ GeV

$\sigma_{t\bar{t}} = 7.50 \pm 0.48$ pb for $m_t = 172.5$ GeV (CDF, 4.6fb^{-1})

Determination of f_R

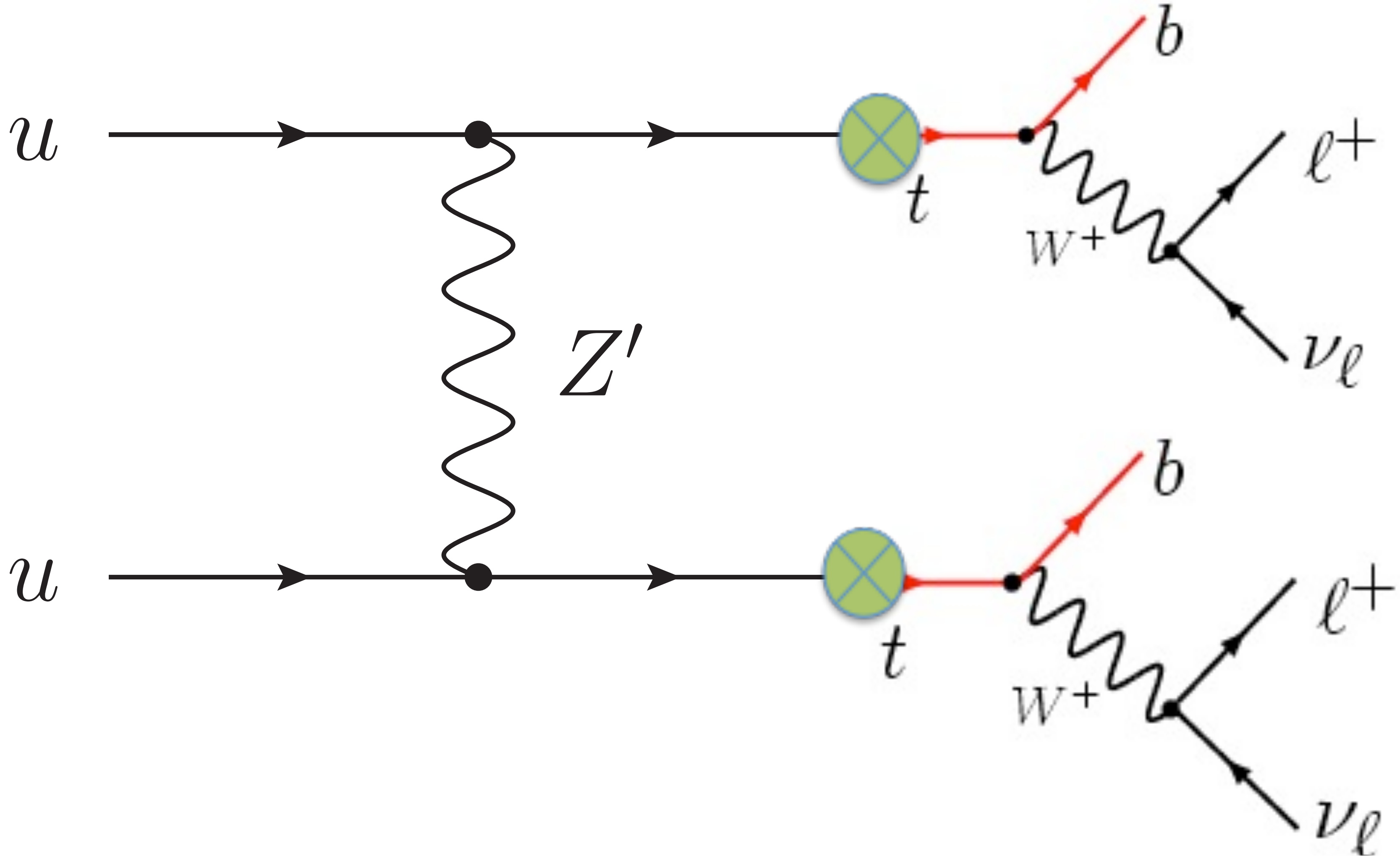


We take the overlap region as a good fit to both:

$\sigma(t\bar{t})$ $\quad A_{FB}$

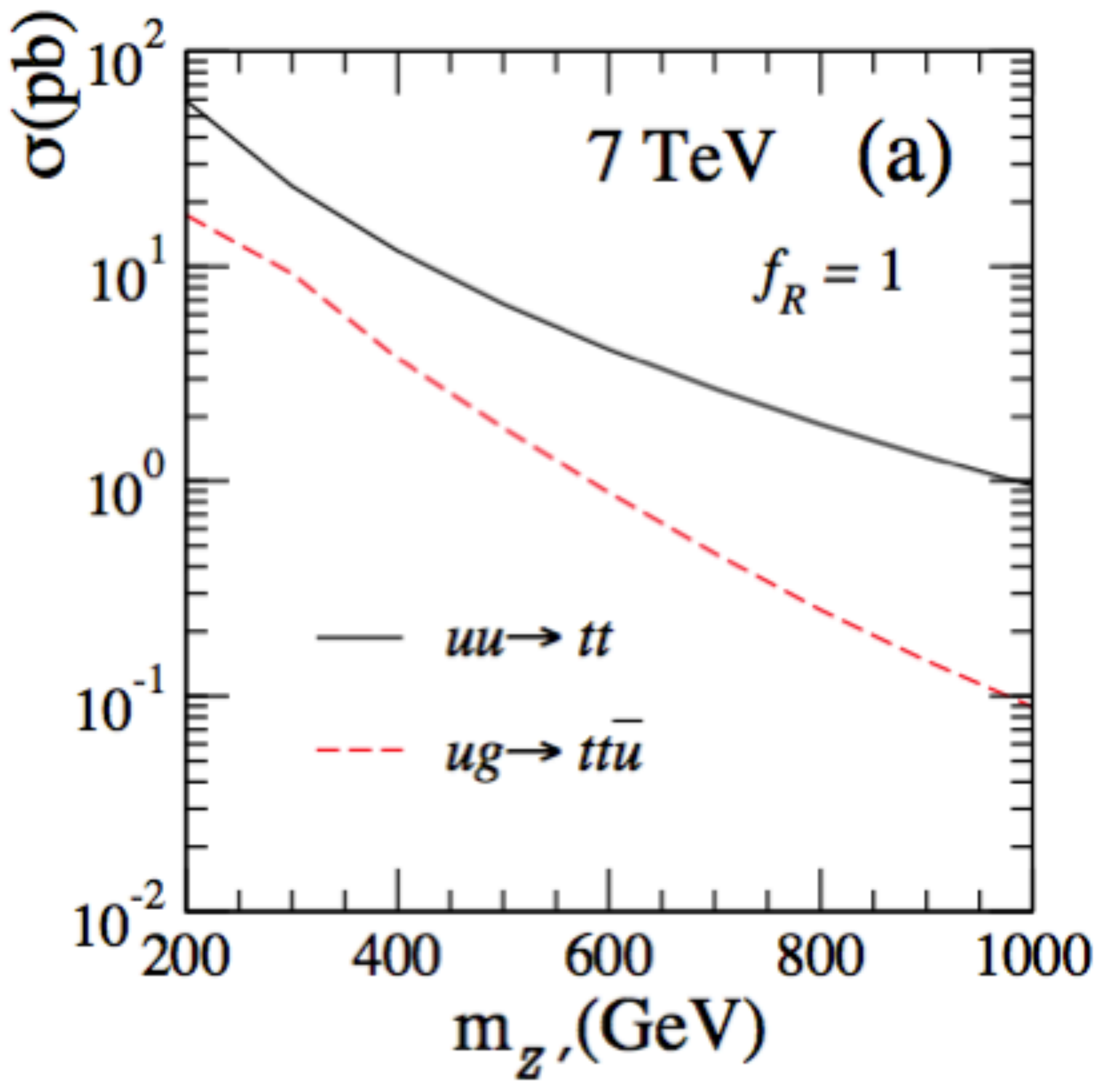
FCNC Z-prime implications

★ Same-sign top quark pair production at the LHC



★ Same-sign dileptons are predicted.

Same-sign top pair production



- **Collider simulation**

  $n_j = 2, \quad n_{\mu^+} = 2,$

  $p_T^j \geq 50\,\text{GeV}, \quad |\eta_j| \leq 2.5,$

  $p_T^\ell \geq 50\,\text{GeV}, \quad |\eta_\ell| \leq 2.0,$

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

  $\not{E}_T \geq 20$ GeV

  two b-tagged jets

The same sign top quark pair cross section grows as f_R^4.

SM backgrounds

$$
\left.\begin{array}{l}
pp \to t\bar{t} \to b\bar{b}W^+W^-,\ W^+ \to \ell^+\nu,\ W^- \to jj,\ \bar{b} \to \ell^+ \\
pp \to W_1^+W_2^+jj,\ W^+ \to \ell^+\nu
\end{array}\right\} \text{Dominant backgrounds}
$$

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

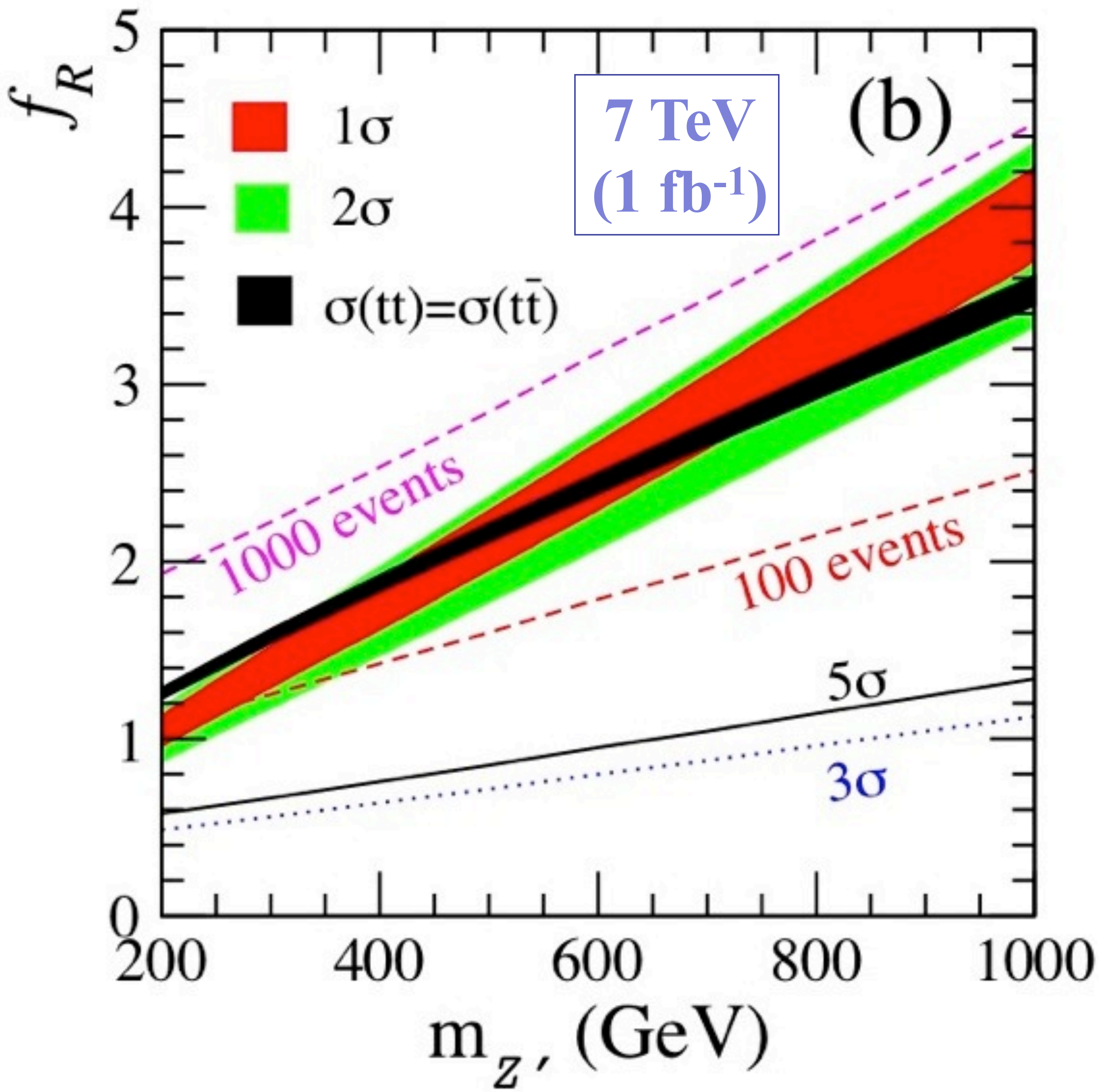
$$pp \to ZW^+W^-,\ Z \to \ell^+\ell^-,\ W^+ \to \ell^+\nu,\ W^- \to jj$$

★ Matrix element calculation of signal and backgrounds retains all spin correlations .

★ About 1 background event survives after all kinematic cuts.

★ Based on Poisson statistics we demand 8 signal events for a 5σ discovery.

Same-sign top pair production



Parameter region to fit A_{FB} is everywhere above the 5σ discovery curve.

A model using Z-prime exchange alone to explain Tevatron A_{FB} is questionable

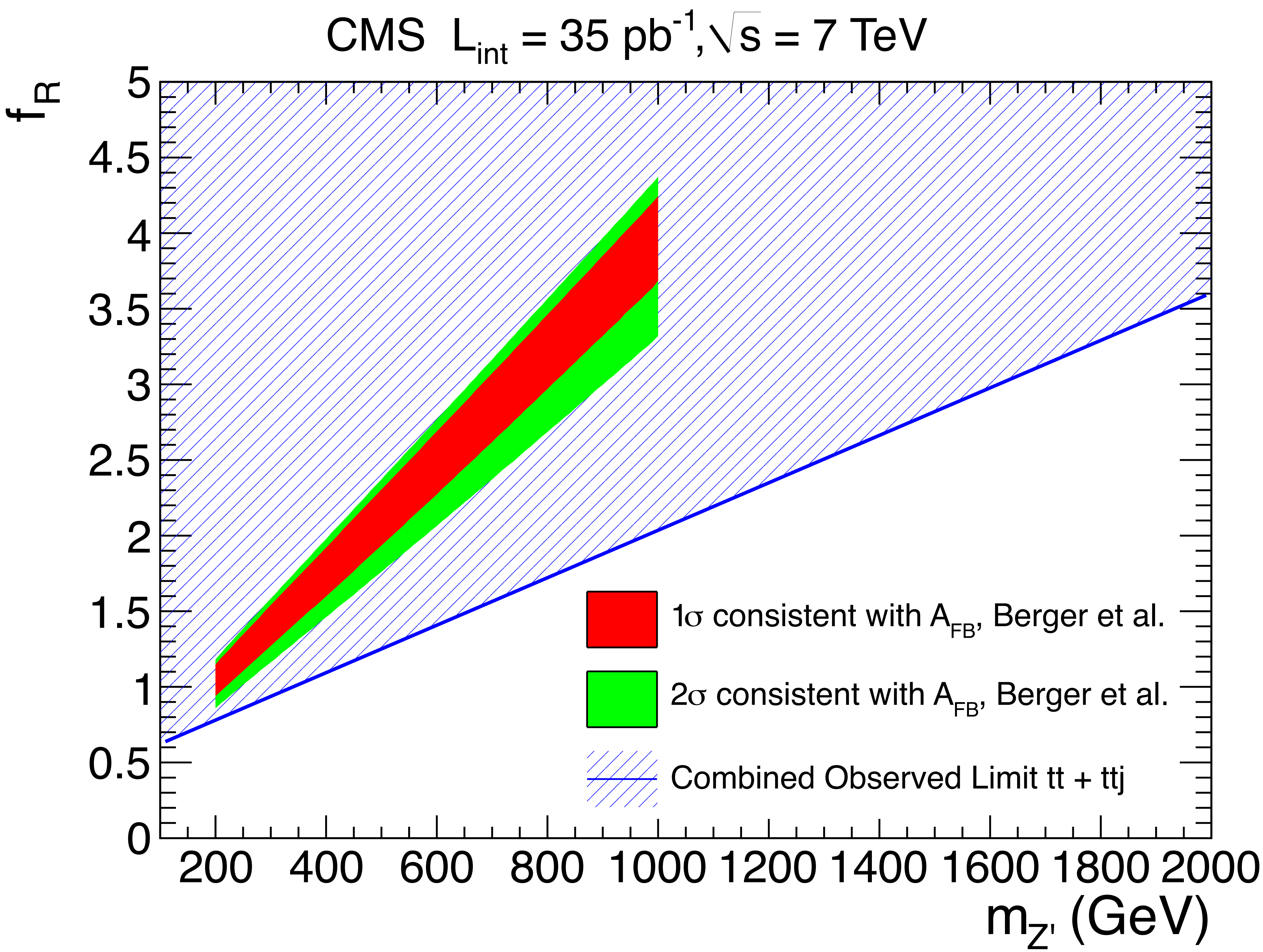
LHC 7 TeV measurements would impose hard constraints on f_R . Search for same-sign top quark pairs is interesting in other model contexts also.

Berger, QHC, Chen, Li, Zhang, arXiv:1101.5625, Phys Rev Lett 106, 201801 (2011)

CMS direct search

★ Disfavor the FCNC Z' model

CMS, JHEP 1108 (2011) 005, arXiv:1106.2142



How to confirm the FCNC Z-prime model?

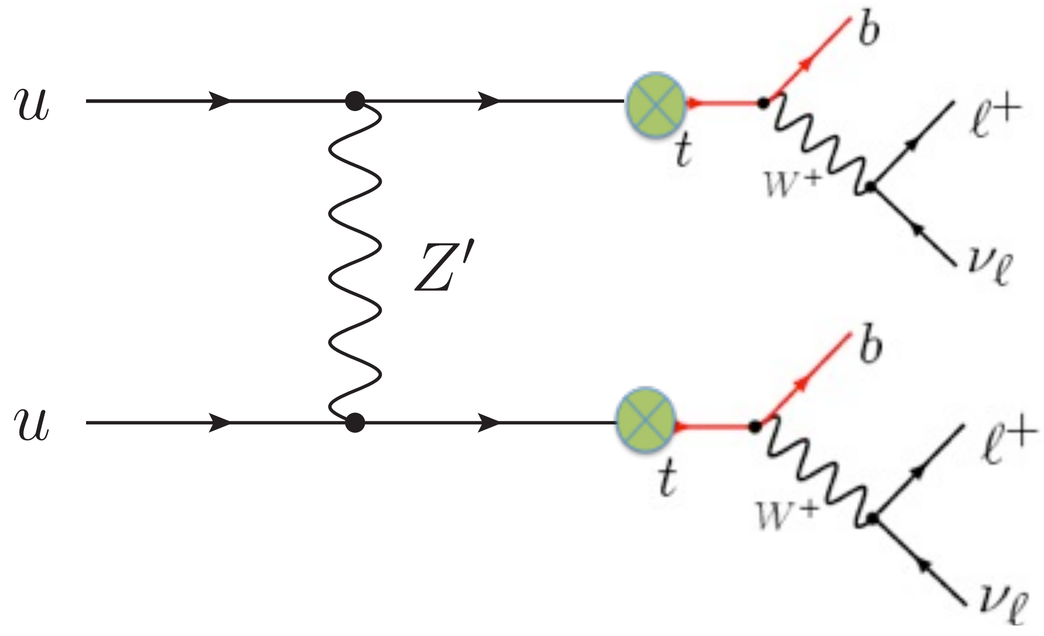
★ No resonance shows in the top pair invariant mass spectrum

★ Top quark polarization would provide addition information.

$$\mathcal{L} = g_W \bar{u}\gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + h.c.$$

Left-handed coupling is highly constrained by $B_d - \bar{B}_d$ mixing.

Top quarks are right-handed.

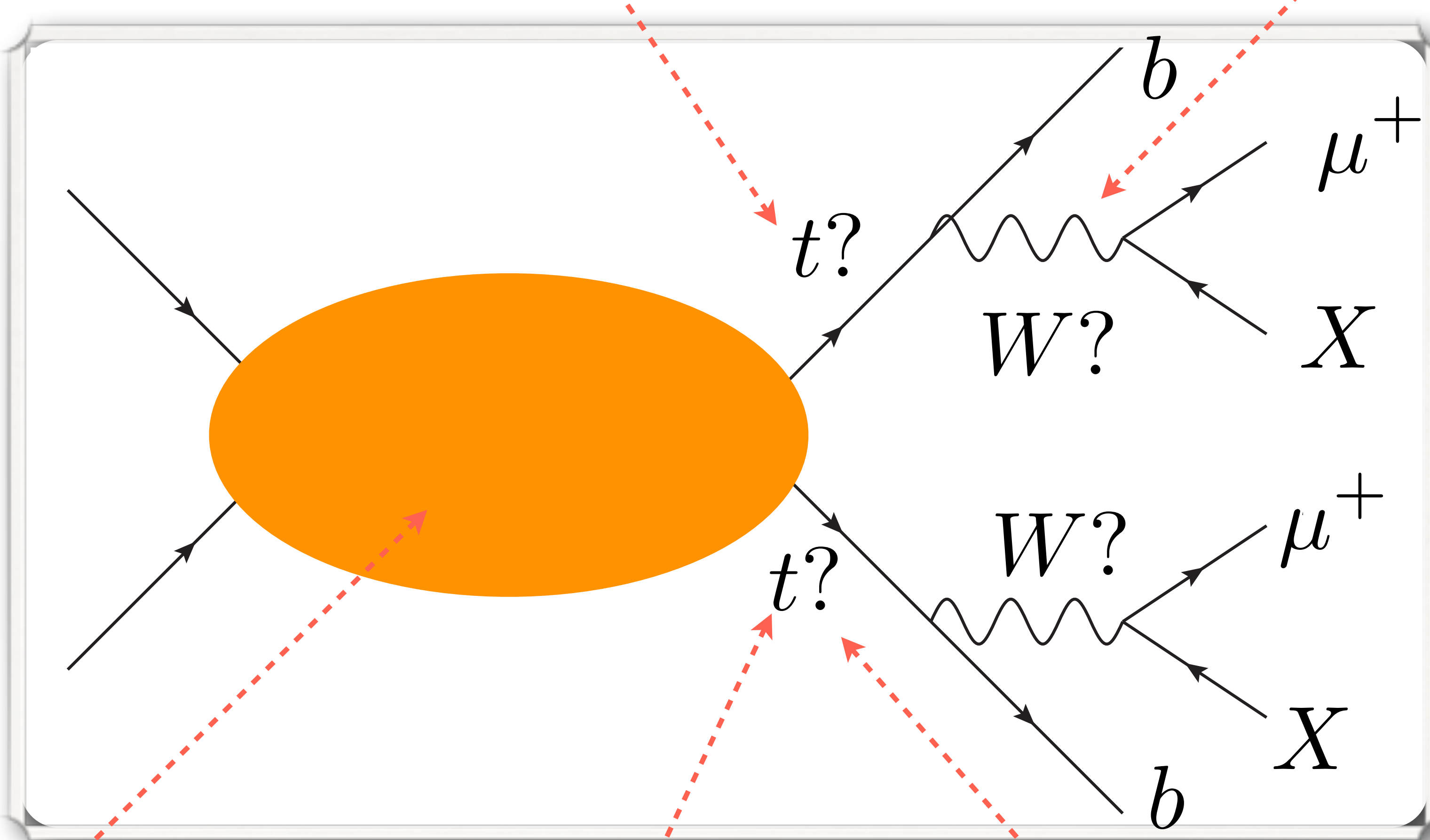


Full event reconstruction is needed.

Questions to be answered

(2) Do the pairs of jet+lepton each 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

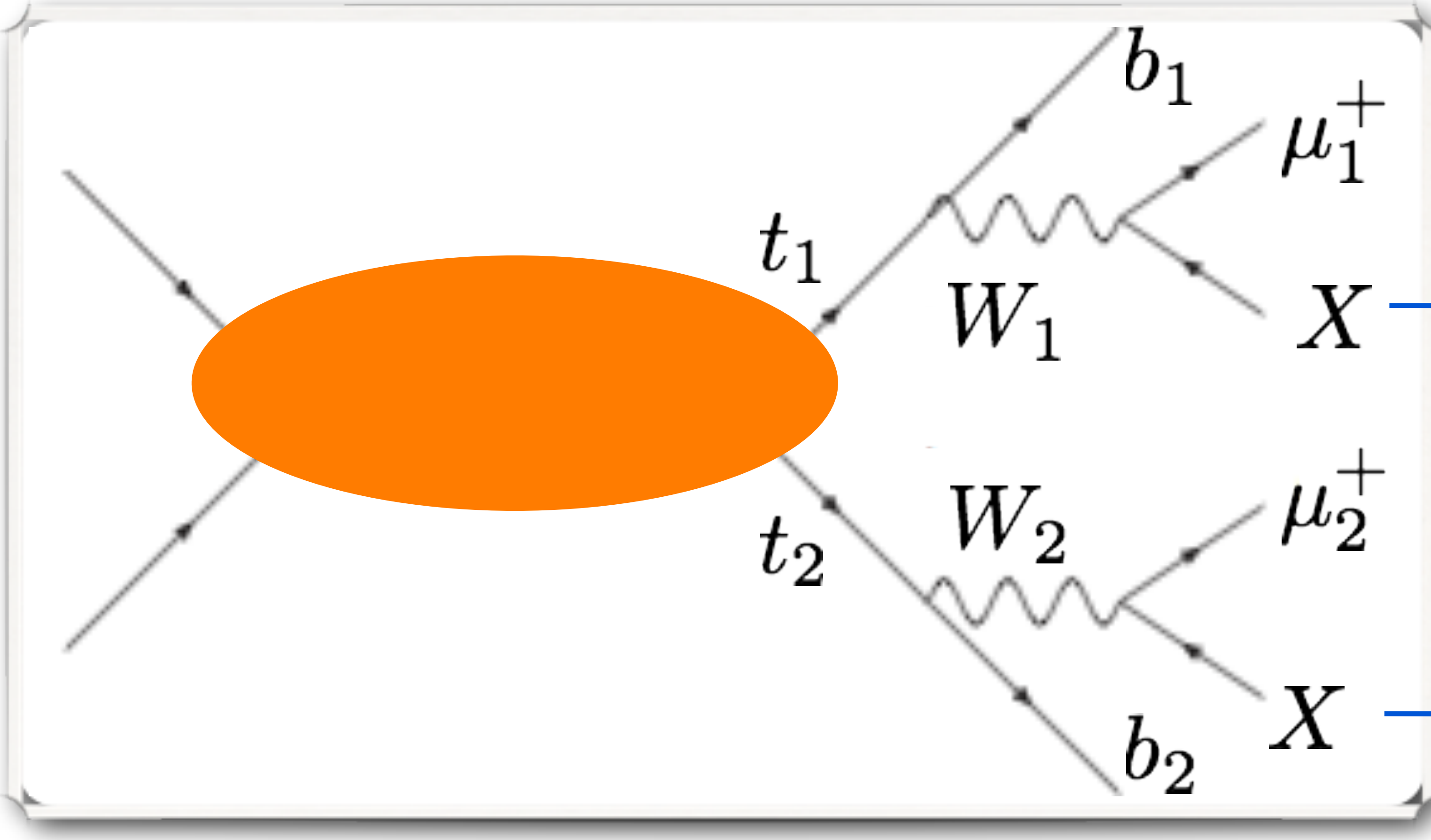
(3) Is there a resonance? s- or t-channel?

