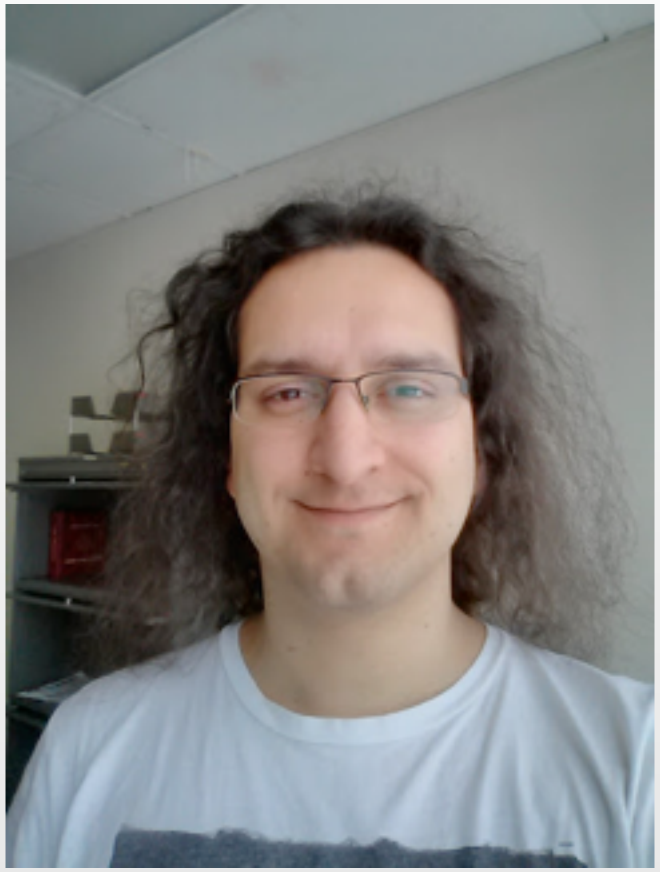
Signatures of Pair-produced Massive Colored Bosons

Yang Bai

University of Wisconsin-Madison

LHC-The First Part of the Journey @KITP

July 11, 2013



Andrey Katz
at Harvard Univ.

Brock Tweedie
at Boston Univ.

Pedro Schwaller
at ANL/UIC

130x.xxxx

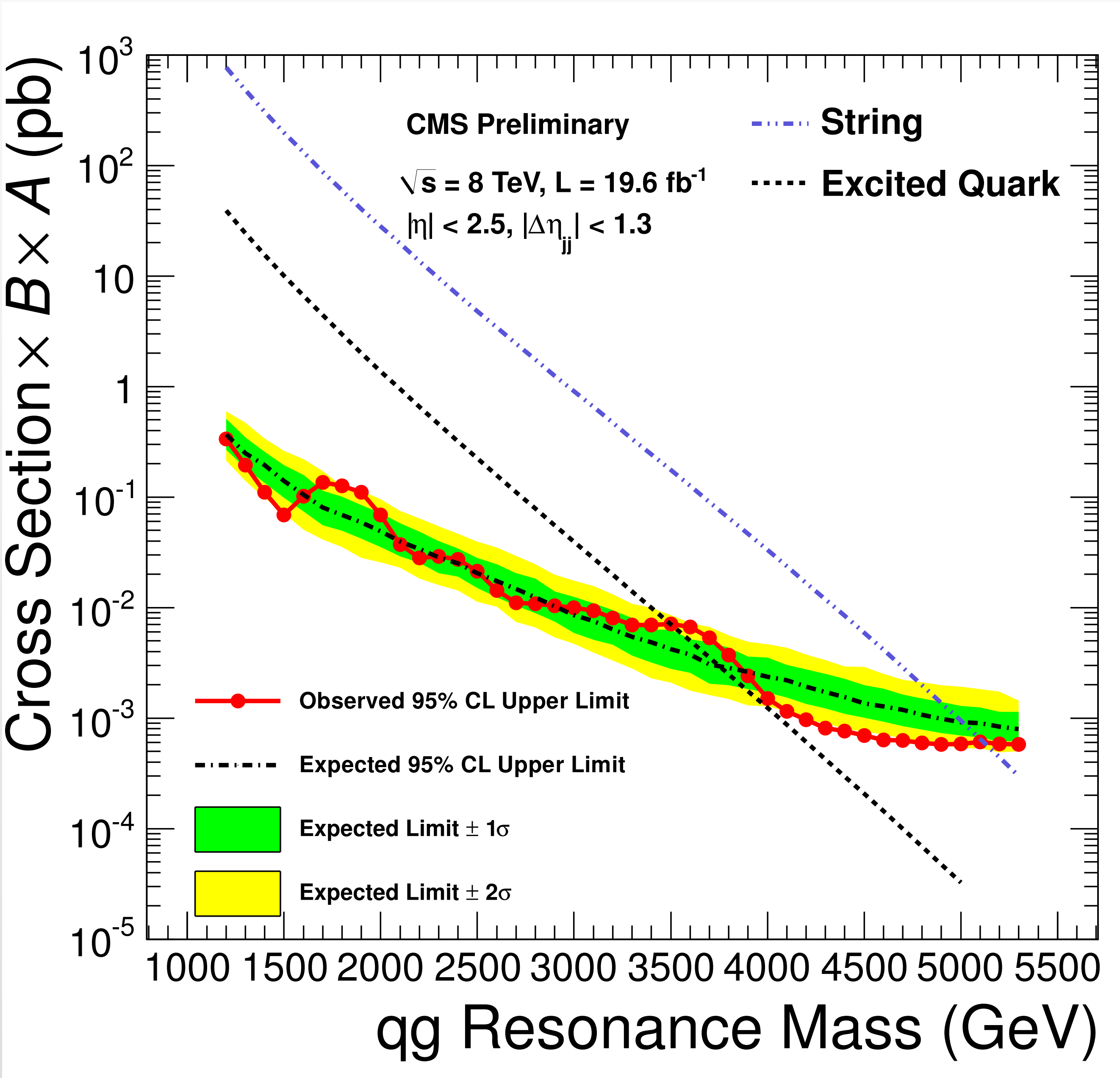
1306.4676

Large Hadron Collider

QCD charged particles have large production cross sections

We may have a better chance to discover a new one

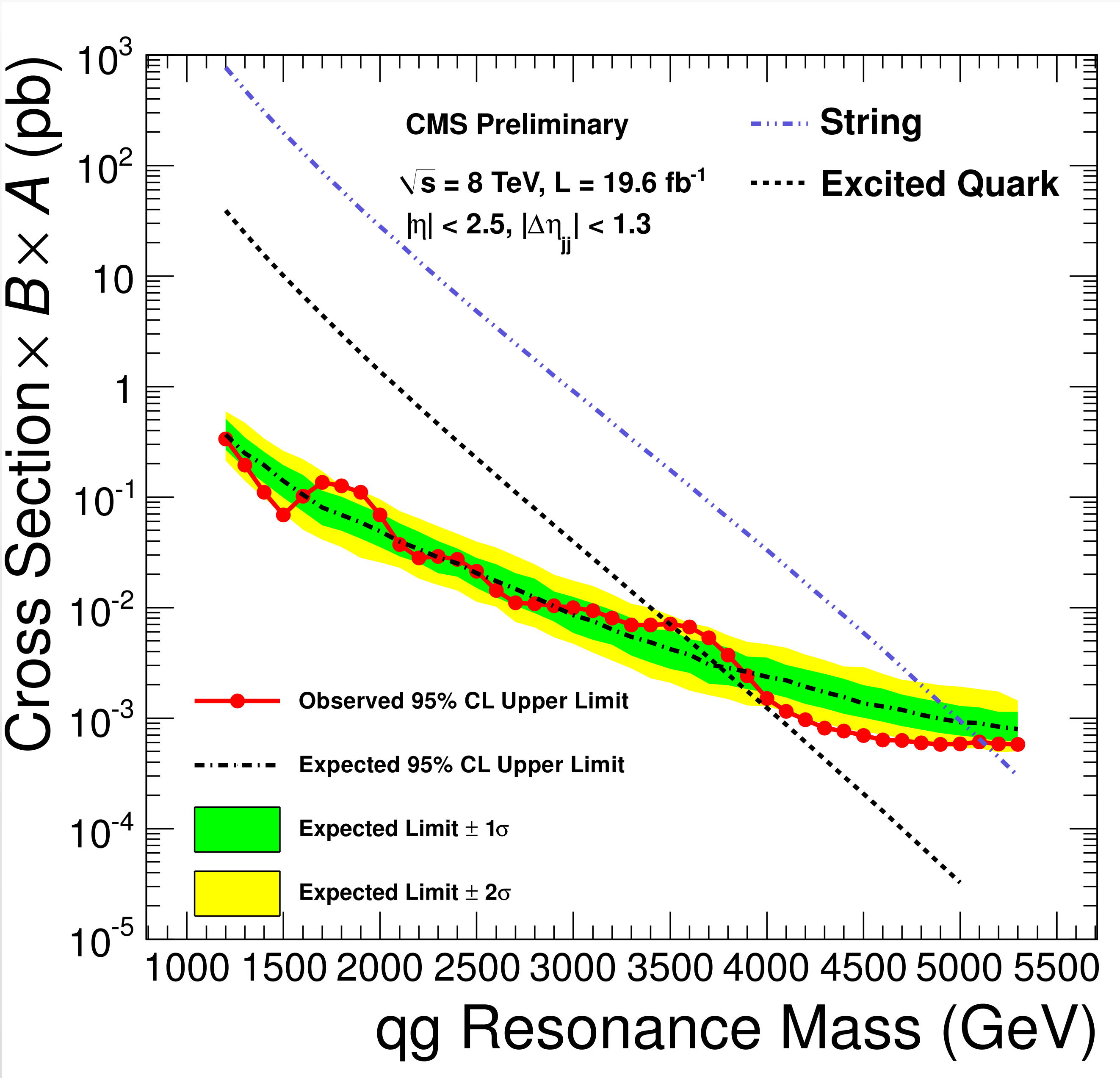
Excited Quark



$$\frac{g_s}{2\Lambda}\overline{f^*}_R\sigma^{\mu\nu}G_{\mu\nu}f_L$$

$$m_{f^*} = \Lambda$$

Excited Quark



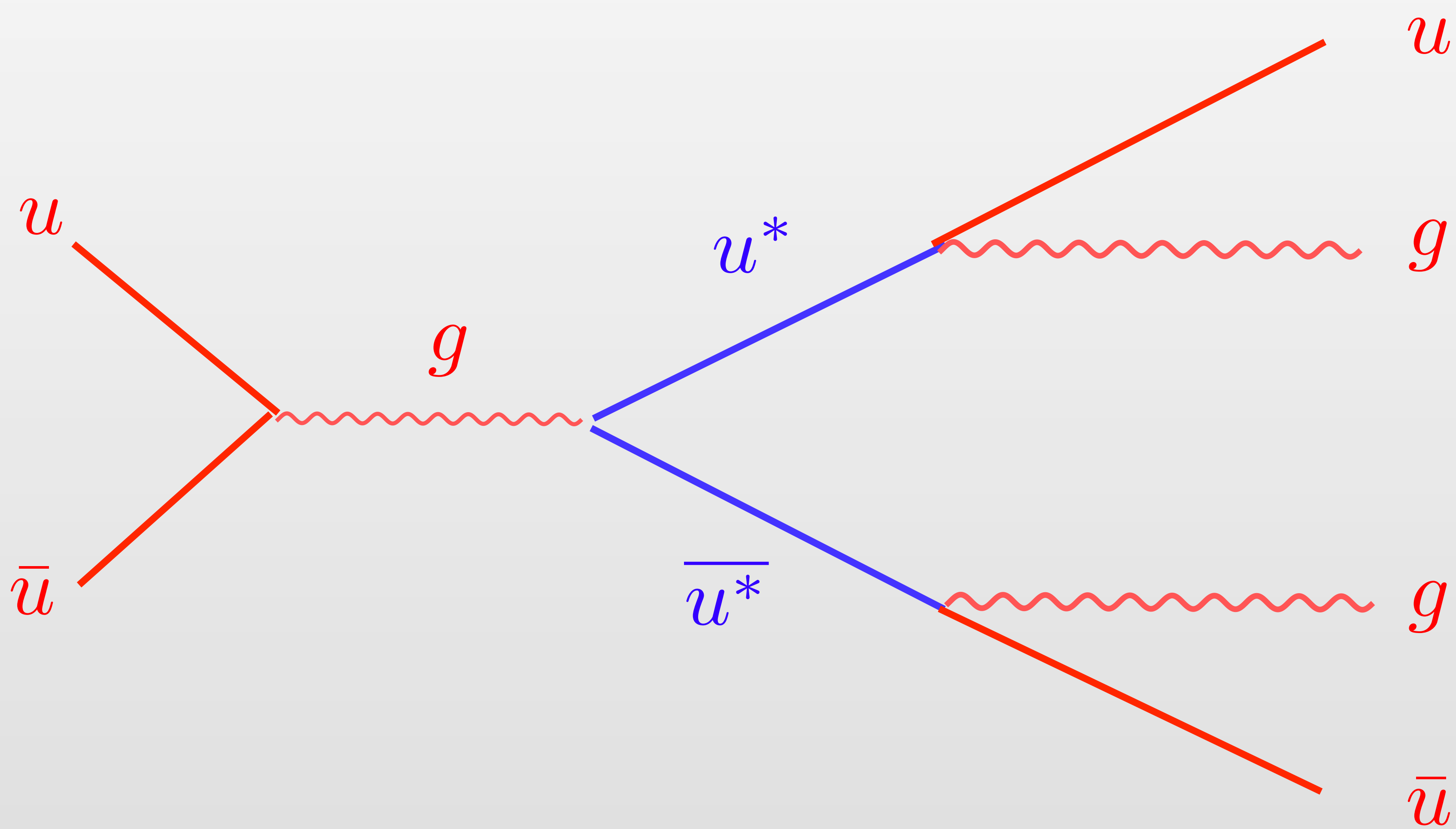
$$\frac{g_s}{2\Lambda}\overline{f^*}_R\sigma^{\mu\nu}G_{\mu\nu}f_L$$

$$m_{f^*} = \Lambda$$

what if $m_{f^*} \ll \Lambda$?

