Beyond Supersymmetry: Finding New Physics at Colliders

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Outline

- BSM Lessons of the Tevatron
- God signature: Black Holes at Future Colliders
- Conclusions

BSM: Lessons from the Tevatron

New Physics' Many Faces

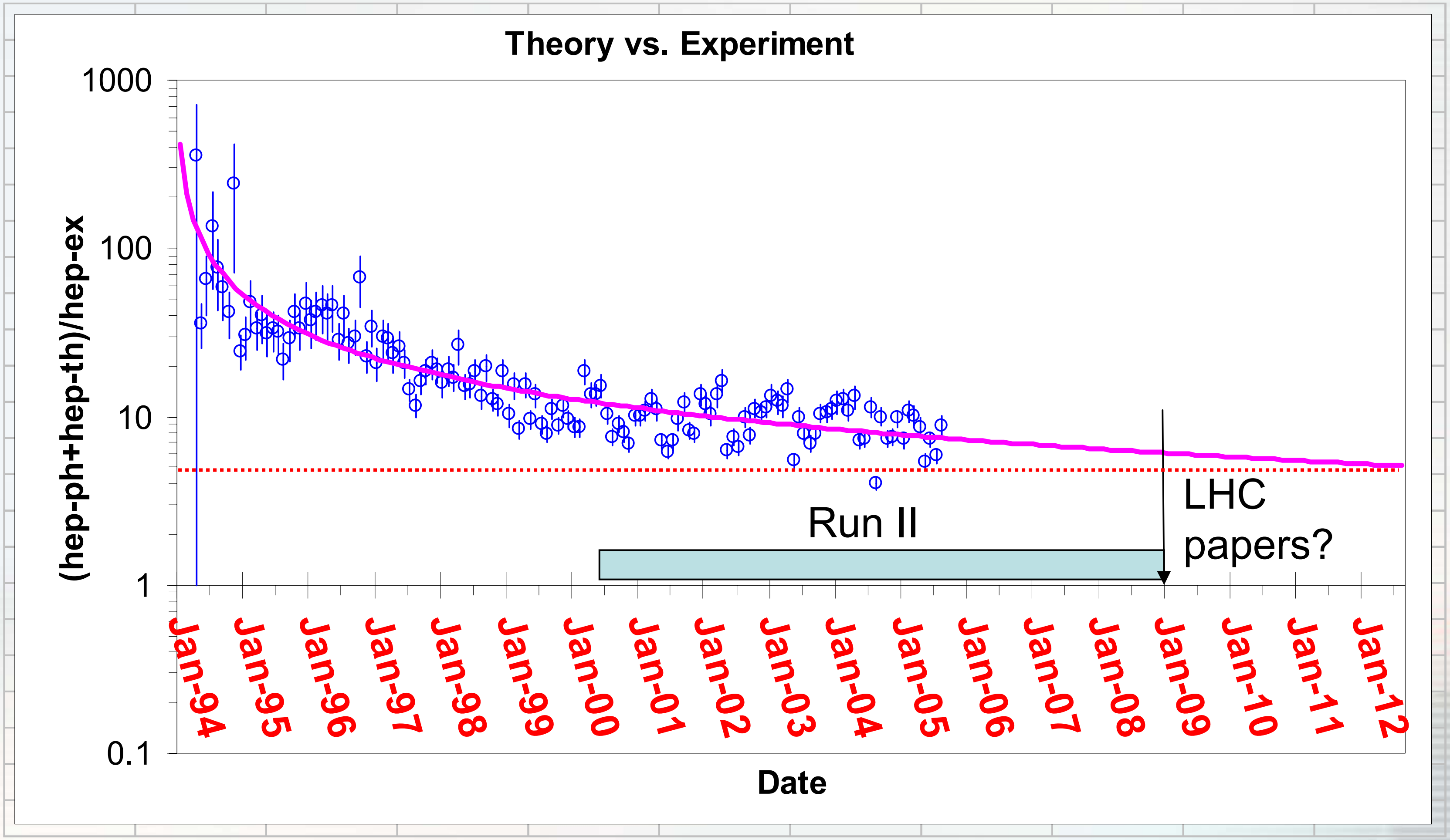
- Supersymmetry (not covered in this talk)
  - mSUGRA like
  - Gauge MSB
  - Gaugino MSB
  - Anomaly MSB
- Strong Dynamics
  - Technicolor
  - Top See-Saw
  - Compositeness
- Exotics
  - Leptoquarks
  - Extra gauge bosons
- Extra Dimensions (See Tao Han's talk)
  - Large/Infinite Volume Extra Dimensions
  - Warped Extra Dimensions
  - Universal Extra Dimensions
- Something COMPLETELY unexpected

Searches for New Physics

- Electroweak/Heavy Flavor/QCD Physics:
  - Most properties are well known
  - Mainly precision measurements
- Higgs physics:
  - Most signatures are known
  - A very few free parameters
  - Well-defined search strategy
- Searches for New Physics:
  - Do not even know what it is and where it is
    - Little doubt exists that it must be there, maybe just around the corner
  - Only vague ideas about signatures
    - Many channels, many possibilities of statistical fluctuations
    - Might not be possible to use 'cousin channels' as a discovery proof (e.g., RPV SUSY)
  - An ultimate challenge and an ultimate prize!

Pick Your Model! – or Maybe Not?

- Do not expect to test EVERY model - we will work with CHANNELS, not MODELS!



Hunting Ground

l+jets+$\not\!\!E_T$

ll+jets+$\not\!\!E_T$

jets+$\not\!\!E_T$

bb+γ

taus+$\not\!\!E_T$

bb+$\not\!\!E_T$

Massive Stable Particles

ll+bb+$\not\!\!E_T$

ll+jets

γ+jets+$\not\!\!E_T$

Undetectable

$llll$+$\not\!\!E_T$

Kinks

monojets

γ+ll+$\not\!\!E_T$

lll+jets+$\not\!\!E_T$

Non-prompt photons
or Z's

$\gamma\gamma$+E_T

It's a MESS!

Searches at the Tevatron

- The Tevatron energy might or might not be in the right range for new physics discovery
  - Perhaps with the exception of minimal technicolor models, the LHC/LC are really the machines for the ultimate test
  - Instead of giving a review of full capabilities of the Tevatron in all possible channels we use for searches, I'll give you my personal view on the most promising discovery strategy
- Consider both targeted and signature-based searches to cover all the bases
  - A few hints from Run I: $ee\gamma\gamma$MET, $e\mu$ + X "top" events, etc.
  - Importance of b's and τ's
  - New physics in top production and decay
  - "Grand finale" model-independent searches a la Sleuth [DØ, PRD **62**, 92004 (2000); PRL **86**, 3712 (2001); PRD **64**, 012004 (2001)]

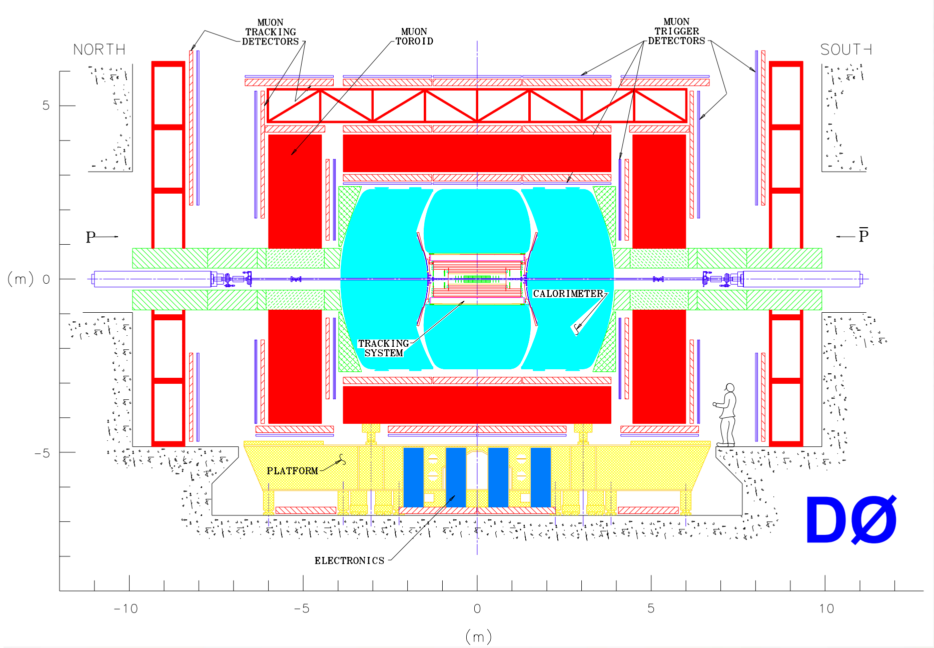
The Tevatron Lessons

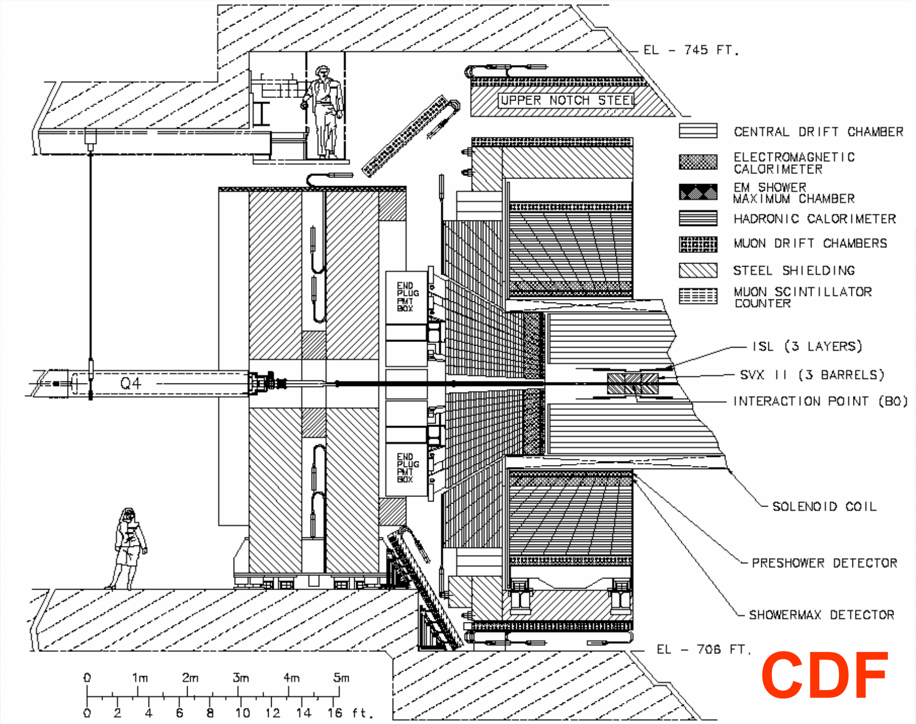
- The upgraded Tevatron with 10% higher energy still has not crossed new energy threshold, so it's unlikely that NP would appear as "spectacular events," such as copious SUSY or black hole production
  - Need to be patient
- It's likely that NP will manifest itself first as a marginal event excess in a number of related channels
  - Need for optimal combination of various channels to reach the discovery significance (cf. Higgs)
- It's likely that NP will be overwhelmed by the SM backgrounds in the channels of interest
  - Need reliable background calculation tools and advanced methods of background suppression, while retaining high sensitivity for the signal
- It's given that with the complexity of modern detectors, particle ID is based on a large number of variables
  - Need for advanced multivariate particle ID techniques
- It's possible that NP searches would require special triggers
  - Need for fast triggering methods in a complex environment

Tevatron Detectors

Significantly upgraded experiments with three major subdetectors:

- Hermetic Calorimeters
- Central Tracker
- Muon Detectors



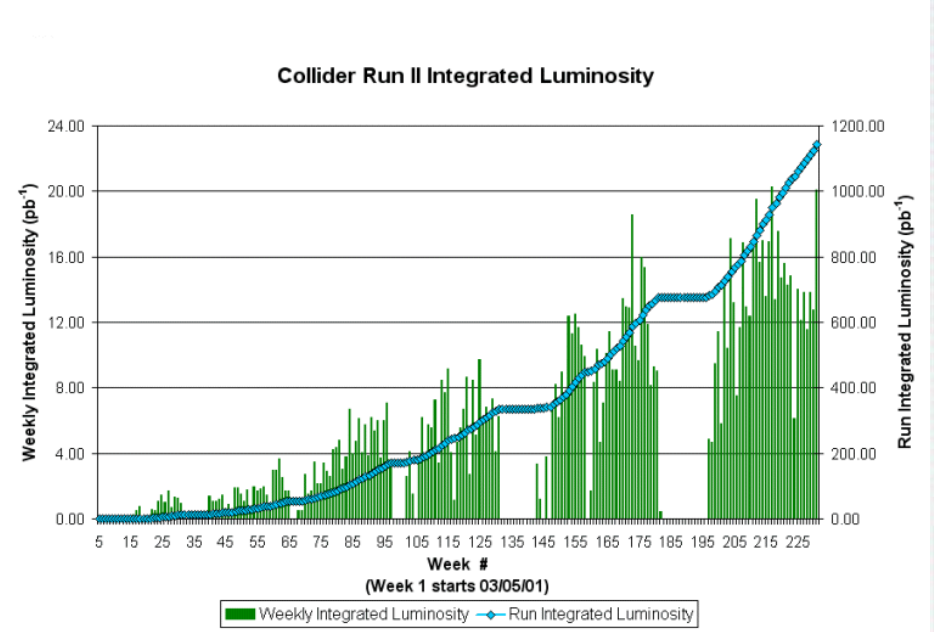


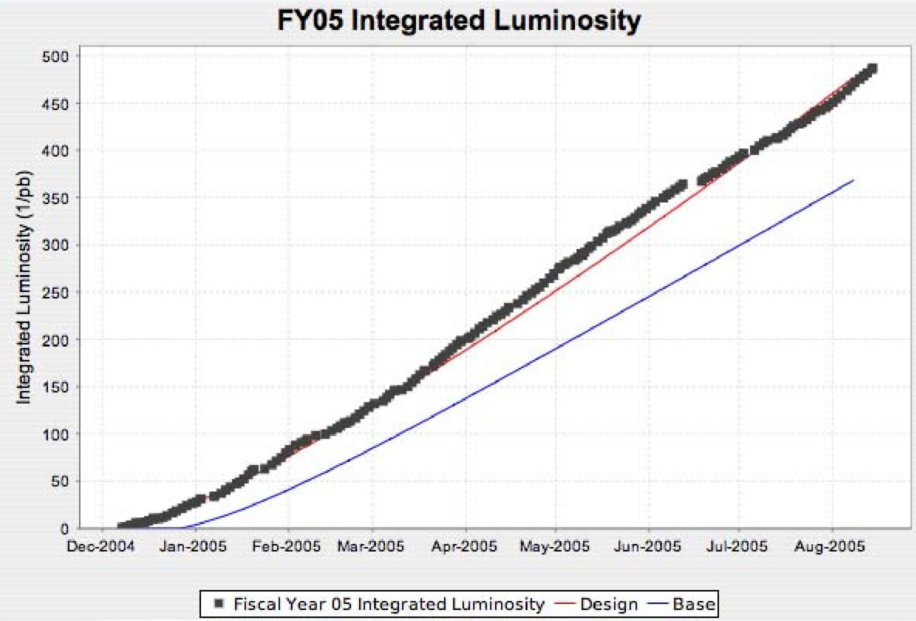
Multiple detectors – multiple handles:

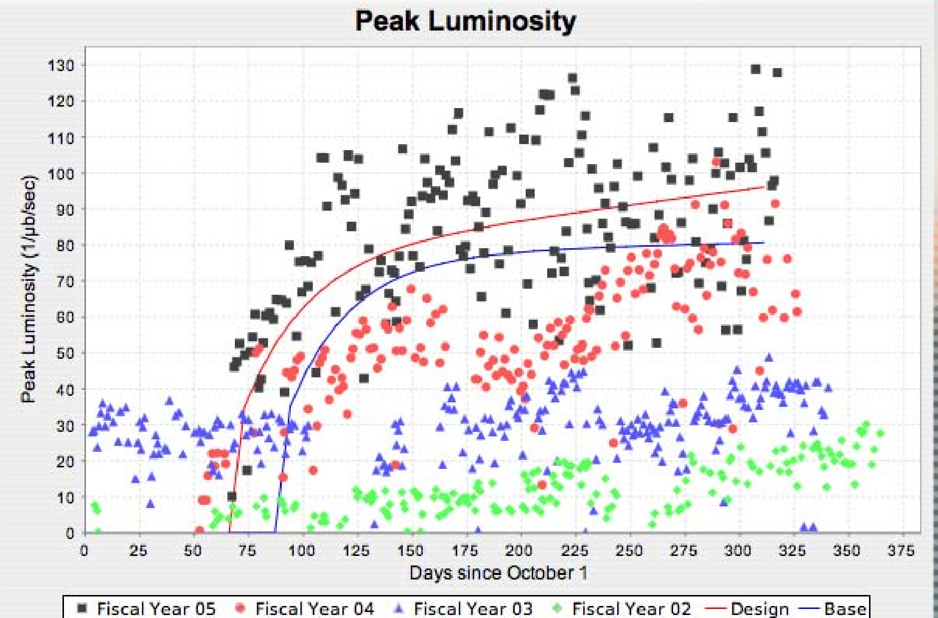
- EM: calorimetry, preshowers, (tracking, ionization)
- Muons: central and outer tracks, ionization, calorimetry
- τ's: tracking, calorimetry
- Jets: tracking, calorimetry

Tevatron Today

- The past two years brought a dramatic enhancement in the Tevatron performance:
  - Luminosity follows the optimistic, "design" curve
  - Experiments take data with >90% efficiency
  - Electron cooling test worked!

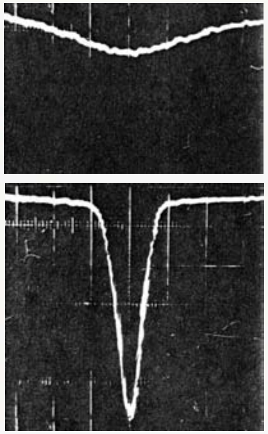






Electron Cooling – A Success

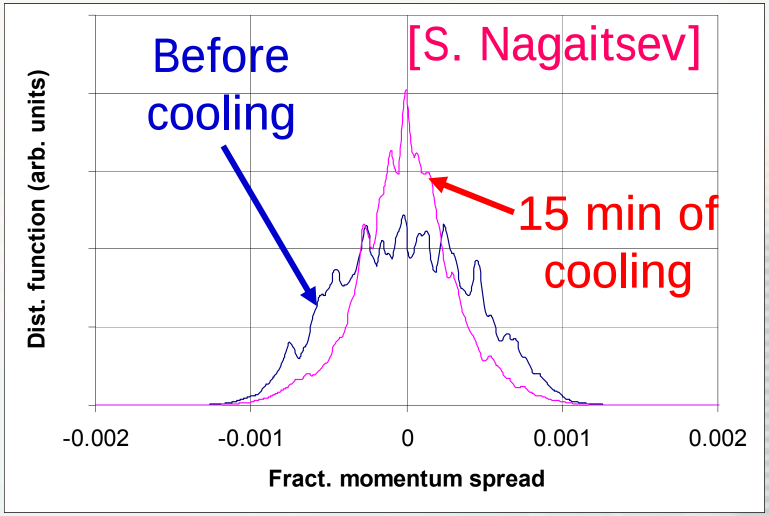
- The 1966 idea of Gersh Budker has been finally implemented on a large scale
- First test of principle has been done in Novosibirsk in 1974 w/ 68 MeV protons:



Before cooling

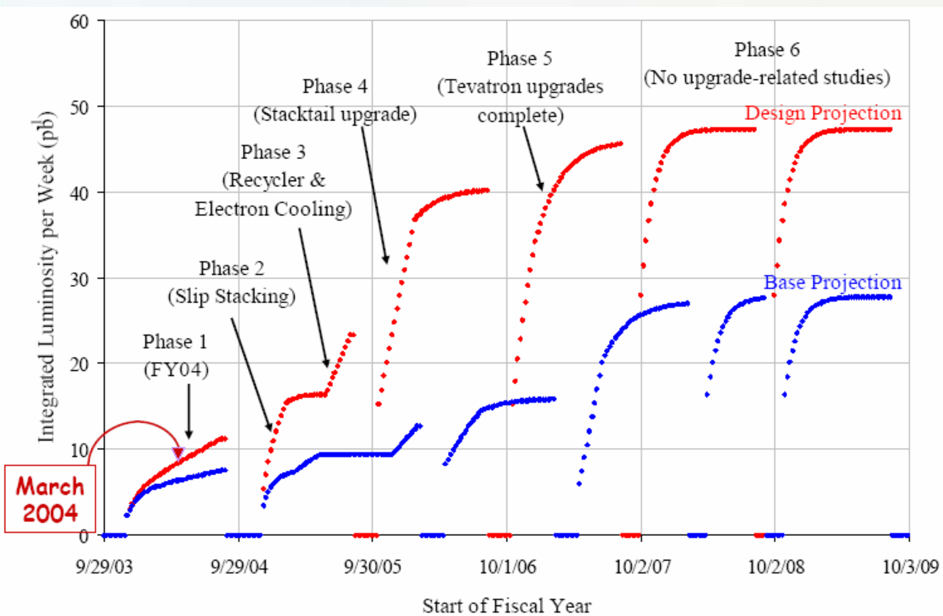
After cooling

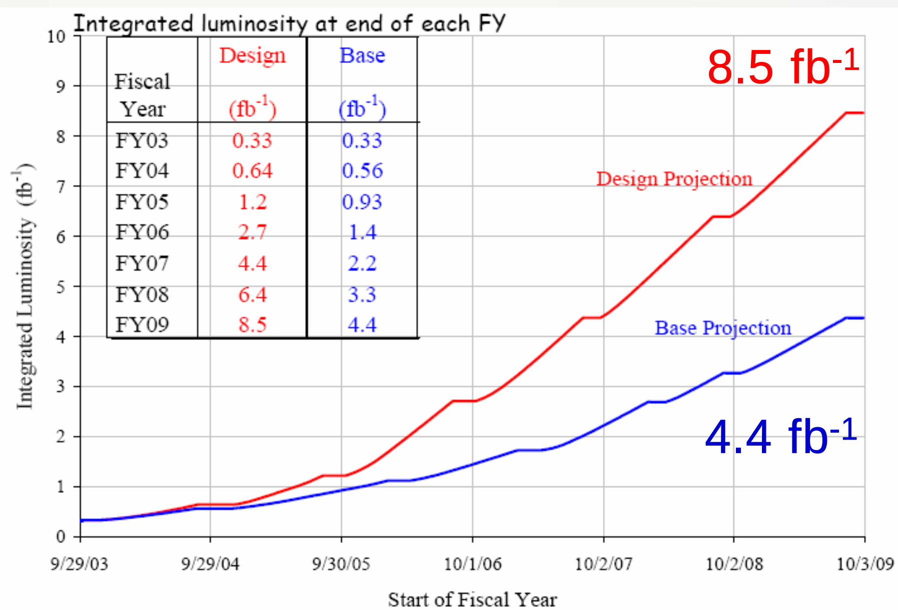
- On July 15, 2005, electron cooling has been successfully demonstrated in the antiproton recycler at Fermilab
- Should allow the Tevatron to deliver at least 5 fb^{-1} by the end of 2009



Where Do We Go from There?

- The Tevatron is likely to achieve its luminosity goal of ~5 fb^{-1} per experiment by 2010
- However, data quality will keep degrading:
  - High-luminosity environment would mean compromises in triggering, higher occupancy, and more backgrounds
  - Aging detectors (e.g., silicon that degrades at ~2%/year)
  - Not enough (wo)manpower to maintain and improve the detector performance because of people leaving for the LHC
- Can we expect a discovery from the Tevatron by 2010?





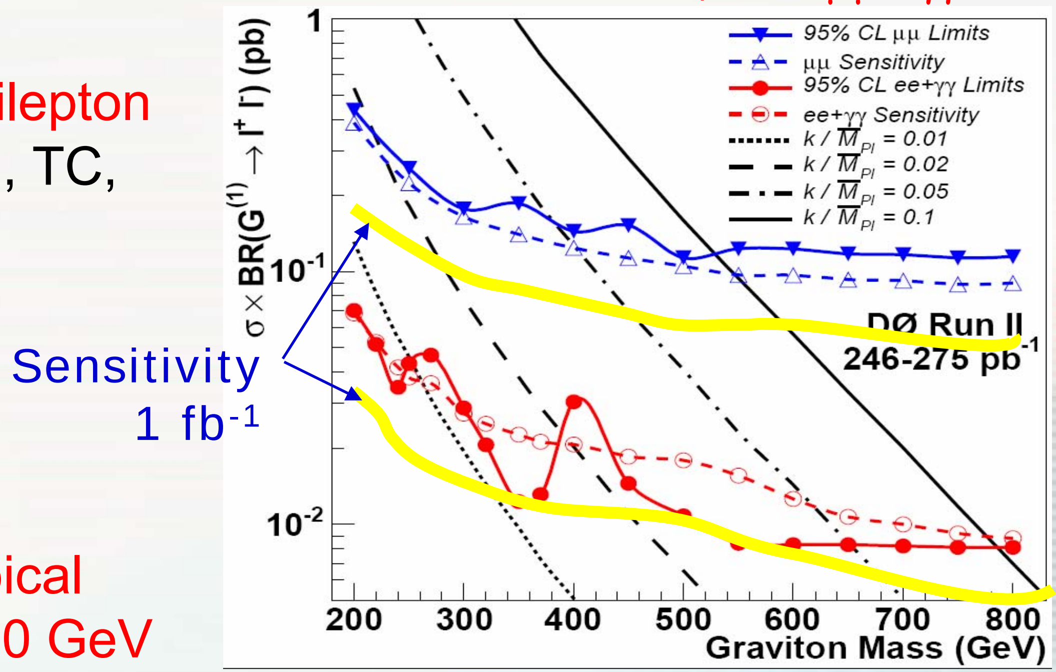
New Physics at the Tevatron ?

- How likely is that the Tevatron will discover new physics, and if so, when would it happen?
- Rule of thumb: for pair production of heavy objects cross section drops by a factor of 2 for every 20 GeV in the object mass:
  - 1 fb^{-1} ⇒ effective x10-15 in accumulated statistics cf. Run I
  - 10 fb^{-1} ⇒ effective x150 in accumulated statistics
  - Constant $S/\sqrt{B}$ (statistics dominated case):
    - 1 fb^{-1}: 20 GeV x $\log_2(10\text{-}15) \sim$ 70-80 GeV increase in mass reach (~40 GeV compared to ~250 pb^{-1} results)
    - 10 fb^{-1}: 20 GeV x $\log_2 150 \sim$ 140 GeV improvement in the mass reach
  - Run I/LEP limits are ~100 GeV ⇒ Run IIa nearly doubles; Run IIb adds only ~30% to the reach
- For singly-produced objects, all the numbers should be multiplied by two:
  - Z': 1 fb^{-1} gives ~Run I + 150 GeV ~ 850 GeV
- Note: if the uncertainty on background is dominated by systematics, the reach does not improve with luminosity, as $S/\delta B = S/(aB) \approx$ const

Consequences for the Future

- In terms of the parameter space, if the Tevatron has the "right" energy scale to find new physics, it would most likely happen with ~1 fb^{-1} statistics, i.e. we will see hints next year!
- Conversely, if we don't, it's likely that we won't find new physics at the Tevatron…
  - N.B., this is not true for the Higgs, where we know everything except for a single parameter – the mass
- An example:
  - Narrow resonances in dilepton or diphoton channels (Z', TC, ZH, RSG, …)
  - Sensitivity increases only by some 75 GeV with 4 fb^{-1}
  - Unlikely to find anything in these channels as typical exclusion is already >500 GeV

RS Gravitons, ee+μμ+γγ



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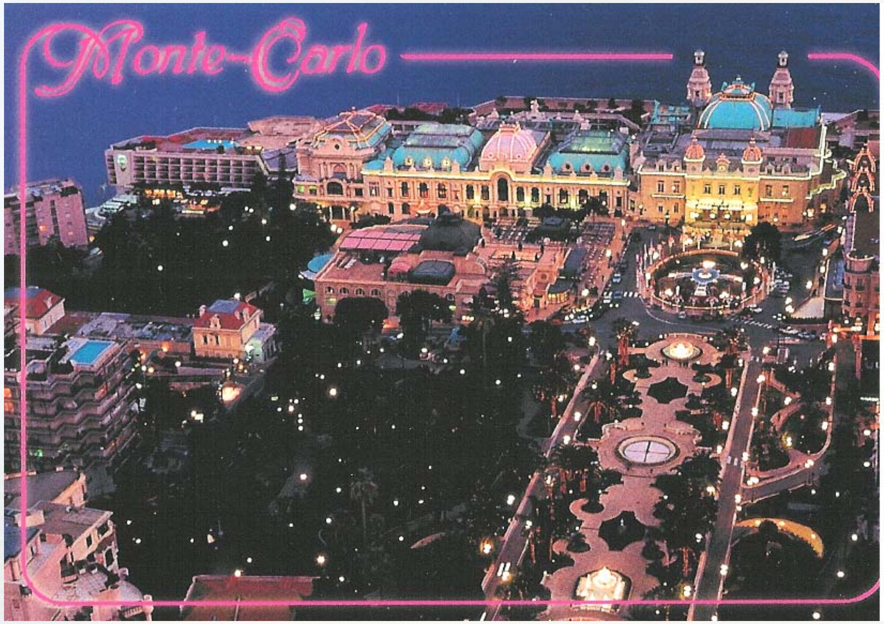
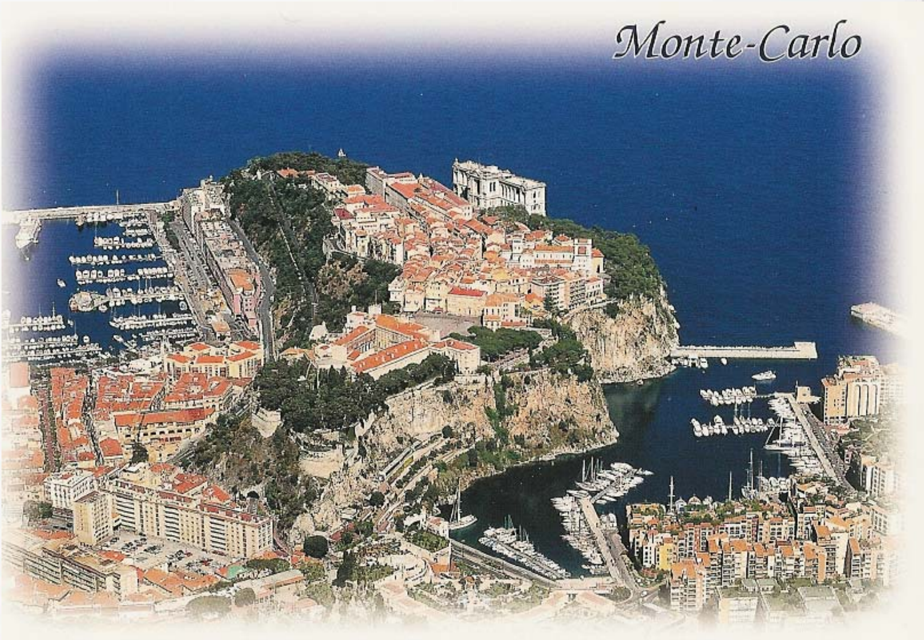
Tevatron Lesson: Triggers