(4) What is top quark polarization?

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

Full kinematic reconstruction

★ Four unknowns and four on-shell conditions



6 unknowns
-2 from MET

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

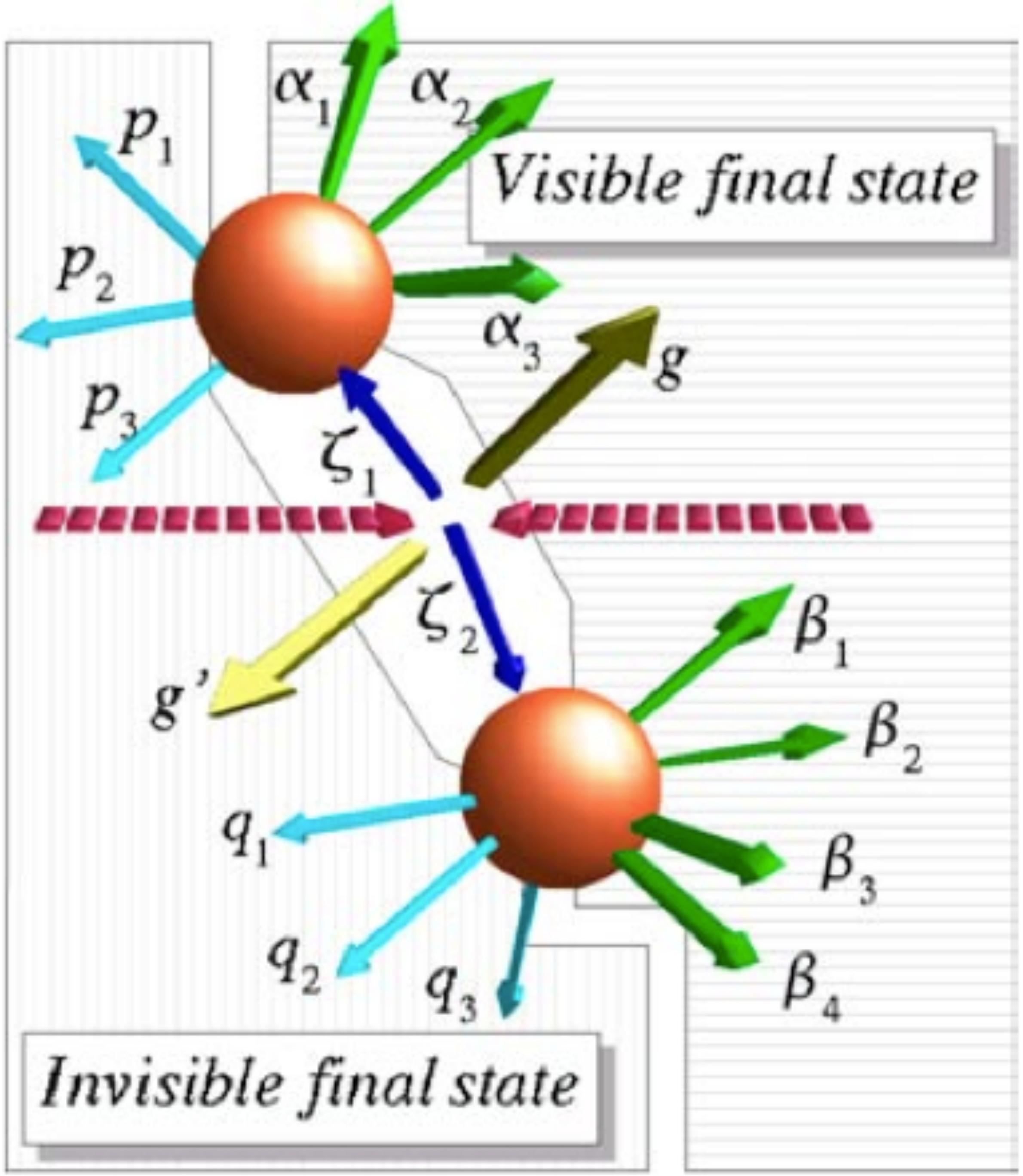
Quartic equation
(correct paring is necessary)

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

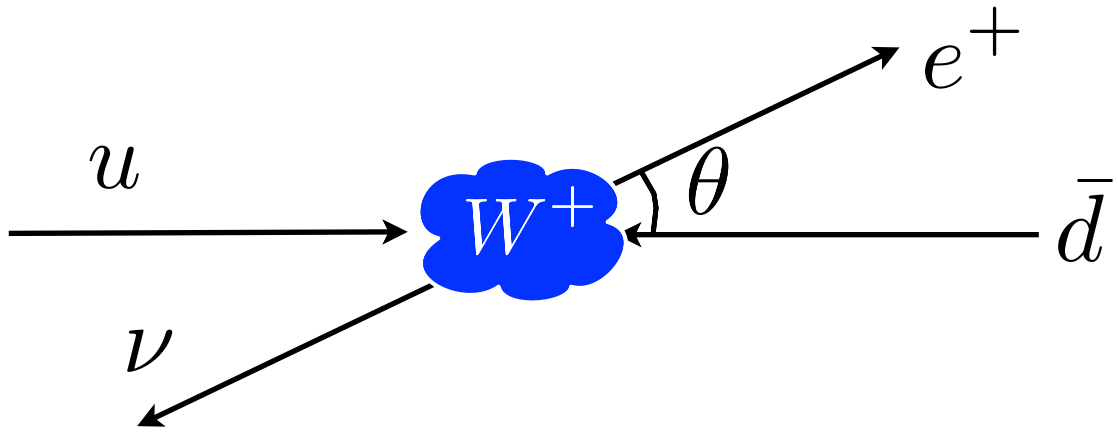
~~Two complex~~, two real solutions

MT2 method

★ Question: how can one measure the mass of heavy particles if they are produced in pairs and then decay into visible and invisible particles?



What we learn from M_W measurements

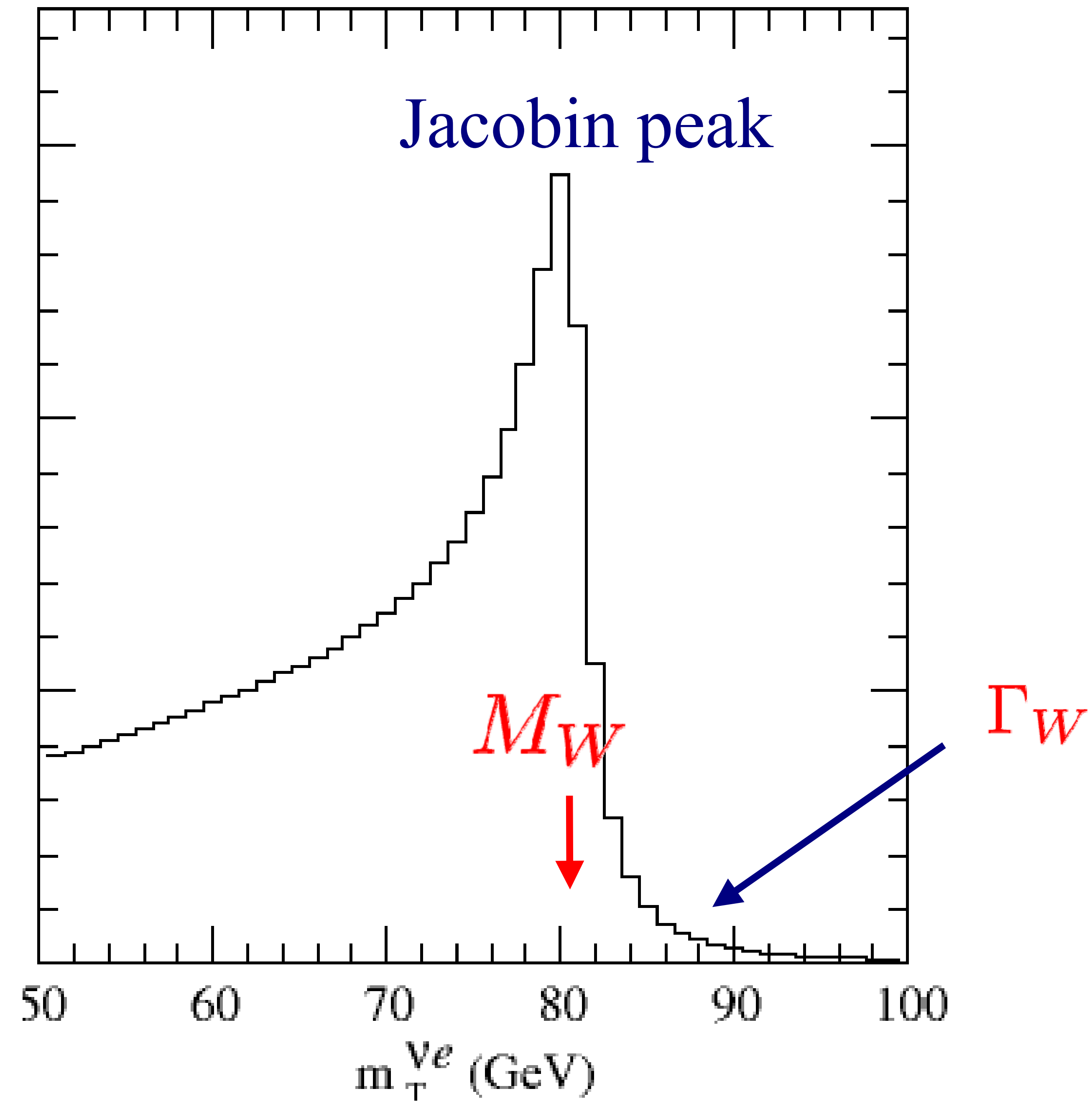


- Warm up: measuring the mass of the W boson in the leptonic decay channel -- MT variable.

$$m_T^2 = 2\left(E_T^e \not{E}_T - \mathbf{p}_T^e \cdot \not{\mathbf{p}}_T \right)$$

- The true mass of the W boson satisfies $m_T^2 \leq m_W^2$

- The end point of the transverse mass distribution is the W boson mass.



$$\frac{d\hat{\sigma}}{dm_T^2} \sim \frac{1}{\sqrt{1 - m_T^2/\hat{s}}}$$

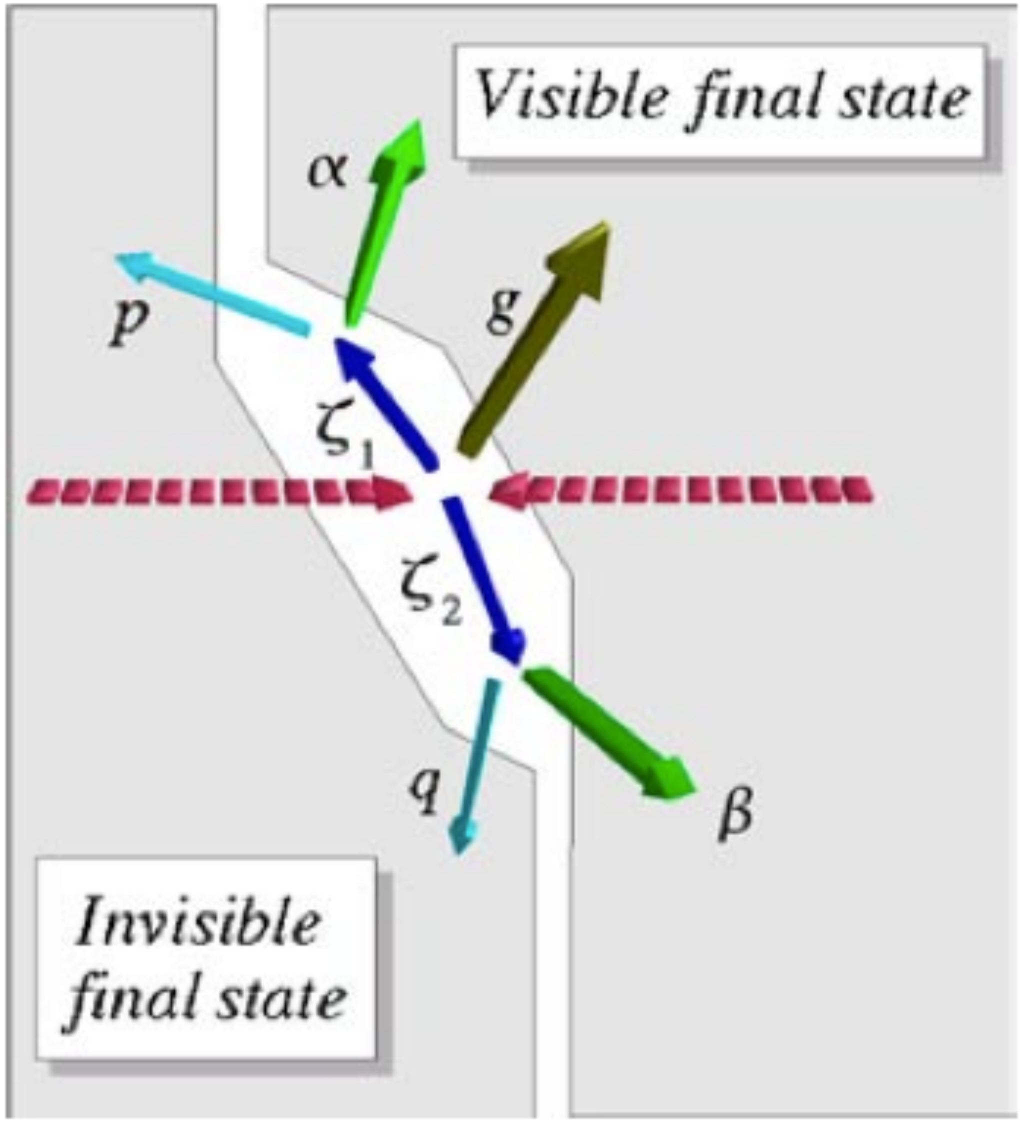
MT2 method

★ When there are two heavy particles decaying into visible particles and invisible particles, the MT2 variable may be used to measure the mass of their parent.

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

$$m_{T2}(m_{invis}) = \min_{\mathbf{p}_T^{(1)},\mathbf{p}_T^{(2)}} \left[\max[m_T(m_{invis};\mathbf{p}_T^{(1)}), m_T(m_{invis};\mathbf{p}_T^{(2)})]\right]$$

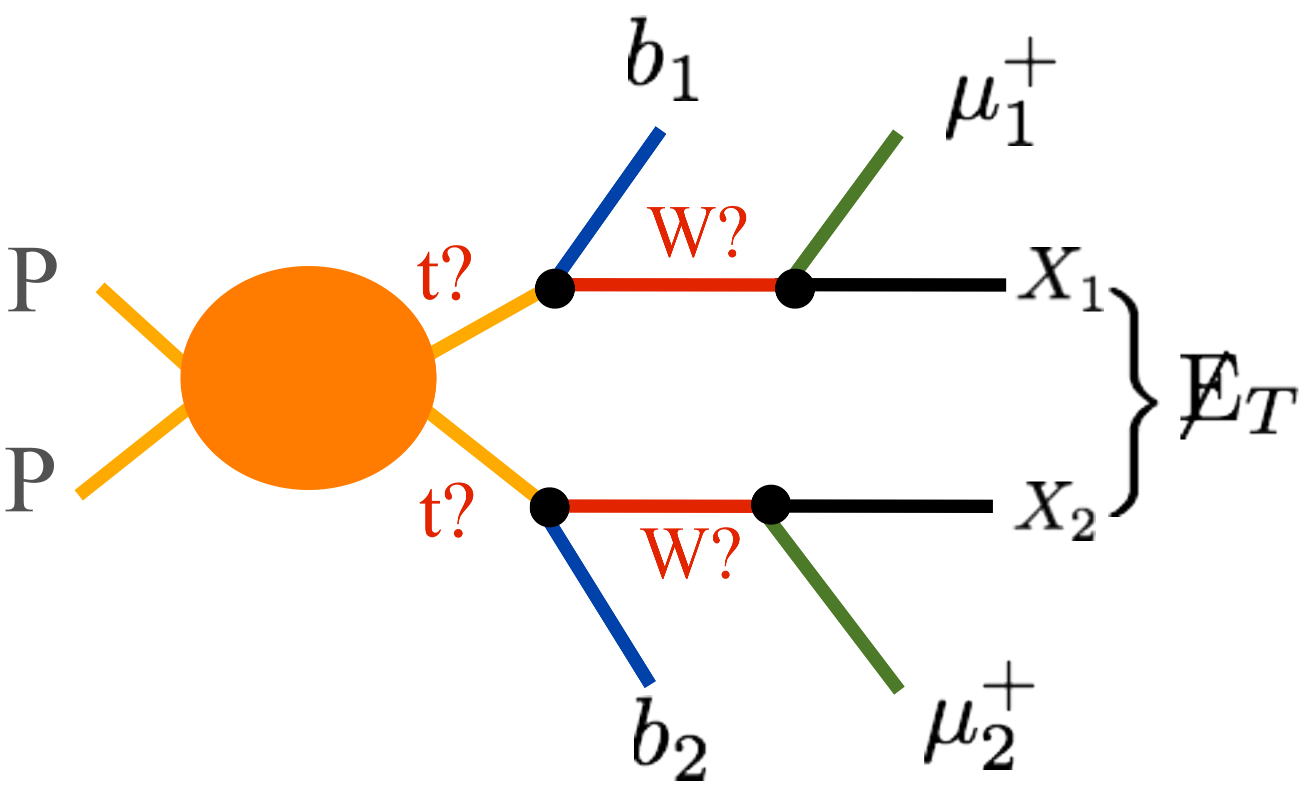
$$m_T(m_{invis};\mathbf{p}_T^{invis}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2(E_T^{vis}E_T^{invis} - \mathbf{p}_T^{vis}\cdot\mathbf{p}_T^{invis})}$$



★ The MT2 variable is a function of the momenta of visible particles (α, β) and missing transverse momentum. Its upper bound yields the mass of the parent particle (ζ) .

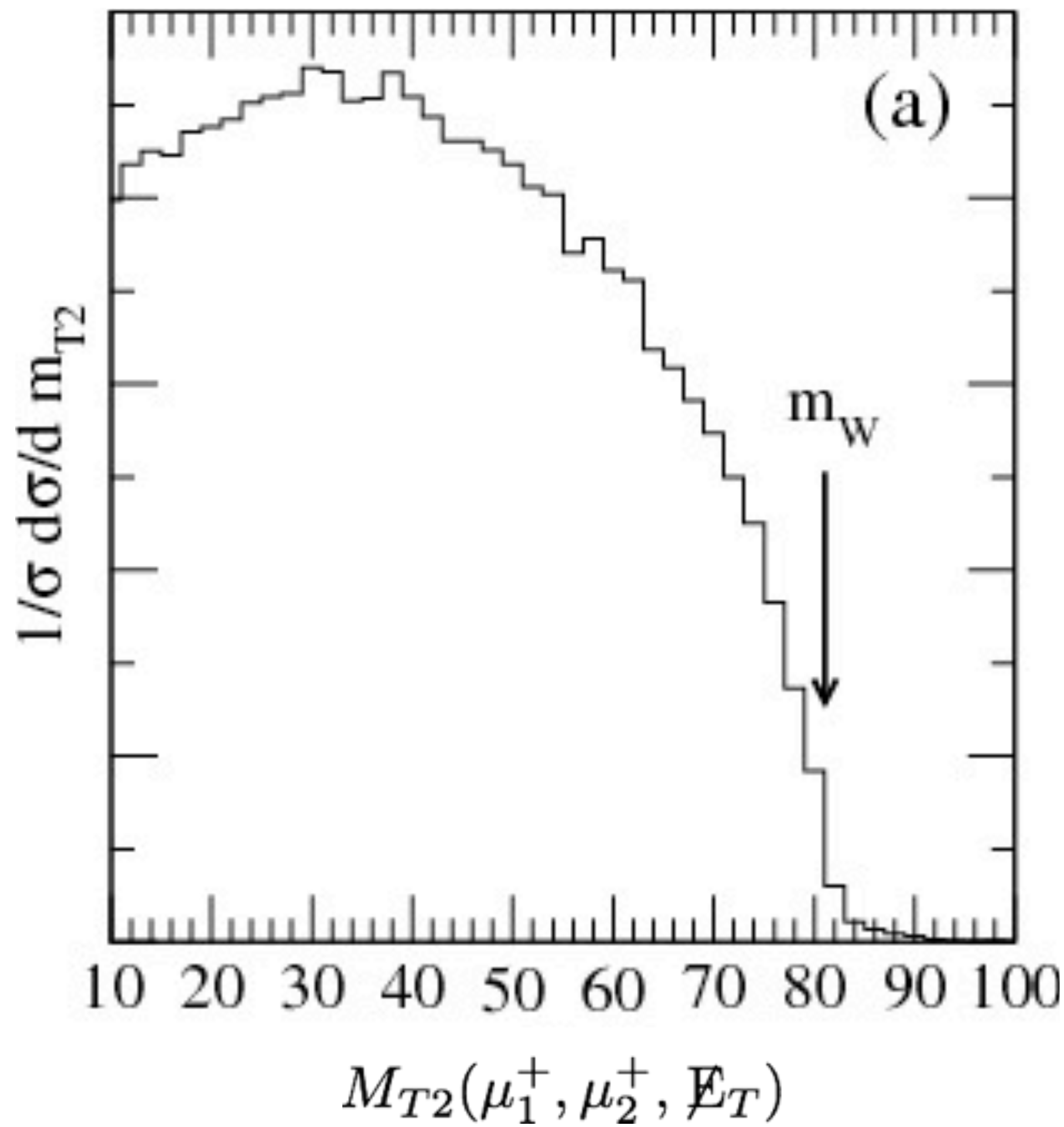
W-bosons in the intermediate state ?

