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Extra-dimensions @ LHC: How to look for gravitons

DISCRETE '08

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A brief sketch about...

- A handful of extra-dimension models: why we need them and how they work
- (some of the) possible experimental signatures at colliders
- an use case: graviton production in the ADD model
  Analysis with the CMS detector at LHC and possibilities for an early stage
- ...how promising can be the searches for extra-dimensioned word!

Large extra dimensions (ADD)

Arkani-Hamed, Dvali, and Dimopoulos (1998)

- n compact extra dimensions, $M_F \sim$ TeV: $M_P^2 \sim R^n M_F^{n+2}$

M_F: quantum gravity scale of the higher dimensional theory

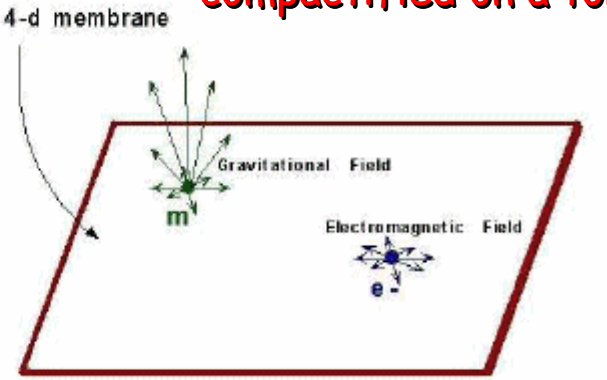
- $R \lesssim$ mm (gravity tests) $\Rightarrow n \geq 2$.

compactified on a torus R

- SM localized on a 3-brane (4D).

- Gravity propagates in all dimensions.

- Gravity "diluted" in extra dimensions.



- Graviton Kaluza-Klein (KK) modes.

- Quantized momenta in extra dimensions:

$m_{KK} = j/R; \quad j = 0, 1, 2, \ldots$

$\mathcal{L} = \frac{-1}{M_P} T^{\mu\nu} \sum_{\{\vec{j}\}} h_{\mu\nu}^{(\vec{j})}$

fm $\lesssim R \lesssim$ mm; $\quad 2 \leq n \leq 6$.

There is a KK tower of graviton modes

- massless state is the 4d graviton
- KK excitations have spin 2
- they couple with SM matter with gravitational strength

→ Gravity is weak because is diluted in a large space

(courtesy of Hooman Davoudiasl, PPC 2008)

Large extra dimensions (ADD)

Key Signals for LED

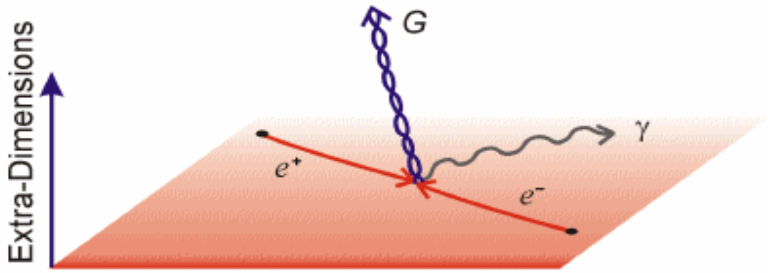
- Missing energy: KK gravitons escape into the "bulk."

$q\bar{q} \to j\, G_{KK}\,(\not{E})$; $e^+e^- \to \gamma\, G_{KK}$ ...

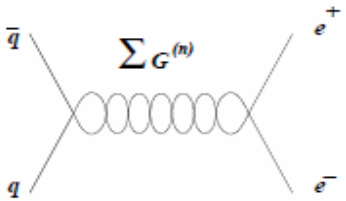
Missing E signature.

Giudice, Rattazzi, Wells 1998

Mirabelli, Perelstein, Peskin, 1998



- Virtual exchange of spin-2 tower.



Spin-2 mediated angular distributions. Han, Lykken, Zhang, 1998

Hewett, 1998

- Black hole production for $\sqrt{s} \gg M_F$. Giddings, Thomas, 2001

Dimopoulos, Landsberg, 2001

- Potentially spectacular signals: energetic multi-jets, leptons, ...
- Under debate.

(courtesy of Hooman Davoudiasl, PPC 2008)

Warped extra-dimensions (RS)

L. Randall and R. Sundrum
Phys. Rev. Lett. 83 (1999) 3370-3373.

5th dim is compactified on a circle projected into a segment

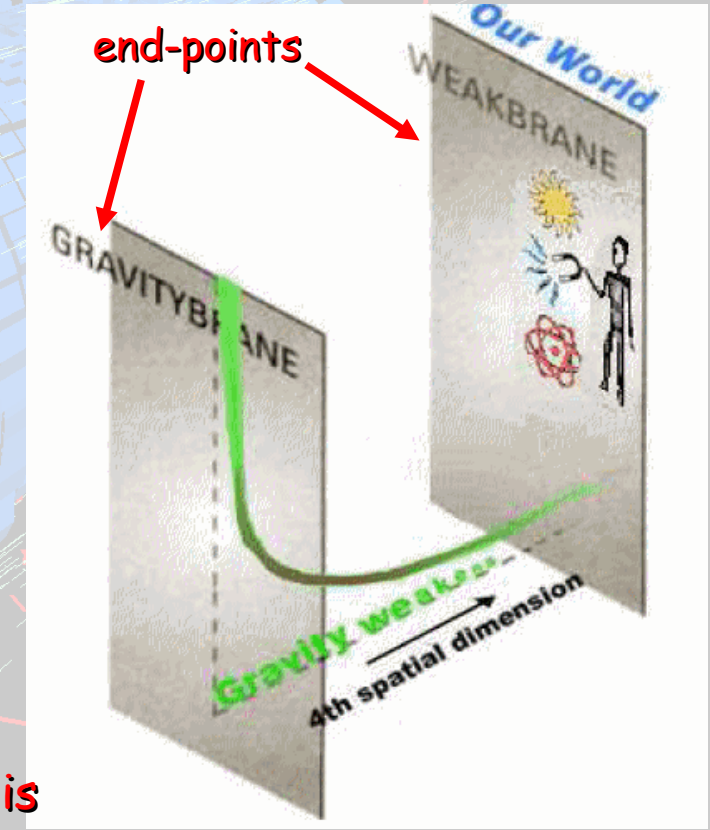
$$ds^2 = \exp\left(-2k|y|\right)\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

the 4-dimensional
l metric depends on the extra-dimensional coordinate y

scale of the IR brane is "red-shifted" wrt UV brane

$$m_{IR} = m_{UV}\exp\left(-\pi kR\right)$$

$m_{IR} \sim M_{EW}$, m_{UV} , $M_{Pl} \rightarrow R \sim 12k^{-1}$



→ Gravity is weak because graviton wavefunction is peaked on the UV brane

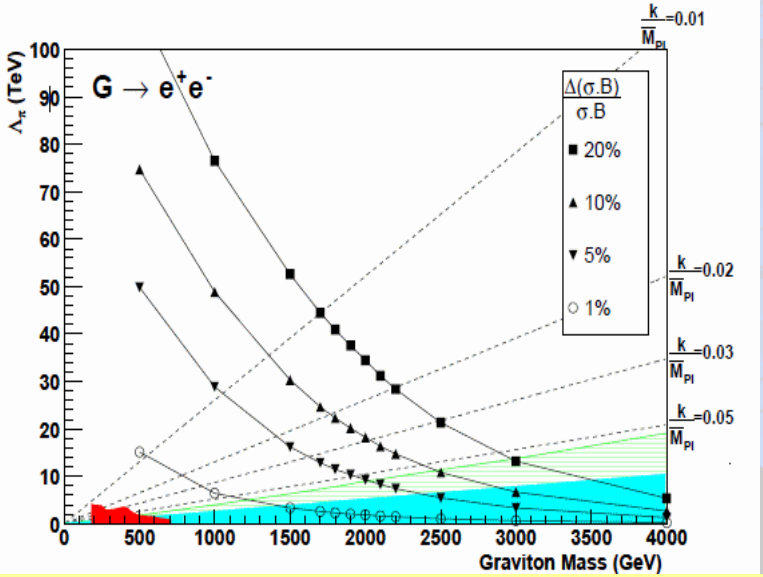
Warped extra-dimensions (RS)

RS signatures:

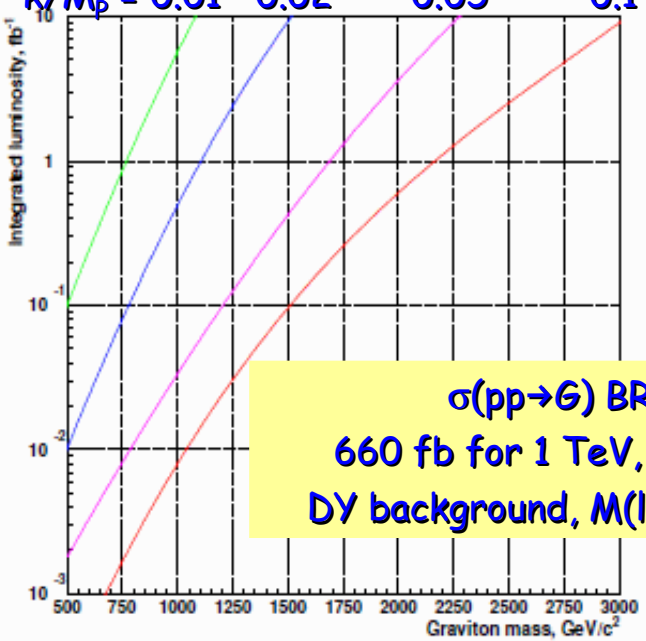
- Coupling to the SM brane ~ TeV-1
- KK graviton spin-2 resonances
- Decay into e^+e^- ,$\gamma\gamma$, $\mu^+\mu^-$

→ Resonant and on-shell production of the nth KK excitations gravitons leads to characteristic peaks in the di-lepton and di-photon invariant mass spectra

Allanach *et al.*, JHEP 0212:039,2002



ATLAS: 100 fb^{-1}, 3.5 TeV for k/MP ~ 0.1



σ(pp→G) BR(→ ee) =
660 fb for 1 TeV, 14 fb for 2 TeV
DY background, M(ll)>1 TeV ~ 50 fb

http://cms-physics.web.cern.ch/cms-physics/public/SBM-07-002-pas.pdf

Universal extra-dimensions (UED)

Phys. Rev. D64, 035002 (2001)

- All SM in TeV^{-1} extra dimensions.

only a discrete KK parirty is conserved

- Bulk momentum conservation: 4D KK number preserved.

