Beyond the Standard Model 2

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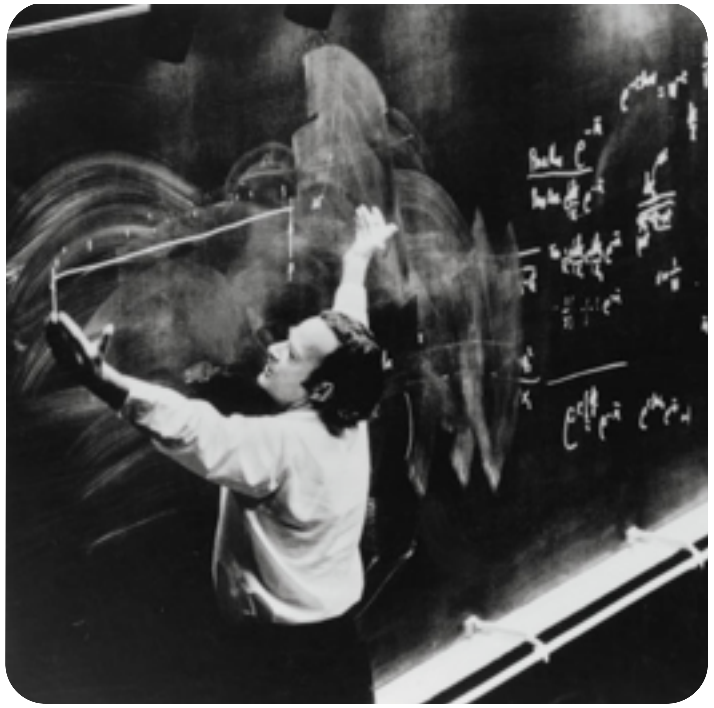
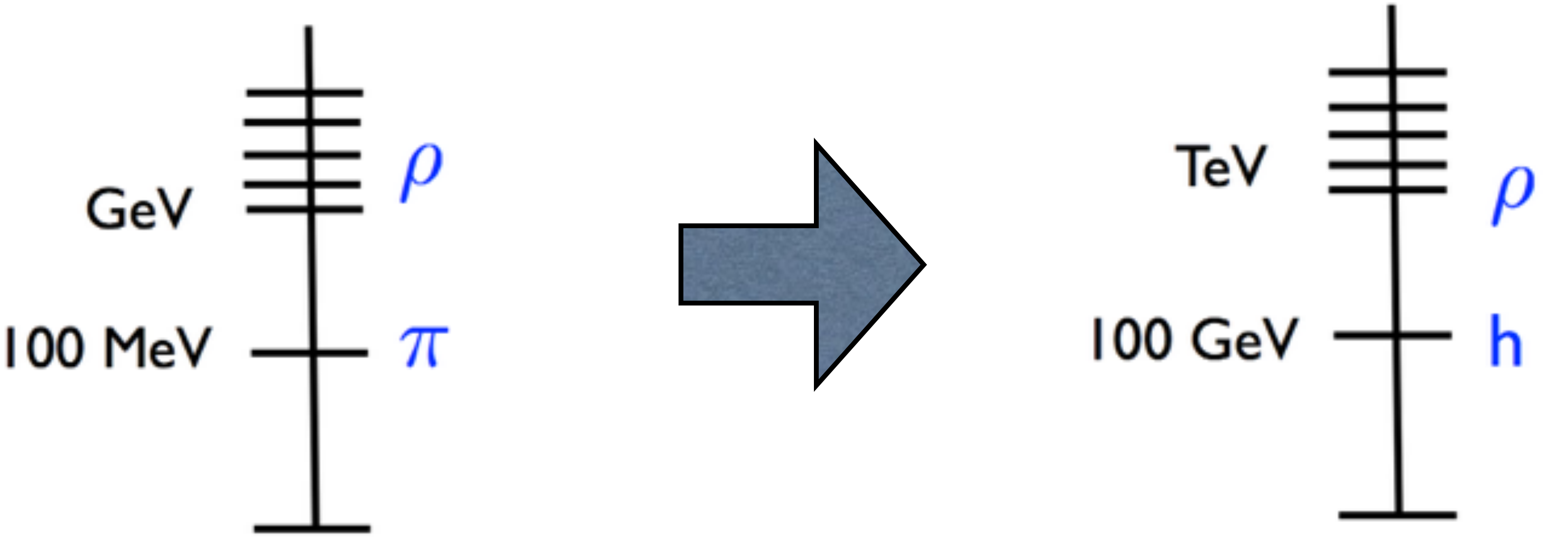
(DESY&CERN)



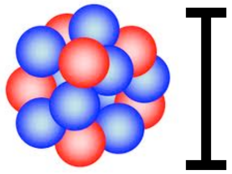
CERN school
2014/6/29



QCD

Higgs as a pGB

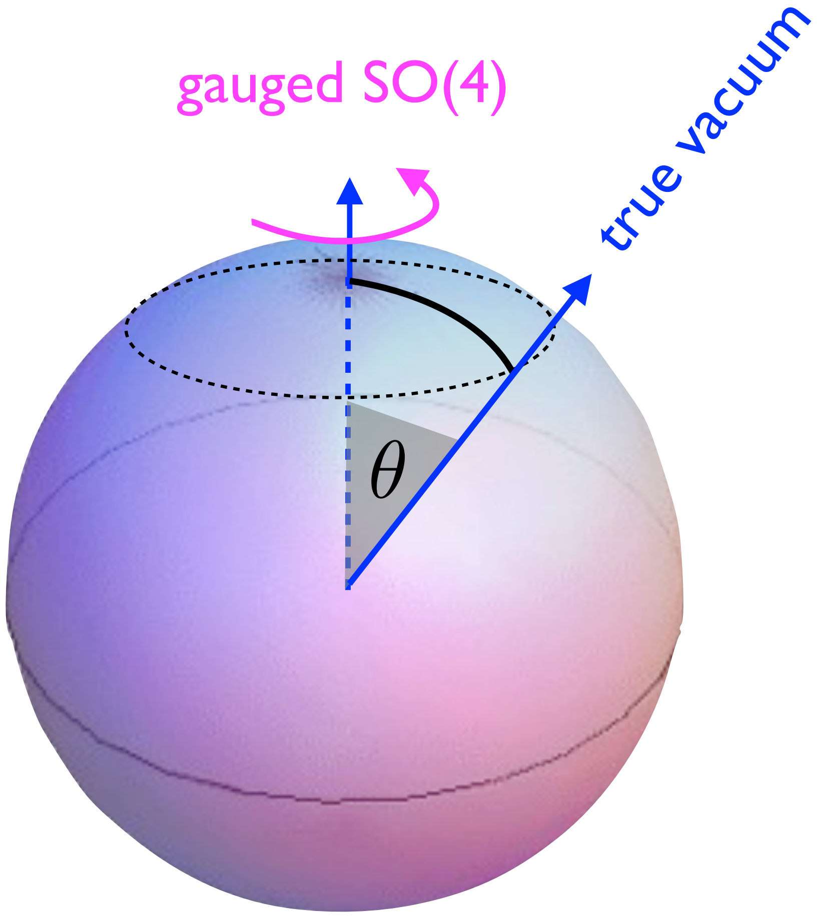
Composite Higgs



l_H

- Higgs is a hadron of a new strong force
- Solves the hierarchy problem (like QCD)
- Higgs is a pseudoGoldstone that's why it is lighter than the other resonances

$SO(5)/SO(4)$



Tree level: gauge SO(4) aligned

Higgs

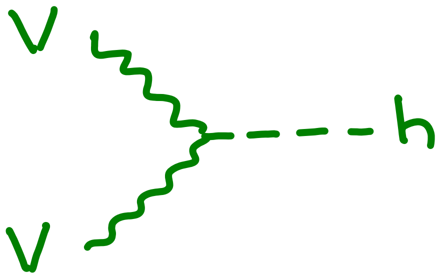
$$\phi = e^{i\pi^{\hat{a}}T^{\hat{a}}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat{\pi}^1\\\hat{\pi}^2\\\hat{\pi}^3\\\hat{\pi}^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta+h(x)/f)\;\; e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta+h(x)/f)\end{pmatrix}$$

1-loop $\langle\phi(x)\rangle = \theta\cdot f$

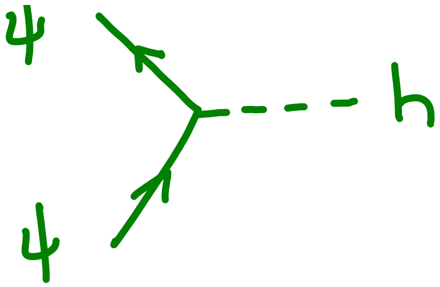
eaten by W_L, Z_L

Higgs couplings

Have been measured to 20-30% precision



$a\, g^{SM}_{hVV}$



$c\, h^{SM}_{\psi\psi h}$

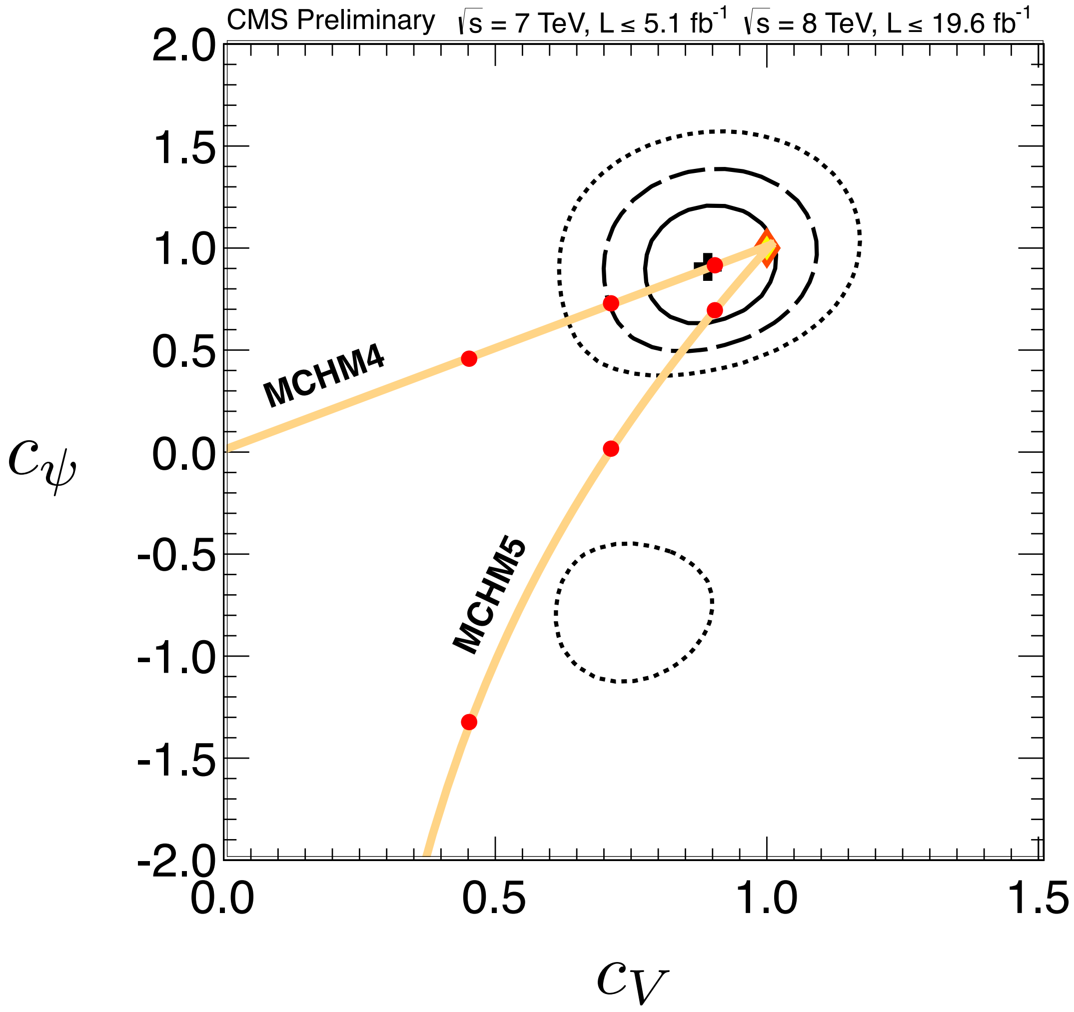
Expect deviations ~ $(v/f)^2$

$$a = \sqrt{1-\xi}$$

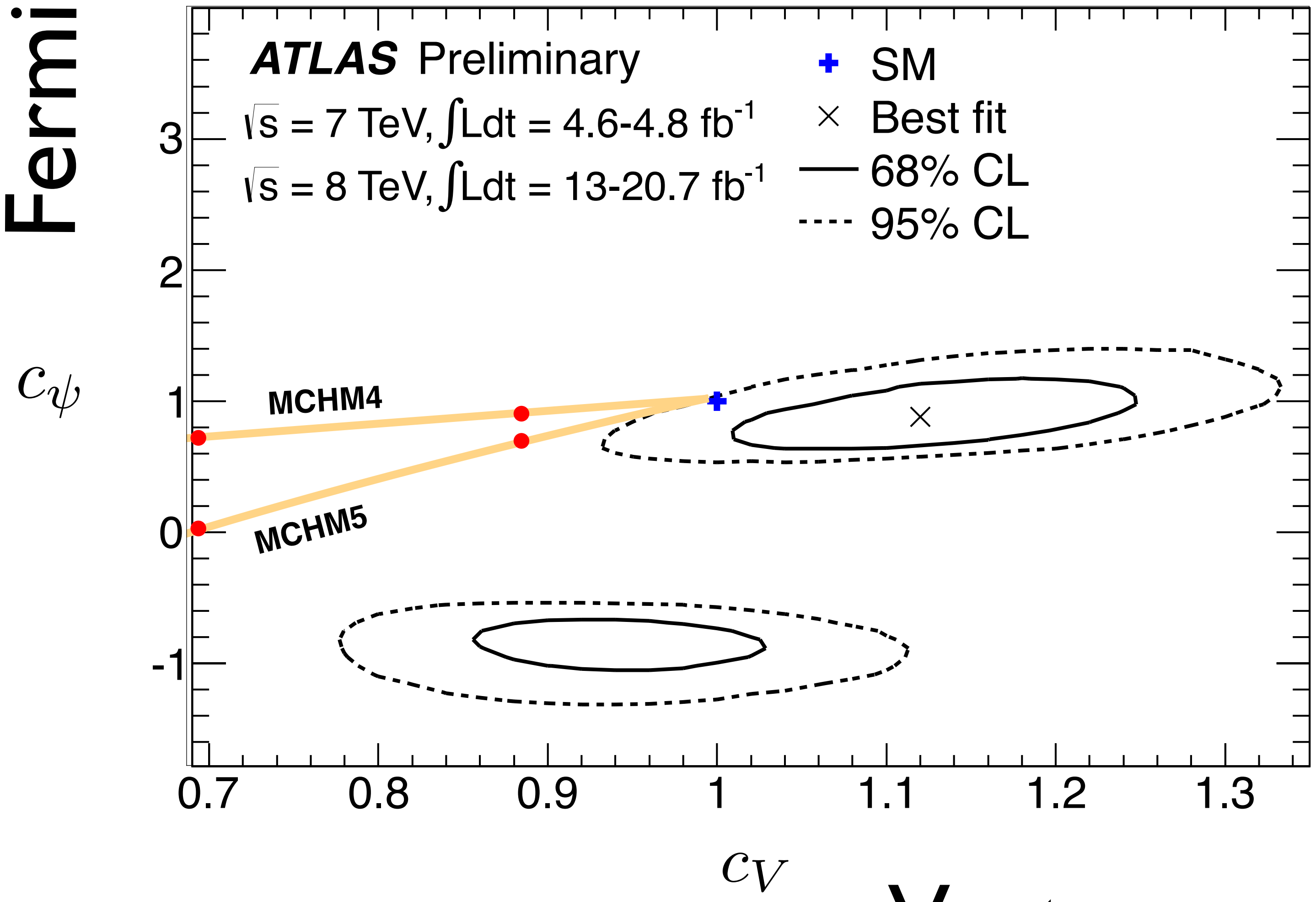
$$\xi \equiv \frac{v^2}{f^2}$$

$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$

Higgs couplings



Fermion



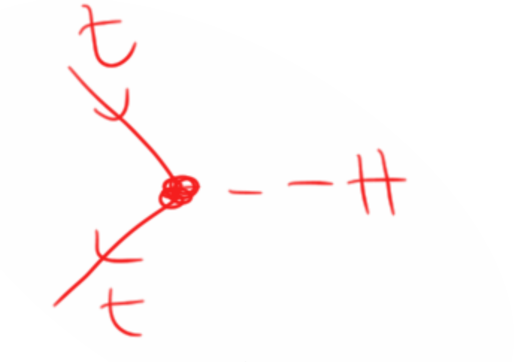
Vector

Red points at $\xi \equiv (v/f)^2 = 0.2,\ 0.5,\ 0.8$

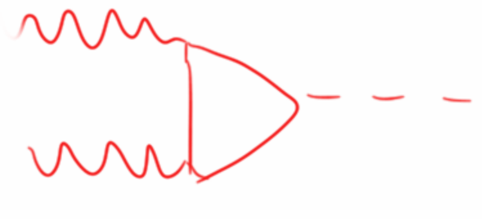
Higgs couplings

SM + $\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$

$$\frac{\sigma(gg \to h)}{\text{SM}} = (1 + (c_g - c_t)v^2)^2$$



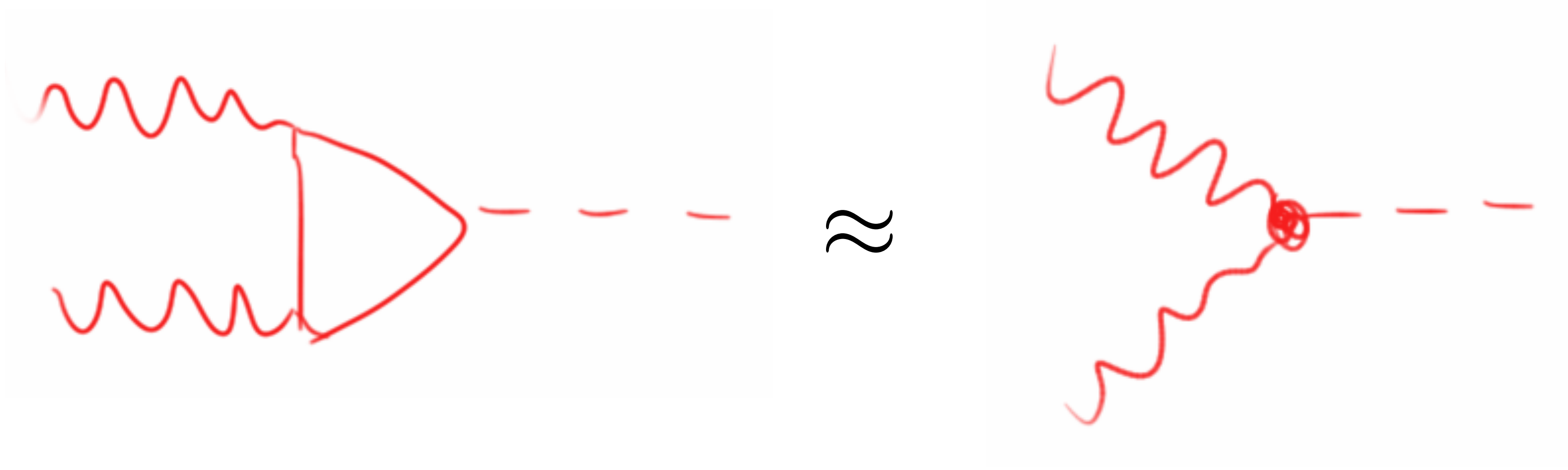
Degeneracy 'short-distance' vs 'long-distance'



E.g. fermionic top partners MCHM: $\Delta c_t = \Delta c_g$

$$\sigma(pp \to H + X)_{\text{inclusive}}$$

Does not resolve short-distance physics

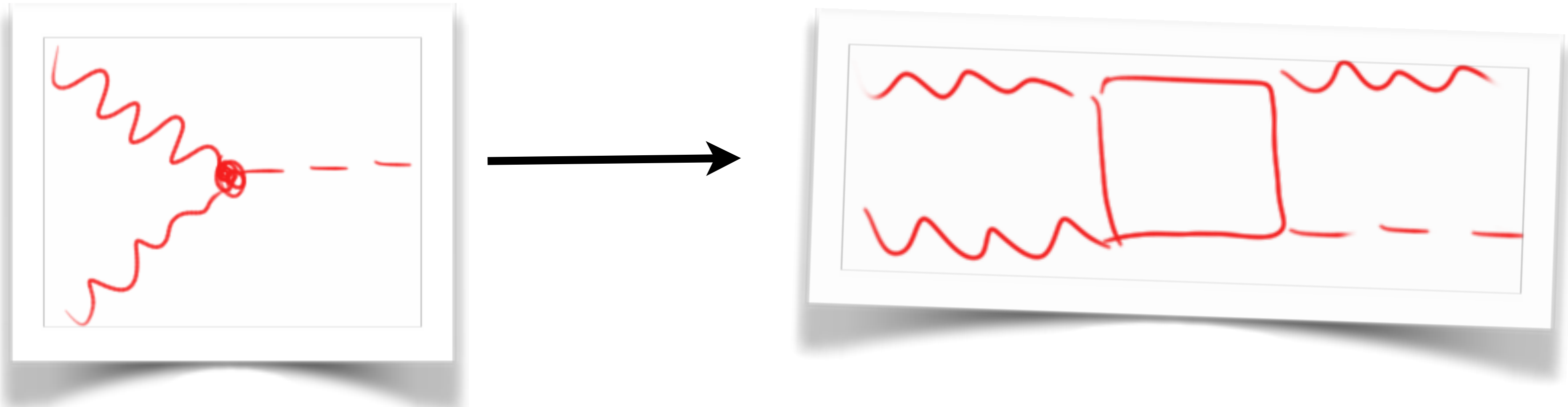


$m_H(\text{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t \to \infty)}$	$\frac{\sigma_{NLO}(m_t, m_b)}{\sigma_{NLO}(m_t \to \infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

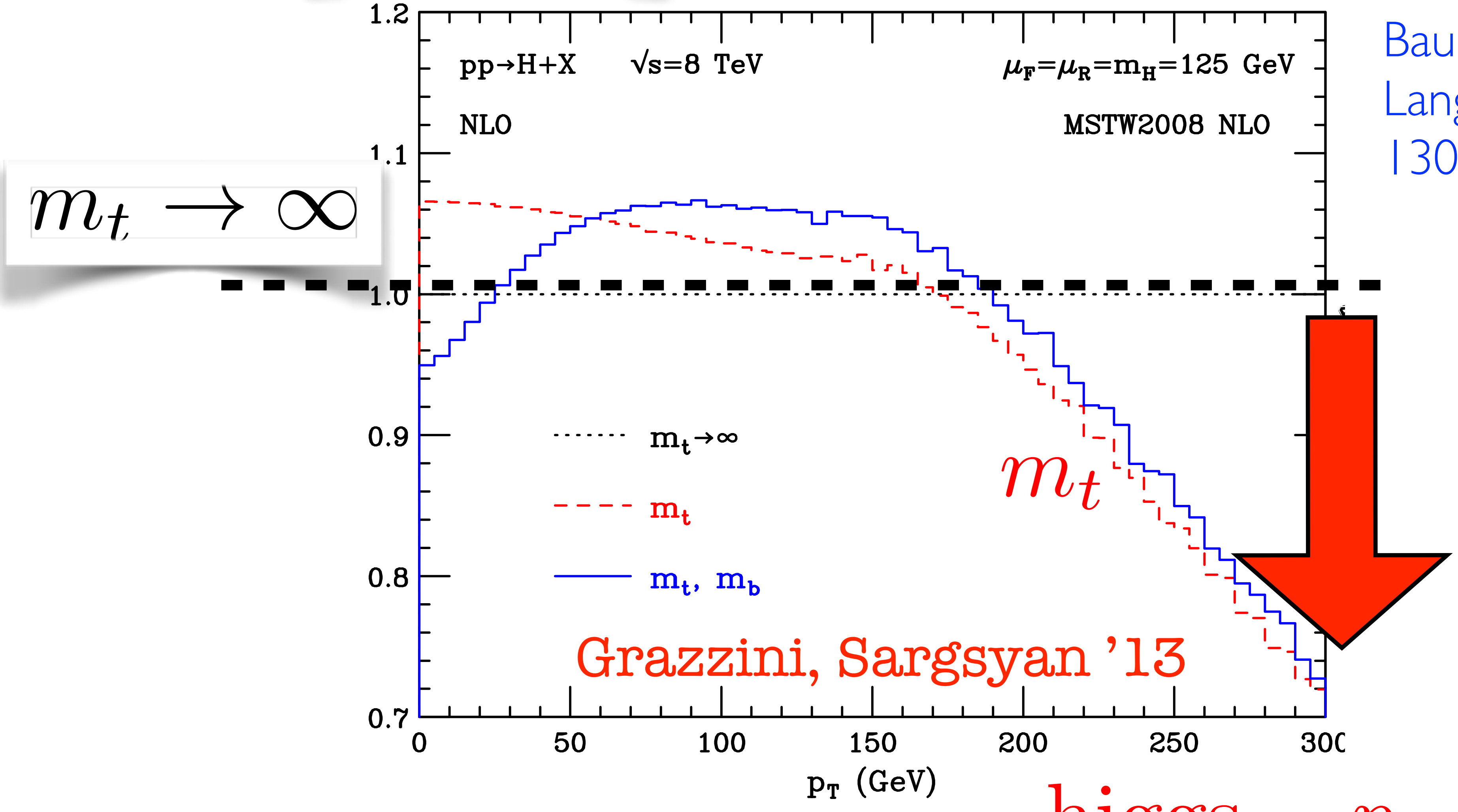
e.g. [1306.4581]

