(Broad Dimuon) Resonance Searches at the LHC

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Status

- LHC up and running
- Physics goals beginning
- Resonances will be first and simplest place to look
- Particularly Drell-Yan processes with decays to muons
  - Background well understood
  - Low background at high invariant mass
- Useful for models
  - Z'
  - RS
  - Understanding detector and experiment reach

Our Work

- Understand reach of various LHC parameters
- When does LHC beat Tevatron, even in early run
  - High mass
  - Resonances from glue-glue initial state
  - Wide resonances
- Focus on wide resonances
  - Especially important since large coupling needed for sufficient event rate at low luminosity
- When can we see resonances?
- When can we distinguish them from contact interactions?
- Can we learn about nature of interaction that produced resonance?

Our Focus

- We study *shape* of distribution
- For much of parameter space can distinguish broad resonance from featureless falling distribution (SM or SM +contact)
- Simple: look for “upturn” or absolute rise in rate
- More sophisticated statistical analysis
  - Use both excess events in some bins and absence in others

Also

- Look at other methods to enhance confidence and learn more
- Angular distribution of muons turns out to be quite interesting
- At high statistics can distinguish SM (which has FB asymmetry) from RS (which does not)

Models: I: Brane RS Models

- Only models with SM on brane give potentially visible signatures in early run
  - Lower masses possible
  - Higher production rate
  - Sizable decay to muons

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda_\pi} T^{\mu\nu} h^{(1)}_{\mu\nu}.$$

$$k/M_{\rm Pl}$$

$$\Lambda_\pi = M_{\rm Pl} e^{-\pi k r_c}$$

$$M_n = k\, x_n\, e^{-\pi k r_c} = \left(\frac{k}{M_{\rm Pl}}\right) x_n \Lambda_\pi,$$

$$M_{\rm Pl}^2 = \frac{M^3}{k}(1 - e^{-2\pi k r_c}) \approx \frac{M^3}{k}.$$

$$\frac{k}{M} = \left(\frac{k}{M_{\rm Pl}}\right)^{2/3}.$$

Parameters and cross sections

$$\hat{\sigma}(q\bar{q} \to \mu\bar{\mu}) = \frac{1}{3840\pi\Lambda_\pi^4} \cdot \frac{\hat{s}^3}{(\hat{s} - M_g^2)^2 + \mathrm{Im}\,\Pi(\hat{s})^2}.$$

$$\hat{\sigma}(gg \to \mu\bar{\mu}) = \frac{1}{2560\pi\Lambda_\pi^4} \cdot \frac{\hat{s}^3}{(\hat{s} - M_g^2)^2 + \mathrm{Im}\,\Pi(\hat{s})^2}.$$

$$\mathrm{Im}\,\Pi(\hat{s}) \approx \mathrm{Im}\,\Pi(M_g^2) = M_g\,\Gamma.$$

$$\Gamma \sim M_g \left(\frac{k}{M_{\mathrm{Pl}}}\right)^2 \left[1 + \mathcal{O}\left(\frac{m^2}{M_g^2}\right)\right].$$

On vs Off Resonance

On peak:

$$\hat{\sigma}(M_g^2) \sim \frac{1}{M_g^2}.$$

Off peak-need to integrate against parton distribution
Estimate using narrow width.

$$\frac{1}{(\hat{s} - M_g^2)^2 + M_g^2\Gamma^2} \approx \frac{\pi}{M_g\Gamma}\delta(\hat{s} - M_g^2)$$

$$\sigma \sim \frac{(k/M_{\rm Pl})^2}{s}\frac{d\mathcal{L}}{d\tau}(M_g^2, s).$$

Favors wide states, large k/M, Resonance mass through luminosity

Z' Models

- New U(1)' gauge symmetry
- Of course analysis could apply to other states as well

$$\mathcal{L}_{Z'} = g_{Z'}\, Z'_\mu J^\mu_{Z'}$$

$$J^\mu_{Z'} = \sum_f Q(f)\, \bar{f}\gamma^\mu f.$$

$$\epsilon = \frac{g_{Z'}}{g_Z}.$$

$$\Gamma \sim M_{Z'}\,\epsilon^2 \left[1 + \mathcal{O}\left(\frac{m^2}{M^2_{Z'}}\right)\right].$$

$$\hat{\sigma} \sim \frac{1}{M^2_{Z'}}$$

$$\sigma \sim \frac{\epsilon^2}{s}\frac{d\mathcal{L}}{d\tau}(M^2_{Z'}, s).$$

Structure just like before, favor large coupling here too, again mass through luminosity

Z’ Model

- Need also in this case to specify what Z’ couples to
- Anomaly cancellation only rigorous constraint
- Minimal models have only right-handed neutrinos
  - Linear combination of hypercharge and B-L for each fermion type
- Hypercharge component leads to mixing with Z
  - Strongly constrained
- B-L: If flavor universal, constrained through electron interactions
  - Muon models have larger parameter space available
  - Especially important when coupling large

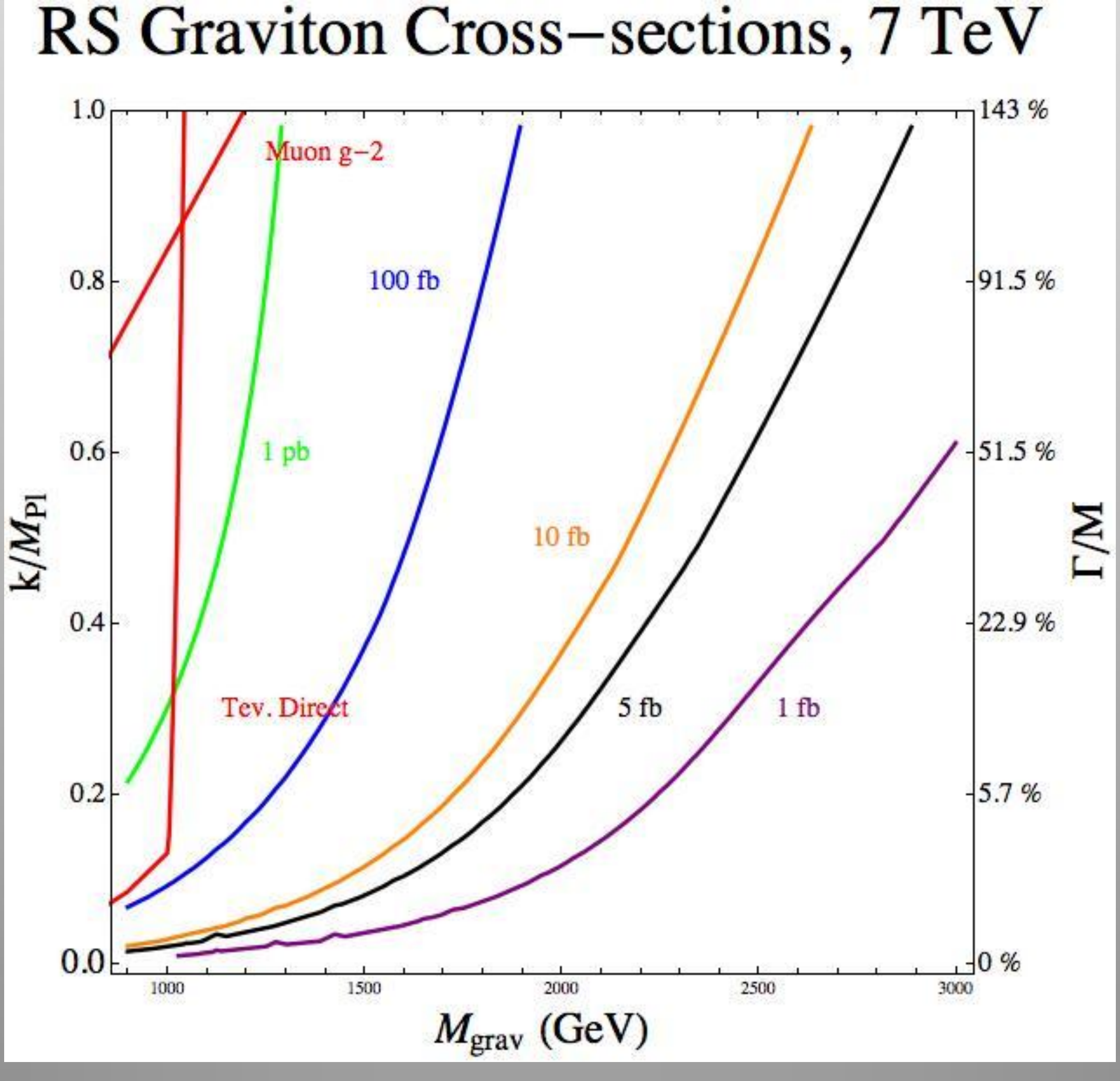
LHC Cross Sections

- Early LHC: 7 TeV, 1 fb-1
- Mid LHC: 10 Tev, 10 fb-1
- Real LHC: 14 TeV, 100 fb-1
- We compute cross sections from RS gravitons and Z', compare to SM and contact interactions
- Do not employ narrow width
- Integrate over 4 Γ

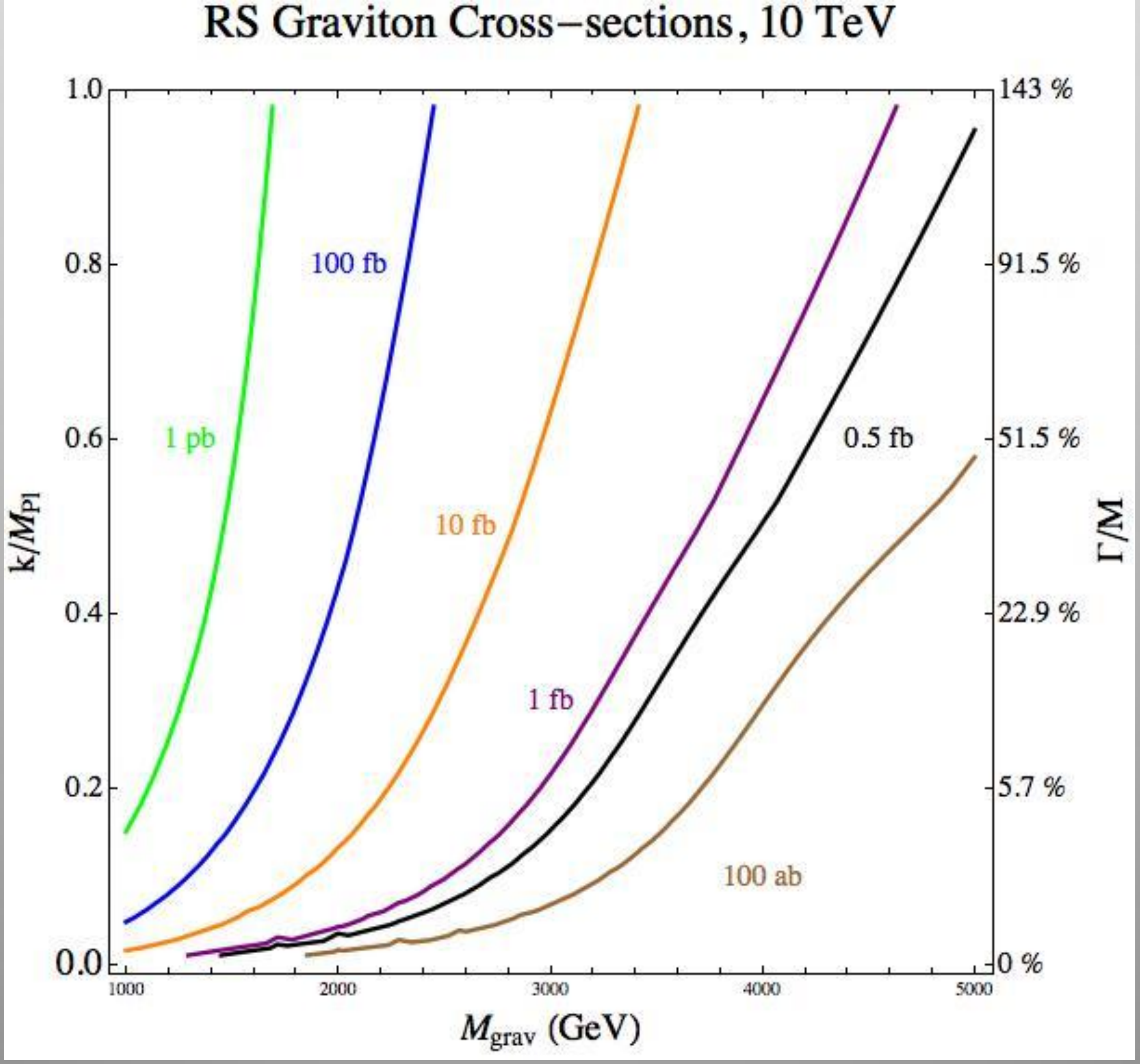
Constraints

- Perturbativity (overly constrained in previous analyses)
- Indirect Searches from LEP and Tevatron (effective contact interactions)
- LEP and Tevatron Direct Bounds
- Muon g-2

