Low scale strings and direct photons at the LHC

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- **D-branes and all that**
- **Extra $U(1)$'s in D-brane constructions**
- **Photons and gluons as quiver neighbors**
- **Jet tests at LHC**

L. Anchordoqui, HG, S. Nawata, T. Taylor, arXiv:0712.0386 [hep-ph], to be published in PRL; arXiv:0804.2013 [hep-ph], submitted to PRD

TeV scale strings

- Large extra spatial dimensions and D-brane constructs allow

→ low string scale compatible with weak 4-D gravity – in toroidal compactification

$$M_{\rm Pl}^2 \sim M_s^2\ (M_s R)^n$$

→ Regge recurrences in TeV region

- Open strings can terminate on stack of N identical D branes

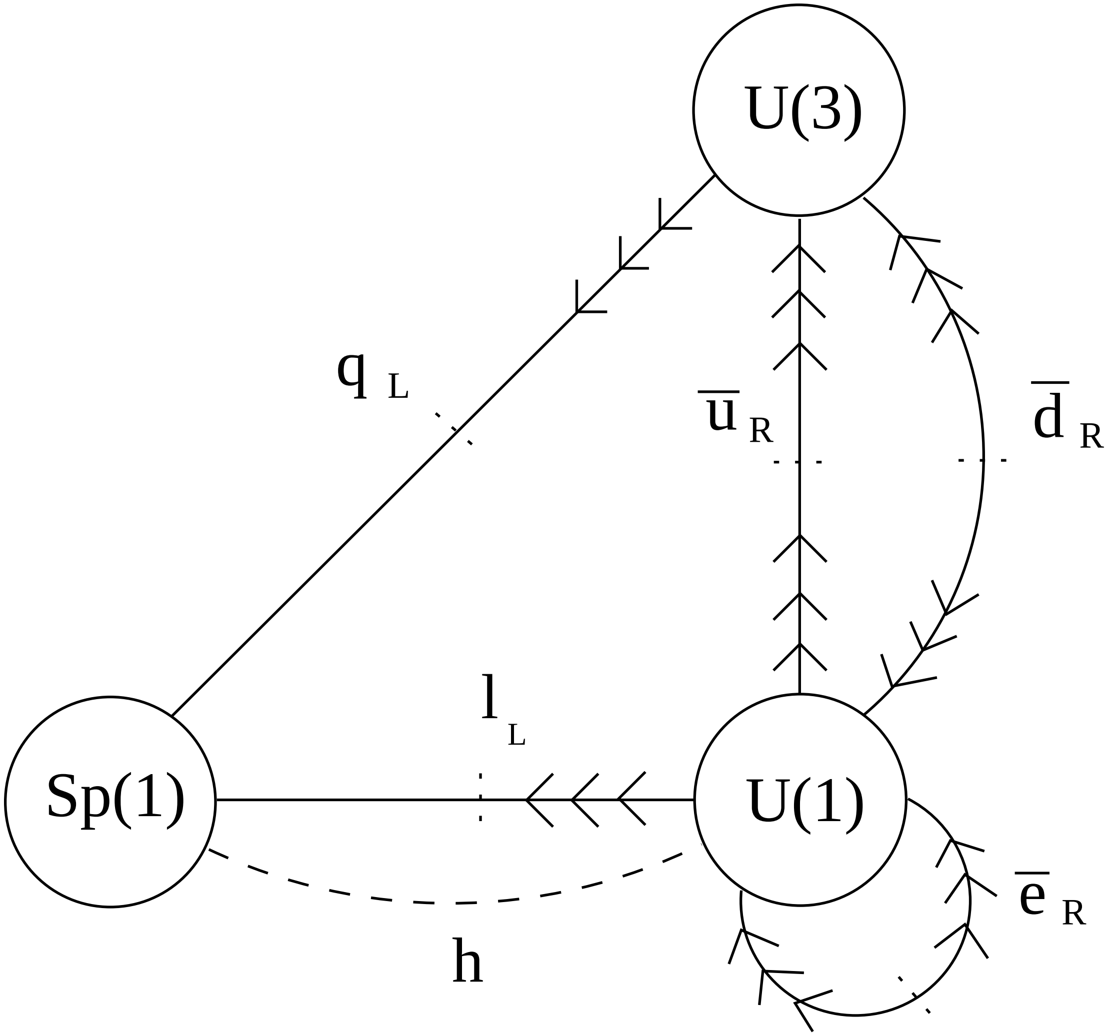
→ $U(N)$ gauge group for each stack if images under orientifolding are different from themselves

TeV scale strings (cont'd)

→ $Sp(N)$ or $SO(N)$ gauge group for each stack if they self-image under orientifolding

- By locating D-branes at singularities of compact space, avoid KK towers.
- Matter fields are in bifundamental representations (N_a, N_b) or $(N_a, \bar{N}_b)$ located at intersections of D-branes

Quivers



Berenstein, Pinansky, hep-th/0610104; Antoniadis, Kiritsis, Tomaras, hep-ph/0004214