Beyond current observables

Cut the loop open, recoil against hard jet



$p_T \gg m_t$



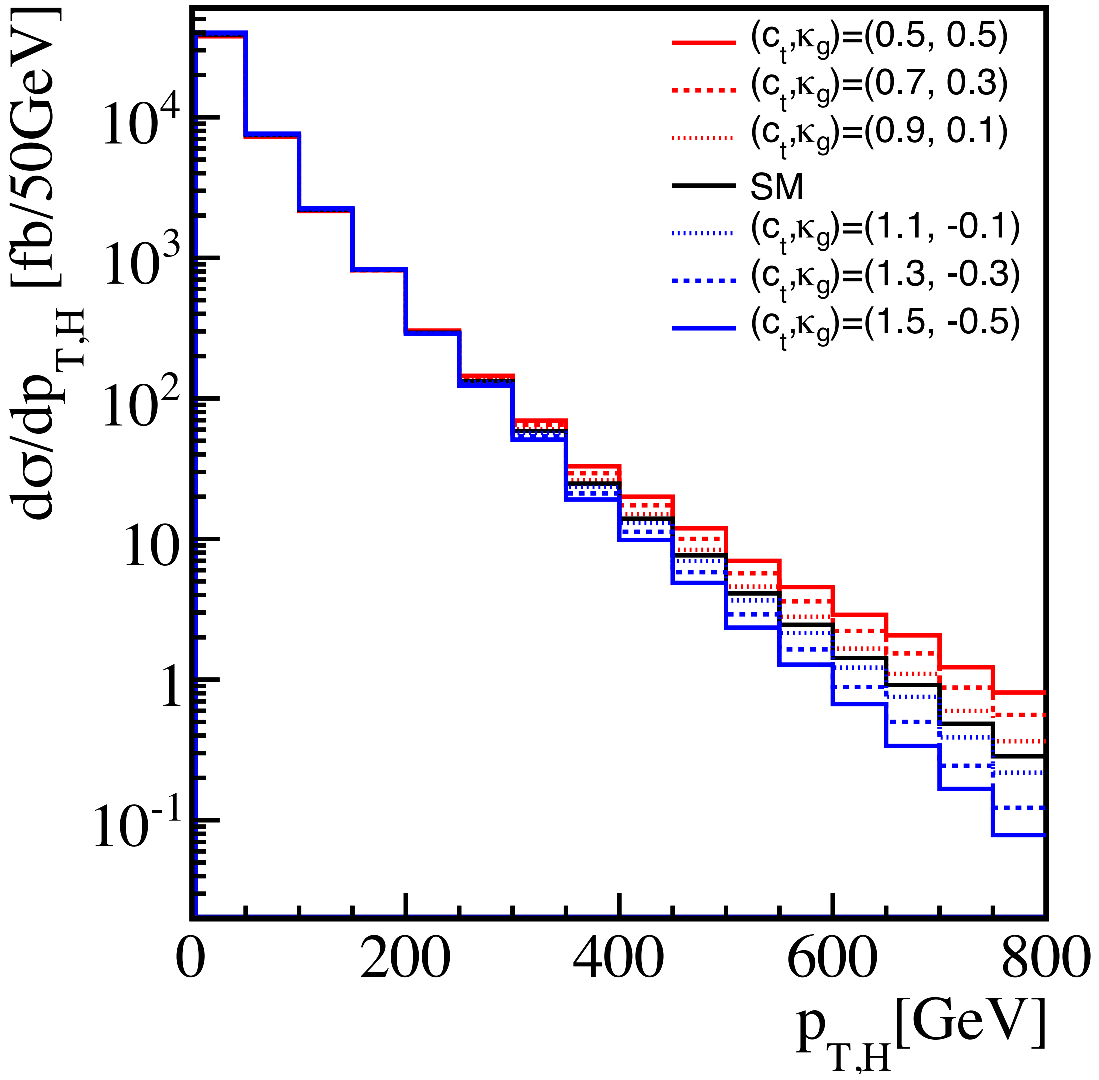
Baur, Glover '90,
Langenegger et. al '06,
1308.4771

high p_T tail resolves
loop dynamics

$\mathrm{higgs} - p_T$

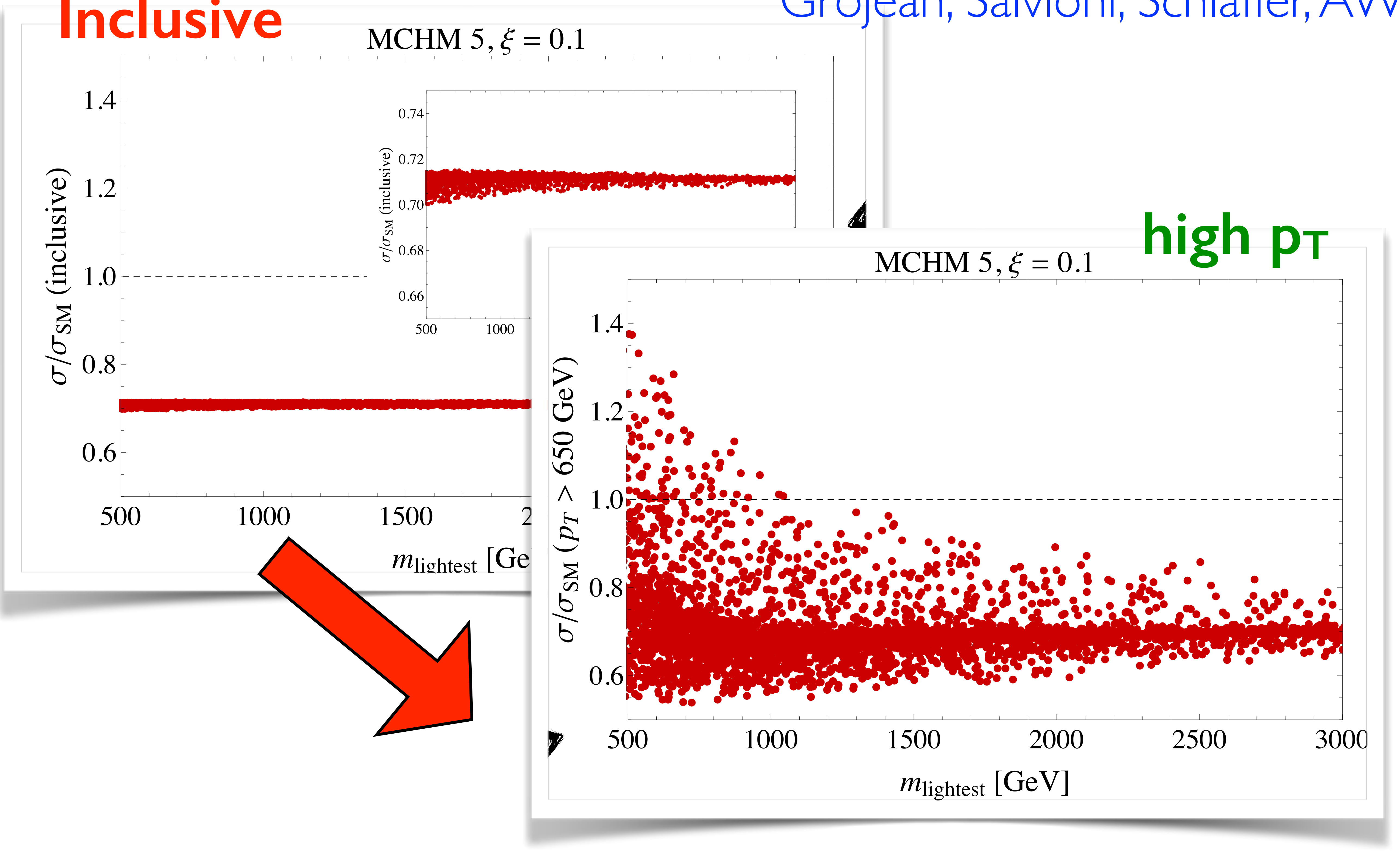
Measurement how-to

worst case: inclusive cross-section = SM



Top partner example

Grojean, Salvioni, Schlaffer, AW

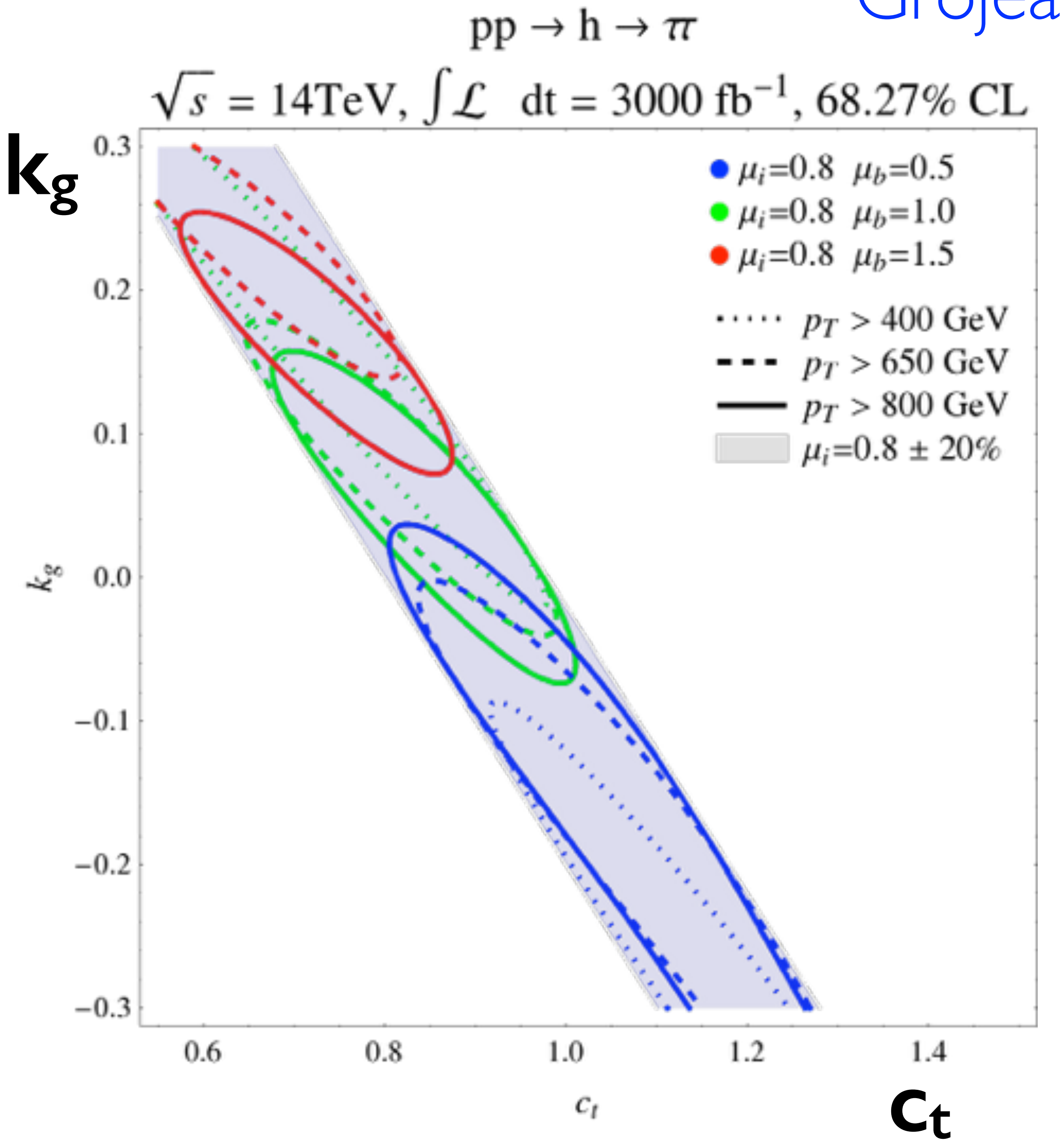


Inclusive

high p_T

Complementary to htt

Grojean, Salvioni, Schlaffer, AW, in progress

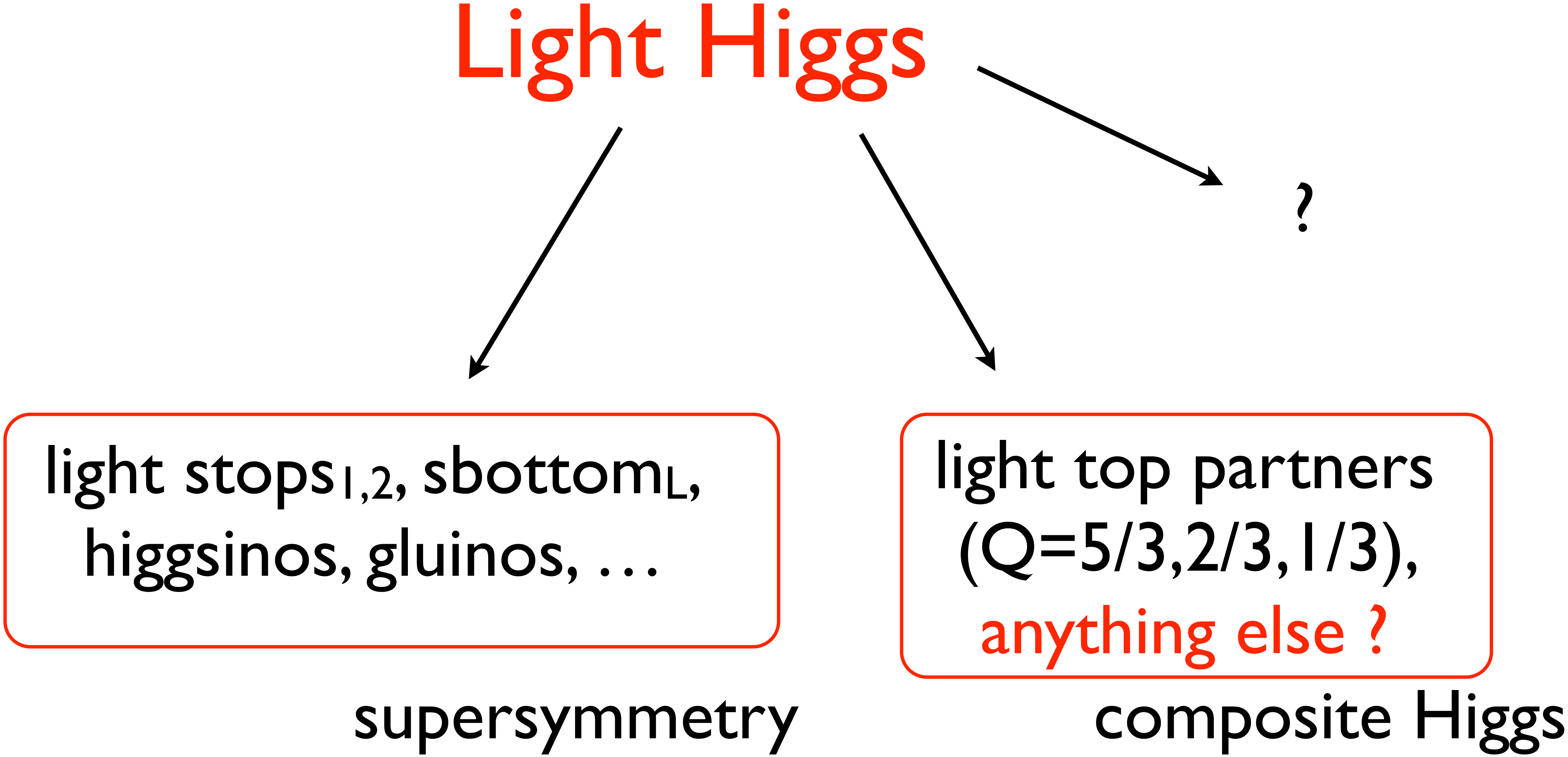


Competitive/complement to notoriously difficult $h\bar{t}t$ channel

Theory frontier:
NLO_{m_t} not yet calculated,
$1/m_t$ known to $\mathcal{O}(\alpha_S^4)$:
few % up to p_T ~150 GeV

Harlander et al '12

New physics & naturalness



Light Higgs

?

light stops$_{1,2}$, sbottom$_L$, higgsinos, gluinos, …

supersymmetry

light top partners (Q=5/3,2/3,1/3), anything else ?

composite Higgs

Flavor used to be a show-stopper

CPV in Kaon mixing

$$|\epsilon| = 2.3 \times 10^{-3} \implies \frac{M_{ETC}}{g_{ETC}\sqrt{\mathrm{Im}(V_{sd}^2)}} \gtrsim 16,000\,\mathrm{TeV}$$

$$m_{q,\ell,T}(M_{ETC}) \simeq \frac{g_{ETC}^2}{2M_{ETC}^2}\langle \bar{T}T\rangle_{ETC} \lesssim \frac{0.1\,\mathrm{MeV}}{|V_{sd}|^2 N^{3/2}}$$

vs. m_{top}

Partial compositeness

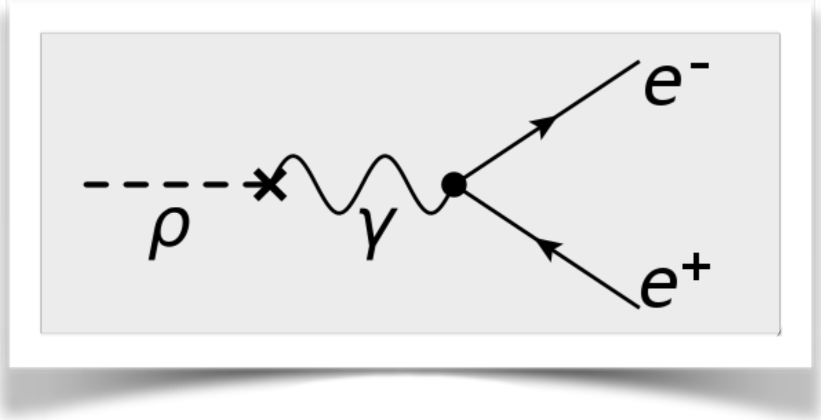
vector-like
composite fermion

Fermionic operators can excite composite fermions at low energy:

$$\langle 0|\mathcal{O}|\chi\rangle = \lambda\, f$$

Analogous to photon-rho mixing

Br(rho → e+e-) ~ 10^{-5}



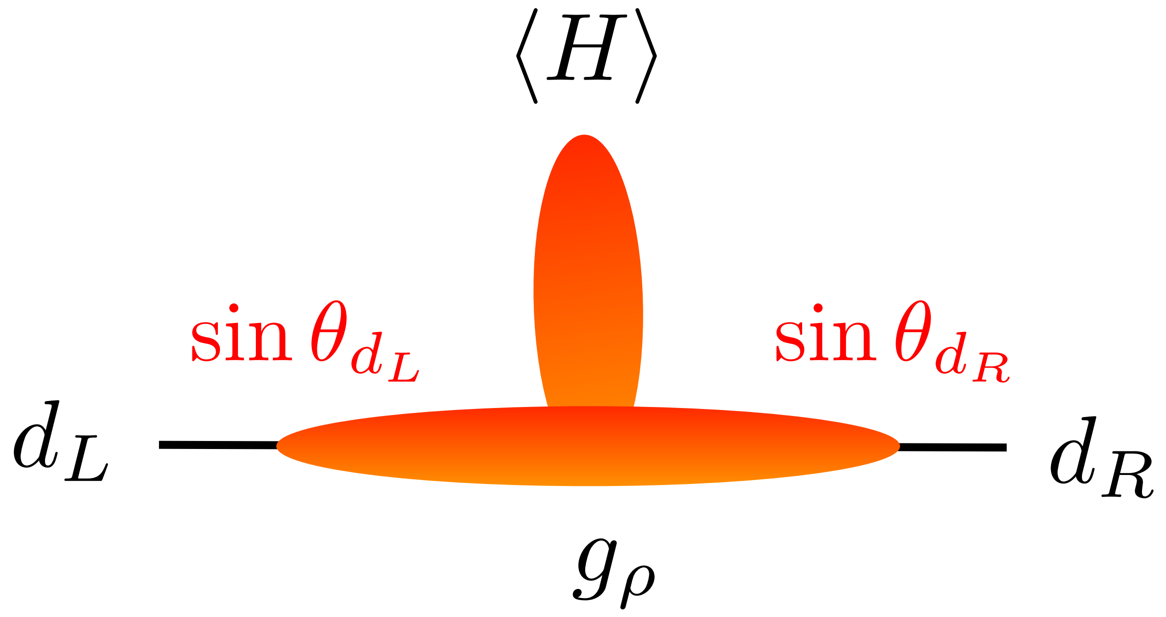
Linear couplings imply mass mixings:

$$\mathcal{L} = \bar{\psi}\, i\not{\partial}\, \psi + \bar{\chi}(\, i\not{\partial} - m_*)\chi + \lambda f\, \bar{\psi}\chi + h.c.$$

Rotate to mass eigenbasis:

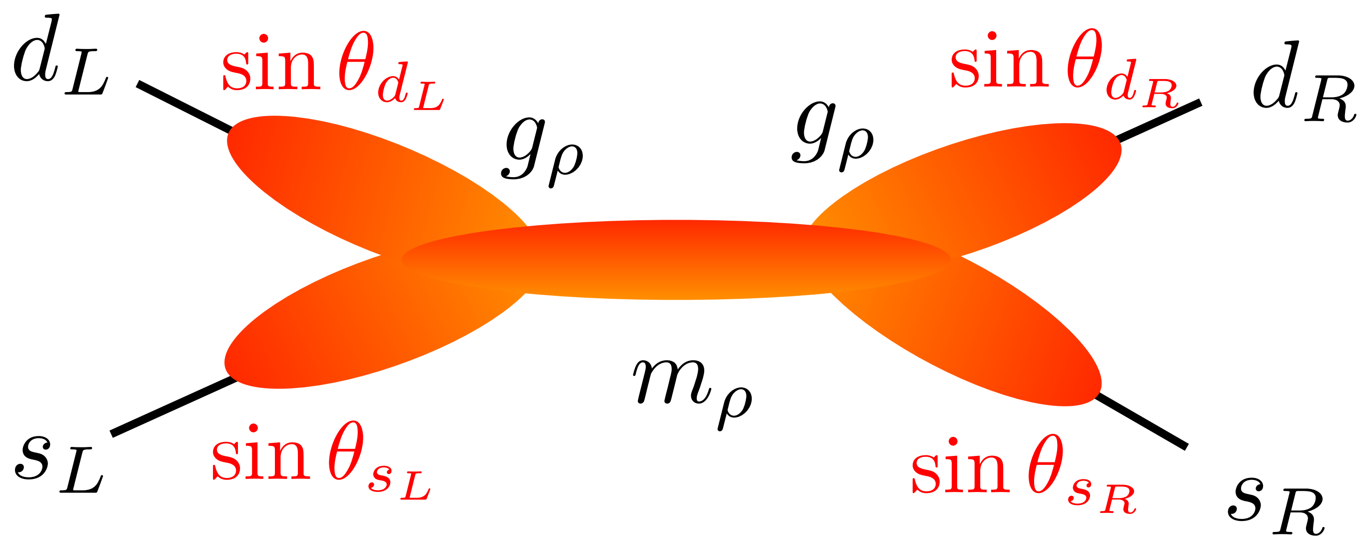
$$\begin{pmatrix} \psi \\ \chi \end{pmatrix} \to \begin{pmatrix} \cos\varphi & \sin\varphi \\ \sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} \psi \\ \chi \end{pmatrix} \qquad \tan\varphi = \frac{\lambda\, f}{m_*}$$

Csaki/Falkowski/AW, Davidson et al, Agashe et. al, …



Yukawa

$$g_\rho \sin\theta_{d_L} \langle H \rangle \sin\theta_{d_R} \sim m_d$$



FCNC

$$\sim s_{d_L} s_{d_L} s_{d_R} s_{s_R} \sim \frac{m_d\, m_s}{v^2}$$

GIM-like protection

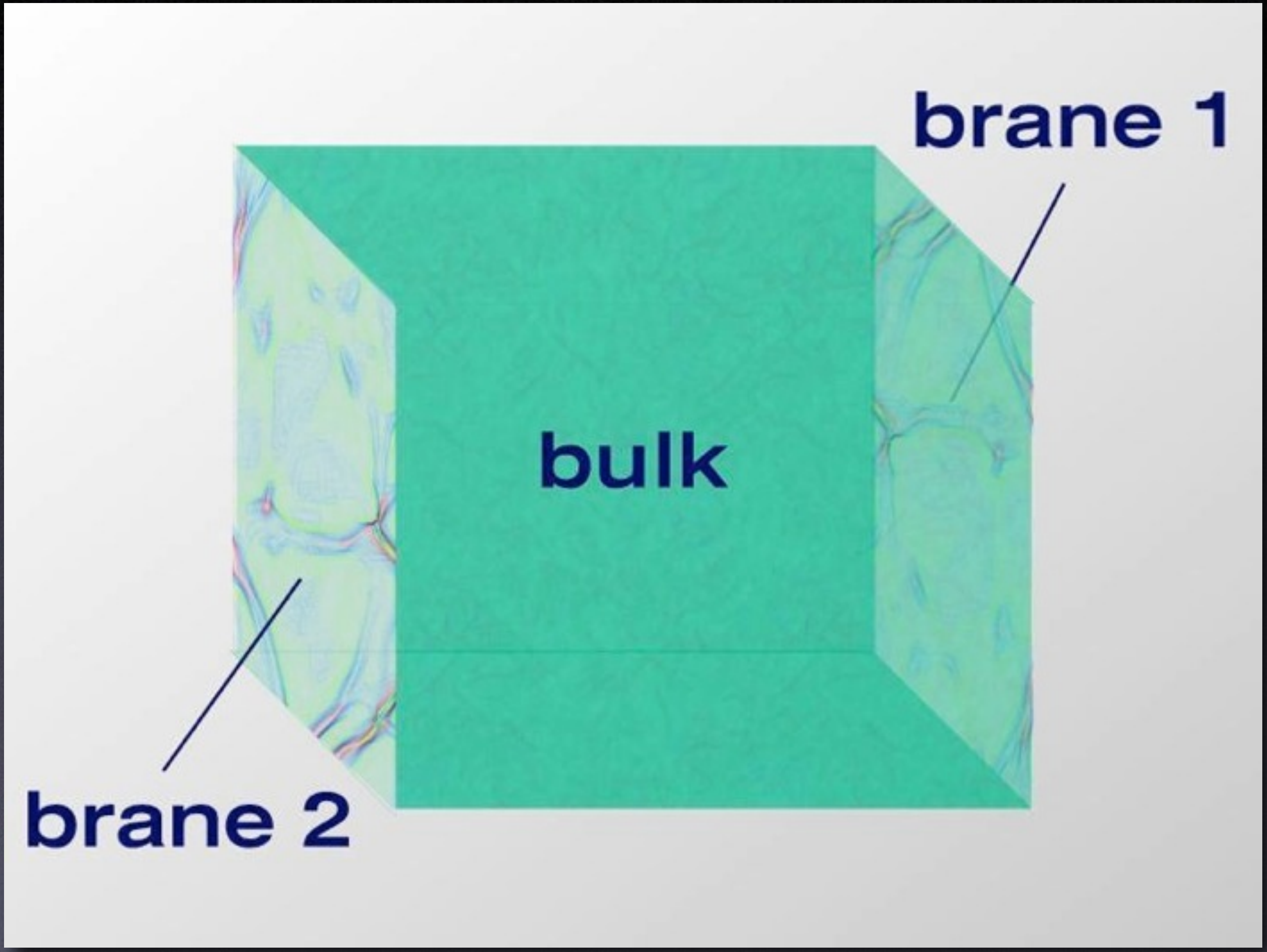
… almost works $\Lambda_{\epsilon_K} = 10^5\,\mathrm{TeV} \;\rightarrow\; m_\rho \gtrsim 10\,\mathrm{TeV}$