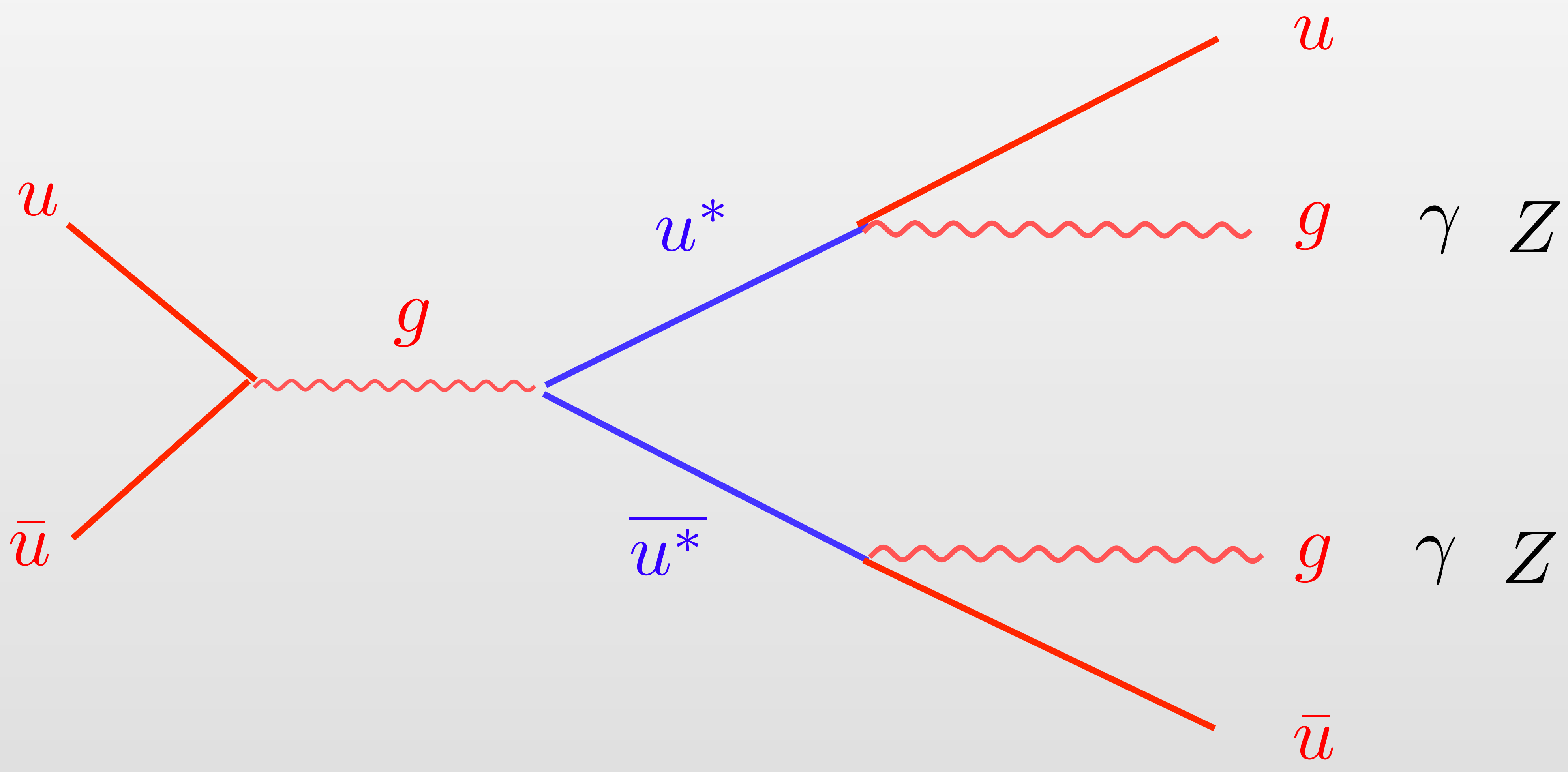
Using QCD Interaction

Pair-produce the excited quarks



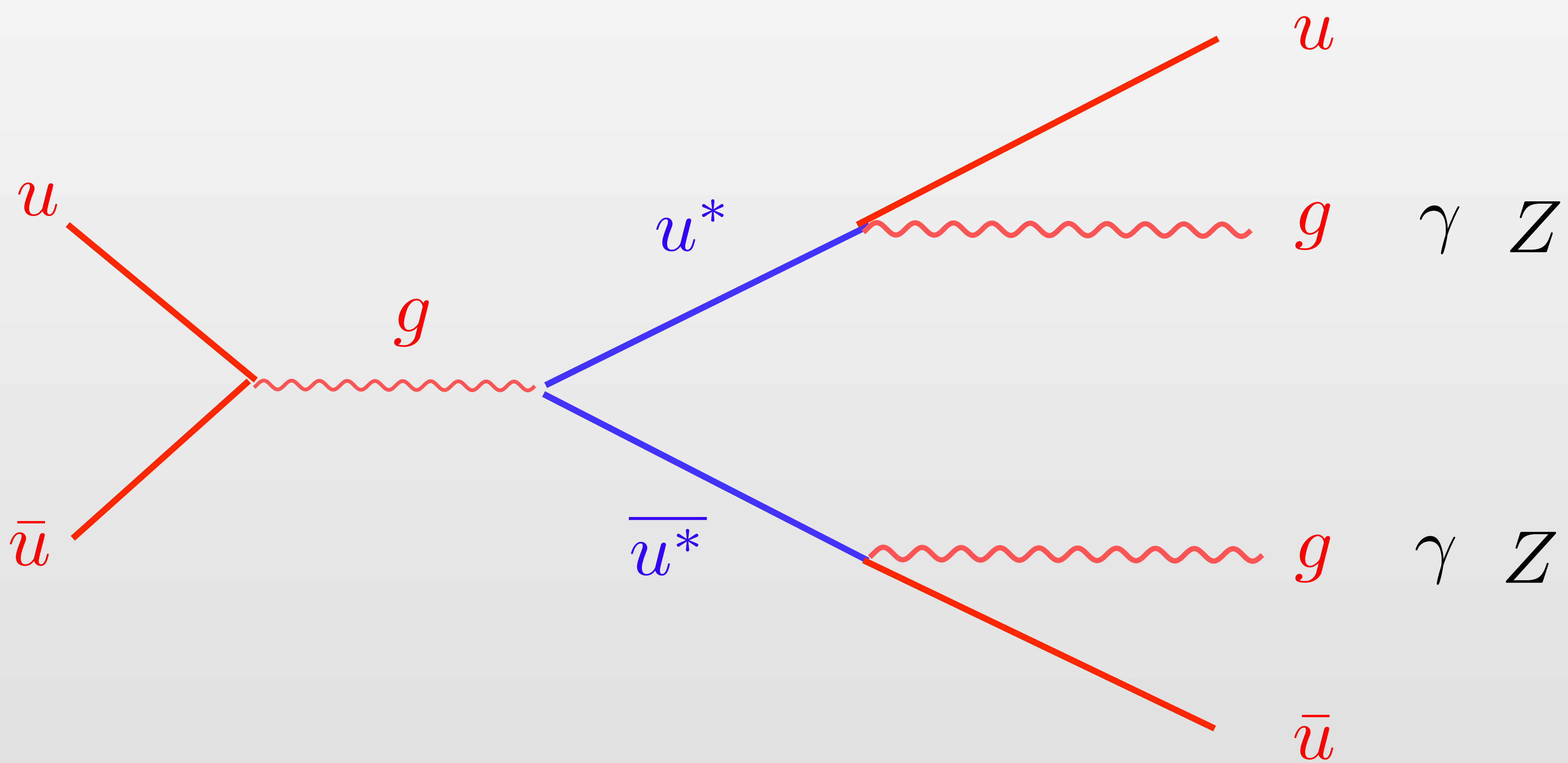
Using QCD Interaction

Pair-produce the excited quarks



Using QCD Interaction

Pair-produce the excited quarks



The four-jet final state is the most challenging one

Signatures of Pair-produced Massive Colored Bosons

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Colored Bosons

- Technipions or Technirho mesons — Eichten, Hinchliffe, Lane, Quigg ‘1984
- Partners of the QCD gluon:
  - Coloron in the top-color models — Hill ‘1991, Chivukula, Cohen, Simmons, ‘1996
  - KK-gluon in the extra-dimension models — Randall, Sundrum ‘1998; Appelquist, Cheng, Dobrescu ‘2000
- New vector-like confining gauge group: — Kilic, Okui, Sundrum ‘2008; YB, Martin, 1003.3006
- Model-independent studies: — Manohar, Wise, ‘2006; Dobrescu, Kong, Mahbubani, ‘2007; YB, Dobrescu, 1012.5814; Chivukula, Farzinnia, Ren, Simmons, ‘2013

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- The most famous particle: stop > 1000 papers

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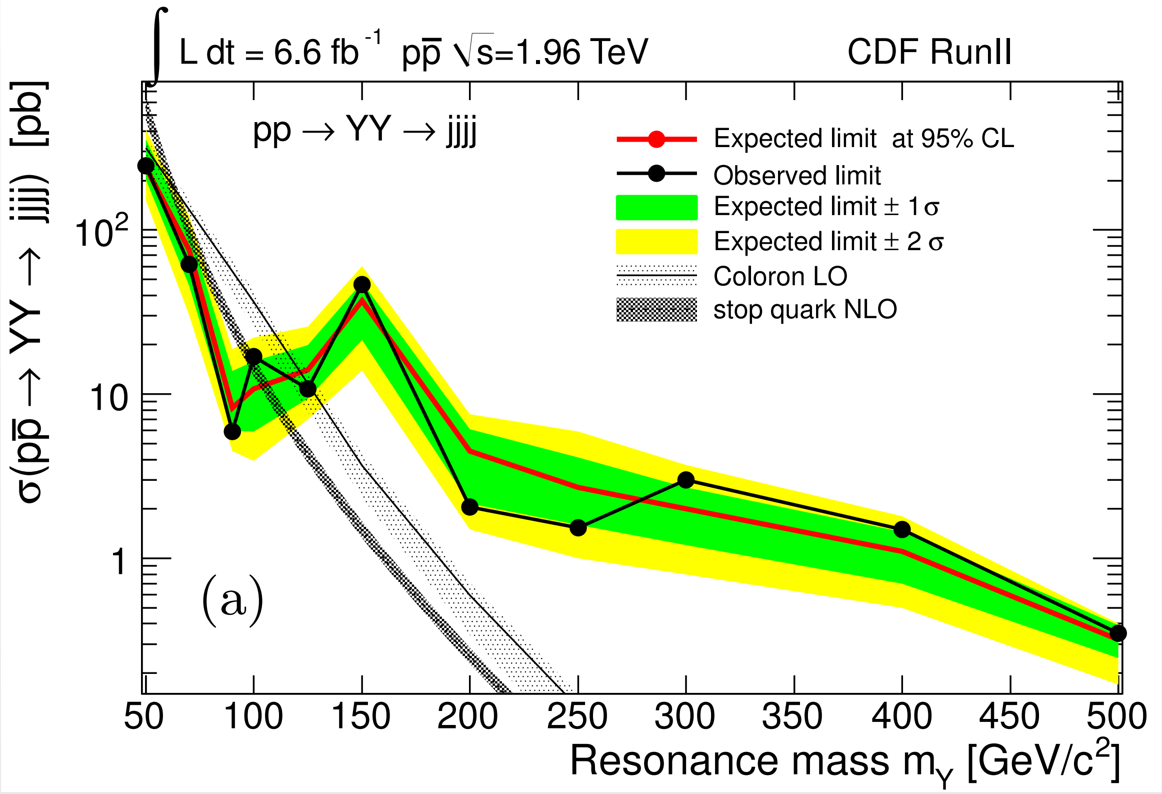
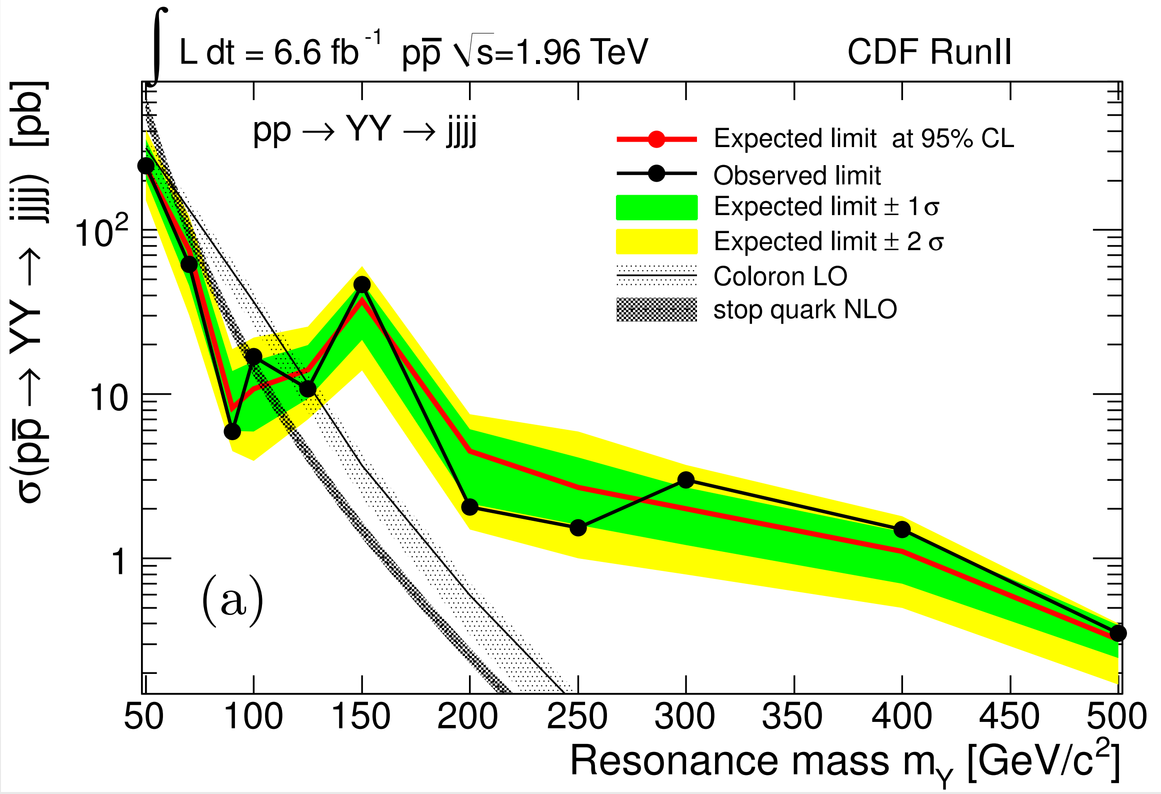
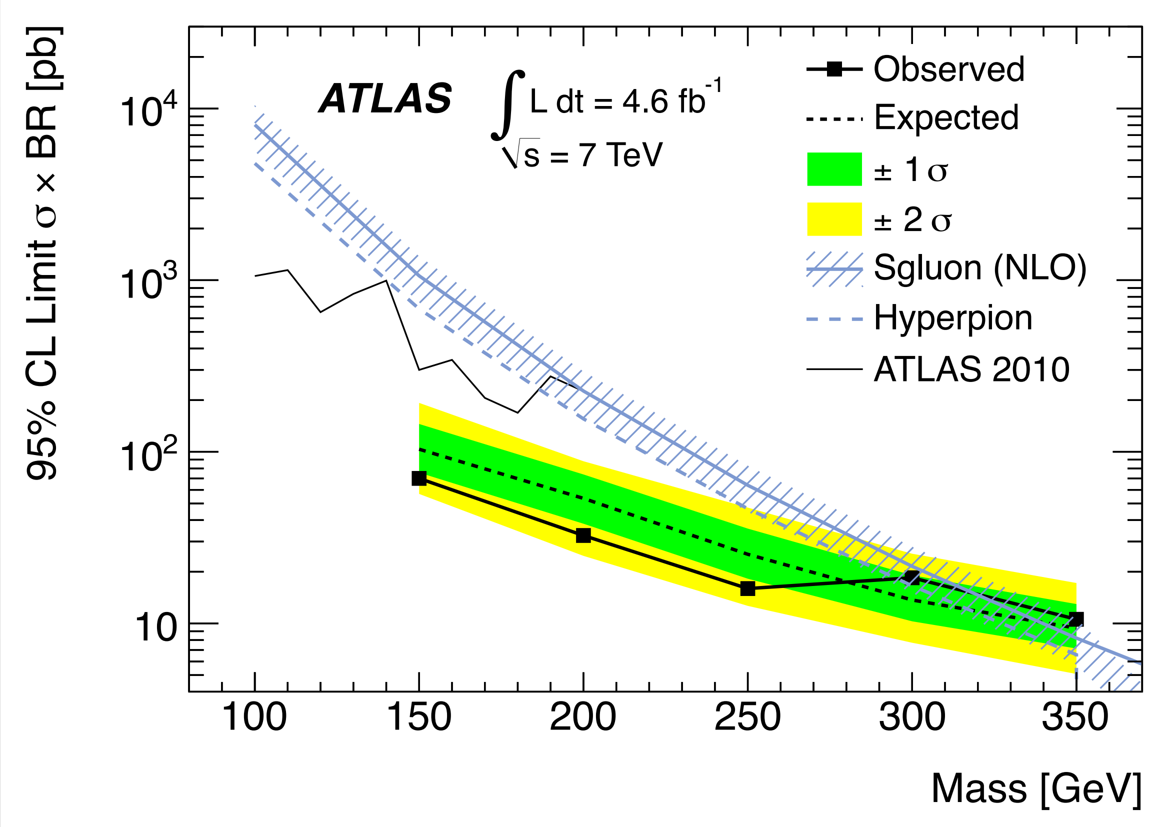
Current Color Octet Searches