- KK particles not singly produced.

- Only loop contributions to EW precision data.

- Less stringent bounds on $1/R$. **(300-500 GeV)**

- Chiral fermions via $\mathbb{Z}_2$ orbifolds: KK number $\rightarrow$ KK-parity.

- Compactification: Lorentz violation along extra dimensions.

- Loops around compact directions: δm_{KK}. Cheng, Matchev, Schmaltz, 2002

- Lightest KK particle (LKP) stable, dark matter candidate.

- Can mimic supersymmetry at the LHC! Cheng, Matchev, Schmaltz, 2002

boosted dijets from decays (E >~ 1 TeV), mono-jet backgrounds

(courtesy of Hooman Davoudiasl, PPC 2008)

Universal extra-dimensions (UED)

UED: Current Status and LHC Prospects

- EW precision:

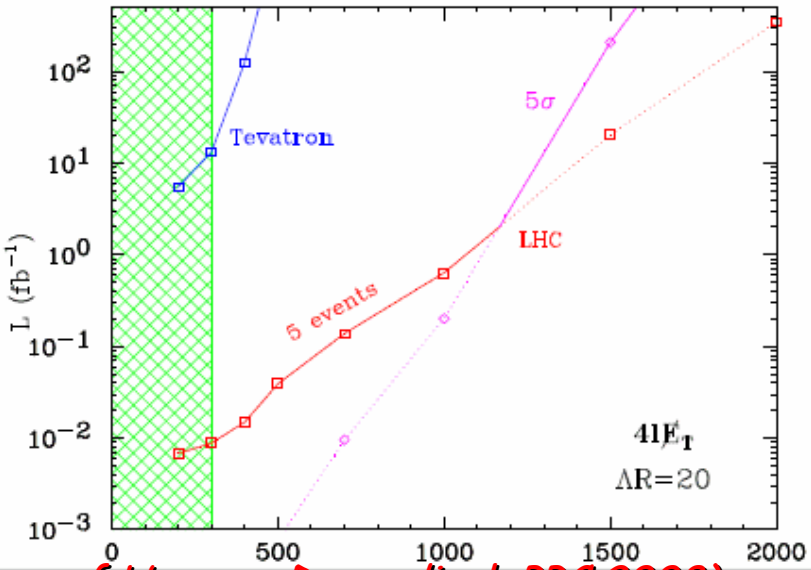
Hooper and Profumo, Phys.Rept.453:29-115,2007

- Tevatron: CDF, Run IB

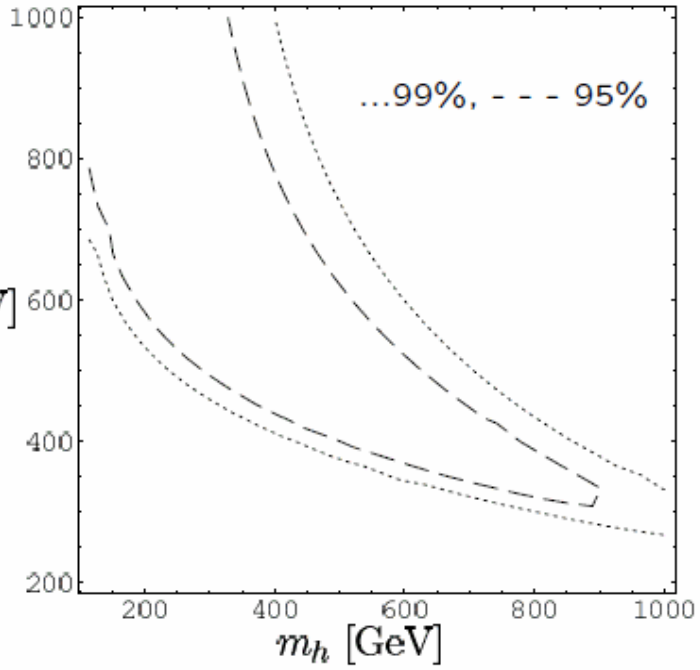
$m_{KK} \gtrsim 280$ GeV

Lin, 2005

- LHC Prospects:



Flacke, Hooper, March-Russell, 2006



Cheng, Matchev, Schmaltz,

Phys.Rev.D66:056006,2002

(courtesy of Hooman Davoudiasl, PPC 2008)

Black Hole production

The Schwarzschild radius $r_{S(4+\delta)}$ is smaller than its version in 4d:

$$r_{S(4+\delta)} = \frac{1}{\sqrt{\pi} M_D}\left[\frac{M_{BH}}{M_D}\left(\frac{8\,\Gamma((\delta+3)/2)}{\delta+2}\right)\right]^{\frac{1}{\delta+1}}$$

Parton level cross sections for $M_D \sim 2$ TeV are in the pb range:

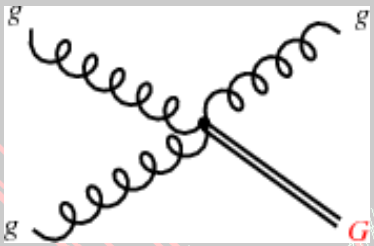
$$\sigma(BH) = \pi\, r_{S(4+\delta)}$$

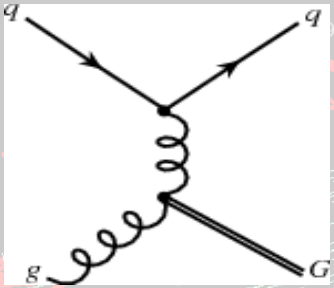
Due to Hawking radiation, BH has short lifetime (~10^{27} s) and decays "democratically" in all SM particles
→ large number of high energy leptons/jets (~ 5:1)

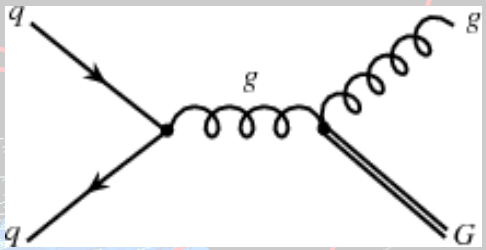
A possible BH production can be seen promptly at LHC from "spectacular" events with high multiplicity, high sphericity, high H_T:

- BH in the 4-14 TeV range can be discovered at 5σ after 2 pb^{-1} (with M_D ~ 2-4 TeV, δ=2-6)
- the lower limit can decrease with integrated luminosity