★ MT2 of charged leptons and MET



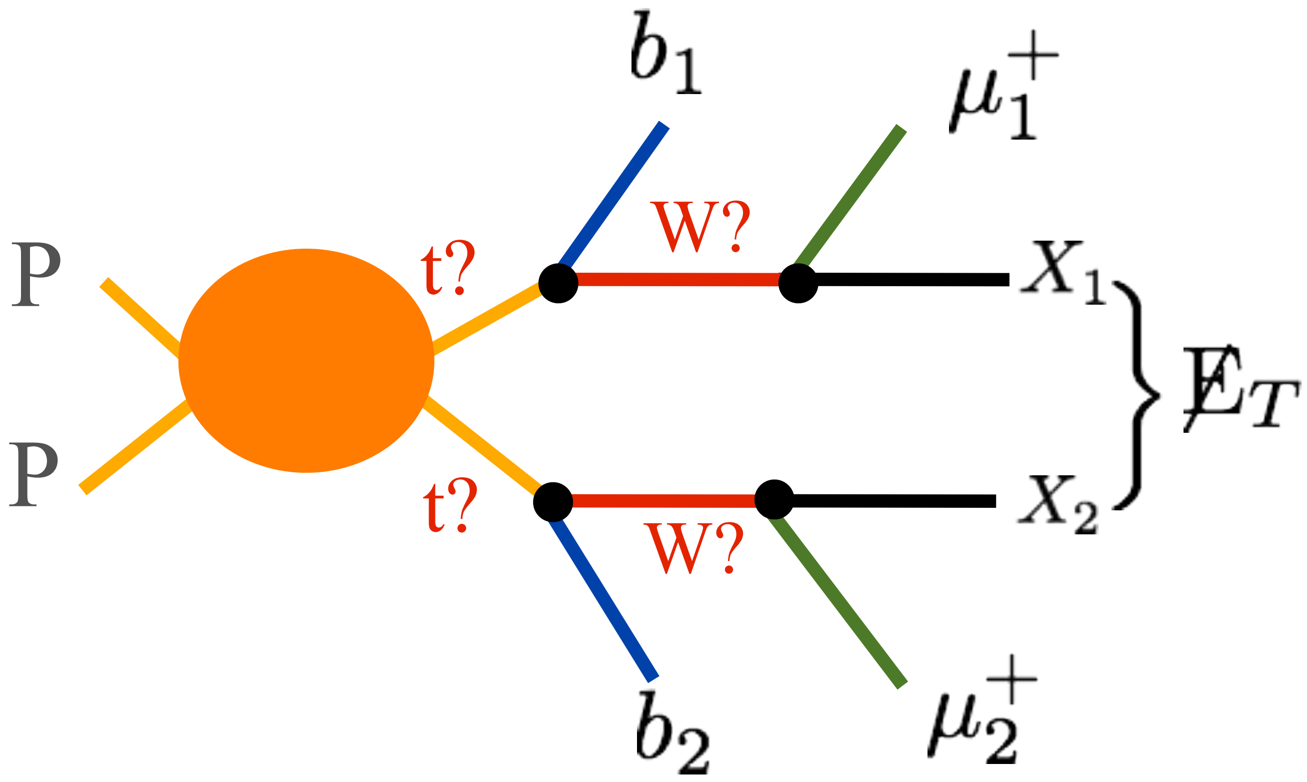
$$M_{T2}^2(\mu_1^+, \mu_2^+, \not{E}_T) \leq m_W^2$$

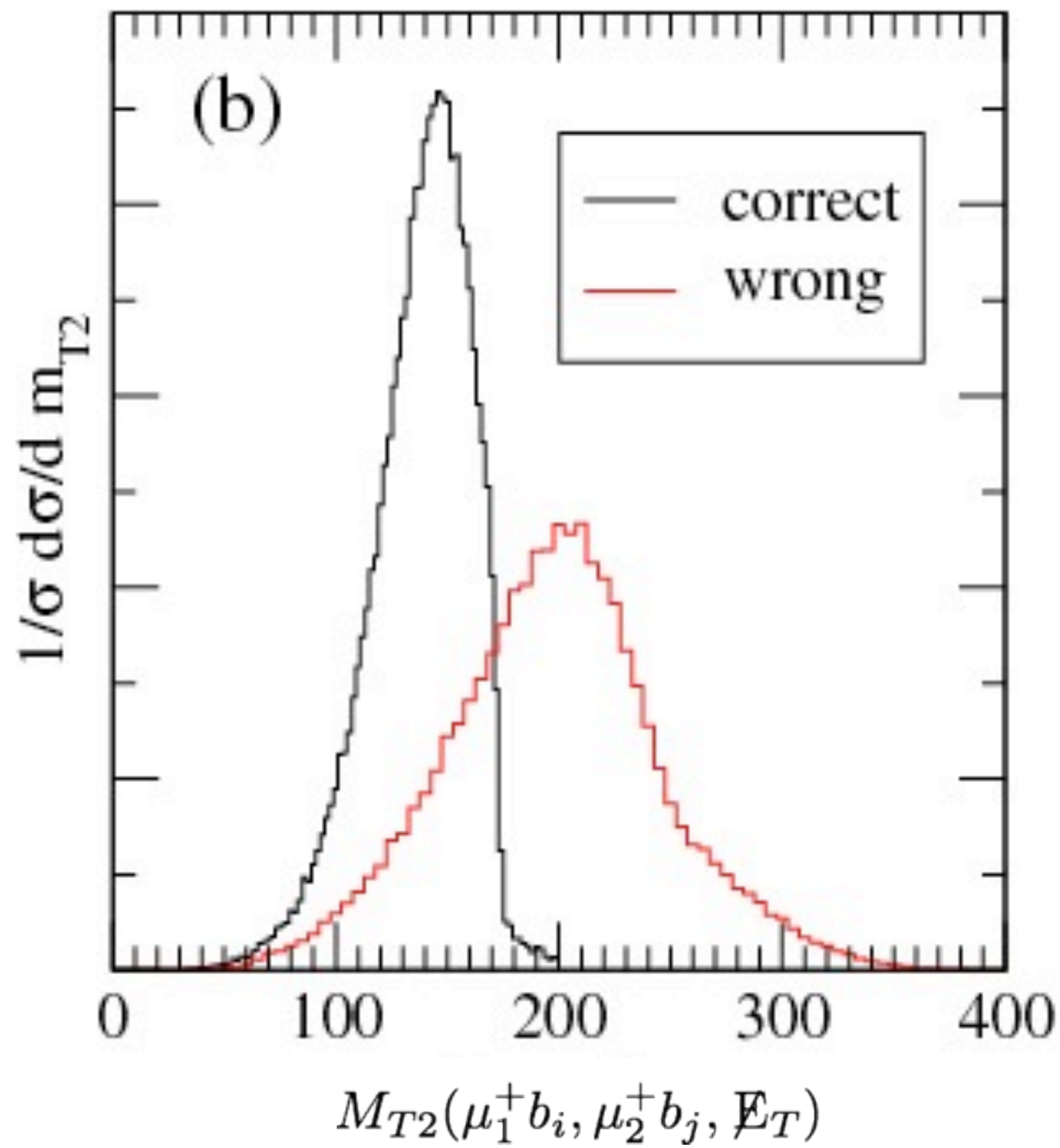
$$M_{T2}^2 \equiv \min_{\not{\vec{p}}_{X_1}+\not{\vec{p}}_{X_2}=\not{E}_T} \left[\max\left\{ m_T^2(\vec{p}_T^{\,\mu_1^+}, \not{\vec{p}}_{X_1}), m_T^2(\vec{p}_T^{\,\mu_2^+}, \not{\vec{p}}_{X_2}) \right\} \right]$$



Top quarks in the intermediate state?

★ MT2 of lepton-b clusters and MET





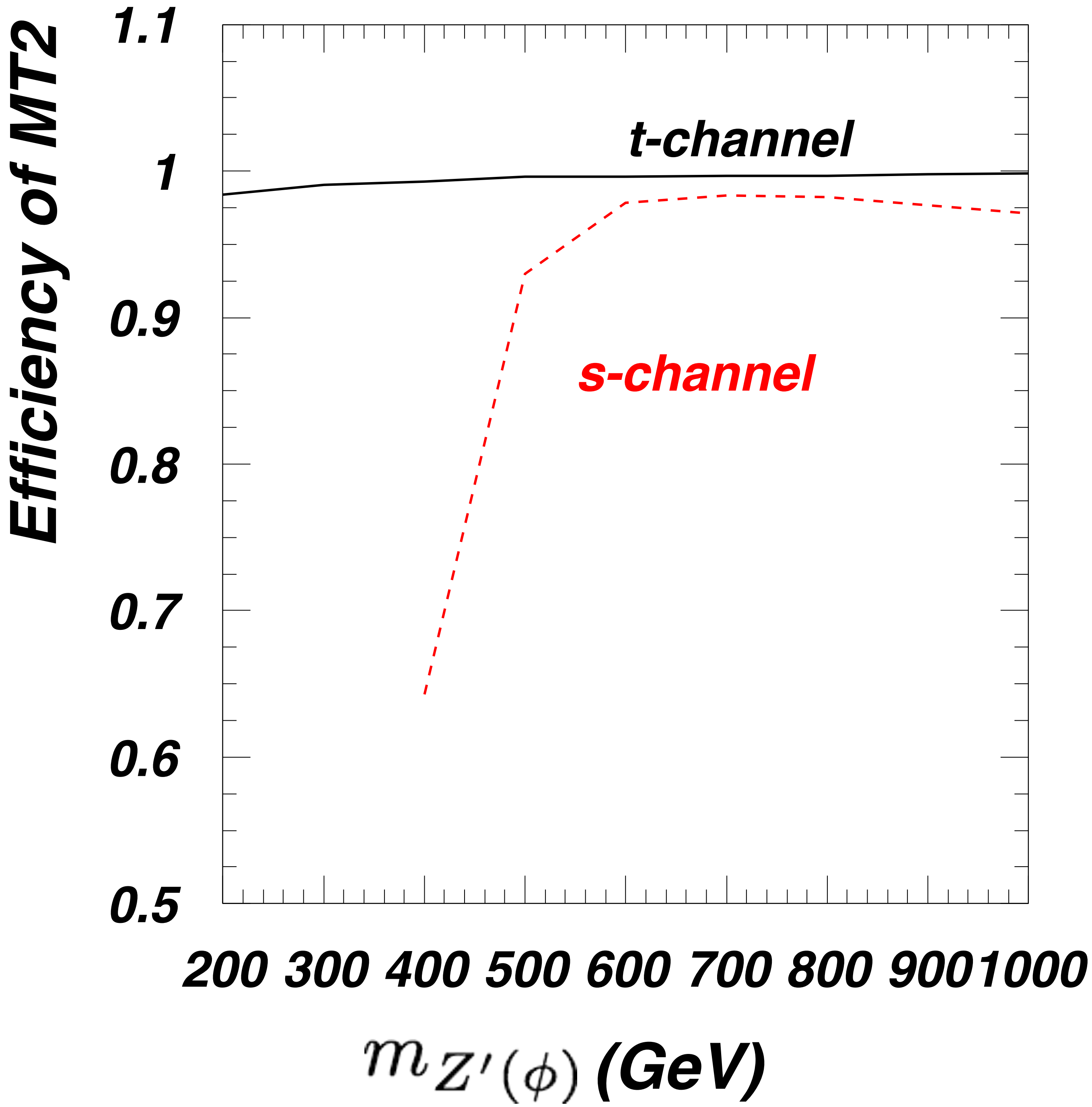
- Two combinations of lepton-b clusters

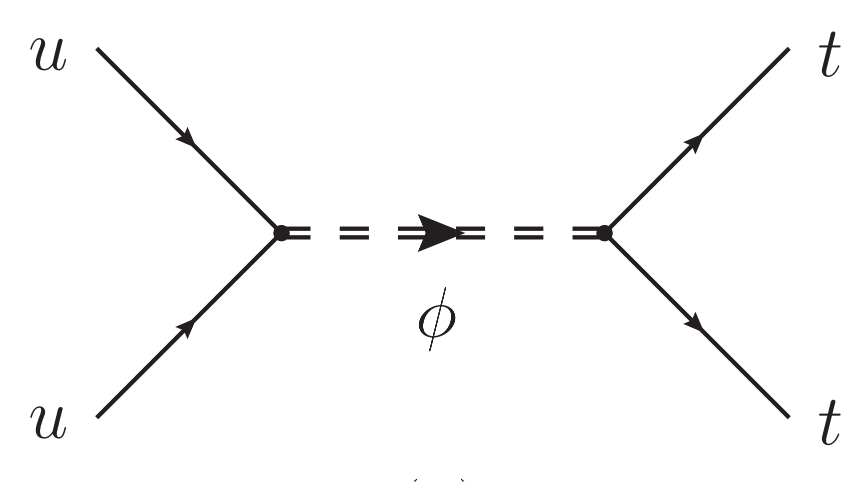
- Choose smaller MT2 (correct combination found with nearly 100% probability)

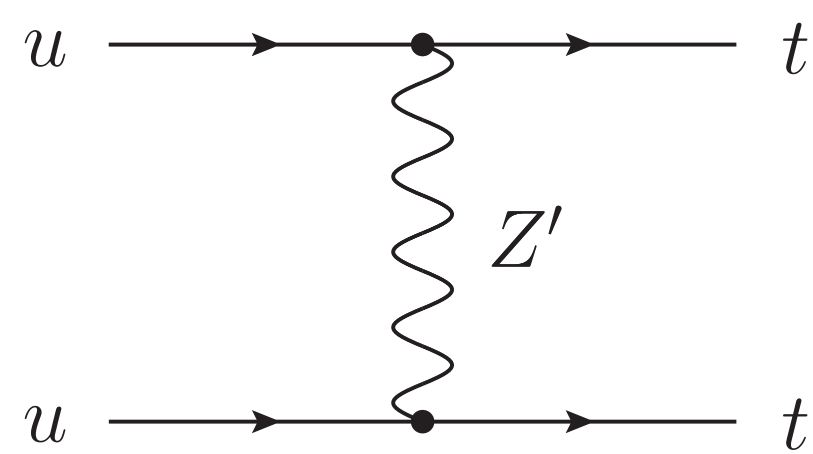
l-b pairing efficiency

★ Nearly 100% for t-channel

★ > 95% for s-channel resonance heavier than 600GeV

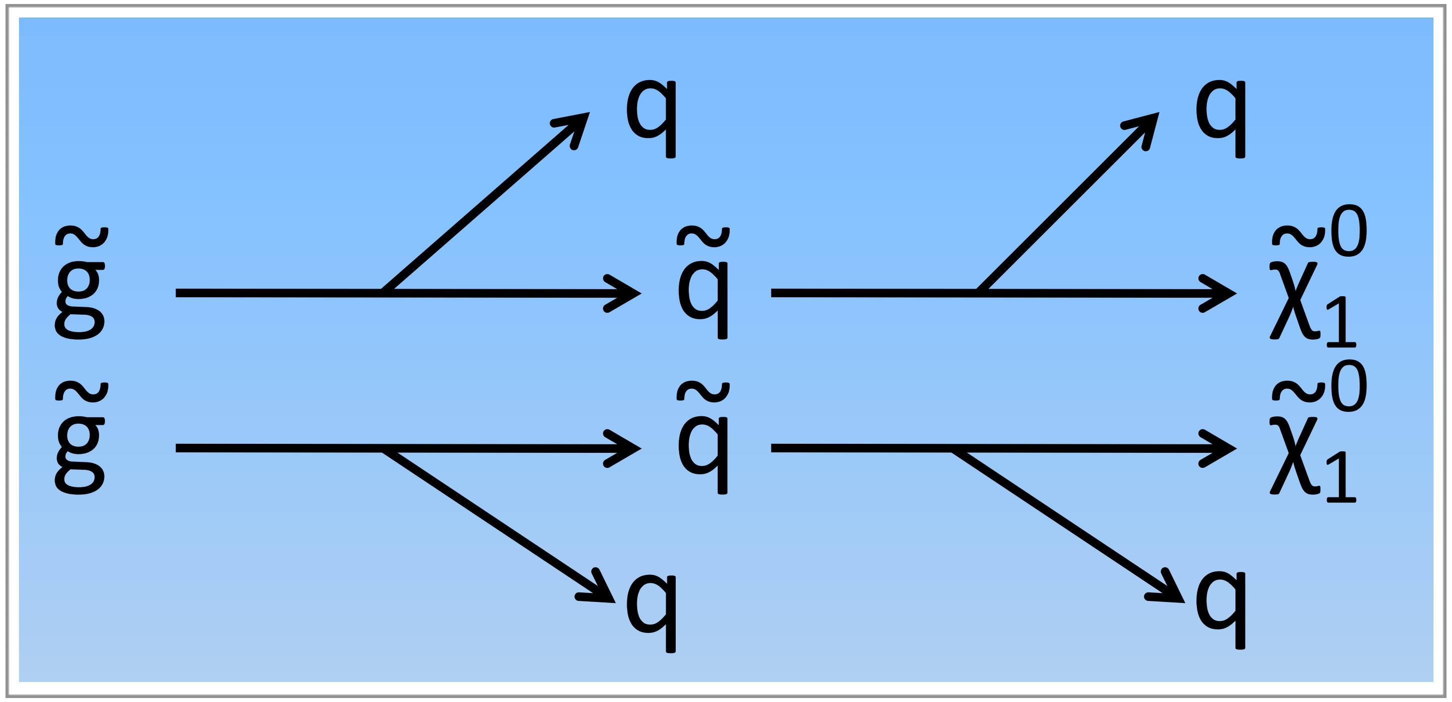






Minimal MT2 is also useful for SUSY/LHT search

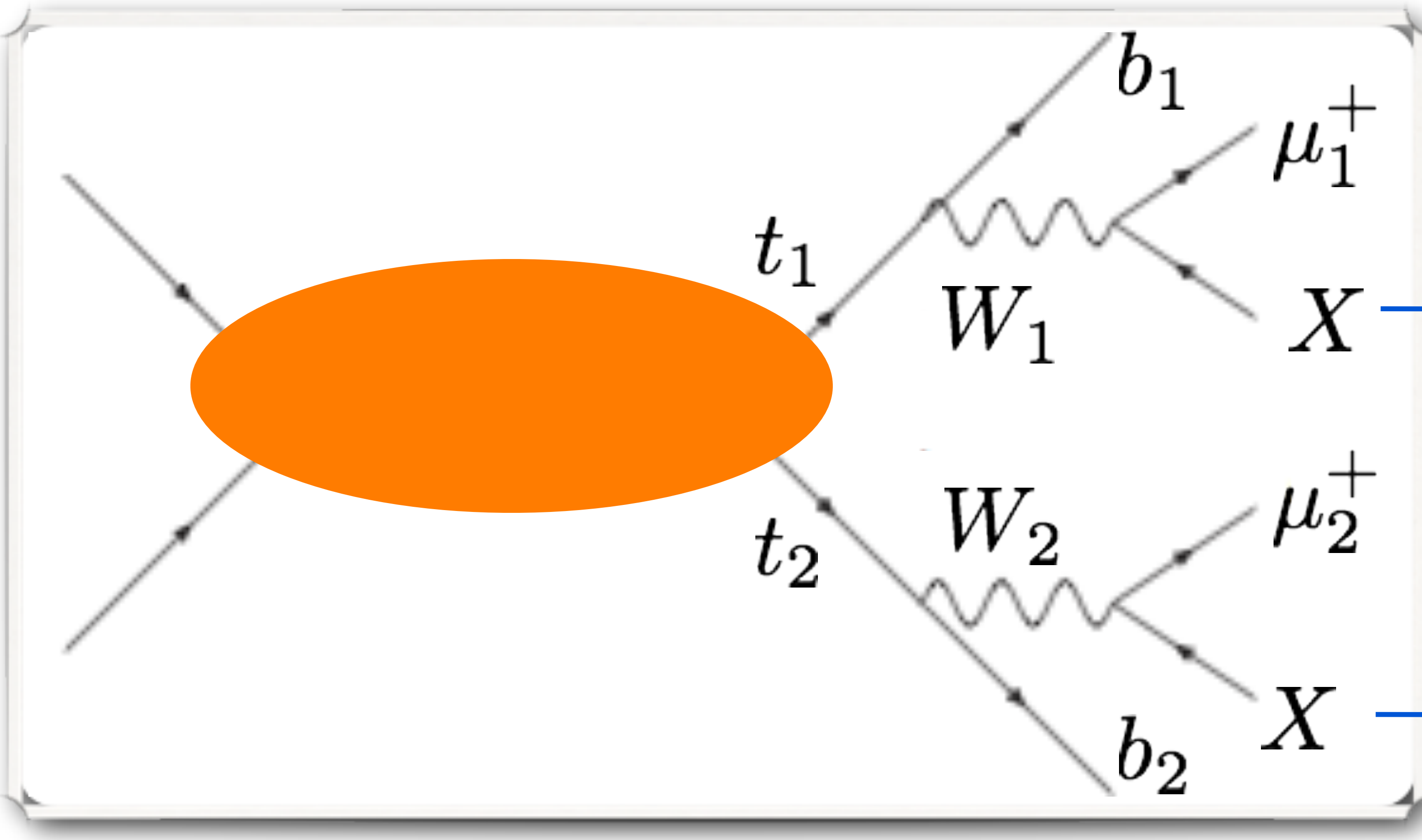
- Resolving combinatorial ambiguities is important for new physics searches at the LHC.
- For example, pair-produced gluinos with subsequent decay to LSP pair and four jets.



K. Choi, D. Guadagnoli and C. B. Park, JHEP 1111, 117 (2011), arXiv:1109.2201
MT2 method
P. Baringer, K. Kong, M. McCaskey and D. Noonan, JHEP 1110, 101 (2011), arXiv:1109.0563
MT2 method

Full kinematic reconstruction

★ Four unknowns and four on-shell conditions



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$$m_{t_2}^2 = (p_{W_2} + p_{b_2})^2$$

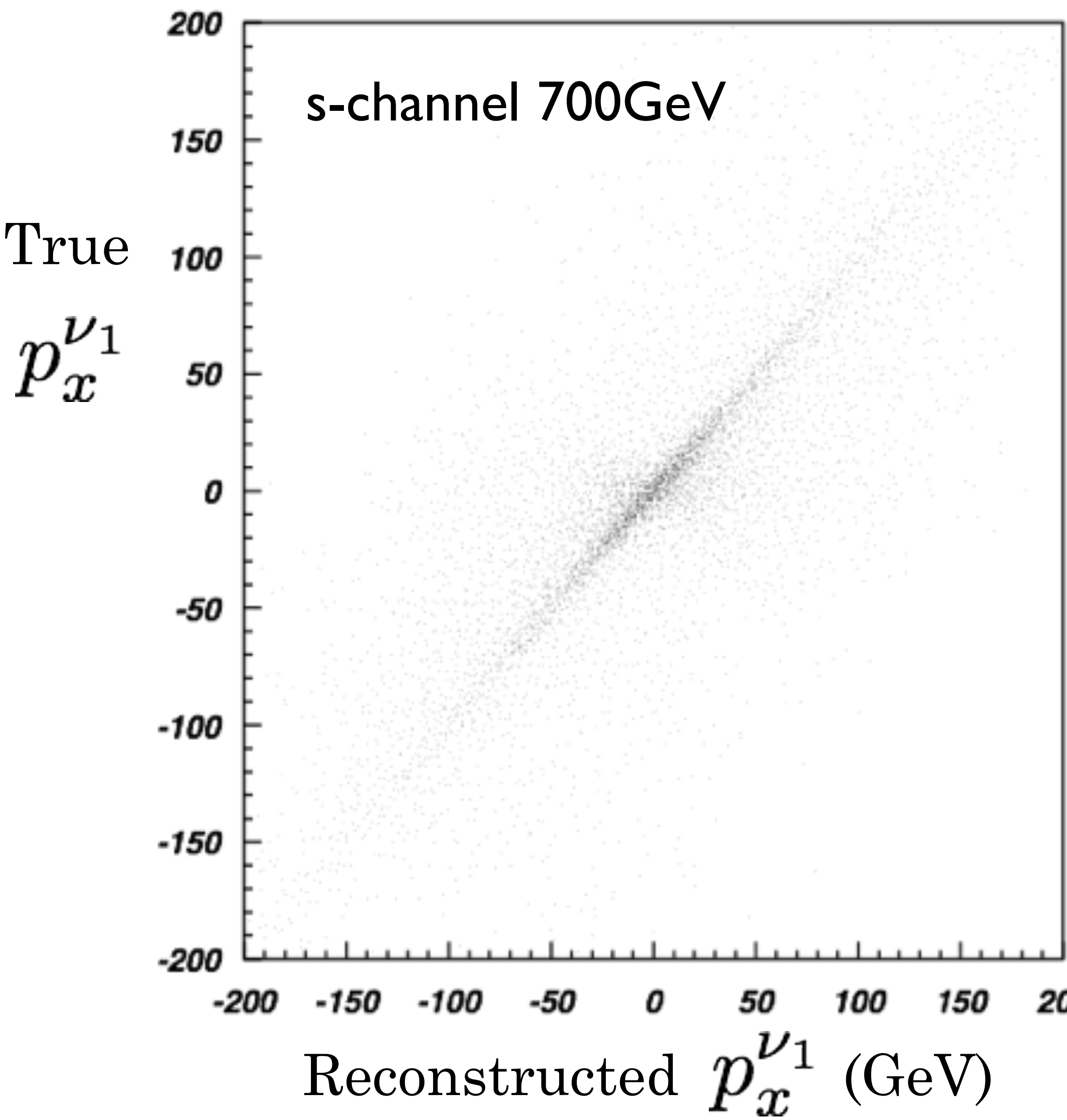
Quartic equation

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

~~Two complex~~, two real solutions

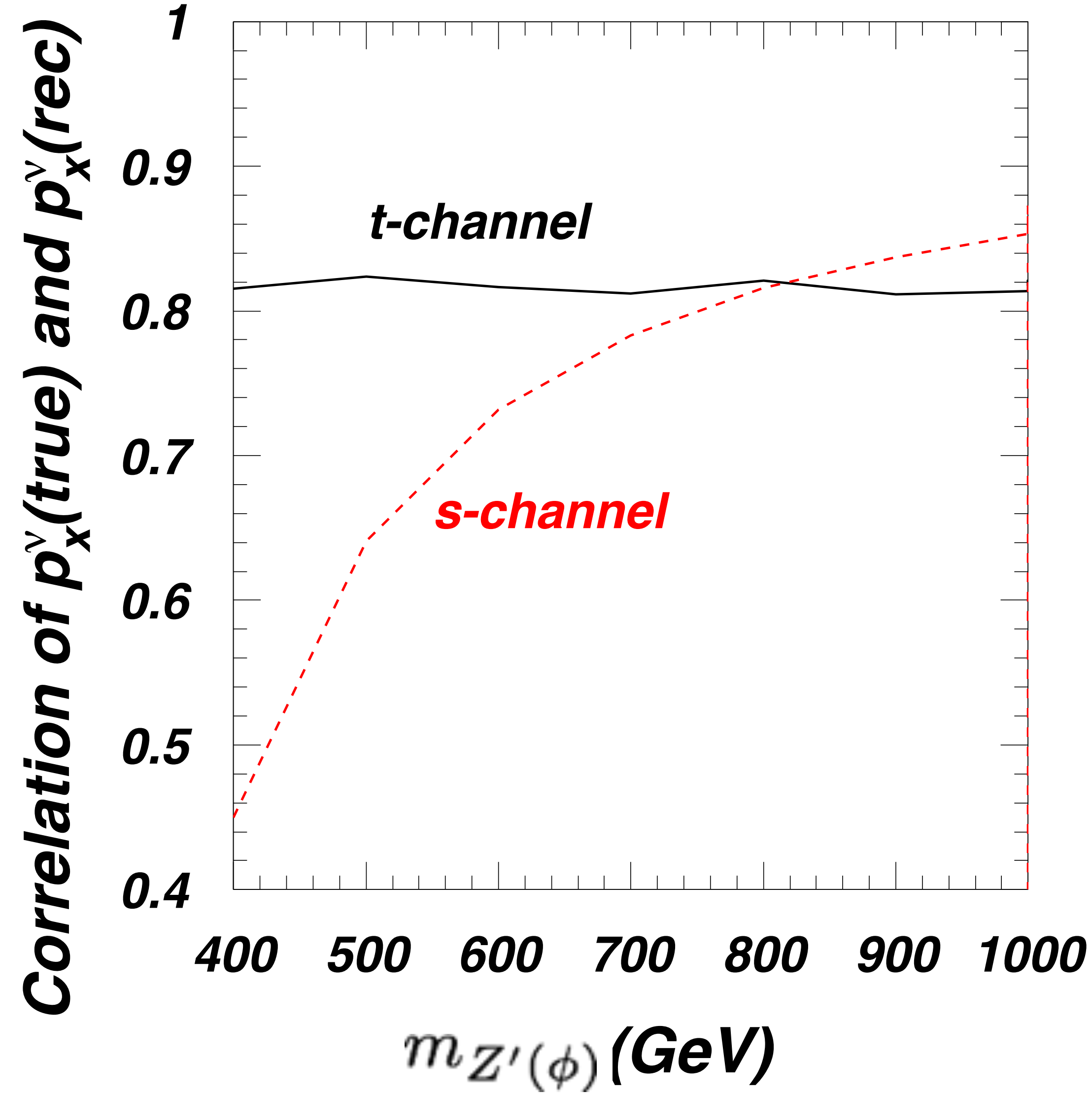
Neutrino momentum reconstruction

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



★ Correlation

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)\sigma_x \sigma_y}$$

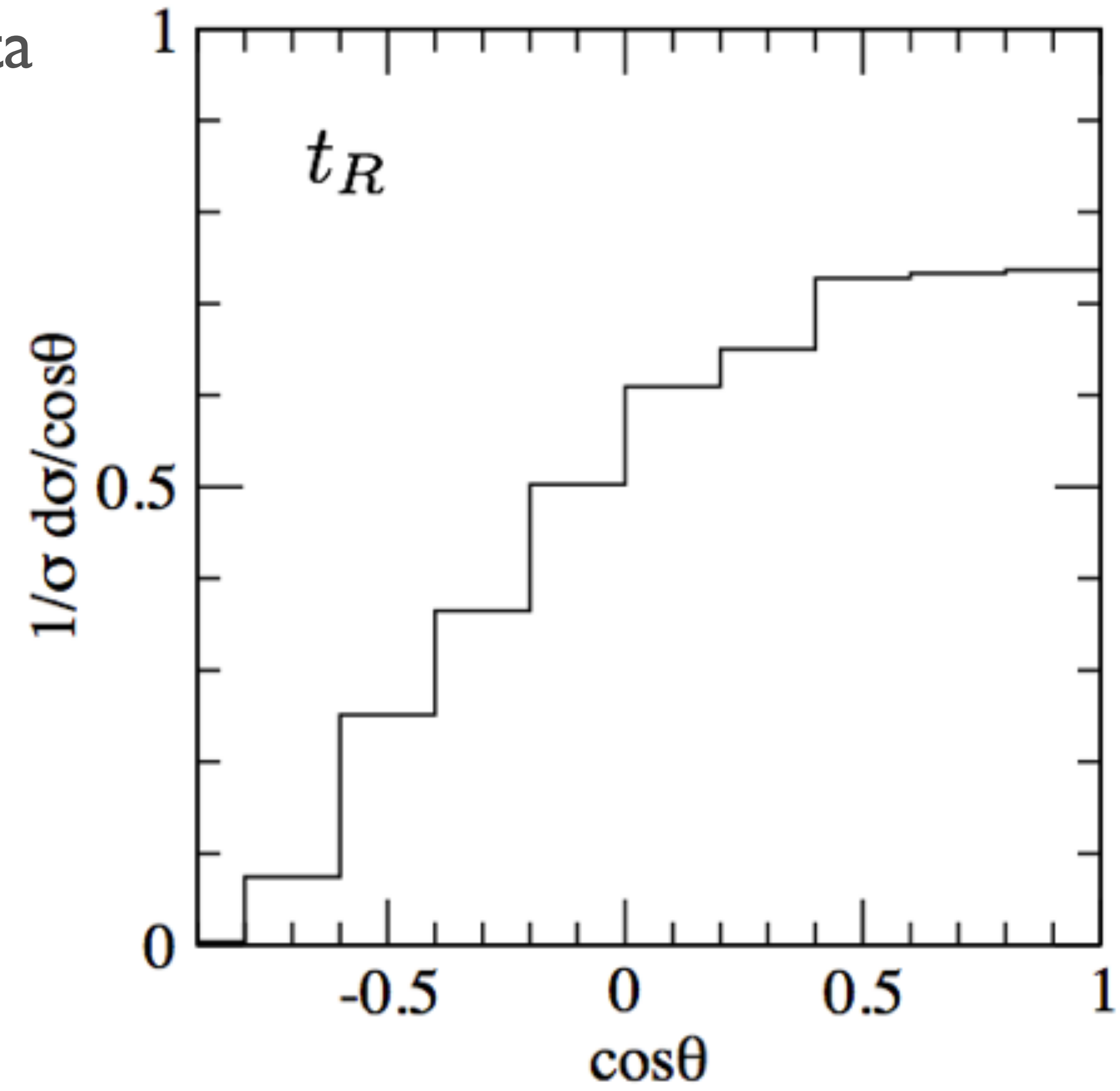


Correlation is larger than 85%.