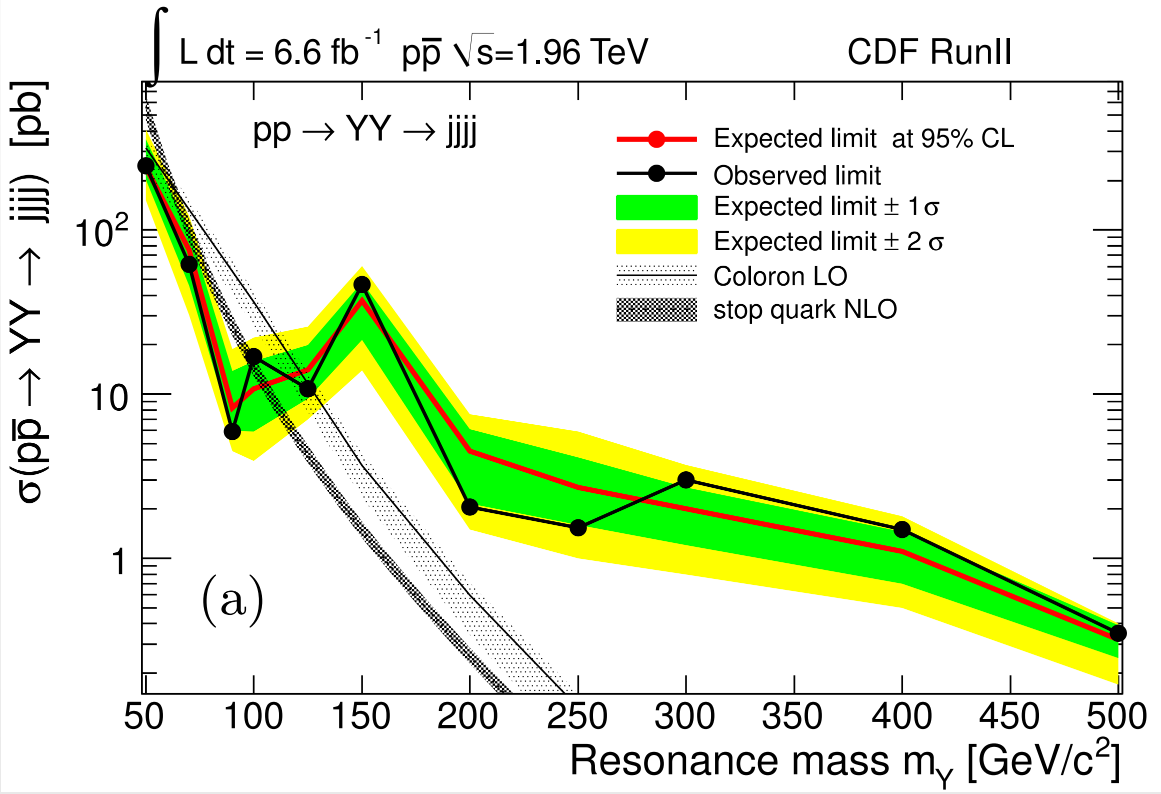


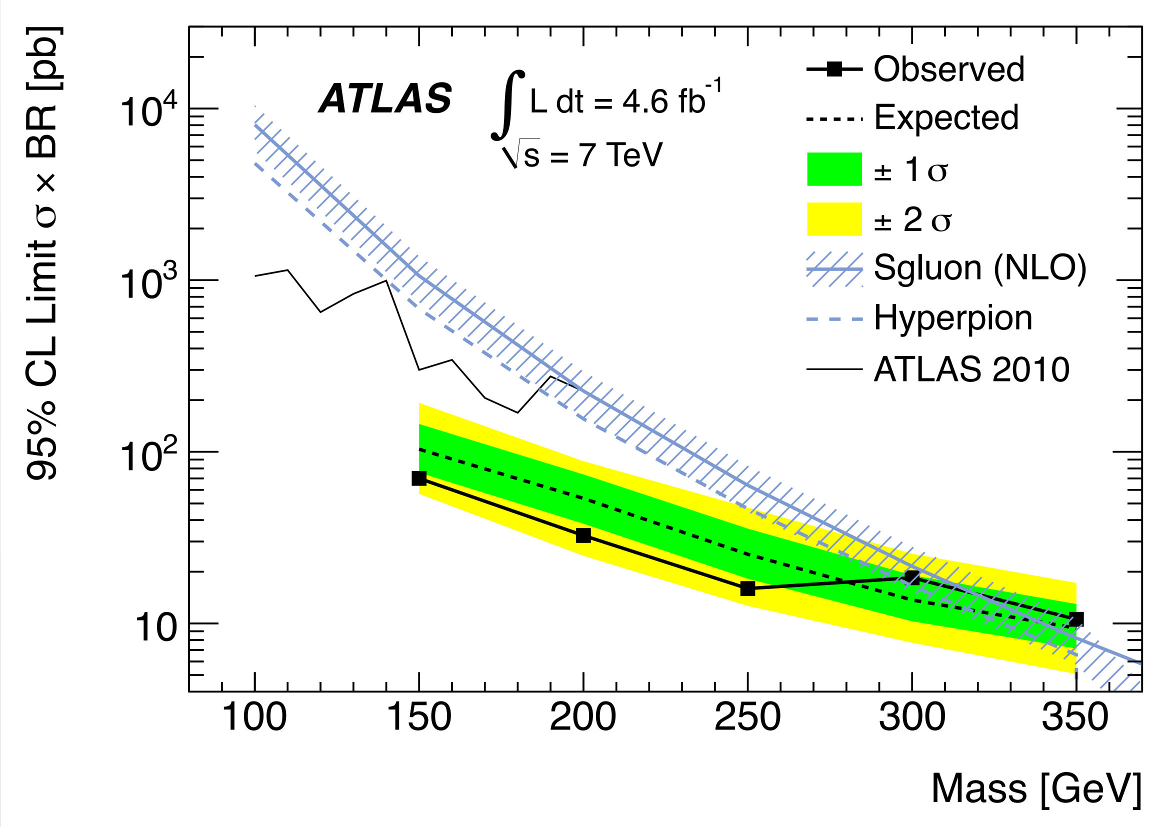
Current Color Octet Searches

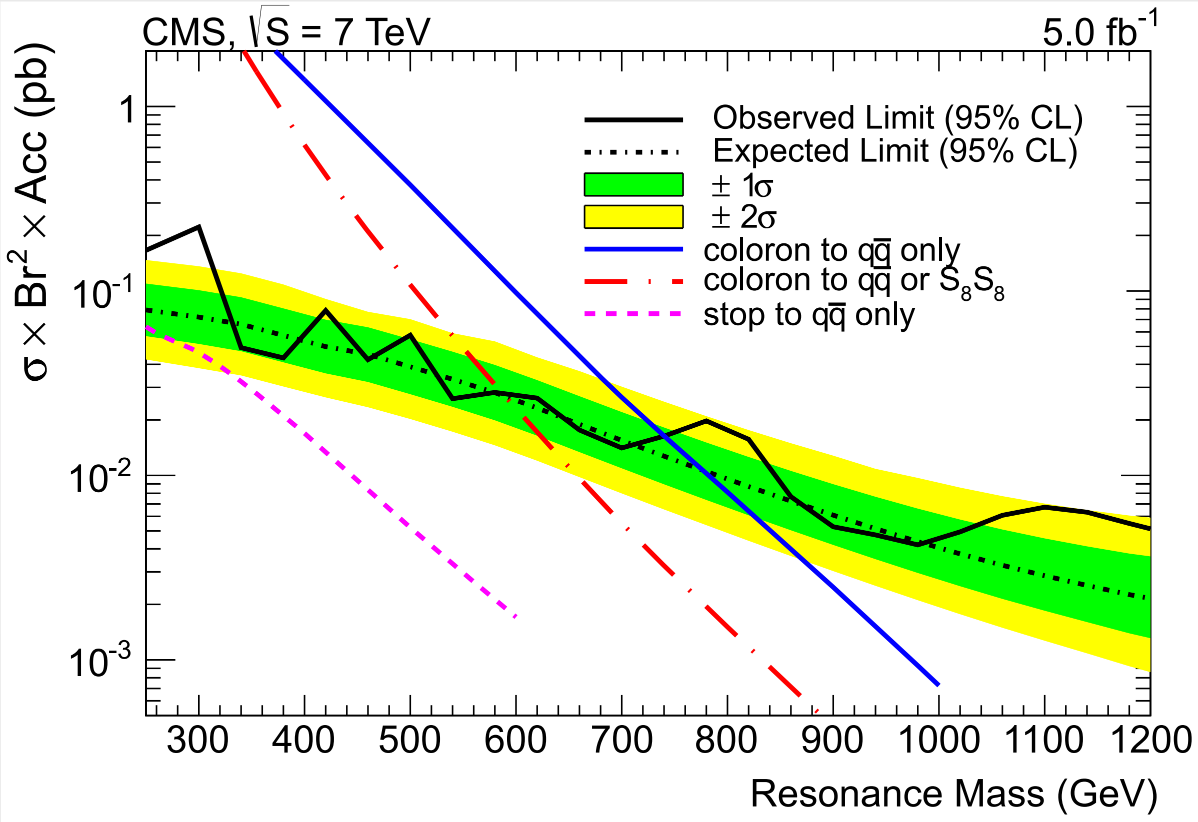




Current Color Octet Searches







What about the particles with the fundamental representation of QCD ?

especially the one Higgs cares: stop

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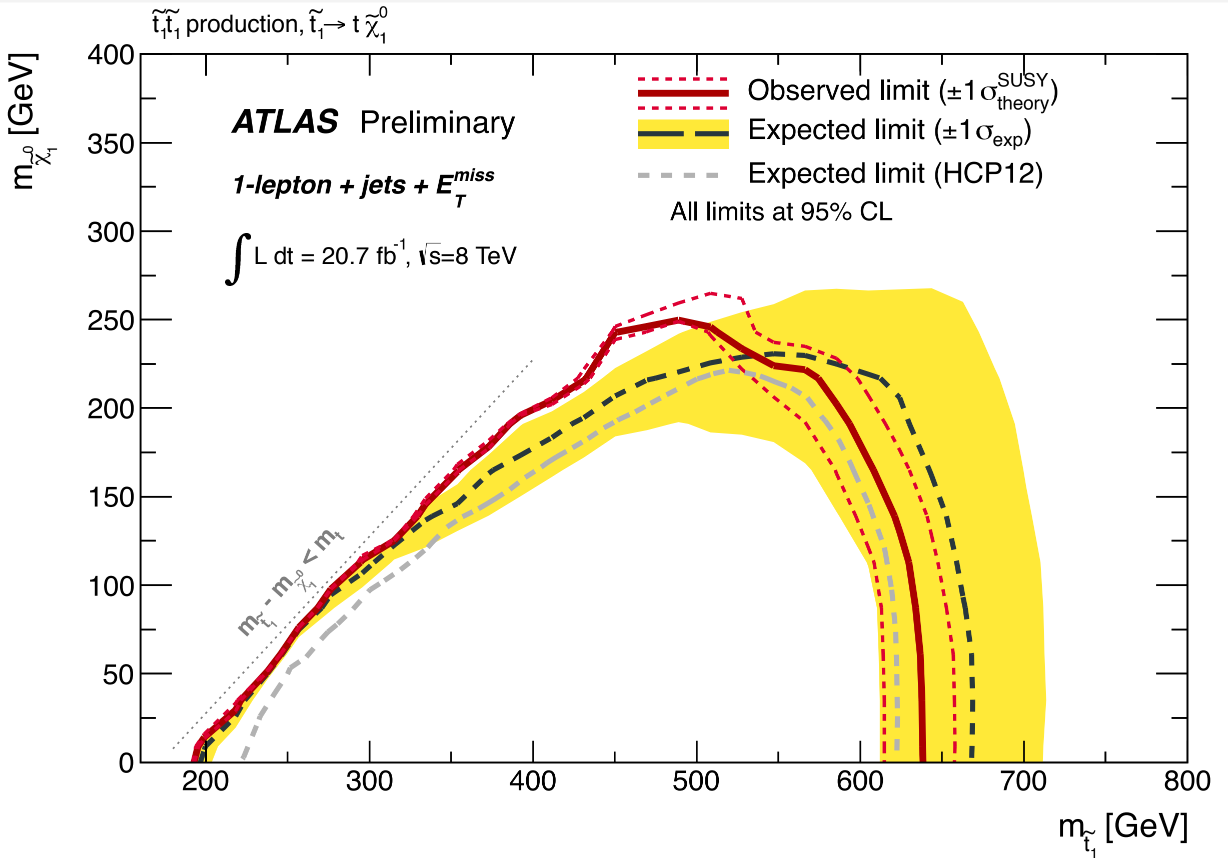
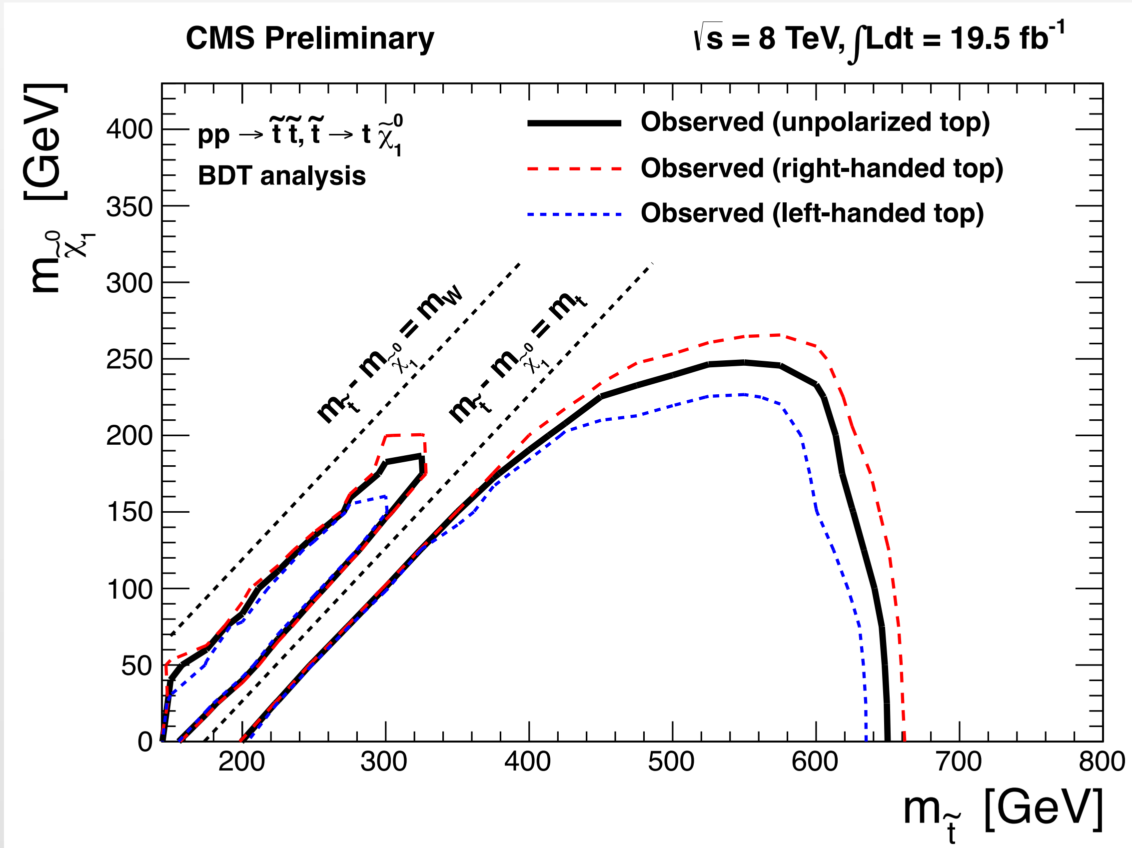
R-parity Conserving Stop Searches

ATLAS-CONF-2013-037

CMS PAS SUS-13-011



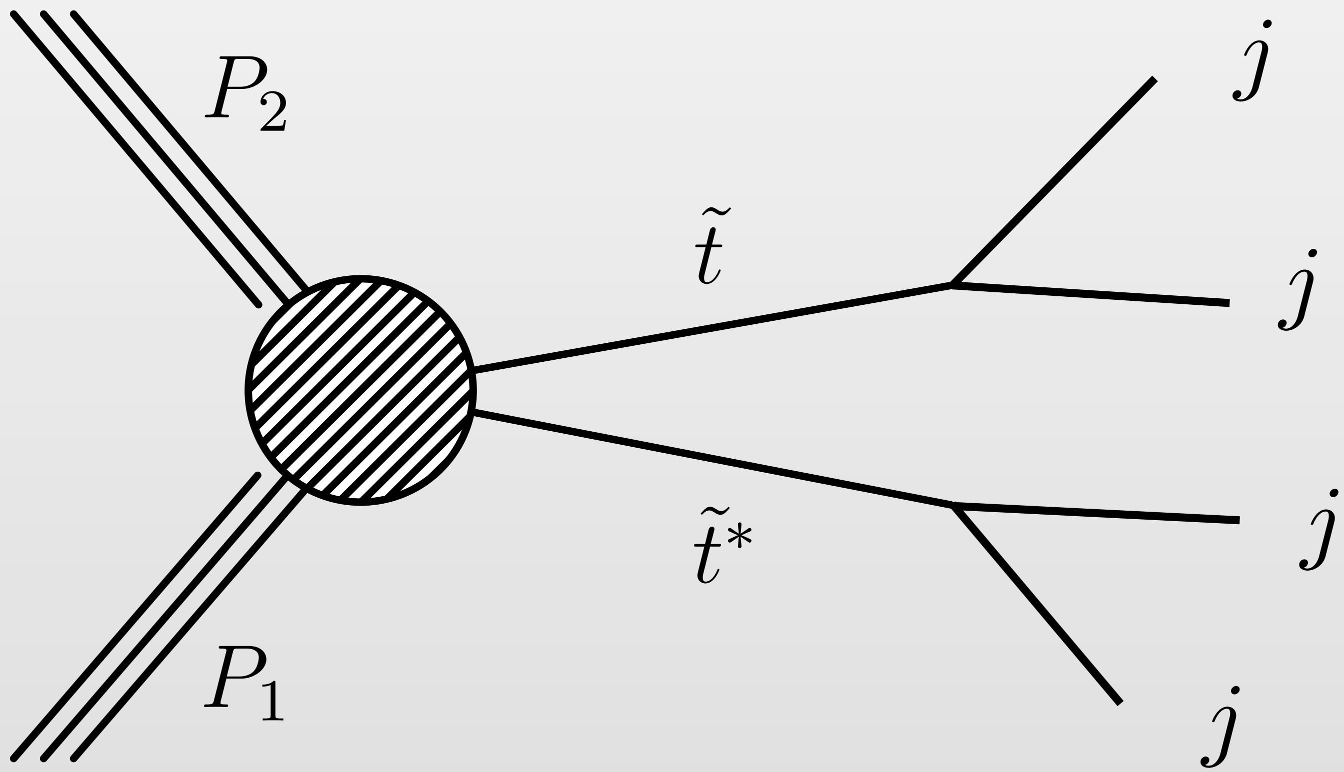


We can wait for the 14 TeV LHC results or explore other alternative options

R-parity Violation

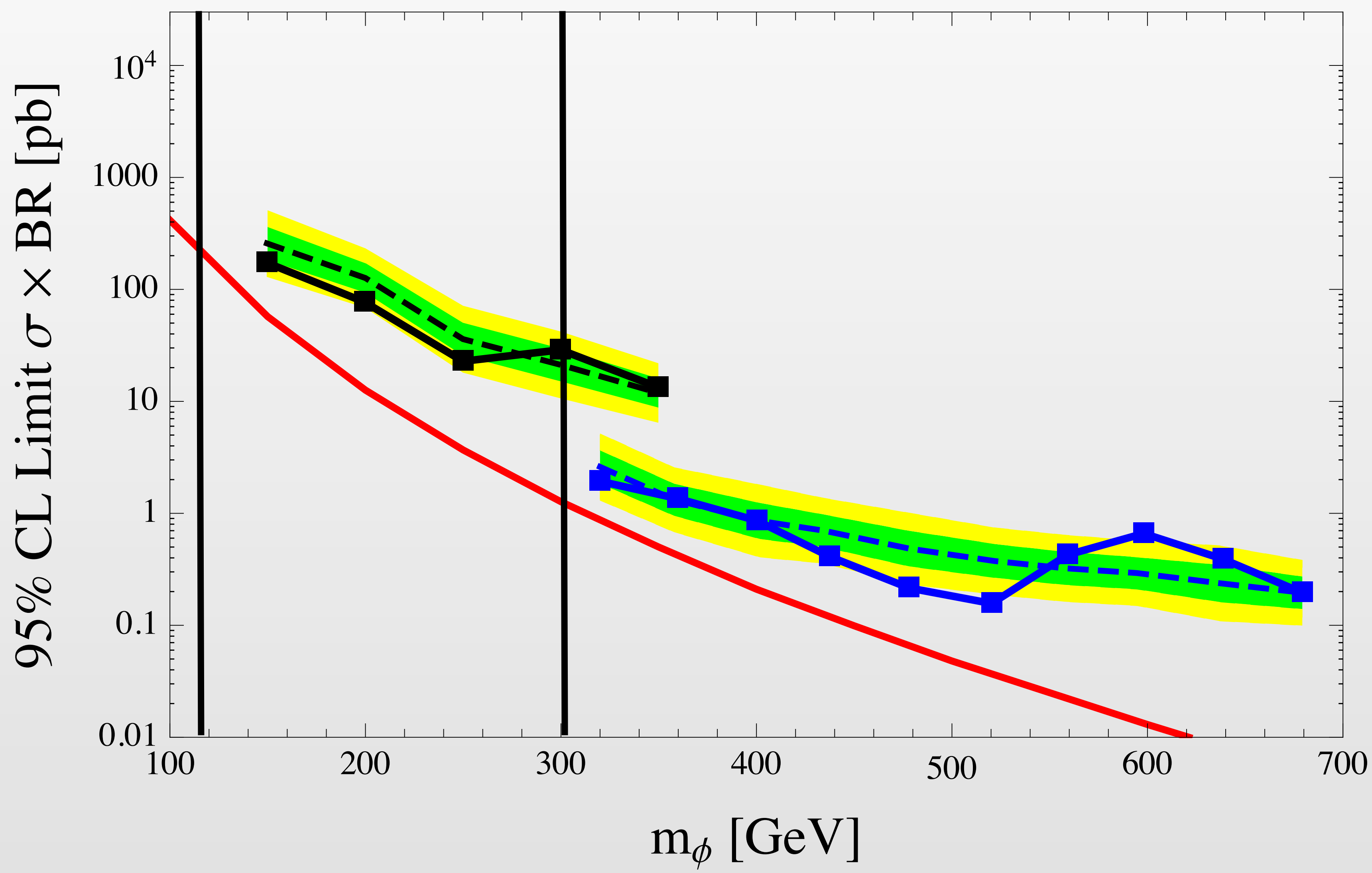
No missing energy. Pure hadronic final states.

The current constraints are much weaker.