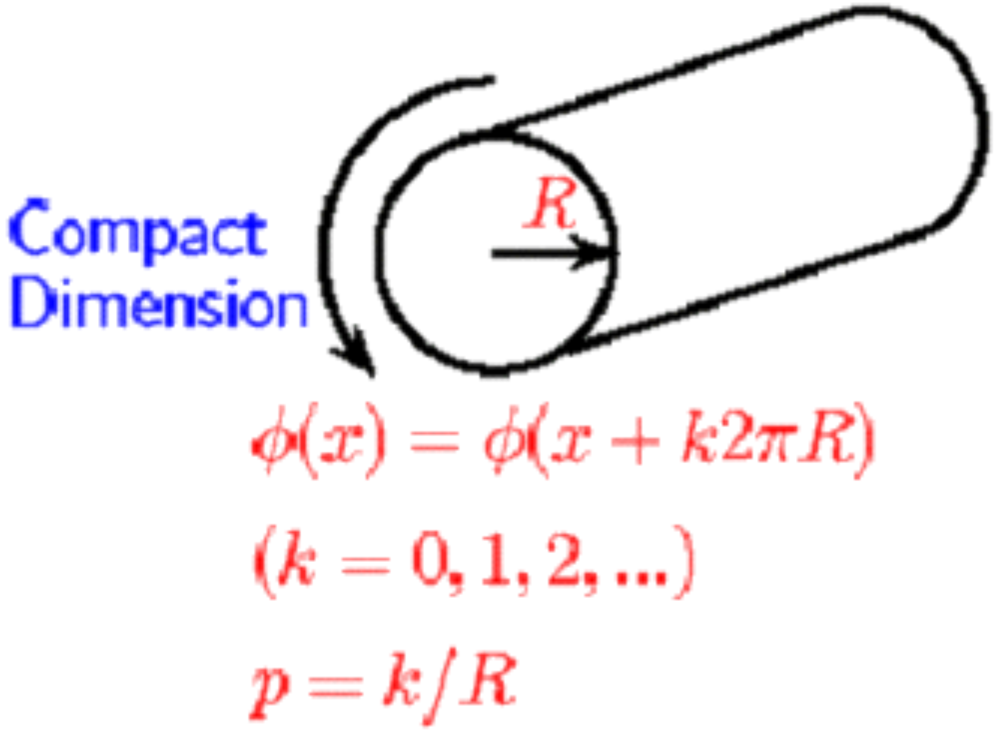
“Into the Extra-dimension and back”

Exciting journey…

Depends on the perspective…

Extra-dimensions





$$\phi(x) = \phi(x + k2\pi R)$$

$$(k = 0, 1, 2, \ldots)$$

$$p = k/R$$

Compact extra dimensions

Compact Extra-dimension => momentum in extra-dim' direction is quantized: p_{ED} = n/(size of ED)

$$p^2 = m^2 \quad \Rightarrow \quad p_{5D}^2 = p^2 - \boxed{(n/R)^2} = m^2$$

4D 5D

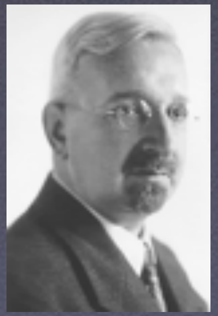
Two pictures (n/R on LHS or RHS):

1) 5D field with quantized momentum and mass m^2

2) infinite tower of 4D fields labeled by 5 momentum n/R with masses

$$M_n^2 = m^2 + \boxed{(n/R)^2}$$

new particles: Kaluza Klein (KK) modes



Kaluza Klein states

Free scalar field, massless

$$S = \int d^5x \; \frac{1}{2} \partial_M \Phi \partial^M \Phi$$

Expand in fourier modes

$$\Phi(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_n \Phi^{(n)}(x) e^{i \frac{n}{R} y}$$

with $(\Phi^{(n)})^\dagger = \Phi^{(-n)}$ to ‘keep it real’

$$\partial_M \phi \, \partial^M \phi = \partial_\mu \phi \, \partial^\mu \phi - (\partial_y \phi)^2$$

orthogonal

$m = -n$

$$S = \int d^4x \sum_{m,n} \int dy \, \frac{1}{2\pi R} \, e^{i\frac{(m+n)}{R} y} \, .$$

$$\cdot \, \frac{1}{2} \left[\partial_\mu \phi^{(m)}(x) \, \partial^\mu \phi^{n}(x) + \frac{m \cdot n}{R^2} \phi^m \cdot \phi^n \right]$$

$$= \frac{1}{2} \sum_n \int d^4x \left[\partial_\mu \phi^{(-n)} \, \partial^\mu \phi^{(n)} - \frac{n^2}{R^2} \phi^{(-n)} \phi^n \right]$$

Infinite tower of massive 4D fields

$$m^{(n)} = \frac{n}{R}$$

The SM flavor puzzle

$$Y_D \approx \mathrm{diag}\left(2 \cdot 10^{-5} \quad 0.0005 \quad 0.02\right)$$

$$Y_U \approx \begin{pmatrix} 6 \cdot 10^{-6} & -0.001 & 0.008 + 0.004i \\ 1 \cdot 10^{-6} & 0.004 & -0.04 + 0.001 \\ 8 \cdot 10^{-9} + 2 \cdot 10^{-8} i & 0.0002 & 0.98 \end{pmatrix}$$

Why this structure?

Other dimensionless parameters of the SM:

$g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{\mathrm{Higgs}} \sim 1$, $|\theta| < 10^{-9}$

Log(SM flavor puzzle)

$$-\log|Y_D| \approx \mathrm{diag}\begin{pmatrix}11 & 8 & 4\end{pmatrix}$$

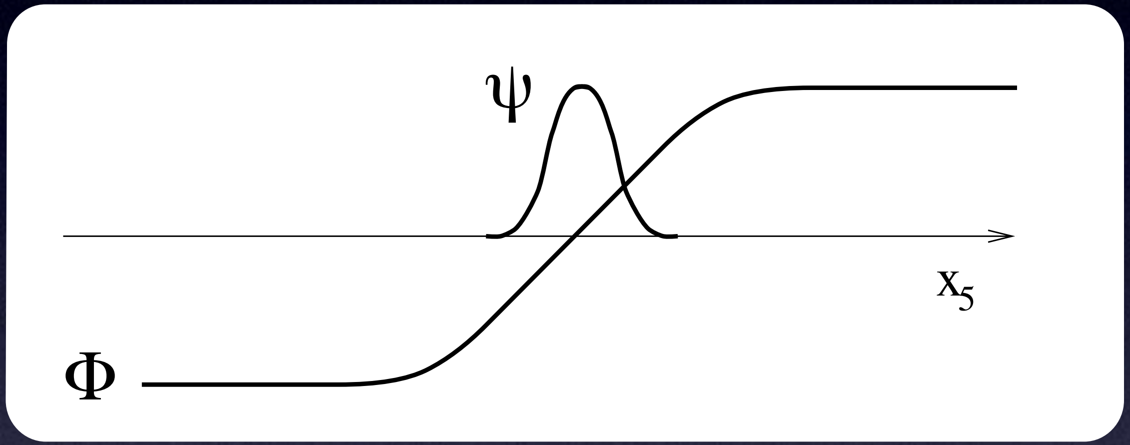
$$-\log|Y_U| \approx \begin{pmatrix}12 & 7 & 5\\ 14 & 6 & 3\\ 18 & 9 & 0\end{pmatrix}$$

If $Y = e^{-\Delta}$, then the Δ don't look crazy.

Hierarchies w/o Symmetries

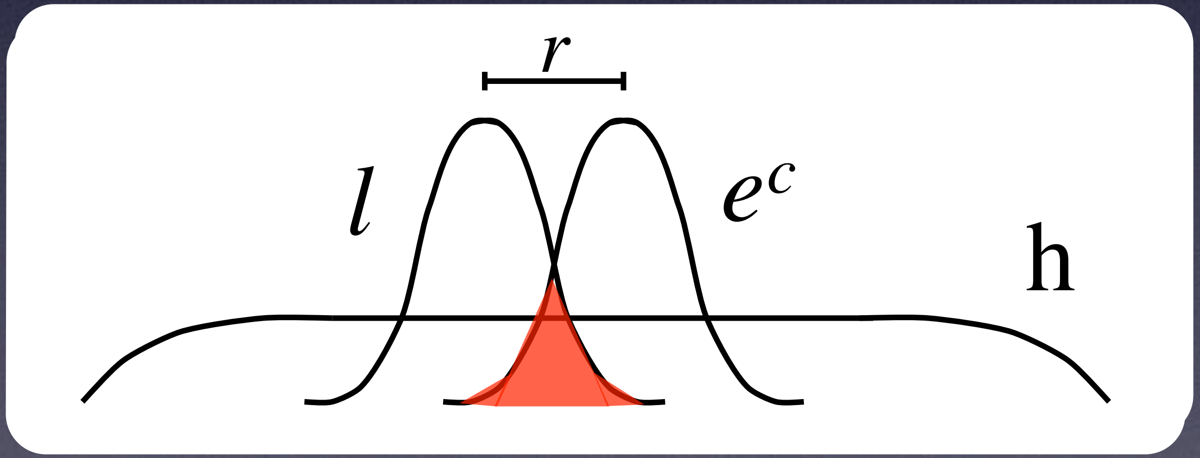
Arkani-Hamed, Schmaltz

SM on thick brane & domain wall ⇒ chiral localization



$$\mathcal{S} = \int \mathrm{d}^5x \sum_{i,j} \bar{\Psi}_i [i \not{\partial}_5 + \lambda\Phi(x_5) - m]_{ij} \Psi_j$$

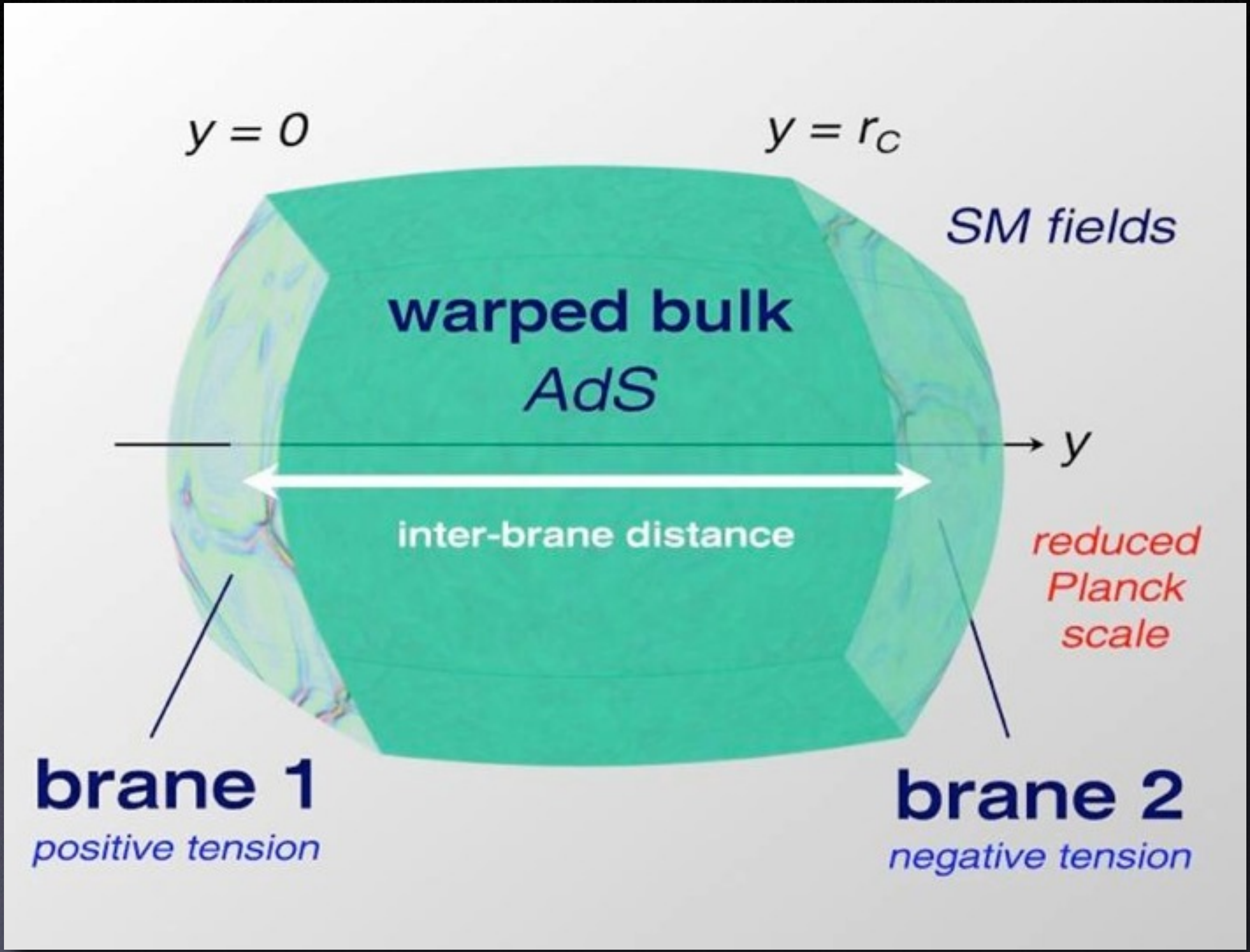
$$\Psi = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} = \underline{\begin{pmatrix} \psi^0_L \\ 0 \end{pmatrix}} + \text{KK modes}$$



Log(flavor hierarchy)!

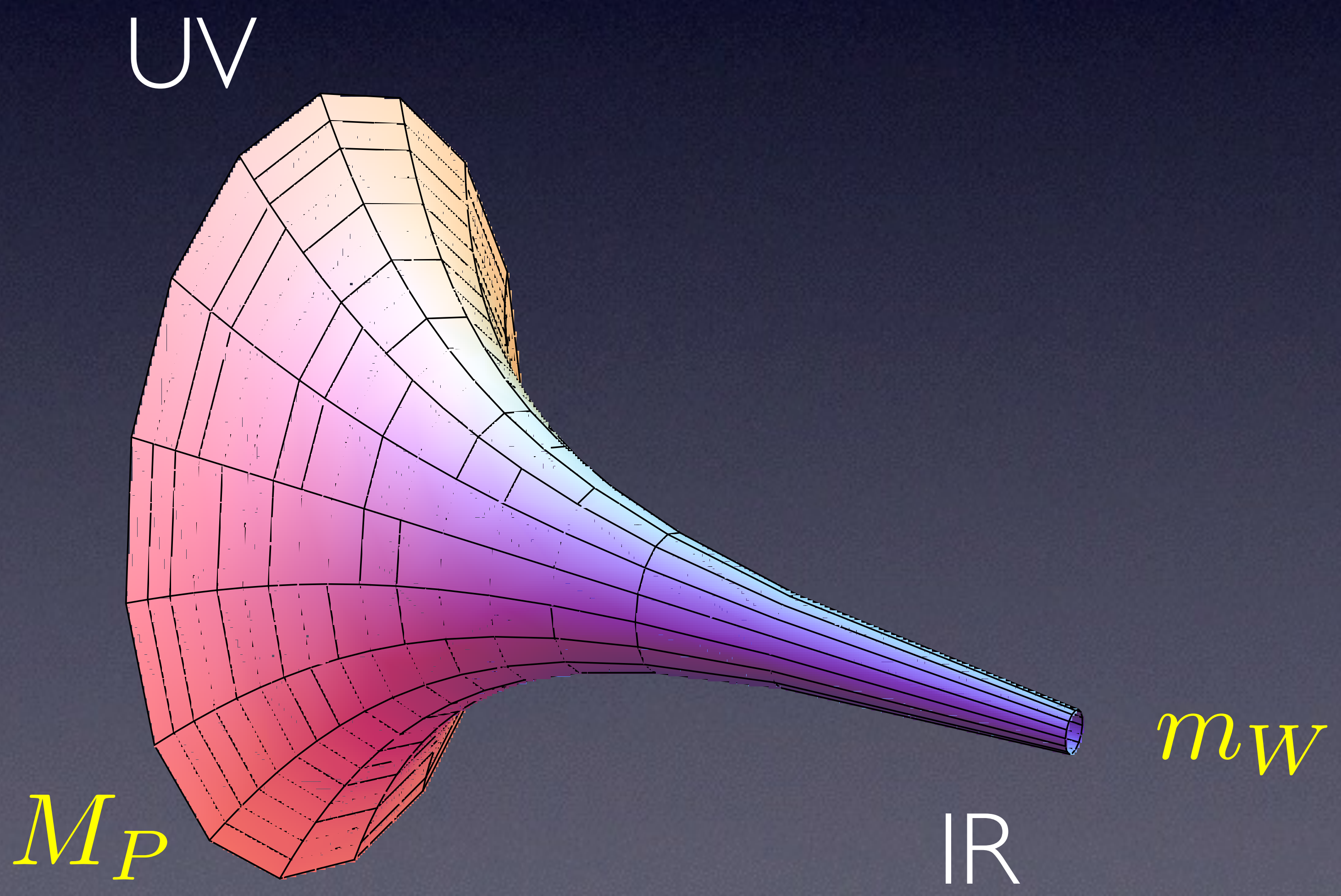
$$\int \mathrm{d}x_5 \; \phi_l(x_5) \; \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int \mathrm{d}x_5 \; e^{-\mu^2 x_5^2} e^{-\mu^2(x_5-r)^2} \underline{= e^{-\mu^2 r^2/2}}$$

Warped Extra Dimensions



How to do calculations in a strongly coupled theory?

Excursion into AdS/CFT



AdS/CFT

Maldacena

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(dx_\mu dx_\nu - dz^2\right)$$

Anti-de-Sitter (AdS) ⟷ Conformal (CFT)

Compactification ⟷ Mass gap

Red-shifting of scales ⟷ Dimensional transmutation

$$m_W = \sqrt{\frac{g(IR)}{g(UV)}} M_P \ll M_P$$

$$m_W \sim e^{-4\pi/\alpha} M_P$$

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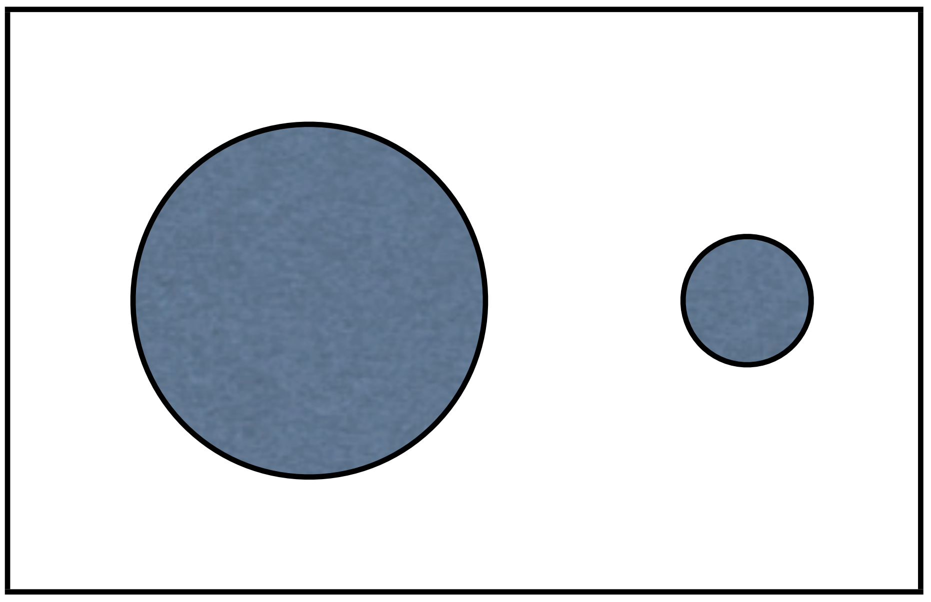
CFT & Extra-dimensions

Question

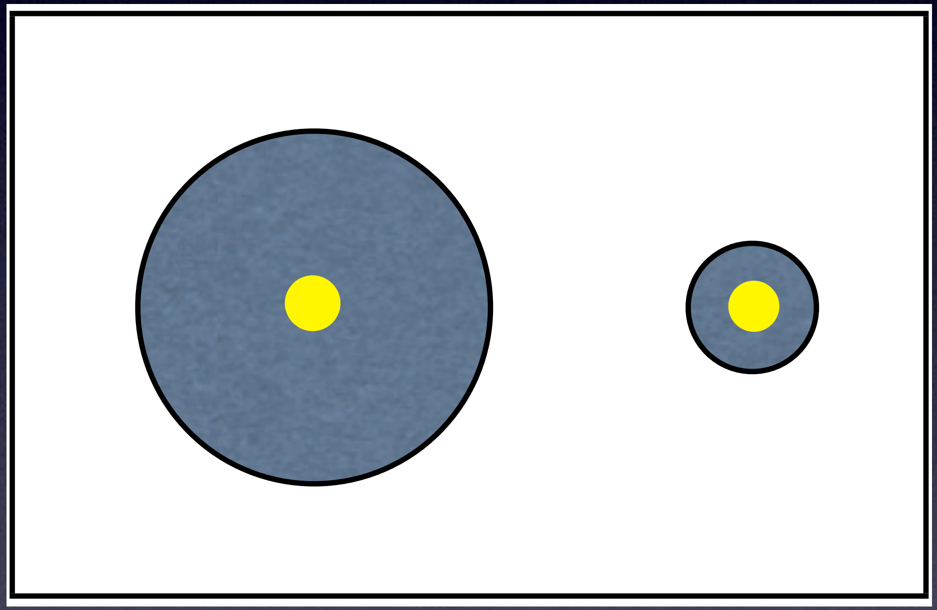
Is this a picture of a big ball and a small ball side-by-side in 2D or two identical balls at different distances in 3D?



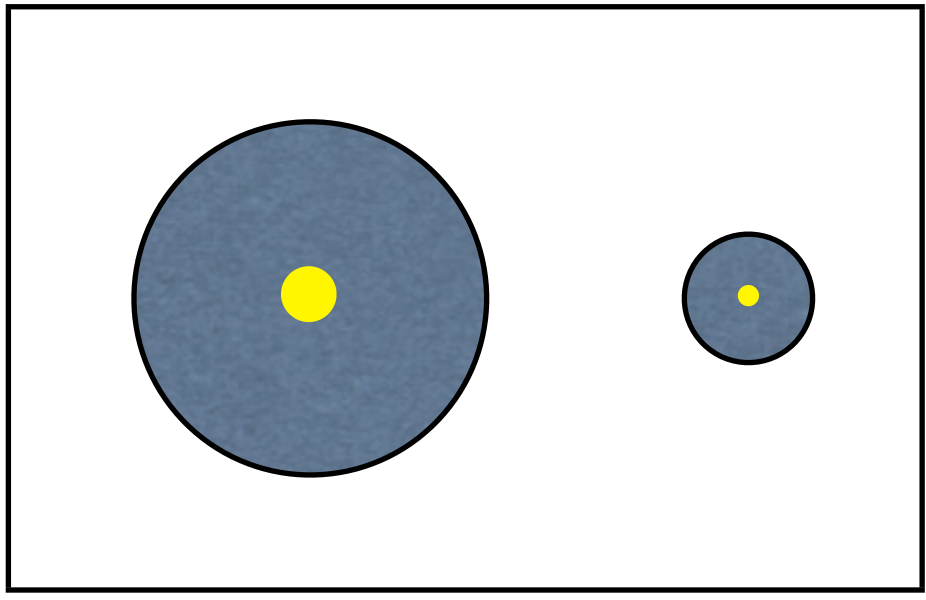
analogy by T. Okui

In the real world, we can tell the difference because atomic size is fixed.

(● Atom)

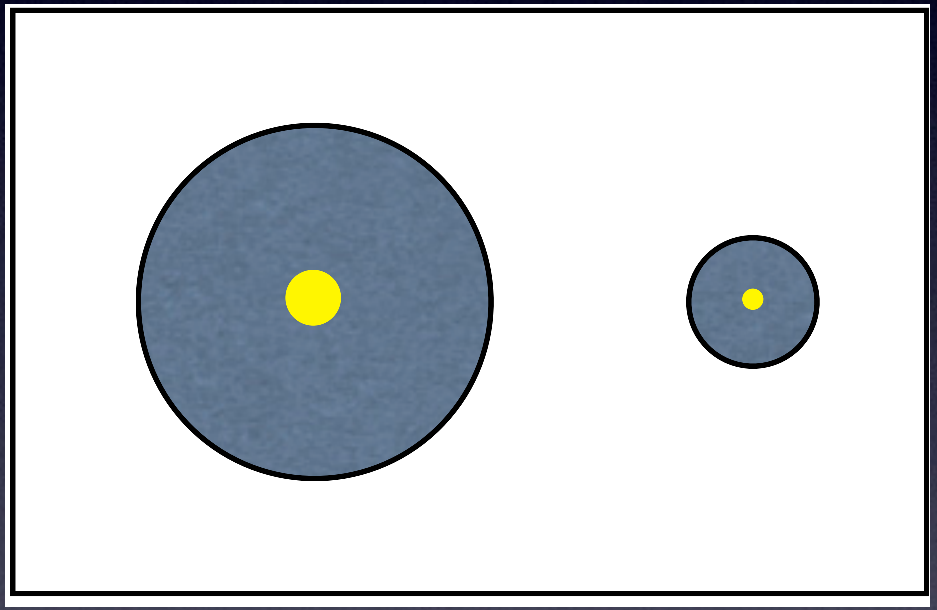


2D: Big & small balls

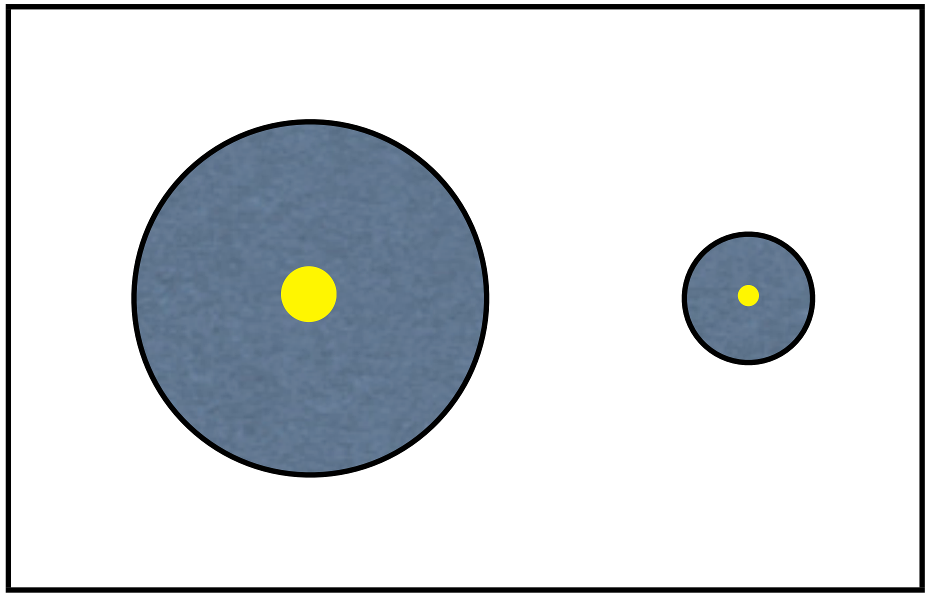


3D: Near & Far

But in a scale invariant world, atomic size ● would also scale.



2D + scale invariance



3D

scale invariance = extra-dimension !