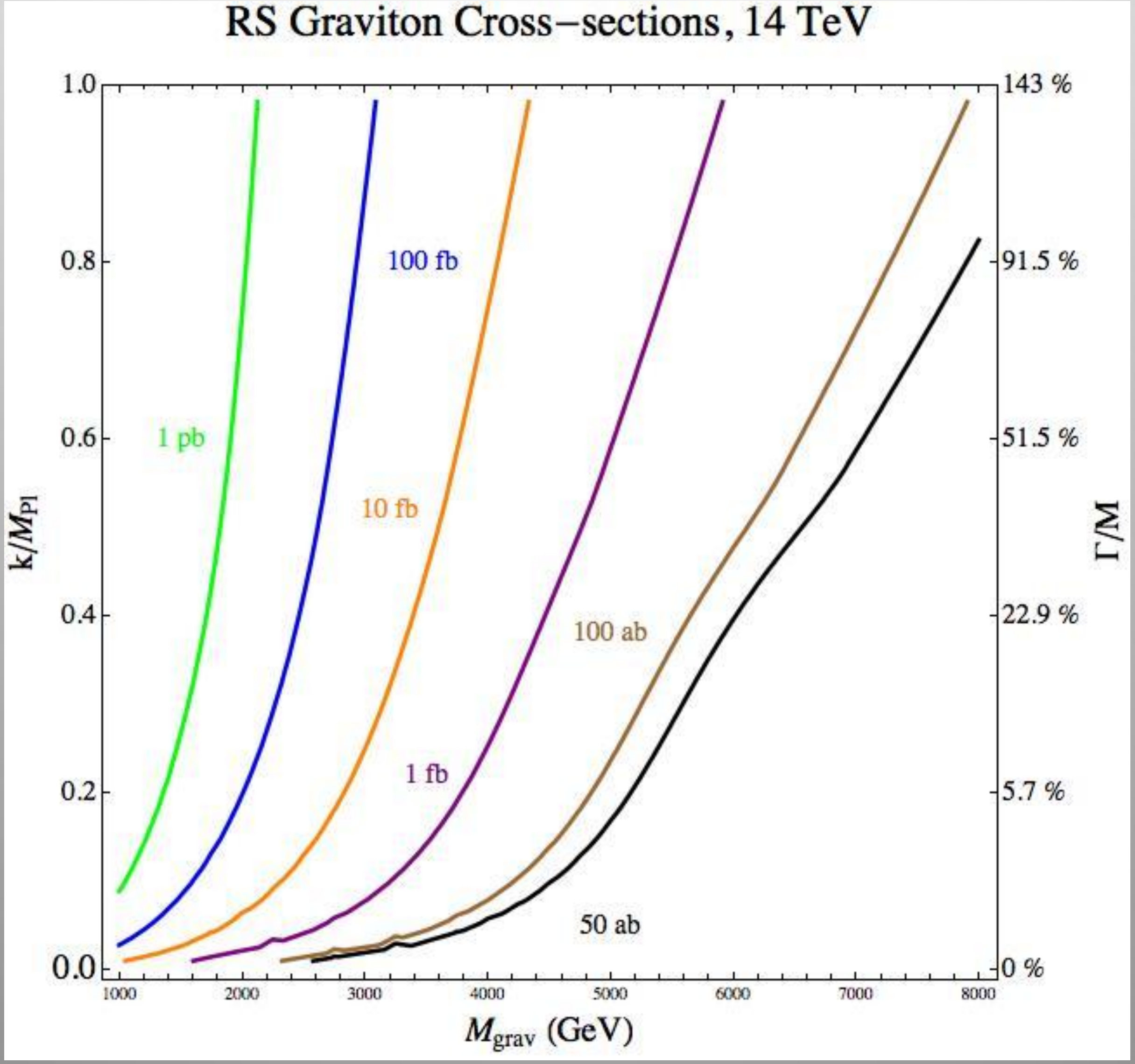
Cross Sections



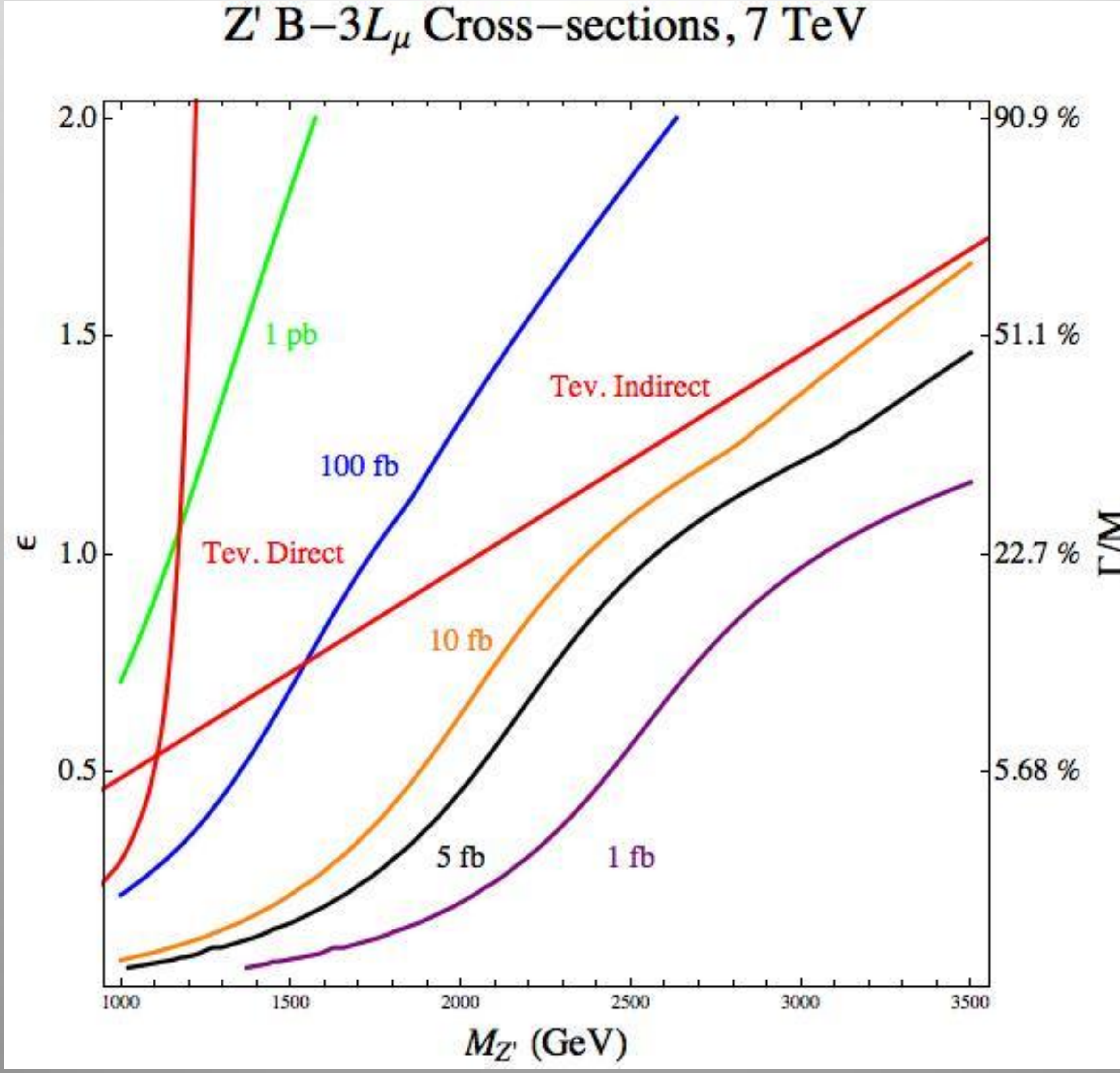
Cross Sections



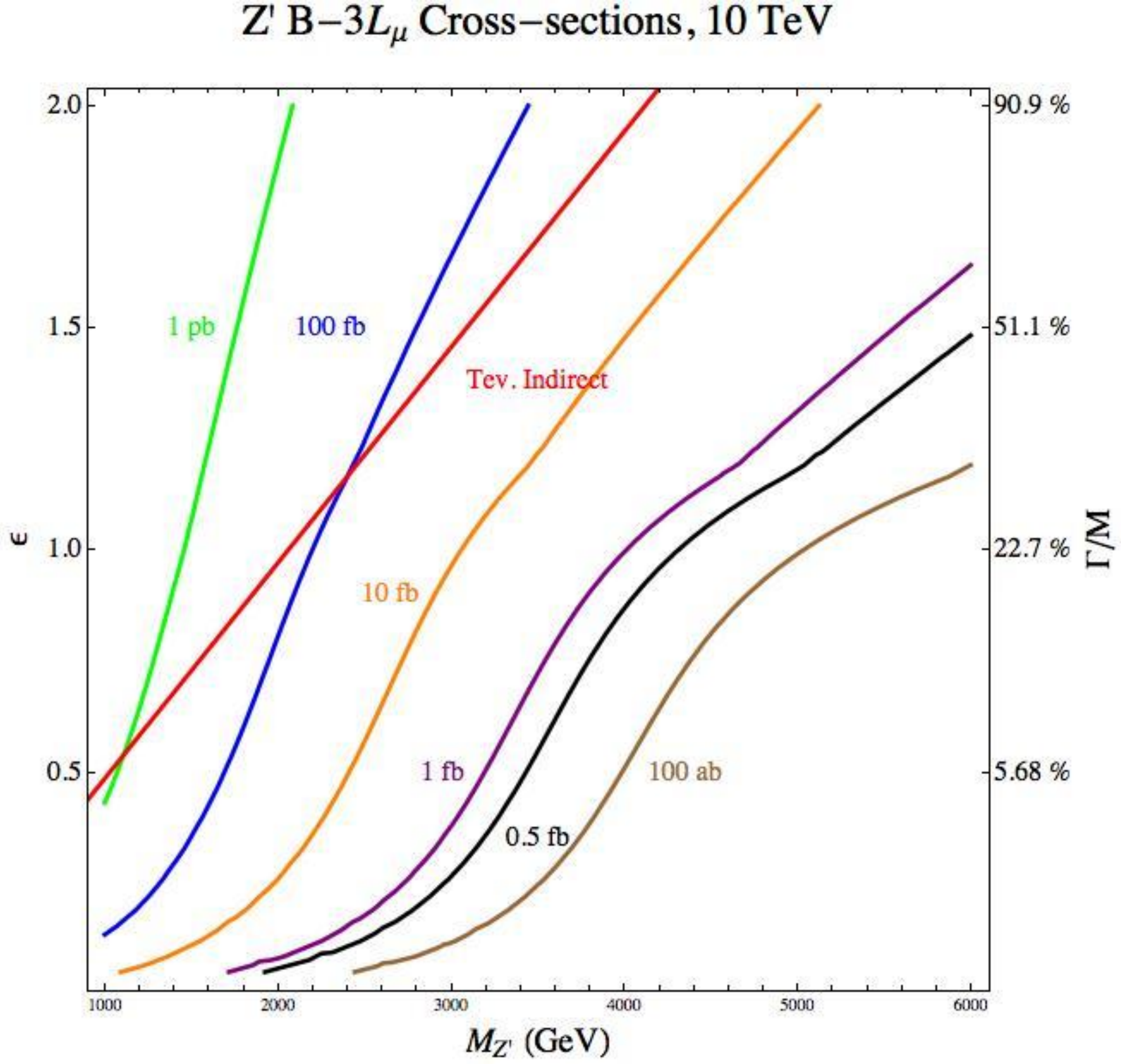
Cross Sections



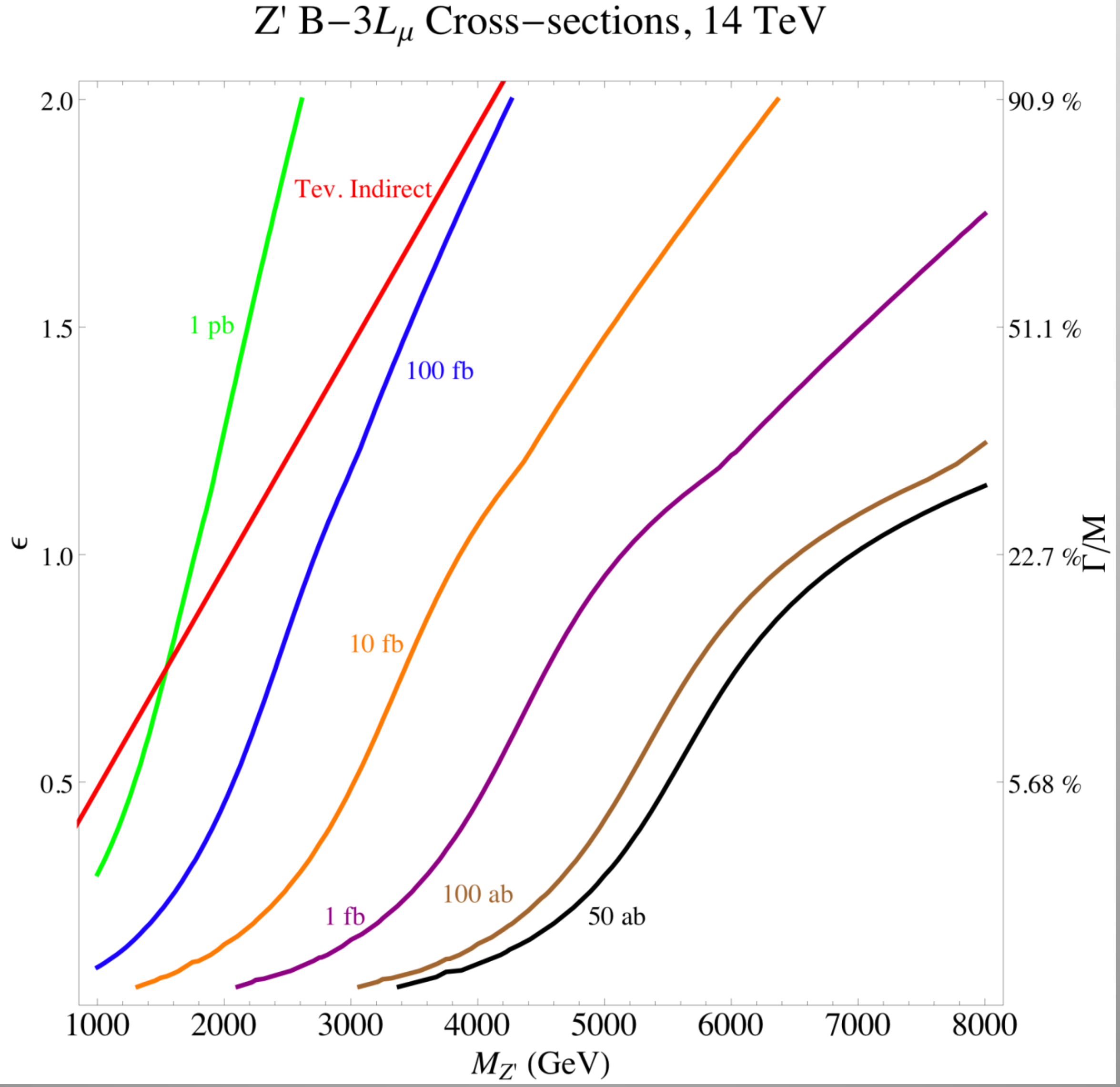
Cross Sections



Cross Sections

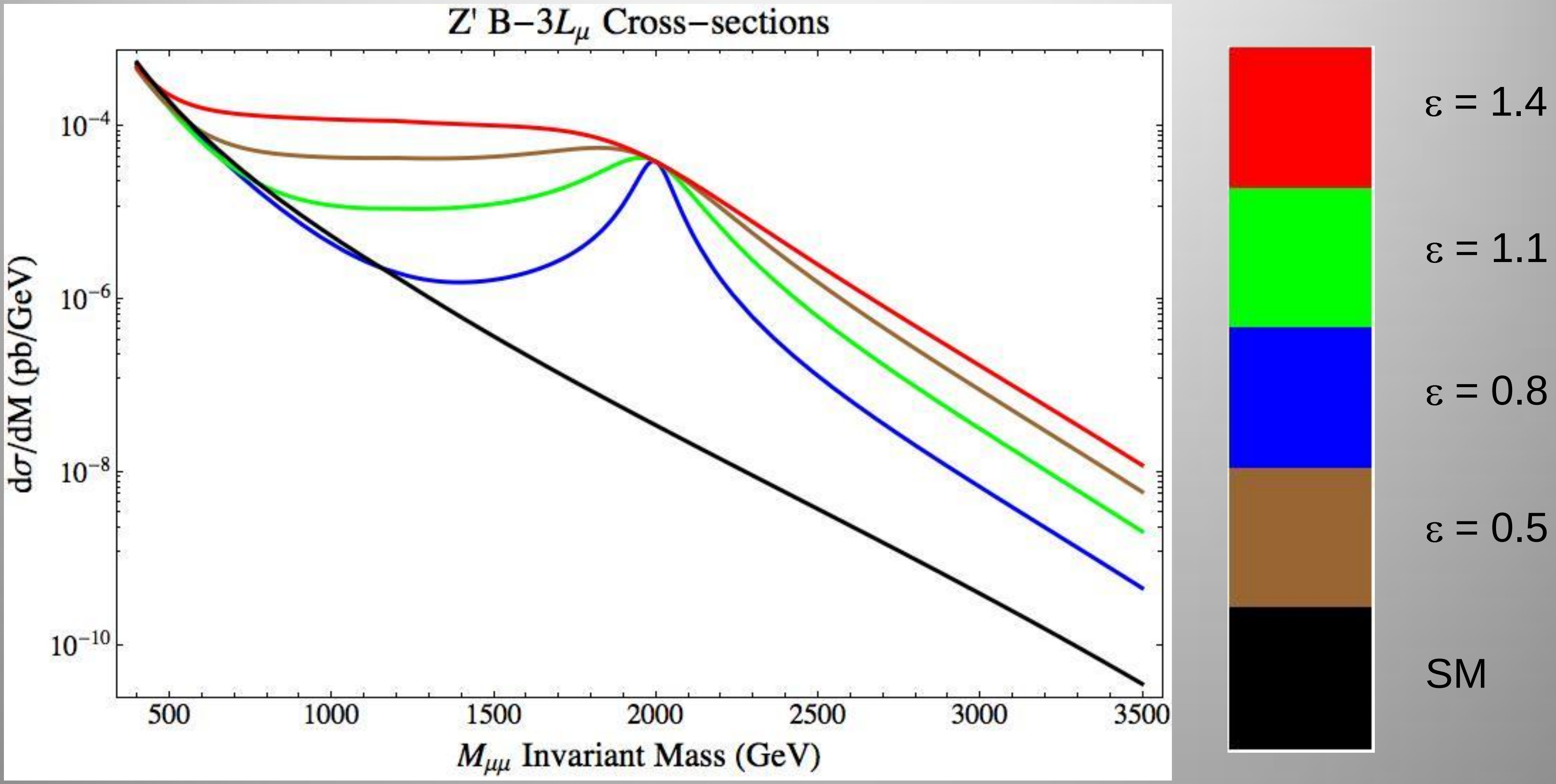


Cross Sections



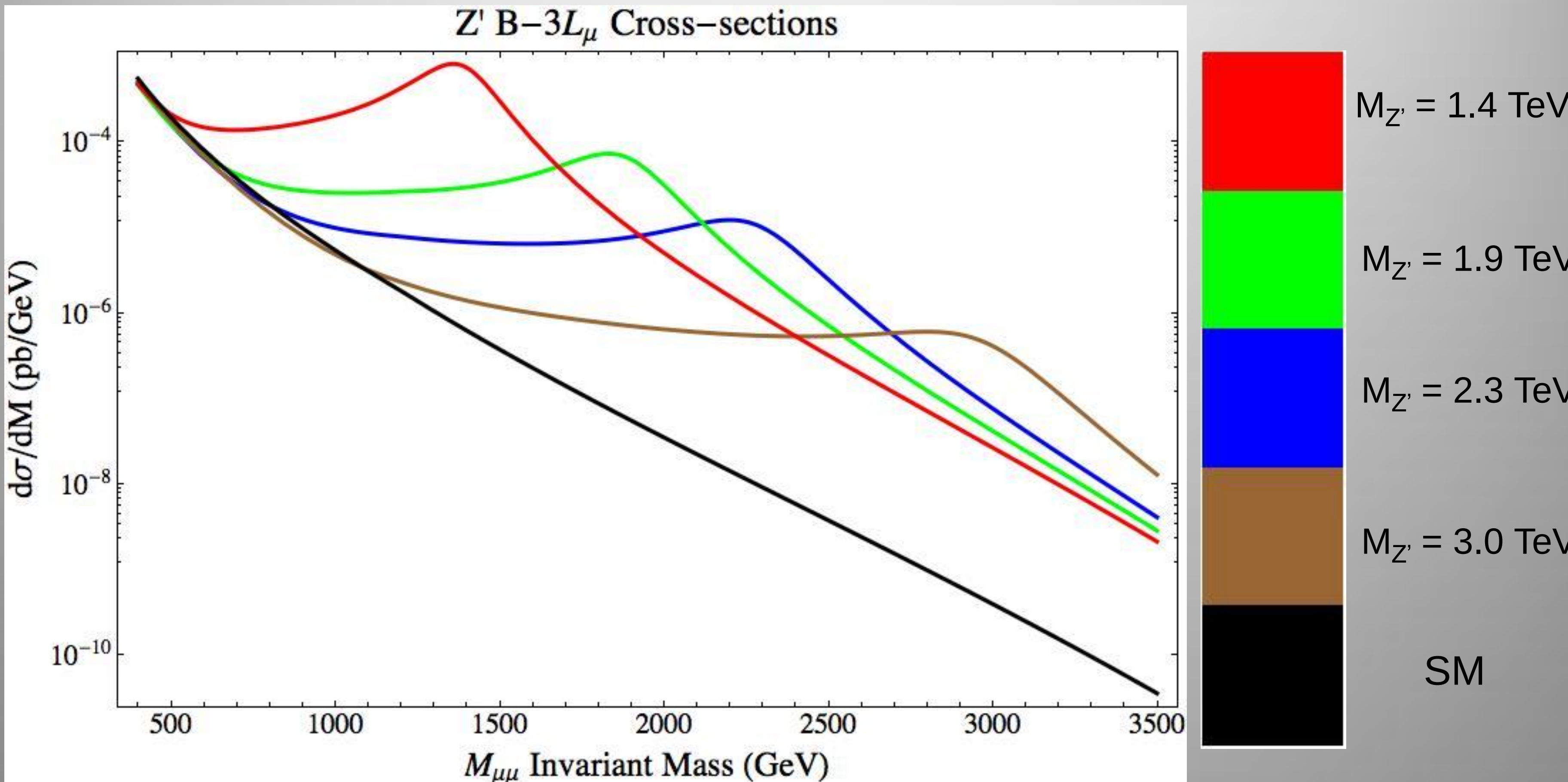
What are we looking for?