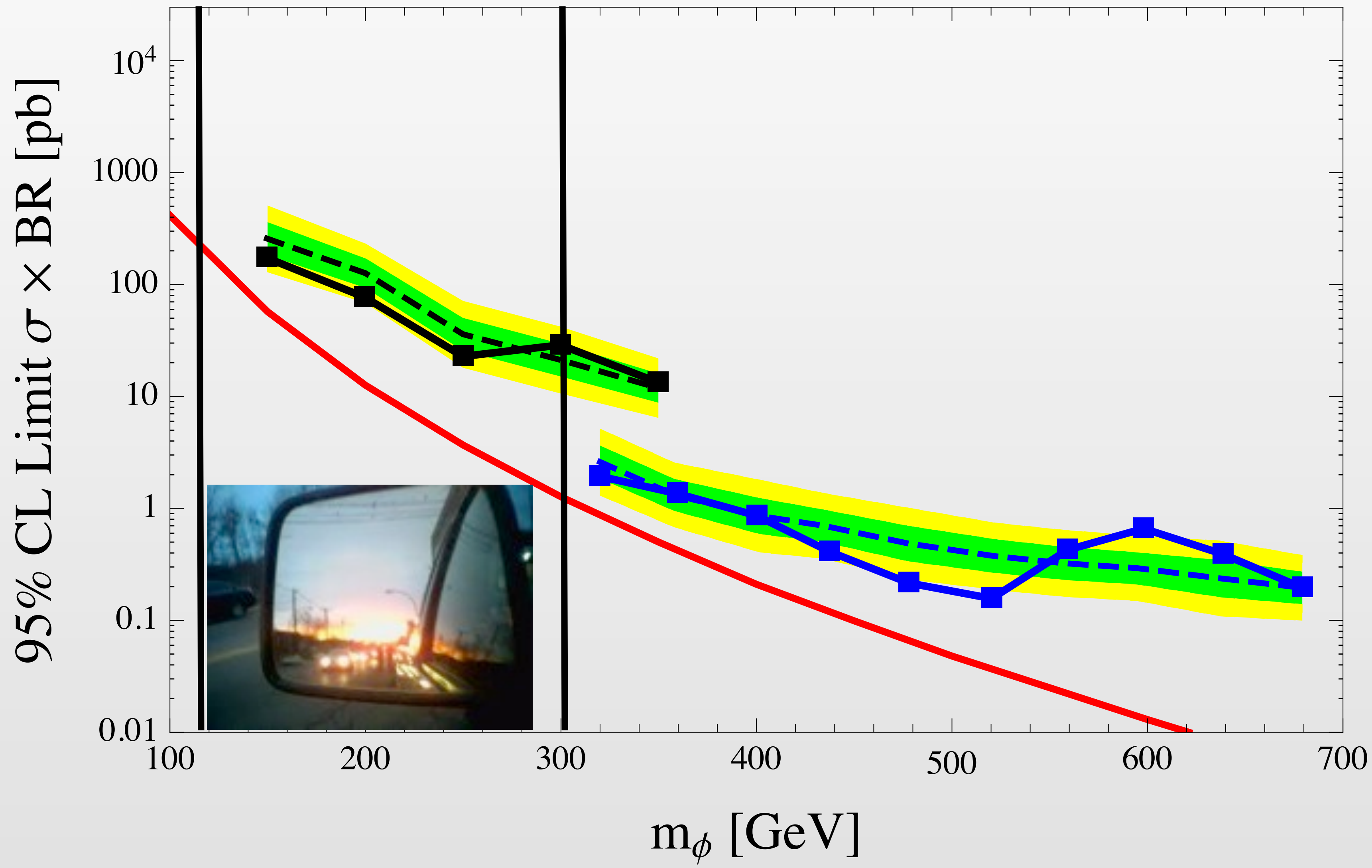
Behave as a pair of dijet resonances

Blind Spot



Full hadronic final state; trigger is an issue

Blind Spot



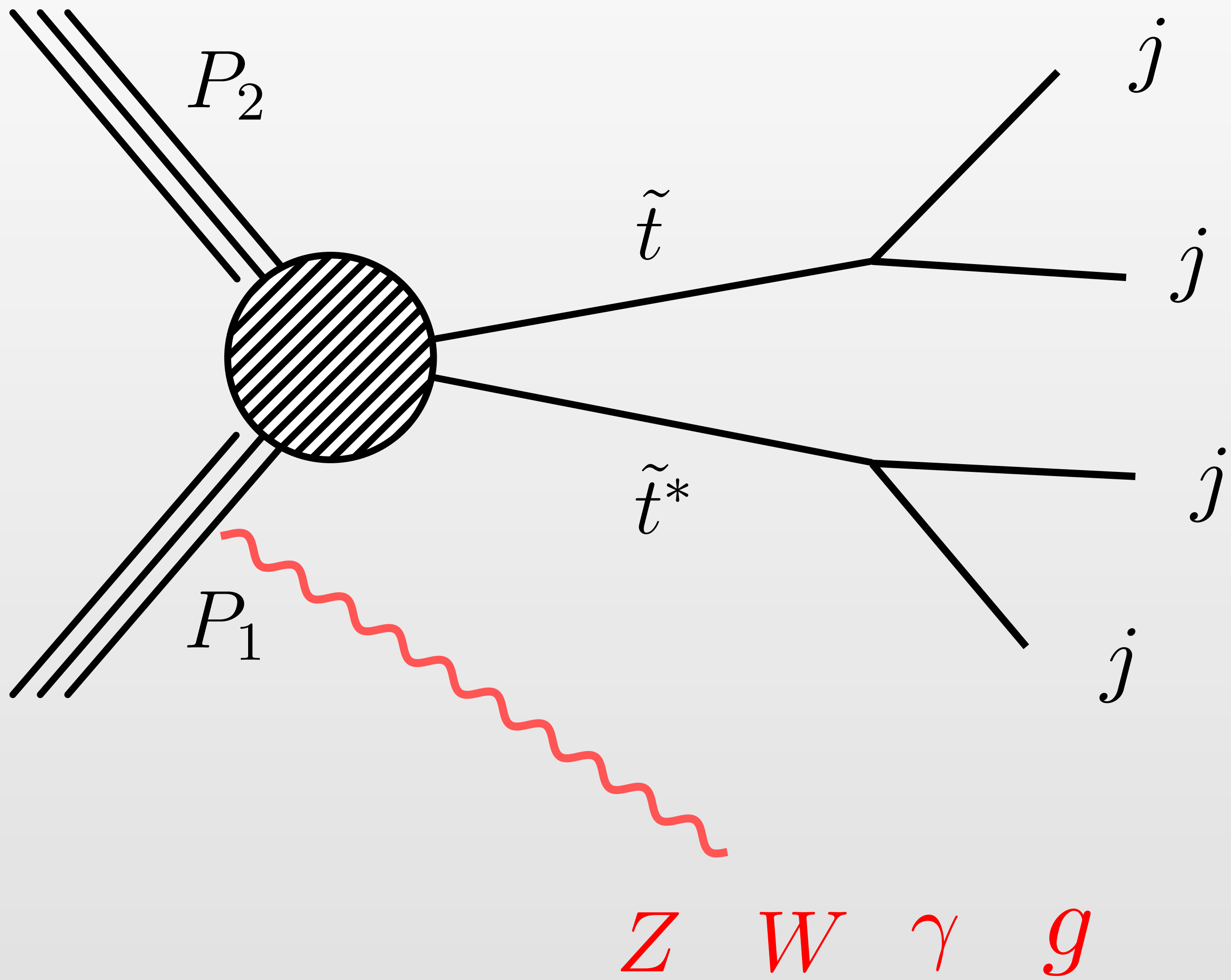
Full hadronic final state; trigger is an issue

Trigger Menu

(Unprescaled) Object	Trigger Threshold (GeV)	Rate (Hz)	Physics
Single Muon	40	21	Searches
Single Isolated muon	24	43	Standard Model
Double muon	(17, 8) [13, 8 for parked data]	20 [30]	Standard Model / Higgs
Single Electron	80	8	Searches
Single Isolated Electron	27	59	Standard Model
Double Electron	(17, 8)	8	Standard Model / Higgs
Single Photon	150	5	Searches
Double Photon	(36, 22)	7	Higgs
Muon + Ele x-trigger	(17, 8), (5, 5, 8), (8, 8, 8)	3	Standard Model / Higgs
Single PFJet	320	9	Standard Model
QuadJet	80 [50 for parked data]	8[100]	Standard Model /Searches
Six Jet	(6 x 45), (4 x 60, 2 x 20)	3	Searches
MET	120	4	Searches
HT	750	6	Searches

S. Beauceron, CMS, ICHEP2012

Initial State Radiation



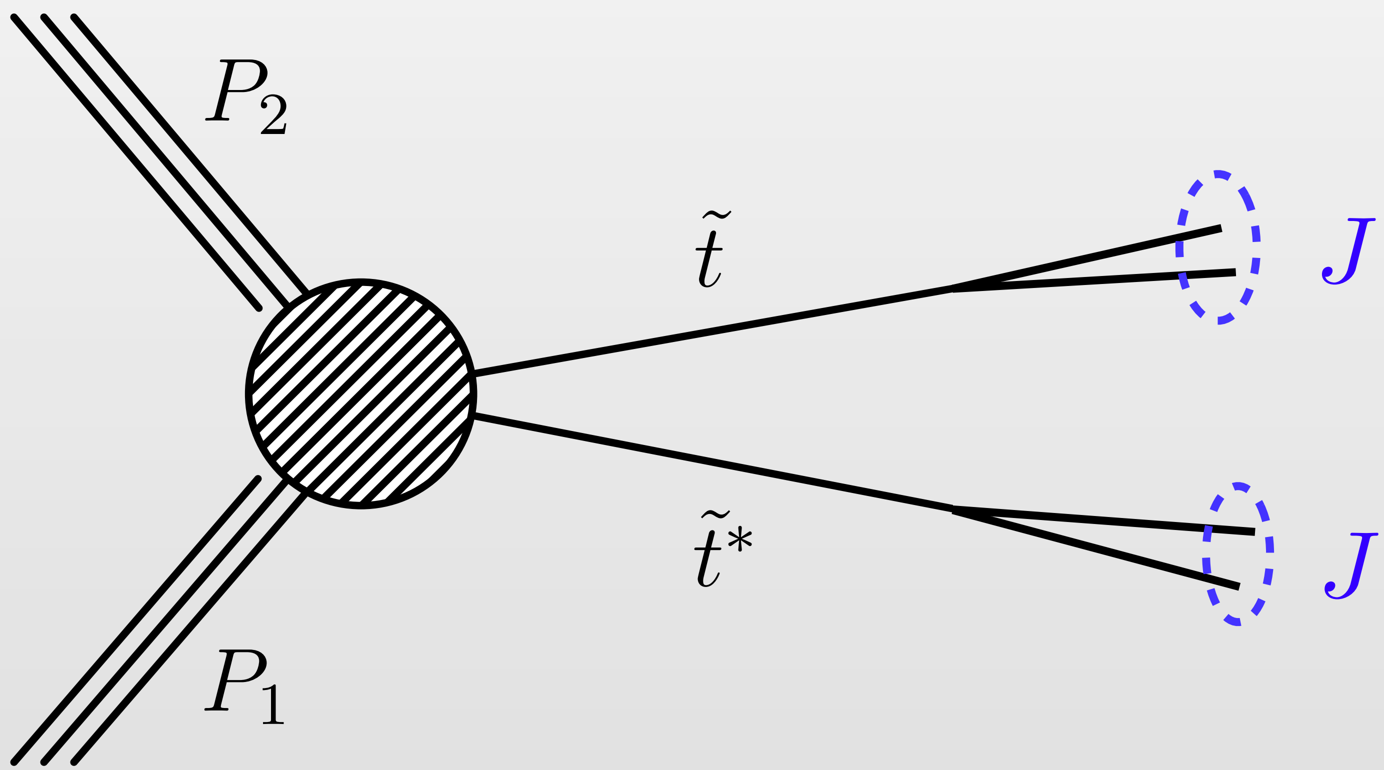
The reduction on signal events is too much

Not the way to go !

“Stop Jet”

For a large center-of-mass energy, stops are boosted

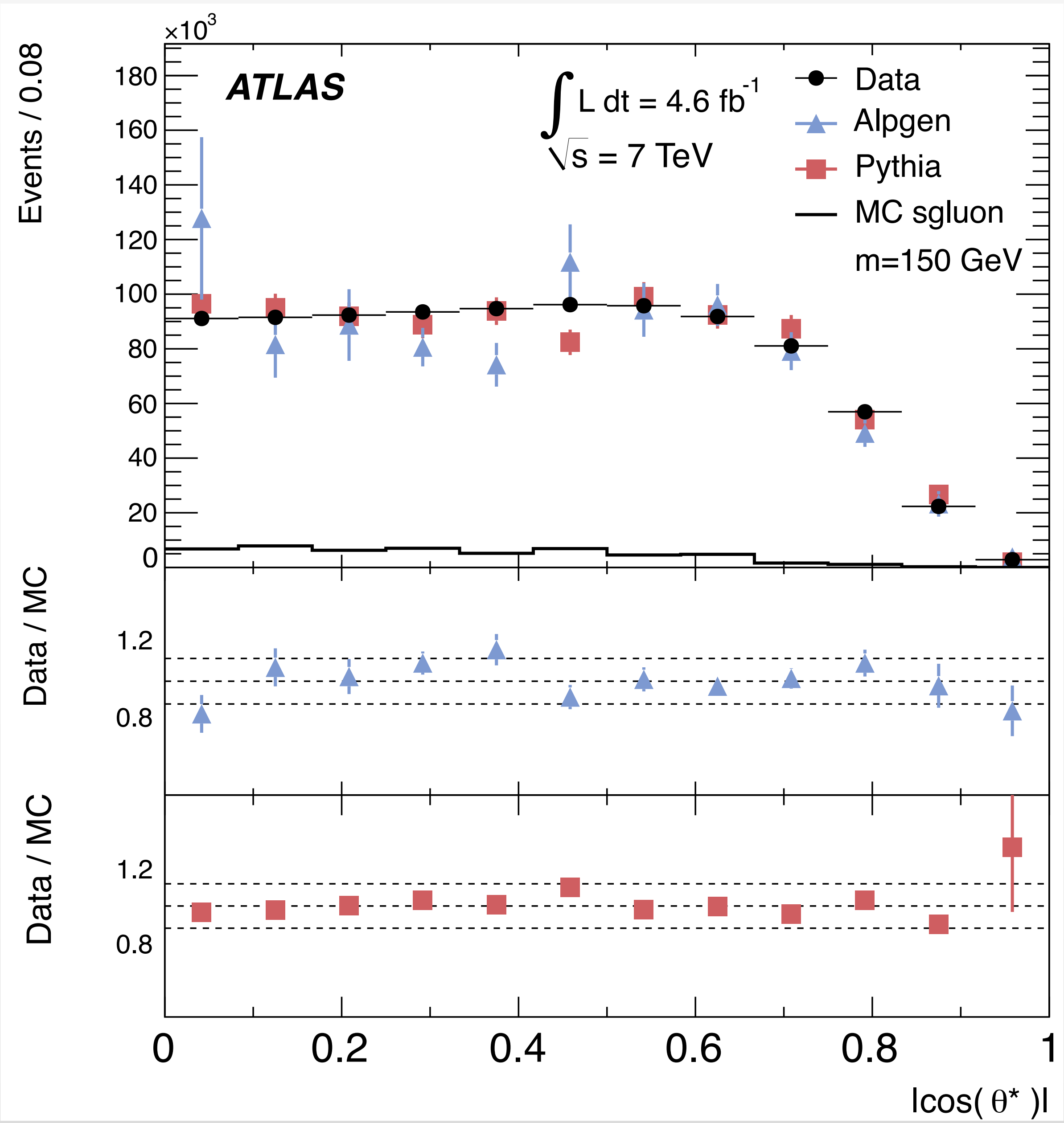
The two jets from its decay are collimated

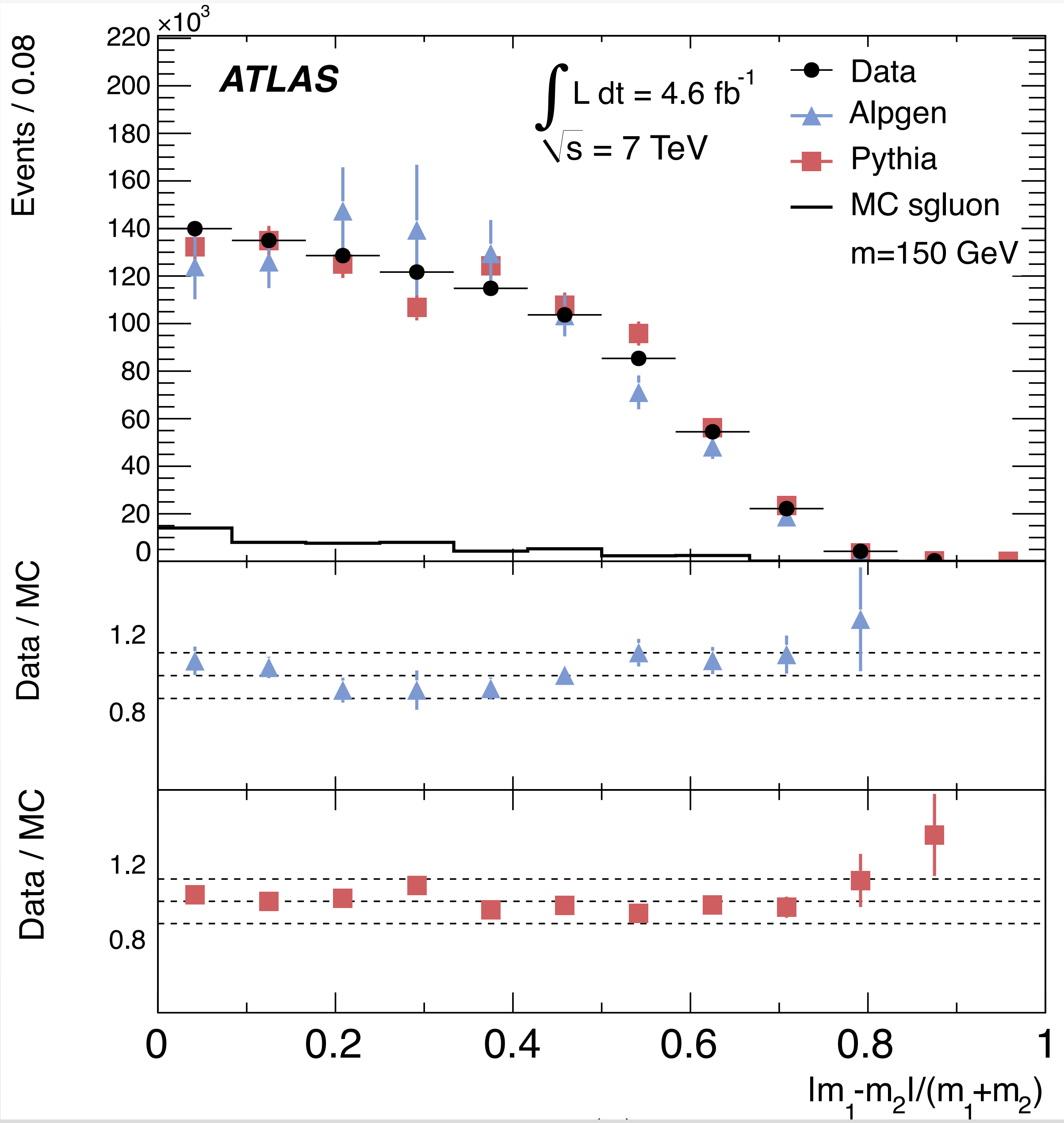


We can use the high H_T trigger

The way to go !