Gauge fields

- $U(3)$: 8 $SU(3)$ gluons, additional $U(1)$ (C_μ) coupled to baryon number $Q_{U(3)}$ with strength $g_3/\sqrt{6}$
- $U(2)$: 3 $SU(2)$ $W's$, additional $U(1)$
- **Minimal:** $Sp(1)$: 3 $W's$, no additional $U(1)$
- $U(1)$: another $U(1)$ (B_μ)

$$\begin{aligned} Y_\mu \ (\text{hypercharge}) &= \sin\theta_P\ C_\mu - \cos\theta_P\ B_\mu \\ Y'_\mu \ (\text{extra } Z') &= \cos\theta_P\ C_\mu + \sin\theta_P\ B_\mu \end{aligned}$$

Charge assignments, anomalies

- **With $Q_{U(1)}$ assignments $(0, -1, 1, 1, 2)$ for $(q_L,\ u_R,\ d_R,\ \ell_L,\ e_R)$, the hypercharge**

$$Q_Y = \frac{1}{6}\, Q_{U(3)} - \frac{1}{2}\, Q_{U(1)}$$

is free of gauge and mixed anomalies.

- **The orthogonal charge $Q_{Y'}$ suffers from anomalies**

- **Cancel via Green-Schwartz mechanism - coupling $\eta F \wedge F$ to RR closed string two-form field**

Mixing angle

- Identification of hypercharge allows calculation of mixing angle
- Find

$$\begin{aligned} \tan\theta_P &= \sqrt{\frac{2}{3}}\,\frac{g_1}{g_3} \\ \frac{1}{4g_1^2} &= \frac{1}{g'^2} - \frac{1}{6g_3^2} \end{aligned}$$

- Running from M_Z to 3 TeV, find

$$\sin\theta_P \equiv \kappa \simeq 0.144$$

Gauging baryon number

- **If left unbroken, long range force coupled to baryon number – violation of everything**

- **If broken via a Higgs mechanism, break global baryon number at TeV scale → fast proton decay**

- **Mixing $B \wedge F$ with closed string two-form $B_{\mu\nu}$ → mass for Y', global baryon number preserved. Akin to Stückelberg mechanism**
- **Allows TeV BH production in νp collisions w/out violation of baryon number via BH**

Mass growth via two-form

$$\mathcal{L} = -\frac{1}{12}H^{\mu\nu\rho}H_{\mu\nu\rho} - \frac{1}{4g^2}F^{\mu\nu}F_{\mu\nu} + \frac{c}{4}\,\epsilon^{\mu\nu\rho\sigma}B_{\mu\nu}\,F_{\rho\sigma},$$

where

$$H_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \partial_\rho B_{\mu\nu} + \partial_\nu B_{\rho\mu}$$

Equivalent to

$$\begin{aligned}\mathcal{L}_0 \;=\;& -\frac{1}{12}H^{\mu\nu\rho}\;H_{\mu\nu\rho} - \frac{1}{4g^2}F^{\mu\nu}\;F_{\mu\nu} \\ & -\frac{c}{6}\,\epsilon^{\mu\nu\rho\sigma}H_{\mu\nu\rho}\;A_\sigma - \frac{c}{6}\eta\epsilon^{\mu\nu\rho\sigma}\partial_\mu H_{\nu\rho\sigma}.\end{aligned}$$

Continued..

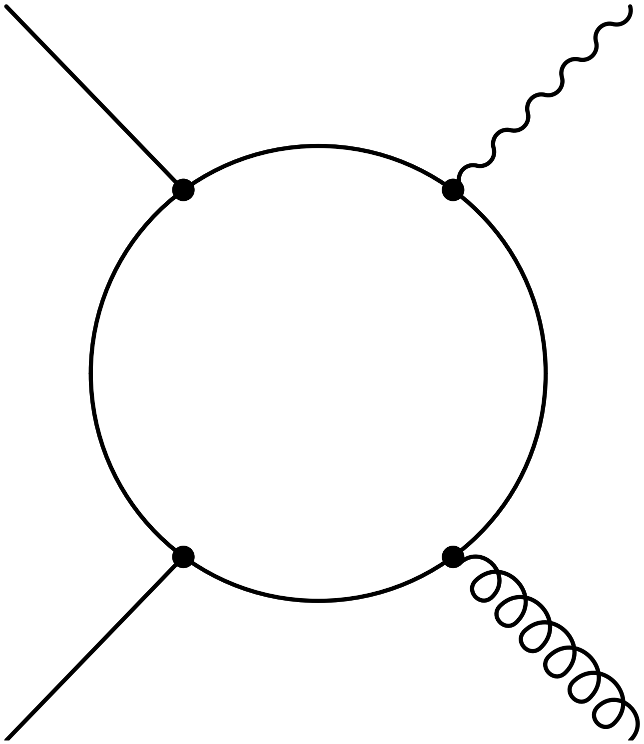
- Integrate out $\eta \longrightarrow d^{*}H = 0 \longrightarrow H = dB \longrightarrow$ original equation
- Integrate by parts the last term $\longrightarrow$

$$\mathcal{L}_A = -\frac{1}{4g^2} F^{\mu\nu} F_{\mu\nu} - \frac{c^2}{2} (A_\sigma + \partial_\sigma \eta)^2$$