- Triggers are of extreme importance at a hadron collider
- Simulations tend to (grossly) underestimate background rate due to detector malfunctions, multiple interactions, and multijet production MC estimates
- Both CDF and DØ changed their trigger menu a few dozens (!) of times during Run II to assure high physics yield
- Typical menu contains >100 various triggers designed for various physics processes, calibration, and turn-on studies
- At the moment neither ATLAS, nor CMS are anywhere close to a realistic trigger list, which won't blow the bandwidth
- Low-level triggering is less powerful at the LHC due to much shorter decision time, which presents additional challenges in order to keep the rates at bay
- Unfortunately, many LHC studies largely ignore trigger effects do not account for turn-on, and/or use unrealistically low thresholds
- This may affect the discovery potential of the LHC during the first few years of running, when triggers will be changed continuously to adapt to the quickly rising instantaneous luminosity

Tevatron Lesson: Monte Carlo

- In a perfect world…
  - –MC is as glamorous as your detector (often not built yet!)
  - –You can bet on it!
  - –Who needs the data?!!
- In the real world…
  - –Only a schematic description
  - –Lack of non-Gaussian effects
  - –The GIGO effect





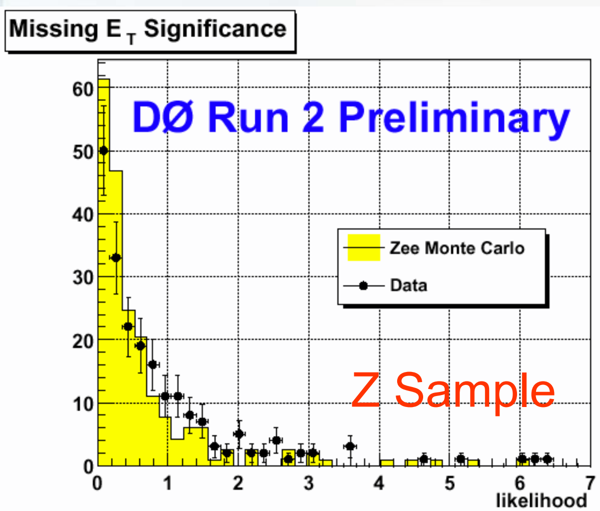
Take MC with a large grain of salt – it will look quite different from the actual data taken with the new detectors; we witnessed this in both Run I and Run II

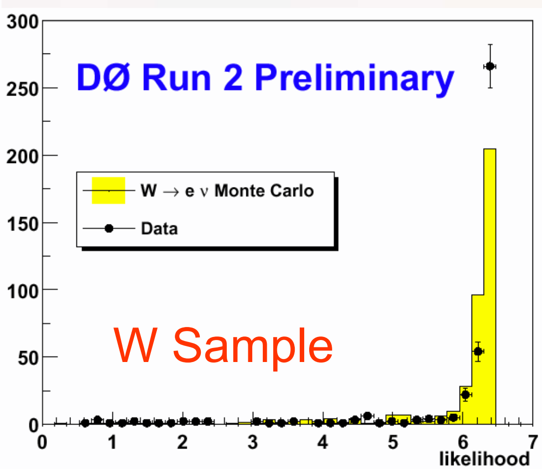
Fast Monte Carlo – A Compromise?

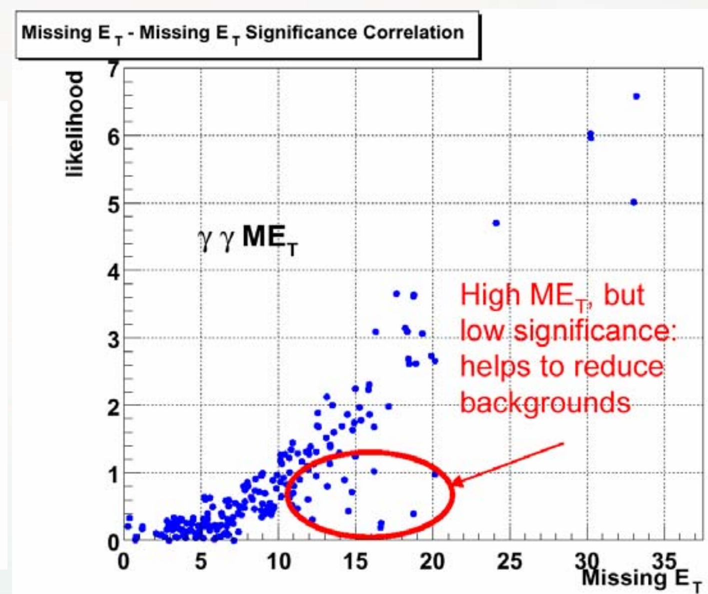
- Parametric fast MC:
  - Is flexible and easily tunable with real data (unlike full simulations)
  - Easily interfaced with modern event generators
  - Able to generate large samples of events on a short time scale
  - Often inadequate for backgrounds, but good for signals

Missing E_T Significance

- Another example of using advanced techniques for particle ID is missing E_T significance (prime SUSY signature):
  - Takes into account PDE for jet energy uncertainties, misvertexing probability, and the probability of a hot cell occurrence to calculate the significance of missing transverse energy on event-by-event basis (i.e., by taking into account the event topology)
  - Gives twice the QCD background rejection for a given efficiency, compared to MET isolation cuts
  - Already being used in DØ Run II analyses!

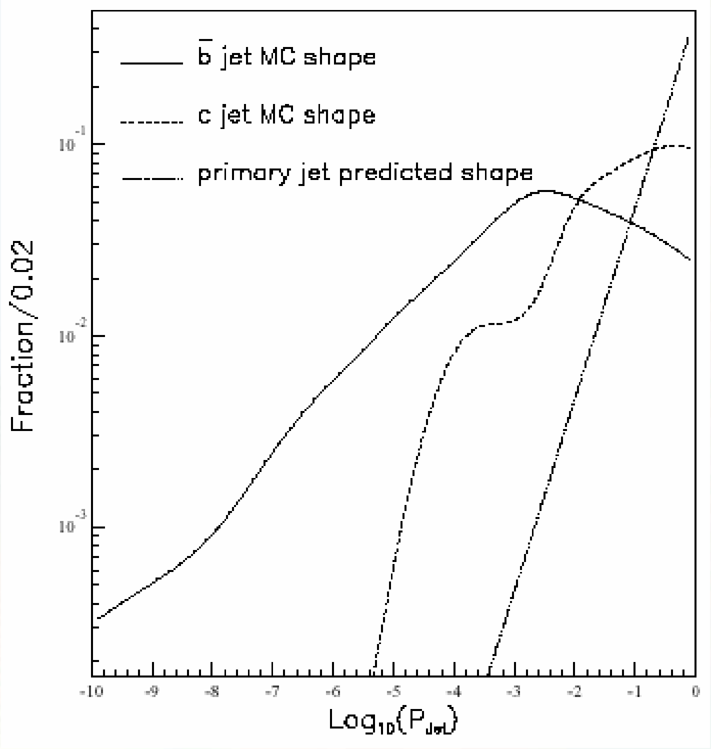


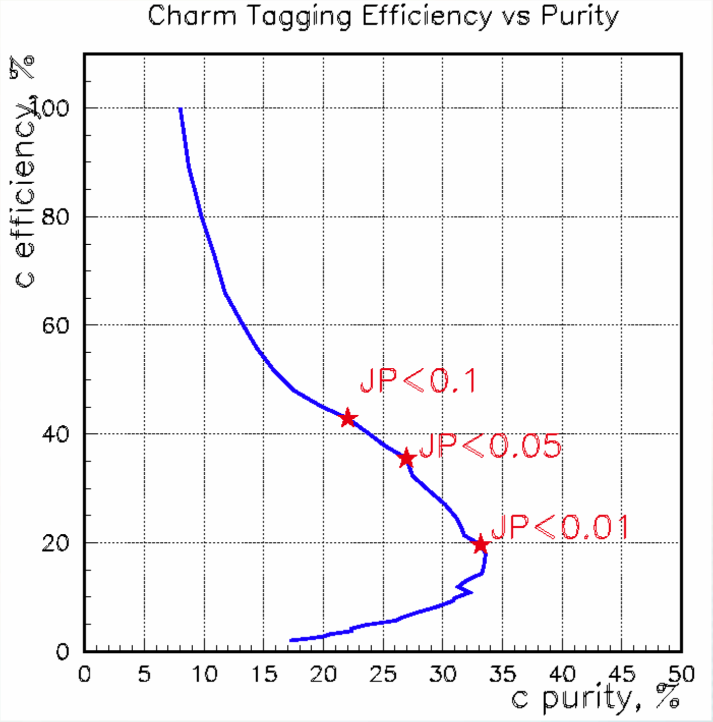




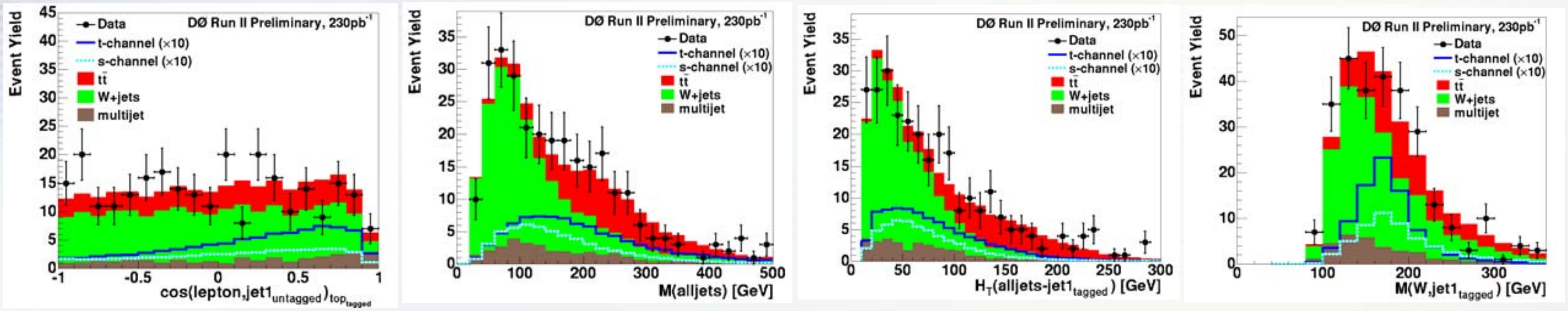
Bottom and Charm tagging

- Multivariate techniques can be used to tag jets coming from charm and bottom quarks
- Example: jet probability used in CDF Run I analyses (stop, sbottom, LQ2, LQ3 searches)
  - Define track probability as a measure of track consistency with the primary vertex
  - Define jet probability as combination of track probabilities for all tracks
  - Use this variable for bottom and charm tagging

