Z' searches: prospects for LHC Phase 2

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Outline

1. Introduction: Searches for heavy resonances at the LHC
   - Motivations for new physics
   - The CMS detector
   - Current results
   - LHC program for the next 20 years
   - Prospects
2. Present work
   - Kinematics of dielectron resonances
   - Studied properties
   - Event selection
   - Spin Measurement
   - A_{FB} Measurement
   - Production modes measurement (gg-$q\bar{q}$ fractions)
3. Conclusions

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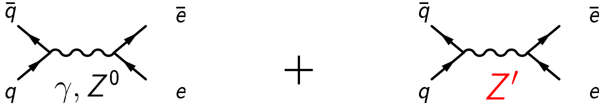
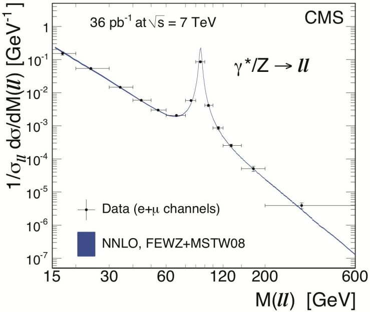
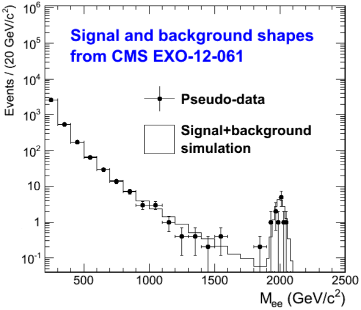
3. Conclusions

- Search for narrow heavy ($\geq$ 1 TeV) resonances decaying into a dielectron pair.
- Generic search also motivated by several theories beyond the Standard Model : Grand Unified Theories (Z'), Large Extra Dimensions (RS gravitons),...
- Main background : Drell-Yan process. Irreducible, interfers with the signal.
- Signature : new peak in the dilepton mass spectrum.



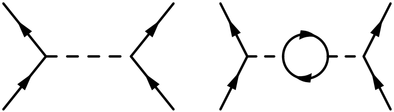




Should we still believe in new physics at the LHC?

- Searches for new physics (i.e. beyond Standard Model) started several decades ago.
- Up to now, despite many efforts, particle colliders didn't find any hint of it...
- The discovery of the scalar boson is an impressive achievement but (so far) doesn't show any deviation from the Standard Model predictions.
- Many BSM theories (e.g. SUSY) are quite tuned:
  *"It is very **natural** that we haven't seen it yet but there's a **strong motivation** that it might be discovered soon..."*

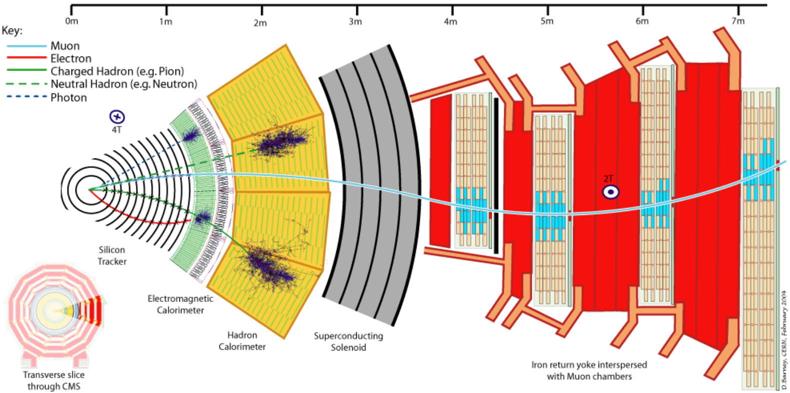
All this is quite depressing.
The only source of hope: loop corrections to the scalar boson.



$$\Delta m_H^2 = m_{1-loop}^2 - m_{tree}^2 = -\frac{|\lambda_t|^2}{8\pi^2}\Lambda_{cutoff}^2 + ... \quad \text{(top quarks)}$$

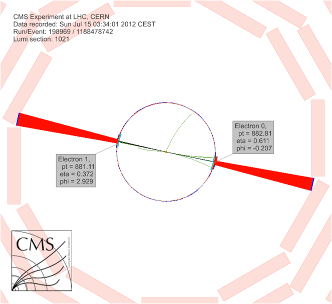
$\rightarrow$ **There should really be something at the TeV scale...**
What? Only ~~God~~ Chuck Norris knows...
One of the simplest things to look at: new peak in the dilepton mass spectrum

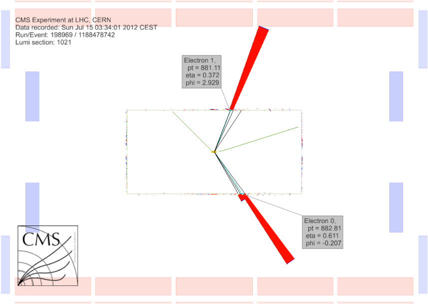
The CMS detector



Event selection

- Selection : 2 isolated high energy electrons.
- Key detectors : tracker, electromagnetic calorimeter.
- Challenge : control electron reconstruction, identification at very high E_T.



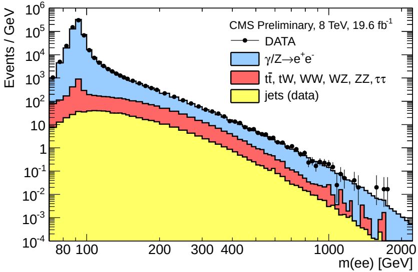


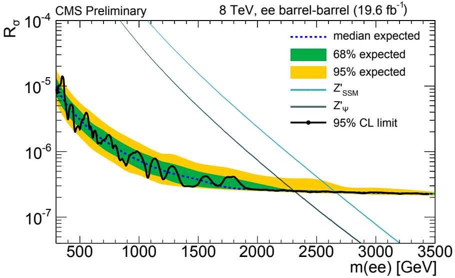
M_{ee}=1776 GeV/c^2

Current results

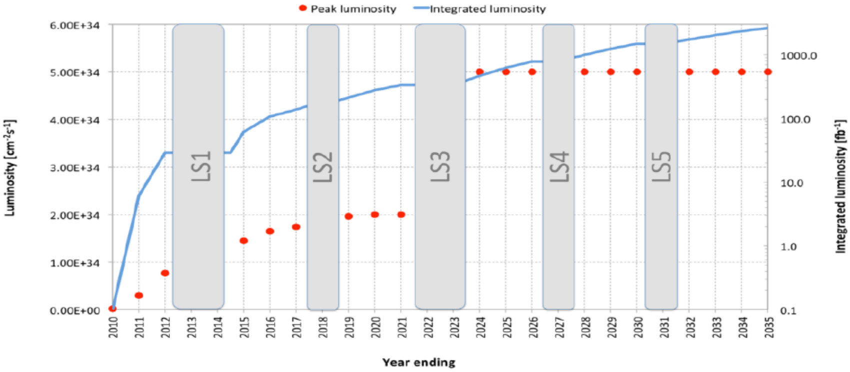
Latest results presented at Moriond 2013.