Z’ X-sections (varying ε)



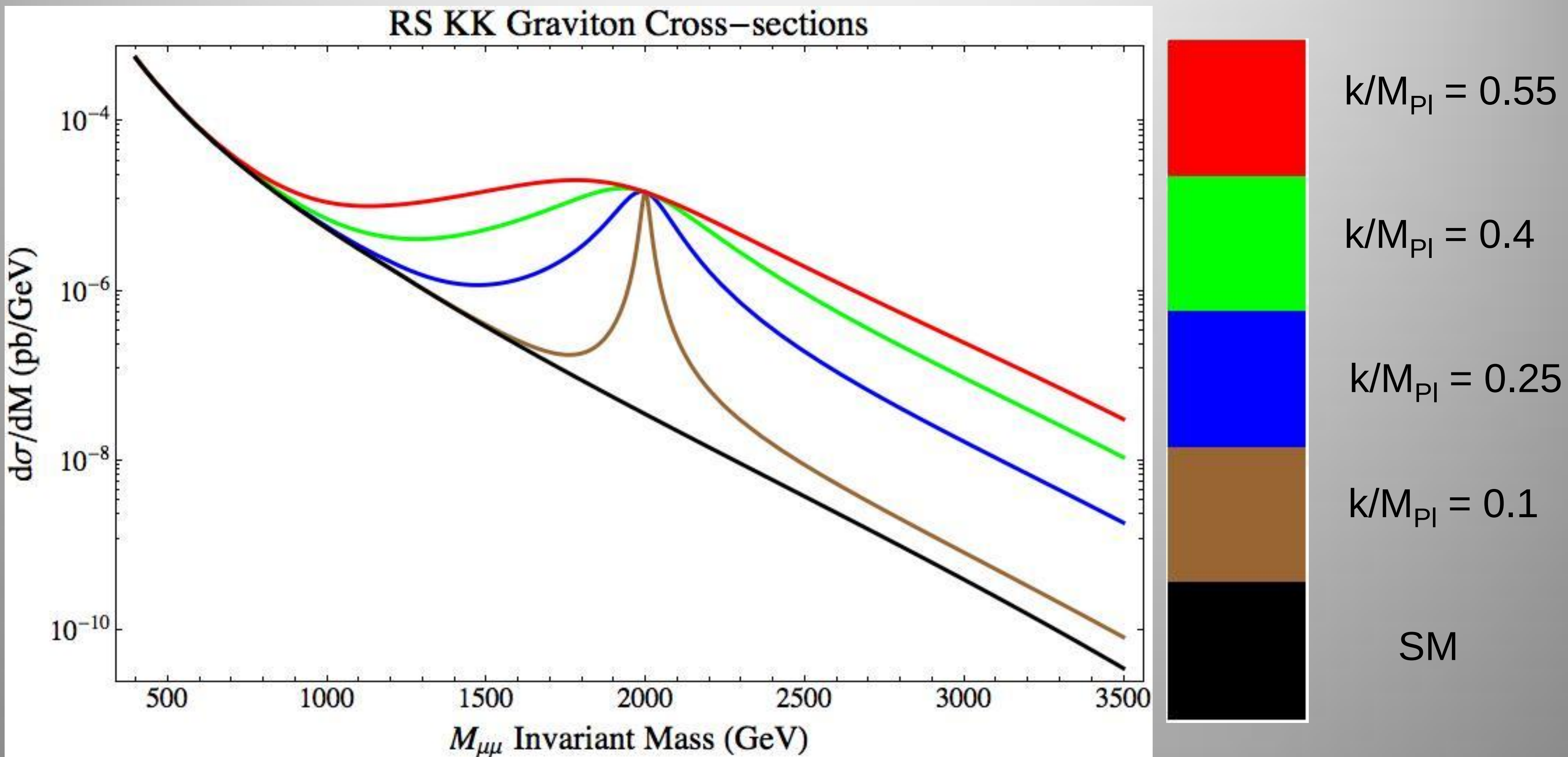
$M_{Z'}$ = 2 TeV

Z’ X-sections (varying mass)



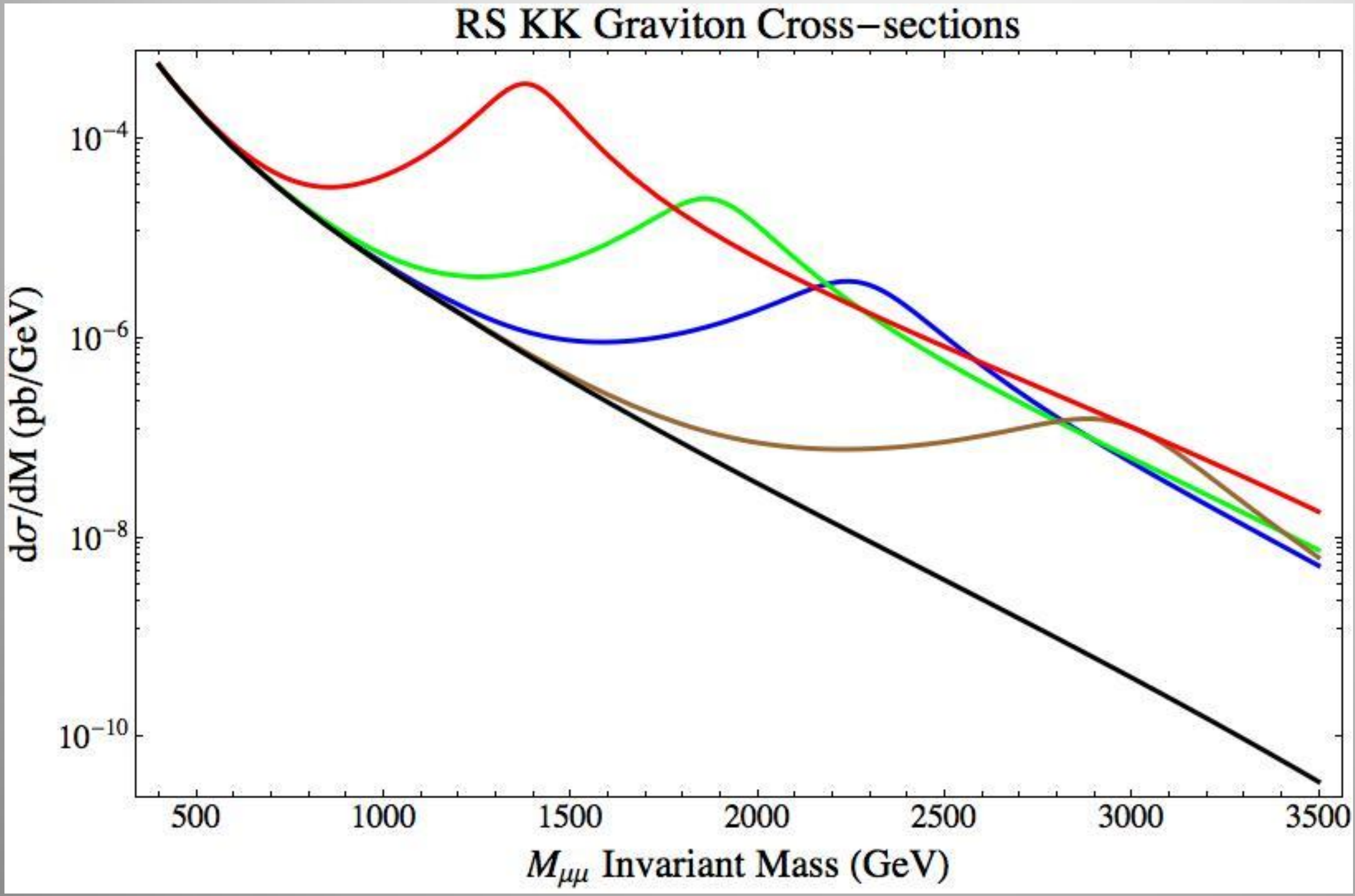
ε = 1.0

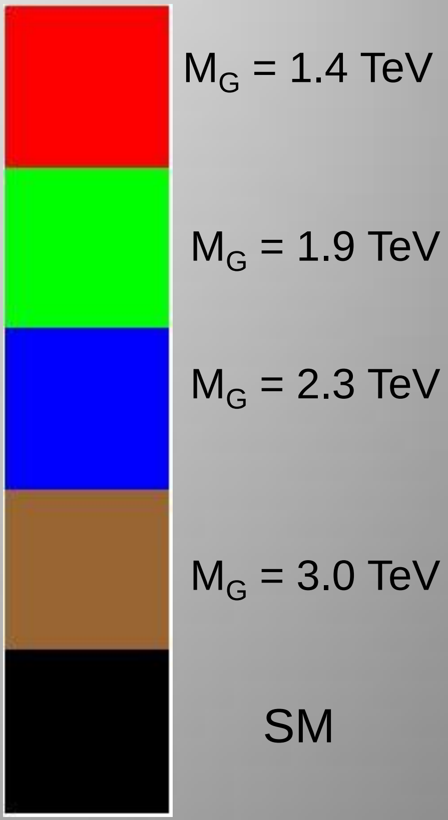
RS X-sections (varying k/M_{Pl})



M_G = 2 TeV

RS X-sections (varying mass)





k/M_{Pl} = 0.35

Statistically Distinguish from Contact Interactions

- Contact interactions also lead to rise in cross section

$$\mathcal{L} = \frac{4\pi}{\Lambda^2}\Big[\eta_{\rm LL}\left(\bar{\psi}_{\rm L}\gamma^\nu\psi_{\rm L}\right)\left(\bar{\chi}_{\rm L}\gamma_\nu\chi_{\rm L}\right) + \eta_{\rm LR}\left(\bar{\psi}_{\rm L}\gamma^\nu\psi_{\rm L}\right)\left(\bar{\chi}_{\rm R}\gamma_\nu\chi_{\rm R}\right)$$
$$+\eta_{\rm RL}\left(\bar{\psi}_{\rm R}\gamma^\nu\psi_{\rm R}\right)\left(\bar{\chi}_{\rm L}\gamma_\nu\chi_{\rm L}\right) + \eta_{\rm RR}\left(\bar{\psi}_{\rm R}\gamma^\nu\psi_{\rm R}\right)\left(\bar{\chi}_{\rm R}\gamma_\nu\chi_{\rm R}\right)\Big]$$

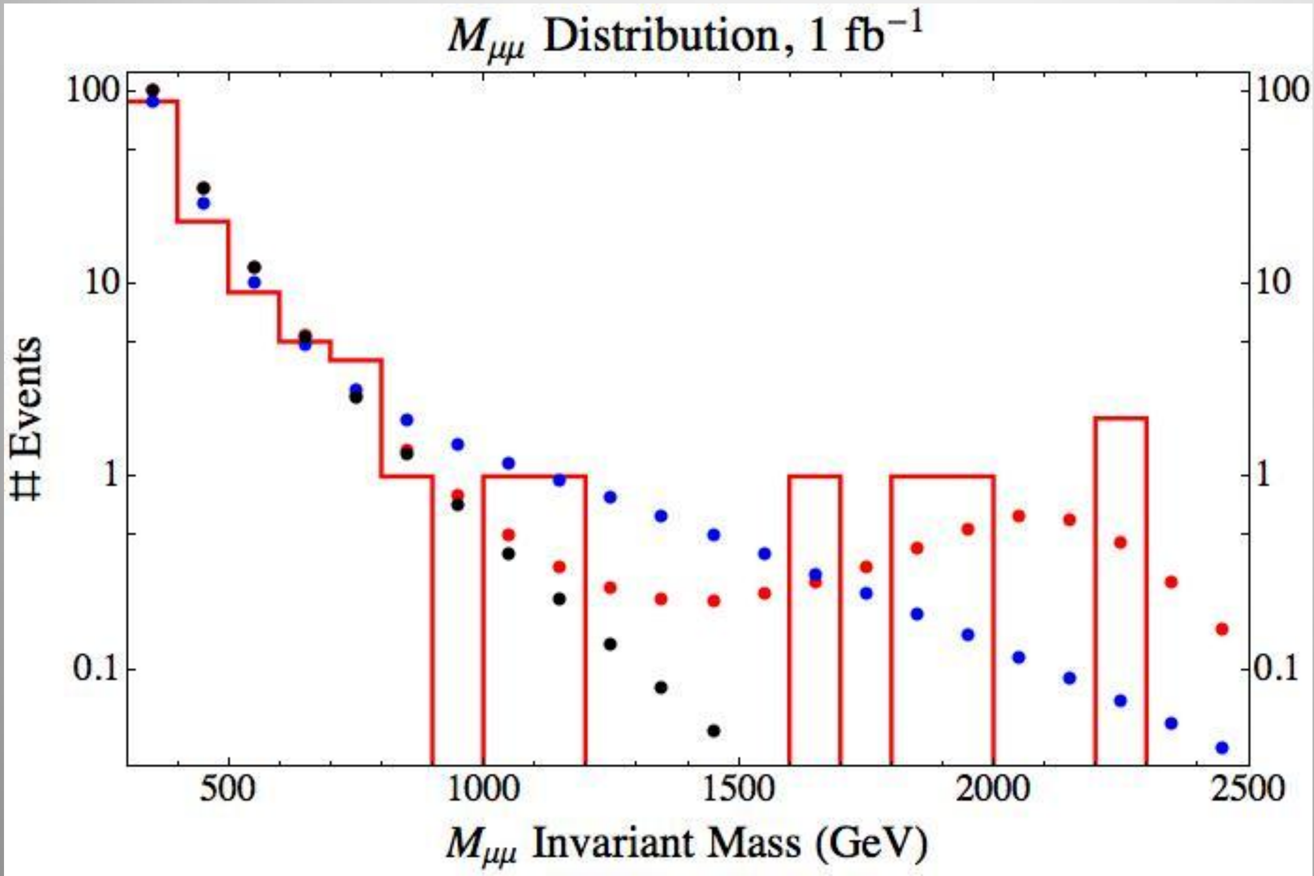
Λ is scale of contact interaction

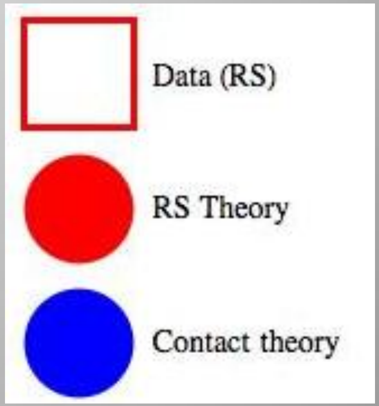
$\eta = -1, 0, 1$

$\eta < 0$ is constructive interference

Shape analysis distinguishes types of new physics as well as help distinguish new physics from background

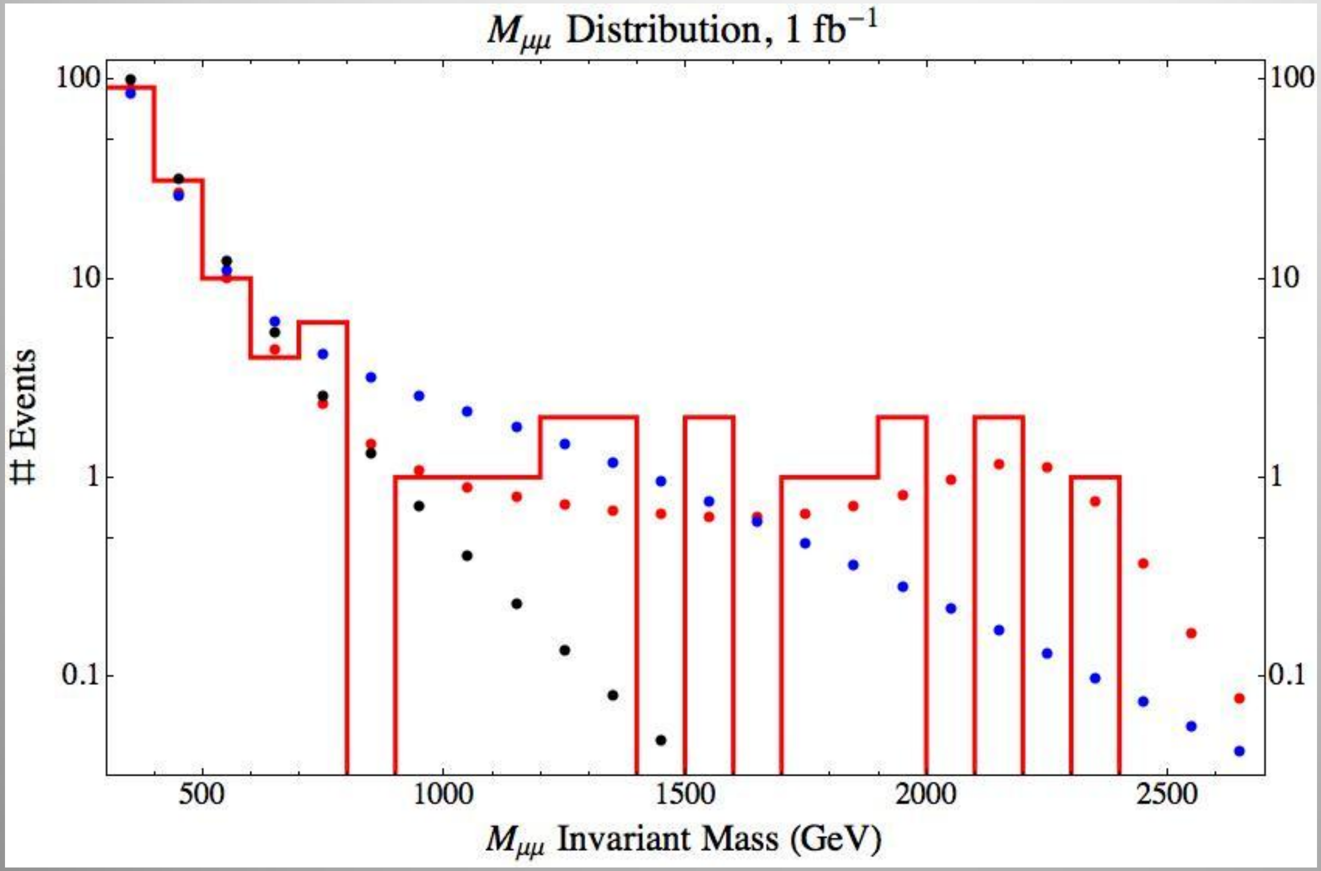
Simulation (RS)

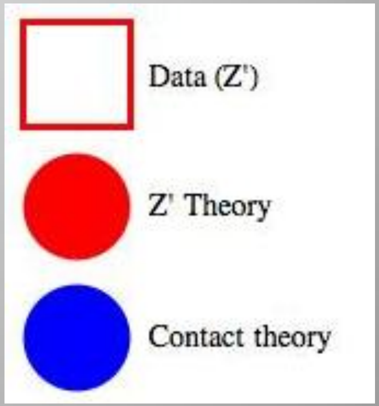




$k/M_{Pl} = 0.425$, $M_G = 2.2$ TeV, $\Gamma/M = 25.8\%$

Simulation (Z')