A use case: Gravitons from ADD







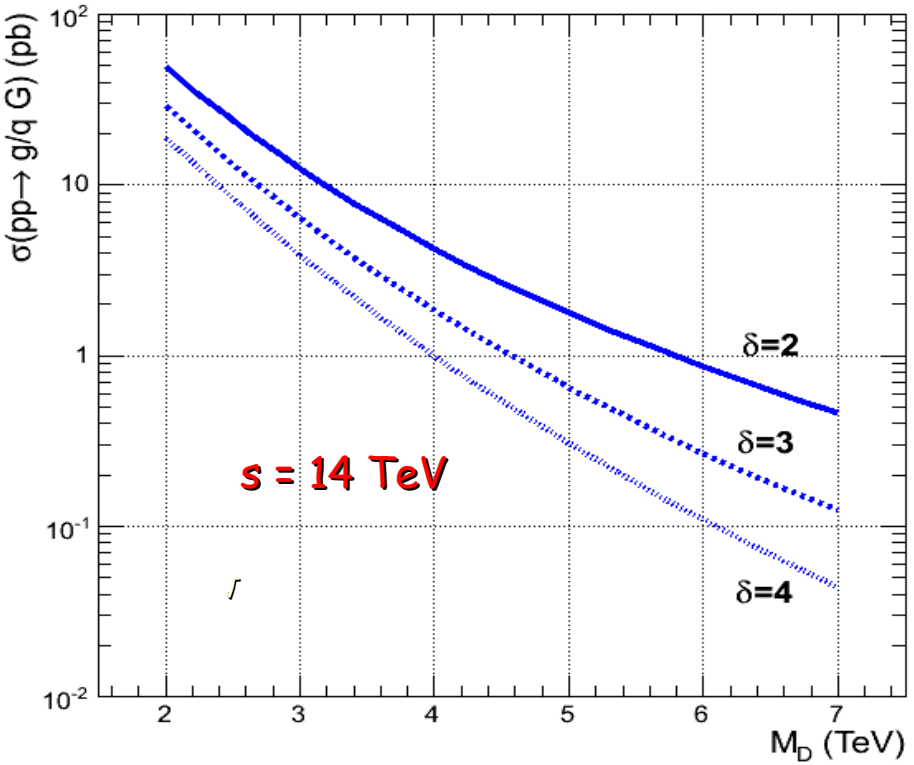
Theory is effective for √ŝ < M

Three different production channels are possible

Cross section scales with M_D

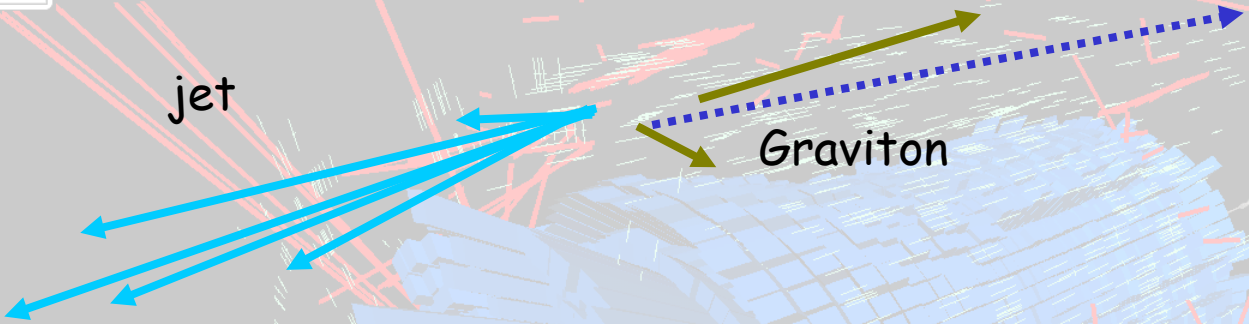
Simulation performed with SHERPA generator (pT (G)>200 GeV) and CTEQ6L

$$\sigma \approx \frac{1}{M_D^2}\left(\frac{\sqrt{\hat{s}}}{M_D}\right)^{\delta}$$



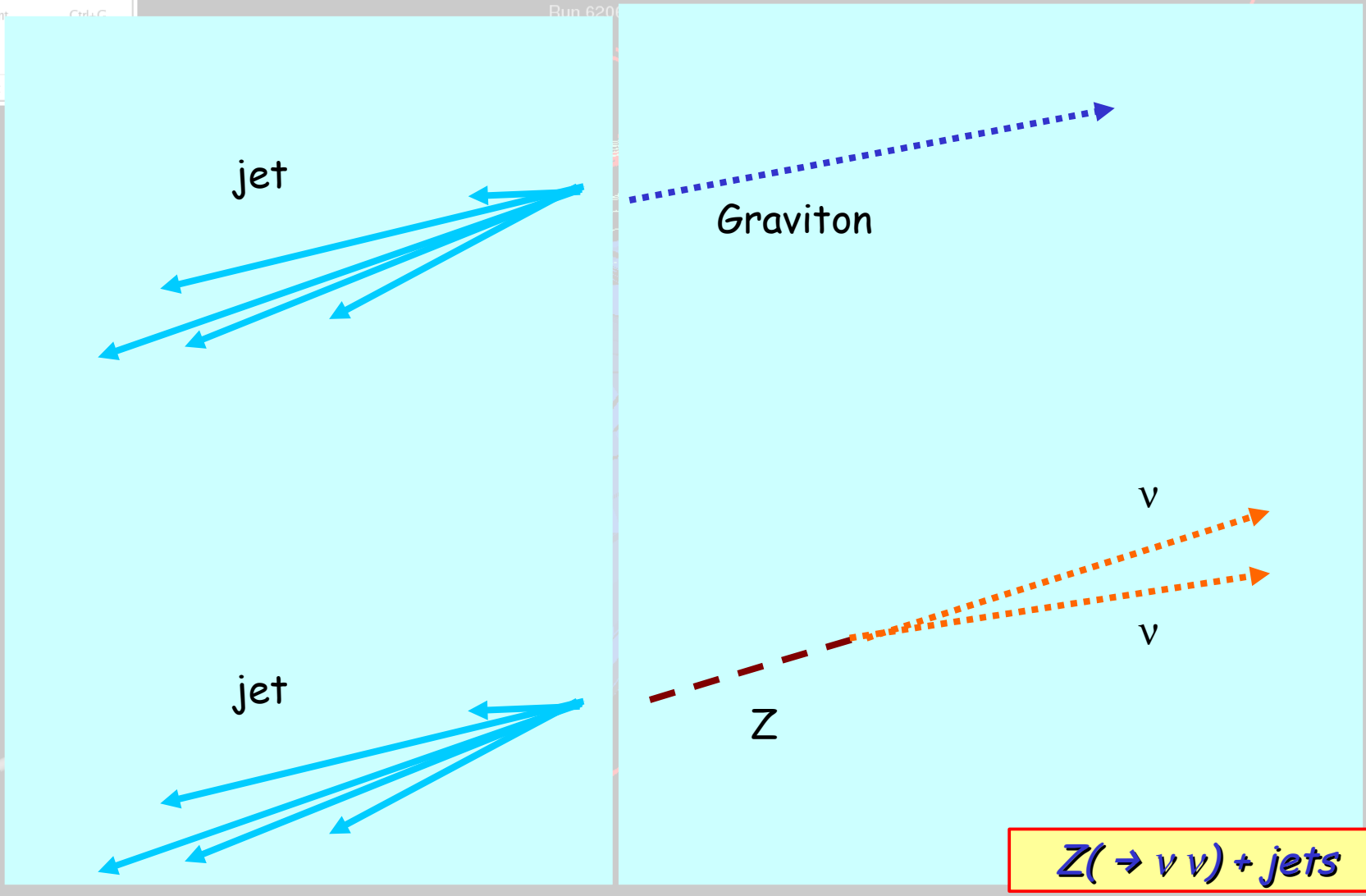
How could it be visible @LHC after 100 pb^{-1} ?

The mono-jet+MET signature



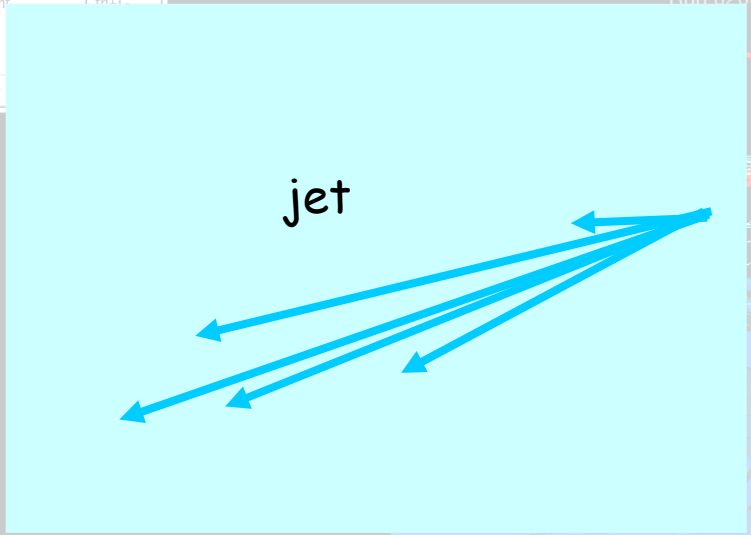
- one high transverse momentum jet (p_T > 300-400 GeV) in the central region of detector ($|\eta|$<1.7) (MONO-JET signature)
- Large Missing Transverse Energy (MET) (same order of p_T (jet)) recoiling almost back-to-back
- possible (1-2) less energetic jets due to initial/final state radiation