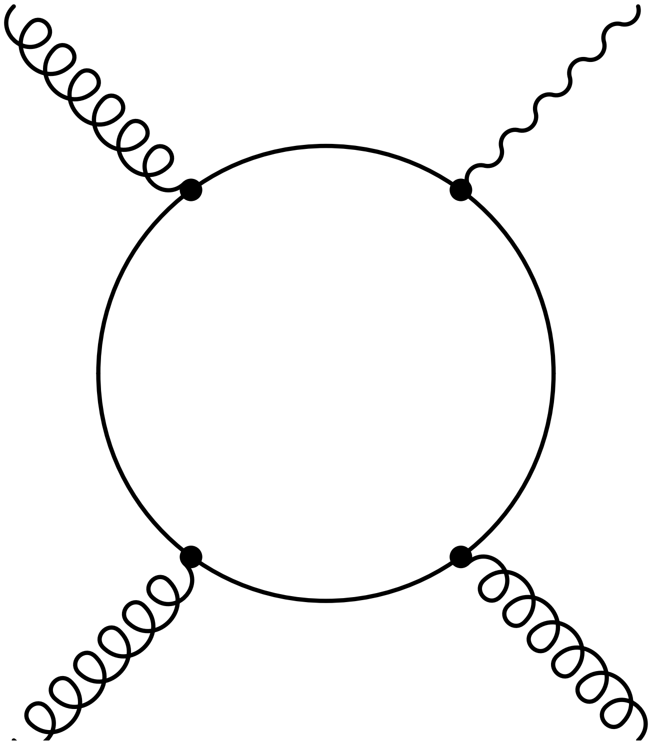
- Mass term for the gauge field A_μ, like Stückelberg mechanism

Ghilencea, Ibanez, Irges, Quevedo, hep-ph/0205083

Photon processes



$qg \rightarrow q\gamma$



$gg \rightarrow g\gamma$

$\boxed{gg \rightarrow \gamma g}$

- Does not exist at tree level in field theory
- But does exist at tree (i.e. disk) level in string theory
- Involves only gauge bosons on a single stack, so is independent of fermion embeddings on the intersecting stacks
- Idea is that

$$\begin{aligned}\mathcal{M}(gg \rightarrow \gamma g) &= \cos\theta_W\ \mathcal{M}(gg \rightarrow Y g) \\ &= \kappa\ \cos\theta_W\ \mathcal{M}(gg \rightarrow C g)\end{aligned}$$

- C_μ couples with strength $g_3/\sqrt{6}$

Amplitudes

The basic string amplitude for one ordering (out of six)of 4 $U(3)$ gauge bosons is

$$\begin{aligned} A(1^-,2^-,3^+,4^+) &= 4\,g^2\,\mathrm{Tr}\;\left(T^{a_1}T^{a_2}T^{a_3}T^{a_4}\right) \\ &\cdot \quad \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 41\rangle} V(k_1,k_2,k_3,k_4) \end{aligned}$$

where

$$\begin{aligned} V(k_1,k_2,k_3,k_4) &= \frac{\Gamma(1-s)\;\Gamma(1-u)}{\Gamma(1+t)} \\ \langle ij\rangle &= \bar{u}_L(k_i)u_R(k_j) \end{aligned}$$

S. Stieberger and T. R. Taylor, hep-th/0609175

Notes

- Only one basic amplitude (MHV, or Maximum Helicity Violating) Parke and Taylor, PRL 1986

- Origin is relation to single 4 scalar amplitude in $N = 2$ supersymmetry

- Obtained as scattering of open strings: insertion of 4 vector vertex functions on the boundary of the disk, which is projection of upper half plane of world sheet complex coordinate

- Reflects $\mathcal{O}\ (g)$ coupling of gauge bosons to resonances, like photoexcitation of neutron.

Squared average

Now permute, square, sum, average, and project onto photon:

$$\begin{aligned}|\mathcal{M}(gg \to g\gamma)|^2 &= g^4 Q^2 C(N) \\ &\cdot \left\{ \left| \frac{s\mu(s,t,u)}{u} + \frac{s\mu(s,u,t)}{t} \right|^2 \right. \\ &+ \left. (s \leftrightarrow t) + (s \leftrightarrow u) \right\}\end{aligned}$$

- $\mu(s,t,u) = \Gamma(1-u)\left(\frac{\Gamma(1-s)}{\Gamma(1+t)} - \frac{\Gamma(1-t)}{\Gamma(1+s)}\right)$
- $Q^2 = \frac{1}{6}\,\kappa^2\ \cos^2\theta_W$
- $C(N) = \frac{4(N^2-4)}{N(N^2-1)}$

Low Energy limit

At low energies $s, t, u \ll M_s^2$

$$|\mathcal{M}(gg \to g\gamma)|^2 \approx g^4 \, Q^2 \, C(N) \, \frac{\pi^4}{4M_s^8}(s^4 + t^4 + u^4)$$

*Note that (unwanted) zero mass poles have cancelled - not trivial! Usually implemented by hand through constraints on Chan-Paton factor *
→unknown constant. We have none.