Top quark polarization

★ 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 follows the top quark spin direction.

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

The road map

- Step 1: Are there top quarks in the intermediate state ?

  The MT2 distribution exhibits an endpoint near m_t

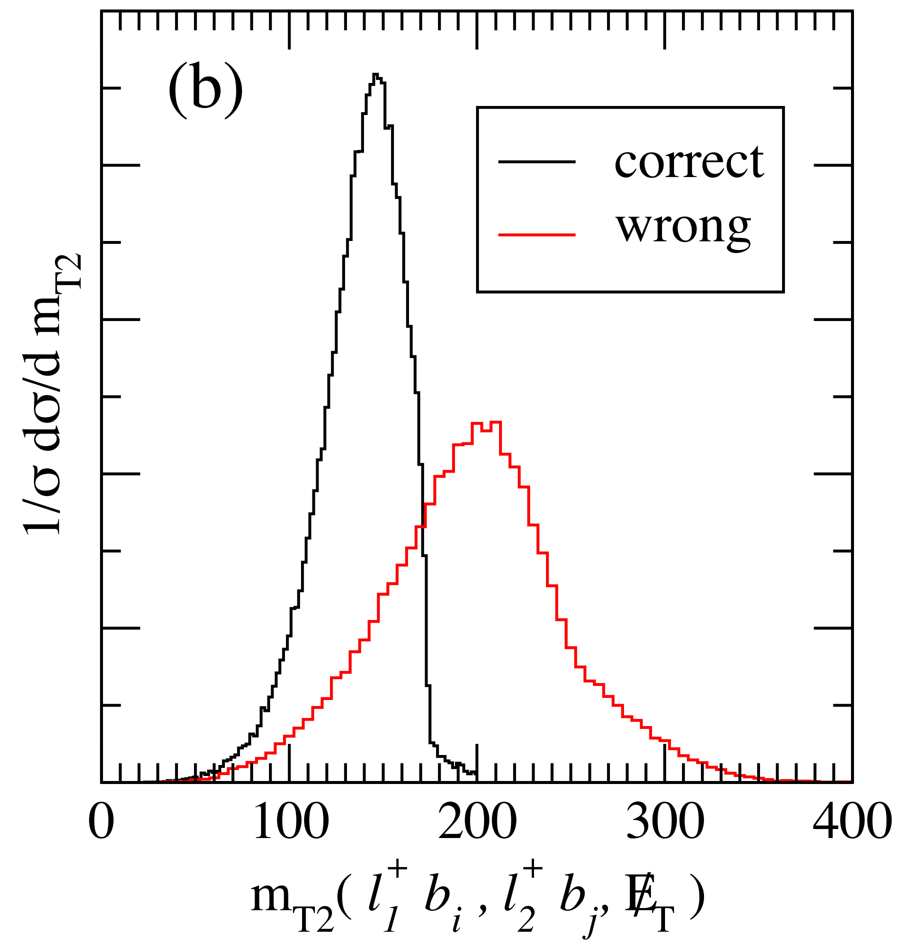
- Step 2: Select the "correct" combination.

  Calculate the MT2 variable, then choose the combination minimizes the MT2 value.

- Step 3: Reconstruct top quark kinematics.

  Solve the kinetic equations of W-boson and top quark on-shell conditions.

- Step 4: Investigate the property of the heavy resonance, top quark polarization, top-top (top-antitop) spin correlation, etc ...



* efficiency > 95% for t-channel
* efficiency > 95% for s-channel resonance heavier than 600GeV

Interim summary

★ Among various NP explanations of top quark A_{FB} data, the FCNC Z-prime is fascinating as it explains the large asymmetry found in large ttbar invariant mass and the forward regions.

★ The FCNC interaction, however, leads to same-sign top quark pair production, which could be easily detected at the 7 TeV.

★ The CMS measurement of top-antitop quark pair productions imposes a very tight constraint on the FCNC couplings.

★ The FCNC Z-prime alone cannot explain A_{FB} data.

Color Sextet Scalar

(s-channel resonance)

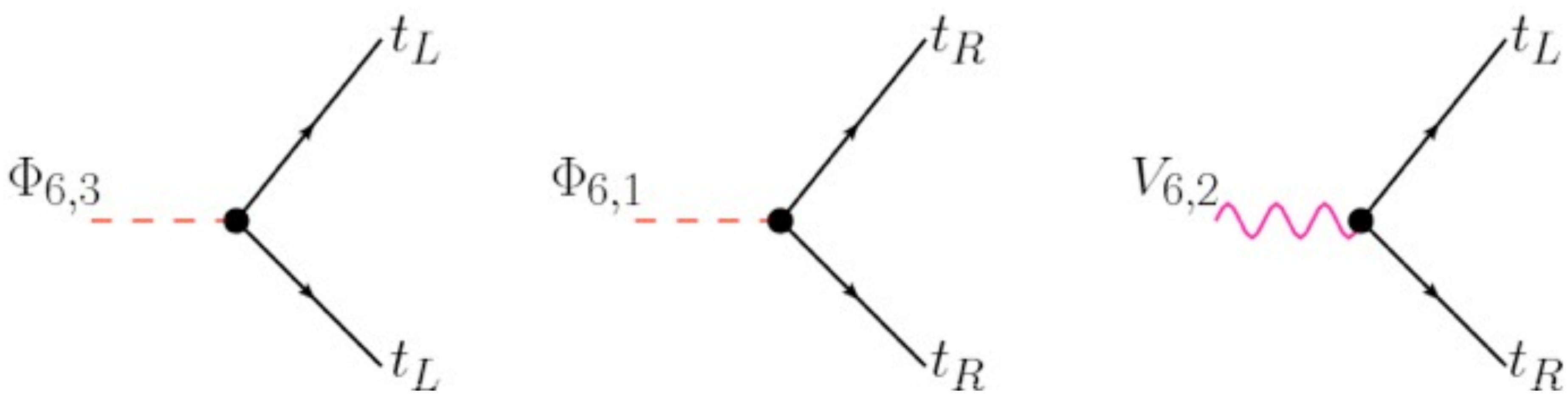
The Model

★ Effective Lagrangian

$$\begin{aligned}\mathcal{L} = & \left(g_{1L}\overline{q_L^c}i\tau_2 q_L + g_{1R}\overline{u_R^c}d_R\right)\Phi_{6,1,1/3} \\ & + g'_{1R}\overline{d_R^c}d_R\Phi_{6,1,-2/3} + g''_{1R}\overline{u_R^c}u_R\Phi_{6,1,4/3} \\ & + g_{3L}\overline{q_L^c}i\tau_2\tau q_L\cdot\Phi_{6,3,1/3} \\ & + g_2\overline{q_L^c}\gamma_\mu d_R V^\mu_{6,2,-1/6} + g'_2\overline{q_L^c}\gamma_\mu u_R V^\mu_{6,2,5/6} + h.c.\,,\end{aligned}$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$q^c = C\bar{q}^T$$



★ One can measure the polarizations of both top quarks to determine the spin of heavy resonances and also determine their gauge quantum numbers.

We implement full spin correlations in our Monte Carlo simulation.

Color sextet scalars

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

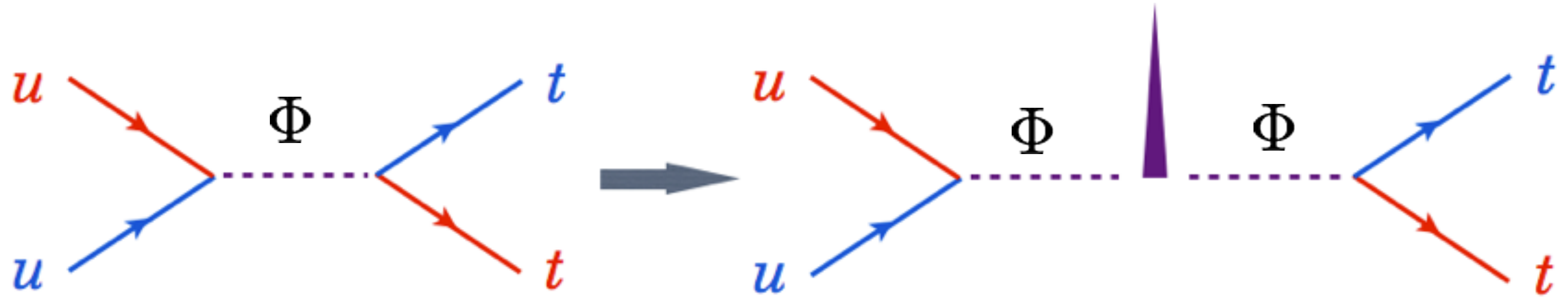
$SU(2)_L$	$U(1)_Y$	$\|Q\| = \|T_3 + Y\|$	couplings to
1	1/3	1/3	QQ, UD
3	1/3	1/3, 2/3, 4/3	QQ
1	2/3	2/3	DD
1	4/3	4/3	UU

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

Narrow decay width

★ $\Gamma(\Phi \to qq) \approx \frac{m_\Phi}{16\pi}\lambda_{qq}^2$, $\Gamma(V \to qq) \approx \frac{m_V}{24\pi} g^2$

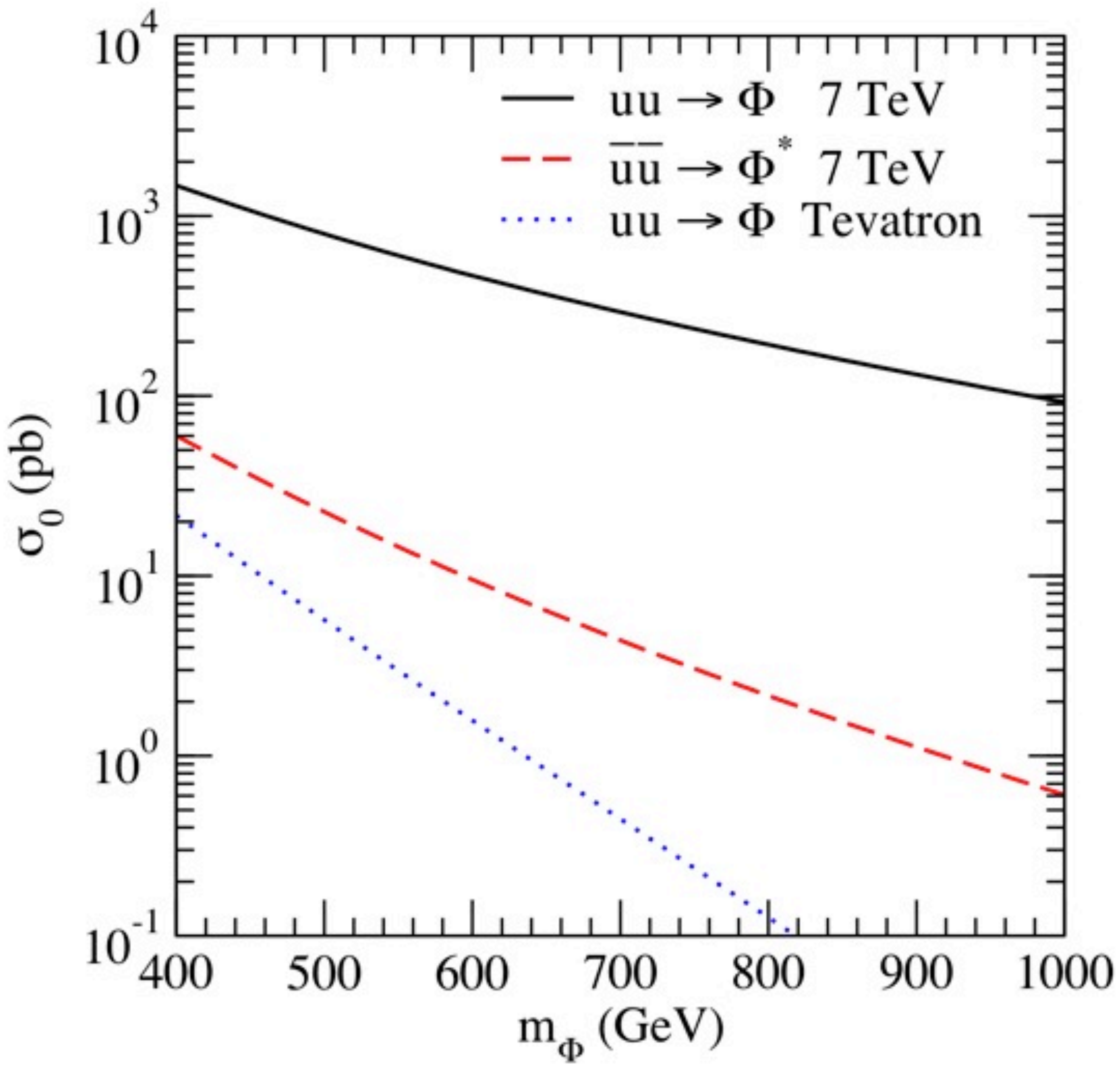
➡ possibly sharp peak in the tt invariant mass spectrum



$$\sigma(uu \to \Phi \to tt) = \sigma_0(uu \to \Phi) \times \lambda_{uu}^2 \mathrm{Br}(tt),$$
$$= \sigma_0(uu \to \Phi \to tt) \times \lambda_{uu}^2 \frac{\mathrm{Br}(tt)}{\mathrm{Br}_0(tt)}.$$

$$\mathrm{Br}(tt) = \frac{\lambda_{tt}^2 R}{\lambda_{uu}^2 + \lambda_{tt}^2 R}, R \equiv \sqrt{1 - \frac{4m_t^2}{m_\Phi^2}}\left(1 - \frac{2m_t^2}{m_\Phi^2}\right)$$

Production cross section



$$\sigma_0 \equiv \sigma(uu \to \Phi)\Big|_{\lambda_{uu}=1}$$

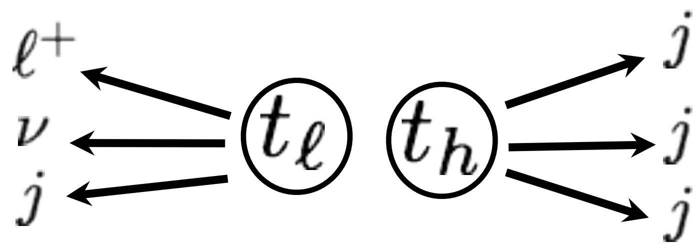
Constraints from the Tevatron

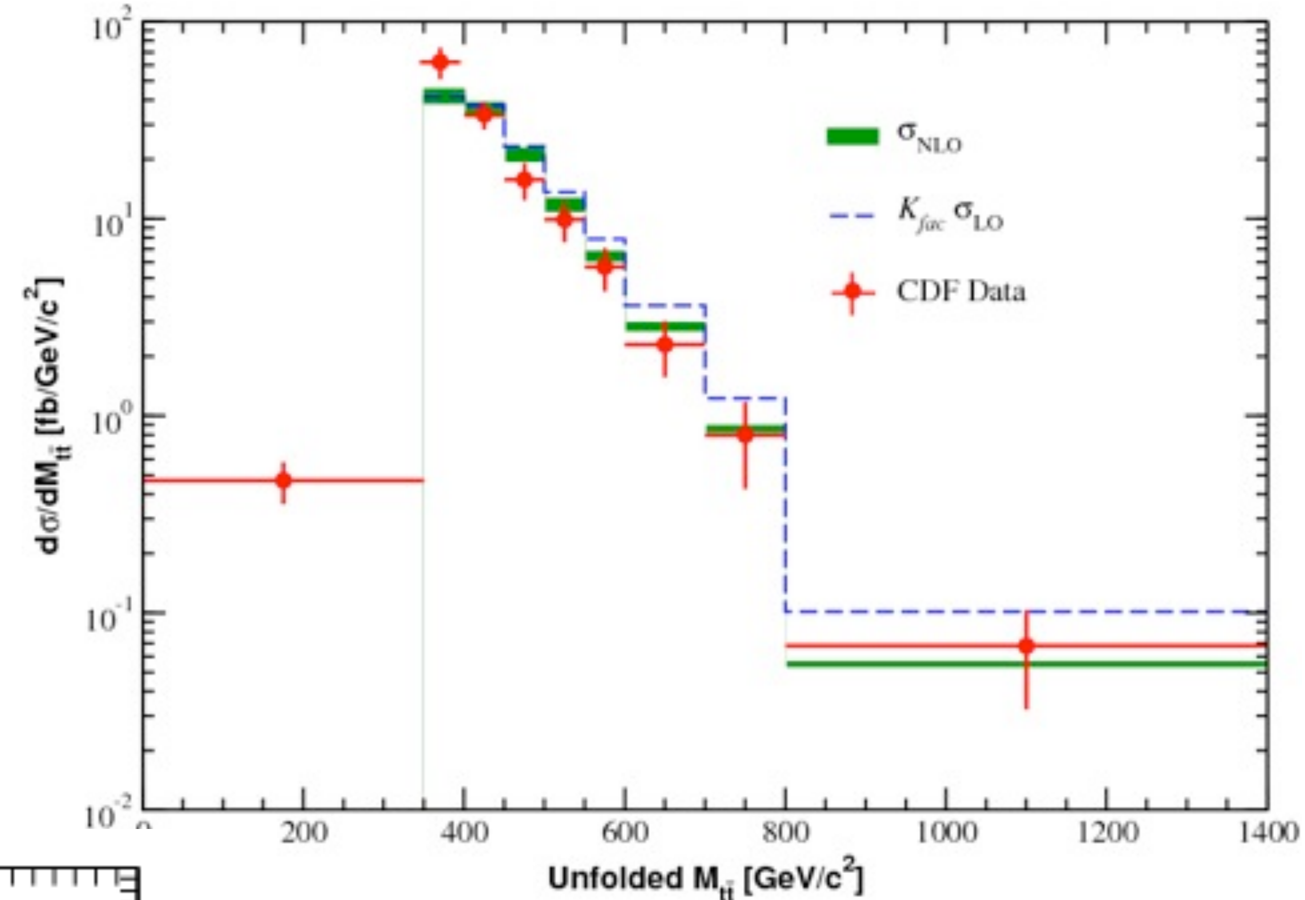
★ Top pair cross section constrained by CDF measurement of