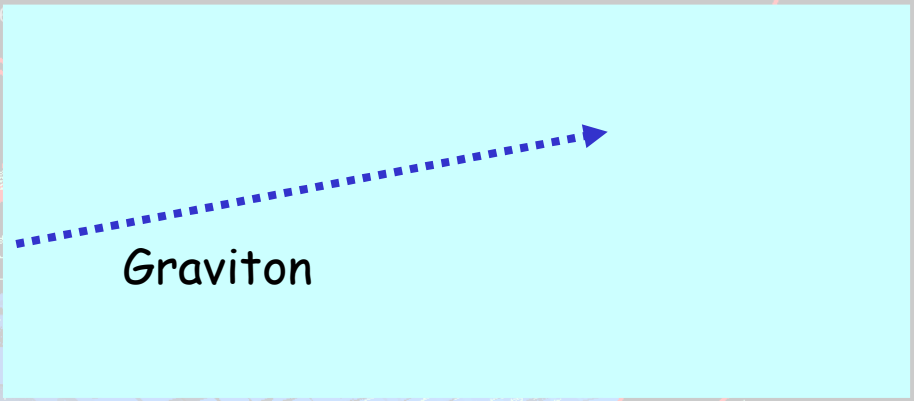
The mono-jet+MET background

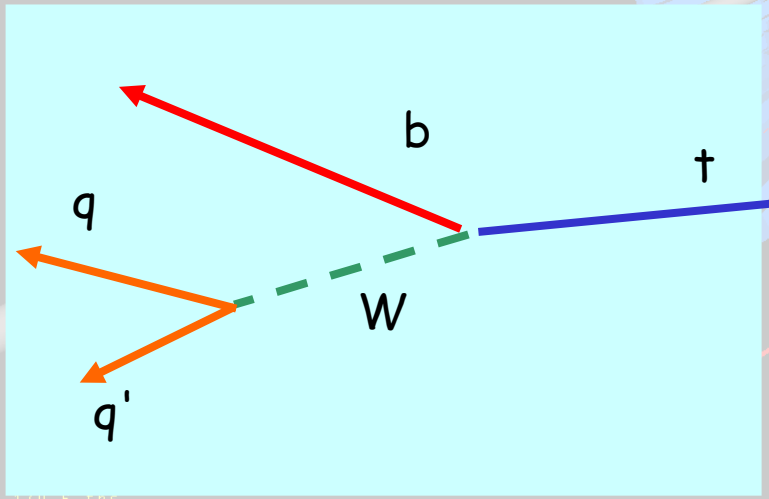


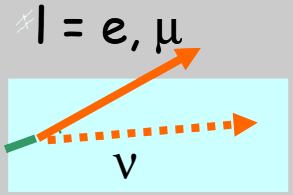
Z(→ ν ν) + jets

The mono-jet+MET background



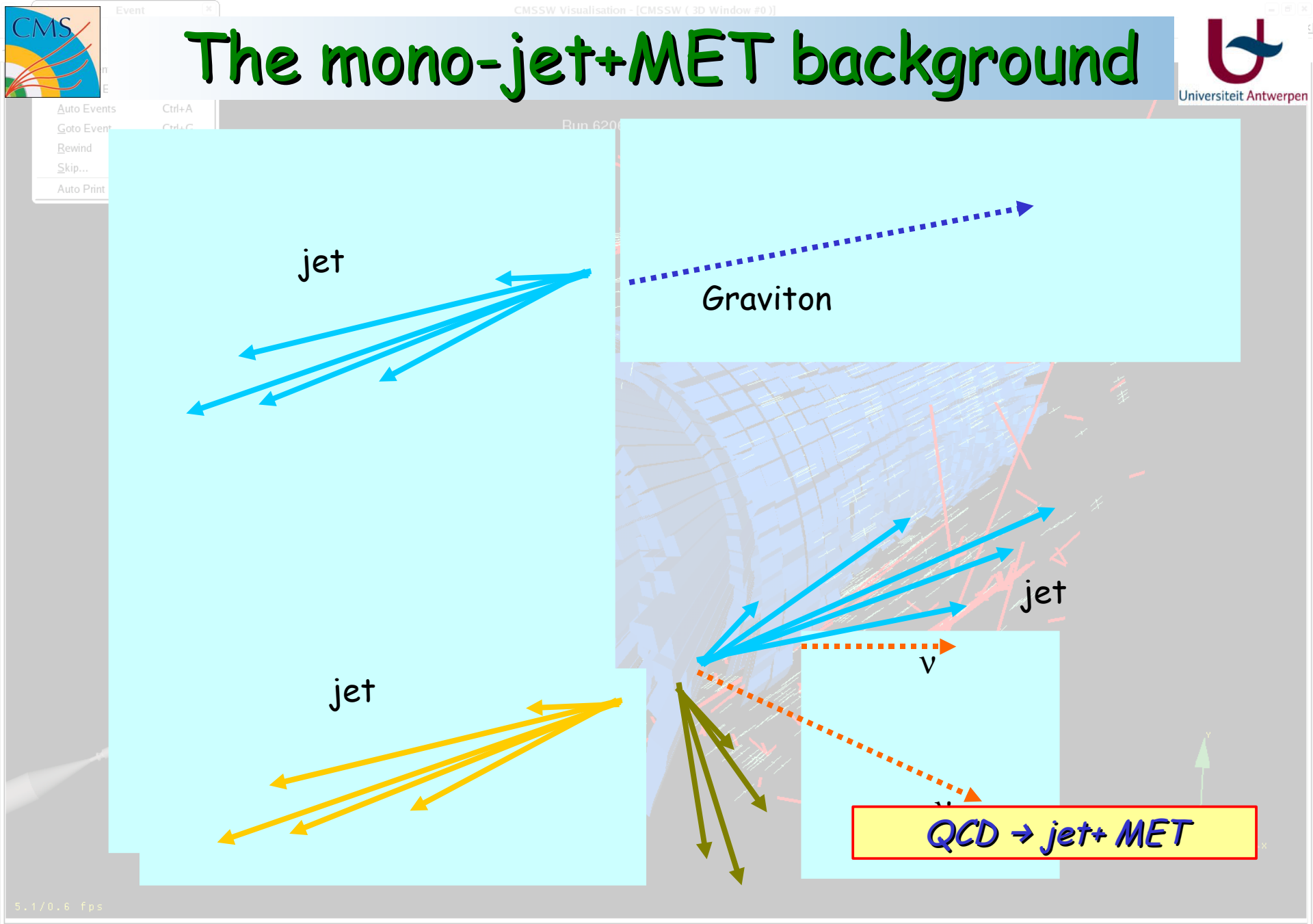






$t\bar{t} \rightarrow WbWb \rightarrow bbqq'l\nu$

The mono-jet+MET background



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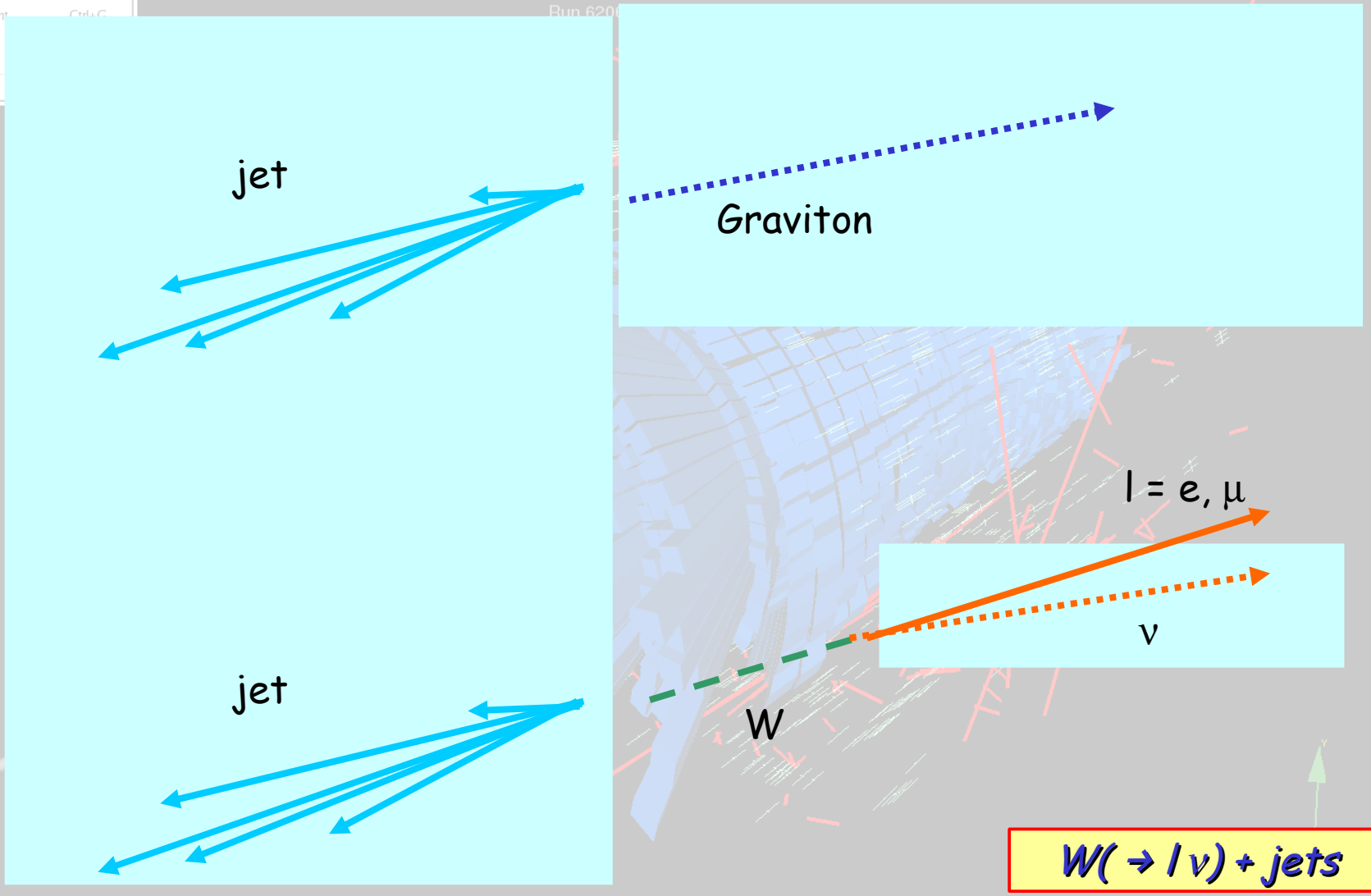