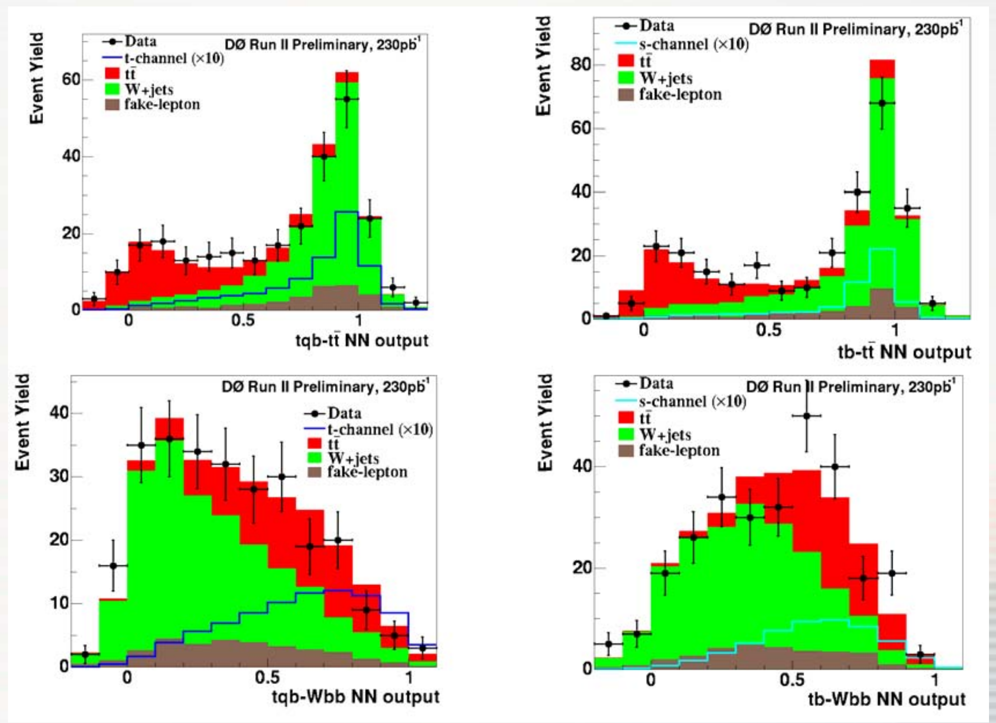




Optimization: Here Neural Nets Help…



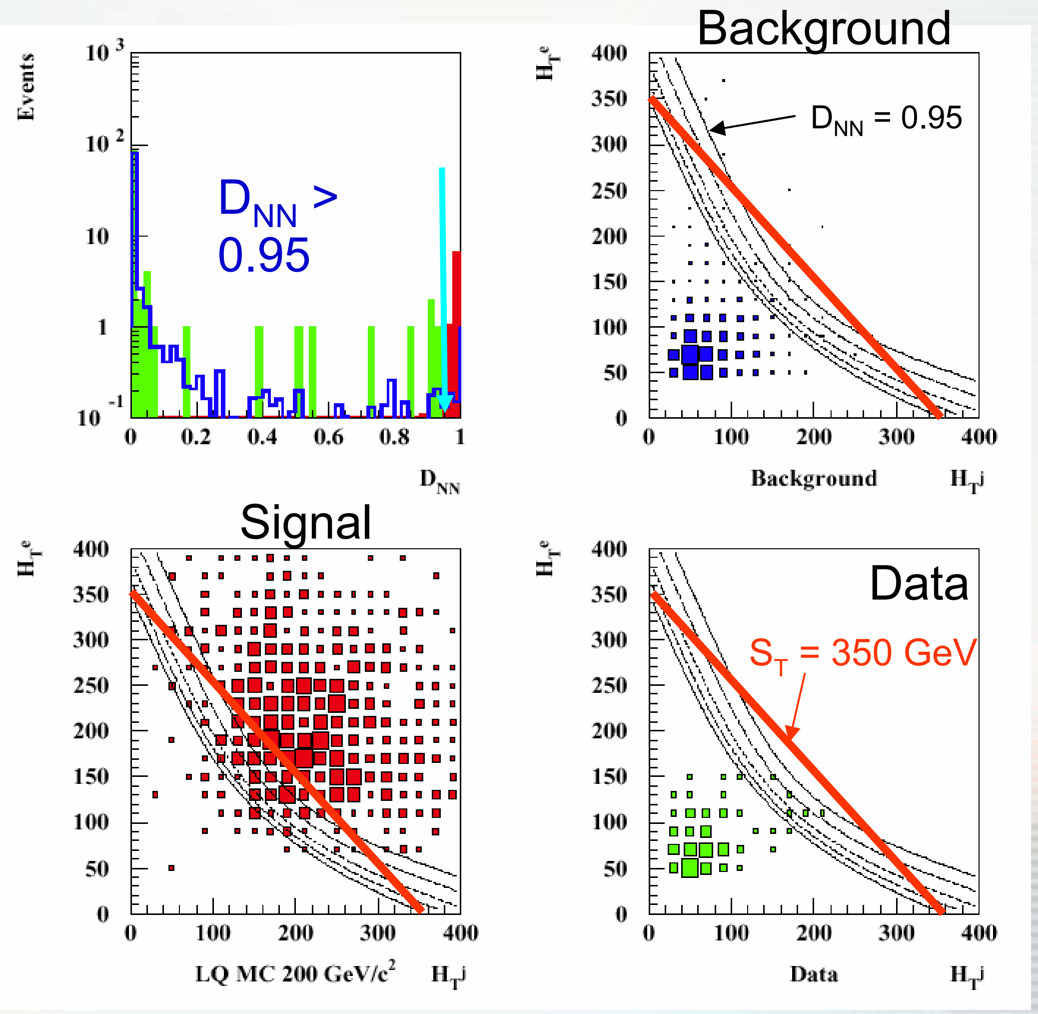
- Multivariate techniques are excellent help when:
  - Backgrounds are large and so are signals (e.g., SUSY in jetty channels)
  - Several background sources with different kinematics
  - There are no mass peaks to look for, i.e. an excess due to new physics is not easily localized in phase space
- An example: DØ Run II search for Single Top quark
  - 16 variables in four networks
  - No "killer" variable
  - W+jets, top, QCD bckgds
  - Factor of 2 improvement



•Many jetty SUSY/ Technicolor channels in Run II benefit from NN

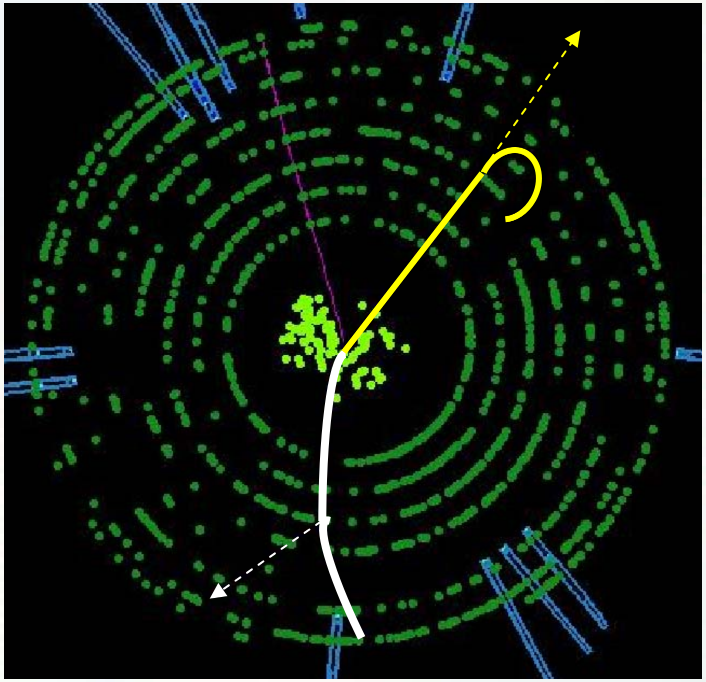
...And Here They Do Not!

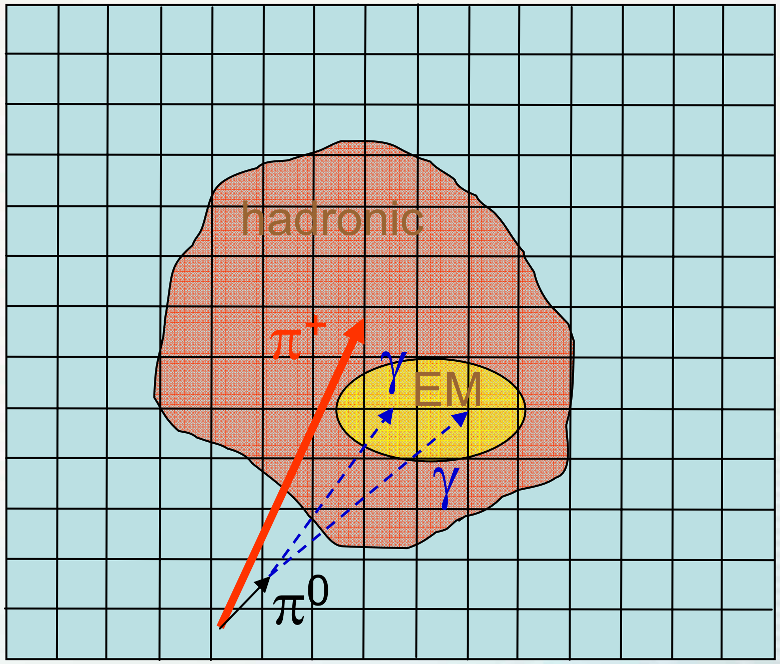
- One does not need multivariate methods if:
  - Backgrounds are low (SUSY in trileptons)
  - There is a single dominant background with the kinematics significantly different from that for signal
  - There is a single physics background, similar to that for signal (QCD $\gamma\gamma$ background for large extra dimensions search)
  - Signal is localized in the phase space (e.g., a mass peak)
- Example: DØ Run I LQ1 search in the eejj channel:
  - Only a marginal improvement compared to a simple one-variable cut



Triggering and Neural Nets

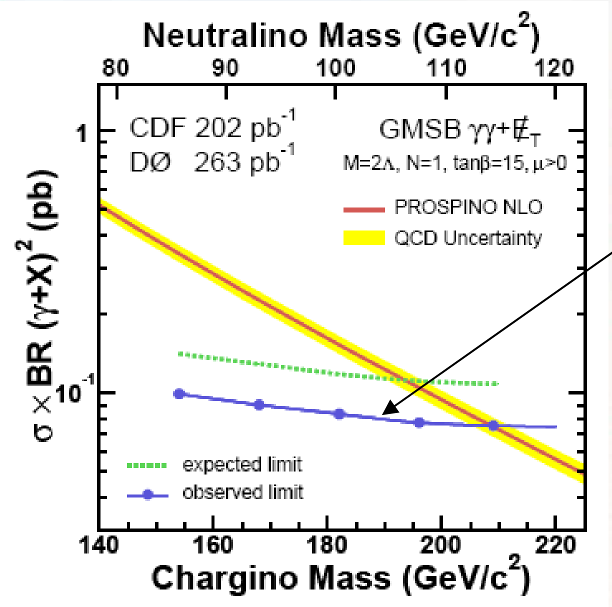
- Although we do not use Neural Nets in triggers yet, they could be very beneficial, both at the hardware and software trigger levels
- Examples:
  - Looking for kinks or stopped tracks due to long-lived charged particles (e.g., AMSB models with highly-degenerate chargino-neutralino)
  - Identifying $\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau$ decays by looking for jet substructure





Combination of Various Channels

- Often have to combine several channels and experiments to improve significance
  - Various channels typically have quite different signal-to-background ratios, hence cannot combine spectra
  - Have to take into account correlated errors
  - For combination of several experiments its desirable to “hide” experiment-specific information
- Solution: use Bayesian-likelihood-based combination, with correlated and uncorrelated errors treated separately

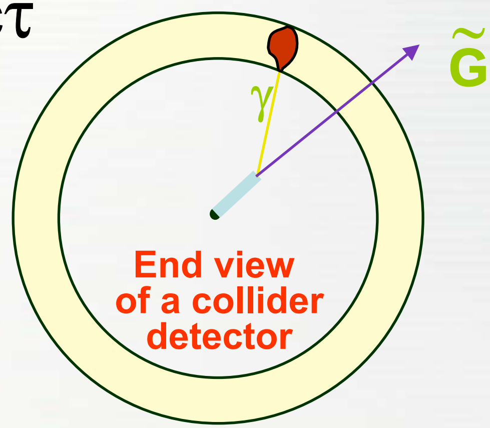


EXAMPLE:
Combined CDF and DØ
GMSB SUSY cross section limit (Mc = 182 GeV)
σ^{95}(CDF) = 0.225 pb
σ^{95}(DØ) = 0.124 pb
σ^{95}(TeV) = 0.083 pb

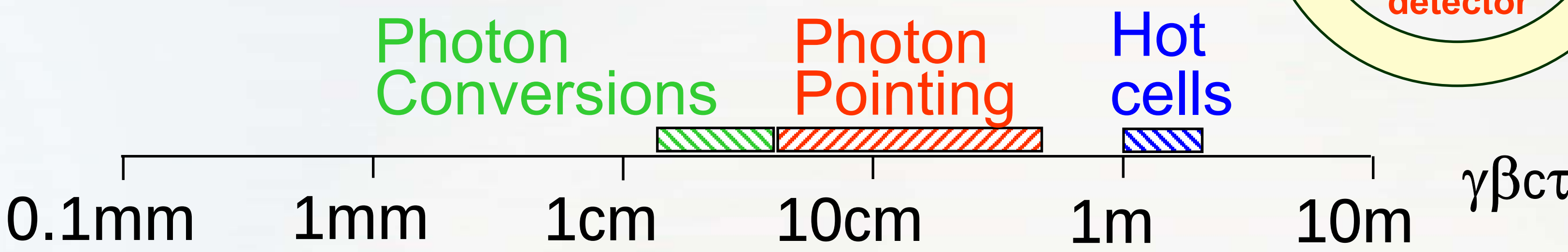
hep-ex/0504004

Search for Long-Lived Particles

- The key question is the lifetime, or $\gamma\beta c\tau$
- The key issue is triggering



Neutral Long-Lived Particles:



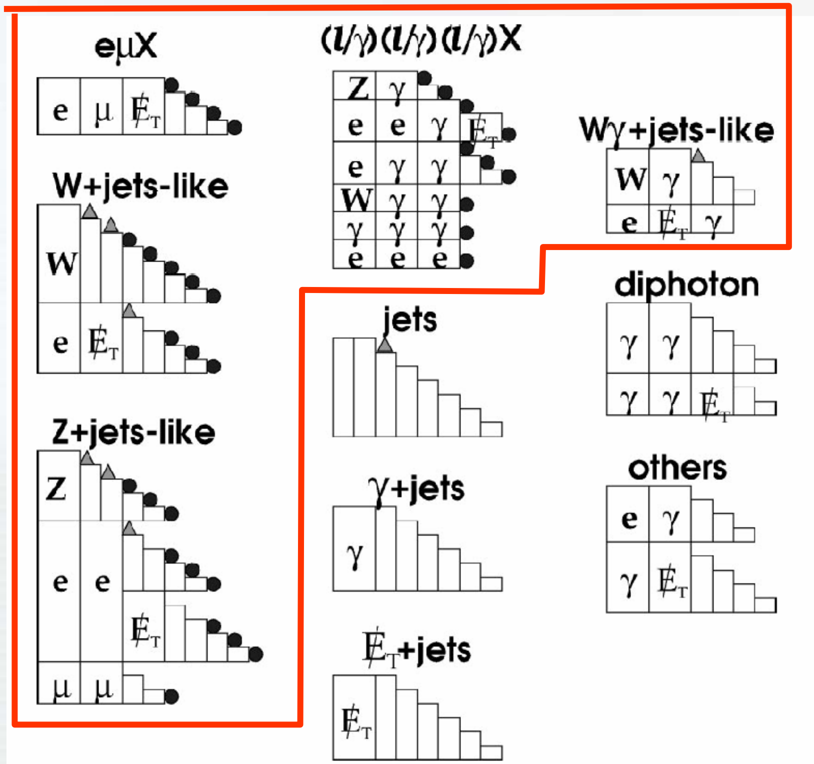
Charged Long-Lived Particles:

Grand Finale: Have We Missed Anything?