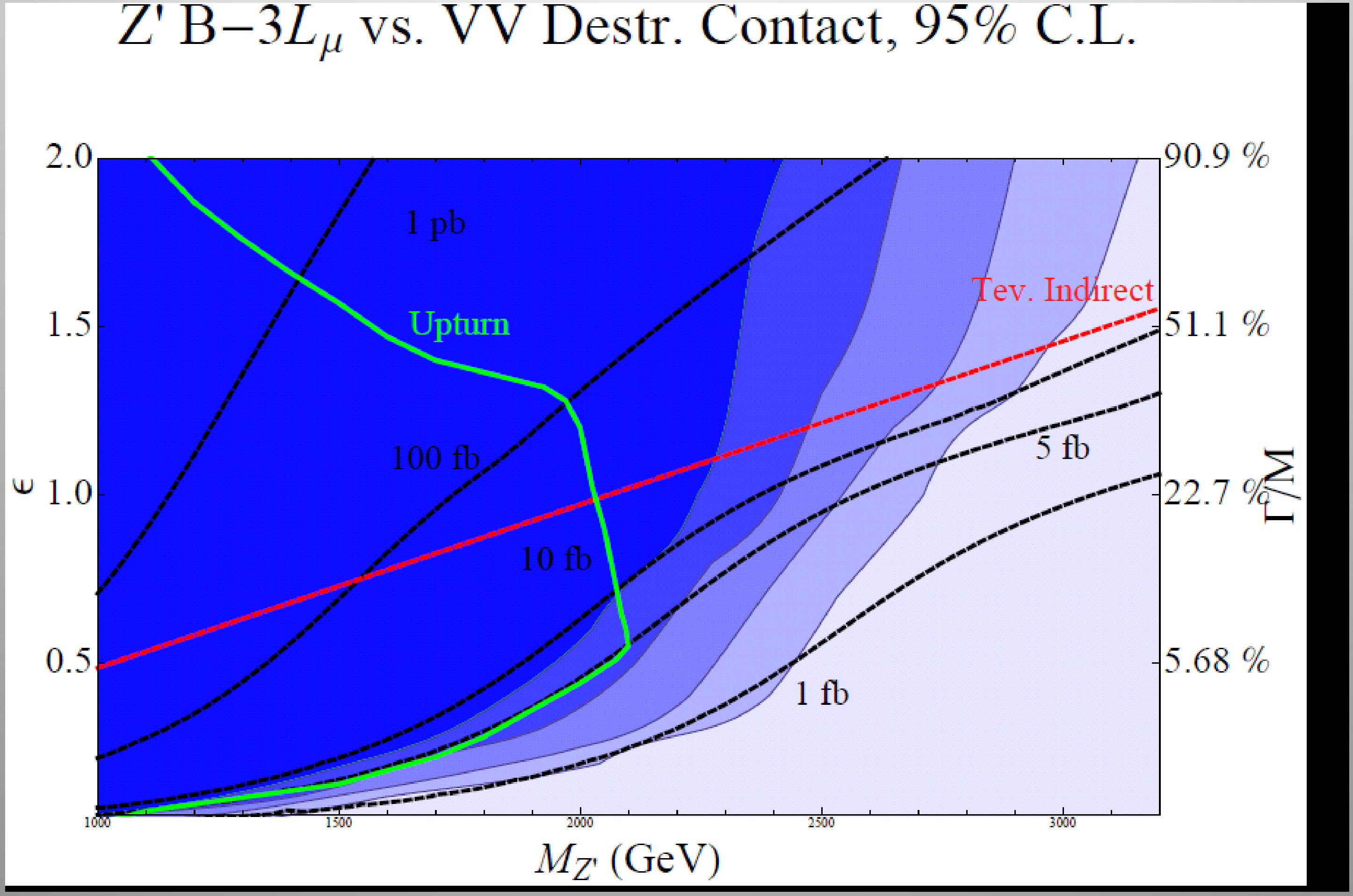


$\varepsilon = 0.9$, $M_G = 2.3$ TeV, $\Gamma/M = 18.4\%$

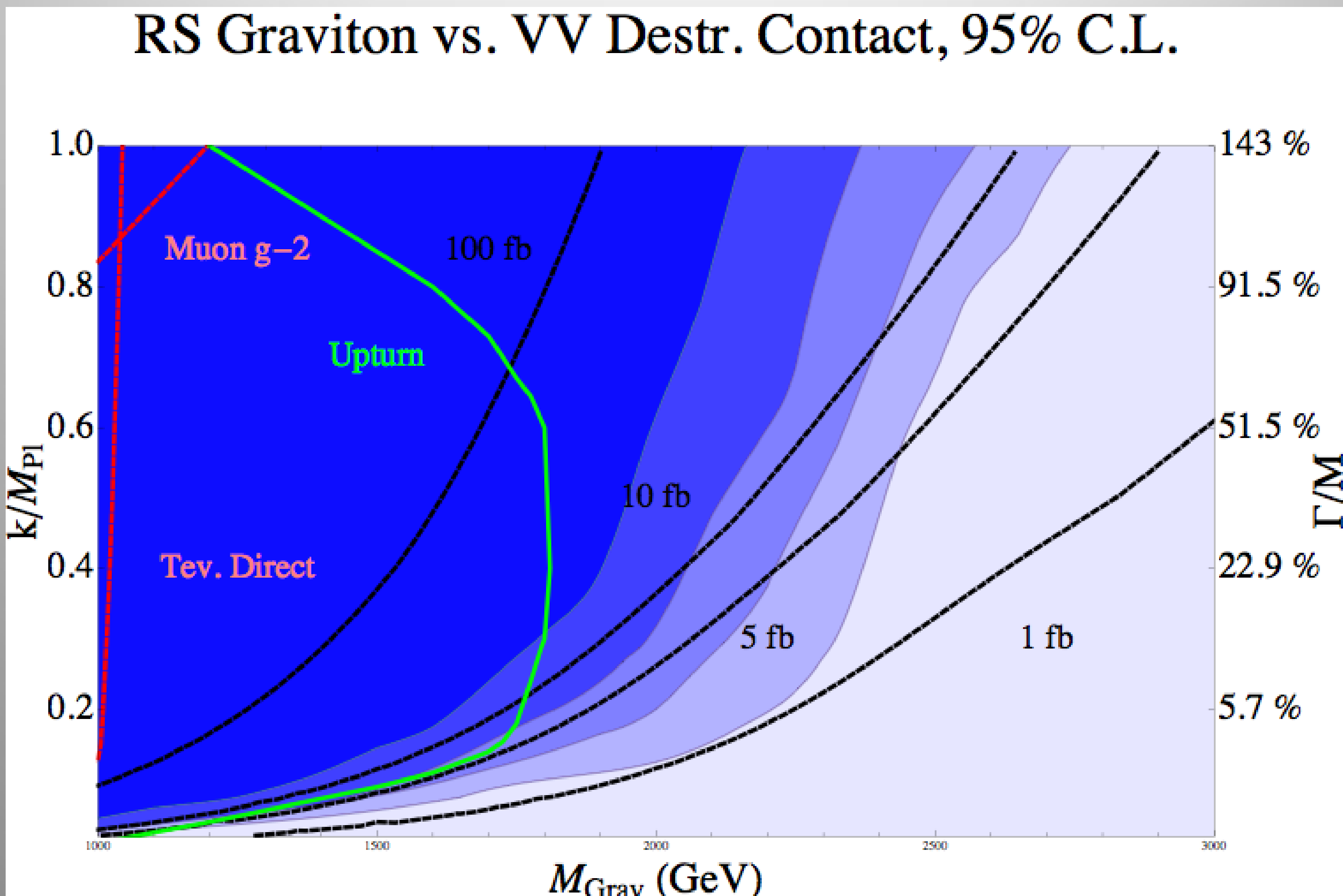
Shape

- Cross section not all the information available
- Shape also important
- Obvious feature: resonance-even broad one-can have increase and then decrease in cross section
  - Successful over low mass, not too broad region
  - Not as accurate as possible (fluctuations?)
  - Also too conservative since background falling, not constant

“Upturn” Analysis



“Upturn” Analysis



Better: Binned Maximum Likelihood Analysis

- Usual χ^2 relies on normal distribution
- High mass and low stats, Poisson and normal distributions will diverge
- Maximize instead full likelihood function

$$L(\mu_i, n_i) = \prod_i f(\mu_i; n_i),$$

$$f(\mu, n) = \frac{e^{-\mu}\mu^n}{n!}$$

i labels bins, μ expected number of events in a bin, n actual number of events, $f(\mu, n)$ is the Poisson distribution probability function

μ function of parameters (eg Λ, or k/m and Mg)

New Statistic

- Construct Maximal Likelihood Ratio
- Poisson maximizes λ for any bin
- λ <1
- μ are functions of parameters of model (eg Λ, k/m, Mg)
- Q=-2 log λ ranges from 0 to infinity (like χ^2)

$$\lambda = \frac{L(\mu_i, n_i)}{L(n_i, n_i)}.$$

Properties

- Good fit: small Q
- Bad fit: large Q
- Large μ: distribution approaches usual χ^2

$$\langle\chi^2\rangle = N \text{ and } \mathrm{Var}(\chi^2) = (2 + 1/\mu)N \text{ for } N \text{ bins}$$

Shortcoming: higher mean bins have somewhat larger effect on Q
Need to check high statistical fluctuations don't mask small ones

Also more difficult to apply: mean and variance of Q depends on bin means
Can't use predetermined Q range to determine goodness of fit
Need to do MC analysis for competing models

Method

- Distinguish Z' or RS from contact interactions
- (SM assumed to be small background)
- Fit Q based on contact interaction (one parameter) and resonance (two parameters) to data: find Q_c, Q_r
- For Poisson distribution:

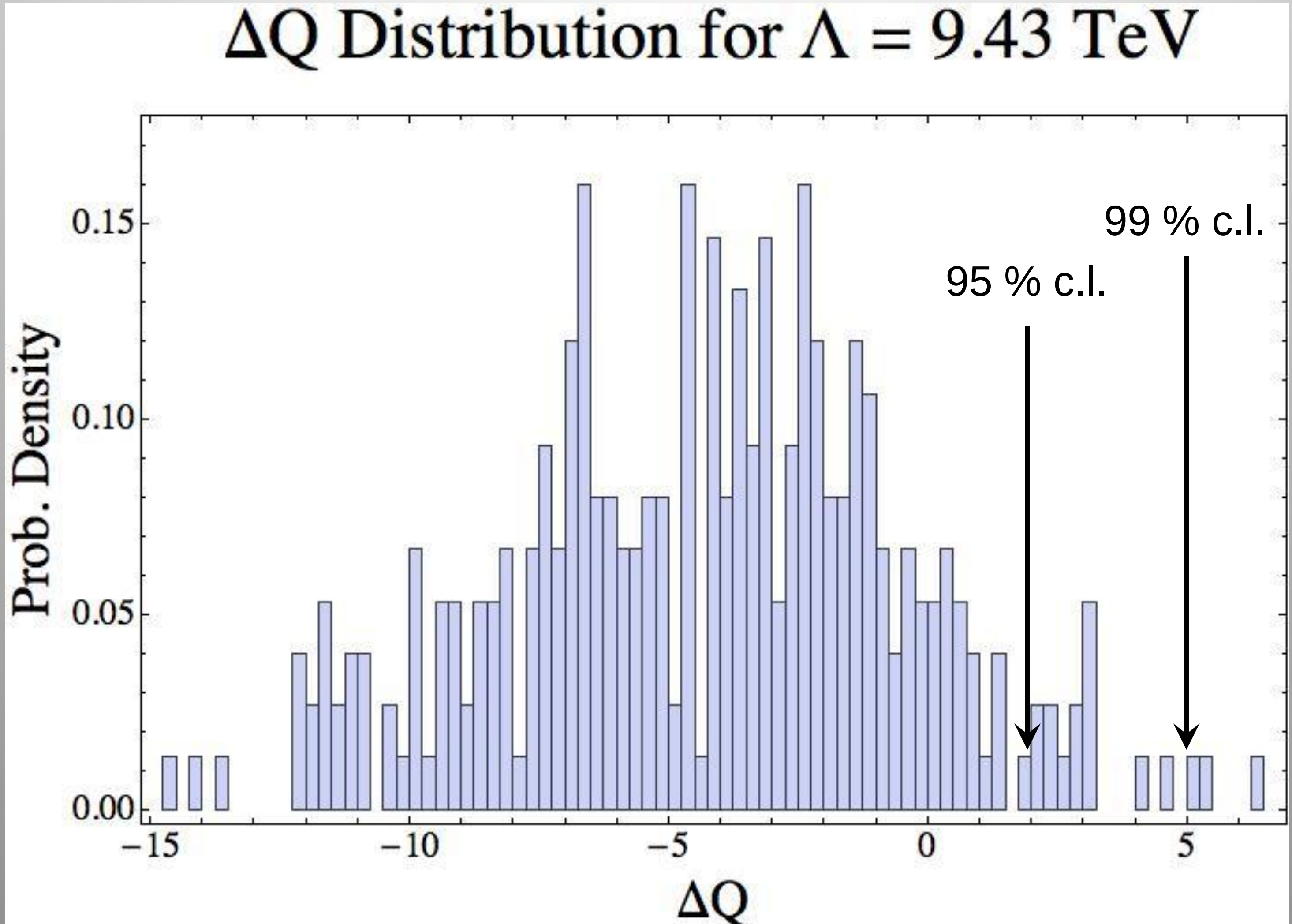
$$Q = 2\sum_i \left(\mu_i - n_i + n_i \ln \frac{n_i}{\mu_i} \right).$$

$$\Delta Q = Q_c - Q_r = 2\sum_i \left(\mu_{i\,c} - \mu_{i\,r} + n_i \ln \frac{\mu_{i\,r}}{\mu_{i\,c}} \right).$$

Which is better fit?

- Negative ΔQ: contact interaction
- Positive ΔQ: resonance
- But how well can they be distinguished?
- Unlike χ^2, need to build up distribution of ΔQ from statistical fluctuations of contact interaction
- Simulate data assuming contact interaction with best fit model for Λ (ultimately from “data”)
- ΔQ distribution based on many MC “runs”
- Normalize histogram and compare to original ΔQ from original “data”
- Eg Need to ensure resonances distinguishable from contact interactions at 95% cl

N.B.: Here, the *contact interaction* is used to generate experiments for this distribution.

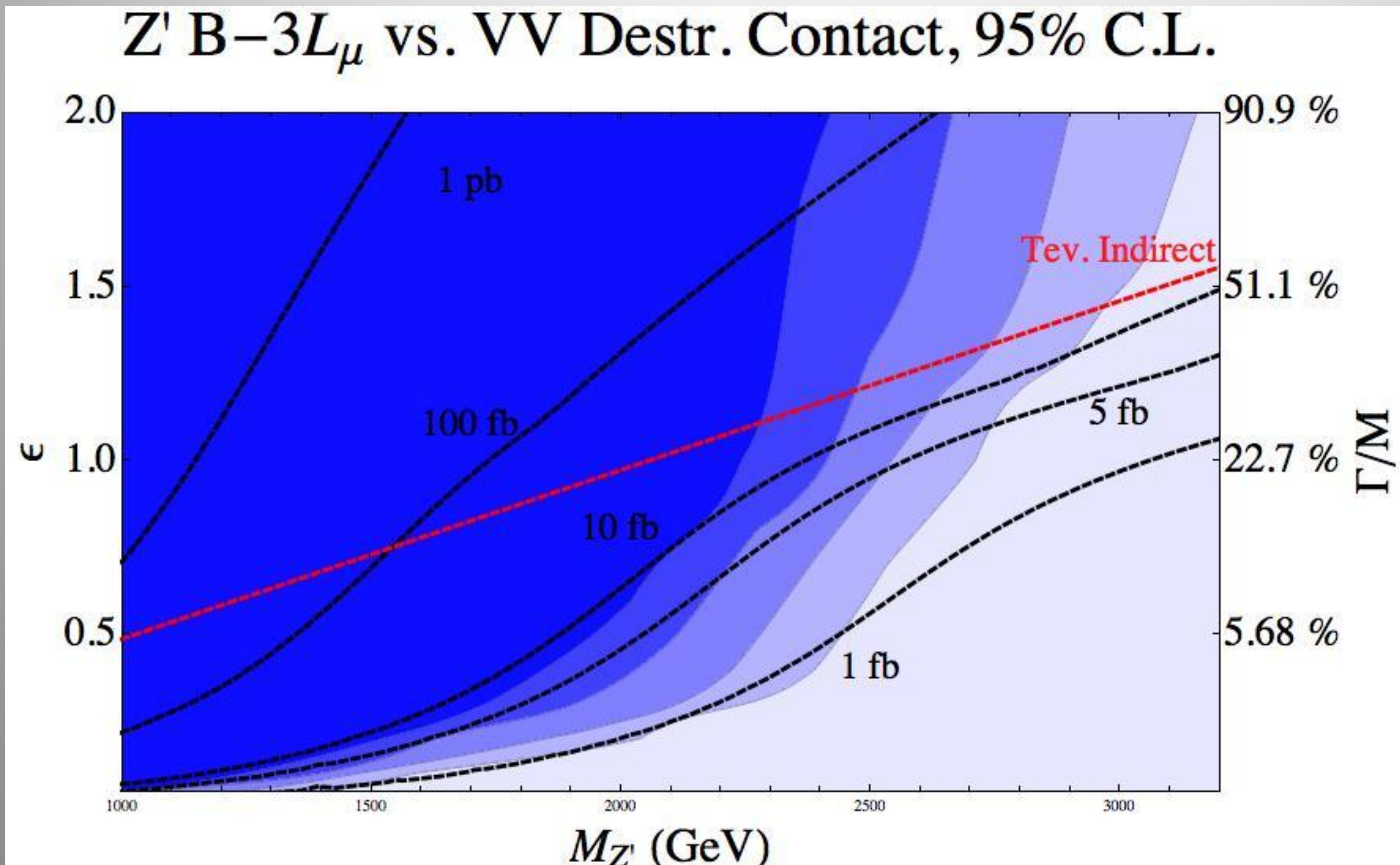


at the 95% confidence level. Then, we need to make sure that the ΔQ from the data is larger than 95% of the values from the contact interaction simulations.

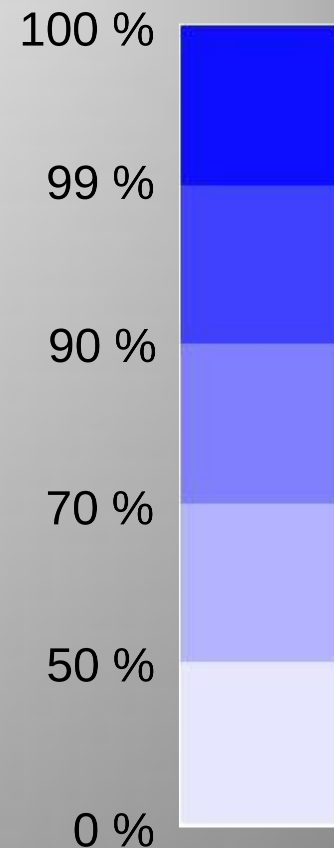
Reliability

- Need to ensure not statistical fluke:
- Run many times and require eg 90% of simulated runs exceed 95% cl
- Curves to show how often fit distinguishable at given confidence level

Results

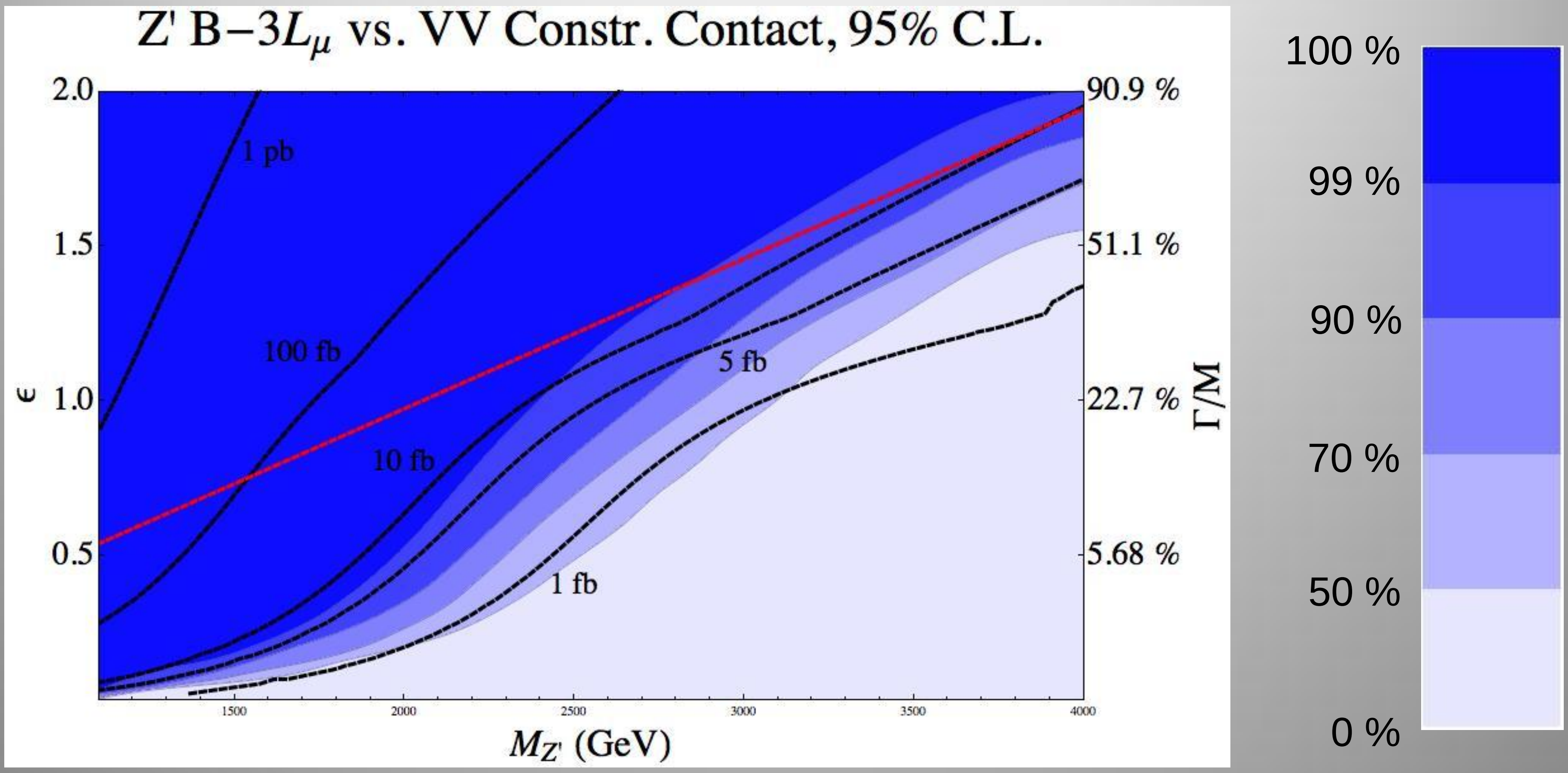


Z' B−3L_μ vs. VV Destr. Contact, 95% C.L.
2.0
1.5
1.0
0.5
ϵ
1 pb
100 fb
10 fb
5 fb
1 fb
Tev. Indirect
90.9 %
51.1 %
22.7 %
5.68 %
Γ/M
1000
1500
2000
2500
3000
$M_{Z'}$ (GeV)