- Full 2012 dataset analyzed.
- No signal observed.
- Current limits of Z' ($\sqrt{s}$ =8 TeV, 20 fb^{-1}):
  M $\gtrsim$ 2.7 TeV for Z'_{SSM} @ 95% CL (ee only)



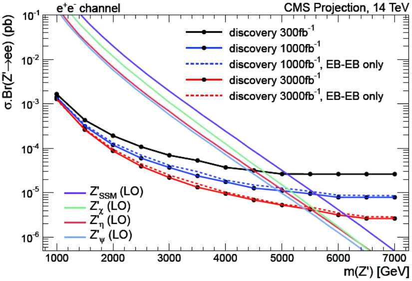


LHC program for the next 20 years



Name	Period	$\sqrt{s}$	Peak luminosity	$\int \mathcal{L}dt$	bunch spacing	Pile up
Run 1	2011-2012	7-8 TeV	7.7 10^{33} cm^{-2}s^{-1}	25 fb^{-1}	50 ns	20
Phase 0	2015-2017	13-14 TeV	1.6 10^{33} cm^{-2}s^{-1}	100 fb^{-1}	25 ns	40
Phase 1	2019-2021	14 TeV	2 10^{33} cm^{-2}s^{-1}	300 fb^{-1}	25 ns	50
Phase 2	2023->2030	14 TeV	5 10^{33} cm^{-2}s^{-1}	300 fb^{-1}	25 ns	140

Projections at 14 TeV:



Lower limit on $M_{Z'_{SSM}}$	$\sqrt{s}$ =8 TeV, 20 fb^{-1} **2.7 TeV** (@95% CL)	$\sqrt{s}$ =14 TeV, 300 fb^{-1} **5 TeV** (@5σ)	$\sqrt{s}$ =14 TeV, 3000 fb^{-1} **6.2 TeV** (@5σ)

- For limits settings, $\sqrt{s}$ more important than integrated luminosity.
  Cross section of a 4 TeV Z' enhanced by a factor ≈ 100 for $\sqrt{s} = 8 \to 14$ TeV
- Three events is enough to make a discovery.
  A discovery in the first months of 2015 is possible !
- In such a case, one wants to characterize the observed signal. → More events needed
  → **Here comes lumi.**

Present work

Philosophy of the present study:

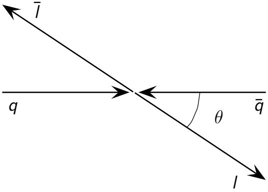
Assume we observe a new resonance at 3-4 TeV in 2015.

- What precision can we reach about its properties?
- Evolution of the uncertainty with lumi? i.e. **Is it worth to collect 3000 fb^{-1}?**
- Use techniques as model independent as possible as the nature of the signal is really unknown.

Practically:

- Take three benchmark models: Z'_ψ, Z'_{SSM}, RS graviton, M = 3 and 4 TeV.
- Compare results for 100 fb^{-1} at $\sqrt{s}$ = 13 TeV, and 300/3000 fb^{-1} at $\sqrt{s}$ =14 TeV.

A 2 body decay provides mainly two observables in addition to the invariant mass:



- $\cos\theta$: angle between the negative lepton and one of the incoming parton (taken to be the quark for $q\bar{q}$ annihilation). Experimentally, approximated by:

$$\cos\theta_{CS_{meas}} = \frac{p_{z,l\bar{l}}}{|p_{z,l\bar{l}}|} 2 \frac{E_l.p_{z,\bar{l}} - E_{\bar{l}}.p_{z,l}}{M_{l\bar{l}}\sqrt{M_{l\bar{l}}^2 + P_{T,l\bar{l}}^2}}$$

- $y_{l\bar{l}}$: The dilepton rapidity:

$$y_{l\bar{l}} = \frac{1}{2}\ln\frac{E_{l\bar{l}} + p_{z,l\bar{l}}}{E_{l\bar{l}} - p_{z,l\bar{l}}}$$

Studied properties

Spin determination:

- Spin affects $\cos\theta_{CS}$ through even terms
- Odd terms responsible for A_{FB}
- Different shape for gg ad $q\bar{q}$ production modes for spin 2.
- No gg production for a colorless spin 1.

resonance spin and production mode	$\frac{d\sigma}{d\lvert\cos\theta_{CS}\rvert}$
Spin 0 (gg or $q\bar{q}$ fusion)	$\propto 1$
Spin 1 ($q\bar{q}$ fusion)	$\propto 1+\cos^2\theta$
Spin 2 (gg fusion)	$\propto 1-\cos^4\theta$
Spin 2 ($q\bar{q}$ fusion)	$\propto 1-3\cos^2\theta+4\cos^4\theta$

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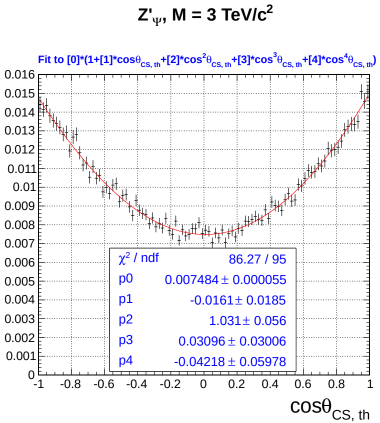

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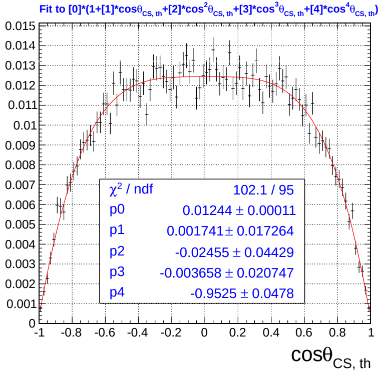
RS graviton (gg fusion), M = 3 TeV/c²



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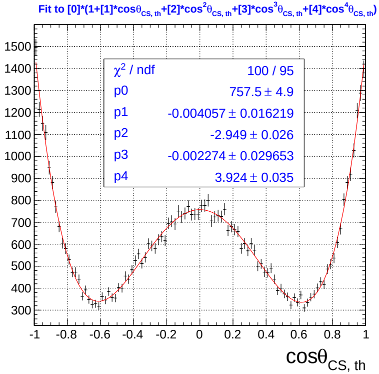
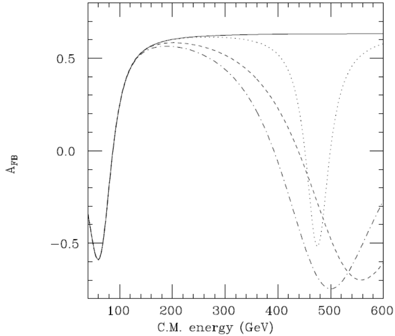


Forward backward asymmetry measurement A_{FB}

- $A_{FB} = \frac{\sigma_{\theta<\pi/2} - \sigma_{\theta>\pi/2}}{\sigma_{\theta<\pi/2} + \sigma_{\theta>\pi/2}}$
- Affects $\cos\theta_{CS}$ through odd terms.
- No A_{FB} for spin 0.