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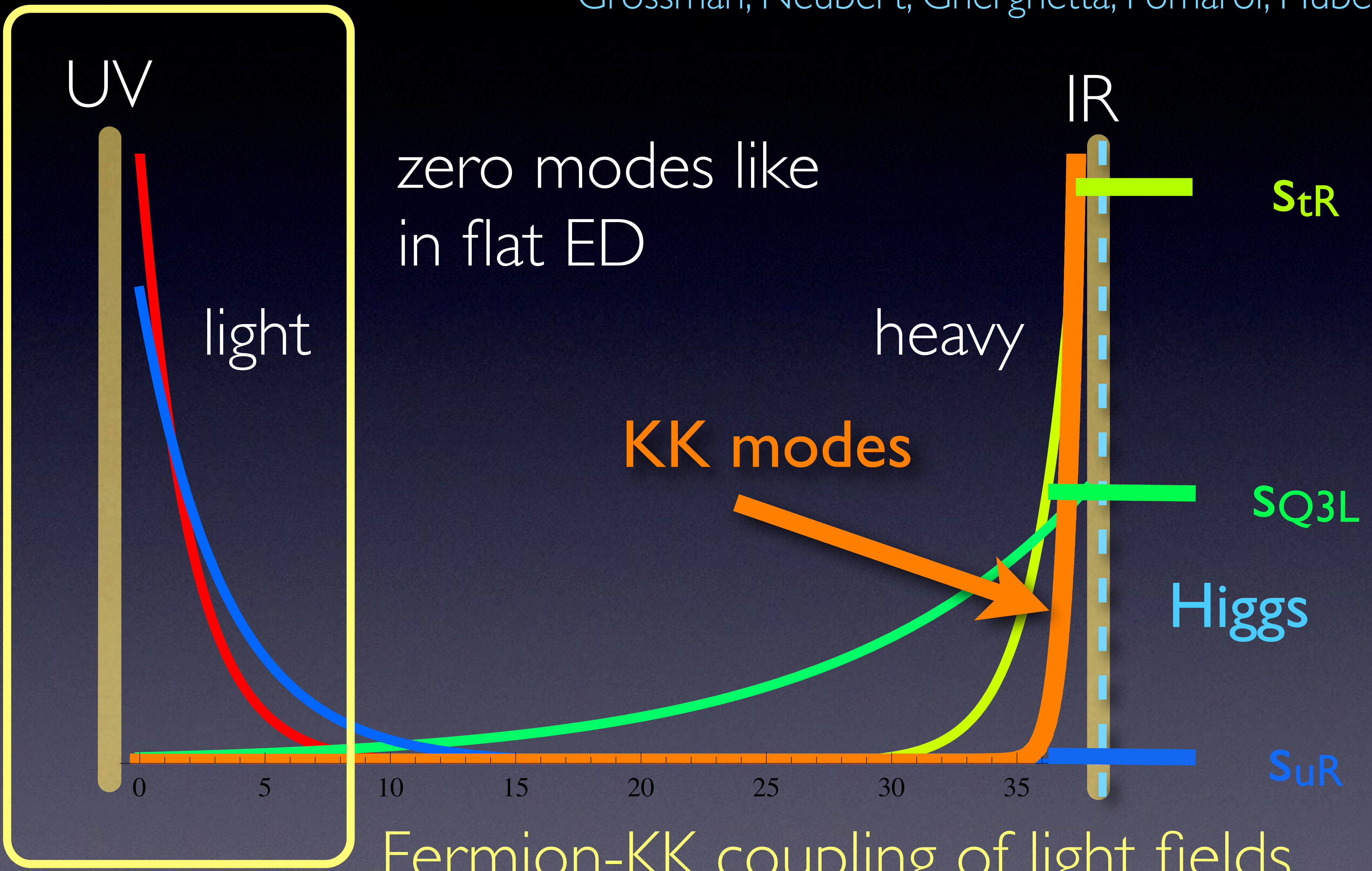
Fermion location in AdS

Grossman, Neubert; Gherghetta, Pomarol; Huber;

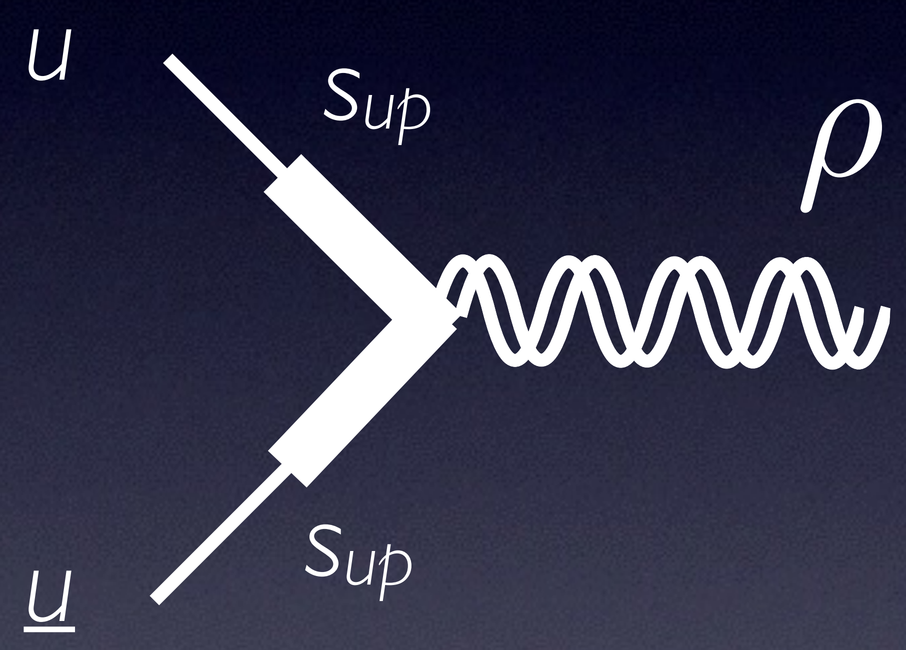


zero modes like in flat ED

Fermion-KK coupling of light fields almost universal!

high p$_T$

Resonance production (option 1)



$$\sim g_*^2 \sin^2 \theta_{u_R}$$

strongly suppressed for light quarks!

high p_T

Resonance production (option 2)

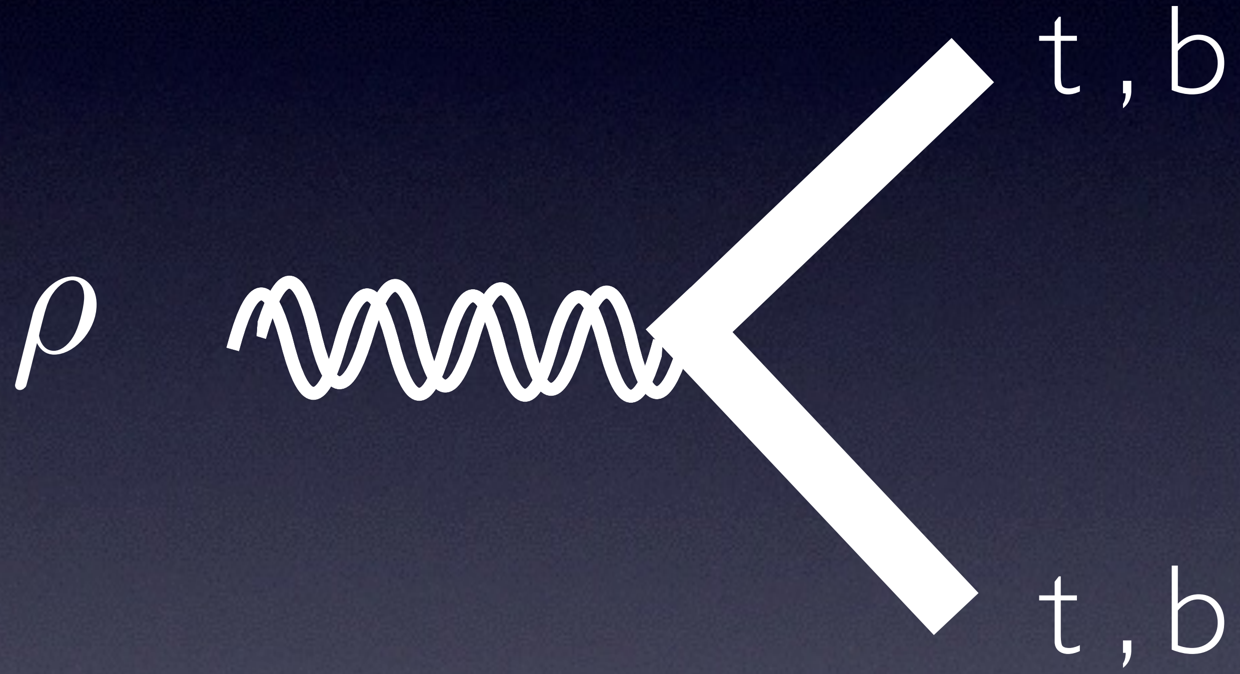
$$\sim \frac{g_s}{g*}$$

similar to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

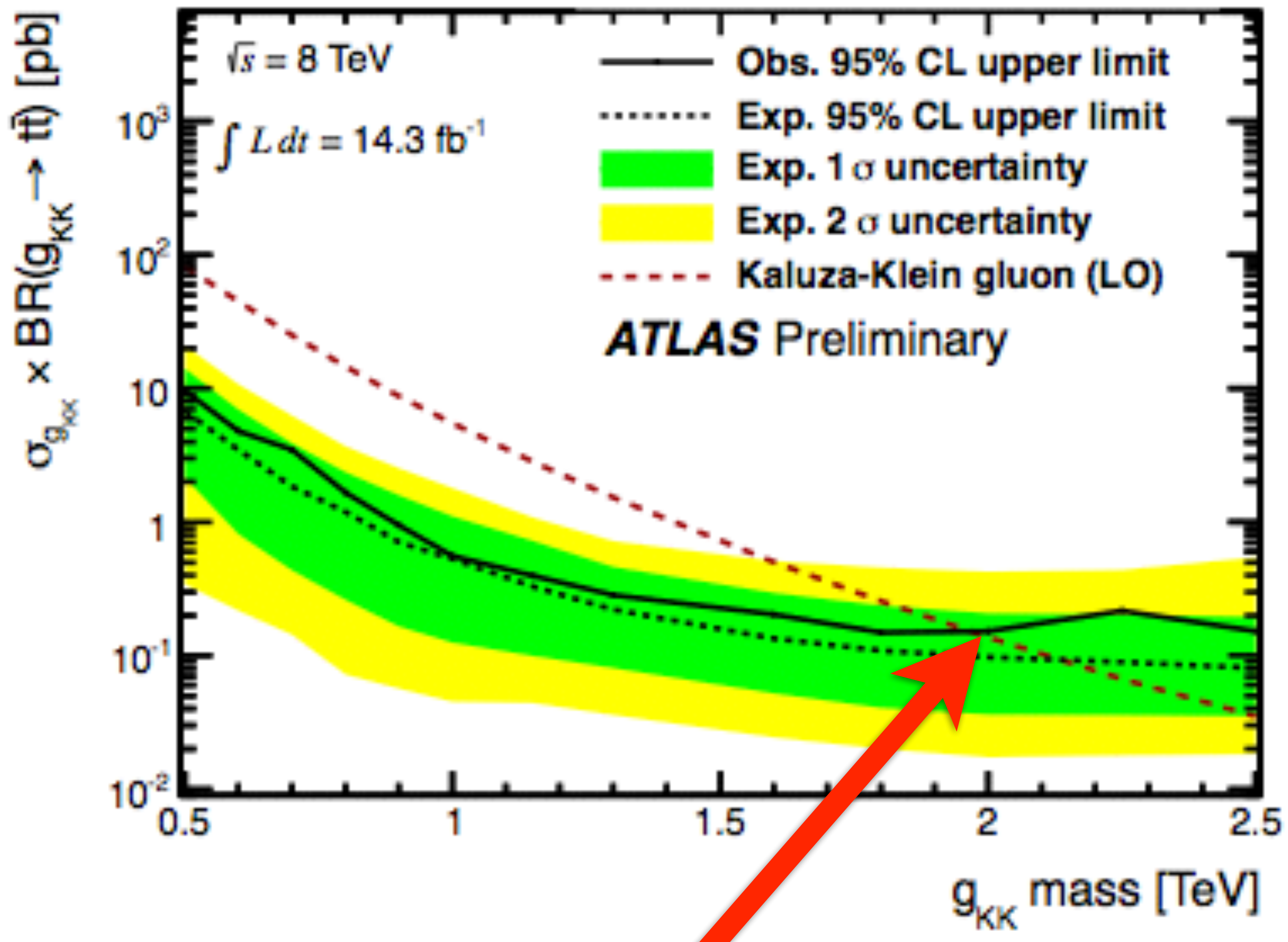
high p_T

Resonance decay



decays dominantly
into 3rd generation!
(tt, bt, bb)

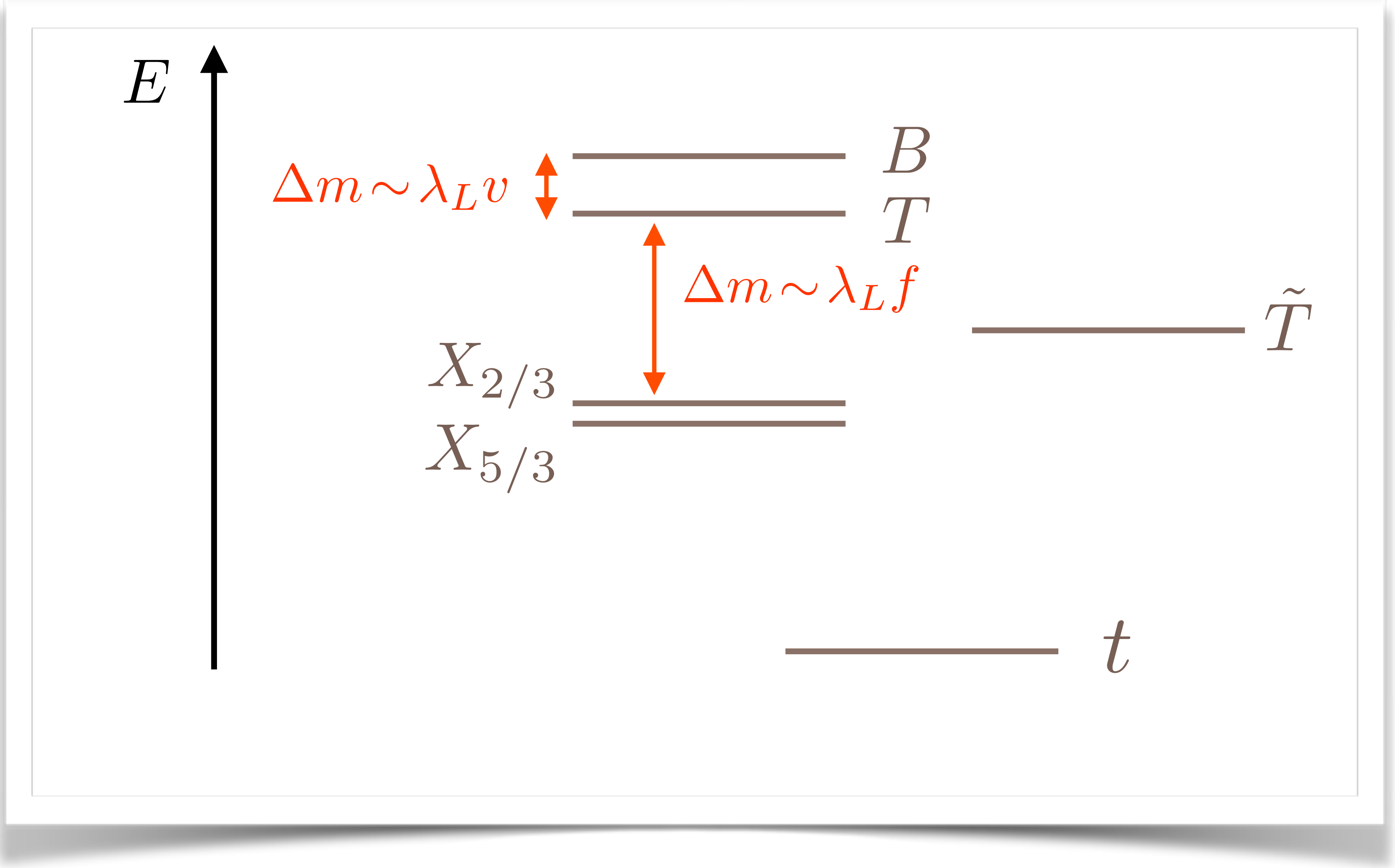
Agashe et al, Lillie et al



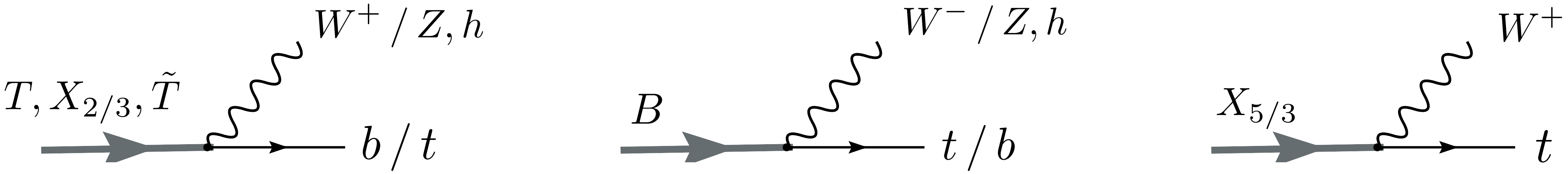
(b) g_{KK} upper cross section limits.

$M_{KK} > 2$ TeV @ 95CL

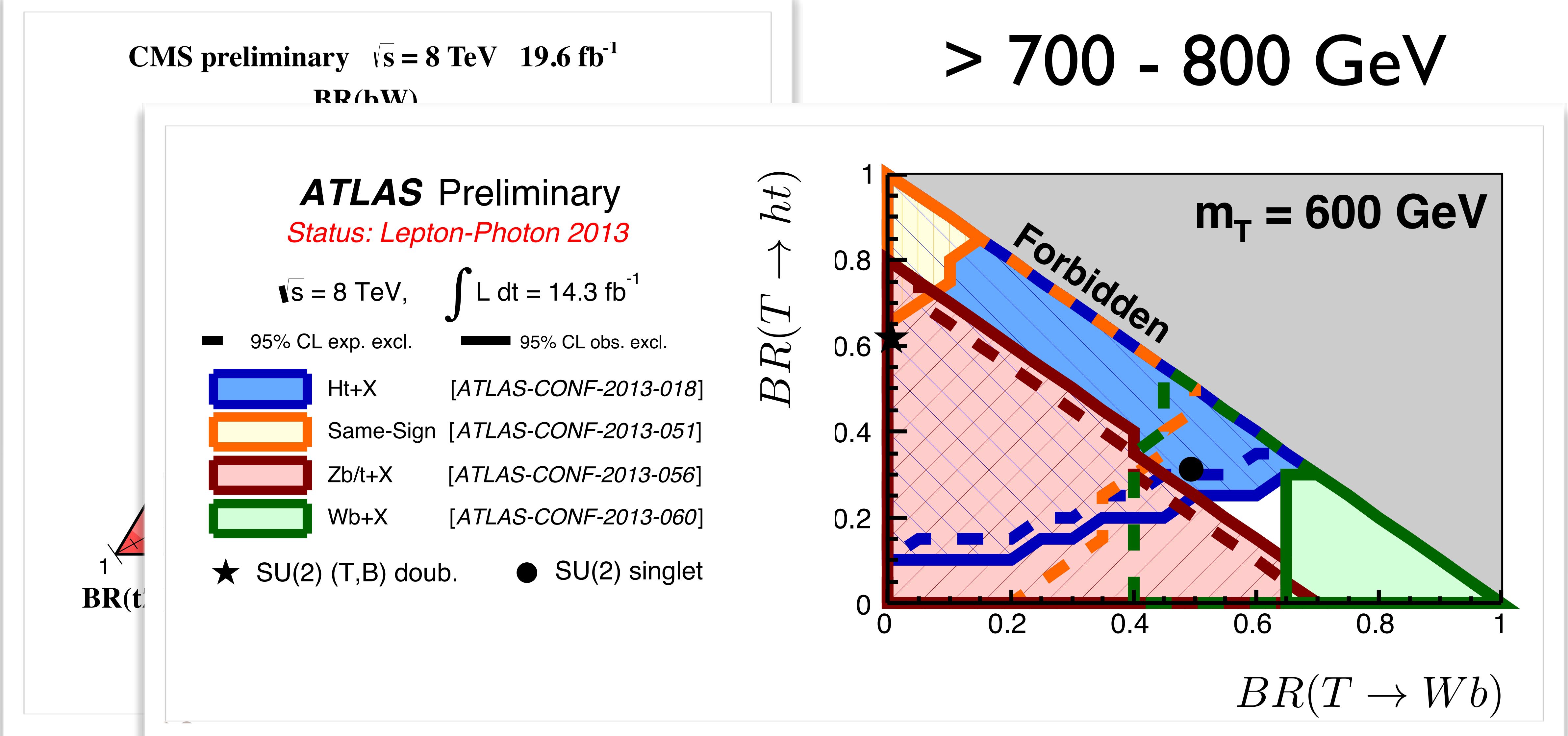
Top partners



Decay modes

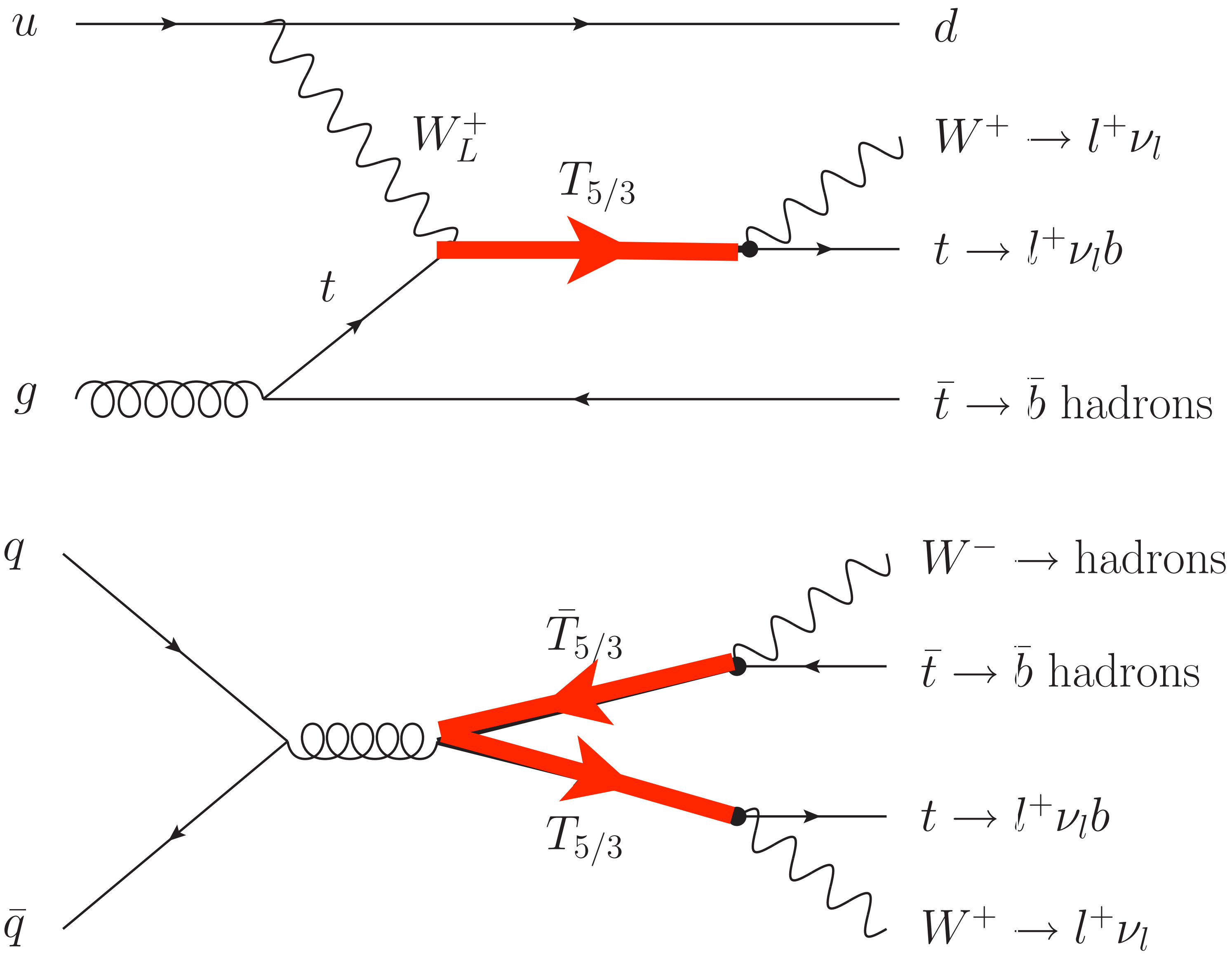


Current limits
> 700 - 800 GeV



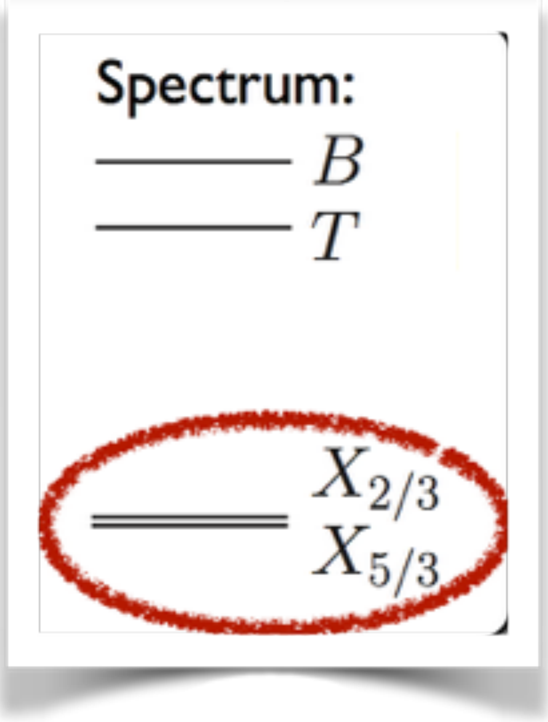
$T_{5/3}$

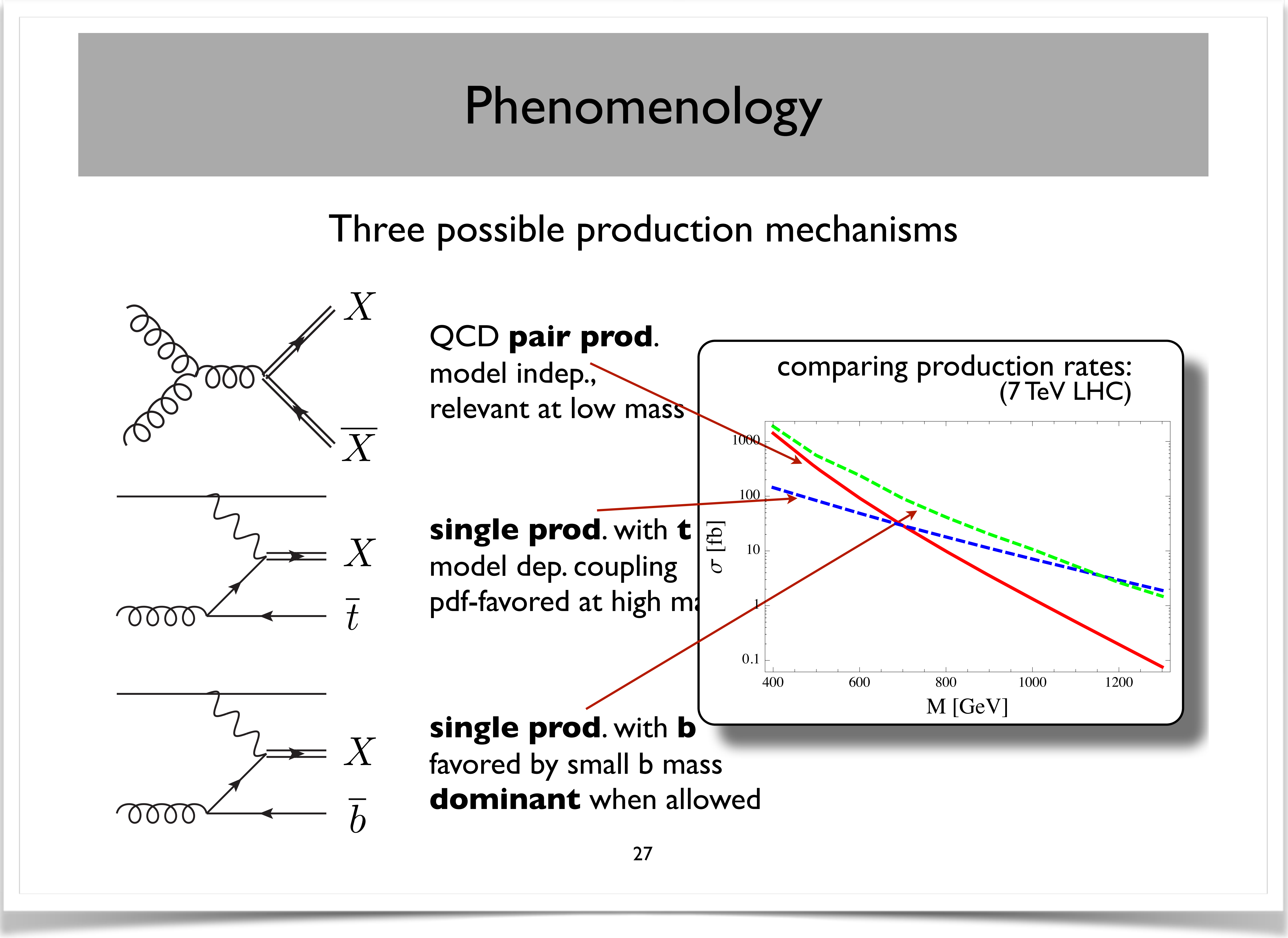
e.g. Perelstein, Pierce, Peskin
Contino, Servant; Mrazek, Wulzer;
De Simone, Matsedonkyi, Rattazzi, Wulzer