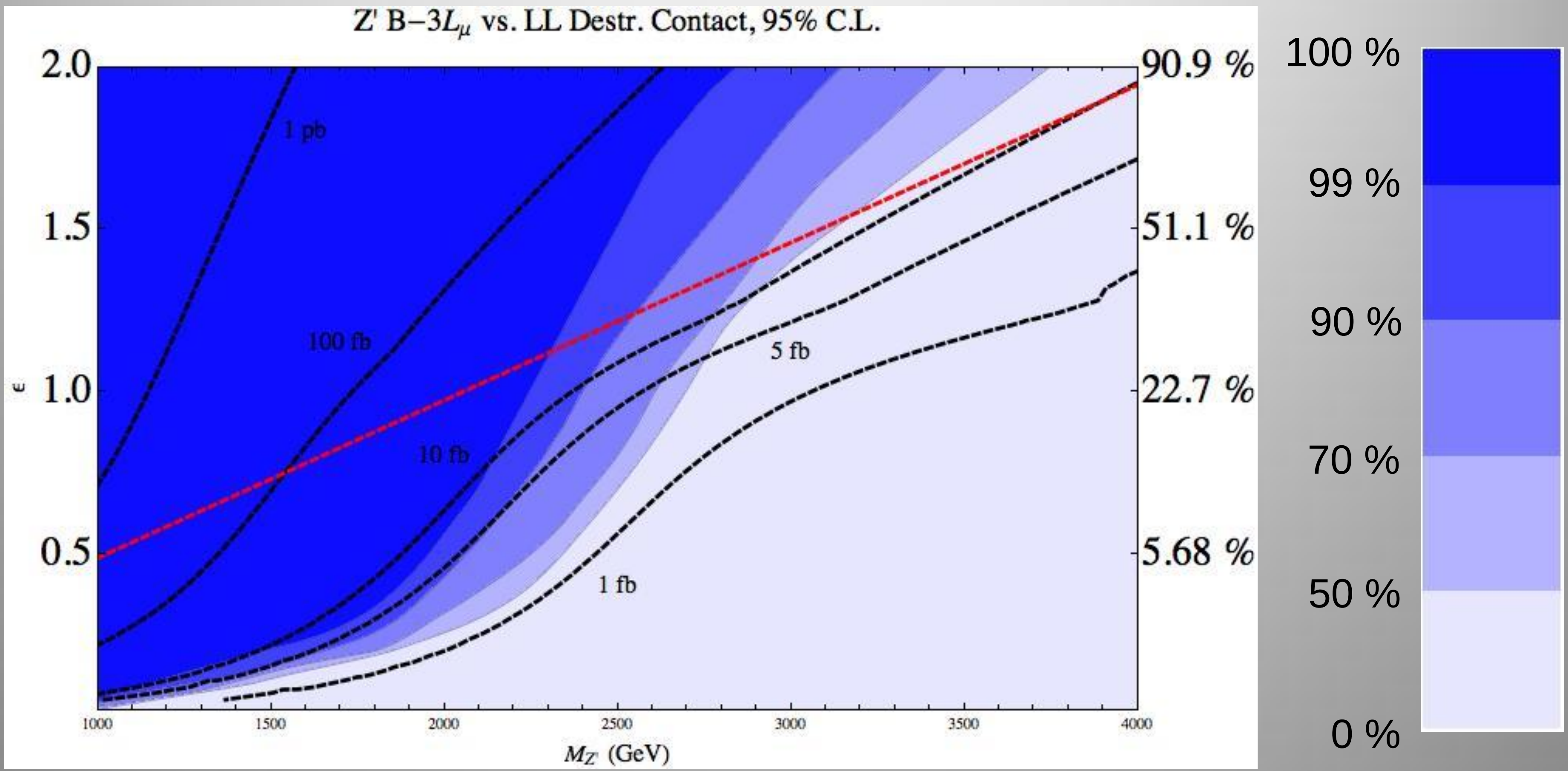
100 %
99 %
90 %
70 %
50 %
0 %

Results



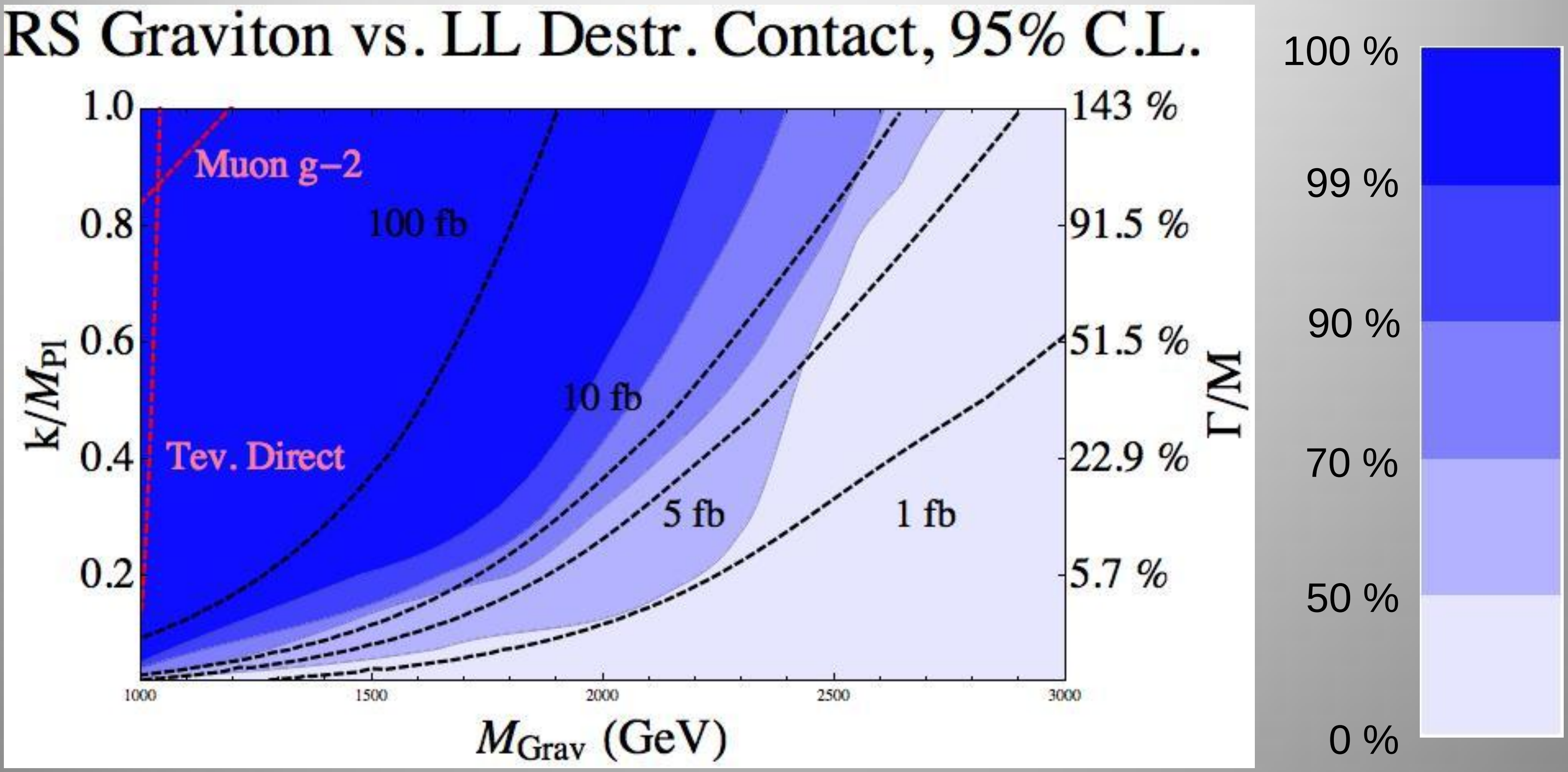
Z' B−3L_μ vs. VV Constr. Contact, 95% C.L.
2.0
1.5
1.0
0.5
ϵ
1500
2000
2500
3000
3500
4000
$M_{Z'}$ (GeV)
90.9 %
51.1 %
22.7 %
5.68 %
Γ/M
1 pb
100 fb
10 fb
5 fb
1 fb
100 %
99 %
90 %
70 %
50 %
0 %

Results



Z' B−3L_μ vs. LL Destr. Contact, 95% C.L.
2.0
1.5
1.0
0.5
ϵ
90.9 %
51.1 %
22.7 %
5.68 %
1 pb
100 fb
10 fb
5 fb
1 fb
1000
1500
2000
2500
3000
3500
4000
$M_{Z'}$ (GeV)
100 %
99 %
90 %
70 %
50 %
0 %

Results



RS Graviton vs. LL Destr. Contact, 95% C.L.
1.0
0.8
0.6
0.4
0.2
k/M_{Pl}
143 %
91.5 %
51.5 %
22.9 %
5.7 %
Γ/M
Muon g−2
Tev. Direct
100 fb
10 fb
5 fb
1 fb
1000
1500
2000
2500
3000
M_{Grav} (GeV)
100 %
99 %
90 %
70 %
50 %
0 %

Can we learn more?

- Seems reasonable event rate
- And distinguishable
- We’ve considered total cross section and distribution with energy so far
- With enough statistics, angular information can also prove valuable

- In particular, can distinguish parity-violating interactions
- SM interactions violate parity whereas new physics does not necessarily

Pseudorapidity distribution

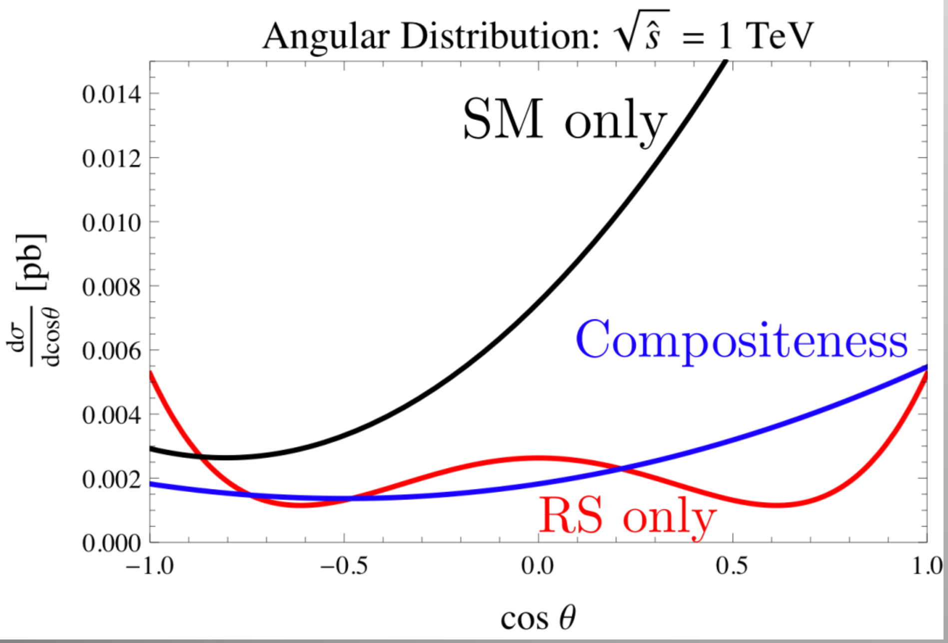
partonic: $u\bar{u} \rightarrow \mu^- \mu^+$

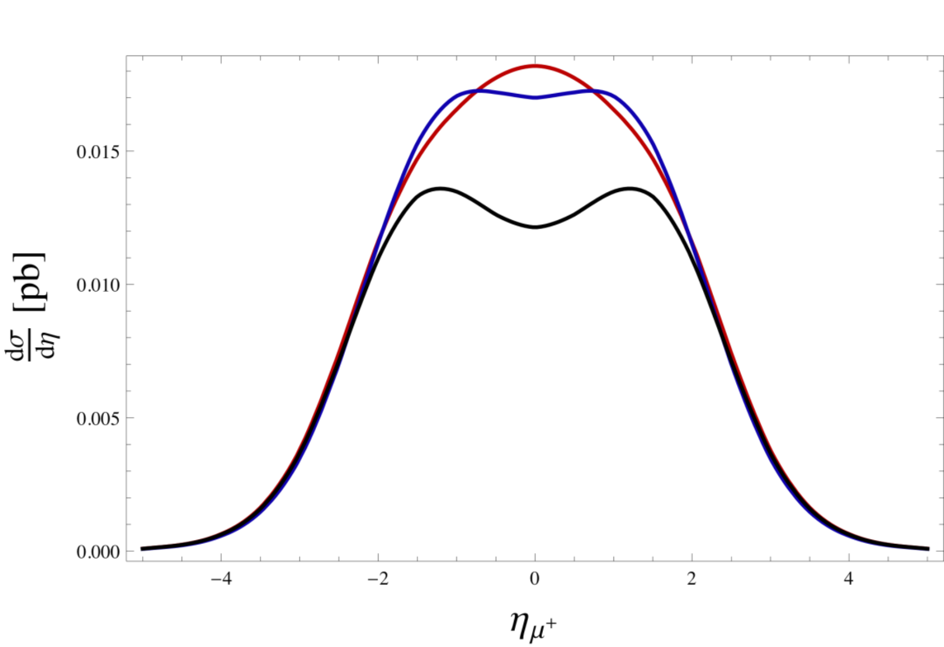
differential in $\cos\theta$

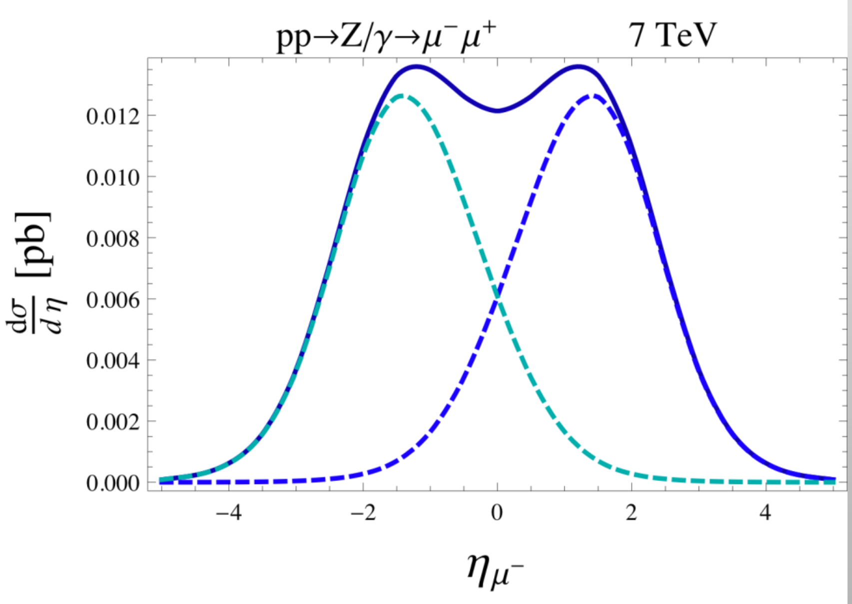
hadronic: $pp \rightarrow \mu^- \mu^+$

differential in η

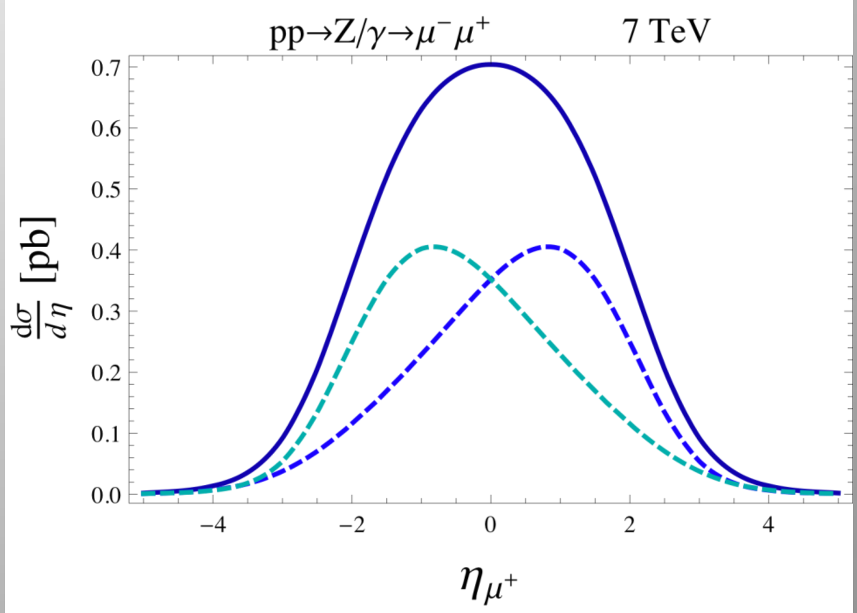
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$







pp→Z/γ→μ⁻μ⁺
7 TeV
dσ/dη [pb]
0.000
0.002
0.004
0.006
0.008
0.010
0.012
−4
−2
0
2
4
η_μ⁻



pp→Z/γ→μ⁻μ⁺
7 TeV
dσ/dη [pb]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
−4
−2
0
2
4
η_μ⁺

Observations

- SM much more asymmetric than either contact interaction or RS
- RS has no parity violation so symmetric
- However, we don't know direction of quark so θ not the best variable
- Can use boost direction to favor quarks, and use θ^* which tells angle between muon and quark
- Requires strong cut on η to very forward events-
- Our signal events are mostly transverse
- A_{fb} therefore not such a great variable for us
- Instead we just use η–much easier to measure and reveals bigger effect