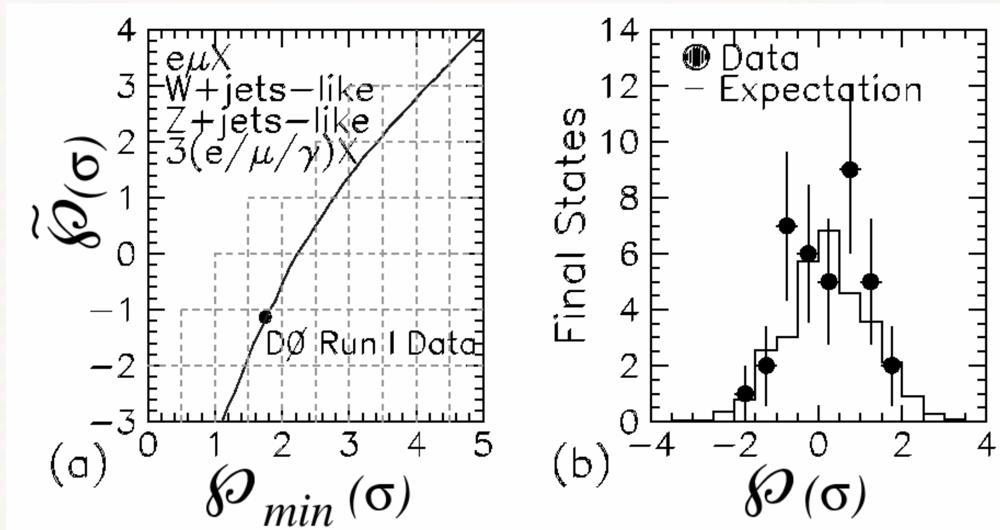
- SLEUTH (formerly known as SHERLOCK) [DØ, PRD **62**, 92004 (2000); PRL **86**, 3712 (2001); PRD **64**, 012004 (2001)] is an attempt to use multivariate techniques to answer the above question
  - Generalizes search for high-p_T physics by identifying global variables, correlated with the p_T of a process, and then looking for "reasonable" contiguous areas in the resulting multivariate space yielding maximum excess of data above the SM background
  - Unusual, data-driven approach; an interesting method to answer the question of whether there was an evidence for new physics in the data *posteriori*
  - Takes into account the fact that search for excesses was performed in many different variables and channels by adjusting the probability accordingly; consequently, trades decreased significance for increased generality
  - Used by DØ to reanalyze Run I data in a semi-model-independent way and quantify the degree of the agreement between the data and the SM predictions in some 30 previously studied channels

DØ Run I Sleuth Results

- Sleuth is a nice tool to use before closing the door and shutting off the lights: have we forgotten or missed anything
- It crucially relies on background understanding and won't help at this (most time-consuming) step
- Not very competitive with direct search for a known signature (e.g., a mass peak)



$\tilde{P}(\sigma) = -1.23\sigma \rightarrow \tilde{P} = 0.89$,
i.e. 89% of hypothetical experiments would have seen more "interesting" results in these 32 channels than DØ



The God Signature: Black Holes at Colliders

Black Holes in General Relativity

- Black holes (BH) are direct prediction of Einstein's General Relativity (GR)
- It's somewhat ironical that Einstein himself never believed in BH!
- Karl Schwarzschild showed (1916) that the space-time metric for a massive body has a singularity at r = $R_S \equiv 2MG_N/c^2$
  - r and t essentially swap places for r < R_S
  - Hence, if the mass M is enclosed within its *Schwarzschild radius* R_S, a "black hole" is formed
- The term coined much later by John Wheeler ~1967

- Naïvely, a black hole would only grow once it's formed
- In 1975 Steven Hawking showed that this is not true [Commun. Math. Phys. **43**, 199 (1975)], as the black hole can evaporate by emitting virtual pairs at the event horizon, with one particle escaping
- These particles have a black-body spectrum at the *Hawking temperature*:

$$T_H = \hbar c / 4\pi k R_S$$

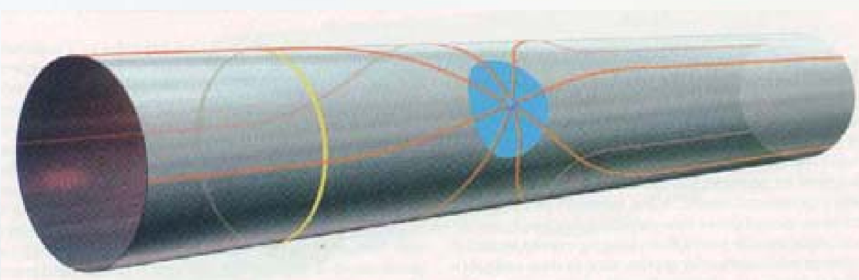
- In natural units ($\hbar = c = k = 1$), one has: $R_S T_H = (4\pi)^{-1}$
- If T_H is high enough, massive particles can be also produced in the process of evaporation

The ADD Model

- SM fields are localized on the (3+1)-brane; gravity is the only force that "feels" the bulk space
- What about Newton's law?

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \rightarrow \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^{n+1}}$$

- Ruled out for infinite extra dimensions, but does not apply for sufficiently small compact ones



$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \quad \text{for } r >> R$$

- Gravity is fundamentally strong force, bit we do not feel that as it is diluted by the volume of the bulk
- $G'_N = 1/\left(M_{Pl}^{[3+n]}\right)^2 \equiv 1/M_D^2$; $M_D \sim 1$ TeV

$$M_D^{n+2} \propto M_{Pl}^2 / R^n$$

- More precisely, from Gauss's law:

$$R = \frac{1}{2\sqrt{\pi} M_D}\left(\frac{M_{Pl}}{M_D}\right)^{2/n} \propto \begin{cases} 8 \times 10^{12} m, & n = 1 \\ 0.7\ mm, & n = 2 \\ 3\ nm, & n = 3 \\ 6 \times 10^{-12} m, & n = 4 \end{cases}$$

- Amazing as it is, but no one has tested Newton's law to distances less than ~ 1mm (as of 1998)
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1
- n=2 is nearly ruled out by now

BH at Accelerators: Basic Idea

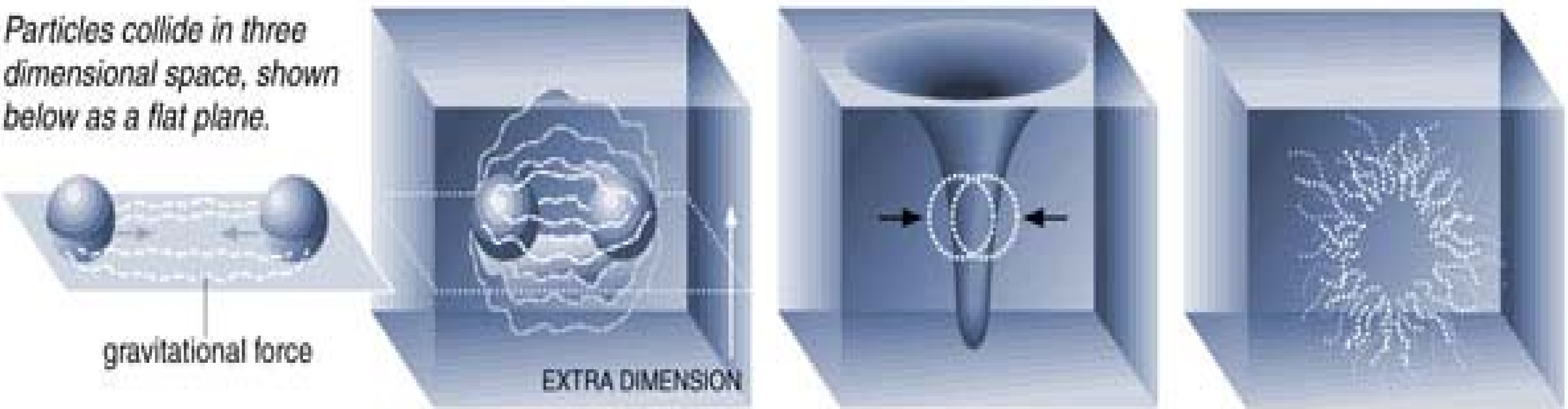
Black Holes on Demand

NYT, 9/11/01

The New York Times ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

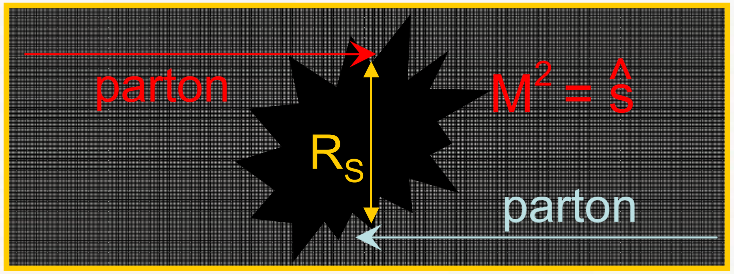
The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Theoretical Framework

- Based on the work done with Savas Dimopoulos a few years ago [PRL **87**, 161602 (2001)]
- Related study by Giddings, Thomas [PRD **65**, 056010 (2002)]
- Extends previous theoretical studies by Argyres, Dimopoulos, March-Russell [PLB **441**, 96 (1998)], Banks, Fischler [JHEP, **9906**, 014 (1999)], Emparan, Horowitz,Myers [PRL **85**, 499 (2000)] to collider phenomenology
- Big surprise: BH production is not an exotic remote possibility, but the dominant effect!
- Main idea: when the c.o.m. energy reaches the fundamental Planck scale, a BH is formed; cross section is given by the black disk approximation:

$$\sigma \sim \pi R_S^2 \sim 1\ \text{TeV}^{-2} \sim 10^{-38}\ \text{m}^2 \sim 100\ \text{pb}$$



- This is an enormous cross section! For a 400 TeV machine, $R_S \sim 1$ fm, so nothing, including diffraction, will be seen except for the BH production!

Assumptions and Approximations

- Fundamental limitation: our lack of knowledge of quantum gravity effects close to the Planck scale
- Consequently, no attempts for partial improvement of the results, e.g.:
  - Grey body factors
  - BH spin, charge, color hair
  - Relativistic effects and time-dependence
- The underlying assumptions rely on two simple qualitative properties:
  - The absence of small couplings;
  - The “democratic” nature of BH decays
- We expect these features to survive for light BH
- Use semi-classical approach strictly valid only for $M_{BH} \gg M_P$; only consider $M_{BH} > M_P$
- Clearly, these are important limitations, but there is no way around them without the knowledge of QG

Black Hole Production

•Schwarzschild radius is given by Argyres et al. [hep-th/9808138], after Myers, Perry [Ann. Phys. **172** (1986) 304]; it leads to:

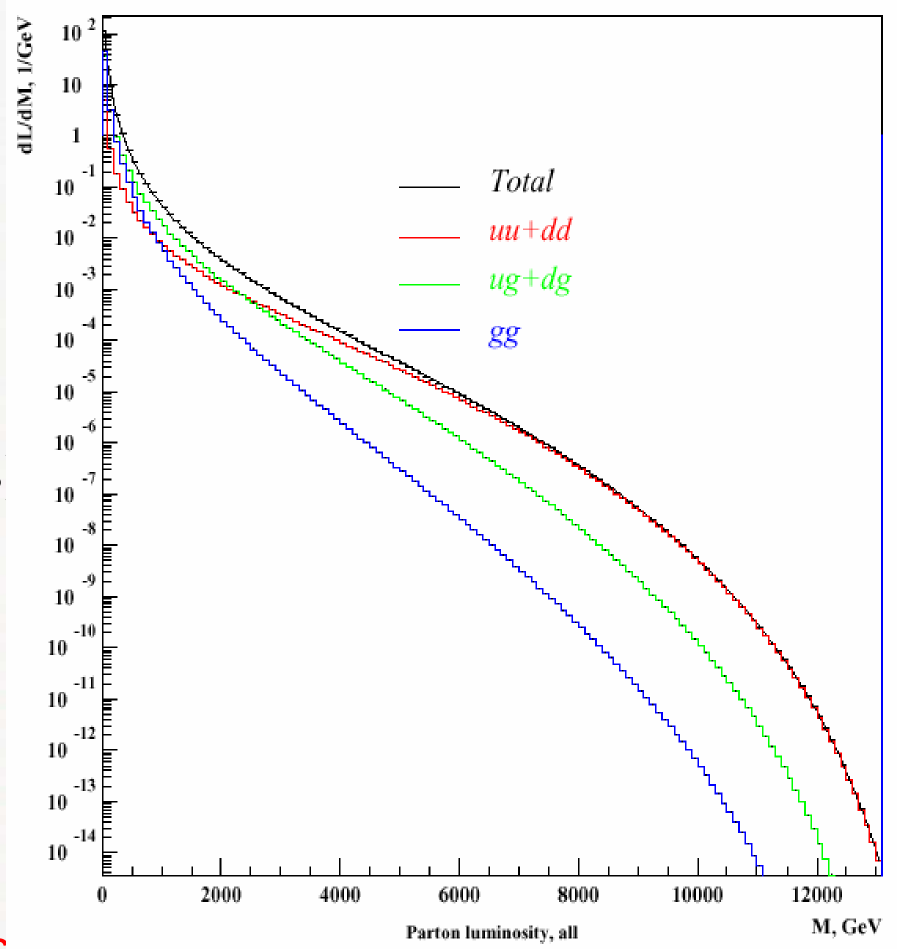
$$\sigma(\hat{s} = M_{BH}^2) = \pi R_S^2 = \frac{1}{M_P^2}\left[\frac{M_{BH}}{M_P}\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{2}{n+1}}$$

•Hadron colliders: use parton luminosity w/ MRSD-' PDF (valid up to the VLHC energies

$$\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}}\hat{\sigma}(ab \to BH)\Big|_{\hat{s}=M_{BH}^2}$$

$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s}\sum_{a,b}\int_{M_{BH}^2/s}^{1}\frac{dx_a}{x_a}f_a(x_a)f_b\left(\frac{M_{BH}^2}{sx_a}\right)$$

•Note: at c.o.m. energies ~1 TeV the dominant contribution is from qq' interactions