Single

Double





Phenomenology

Three possible production mechanisms

QCD **pair prod**.
model indep.,
relevant at low mass

single prod. with **t**
model dep. coupling
pdf-favored at high ma

single prod. with **b**
favored by small b mass
dominant when allowed

comparing production rates:
(7 TeV LHC)

slide by A. Wulzer

Exotics

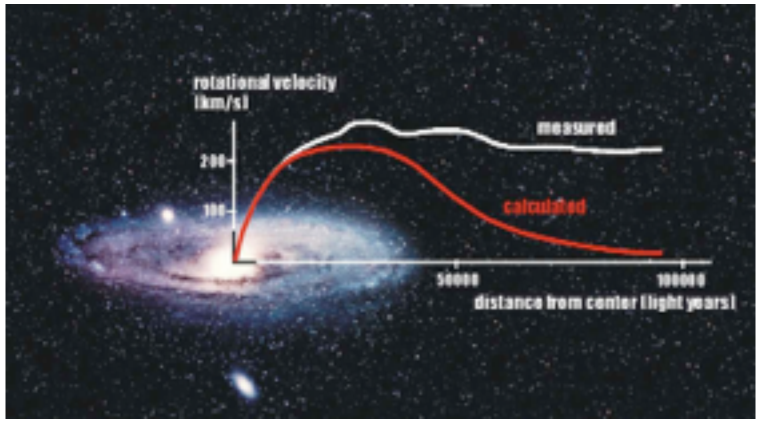
Have we thought hard enough
about non-standard options?

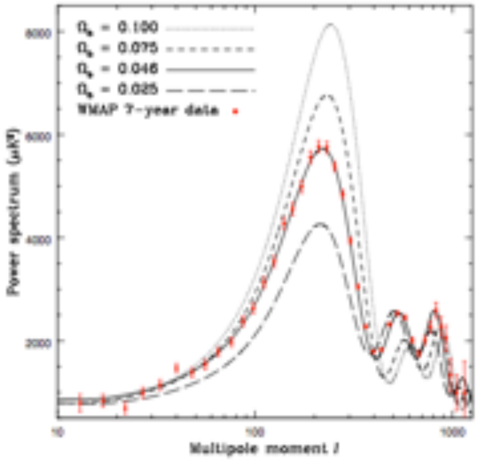
DM emerging jets

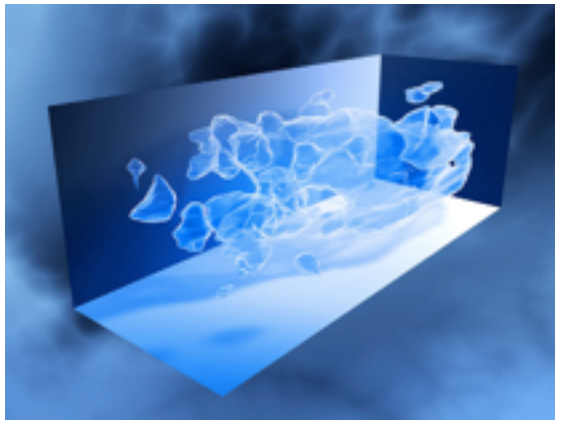
with D. Stolarski and P. Schwaller

Maybe DM is just part of a larger dark sector

- Example: Proton is massive, stable, composite state
- DM self interactions solve structure formation problems
- New signals, new search strategies!

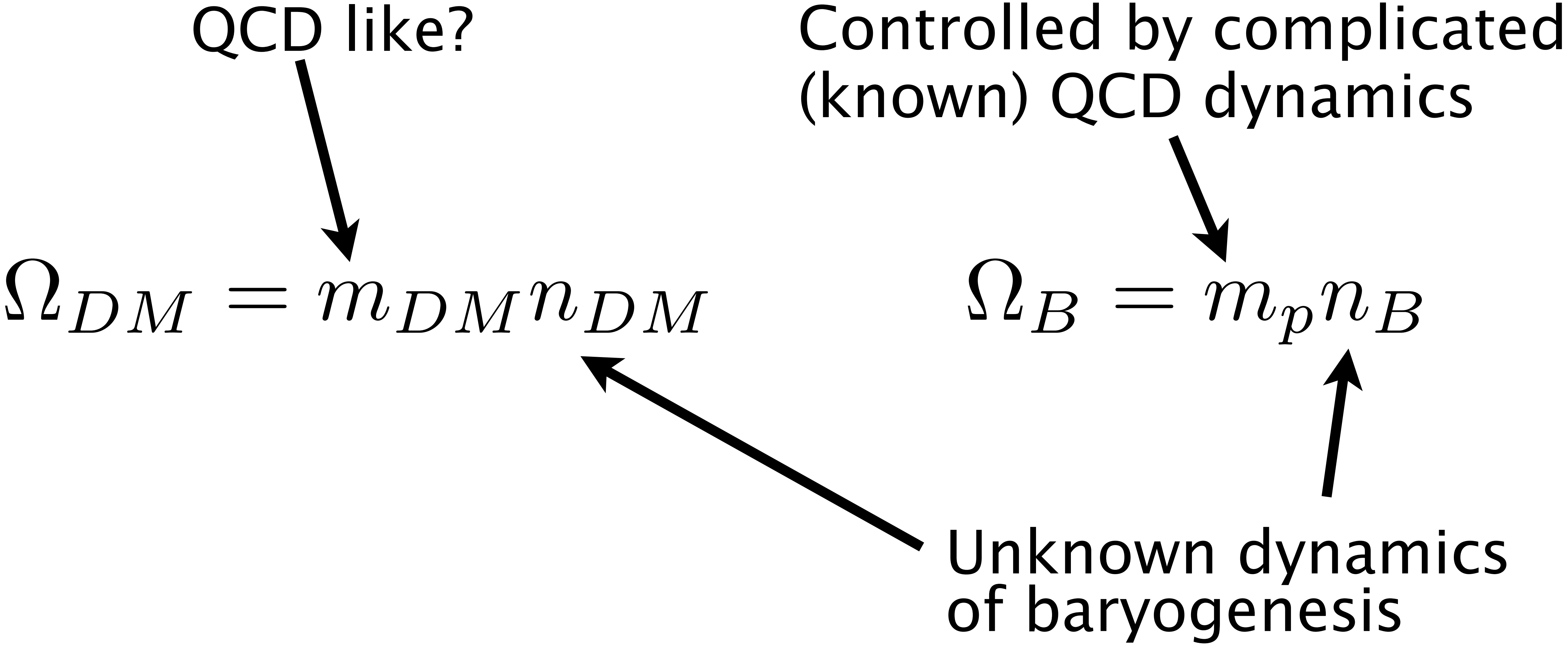






Coincidence?

$$\Omega_{DM} \simeq 5\Omega_B$$



QCD like?

Controlled by complicated (known) QCD dynamics

$$\Omega_{DM} = m_{DM} n_{DM}$$

$$\Omega_B = m_p n_B$$

Unknown dynamics of baryogenesis

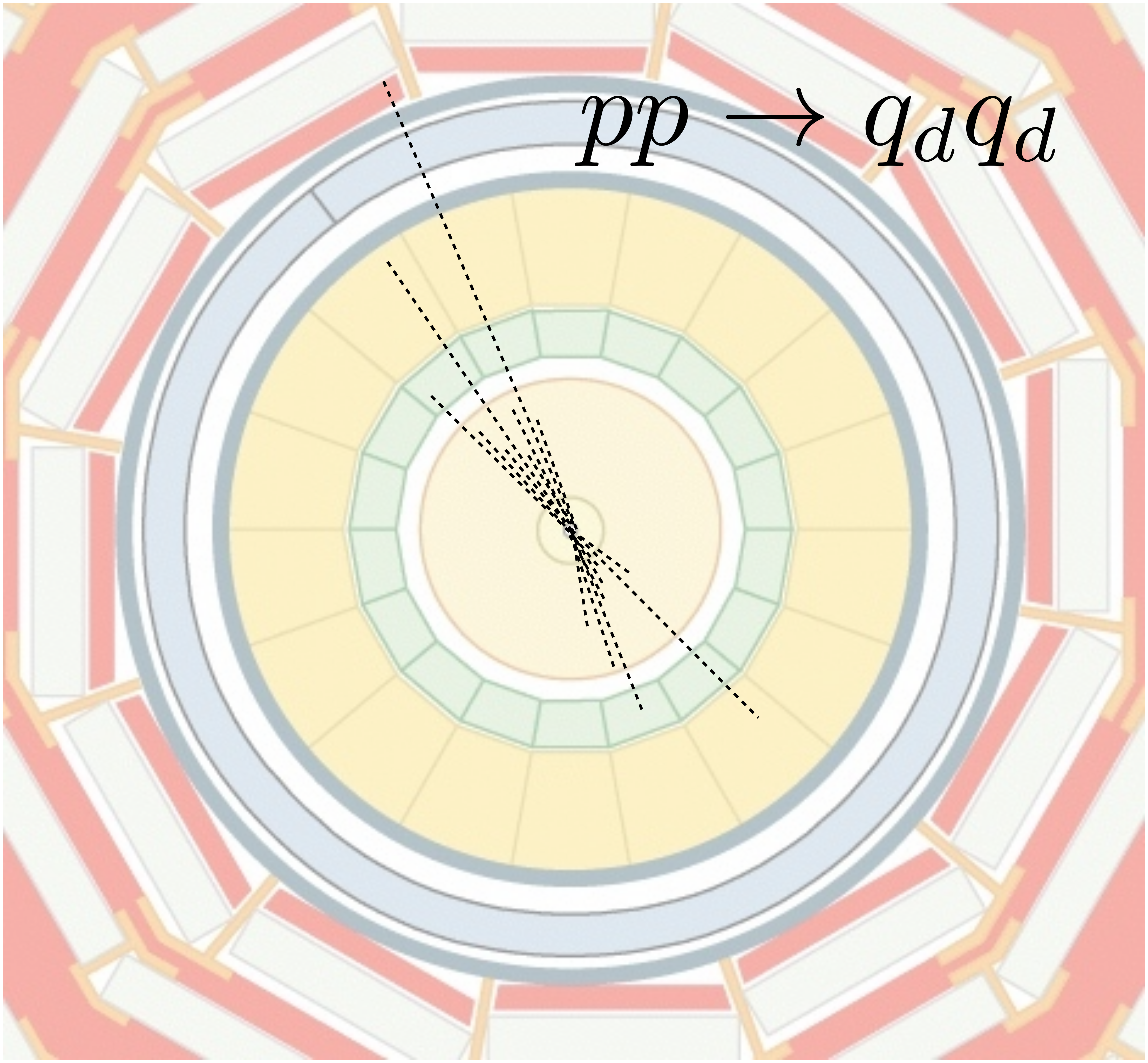
Dark QCD

Imagine a QCD like “dark sector” with 1–10 GeV mass scale

$$p_d \quad \pi_d \quad \text{Zoo}_d$$

Connected to SM in two ways:

- TeV scale mediator (hidden valley)
  Strassler, Zurek, PLB 07.



$$pp \to q_d q_d$$

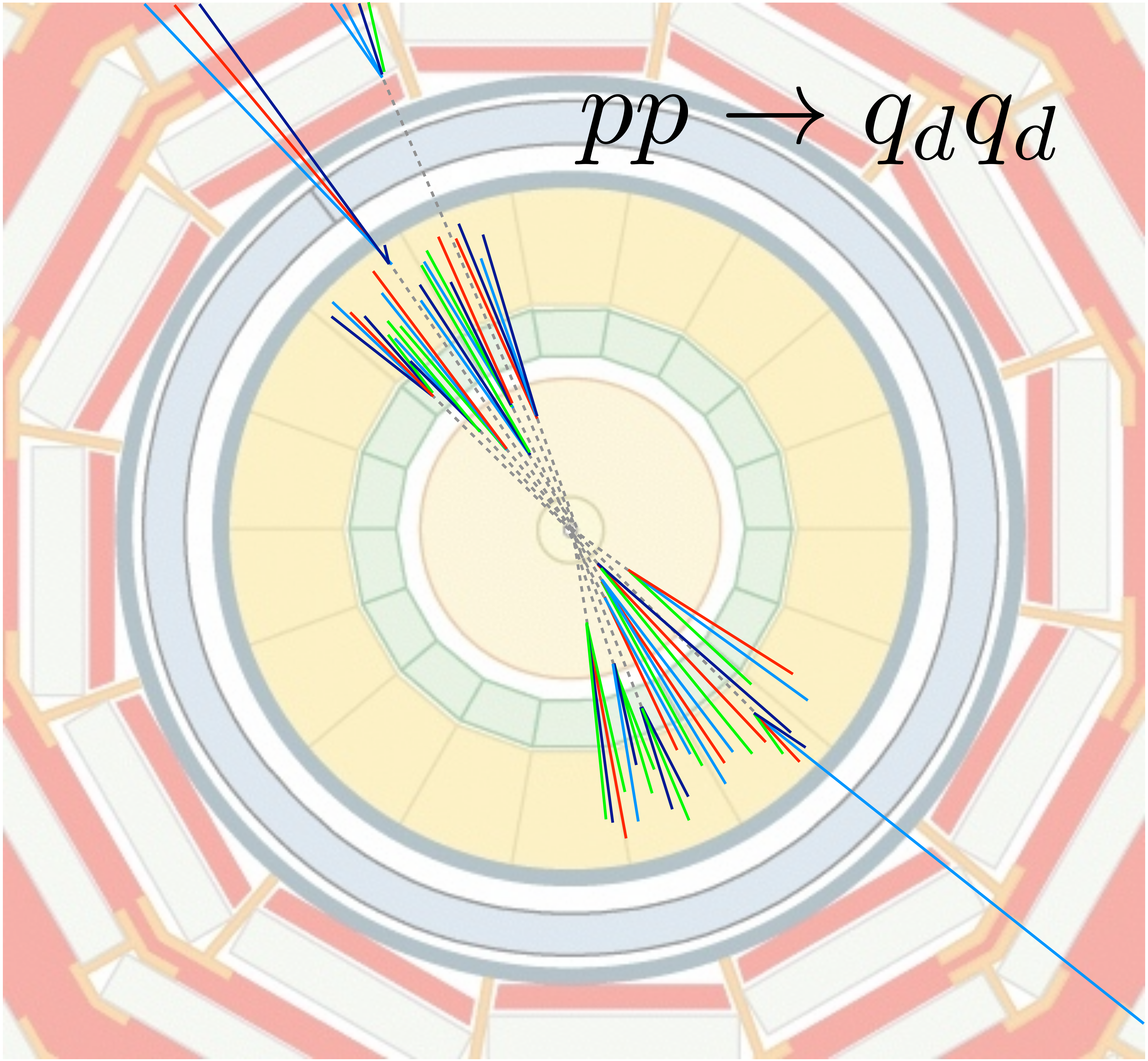
Dark QCD

Imagine a QCD like "dark sector" with 1–10 GeV mass scale

$$p_d \quad \pi_d \quad \mathrm{Zoo}_d$$

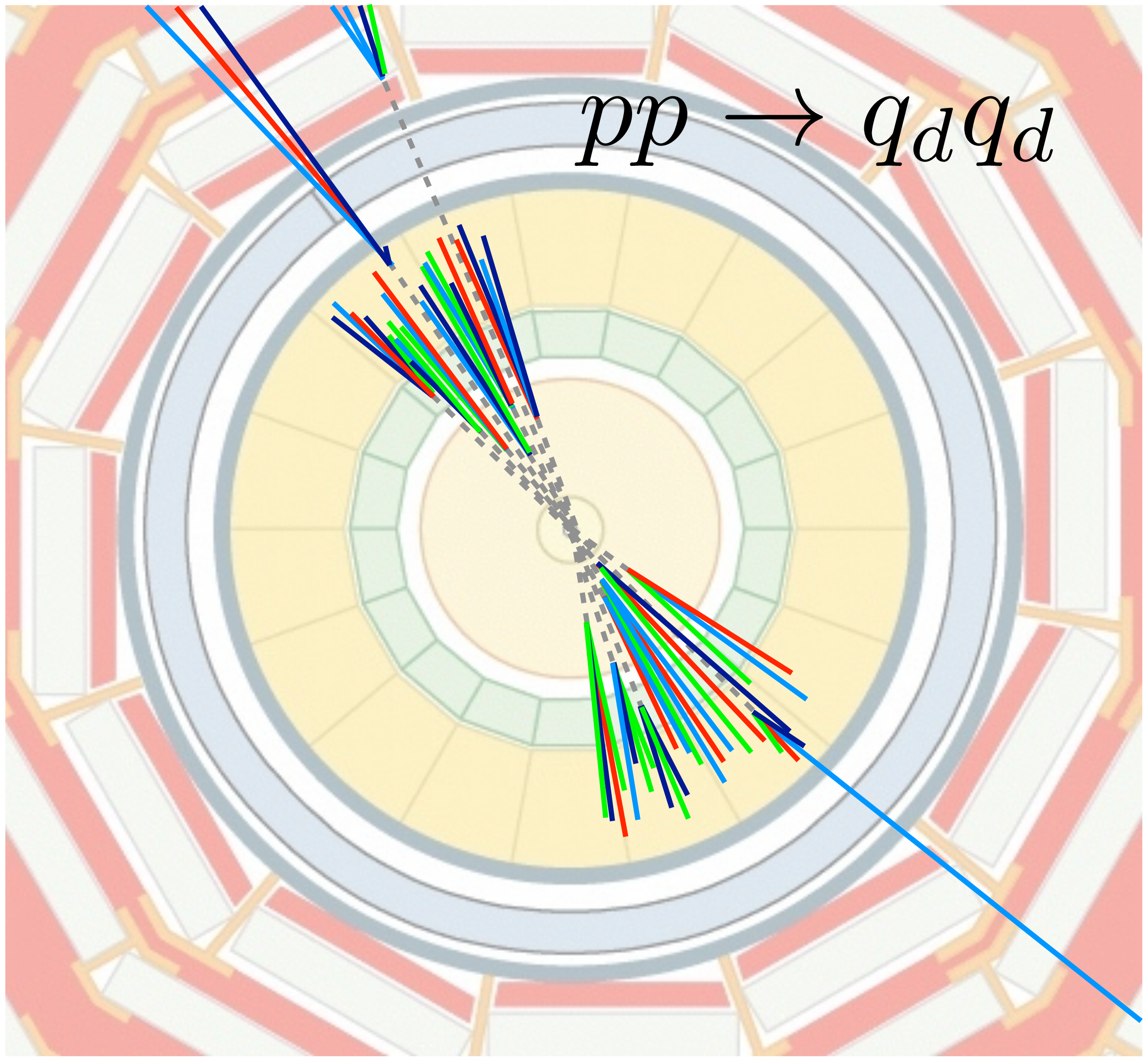
Connected to SM in two ways:

- TeV scale mediator (hidden valley)
  Strassler, Zurek, PLB 07.
- Weak pion decay operator



$pp \to q_d q_d$

emerging jets

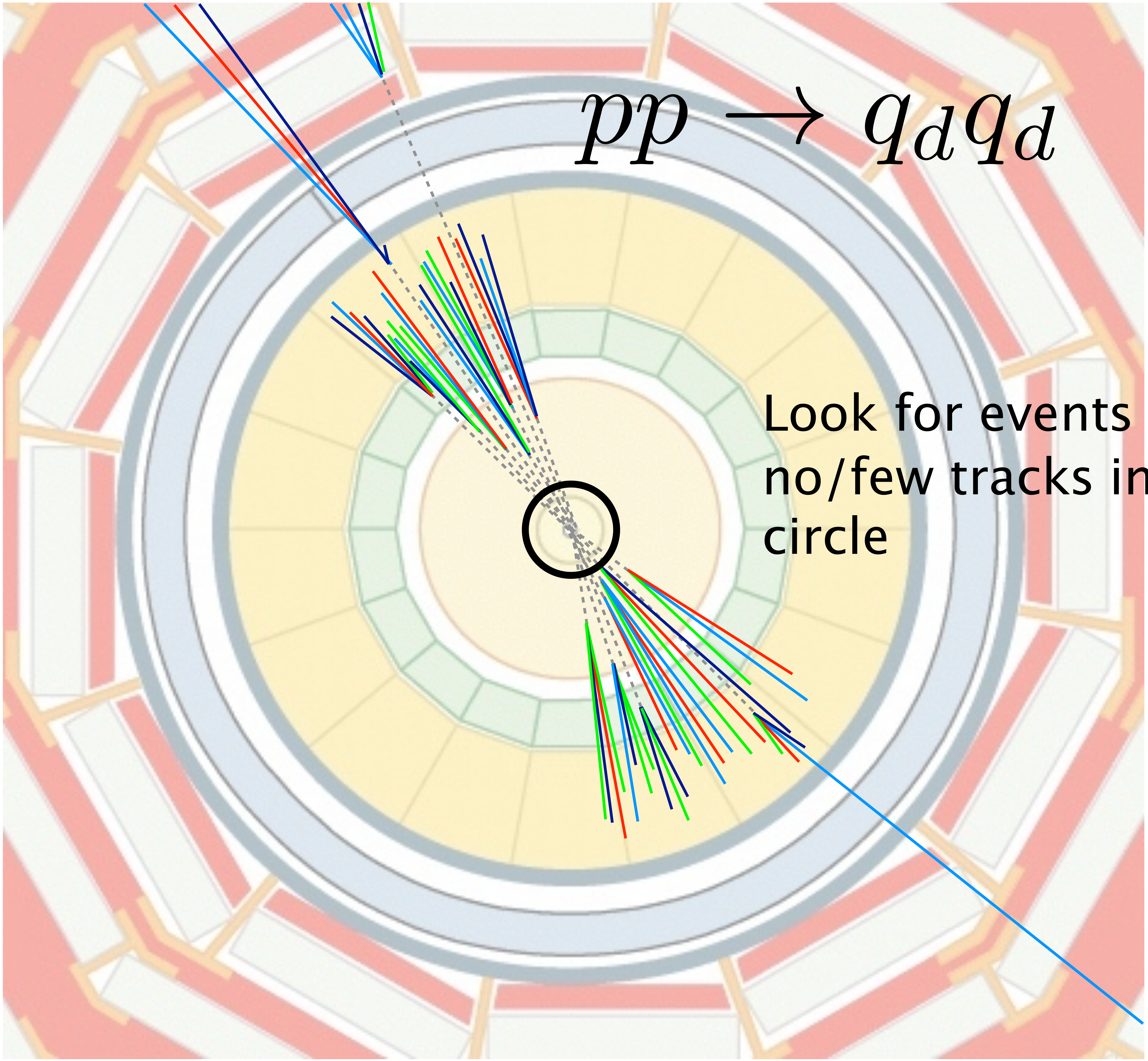


Decay lifetime of ~ cm

Exponential decay means jets emerge at different distances

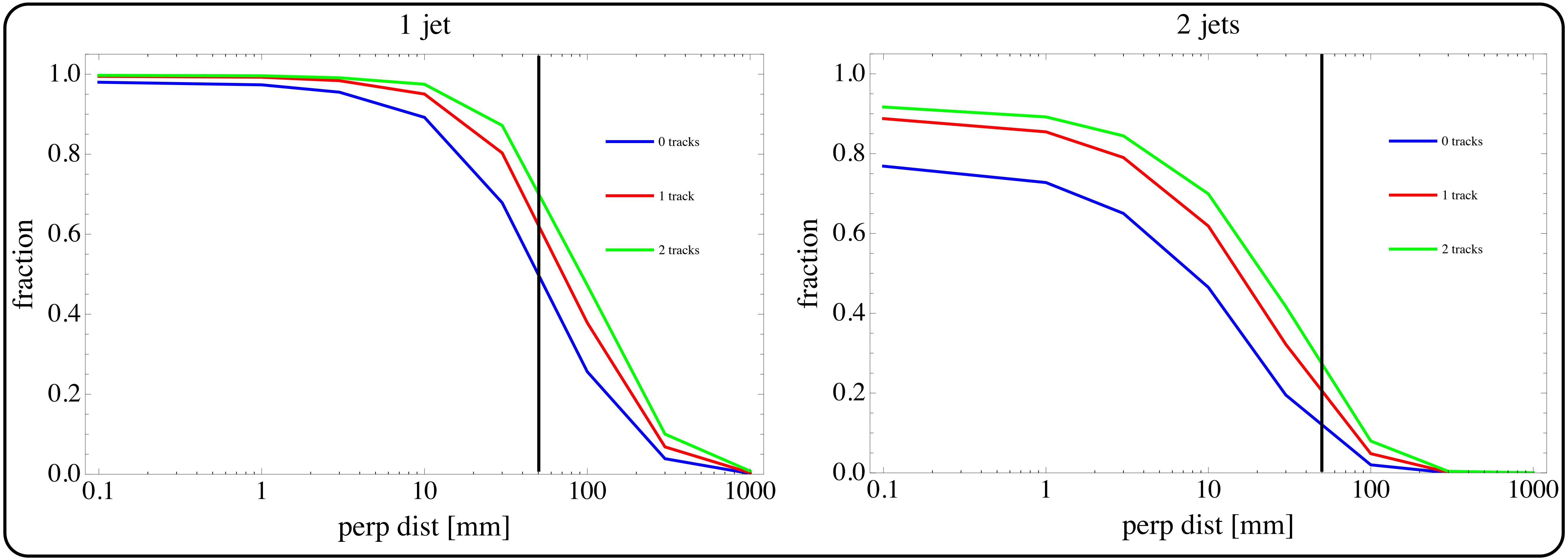
No/few tracks originating from interaction point