(see, however, Cullen, Perelstein, Peskin hep-ph/0001166) Other work on colliders:

P. Burikham,T.Figy,T.Han hep-ph/0411094; P. Meade, L. Randall, 0708.3017

- For 4 γ case, compare with Euler-Heisenberg:

$$M_{\rm EH} \sim e^4/16\pi^2 \, (E/m_e)^4 \quad M_s \sim g^2\pi^2 \, (E/M_s)^4$$

Resonance region

Near string threshold $s \approx M_s^2$

$$|\mathcal{M}(gg \to g\gamma)|^2 \approx 4g^4 Q^2 C(N) \frac{M_s^8 + t^4 + u^4}{M_s^4[(s - M_s^2)^2 + (\Gamma M_s)^2]}$$

$$\Gamma \approx \tfrac{1}{4}\alpha_s/(2J+1)\; M_s$$

Result for $gg \to \gamma\gamma$ given by

$$|\mathcal{M}(gg \to \gamma\gamma)|^2 = \frac{4NQ^2}{N^2 - 4} |\mathcal{M}(gg \to g\gamma)|^2$$

Phenomenology

- At collider, resonance formation and decay will populate the high p_T region
- SM processes for $pp \longrightarrow \gamma + jet$

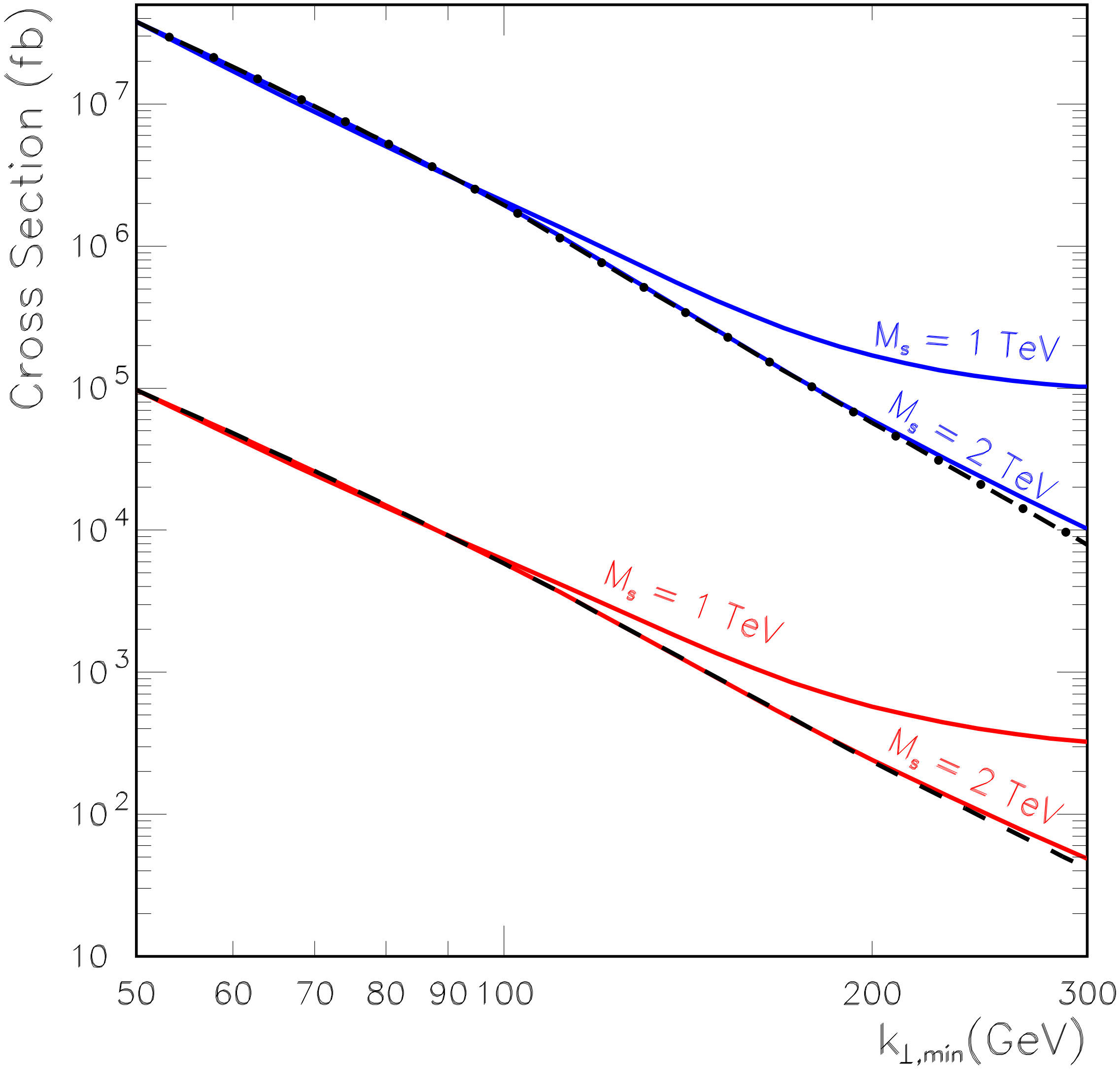
$$gq \longrightarrow \gamma q, \qquad g\bar{q} \longrightarrow \gamma\bar{q} \qquad q\bar{q} \longrightarrow \gamma g$$

lead to rapid $\sim p_T^{-5}$ falloff

- For a start, take as our signal N_{ev} above SM background for integrated cross section (bump search later)

$$\sigma(pp \longrightarrow \gamma + jet)|_{p_{\mathrm{T}}(\gamma) > p_{\mathrm{T,min}}}$$