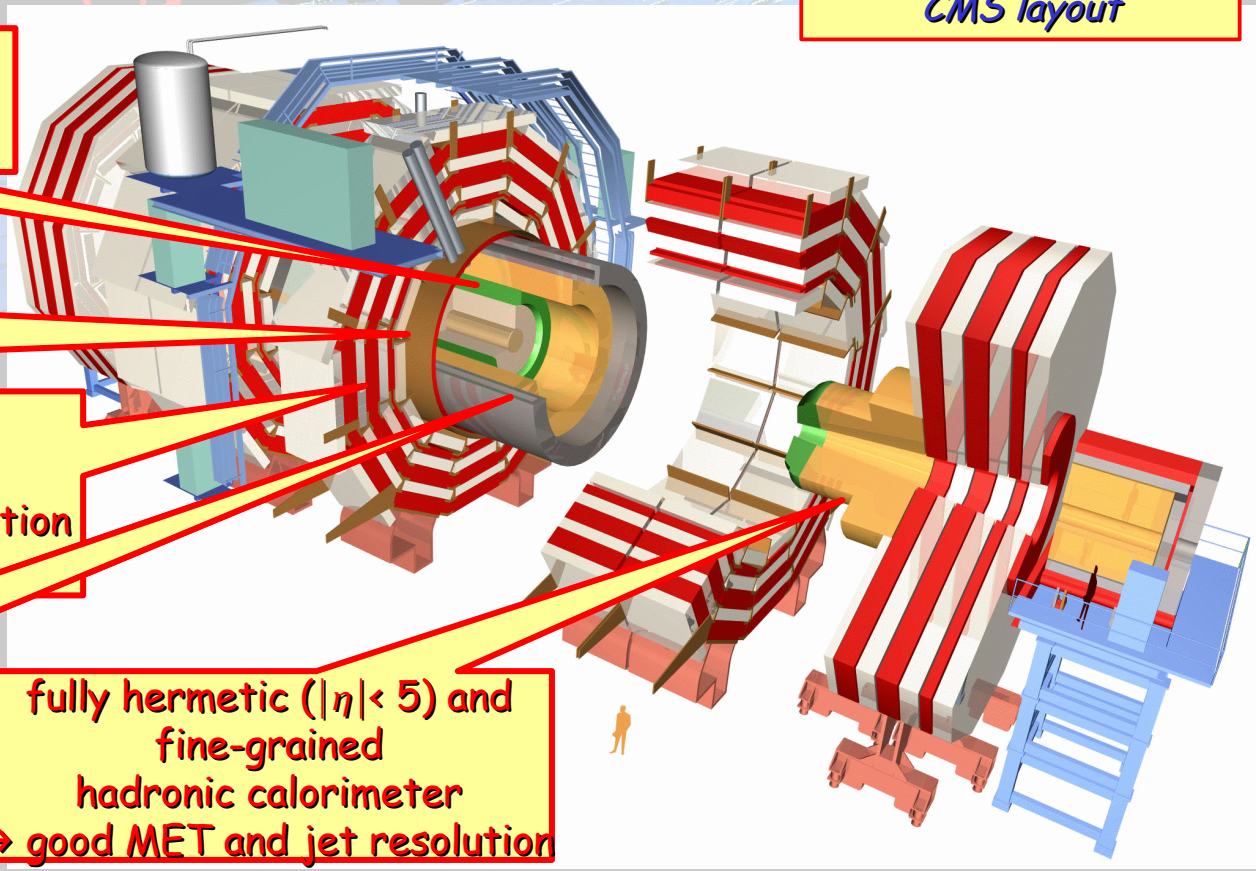
The tool for mono-jet analysis

The proposed studies are performed @LHC, with a 14 TeV center of mass energy

- 10^{32} - 10^{33} cm^{-2} s^{-1} initial luminosity
- 10^{34} cm^{-2} s^{-1} design luminosity

→ It can be an ideal tool to study the MET+jet signature

CMS layout



efficient tracking system
→ detection of isolated leptons

4 T B field
→ precise pT measurement

redundant muon system
→ efficient high pT lepton rejection

excellent resolution electromagnetic calorimeter
→ efficient γ + e rejection

fully hermetic ($|\eta|$< 5) and fine-grained hadronic calorimeter
→ good MET and jet resolution

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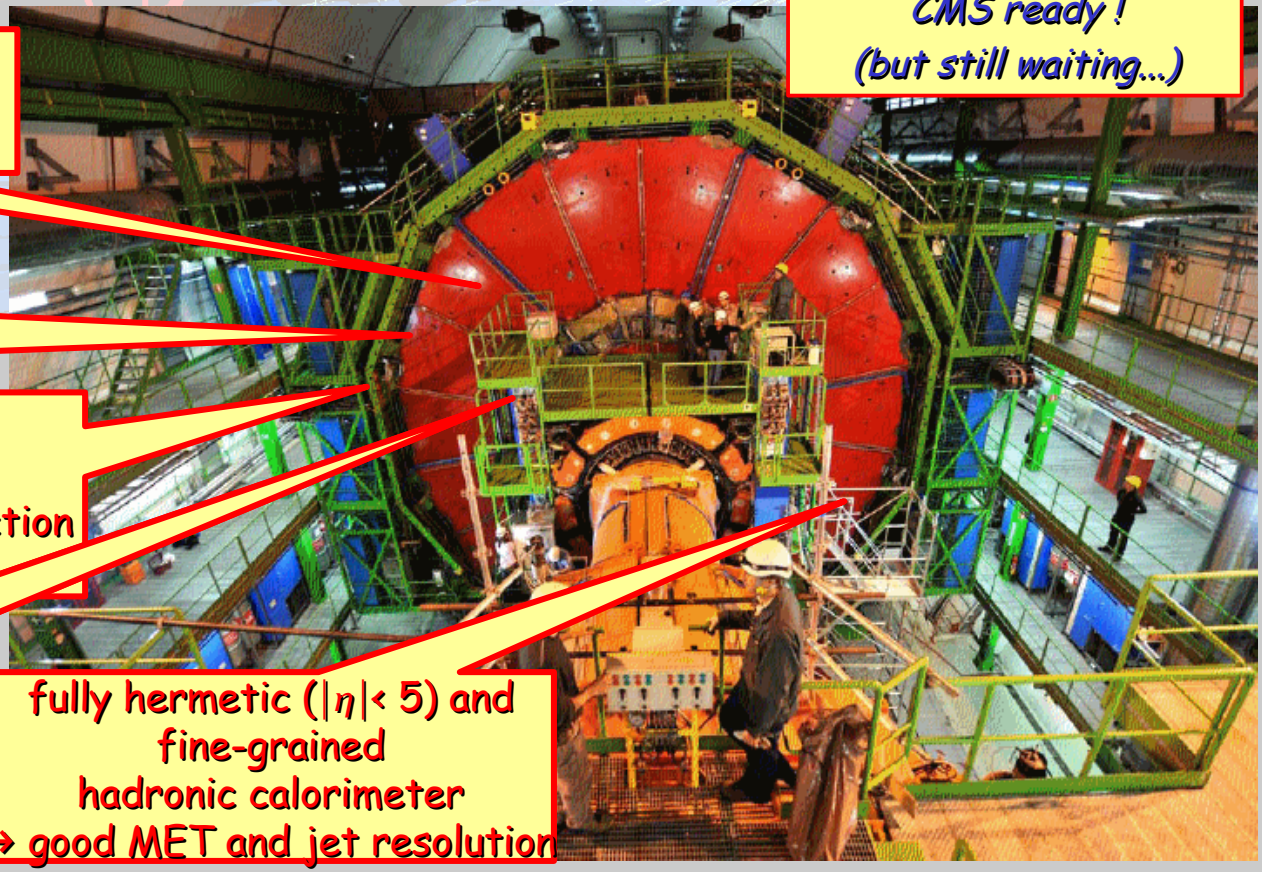

CMS ready !
(but still waiting...)

efficient tracking system
→ detection of isolated leptons

4 T B field
→ precise pT measurement

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excellent resolution electromagnetic calorimeter
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What we need for mono-jet

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- Very basic objects:
- Missing energy calculated from jets
- A trigger based on H_T and MH_T :
  - HT > 200 GeV at the first level trigger (L1)
  - HT > 250 GeV + MH_T > 100 GeV t the high level trigger (HLT)