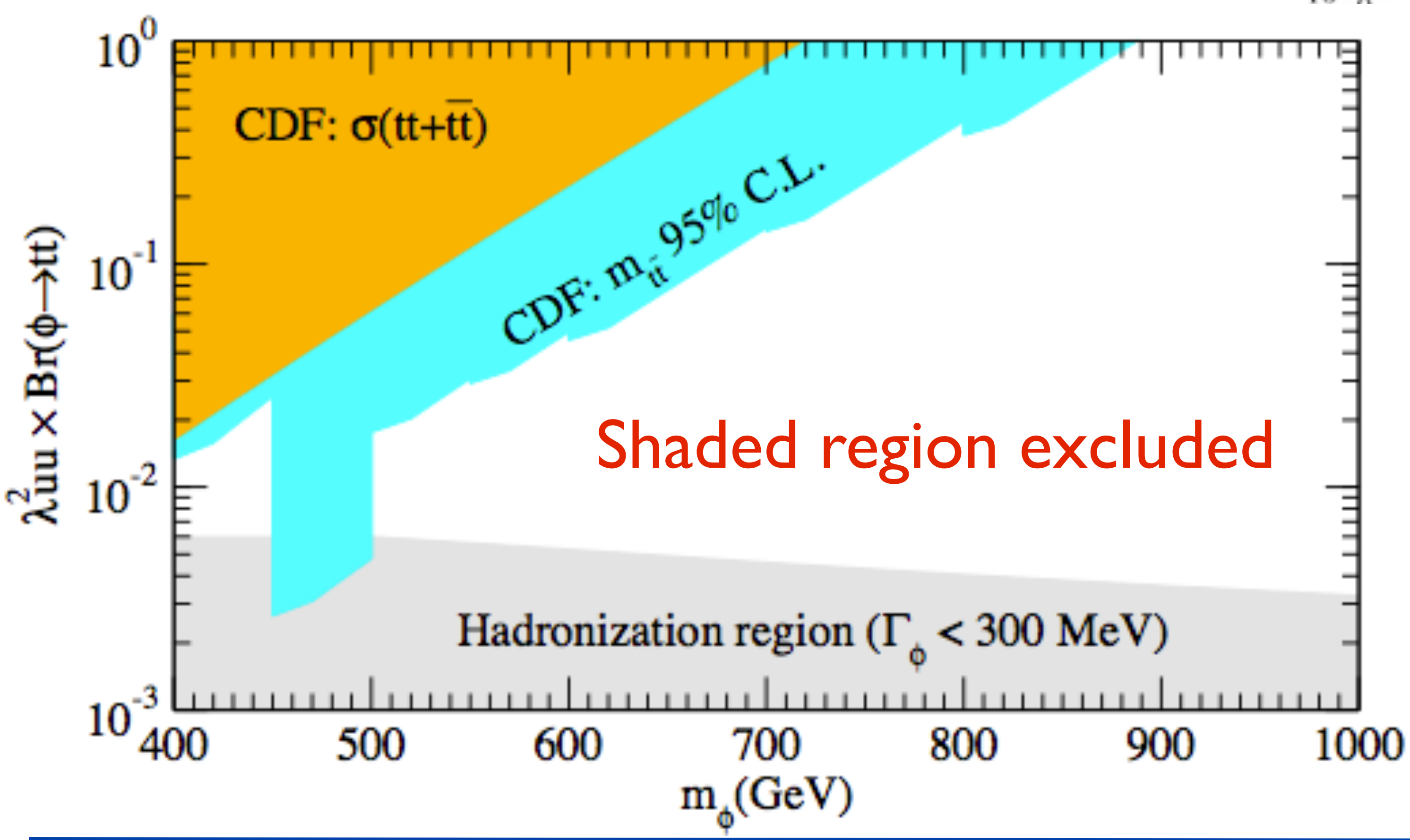
- ✳ Same-sign top pair search

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

- ✳Distribution in $M_{t_\ell t_h}$





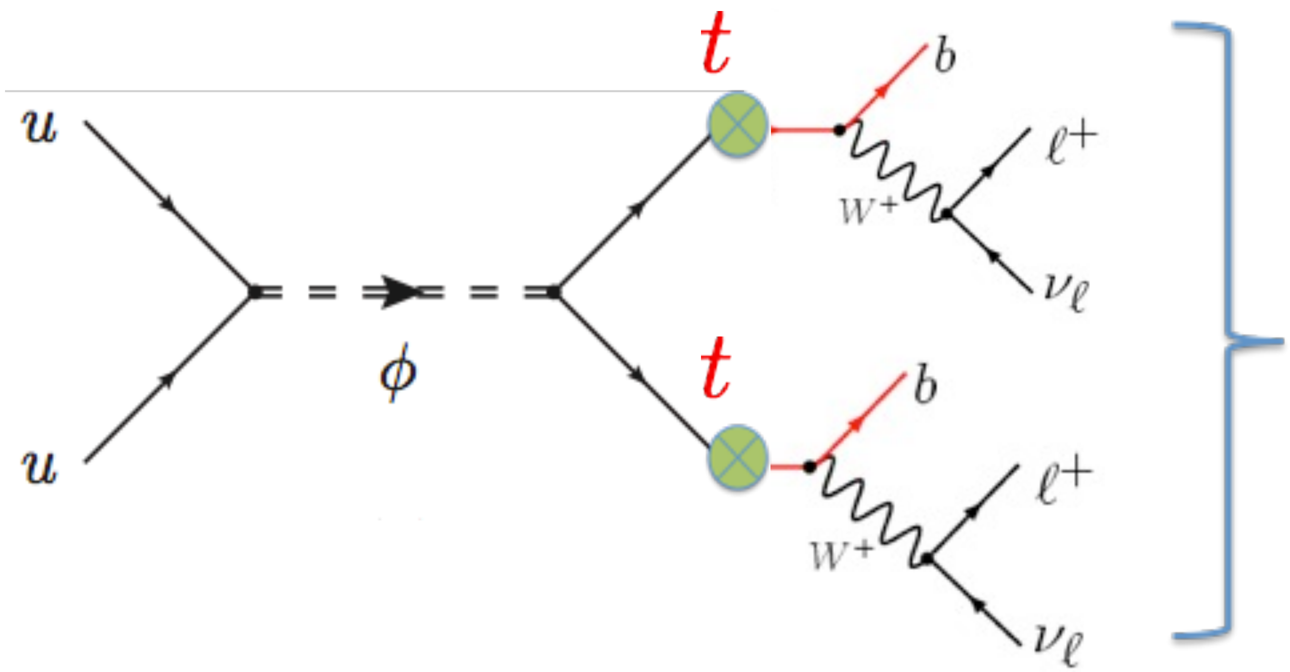


Shaded region excluded

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

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

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

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 rate

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

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

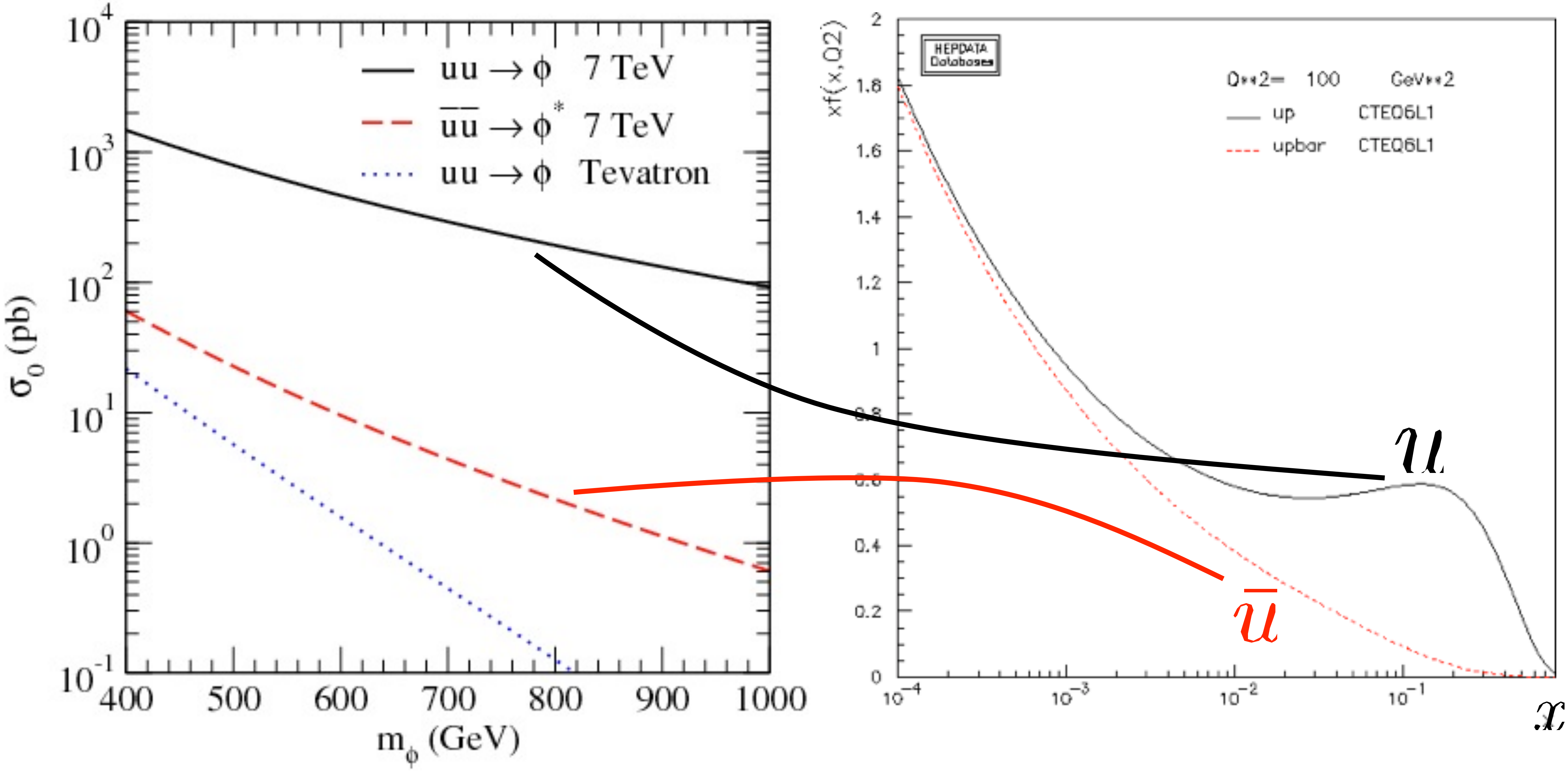
★ Signal and background (pb) before and after cuts, for 6 values of mass

m_Φ	Br(tt)	No cut	With cut	m_Φ	Br(tt)	No cut	With cut	Background	No cut	With cut
500	0.35	288.44	1.71	800	0.45	91.04	0.65	$t\bar{t}$	97.62	0.0032
600	0.41	193.67	1.30	900	0.46	65.14	0.45	$WWjj$	9.38	0.0014
700	0.43	133.46	0.93	1000	0.47	46.72	0.31	WWW/Z	0.03	0

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

Discovery potential

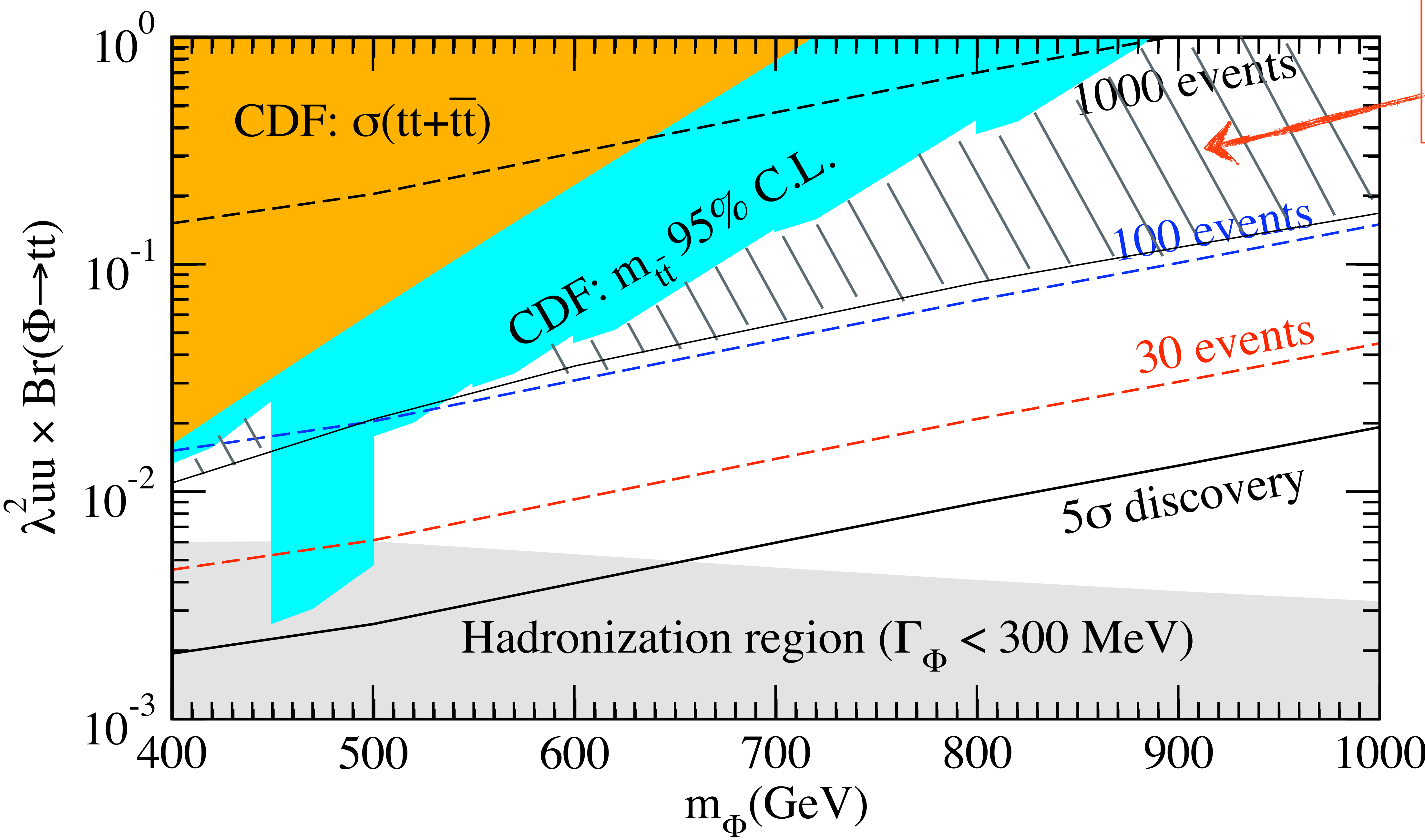
★ Simple cuts to extract signal:

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

✳ Shown are numbers of signal events;

✳ about 4.6 background events

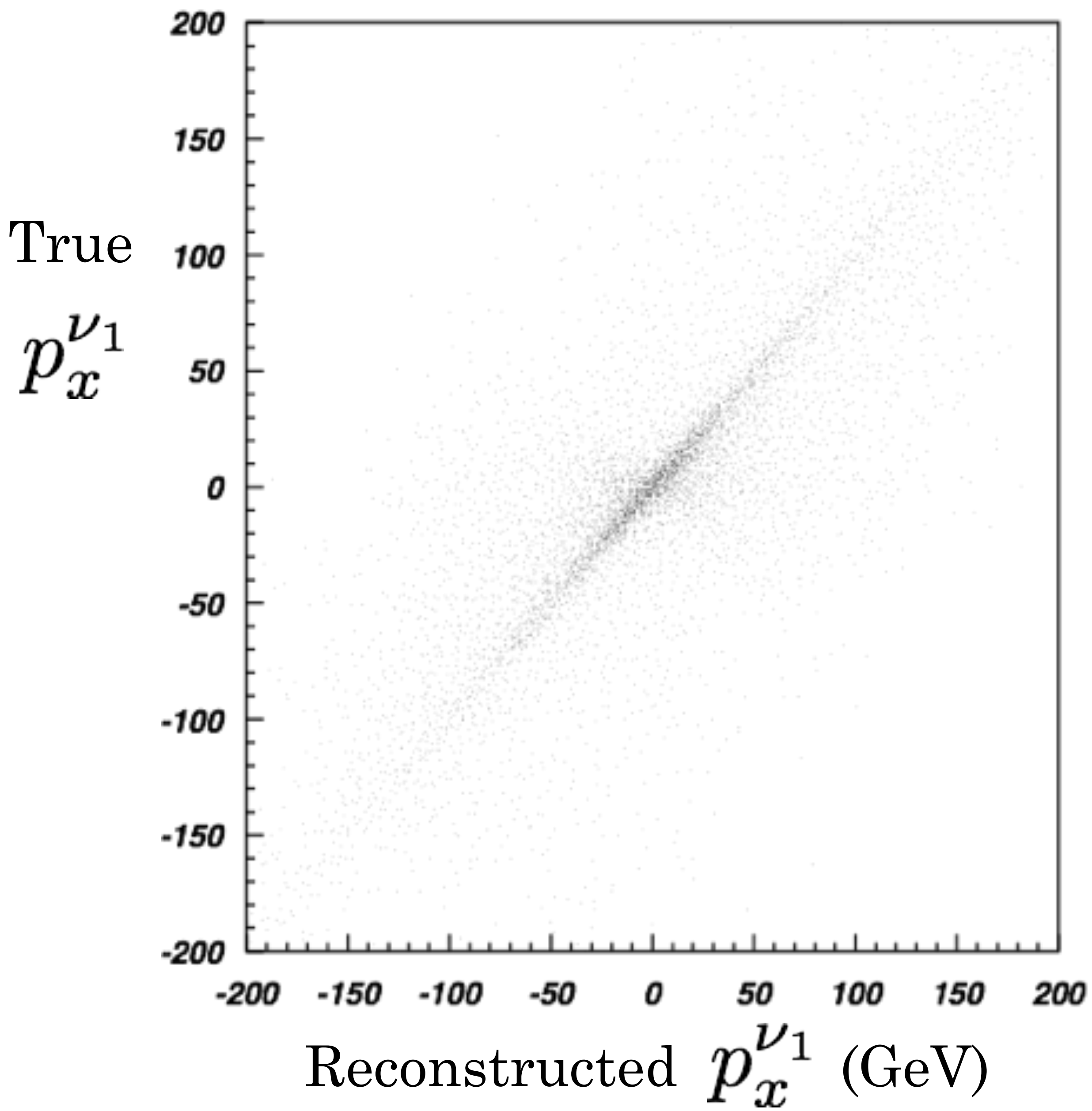
7 TeV $\mathcal{L} = 1\ \text{fb}^{-1}$



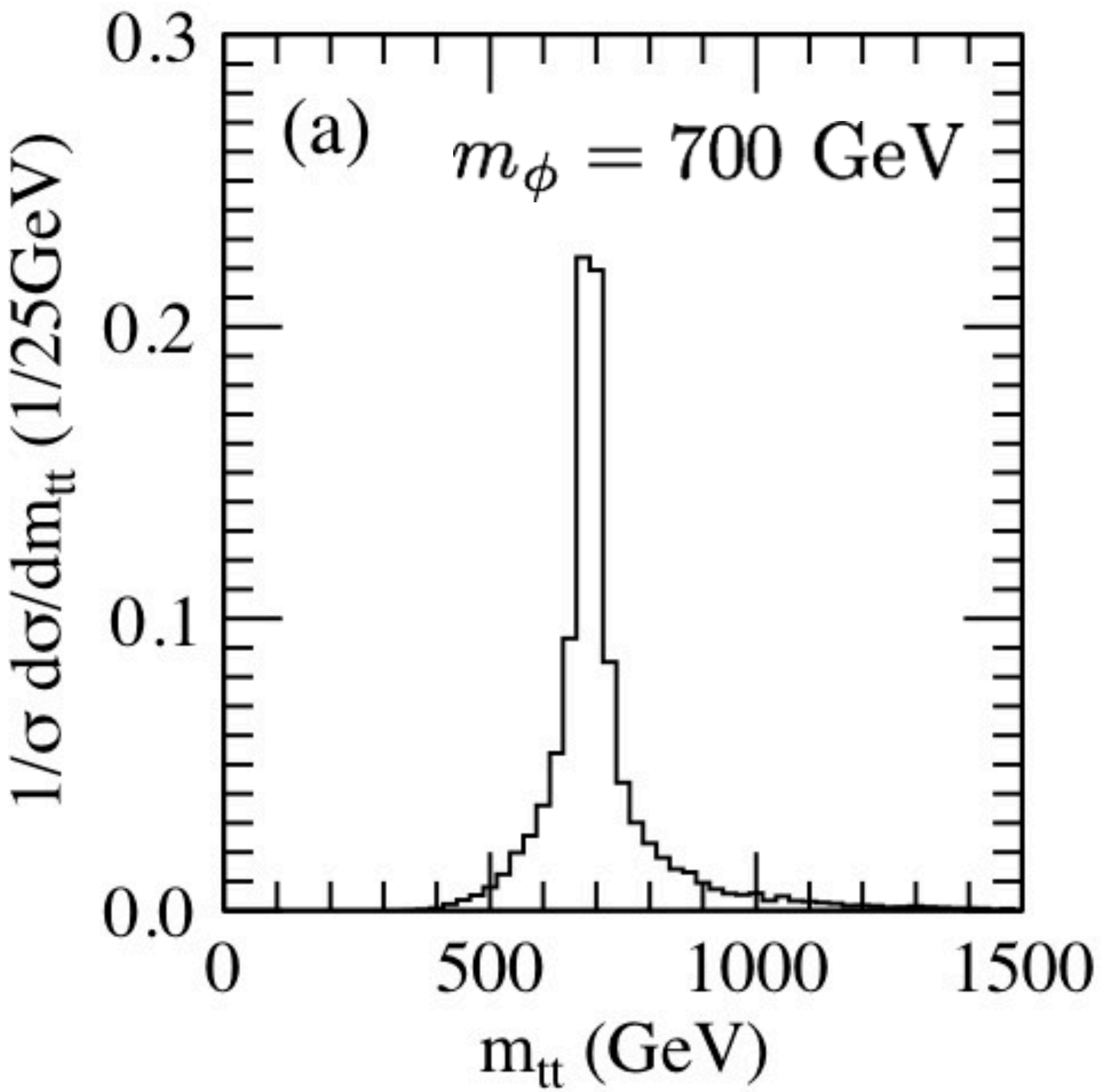
CMS & ATLAS constraints

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:



Top quark polarization and resonance spin

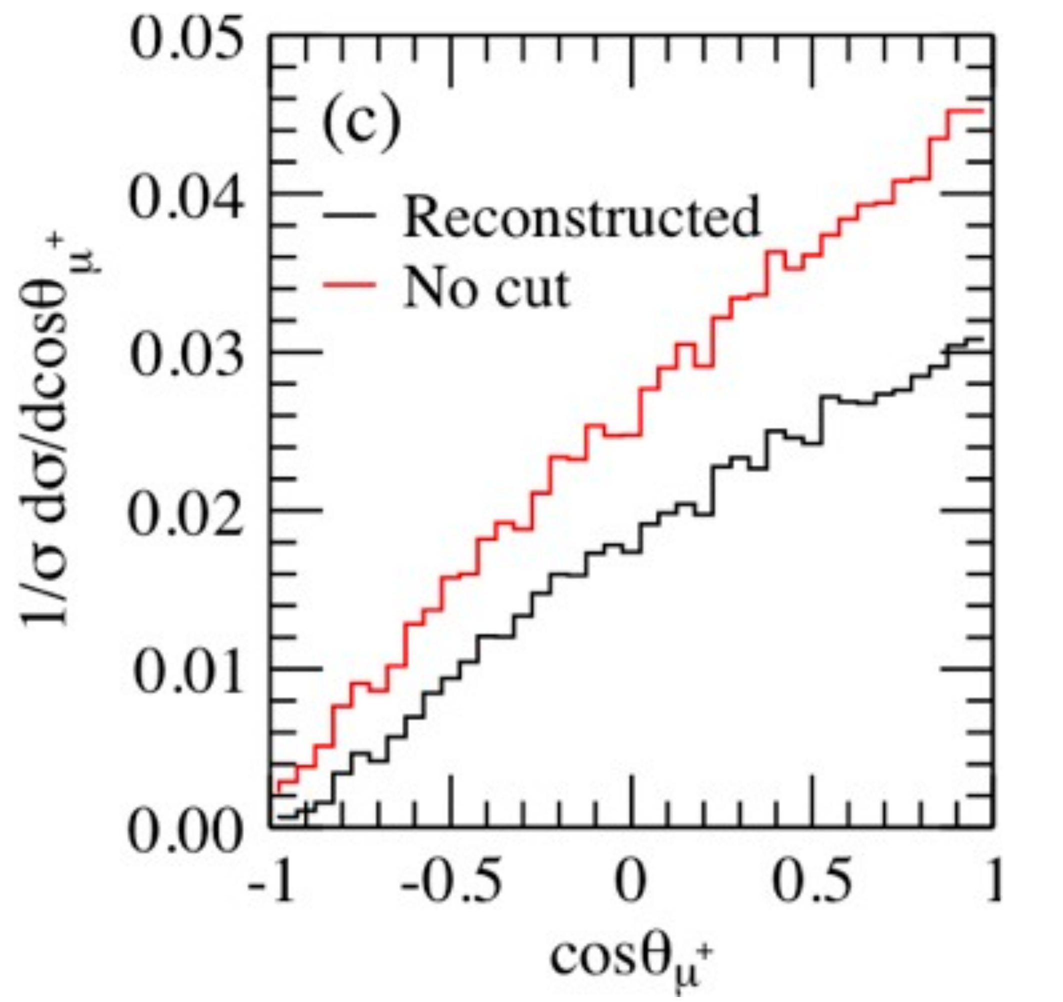
★ Polarization correlates with angle between top quark spin and charged lepton momenta

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

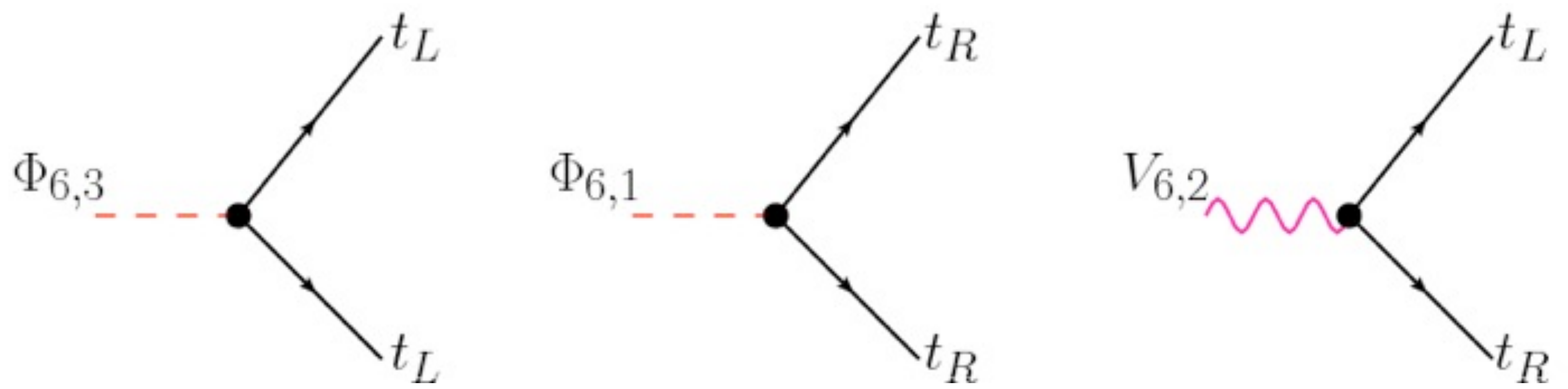
✳ Charged lepton typically follows top quark spin

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

✳ Roughly 30 events required to distinguish from unpolarized case



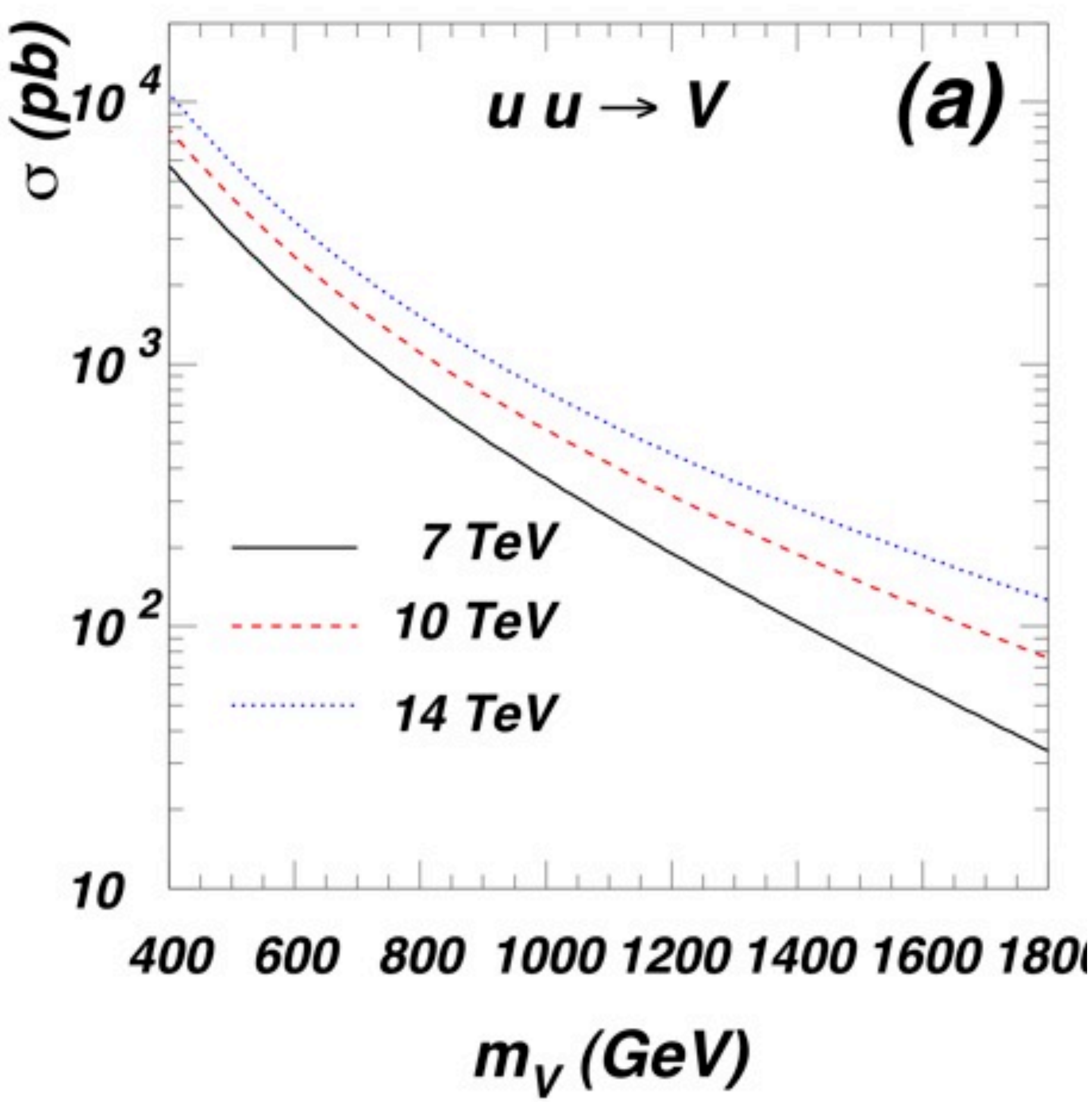
Polarization of the top quarks can be determined.