Useful Traditional Variables





ATLAS, 1210.4826

Useful Jet-substructure Variables

- "Mass-drop declustering":

  and jet filtering

Butterworth, Davison, Rubin, Salam: 0802.2470

- "pT-drop declustering":

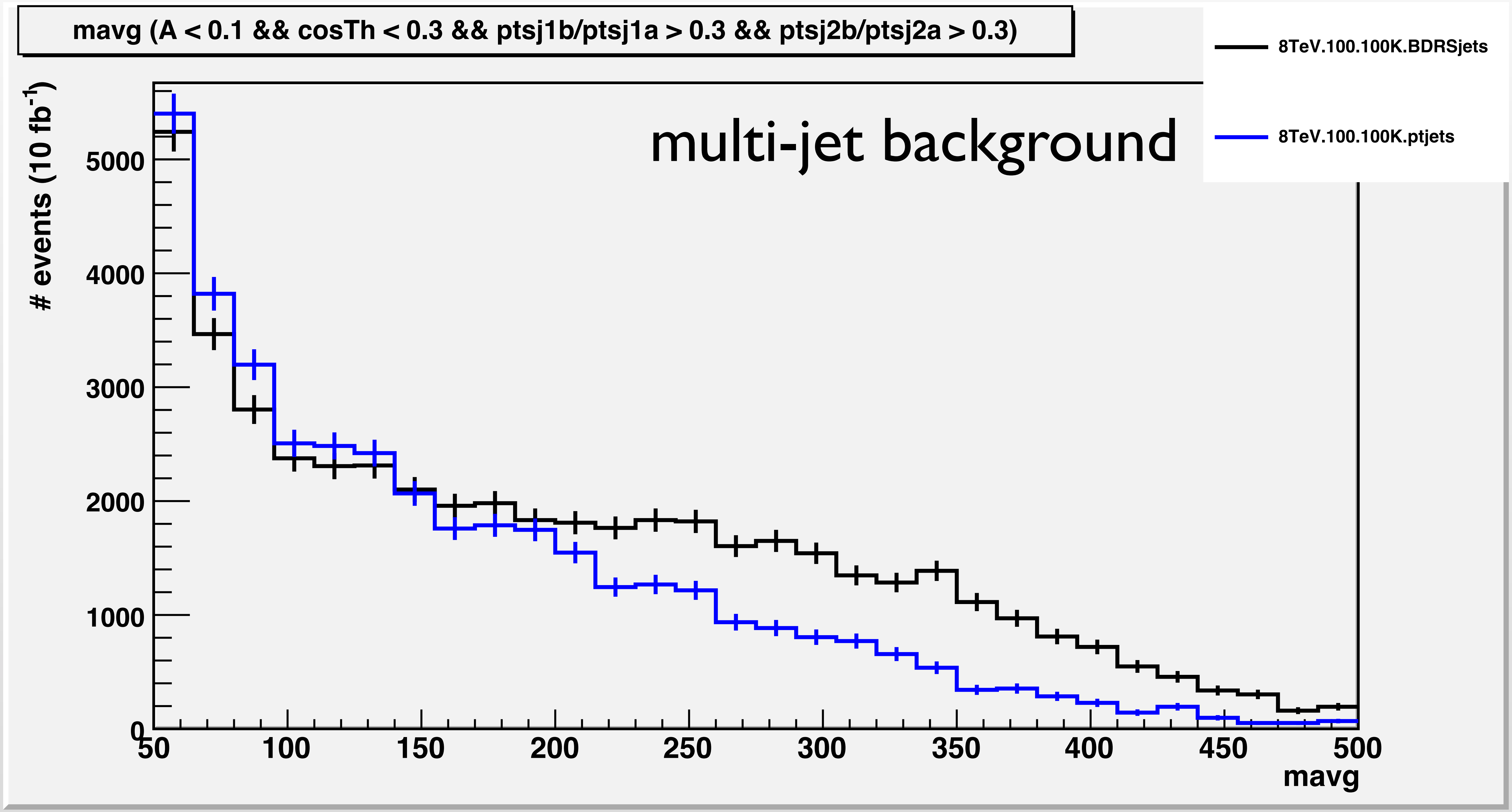
Kaplan, Rehermann, Schwartz, Tweedie: 0806.0848

- "jet trimming":