σ vs. $p_{\mathrm{T,min}}$



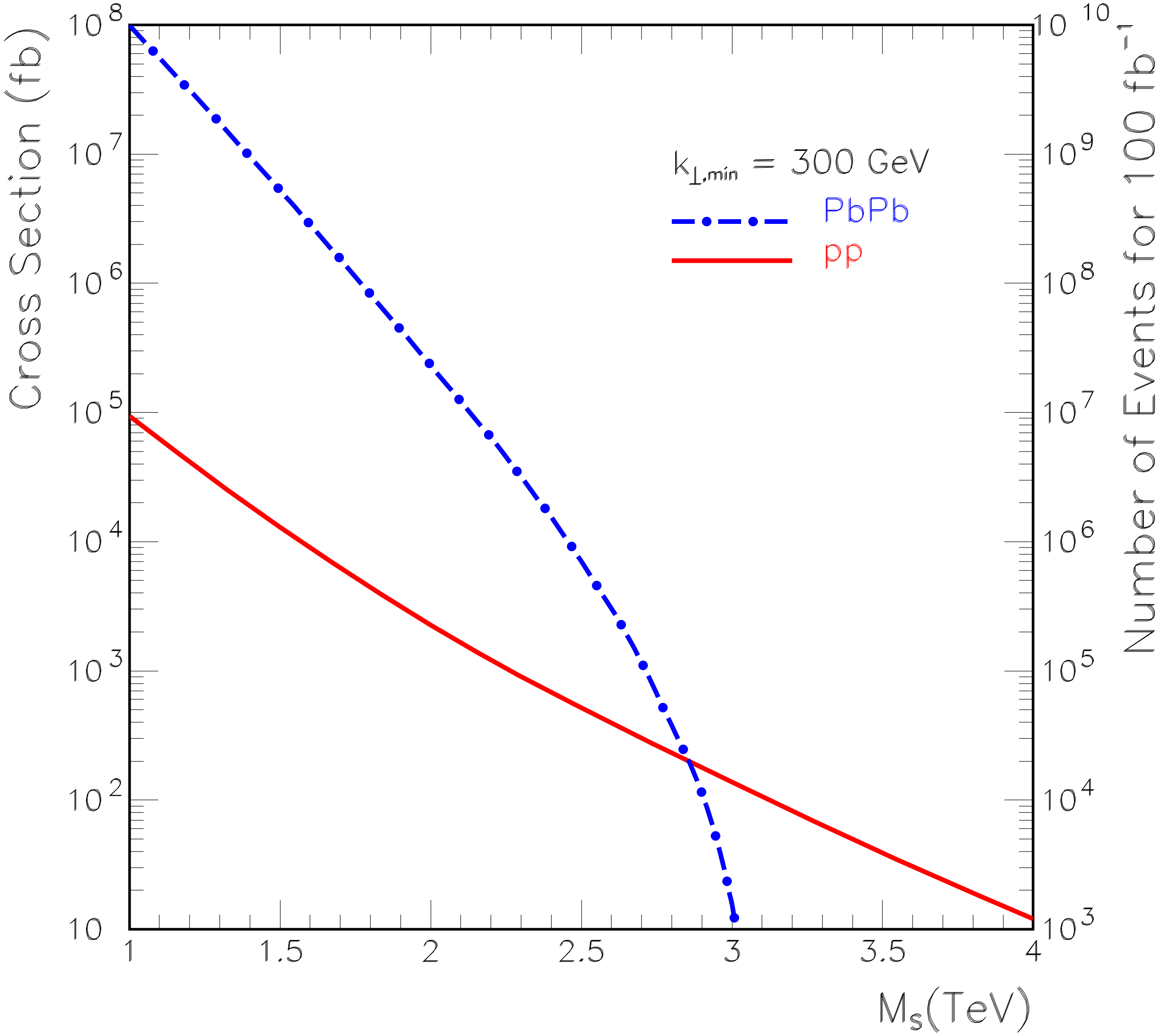
ALICE

- We may simultaneously compare the colliding PbPb facility at LHC with the proton beam for our search, since event rate is an issue at large p_T
- Ignore parton shadowing, assume