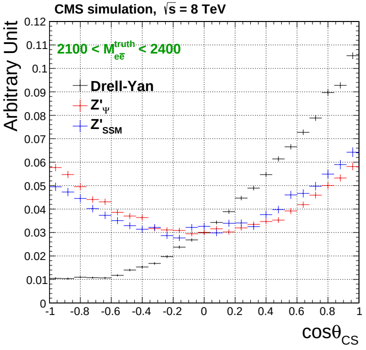


Figure: Left: A_{FB} vs mass for $d\bar{d} \to e\bar{e}$ for the Standard Model (solid line) and various 500 GeV Z' models (dashed lines). Right: $\cos\theta_{CS}$ for Drell-Yan events and two Z' models.

Production mode fractions

- gg ad $q\bar{q}$ production modes possible for a spin 0/2.
- $q\bar{q}$ only for a colorless spin 1.
- Production mode affects the rapidity distribution.

- 2 high energy electrons ($E_T > 35$ GeV)
- For the A_{FB} measurement only: opposite charge requirement (93% efficient for M=3 TeV).

$$\text{Acc} \times \text{Eff} = \frac{\text{Selected events with} |M_{reco} - M_{res}|/M_{gen} < 10\%}{\text{Nb of generated events}}$$

Model, mass	XS (pb)	Acc. × Eff.	Evts 100 fb^{-1}	Evts 100 fb^{-1} (Opp. sign)
RS Grav (c=0.1), M=3 TeV	6.1e-04 ± 1.3e-05	0.644	39	37
RS Grav (c=0.1), M=4 TeV	5.5e-05 ± 1.2e-06	0.637	4	3
Z'_{SSM} M=3 TeV	1.7e-03 ± 3.5e-05	0.495	84	78
Z'_{SSM} M=4 TeV	2.6e-04 ± 4.7e-06	0.372	10	9
Z'_{ψ} M=3 TeV	4.5e-04±1.0e-05	0.630	28	26
Z'_{ψ} M=4 TeV	5.1e-05±1.1e-06	0.596	3	3
DY M>3 TeV	1.2e-05 ± 2.2e-07	0,666	1	1
DY M>4 TeV	1.2e-06 ± 2.1e-08	0,673	0	0

- Low Acc. × Eff. for Z'_{SSM} because of the cut $|M_{reco} - M_{res}|/M_{res} < 10\%$
- **Background free region.**

Spin Measurement: Models considered and alternative hypotheses

Two benchmarks considered here: Z'_ψ, RS graviton (c=0.1).

- Same coupling to up and down quarks
- $A_{FB} = 0$ for both

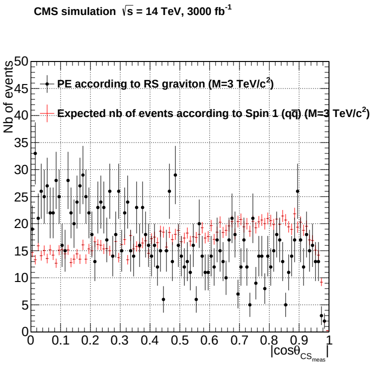
Hypothesis test using a likelihood ratio.
Alternative hypotheses:

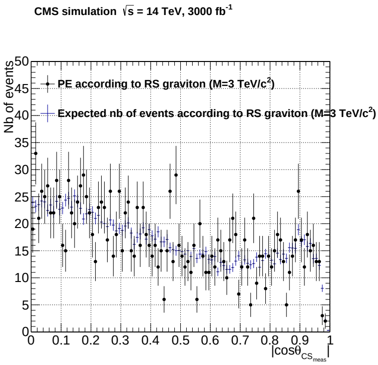
- Spin 0 (100% $q\bar{q}$, 50% gg-50%$q\bar{q}$, 100% gg) built by reweighting the $|\cos\theta_{CS,th}|$ distribution of RS gravitons events.
- Spin 1 (100% $q\bar{q}$), using the Z'_ψ distribution
- Spin 2 (100% $q\bar{q}$, 50% gg-50%$q\bar{q}$, 100% gg) built by reweighting the $|\cos\theta_{CS,th}|$ distribution of RS gravitons events.

N.B. Distributions used for the pseudo-experiments generation and for the likelihood calculation use disjoint events.

1. Generate n events according to H1 (RS graviton or Z' Psi).
2. Compute $Q = \ln \frac{\mathcal{L}_0}{\mathcal{L}_1} = \ln \frac{\prod_{i=1}^{n} p_0(\vec{x}_i)}{\prod_{i=1}^{n} p_1(\vec{x}_i)}$ where $\vec{x}_i = |\cos\theta_{CS}|$ **(1D)** or $(|\cos\theta_{CS}|, |y_{ee}|)$ **(2D)**.

1D





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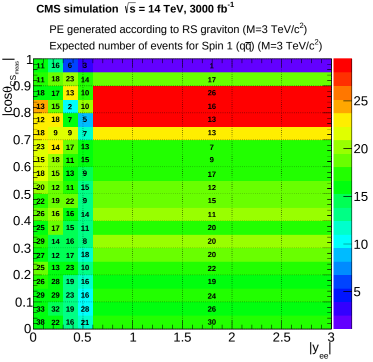
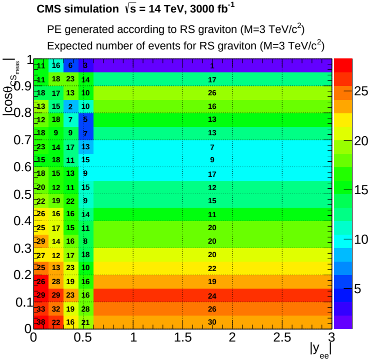
2D