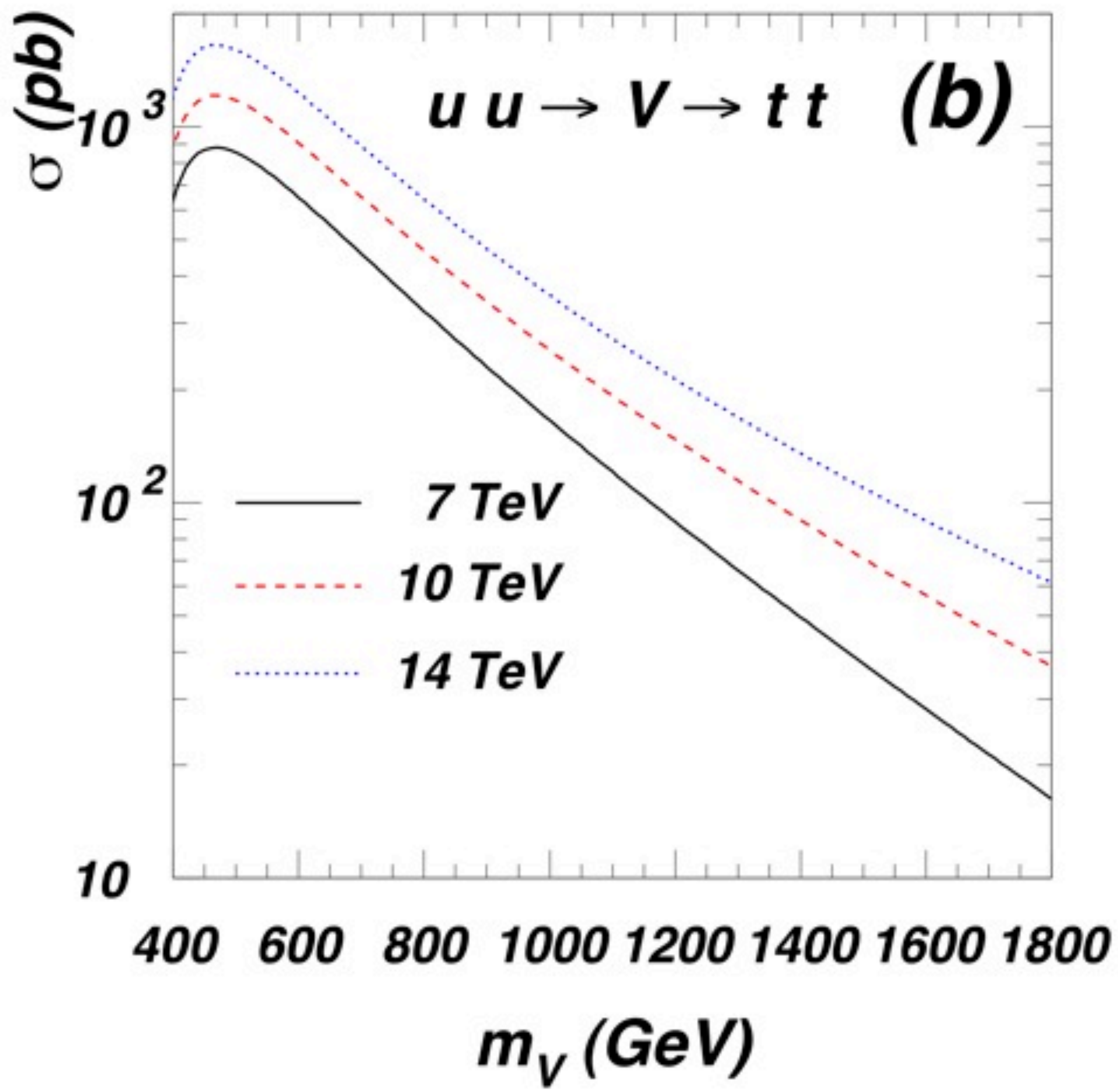


Color Sextet Vector
(s-channel resonance)

Color sextet vector mesons

★ Production cross sections

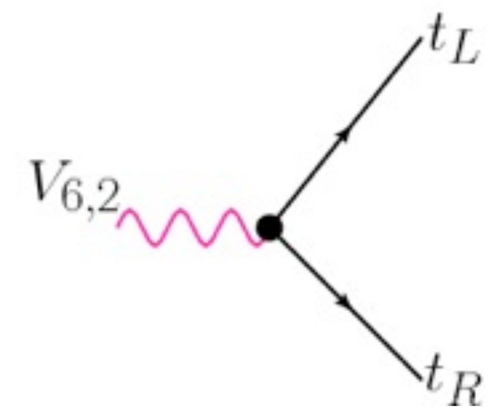




Color sextet vector meson

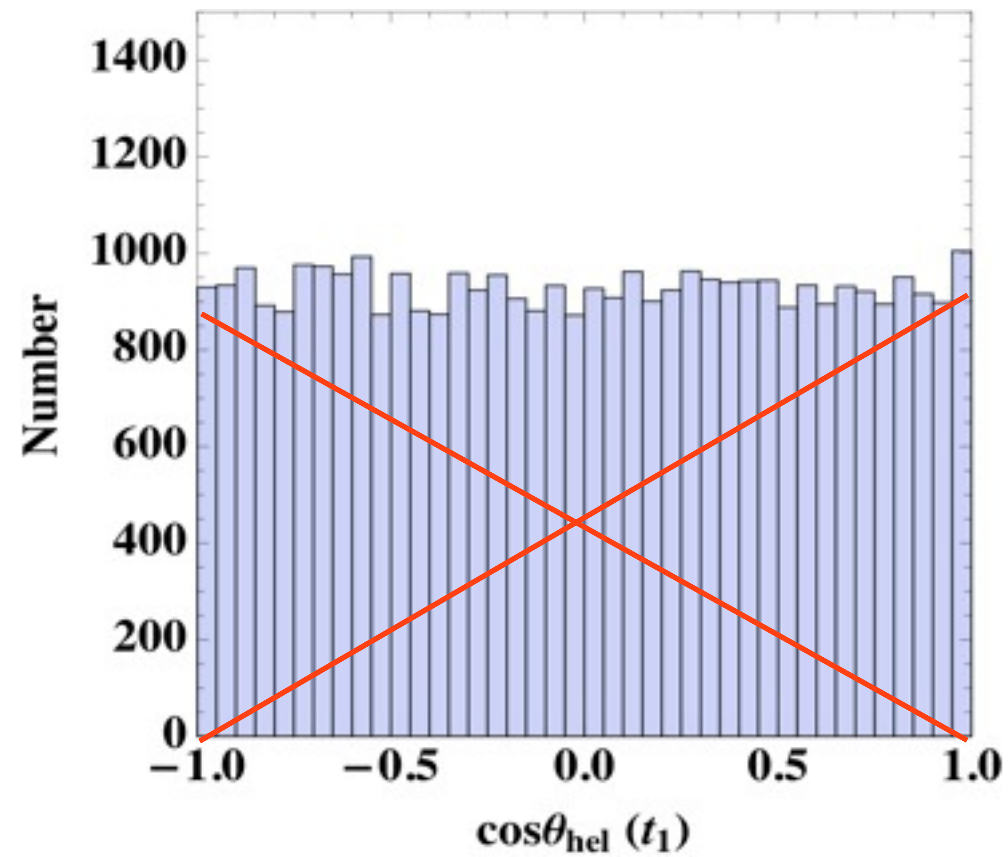
★ The vector sextet must be a SU(2) doublet. It couples to a left-handed quark and a right-handed quark according to:

$$(6,2)_{\frac{5}{6}} \; : \; \epsilon_{ij}\bar{Q}^c_i \gamma^\mu P_R U \; V_{j\mu} + \text{h.c.}$$



★ Top quarks are oppositely polarized, but the net polarization distribution of the two identical top quarks exhibits a flat profile (i.e. like unpolarized top quarks).

★ Even though the flat profile of sextet vectors is different from the one for scalars, it is interesting to see if we could determine that the top quarks have L and R polarizations.

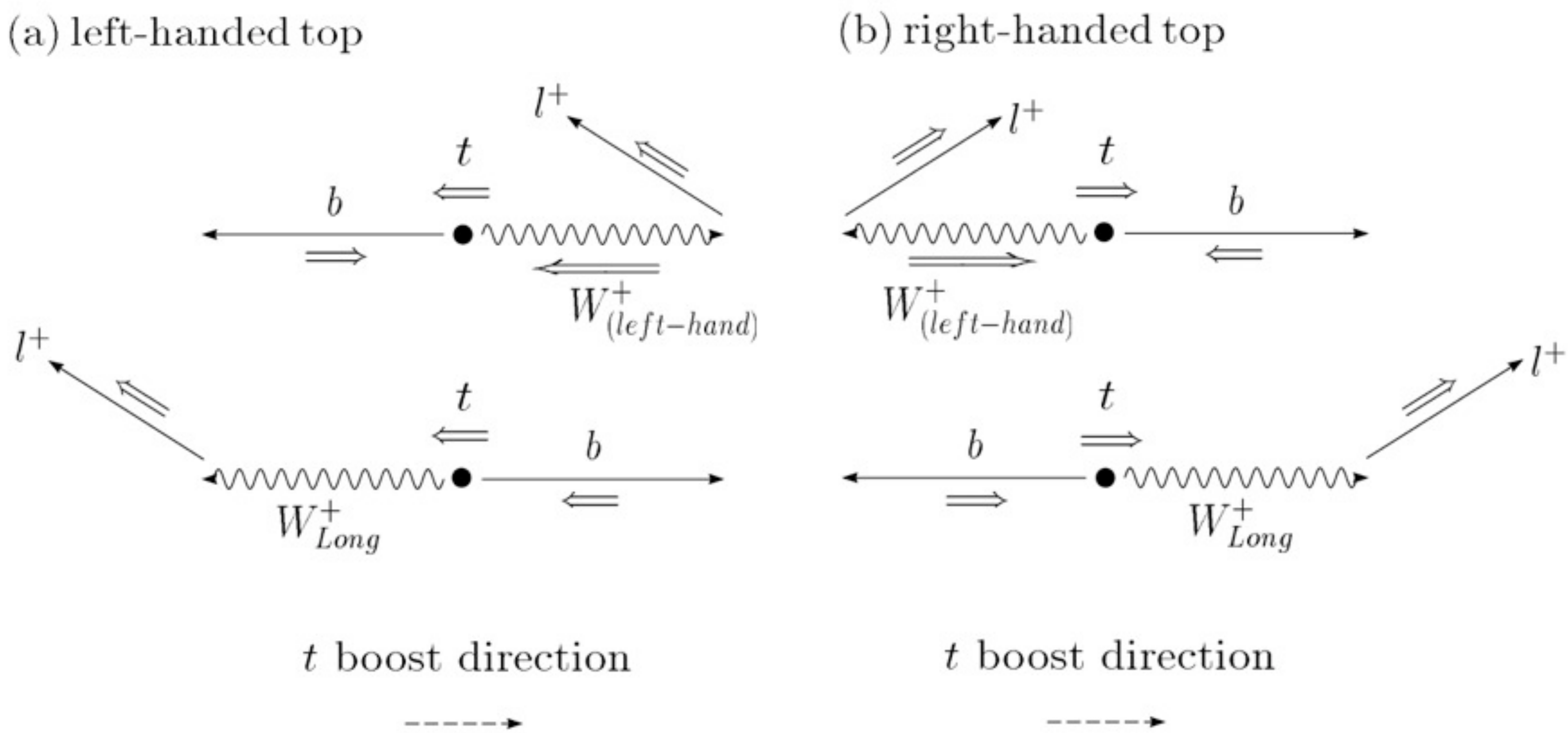


★ Can we measure the polarizations of the top quarks to distinguish the color sextet vector and scalar mesons?

YES!!!

Lepton energy and top quark polarization

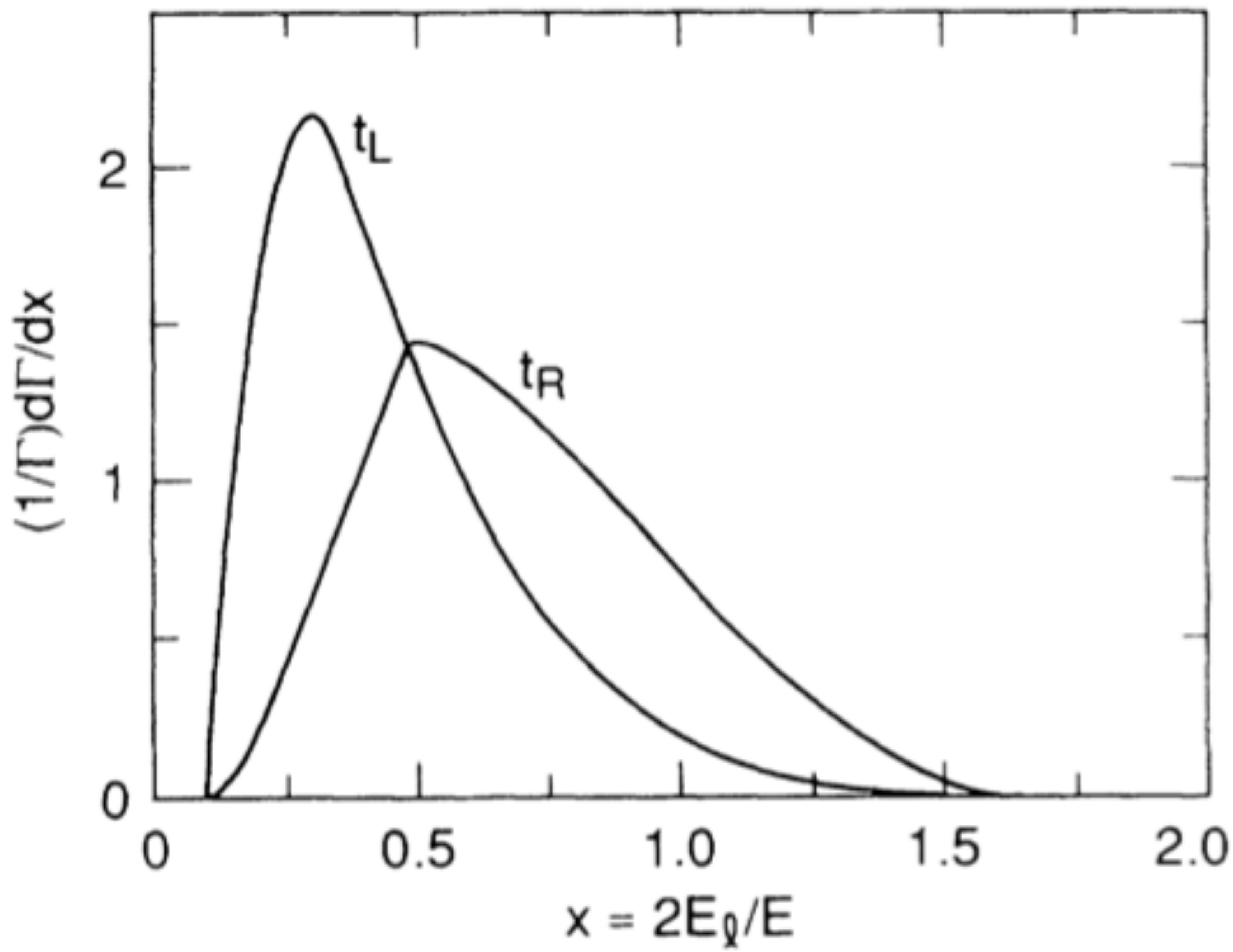
★ Lepton energy distribution is sensitive to top quark polarization.



Leptons from right-handed top quark decay are more energetic than those from left-handed top quark decay.

Lepton energy and top quark polarization

★ Lepton energy distribution is sensitive to top quark polarization.



C. R. Schmidt and M. E. Peskin, Phys. Rev. Lett. 69, 410(1992)

Discovery potential

★ LHC (7 TeV and 1 inverse fb luminosity)