$$f_{i/A}(x, Q^2) \simeq A\ f_{i/p}(x, Q^2)$$

- Flux greater by factor of A, energy/parton less by factor of $Z/A \simeq 0.3$

$\mathbf{N_{ev}/100\ fb^{-1}}$ vs. M_s



Isolated hard photons

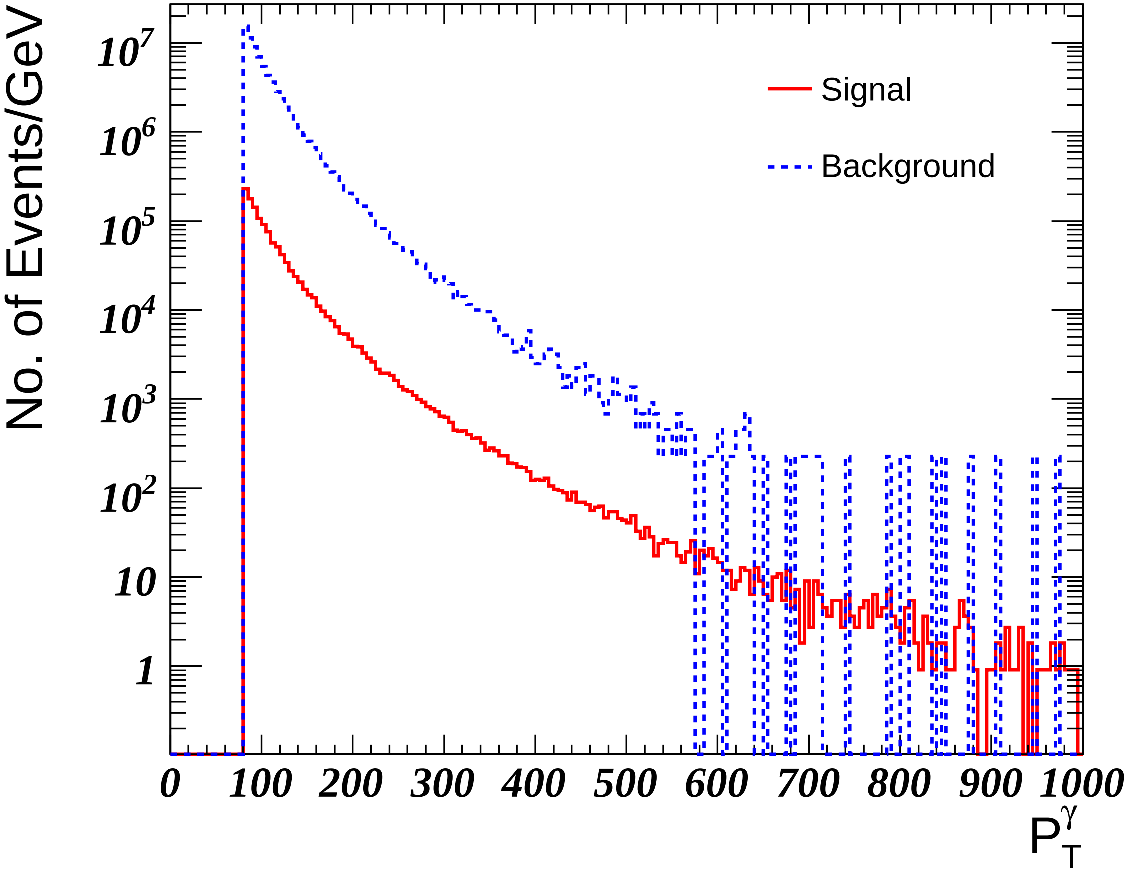
- Major experimental background: misidentification with high $k_\perp \pi^0$ – $\mathcal{O}(10^3)$ multiplier

- Imposition of isolation cuts reduces event rate for the high $k_\perp \pi^0$ background to almost the direct photon QCD rate, with negligible effect on the direct photon QCD rate or on our signal

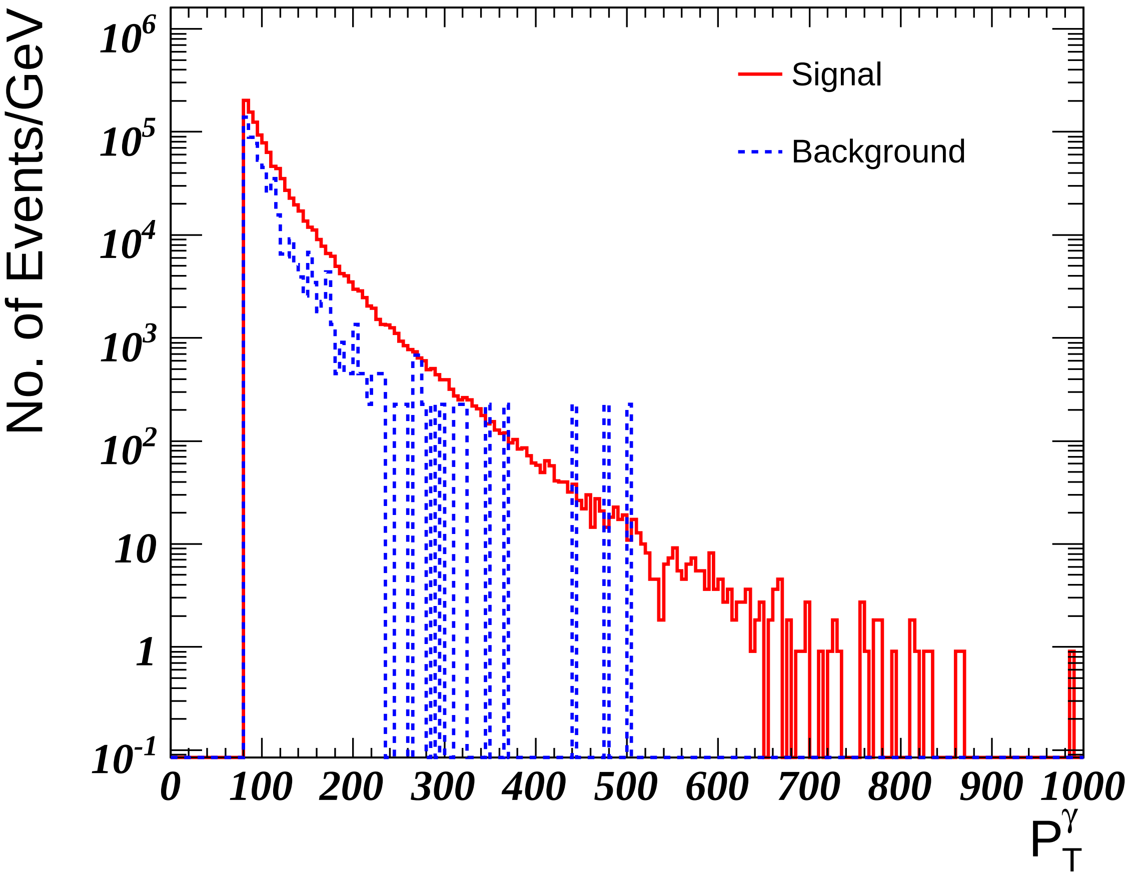
  P. Gupta et al, arXiv: 0705.2740 (for CMS)