Cacciari, Rojo, Salam, Soyez: 0810.1304

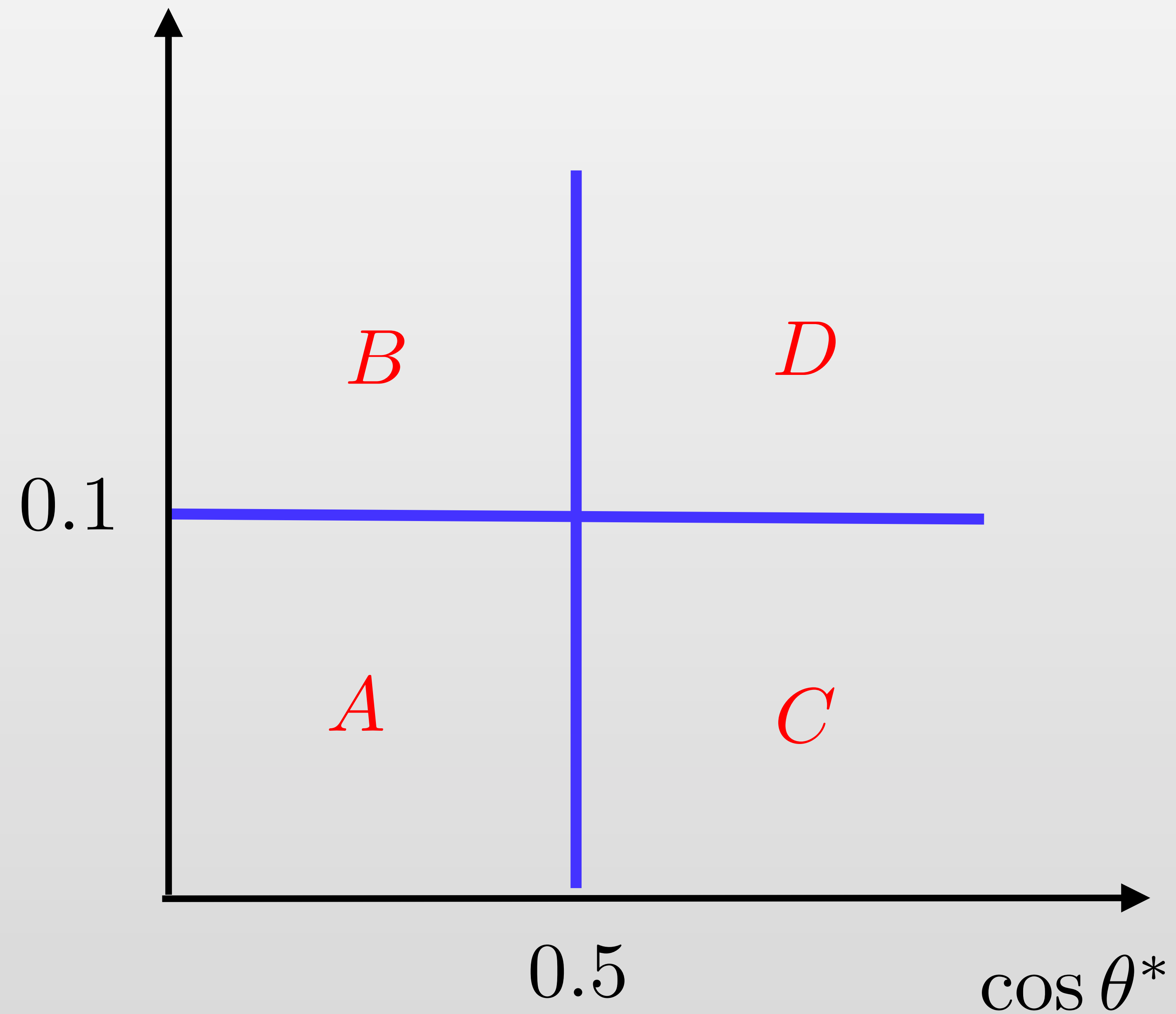
Krohn, Thaler, Wang: 0912.1342

pTjet vs. BDRSjet

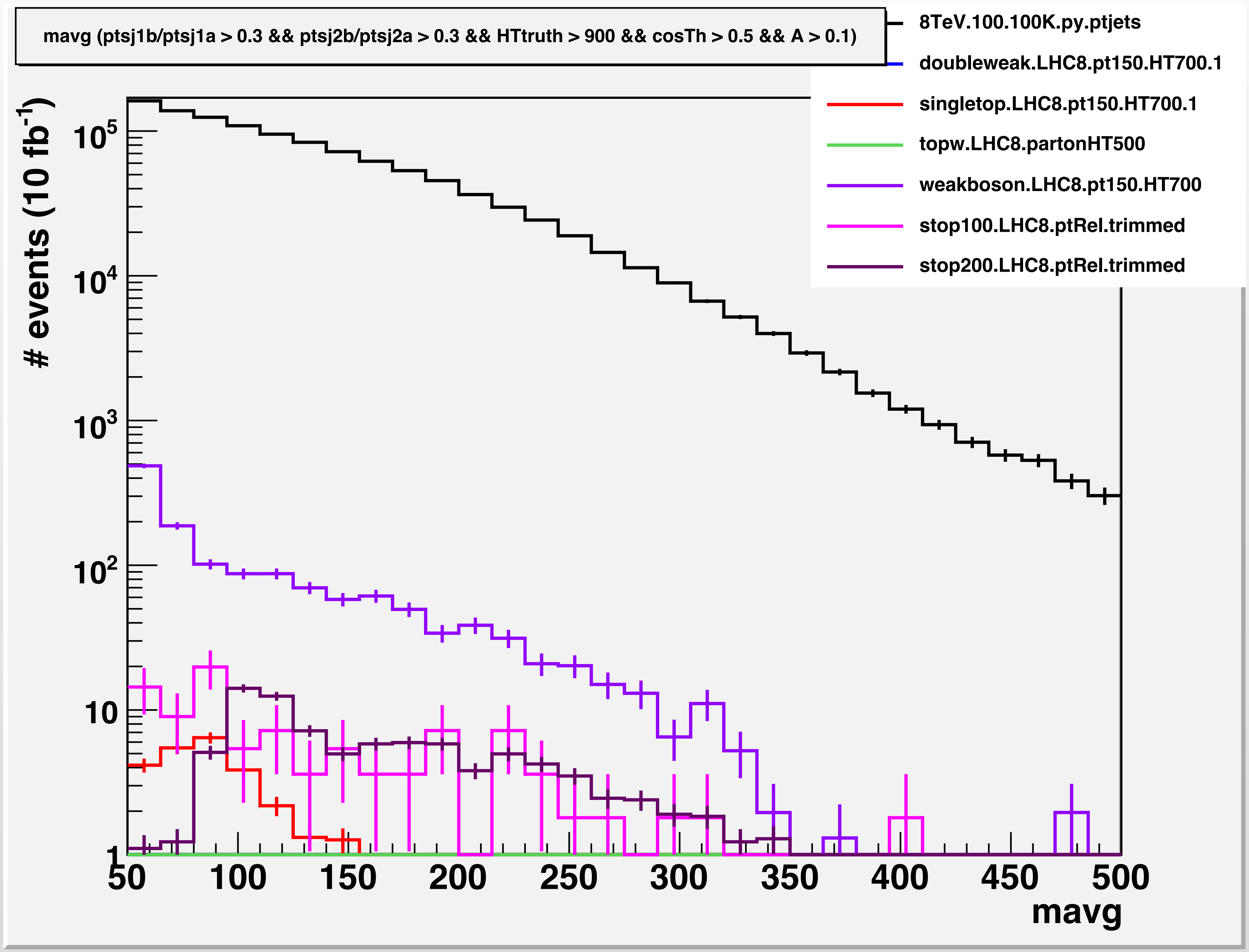


ABCD Method

$$A \equiv \frac{|m_1 - m_2|}{m_1 + m_2}$$

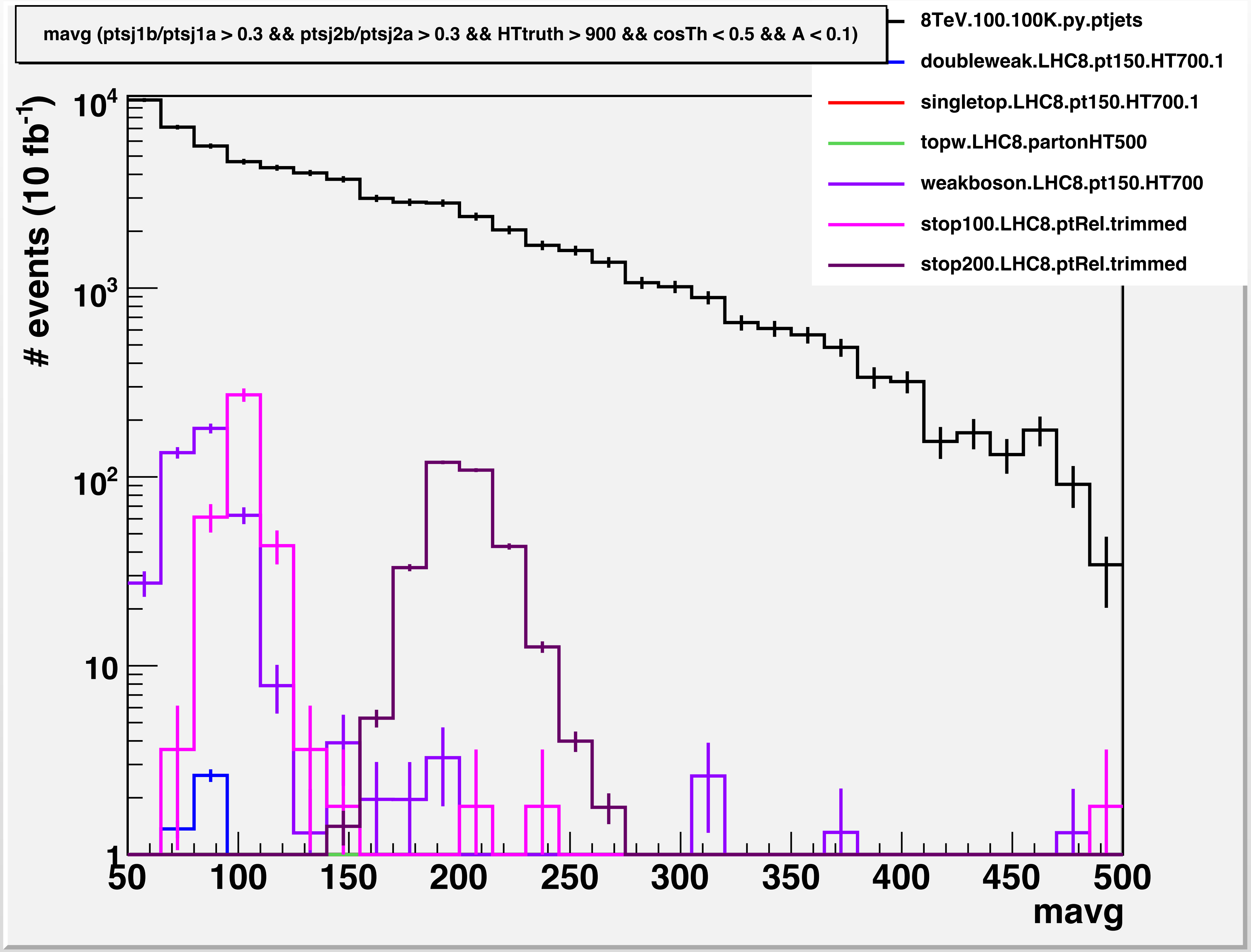


“D” region



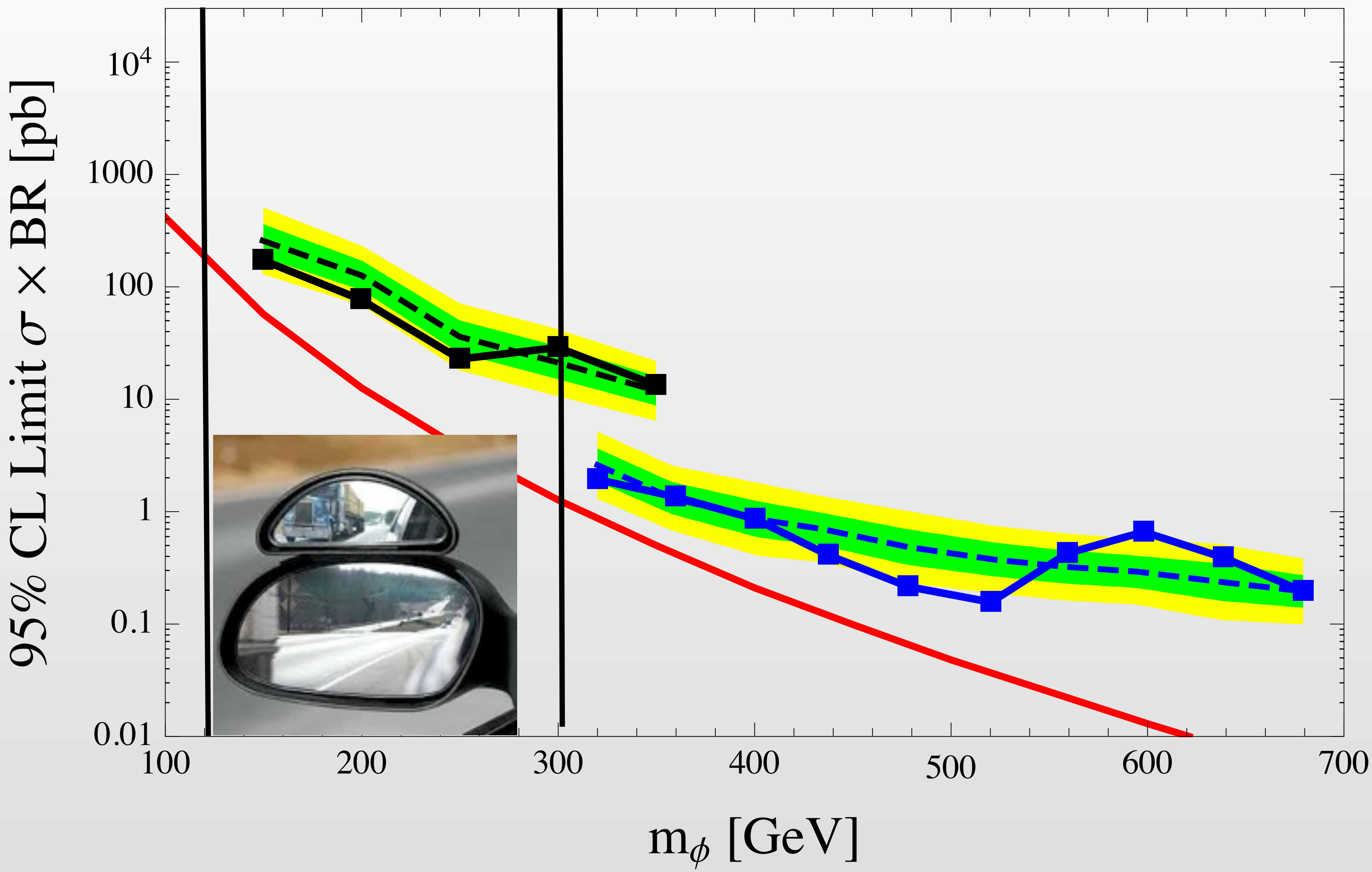
YB, Katz, Tweedie; 130x.xxxx

“A” region



YB, Katz, Tweedie; 130x.xxxx

Blind Spot: not anymore



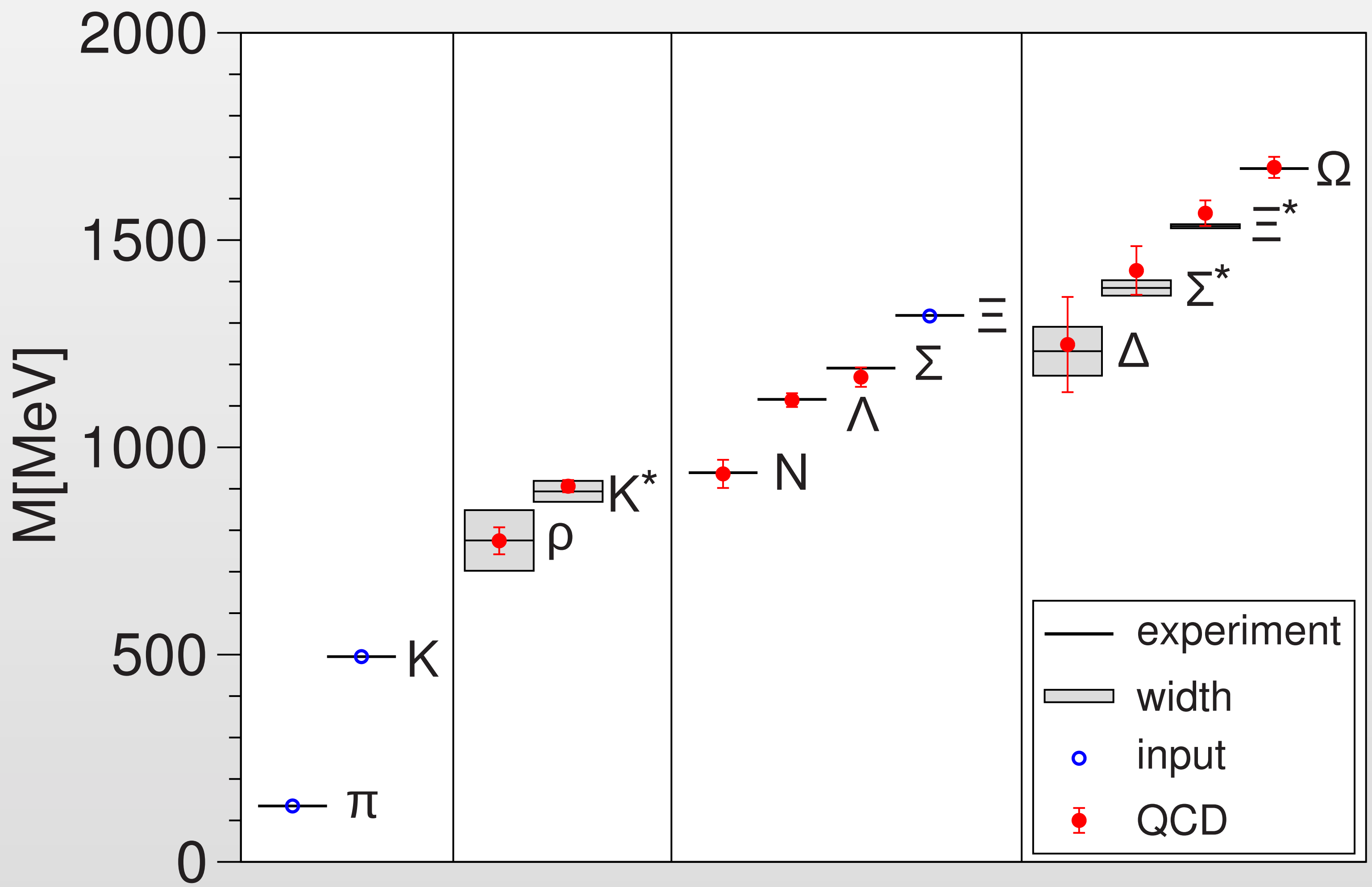
Our strategy can be used to cover this mass region

The importance of QCD is beyond the LHC

Ordinary Matter

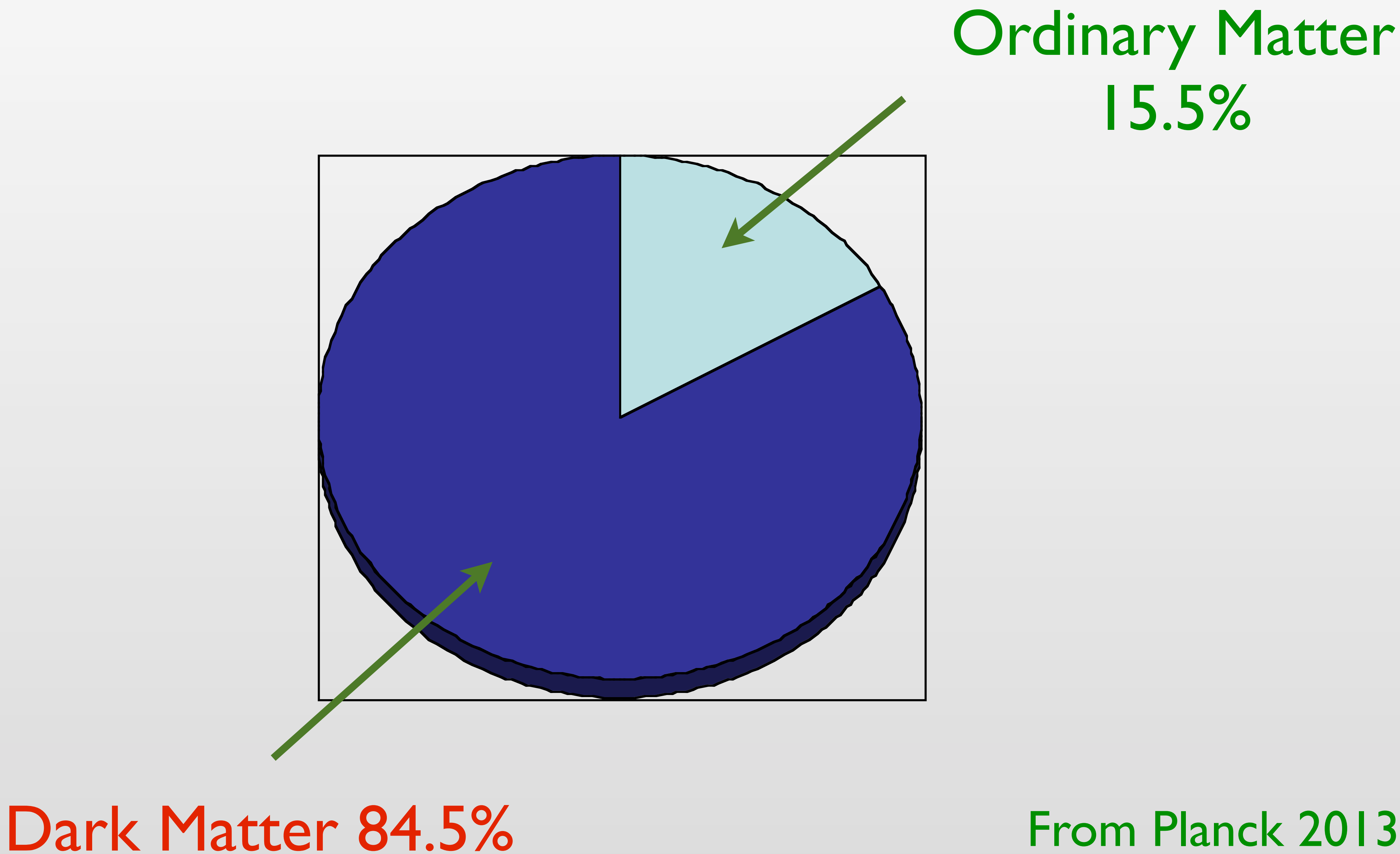
The ordinary matter has its mass from protons and neutrons

Durr, et.al., Science 322, 1224 (2008)



90% of the mass of ordinary matter emerges from QCD

Dark Matter Energy Density



From Planck 2013

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Introduction of Dark QCD

A simple-minded conjecture:

Dark QCD

dark quarks, dark pions,
dark baryons, dark axions

...

The dark matter has its mass from a “dark QCD”

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Is it new?

TECHNOCOSMOLOGY – COULD A TECHNIBARYON EXCESS PROVIDE A "NATURAL" MISSING MASS CANDIDATE?

S. NUSSINOV

Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853, USA
and Physics Department, Sackler Faculty of Science, Tel Aviv University, Ramat Aviv, Tel Aviv [1], Israel

Received 7 October 1985

asymmetric dark matter

TECHNICOLOR COSMOLOGY

R.S. CHIVUKULA

Department of Physics, Boston University, Boston, MA 02215, USA

Terry P. WALKER

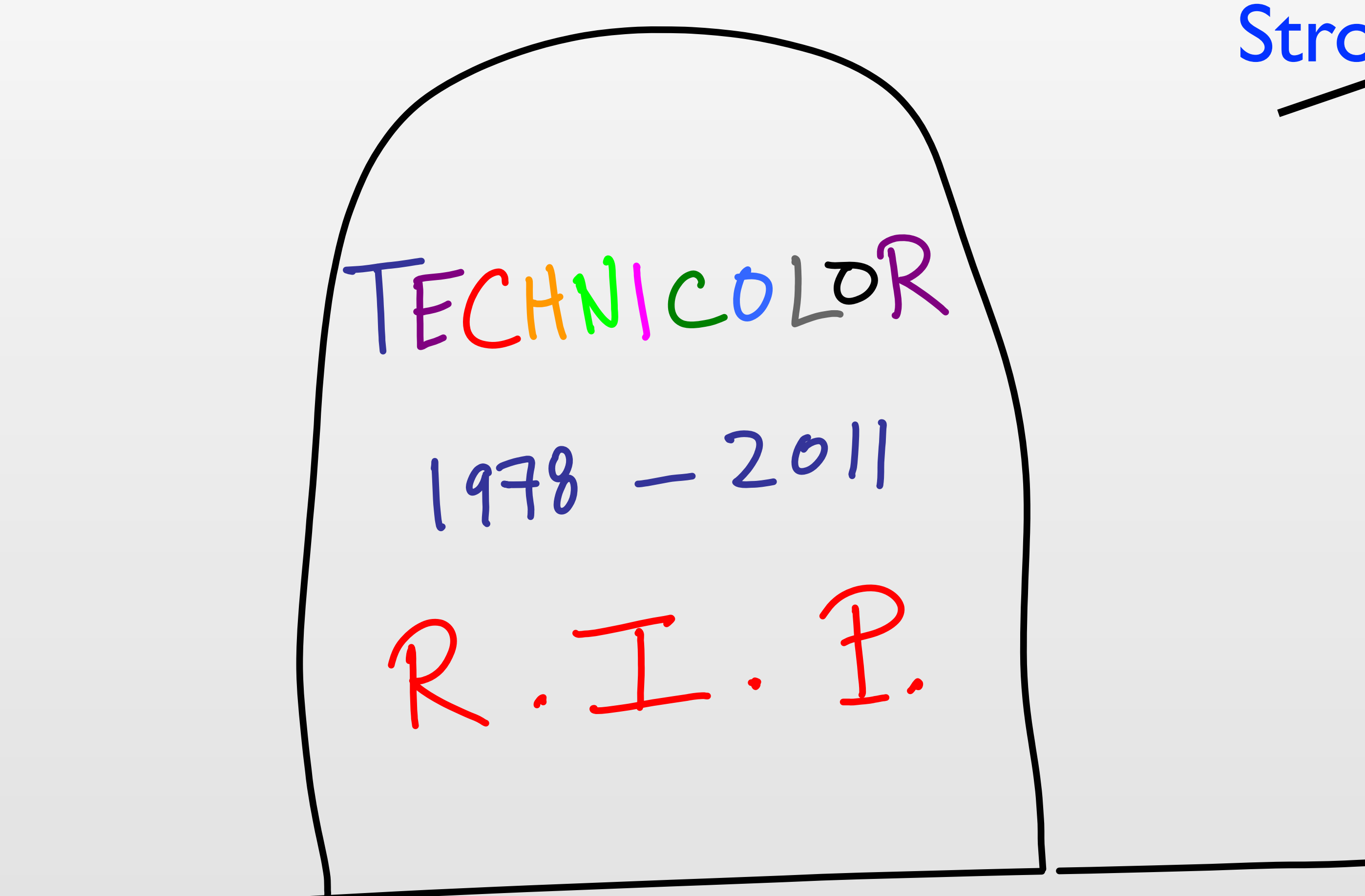
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

Received 16 June 1989

WIMP

The Discovery of Higgs Boson

~~Strong dynamics~~



Nima Arkani-Hamed, talk at SavasFest, May 2012

The dynamics in the dark sector may have nothing to do with the electroweak symmetry breaking !!!

We need to study dark matter for its own purpose

One Number to Explain

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{m_{\rm DM} n_{\rm DM}}{m_{\rm p} n_p} \approx 5 \sim 6$$

Most popular models: “WIMP miracle”

$$\Omega_{\rm DM} = \frac{s_0}{\rho_c} \left(\frac{45}{\pi g_*}\right)^{1/2} \frac{x_f}{m_{\rm pl}} \frac{1}{\langle \sigma v \rangle} \qquad \langle \sigma v \rangle \approx 1 \text{ pb} \approx \frac{\pi \alpha^2}{8 m_{\rm DM}^2}$$

for $m_{\rm DM} = 100$ GeV

This could be just one option:

dark matter is related to the electroweak scale

The Second Option

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{m_{\rm DM} n_{\rm DM}}{m_{\rm p} n_p} \approx 5 \sim 6$$

Two conditions:

(1): $n_{\rm DM} \sim n_p$

(2): $m_{\rm DM} \sim m_p$

(1): $n_{\rm DM} \sim n_p$

The first condition can be satisfied by introducing some non-trivial number density history

Barr, Chivukula, Farhi, PLB, 241, 387 (1990)

David B. Kaplan, PRL, 68, 741 (1992)

Dodelson, Greene, Widrow, NPB, 372, 467 (1992)

Fujii, Yanagida, PLB, 542, 80 (2002)

Kitano, Low, PRD, 71, 023510 (2005)

Farrar, Zaharijas, PRL, 96, 041302 (2006)

Kaplan, Luty, Zurek, PRL, 79, 115016 (2009)

Shelton, Zurek, PRD, 82, 123512 (2010)

Davoudiasl, Morrissey, Sigurdson, Tulin, PRL, 105, 211304 (2010)

Buckley, Randall, JHEP, 1109, 009 (2011)

……

(2): $m_{\rm DM} \sim m_p$

The dark matter could be like ordinary baryons from an asymmetry mechanism

The dark matter mass is related to the QCD scale

If dark matter is a "dark baryon" from a new QCD-like strong dynamics in the dark matter sector

$$\Lambda_{\mathrm{dQCD}} \sim \Lambda_{\mathrm{QCD}} \quad ?$$

Need to have QCD and dQCD gauge couplings related to each other

Dimensional Transmutation

$$\Lambda^2_{\rm QCD} \approx M^2_{\rm Pl}\, e^{4\pi/[\beta_0^s\, \alpha_s(M^2_{\rm Pl})]} \qquad\qquad \beta_0 < 0$$

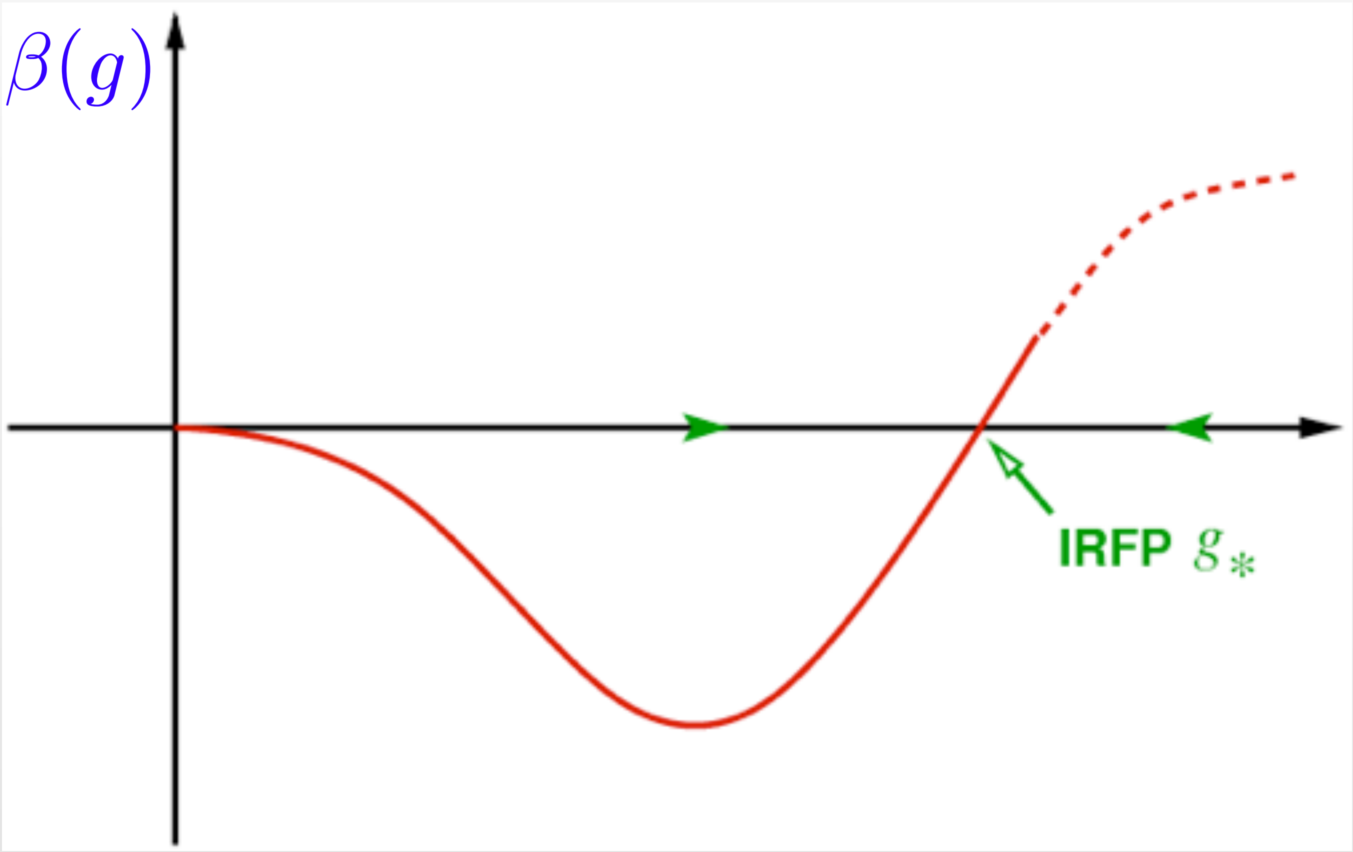
$$\Lambda^2_{\rm dQCD} \approx M^2_{\rm Pl}\, e^{4\pi/[\beta_0^d\, \alpha_d(M^2_{\rm Pl})]}$$