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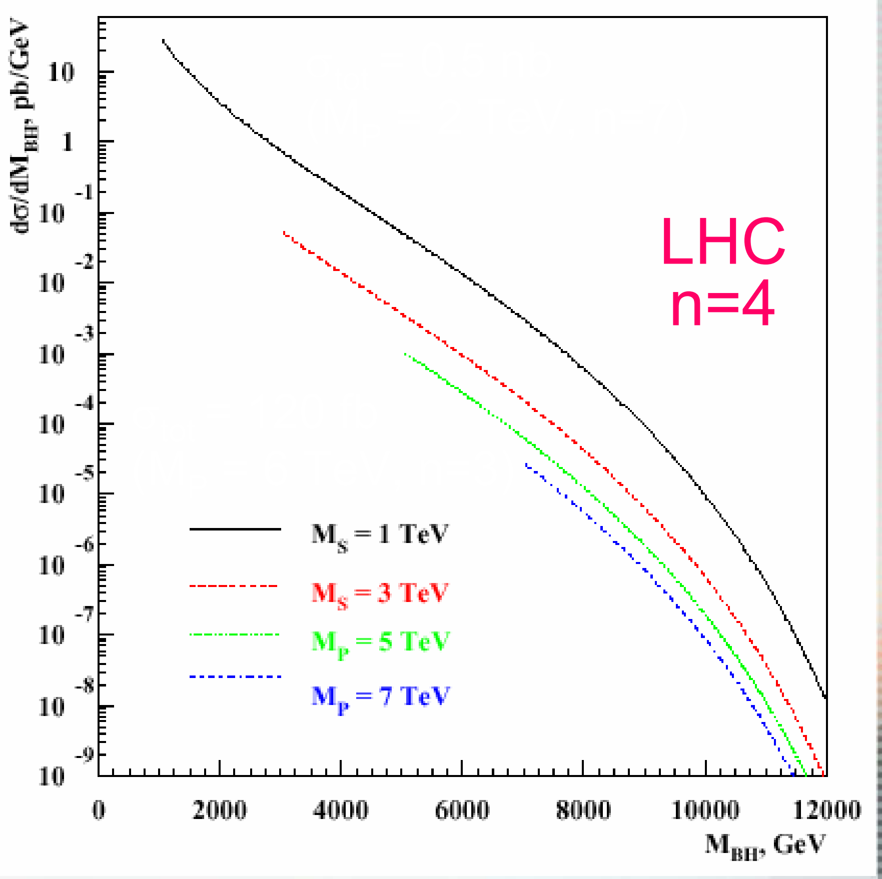
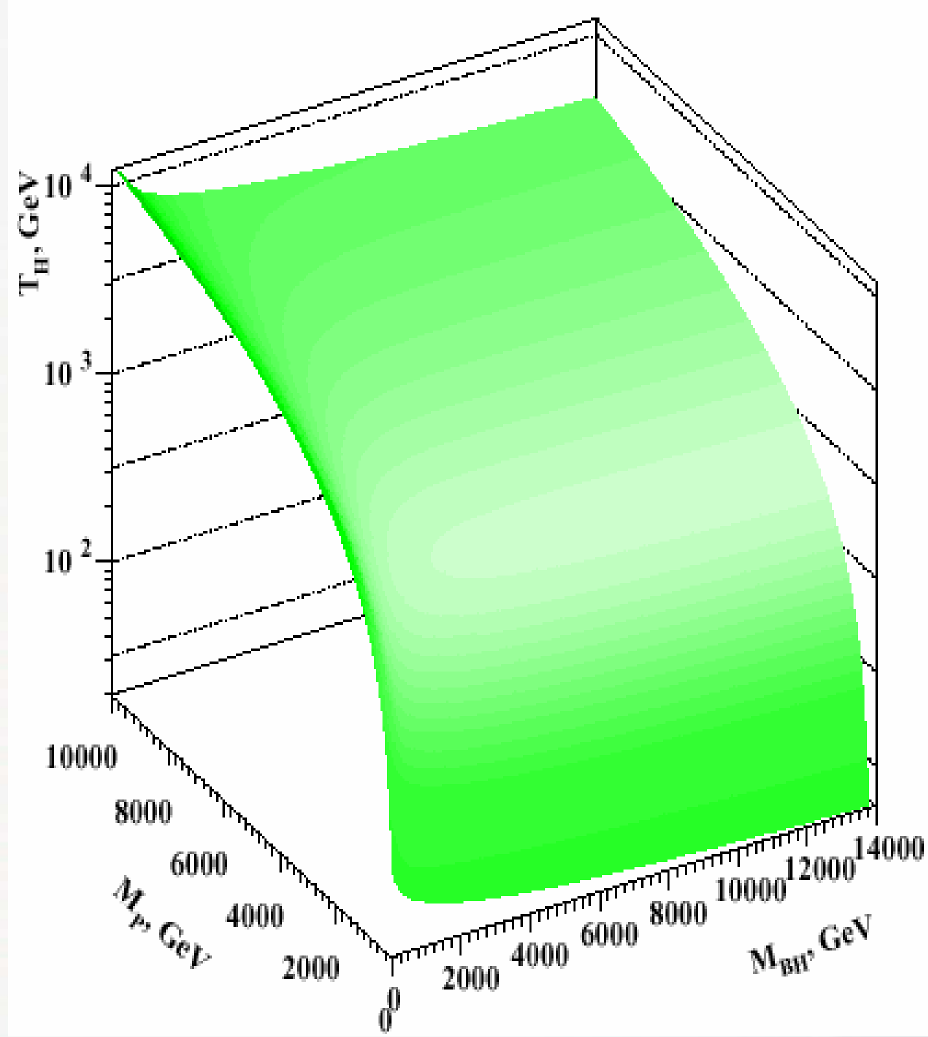
[Dimopoulos, GL, PRL **87**, 161602 (2001)]



Black Hole Decay

- Hawking temperature: $R_S T_H = (n+1)/4\pi$
- BH radiates mainly on the brane
Emparan, Horowitz, Myers,
[hep-th/0003118]
  - $\lambda \sim 2\pi/T_H > R_S$; hence, the BH is a point radiator, producing s-waves, which depends only on the radial component
  - The decay into a particle on the brane and in the bulk is thus the same
  - Since there are much more particles on the brane, than in the bulk, decay into gravitons is largely suppressed
- Democratic couplings to ~120 SM d.o.f. yield probability of Hawking evaporation into γ, $l^\pm$, and ν ~2%, 10%, and 5% respectively
- Averaging over the BB spectrum gives average multiplicity of decay products:

$$\langle N \rangle \approx \frac{M_{BH}}{2T_H}$$



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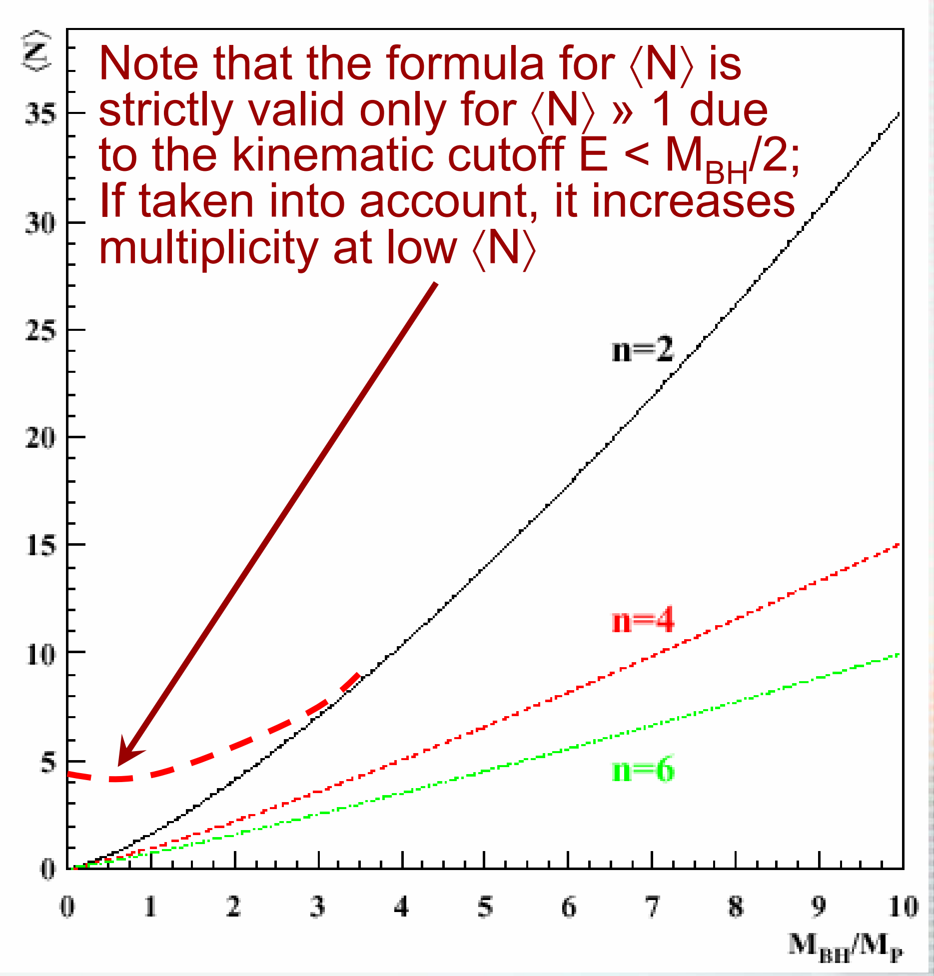
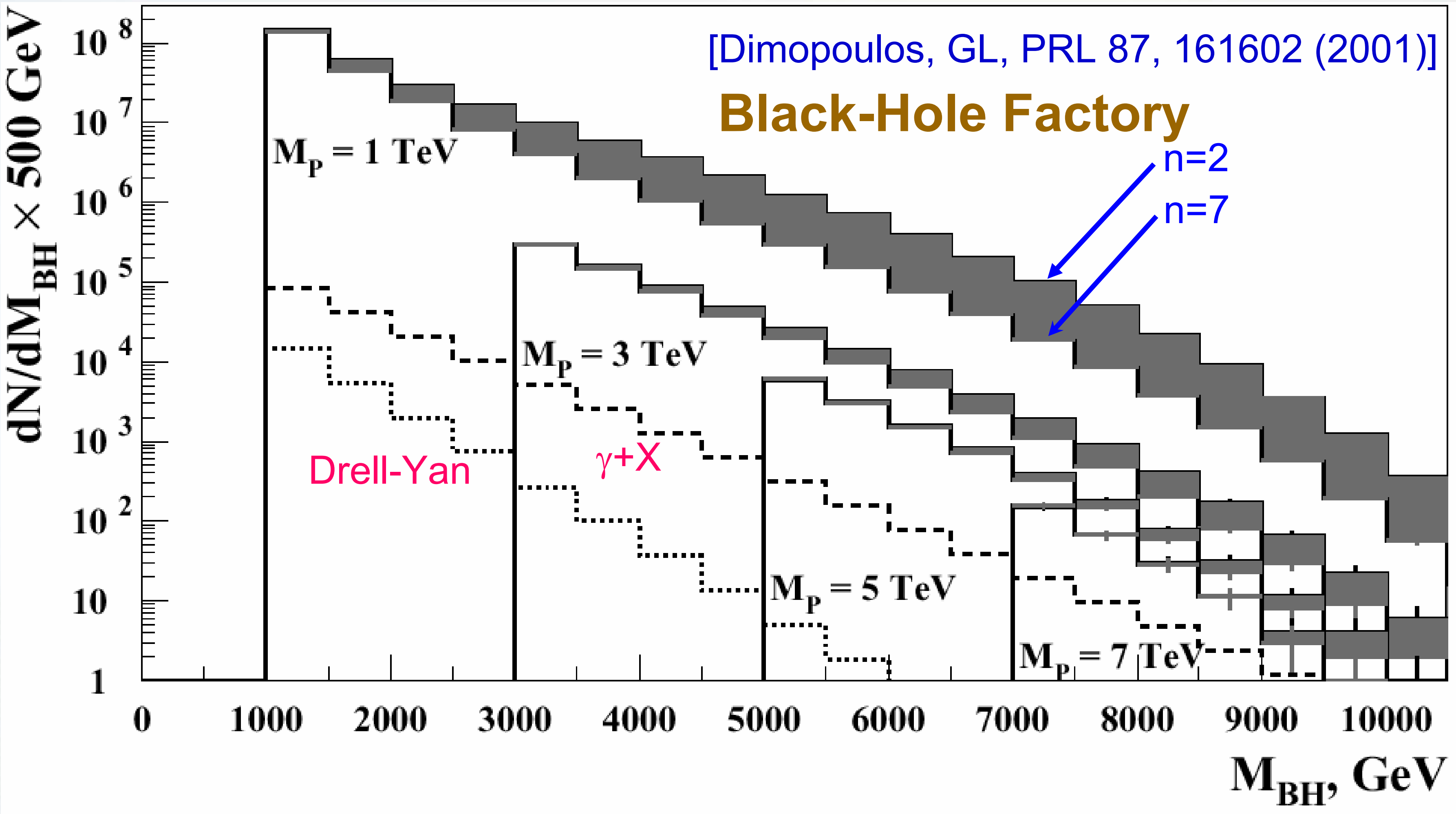


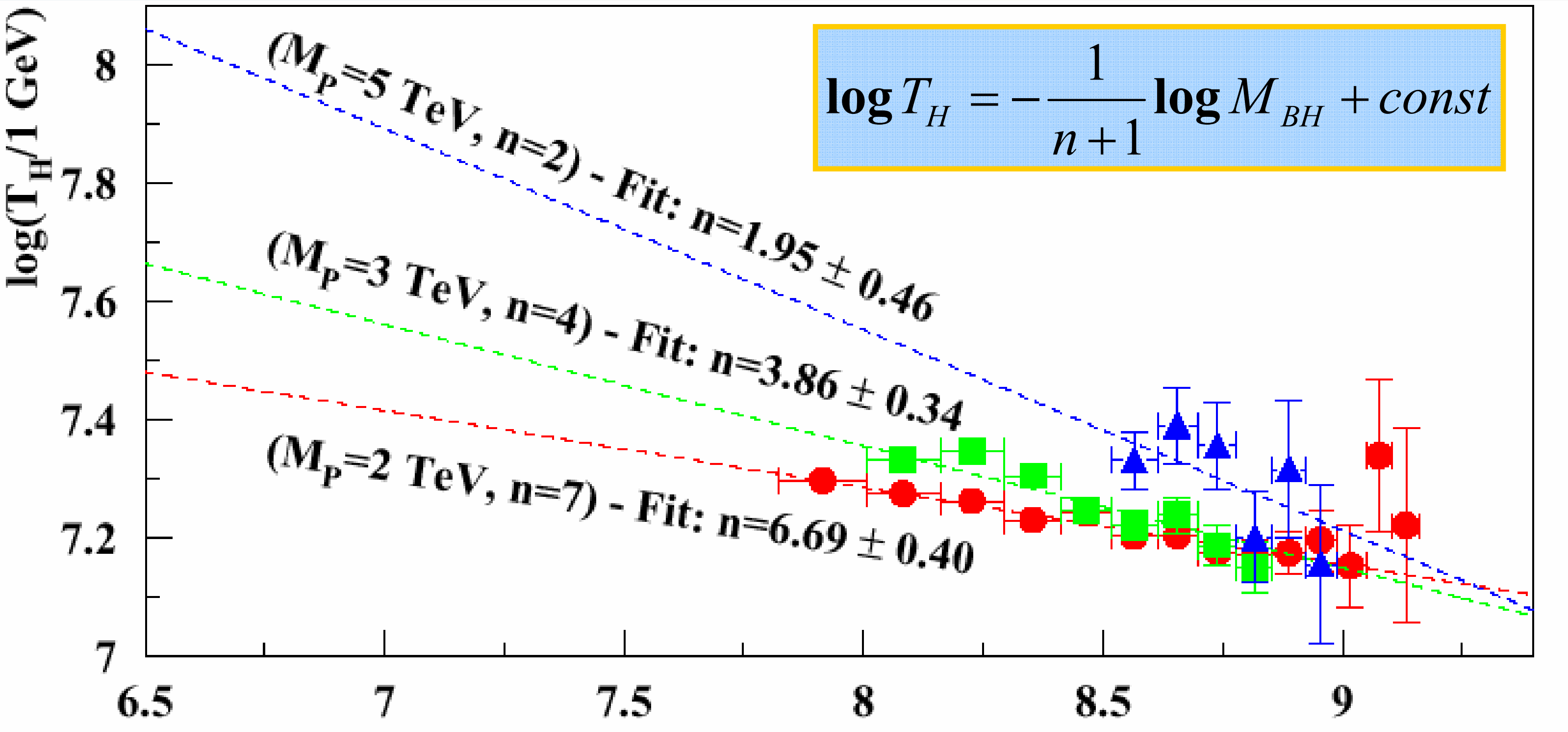
- Stefan's law: $\tau \sim 10^{-26}$ s

Black Hole Factory



Spectrum of BH produced at the LHC with subsequent decay into final states tagged with an electron or a photon