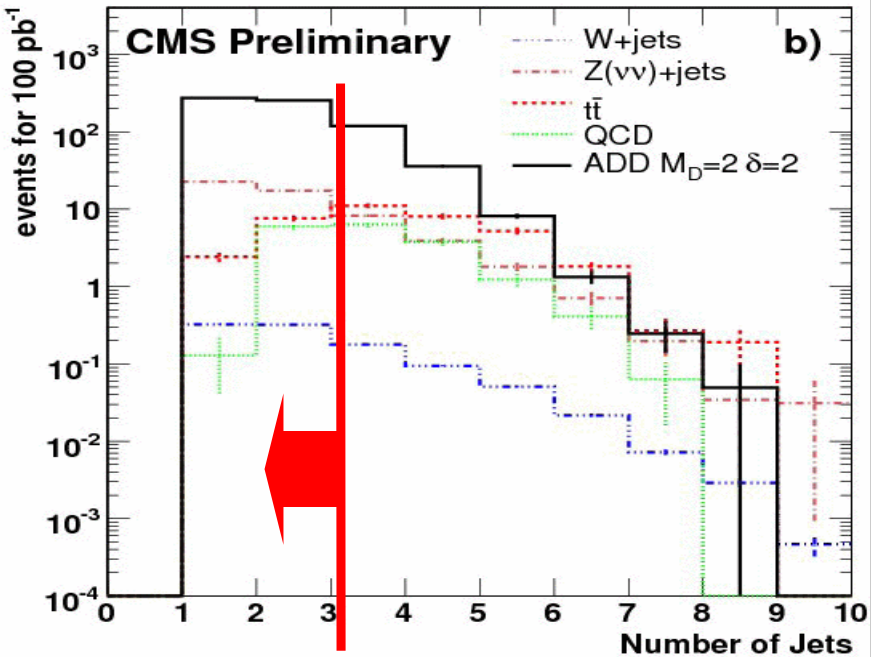
→ the approach is the most affordable in the early LHC stage

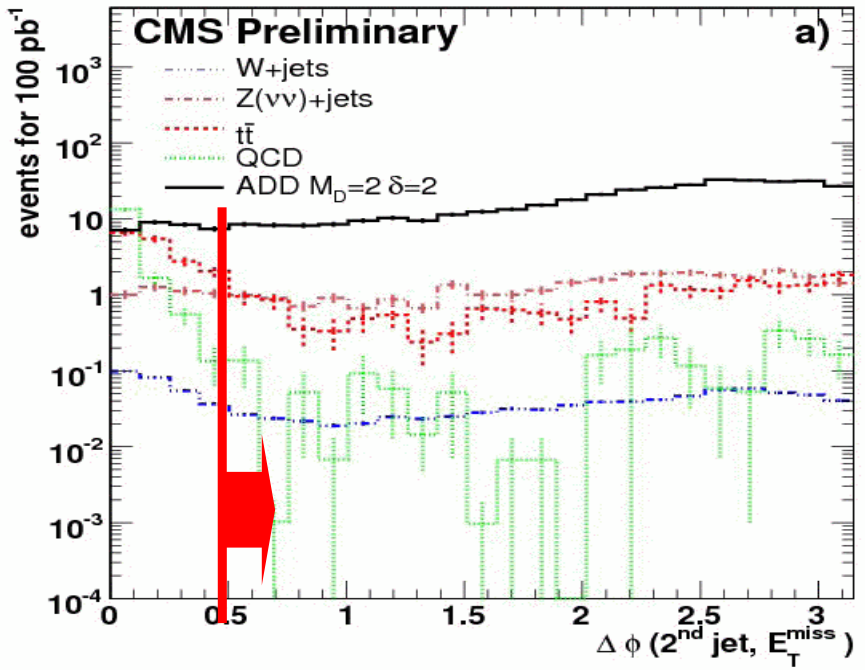
$$H_T = \sum_{p_T(j) > p_T^0} \left| \vec{p}_T(j) \right| \qquad MH_T = \left| \sum_{p_T(j) > p_T^0} \vec{p}_T(j) \right|$$

p^0_T = 10 GeV at L1 and 20 GeV at HLT

How to discover mono-jet + MET

- Preselection on jets: p_T > 40 GeV , $|\eta|$<3
- Leading jet: p_T > 350 GeV , $|\eta|$<1.7
- MET > 400 GeV
- Cleaning of jets from leptons:
- Jet Electromagnetic Fraction < 0.9
- no isolated leptons with p T > 15 GeV

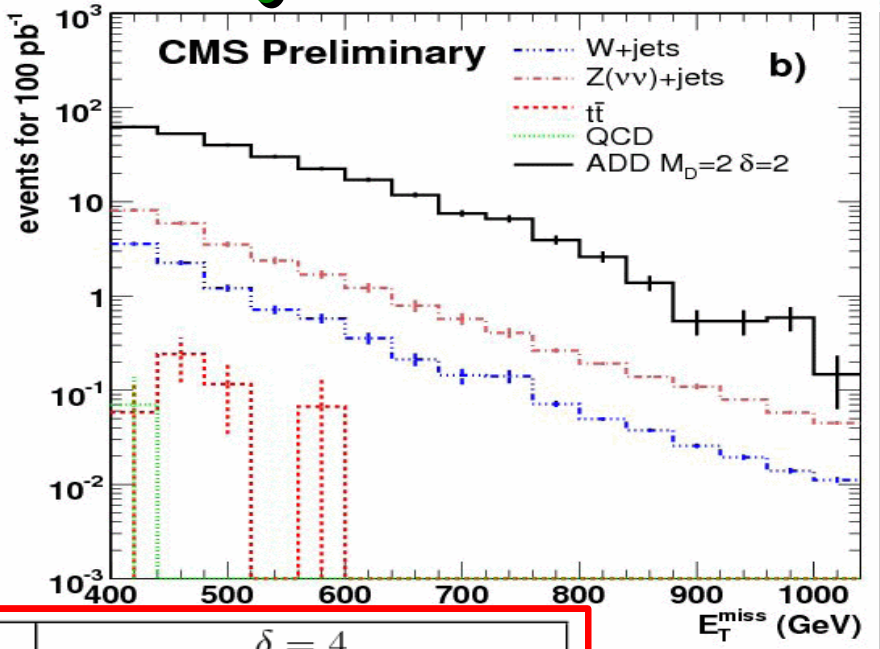




- Leading jet: p_T > 350 GeV , $|\eta|$<1.7
- Only 2 jets in the event
- $\Delta\phi$ (1 jet – MET) > 2.8
- $\Delta\phi$ (2 jet – MET) > 0.5

How to discover mono-jet + MET

The signal can be viewed as an excess above the MET tail



number of selected events after 100 pb $^{-1}$ (% rel. eff. of the cuts) :

	$\delta = 2$		$\delta = 4$	
	$M_D = 2$ TeV	$M_D = 6$ TeV	$M_D = 2$ TeV	$M_D = 6$ TeV
Trigger	3060	54.4	1190	7.98
$E_T^{miss} > 400$ GeV	691 (23)	12 (22)	245 (21)	3.0 (38)
$JEMF < 0.9$	659 (95)	11 (96)	232 (95)	2.9 (95)
$TIV < 0.1$	539 (82)	9.5 (82)	185 (80)	2.2 (76)
$p_T(\text{jet 1}) > 350$ GeV, $\lvert\eta(\text{jet 1})\rvert < 1.7$	343 (64)	6.5 (68)	117 (63)	1.6 (73)
Number of jets < 3	287 (84)	5.4 (83)	98.3 (84)	1.2 (75)
$\Delta\phi(\text{jet 1}, E_T^{miss}) > 2.8$, $\Delta\phi(\text{jet 2}, E_T^{miss}) > 0.5$	261 (91)	4.9 (91)	90.1 (92)	1.1 (92)
Total Efficiency (%)	8.1 ± 0.5	8.5 ± 3.8	7.1 ± 0.7	13.2 ± 13.2

How to discover mono-jet + MET

	$t\bar{t}$	$Z(\nu\nu)$+jets	QCD	$W(e\nu)$+jets	$W(\mu\nu)$+jets	$W(\tau\nu)$+jets
Trigger	3860	1280	$4.92 \cdot 10^5$	1199	1617	1488
$E_T^{miss} > 400\,GeV$	36.6	54.8	17.9	19.5	63.7	36.3
$JEMF < 0.9$	32.0	52.4	17.2	8.8	60.6	32.0
$TIV < 0.1$	12.2	46.3	14.2	4.3	5.9	13.0
$p_T(\text{jet}\,1) > 350\,GeV$, $\lvert\eta(\text{jet}\,1)\rvert < 1.7$	9.8	36.6	11.8	3.3	4.5	9.9
Number of jets < 3	2.2	28.9	4.6	2.3	2.8	6.9
$\Delta\phi(\text{jet}\,1, E_T^{miss}) > 2.8$, $\Delta\phi(\text{jet}\,2, E_T^{miss}) > 0.5$	0.5	25.7	< 0.6	2.0	2.0	5.5