$$pp \to q_d q_d$$



Look for events with no/few tracks in the circle

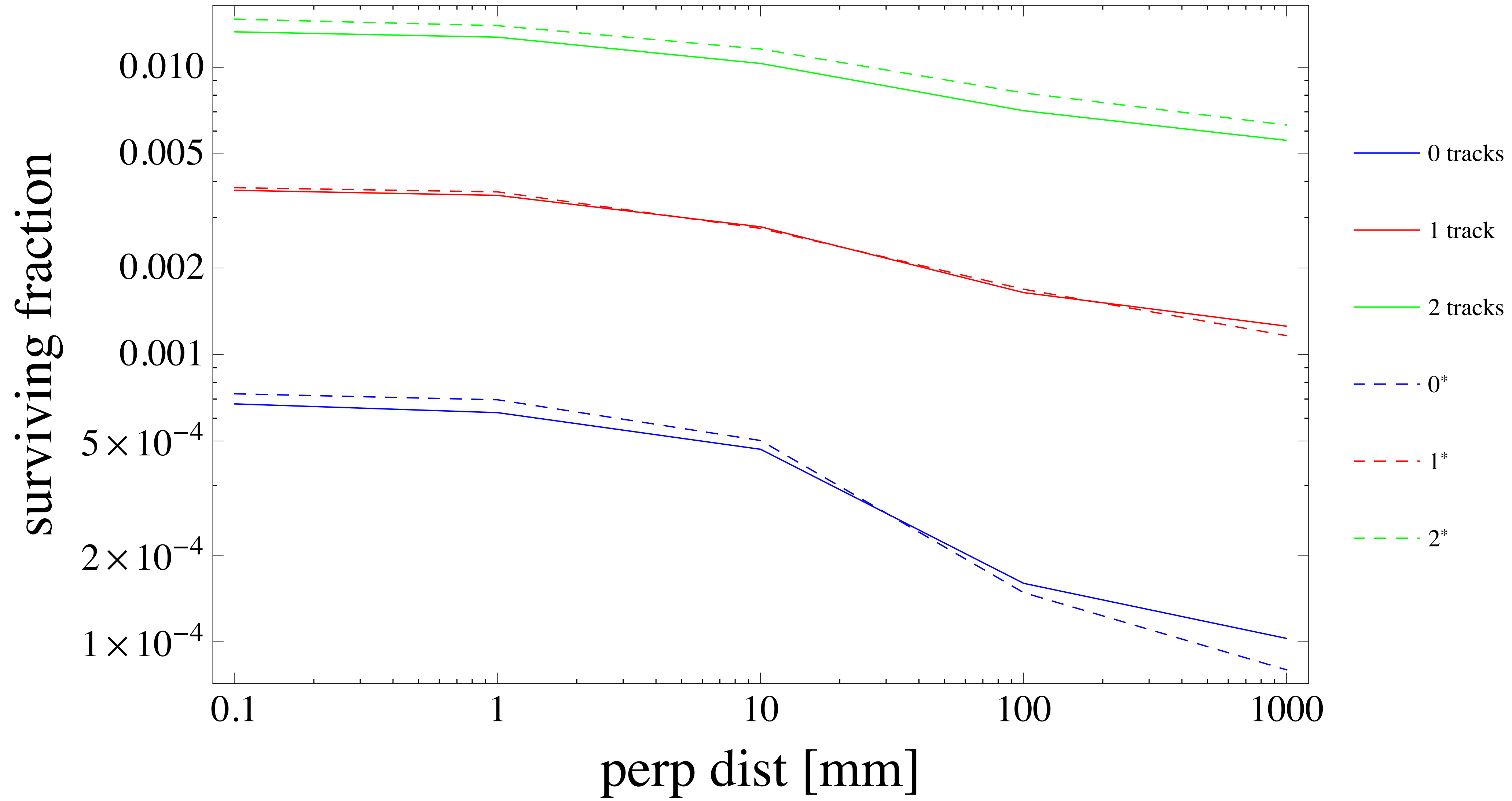
$$pp \to \Phi\Phi^{\dagger} \to \bar{q}\, Q_d\, \bar{Q}_d\, q$$



$$m_{\pi_d} = 5\,\mathrm{GeV} \qquad c\tau_{\pi_d} = 50\,\mathrm{mm}$$

QCD bgd’s

QCD 4–jet production in Pythia8



* – modified Pythia settings to increase QCD contribution

What will we learn from run II?

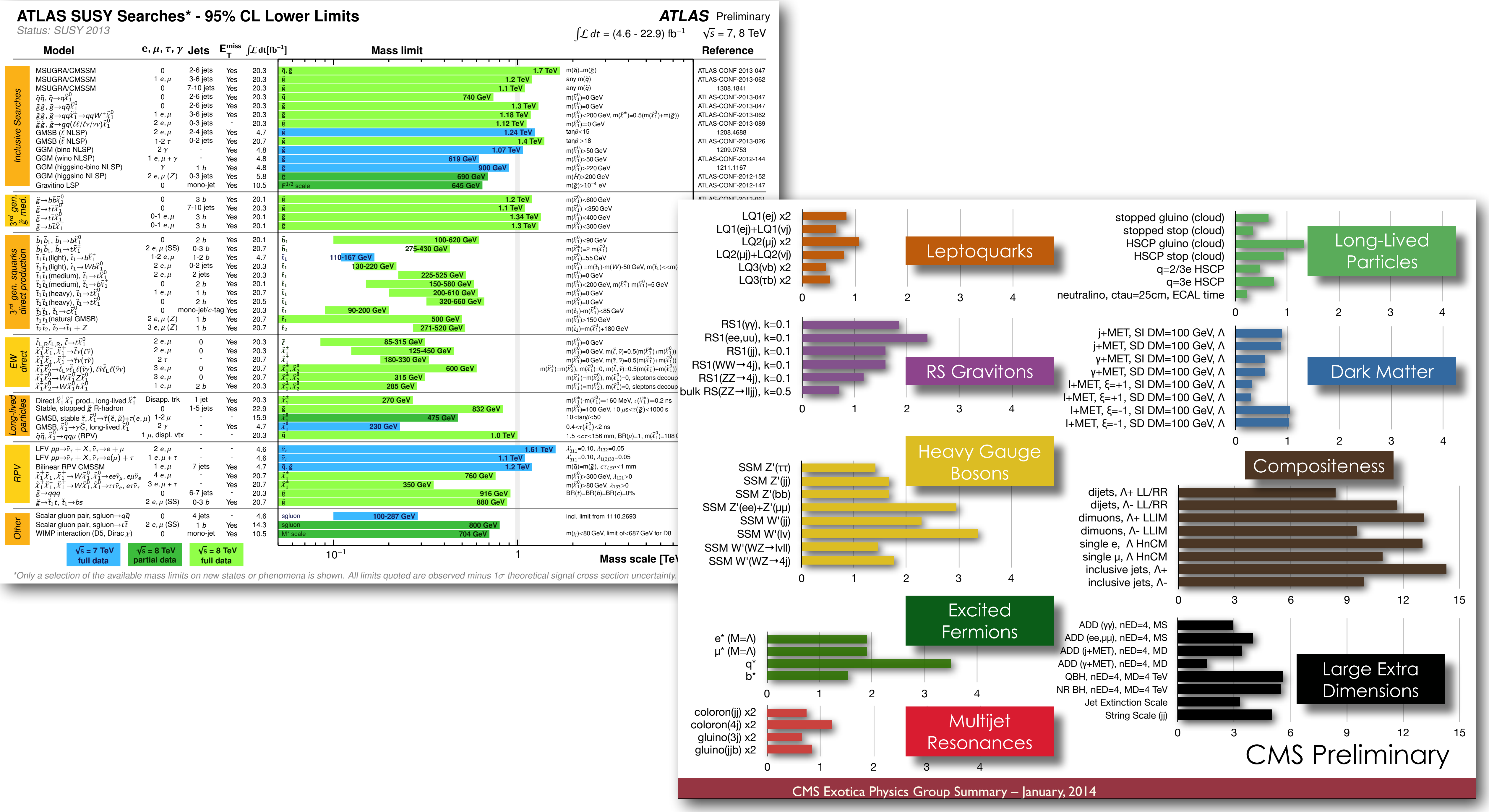
Collider-reach

w/ Gavin Salam (CERN)

estimates of the reach of future colliders
based on existing limits

www.cern.ch/collider-reach

There are already many well-designed searches



How do we leverage that experience to estimate future reaches?

A rough way of doing it

Suppose ATLAS/CMS are currently sensitive to gluinos of 1250 GeV (95% CL_s, 8 TeV, 20 fb^{-1})

Work out how many signal events that corresponds to

Find out for what gluino mass you would get the same number of signal events at 14 TeV with 300 fb^{-1}
(assume # of background events scales same way)

Too simplistic

Backgrounds may not scale in the same way as signal

New irreducible backgrounds may appear at higher scales

Reconstruction efficiencies may depend on mass scale

Detector effects (e.g. granularity), and run conditions (pileup) vary across energy scales and luminosities

It can't possibly work!

Too complicated

Calculating mass for constant # of signal events is pretty straightforward

But it still requires some work and setup

E.g. need cross section calculators for each new physics process (Prospino/Pythia/…), run them for a range of masses, etc.

an iPhone app?

$$\frac{N_{\text{signal-events}}(M^2_{\text{high}},\,14\,\text{TeV},\,\text{Lumi})}{N_{\text{signal-events}}(M^2_{\text{low}},\ 8\,\text{TeV},\ 19\text{fb}^{-1})} = 1$$

Coupling constants & other prefactors mostly cancel in the ratio.

Dependence on *M* and on √s mostly comes about through parton distribution functions (PDFs) & simple dimensions.

Z' example

$$\hat{\sigma}_0(\hat{s}) = C\,\frac{\hat{s}}{(\hat{s} - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}$$

$$\frac{d\sigma}{dm^2} = \int dx_1 dx_2\,\left[f_1(x_1)f_2(x_2)\right]\,\hat{\sigma}_0(\hat{s})\delta(m^2 - \hat{s}^2),$$

$$= \sum_{ij}\left[\tau\int\frac{dx}{x}\,f_i(x)f_j(\tau/x)\right]\frac{C}{(m^2 - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}$$

$$\sigma \approx \int dm^2 \sum_{ij}\mathcal{L}_{ij}(m^2, s)\,C\,\frac{\pi}{\Gamma_{Z'}M_{Z'}}\,\delta(m^2 - M_{Z'}^2)$$

$$\Gamma_{Z'} \propto M_{Z'}$$

$$= \frac{1}{M_{Z'}^2}\sum_{ij}C'\mathcal{L}_{ij}(M_{Z'}^2, s)$$

"1/M^2 x parton-lumi"

$$= N(M_{Z'}, s)$$

Instead of cross section ratio, use **parton luminosity ratio**

Equation we solve to find M_{high} is then

$$\frac{\mathcal{L}_{ij}(M^2_{\text{high}}, s_{\text{high}})}{\mathcal{L}_{ij}(M^2_{\text{low}}, s_{\text{low}})} \times \frac{\text{lumi}_{\text{high}}}{\text{lumi}_{\text{low}}} = \frac{M^2_{\text{high}}}{M^2_{\text{low}}}$$

The tools we use for this are

LHAPDF and HOPPET

most plots with MSTW2008 NNLO PDFs

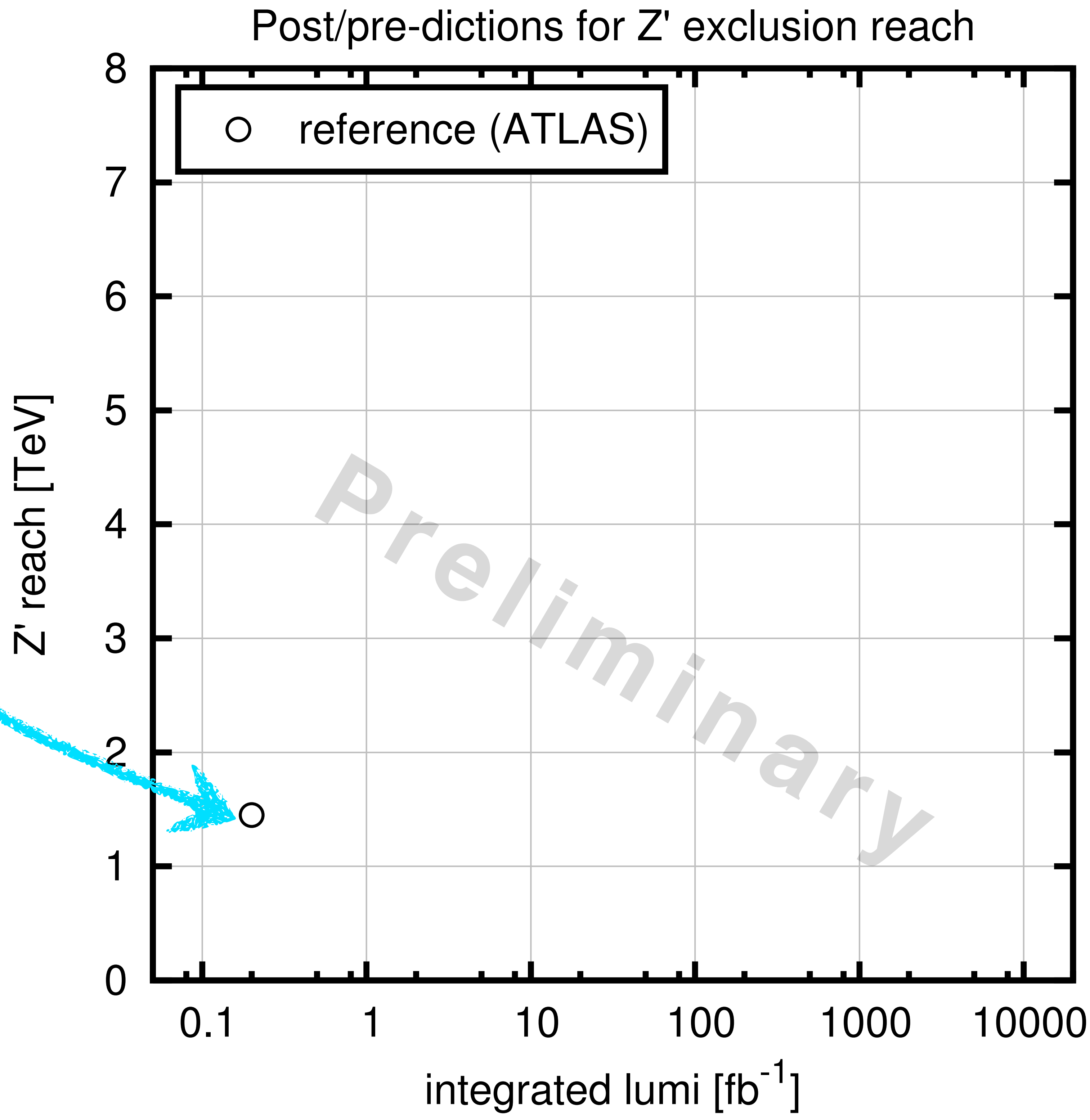
$$\mathcal{L}_{ij}(M^2, s) = \int_\tau^1 \frac{dx}{x} x f_i(x, M^2) \frac{\tau}{x} f_j\left(\frac{\tau}{x}, M^2\right) \qquad \tau \equiv \frac{M^2}{s}$$

i & j parton

Does it work?

Try a Z’ search. Take a baseline analysis:

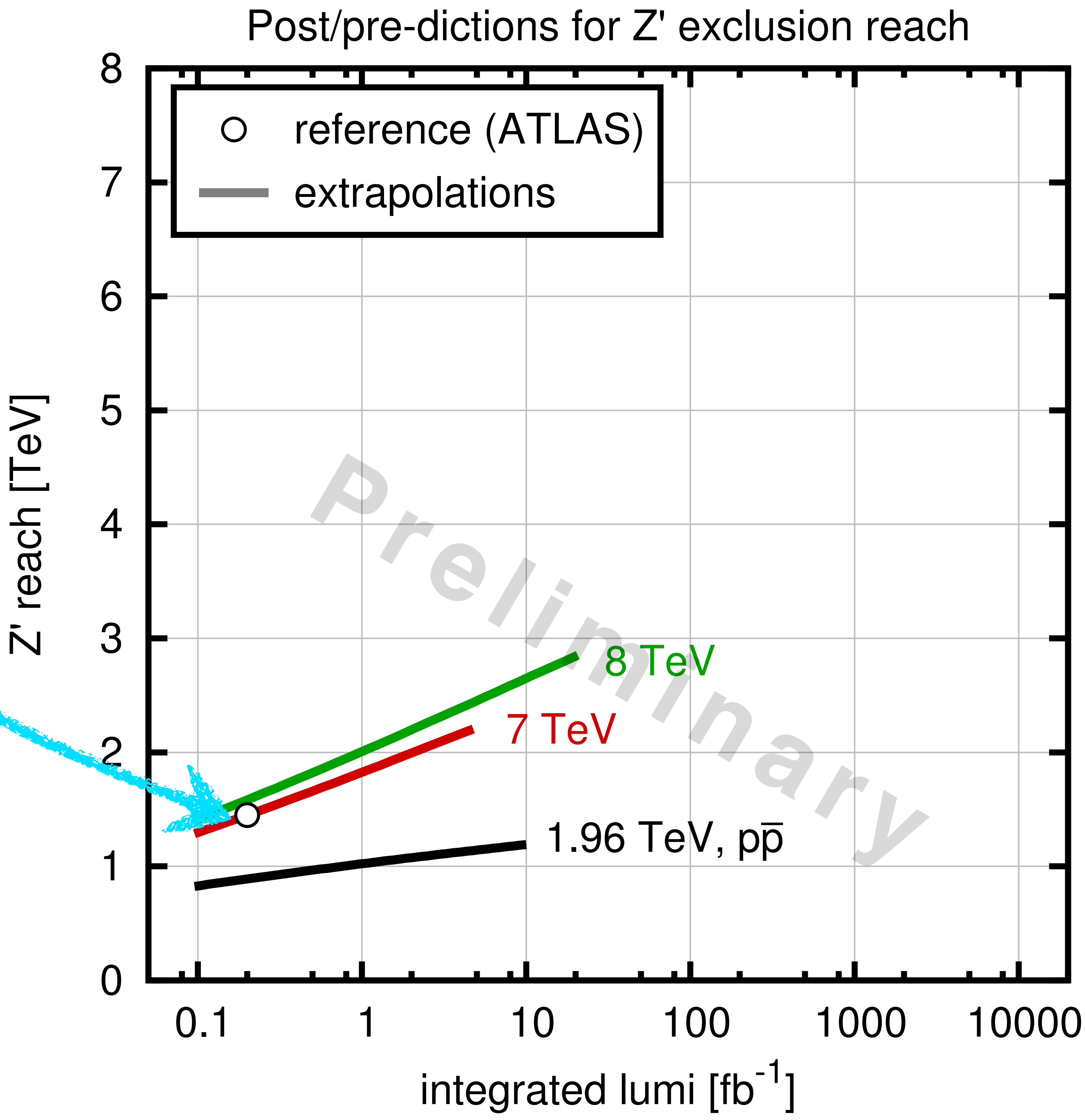
ATLAS,
0.2 fb^{-1} @ 7 TeV
excludes M < 1450 GeV



Try a Z' search. Take a baseline analysis:

ATLAS,
0.2 fb^{-1} @ 7 TeV
excludes M < 1450 GeV

"Predict" exclusions at other lumis & energies (assume $q\bar{q}$)



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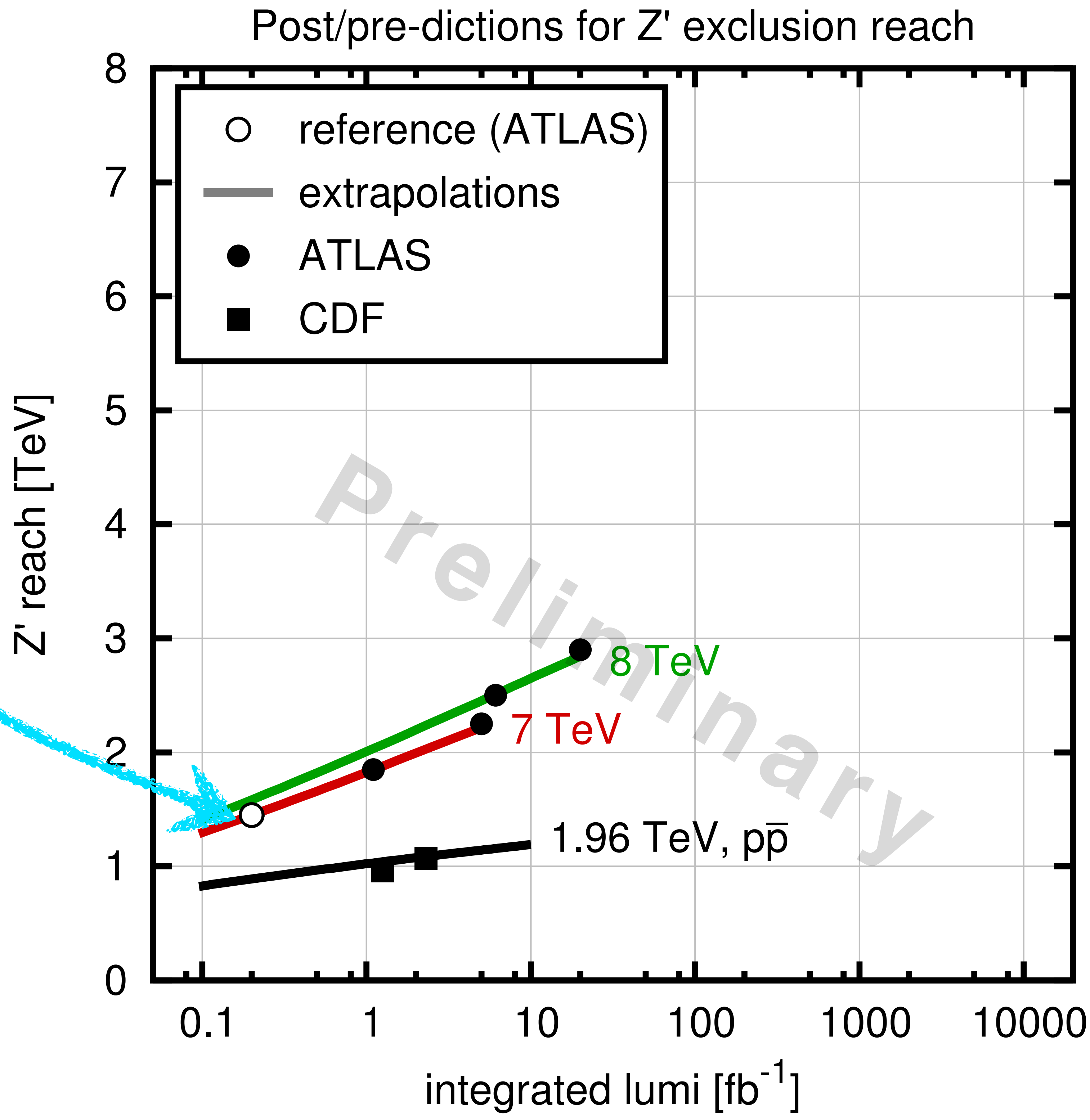
Compare to actual exclusions