Interpretation

- Muon preferentially forward (wrt quark) due to parity violating SM interactions
- Quark has on average more momentum (larger x) therefore boosted more forward
- Large η, small θ, large cos θ
- Sum curves and get the McD curve
- Wider with less hard invariant mass cut

Predictions

$$\frac{d\sigma}{dM^2 d\cos\theta} = \frac{1}{E_{\rm cm}^2}\sum_q \int_\tau^1 \frac{dx}{x}\left[f_{q/P}(x)f_{\bar{q}/P}(\tau/x)f_{q/P}(\tau/x)f_{\bar{q}/P}(x)\right]\frac{d\hat{\sigma}}{d\cos\theta^*}$$

Also gluon initial state

Now change variables: rapidity of muon and antimuon

$$y = \cosh^{-1}\frac{E}{P_T}$$

$$Y = \frac{y_{\mu^-} + y_{\mu^+}}{2} \qquad y^* = \frac{y_{\mu^-} - y_{\mu^+}}{2}$$

$$x = \frac{M}{\sqrt{s}}e^Y = \sqrt{\tau}e^Y \qquad \cos\theta^* = \tanh y^*,$$

Jacobian:

$$J \equiv \frac{\partial(x, \cos\theta^*)}{\partial(y_{\mu^-}, y_{\mu^+})} = \frac{1}{2\cosh^2 y^*}\sqrt{\tau}e^Y$$

Integration region:

$$-\infty < y_{\mu^-} - y_{\mu^+} < \infty$$
$$\ln\tau < y_{\mu^-} + y_{\mu^+} < \ln\frac{1}{\tau}$$

Quark could come from either proton—
forward or backward

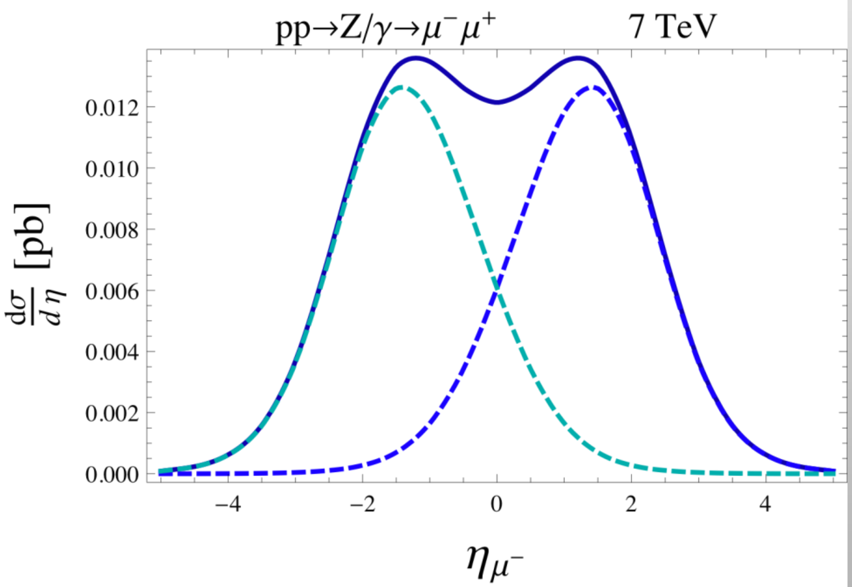
$$\frac{d\sigma}{dM^2 dy_{\mu^-} dy_{\mu^+}} = \frac{1}{E_{\rm cm}^2}\frac{1}{2\cosh^2 y^*}\left\{ f_{q/P}(\sqrt{\tau}e^{-Y}) f_{\bar{q}/P}(\sqrt{\tau}e^{Y}) \frac{d\hat{\sigma}}{d\cos\theta^*}\bigg|_{\cos\theta^*=\tanh y^*} \right.$$
$$\left. + f_{q/P}(\sqrt{\tau}e^{Y}) f_{\bar{q}/P}(\sqrt{\tau}e^{-Y}) \frac{d\hat{\sigma}}{d\cos\theta^*}\bigg|_{\cos\theta^*=-\tanh y^*} \right\}$$

replace $y_{\mu^\pm}$ with the $\eta_{\mu^\pm}$, the pseudorapidity

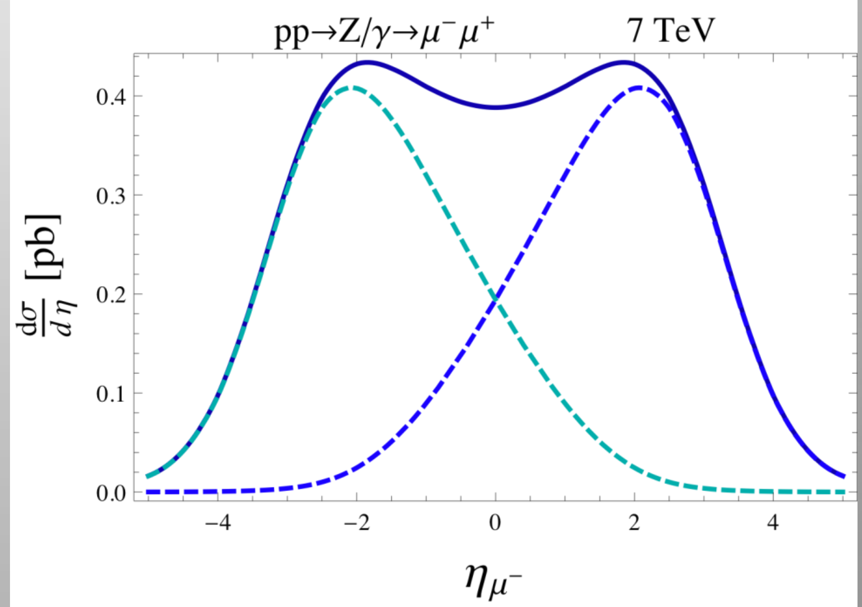
$$y \longrightarrow \eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

μ^- pseudorapidity

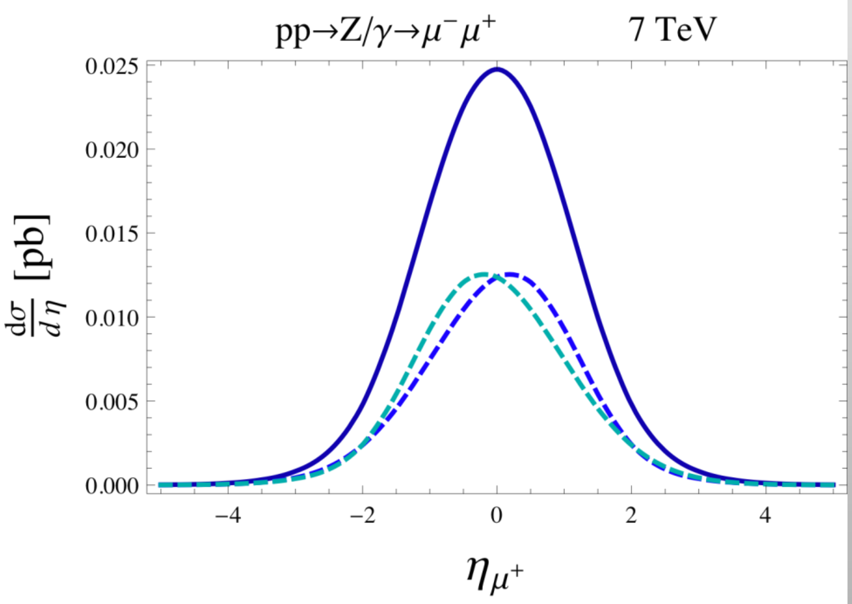
$M_{\mu\mu} > 400$ GeV

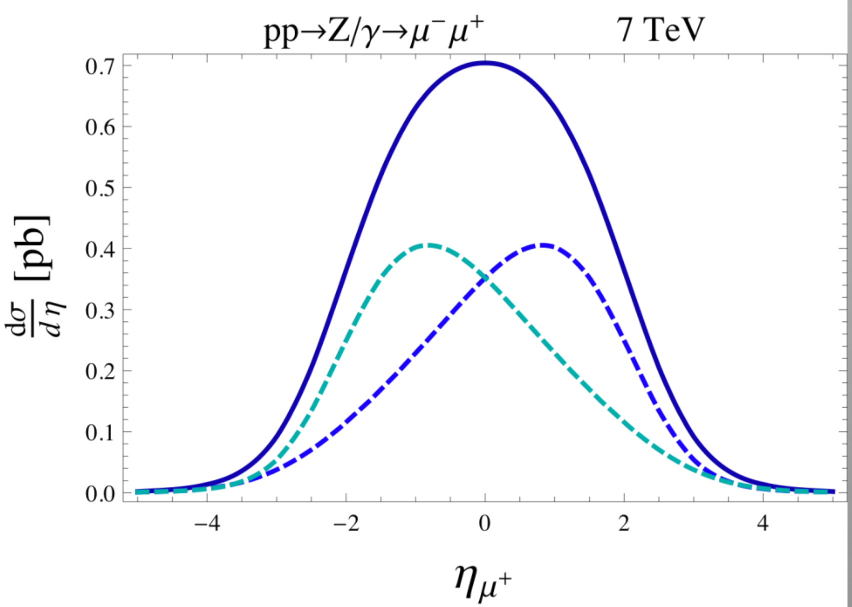


$M_{\mu\mu} > 150$ GeV

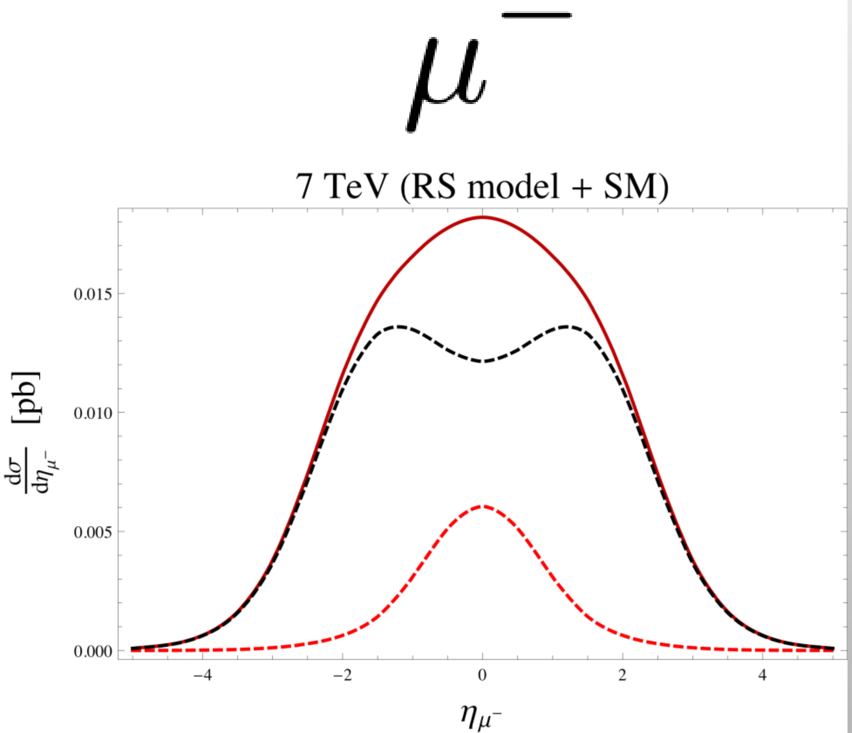


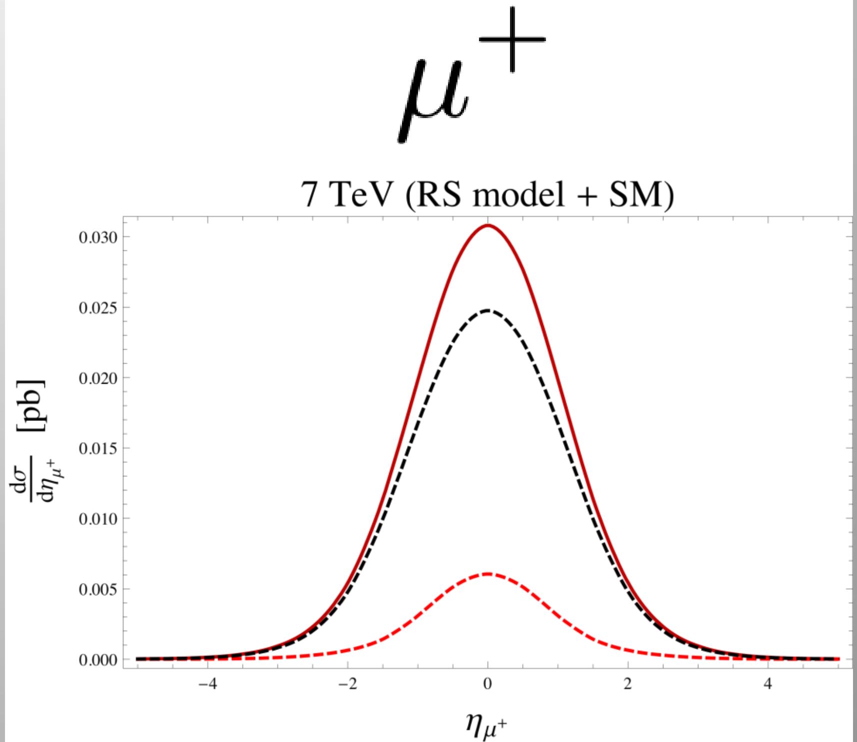
μ^+ pseudorapidity





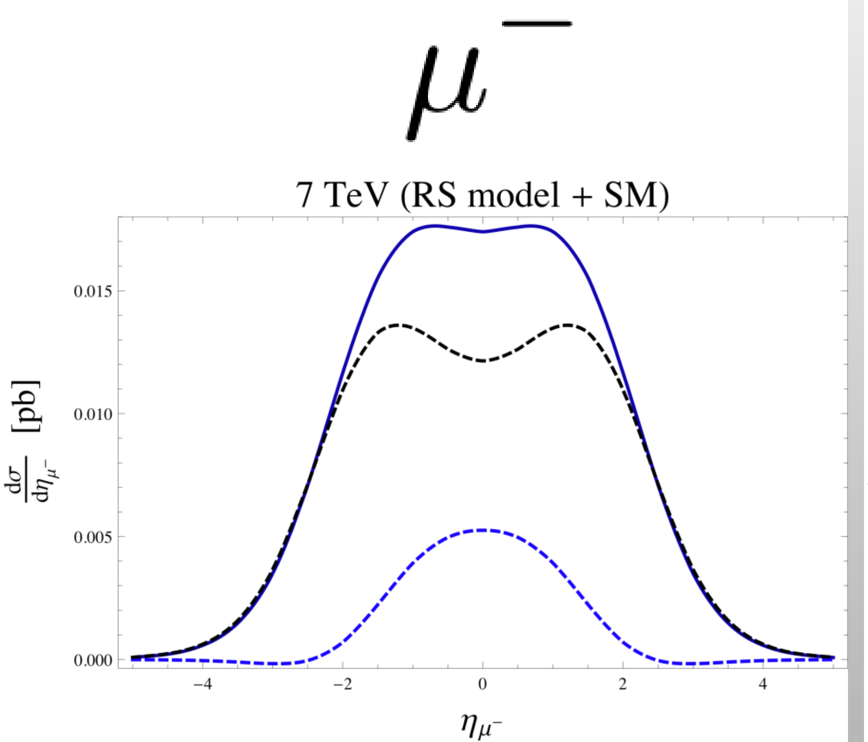
RS model



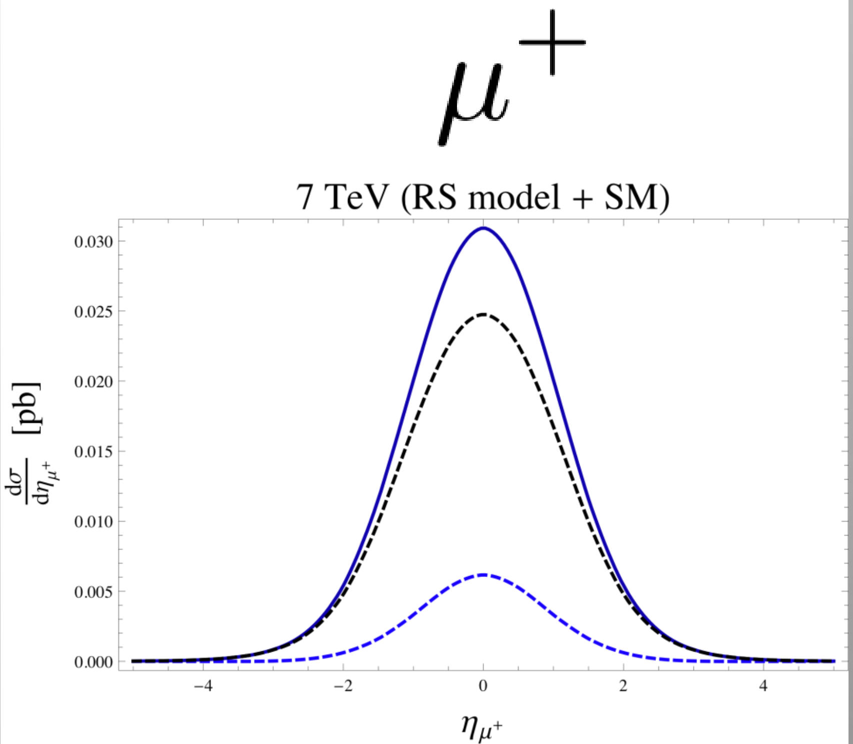


dashed black: $pp \to \gamma/Z^0 \to \mu\mu$

Composite Model (LL)



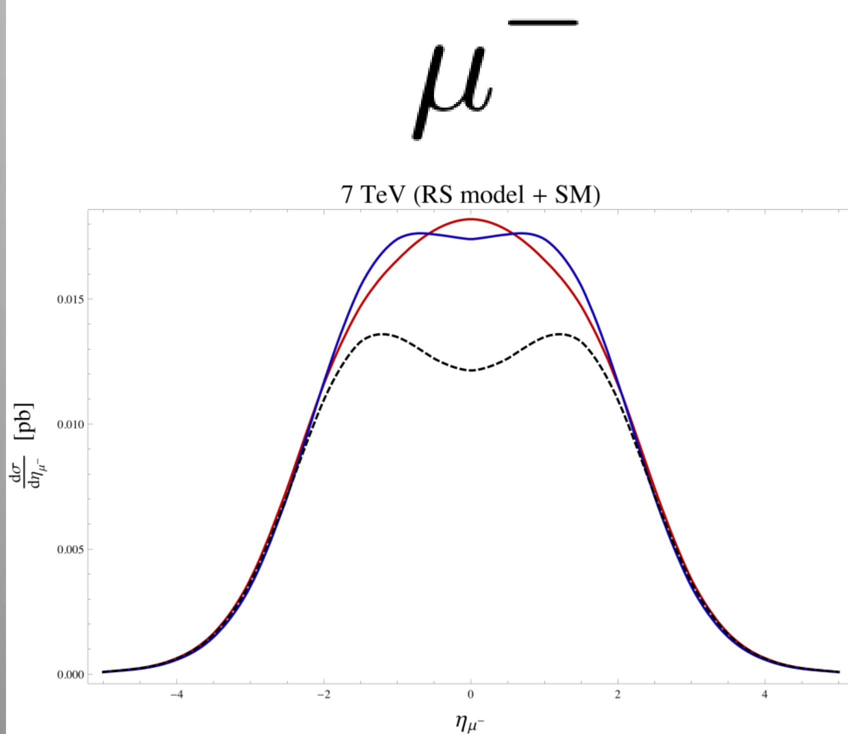
dashed blue: composite constribution



dashed black: $pp \to \gamma/Z^0 \to \mu\mu$

$E_{cm} = 7$ TeV
$k/M_{\rm pl} = 0.1$
$M_{\rm g} = 1300$ GeV
$\Lambda = 6590$ GeV