Shape of Gravity at the LHC

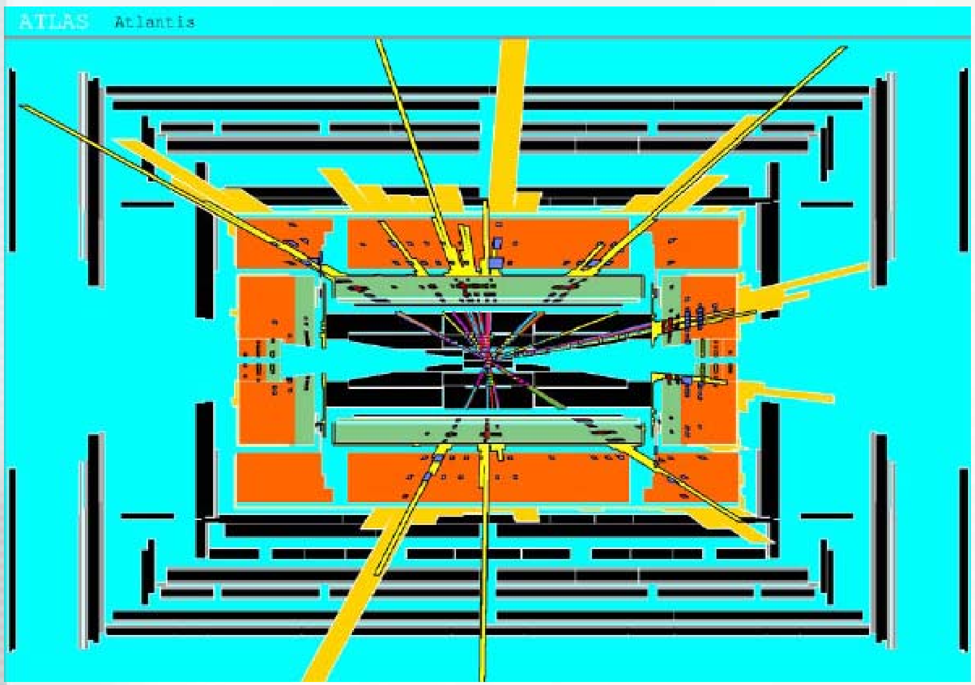


[Dimopoulos, GL, PRL **87**, 161602 (2001)]

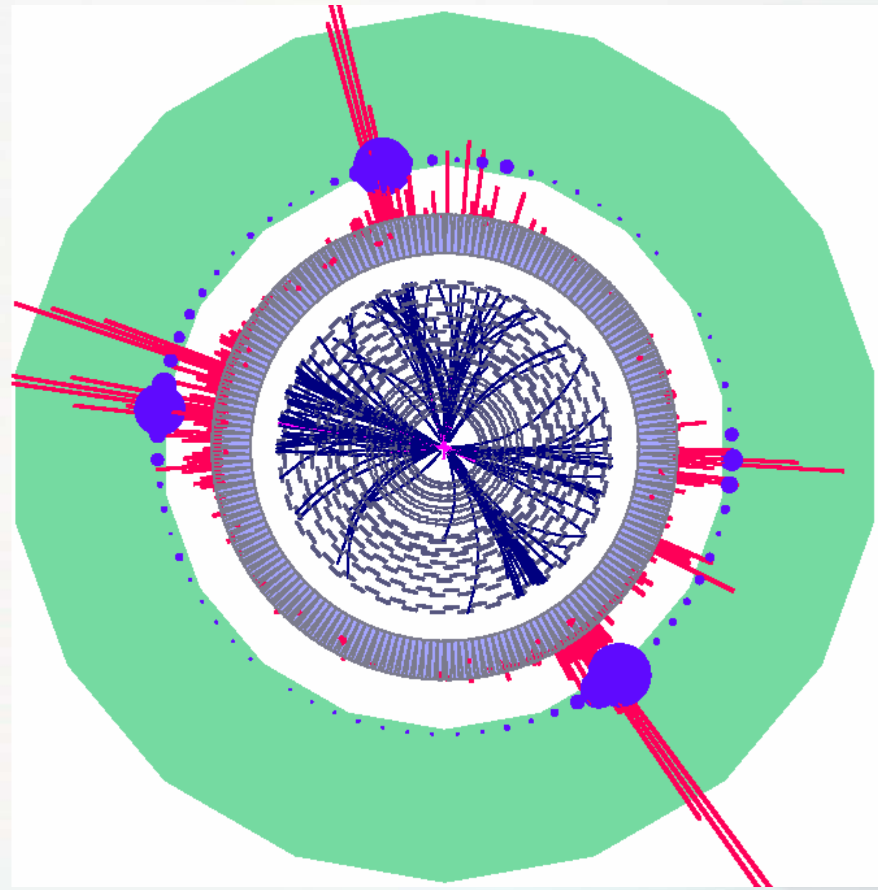
- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED,
- This result is independent of their shape!
- This approach drastically differs from analyzing other collider signatures and would constitute a "smoking cannon" signature for a TeV Planck scale

First Detailed LHC Studies

- First studies already initiated by ATLAS and CMS
  - ATLAS –CHARYBDIS HERWIG-based generator with more elaborated decay model [Harris/Richardson/Webber, hep-ph/0307305]
  - CMS – TRUENOIR [GL]



Simulated black hole event in the ATLAS detector [from ATLAS-Japan Group]



Simulated black hole event in the CMS detector [A. de Roeck & S. Wynhoff]

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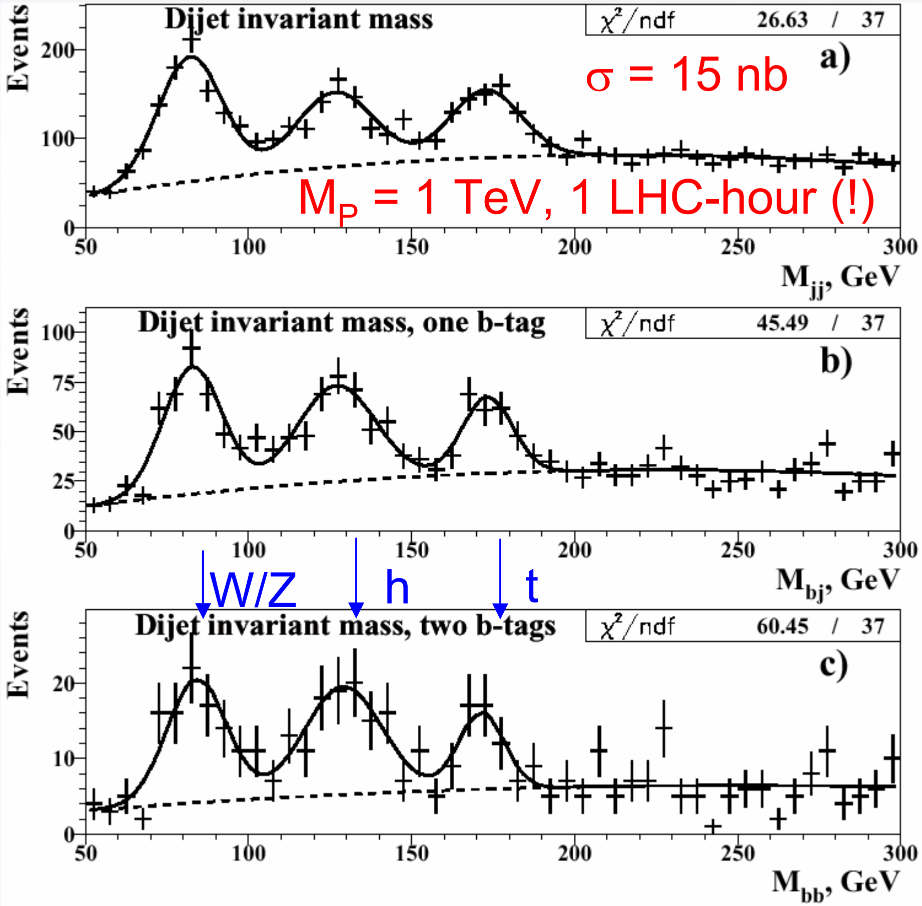
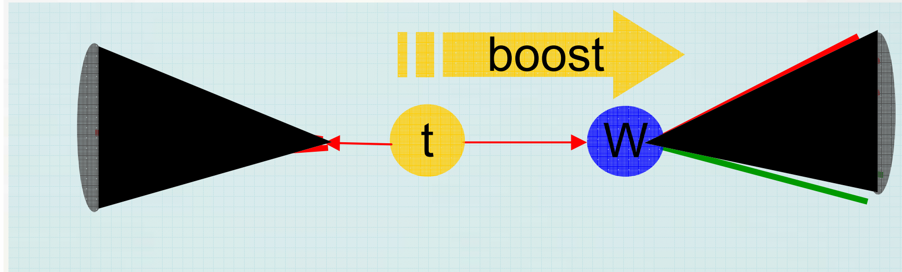
New Physics in BH Decays

- Example: Higgs with the mass of 130 GeV decays predominantly into a $b\bar{b}$-pair
- Example: 130 GeV Higgs boson – tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use typical LHC detector response to obtain realistic results





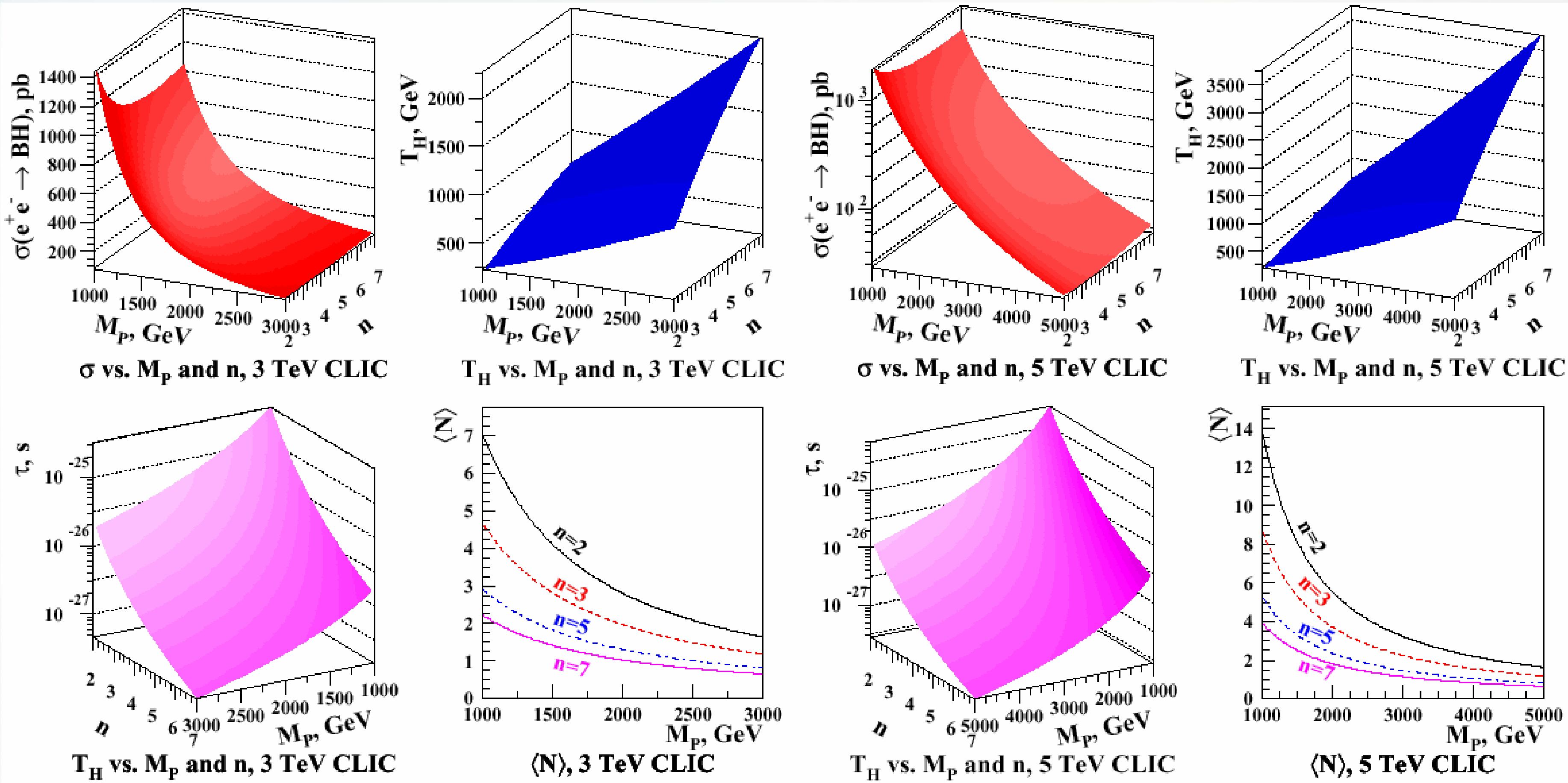
- Higgs observation in the black hole decays is possible at the LHC as early as on the first day of running even with the incomplete and poorly calibrated detectors!
- For M_P = 1, 2, 3, and 4 TeV one needs 1 day, 1 week, 1 month, or 1 year of running to find a 5σ signal
- Higgs is just an example – the conclusions apply to most of the new particles with the mass ~100 GeV

[GL, PRL **88**, 181801 (2002)]