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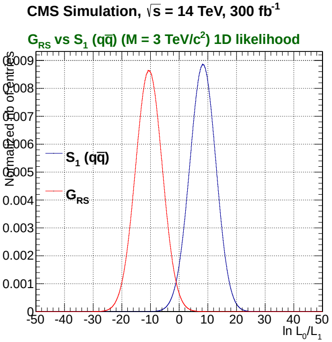
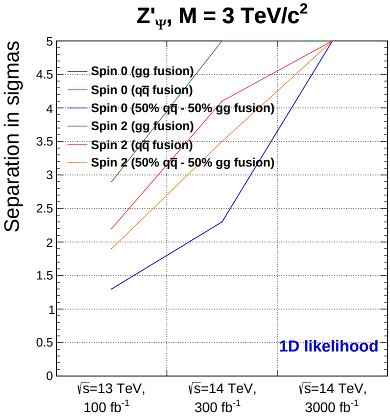
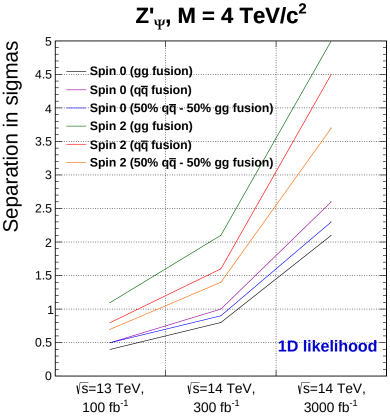
3. Do the same for events generated according to H0 (alternative hypothesis).
4. Repeat step 1-3 >1 million times and plot Q for the two scenarios (H0 and H1).
5. In the data H1 will be favoured compared to H0 by a confidence level CL_s given by:
   $$CL_s = \frac{\int_{-\infty}^{Q_{obs}} q_1 \, dQ}{\int_{-\infty}^{Q_{obs}} q_0 \, dQ}$$
6. For projections, take $Q_{obs} = Q_{mean}(H1\ true)$.
7. Separation in σ obtained by: $\sqrt{2}$ InverseErf$(1 - CL_s)$



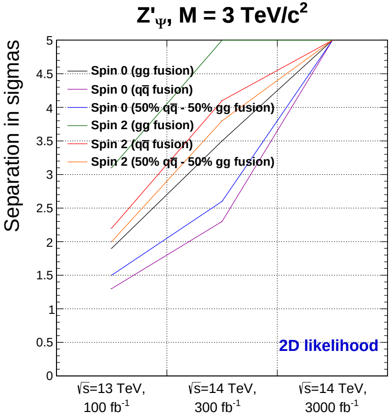
Spin Measurement: Results 1D

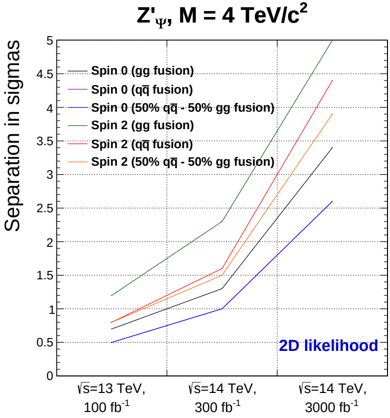




- 3000 fb^{-1} allows one to exclude all wrong spin hypotheses for a 4 TeV Z'_Ψ at $> 2\sigma$.
- 3000 fb^{-1} allows one to exclude all wrong spin hypotheses for a 3 TeV Z'_Ψ at $> 5\sigma$. Similar results for RS graviton.

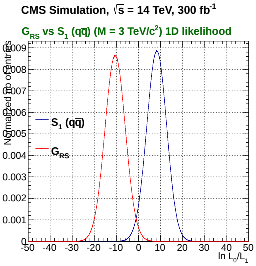
Spin Measurement: Results 2D

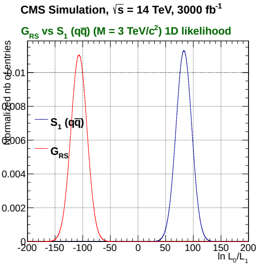


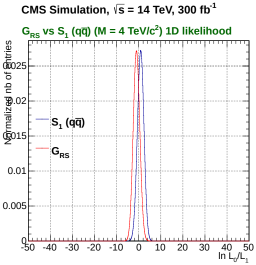


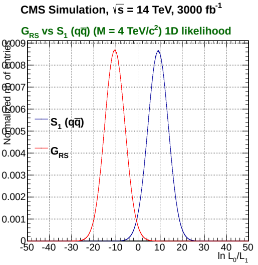
- Slight improvement compared to the 1d method. → Information better used. Similar results for RS graviton.

Spin measurement: Likelihood ratios 1D

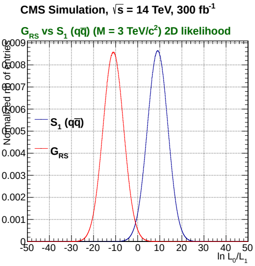


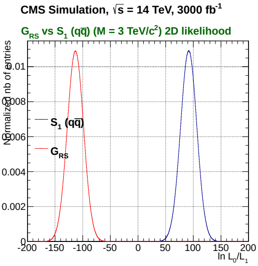


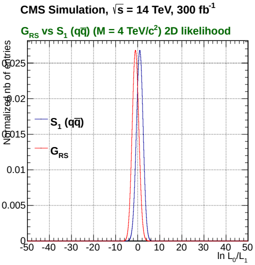


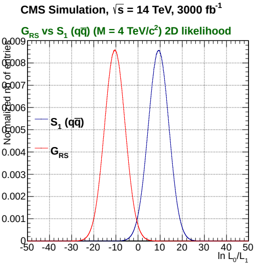


Spin measurement: Likelihood ratios 2D

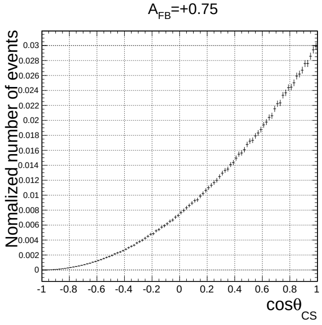


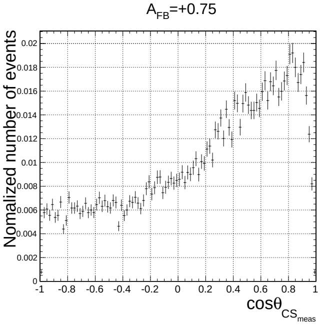






- Only non zero for a spin 1 or 2 resonance. (also 0 for spin 2 gravitons)
- Here focusing on spin 1 particle.
- Needs to distinguish the electron from the positron
- The $\cos\theta$ distribution for a spin 1 is $\propto 1 + \cos^2\theta + \frac{8}{3} A_{FB} \cos\theta$ (with $A_{FB} \in [-0.75, 0.75]$)
- Experimental $\cos\theta_{CS}$ distorted by ambiguity in quark direction determination.