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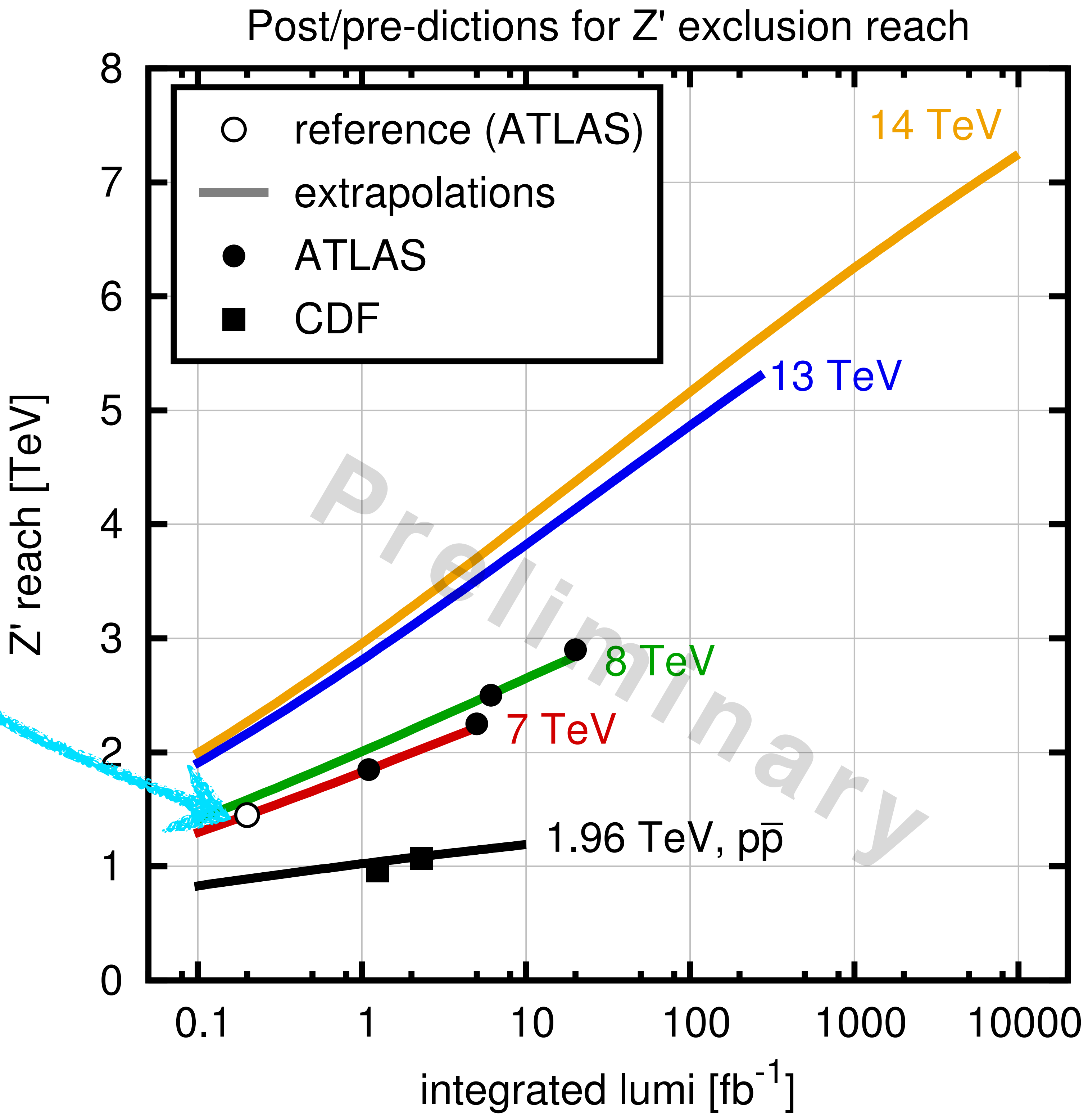
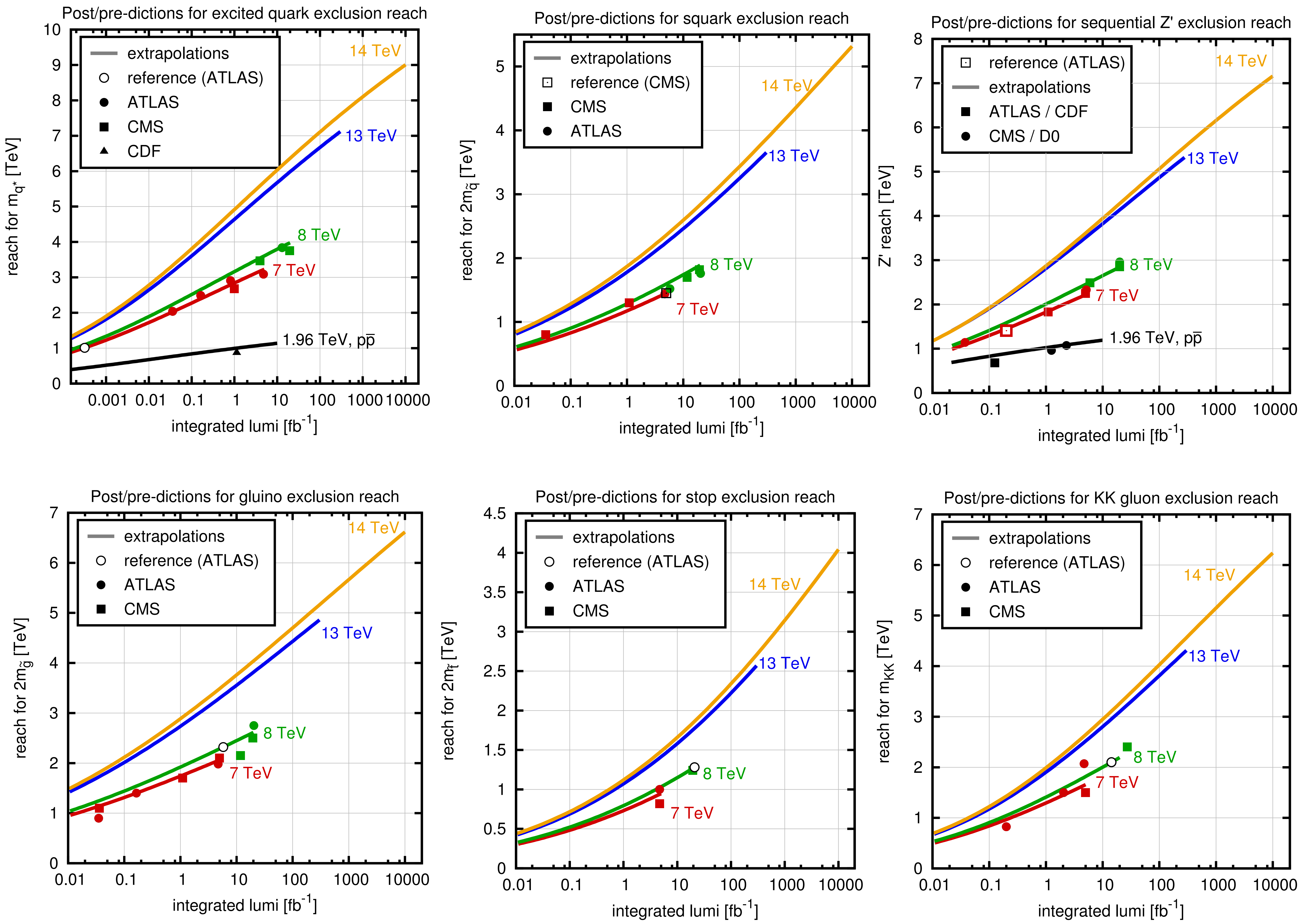


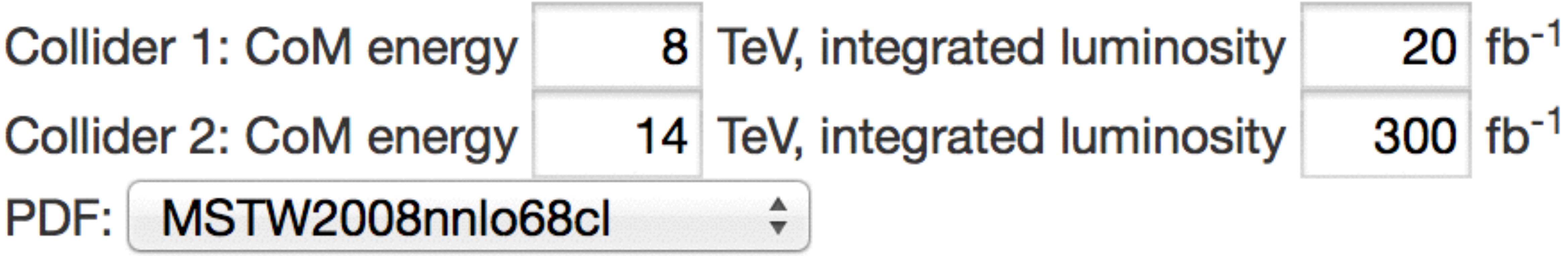
Maybe it only works so well because it's a simple search?
(Signal & Bkgd are both $q\bar{q}$ driven)


Post/pre-dictions for excited quark exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
CDF
14 TeV
13 TeV
8 TeV
7 TeV
1.96 TeV, $p\bar{p}$
reach for m_{q^*} [TeV]
integrated lumi [fb^{-1}]
0 1 2 3 4 5 6 7 8 9 10
0.001 0.01 0.1 1 10 100 1000 10000
Post/pre-dictions for squark exclusion reach
extrapolations
reference (CMS)
CMS
ATLAS
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{q}}$ [TeV]
integrated lumi [fb^{-1}]
0 1 2 3 4 5
0.01 0.1 1 10 100 1000 10000
Post/pre-dictions for sequential Z' exclusion reach
reference (ATLAS)
extrapolations
ATLAS / CDF
CMS / D0
14 TeV
13 TeV
8 TeV
7 TeV
1.96 TeV, $p\bar{p}$
Z' reach [TeV]
integrated lumi [fb^{-1}]
0 1 2 3 4 5 6 7 8
0.01 0.1 1 10 100 1000 10000
Post/pre-dictions for gluino exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{g}}$ [TeV]
integrated lumi [fb^{-1}]
0 1 2 3 4 5 6 7
0.01 0.1 1 10 100 1000 10000
Post/pre-dictions for stop exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{t}}$ [TeV]
integrated lumi [fb^{-1}]
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
0.01 0.1 1 10 100 1000 10000
Post/pre-dictions for KK gluon exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
14 TeV
13 TeV
8 TeV
7 TeV
reach for m_{KK} [TeV]
integrated lumi [fb^{-1}]
0 1 2 3 4 5 6 7
0.01 0.1 1 10 100 1000 10000

From your iPhone/Android

(or a generic browser)

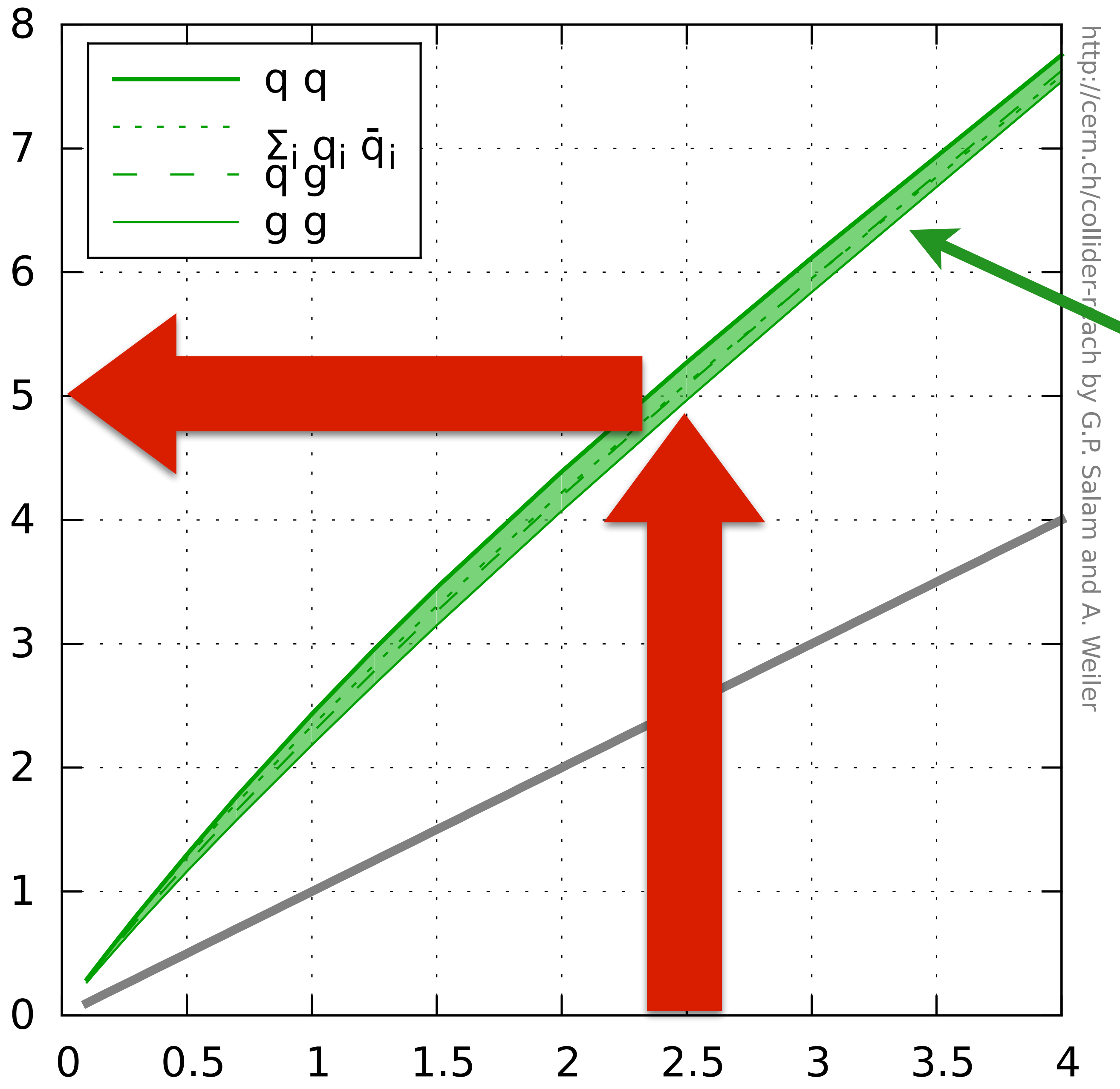
cern.ch/collider-reach



Collider 1: CoM energy 8 TeV, integrated luminosity 20 fb^{-1}

Collider 2: CoM energy 14 TeV, integrated luminosity 300 fb^{-1}

PDF: MSTW2008nnlo68cl

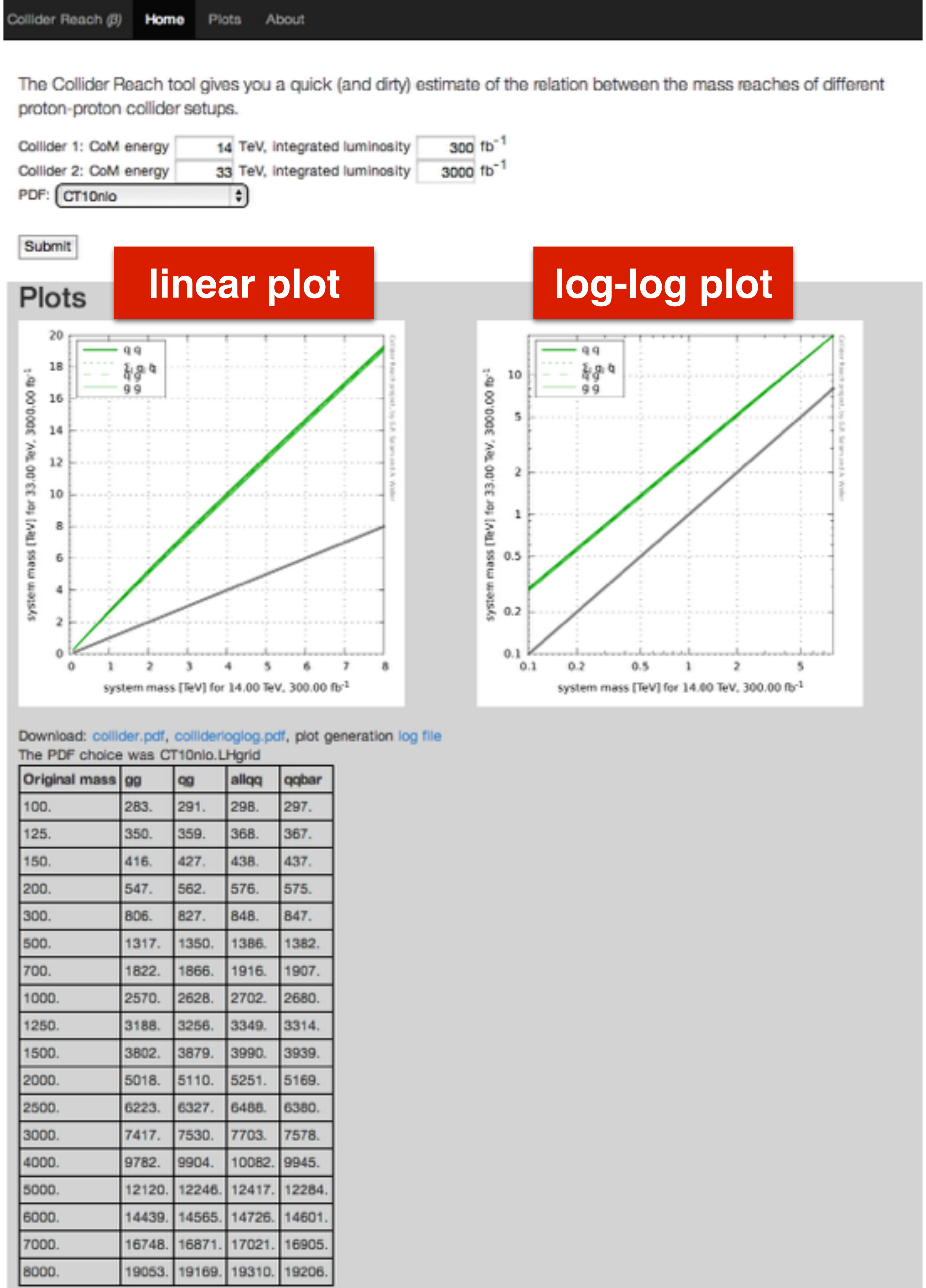


Mass [TeV] at collider #2

Mass [TeV] at collider #1

Spread of partonic channels (assume same channel for S & B)

cern.ch/collider-reach *



linear plot

log-log plot

The Collider Reach tool gives you a quick (and dirty) estimate of the relation between the mass reaches of different proton-proton collider setups.

Collider 1: CoM energy 14 TeV, integrated luminosity 300 fb^{-1}

Collider 2: CoM energy 33 TeV, integrated luminosity 3000 fb^{-1}

PDF: CT10nlo

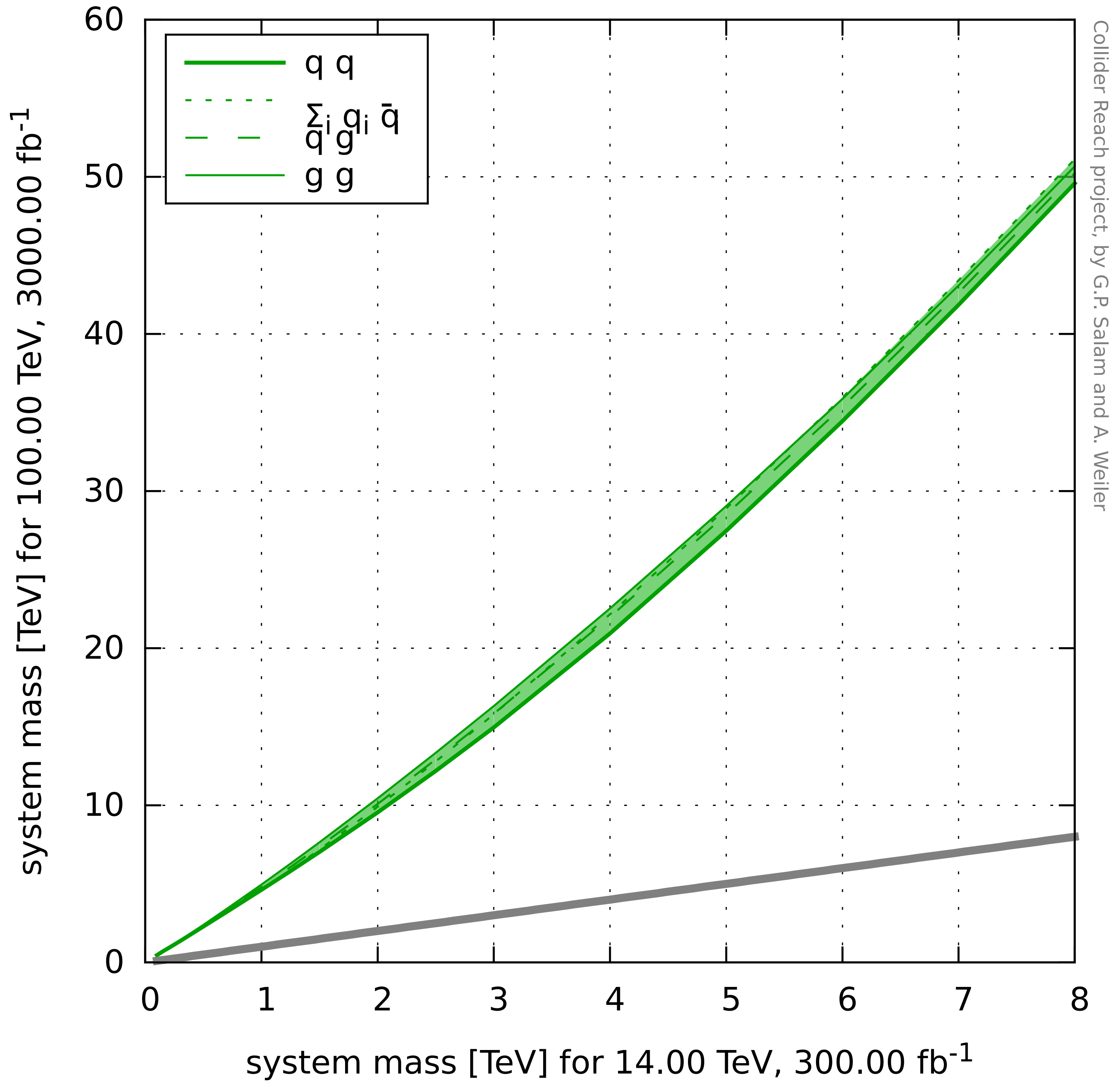
Plots

Download: collider.pdf, colliderloglog.pdf, plot generation log file

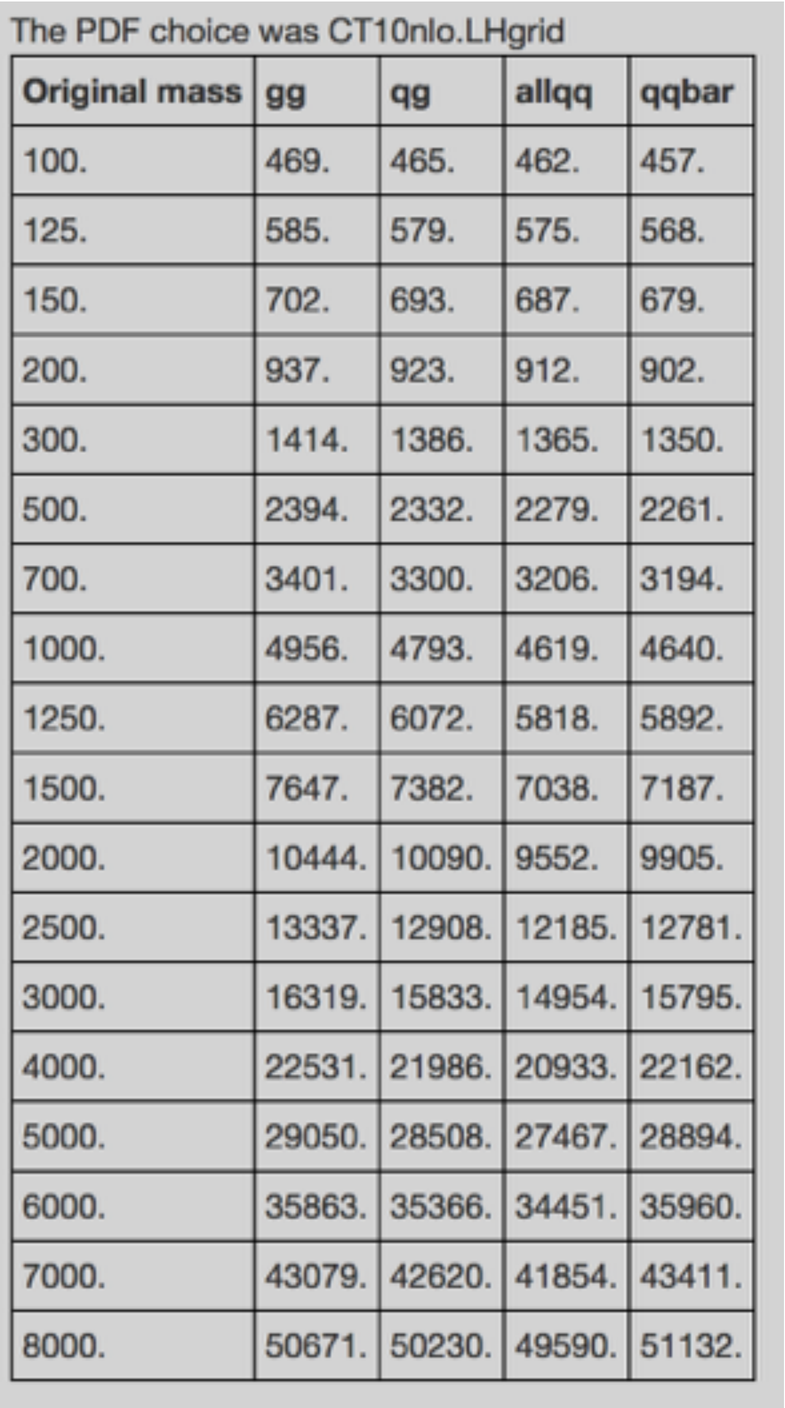
The PDF choice was CT10nlo.LHgrid

Original mass	gg	qg	allqq	qqbar
100.	283.	291.	298.	297.
125.	350.	359.	368.	367.
150.	416.	427.	438.	437.
200.	547.	562.	576.	575.
300.	806.	827.	848.	847.
500.	1317.	1350.	1386.	1382.
700.	1822.	1866.	1916.	1907.
1000.	2570.	2628.	2702.	2680.
1250.	3188.	3256.	3349.	3314.
1500.	3802.	3879.	3990.	3939.
2000.	5018.	5110.	5251.	5169.
2500.	6223.	6327.	6488.	6380.
3000.	7417.	7530.	7703.	7578.
4000.	9782.	9904.	10082.	9945.
5000.	12120.	12246.	12417.	12284.
6000.	14439.	14565.	14726.	14601.
7000.	16748.	16871.	17021.	16905.
8000.	19053.	19169.	19310.	19206.

14 TeV$_{300\ \mathrm{fb}^{-1}}$ → 100 TeV$_{3\ \mathrm{ab}^{-1}}$



Collider Reach project, by G.P. Salam and A. Weiler



The PDF choice was CT10nlo.LHgrid

Original mass	**gg**	**qg**	**allqq**	**qqbar**
100.	469.	465.	462.	457.
125.	585.	579.	575.	568.
150.	702.	693.	687.	679.
200.	937.	923.	912.	902.
300.	1414.	1386.	1365.	1350.
500.	2394.	2332.	2279.	2261.
700.	3401.	3300.	3206.	3194.
1000.	4956.	4793.	4619.	4640.
1250.	6287.	6072.	5818.	5892.
1500.	7647.	7382.	7038.	7187.
2000.	10444.	10090.	9552.	9905.
2500.	13337.	12908.	12185.	12781.
3000.	16319.	15833.	14954.	15795.
4000.	22531.	21986.	20933.	22162.
5000.	29050.	28508.	27467.	28894.
6000.	35863.	35366.	34451.	35960.
7000.	43079.	42620.	41854.	43411.
8000.	50671.	50230.	49590.	51132.