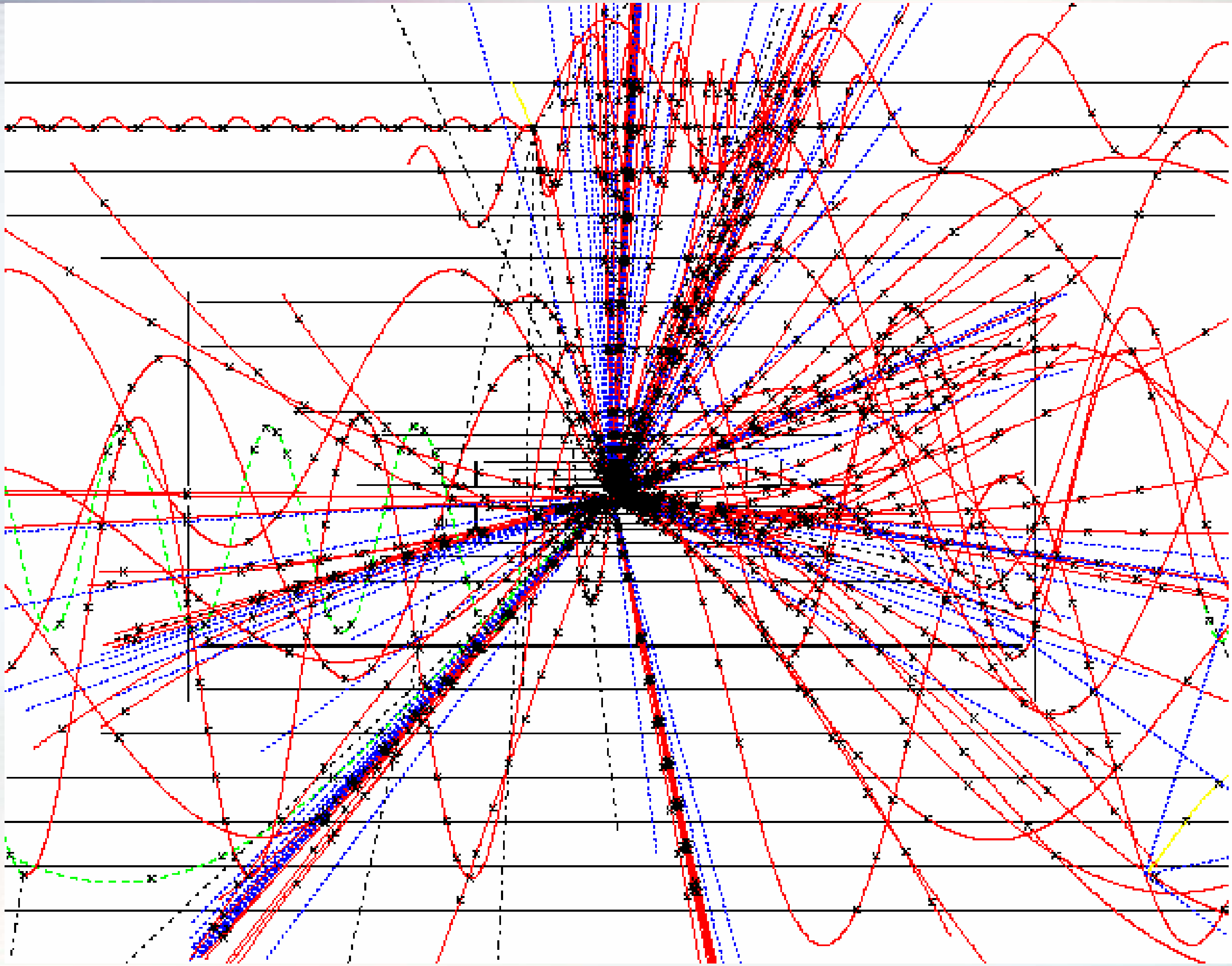
BH Production at CLIC

3 TeV

5 TeV

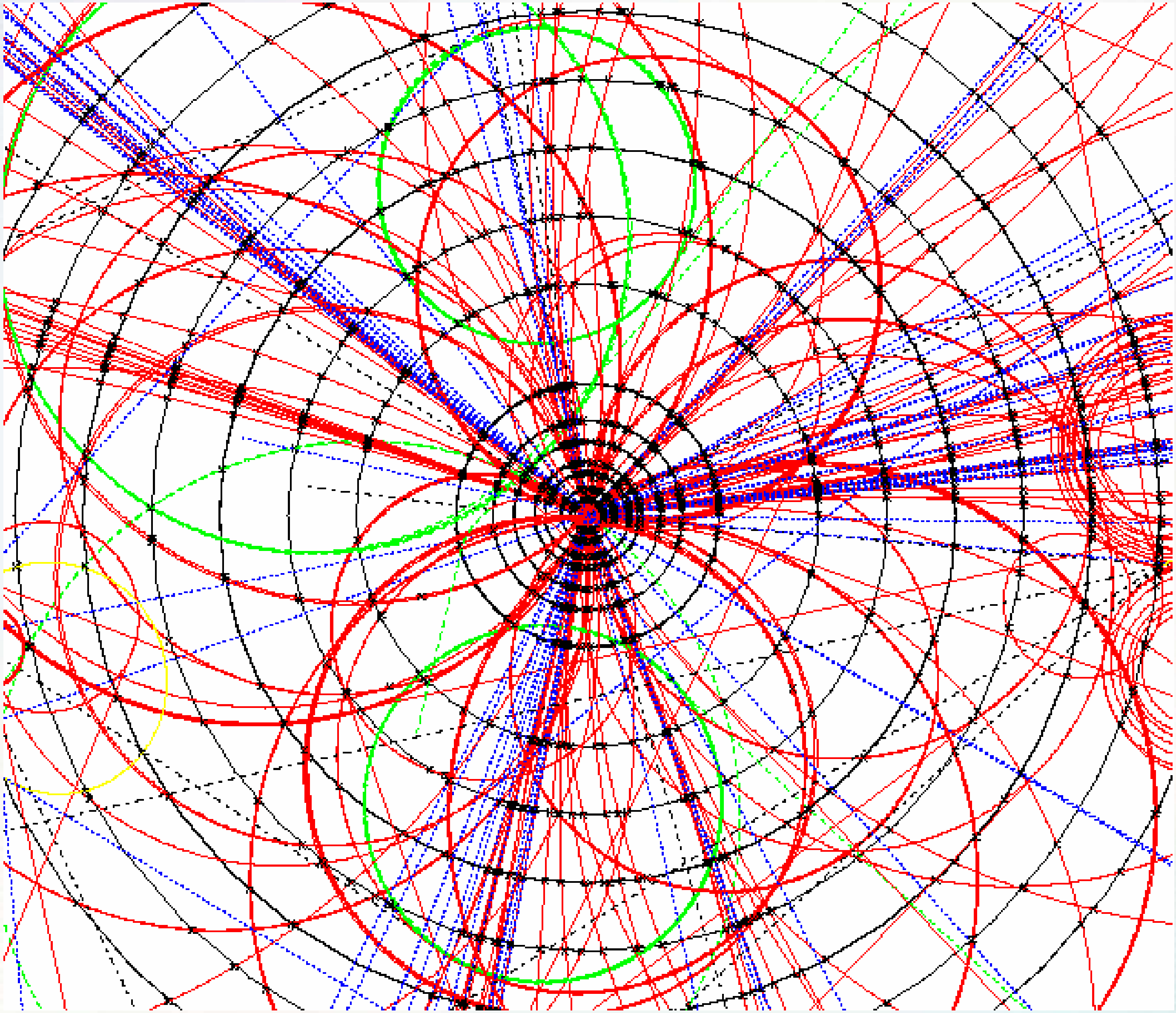


BH Event at CLIC



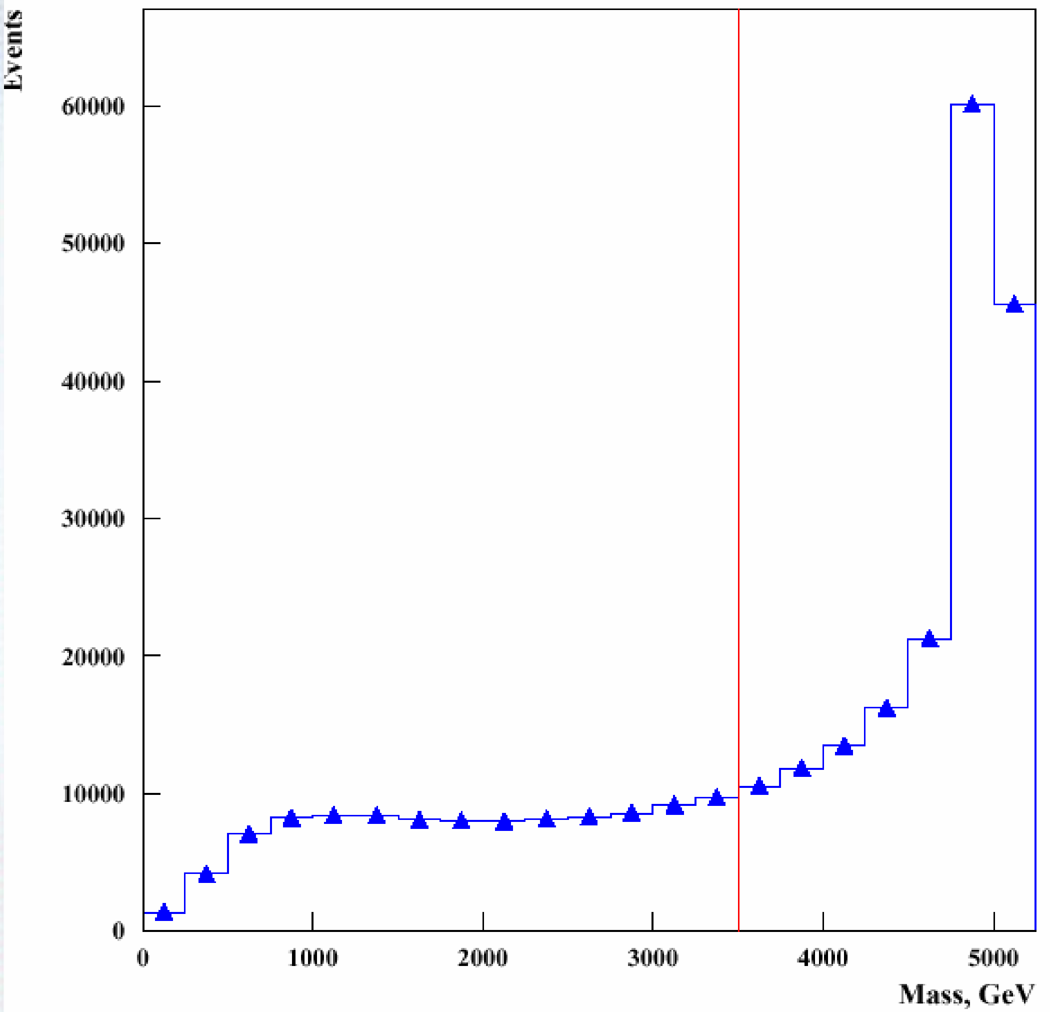
[Courtesy Albert De Roeck and Marco Battaglia]

BH Event at CLIC



[Courtesy Albert De Roeck and Marco Battaglia]

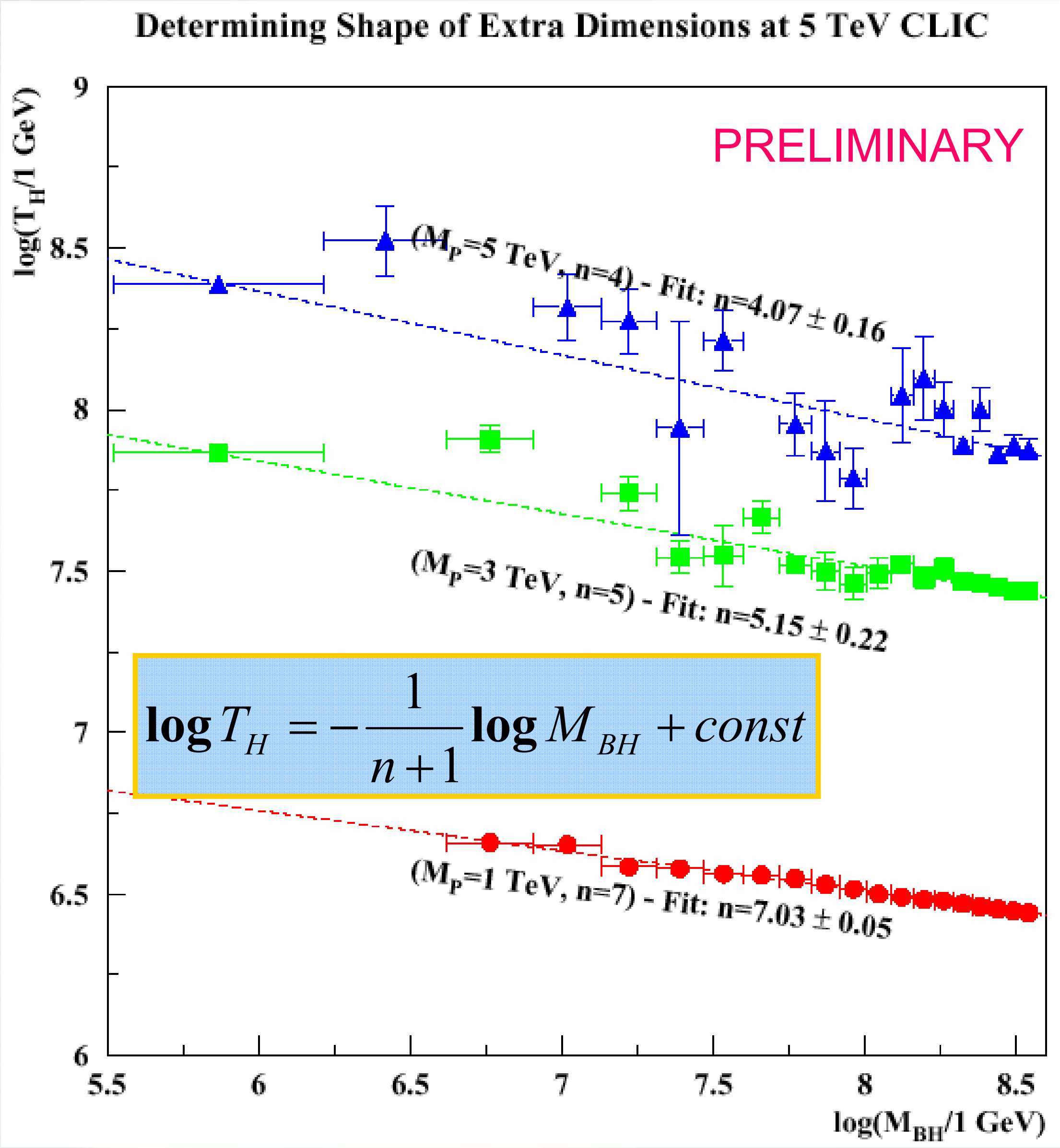
Number of Events at CLIC



Number of e,γ events at the CLIC/250 GeV, MS = 3500 GeV, n = 5

- We use beamsstrahlung at CLIC to our advantage, by converting CLIC into a broad-band machine to test Hawking's law of radiation

Testing Hawking Radiation @ CLIC



$$\log T_H = -\frac{1}{n+1} \log M_{BH} + const$$

- Number of ED can be determined independently of their shape by analyzing the M_{BH} vs. T_H dependence [Dimopoulos, GL]
- This is VERY different from other processes probing M_P, n at colliders
- CLIC has a potential to exceed the LHC sensitivity for M_P ~ 3-5 TeV

Conclusions

- If the Tevatron is posed to find new physics, it would likely to happen in the next year
- Challenges of finding new physics are many; the best way to proceed is to learn from previous experience with energy frontier machines
- LHC is likely to be the discovery machine, with ILC being a tool for precision studies of the LHC discoveries
- Nevertheless, some of the signatures for new physics are very convoluted and may not be explored at the LHC
  - The big question is whether the ILC can discover stuff missed by the LHC…
- Black holes in large ED are a "God signature" and may make an early discovery at the LHC, with a possibility of detailed studies at high-energy LC