The confinement scale is sensitive to the beta function (matter content) and the coupling at a UV scale

Need a mechanism to relate the gauge couplings of two gauge groups in an infrared scale

Our Idea

Banks-Zaks fixed point



Particles charged under both gauge groups can induce Infrared Fixed Points (IRFP) and have both gauge couplings related to each other in the IR

Matter Content

$$G_{\text{gauge}} = SU(N_c)_{\text{QCD}} \times SU(N_d)_{\text{dQCD}}$$

Field	$SU(N_c)_{\text{QCD}}$	$SU(N_d)_{\text{darkQCD}}$	multiplicity
SM fermion	N_c	1	n_{f_c}
SM scalar	N_c	1	n_{s_c}
DM fermion	1	N_d	n_{f_d}
DM scalar	1	N_d	n_{s_d}
joint fermion	N_c	N_d	n_{f_j}
joint scalar	N_c	N_d	n_{s_j}

a general matter content

upper bounds on multiplicities from asymptotic freedom

Gauge Coupling Running

$$\frac{dg_c}{d(\log\mu)} = \beta_c(g_c, g_d)\,, \qquad \frac{dg_d}{d(\log\mu)} = \beta_d(g_c, g_d)$$

Jones, PRD, 25, 581 (1982)

$$\begin{aligned}
\beta_c(g_c, g_d) \;=\; & \frac{g_c^3}{16\pi^2}\left[\frac{2}{3}\,T(R_f)\,2(n_{f_c} + N_d\, n_{f_j}) + \frac{1}{3}\,T(R_s)\,(n_{s_c} + N_d\, n_{s_j}) - \frac{11}{3}\,C_2(G_c)\right] \\
& + \frac{g_c^5}{(16\pi^2)^2}\left[\left(\frac{10}{3}C_2(G_c) + 2C_2(R_f)\right)\,T(R_f)\,2\,(n_{f_c} + N_d\, n_{f_j})\right. \\
& \qquad \left. + \left(\frac{2}{3}C_2(G_c) + 4C_2(R_s)\right)\,T(R_s)\,(n_{s_c} + N_d\, n_{s_j}) - \frac{34}{3}\,C_2^2(G_c)\right] \\
& + \frac{g_c^3\, g_d^2}{(16\pi^2)^2}\left[2C_2(R_f)\,T(R_f)\,2\,N_d\, n_{f_j} + 4C_2(R_s)\,T(R_s)\,N_d\, n_{s_j}\right]\,.
\end{aligned}$$

$c \leftrightarrow d$ for $\beta_d(g_c, g_d)$

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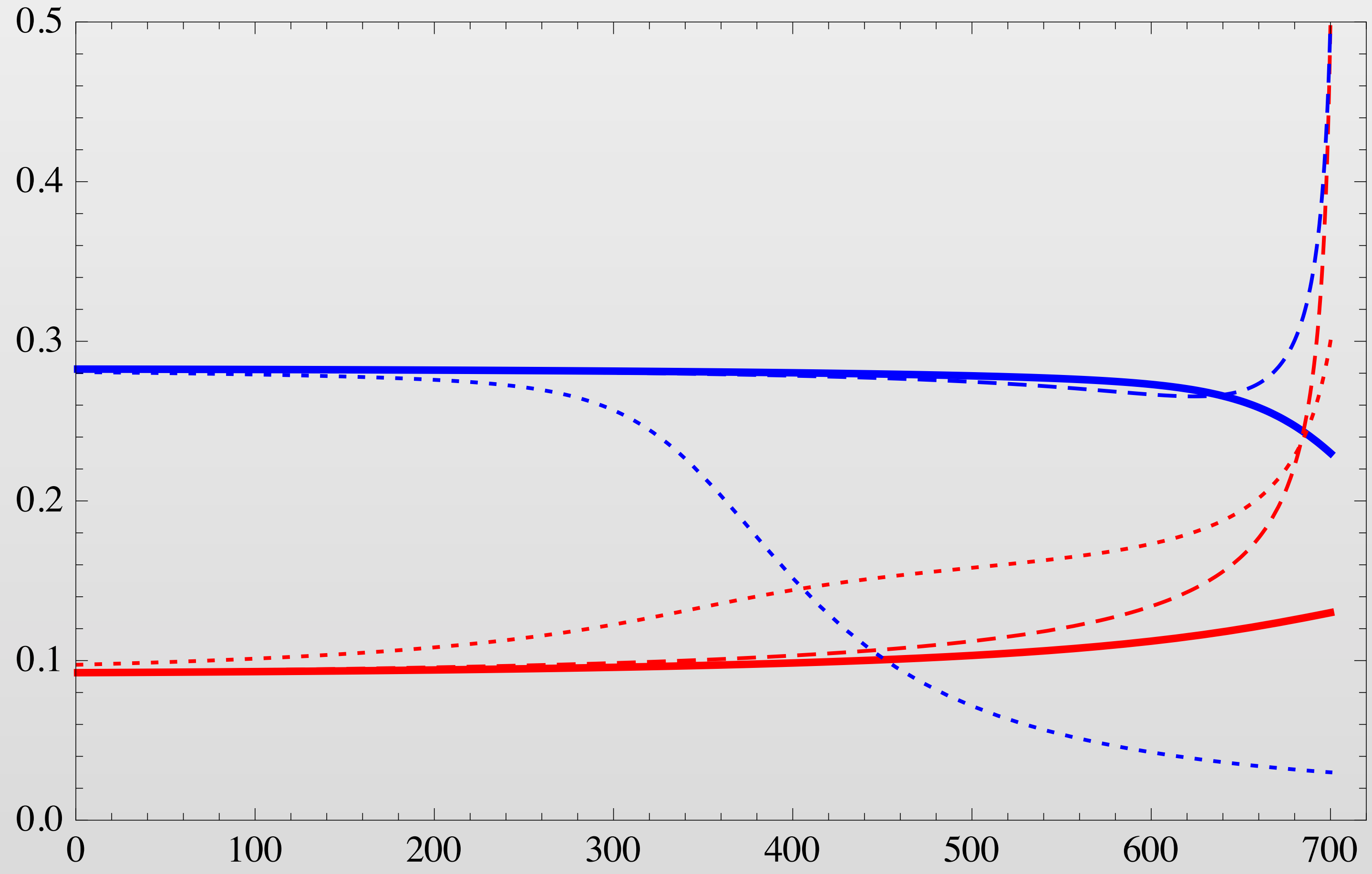
Infrared Fixed Point

$$\beta_c(g_c, g_d) = \beta_d(g_c, g_d) = 0$$

$$\begin{aligned}
\alpha_s^* &\equiv \alpha_s^*(n_{f_c}, n_{s_c}, n_{f_d}, n_{s_d}, n_{f_j}, n_{s_j}) \\
\alpha_d^* &\equiv \alpha_d^*(n_{f_c}, n_{s_c}, n_{f_d}, n_{s_d}, n_{f_j}, n_{s_j})
\end{aligned}$$



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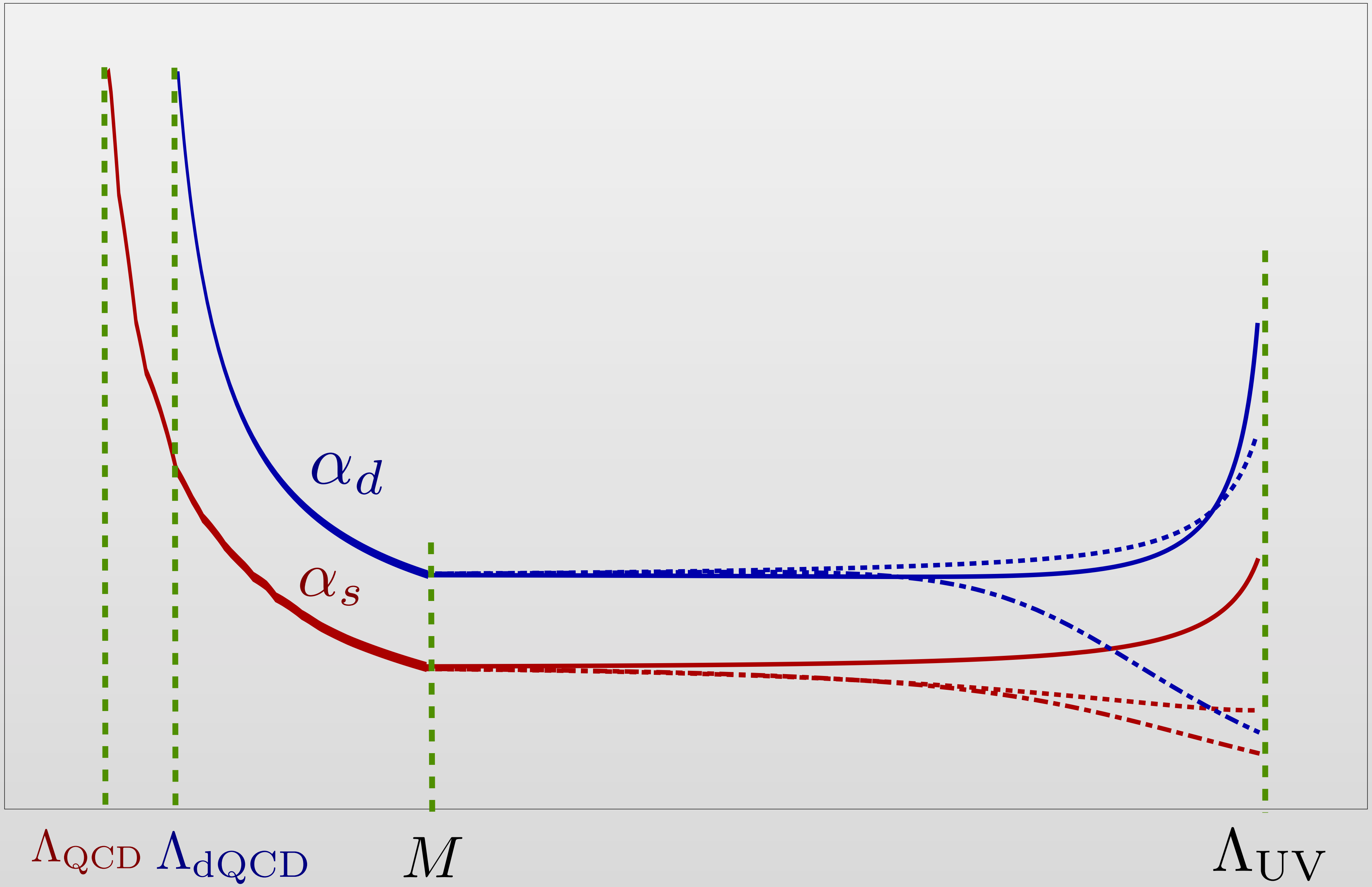
Dark QCD Scales

Decouple all particles except dark quarks at a common scale M



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Dark QCD Scales

$$
\begin{tikzcd}
 & \alpha_s(M_Z) + \alpha_s^* \arrow[dl] \arrow[d] \\
\Lambda_{\mathrm{QCD}} & \begin{array}{c} M \\ + \ \alpha_d^* \end{array} \arrow[d] \\
 & \alpha_d(\Lambda_{\mathrm{dQCD}}) \arrow[d] \\
 & \Lambda_{\mathrm{dQCD}}
\end{tikzcd}
$$

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Estimation of Dark Baryon Masses

Require non-perturbative tools like Lattice QCD

Following the analysis of the Cornwall, Jackiw, Tomboulis effective potential for chiral symmetry breaking, one has

$$\alpha_d C_2(R_f) > \pi/3 \qquad \alpha_d > \pi/4$$

Using this condition to approximately determine the confinement scales, we have

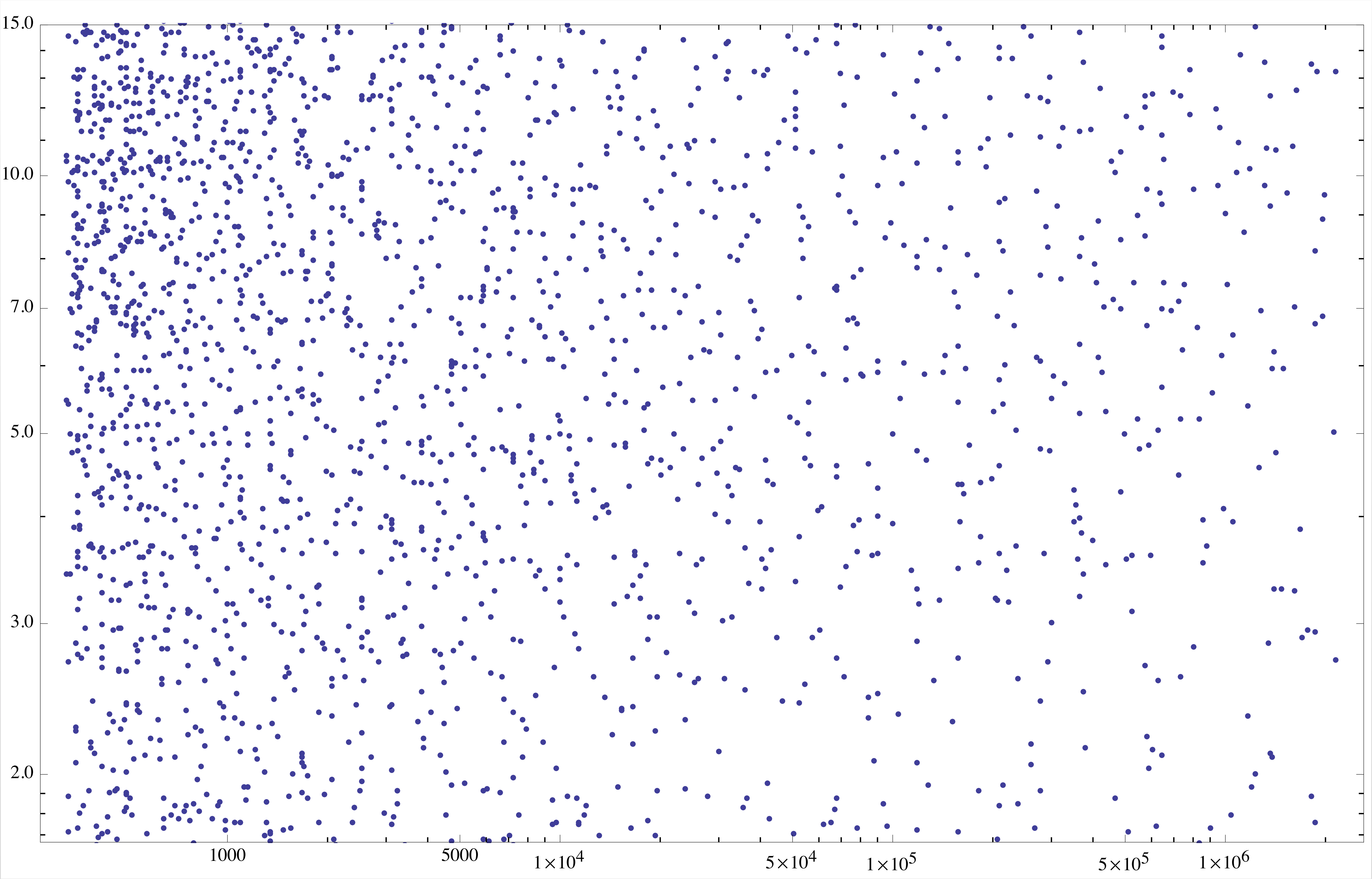
$$m_p \approx 1.5\Lambda_{\mathrm{QCD}}$$