- Some small additional background due to inner bremsstrahlung photons

QCD signal and π^0 b'k'd – no isolation cuts



QCD signal and π^0 b'k'd – with isolation cuts



$\boxed{\beta}$

- We will simulate this by defining, after isolation cuts, a quantity

$$\beta \equiv 1 + \frac{\text{background due to misidentified } \pi^{0\prime}s}{\text{QCD b}'\text{k}'\text{d due to direct photons}}$$

- Increases effective b'k'd for our signal by factor β $\longrightarrow$ decreases our S/N ratio by $1/\sqrt{\beta}$

- According to the estimate in Gupta et al, $\beta \simeq 2$ for $k_{\perp,\mathrm{min}} = 300\ \mathrm{GeV}$

Discovery reaches

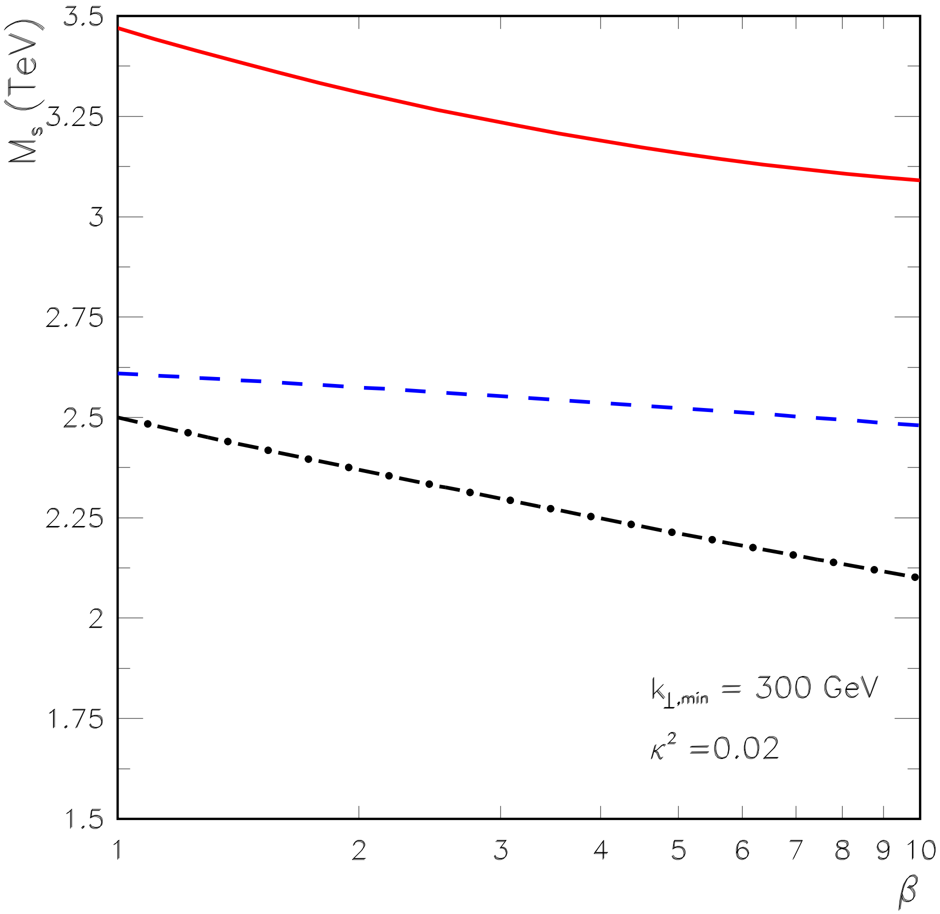


Figure 1: 5σ contours in (M_s, β) plane for 100 fb^{-1}. Solid: for $pp \to \gamma+\text{jet}|_{k_\perp(\gamma)>300\ \text{GeV}}$; dashed: $\text{PbPb} \to \gamma+\text{jet}|_{k_\perp(\gamma)>300\ \text{GeV}}$; dot-dashed: $pp \to \gamma\gamma|_{k_\perp(\gamma)>300\ \text{GeV}}$.