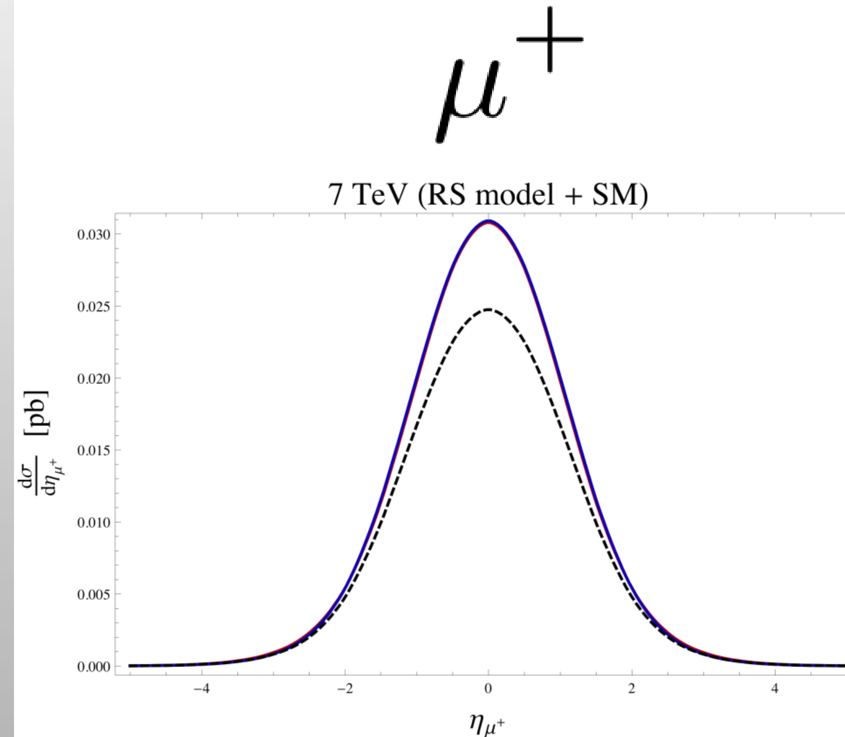
Compare Models



dashed black: SM

solid blue: composite (LL) model

solid red: RS model



Define observable

$$R_\eta = \frac{\int_{-1}^{1} d\eta \, \frac{d\sigma}{d\eta}}{\int_{-\eta_{\max}}^{\eta_{\max}} d\eta \, \frac{d\sigma}{d\eta}}$$

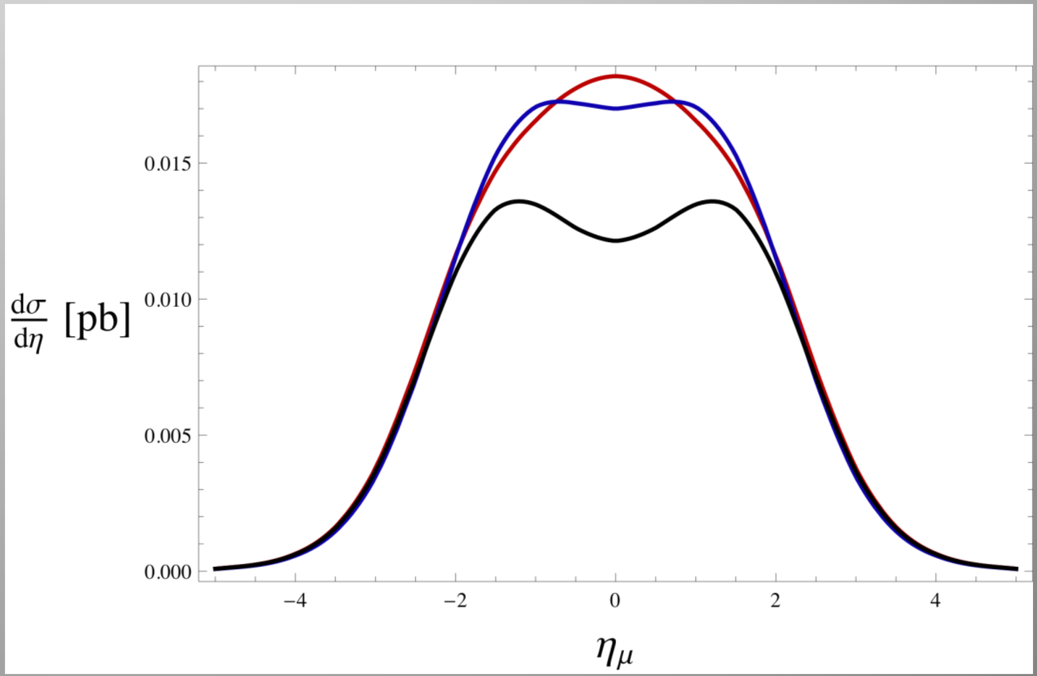
$$E_{cm} = 7 \text{ TeV}$$
$$k/M_{\text{pl}} = 0.1$$
$$M_{\text{g}} = 1300 \text{ GeV}$$
$$\Lambda = 6590 \text{ GeV}$$

Compare RS model with best fit Λ-model

RS is narrower due to gg initial state

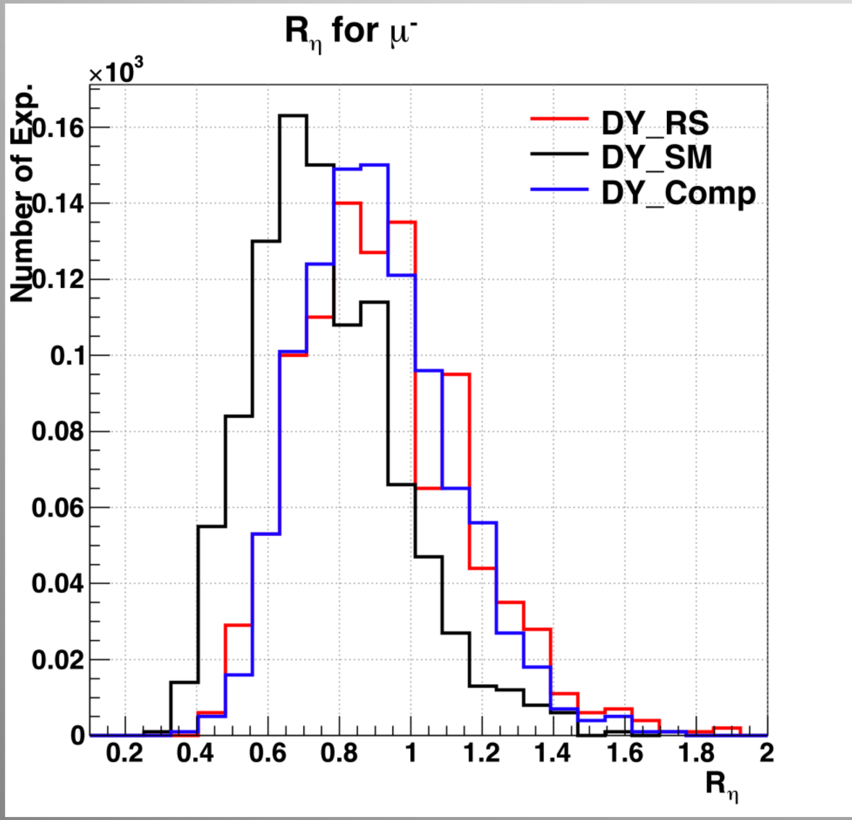
Repeat for many pseudo-experiments to build up a distribution

If distribution separate, the models will be distinguishable

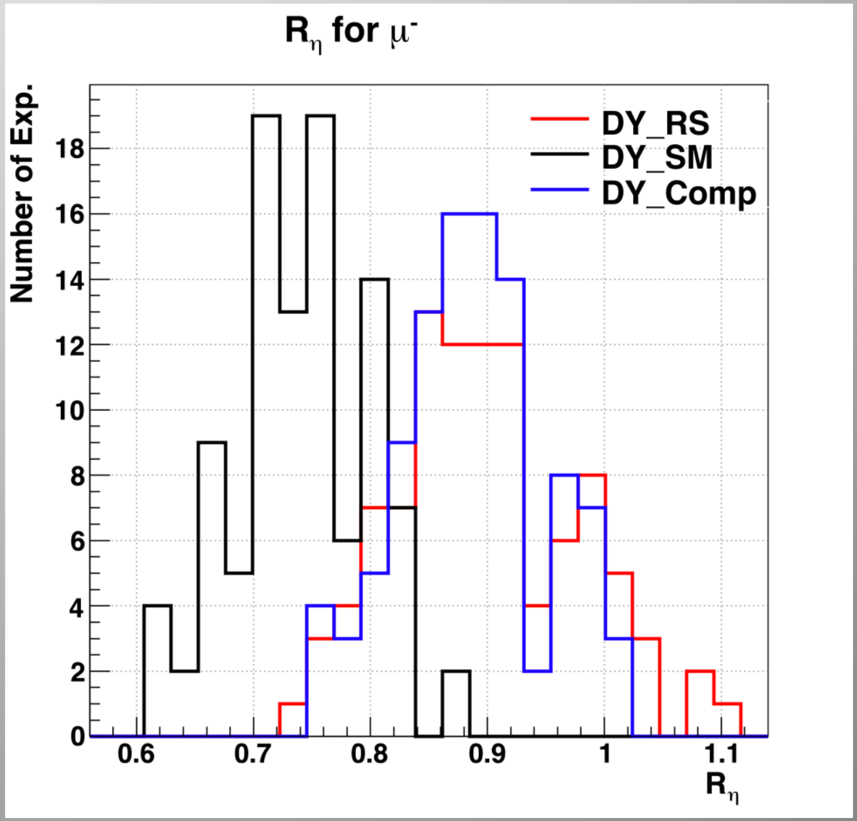


Separation of Distributions

$1\ \mathrm{fb}^{-1}$



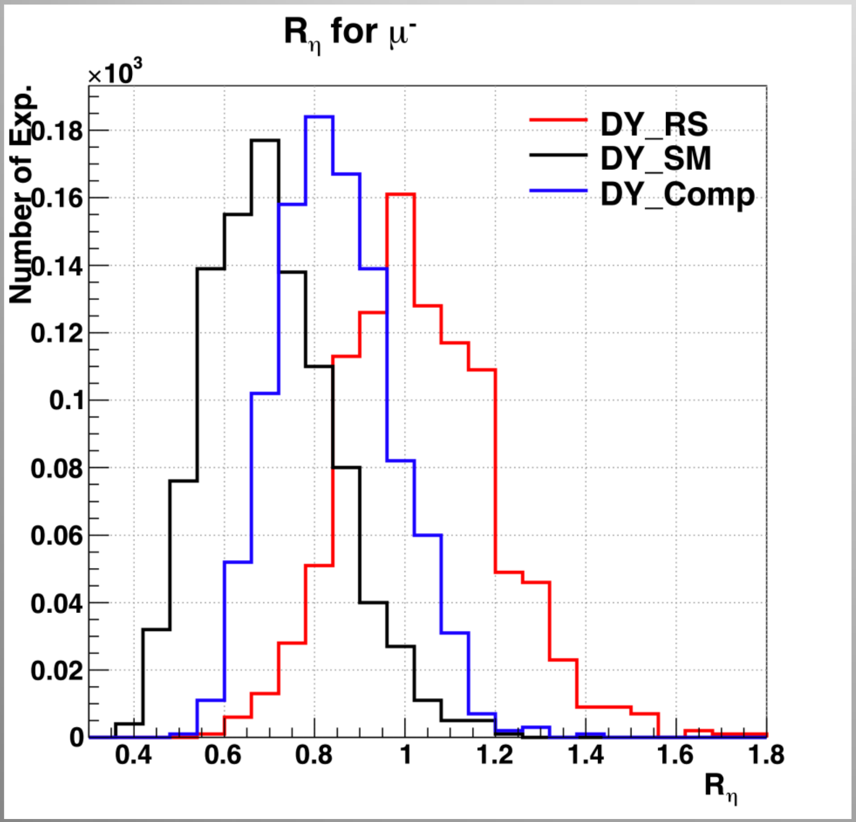
$10\ \mathrm{fb}^{-1}$



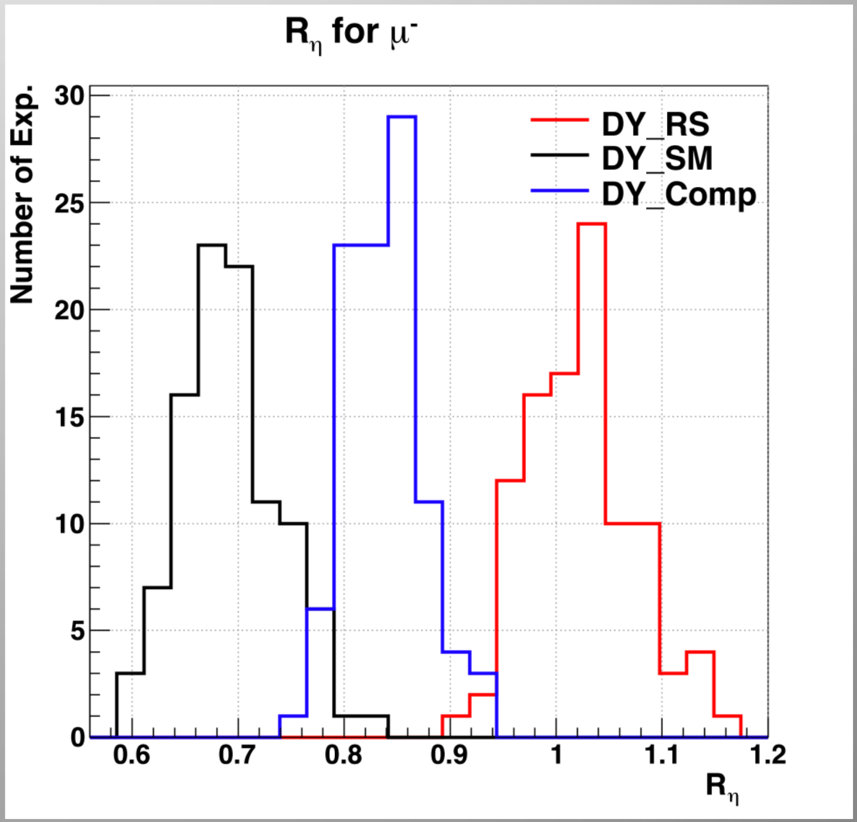
Better at Higher Energy

$E_{cm} = 10$ TeV
$k/M_{\rm pl} = 0.1$
$M_{\rm g} = 1300$ GeV
$\Lambda = 6250$ GeV

$1\ \mathrm{fb}^{-1}$



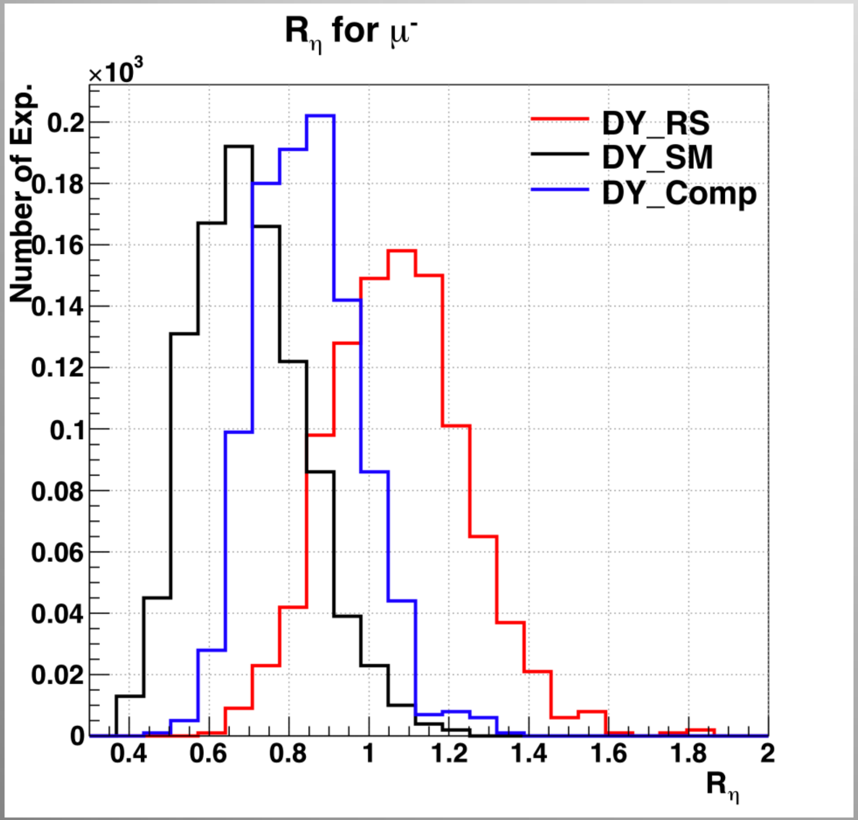
$10\ \mathrm{fb}^{-1}$



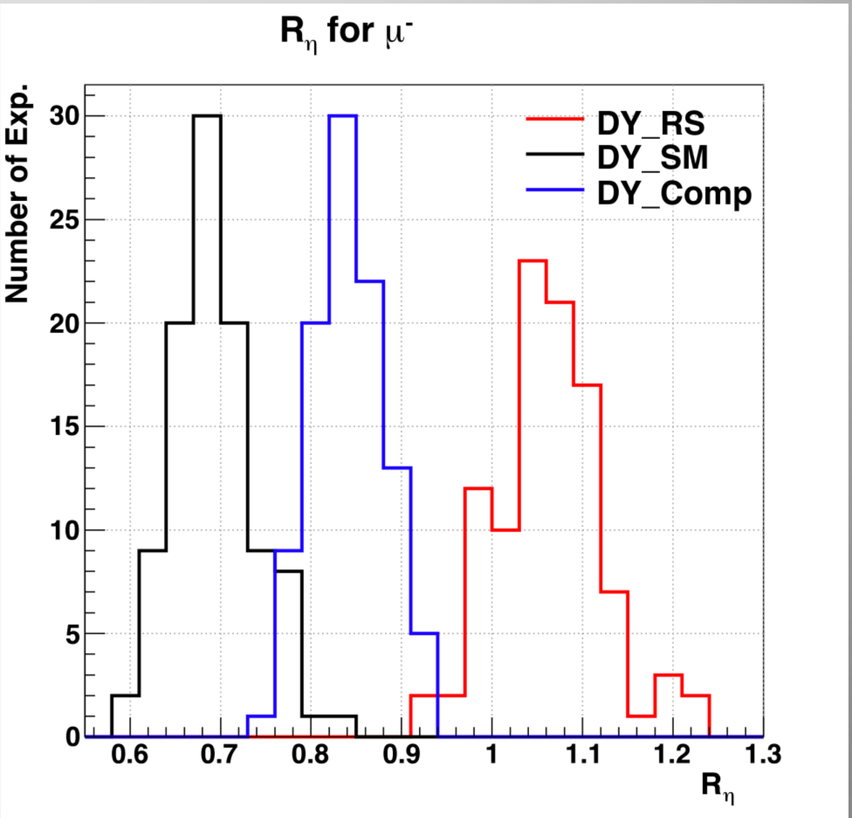
Higher Coupling

$E_{cm} = 10$ TeV
$k/M_{\rm pl} = 0.3$
$M_{\rm g} = 1800$ GeV
$\Lambda = 6120$ GeV