so, $$m_D \approx 1.5\Lambda_{\mathrm{dQCD}}$$

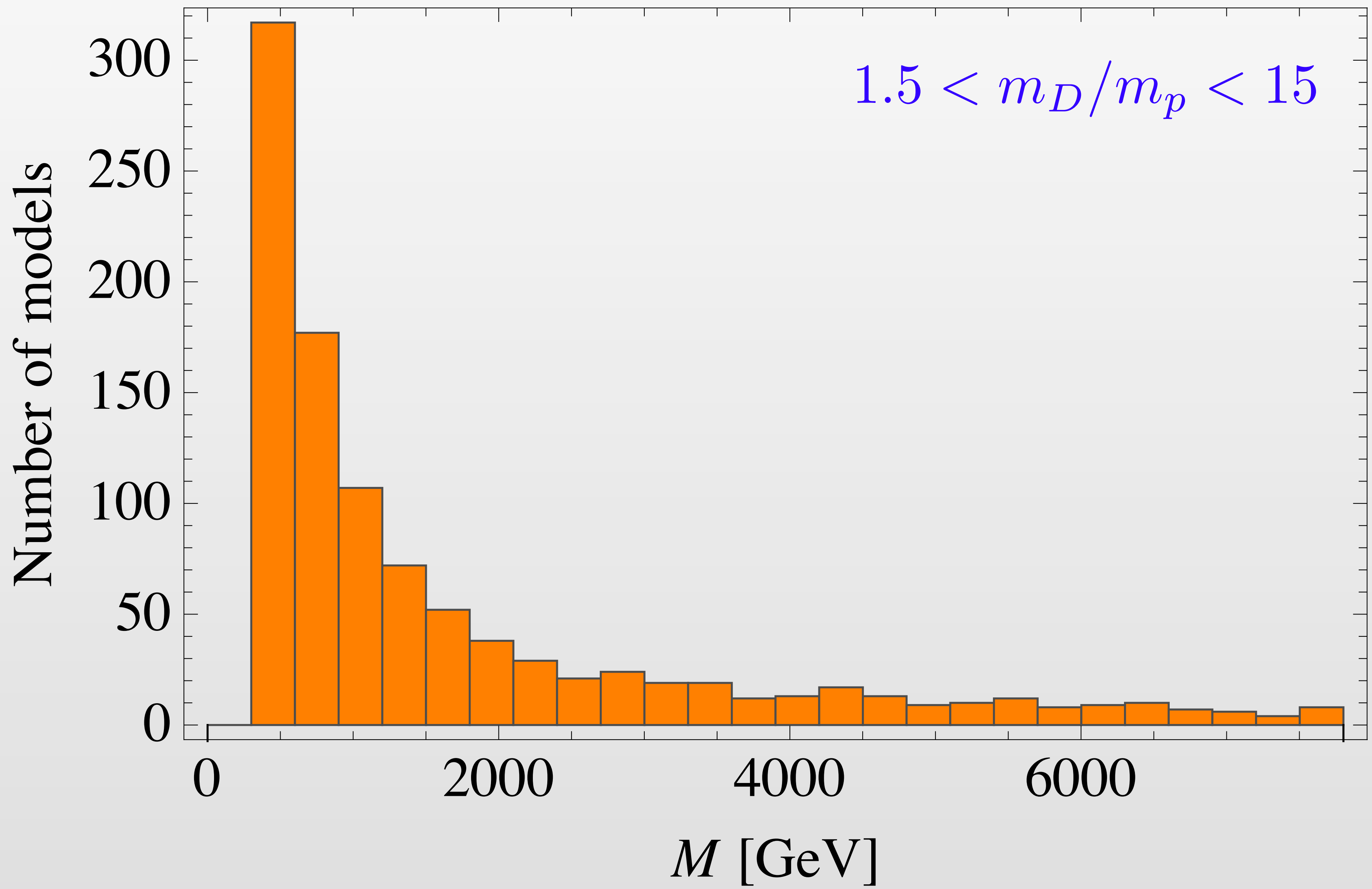
A Sample of Representations

Model	n_{f_c}	n_{f_d}	n_{f_j}	n_{s_c}	n_{s_d}	n_{s_j}	α_s^*	α_d^*	M (GeV)	m_D (GeV)
A	6	5	3	0	2	0	0.095	0.175	518	31
B	6	6	3	1	0	0	0.083	0.120	2030	8.6
C	6	6	3	2	2	0	0.070	0.070	13500	0.32
D	7	7	2	2	0	2	0.078	0.168	3860	72
E	7	7	2	2	1	2	0.090	0.133	869	3.5
F	8	8	2	2	0	1	0.074	0.149	7700	29
G	8	8	2	2	1	1	0.082	0.118	2244	1.2

Many Models



Statistic Distribution of M



The bi-fundamental of QCD and dark QCD prefers to have masses below 2 TeV

Example Model for Number Density

(I): $n_{\rm DM} \sim n_p$

The general idea: generating asymmetry for the bi-fundamental particles

$$\Phi: \ (\bar{3}, 3)_{1/3}$$

The baryon and dark baryon have comparable number densities from its decay

$$\Phi \to X_L \bar{d}_R$$

$$\downarrow$$

$$n_D \sim n_p$$

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Asymmetry of the bi-fundamental

$$\mathcal{L} \supset k_i \bar{Y}_1 \Phi N_i + \text{h.c.}.$$

Generate number asymmetries for $\Delta n_\Phi = -\Delta n_{Y_1}$

$$\epsilon = \frac{\Gamma(N_1 \to Y_1 \Phi^\dagger) - \Gamma(N_1 \to \bar{Y}_1 \Phi)}{\Gamma(N_1 \to Y_1 \Phi^\dagger) + \Gamma(N_1 \to \bar{Y}_1 \Phi)} \approx -\frac{3}{2}\frac{1}{8\pi}\frac{\Im m[k_1^2 (k_2^*)^2]}{|k_1|^2}\frac{M_1}{M_2}$$

$$\mathcal{L} \supset \kappa_1 \Phi \bar{Y}_1^c Y_2 + \kappa_2 \Phi \bar{Y}_2 e_R + \kappa_3 \Phi \bar{X}_L d_R + \text{h.c.},$$

$$Y_1 \to \bar{Y}_2 \Phi^\dagger \qquad Y_2 \to \Phi e_R$$

$$\downarrow$$

$$\Delta n_\Phi = -3\Delta n_{Y_1}$$

Asymmetries of Baryon and Dark Baryon

Without weak interaction and electroweak sphaleron processes

$$\Phi \to X_L \bar{d}_R \quad \longrightarrow \quad \begin{aligned} \Delta n_{d_R} &\equiv 3\, n_B = 3\, \Delta n_{Y_1}\,, \\ \Delta n_{e_R} &\equiv n_L = -\Delta n_{Y_1}\,, \\ \Delta n_X &\equiv 3\, n_D = -3\, \Delta n_{Y_1}\,, \end{aligned}$$

After taking the weak processes into account

$$n_B = \frac{28}{79} n_{B-L}$$

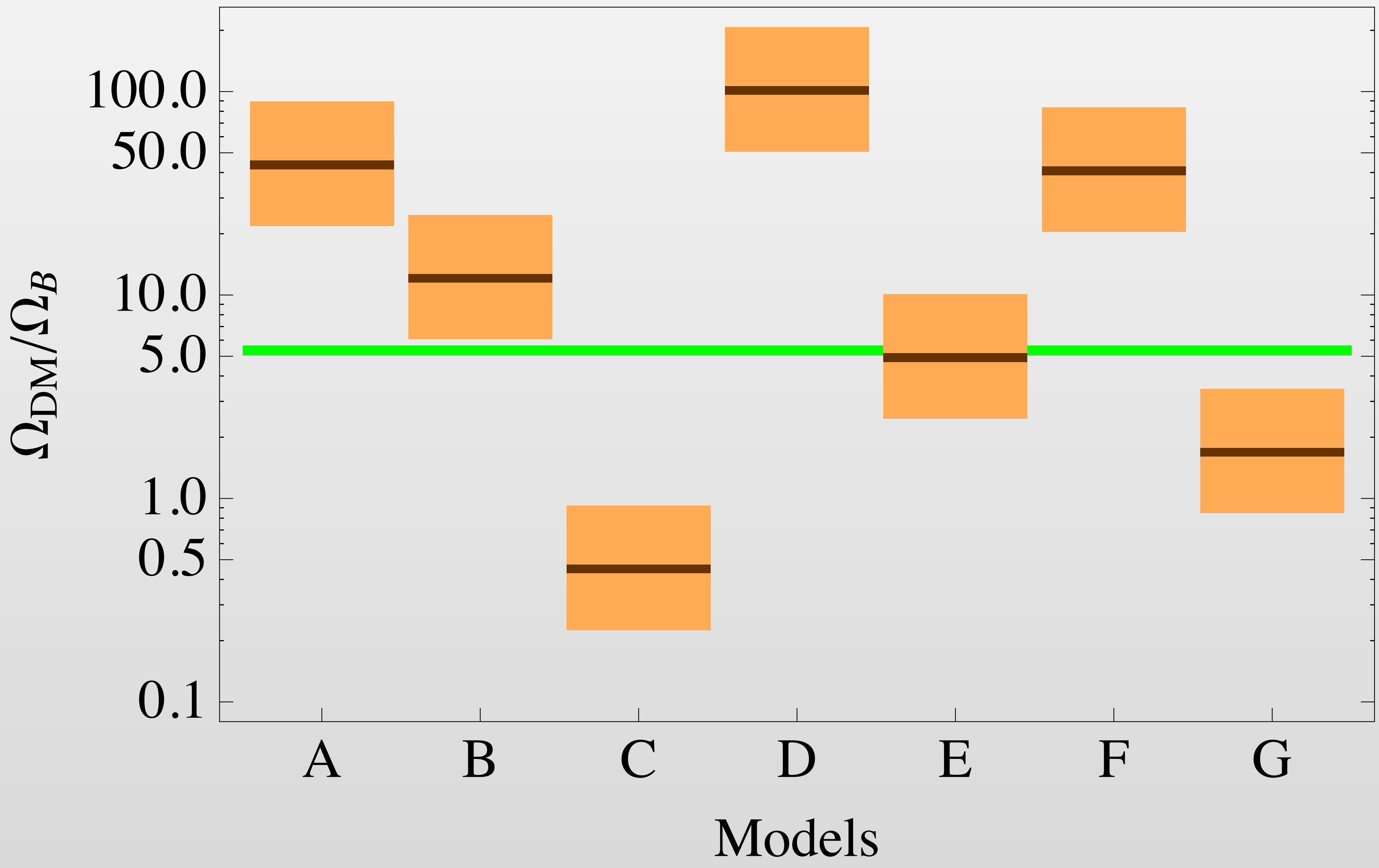
Chung, Garbrecht, Tulin
0807.2283

$$\downarrow$$

$$\frac{|n_D|}{n_B} = \frac{79}{56}$$

Ratios of Energy Densities

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{n_D m_D}{n_B m_p} \approx \frac{79}{56}\frac{m_D}{m_p}$$



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Dark Matter Phenomenology

All relevant phenomenology depends on the bi-fundamental particles, which have a mass at 1-2 TeV

Integrate out the Φ field

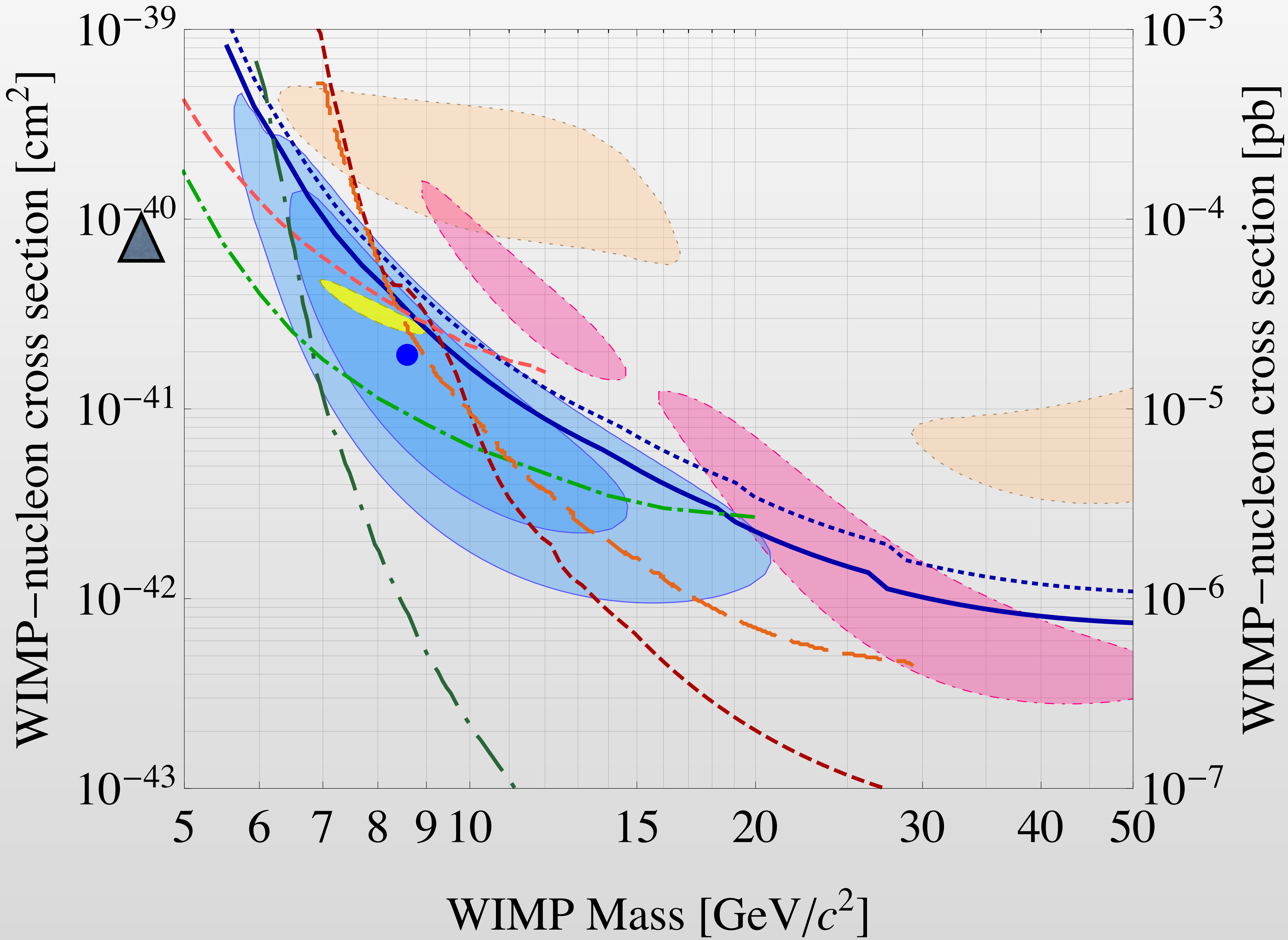
$$\frac{\kappa_3^2\, \overline{X}_L \gamma_\mu X_L\, \overline{d}_R \gamma^\mu d_R}{M_\Phi^2}$$

Spin-independent dark baryon-neutron cross section

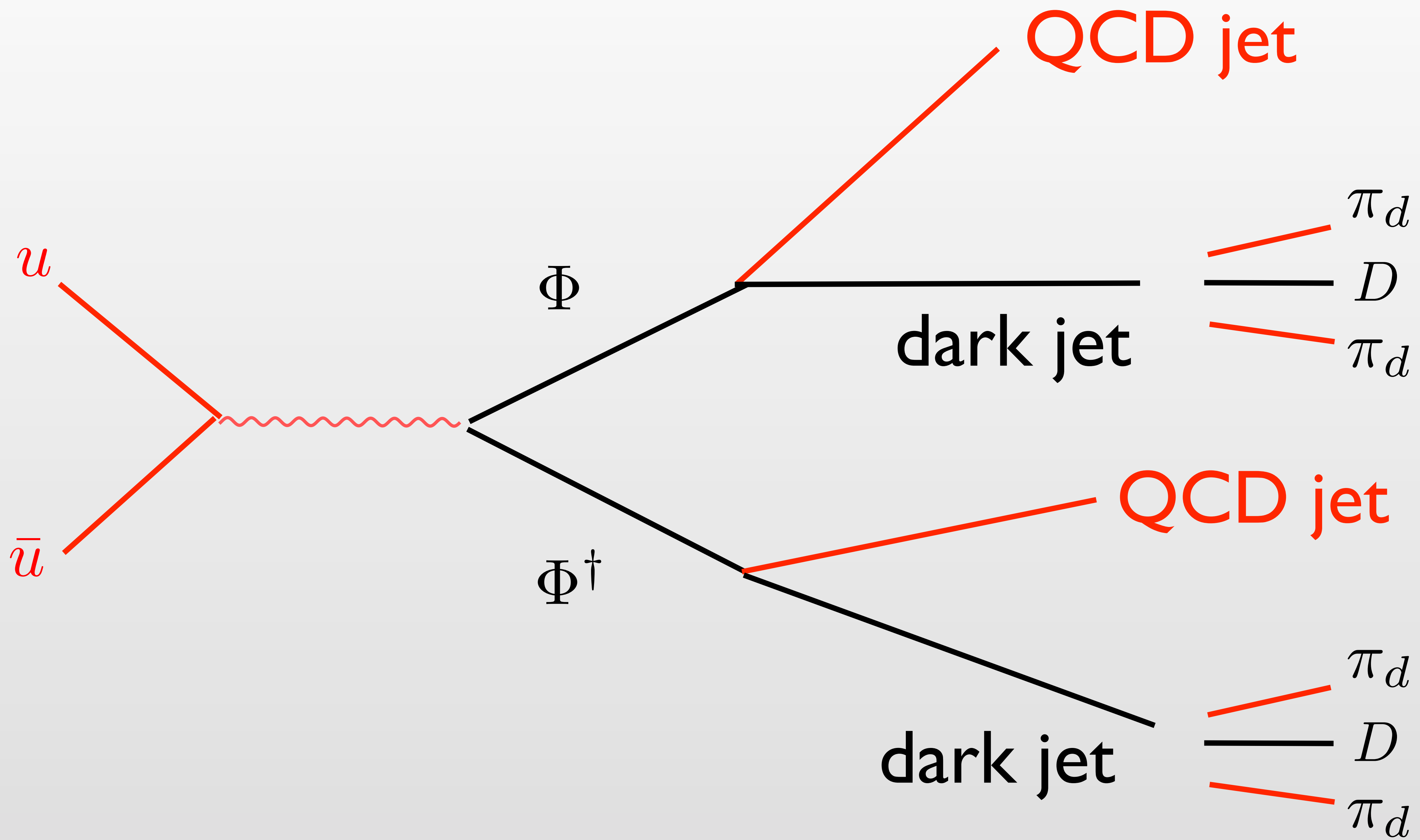
$$\sigma_{D-n}^{\mathrm{SI}} = \frac{2^2\, 3^2\, \kappa_3^4\, \mu_{D-n}^2}{16\, \pi\, M_\Phi^4} = \left(\frac{1\ \mathrm{TeV}}{M_\Phi/\kappa_3}\right)^4 \times 3 \times 10^{-40}\ \mathrm{cm}^2$$

Dark Matter Phenomenology

CDMS, 1304.4279



Collider Phenomenology



missing energy could be reduced

Conclusions

- ★ Using the high Ht trigger and jet substructure techniques, the RPV stop may be discovered at the 8 TeV LHC with a mass around 200 GeV.
- ★ Dark baryon mass could be related to our proton mass through (approximate) infrared fixed points
- ★ Dark matter and collider phenomenologies are controlled by the bi-fundamental mass, which is below 2 TeV for the majority of models

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LHC-The First Part of the Journey is almost over

LHC-The Second Part of the Journey: tricky signals

Thanks