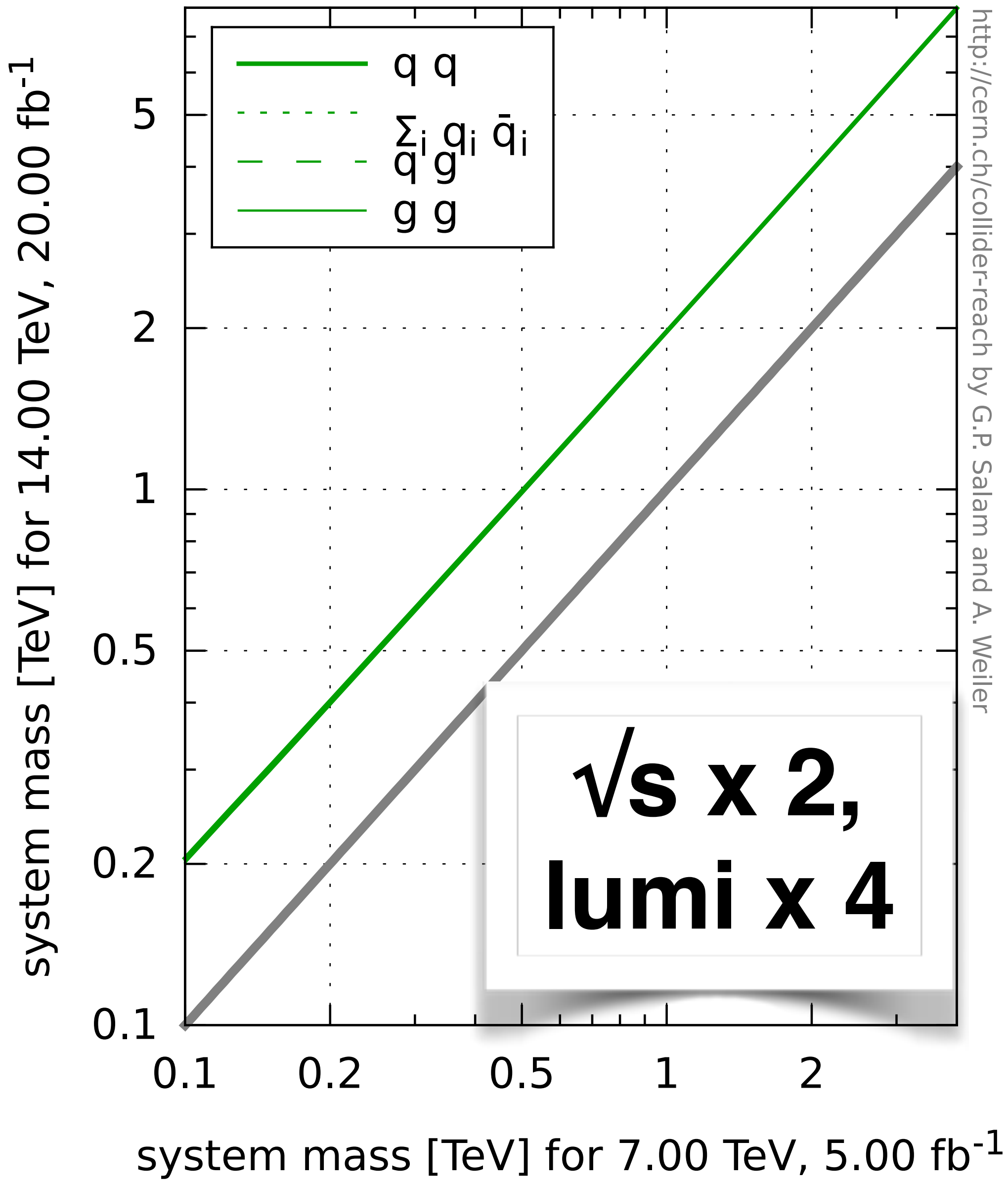
Rule of Thumb #1

Increase collider energy by **X**
& increase luminosity by a factor **X²**

→ reach goes up by a factor X

Because you keep same Bjorken-x &
luminosity increase compensates for
1/mass² scaling of cross sections

PDF scaling variations are small effect



http://cern.ch/collider-reach by G.P. Salam and A. Weiler

Rule of Thumb #2

(apparently not widely known previously)

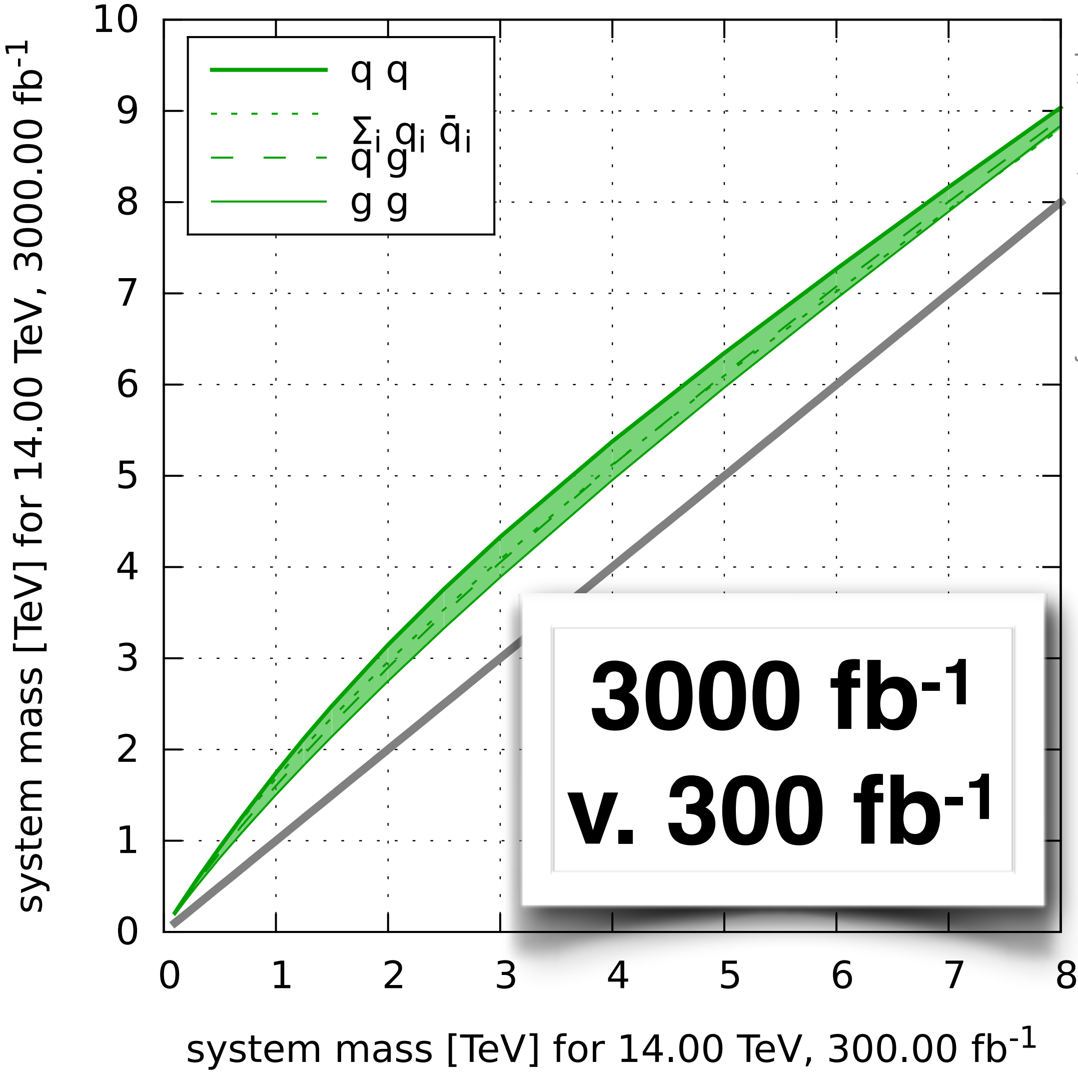
Increase luminosity by factor 10

→ reach increases by constant $\Delta m \simeq 0.07\sqrt{s}$

i.e. for $\sqrt{s}$=14 TeV, reach goes by up 1 TeV

No deep reason — a somewhat random characteristic of large-x PDFs.

Only holds for $0.15 \lesssim M/\sqrt{s} \lesssim 0.6$



3000 fb^{-1} v. 300 fb^{-1}

Consequence of rule #2

(may be a bit fragile & only for S ≲ B)

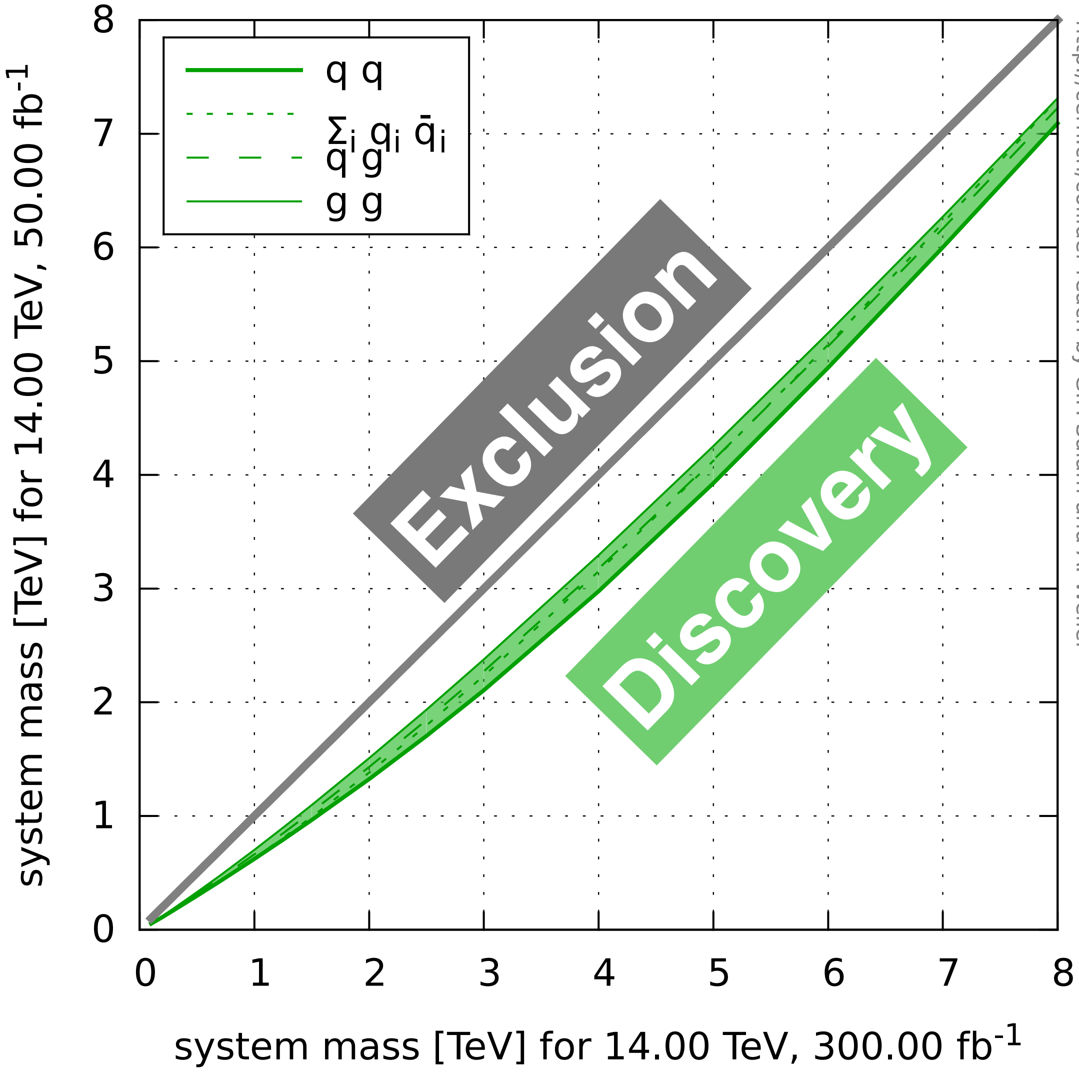
Exclusion is 2-σ
Discovery is 5-σ

Need $(5/2)^2 = 6.25$ increase in lumi to go from one to the other.

Using rule #2:

discovery reach is about $0.05\sqrt{s}$ below exclusion reach

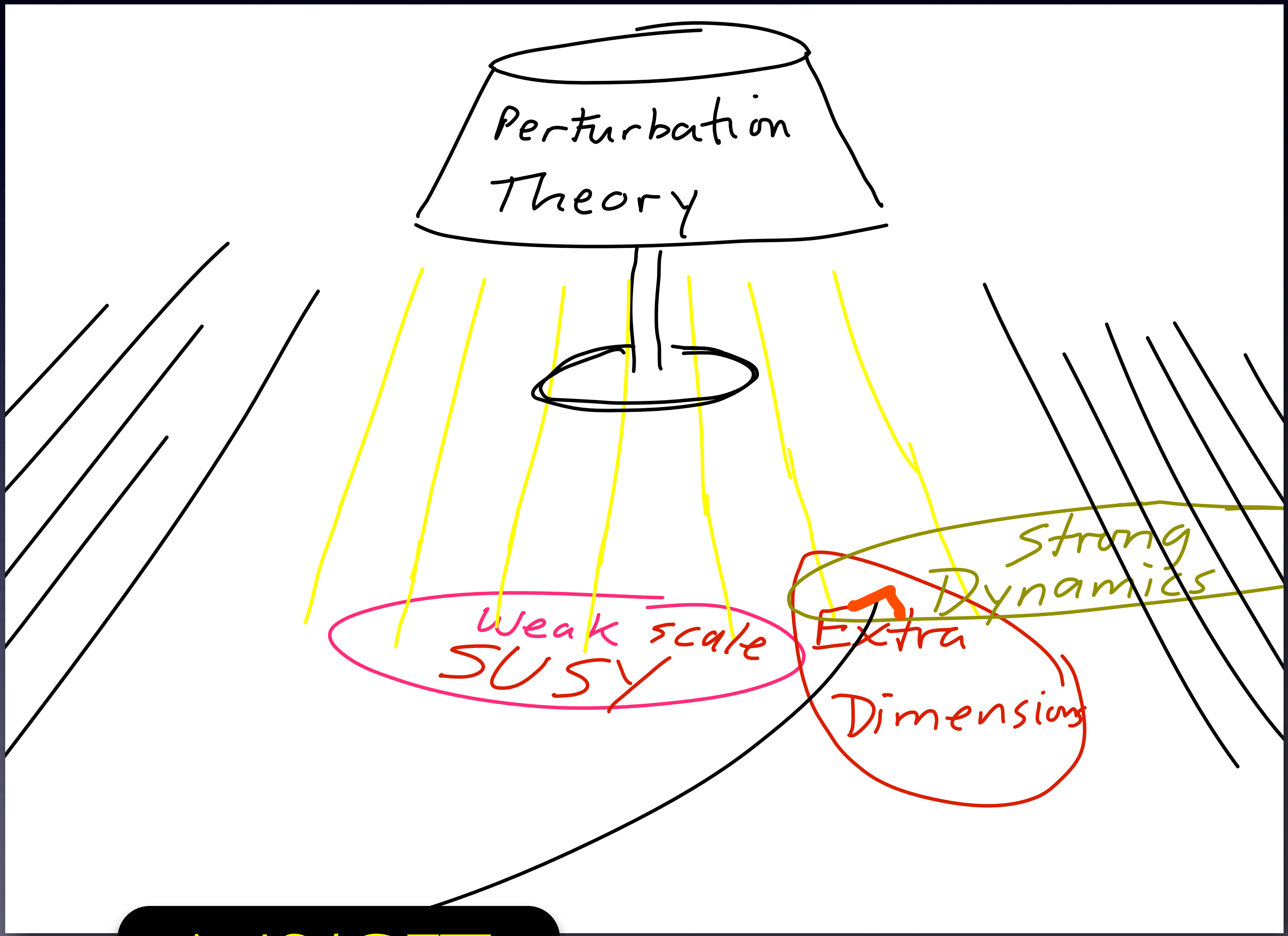
~ 0.8 TeV at 14 TeV



What else?

- We are preparing for run II
- Maybe we won't see a natural resolution of the hierarchy problem
- Need to cover all bases: consider more exotic signatures, think hard about triggers

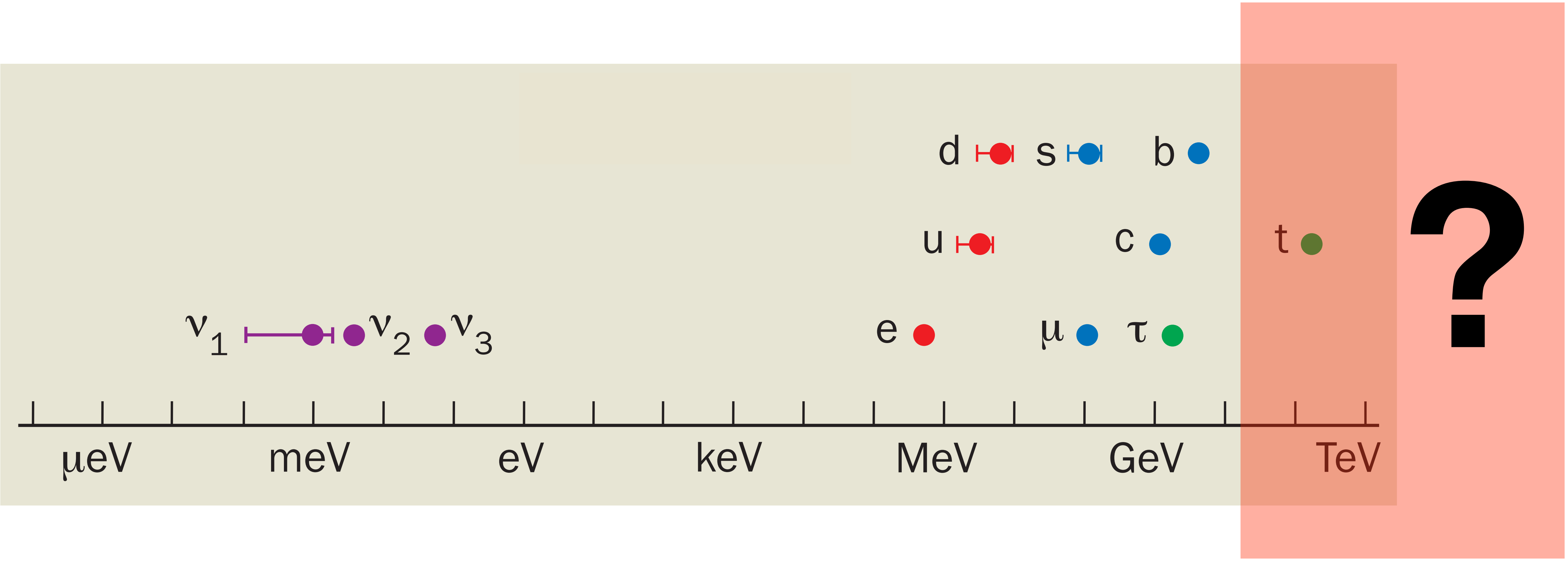
Looking under the lamp-post



AdS/CFT

Home-work

Find the TeV theory
beyond the SM



Conclusion

LHC$_{14}$ will be exciting (tuning $\propto E^2$). Let's be prepared and leave no stone unturned.

Implications of m_H = 125 GeV

Potential is fully radiatively generated

Agashe et. al

$$V_{gauge}(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4} \log\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right)$$

$$s_h \equiv \sin h/f$$

$$\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p)\ , \qquad \Pi_1(p) = 2\left[\Pi_{\hat{a}}(p) - \Pi_a(p)\right]$$

$$\int d^4p\, \Pi_1(p)/\Pi_0(p) \quad < \infty$$

Higgs dependent term UV finite

→ 'Weinberg sum rules'

$$\lim_{p^2\to\infty} \Pi_1(p) = 0\ , \qquad \lim_{p^2\to\infty} p^2\Pi_1(p) = 0$$

UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2+m_\rho^2)(p^2+m_{a_1}^2)}$$

spin 1

Similarly for SO(5) fermionic contribution

Pomarol et al; Marzocca

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

similar result in deconstruction:
Matsedonskyi et al; Redi et al

$5 = 4 + 1$ with EM charges 5/3, 2/3, -1/3

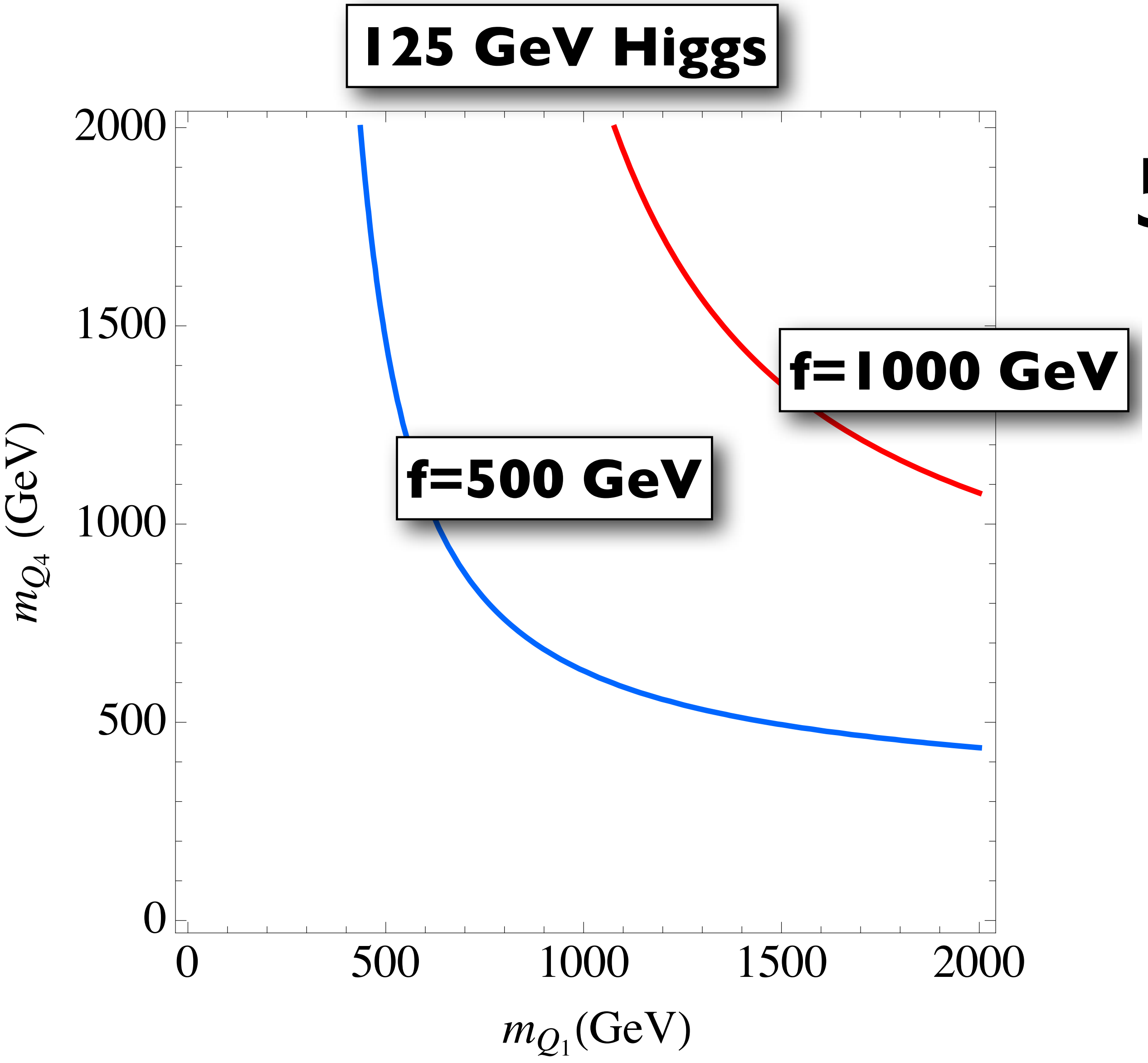
Q_4 Q_1

→ solve for m_h = 125 GeV

Light Higgs implies light fermionic top partners

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

Pomarol et al; Marzocca



5 = 4 + 1

Q_4 Q_1

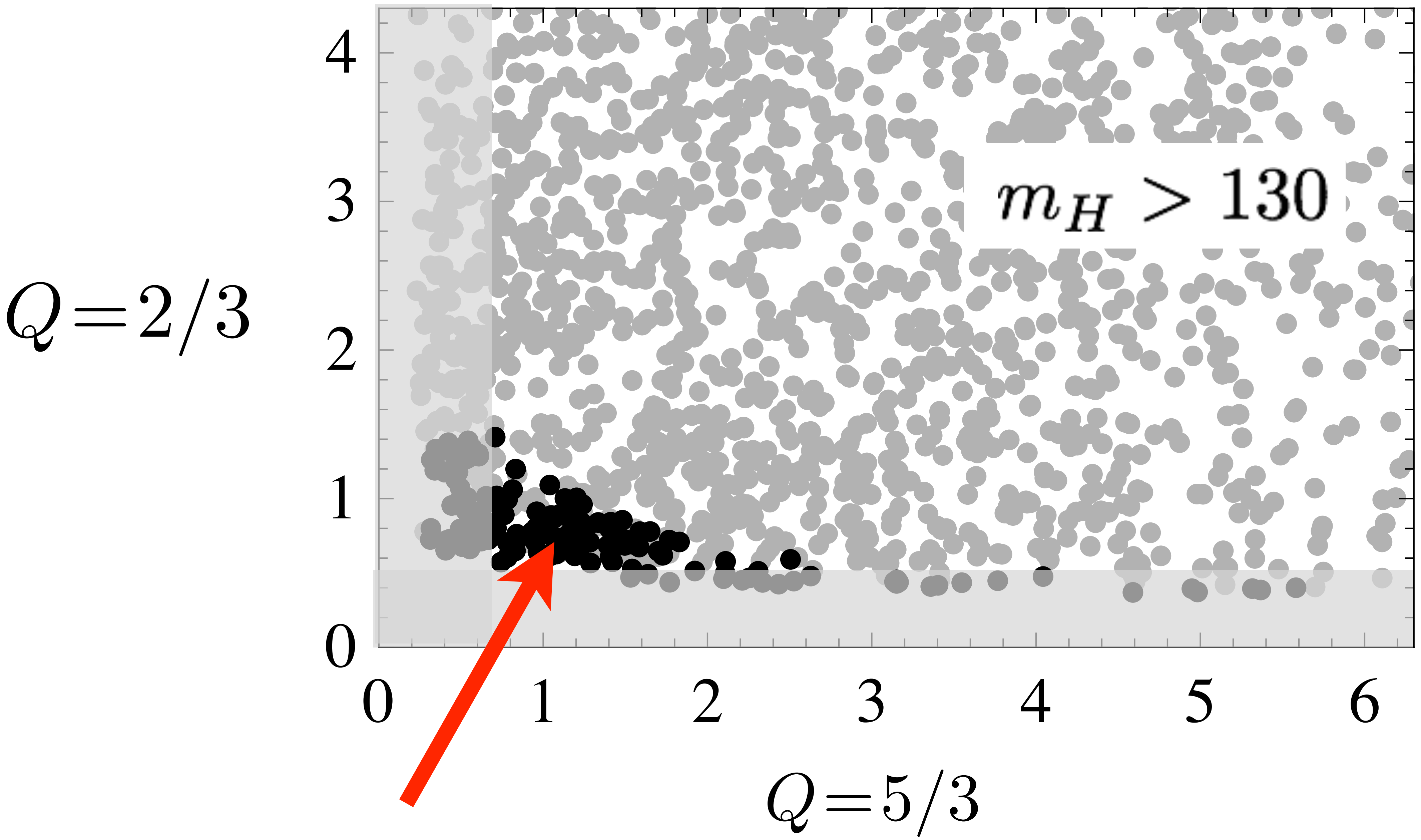
with EM charges 5/3, 2/3,-1/3

Contino et al; Pomarol, Riva;
Matsedonskyi,Panico,Wulzer; Redi,Tesi;
Marzocca,Serone,Shu;

Scan over composite Higgs parameter space

$\xi = 0.2$

from 1204.6333



m_H = 115 … 130 GeV

see e.g. ATLAS-CONF-2013-051