A_{FB} measurement: Generalities (2)

- Only non zero for a spin 1 or 2 resonance. (also 0 for spin 2 gravitons)
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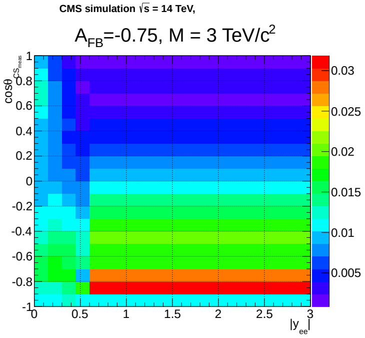
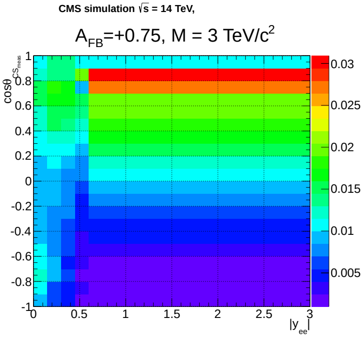
- Experimental $\cos\theta_{CS}$ distorted by ambiguity in quark direction determination. $\Longrightarrow |y_{ee}|$ **can improve the measurement.**





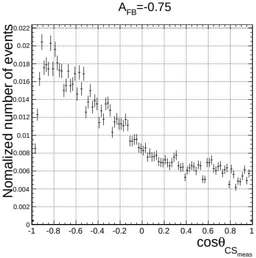
Quark direction better identified at high y_{ee}

1. Generate events according to the studied sample (Z'_ψ or Z'_{SSM})
2. Generate the $\cos\theta_{CS}$ distribution for a model with $A_{FB} = \pm 0.75$: $p_{A_{FB}=-1}(\cos\theta_{CS_{meas}})$, $p_{A_{FB}=+1}(\cos\theta_{CS_{meas}})$,
3. Find κ such that:

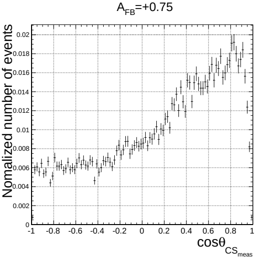
$$\kappa * p_{A_{FB}=-1}(\cos\theta_{CS_{meas}}) + (1-\kappa) * p_{A_{FB}=+1}(\cos\theta_{CS_{meas}})$$

maximizes the likelihood.

$\kappa\times$



$+\ (1-\kappa)\times$

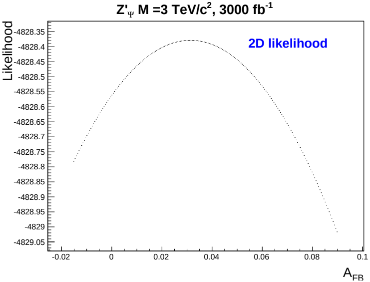


1. Generate events according to the studied sample (Z'_{Ψ} or Z'_{SSM})
2. Generate the $\cos\theta_{CS}$ distribution for a model with $A_{FB} = \pm 0.75$: $p_{A_{FB}=-1}(\cos\theta_{CS_{meas}})$, $p_{A_{FB}=+1}(\cos\theta_{CS_{meas}})$,
3. Find κ such that:

$$\kappa * p_{A_{FB}=-1}(\cos\theta_{CS_{meas}}) + (1-\kappa) * p_{A_{FB}=+1}(\cos\theta_{CS_{meas}})$$

maximizes the likelihood.

4. $A_{FB,meas} = \frac{3}{4}(2\kappa - 1)$ [1]



[1] see backups

1. Generate events according to the studied sample (Z'_Ψ or Z'_{SSM})
2. Generate the $\cos\theta_{CS}$ distribution for a model with $A_{FB} = \pm 0.75$: $p_{A_{FB}=-1}(\cos\theta_{CS_{meas}})$, $p_{A_{FB}=+1}(\cos\theta_{CS_{meas}})$,
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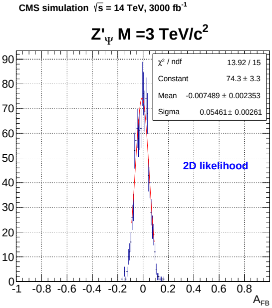
$$\kappa * p_{A_{FB}=-1}(\cos\theta_{CS_{meas}}) + (1-\kappa) * p_{A_{FB}=+1}(\cos\theta_{CS_{meas}})$$

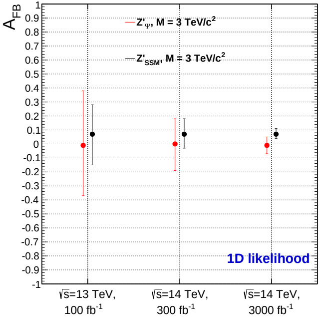
maximizes the likelihood.

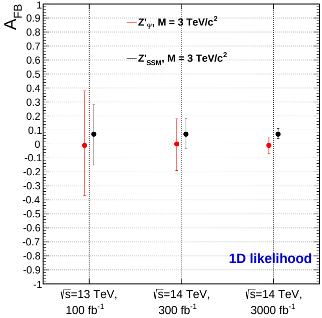
4. $A_{FB,meas} = \frac{3}{4}(2\kappa - 1)$
5. **Repeat the procedure 1000 times to find the median and the $\pm 1\sigma$ band.**



Same technique is applied for the 2D distributions $(\cos\theta_{CS_{meas}}, |y_{ee}|)$.

A_{FB} measurement: Results 1D

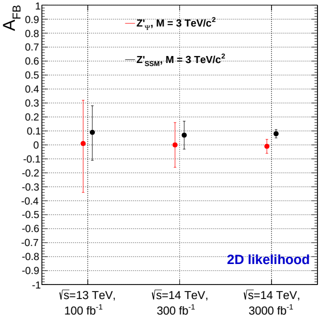


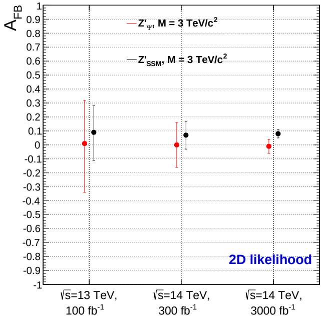


Predicted values:

	up quarks	down quarks	$\sqrt{s} = 13$ TeV pp collisions
Z'_{Ψ}	0	0	0
Z'_{SSM}	0.075	0.105	0.08
Drell-Yan M$>$ 3 TeV	0.595	0.625	0.60

(Results for M=4 TeV in the backups)





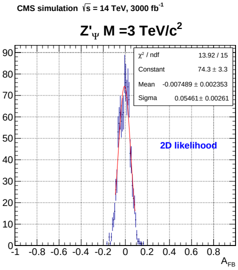
Predicted values:

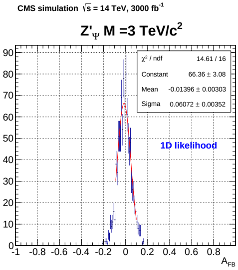
	up quarks	down quarks	$\sqrt{s} = 13$ TeV pp collisions
Z'_{ψ}	0	0	0
Z'_{SSM}	0.075	0.105	0.08
Drell-Yan M$>$ 3 TeV	0.595	0.625	0.60

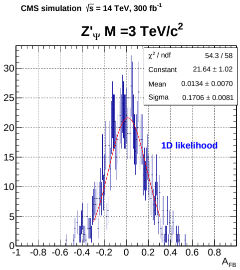
2D method improves precision by $\approx$10%.