$$p_T^j \geq 50\ \text{GeV}$$

$$|\eta_j| \leq 2.5$$

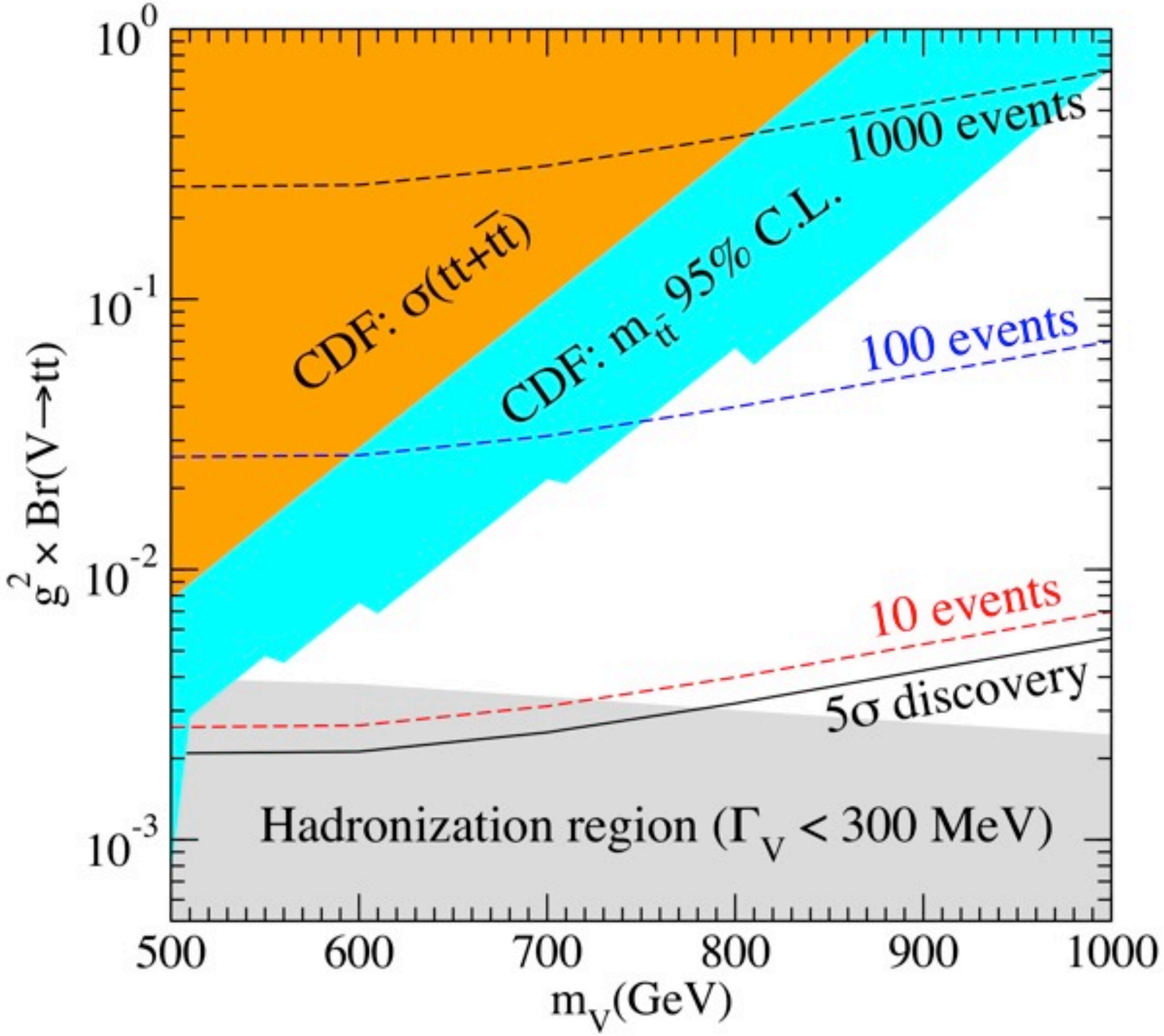
Asymmetric cuts on lepton pT

$$p_T^{\ell\text{Greater}} \geq 50\ \text{GeV}$$

$$p_T^{\ell\text{Lesser}} \geq 20\ \text{GeV}$$

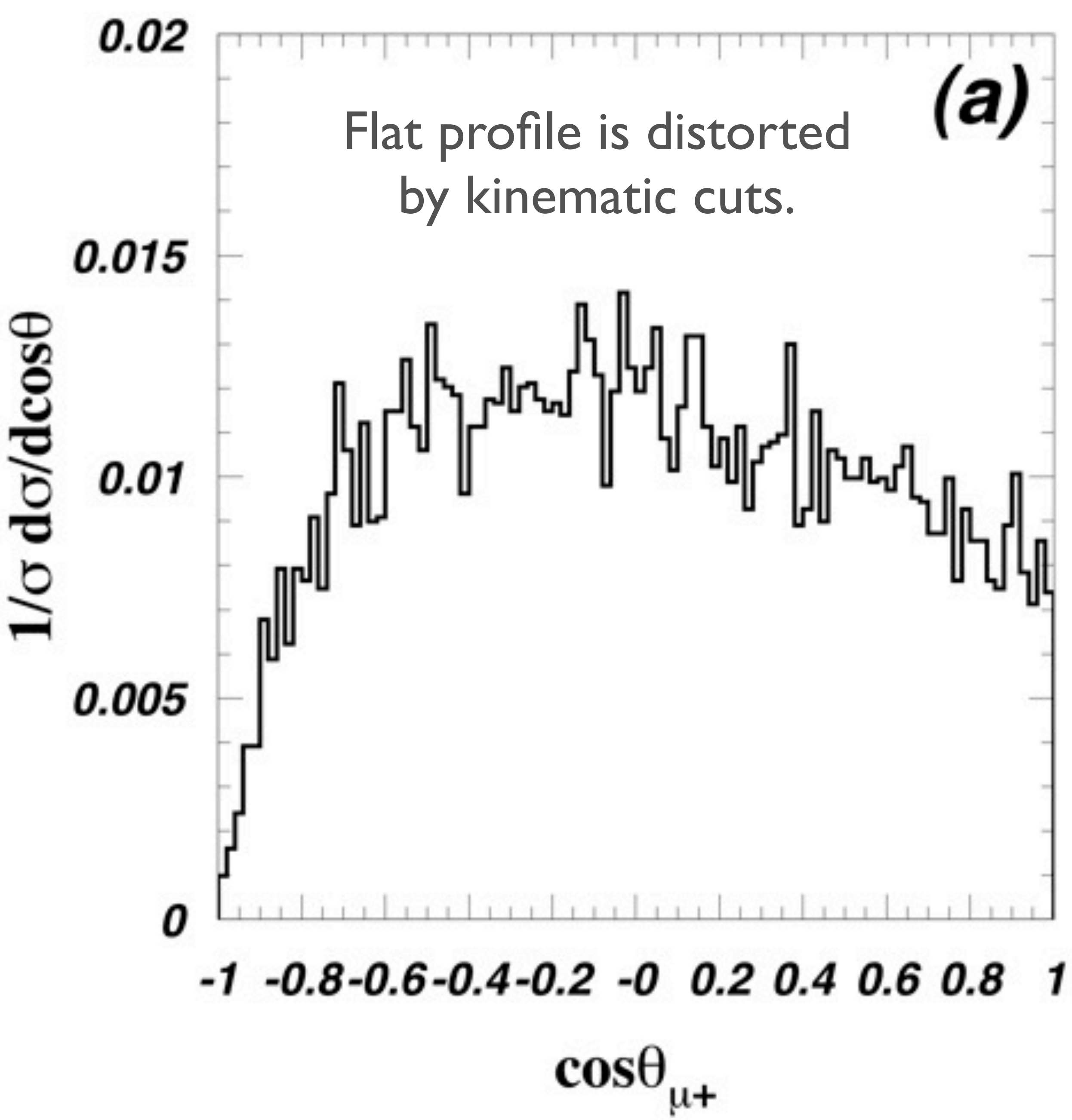
$$|\eta_\ell| \leq 2.0$$

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

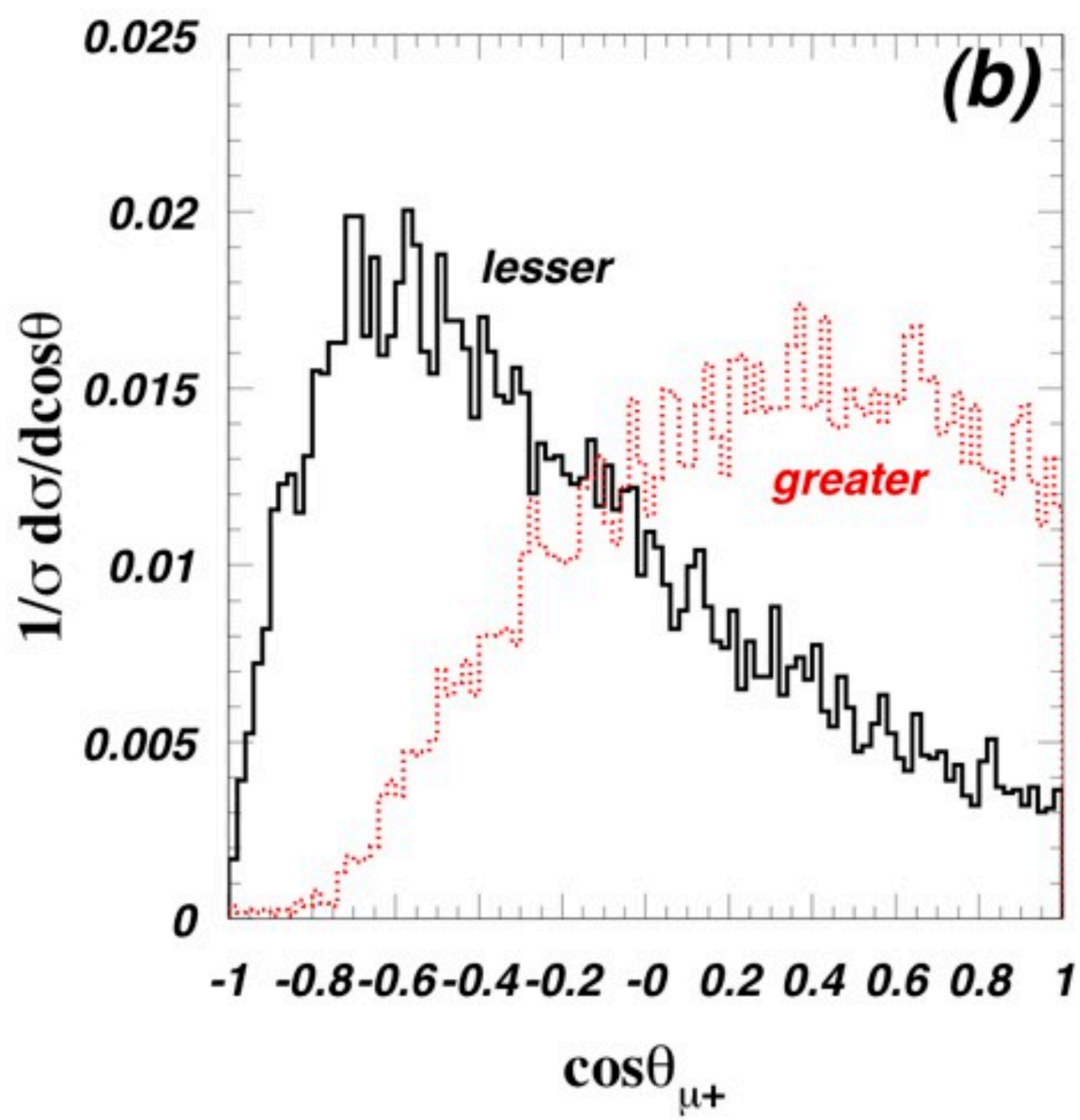


Top quark polarization measurement

★ Before lepton energy selection



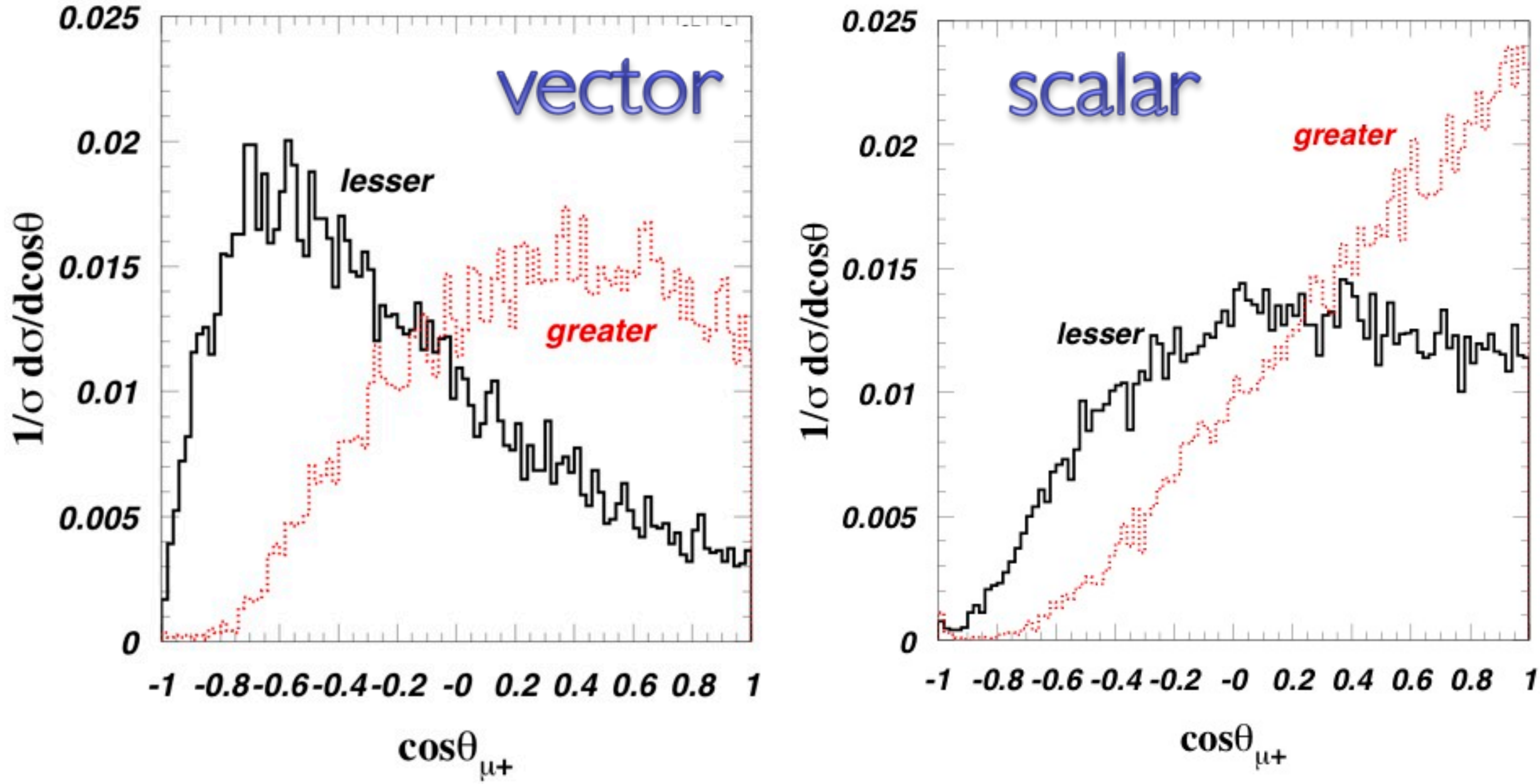
★ After lepton energy selection



✳ Roughly 98 (67) events required to distinguish vector lesser (greater) from vector unpolarized case

Top quark polarization measurement

★ Apply the same analysis to sextet scalar (gauge singlet)



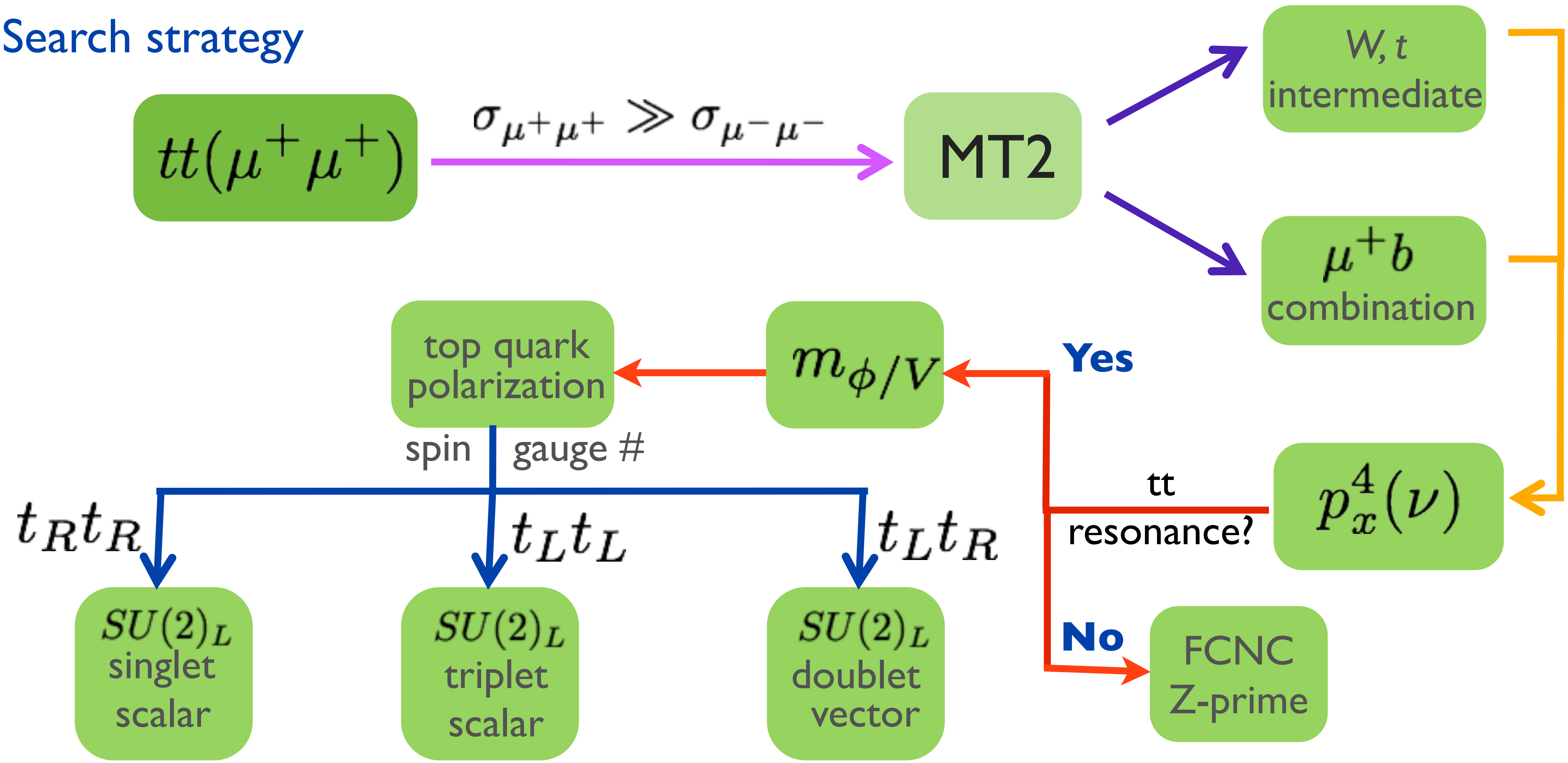
The $\frac{1}{2}(1+\cos\theta)$ shape of sextet scalar still remains with a moderate distortion.

Summary

★ Color sextet scalar and vector mesons may be a long shot they offer good discovery potential in early LHC running at 7 TeV

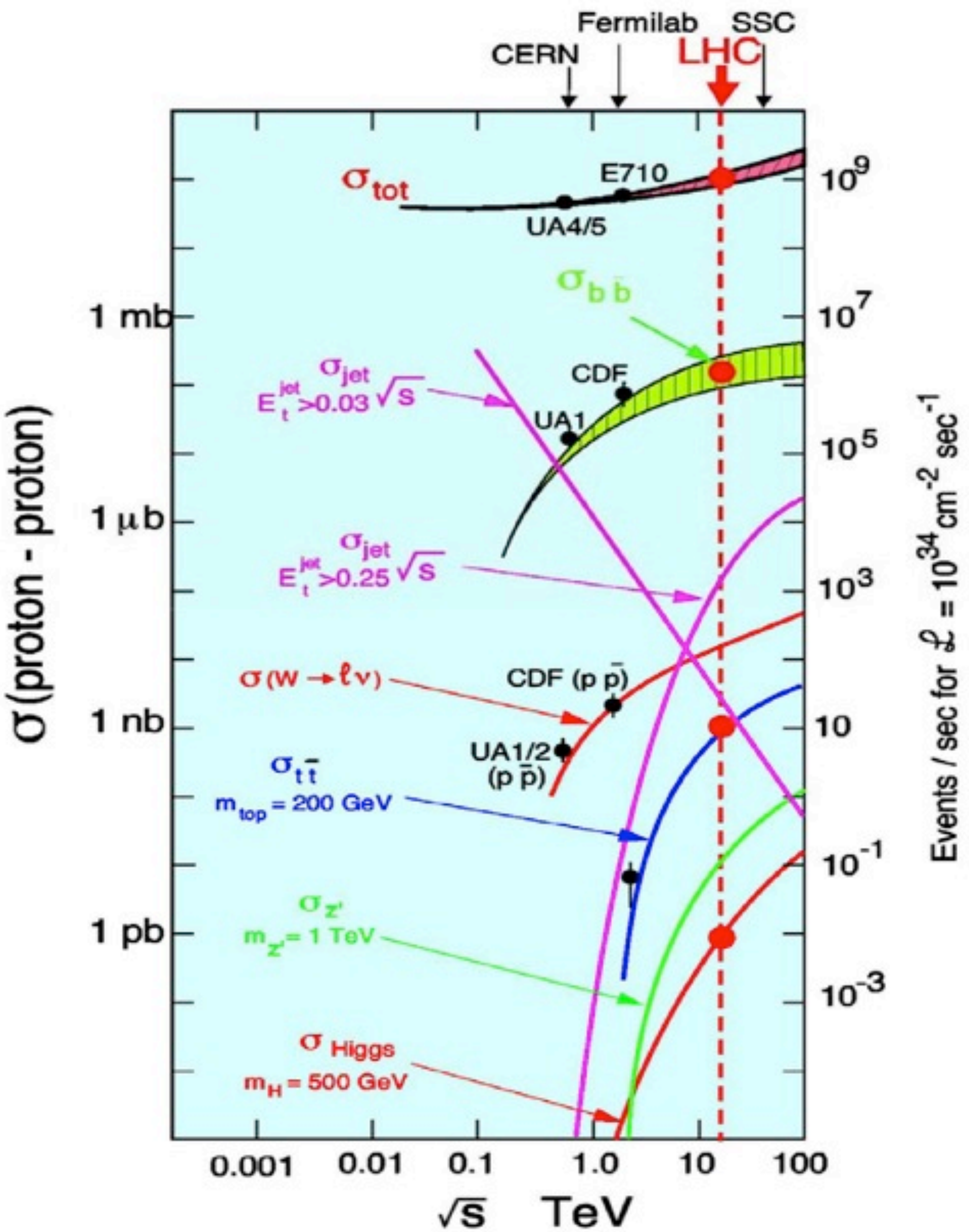
- ✳ Enhanced cross sections relative to EW scale new physics
- ✳ 30 events (scalar) and 100 events (vector) sufficient
- ✳ Naturally large same-sign dilepton rates allow background rejection

★ Search strategy



Backup Slides

LHC decade

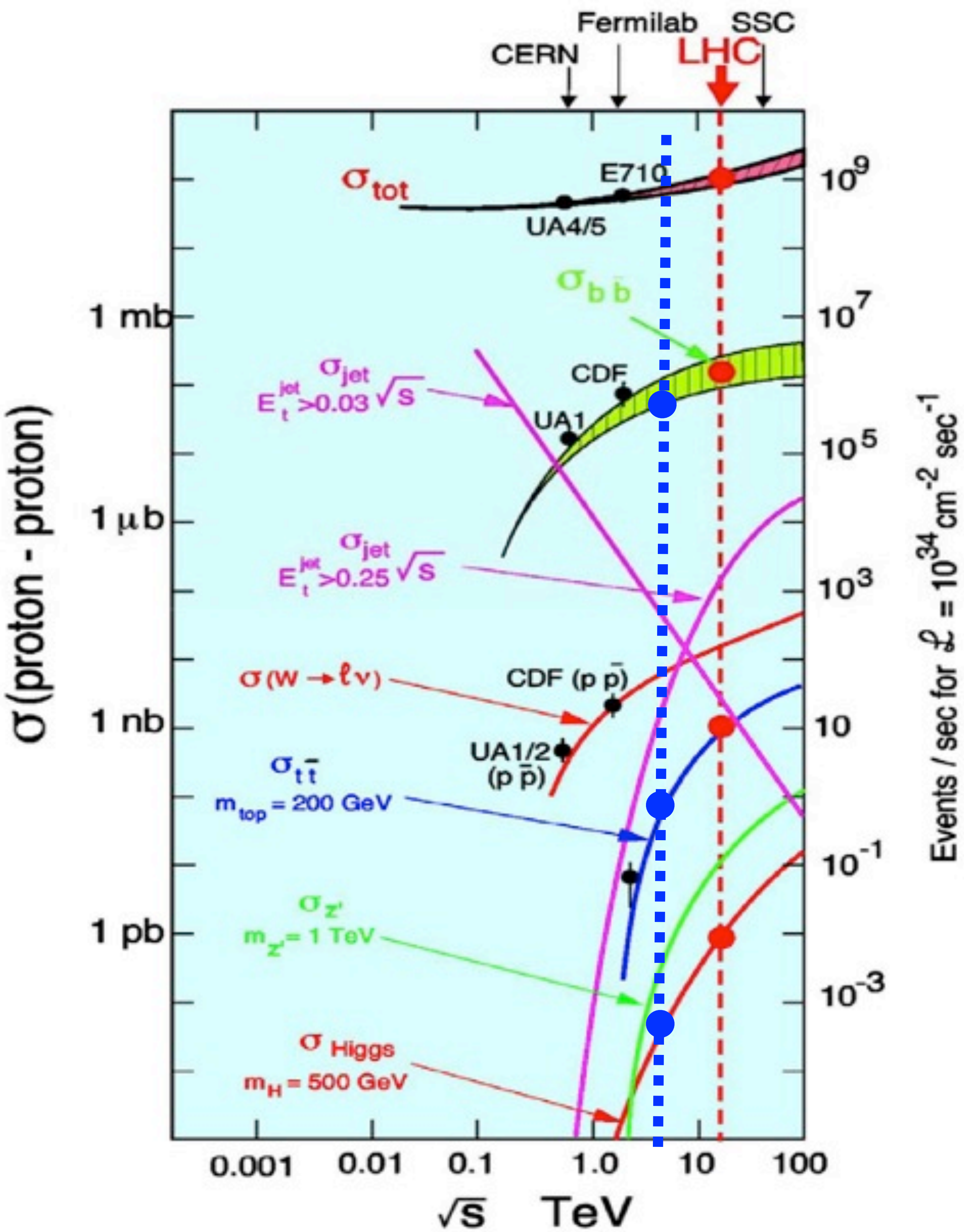


★ Rate for $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}s^{-1}$

- 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.

LHC decade



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

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

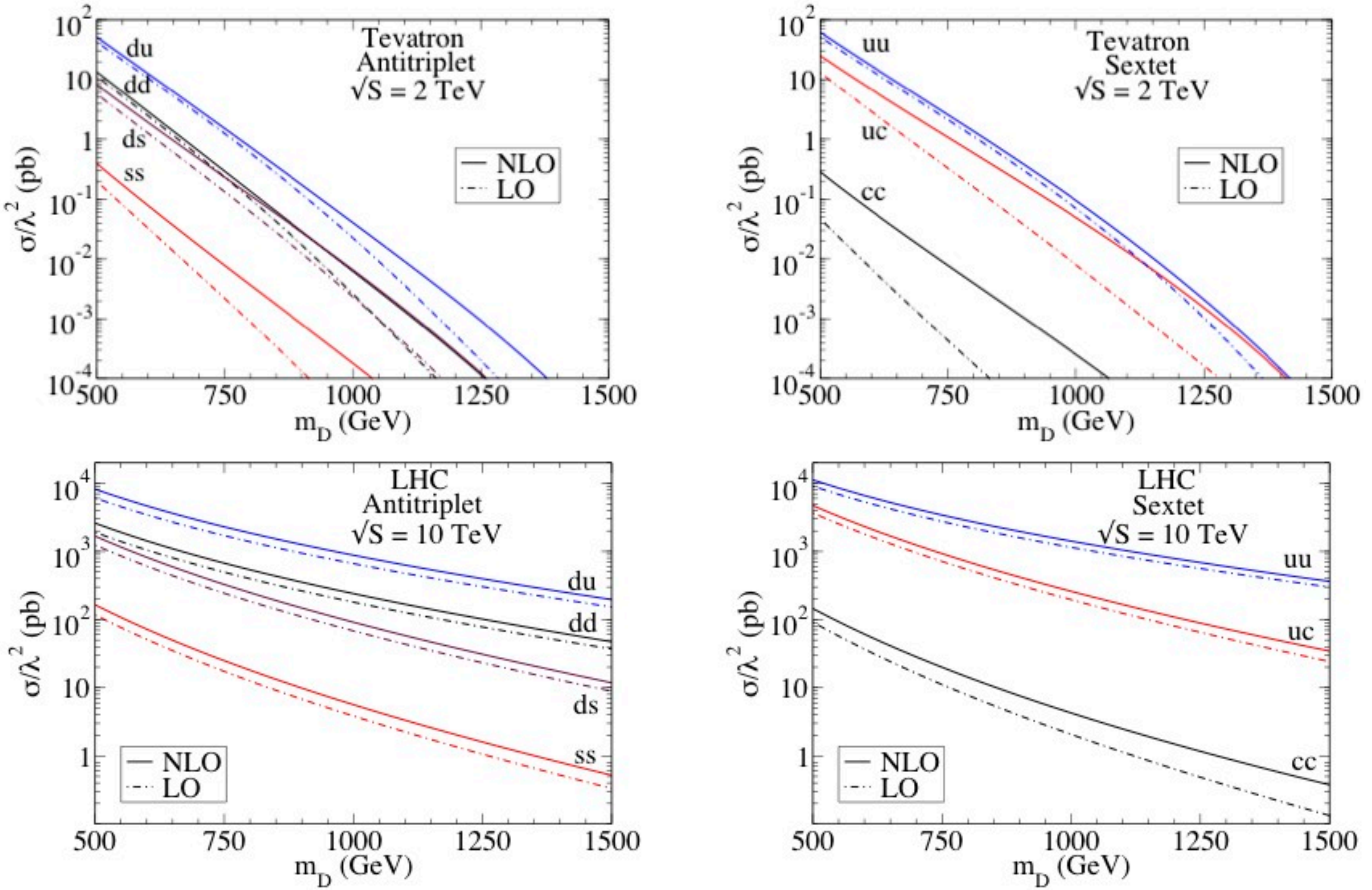
(1) LHC is a factory for SM and new TeV scale physics.

(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

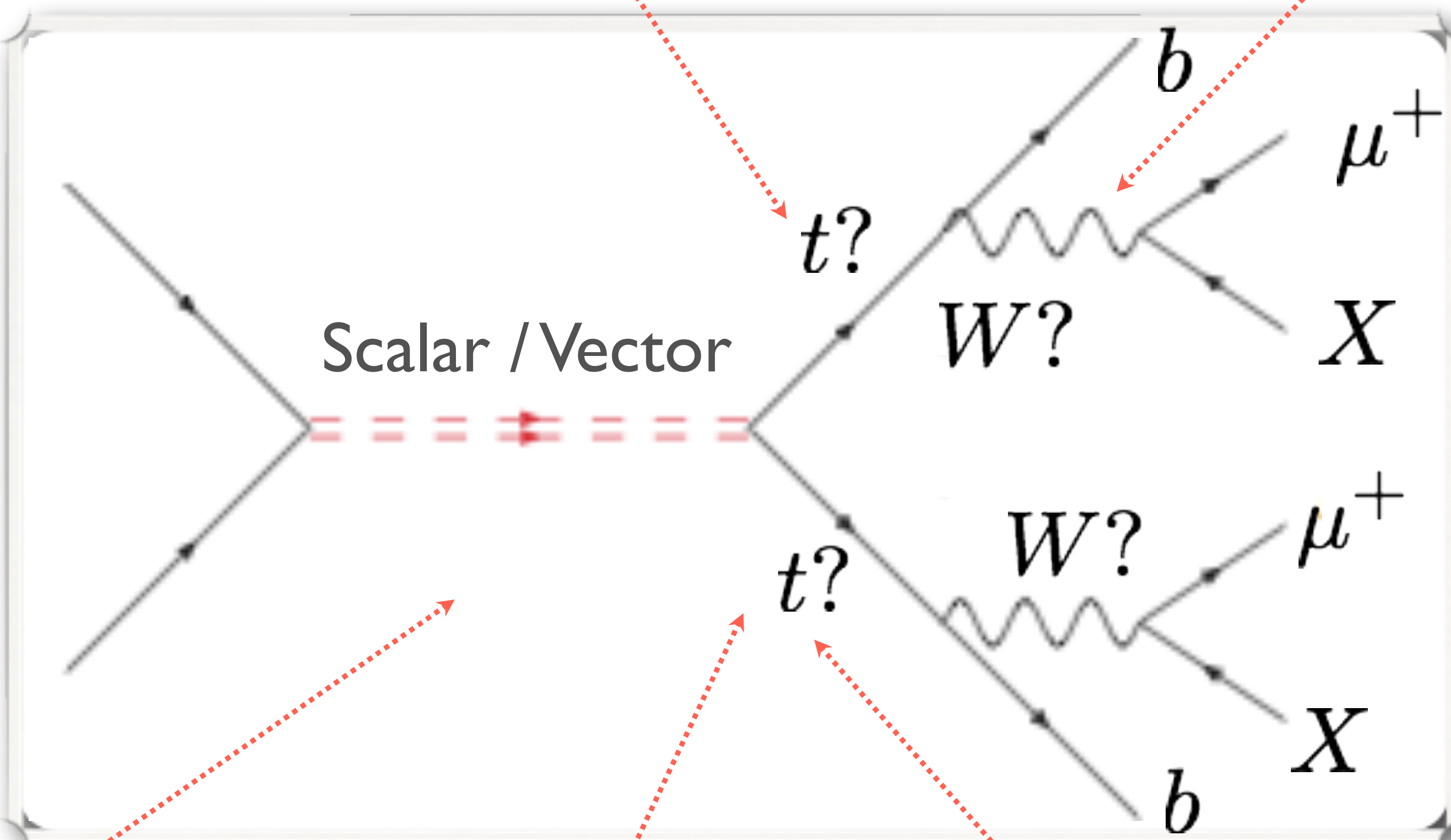
Han, Lewis, McElmurry, 0909.2666



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

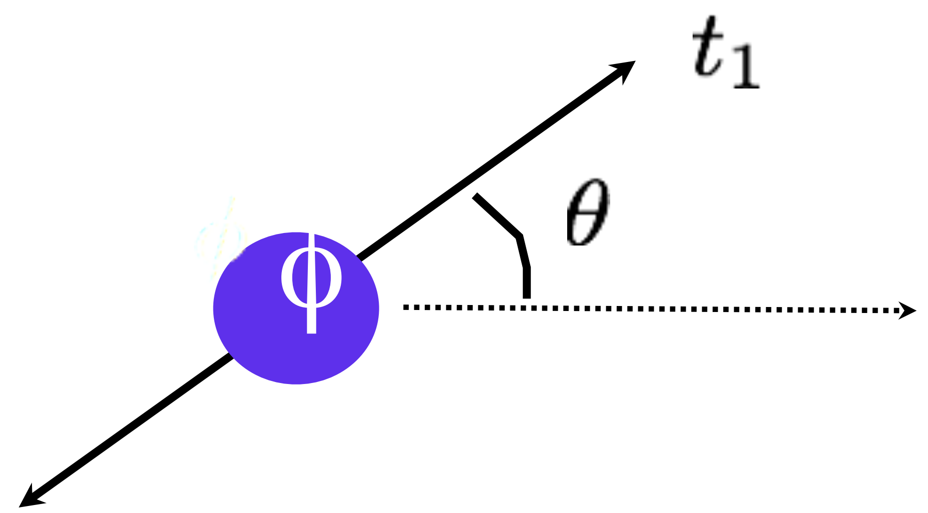
Difficulty:
identical muons and b jets

(3) What is the mass of the resonance?