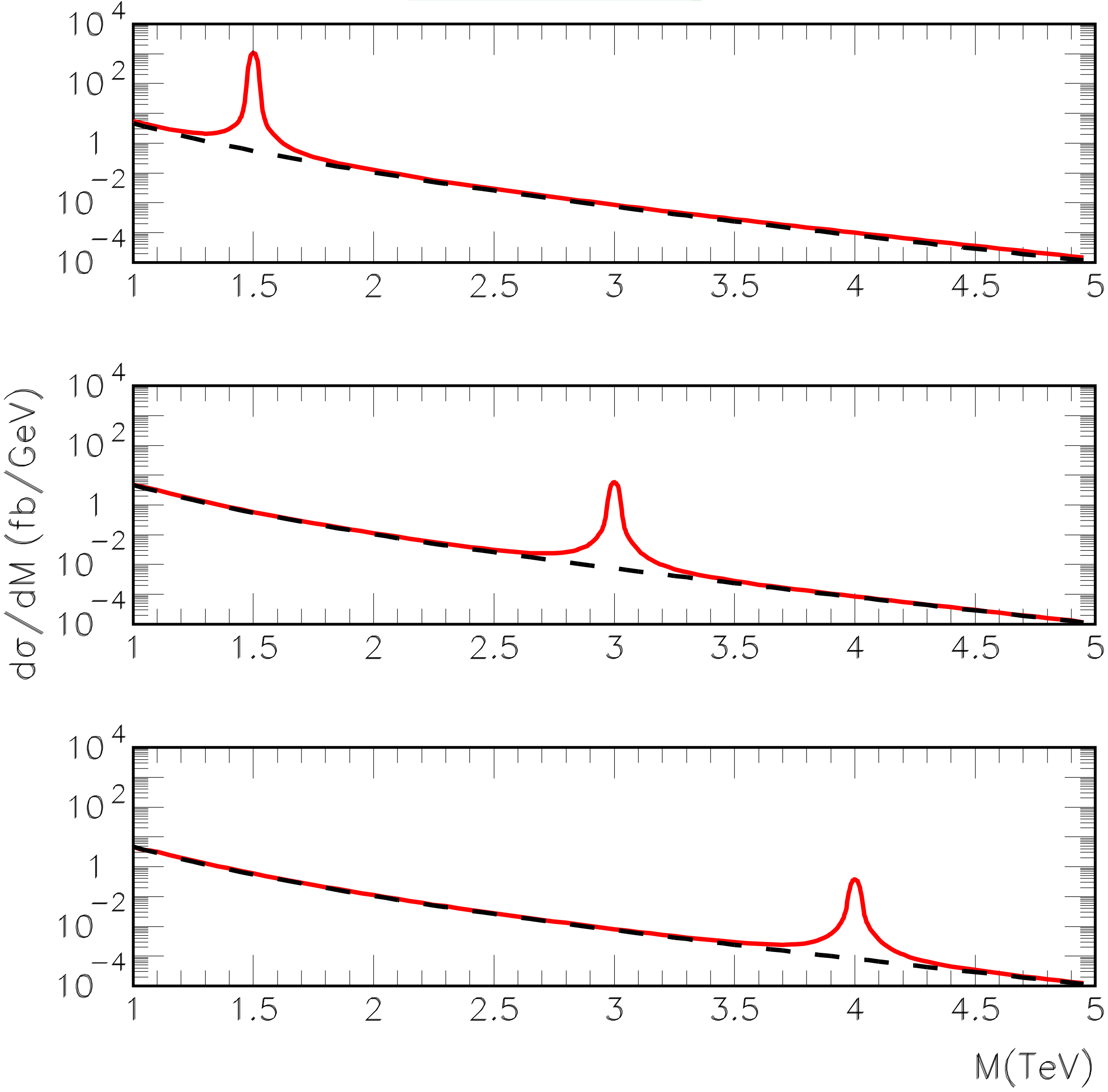
Bump-hunting

- Hope to see resonance bumps in data binned in $M =$ invariant mass of $\gamma +$ jet
- Impose rapidity (y) and $p_{\rm T}$ cuts on photon and jet and measure cumulative cross sections,

$$\sigma(M_0) = \int_{M_0}^{\infty} \frac{d\sigma}{dM}\, dM$$

- Look for regions with significant deviations from QCD b'k'd, find interval with bump!
- Integrate over $[M_s - 2\Gamma,\ M_s + 2\Gamma]$ find S/N

Resonances



Cuts

- With cuts $|y| < 2.4$ GeV, we find about same 5σ discovery region as with previous $p_\mathrm{T} > 300$ GeV
- Reason is that

$$p_\mathrm{T} = \frac{M}{2\cosh y}$$

implies that for $M \gtrsim 2~\mathrm{TeV},~~|y| < 2.4$ $p_{\mathrm{T},~\mathrm{min}}$ does not differ significantly from 300 GeV.

Concluding remarks

- Single photon production via gluon fusion $gg \longrightarrow g\gamma$ in pp scattering at the LHC presents a singular opportunity to probe for the resonant structure of TeV-scale string theory since there is no massless tree level QCD contribution to this channel

- If photon mixes with gauge boson coupled to baryon number (common feature of D-brane quivers), process appears at string disk level.In simplest model, amplitude completely determined –no arbitrary Chan-Paton factors, no dependence on compactification scheme, no dependence on fermion embeddings

Concluding remarks (cont'd)

- 100 fb^{-1} of LHC data, with signal $pp \longrightarrow \gamma +$ jet can probe deviations from SM physics at 5σ significance for M_s as large as 3.3 TeV.

- Also studied $pp \longrightarrow \gamma\gamma + X$, and showed that for $M_s \lesssim 2.5$ TeV,this process could provide corroborative evidence for the $U(3)$ D-brane picture.

- Z production: Signal cross section for transverse Z's is down by $\tan^2\theta_W \simeq 0.3$, SM b'k'd somewhat larger, but π^0 b'k'd is absent