to select only the MET tail

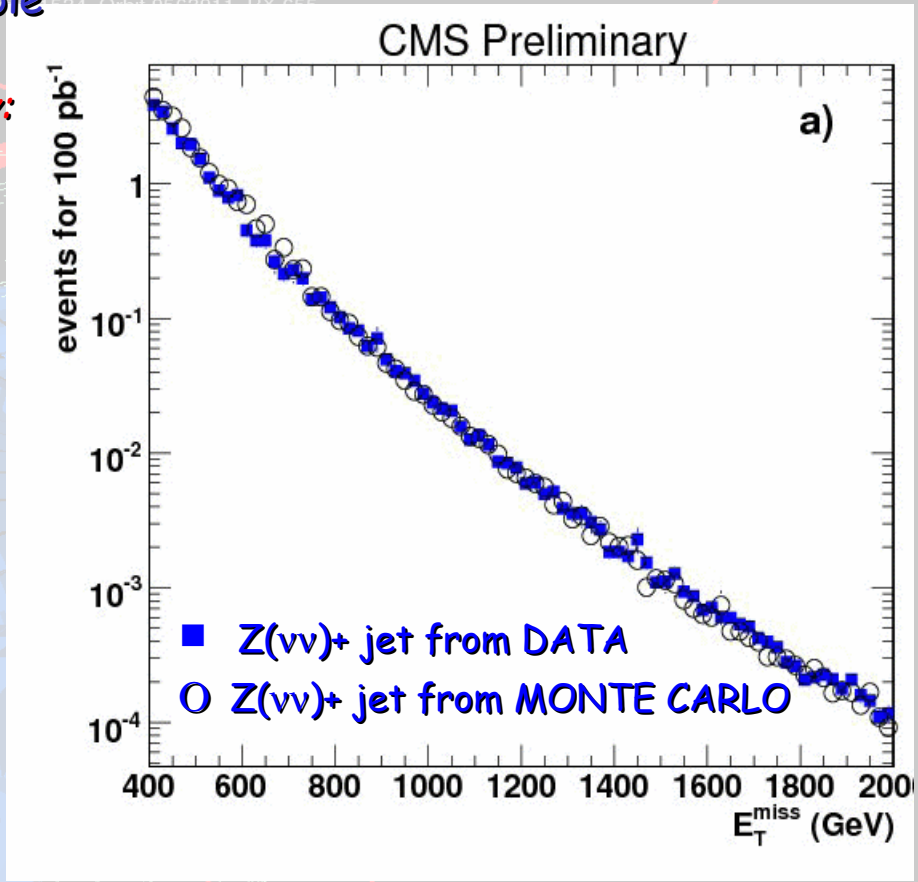
to reduce the W(l ν)+jet

to reject most of ttbar

to reduce QCD as much as possible

How to control the background

- Z(νν)+ jet is the most important, irreducible background
- → *it can be estimated in a data-driven way:*
- Select a control region of W(μν)+ jet by requiring:
  - trigger from a single muon
  - only one isolated muon
  - all the other selection as in the signal region
- Control region can then be rescaled for:
  - isolation and trigger efficiency
  - σ(Z(νν)+ jet) / σ(W(μν)+ jet)



- N (Z(νν)+ jet) DATA = 21.9 ± 4.9 (stat) +2.1 -1.4 (syst)
- N (Z(νν)+ jet) MC = 25.7 ± 5.1 (stat)

How to control the background

- QCD can be considered negligible in a first approximation
- W(τν)+ jet is addressed by rescaling the same control region with W(μν)+ jet
- W(e/μν)+ jet are measured after the W(τν)+ jet with factor from Monte Carlo
- ttbar contamination is assumed as a systematic effect

N (Total Backg) DATA = 30.7 ± 6.8 (stat) +2.7 -1.5 (syst)

Effect of Systematic uncertainties

Source	Effect on number of signal events (%)
Hard process scale	$^{+11}_{-13}$
Background modeling	5.0
PDF	$^{+8.7}_{-6.7}$
Jet energy scale (10%)	$^{-0.8}_{-4.0}$
E_T^{miss}	$^{+17.5}_{-15.9}$
Total theoretical uncertainty on signal	$^{+14.0}_{-14.6}$
Total instrumental uncertainty on signal	$^{+16.7}_{-19.9}$
Luminosity with 100 pb^{-1}	10.0

Q/2 < √s <2Q

CTEQ6M+CTEQ5L/CTEQ6L diff.

compensation effect between cut on p_T and jet veto

applying a ±σ (MET) shift to the uncorrected MET

full correlation between MET and jet energy scale taken into account

lumi uncertainty after 100 pb^{-1}

The sensitivity we can reach

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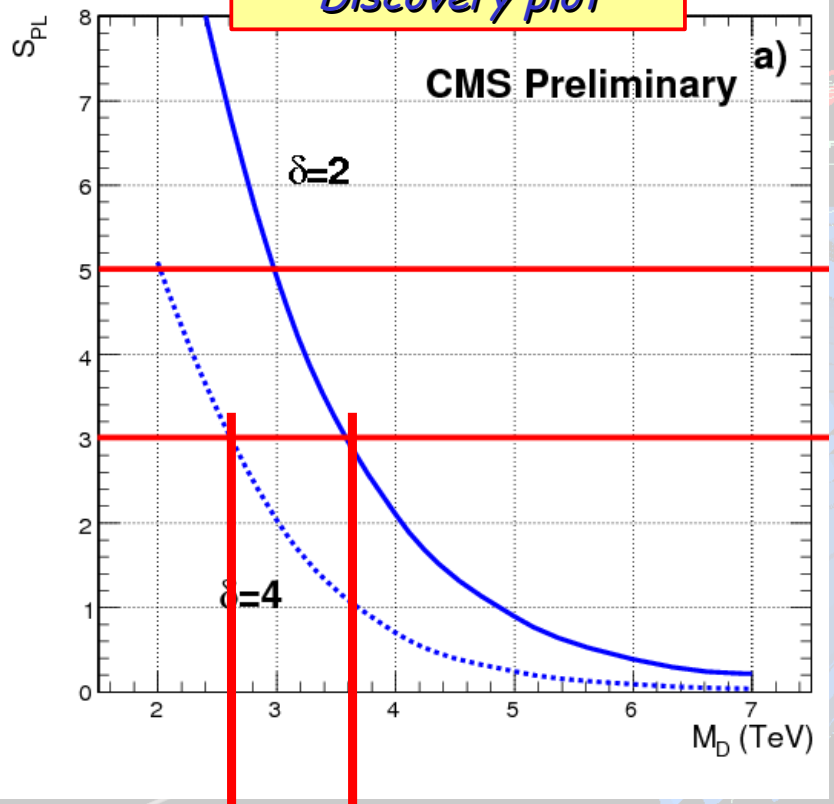
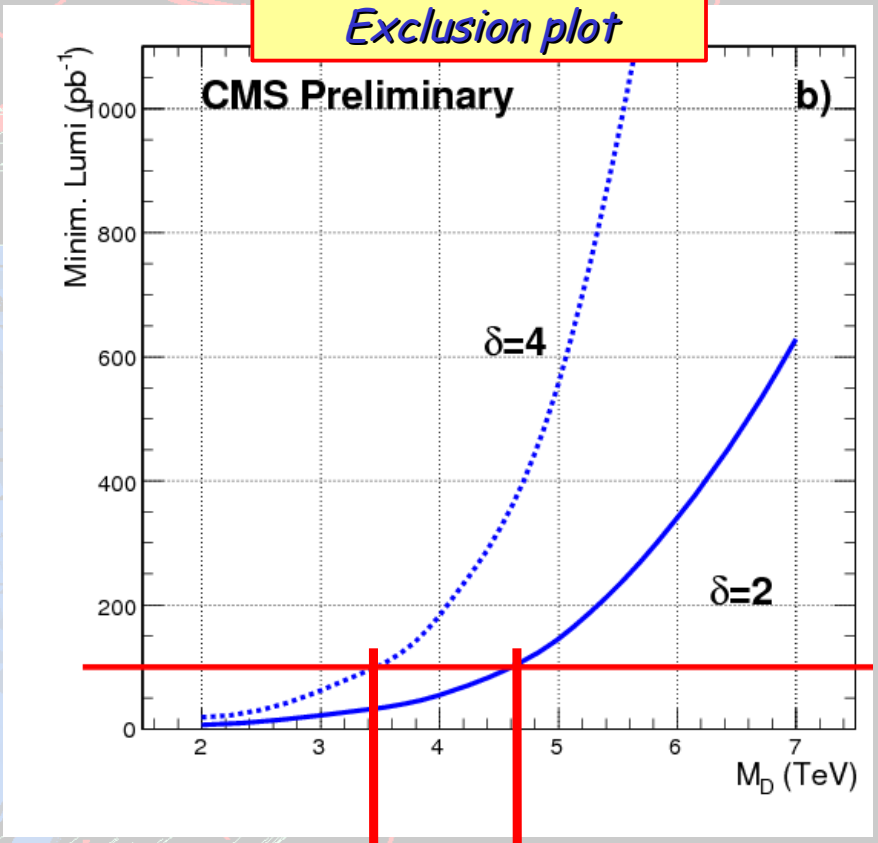
Discovery plot