(4) What is top quark polarization?

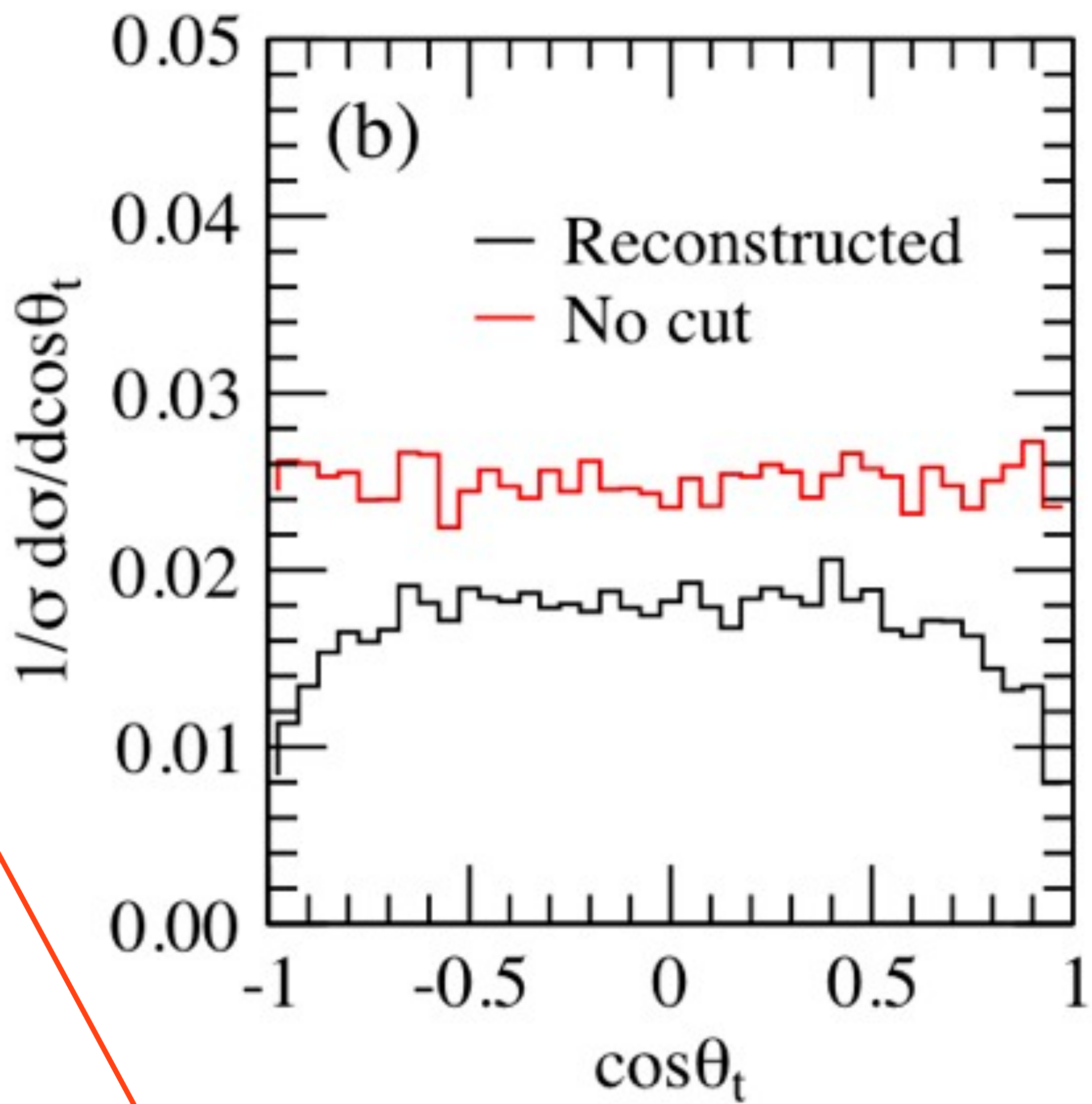
(5) Are the top quarks from a scalar or vector decay?

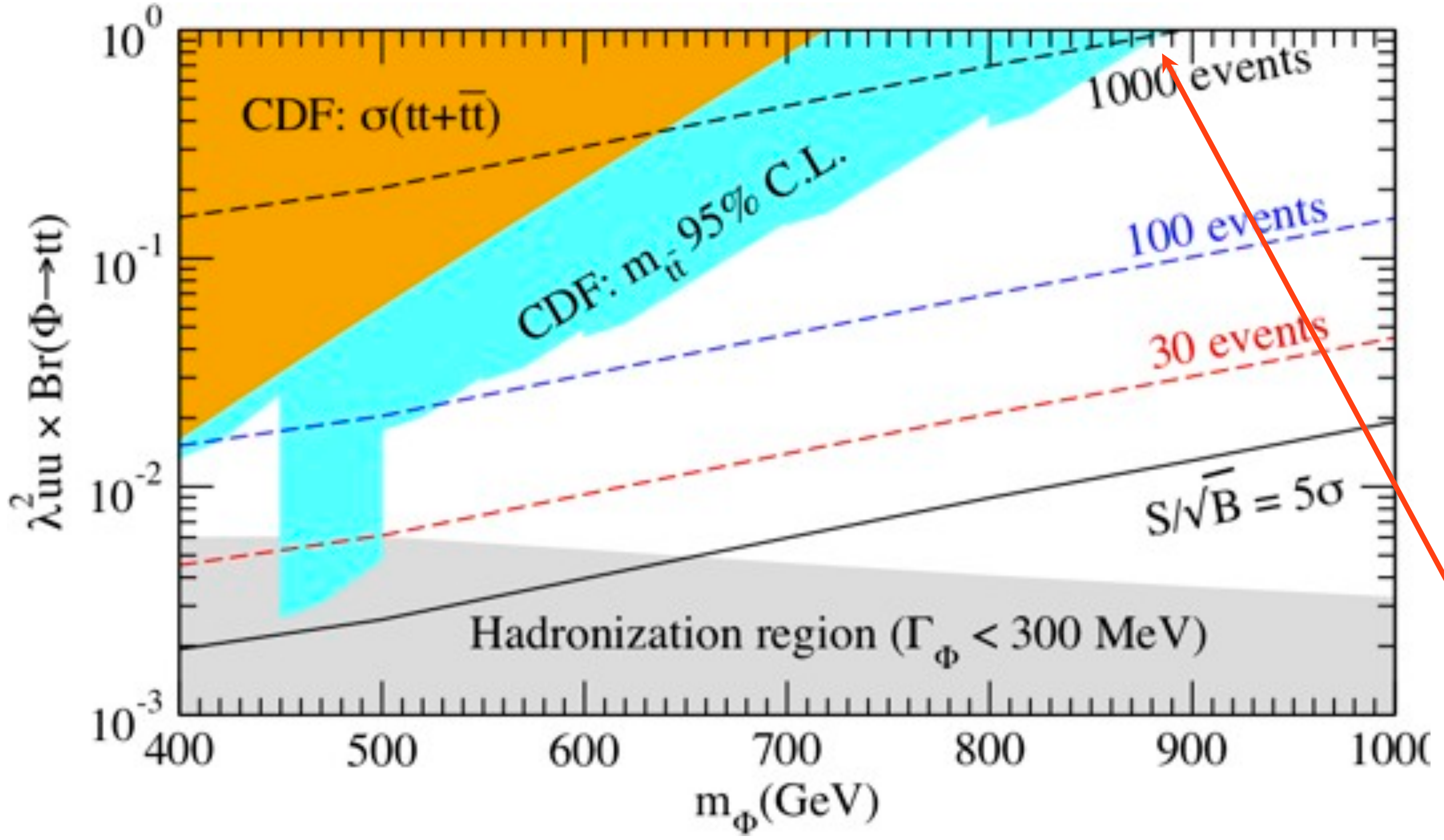
Reconstructed event distribution



★ Can we determine the spin of the heavy resonance?

Not easy !





Not realistic for early LHC!

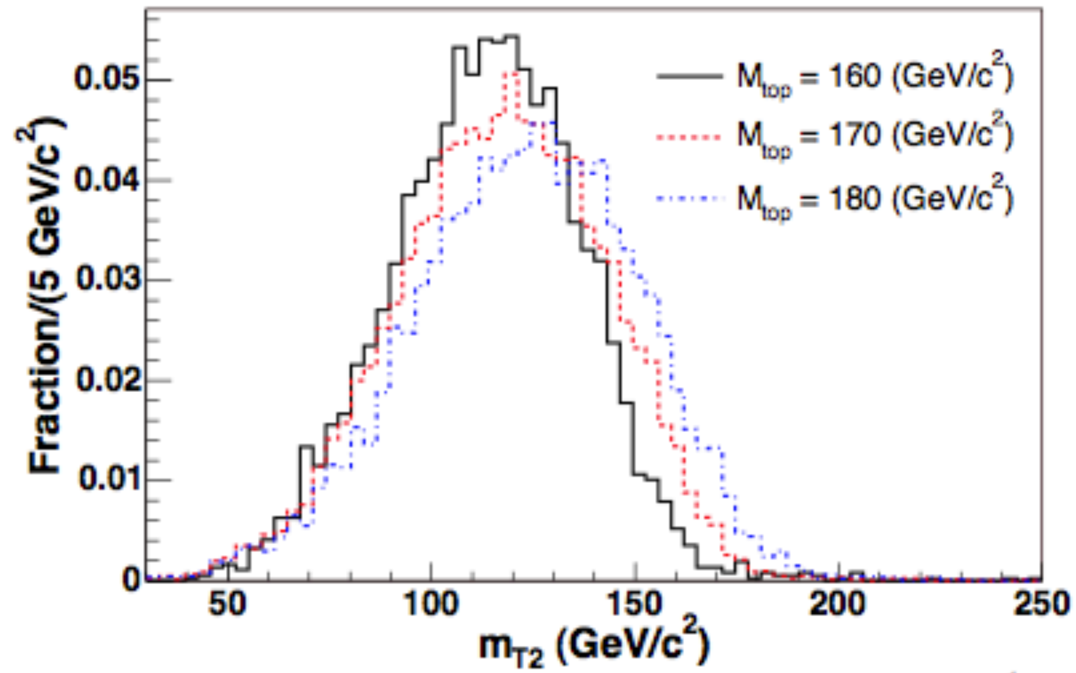
It requires ~ O(1000) events to verify the flat distribution.

MT2 method

★ When there are two heavy particles decaying into visible particles and invisible particles, the MT2 variable may be used to measure the mass of their parent.

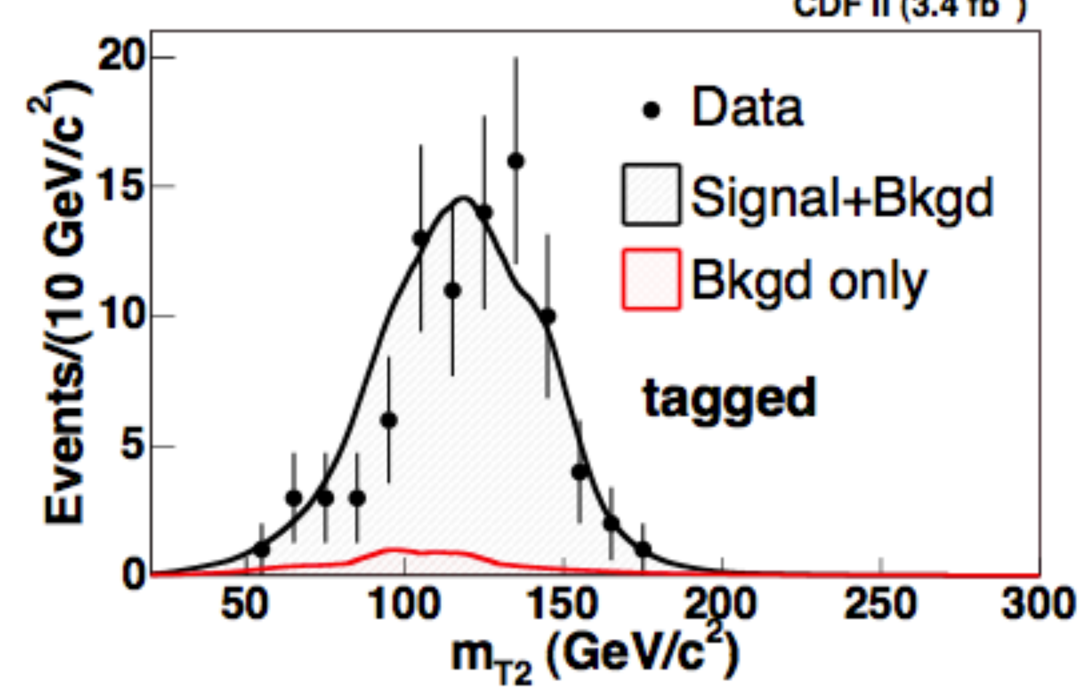
$$m_{T2}(m_{invis}) = \min_{\mathbf{p}_T^{(1)},\mathbf{p}_T^{(2)}} \left[\max[m_T(m_{invis};\mathbf{p}_T^{(1)}), m_T(m_{invis};\mathbf{p}_T^{(2)})] \right]$$

$$m_T(m_{invis};\mathbf{p}_T^{invis}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2(E_T^{vis}E_T^{invis} - \mathbf{p}_T^{vis}\cdot\mathbf{p}_T^{invis})}$$



★ The MT2 variable is a function of the momenta of visible particles (α, β) and missing transverse momentum. Its upper bound yields the mass of the parent particle (ζ) .

★ The method has been used in the top quark mass measurement at the Tevatron.



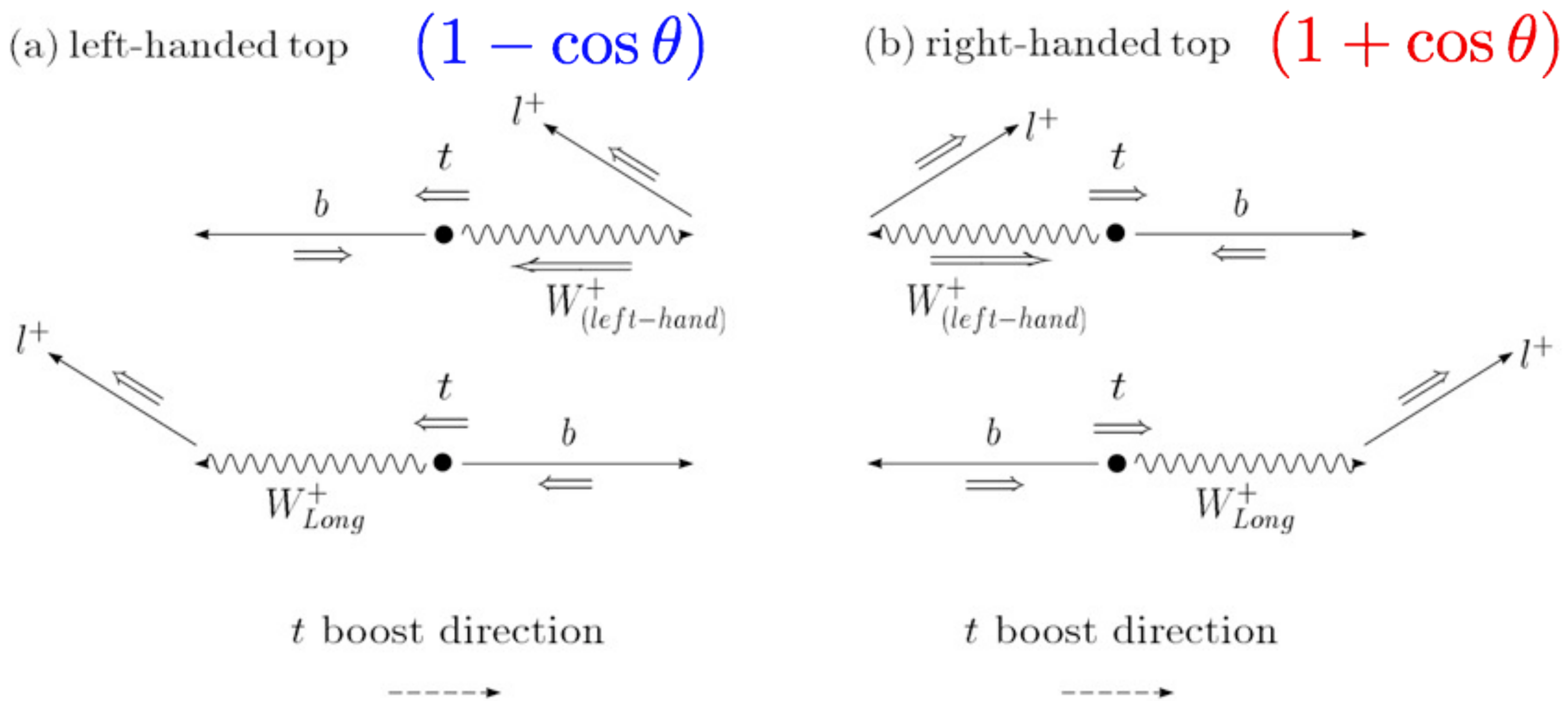
CDF collaboration, Phys. Rev. D 77, 112001 (2008)

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.



Lepton energy and top quark polarization

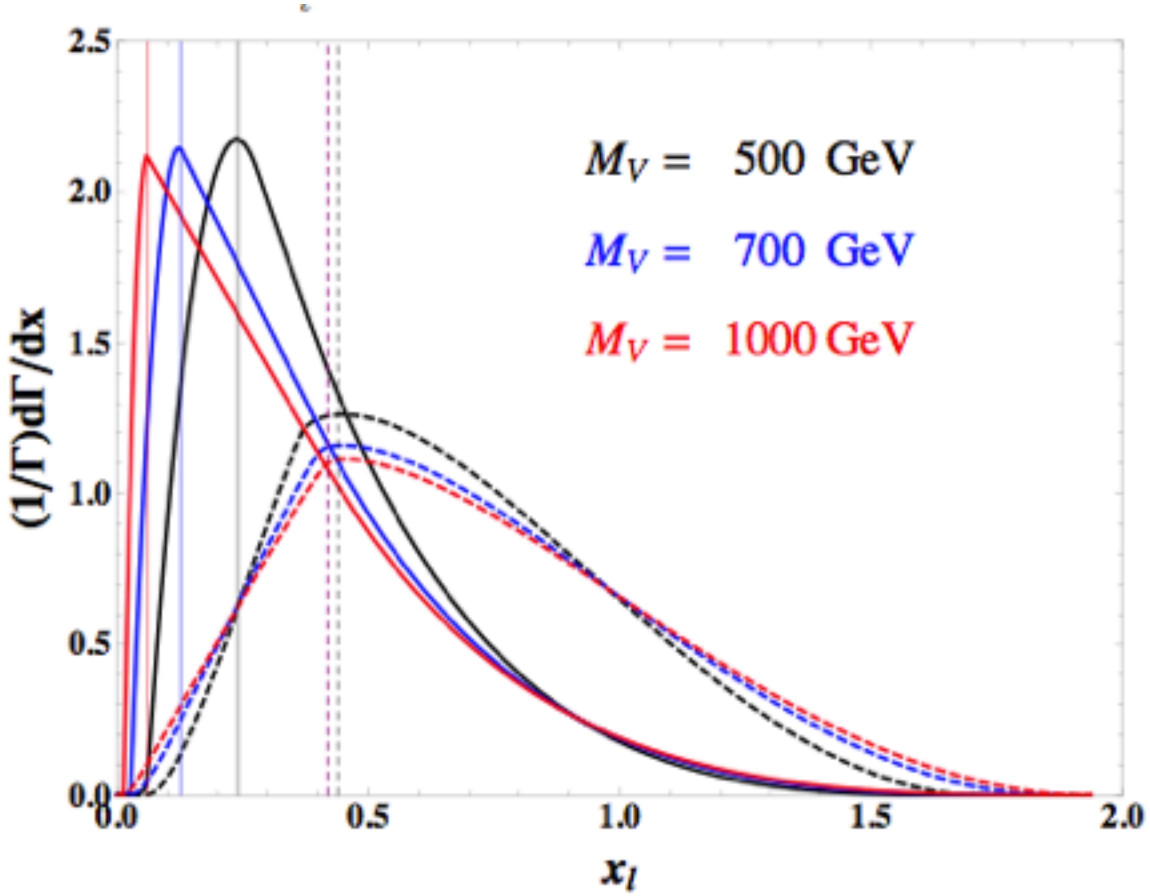
★ Peak positions are listed as follows:

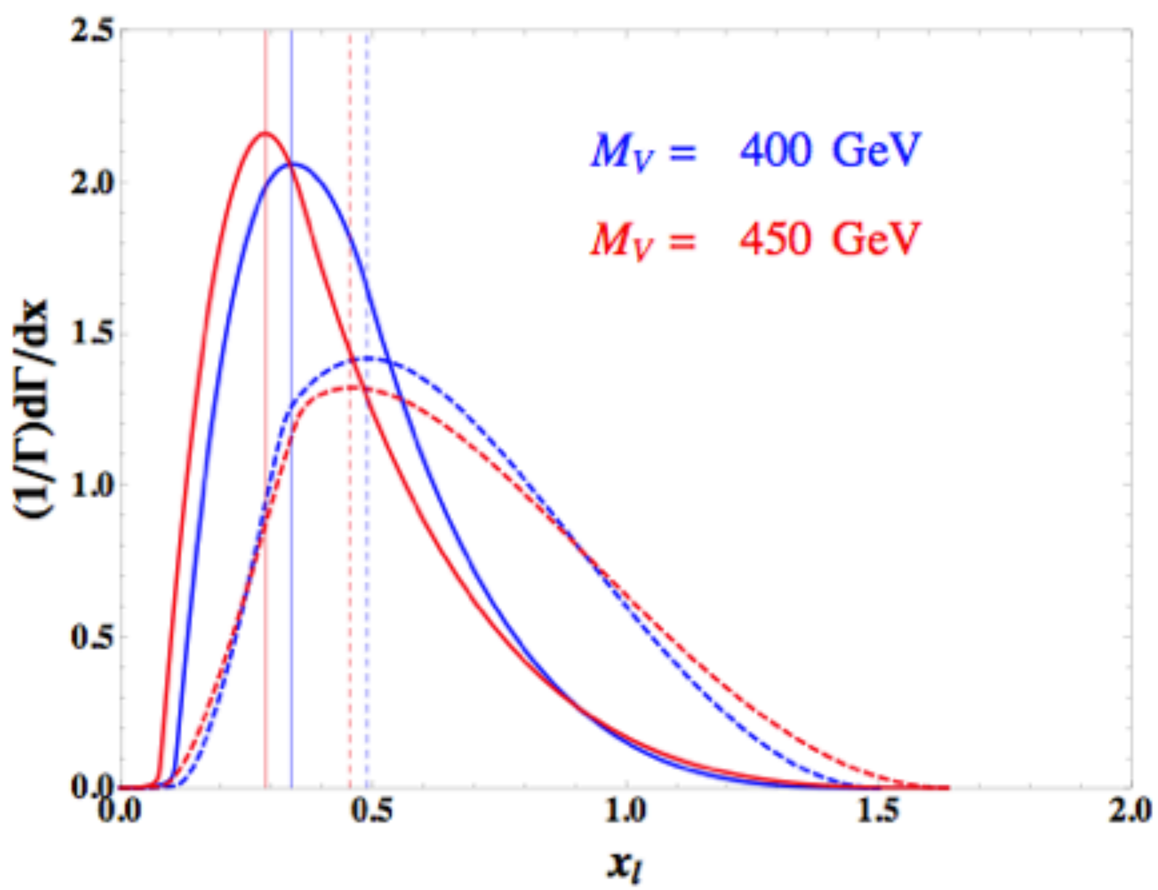
Hao Zhang, EB, Qing-Hong Cao, in preparation.

β value	left-handed top quark	right-handed top quark
$(0.91, 1)$	$-\frac{(1-\beta)^2}{1-3\beta} W\left[-\frac{1-3\beta}{1-\beta}\exp\left(-B+\ln B+\frac{2\beta}{1-\beta}\right)\right]$	$B(1+\beta)$
$(0.52, 0.91)$	$-\frac{(1-\beta)^2}{1-3\beta} W\left[-\frac{1-3\beta}{1-\beta}\exp\left(-B+\ln B+\frac{2\beta}{1-\beta}\right)\right]$	$-\frac{(1+\beta)^2}{(1+3\beta)} W\left[-\frac{(1+3\beta)}{(1+\beta)}\exp\left(-\frac{1+3\beta}{1+\beta}\right)\right]$
$(0, 0.52)$	$\frac{(1-\beta^2)}{2\beta}\left(1-\frac{1-\beta}{\beta}\text{arctanh}\beta\right)$	$-\frac{(1-\beta^2)}{2\beta}\left(1-\frac{1+\beta}{\beta}\text{arctanh}\beta\right)$

$B = \frac{m_W^2}{m_t^2}$

W is the Product Logarithm function





NNLO QCD corrections

- ★ A calculation of full NNLO QCD corrections is highly desired
  - ✳ NLO corrections to ttbar + j production

    (Dittmaier, Uwer, Weinzierl, 2007; Melnikov, Schulze, 2010)
  - ✳ NLL threshold resummation effects (Almeida, Sterman, Vogelsang, 2008)
  - ✳ NNLL threshold resummation effects : asymmetry is not expanding in $O(\alpha_s)$

    Asymmetry is reduced by 20% at NLO but only by 5% at NLO+NNL.

    (Ahrens, Ferroglia, Neubert, Pecjak, Yang 2010)
- ★ Corrections to inclusive asymmetry at NNLO are not known.
- ★ It would be good to have NLO implemented in an event generator, including spin correlations and top decays to leptons, so that experimental cuts can be fully matched