(Results for M=4 TeV in the backups)

PE Distributions







Production modes measurement (gg-$q\bar{q}$ fractions)

- Angular distribution and rapidity distributions affected by production mode for spin 2.
- Only rapidity distributions affected by production mode for spin 0.
- Those fractions are mass dependent (related to the pdfs).
- Here, we focused on the measurement of the RS graviton $qq/q\bar{q}$ fractions for M = 3, 4 TeV/c^2.
- **Those fractions are also $\sqrt{s}$ dependent. This was neglected in the 13 TeV $\rightarrow$ 14 TeV extrapolation**

Procedure:

- same than for A_{FB} measurement. This time, κ runs from 0 (pure gg fusion) to 1 (pure $q\bar{q}$ fusion)

gg fraction measurement: results

1D

	100 fb^{-1} (13 TeV)	300 fb^{-1} (14 TeV)	3000 fb^{-1} (14 TeV)
R-S graviton (M = 3 TeV/c^2) 1D	$0.35^{+0.33}_{-0.32}$	$0.36^{+0.16}_{-0.15}$	$0.36^{+0.05}_{-0.05}$
R-S graviton (M = 4 TeV/c^2) 1D	$0.34^{+0.67}_{-0.34}$	$0.19^{+0.56}_{-0.19}$	$0.24^{+0.15}_{-0.16}$

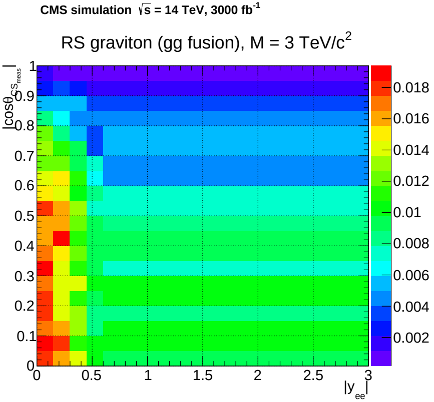
2D

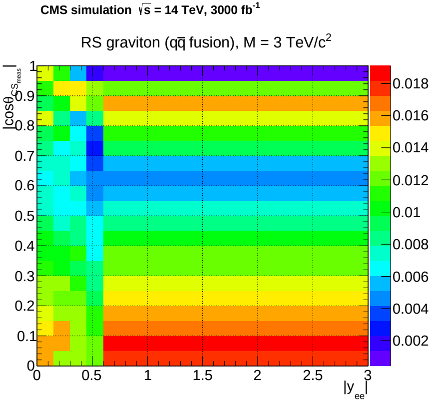
	100 fb^{-1} (13 TeV)	300 fb^{-1} (14 TeV)	3000 fb^{-1} (14 TeV)
R-S graviton (M = 3 TeV/c^2) 2D	$0.37^{+0.31}_{-0.30}$	$0.36^{+0.13}_{-0.13}$	$0.37^{+0.05}_{-0.04}$
R-S graviton (M = 4 TeV/c^2) 2D	$0.34^{+0.66}_{-0.34}$	$0.20^{+0.45}_{-0.20}$	$0.24^{+0.13}_{-0.15}$

Predicted values

RS graviton M = 3 TeV	0.38
RS graviton M = 4 TeV	0.25

gg fraction measurement: templates 2D





N.B. The drop at $|\cos\theta_{CS}| \approx 0.6$ and $|y_{ee}| > 0.6$ in the right distribution is an acceptance effect (one of the electrons often in the gap).

Conclusions

- The increase of the LHC beams energy in 2015 will strongly enhance the production cross sections of TeV particles
- The dielectron decay mode is a clean channel where a discovery could me made in the first months of the data taking.
- In such a case, the measurement of three properties were investigated: spin, A_{FB}, production mode.
- The expected separation and measurement uncertainties were computed for different scenarios covering the mass range to which the next LHC runs will be sensitive.
- The performances of a 1d method (based on $\cos\theta_{CS}$) were compared to a 2d method (based on $\cos\theta_{CS}$, $|y_{ee}|$).
- The second method leads to slightly better results although being more model dependent.
- **Precision strongly improved from 300 fb^{-1} $\rightarrow$ to 3000 fb^{-1}**

Stay tuned !

Afb formula

$$\begin{aligned}
&\kappa * p_{A_{FB}=-1} + (1-\kappa) * p_{A_{FB}=+1} \\
&\propto \kappa(1+\cos^2\theta + 2\cos\theta) + (1-\kappa)(1+\cos^2\theta + 2\cos\theta) \\
&\propto 1+\cos^2\theta + (4\kappa - 2)\cos\theta \\
&\propto 1+\cos^2\theta + \frac{8}{3}A_{FB}\cos\theta
\end{aligned}$$

Where the last equation comes from the fact that:

$$\sigma_F = K \times \int_0^{2\pi} d\phi \int_0^1 d\cos\theta(1+\cos^2\theta + \frac{8}{3}A_{FB}\cos\theta) = 2\pi K(\frac{4}{3} + \frac{4}{3}A_{FB})$$
$$\sigma_B = K \times \int_0^{2\pi} d\phi \int_{-1}^0 d\cos\theta(1+\cos^2\theta + \frac{8}{3}A_{FB}\cos\theta) = 2\pi K(\frac{4}{3} - \frac{4}{3}A_{FB})$$

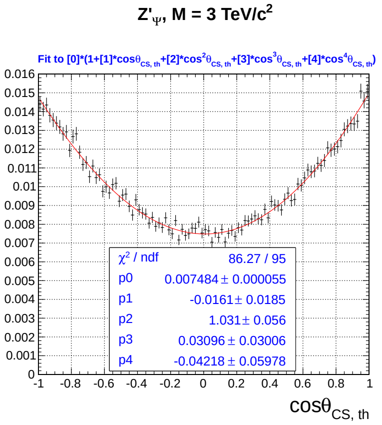
Hence

$$\frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = A_{FB}$$

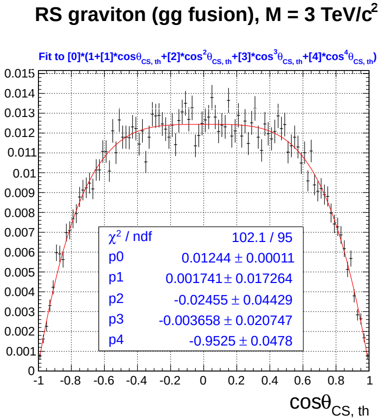
Therefore:

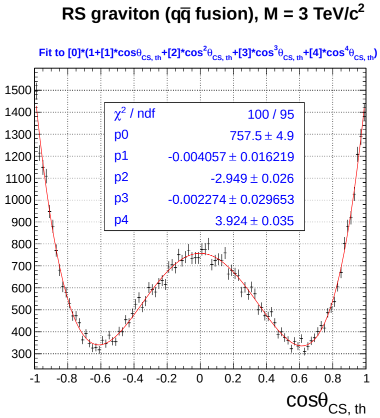
$$A_{FB} = \frac{3}{4}(2\kappa - 1)$$

Z'_ψ $\cos\theta_{CS,th}$ distribution

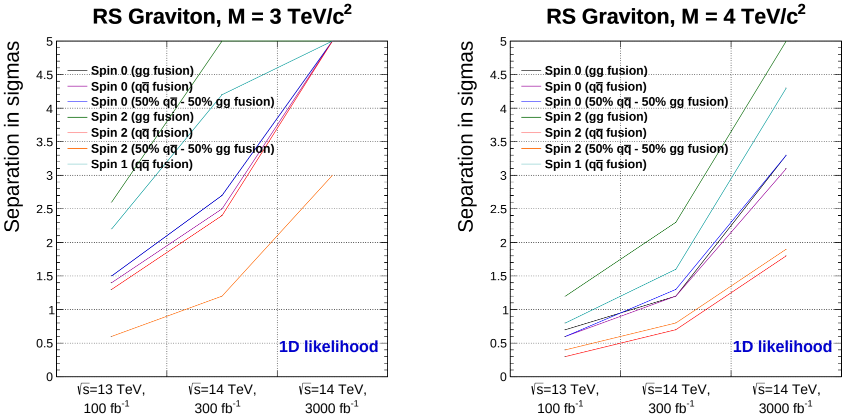


RS graviton: $\cos\theta_{CS,th}$ distributions for gg vs $q\bar{q}$

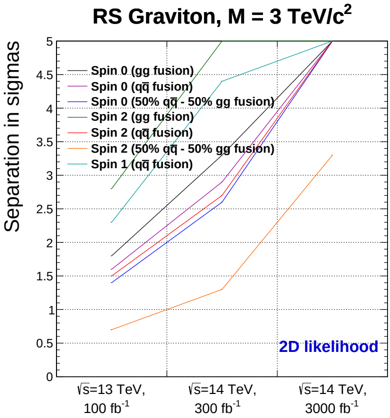


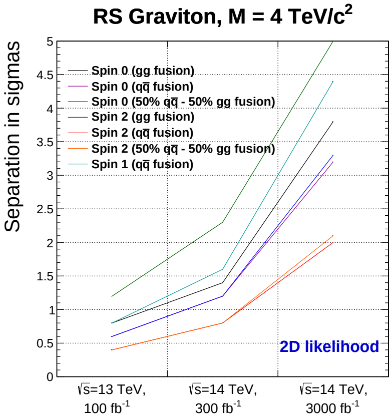


Left: $\propto 1 - \cos^4\theta_{CS,th}$
Right: $\propto 1 - 3\cos^2\theta_{CS,th} + 4\cos^4\theta_{CS,th}$


RS Graviton, M = 3 TeV/c2
Separation in sigmas
Spin 0 (gg fusion)
Spin 0 (qq̄ fusion)
Spin 0 (50% qq̄ - 50% gg fusion)
Spin 2 (gg fusion)
Spin 2 (qq̄ fusion)
Spin 2 (50% qq̄ - 50% gg fusion)
Spin 1 (qq̄ fusion)
1D likelihood
√s=13 TeV, 100 fb-1
√s=14 TeV, 300 fb-1
√s=14 TeV, 3000 fb-1
RS Graviton, M = 4 TeV/c2
Separation in sigmas
Spin 0 (gg fusion)
Spin 0 (qq̄ fusion)
Spin 0 (50% qq̄ - 50% gg fusion)
Spin 2 (gg fusion)
Spin 2 (qq̄ fusion)
Spin 2 (50% qq̄ - 50% gg fusion)
Spin 1 (qq̄ fusion)
1D likelihood
√s=13 TeV, 100 fb-1
√s=14 TeV, 300 fb-1
√s=14 TeV, 3000 fb-1

Spin Measurement: Results 2D





Spin Measurement: Results 1D

	100 fb^{-1} (13 TeV)	300 fb^{-1} (14 TeV)	3000 fb^{-1} (14 TeV)
RS grav (3 TeV) vs Spin 0 (gg), 1D	1.5	2.7	> 5
RS grav (3 TeV) vs Spin 0 (qqbar), 1D	1.4	2.5	> 5
RS grav (3 TeV) vs Spin 0 (qqbar-gg), 1D	1.5	2.7	> 5
RS grav (3 TeV) vs Spin 2 (gg), 1D	2.6	> 5	> 5
RS grav (3 TeV) vs Spin 2 (qqbar), 1D	1.3	2.4	> 5
RS grav (3 TeV) vs Spin 2 (qqbar-gg), 1D	0.6	1.2	3
RS grav (3 TeV) vs Spin 1 (qqbar), 1D	2.2	4.2	> 5
RS grav (4 TeV) vs Spin 0 (gg), 1D	0.7	1.2	3.3
RS grav (4 TeV) vs Spin 0 (qqbar), 1D	0.6	1.2	3.1
RS grav (4 TeV) vs Spin 0 (qqbar-gg), 1D	0.6	1.3	3.3
RS grav (4 TeV) vs Spin 2 (gg), 1D	1.2	2.3	> 5
RS grav (4 TeV) vs Spin 2 (qqbar), 1D	0.3	0.7	1.8
RS grav (4 TeV) vs Spin 2 (qqbar-gg), 1D	0.4	0.8	1.9
RS grav (4 TeV) vs Spin 1 (qqbar), 1D	0.8	1.6	4.3

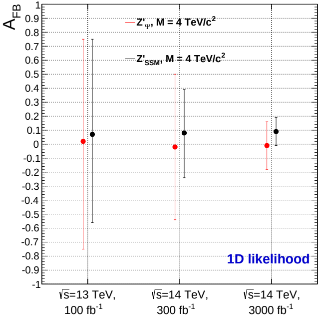
Z' Psi (3 TeV) vs Spin 0 (gg), 1D	1.3	2.3	> 5
Z' Psi (3 TeV) vs Spin 0 (qqbar), 1D	1.3	2.3	> 5
Z' Psi (3 TeV) vs Spin 0 (qqbar-gg), 1D	1.3	2.3	> 5
Z' Psi (3 TeV) vs Spin 2 (gg), 1D	2.9	> 5	> 5
Z' Psi (3 TeV) vs Spin 2 (qqbar), 1D	2.2	4.1	> 5
Z' Psi (3 TeV) vs Spin 2 (qqbar-gg), 1D	1.9	3.5	> 5
Z' Psi (4 TeV) vs Spin 0 (gg), 1D	0.4	0.8	2.1
Z' Psi (4 TeV) vs Spin 0 (qqbar), 1D	0.5	1.0	2.6
Z' Psi (4 TeV) vs Spin 0 (qqbar-gg), 1D	0.5	0.9	2.3
Z' Psi (4 TeV) vs Spin 2 (gg), 1D	1.1	2.1	> 5
Z' Psi (4 TeV) vs Spin 2 (qqbar), 1D	0.8	1.6	4.5
Z' Psi (4 TeV) vs Spin 2 (qqbar-gg), 1D	0.7	1.4	3.7