$1\ \mathrm{fb}^{-1}$



$10\ \mathrm{fb}^{-1}$

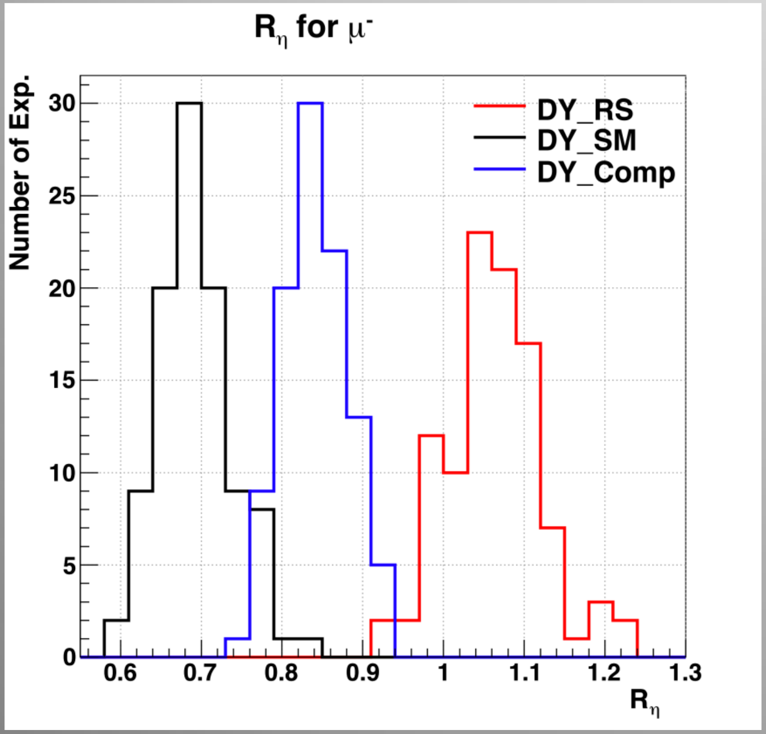


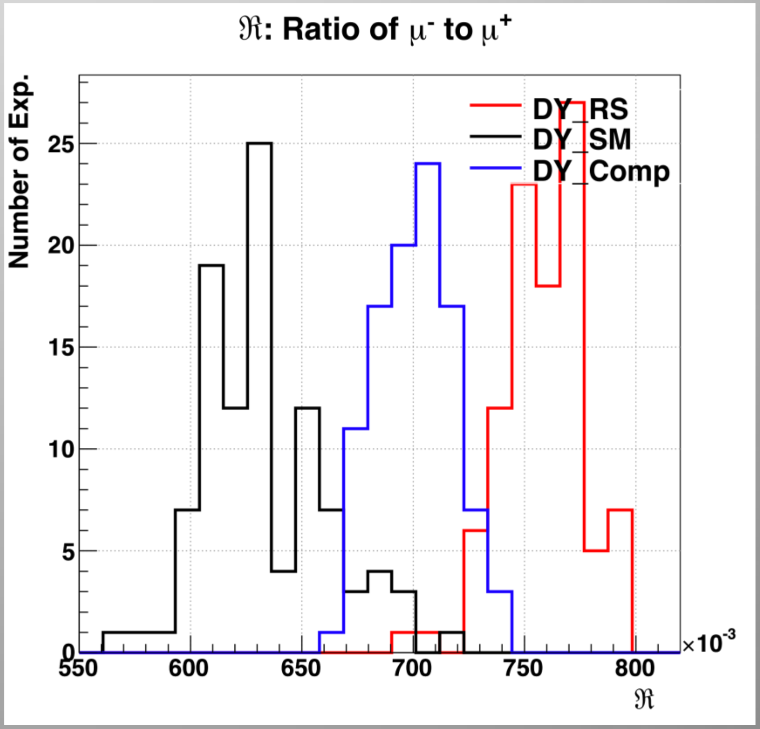
Other Observables

$$\Re = \frac{\int_{-1}^{1} d\eta \frac{d\sigma}{d\eta}(\mu^-)}{\int_{-1}^{1} d\eta \frac{d\sigma}{d\eta}(\mu^+)}$$

$$E_{cm} = 10 \text{ TeV}$$
$$k/M_{\text{pl}} = 0.3$$
$$M_{\text{g}} = 1800 \text{ GeV}$$
$$\Lambda = 6120 \text{ GeV}$$

10 fb^{-1}

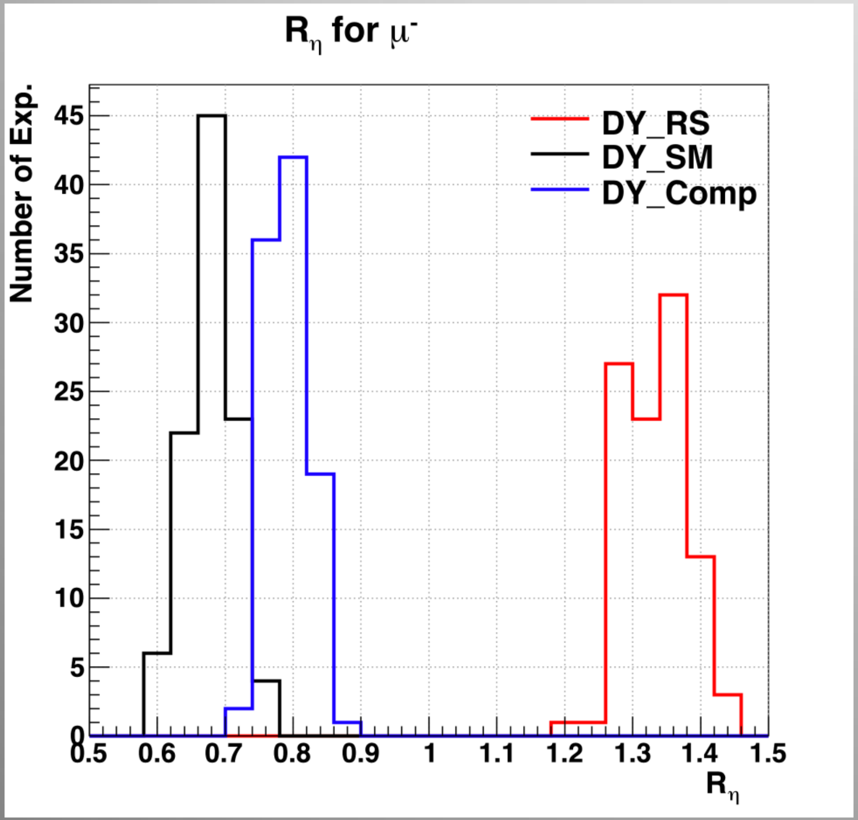




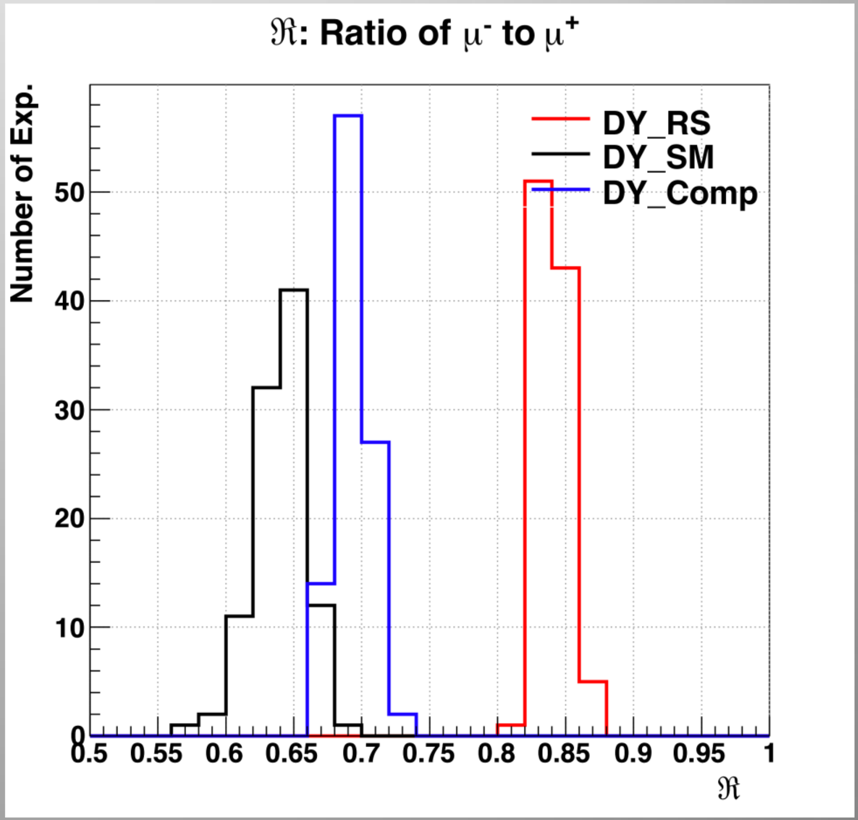
Design Energy

$$E_{cm} = 14 \text{ TeV}$$
$$k/M_{\text{pl}} = 0.3$$
$$M_{\text{g}} = 1800 \text{ GeV}$$
$$\Lambda = 5600 \text{ GeV}$$

10 fb^{-1}



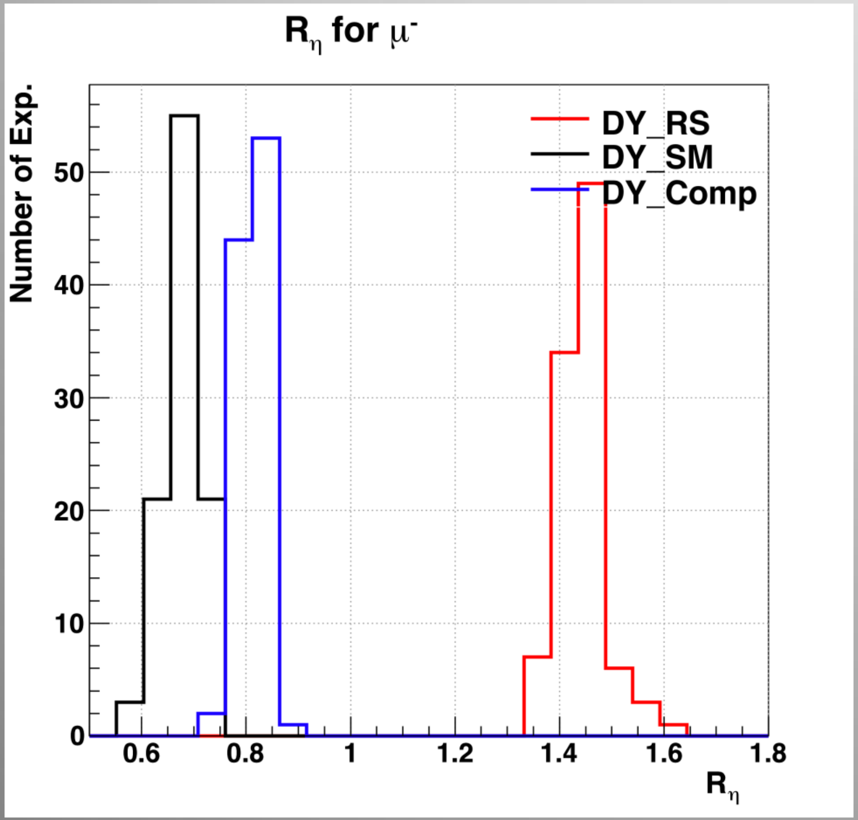
10 fb^{-1}



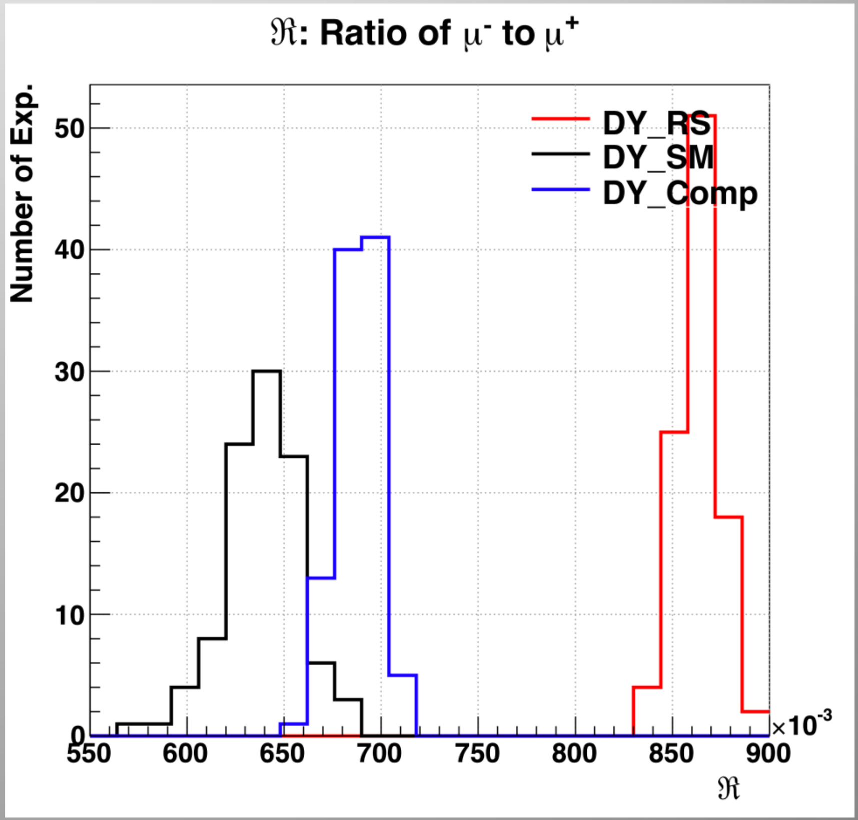
Even Very Wide Resonance

$E_{cm} = 14$ TeV
$k/M_{\rm pl} = 0.5$
$M_{\rm g} = 2000$ GeV
$\Lambda = 5330$ GeV

$10\ \mathrm{fb}^{-1}$



$10\ \mathrm{fb}^{-1}$

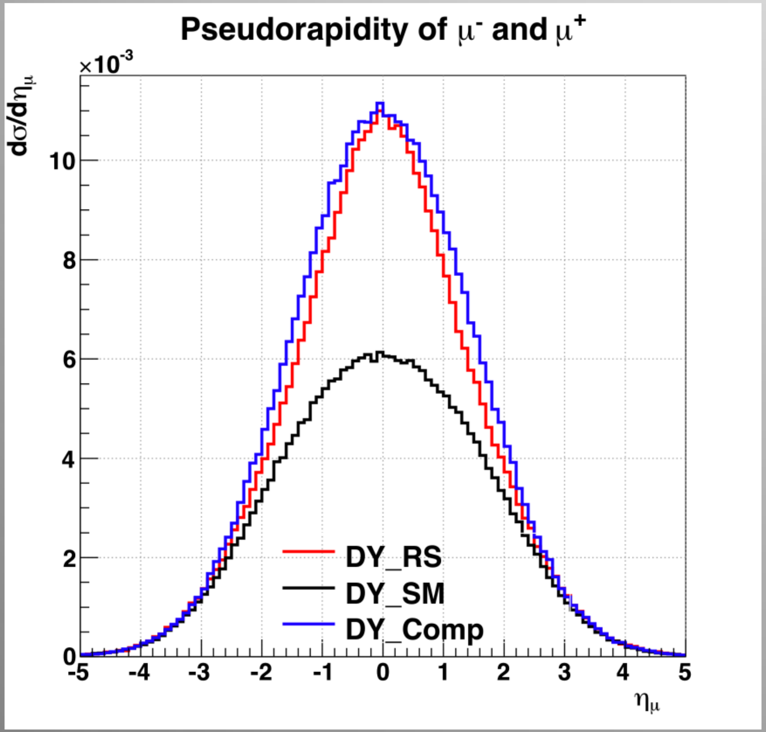


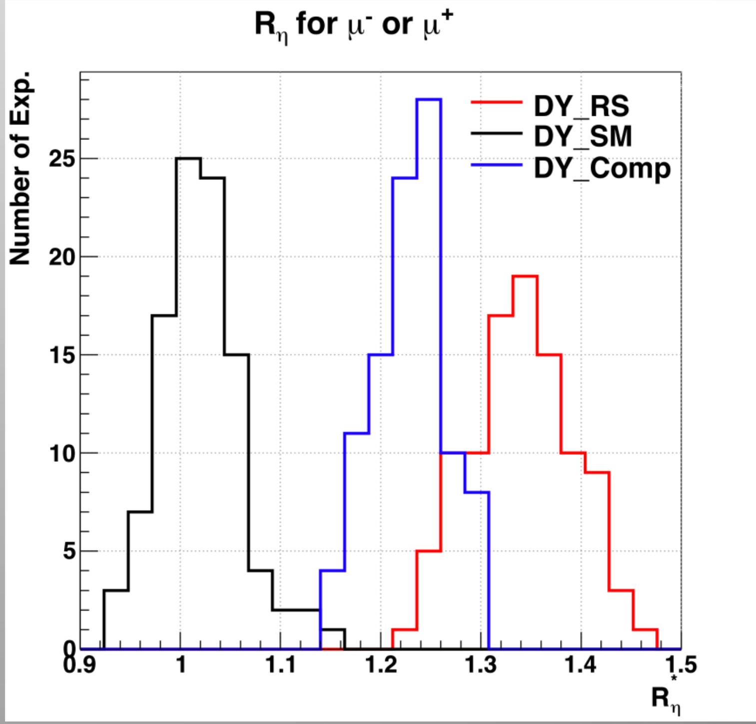
Other Observables

$$R_\eta^* = \frac{\displaystyle\int_{-1}^{1} d\eta \frac{d\sigma}{d\eta}(\mu^- \text{or } \mu^+)}{\displaystyle\int_{-\eta_{\max}}^{\eta_{\max}} d\eta \frac{d\sigma}{d\eta}(\mu^- \text{or } \mu^+)}$$

$$E_{cm} = 10 \text{ TeV}$$
$$k/M_{\text{pl}} = 0.3$$
$$M_{\text{g}} = 1800 \text{ GeV}$$
$$\Lambda = 6120 \text{ GeV}$$

10 fb^{-1}





Conclusions

- Highest energy and luminosity obviously the goal
- But then and now (!) there is a lot of parameter space to explore
- Real chance of finding resonances
- Distinguish from background
- Distinguish from contact
- Further confirm details –and even learn about production