Exclusion plot



2.62 TeV

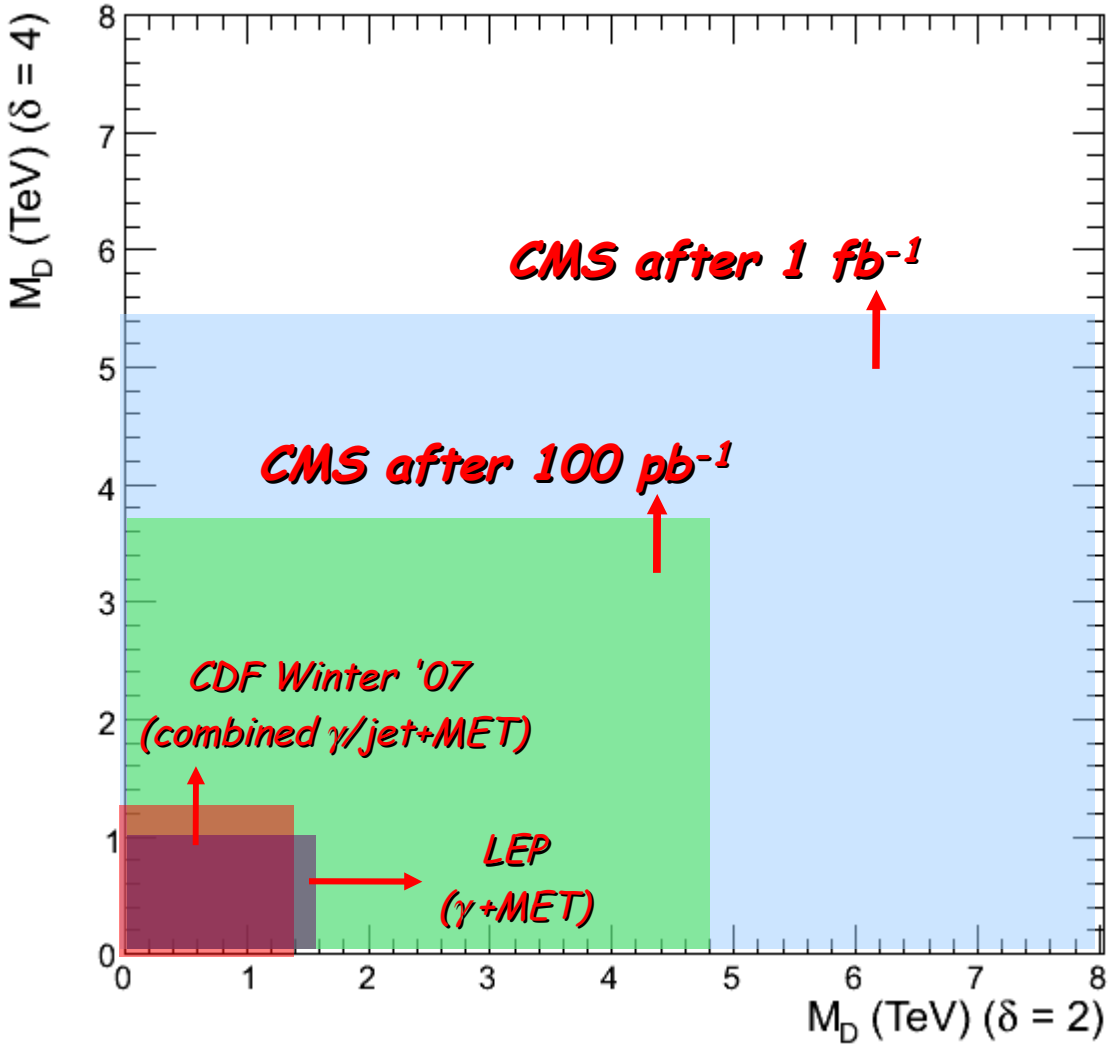
3.58TeV

Profile Likelihood estimator

3.46TeV

4.61 TeV

95% Exclusion limits



http://cms-physics.web.cern.ch/cms-physics/public/EXO-08-011-pas.pdf

Conclusions

The Hierarchy Problem can be solved with several extra-dimension model
→ they imply new phenomena at the LHC scale

- RS models can probe the KK spectrum

- If R is large enough, M_D ~ TeV can be detected
(here the pp → g/q + G is tested)

with CMS detector, current limits on M_D can improve by more than a factor 3 even with low integrated luminosity and sub-optimal perfarmance

- techniques to evaluate background from future data-samples are in place and result are robust against many background sources

Discovery of extra-dimensional world would be a fundamental revolution in science

...CMS is ready to start looking to the extra-dimension world!

...not only my effort!

- I am indebted to co-authors of the work:

- *Leonardo Sala*
- (Univ. Milano Bicocca, INFN Milano Bicocca, Milano, Italy)

- *Marco Cardaci*
- (Univ. of Antwerp, Antwerp, Belgium)

- *Albert De Roeck*
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- *Ugur Emrah Surat*
- (Middle East Technical Univ, Turkey)

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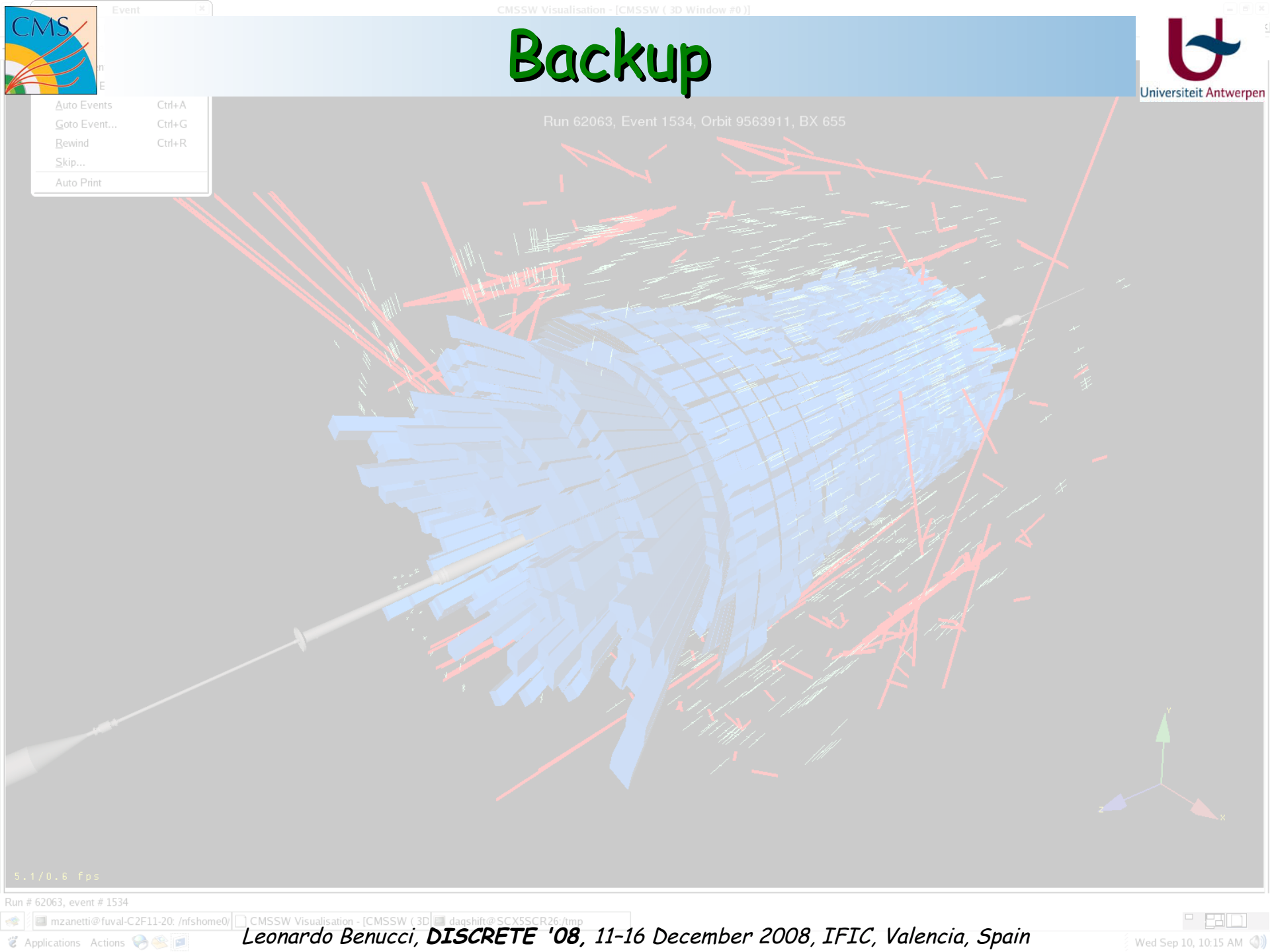
Backup


Event
Auto Events Ctrl+A
Goto Event... Ctrl+G
Rewind Ctrl+R
Skip...
Auto Print
CMSSW Visualisation - [CMSSW (3D Window #0)]
Run 62063, Event 1534, Orbit 9563911, BX 655
5.1/0.6 fps
Run # 62063, event # 1534

Also gauge fields live in extra-dim:

KK excitations of vector boson → shift of weak observables → limits on compatification radius R

LHC with 100 fb^{-1}: $R^{-1} > 16$ TeV, hep-ph/0204031

There should be a scalar massive field to set the size of warped extra-dim space: the radion

- Typically lighter than KK modes
- Couplings similar to Higgs.
- Can mix with Higgs through curvature-scalar coupling

→ Search for a direct radion production: gg-->r

Goldberger, Wise, 1999

Csaki, Graesser, Kribs, 1999

Profile likelihood estimator

$$S_{PL} = \sqrt{2}\left(n_{on} \ln \frac{n_{on}(1+\tau)}{n_{on}+n_{off}} + n_{off} \ln \frac{n_{off}(1+\tau)}{\tau(n_{on}+n_{off})} \right)^{1/2}$$

where $\tau = N_B / (\Delta N_B)^2$, $n_{off} = \tau N_B$, $n_{on} = N_S + N_B$

(see arXiv:physics/0702156v3)

W/Z ratio can be assumed constant