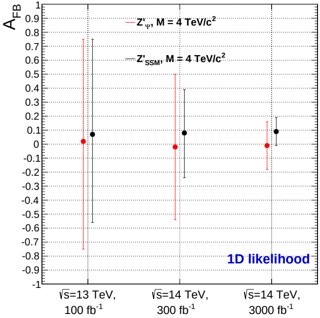
Spin Measurement: Results 2D

	100 fb^{-1} (13 TeV)	300 fb^{-1} (14 TeV)	3000 fb^{-1} (14 TeV)
RS grav (3 TeV) vs Spin 0 (gg), 2D	1.8	3.3	> 5
RS grav (3 TeV) vs Spin 0 (qqbar), 2D	1.6	2.9	> 5
RS grav (3 TeV) vs Spin 0 (qqbar-gg), 2D	1.4	2.6	> 5
RS grav (3 TeV) vs Spin 2 (gg), 2D	2.8	> 5	> 5
RS grav (3 TeV) vs Spin 2 (qqbar), 2D	1.5	2.7	> 5
RS grav (3 TeV) vs Spin 2 (qqbar-gg), 2D	0.7	1.3	3.3
RS grav (3 TeV) vs Spin 1 (qqbar), 2D	2.3	4.4	> 5
RS grav (4 TeV) vs Spin 0 (gg), 2D	0.8	1.4	3.8
RS grav (4 TeV) vs Spin 0 (qqbar), 2D	0.6	1.2	3.2
RS grav (4 TeV) vs Spin 0 (qqbar-gg), 2D	0.6	1.2	3.3
RS grav (4 TeV) vs Spin 2 (gg), 2D	1.2	2.3	> 5
RS grav (4 TeV) vs Spin 2 (qqbar), 2D	0.4	0.8	2
RS grav (4 TeV) vs Spin 2 (qqbar-gg), 2D	0.4	0.8	2.1
RS grav (4 TeV) vs Spin 1 (qqbar), 2D	0.8	1.6	4.4

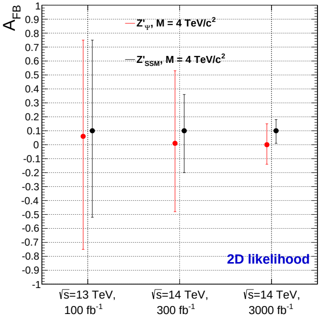
Z' Psi (3 TeV) vs Spin 0 (gg), 2D	1.9	3.5	> 5
Z' Psi (3 TeV) vs Spin 0 (qqbar), 2D	1.3	2.3	> 5
Z' Psi (3 TeV) vs Spin 0 (qqbar-gg), 2D	1.5	2.6	> 5
Z' Psi (3 TeV) vs Spin 2 (gg), 2D	3.1	> 5	> 5
Z' Psi (3 TeV) vs Spin 2 (qqbar), 2D	2.2	4.1	> 5
Z' Psi (3 TeV) vs Spin 2 (qqbar-gg), 2D	2	3.8	> 5
Z' Psi (4 TeV) vs Spin 0 (gg), 2D	0.7	1.3	3.4
Z' Psi (4 TeV) vs Spin 0 (qqbar), 2D	0.5	1.0	2.6
Z' Psi (4 TeV) vs Spin 0 (qqbar-gg), 2D	0.5	1.0	2.6
Z' Psi (4 TeV) vs Spin 2 (gg), 2D	1.2	2.3	> 5
Z' Psi (4 TeV) vs Spin 2 (qqbar), 2D	0.8	1.6	4.4
Z' Psi (4 TeV) vs Spin 2 (qqbar-gg), 2D	0.8	1.5	3.9

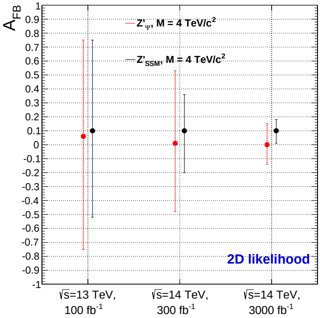
A_{FB} measurement, M=4 TeV: Results 1D





A_{FB} measurement, M=4 TeV: Results 2D





A_{FB} measurement: Tables

	100 fb^{-1} (13 TeV)	300 fb^{-1} (14 TeV)	3000 fb^{-1} (14 TeV)
Z'_ψ (M = 3 TeV/c^2) 1D	$-0.01^{+0.39}_{-0.36}$	$0.00^{+0.18}_{-0.19}$	$-0.01^{+0.06}_{-0.06}$
Z'_{SSM} (M = 3 TeV/c^2) 1D	$0.07^{+0.21}_{-0.22}$	$0.07^{+0.11}_{-0.10}$	$0.07^{+0.04}_{-0.03}$
Z'_ψ (M = 4 TeV/c^2) 1D	$0.02^{+0.73}_{-0.77}$	$-0.02^{+0.52}_{-0.52}$	$-0.01^{+0.17}_{-0.17}$
Z'_{SSM} (M = 4 TeV/c^2) 1D	$0.07^{+0.68}_{-0.63}$	$0.08^{+0.31}_{-0.32}$	$0.09^{+0.10}_{-0.10}$

Drell-Yan (1056 evts, M > 3 TeV/c^2) 1D $\quad 0.59^{+0.06}_{-0.06}$

	100 fb^{-1} (13 TeV)	300 fb^{-1} (14 TeV)	3000 fb^{-1} (14 TeV)
Z'_ψ (M = 3 TeV/c^2) 2D	$0.01^{+0.31}_{-0.35}$	$0.00^{+0.16}_{-0.16}$	$-0.01^{+0.05}_{-0.05}$
Z'_{SSM} (M = 3 TeV/c^2) 2D	$0.09^{+0.19}_{-0.20}$	$0.07^{+0.10}_{-0.10}$	$0.08^{+0.03}_{-0.03}$
Z'_ψ (M = 4 TeV/c^2) 2D	$0.06^{+0.69}_{-0.81}$	$0.01^{+0.52}_{-0.49}$	$-0.00^{+0.15}_{-0.14}$
Z'_{SSM} (M = 4 TeV/c^2) 2D	$0.10^{+0.65}_{-0.62}$	$0.10^{+0.26}_{-0.30}$	$0.10^{+0.08}_{-0.09}$

Drell-Yan (1056 evts, M > 3 TeV/c^2) 2D $\quad 0.62^{+0.04}_{-0.04}$

Predicted values

	up quarks	down quarks	$\sqrt{s} = 13$ TeV pp collisions
Z'_ψ	0	0	0
Z'_I	(no coupling)	-0.75	-0.75
Z'_{SSM}	0.075	0.105	0.08
Drell-Yan M> 3 TeV	0.595	0.625	0.60

Differences between median and predicted values (≈ 0.01) due to limited statistics used to build the pdf for generation and likelihood and to limited nb of PE generated (1000).

$$\cos\theta_{CS_{meas}} = \frac{p_{z,l\bar{l}}}{|p_{z,l\bar{l}}|} 2 \frac{E_l.p_{z,\bar{l}} - E_{\bar{l}}.p_{z,l}}{M_{l\bar{l}}\sqrt{M_{l\bar{l}}^2 + P_{T,l\bar{l}}^2}}$$